100 MeV H- CYCLOTRON AS AN RIB DRIVING ACCELERATOR[1]

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Abstract

For productions of intense proton and radioactive ion beam (RIB) used in fundamental and applied research, e.g., neutron physics, nuclear structure, material and life sciences and medical isotope production, a new RIB facility, Beijing Radioactive Ion-beam Facility (BRIF) is started in CIAE recently. In this project, a 100 MeV H- cyclotron is selected as the driving accelerator. It will provide a 75 MeV - 100 MeV, 200 μA - 500 μA proton beam. In this paper, BRIF will be described briefly. Then, various aspects about the 100 MeV Cyclotron including the general description, specification, beam dynamics, design features of the magnet, RF system etc. will be described respectively. And some R&D for this machine will be given too.

INTRODUCTION

BRIF, Beijing Radioactive Ion-beam Facility is a new project of cyclotron base radioactive ion beam facility which was proposed by the China Institute of Atomic Energy (CIAE) in 1999[1] and was approved by the Chinese government in July 2003. It consists of a 100 MeV cyclotron, a two-stages isotope separator on line system, modification of the existing tandem, a super conducting Linac booster, various experimental terminals and an isotope production station. The layout of upgrade project is shown in Fig. 1. A 100 MeV cyclotron and an isotope separator on line system will be installed in a new building west of the tandem. A super conducting Linac booster will be installed in the existing hall of the tandem. Two proton beams will be provided simultaneously by the cyclotron to south for applications of proton beam directly and to north for RIB generation. More than 40 proton-rich beams and 80 neutron-rich beams with beam intensity higher than 10^6 pps will be provided by this facility.

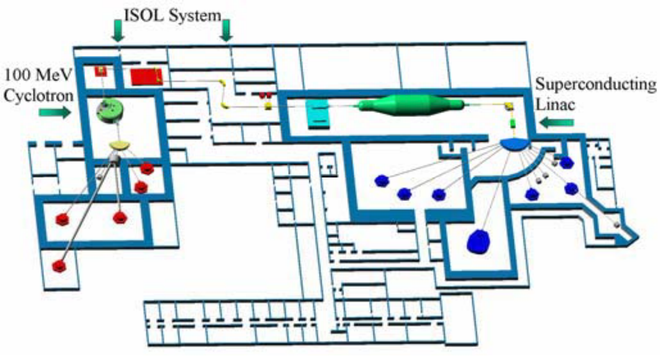

Figure 1: The layout of BRIF

100 MEV H- CYCLOTRON

General Description

The driving accelerator, a 100 MeV H^4 cyclotron, will provide a 75 MeV - 100 MeV, 200 μA - 500 μA proton beam. For a final energy of 100 MeV or below and beam intensity of less than 1 mA, a compact magnet and H^4 acceleration with stripping extraction might lead to a smaller and cheaper machine. This driving accelerator is a fixed field, four sectors cyclotron. The magnet is 2.6 m in height and 6.4 m in diameter. Tow cavities installed into the valleys of the magnet will accelerate beam 4 times per turn. The machine will possess the following features:

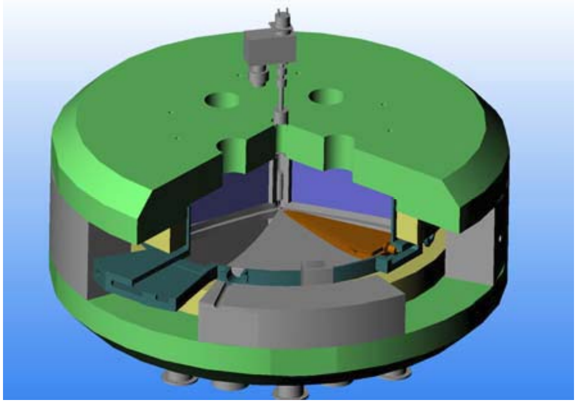

Figure 2: The structure of 100 MeV, H^4 cyclotron

∉ The compact magnet will provide high enough flutter and lower first harmonic though the harmonic coils will be absent.

∉ The H- acceleration permits us to extract the beam by stripping from the compact machine.

∉ The external source not only provides higher beam intensity, but also shows us a possibility to provide pulse proton beam by the cyclotron.

∉ The magnetic field of less than 1.35 T in the hill region will guarantee a low rate of dissociation of H- ions during the whole acceleration.

∉ Two triangle, half wave cavities are installed into the valleys of the magnet. They are connected together at the central region of the machine. The RF power from

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coaxial transmission line is coupled into the cavities capacitively.

Specification

The specification of principal parts are given as following:

¸ Ion source / Injection

Source		Injection	
Type	Multi-cusp	Energy	~ 40 kV
Current	> 5 mA	Inflector	Spiral

¸ Magnet

Number of Ssctors	4
Sector Angle	~47^o
Field in Hill	1.35 T
Radius of the Pole	2000 mm
Inner Radius of the Yoke	2410 mm
Outer Radius of the Yoke	3080 mm
Gap between the valley	1200 mm
Gap between the Hills	40~50 mm
Total Weight of Iron	~433 t

¸ Main Coils / Power Supply

Ampere-Turn Number	70 kAT
Copper Weight	24 t
D.C Power	30 kW

¸ RF System

Number of Dees	2	Dee Voltage	60~120kV
Dee Angle	38 ^{o}	Harmonic Mode	4
Frequency		44.3722 MHz	

Basical Magnetic Field and Orbit Calculations

Magnet and Beam Dynamics from EO Calculation

Four simple sectors structure is selected for the main magnet. 54° of sectors with 5° of extended angle at the extraction region are used for 3D field computation firstly. BH curve of AISI 1008 Steel at room temperature (300 K) is used in the field computation. The isochronous field can be achieved by some adjustment of the shimming bar attached at both sides of the sectors. However, the simulation results show us that the τ_z going down quickly in the high energy region during the magnetic field isochronising. The Walkinshaw resonance occur in the low energy region and the extraction region. The fast crossing of Walkinshaw resonance in the low energy region will not cause any problem. To avoid Walkinshaw resonance at the extraction region, one may use the spiral sectors to provide a stronger axial focus, but it will bring more complication to the RF cavities and the beam diagnostic system. For such an AVF machine with energy not too high, we still prefer to use the simple sectors structure. Therefore, a non-uniform hill gap, as is shown in Figure 3, is used to improve the axial focusing.

When the hill gap is changed from 5 cm at the central region to about 4 cm at the extraction region and extended angle of the sector magnet is removed, the field distribution by adjusting the shimming bar attached at both sides of the sectors reaches a good isochronism. The integral of phase shift is limited within ∂10∀. In this case, the tune diagram based on the field calculation is illustrated in figure 4. It can be found that the τ_z is high enough and the $\tau_r \mid 2\tau_z$ resonance should be avoided.

The vertical tune shift by space charge effect is estimated by:

$$\div\tau_Z \mid 4\frac{1}{\eta}\frac{\overset{\langle}{I}}{15.69\Delta 10^6}\frac{R_{\leftarrow}}{\kappa_n(\sqrt{\frac{\Upsilon_Z}{\Upsilon_R}}\;2\,1)}$$

The results are also given in figure 4 for comparison.

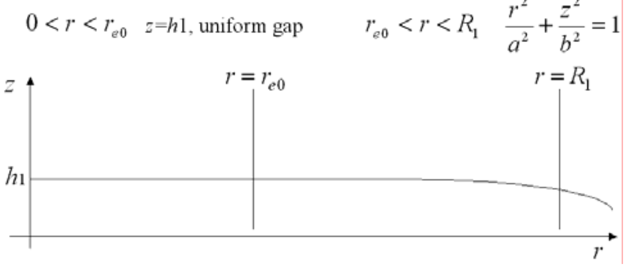

Figure 3: The non-uniform hill gap of simple sector magnet.

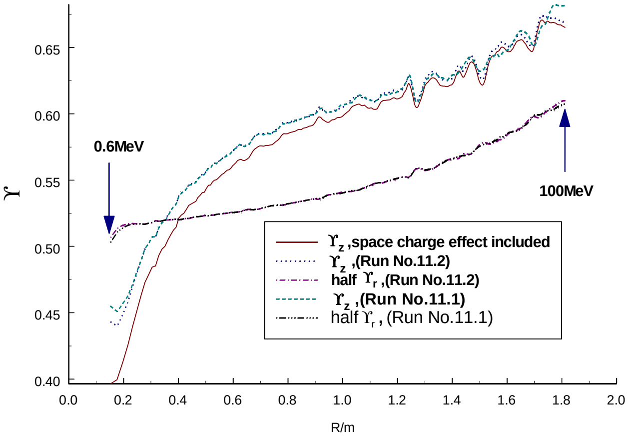

Figure 4: The tune diagram.

GOBLIN Calculation of the Radial and Vertical Motion

The tracking of accelerated orbit shows that the vertical envelop at the extraction region can be kept small when the off centre is limited in 5 mm.

The tracking for the radial motion and vertical motion of accelerating orbit have been done by Goblin[2], which is modified to run on PC/Windows by CIAE. For such a compact cyclotron, one may pay more attention to the vertical envelop of accelerating orbit. The vertical orbit behaviour of centered beam and ±5 mm off centered beam are investigated in detail with various different conditions as following:

RF phase: λ_{RF}=145°, 150°, 160°, 170°, 180°, 190°, 195°

Vertical displacement: z_0=0.3 cm, 0.6 cm, 1.0 cm

The simulation results show that the vertical envelop can be kept small enough while accelerating from 1 MeV to 100 MeV if the initial beam off centre is limited within

±5 mm. The uniform Dee voltage of 65 kV is used in the calculation.

The static ellipses are calculated at several different energies. The initial conditions for the simulation are listed as following:

Static vertical ellipses	Static radial ellipses
Energy: E_0=1 MeV, 11 MeV, 51 MeV, 100 MeV	Energy: E_0=1 MeV, 11 MeV, 51 MeV, 100 MeV
Displacement: z_0=0.3 cm, 0.6 cm, 1.0 cm	Displacement: x_0=0.3 cm, 0.5 cm

As an example, one of the results is given in figure 5. Starting from this vertical ellipse, the vertical beam profile from 1 MeV to 100 MeV is illustrated in figure 6. It shows us again that the axial focusing is able to keep the beam within a small vertical dimension.

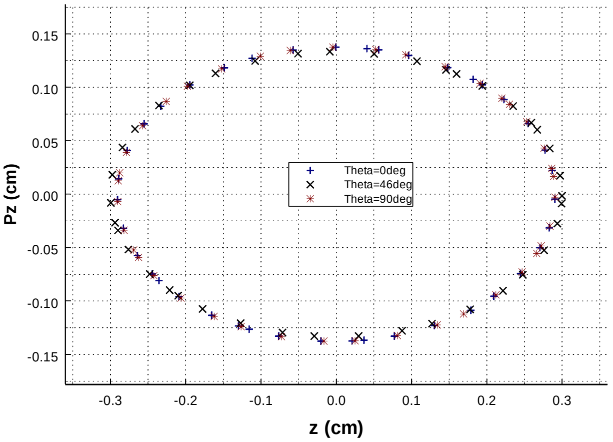

Figure 5: Static Vertical Phase Ellipses at Energy of 1 MeV

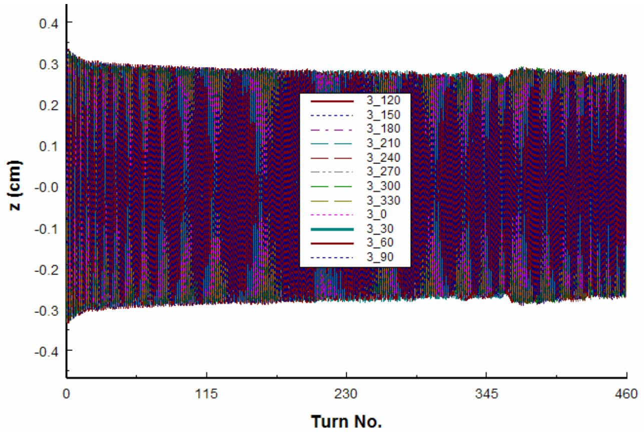

Figure 6: Vertical beam profile tracked from 12 points on the static vertical ellipse at energy of 1 MeV

Beam Losses

Although high efficiency H- extraction systems have become increasingly popular with cyclotron designers, the H- dissociation during acceleration caused by residual gas and Lorentz stripping should be a problem.

Beam Losses by Lorentz Stripping

The Lorentz stripping loss is usually evaluated with some simplified formulas assuming a uniform magnetic field [3,4]. It is generally accepted that Lorentz stripping will not become a problem provided the relativistic electric field is less than $2\Delta10^{8}$ V/m, which was used as a design criteria for the CP-42[5]. As the cyclotron energy is raised, H- dissociation becomes more of a problem, and a more detailed calculation is warranted. To obtain more detailed estimates of the Lorentz losses, the equation for the fractional losses has been embedded into the orbit calculation code. This enables us to calculate the losses in a step by step fashion along orbits as the beam travels from the central region to extraction. This calculation takes into account the radial and azimuthal magnetic field variations within the cyclotron.

To limit the losses to less than 2 σA with a circulating current of ~500 σA, the pole radius is increased to 2.0 m. The accumulated losses are down to $3.077\Delta10^{-3}$. This magnet would weigh ~433 tons as shown in Section 2.2.

Beam Losses by Vacuum Dissociation

The beam losses by residual gas dissociation is also investigated. A code for calculation of residual gas dissociation is implemented and has been embedded into the orbit calculation code so that the evaluation of beam losses by residual gas and Lorentz stripping can be done freely during the beam dynamics calculations and magnet design. The beam losses calculations were carried out and the radiation was limited efficaciously for the 100 MeV H- cyclotron. For the energy gain per turn of 200 keV, beam losses at different energy region are given below.

Table 1: Percentage of Beam Losses at Various Energy Regions by Vacuum Dissociation

N_2ESP (Torr)	Vacuum level (Torr)	Beam Loss 0-20 MeV	Beam Loss 20-70 MeV	Beam Loss 70-100 MeV
1.00E-7	2.61E-7	1.22 %	1.16 %	0.50 %
8.00E-8	2.08E-7	0.98 %	0.93 %	0.40 %
6.00E-8	1.56E-7	0.73 %	0.71 %	0.30 %
4.00E-8	1.04E-7	0.49 %	0.47 %	0.20 %
2.00E-8	5.18E-8	0.24 %	0.24 %	0.10 %

RF System

General Requirements

Operating Frequency: 42MHz--46MHz (will be fixed at one point after mapping)

RF Output Power: 150 kW

RF Frequency Stability: $\frac{\div f}{f} \mid \partial 5\Delta10^{48}$

Dee Voltage Stability: $\frac{\div U}{U} \mid \partial 5\Delta10^{44}$

Phase Stability: ±0.3°

The capacitive coupling mode between the RF power source and the cavity is preliminarily decided. The Dee voltage distribution along radius of the accelerating gap should be from 60kV at the central region to 120 kV at the extraction region.

The layout of RF system, amplifier, control loop, transmission line and matching etc are described in more detail elsewhere[6].

Cavity and RF Leakage

In order to make full use of the space inside the valleys, the two cavities are designed to be located among the two opposite valleys. They are connected together at the central region. The outer part of the cavity takes the shape of a triangle like.

The preliminary consideration is to adopt the two stems structure to control the voltage distribution well and adjust the frequency by changing the position and diameter of the stems[7]. The half of cavity is shown in figure 7. The numerical simulation have been done for the cavity design. One results of changing the voltage distribution is given below. The position of the larger inner stem is kept same, and the position of smaller inner stem is changing, the horizontal coordinate of its circle center x is respectively 40cm, 50cm and 60cm. The result comparison of Dee voltage distribution vs. radius is shown in Figure 8.

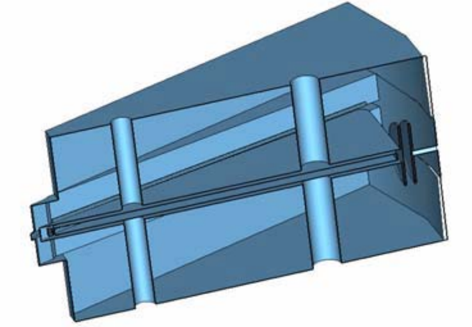

Figure 7: The structure of two stem cavity

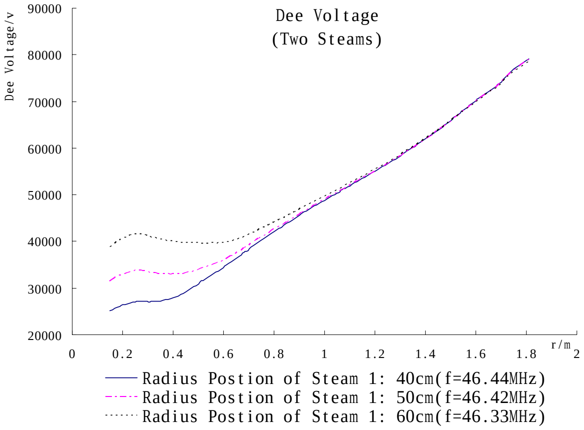

Figure 8: The voltage distribution vs. radius

The RF leakage is also investigated numerically. The results show that the fringe RF field is insufficient beyond 3 cm from the accelerating gap. So, the dummy Dee will be used instead of the RF liner, which may make the hill gap tighter. We do not expect that the temperature of pole will be changed very much by RF leakage if we plate the pole surface by Ni and Cu and arrange water cooling at both side of the poles.

Injection and Extraction

Ion source, injection line and central region

A test stand has been developed for ion source, injection line and central region. The design of H^4 cusp source is based on TRIUMF's experience[8]. More than 10 mA of H^4 beam with a measured emittance of 0.65 ϕ mm mrad are got at a voltage of 28 kV from an extraction hole of 11mm in diameter. The optics of injection line is calculated by TRACE3D[9]. And the central region is design by TRIUMF's codes Casino[10] and Cyclone[11], and by CIAE's code CYCCEN. The preliminary results are described in more detail elsewhere[12,13,14].

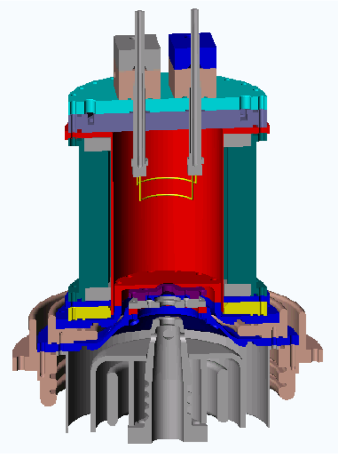

Figure9: The H^4 source

Extraction

Two proton beams will be extracted by stripping the H- by two set of stripping probes. The extraction system includes the following parts:

- Stripper Probes,
- Positioning and driving system,
- Foil changing system.

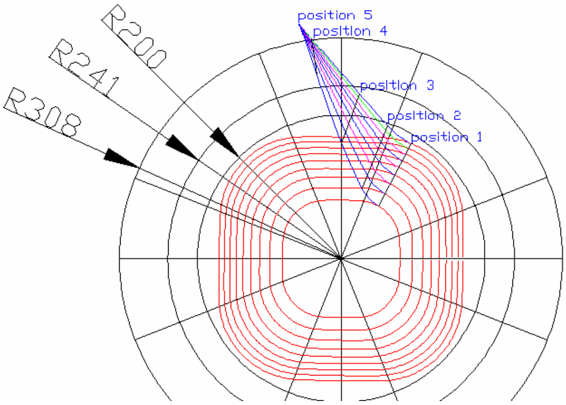

Figure 10: The equilibrium orbits and extraction orbits with energies from 20 MeV to 100 MeV

The energy from 75 MeV to 100 MeV of proton beam is demanded to be extracted. We also try to extract beam with lower energy. The extraction optics is investigated by numerical tracking started from the equilibrium orbits of various energies down to 20 MeV. All these beams will be deliver from the stripping points to the center of switching magnet right outside the return yoke. The equilibrium orbits and extraction orbits with energies from 20 MeV to 100 MeV are shown in Figure 10. The location of stripping points and four other positions including the position of the center of the switching magnet are also given in this figure. The vertical and horizontal phase ellipses at different positions for the energies of 100 MeV, 70 MeV and 20 MeV are investigated. The Vertical and Horizontal Emittance Evolution of 100 MeV Extracted Beam are given in Figure 11.

Fron this initial extracted orbit tracking, it can be found that the H- beam can be stripped and extracted at energy from 70 MeV to 100 MeV. It also shows a possibility to extracted beam with lower energy though the beam size will become bigger.

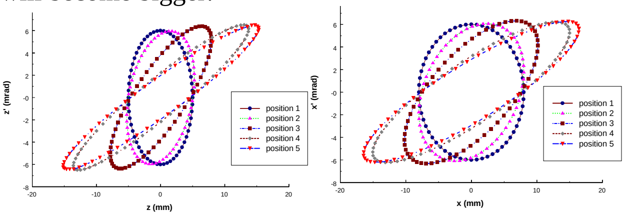

Figure 11: Vertical and Horizontal Emittance Evolution of 100 MeV Extracted Beam

General Engineering

Deformation calculation and structure design of magnet

The force between the top yoke and sector magnet is estimated firstly. Then the magnetic field distribution from a FEM code is used to calculate the force numerically based on a new code implemented on MATLAB. And the deformation of the top yoke, as well as the hill gap profile, are investigated in detail by taking the electromagnetic force, weight of magnet and atmospheric pressure into account. The investigation of deformation Vs several different thicknesses of the top yoke have been done. From the results, it can be seen that the maximum deformation of hill profile is about 60 σm when the thickness of top yoke is 50 cm.

The structure of the magnet is published separately[15].

Beam Diagnostics

The design of the beam diagnostics system of 100 MeV cyclotron is trying to measure and to monitor the basic and important beam parameters at every stage, which play a vital role in the running of the machine. They include beam intensity, beam position, beam profile, beam emittance and beam transportation efficiency, the pickup structures are designed as simple as possible, some devices are multifunctional or used in combination with each other, such as the specially designed FC at injection line and BPM+BEM combination at beam transportation lines. In order to meet the requirements of real time beam monitoring and close loop control during routine operations, most of beam diagnostics are no-interceptive, such as CT, BP, which could provide dynamic message. But there are also some interceptive detectors such as FC, BS, BPM, BEM, IBP, which are needed at beam test and improvement to optimize the key parameters of the machine.

The design of vacuum system, control system, power supplies and water cooling etc. are described in more detail separately [16].

SUMMARY

A compact H- cyclotron is designed as the driving accelerator for the project BRIF in Beijing. It will provide a 75 MeV - 100 MeV, 200 μA - 500 μA proton beam for RIB generation and other application with proton directly. Its main parts, the magnet and RF cavity are being designed. A test stand for cusp source and injection line has been developed. The general engineering including the civil engineering is now under consideration.

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