HEAVY ION FUSION REACTOR

"HIBLIC-I"

Conceptual Design of Heavy Ion Fusion Reactor

The Working Group on "HIBLIC-I"
Research Information Center
Institute of Plasma Physics, Nagoya University
(Received - Jan. 11, 1984)

IPPJ - 663  Jan. 1984

RESEARCH REPORT

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Abstract

An inertial confinement fusion reactor plant named HIBLIC-I (Heavy Ion Beam and Lithium Curtain) is proposed as a conceptual design, which has been worked out in the course of feasibility studies on the heavy ion fusion approach. An accelerator complex (RF linacs, storage rings and linear beam compressors) is adopted as the driver system to provide 6 beams of $^{208}$Pb$^+$ ions at 15GeV. Total beam energy of 4MJ with 160TW power is focused on a single shell, three-layered target of 4mm$^3$ sphere. This target will give an energy gain of 100. A cylindrical double walled reactor chamber is made of HT-9 ferritic steel with three layers of liquid Li flow inside. The innermost layer forms a Li curtain, which is effective to recover the cavity pressure down to $10^{-4}$ Torr within a repetition time of 1s. A thick upward flow of liquid Li plays the role of coolant and tritium breeder. A driver system is operated at the repetition rate of 10Hz and supplies beams for 10 reactor chambers, each of which is operated at 1Hz repetition. So, the plant yield of fusion power is 4000 MW$_{th}$, corresponding electric power output of 1.5GW.
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CHAPTER I INTRODUCTION

Heavy ion driven inertial confinement fusion (HIF) is one of the latest contenders in the controlled thermonuclear research. It is generally expected that the properties of the reactor concept required in this approach would be quite different from those we have met in the usual magnetic fusion approach. Furthermore, even within the category of inertial confinement fusion the characteristics of heavy ion beams differ in many respects from other candidates of energy drivers such as lasers or light ion beams.

Some of the advantages for HIF are given as:

a) high driver efficiency (20-30% attainable),
b) high repetition rate of accelerator,
c) high beam energy, which allows low beam current and good energy deposition in the target pellet,
d) high reliability in accelerator technology.

On the other hand, there seems to be the following disadvantages:

e) very big and complex accelerator system associated with relatively small reactor chambers,
f) large investment cost for construction,
g) big area of site and long beam lines to be handled.

Since 1980, a survey work on the feasibility of ion-beam driven inertial fusion schemes has been carried out in Japan under the auspices of "Working Group on Fusion Reactors" in the Research Information Center, IPP, Nagoya University, with the financial support from the Grant-in-Aid for Fusion Research, Ministry of Education, Science and Culture. After a two-year
preparatory investigation\textsuperscript{1)-3)}, the work was concentrated in
FY 1982-83 on the HIF feasibility study by means of making up a
reference system design consistent with the near future (within
a few tens of years) level of science and technology. This ef-
fort gives rise to a conceptual design of HIP power plant,
HIBLIC-I (Heavy Ion Beam and Lithium Curtain), which is still
very preliminary in many details but is useful enough to find
critical key issues to be developed in this approach and to make
its present status and future aspect much clearer. The design
study was carried out by a working group of about 30 members,
which was organized on the basis of interdisciplinary collabora-
tion in the country from major institutes for accelerator and
plasma-fusion research, universities and industries.

References
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Heavy Ion Beam (INS, Tanashi, Oct. 22, 1980; T. Katayama, ed.),
INS-NUMA-28, p.6 (1981), See also other papers in these Pro-
ceedings.
2) S. Hayakawa et al.; Presentation at the 3rd IAEA Technical
Committee Meeting and Workshop on Fusion Reactor Design and
Technology (Tokyo, Oct. 5-16, 1981)
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Heavy Ion Fusion (GSI, Darmstadt, Mar. 29-Apr. 2, 1982;
Acknowledgement

We wish to acknowledge Drs. S. Nagao, M. Kasuya, S. Kawasaki, Y. Kikuchi, K. Kitamura, J. Mizui, C. Namba, K. Nishina, T. Tazima, K. Yatsui and C. Yamanaka for valuable discussions and suggestions. Drs. I. Hofmann (GSI) and H. Eickhoff (GSI) are greatly acknowledged for their helpful discussions on the beam transport and multi-turn injection simulations. This work is financially supported by the Grant-in-Aid for Fusion Research from the Ministry of Education, Science and Culture.
2.1 HIBLIC-I Overview

A heavy ion fusion (HIF) system is composed of three parts: beam driver, target pellet and reactor cavity structure. In the case of HIBLIC-I (Heavy Ion Beam and Lithium Curtain; a plant layout is given in Fig. 2.2.1.) the driver system consists of a triple of RF-linacs (RFQ linacs, IH linacs and Alvarez linacs; with 4 steps of beam funneling procedure), storage rings (one accumulator ring and three buncher rings) and linear beam compressors (induction linacs). This accelerator complex provides 6 beams of $^{208}$Pb$^{41}$ ions at 15 GeV to be focused simultaneously on a target. Each beam carries 1.78 kA current with 25 ns pulse duration, i.e., the total incidence of energy on the target becomes 4 MJ, 160 TW per shot. Superconducting coils are used in most parts of the magnet systems to reduce power consumptions. The net efficiency of driver system is estimated to be 20 - 25 %.

The target pellet is designed in a rather conservative way as a single-shell three-layered (DT-fuel, Al-pusher and Pb-tamper) cryogenic hollow sphere of 4 mm in radius. (see Fig. 2.2.2) Target irradiation with 6 beams is found sufficient and tractable for a uniformity within 15 %. Owing to the large density difference between Al-layer and DT-layer, the target is stable with respect to the Rayleigh-Taylor instability., which might be dangerous in the initial phase of implosion. With 7.37 mg of DT fuel installed, the fusion parameters $\langle \rho R \rangle = 5.47$ g/cm$^2$, $T_i = 5.27$ keV are reached at a target implosion, and an energy gain of
100 is reasonably obtained on the basis of simulation results. An incident beam energy 4 MJ will release 400 MJ of fusion energy per shot.

It is required of a HIF reactor chamber that the cavity room should be a good vacuum for the incident beam propagation (as low residual pressure as $10^{-4}$ Torr needed) while the chamber walls have to be well protected against the pulsively repeated and heavily energetic loading caused by thermonuclear explosions. In the HIBLIC-I reactor concept the chamber is assumed roughly cylindrical in shape ($6 \text{ m} \times 10 \text{ m}$) with double wall structures made of HT-9 ferritic alloy, and the required features are furnished with three layers of liquid Li flow: an innermost free falling layer to form a Li curtain, a thin draining layer of Li on the surface of the first wall, and a thick upward Li flow between the two walls. (see Fig. 2.2.3) The Li curtain, which characterizes the present design, is 3 - 5 cm thick and is to be disrupted into small fragments at every target implosion. A continuous supply of low temperature Li which flows from the upper plenum will re-establish it quickly enough to prepare the vacuum condition for the next shot within a repetition time of 1 s. The first wall, being protected only by the disrupting curtain and the draining surface layer, is short-lived ($\sim 2$ FPY) and sacrificial, whereas the second wall stands well for a much longer lifetime ($\sim 30$ FPY) behind the thick ($\sim 1$ m) layer of upward Li flow, which plays the role of coolant and tritium breeder. In a reactor chamber 50 ton of liquid Li is circulating with inlet temperature 280 °C and outlet temperature 500 °C. The tritium breeding ratio is 1.65, the inventory being 5 kg. The tritium recovery from Li will be
performed outside the chamber system by means of yttrium metal getters. Any details of pellet fabrication factory and power generator system are not given in the present consideration.

Since the accelerator repetition rate (10 Hz) is ten times higher than the chamber cavity repetition (1 Hz), a single driver system is able to supply heavy ion beams successively for 10 reactor chambers. Therefore, the total thermonuclear fusion power yielded by HIBLIC-I plant becomes 4000 MW$_{\text{th}}$, and its net electric output power is estimated to be 1.5 GW.

2.2 Summary of Parameters

Main parameters of HIBLIC-I and its subsystems are summarized in Tables 2.2.1 - 2.2.4, and illustrated in Figs. 2.2.1 - 2.2.3.
Table 2.2.1 HIBLIC-I Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT thermal power</td>
<td>4000 MW</td>
</tr>
<tr>
<td>Gross thermal power</td>
<td>4700 MW</td>
</tr>
<tr>
<td>Gross electrical output</td>
<td>1800 MWe</td>
</tr>
<tr>
<td>Net electrical output</td>
<td>1500 MWe</td>
</tr>
<tr>
<td>Driver type</td>
<td>RF-Linac</td>
</tr>
<tr>
<td>Driver efficiency</td>
<td>25 Z</td>
</tr>
<tr>
<td>Ion species</td>
<td>( ^{208} \text{Pb}^+ )</td>
</tr>
<tr>
<td>Ion energy</td>
<td>15 GeV</td>
</tr>
<tr>
<td>Beam energy</td>
<td>4 MJ</td>
</tr>
<tr>
<td>Beam power</td>
<td>160 TW</td>
</tr>
<tr>
<td>Driver repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>No. of beams/cavity</td>
<td>6</td>
</tr>
<tr>
<td>Current intensity/beam</td>
<td>1.78 KA</td>
</tr>
<tr>
<td>Cavity pressure at RT</td>
<td>( 10^{-4} ) Torr</td>
</tr>
<tr>
<td>Target</td>
<td>Pb-Al-DT</td>
</tr>
<tr>
<td>Target mass/target</td>
<td>7.37 mg</td>
</tr>
<tr>
<td>Target yield</td>
<td>400 MJ</td>
</tr>
<tr>
<td>Target gain</td>
<td>100</td>
</tr>
<tr>
<td>Target shot rate/cavity</td>
<td>1 Hz</td>
</tr>
<tr>
<td>No. of cavity</td>
<td>10</td>
</tr>
<tr>
<td>Coolant and breeder</td>
<td>Li</td>
</tr>
<tr>
<td>Maximum coolant temp.</td>
<td>500°C</td>
</tr>
<tr>
<td>Tritium breeding ratio</td>
<td>1.65</td>
</tr>
<tr>
<td>Tritium inventory</td>
<td>5 kg</td>
</tr>
<tr>
<td>Structural material</td>
<td>HT-9</td>
</tr>
<tr>
<td>First wall (Sacrificial wall) protection scheme</td>
<td>Li-Curtain</td>
</tr>
<tr>
<td>Max. dpa rate in 1st wall</td>
<td>36.6/FPY</td>
</tr>
<tr>
<td>Max. dpa rate in 2nd wall</td>
<td>0.91/FPY</td>
</tr>
<tr>
<td>Life time of 1st wall</td>
<td>2 FPY</td>
</tr>
<tr>
<td>Life time of 2nd wall</td>
<td>30 FPY</td>
</tr>
<tr>
<td>Wall loading (1st wall)</td>
<td>5 MW/m²</td>
</tr>
</tbody>
</table>
### Table 2.2.2 HIBLIC-I Target Parameters

**Pellet Initial State**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet radius</td>
<td>$r_t = 4 \text{ mm}$</td>
</tr>
<tr>
<td>Tamper (Pb) thickness</td>
<td>$\Delta r_{\text{Pb}} = 75 \mu\text{m}$</td>
</tr>
<tr>
<td>Tamper (Pb) mass</td>
<td>$m_{\text{Pb}} = 170 \text{ mg}$</td>
</tr>
<tr>
<td>Pusher (Al) thickness</td>
<td>$\Delta r_{\text{Al}} = 410 \mu\text{m}$</td>
</tr>
<tr>
<td>Pusher (Al) mass</td>
<td>$m_{\text{Al}} = 223 \text{ mg}$</td>
</tr>
<tr>
<td>Fuel (DT) thickness</td>
<td>$\Delta r_{\text{DT}} = 270 \mu\text{m}$</td>
</tr>
<tr>
<td>Fuel (DT) mass</td>
<td>$m_{\text{DT}} = 7.37 \text{ mg}$</td>
</tr>
<tr>
<td>Void radius</td>
<td>$r_v = 3.24 \text{ mm}$</td>
</tr>
</tbody>
</table>

**Compressed Fuel**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature at center</td>
<td>$T_i = 5.27 \text{ KeV}$</td>
</tr>
<tr>
<td>Fusion parameter</td>
<td>$&lt;\rho R&gt; = 5.47 \text{ g/cm}^2$</td>
</tr>
<tr>
<td>Density (Average)</td>
<td>$\rho = 3.06 \times 10^2 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>Radius</td>
<td>$R = 179 \mu\text{m}$</td>
</tr>
<tr>
<td>Compression rate</td>
<td>$R_c = 1,400$</td>
</tr>
</tbody>
</table>

**Pusher (Al) at max. compression**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Average)</td>
<td>$\rho_{\text{Al-C}} = 1.20 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T_{\text{Al-C}} = 100 \text{ eV}$</td>
</tr>
<tr>
<td>Kinetic Energy (MeV/u)</td>
<td>0.3</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Stack Factor</td>
<td>2</td>
</tr>
<tr>
<td>Dilution Factor</td>
<td></td>
</tr>
<tr>
<td>( \epsilon_x ) (mm-mrad)</td>
<td>27.19</td>
</tr>
<tr>
<td>( \epsilon_y ) (mm-mrad)</td>
<td>27.19</td>
</tr>
<tr>
<td>Bunching Factor</td>
<td>0.99</td>
</tr>
<tr>
<td>Bunch Length</td>
<td></td>
</tr>
<tr>
<td>Momentum Spread</td>
<td>( \frac{\text{MeV}}{\text{m}} )</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>( 32 \times 10^{-3} )</td>
</tr>
<tr>
<td>Revolution Time (us)</td>
<td>35</td>
</tr>
<tr>
<td>Momentum Beam</td>
<td></td>
</tr>
<tr>
<td>Residence Time (us)</td>
<td>173</td>
</tr>
<tr>
<td>&quot;coulomb shift due to space charge&quot;</td>
<td>0.174</td>
</tr>
</tbody>
</table>

Table 2.2.3 HIBLIC-I Driver Line Up
Fig. 2.2.3 Overview of HIBLIC-I Reactor
### Table 2.2.4 HIBLIC-I Chamber Parameters

**CAVITY**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron &amp; gamma energy/shot</td>
<td>244 MJ</td>
</tr>
<tr>
<td>X-ray &amp; debris energy/shot</td>
<td>156 MJ</td>
</tr>
<tr>
<td>Cavity shape</td>
<td>cylindrical</td>
</tr>
<tr>
<td>Cavity (2nd wall) diameter</td>
<td>6 m</td>
</tr>
<tr>
<td>Height at center</td>
<td>10 m</td>
</tr>
<tr>
<td>Li-curtain radius</td>
<td>1 m</td>
</tr>
<tr>
<td>Height</td>
<td>5 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>5 cm</td>
</tr>
<tr>
<td>Velocity</td>
<td>6 m/sec</td>
</tr>
<tr>
<td>1st wall (sacrificial) radius</td>
<td>2 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>1 cm</td>
</tr>
<tr>
<td>Material</td>
<td>HT-9</td>
</tr>
<tr>
<td>Cooling &amp; breeding blanket material</td>
<td>Li</td>
</tr>
<tr>
<td>Thckness</td>
<td>1 m</td>
</tr>
<tr>
<td>Bottom region Li thickness</td>
<td>1 m</td>
</tr>
<tr>
<td>Weight of Li in cavity</td>
<td>50 t</td>
</tr>
<tr>
<td>Number of beam penetrations</td>
<td>6</td>
</tr>
<tr>
<td>Ratio of beam penetration area to curtain and wall surface</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Pressure in Li-curtain just before shot</td>
<td>$10^{-4}$ Torr</td>
</tr>
</tbody>
</table>

**2nd WALL**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural material</td>
<td>HT-9</td>
</tr>
<tr>
<td>Inside radius</td>
<td>3 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>10 cm</td>
</tr>
</tbody>
</table>

**REFLECTOR**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural material</td>
<td>90% HT-9 + 10% Li</td>
</tr>
<tr>
<td>Coolant</td>
<td>Li</td>
</tr>
<tr>
<td>Inside radius</td>
<td>3.1 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>40 cm</td>
</tr>
</tbody>
</table>

**SHIELD**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural material</td>
<td>Concrete</td>
</tr>
<tr>
<td>Coolant</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>Inside radius</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>3 m</td>
</tr>
</tbody>
</table>

**Li-COOLANT (including Li-curtain)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature</td>
<td>280°C</td>
</tr>
<tr>
<td>Temperature at Bottom</td>
<td>350°C</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>470°C</td>
</tr>
</tbody>
</table>
CHAPTER III  TARGET

3.1 Summary

The purpose of this chapter is to design the target for heavy ion beams. The target gain of 100 is required from the point of view of the output power from the fusion reactor. The target gain depends strongly on the beam quality of the energy driver. Here the atomic number $Z_b$, atomic weight $A_b$ and particle energy $e_p$ of the heavy ion beam as an energy driver are supposed respectively to be $Z_b = 80$, $A_b = 200$ and $e_p = 15$GeV. In order to reduce the beam current in the reactor cavity, and in order to realize the uniform irradiation of beams on the target surface, a finite number of beams must be supplied to the target. But from the point of view of the simple structure of the reactor, the beams are hoped to reduce their number as small as possible. In this study, 6 beams are chosen for the most preferable beam number.

If the beam radius is $r_b = 3.2\text{mm}$ for the target radius of $r_t = 4\text{mm}$, and the intensity distribution of a beam is like a double step type (in reality, flat top Gaussian), it is shown that the inhomogeneity of the radiation beam intensity on the target surface is less than 15%. With this order of irradiation inhomogeneity, the target is expected to do implosion in an approximately spherically symmetric way. In view of the simple interaction between the beam ion and the target plasma, the target structure is chosen to be simple; cryogenic hollow shell target which consists of three layers of lead (Pb), aluminium (Al) and deuterium-
tritium (DT) fuel. The materials of the target except the fuel have to have weak induced radio-activities and be compatible with the liquid lithium as the coolant of the reactor (as well as the breeder of tritium). The lead and aluminium are preferable materials which satisfy the conditions described above. The heavy Pb layer plays a role of tamper. The density of Al layer as the pusher is initially 14.7 times larger than that of the solid fuel. Owing to this large density difference between the Al layer and the fuel layer, the target is stable with respect to the Rayleigh-Taylor instability for the initial extremely strong acceleration. The input beam energy of 4MJ can ignite the DT reactions in the target and the thermal output energy of about 400MJ is expected to be released from the target.

3.2 Beam Irradiation on Target

In order to supply the beam energy of 4MJ with the particle energy of 15GeV into the target, the number of beams is necessarily more than 6. On the other hand, the reactor system including pellet supply, evacuation pump, coolant inlet and outlet etc. requires some spaces at the ceiling and bottom of the reactor cavity. The total area of holes through which ion beams are lead into the reactor cavity is hoped to be small. From these points of view, the number of beams is hoped to be small. In this design, the number of beams is chosen as 6. The irradiation inhomogeneity of the six beams on the target surface is examined here.
3.2.1 Inhomogeneity of Beam Irradiation

Beam particles are hoped to impinge on the target in a spherically symmetric way. Thus the irradiation method of 6 beams on the target is chosen as shown in Fig. 3.2.1. The target is located at the center 0. Each beam impinges on the target normally to the surface of the hexahedron. The angle between the vertical line and a beam, for example the angle AOP, is 54.7 degrees. Of course the angle between the nearest beams is 90 degrees. The target surface on which beams are impinging is illustrated in Fig. 3.2.2. A relation between the target radius \( r_t \) and the beam radius \( r_b \) with which any part of the area on the target surface is irradiated by at least one beam but the overlap regions by two beams is least on the surface (no region is overlapped by three or more beams) is given by

\[
r_b = r_t \cos 35.3^\circ = 0.816r_t .
\]  

(3.2.1)

If \( r_t \) is chosen as 4mm, then \( r_b \) becomes 3.26mm. But the inhomogeneity of the beam intensity on the target surface is too strong when the six beams with \( r_b = 3.3 \)mm, inside of which the beam intensity is homogeneous, impinge on the target with \( r_t = 4 \)mm. In Fig. 3.2.3., \( a = r_t \sin 35.3^\circ = 0.578r_t = 2.31 \)mm, \( b = r_b - a = 0.95 \)mm, \( r_i = a - b = 1.36 \)mm, \( r_0 = (r_b^2 - r_i^2)^{1/2} = 3.76 \)mm. Now the intensity distribution \( P_b \) of a beam is chosen like double steps as shown in Fig. 3.2.4. Then the distributions of the beam intensity \( I_a \) deposited on the surface \( (I_a = P_b \cos \theta, \theta \) being the incident angle)
of the beam on the target surface) are shown in Fig. 3.2.5(a) and (b), respectively, along the two lines on EB and EQ in Fig. 3.2.3. Locally \( I_a \) deviates more than ten per cent from \( I_E \) (at E) but the dispersion of \( I_a \) is less than ten per cent.

3.2.2 Decrease in Pellet Gain Due to Inhomogeneity of Beam Irradiation

In our research group, there is no three-dimensional hydrodynamic simulation code to investigate the effects of inhomogeneities on pellet gain. Two-dimensional simulations suggest that the temperature inhomogeneity of the pusher due to the inhomogeneity of beam-energy deposition is expected to be less than \( 10^{-3} \) in order to obtain a high pellet gain. Even in a spherically symmetric implosion motion of the target, the deviation of incident angles of beam particles on the target surface and the spread of particle energies induce the reduction in the pellet gain\(^1\). Owing to 18% of the maximum fluctuation of the irradiated beam intensity appearing in Fig. 3.2.5(b), the effective beam energy \( E_e \) in the total beam energy \( E_b \) of 4MJ is considered to reduce to 2.25MJ.

References


3.3 Target Structure

A target structure is proposed for the heavy ion beam of \( Z_b = 80, A_b = 200, \epsilon_p = 15 \text{ GeV} \) and \( E_e = 2.25 \text{ MJ} \). Since the target has an enough high hydrodynamic efficiency because of the cannon ball type of implosion, the target is a single shell, cryogenic hollow one.

3.3.1 Tamper and Pusher

As the metal layers for the tamper and pusher of the pellet, the lead (Pb) and aluminum (Al) are chosen, respectively. Radioactivities of these substances activated by high energy neutrons are weak or half lives are short. These metals do not react with the liquid lithium which flows inside the reactor wall as the coolant of the reactor and the breeder of tritium. The densities of Pb, Al and solid DT are \( \rho_{\text{Pb}} = 11.3 \text{ g/cm}^3 \), \( \rho_{\text{Al}} = 2.79 \text{ g/cm}^3 \) and \( \rho_{\text{DT}} = 0.19 \text{ g/cm}^3 \), which are shown in Fig. 3.3.1. These large density differences may prevent the pellet implosion from the Rayleigh-Taylor instability.\(^1\)

The stopping power of the ion beam in the metal is expressed as\(^2\)

\[
- \frac{dE}{dr} = \frac{4e^2 n Z}{m_e v_p^2} \epsilon_e^2 \left[ \ln \left( \frac{2m_e v_p^2}{v_p^2} \right) - \ln 1 - \ln (1 - B^2) - B^2 \right]. (3.3.1)
\]

Here \( E \) is the particle energy of the ion beam, \( r \) is the radius, \( -e \) is the electron charge, \( n \) is the number density of the metal ion, \( Z \) is the atomic number of the metal, \( m_e \) is the electron mass,
$v_p$ is the particle velocity of the ion beam, $q_e$ is the effective charge of the beam particle in the metal, $I$ is the average ionization potential of the metal and $B = \frac{v_p}{c}$, $c$ being the light speed. The average ionization potential is estimated by

$$I = 9.1 \times Z \times (1 + 1.9 \times Z^{-2/3}) \text{ (eV)} .$$  \hspace{1cm} (3.3.2)$$

With respect to the effective charge, the approximate equation

$$q_e = Z_p \left[ 1 + \left( \frac{0.45 \times 3.6 \times 10^8 / v_p}{Z_p} \right)^{1/0.6} \right]^{-0.6}$$ \hspace{1cm} (3.3.3)$$
is used.\textsuperscript{3) Equation (3.3.1) is rewritten by}

$$\frac{dE}{dr} = - S_m(E) .$$ \hspace{1cm} (3.3.4)$$

The suffix $m$ is replaced by Pb for the lead layer and by Al for the aluminum layer. The thickness $\delta_{Pb}$ and $\delta_{Al}$ of the Pb and Al layers are obtained respectively by

$$\delta_{Pb} = \int_{c'e_p}^{e_p} \frac{dE}{S_{Pb}} ,$$ \hspace{1cm} (3.3.5)$$

$$\delta_{Al} = \int_{0}^{c'e_p} \frac{dE}{S_{Al}} ,$$ \hspace{1cm} (3.3.6)$$

where $c'$ is the rate of particle energy of the beam deposited in the Al layer. If $c'$ is chosen as 0.8 (for $e_p = 15$ GeV), eqs. (3.3.5) and (3.3.6) lead to

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\[
\delta_{\text{Pb}} = 0.075 \text{ mm}, \quad (3.3.7) \\
\delta_{\text{Al}} = 0.410 \text{ mm}, \quad (3.3.8)
\]

The stopping powers \(\frac{dE}{dx}\) in the Pb tamper and in the Al pusher are shown in Fig. 3.3.2 versus the depth \(x\) from the target surface. The target radius is chosen as \(r_t = 4 \text{ mm}\). Since the temperature inhomogeneity of the pusher is more than ten per cent, the target radius \(r_t\) is chosen to be relatively small from the point of view of spherically symmetric implosion.\(^4\) If the implosion motion is completely spherically symmetric, the optimum target size is larger than \(r_t = 4 \text{ mm}\).\(^5\) With \(r_t = 4 \text{ mm}\), the masses of Pb and Al layers are respectively

\[
M_{\text{Pb}} = 4\pi r_t^2 \rho_{\text{Pb}} \delta_{\text{Pb}} = 170 \text{ mg}, \quad (3.3.9) \\
M_{\text{Al}} = 4\pi r_t^2 \rho_{\text{Al}} \delta_{\text{Al}} = 213 \text{ mg}, \quad (3.3.10)
\]

### 3.3.2 Implosion Velocity

Let us assume that after the beam energy \(E_e\) is poured into the Al layer homogeneously and instantaneously at the initial time, the Al layer adiabatically and homogeneously expands. The final implosion velocity of the fuel in the target is derived as\(^5\)

\[
u' = \left[ \frac{2C_{\text{Al}} E_e \left[ 1 - (3r_t^2 \delta_{\text{Al}} / (r_t^3 - r_{DT}^3))^{\gamma-1} \right]}{M_{\text{DT}} + M_{\text{Ale}} + M_{\text{DT}}^2 / M_{\text{Pb}}} \right]^{1/2}, \quad (3.3.11)
\]

where \(C_{\text{Al}}\) is the rate of beam energy deposition in the Al layer and

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The fuel radius \( r_{DT} \) is related with the fuel mass \( M_{DT} \) through

\[
M_{DT} = 4\pi r_{DT}^3 \rho_{DT}/3 = 7.96 \times 10^2 r_{DT}^3 \quad (r_{DT} : \text{m}, M_{DT} : \text{kg}). \quad (3.3.12)
\]

The implosion velocity \( u' \) derived from eq. (3.3.11) is optimistic and divided by a correction factor 2.11, i.e., \( u = u'/2.11 \).

### 3.3.3 Output Thermal Energy

After the fuel collides with itself at the target center, the ion temperature \( T_i \) of the fuel at the central part and the fusion parameter \( \langle \rho R \rangle \) are expected to reach

\[
T_i = 37 \times (u/10^7)^{2.2} \times T_0^{-0.15} \times M^{0.84}, \quad (3.3.13)
\]

\[
\langle \rho R \rangle = 7.1 \times 10^{-2} \times (u/10^7)^{1.7} \times T_0^{-0.40} \times M^{0.56} \times M_{DT}^{-0.33}. \quad (3.3.14)
\]

In eq. (3.3.14), \( \langle \rho R \rangle \) is defined by

\[
\langle \rho R \rangle = \int_0^R 4\pi r^2 \rho \, dr, \quad (3.3.15)
\]

where \( \rho \) is the fuel density and \( R \) is the final radius of the fuel. In eqs. (3.3.13) and (3.3.14),

\[
M = M_{DT} + M_{Al}/3, \quad (3.3.16)
\]

and the units are used here as \( T_i(\text{keV}), \langle \rho R \rangle (\text{g/cm}^2), u(\text{cm/s}), \)
M(g), M_{DT}(g) and the fuel temperature at the final stage of implosion T_0(K). Now we assume that T_0 = 1000 K. The average reaction rate Y is given by

\[ Y = \frac{\langle \rho R \rangle \langle \sigma v \rangle}{2\sqrt{3} km \cdot T_i^2 + \langle \rho R \rangle \langle \sigma v \rangle}, \]  

(3.3.17)

where k is the Boltzmann constant and the ion mass is m_i = 4.18 \times 10^{-24} g. The fusion reaction rate parameter \langle \sigma v \rangle is approximated by

\[ \langle \sigma v \rangle = 3.68 \times 10^{-12} T_i^{-2/3} \exp(-19.94 T_i^{-1/3}). \]  

(3.3.18)

The number of deuterium in a target is

\[ N_D = \frac{4}{3} \pi r_{DT}^3 n_s / 2 = 9.42 \times 10^{28} r_{DT}^3, \]  

(3.3.19)

where the solid number density of the fuel is n_s = 4.5 \times 10^{22} \text{ cm}^{-3}.

Since the fusion energy Q_f released by one DT reaction is

\[ Q_f = 17.6 \text{ MeV} = 2.82 \times 10^{-18} \text{ J}, \]  

(3.3.20)

the output thermal energy \( E_f \) released from a target is

\[ E_f = N_D Y Q_f. \]  

(3.3.21)

By using eqs. (3.3.11) - (3.3.20), the maximum \( E_f \) is obtained when

\[ r_{DT} = 2.10 \text{ mm}, \]  

(3.3.22)

and other related values are

\[ M_{DT} = 7.37 \text{ mg}, \quad u = 1.72 \times 10^5 \text{ m/s}, \]  

\[ T_i = 5.27 \text{ keV}, \quad \langle \rho R \rangle = 5.47 \text{ g/cm}^2, \]  

(3.3.23)
\[ Y = 0.170, \quad E_f = 418 \text{ MJ}, \quad G = 105. \]

A relation between \( E_f \) and \( r_{DT} \) is shown in Fig. 3.3.3.

References


3.4 Target Parameters

The target employed for the heavy ion beam of \( E_b = 4 \text{ MJ} \), \( e_p = 15 \text{ GeV} \), \( A_b = 200 \) and \( Z_b = 80 \) is summarized as follows:

3.4.1 Initial state

Before the beam energy is deposited,
the target radius is \( r_t = 4 \text{ mm} \),
the thickness and mass (density) of the Pb layer are
\( \delta_{\text{Pb}} = 75 \text{ \mu m} \) and \( M_{\text{Pb}} = 170 \text{ mg} \) (\( \rho_{\text{Pb}} = 11.3 \text{ g/cm}^3 \)),
the thickness and mass (density) of the Al layer are
\( \delta_{\text{Al}} = 410 \text{ \mu m} \) and \( M_{\text{Al}} = 223 \text{ mg} \) (\( \rho_{\text{Al}} = 2.7 \text{ g/cm}^3 \)).
the thickness and mass (density) of the DT layer are 

\[ \delta_{DT} = 270 \ \mu m \quad \text{and} \quad M_{DT} = 7.37 \ \text{mg} \quad (\rho_{DT} = 0.19 \ \text{g/cm}^3), \]

the radius of vacuum is \( r_V = 3.24 \ \text{mm} \).

3.4.2 DT Fuel after Collision at Target Center

The conditions of the DT fuel after collision at the target center are,

- the ion temperature at the center is \( T_i = 5.27 \ \text{keV} \),
- the fusion parameter is \( <p_R> = 5.47 \ \text{g/cm}^3 \),
- the average density of the fuel is \( \rho_{DT_f} = 3.06 \times 10^2 \ \text{g/cm}^3 \),
- the radius of the fuel is \( R = 0.179 \ \text{mm} \).

3.4.3 Al Layer after Implosion

The condition of the Al layer just after the fuel collides with itself at the target center are,

- the average density is \( \rho_{Al_f} = 1.20 \ \text{g/cm}^3 \),
- the thickness of the layer is \( \delta_{Al_f} = r_{Al} - R = 3.85 \ \text{mm} \),
- the average temperature is \( T_{Al_f} = 100 \ \text{eV} \).

3.4.4 Pb Layer after Implosion

The Pb layer does not move and expand so much during the fuel implosion because of its large mass and small thermal velocity. Therefore, the density and the thickness are considered to remain almost unchanged. The temperature increases to about 100 eV by the beam-energy deposition.
3.4.5 Neutrons Released by Fusion Reactions

The neutron and γ-ray energies deposited in the target per DT reaction are $E_{\text{n}} = 3.35 \text{ MeV}$ and $E_{\gamma} = 5.13 \times 10^{-4} \text{ MeV}$, respectively. The neutron and γ-ray energies escaping from the target per DT reaction are $E_{\text{n}_{\text{esc}}} = 10.62 \text{ MeV}$ and $E_{\gamma_{\text{esc}}} = 3.64 \times 10^{-2} \text{ MeV}$, respectively. The breeding factor of neutron by (n, 2n) reaction in the target is $B_{\text{n}} = 1.094$.

3.5 Discussion

Due to the finite stopping range of the ion beam in the metal layers, the ion beam has the remarkable advantage as an energy driver to perform a cannon ball type of implosion of the fuel and to extract large fusion energy from the target. The estimation of the target gain in this chapter, however, includes several unclear factors.

3.5.1 Implosion Dynamics and Inhomogeneity of Beam Irradiation

In Sec. 3.2.1, the inhomogeneity of the beam irradiation on the target surface was taken into consideration to reduce the beam energy to the effective value of 2.25 MJ from the total 4 MJ. The location where the main part of the beam energy is deposited depends on the incident angle of the beam on the target surface. The target gain ought to be examined by using a three-dimensional
simulation code since the implosion dynamics differs according to the way how the beam deposits its energy in the target.

3.5.2 Fuel Properties

As eqs. (3.3.13) and (3.3.14) show, \( T_i \) and \( R \) depend on the preheat temperature \( T_0 \) of the fuel. The temperature of the fuel during the implosion is affected mainly by the energy transfers from the pusher (or tamper) through the radiation and/or the thermal conduction. But the transport coefficients of the fuel in the low temperature are not clear. In this chapter, \( T_0 \) is assumed to be 1000 K. Equations (3.3.13) and (3.3.14) have been obtained empirically through simulation, with the assumption that the fuel is in a gaseous state when it collides with itself at the target center. The fuel is solid, however, before the implosion. The fuel properties must be examined carefully in order to secure the target gain.

3.5.3 Beam Pulse Shape

For the target which does a cannon ball type of implosion, the temporal shape of the beam pulse is related with the occurrence of the shock wave in the fuel during the process of implosion. At the early stage of the implosion, the fuel is in the solid state, in which the energy dissipation by the shock wave is much smaller than that in the gaseous state. The necessity of the control of the pulse shape remains unclear, depending on the behavior of the fuel during the implosion.
3.5.4 Tamper Motion

In Sec. 3.4.4, the Pb tamper is assumed to be unmoved. Of course the tamper moves outward. This motion was taken into account in the estimation of the implosion velocity of the fuel.

3.5.5 Burning Wave

Equation (3.3.17) does not include the effect of \( \alpha \)-particles released by fusion reactions. The burning wave supported mainly by \( \alpha \)-particles contributes on increasing the reaction rate in the target. The fusion output energy \( E_f \) or the target gain \( G \) in eq. (3.3.23) is rather pessimistic one.
3.2.1 Directions of beam irradiations.

Fig. 3.2.1 Directions of beam irradiations.

Fig. 3.2.2 Beam irradiations and target surface. Two beams are overlapped on dark regions.
Fig. 3.2.3 Target surface. In the figure, $r_c = 4.0 \text{mm}$, $r_o = 3.76 \text{mm}$, $r_b = 3.3 \text{mm}$, $r_1 = 1.36 \text{mm}$, $a = 2.31 \text{mm}$ and $b = 0.95 \text{mm}$.

Fig. 3.2.4 Beam intensity of double step type.
Fig. 3.2.5 Distributions of beam intensity, (a) along EB and (b) along EO₅.
Fig. 3.3.1 Three Layers of the target and their densities.
Fig. 3.3.2 The stopping power in the Pb tamper and in the Al pusher.
Fig. 3.3.3 The fusion output energy $E_f$ versus the fuel radius $r_{DT}$ (the fuel mass $M_{DT}$ is related by $r_{DT}$ through $M_{DT} = \frac{4}{3} \pi r_{DT}^3 d_{DT}$).
CHAPTER IV DRIVER

4.1 Summary of Driver System

Beam parameters for the production of fusion energy are largely dependent upon the structure of the pellet containing the fuel of deuterium and tritium. In the present conceptual design, the target is designed as cryogenic hollow shell of three concentric layers of lead, aluminium and fuel. It is shown that relatively large target \( r_t = 4 \text{ mm} \), implosed with 15 GeV Pb ions of 4 MJ, could produce a thermal output energy of 400 MJ. The peak power is 150 TW and the peak current and the total number of particle at the target are 15.7 kA and \( 1.7 \times 10^{15} \) per shot, respectively. In Table 4.1.1, the beam parameters from target design are tabulated and the main data and the layout are shown in Fig. 4.1.1 and 4.1.2.

The number of beam lines is determined from two points of view. A uniform irradiation of the target surface by the beams is required to attain a high gain pellet design; hence a large number of beam lines are preferable. On the other hand, simpler reactor design and beam transport system are possible for a small number of beam lines. Taking account of the beam transport capabilities per channel, the number of beam lines is optimized to be six.

The particle momentum spread at the final focus element has to be \( \leq 1\% \), otherwise the full beam can not hit the target due to the chromatic aberration of the lenses, i.e. a large fraction of beam misses the target. This constraint implies a momentum spread at the linac output of \( \pm 7 \times 10^{-3} \) which imposes careful designs of
the linac itself and the debuncher system. The admissible transverse emittance is determined by considerations on the chromatic aberrations of the final focusing elements, space charge repulsive forces in the reactor and the stand off distance D from the target to the focusing elements. For a beam radius of 3.2 mm and a D of 5.5 m, the emittance should not be larger than 80 \text{mm-nrad}.

As already noted it is necessary to attain a beam pulse of 25 ns pulse width and 10.7 kA peak current at the target. In present RF linacs it is impossible to accelerate such a high current beam and it is inevitable to provide some current multiplication after the beam acceleration in the linac. In the present concept buncher rings are used for the current gain.

With $I_L$ the peak current of linac, $S$ the stacking number in the ring, $N_C$ the bunch compression factor and $N_B$ the number of beam lines, the peak current $I$ on the pellet is given by

$$I = I_L \cdot S \cdot N_C \cdot N_B . \quad (4.1.1)$$

Here the number of buncher ring is three and there are two bunches in each ring, and hence $N_B = 6$. The reason why these values are employed in the present design, is given in the section of beam instabilities. The bunch compression factor is 14 in the ring and 10 in the beam transport line, and therefore the total bunch compression factor $N_C$ is 140. In order to obtain the current of 10.7 kA on the pellet, $I_L \cdot S$ should be 12.7 A. If we stack the beam for five turns both in the horizontal and vertical directions in the buncher ring, $S$ is 25 and the linac current $I_L$ is 510 mA, which should be attainable with the RF linac system.

When five turn injection into the betatron phase space is performed, blow up of the beam emittance is expected due to the
space charge tune depression and the multiturn injection method itself. The dilution factor is assumed to be 2.67. Then the transverse emittance of the linac beam $\epsilon_L$ becomes

$$5 \times \epsilon_L \times 2.67 \leq 80 \quad \text{(mm.mrad)}$$

$$\epsilon_L \leq 6.0 \quad (\ " )$$

and the normalized emittance $\epsilon_L^n$ is

$$\epsilon_L^n = \epsilon_L \beta \gamma = 2.46 \quad \text{(mm.mrad)}.$$

The physical bunch length $l_b$ at the pellet is given by

$$l_b = \beta c \tau$$

where $\beta$ is $v/c$ and $\tau$ the pulse duration. In the present case, $\beta = 0.3722$ and $\tau = 25$ ns, and $l_b = 2.79$ m.

As the total bunch compression factor is 140, the bunch length in the ring before the compression, should be 140 $l_b = 390.6$ m, and the ring circumference 781.7 m as the harmonic number is two.

The maximum magnetic field strength of the dipole magnet in the ring is assumed as 5 Tesla and the radius of curvature $\rho$ is given by

$$\rho(r) = \frac{10 \ p \ (GeV/c)}{3qB(T)} \quad (4.1.2)$$

where $p$ is a momentum of the ions of charge state $q$. In the present case, $p$ is 79 GeV/c for the kinetic energy of 15 GeV, and the relation of average radius $R$ and $\rho$ is nearly $R = 2.4 \rho$ and finally the parameters of the buncher ring are as in Table 4.1.2.

The number of ions which can be stored in a ring is limited by various beam instabilities. Firstly, the incoherent space charge force of the beam itself disturbs the focusing field of the magnet system. The maximum number of ions $n$ is given by

$$n = \frac{2\pi \Delta \nu A}{Br_p} \frac{A}{q^2} \epsilon \beta^2 \gamma^3 \quad (4.1.3)$$

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where $B$ is a bunching factor, $r_p \left(= \frac{1}{4\pi\varepsilon_0} \frac{e^2}{M c^2} \right)$ is a "classical proton radius", $A$ is the mass number, $q$ is a charge state and $\varepsilon$ is the unnormalized beam emittance. For the values of $B=1$, $A=208$, $q=1$, $\varepsilon=80 \text{ mm-mrad}$, $\Delta v=0.25$, $n$ is calculated at $2.2 \times 10^{15}$ particles. From this argument, the minimum number of storage ring is one.

Secondly, coherent beam instabilities make the amplitude of collective motion of ions grow larger. They have been extensively studied at the ISR of CERN for the high energy proton beam, and if we scale the data to the low energy heavy ion beam, the growth rates of instability are $150 \text{ ms}$ in the longitudinal motion and $12.4 \text{ ms}$ for the transverse motion. Thus for the longitudinal instability might give a severe limit on the number of ions in the ring.

An accumulator ring with the circumference of 5 times larger than the buncher ring is prepared to perform the five turn injection into the buncher ring. Ions are injected in the accumulator ring from the linac also with five turn injection method and are extracted by the one turn, fast ejection method. The extracted beam is x-y rotated in the transport line and is injected in the buncher ring. Hence 25 turn beams can be injected in the x-y betatron phase spaces in the buncher rings.

The linear accelerator system for the heavy ion fusion project is required to accelerate high intensity heavy ions up to 15 GeV (75 MeV/u). The high brightness and high energy resolution are also important requirements for the output beam.

At the low velocity region, the required current of more than 0.5 A is far above the limiting current due to space charge
effects. The limiting current, however, depends strongly on the ion velocity, so the funneled tree system of linacs is proposed to avoid the difficulty.

In the present design, 0.58 A of Pb$^+$ ions are produced by 16 ion sources of 32 mA each, and preaccelerated by 16 Cockcroft-Walton accelerators of 1 MV. The singly charged Pb ions are then bunched and accelerated to 0.30 MeV/u by 16 RFQ linacs followed by 8 funneling sections. The resonant frequency of the RFQ linacs is chosen at 12.5 MHz, and the output beam bunches emerge from the linacs with the same frequency. Since the next interdigital H-type linac tanks have the doubled resonant frequency of 25 MHz, each IH linac can accept a pair of RFQ beams without decreasing the longitudinal phase space density. The transverse emittance can be kept constant if a carefully designed funneling system is installed.

Similar funneling sections are introduced at the particle energies of 1.16, 4.51 and 17.8 MeV/u, and a pair of linac beams is combined into single beam at each section. The final stage of the linac system has an Alvarez type accelerating structure with a resonant frequency of 200 MHz. Therefore, the macroscopic peak current can be increased by a factor of 16 when the rf buckets of the 200 MHz Alvarez linac are all filled.
### Table 4.1.1  Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>$^{208}\text{Pb}^{1+}$</td>
</tr>
<tr>
<td>Total beam energy</td>
<td>4 MJ</td>
</tr>
<tr>
<td>Beam power</td>
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</tr>
<tr>
<td>Pulse duration</td>
<td>25 ns</td>
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<tr>
<td>Total beam current</td>
<td>10.7 kA</td>
</tr>
<tr>
<td>Ion kinetic energy</td>
<td>15 GeV</td>
</tr>
<tr>
<td>Number of beams</td>
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</tr>
<tr>
<td>Radius of beam spot</td>
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</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Beam emittance</td>
<td>30 mm·mrad</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Table 4.1.2  Parameters of the Buncher Rings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of curvature</td>
<td>$c = 51.80\ m$</td>
</tr>
<tr>
<td>Average radius</td>
<td>$R = 124.41\ m$</td>
</tr>
<tr>
<td>Circumference</td>
<td>$C = 781.66\ m$</td>
</tr>
<tr>
<td>Number of bunches in one ring</td>
<td>$h = 2$</td>
</tr>
<tr>
<td>Strength of magnetic field</td>
<td>$B = 5$ Tesla</td>
</tr>
<tr>
<td>Number of ions in one ring</td>
<td>$N = 5.57 \times 10^{15}$</td>
</tr>
</tbody>
</table>
Table 4.1.3  Main Linac Parameters

<table>
<thead>
<tr>
<th></th>
<th>RFQ</th>
<th>Linac</th>
<th>Alvarez</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input energy</td>
<td>5 keV/u</td>
<td>300 keV/u</td>
<td>4.5 MeV/u</td>
</tr>
<tr>
<td>Output energy</td>
<td>500 keV/u</td>
<td>4.5 MeV/u</td>
<td>75 MeV/u</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>12.5</td>
<td>25, 50</td>
<td>100, 200</td>
</tr>
<tr>
<td>Length (m)</td>
<td>500</td>
<td>238, 741</td>
<td>2000, 7400</td>
</tr>
<tr>
<td>Number</td>
<td>16</td>
<td>8, 4</td>
<td>2, 1</td>
</tr>
<tr>
<td>Output current (mA)</td>
<td>35</td>
<td>65, 130</td>
<td>260, 520</td>
</tr>
</tbody>
</table>
Fig. 4.1.2  HIBLC Plant Layout

Ion Source (16) RFQ (16) IH-A (8) IH-B (4) Alvarez-A (2)

Pb⁺ 12.5 MHz 25 MHz 50 MHz 100 MHz

1.7 GeV (17.8 MeV/μ)

3.7 GeV (17.8 MeV/μ)

15 GeV (17.8 MeV/μ)

1 MeV (0.3 MeV/μ) 0.24 GeV (1.2 MeV/μ) 0.34 GeV (4.5 MeV/μ)
### Fig. 11.1: Driver Main Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy (MeV/u)</td>
<td>0.00</td>
</tr>
<tr>
<td>Stack Factor</td>
<td>2</td>
</tr>
<tr>
<td>Dilution Factor</td>
<td>2.67</td>
</tr>
<tr>
<td>$t_x$ (mm-mrad)</td>
<td>27.19</td>
</tr>
<tr>
<td>$t_y$ (mm-mrad)</td>
<td>27.19</td>
</tr>
<tr>
<td>Bunching Factor</td>
<td>0.75</td>
</tr>
<tr>
<td>Bunch Length</td>
<td></td>
</tr>
<tr>
<td>Momentum Spread (dp/dp')</td>
<td></td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>36 x 10^{-3}</td>
</tr>
<tr>
<td>Revolution Time (usec)</td>
<td>3.56</td>
</tr>
<tr>
<td>Maximum Beam</td>
<td></td>
</tr>
<tr>
<td>Residence Time (usec)</td>
<td>35</td>
</tr>
<tr>
<td>Δt (time shift due to space charge)</td>
<td>0.24</td>
</tr>
</tbody>
</table>

-Δt (time shift due to space charge)

0.48 - 0.67
4.2 LINAC System

4.2.1 Introduction

The linear accelerator system for the heavy ion fusion project is required to accelerate high intensity heavy ions up to 15 GeV (75 MeV/u). The high brightness and high energy resolution are also important requirements for the output beam. The summary of required specifications of the linac beam is given in Table 4.2.1 comparing with the HIBALL linac.

At the low velocity region, the required current of more than 0.5 A is far beyond the limiting current due to space charge effects. The limiting current, however, depends strongly on the ion velocity, so the funneled tree system of linacs is proposed to avoid the difficulty.

In the present design, the Pb$^+$ ions of 0.58 A are produced by 16 ion sources, and preaccelerated by 16 Cockcroft-Walton accelerators of 1 MV. The singly charged Pb ions are then bunched and accelerated to 0.30 MeV/u by 16 RFQ linacs followed by 8 funneling sections. The resonant frequency of the RFQ linacs is chosen at 11.5 MHz, and the output beam bunches emerge from the linacs with same frequency. Since the next interdigital H-type linac tanks have the doubled resonant frequency of 25 MHz, each IH linac can accept a pair of RFQ beams without decreasing the longitudinal phase space density. The transverse emittance is also possible to remain constant if the carefully designed funneling apparatus are installed.

Similar funneling sections are introduced at the particle energies of 1.16, 4.51 and 17.8 MeV/u, and a pair of linac beams
is combined into single beam at each section. The final stage of
the linac system has the Alvarez type accelerating structure with
the resonant frequency of 200 MHz, and therefore, the macroscopic
peak current is possible to increase by a factor of 16 when the rf
buckets of the 200 MHz Alvarez linac are all filled.

The schematic diagram of the designed linac system is shown
in Fig. 4.2.1. The list of the important parameters of the linac
tree system is given by Table 4.2.2. The more detailed discus-
sions will be given in the following subsections.

4.2.2 Emittance Considerations

The normalized longitudinal emittance of the output beam is
required to be less than 7.7 mm·mrad, corresponding to an energy
resolution of less than $10^{-9}$ (half value) after the debuncher.
This high energy resolution is far better than those achieved by
conventional proton linacs. In the case of heavy ions, however,
the separatrix height of the rf buckets is reduced by a factor
$q/A$, where $q$ and $A$ are the charge state and mass number of the
heavy ions to be accelerated. In the present case, this factor is
about 14 and such a high energy resolution is not an unreasonalbe
value.

The longitudinal emittance growtr is serious especially
during the bunching process due to the strong space charge forces.
In the present design, the longitudinal emittance growth during
the bunching process is estimated at factor of about 30.
Qualitatively, the emittance growth can be reduced by adopting the
slow bunching which lead to the long linacs.
At the output end of the IFQ linacs, the normalized longitudinal emittance and the energy resolution are $2.3 \, \mu \text{mm-mrad}$ and $2.4 \times 10^{-3}$ for a phase spread of 70 degree.

The normalized value of the required transverse emittance is less than $2.5 \, \mu \text{mm-mrad}$ and about 5 times larger than the estimated emittance of the ion sources. The main sources of the transverse emittance growth are funneling process, the space charge effects, the misalignments of the Q-lenses in the drift tubes and etc. These effects must be kept as low as possible.

In the Table 4.2.3, the assumed values of emittances are given at each stage of the linac system.

4.2.3 Focusing by Quadrupole Magnets in the Drift Tubes

As focusing elements in the drift tubes, magnetic quadrupoles are preferable to electrostatic quadrupoles because of the high voltages required by quadrupole electrodes. The focusing sequence of FFDDD is chosen in order to maintain the pole-tip magnetic field less than 10 kG. In conventional proton linacs, this focusing sequence is not adopted because the stable region of the betatron oscillations is quite narrow compared with the FD or FFDD sequences. For heavy ions, however, it is possible to keep the transverse acceptance stable due to the small value of the charge to mass ratio. The focusing strength is as small as 0.5 for the 25 MHz IH linac and 0.07 for the 200 MHz Alvarez. The bore radius of the Q-magnets varies from 0.7 cm for the 25 MHz IH to 1.2 cm for the 200 MHz Alvarez. The more detailed parameters are given in Table 4.2.4.
4.2.4 Accelerating Field and Synchronous Phase

The effective accelerating field, \( E_3 T \), where \( L_3 \) and \( T \) are the average field along the beam axis and the transit time factor, is chosen somewhat conservatively to operate the linac system reliably. Since the focusing strength of the synchrotron oscillations depends on the synchronous phase angle and the accelerating field, the longitudinal space charge limit is proportional to \( E_3 T \cdot |\phi_s|^3 \), where \( \phi_s \) is the synchronous phase angle. The ion currents, which are accelerated without serious reduction of beam quality, must be far below this limiting current.

The accelerating field and the synchronous phase also affect the radial defocusing forces at the accelerating gaps. In the square wave approximation, the defocusing parameter is proportional to \( E_3 T \sin \phi_s \), and this value is very important for choosing the focusing strength of the Q-magnets. The design values of \( E_3 T \) and \( \phi_s \) are also given in Table 4.2.4.

4.2.5 Funneled Section

As already mentioned, the funneled sections combine a pair of low frequency beams into single beam with the higher frequency. Each beam bunch is captured into one rf-bucket. So, the macroscopic peak currents increase by a factor of 2 maintaining the longitudinal emittance constant. Of course, the number of the funneled beams is not necessarily two. The apparatus for three or four beams funneling will be more and more intricate, and tends to increase the beam emittances especially in transverse plane.

The size of the beam bunches before and after the funneling process are not much different. The space charge forces in the
bunch, therefore, will not be affected much.

In order to realize the funneling process, the high frequency deflector system must be installed. A rectangular waveform of the deflector voltage is the best to avoid transverse emittance growth. A sinusoidal waveform will also be acceptable if the special care is taken to shape the longitudinal emittance. With the sinusoidal deflection, the sharp phase focusing is required at the deflector positions. Since the short beam bunches produce strong space charge forces, sinusoidal deflection necessarily brings about the emittance growth. In the present design, the low velocity funneling sections, where the space charge forces play the more important roles, are designed with the rectangular waveform. A summary of the important parameters of the funneling sections are given in Table 4.2.5.

4.2.6 Power Considerations

The electric power required to accelerate Pb ions are given in Table 4.2.6. As shown in the table, the main part of the estimated power is the beam power which is carried by the ions themselves. The wall loss is about 1/5 of the beam power, and this fact implies that the important criterion for choosing the accelerating structure is not the shunt impedance but simplicity and the reliability. The quadrupole magnets in the drift tubes are possibly excited by sinusoidal half-wave currents, and this technique reduces the required power considerably. The electric power for the vacuum system is not so small because the system must be operated continuously. In the funneling sections, the main power is for the DC magnets. The total required peak power...
is as high as about 8.8 TW and the average power is about 88 MW (the duty factor of the output beam is assumed to be 0.7%).
Table 4.2.1
Requirements for the Linac Output Beam

<table>
<thead>
<tr>
<th></th>
<th>Present Design</th>
<th>HIBALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Species</td>
<td>$^{208}\text{Pb}^+$</td>
<td>$^{209}\text{Bi}^{2+}$</td>
</tr>
<tr>
<td>Output Energy</td>
<td>15 GeV (75 MeV/u)</td>
<td>10 GeV (50 MeV/u)</td>
</tr>
<tr>
<td>Peak Current</td>
<td>0.52 A</td>
<td>0.15 A</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>$\pm 1.0 \times 10^{-4}$</td>
<td>$\pm 1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>after Debuncher</td>
<td></td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>2.5 $\pi$ mm·mrad</td>
<td>0.6 $\pi$ mm·mrad</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>7.7 $\pi$ mm·mrad</td>
<td>1.3 $\pi$ mm·mrad</td>
</tr>
</tbody>
</table>
### Table 4.2.2
List of Main Parameters of the Linac Tree System

<table>
<thead>
<tr>
<th>Accelerating Structure</th>
<th>RFQ</th>
<th>IH</th>
<th>IH</th>
<th>Alvarez</th>
<th>Alvarez</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>12.5</td>
<td>25</td>
<td>50</td>
<td>.00</td>
<td>200</td>
</tr>
<tr>
<td>Number of Branches</td>
<td>16</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Peak Current per Branch (mA)</td>
<td>35</td>
<td>65</td>
<td>130</td>
<td>260</td>
<td>520</td>
</tr>
<tr>
<td>Kinetic Energy (MeV/u)</td>
<td>0.005</td>
<td>0.30</td>
<td>1.16</td>
<td>4.51</td>
<td>17.78</td>
</tr>
<tr>
<td>Particle Velocity (%)</td>
<td>0.33</td>
<td>2.5</td>
<td>5.0</td>
<td>9.8</td>
<td>19.3</td>
</tr>
<tr>
<td>Accelerating Voltage (MV)</td>
<td>59</td>
<td>172</td>
<td>670</td>
<td>2654</td>
<td>11444</td>
</tr>
<tr>
<td>Synchronous Phase (deg)</td>
<td>-90~ -45</td>
<td>-43.6</td>
<td>-41.1</td>
<td>-33.5</td>
<td>-30.7</td>
</tr>
<tr>
<td>Accelerating Field (MV/m)</td>
<td>-</td>
<td>1.0</td>
<td>1.2</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Length (m)</td>
<td>500</td>
<td>238</td>
<td>741</td>
<td>1989</td>
<td>7394</td>
</tr>
</tbody>
</table>

Normalized Emittance ($\pi \text{mm}\cdot\text{mrad}$)

<table>
<thead>
<tr>
<th></th>
<th>Transverse</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.69</td>
<td>0.95</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
<td>2.3</td>
<td>3.1</td>
<td>4.2</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Focusing Strength

<table>
<thead>
<tr>
<th>Field Gradient (kG/cm)</th>
<th>-</th>
<th>8.5~4.3</th>
<th>8.7~4.4</th>
<th>9.9~5.1</th>
<th>10.2~5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Flux at Pole Tip (kG)</td>
<td>-</td>
<td>5.9~3.4</td>
<td>5.7~3.3</td>
<td>9.2~5.5</td>
<td>10.6~6.6</td>
</tr>
</tbody>
</table>

Effective Shunt Impedance (M\Omega/m)

<table>
<thead>
<tr>
<th></th>
<th>2.3</th>
<th>55</th>
<th>45</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Loss (MW)</td>
<td>3.0 x 16</td>
<td>4.3 x 8</td>
<td>23.7 x 4</td>
<td>145.5 x 2</td>
<td>598.7</td>
</tr>
<tr>
<td>Beam Power (MW)</td>
<td>2.1 x 16</td>
<td>11.0 x 8</td>
<td>85.8 x 4</td>
<td>676.8 x 2</td>
<td>5836.4</td>
</tr>
<tr>
<td>Q-magnet Power (MW)</td>
<td>-</td>
<td>0.3 x 8</td>
<td>0.6 x 4</td>
<td>4.6 x 2</td>
<td>14.2</td>
</tr>
<tr>
<td>Vacuum Power (MW)</td>
<td>0.5 x 16</td>
<td>0.2 x 8</td>
<td>0.7 x 4</td>
<td>2.0 x 2</td>
<td>7.4</td>
</tr>
<tr>
<td>Total Peak Power (MW)</td>
<td>5.6 x 16</td>
<td>16.0 x 8</td>
<td>111.0 x 4</td>
<td>830.6 x 2</td>
<td>6464.1</td>
</tr>
</tbody>
</table>
Table 4.2.3

Normalized Longitudinal and Transverse Emittances at Each Stage of the Linac System

<table>
<thead>
<tr>
<th>Stage</th>
<th>Transverse (π mm·mrad)</th>
<th>Longitudinal (π mm·mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>After Preaccelerators</td>
<td>0.50</td>
<td>0.083</td>
</tr>
<tr>
<td>12.5 MHz RFQ</td>
<td>0.69</td>
<td>2.3</td>
</tr>
<tr>
<td>25 MHz IH</td>
<td>0.95</td>
<td>3.1</td>
</tr>
<tr>
<td>50 MHz IH</td>
<td>1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>100 MHz Alvarez</td>
<td>1.8</td>
<td>5.7</td>
</tr>
<tr>
<td>200 MHz Alvarez</td>
<td>2.5</td>
<td>7.7</td>
</tr>
</tbody>
</table>
Table 4.2.4

Specifications of Quadrupole Magnets in the Drift Tubes

The focusing sequence is FFFDDD.

<table>
<thead>
<tr>
<th></th>
<th>IH 20 MHz</th>
<th>IH 50 MHz</th>
<th>Alvarez 100 MHz</th>
<th>Alvarez 200 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accelerating Field (MV/m)</strong></td>
<td>1.0</td>
<td>1.2</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Synchronous Phase (deg)</strong></td>
<td>-3.6</td>
<td>-41.1</td>
<td>-33.5</td>
<td>-30.7</td>
</tr>
<tr>
<td><strong>Focusing Strength</strong></td>
<td>0.5</td>
<td>0.25</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>RF Defocusing Parameter (×10^-4)</strong></td>
<td>-10^-9.6</td>
<td>-9.5</td>
<td>-5.8^-2.9</td>
<td>-1.7^-0.87</td>
</tr>
<tr>
<td><strong>Field Gradient (kG/cm)</strong></td>
<td>8.5^-4.3</td>
<td>8.7^-4.4</td>
<td>9.9^-3.1</td>
<td>10.2^-5.5</td>
</tr>
<tr>
<td><strong>Bore Radius of Q-magnets (cm)</strong></td>
<td>0.69^-0.79</td>
<td>0.56^-0.76</td>
<td>0.93^-1.1</td>
<td>1.0^-1.2</td>
</tr>
<tr>
<td><strong>Magnetic Flux at the Pole Tip (kG)</strong></td>
<td>5.9^-3.4</td>
<td>5.7^-3.3</td>
<td>9.2^-5.5</td>
<td>10.6^-6.6</td>
</tr>
</tbody>
</table>

IV-20
### Table 4.2.5

**Parameters List of Funneling Sections**

<table>
<thead>
<tr>
<th></th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ (MeV/u)</td>
<td>0.3</td>
<td>1.16</td>
<td>4.51</td>
<td>17.78</td>
</tr>
<tr>
<td>$\beta\lambda/2$ (m)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.29</td>
<td>0.28</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>12.5</td>
<td>25</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Number of deflector</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Deflector field* (MV/m)</td>
<td>0.542</td>
<td>2.09</td>
<td>9.8</td>
<td>19.3</td>
</tr>
<tr>
<td>Voltage** (KV)</td>
<td>22</td>
<td>84</td>
<td>390</td>
<td>770</td>
</tr>
<tr>
<td>Buncher voltage (MV)</td>
<td>—</td>
<td>—</td>
<td>5.3</td>
<td>10.6</td>
</tr>
<tr>
<td>Length between buncher and deflector (m)</td>
<td>176</td>
<td>34.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The gap between the deflector plates is assumed to be 4 cm.

** The waveforms of the high voltage applied to the deflectors are rectangular for F1 and F2, and sinusoidal for F3 and F4.
Table 4.2.6

Power Estimation of the Linac Tree System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RFQ</th>
<th>1H</th>
<th>1H</th>
<th>Alvarez</th>
<th>Alvarez</th>
<th>Total Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>12.5</td>
<td>25</td>
<td>50</td>
<td>100</td>
<td>200</td>
<td>—</td>
</tr>
<tr>
<td>Number of Branches</td>
<td>16</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Effective Shunt Impedance (M?/m)</td>
<td>2.3</td>
<td>55</td>
<td>45</td>
<td>35</td>
<td>40</td>
<td>—</td>
</tr>
<tr>
<td>Length (m)</td>
<td>500</td>
<td>238</td>
<td>241</td>
<td>1989</td>
<td>7394</td>
<td>—</td>
</tr>
<tr>
<td>Accelerating Voltage (MV)</td>
<td>59</td>
<td>172</td>
<td>670</td>
<td>2654</td>
<td>11444</td>
<td>—</td>
</tr>
<tr>
<td>( \cos \theta )</td>
<td>—</td>
<td>0.724</td>
<td>0.754</td>
<td>0.834</td>
<td>0.860</td>
<td>—</td>
</tr>
<tr>
<td>Wall Loss (MW)</td>
<td>(1.0 \times 16)</td>
<td>(4.3 \times 8)</td>
<td>(23.7 \times 4)</td>
<td>(145.5 \times 2)</td>
<td>(598.7)</td>
<td>1066.9</td>
</tr>
<tr>
<td>Peak Current (mA)</td>
<td>(35 \times 16)</td>
<td>(65 \times 8)</td>
<td>(130 \times 4)</td>
<td>(260 \times 2)</td>
<td>(520)</td>
<td>—</td>
</tr>
<tr>
<td>Beam Power (MW)</td>
<td>(2.1 \times 16)</td>
<td>(11.0 \times 8)</td>
<td>(85.8 \times 4)</td>
<td>(676.8 \times 2)</td>
<td>(5836.4)</td>
<td>7654.8</td>
</tr>
<tr>
<td>No. of Q-magnets</td>
<td>—</td>
<td>(1051 \times 8)</td>
<td>(3301 \times 4)</td>
<td>(4402 \times 2)</td>
<td>(14923)</td>
<td>—</td>
</tr>
<tr>
<td>Q-magnet Power (MW)</td>
<td>—</td>
<td>(0.3 \times 8)</td>
<td>(0.6 \times 4)</td>
<td>(4.6 \times 2)</td>
<td>(14.2)</td>
<td>28.2</td>
</tr>
<tr>
<td>Vacuum Power (MW)</td>
<td>(0.5 \times 16)</td>
<td>(0.2 \times 8)</td>
<td>(0.7 \times 4)</td>
<td>(2.0 \times 2)</td>
<td>(7.4)</td>
<td>23.8</td>
</tr>
<tr>
<td>Power loss at funneling sections</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(0.1 \times 9 \times 2)</td>
<td>(0.5 \times 12)</td>
<td>7.8</td>
</tr>
<tr>
<td>Deflector (MW)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(0.5 \times 2)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Synchro (MW)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>(0.1 \times 8)</td>
<td>(0.1 \times 4)</td>
<td>0.2</td>
</tr>
<tr>
<td>Bending Magnet (MW)</td>
<td>—</td>
<td>(0.1 \times 8)</td>
<td>(0.1 \times 4)</td>
<td>(0.2 \times 2)</td>
<td>(0.2)</td>
<td>1.8</td>
</tr>
<tr>
<td>Vacuum System (MW)</td>
<td>—</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Total Peak Power* (MW)</td>
<td>(5.6 \times 15)</td>
<td>(15.0 \times 8)</td>
<td>(111.0 \times 4)</td>
<td>(850.6 \times 2)</td>
<td>(6464.1)</td>
<td>8786.9</td>
</tr>
</tbody>
</table>

* The average power is estimated at about 88 MW (duty factor 0.7%).
4.3 Lattice Structure of Accumulator and Buncher Rings

4.3.1 Lattice Structure of the Accumulator Ring

In the design of the accumulator ring, the following conditions should be taken into account.

1) The circumference of the accumulator ring should be 5 times that of the buncher rings so as to perform 5 turn injection into the buncher ring.

2) It is necessary to shorten the filling time of three buncher rings, because the growth rate of longitudinal coherent instability in the buncher ring is as short as 150 \(\mu\mathrm{s}\).

From the first condition, the circumference of the accumulator ring is determined to be 3908.31 m. From the second condition, it is needed that the three successive injections into the accumulator ring to provide the beams for the three buncher rings should be done as fast as possible. Considering the limited repetition rate of bumper magnets for injection as described in another section, three different injection systems would be necessary. Assuming three long straight sections for each injection system, nine straight sections are needed for injection. Similar problems due to the limited repetition rate is anticipated also for the kicker magnets for beam ejection from the accumulator ring, so that three different ejection systems are needed. Providing 2 long straight sections for each ejection system, a total 6 straight sections are required for ejection. Considering the above conditions, the superperiodicity is determined to be 16. So as to reduce the number of magnets and to make smooth focusing, the cell length is chosen rather long (59 m) and the number of
normal FODO cells are set to be 64. The average radius of the accumulator ring is five times larger than the buncher ring of the same magnetic rigidity of the beam, so a bending field of 1T is sufficient. In order to facilitate 5 turn injection with large space charge tune depression, the betatron tune value is set around 12.25. The main parameters of the accumulator ring are listed in Table 4.3.1.

3.2 Lattice Structure of the Buncher Ring

The requirements from the target design are already listed in Table 4.1.1. From these parameters, beam length at the target is calculated at 2.79 m, which leads to the circumference of 781.66 m for the buncher ring if total 140 times beam compression and harmonic number 2 are assumed. The magnetic rigidity of $^{208}$Pb$^{1+}$ beam with the kinetic energy of 15 GeV is 259.01 T·m, so the radius of curvature becomes 51.80 m if the superconducting dipole strength of 5T is assumed. The basic focusing structure is chosen to be FODO so as to make the drift spaces as long as possible within the same circumference. For the long straight sections, a FOF structure is used to make $\alpha = -\frac{16\delta}{2ds}$ zero at the position of the inflector septum, which seems to be essential to make a 5 turn injection without beam loss on the septum. From the point of view of providing enough space for RF cavities for bunch compression and equipment for injection and ejection, 3 long straight sections are to be made, so the superperiodicity of the ring becomes 8. It is desirable that the beam size should vary smoothly to reduce the defocusing effect due to space charge force. From this point of view, the cell length is chosen rather long and the betatron tune
value is set to be relatively low, viz. 6.25. The lattice
structure is illustrated in Fig.4.3.1. In this design, drift
spaces of total length 220 m are available, which seems adequate
to attain necessary bunch-compression voltage. In Table 4.3.2,
main parameters of the buncher ring lattice are listed.
Table 4.3.1  HIF Accumulator Ring Parameter List

<table>
<thead>
<tr>
<th>Focusing Structure</th>
<th>FODO</th>
<th>FOF at long straight section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Radius</td>
<td>622.03 m</td>
<td></td>
</tr>
<tr>
<td>Circumference</td>
<td>3908.31 m</td>
<td></td>
</tr>
<tr>
<td>Number (Length) of Normal Periods</td>
<td>64(59.07 m)</td>
<td></td>
</tr>
<tr>
<td>Number (Length) of Long Straight Sections</td>
<td>16(8 m)</td>
<td></td>
</tr>
<tr>
<td>Number of Betatron Oscillations per turn</td>
<td>12.25</td>
<td></td>
</tr>
<tr>
<td>Betatron Phase Advance per Period</td>
<td>~ 70°</td>
<td></td>
</tr>
<tr>
<td>Radius of Curvature</td>
<td>259.01 m</td>
<td></td>
</tr>
<tr>
<td>Bending Field</td>
<td>1 T</td>
<td></td>
</tr>
<tr>
<td>Length of Bending Magnet</td>
<td>3.178 m</td>
<td></td>
</tr>
<tr>
<td>Bending Angle</td>
<td>0.703125°</td>
<td></td>
</tr>
<tr>
<td>Number of Bending Magnets</td>
<td>512</td>
<td></td>
</tr>
<tr>
<td>Field Gradient of the Quadrupole Magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_F$ ($Q_F/2$)</td>
<td>20.03 T/m</td>
<td></td>
</tr>
<tr>
<td>$Q_D$</td>
<td>19.74 T/m</td>
<td></td>
</tr>
<tr>
<td>Length of the Quadrupole Magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_F$, $Q_D$</td>
<td>0.5 m</td>
<td></td>
</tr>
<tr>
<td>$Q_F/2$</td>
<td>0.25 m</td>
<td></td>
</tr>
<tr>
<td>Number of Quadrupole Magnets</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>Number of Superperiods</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Beta Functions</td>
<td>Horizontal</td>
<td>Max. 101.3 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min. 27.0 m</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>Max. 113.1 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min. 24.1 m</td>
</tr>
<tr>
<td>Dispersion Function</td>
<td></td>
<td>Max. 5.08 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min. 3.19 m</td>
</tr>
<tr>
<td>Length of Short Straight Section</td>
<td></td>
<td>3.264 m</td>
</tr>
<tr>
<td>Space charge limit for 208 Pb(^{1+}) with 15 GeV</td>
<td>(6.9 \times 10^{14})</td>
<td></td>
</tr>
</tbody>
</table>
### Tablo 4.3.2 HIF Buncher Ring Parameter List

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focusing Structure</td>
<td>FODF at Long Straight Section</td>
</tr>
<tr>
<td>Average Radius</td>
<td>124.41 m</td>
</tr>
<tr>
<td>Circumference</td>
<td>781.66 m</td>
</tr>
<tr>
<td>Number (Length) of Normal Periods</td>
<td>32(19.54 m)</td>
</tr>
<tr>
<td>Number (length) of Long Straight Sections</td>
<td>8(19.54 m)</td>
</tr>
<tr>
<td>Number of Betatron Oscillations per Turn</td>
<td>6.25</td>
</tr>
<tr>
<td>Betatron Phase Advance per Period</td>
<td>~ 60°</td>
</tr>
<tr>
<td>Radius of Curvature</td>
<td>51.80 m</td>
</tr>
<tr>
<td>Bending Field</td>
<td>5 T</td>
</tr>
<tr>
<td>Length of Bending Magnet</td>
<td>2.543 m</td>
</tr>
<tr>
<td>Bending Angle</td>
<td>2.8125°</td>
</tr>
<tr>
<td>Number of Bending Magnets</td>
<td>128</td>
</tr>
<tr>
<td>Field Gradient of the Quadrupole Magnets</td>
<td></td>
</tr>
<tr>
<td>$Q_F$ ($Q_F/2$)</td>
<td>23.45 T/m</td>
</tr>
<tr>
<td>$Q_D$</td>
<td>22.01 T/m</td>
</tr>
<tr>
<td>Length of the Quadrupole Magnet</td>
<td></td>
</tr>
<tr>
<td>$Q_F$, $Q_D$</td>
<td>1.25 m</td>
</tr>
<tr>
<td>$Q_F/2$</td>
<td>0.425 m</td>
</tr>
<tr>
<td>Number of Quadrupole Magnets</td>
<td>72</td>
</tr>
<tr>
<td>Number of Superperiods</td>
<td>8</td>
</tr>
<tr>
<td>Beta Functions</td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>Max. 39.79 m</td>
</tr>
<tr>
<td></td>
<td>Min. 9.36 m</td>
</tr>
<tr>
<td>Vertical</td>
<td>Max. 72.60 m</td>
</tr>
<tr>
<td></td>
<td>Min. 5.14 m</td>
</tr>
<tr>
<td>Dispersion Function</td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>4.19 m</td>
</tr>
<tr>
<td>Min.</td>
<td>2.34 m</td>
</tr>
<tr>
<td>Length of Short Straight Section</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Space Charge Limit for $^{208}$Pb$^{1+}$ with 15 GeV</td>
<td>$2.2 \times 10^{15}$</td>
</tr>
</tbody>
</table>
Fig. 4.1.1 Lattice Structure of Buncher Ring

Super Period NNNNL
4.4 Multi-turn Injection into Rings

4.4.1 Five-turn Injection into Buncher and Accumulator Rings

From the requirement by the target design, peak current of 10.7 kA with a duration of 25 ns is needed for the 15GeV $^{208}$Pt$^{1+}$ beam. This is reduced to 1.78 kA with the configuration of 6 beams at the final transport. Assuming a 140 fold bunch compression in the bunch ring and transport line, the current requirement is reduced to 2.54 A just after the injection at the buncher ring. So as to achieve this value with the current attainable in the injector linac system, multi-turn injection into transverse phase space should be applied both at the accumulator and buncher rings. The energy of the beam to be injected into a given ring amounts to 1.3 MJ for the present scenario, so that the usual multi-turn injection which involves beam collision with the inflector septum cannot be used, because the septum would melt away in a short moment. In this section an injection scheme is described which attains a 5 fold increase of the peak current without beam loss, and within a limit of transverse beam emittance acceptable for the target and beam transport design. A beam emittance (unnormalized) of 6 $\pi$ mm-mrad is assumed and five turn injection into an acceptance of 80 $\pi$ mm-mrad is discussed.

1) Basic Concept of Five-turn Injection

To perform five-turn injection under the condition of rather larger space charge tune depression, the following injection scheme is conceived.

a) The beam is injected into the center of the acceptance ellipse in x-x' phase space. At that time, the beam ellipse is
matched to the acceptance shape as shown in Fig. 4.4.1 by adjustment of magnet elements of the transport system. The orbit position with respect to the inflector septum is set at \( x_1 \).

b) After 1 turn, the orbit position is shifted to \( x_2 \) and beam is injected into the outer shell of the acceptance ellipse during four turns.

c) After five turns, the inflector position is shifted outside the acceptance ellipse \( (x_3) \). It should be noted that the condition of \( a = -\frac{1}{2} \frac{d\phi}{ds} \) to be zero at the inflector position is indispensable in order to perform the above injection scheme without beam collision with the septum.

2) Orbit Distortion made by Bumper Magnets

The control of the orbit position with respect to the septum position is done by exciting pulsed magnets (called "Bumper Magnets" hereafter). The relative septum position is \( x_3 \) when these magnets are not excited. For process a), the closed orbit should be displaced by \( x_3 - x_1 \). To make this displacement without affecting the orbit at other positions, two bumper magnet should be located at positions separated from each other by an integral multiple of \( \pi \) in betatron phase advance as illustrated in Fig. 4.4.2. The required deflection angle for the bumper magnet is 2.02 mrad for the case of \( x_1 = -14 \text{ mm} \) and \( x_3 = 44 \text{ mm} \), respectively. So as to adjust the orbit position for \( x_2 \), the excitation of the bumper magnets should be reduced, for the case where \( x_2 = 15.7 \text{ mm} \), the required deflection angle is calculated at 0.99 mrad. With a magnetic rigidity of the 15 GeV \(^{208}\text{Pb}^{1+}\) beam of 259 T·m, the magnetic strength \((B\cdot\ell)\) of the bumper magnets should be 0.523 T·m and 0.256 T·m for \( x_1 \) and \( x_2 \), respectively as.
shown in Fig. 4.4.3. It should be noted that the transient time of these bumper magnets amount to 200 ns considering the needed magnetic strength as described in the following paragraph. The time structure of the injected beam should be suitably arrayed so as to avoid beam collision with the inflector septum during this transient time.

3) Time Structure of the Beam

The time structure of the beam from the accumulator ring to the buncher ring should be shaped as shown in Fig. 4.4.4, otherwise the beam comes into the buncher ring will collide with the septum during the shift of the closed orbit. To assure a beam void of 200 ns after five revolutions in the accumulator ring, a void of 250 ns just before the injection into the accumulator ring is enough. The debunching effect of the beam during five turns in the accumulator ring is estimated as less than ±7.5 ns for a beam with a momentum spread of ±5 × 10⁻⁵. Hence the time structure of the beam to be injected into the accumulator ring should be as shown in Fig. 4.4.5.

In the above scheme, the dilution factor of transverse phase density is 2.67 for a five times peak current increase. Detailed numerical calculations of this injection scheme which take the space charge effect into account are described in the following section.

4.4.2 Computer Simulation of Multiturn Injection into the Accumulator and the Buncher Rings

In the present section we report the results of the simulation of multiturn injection into the accumulator and the buncher
rings, using two-dimensional program which takes account of the space charge effect.

The injection of 5 turns is studied for the accumulator ring where the $^{208}\text{Pb}^{+1}$ beam with the velocity of $\beta = 0.37$, the intensity of $I/\text{turn} = 0.51$ A, and the emittance of $\varepsilon_x = \varepsilon_y = 6 \text{ mm.mrad}$ is injected from the linac system. During the injection, the emittance parameters ($\alpha_i, \beta_i$; $i = x, y$) of the injected beam are kept fixed and the equilibrium orbit is shifted once.

SCOP2 is a two-dimensional simulation program which has been developed to study space charge effects on an ion beam passing through a multturn-injected beam in the ring. Each turn is assumed to be represented by a macrocanonical distribution simulated by 256 macro-particles.

As a lattice structure of the accumulator ring, a continuous focusing system is assumed to avoid too much CPU time. The acceptance at the injection point is $\alpha_x = \alpha_y = 0$ and $\beta_x = \beta_y = 50.3$ m for the accumulator ring and those of the buncher ring are $\alpha_x = \alpha_y = 0$, $\beta_x = 28.4$ m and $\beta_y = 13.2$ m, respectively.

Simulations are carried out by injecting beamlets without beam loss at the inflector septum of 2 mm thickness so that after 5 turns the beamlet of the first turn populates on the central region in the x-x' plane and those of the other four turns circulate around the central region at intervals of about 90°. Additionally, the tune is adjusted so as to compensate the tune shift induced by the space charge effect. Following results are obtained from the simulations.

On the first turn in the accumulator ring the space charge induces a Laslett-tune shift of 0.127 for $\nu = 12.25$. 

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On successive beam injections, beamlets rotate in the phase plane by the angle less than 30° due to the tune depression. Finally the beam distribution is given as in Fig.4.4.6. When the tune value is shifted to 12.27, however, the beamlets of the four turns rotate just 90° on the x-x' plane and the tune depression is compensated (Fig.4.4.7). The distortion of beam emittance becomes larger near the central region. The emittances \( \varepsilon_x \) and \( \varepsilon_y \) after the injection of 5 turns are estimated 80 mm•mrad and 6.6 mm•mrad, respectively and there is no beam loss at the septum. The same results have been obtained for the tune values from 12.25 to 12.28.

A Laslett-tune shift of 0.029 is found in the buncher ring for \( v = 6.75 \). The injection of 5 turns into the buncher ring suffers less from space charge effects than that in the accumulator ring. The typical simulation results are shown in Fig.4.4.3. \( \Delta K/K \) (\( K = \) quadrupole gradient \( B'/B_0 \)) has been adjusted to be 0.006, which corresponds to the tune variation of \( \Delta v/v = 0.003 \). No vertical emittance growth is observed. The horizontal emittance is increased from 6\( \pi \) mm•mrad to 77 \( \pi \) mm•mrad during the multi-turn process. When the fractional value of \( v \) is 0.75, the central beamlets in the x-x' plane gets near the septum just after two turns due to the repulsive force from the beamlet of the second turn. When the fractional value is 0.25, the central beamlet goes away from the septum. Then even if initial horizontal emittance is 7.5 \( \pi \) mm•mrad, the injection of 5 turns is still possible with \( v = 6.25 \).

Conclusively we can say as follows. For a series of multi-turn injections of 5 turns into the accumulator and the buncher...
rings, the initial \( \varepsilon_x \) and \( \varepsilon_y \) are assumed to be 6 mm•mrad and final ones are required to be smaller than 80 mm•mrad from the ring to the target. The two-dimensional simulations taking account of space charge effects show that the \(^{208}\text{Pb}^+1\) with \( \beta = 0.37 \) and \( I/\text{turn} = 0.51 \) A (or 2.55 A) is able to be injected via 5 turns into the accumulator ring (or the buncher ring) under the above emittance condition. The multturn injection can be performed in the simple way, during which the emittance parameters \( \alpha \) and \( \beta \) of the injected beam are kept fixed, the equilibrium orbit is shifted once, and the tune value \( v \) is adjusted so as to compensate the tune shift induced by the space charge.
Fig. 4.4.1. Acceptance Ellipse in $x-x'$ phase space and injected beam shapes.

Septum Position during 1-st turn  

Septum Position at 2-5 turns  

Septum Position after 5 turns
Fig. 4.4.2. Locations of Bumper Magnets.

Fig. 4.4.3. Time Structure of Magnetic Strength of the Bumper Magnet.

Fig. 4.4.4. Time Structure of the Beam from Accumulator Ring.
Fig. 4.4.5. Time Structure of the Beam from the Injector Linac to the Accumulator Ring.
Fig. 4.46. X-emittance during the injection of 5 turns into the accumulator ring, $\tau = 12.25$. 
Fig. 4.4.7. X-emittance during the injection of 5 turns into the accumulator ring ($v_0=12.25$, $v=12.27$).
Fig. 4.4.8. X-emittance during the injection of 5 turns into the buncher ring ($v_0=6.75$, $\Delta k/K=0.006$).
4.5 Beam Instabilities in Rings

In the present scenario, an accumulator ring and three buncher rings are to be used to achieve the required peak intensity on the target. In these rings various kinds of beam instabilities are anticipated which lead to emittance dilution in transverse and longitudinal phase spaces. Hence it is important to study these instabilities in connection with the beam requirements resulting from target physics.

4.5.1 Buncher Ring

Incoherent Space Charge Limit

The incoherent tune shift due to the space charge force in the ring is given by

$$
\Delta \nu = \frac{N R r}{\sqrt{3} \beta \beta' (a-b) / a} \left( \frac{q^2}{A} \right), \tag{4.5.1}
$$

where $N$, $R$ and $B$ are the number of circulating beam, the average radius of the ring and the bunching factor, respectively and $a$ and $b$ are longer and shorter beam radii, respectively. Taking the admissible tune shift, $\Delta \nu$, to be 0.25, the intensity limit of $^{197}$Pb$^{+}$ ions is $2.2 \times 10^{15}$. The number of ion is $1.67 \times 10^{15}$ to attain 4 MJ with a beam of kinetic energy 15 GeV, which should be provided from three buncher rings. So the accumulated ion number in each ring is $5.56 \times 10^{14}$, which is well under the calculated space charge limit before bunching.

Transverse Coherent Instability

The coasting beam stability limit for the transverse coherent resistive wall instability is given as follows

\[ \Delta \nu = \frac{N R r}{\sqrt{3} \beta \beta' (a-b) / a} \left( \frac{q^2}{A} \right), \tag{4.5.1} \]
\[ I_c \leq 4P \frac{AE_0 \nu \gamma}{q e |Z| R} \left[ \left( (n-\nu)n+\xi \right) \frac{\Delta p}{P} + \frac{3\nu}{3\sigma^2} \Delta \sigma^2 \right], \quad (4.5.2) \]

where \( I_0, E_0 \) and \( \Delta p \) are electric current of the beam, the rest mass of the proton and the full momentum spread at half height respectively and, \( Z \) represent the beam's transverse coupling impedance with the environment such as vacuum chambers and can be written as:

\[ Z = i\pi Z_0 \left[ \frac{1}{\beta^2 \gamma^2} \left( \frac{1}{a^2} - \frac{1}{b^2} \right) - (1+i) \frac{\delta}{b} \right]. \quad (4.5.3) \]

In the present case of the HIF buncher ring, real and imaginary parts of \( Z \) are \( 3.7 \times 10^5 \) (\( \Omega/m \)) and \( 1.7 \times 10^6 \) (\( \Omega/m \)), respectively. Assuming \( \xi = -\frac{3\nu}{3\sigma^2} \) to be -10 and no amplitude-dependent tune spread, the threshold current of this instability is calculated at 0.215 A, which corresponds to the circulating ion number of \( 9.4 \times 10^{11} \). Hence the threshold of this instability is more than 1 order lower than the number of ions to be accumulated in a buncher ring.

The e-folding growth time, \( \tau \) is given by the relation

\[ \frac{1}{\tau} = \frac{cI_0 Re(Z) q e}{4\pi \nu \gamma A}, \quad (4.5.4) \]

and is calculated at 12.4 ms, which is long enough compared with the time necessary for beam bunch compression in the buncher ring.

Summarizing the above discussion, the transverse resistive wall instability will occur, but is should not be harmful until the bunch compression is completed and beam is extracted.

**Longitudinal Coherent Instability**

The threshold current of this instability is given by the Keil-Schnell criterion:

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where \( Z_{11} \) is the longitudinal coupling impedance of the beam with the environment such as vacuum chambers. For the ideal case of cylindrical beam and vacuum chamber, \( Z_{11} \) is given as follows:

\[
\frac{Z_{11}}{n} = \frac{i}{2} \cdot \frac{Z_0}{\beta_Y^2} \left[ 1 + 2\ln\left( \frac{b}{a} \right) \right]. \tag{4.5.6}
\]

Assuming the value of 2 for \( \gamma = 1 + 2\ln\left( \frac{b}{a} \right) \), \( \left| \frac{Z_{11}}{n} \right| \) is calculated at 872.5 (\( \Omega \)) and the threshold current is estimated at 1.114 (A), which corresponds to ion number of \( 4.87 \cdot 10^3 \). Thus also this instability is anticipated to occur.

From the dispersion relation:

\[
(V' + iU')J = 1, \tag{4.5.7}
\]

the stable region for this instability is calculated for parabolic distribution as shown in Fig. 4.5.1. From the relation

\[
V' + iU' = \frac{2I, e^q}{\Delta m_0 c^2 \beta^2 Y - \left( \frac{Z_j}{P} \right)^2} \left( \frac{Z_r}{n} + \frac{Z_i}{n} \right), \tag{4.5.8}
\]

where \( Z_r \) and \( Z_i \) denote real and imaginary parts of \( Z_{11} \), respectively, \( V' \) and \( U' \) are calculated at 0.21 and 7.26, respectively if the value of 25 \( \gamma \) is assumed for \( \frac{Z_j}{n} \). In the figure this is indicated together with the case of accumulator ring. It is known that both cases are far from the stable region.

The \( I_m(x) \) for the present case is read to be 0.036 and the maximum mode number of this instability is thought around 2500, so the growth rate \( \tau \) is calculated by the relations:

\[
\frac{1}{\tau} = n S I_m(x), \quad S = -\frac{1}{2} \eta \omega_0 \frac{\Delta P}{P}, \tag{4.5.9}
\]
which lead to the result of $\tau = 150$ $\mu$s. This time is rather short compared with the necessary time for bunch compression. Experimental approach to reduce the real part of $Z_{11}$ would be inevitable to manage this instability for HIF buncher ring.

4.5.2 Accumulator Ring

Incoherent Space Charge Limit

The intensity limit of the accumulator ring due to incoherent tune shift is calculated at $6.3 \times 10^{14}$ which is higher than the number of ions to be stored in the accumulator ring $5.6 \times 10^{14}$.

Transverse Coherent Instability

The threshold current for the present case is calculated at 4 mA, which corresponds to the ion number of $9.4 \times 10^{11}$. This value is far lower than the accumulated intensity of $5.6 \times 10^{14}$, but the growth rate is estimated at 1.6 ms for the present case, which is much longer compared with the residence time of beam in the accumulator ring $\sim 200$ $\mu$s. So this instability is expected to cause no serious problem also for the case of the accumulator ring.

Longitudinal Coherent Instability

Assuming the value of $g$ as 2, $\frac{Z_{11}}{2}$ is 872.5 $\mu$s for the accumulator ring and the Keil-Schnell criterion gives threshold current of 1.128 A for the present case. Corresponding ion number is $2.5 \times 10^{14}$, which is nearly half of the accumulated ion number $5.5 \times 10^{14}$. The situation is well understood from Fig.4.5.1, where the case of the accumulator ring locates outside the stable region. For the accumulator ring case, $I_m(x_1)$ and $n_{\text{max}}$ (maximum mode number) are estimated at 0.01 and around 20000, respectively.
so the growth time is calculated at 330 μs. This is a little longer than the beam residence time in the accumulator ring. Five times e-folding time might be safe even if a memory of linac bunch structure remains and this instability can be considered to cause no serious problem in the accumulator ring.

4.5.3 Conclusion

From the above discussion, it is found that only the longitudinal coherent instability in the buncher rings might cause severe problem. However we have assumed the real part of longitudinal coupling impedance of 25 Ω from the experience at CERN ISR. The growth rate largely depend on this value, so experimental approach to reduce $Z_r$ might be inevitable to manage this instability in connection with HIF driver design. It is also important to study how many e-folding times are tolerable for various beam characteristics such as energy distribution and beam profile etc.
References


3) B. Zotter, "Transverse Instabilities of Relativistic Particle Beams in Accelerators and Storage Rings", CERN 77-13 (1977) 175.


FIG. IV-48 Stability Diagram of Longitudinal Instabilities.
4.6 Beam Bunching in the Buncher Ring

In this scenario, bunching by a factor 14 is assumed in the buncher ring where two bunches, containing $2.8 \times 10^{11}$ ions each, are made to rotate in $(\Delta \rho/\rho, \phi)$ space by applying a linear RF field. A linear rotation is necessary to prevent filamentation. Careful attention should be paid to both the space charge compensation and bunch rotation voltages, and the bunching time should at most comparable to the blow up time of longitudinal and transverse microwave instabilities. Horizontal beam emittance growth due to the crossing of resonance lines during the bunching is a critical problem with the tight emittance limit of 80 nm-mm-mrad imposed by the small beam spot on the target.

The space charge field per unit length in the ring is given by

$$E_z = -\frac{qge}{4\varepsilon_0 Y^2} \frac{\partial \lambda}{\partial z}$$  \hspace{1cm} (4.6.1)

where $g$ is a geometrical factor $g = 1 + 2\ln \frac{b}{a} - \left(\frac{\rho}{a}\right)^2$, and $\lambda$ is the line density.

We assume parabolic beam distribution:

$$\lambda(z) = \lambda_0 \left[1 - \left(\frac{2z}{\lambda}\right)^2\right]$$  \hspace{1cm} (4.6.2)

where $\lambda$ is total bunch length. Substituting $\lambda(z)$ in the relation (4.6.1) we get

$$E_z = -\frac{3qgeN}{2\varepsilon_0 Y^2 \lambda^2}$$  \hspace{1cm} (4.6.3)

at the bunch ends where the space charge field is maximum. The maximum voltage per turn in the ring is then $2\varepsilon E_z$ which can be rewritten as

$$V = \frac{3Nge}{2T^2} L$$  \hspace{1cm} (4.6.4)
where $2T$ is the bunch length in sec and $L$ is space charge inductance

$$L = \frac{gZ_0}{28\gamma^2 \omega_0} \quad (4.6.5)$$

with $\omega_0$ = revolution angular frequency, and $Z_0 = \text{characteristic impedance of free space (120 \, \text{mohms)}$.}

Initially, this longitudinal space charge force is small compared with the bunch rotation voltage, but the forces at the bunch ends drastically increase, inversely as the square of the bunch length. As shown in Table 4.6.1, it needs up to 4.2 MV to compensate the repulsive space charge forces.

If the space charge force is continuously compensated by RF cavities in the ring, the number of revolutions to reach a peak value of the momentum spread $\Delta p/p$ at the quarter synchrotron oscillation point, $n$, is given by

$$n = \gamma/(4\eta h \Delta p/p) \quad (4.6.6)$$

and the RF voltage required to produce the bunch rotation is

$$q\text{eV} = \pi^2 \beta^2 \gamma A m_0 c^2 / (8\eta h n^2) \quad (4.6.7)$$

where $\gamma = |\gamma^2 - \gamma^2_c| = 0.832$ is a dispersion of the ring, and $A$ is the mass number. For 15 GeV Pb$^{1+}$ ions, a linear RF focusing field of 250 KV is sufficient; $n$ is 295 turns for the max $\Delta p/p$ of $1.6 \times 10^{-3}$. Bunching time $nT$ is then 2.02 ms which might be too long considering the blow-up time of longitudinal microwave instabilities.

A ferrite loaded resonant cavity module can produce a low frequency 300 KHz RF field with an amplitude of 50 KV.
Using improved Mn-Zn ferrites with a permeability of \( \mu \approx 5000 \mu_0 \), a one meter long module can be tuned to the desired frequency with an extra gap capacitance of 2000 pF. In the buncher ring 90 cavities are installed to produce the peak voltage of 4.5 MV and nearly the same number of cavities can be used to excite the higher harmonics so as to obtain the linearly rising field.
Table 4.6.1  Compression in Buncher Ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of particles/bunch</td>
<td>$2.83 \times 10^{14}$</td>
</tr>
<tr>
<td>Initial bunch width</td>
<td>$\pm 1.72 \ \mu$s</td>
</tr>
<tr>
<td>Final bunch width</td>
<td>$\pm 0.123 \ \mu$s</td>
</tr>
<tr>
<td>Frequency of saw tooth wave</td>
<td>300 KHz</td>
</tr>
<tr>
<td>Longitudinal space charge impedance</td>
<td>$-850.6 \ \Omega$</td>
</tr>
<tr>
<td>Inductance</td>
<td>$9.28 \times 10^{-11} \ \text{H}$</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>$1.14 \times 10^{-3}$</td>
</tr>
<tr>
<td>Compensation voltage for space charge force</td>
<td>$4.26 \ \text{MV}$</td>
</tr>
<tr>
<td>Bunch rotation voltage</td>
<td>$260 \ \text{KV}$</td>
</tr>
</tbody>
</table>
4.7 Beam Transport, Bunch Compression and Final Focusing

4.7.1 Introduction

Stable transport of intense heavy ion beams from the accelerator to the fusion reactor chamber and focusing on a small target pellet are the most crucial problems in heavy ion fusion (HIF). Their solutions determine most of the parameters of the accelerators. The ballistic beam transport through long periodic transport lines in vacuum ($< 10^{-7}$ Torr) has been recognized to be more tractable than a plasma channel transport.

A critical reactor design parameter which affects the final transport is the stand-off distance from the final focusing Q-magnet to the target (5.5 m). The number of beam lines has been fixed at six. The power necessary to initiate fusion reaction then demands a particle current per beam (Pb$^+$ beam of 15 GeV kinetic energy) of about 1.8 kA at the target.

To obtain these high current beams, the beams extracted from the storage rings are compressed longitudinally during their drift through transport lines. The current limit transportable through the long periodic transport line is not so serious as long as a low charge state ion is chosen ($q = 1$). Space charge repulsion in the final focusing can be compensated by increasing the beam divergence, hence the radius of the entry port of the reactor. The lens apertures are limited by spherical aberrations. From the point of view of the chromatic aberrations, the transverse emittance and momentum spread should be as small as possible. A reasonable compromise between accelerators and final focus design has been found around 80 μm·mrad transverse emittances and 0.5 - 1.0% momentum spread.
Beam dynamic effects due to space charge play an important role in all of these processes: periodic transport, longitudinal bunch compression and final focusing. These subjects have been studied at the various HIF workshops. Here space charge aspects are recalled and the numerical calculations for HIBLIC scenario are presented.

4.7.2 Periodic Transport and Transverse Stability

Beam transport from the buncher ring to the reactor chamber requires a length of 1 to 2 km to perform a longitudinal bunch compression. It is then necessary to ensure a stable beam transport over a large number of periods of a quadrupole FODO focusing lattice without emittance growth. Space charge induced instabilities, i.e., emittance growth limits the transport current.

1. Sources of space charge induced instabilities

The mechanisms through which space charge induced electrostatic self-field can cause emittance growth are classified as collective instabilities that render a phase space unstable because of either a resonant coupling to the periodic structure, anisotropy between different degrees of freedom and non-monotonic distribution function.

Coupling to periodic structure

For zero current, the requirement for stable transport is

\[ \sigma < 180^\circ \]

where \( \sigma \) is the phase advance per focusing period, to avoid a half-integer resonance with the focusing period. For finite current, the space charge force depresses the tune to a value

\[ 0 < \sigma < \sigma_0 \]

and coherent oscillation of the beam can be in
resonance with the period of focusing system.

Analytic theory\(^9,10\) and computer simulations\(^11,14\) show that the quadrupole (i.e., envelope) modes of oscillation are stable if \(\sigma_0 \leq 90^\circ\), whereas the sextupole (i.e., third-order) modes require \(\sigma_0 \leq 60^\circ\) to avoid resonance. The higher order modes of oscillation have no effect on the r.m.s. emittance.

Anisotropy between different degrees of freedom

In a two or three-dimensional charge distribution, there can be a collective instability which transfers energy (emittance) from one degree of freedom to another, if the anisotropy in different degree of freedom is strong enough. This type of instability may be important in a transport system if transverse emittances in \(x, y\) are different. However a computer simulation\(^8\) shows that this instability is suppressed if strong tune depression is avoided.

Non-monotonic distribution function

If the phase space distribution is not uniform, such that there is considerably less density in the center of the distribution, the denser phase space elements tend to penetrate into the less dense region. This type of instability has been found in analytical theory for a Kapchinskij-Vladimirskij distribution\(^1\) (which covers only an ellipsoidal surface in the four-dimensional phase space). Computer simulation\(^5\) shows, however, that this source of instability is negligible in practice.

2) Scaling Laws for Current Transport

The considerations on coherent instabilities show the possibility of unlimited current transport through periodic channels with a zero intensity-phase advance \(\sigma_0 = 60^\circ\) for beams with equal
or almost equal horizontal and vertical emittances. Hence the practical limitation on current intensity is set by the design of the magnet lattice of the periodic transport channel.

By solving the scaled Kapchinskij-Vladimirskij (K-V) envelope equations,\(^{(15,16)}\)

\[
\frac{d^2 U_x, y}{d \theta^2} = - S_{x,y} U_x, y + \frac{1}{U_x^3} + \frac{Q'}{U_x + U_y} \quad (4.7.1)
\]

the scaled space charge parameter \(Q'\) and maximum envelope \(U_{\text{max}}\) can be determined for a given \(\sigma / \sigma_0\) and lattice arrangement (with magnet occupancy factor \(\eta\)). By descaling, the scaled quantities or a given \(\sigma / \sigma_0\) can be related to the current \(I\), the maximum beam envelope \(a_{\text{max}}\) and the length of a quadrupole magnet of the cell. And the following scaling laws are obtained.

\[
I = 3.66 \times 10^5 \left(\frac{A}{q}\right)^{1/3} \beta_0^{2/3} (\beta Y)^{7/3} \epsilon^{2/3} \frac{Q'}{U_{\text{max}}} \quad [A] \quad (4.7.2)
\]

\[
a_{\text{max}} = 1.46 \cdot \left(\frac{A}{q}\right)^{1/3} (\beta Y)^{1/3} U_{\text{max}}^{2/3} \epsilon^{2/3} B_0^{-1/3} \quad [m] \quad (4.7.3)
\]

\[
\lambda = H \left| K \right|^{-1/2} \quad [m] \quad (4.7.4)
\]

where

- \(L\) magnet length (m)
- \(H = H(\sigma_0, \eta)\) scaled magnet length
- \(B_0\) magnetic field in Tesla at the maximum beam radius \(a_{\text{max}}\)
- \(K = \frac{B_0}{a_{\text{max}}}\)
- \(A\) mass number
- \(q\) charge state of ion
- \(\epsilon = \frac{1}{\pi} \times \text{Emittance (m\cdot rad)}\)
- \(\beta = v/c\) \quad \(\gamma^2 = (1 - \beta^2)^{-1}\)
Fig. 4.7.1 shows the numerical results of the scaling laws for the case of a Pb$^+$ beam with a kinetic energy of 15 GeV and $\epsilon = 8 \times 10^{-5}$ m·rad transported through a FODO lattice with $\sigma_0 = 60^\circ$ and $\eta = 1/2$. The three curves correspond to different field strengths at the maximum envelope.

4.7.3 Longitudinal Bunch Compression in the Final Beam Line

To obtain high current beams at the target in the fusion reactor, the ion beams extracted from the buncher ring are longitudinally compressed during the final beam transport. This longitudinal bunching process is explained in longitudinal phase space (Fig. 4.7.2). The initial beam with longitudinal bunch length $L_0$ and momentum spread $(\Delta p/p)_0$ is presented as phase space ellipse. The initial tilt of the phase space ellipse is obtained by the ramped voltage of an induction linac of several hundred meters length. The phase space rotation is performed in a drift section of about 1 kilometer length. During this drift, $\Delta p/p$ is reduced by space charge repulsive force $(\Delta p/p)_z \cdot (\Delta p/p)_t$.

Longitudinal bunch compression is described by an envelope equation:

$$\frac{d^2z_m}{ds^2} = -\frac{qeE_0\alpha}{Amc^2\gamma^3\epsilon^2} z_m + \frac{\epsilon^2}{\gamma z_m^3} + \frac{3}{2} A \frac{q^2}{\epsilon^2\gamma^5} \frac{\Delta p}{p} z_m^2$$

(4.7.5)

with:

- $z_m$ longitudinal envelope (bunch half-length) in $z$
- $\epsilon$ $1/\pi \times$ longitudinal emittance in $(z, \Delta p/p) = \frac{\Delta p}{p} \cdot z_m$ for upright ellipse
- $q$ charge state
- $A$ Mass number
\( r_i \) classical proton radius (\( \approx 1.546 \times 10^{-18} \) m)

\( N \) total number of ions in bunch

\( g \) geometric factor \( \approx 1 + 2 \ln \frac{R_{wall}}{R_{beam}} \)

\( q \) linear bunching force of linac.

This equation assumes a linear space charge force, i.e. parabolic line density. Assuming constant longitudinal emittance during bunching, the momentum spread \((\Delta p/p)_i\) necessary to achieve the designed final beam half-length \(z_t\) and final momentum spread \((\Delta p/p)_t\) with \( \varepsilon = z_t \cdot (\Delta p/p)_t \) is given by

\[
(\frac{\Delta p}{p})_i^2 = (\frac{\Delta p}{p})_t^2 + 3 \frac{q^2}{A} \frac{\varepsilon}{\beta^2 \gamma} \frac{N r_i}{z_t} . \quad (4.7.6)
\]

The total voltage necessary to obtain this tilt of phase space ellipse with \((\Delta p/p)_i\) is given by,

\[
q \varepsilon E_0 a_2 s = \frac{\gamma + 1}{\gamma} T (\frac{\Delta p}{p})_i \quad [\text{coulomb} \cdot \text{Volt}] \quad (4.7.7)
\]

where:

- \( T \) kinetic energy
- \( s \) length of the linac section.

\((\Delta p/p)_t\) is limited by chromatic aberration of the final focusing system. We take \((\Delta p/p)_t = 0.5 \times 1.0\%). In real case, dilution of the emittance due to non parabolic shape and finite \( \Delta q/g \)-effect may occur.

Fig.4.7.3 shows the solution of the envelope equation for the example of ten-fold bunch compression. Two cases (A & B in Fig.4.7.3) of final momentum spread at target \((\Delta p/p)_t\) are presented. The calculations are performed for the following values of the parameters.

**Ion Pb**

\( A = 208, \quad q = 1, \quad T = 15 \text{ GeV.} \)

\( \beta = 0.37222, \quad N = 2.783 \times 10^{14} \) (1.78 kA at target).
\[ z_0 = 14 \text{ m} \quad \text{\( \Delta p/p \)}_0 = \pm 0.5 \times 10^{-3} \]
\[ z_t = 1.4 \text{ m} \quad \text{\( \Delta p/p \)}_t = \pm 0.5 \times 10^{-7} \quad (A) \]
\[ = \pm 1.0 \times 10^{-3} \]
\[ = \pm 1.0 \times 10^{-2} \quad (B) \]

Total voltages \( V/q = eE_0 \alpha z_0 s \), necessary to tilt the ellipse are

\[ V/q = 254 \text{ MV} \quad \text{for} \quad \text{\( \Delta p/p \)}_t = 0.5 \times 10^{-7} \quad (A) \]
\[ = 364 \text{ MV} \quad \text{\( \Delta p/p \)}_t = 1.0 \times 10^{-7} \quad (B) \]

respectively.

We further assume that the bunching voltage \( V/s = 1 \text{ MV/m} \) and \( \alpha = 2 \). \((R_b/R_0 = 1.05)\). It is concluded that the total length of the final transport line from the buncher ring to the target is about 1.58 km in the case \( (\Delta p/p)_t = 1\% \).

4.7.4 Final Focusing on the Target

1) Final Drift from the Last Focusing Element to the Target

Kachinshkij-Vladimirskij (KV-) envelope equation\(^{15,16}\) is solved to see the beam radius at the entry of the reactor chamber (5.5 m from the target) for different beam sizes at the target.

Fig.4.7.4 shows the envelope solutions for the final current 1.78 kA of a 15 GeV Pb\(^+\) beam with \( \alpha = 80 \text{ mm-mrad} \). It is concluded that the beam radius at the entry is \( \sim 15 \text{ cm} \) to have a 3 mm radius spot at the target.

2) Final Focusing Constraints

Focusing beams on the small target pellet requires some considerations on chromatic and geometrical aberrations.
To keep the spot size diffusion on the target due to the chromatic aberration below the target size, $\Delta p/p$ must satisfy the following condition,\textsuperscript{14,16}:

$$\Delta p/p \leq \frac{r_t^2}{cL} \frac{1}{1+\alpha}$$

where $r_t = \text{target radius } 4 \text{ mm}$

$L = 5.5 \text{ m distance between target and final focusing element}$

$\alpha = 5 \sim 6$ is related to the variation of the envelope and can be minimized by keeping the envelope as smooth as possible. Hence $\Delta p/p \leq 0.6\%$. To keep $\gamma$ small, steep waists in the envelope must be avoided.

However, to protect the bending magnets and the quadrupole magnets in the transport and focusing system from the radiation coming from the reactor, we must put a waist in the envelope for shielding between the final quadrupole triplet and the upstream transport system. Fig.4.7.5 shows an example of envelope solution with space charge\textsuperscript{13} between the target and the waist through the final quadrupole triplet. In this example, the spot size is also affected by geometric aberrations. Hence it is necessary to take into account the aberration correction with space charge in a more practical design of the focusing system.
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17) L. Smith, Proc. of Heavy Ion Fusion Workshop, Berkeley, 1976,
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18) K. G. Steffen, High Energy Beam Optics, Interscience Publishers,
19) Envelope Solutions with space charge was obtained by program
    code SCOP1. I. Bozsik and I. Hofmann, Nucl. Instr. and
Fig. 4.7.1. Scaling Laws for Periodic Transport.

Phase Advance in Degree.

Maximum Envelope.

At

B_0 : Field Strength

\( B_0 = 30 \text{ mT} \) and
\( p_b = 15 \text{ GeV} \)
\( \theta_0 = 60^\circ \)
\( F_0 = \frac{1}{2} \)

Maximum Envelope (cm)
Fig. 4.7.2. Bunch Compression with Linear Induction Voltage Ramp and Subsequent Drift Section.
Fig. 4.7.3.-b Longitudinal Envelope Solution \( (\Delta P/P) = 1.0 \% \).

\( \Delta P/P \)

\( S (\text{M}) \)

\( (\Delta P/P)_T = 1,0 \% \)

\( Z_T = 1,4 \text{M} \)
Fig. 4.7.4. Envelope Solutions in Final Focusing Drift Section for Different Beam Sizes at Target.

$E_B = 2.0 \text{ mm}$

$3.00 \text{ mm}$

$3.2 \text{ mm}$

$4.0 \text{ mm}$

$P_B = 15 \text{ GeV}$

$I = 1.78 \text{ kA}$

$\epsilon = 80 \text{ mm-kG}$
Fig. 4.7.5. Envelope Solutions with Space Charge in the Final Quadrupole Triplet.

$I = 1.78 \text{ kA}$
$
\epsilon = 80 \text{ mm-Mrad}$,

$P_B = 15 \text{ GeV}$.
4.8 Final Focusing Elements

4.8.1 Introduction

Final focusing elements in the Heavy Ion Fusion (HIF) reactor have to concentrate the ion beams on a tiny target pellet. In the HIBLIC design, several three-dimensionally arranged ion beams hit the target at the reactor center from each corner of a rectangular prism around the reactor furnace. Such an arrangement of the focusing elements will need detailed study of the difficult mechanical, operational and civil engineering problems before the construction. For example, the three-dimensional supporting structures and the tunnels for the installation of the beam transport elements will be complicated.

In regard to the length of the final focusing section, a longer section is preferable to accommodate the focusing elements. If a long focusing section is chosen, there are many options for the beam optics, including present conventional beam focusing devices. In this design a compact HIF system is studied. Therefore, the following design study is concentrated on a modern and short focusing system.

4.8.2 Beam Optics

A short and strong beam focusing element always requires large beam apertures and high magnetic fields at the pole races or in the coil windings. Figure 4.8.1 shows a beam envelope in the final focusing system of the HIF design, calculated with the program TRANSPORT. The symbols used in Fig.4.8.1 are the same as used by K. G. Steffen. The beam design criteria are as
follows.

- The ion beams should be concentrated on the target pellet, having a diameter of 6.4 mm.
- The total length of the final focusing system from the intermediate focal point to the target is about 30 m.
- The downstream end of the final quadrupole magnet is at the distance of 5.5 m from the target.
- There is no bending magnet on the downstream side of the intermediate focal point.
- The maximum beam momentum of the 'Pb' ion beam is near 80 MeV/c.
- The horizontal and vertical unnormalized phase space beam emittances are the same and equal to 60 mm·mrad.
- The density distribution in the beam profile is Gaussian.
- The maximum magnetic field induction in the quadrupole magnets is below 12 T.
- The focusing structure is a horizontal FDF.

The results of this calculation show the necessity of the large aperture and high field gradient quadrupole magnets. These quadrupole magnets could be developed in the future by the use of the superconducting technology.

The inside radiation shields around the beam aperture will be required to protect the coils from the radiation damage by neutrons from the target as well as by heavy ion stray beams.

The beam profiles and the phase space emittances at the intermediate focal point and the target are given in Figures 4.8.2 and 4.8.3.
4.8.3 Superconducting Material

Recent rapid developments in the superconducting magnet technology are convincing us that it should be possible in the near future to make quadrupole magnets, having beam apertures over 1 m and field gradients near 10 T/m.

Even at present we can utilize two kinds of superconductors in the region above 10 T. One is the NbTi(Ta) alloy stabilized conductor at 1.8 K and the other is the A15 compound stabilized conductor such as Nb₃Sn, operating at 4.2 K.

The problems are not in the superconductors themselves but in the manufacturing techniques, electromagnetic forces and radiation sources of the magnets.

Many excellent superconductors such as Nb₃Sn, V₃Ga, and Nb₃(Al, Ge), having very high critical temperatures and magnetic fields, are now in the improvement stage for practical applications. These conductors could be selected in the future depending on the requirements for the final focusing elements.

4.8.4 Quadrupole Magnet Design

The cross sectional structure of the superconducting quadrupole has to have an approximated cos² current configuration as shown in Fig.4.8.4.¹) According to the magnetic iron temperature, there are two kinds of the superconducting quadrupole magnets. One is the so-called warm iron magnet, because the magnetic iron yoke is in the outside of the cryostat. The other is called as the cold iron quadrupole magnet and the iron yoke is cooled with liquid helium together with the superconducting coils. Each type of quadrupole magnet has its own merits and demerits.
For the future HIF final focusing elements, a warm iron quadrupole of Al5 superconductors seems to be preferable, because of the small cold mass to be cooled with liquid helium and the high critical temperatures of the superconductors. In this type of quadrupole magnet, the superconducting coils should be tightly clamped with non-magnetic, radiation resistant supporting structures as shown in Fig.4.8.4. The superconducting cables in the coils should also be strong enough to stand against the huge electromagnetic forces.

Typical parameters of the final focusing quadrupole magnet are given in Table 4.8.1.

4.8.5 Radiation Damages

There are few reports which describe the superconductor performance deterioration after a neutron flux irradiation over \(3 \times 10^{13} \text{ n/cm}^2\).\(^{3,4}\)

After a neutron irradiation of \(3 \times 10^{19} \text{ n/cm}^2\), the critical temperatures of the Al5 compounds decrease to about 80\% and the critical current densities are reduced to one half of that before the irradiation.

Therefore the direct neutron irradiation of the superconducting coils in the final focal elements should be avoided. Otherwise the elements could not survive for a long time.

The conventional method to prevent the neutron irradiation is to put some radiation shielding material at the inside of the coils. An alternative is to provide radiation resistant coils at the inside of the superconducting coils, made of mineral insulated normal conductors. In this case, the final focusing quadrupole
magnet should have a hybrid coil configuration. The larger part of focusing power will be provided by the outside superconducting quadrupole coils, and a small part by the inside normal conducting coils, placed in the neutron shielding space.

With respect to the radiation damage of the superconductors, there are new excellent Cl5 materials such as $\text{V}_2(\text{HfZr})$ and $\text{V}_2(\text{HfNb})$ which could stand against neutron irradiations for almost one order of magnitude higher. The critical temperature and the upper critical field of these conductors are about 10 K and 20 to 26 T at 4.2 K, respectively.\textsuperscript{5)} If these superconductors are available in the future, the difficulties with the radiation damages in the final focusing superconducting quadrupole magnets will be greatly reduced.
Table 4.8.1  Parameters of the Final Focusing Quadrupole Magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner coil diameter</td>
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</tr>
<tr>
<td>Outer coil diameter</td>
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</tr>
<tr>
<td>Radiation shield thickness</td>
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<tr>
<td>Field gradient in the beam aperture</td>
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</tr>
<tr>
<td>Average current density in the coil</td>
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</tr>
<tr>
<td>Peak field in the coil</td>
<td>&lt; 12 T</td>
</tr>
<tr>
<td>Superconductor</td>
<td>Nb₃Sn/Cu(Ti)/Al and/or V₁(HfZr)/Cu/Al</td>
</tr>
<tr>
<td>Length of the coil</td>
<td>&lt; 5.0 m</td>
</tr>
<tr>
<td>Magnetic iron shield outer diameter</td>
<td>2.5 m</td>
</tr>
</tbody>
</table>
References


Fig. 4.8.1. Beam Envelope of 80 GeV/c Heavy Ion and the First Order Beam Optics.

Beam Envelope of 80 GeV/c Heavy Ion

Horizontal Plane

Vertical Plane

Field Gradient and Beam Optics Parameters

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Fig. 4.8.2. Beam Profiles at the Intermediate Focal Point and the Target Position.

**Horizontal Image**

<table>
<thead>
<tr>
<th>$X_0$ [mm]</th>
<th>At Intermediate Focus</th>
<th>At Final Focus</th>
</tr>
</thead>
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<tr>
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<tr>
<td>-10</td>
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**Vertical Image**

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<tr>
<td>0</td>
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<tr>
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**Horizontal Gradient**

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<td>0</td>
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</tr>
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<td>-5</td>
<td></td>
</tr>
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<td>-10</td>
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<table>
<thead>
<tr>
<th>$Y'$ [mr]</th>
<th>At Intermediate Focus</th>
</tr>
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<tbody>
<tr>
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<td>-5</td>
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</tbody>
</table>
Fig. 4.8.3. Phase Space Emittances at the Intermediate Focal Point and the Target Position.

at Intermediate Focus

- Beam Image
  - $\sim 20\text{mm}$

- Solid-Angle Acceptance
  - $\sim 200\text{ mrad}$

- Horizontal Emittance
  - $\sim 80\times\text{mm-mrad}$

at Final Focus

- $\sim 6\text{mm}$

- $\sim 80\text{ mm-mrad}$

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Fig. 4.8.4. Cross Sectional Structure of a Warm Iron Final Focusing Superconducting Quadrupole Magnet.
4.9 Method of Preheating

It is believed that preheating may be necessary in the heating process through projection of heavy ion beams unto a fuel pellet. The following is a suggestion for preheating the pellet.

Compression of the beam in the buncher rings is performed by way of rotation of the particles in the longitudinal phase space. For example, Fig. 4.9.1 shows the buncher voltage (a) and the resulting rotation of the beam in phase space (b). When the voltage has the sawtooth wave form, figure, the beam rotates like a propeller as shown in the figure and the line density becomes rectangular if the initial momentum distribution is uniform (c).

In this case, an effect of preheating cannot be expected. However, if the wave form of the compressing voltage is of triangular (or sinusoidal), preheating can be expected. In this case, the beam rotates taking the tail parts with it, and the particles in one of these tail parts serve as preheaters. (see Fig. 4.9.2).

Fig. 4.9.3 shows a concrete example.

\[ V = V_p \frac{t}{t_c}, \quad -t_c < t < t_c \]
\[ = V_p \left( -bt + \frac{Tb}{2} \right), \quad t_c < t < T/2 \]
\[ = V_p \left( -bt - \frac{Tb}{2} \right), \quad T/2 < t < -t_c \]

\[ b = \frac{2}{T - 2t_c}, \quad T: \text{period of the voltage} \]

\[ V_p: \text{peak voltage} \]

\[ \phi = ft, \quad f: \text{frequency of the voltage} \]
However, the two tail parts are formed symmetrically to both sides of the compressed part of the beam in the above case and the particles in the posttail are perhaps useless for heating the pellet. This situation brings some reduction of the driver efficiency. A method to improve the situation is to modify the voltage waveform as in the Fig. 4.9.4. Although the design of the cavities system may be tricky in this case, the driver efficiency is improved by the entry of the postheating particles into the compressed part of the beams (see Fig. 4.9.5).
Fig. 4.9.1

Fig. 4.9.2
4.10 Charge Transfer Processes of Low Charge State Heavy Ions

4.10.1 Introduction

With advent of powerful heavy ion accelerators, some significant progress has recently been made in investigations of the charge transfer processes involving high energy heavy ions. Data obtained in such investigations are, in turn, found to be very useful to develop efficient heavy ion accelerators. Particularly informations on electron capture and stripping (loss) of heavy ions are vital for designing very high energy heavy ion accelerator systems such as the NUMATRON. Up to now the main research effort has been devoted to the question of how to attain the highest charge state heavy ions in order to get the most efficient acceleration in heavy ion accelerators where the beam intensity is moderate or relatively low but higher energies are most paramount.

Over the past few years, another interesting aspect has arisen in application of heavy ion accelerators in nuclear fusion devices (Inertial Confinement Fusion system — ICF). For such a purpose, the most important requirement is an ion beam with very high intensity (up to a few tens of kA) but moderately high energy (up to 15 GeV). As a consequence ions with a low charge state can be one of the best choices. Then, the main effort is therefore now concentrated on how to produce, accelerate, and accumulate such heavy ions with highest intensity. In such accelerators the ion beam loss due to collisions with residual gas atoms is an even more serious problem than in conventional accelerators. Also, in such high intensity ion beams,
the ion-ion collisions can occur among the accelerating ions, a feature which can be neglected in conventional accelerators. These ion-atom and ion-ion collisions lead to beam loss of the accelerating and accumulating heavy ions. Thus, the results of charge changing processes may give rise to serious damage to the accelerator and storage ring structures. Unfortunately experimental and theoretical investigations of the collision processes involving heavy ions are very scarce except for those at very low energies, less than a few keV.

In this paper we review some aspects of the collision processes of heavy ions with very low charge state and estimate the beam loss due to such collisions.

4.10.2 Electron Capture, Stripping and Ion Beam Loss in Ion-Atom Collisions

General

When low charge state heavy ions are being accelerated in particle accelerators and accumulated in storage rings, the following processes can occur in collisions with residual neutral gas atoms or molecules in these systems (Xe ion is taken as an example of very heavy ions):

\[
\begin{align*}
\text{Xe}^+ + A & \rightarrow \text{Xe} + A^+ ; \quad \text{electron capture} \quad \rightarrow \mathcal{C}_e \quad (4.10.1) \\
\text{Xe}^{++} + A (\bar{z}) + e & \rightarrow \text{Xe} + A (\bar{z}) ; \quad \text{stripping} \quad \rightarrow \mathcal{C}_s = \mathcal{C}_{1n} \quad (4.10.2) \\
\text{Xe}^{++} + A (\bar{z}) + 2e & \rightarrow \text{Xe}^+ + A (\bar{z}) \quad \text{(projectile ionization)} \\
\text{Xe}^+ + A^+ + e & \rightarrow \text{target ionization} \quad \rightarrow \mathcal{C}_i \quad (4.10.3)
\end{align*}
\]

where $A$ represents the residual gas atom and $A(\bar{z})$ means all the possible states including ionization. The processes (4.10.1) and
result in the loss of the accelerating heavy ions. (Here we are not interested in the simple target ionization processes (4.10.3)).

The first process of the electron capture is usually dominant at relatively low energies and becomes insignificant at higher energies. On the other hand, the second process of electron stripping (ionization) from heavy ions becomes dominant over the first process at high energies. In order to see the dependence of these cross sections on the collision energy, the experimentally observed cross sections for electron transfer of all charge state hydrogen ion beam in H$_2$ gas are shown in Fig.4.10.1, which is one of the most thoroughly studied processes.

Similar data for charge transfer of He ions are shown in Fig.4.10.2. It is concluded from these figures that the stripping cross sections decrease slowly at high energies and are much larger than the electron capture cross sections which decrease very rapidly with increasing ion energy. For low charge state heavy ions, systematic investigations of the charge transfer processes are very scarce. Only in a limited energy range, data have been reported for heavy ions (see Fig.3). As seen in Fig.4.10.3, the relative contribution of the processes (4.10.1) and (4.10.2) in heavy ions seems to be very similar to those in H and He ion beams in Fig.4.10.1 and 4.10.2.

Collision and Beam Loss near Ion Source and Preaccelerator

As mentioned above, a low energies the electron capture processes are dominant. Particularly, they play a role near ion source and preaccelerator regions. There are a lot of neutral gases which are not ionized in the ion source and escape into
the preaccelerator column from the ion source. In that region, therefore, the symmetric electron transfer processes

\[ \text{Xe}^+ + \text{Xe} + \text{Xe} + \text{Xe}^+ \rightarrow \text{Xe} + \text{Xe}^+ + \sigma_{10} \]  

(4.10.4)

play a key role and have very large cross sections of the order of $10^{-14}$ cm$^2$ at the energy of 10 - 20 keV. Previously the beam loss due to the process (4.10.4) has not been taken into account properly. In order to keep the beam loss less than 0.1%, it is estimated that the average vacuum of the order of $10^{-7} - 10^{-8}$ Torr is required over the total length of 1 m along the ion source-preaccelerator column. As a result, it is concluded that the preaccelerator column length should be as short as possible to minimize the beam loss due to the electron capture processes in ion-atom collisions in that region.

**Estimation of Stripping Cross Section**

Once the heavy ions begin to be accelerated in the main accelerator such as a linac, the stripping processes (4.10.2) become dominant. However, no experimental data have been reported so far of the cross sections for low charge state heavy ions at such high energies. Fortunately, it is possible to estimate and calculate such stripping cross sections using the existing simple theoretical and empirical formulas for ionization by ion and electron impact.$^8$

According to the Born approximation valid at sufficiently high velocities, the cross sections for ionization ($\sigma_i$) by structureless charged particles like protons and electrons are given as follows:

---

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For ion impact:

\[ \sigma_i = \sum \frac{B \cdot n \cdot Z_{\text{eff}}^2}{I_0^2(E_i/I_0)} \ln(E_i/I_0) \quad (4.10.5) \]

where \( B \) is a constant depending on the target atom to be ionized, \( n \) is the number of electrons in the shell concerned whose binding energy is \( I_0 \), \( E_i \) is the ion energy per amu and \( Z_{\text{eff}} \) is the effective nuclear charge of ions.\(^9\)

For electron impact:

\[ \sigma_i^e = \gamma \frac{b \cdot n}{I_0^2(E_e/I_0)} \ln(E_e/I_0) \quad (4.10.6) \]

where \( b \) is a constant depending on the target atom\(^6\) and \( E_e \) is the electron energy.

Both formulas indicate that the product of \( \sigma_i \) and \( I_0^2 \) for electrons and of \( \sigma_i^e \) and \( I_0^2/Z_{\text{eff}}^2 \) for heavy ions can be given in a single scaling curve as a function of \( E/I_0 \), but not \( E \). In fact, this is shown in Fig.4.10.4(a) and (b) for He(1s) and C(1s) shell electron ionization for proton and electron impact, respectively.\(^10\)

It should be also noted that these cross section curves for two different atoms almost completely coincide with each other when the cross sections are scaled with \( I_0^2(C-1s)/I_0^2(He-1s) \) and the energy with \( I_0^2(He-1s)/I_0^2(C-1s) \).

From equations (4.10.5) and (4.10.6), it is found that, at sufficiently high energies \( (E_e \gg 30 I_0) \), the ionization cross section by ion impact is equal to \( Z_{\text{eff}}^2 \) times the ionization cross section by electron impact:

\[ \sigma_i^I(E_i/I_0) = Z_{\text{eff}}^2 \sigma_i^e(E_i/I_0) \quad (4.10.7) \]
where $\lambda$ is the mass ratio between electron and proton. There exists a good deal of experimental data on validity of formulas (4.10.5) and (4.10.6) and corresponding empirical formulas. The ionization cross sections pertaining heavy ions can be estimated from equation (4.10.7) using those for electrons which have been studied rather well.

According to the above discussions, we can formulate an empirical formula to calculate the stripping cross sections of low charge state heavy ions in collisions with, for example, $H_2$ molecules, by assuming that the stripping cross sections of, for example, $Xe^+$ ions incident upon $H$ atom are equal to the ionization cross sections of $Xe^+$ ions by $H$ atom impact at the same velocities:

$$
\sigma_s(Xe^+ + H; E_i/I_o) = \sigma_i(H - Xe^+; E_i/I_o) \quad (4.10.6)
$$

$$
= Z_{eff} \sigma_s(H^+ - Xe^+; I/H_2) \quad (4.10.9)
$$

$$
= Z_{eff} \sigma_s(e - Xe^+; E_i/I_o) \quad (4.10.10)
$$

If it is assumed that the residual gas consist mainly of $H_2$ molecules $Z_{eff}$ for $H$ impact equals 0.3, based on investigations by Buckett et al. 9) ($H_2$ is assumed to be two independent $H$ atoms). However, the determination of $Z_{eff}$ for neutral heavy atoms is very difficult. In fact, no conclusions concerning $Z_{eff}$ could be drawn even for $He$ impact. 9) However it may be safe to take $Z_{eff}$ equal to unity for most of the residual neutral gas atoms.

Using the above formula (4.10.9) or (4.10.10), the cross sections of electron stripping for $Kr^+$ ions incident on $H_2$
molecules can be calculated, as shown in Fig.4.10.5, using experimental cross sections available for ionization of Kr gas atoms by electron impact.\textsuperscript{11) It is found that the stripping cross sections for Kr\textsuperscript{+} ions are about a factor of 3 smaller than those for neutral Kr atoms due to the difference of the binding energy.

**Beam Loss during Acceleration and Accumulation**

With these numbers we can estimate the beam loss due to ion-atom collisions. During acceleration up to 1 MeV/amu, the average stripping cross section is about 10\textsuperscript{-14} cm\textsuperscript{2} which may be much larger than electron capture cross sections. Then, the beam loss is estimated to be about 0.1 - 0.03% at the background gas pressure of 10\textsuperscript{-8} - 10\textsuperscript{-9} Torr over the accelerator length of 1 km.

During accumulation, the beam loss due to stripping processes becomes increasingly significant. The average beam losses of 10 MeV/amu heavy ions during accumulation of 1 sec. are shown in Table 4.10.1. It is clear from this table that, in order to reduce the beam loss to about 0.8% level for ions with the average stripping cross sections of 1 \times 10\textsuperscript{-17} cm\textsuperscript{2} which seem to be a reasonable estimate for singly charged heavy ions, background gas pressure should be in the range of 1 \times 10\textsuperscript{-11} Torr. It is also found that the heavy ions having a configuration with stripping cross sections less than 1 \times 10\textsuperscript{-19} cm\textsuperscript{2} should be chosen as a candidate of the accelerating ions in order to keep the beam loss to level of 0.1% or less.
4.10.3 Electron Capture, Stripping and Ion Beam Loss Due to Ion-Ion Collisions

General

In ICF accelerators, where the ion beam intensities are many orders of magnitude higher than those in conventional accelerators, it is expected that charge transfer and stripping (ionization) processes between the accelerating ions may occur with substantial probabilities during acceleration and particularly during accumulation in storage rings.

The relative energy variation among the accelerating ions during these periods may be of the order of a few hundreds of keV at total energy of 10 GeV. These processes again result in the loss of the accelerating beams and then the charge-charged ions strike the walls of the accelerators and storage rings and sputter them away.

Typical processes in ion-ion collisions are almost the same as those in ion-atom collisions:

\[ \text{Xe}^+ + \text{Xe}^+ \rightarrow \text{Xe} + \text{Xe}^{2+} \text{; charge transfer} \quad \sigma_c \quad (4.10.11) \]

\[ \text{Xe}^+ + \text{Xe}^+ \rightarrow \text{Xe}^+ + (n-1)e \text{; stripping} \quad \sigma_s \quad (4.10.12) \]

To differentiate between the processes (4.10.11) and (4.10.12), the coincidence experiments are necessary.

Because of technical difficulties in ion-ion collision experiments, only a few experimental results of the cross section measurements have been reported so far. Very recently the Belfast group has reported total cross sections for production of doubly...
charged ions (sum of processes (4.10.11) and (4.10.12)) for 
Cs$^+ +$ Cs$^+$ and Xe$^+ +$ Xe$^+$ collisions. Only minor variations of the 
cross sections have been observed over the energy range 50 - 300 
keV (see Fig.4.10.6).$^{12}$

As the effective target thickness in such ion-ion collision 
experiments is far less than that of neutral background gases, 
ultra-high vacuum systems of the order of $10^{-10} - 10^{-11}$ Torr and 
the beam chopping techniques are required for such investigations 
in order to get reasonable signal-to-noise ratios.

According to some theoretical estimation, the contribution 
of the processes (4.10.11) and (4.10.12) depends on the electron 
configuration of the accelerating ions. For ions with the closed 
shell configurations such as Cs$^+ +$ Cs$^+$ or Xe$^{6+} +$ Xe$^{6+}$ systems, for 
example, the cross sections for ionization process (4.10.12) are 
large, compared with those for the charge transfer processes 
(4.10.11). Because the ionization cross sections are strongly 
dependent on the binding energy of ions, those for Cs$^+ +$ Cs$^+$ 
collisions are on the order of $10^{-16}$ cm$^2$ at about 100 keV,$^{13}$ 
whereas those for Xe$^{6+} +$ Xe$^{6+}$ collisions are about $10^{-15}$ cm$^2$. $^{14}$
For open shell ions such as Ba$^+ +$ Ba$^+$ systems, $^{15}$ the electron 
transfer cross sections are quite large and on the order of 
$10^{-14}$ cm$^2$.

As a complementary process to the electron transfer process 
(4.10.11), the following electron transfer process 

$$\text{Xe}^{2+} + \text{Xe} \rightarrow \text{Xe}^+ + \text{Xe}^+ \quad \text{(4.10.13)}$$

can also be investigated with the usual techniques. It is 
important to note that, if all ions and atoms concerned are in
the ground states, the cross sections for the electron transfer processes (4.10.11) and (4.10.13) should be the same; that is,
\[ \sigma_c(4.10.11) = \sigma_c(4.10.13) . \]  
(4.10.14)

This is verified for some processes such as Ti^2+ + H \rightarrow Ti^+ + H^+ collisions. This fact is quite helpful to estimate and calculate the cross sections for process (4.10.11). However, this is not applicable to the ionization process (4.10.12).

**Beam Loss Due to Ion-Ion Collisions**

Based upon these data mentioned above, the ion beam loss due to the ion-ion collisions can be estimated by using the following formula for ions with equal masses:
\[ I = c \left( \frac{M}{E_i} \right)^\frac{1}{2} \left( \frac{W}{E_i} \right)^\frac{1}{2} \int J_i J_i ds \]  
(4.10.15)

where \( I \) is the number of ions per sec. originating from collision processes (4.10.11) and (4.10.12), \( \sigma \) is the cross section in cm^2 per ion, \( E_i \) is the energy of ions with mass \( M \), \( W \) is the relative energy of ions, \( J_i \) and \( J_j \) are the ion beam fluxes per cm^2 per sec., \( s \) is the cross sectional area of the ion beam and \( l \) is along the beam axis in the interaction region.

It is assumed that 10 kA of 10 GeV U^+ ions with a bunch width of 10 nsec. are being accumulated in a storage ring, the energy variation in the beam is about 100 keV, and the cross section for charge transfer + ionization processes is about \( 10^{-16} \) cm^2. Then, the ion loss is estimated to be about 0.1%, assuming the uniform ion distribution over the area of the bunched beam of 1 cm^2 \times 100 cm. Even though the relative ion beam loss seems to be small, ions equivalent to 10 A peak current strike the walls of storage.
ring and, therefore, to choose ions with an appropriate electron configuration with smaller charge transfer + ionization cross sections for acceleration and accumulation in order to minimize the beam loss due to ion-ion collisions.

4.10.4 Concluding Remarks

We have discussed the ion-atom and ion-ion collision processes involving the low charge state heavy ions relevant to the beam loss in the ICF accelerators and accumulators. It has been shown that for such ions the electron capture processes are important only near the ion source and preaccelerator region and at energies higher than a few hundreds of keV/amu the electron stripping processes, whose cross section decreases slowly with increasing the impact energy, become dominant over the electron capture processes. Also it has been discussed that for acceleration and accumulation of low charge state heavy ions with very high intensity it is important to choose heavy ions with the closed shell configurations which correspond to the slightly more ionized states than the singly ionized state, in order to minimize the ion beam loss due to the charge changing processes. Then, by using such ions the accelerating efficiency is much more improved, compared with that for singly ionized ions. Furthermore, very high vacuum of the order of $1 \times 10^{-11}$ Torr is required for the minimum beam loss.

To have more accurate estimation of the losses of heavy ions, it is urgently needed to calculate and measure the cross sections of electron capture and stripping processes for ions with various electron configurations in ion-atom and ion-ion collisions over a wide range of the energy.
References

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4. H. Tawara, IPPJ-AM-1 (Nagoya University, 1977)
5. H. Tawara and A. Russek, Rev. Mod. Phys. 45 (1973) 178
13. F. E. Olson, ANL-79-41, p. 171
15. S. Sramek, J. Gallup and J. Macek, ANL-79-41, p. 153

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Table 4.10.1  Losses of 10 MeV/amu Ion Beams Due to Stripping in Ion-Atom Collisions during 1 sec. Accumulation Time.

<table>
<thead>
<tr>
<th>$P_0$ (Torr)</th>
<th>$\sigma_s (cm^2)$</th>
<th>average loss</th>
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<tr>
<td>$1 \times 10^{-11}$</td>
<td>$10^{-16}$</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>$10^{-17}$</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>$10^{-18}$</td>
<td>0.001</td>
</tr>
<tr>
<td>$5 \times 10^{-11}$</td>
<td>$10^{-16}$</td>
<td>0.236</td>
</tr>
<tr>
<td></td>
<td>$10^{-17}$</td>
<td>0.041</td>
</tr>
<tr>
<td></td>
<td>$10^{-18}$</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Fig. 4.10.1 Electron transfer cross section of hydrogen beams in H₂.
4.10.2 Electron transfer cross sections of Helium ion beams in $N_2$.

4.10.3 Electron transfer cross section of $Xe^+$ ions in $N_2$. 

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Fig. 4.10.4(a) Ionization cross sections of He 1-s shell electrons by protons and electrons.

Fig. 4.10.4(b) The same of C 1-s shell electrons as in Fig. 4.10.4(a).
Fig. 4.10.5 Estimated stripping cross sections of Kr⁺ ion, compared with ionization cross sections of Kr atom.

Fig. 4.10.6 Cross sections for production of Xe²⁺ ions in Xe⁺ + Xe⁺ collisions.
CHAPTER V  REACTOR SYSTEM

In the present HIF reactor design, a first structural wall of reactor cavity is protected from direct exposure to thermo-nuclear explosion by a liquid Li curtain introduced between the wall and target. This Li curtain is disrupted and its portion is evaporated at each target implosion. The Li vapor generated in the reactor cavity, however, prevents beam transport to the target, i.e., the beams diverge because of the space charge effect increased by ionizations that become considerable under the condition of the vapor pressure being greater than \(10^{-2}\) Pa. Therefore, the Li vapor must be condensed sufficiently within a repetition time (~1s) of target implosion.

5.1 Behavior of Li Curtain and Condensation Process of Li Vapor

Just after the target implosion, a thin layer near the inside surface of the curtain is irradiated by charged particles and target debris. This layer is imploded toward the center axis of the cavity and vaporized. At the same time, the Li curtain is volumetrically heated by X-rays and neutrons to be disrupted and spread over the reactor cavity in the form of liquid droplets. This phenomenon drastically enhances the condensation area for the vapor that also expands over the cavity after the curtain disruption and mixes with the Li droplets. The vapor pressure is thus reduced to ~10 Pa until the dispersing droplets reach the cavity wall or its center axis. After all Li droplets fall
into a Li pool at the bottom of the cavity, the residual Li vapor continuously condenses on the Li curtain re-established for the next cycle and its pressure becomes $\approx 10^{-2}$ Pa within a time of 0.1 s.

5.1.1 Energy Deposition in Li Curtain

In the cavity design, the cylindrical Li curtain with a radius of 1m and thickness of 3-5cm is directly exposed to a 400 MJ target implosion, where released energy is divided into 30 MJ of charged particles and target debris, 127 MJ of X-rays, and 243 MJ of neutrons. If the spectrum of X-rays is assumed to be of HIBALL design\(^1\) and the attenuation constant of neutrons to be $1/70 \text{ cm}^{-1}$ from Ref. 2, we obtain the energy deposition profile shown in Fig. 5.1.1.

References


5.1.2 Disruption of Li Curtain

The Li curtain is heated by X-rays and neutrons so rapidly that its thermal expansion cannot be accomplished due to the inertia constraint that generates the pressure of
\[ P = K\left(\frac{\rho}{\rho_0}\right)^2\left(\frac{\rho}{\rho_0} - 1\right) , \quad (5.1.1) \]
\[ \frac{\rho}{\rho_0} = 1 + \beta \varepsilon / C_p , \quad (5.1.2) \]

where \( K \) : bulk modulus (=10^10 Pa), \( \rho \) : density
\( \rho_0 \) : density at \( P = 0 \) (=500 kg/m^3)
\( \beta \) : coefficient of thermal expansion (=1.7\times10^{-4} \text{ deg}^{-1})
\( C_p \) : heat capacity (=4kJ/kg\cdot\text{deg})
\( i \) : deposited energy density shown in Fig. 5.1.1

Figure 5.1.2 shows the pressure profile in the curtain just after the target explosion. This pressure is relaxed by the rarefaction wave propagating from the inside and outside surfaces of the curtain and the compressional energy is converted into the radial kinetic energy. When the radial motion of the curtain expands its volume with generating the negative pressure, i.e., the tension, the curtain is cavitated and disrupted because the liquid Li has no tensile strength. The radial profile of the expansion velocity is also shown in Fig. 5.1.2.

On the other hand, the layer with a thickness of \(~1\mu\text{m}~\) near the inside surface of the curtain is heated by charged particles to be imploded toward the center axis and vaporized\(^2\). The interval of time taken for the vapor to implode and expand in the space enclosed by the Li curtain is roughly estimated to be \(2R/C_v\) (=200\mu s), where \( R \) is the curtain radius and \( C_v \) the velocity of sound of the vapor (~10 km/s for the vapor temperature of 10^5 K), during which the Li curtain can be freely expanded. Figure 5.1.3 shows the radial profile of void fraction \( \alpha \) in the Li curtain at 200\mu s after the target implosion. We find from this
figure that the mean void fraction in the curtain with the initial thickness $A_i$ of 3cm grows up to 40\textendash 50\% before the vapor pressure affects its motion significantly. Therefore, the interaction between the cavitated curtain and vapor will be small as the latter expands through the former that also continues to expand roughly with the velocity shown in Fig. 5.1.2.

References


5.1.3 Condensation of Li Vapor

As mentioned in the summary of this chapter, the evaporated Li must be condensed sufficiently within the repetition time of target implosion for the beam transports that requires the vapor pressure being less than $10^{-2}$ Pa. For the consideration of the condensation process of Li vapor, it is assumed that the Li vapor is initially in the thermal equilibrium with the inside surface of the Li curtain and then it expands adiabatically in the reactor cavity due to the curtain disruption. The initial temperature $T_s$ determined by the pressure $P_v$ of Li vapor inside the curtain. It should be noted that the calculation of the condensation time of Li vapor with this assumption gives a conservative result for the present problem, because the mass and thermal energy of initially evaporated Li takes their maximum values.

The mass $M$ of the evaporated layer of the Li curtain is
determined from the energy balance:

\[ e_M = M \left[ C_p (T_s - T_0) + L + \frac{3}{2} k (T_v - T_s) / m_{Li} \right] \] (5.1.3)

where \( e_M \) is the energy absorbed by the Li layer with the resultant temperature exceeding \( T_s \), and

- \( T_0 \) : initial temperature of Li curtain
- \( m_{Li} \) : mass of Li atom
- \( T_v \) : vapor temperature
- \( L \) : latent heat (=20 MJ/kg)
- \( k \) : Boltzmann constant.

The results are \( M=1.2 \text{kg}, T_v = 3.4 \times 10^4 \text{K}, T_s = 2000 \text{K} \) and \( P_v = 3.4 \text{MPa} \) (0.84 MPa after adiabatic expansion) for \( T_0 = 560 \text{K} \) under the present conditions. Figure 5.1.4 shows the temperature profile in the residual Li curtain to be disrupted. The disruption and fragmentation of Li curtain drastically increase the Li surface area for the condensation of Li vapor. For simplicity, the disrupting curtain is assumed to spread over the reactor cavity in the form of spherical liquid droplets with the same radius.

When the liquid Li with the surface temperature of \( T_{LS} \) is surrounded by the vapor with the pressure of \( P_v \) and the temperature of \( T_v \), the condensing particle flux \( J_c \) and the evaporating particle flux \( J_e \) are given from the kinetic theory as follows:

\[ J_c = C (2 \pi m_{Li} k T_v)^{-1/2} P_v \] (5.1.4)

\[ J_e = C (2 \pi m_{Li} k T_{LS})^{-1/2} P^* (T_{LS}) \] (5.1.5)
where $P^*(T_{LS})$ is the saturation pressure at $T_{LS}$ and $C (\ll 1)^2$ the coefficient of condensation (=coefficient of evaporation).

Dividing the Li droplets with different temperatures into 7 groups on the basis of Fig. 5.1.4, their surface temperatures ($T_{LS}$) are determined from the time dependent equation of thermal conduction.

The pressure $P_v$ with the number density $n_v$ of the Li vapor are obtained from the equations of particle balance and energy balance with account taken of the radiation heat transfer:

$$\frac{d}{dt} n_v = \frac{1}{V_c} \left\{ J_e dS(T_{LS}) - J_c S \right\}$$  \hspace{1cm} (5.1.6)

$$\frac{d}{dt} P_v = \frac{d}{dt} (n_v T_v) = \frac{k}{V_c} \left\{ J_e T_{LS} dS(T_{LS}) - J_c T_v S \right\}$$

$$- \frac{2}{3} K_p n_v m_{Li} \sigma T_v^4,$$ \hspace{1cm} (5.1.7)

where $V_c$ is the volume of reactor cavity, $\sigma$ the Stefan-Boltzmann constant, $K_p$ the Planck mean opacity \(^3\), $S$ the total area of liquid Li surface, and $dS(T_{LS})$ the surface element of liquid Li with the temperature of $T_{LS}$.

Figure 5.1.5 shows the time dependence of vapor pressure $P_v$ in the cavity, where the following values of parameters are used in the calculation:

- thickness of Li curtain = 3cm ,
- height of disrupted curtain = 2cm ,
- radius of Li droplet = 1mm ,
- evaporation coefficient (=condensation coefficient) $C = 0.1$.

We see from Fig. 5.1.5 that the vapor pressure is reduced only to $\approx 10$ Pa at 0.1s after explosion, when all Li droplets reach
the cavity wall or the center axis. This means that condensation of Li vapor can not be accomplished by the disrupted Li curtain and it is necessary to find other liquid Li surface for the condensation of residual vapor.

A succesive calculation of the condensation process is made by taking into account the presence of the curtain reestablished for the next target implosion. The result (Fig. 5.1.6) shows that the time necessary for the vapor pressure to be less than $10^{-2}$ Pa is $0.1$ s after all Li droplets fall into the Li pool at the bottom of the cavity.

Therefore, it is concluded that the Li vapor can be condensed within the repetition time ($=1$s) of the target implosion.

References

1) H1B Fusion Workshop Memo (1982).

2) S. Urata; Master thesis, Nuclear Engineering Faculty of Engineering, Osaka University (1981).


5.1.4 Hoop Stress Acting on First Structural Wall

As mentioned in Sec. 5.1.3, the reactor cavity is filled with the Li vapor with the pressure of 0.84MPa just after the curtain disruption. This vapor pressure gives a hoop stress of 170MPa to the first structural wall with the thickness of 1cm.

The practical hoop stress, however, will be less than this value because a time of $\sim 100\mu$s is necessary for the expansion
of Li vapor due to the finite velocity of sound, during which the condensation of the vapor decreases its pressure to 0.15MPa as shown in Fig. 5.1.5. Then, the hoop stress becomes 30MPa.

On the other hand, the fragments of the disrupted Li curtain also impact the first structural wall. The resulting hoop stress \( \sigma_g(t) \) is calculated by

\[
\sigma_g(t) = 2E_w(\rho_{Li}/\rho_w)(R_{Li}/R_w)(\Lambda_wR_w)^{-1}\int_{R_{Li}+\Lambda_{Li}}^{R_{Li}+\Lambda_{Li}} f(r,t)dr \quad (5.1.8)
\]

\[
f(r,t) = \sin(t-t'(r)) \quad \text{for} \quad t'(r) = (R_w-R_{Li})/u(r) \leq t ,
\]

\[
= 0 \quad \text{for} \quad t'(r) > t \quad (5.1.9)
\]

where

- \( E \): Young's modulus,
- \( \rho \): density,
- \( A \): thickness,
- \( R \): radius,
- \( \omega \): \( (E_w/\rho_w)^{1/2}/R_w \) \((2\pi/\omega): \text{natural period of wall}) ,
- \( u(r) \): radial velocity of Li droplet as function of its initial position \( r \),

and the subscript \( w \) indicates the quantities of the first structural wall and Li of the Li curtain.

By setting \( \sigma_g(t)=F(t)\sin \omega t \), the maximum amplitude \( F(t) \) of the oscillating hoop stress is found from the calculation to be \( \approx 6 \text{MPa} \) for \( E_w=200 \text{GPa}, \rho_w=7800 \text{ kg/m}^3, R_w=2 m, R_{Li}=1 m, \Lambda_{Li}=3 \text{cm}, (2\pi/\omega=2.48 \text{ms}) \), (see Fig. 5.1.7).

Therefore, the hoop stress acting on the first structural
wall will be tolerated if the yield stress of the wall material is several hundred MPa.

Reference

5.2 Neutronics Analysis

The neutronics analysis for HIBLIC is presented in this section. Neutron and gamma ray spectra leaking from the target are obtained from a one-dimensional spherical geometry analysis. A detailed three-dimensional neutronics analysis is performed using the actual cylindrical cavity model. Finally, are given the results of radiation damage rates and dose rate distributions in the reactor cavity, obtained from a one-dimensional spherical geometry analysis.

5.2.1 Target Neutronics and Photonics

The target model used in the HIBLIC reactor design is given in Fig. 5.2.1. The target consists of DT fuel, Al pusher and Pb pusher tamper. Table 5.2.1 gives the density data for the final target stage used in this analysis.

The transport calculations presented here have been performed with the one-dimensional, discrete-ordinate code ANISN\textsuperscript{1}) using 63 energy groups (42-neutron and 20-gamma) in P\textsubscript{3}-S\textsubscript{8} approximation.
The neutron and gamma-ray cross section set including kerma factors is derived from GICX 40 library\textsuperscript{2).}

The calculated results are summarized in Table 5.2.2. A target neutron multiplication of 1.094 is obtained, due to the \((n, 2n)\) reaction in the dense DT fuel.

The spectrum of neutrons leaking from the target is given in Fig. 5.2.2. The spectrum shows a large peak at 14MeV corresponding to the neutrons escaping without interaction within target materials. This amounts to \(\cdot 50\%\) of neutrons leaking.

5.2.2 Cavity Neutronics and Photonics

Figure 5.2.3 schematically illustrates the cavity configuration for the HIBLIC reactor. The 1cm-thick first wall (Region 3) is made of ferritic steel (HT-9), and it is protected by a 5cm-thick Li layer (Region 2) against X-ray and target debris. A 99cm-thick Li layer (Region 4) serves as the coolant and tritium breeder. The reflector (Region 6) consists of 90\% HT-9 and 10\% Li. A 120-cm deep Li pool (Region 1) exists at the bottom of the reactor cavity.

The neutronics and photonics calculations were performed using the three-dimensional Monte Carlo code MORSE-I\textsuperscript{3).} Track length estimators were used to estimate the quantities of interest. A point isotopic source was used at the center of the reactor cavity with neutron and gamma spectra obtained from the previous target neutronics and photonics calculations. 4,000 histories were used in the Monte Carlo calculations.
Table 5.2.3 shows the results for tritium production per DT fusion reaction in the different reactor regions. Region 4, 99 cm-thick Li layer, dominates the tritium production. The overall tritium breeding ratio is found to be \( \sim 1.6 \), of which 37\% is contributed by \(^7\)Li(n, n'\alpha) reaction.

Table 5.2.4 gives the nuclear energy deposition for neutrons and gammas in the different regions. Region 4 dominates the heating rate. The total nuclear heating in the reactor cavity per DT fusion is 15MeV, of which about 80\% is contributed by neutron heating.

The energy flow for the HIBLIC reactor is given in Fig. 5.2.4. The total energy deposition in the system, which includes the energy deposited by X-rays and target debris at the first surface of the blanket, is 21.7MeV per DT fusion. The overall energy multiplication which is obtained by dividing the total energy deposition by the fusion reaction yield of 17.6MeV, is 1.25.

A one-dimensional spherical geometry analysis was performed to determine the time integrated radiation damage in the HT-9 first and second walls, and the dose values at the outer surface of the shield. Since a spherical geometry illustrated in Fig. 5.2.5 was used in the transport calculation, the results present the worst conditions at the central plane of the cylindrical reactor. The results presented here are based on \( 1.42 \times 10^{20} \) source neutrons per pulse, corresponding to a DT yield of 400 MJ. A repetition rate of 1Hz and duty factor of 100\% are used to determine the total atomic displacement and helium production in the walls per year.
The results are summarized in Table 5.2.5. When considering the design criteria for the SUS wall operated at 500°C, that is, 165 dpa for the atomic displacement and 500 appm for the helium production, which would be conservative for the HT-9 case, the first wall is expected to be replaced by every 2 year, however, the second wall would last through the reactor lifetime without replacement. With a thick Li layer in the cavity, we could obtain a large tritium production and long wall-lifetime.

The shield for HIBLYC consists of ordinary concrete. Figure 5.2.6 shows the dose rate distribution in the cavity during operation. A shield thickness of 3m results in a dose rate of 0.7mrem/hr at the outer surface of the shield, which is less than the design limit of 2.5mrem/hr, allowing hand-on maintenance of auxiliary components outside the reactor during operation. The dose rate in the shield region is dominated by gamma rays.

Radioactivity calculations were performed by using the THIDA code system for the geometrical model shown in Fig. 5.2.5. The activity was calculated for an operating time of two years. The results therefrom are presented in Fig. 5.2.7, together with the contribution from individual isotopes and that from the first wall (dashed line). The level at shutdown is 0.2 Ci/Wth, which is about 1/5 of those obtained in the studies on the magnetic confinement reactors. This is due to the small amount of structural material (HT-9) present in the cavity region. About 80% of the activity is contributed by the HT-9 first wall. The activity falls off rather slowly with time after shutdown.
5.2.3 Time Dependent Analysis

Due to the pulsed nature of the neutron source, the radiation environment in inertial fusion reactors, and hence the radiation damages to materials for the first wall and blanket structure are believed to be much different from any other system. For example, some theoretical analysis implied that swelling may be less in inertial confinement systems than in a steady state damage environment, due to the increased point defect recombination during the neutron pulse and increased void annealing in between pulses. Therefore, time dependent neutronics calculations are necessary for the analysis of the radiation damages in the inertial confinement reactors.

The purpose of the present study is to perform time dependent neutronics analysis of the HIBLIC by using a version of Monte Carlo code MORSE-CG which is modified to account for the time of flight spread of neutrons.

The blanket configuration adopted here is given in Fig. 5.2.5 in one-dimensional spherical geometry.

In the MORSE calculation, neutrons are assumed to be emitted at t=0 with the spectrum given in Fig. 5.2.2. Direction cosines were sampled isotropically. It is further assumed that the neutron source is represented by a point source at the center of the reactor.

To examine the effects of protecting the first wall with 5-cm thick Li layer, we will here consider the two cases, (a) with Li layer protection and (b) without Li layer.
The collision density estimator was used in conjunction with region detectors to estimate the damage. The random walk calculations were carried out for 16,000 source particles.

The results presented here for the damage and energy deposition are based on $1.42 \times 10^{20}$ source neutrons per pulse, corresponding to a DT yield of 400 MJ.

The average and peak instantaneous rates obtained for the atomic displacement, helium production and energy deposition are summarized in Table 5.2.6.

A peak displacement rate of 193 dpa/sec is obtained for the protected first wall, which should be compared to the average rate of $1.03 \times 10^{-6}$ dpa/sec.

The 5-cm thick Li layer reduces the average and peak instantaneous rates by 10 and 31%, respectively. Much larger reduction is obtained in the HIBALL reactor design. An effective thickness of 60cm is adopted for the LiPb layer as compared to the 5-cm thick Li in the HIBLIC. The corresponding decreases in the rates are factors of 17 and 780, respectively. Figure 5.2.8 shows the instantaneous displacement rate in the protected first wall as function of time from burn, whereas in Fig. 5.2.9 illustrated the rate for the unprotected wall.

A peak helium production rate of 2845 appm/sec is obtained for the protected first wall, which is the contrast to the average rate of $7.96 \times 10^{-6}$ appm/sec. The 5-cm thick Li layer is found to reduce the average and peak rates by 14 and 34%, respectively. Much larger reduction is achieved in the HIBALL design. In this case, the average rate is found to decrease by a factor of 370,
while the peak instantaneous rate is found to decrease by a factor of 1030. Figure 5.2.10 shows the instantaneous helium production rate in the protected first wall, whereas in Fig. 5.2.11 illustrated the rate for the unprotected wall.

A peak energy deposition rate is found to be 5.63x10⁹ watt/cc for the protected first wall, which is the contrast to the average rate of 23.2 watt/cc. The 5-cm thick Li layer is found to reduce the average and peak rates by 53 and 16%. The corresponding decreases in the HIBALL are factors of 10 and 760, respectively. Figure 5.2.12 shows the instantaneous energy deposition rate in the protected first wall, whereas in Fig. 5.2.13 the rate for the unprotected wall is given.

5.2.4 Analysis of Radiation Streaming through Beam Ports

The cavity of the HIBLIC is required to accommodate six beam ports used for the driver energy introduction to uniformly illuminate the target. Structurally, the beam ports are placed so as to see the microexplosion source neutrons in a line-of-sight manner. Therefore, neutrons streaming through these ports will damage the vital components, such as superconducting magnet used to focus the ion beam line. Furthermore, it is reported that excessive high radiation leakage through these ports will lead to uncontrollably serious operational and safety problems.

The present study is concerned with the radiation streaming analysis of the beam ports of the HIBLIC. The calculational model adopted here is shown in Fig. 5.2.14. In this modelling,
we considered two focusing magnets (each separated by 1m-long drift shield) and a collimator (made of ordinary concrete, used to reduce the radiation leakage through the beam ports). The inner part of the ports is tapered so as to eliminate the direct line-of-sight component of the source neutrons. No shield is provided for the inner part. Because of symmetry, only 1/12 of the reactor is modeled with reflecting albedo boundaries used at the planes of symmetry.

The neutronics and photonics calculations were performed using the three-dimensional Monte Carlo code MORSE-I. Track length estimators were used to estimate the quantities of interest. A point isotropic source was used at the center of the reactor cavity with neutron and gamma spectra obtained from the previous target neutronics and photonics calculations. Some ten thousands histories were used in the Monte Carlo calculations.

To improve the computational efficiency, use is made of the same biasing techniques as in the HIBALL analysis. 90% of the source neutrons are forced to fall around the beam port direction. The calculational results are summarized in Table 5.2.7.

Without collimator behind the focusing magnets, the very small fraction of neutrons can reach the magnet regions (Zone 14-17 and 20-23) through collisions in other regions; thus indicating the effectiveness of tapering the beam port for reducing the radiation damage in the magnet. However, the collimator tends to increase the damage rate by reflecting neutrons into the magnet region; the dpa rate in the copper stabilizer exceeds the tentatively adopted design limit of $1.4 \times 10^{-4}$ dpa in
\[ 27 \text{ days}; \] requiring the frequent annealing of the magnet.

To remedy the situation, we further examined the following two cases; (i) the collimator is moved far away from the magnet with 5m-long drift shield as compared to the original design with 1m-long drift shield, and (ii) the collimator is also tapered along the direct line-of-sight component of the source neutrons with vertical neutron dump (Zone 30), as shown in Fig. 5.2.14 as dashed line.

The calculational results for the above two cases are summarized in Table 5.2.8. Tapering the collimator is effective for reducing the damage rate and thus prolonging the annealing period from 27 days to 1.2 yr. Furthermore, when the geometry of the neutron dump is modified as shown in Fig. 5.2.15 (Option B), the annealing period could be further prolonged to 2.2 yr as given by Table 5.2.9.

References
1) W.W. Ingel Jr.; K-1693 (1967)
2) Y. Seki, H. Iida; JAERI-M 8818 (1980)
Fig. 5.1.1 Radial profile of energy density of Li curtain
Fig. 5.1.2 Radial profile of pressure and expansion velocity of Li curtain.
Fig. 5.1.3 Radial profile of void fraction in Li curtain
Fig. 5.1.4 Radial profile of temperature of Li curtain
Fig. 5.1.5 Time dependence of Li vapor pressure in reactor cavity after curtain disruption
Fig. 5.1.6 Time dependence of Li vapor pressure in reactor cavity after re-establishment of Li curtain
Fig. 5.1.7 Time dependence of hoop stress acting on first structural wall
Table 5.2.1 Atomic Densities used for Target Calculation

<table>
<thead>
<tr>
<th>Region</th>
<th>Composition</th>
<th>Density [g/cm³]</th>
<th>$\rho R$ [g/cm²]</th>
<th>Atom Density [atoms/b-cm]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>306</td>
<td>5.47</td>
<td>36.86</td>
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<td></td>
<td>T</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Al</td>
<td>1.2</td>
<td>0.438</td>
<td>0.02679</td>
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<td>3</td>
<td>Pb</td>
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<td>0.0848</td>
<td>0.0343</td>
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Table 5.2.2 Summary of Calculated Results

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<tr>
<th>ANISN Run: P₃-S₈</th>
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<tr>
<td><strong>M</strong></td>
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<tr>
<td>Number of neutrons from pellet</td>
<td>3.37 MeV/fusion</td>
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<tr>
<td><strong>Hₙ</strong></td>
<td>3.91x10⁻⁴ MeV/fusion</td>
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<tr>
<td>Neutron energy deposition in pellet</td>
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<tr>
<td><strong>Hᵧ</strong></td>
<td>10.7 MeV/fusion</td>
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<tr>
<td>γ-ray energy deposition in pellet</td>
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<tr>
<td><strong>Lₙ</strong></td>
<td>3.12x10⁻² MeV/fusion</td>
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<tr>
<td>Neutron energy leakage from pellet</td>
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<tr>
<td><strong>Lᵧ</strong></td>
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<tr>
<td>γ-ray energy leakage from pellet</td>
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Table 5.2.3 Tritium Production (Tritons/fusion)

<table>
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<tr>
<th>Region Number</th>
<th>Breeding Blanket</th>
<th>Reflector</th>
<th>System Total</th>
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<tr>
<td>1</td>
<td>0.070</td>
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<tr>
<td>2</td>
<td>0.053</td>
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<tr>
<td>4</td>
<td>0.787</td>
<td>0.449</td>
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<tr>
<td>7</td>
<td>0.077</td>
<td>0.033</td>
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</tr>
<tr>
<td>8</td>
<td>0.035</td>
<td>0.005</td>
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<tr>
<td>6</td>
<td>0.011</td>
<td>0.0</td>
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<tr>
<td>System Total</td>
<td>1.033</td>
<td>0.613</td>
<td>1.646</td>
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Table 5.2.4 Nuclear Heating

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<th>Region Number</th>
<th>Energy Deposition (MeV/fusion)</th>
<th>Neutrons</th>
<th>Gammas</th>
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<td>7</td>
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<tr>
<td>8</td>
<td>0.232</td>
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<tr>
<td><strong>Region Total</strong></td>
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<td><strong>First Wall</strong></td>
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</tr>
<tr>
<td>3</td>
<td>0.212</td>
<td>0.475</td>
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<td><strong>Second Wall</strong></td>
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</tr>
<tr>
<td>5</td>
<td>0.032</td>
<td>0.374</td>
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<td><strong>Region Total</strong></td>
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<td><strong>Reflector</strong></td>
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<td><strong>Distributor</strong></td>
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<td><strong>System Total</strong></td>
<td>12.427</td>
<td>2.651</td>
<td>15.078</td>
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Table 5.2.5 Summary of ANISN Calculation

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<thead>
<tr>
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<th>First Wall</th>
<th>Second Wall</th>
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<tr>
<td>DPA rate (dpa/FPY)</td>
<td>36.6</td>
<td>0.93</td>
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<tr>
<td>He production rate (appm/FPY)</td>
<td>284</td>
<td>2.33</td>
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Table 5.2. Summary of average and peak rates for the HT-9 first wall  
(time of flight spread included)

<table>
<thead>
<tr>
<th>HT-9 wall protection</th>
<th>Bare wall</th>
<th>5cm Li</th>
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<tbody>
<tr>
<td>Displacement rate(DPA/sec)</td>
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<tr>
<td>Average($\times 10^{-6}$)</td>
<td>1.13(0.02)</td>
<td>1.03(0.01)</td>
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<tr>
<td>Peak</td>
<td>253(0.06)</td>
<td>193(0.07)</td>
</tr>
<tr>
<td>Helium production rate(adpm/sec)</td>
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<tr>
<td>Average($\times 10^{-6}$)</td>
<td>9.06(0.02)</td>
<td>7.96(0.02)</td>
</tr>
<tr>
<td>Peak</td>
<td>3800(0.06)</td>
<td>2845(0.08)</td>
</tr>
<tr>
<td>Energy deposition rate(Watt/cm$^3$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>35.4(0.02)</td>
<td>23.2(0.02)</td>
</tr>
<tr>
<td>Peak($\times 10^9$)</td>
<td>6.54(0.08)</td>
<td>5.63(0.10)</td>
</tr>
<tr>
<td>history</td>
<td>16000</td>
<td>16000</td>
</tr>
</tbody>
</table>
Table 5.2.7 DPA rate in the copper stabilizer

DPA Rate (dpa/FPY)

<table>
<thead>
<tr>
<th>Zone Number</th>
<th>with Collimator</th>
<th>without Collimator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>6.01×10⁻⁴ (0.09)</td>
<td>NS</td>
</tr>
<tr>
<td>15</td>
<td>5.69×10⁻⁶ (1.0)</td>
<td>NS</td>
</tr>
<tr>
<td>16</td>
<td>1.87×10⁻³ (0.06)</td>
<td>NS</td>
</tr>
<tr>
<td>17</td>
<td>5.08×10⁻⁵ (0.60)</td>
<td>NS</td>
</tr>
<tr>
<td>20</td>
<td>7.65×10⁻⁶ (1.0)</td>
<td>1.98×10⁻⁴ (0.93)</td>
</tr>
<tr>
<td>21</td>
<td>4.44×10⁻⁷ (1.0)</td>
<td>NS</td>
</tr>
<tr>
<td>22</td>
<td>1.90×10⁻⁴ (0.63)</td>
<td>3.47×10⁻⁴ (0.85)</td>
</tr>
<tr>
<td>23</td>
<td>1.03×10⁻⁵ (1.0)</td>
<td>6.62×10⁻⁹ (0.98)</td>
</tr>
</tbody>
</table>

* Numbers in parentheses are fractional standard deviations

** No score in this zone for the 10,000 histories used

* Design Limit *1.4×10⁻⁴ dpa*
Table 5.2.8 DPA rate in the copper stabilizer

DPA Rate (dpa/FPY)

<table>
<thead>
<tr>
<th>Zone Number</th>
<th>with Collimator (5m Drift Shield)</th>
<th>with Collimator (Neutron Dump)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>$4.22 \times 10^{-4}$ (0.12)*</td>
<td>$2.60 \times 10^{-5}$ (0.35)</td>
</tr>
<tr>
<td>15</td>
<td>$4.45 \times 10^{-11}$ (1.0)</td>
<td>$1.64 \times 10^{-6}$ (1.0)</td>
</tr>
<tr>
<td>16</td>
<td>$1.35 \times 10^{-3}$ (0.08)</td>
<td>$1.16 \times 10^{-4}$ (0.23)</td>
</tr>
<tr>
<td>17</td>
<td>$9.20 \times 10^{-6}$ (0.72)</td>
<td>$2.51 \times 10^{-5}$ (0.89)</td>
</tr>
<tr>
<td>20</td>
<td>$4.43 \times 10^{-6}$ (1.0)</td>
<td>$4.83 \times 10^{-9}$ (1.0)</td>
</tr>
<tr>
<td>21</td>
<td>$5.30 \times 10^{-6}$ (1.0)</td>
<td>$3.42 \times 10^{-11}$ (1.0)</td>
</tr>
<tr>
<td>22</td>
<td>$9.92 \times 10^{-6}$ (1.0)</td>
<td>$8.75 \times 10^{-5}$ (0.81)</td>
</tr>
<tr>
<td>23</td>
<td>$2.29 \times 10^{-5}$ (0.92)</td>
<td>$1.55 \times 10^{-11}$ (1.0)</td>
</tr>
<tr>
<td>history</td>
<td>9500</td>
<td>10000</td>
</tr>
</tbody>
</table>

* Numbers in parentheses are fractional standard deviations

Design Limit 1.4×10⁻⁴ dpa
Table 5.2.9 DPA rate in the copper stabilizer

DPA Rate (dpa/FPY)

<table>
<thead>
<tr>
<th>Zone Number</th>
<th>with Neutron Dump (Option B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>$2.00 \times 10^{-5}$ (0.36)</td>
</tr>
<tr>
<td>15</td>
<td>$1.02 \times 10^{-5}$ (1.0)</td>
</tr>
<tr>
<td>16</td>
<td>$6.26 \times 10^{-5}$ (0.25)</td>
</tr>
<tr>
<td>17</td>
<td>$1.55 \times 10^{-5}$ (0.85)</td>
</tr>
<tr>
<td>20</td>
<td>$2.71 \times 10^{-5}$ (0.58)</td>
</tr>
<tr>
<td>21</td>
<td>$2.70 \times 10^{-6}$ (0.77)</td>
</tr>
<tr>
<td>22</td>
<td>$3.32 \times 10^{-3}$ (0.97)</td>
</tr>
<tr>
<td>23</td>
<td>$1.35 \times 10^{-5}$ (0.97)</td>
</tr>
</tbody>
</table>

* Numbers in parentheses are fractional standard deviations

**Design Limit** $1.4 \times 10^{-4}$ dpa
Final Target Stage

Fig. 5.2.1 Target Model for ANISN Calculation
Fig. 5.2.2 Spectrum of Neutrons Leaking from HIB Target
Fig. 5.2.3(a) Cavity Model (Vertical cross-section)
Fig. 5.2.3(b) Cavity Model (Horizontal cross-section)
TARGET
17.6 MeV/Fusion

<table>
<thead>
<tr>
<th>Neutron &amp; Gamma</th>
<th>X-ray &amp; Debris</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.7 MeV</td>
<td>6.37 MeV (= 3.5 + 3.37)</td>
<td></td>
</tr>
<tr>
<td>a-particle</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lost in Endoergic Reactions
0.03 MeV

Overall Energy Multiplication = \( \frac{21.948}{17.6} \) = 1.247

Fig. 5.2.4 Energy Flow
Fig. 5.2.5  Cavity Model for ANISN Calculation
Fig. 5.2.6 Dose rate distribution at reactor operation
Fig. 5.2.7

Time after Shutdown

Fig. 5.2.7
CASE-1 FIRST WALL

With Li Curtain

Fig. 5.2.8
Fig. 5.2.9

CASE-1 FIRST WALL

Without Li Curtain

TIME FROM BURN (NSEC)

DISPLACEMENT RATE (PA/SECOND)
Fig. 5.2.10

CASE-1  FIRST WALL

With Li Curtain

HELIUM PRODUCTION RATE (APPN/SEC) 1.0E-1

TIME FROM BURN (NSEC)
Fig. 5.2.12

CASE-1 FIRST WALL

With Li Curtain

TIME FROM BURN (NSEC)

ENERGY DEPOSITION RATE (MH/CC) \times 10^{-4}

80.00 180.00 240.00 280.00 320.00 360.00 400.00 440.00 480.00 520.00 560.00 600.00 640.00 680.00 720.00 760.00 800.00
Fig. 5.2.13

CASE-1 FIRST WALL

Without Li Curtain

ENERGY DEPOSITION RATE (MW/CC) x 10^4

TIME FROM BURN (NSEC)
Zone 14 ~ 17: SCM
20 ~ 23: SCM
18, 24: Drift Shield

Concrete Shield

Collimator (Ordinary Concrete)

Vacuum
Appendix

Formation of Closed Liquid Li Envelope

Since an exploding target releases X-rays and energetic particles spherically, it is desirable to use a closed liquid Li envelope for the protection of the first structural wall, especially a ceiling of reactor cavity. Here, considerations are presented on the formation of the liquid Li envelope.

As shown in Fig. A.1, a cylindrical curtain of falling liquid Li is introduced into the reactor cavity. Along the length of its fall through the reactor, the curtain is girded at intervals by single turn cusp-field driver coils of circular cross section, and which are connected to capacitor banks. Each time the electrical circuit is closed, the liquid curtain near the coils is locally constricted by the magnetic pressure of the cusp field. In this manner, instantaneously before each target implosion, a liquid Li envelope is formed in free space to shield the first structural wall from the energy released from an exploding target contained therein.

In numerically simulating the motion of the liquid Li curtain during its constriction, it is assumed for simplicity that the curtain is infinitely thin, infinitely long and has infinite conductivity. The displacement of the falling Li curtain is further neglected for the interval of time taken for the constriction. The cusp-field driver coils with circular cross section (major and minor radii a, p, respectively) are placed at z=±b in the cylindrical coordinates. Figure A.2 shows profiles of the Li curtain in the (r, z) plane at various lapse of time.
(\(=t/r\)) in the course of constriction, where \(T=\left(8\pi^2\sigma R^3/\mu_0 I^2\right)^{1/2}\), 
\(\sigma: \) surface density of Li curtain, \(R: \) initial curtain radius, 
\(\mu_0 : \) magnetic permeability of free space, \(I: \) initial coil current).
The required coil current \(I\) and the inductive energy \(e\) of coils 
for a given constriction time \(T\) are found from the numerical 
calculation as follows:

\[ I = \left(8\pi^2\sigma R^3/\mu_0\right)^{1/2} T^{-1} t_f(\hat{a}, \hat{b}, \hat{\rho}), \quad (A.1) \]

\[ e = \left(8\pi^2\sigma R^4/\mu_0 T^2\right) e(\hat{a}, \hat{b}, \hat{\rho}), \quad (A.2) \]

where \(\hat{a}=a/R, \hat{b}=b/R, \hat{\rho}=\rho/R\), and the values of \(t_f\) and \(e\) are shown 
in Fig. A.3 (a), (b). Table A.1 shows an example of design 
parameters for the present system.
Fig. A.1 Liquid Li curtain falling through driver coils
Fig. A.2 Profiles of constricted Li curtain
Fig. A.3 Quantities of \( \hat{c}_f \) and \( \hat{e} \)
Table A.1  Design parameters of present system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curtain material</td>
<td>Liquid lithium</td>
</tr>
<tr>
<td>Initial curtain thickness (surface mass density)</td>
<td>5 cm (25 kg/m²)</td>
</tr>
<tr>
<td>Initial curtain radius</td>
<td>1 m</td>
</tr>
<tr>
<td>Coil major radius</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Coil minor radius</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Coil distance</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Constriction time</td>
<td>30 ms</td>
</tr>
<tr>
<td>Driving field energy</td>
<td>4.4 MJ</td>
</tr>
<tr>
<td>Initial coil current</td>
<td>1.9 MA</td>
</tr>
<tr>
<td>Maximum hoop stress of coil</td>
<td>12 MPa</td>
</tr>
</tbody>
</table>
In carrying out the present HIF conceptual design study, it has been emphasized that a consistent aspect of the whole system is as important and critical as considerations of individual constituent components. Interfaces between different main sub-systems, i.e., target, driver and reactor cavity, have sometimes brought trade-offs and have sometimes opened new scopes. Among others the following features of HIBLIC-I may be pointed out.

i) By introducing the Li curtain concept into the reactor design, the chamber is favorably reduced in size and becomes much simpler without any huge pumping power required.

ii) With the target conditions appropriate to the incident ion beam energy of 15 GeV, rather than 10 GeV, the required beam current goes down to a reasonable level, so that a number of critical issues of the driver system, such as beam instabilities in accelerators, are well relaxed or eliminated.

iii) Choice of the least number of beams on a target, within an allowable limit of uniformity for implosion, gives rise to a tractable configuration of beam port structures on the reactor cavity and of final beam focusing elements.

One of the most critical issues arising from the reactor technology is the problem of material choice. The HT-9 steel, selected as the reference material for the chamber structure, is expected to be compatible with liquid Li in the reactor operation mode. Contamination of lead in Li will, however, make the
problem more complex from erosion and other point of view. Lead from the target tamper may considerably solved and concentrated into the liquid Li after a long term operation and this could change the material properties. Similar thing will also happen with alminum from the target pusher, although it is thought to be harmless. Anyway, the compatibility study of different materials under the reactor condition should be investigated in more detail.

There are a number of subjects to undergo research and development, if we wish to make a step further in the HIF design studies. The following experiments or studies would be of crucial importance to give a firm and reliable data base for the present system design:

<Target>

- High temperature experiments of heavy ion - target plasma interaction
- Simulation experiments with 3-dimensional codes

<Driver>

- Experiments and simulations on beam instabilities in ranges extensible to HIF requirements
- Developments of HIF ion source, low-β linac and beam handling techniques

<Reactor>

- Experiments on liquid Li behaviors in relation to Li curtain formation, disruption and vapor-recondensation processes

VI-2
Investigation of Pb/Li/T and ferritic steel compatibility

Several important items necessary for a complete design work on HIF reactor system, such as pellet fabrication, pellet delivery, safety analysis and cost estimate, have not been included in this preliminary report due mainly to the short study time. The detailed considerations to optimize the whole system parameters are also left for further investigation as well as comparison studies with other existing proposals.