# 100 MeV $H^-$ CYCLOTRON DEVELOPMENT AND 800 MeV PROTON CYCLOTRON PROPOSAL*

Tianjue Zhang† and Jianjun Yang, China Institute of Atomic Energy, Beijing, 102413, China
on behalf of the BRIF Project Team

*Abstract*

Since the last cyclotron conference in Vancouver, significant milestones have been achieved on the BRIF (Beijing Radioactive-Ion Beam Facility) project. On July 4, 2014 the first 100MeV proton beam was extracted from the H- compact cyclotron. The cyclotron passed beam stability test with beam current of 25 μA for about 9 hours operation. In the year of 2015, the first radioactive ion beam of K-38 was produced by the ISOL system, and the beam current on the internal target of the 100 MeV cyclotron was increased to 720 μA. In the year of 2016, the cyclotron was scheduled to provide 1000 hours beam time for proton irradiation experiment, single-particle effects study and proof-of-principle trial on the proton radiography technology. It is also planned to build a specific beam line for proton therapy demonstration on the 100 MeV machine. In this talk, I will also introduce our new proposal of an 800 MeV, room temperature separate-sector proton cyclotron, which is proposed to provide 3~4 MW proton beam for versatile applications, such as neutron and neutrino physics, proton radiography and nuclear waste treatment.

## INTRODUCTION

The Cyclotron Laboratory at China Institute of Atomic Energy (CIAE) has been devoting to cyclotron development and related applications since it was established in 1956 [1]. An 100 MeV high intensity H- cyclotron, CYCIAE-100, is being built at CIAE. The machine is selected as the driving accelerator for the Beijing Radioactive Ion-beam Facility (BRIF). Figure 1 shows the layout of this project. The energy range of extracted proton beam for CYCIAE-100 can be adjusted continuously from 75 MeV to 100 MeV and 200 - 500 μA CW beam will be provided at the initial stage [2]. The first beam of CYCIAE-100 was extracted on July 4, 2014 [3], the operation stability have been improved and beam current have been increased gradually. On May 4, 2015, the first radioactive ion beam of $^{38}K^+$ was produced by bombarding CaO target by the 100 MeV proton beam. The effort for mA beam is continuing and 1135 μA beam was got on the internal target in June of this year.

In this paper, the beam commissoning progress and subsystem improvment of the 100 MeV $H^-$ cyclotron since last cyclotron conference in Vancouver will be presented, including the multi-cusp source, buncher, matching from the energy of the injected beam, vertical beam line and central region, beam loading of the RF system and instrumentation for beam diagnostics etc. In addition, this paper also introduces the recent conceptual design progress of the pre-study of an 800 MeV, 3-4 MW separate-sector proton cyclotron, referred to as CYCIAE-800 [4], which is aimed to provide high power proton beam for various applications, such as neutron and neutrino physics, proton radiography and nuclear data measurement and ADS system.

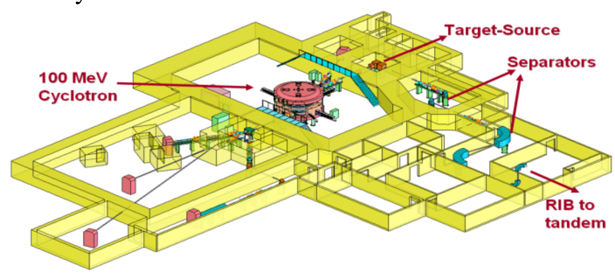


Figure 1: The layout of the BRIF project.

## BEAM COMMISSIONING

By the end of 2013, all the sub-systems of CYCIAE-100, including the main magnet, the main coil, the rf system, the vacuum system, the injection system, the ion source, the diagnosis and extraction units, the lifting system and the power supply systems, were installed and assembled on site. Figure 2 shows the photograph of the cyclotron, which was taken at the time all the subsystems were installed on site. The construction of CYCIAE-100 takes the advantages of both high precision typically seen in AVF cyclotrons and strong focusing in separated sector cyclotrons. The main parameters for CYCIAE-100 are presented in Ref. [5].

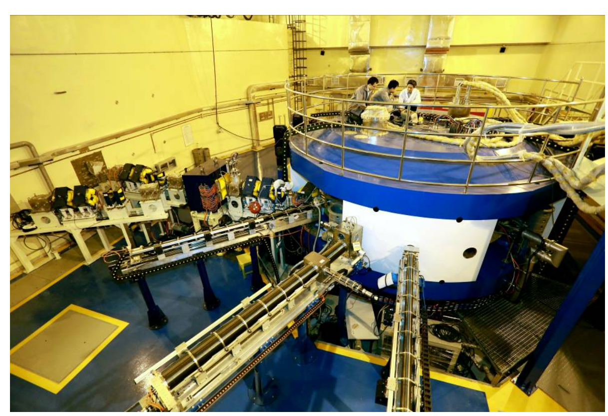

Figure 2: The 100 MeV compact cyclotron.

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† tjzhang@ciae.ac.cn

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By the end of July 2013, the field mapping and shimming were finished and the required isochronous field was obtained under vacuum condition. The trim-coils system, which is usually used in this type of compact cyclotron as a supplementary method to adjust local magnetic field, is unnecessary in the CYCIAE-100 cyclotron since a small integral phase slip of less than ±10° can be reached simply by properly trimming the 16 shimming-bars. After that, the resonator conditioning was started and the multi-pacting effects at low RF power region were eliminated successfully.

The beam commissioning was launched in November, 2013. The ion source was tuned up and could provide 5mA, 35 keV $H^-$ beam. After that, the functionality of injection line and the electrostatic inflector were tested and verified. On December 18 of 2013, we got a 320 μA DC beam on an internal target, which was positioned at the first accelerating gap. The transmission efficiency from the ion source to the exit of inflector is higher than 60%. On June 16 of 2014, the internal target was moved to 1 MeV region and a 109 μA beam current is measured under the condition of 20% rf duty cycle, corresponding to an injection efficiency of more than 10%. After that, we gradually increased the duty cycle and eventually reached CW mode operation. It is usually repeatable to get beam at 500 to 600 μA level at 1 MeV. Finally on July 4, we saw the first 100MeV beam on the extraction beam line of the cyclotron, which is a milestone of this project. Figure 3 shows the beam intensity signal on a radial probe.

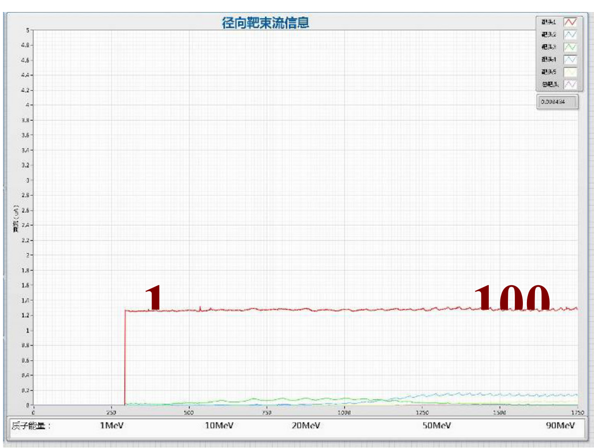

Figure 3: The beam intensity signal from a radial probe head when it slowly moved from the center to the extraction.

The beam stability was test for 12 hours on July 24. In the beginning, several beam trips happened, caused by the sparking between the two electrodes of the spiral inflector, then the major failure of a power supply device of the ion source caused beam off twice. After that the beam current was stably maintained at above 25 μA for 8 hours and 50 minutes, despite several fast beam trips caused by rf failures. This result met the requirement of acceptance for the first phase of this project.

On May 4, 2015, the first radioactive ion beam of $^{38}K^+$ was produced when the 100 MeV proton bombarded the CaO target station of ISOL system. The production of $^{38}K^+$ was $10^6$ pps when the proton beam current was 1 μA. This is another milestone of the BRIF project.

## BEAM INTENSITY UPGRADE

For CYCIAE-100, the ion source and injection line are installed underneath the main magnet, as is shown in Figure 4. The injection line adopts S-B-QQQ-S (S-solenoid, Q-quadrupole, B-buncher) focusing structure. The total length is about 250cm.

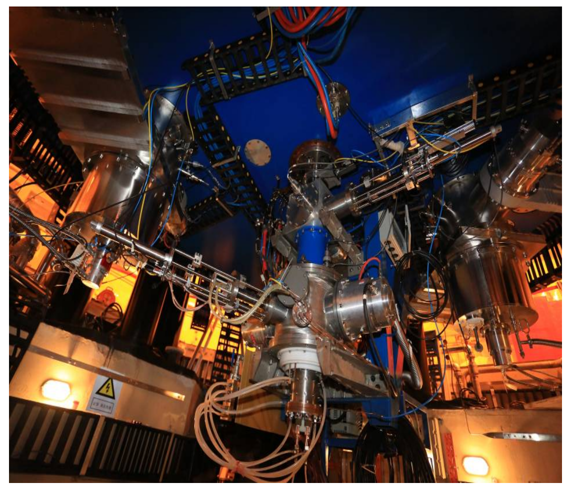
Figure 4: Ion source and the injection line.

In order to further increase beam intensity, several aspects were improved on the ion source, buncher, beam loading of the RF system, beam matching from ion source to the central region, etc.

### *Improvements of the Ion Source*

A multi-cusp $H^-$ ion source was adopted for the CYCIAE-100, which could supply about 10 mA DC $H^-$ beam [6]. In order to improve the beam quality and decrease sparking events and improve the beam stability, some optimization were done on the extraction system of the ion source. The geometry of the extraction system is shown by the cross section in Fig. 5(left). It is an axially symmetric three-electrode structure including plasma, lens and ground electrodes. Sparking events were found at between the lens electrode and the x-y steering magnet, which was installed around the ground electrode. So a protection cover was placed on the steering magnet to prevent the electrons from bombarding the steering magnet. Twenty holes with diameter of 10 mm on the protection cover are drilled to ensure the gas flow and sufficient vacuum pressure.

On the other hand, in order to decrease the distance between the lens and the x-y steering magnet, a new x-y steering magnet with the shorter length was installed , for which the coil turn number is increase accordingly to maintain its deflection capability. This resulted in a smaller size of the ground electrode. So a new ground



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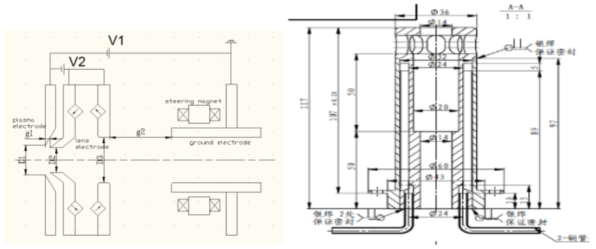


Figure 5: The geometry of the ion source extraction system and the cross-section drawn of ground electrode.

electrode was also designed. The cross-section drawn of ground electrode is shown in Fig. 5 (right).The distance between the beam limit hole and the ground electrode extraction hole is 67 mm. In order to reduce gas stripping in the ground electrode extraction region and to run the sources at optimum gas pressure in the ground electrode, 6 holes with every the size of 12 mm ×5 mm were bored on the head of the ground electrode. During the ground electrode design, the distance between the two lens was increased from 11 mm to 12 mm to improve the beam quality. By taking these measures, the extraction energy from the ion source was increased from 35 keV to 40 keV and the extracted beam current was increased from 5 mA to 10 mA DC, without sparking events during the beam stability test of one week long.

### *Improvements of the Buncher System*

The DC beam generated by $H^-$ cusp source is bunched by a first-harmonic non-intercepting two-gap buncher, which locates between the first solenoid and the triplet, approximately 1.1 m away from the inflector. The gap length is 5 mm and the required distance between two gaps is determined by $1/2\beta\lambda$, which is 31 mm for 40 keV energy. The beam radius is limited by a collimator installed in front of the buncher and the effective buncher radius is 10 mm formed by gold plated tungsten wires, which is similar to TRIUMF design [7]. The RF-feeding system of the buncher consists of a LC matching circuit, a 600W RF solid state amplifier and an amplitude/phase control unit. The mechanical structure of the buncher is shown in Figure 6.

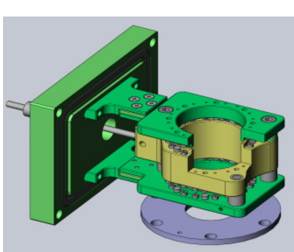

Figure 6: The mechanical structure of the buncher.

Before the beam commissioning with buncher, three major improvements were made, including the modification of the power supervising system, the measurement of the shunt impedance of the buncher and the fine tuning of the LC matching circuit.

(1) An EPICS based power monitor system was developed to monitor the RF power flow to the buncher. The system consists of a digital control board and a RF analog board. The digital control board is based on ARM Cortex-A7 CPU and run Linux OS. The RF analog board demodulates the forward power and the reflected power through two RF power detectors. A 16 bits four-channel ADC is used to digitalize the output of the power detector.

The digital control board accesses the ADC through the SPI bus and fills the sampled value of the related EPCIS process variables. The interlock is also included in the power monitor system to avoid damage.

(2) The shunt impedance of the buncher was measured by the Agilent E5070B vector network analyzer. The vector network analyzer measured the S21, using a 50 Ω loaded probe connected with the grid of the buncher as port 2, meanwhile port 1 was the conversional coupling port of the buncher. Afterward, the shunt impedance for the buncher structure was calculated as 3.5 KΩ. By knowing this value, one may calculate the beam bunching voltage by using the forward power readings.

(3) The capacitor of the LC matching circuit is coarse, which has a big temperature drift. This drift has significant adverse impact on the bunch RF matching when the RF power is switched on. The LC matching circuit has to be adjusted online, manually. To protect the 600 W RF power amplifier, a pulse signal with a duty factor is 1/10 was used to drive the buncher system. The capacitor was fixed when the amplitude of the pickup signal reached its maximum. Then the system was changed to automatic mode.

### *Improvements of the RF System*

The RF system [8] of the 100MeV cyclotron consists of two sets of identical RF cavities [9] power transmission systems and two 100kW tetrode RF amplifiers [10] LLRF systems [11,12]. The high power level RF parts of the system are fully independent from each other, while the Low Level RF parts share one common reference clock. Thus, the LLRF systems can align the two cavities to the same phase for proton beam acceleration. The RF system has been improved for two aspects before the mA level beam commissioning, including LLRFs and cavities.

(1) The P.I. controller in amplitude control loop is an analog regulator. When the beam current is increased, the beam loading may cause an open-loop condition for the Dee voltage regulation. After the amplitude loop is closed, the RF driven signal amplitude is determined by the DSP and DDS of the LLRF system. In another word, to achieve an accurate amplitude control, the LLRF adopts a self-adaptation strategy to ensure the amplitude control loop is always closed, unless the power requirement exceeds 120% of nominal value.

(2) The tuner of the cavity consists of two DC motors, which drive a fine capacitor and a coarse capacitor, respectively. The coarse capacitor is controlled manu-

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ally, while the fine capacitor is controlled by the tuning loop and works online. The fine tuner was changed to a smaller disk before the beam commissioning to achieve a better tuning performance of the RF cavity. This effort was observable in the commissioning, e.g. the residual tuning errors were reduced to less than 3 degrees for both cavities of the CYCIAE-100 cyclotron.

### *Installation of the Removable Internal Target*

The removable target locates at the center of the magnet valley area. Driven by the cylinder and travel switch, the target could move onto the median plane and stop the arriving particles. The head of removable target is a cube made by copper and cooled by water. In order to eliminate the influence of secondary electron emission, a wing with two thin copper pieces are added on the side face of the target head. Figure 7 shows the removable internal target and the beam spot.

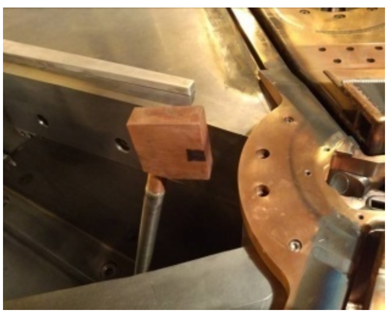

Figure 7: The removable internal target.

### *Beam Intensity Upgrade*

The Beam Commissioning at higher intensity has been carried out after above mentioned improvements. Figure 8 shows the beam current history measured by the internal target at 1MeV, which shows the beam current on the internal target reaches 1.1 mA. Table 1 shows the bunching efficiency and acceleration efficiency for different DC beam current of $H^-$ ion source. It shows the bunching factor can go up to factor of 2 at 3 mA beam current. It clearly shows that the bunching efficiency is in decrease with the ion beam current. However, the bunching factor can still reach 1.66 at around 9 mA beam curren. Table 1 also shows the influence of the wing on the internal target. The measured beam current will increase about 6.3% when the secondary electron emission is suppressed by the wing.

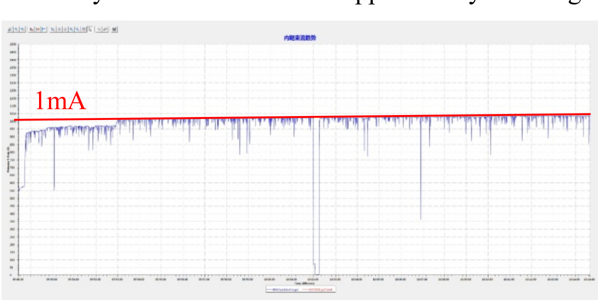


Figure 8: The beam current history measured by the internal target at 1 MeV.

Table 1: The Bunching Efficiency and Transmission Efficiency from the Ion Source to the Internal Target

| Ion Source (mA) | No Buncher (μA) | With Buncher (μA) | Bunching Factor | Transmission Efficiency (%) |
|---|---|---|---|---|
| 1.33 | 100 | 201 | 2.01 | 15.1 |
| 1.91 | 145 | 310 | 2.14 | 16.2 |
| 3.25 | 201 | 399 | 1.99 | 12.3 |
| 4.27 | 258 | 490 | 1.90 | 11.5 |
| 8.69 | 610 | 950 | 1.56 | 10.9 |
| 8.67 | 608 | 1010 | 1.66 | 11.6** |

**Measured data when a wing with two thin copper pieces is added to eliminate the secondary electron emission.

## A 800 MeV PROTON CYCLOTRON PROPOSAL

High power proton beam has wide applications in radiation physics, neutron science, neutrino physics, radioactive beam production and ADS system. The cyclotron is an intrinsic CW mode particle accelerator, which has the following distinguishing features: (a) low construction costs; (b) high effective power conversion rate; (c) compact structure; (d) no needs for superconducting resonators, etc. Therefore, the cyclotron can be a competitive candidate for MW-level proton beam driver. CIAE proposed a multi-functional research facility based on cascaded cyclotrons [13].

### *Layout of the Facility*

In the latest proposal, this project will be split into three stages. In the first stage, it is proposed to construct the 800 MeV ring cyclotron and to utilize the 100 MeV, 200 μA compact $H^-$ cyclotron CYCIAE-100 of the BRIF project as its injector; The experimental instruments for nuclear data measurement, single event effects, radiation physics and isotope production facility will be constructed as well. Then in the second stage, in order to achieve more than one MW beam power on target, the CYCIAE-100 will be superseded by a dedicated 100 MeV separated-sector injector cyclotron [14]. The spallation neutron source, proton radiography device and spent fuel post-process platform will be constructed in this phase as well. In the final stage, when the beam power reach the design of 3 MW, the beam can be deliver to the China Fast Neutron Reactor (CEFR) to compose a ADS facility.

### *Conceptual Design Progress*

Since the year of 2009, the pre-study of this cyclotron complex was carried out, including general design [13] space charge limit [15] and the main magnet design and optimization of the main cyclotron design [16]. The main accelerator is a PSI-like ring cyclotron [17] with the beam power of 3 to 4 MW and kinet-



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ic energy of 800 MeV, referred to as CYCIAE-800.

In the conceptual design, two solutions are considered. one is the proton cyclotron with conventional coils and another is the $H_2^+$ (two protons plus one electron) cyclotron with superconducting coils. Table 2 briefly summaries the advantages and disadvantages of the two solutions. Considering the maturity of the existing technologies and construction risk, we chose the proton cyclotron with warm magnet.

Table 2: Comparison of the Proton and H2+ Solutions

| | H2+ | Proton |
|---|---|---|
| pro | a) Multi-turn stripping extraction;<br>b) low RF voltage is OK;<br>c) Smaller space charge effects | a) Mature technology at MW level (PSI, TRIUMF);<br>b) Require low B field, warm magnet is OK;<br>c) Good extraction beam quality;<br>d) Low Vacuum is OK |
| con | a) Long-lived vibrational states →dissociate<br>b) Require SC magnet<br>c) Need high vacuum<br>d) No construction experience at MW level | a) Require single-turn extraction;<br>b) Require high RF voltage;<br>c) Larger space charge effects;<br>d) Need flat-top cavities and/or buncher |

The latest layout of the main magnet is shown in Fig. 9. The diameter and height of the magnet system is 16 m and 5.8 m, respectively. The total weight of the magnet is 3420 t and the total stored energy is 3.96 MJ.

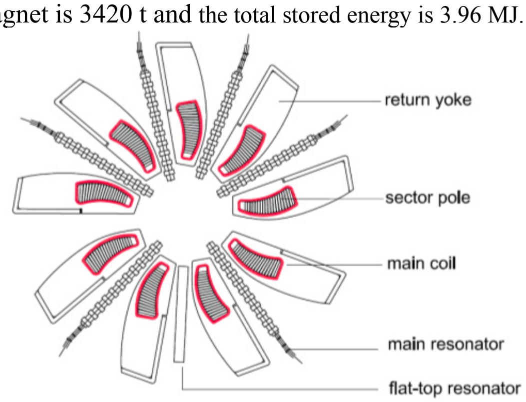


Figure 9: Schematic plot of the main magnet system of the 800 MeV cyclotron together with the rf resonators.

In this cyclotron, the rf system is a very challenging subsystem, which requires sophisticated monitoring and protection systems and components. The parameter analysis shows that, in order to extract the MW level proton beam, a single amplifier is incapable to transfer adequate power to a cavity of the design mentioned above, even if the most powerful tetrodes and state-of-the-art components are used. A possible alternative is that a cavity is fed with two complete power chains, namely two separate amplifiers, transmission lines and coupling loops. The rf resonator is modelled in 3D and the result is shown in Fig. 10. Thanks to the adequate free space between magnet sectors, the Q factor of the main resonator can reach 20,000.

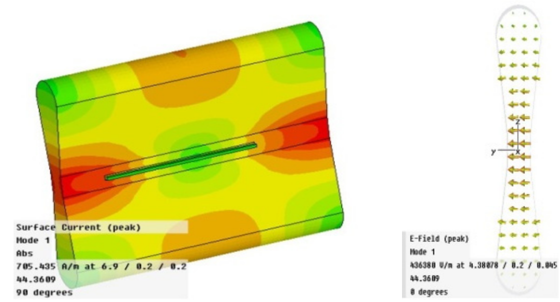


Figure 10: Surface current and E-field distribution of the rf resonators.

In this high beam power cyclotron, space charge force can play a import role in the beam dynamics. Large scale parallel particle simulation shows that the beam can be cleanly extracted from the ring cyclotron when the beam current is 3 mA (2.4 MW). Further optimization will be carried out to further increase the beam current limits.

## CONCLUSION AND OUTLOOK

The beam commissioning of the 100 MeV cyclotron proceeds smoothly to high beam current. More than 1 mA beam current is already reached in the interval target. It is expected this cyclotron is capable to provide 200 to 500 µA proton beam in the coming years. More radioactive beam production experiment will be carried out on the ISOL system to optimize the charge exchange efficiency and to improve the positive surface ion source. Meanwhile, the cyclotron team has already launched the pre-study of the future high power proton cyclotron. From the pre-study, it is confirmed that a 3 MW level CW proton cyclotron with conventional coils should be feasible based on our existing technologies.

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