NEW DEVELOPMENT OF THE HIGH POWER PROTON CYCLOTRONS AT CIAE*

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Abstract

The high power proton beam has wide application potentials in future clean nuclear energy system, neutron physics study, RIB production and particle physics research. Cyclotrons are intrinsic in continuous-wave beam mode, which has the characteristics of high efficient power conversion rate, compact structure and relatively low construction cost. CIAE is dedicated to developing high power proton cyclotron in China for a long time. In this talk, the recent construction progress of the 100MeV cyclotron will be presented in detail. The commissioning of this cyclotron is in progress and we got the first beam on July 4, 2014. In additions, this talk also introduce the recent progress of the pre-study of a high power 800 MeV separate-sector ring cyclotron, which is proposed to provide high power proton beam for applications neutron and neutrino physics, proton radiography and nuclear data measurement.

CONSTRUCTION OF CYCIAE-100

Installing and Assembling

As a driving accelerator for Beijing Radioactive Ion-beam Facility (BRIF), a 100 MeV H- compact cyclotron, normally referred to as CYCIAE-100, is being constructed to provide the proton beam of 70-100 MeV with beam current of 200-500 μA [1]. By the end of 2013, the main magnet, the main coil, the rf system, the vacuum system, the inject system, the ion source, the diagnosis and extraction systems, the lifting system and the power supply systems are installed on site. Figure 1 shows the photo of the assembled cyclotron.

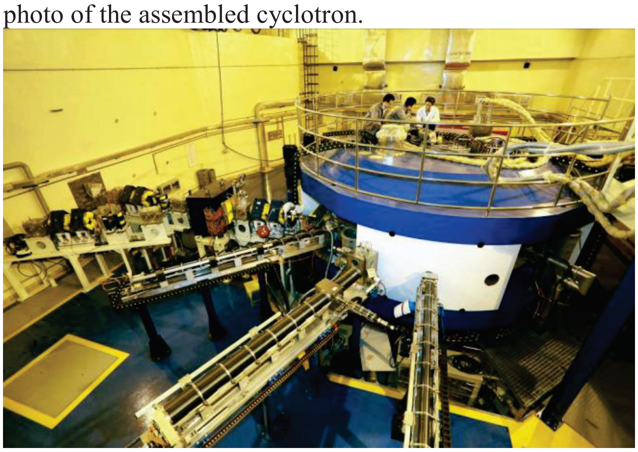

Figure 1: Photo of the assembled 100MeV compact cyclotron.

The total weight of the main magnet is 436 tons and the overall accuracy is 0.05 mm. The quality factor of the two rf resonators reach 9500, which is highest value among the existing compact cyclotrons in the world. In order to reduce the beam loss caused by residual gas stripping, the high-speed cryo-panel system is utilized used so as to further increase the vacuum to 5×10^{-8} torr level.

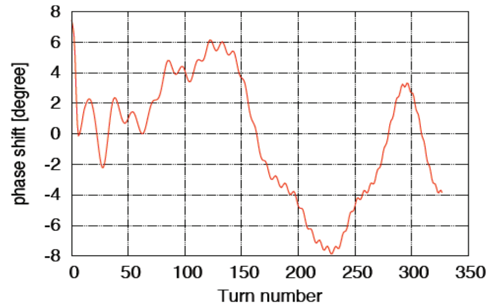

Figure 2: The integral phase slip of the final field map.

By the end of July 2013, we finished the field mapping and shimming. In order to correct the magnetic field error caused by air pressure during operation, the field map was accurately measured under vacuum condition for the first time. The trim-coils system, which is usually used in this type of cyclotrons as a supplementary method to adjust local magnetic field, is proved unnecessary in the CYCIAE-100 cyclotron since a small integral phase slip of less than ±10° (see Fig. 2) can be reached simply by properly trimming the 16 shimming-bars. The operating RF frequency for the final field map is 44.8125 MHz. Furthermore, profiting from the deep-valley structure of the magnet, the vertical betatron frequency is kept above 0.5 and the crossing of dangerous Walkenshaw resonance line at high energy region is avoided, as is shown Fig. 3.

Since November 2013, we started the rf resonator conditioning, which is a time-consuming work. The main purpose is to eliminate the multipacting effects at low rf power region and to reduce the rf sparking at high rf power region. The multipacting effects can cause the mismatching of impedance and reflect the rf power back to the amplifier. In order to speed up the conditioning process, some aquadag solution is printed to the sensitive surfaces of the resonators to repress secondary electron emission. Finally, the 33 kW rf power can be fed into both resonator within one hour, which is good enough to carry out beam commissioning.

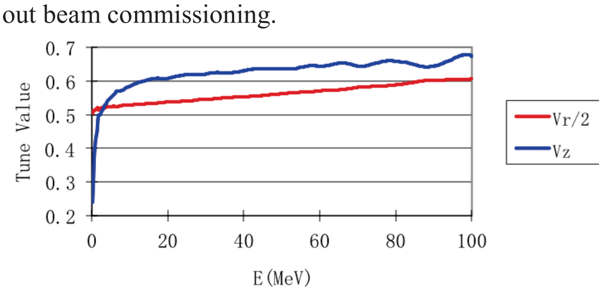

Figure 3: The betatron tune of the final field map.

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Beam Commissioning

Just after finishing the assembling and joint commissioning of all the sub-systems, the beam commissioning is launched. On December 18 of 2013, we got 320 μA DC beam on an internal target, which is positioned in front of the first accelerating gap. The transmission efficiency from the ion source to the exit of inflector is higher than 50%. On June 16 of 2014, the internal target is moved to 1 MeV region, which is about 6 revolutions in the cyclotron, and successfully got 109 μA beam. This corresponds to an injection efficiency of 10%, which is acceptable given the face no buncher is installed on the inejection line. Finally on July 4, we saw the first 100MeV beam on the extraction beam line of the cyclotron, as is shown in Fig. 4.

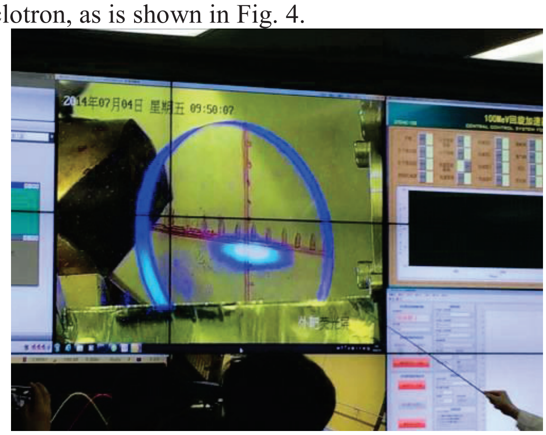

Figure 4: The quartz plate diffuses blue light when it is penetrated by the 100 MeV proton beam.

In order to check the stability of this cyclotron, we carried out beam test for 12 hours on July 24. The beam current history is recorded in Fig. 5. In the beginning, several beam trips happened which were 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.

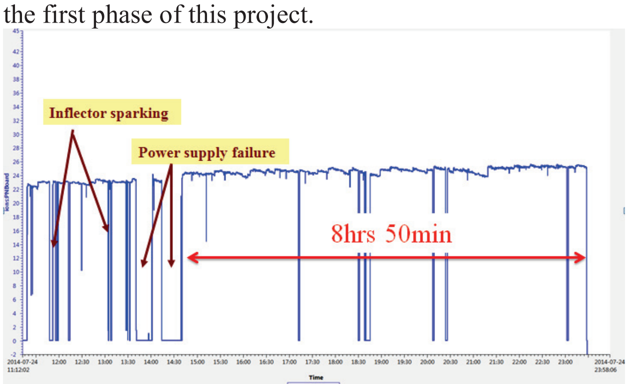

Figure 5: Beam current history during 12 hours continuous operation.

In the next step, it is planned to gradually increase beam current to 200-500 μA. Meanwhile, the radiation dose must be kept at acceptable level. As the most significant collective effects in cyclotron, space charge effects are one of the main causes of beam loss and radiation dose. According to the result given by large scale particle simulation using OPAL-CYCL [2], in the CYCIAE-100 cyclotron no beam loss will be introduced by space charge effects when the beam current is less than 1 mA [3].

PRE-STUDY ON AN 800 MEV CYCLOTRON

Over the past few years, high power proton cyclotrons come full circle. In the year of 2012, BNL proposed an ADS project based on three superconducting cyclotron modules [4]. In 2010, MIT launched an international collaboration project DAEδALUS for searching CP-violation in neutrino sectors [5]. The DAEδALUS experiment calls for measurements at three distances: 1.5 km, 8 km and 20 km. Three accelerator modules, called near-, mid- and far-site are used, providing 800 MeV protons with 0.8, 1.6 and 4.8 MW average beam power respectively. We participated in the pre-study on the accelerator system of this programme, undertaking research in high power beam dynamic issues including space charge effects [6].

In additions, CIAE independently proposed a multi-functional research facility based on a 3 MW, 800MeV proton cyclotron, referred to as CYCIAE-800, for neutron and neutrino physics, proton radiography, RI production and other applications [7]. Figure 6 shows the block diagram of our proposal.

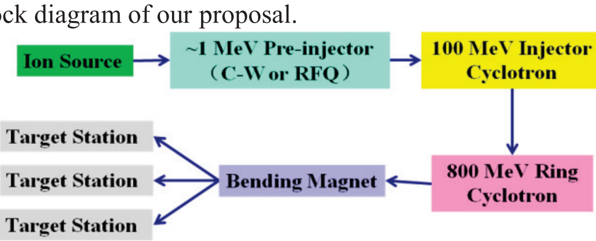

Figure 6: The block diagram of the proposed high power cyclotron complex.

Table 1: Comparison of the Two Solutions

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

The major difference between CIAE solution and DAEδALUS solution is the particle type. The former accelerates proton, while the latter accelerates H_2^+ (two

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protons plus one electron). Table 1 briefly summaries the advantages and disadvantages of the two solutions.

Overall Design of CYCIAE-800

In the conceptual design, an ideal isochronous magnetic field map model was built by using the scaling laws. Based on that, the basic fundamental beam dynamics was studied and show the feasibility of this solution [7]. Since then we managed to build a three-dimensional finite element model of the main magnet and to calculate the practical magnetic field by using numerical methods. In 2013, we reported the progress of the physical design [8]. In that version, both the $Q_r=2Q_z$ coupling resonance line and $Q_z=1$ integral resonance line are crossed at large energy region, as are shown by the red curve in Fig. 8. Large scale particle simulation shows that the crossings of these two resonance lines evidently increase vertical beam envelop. Therefore, in this year the magnet structure is further optimized. The spiral angle of the pole is increased by 1.1 times and the profile of the pole is finely tuned. The latest version of the layout sketch of the cyclotron is shown in Fig. 7. The blue broken curve in Fig. 8 represents the tune diagram of current version, which shows the crossing of $Q_r=2Q_z$ and $Q_z=1$ lines are avoided.

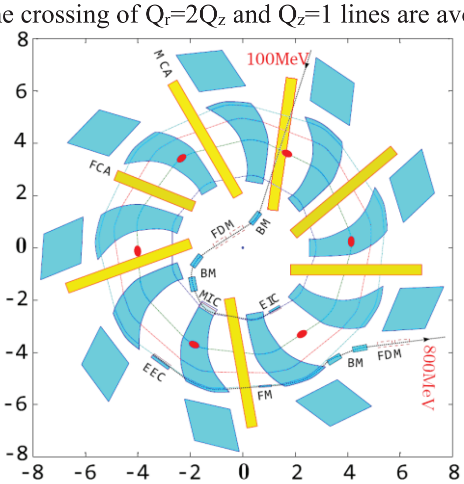

Figure 7: The latest layout sketch of the 800 MeV cyclotron solution, including injection and extraction elements (MCA: main cavity, FCA: flat-top cavity, FDM: focusing doublet, BM: bending magnet, MIC: magnetic injection channel, EIC: electric injection channel, FM: focusing magnet, EEC: electric extraction channel).

Space Charge Effects

Space charge is the dominated factor for beam loss in high intensity cyclotrons which adopt single-turn extraction scheme. For the current version, space charge effects are quantitatively studied by using the OPAL-CYCL code. Since the injector cyclotron and the transport line is not designed yet, in the simulation we assume a typical gaussian distribution with conservative values for the normalized rms emittances of 0.2π mm-mrad in both the transverse directions, full phase width of $\pm 10^{o}$ and energy spread of zero. The beam is injected eccentrically with the optimized settings to enlarge the turn separation at extraction. In the simulation, 5×10^{5} macro-particles are tracked simultaneously and a co-moving 64x64x32 grid is utilized to solve space charge field. The simulation for 0, 1, 2, 3, 4 and 5 mA beam current scenarios are carried out for comparison. The result shows the space charge have significant influence on the beam's behaviour. Along with the beam current increases, the longitudinal rms size is shorten, which is helpful for repressing energy spread increase during acceleration; Nevertheless, the radial size is lengthen, which is unfavourable for single-turn extraction. The beam's radial profiles of the last few turns are shown in Fig. 9. The results shows that for up to 2 mA beam current, the beam profile of extracting turn is clearly separated with the circulating turns, but for higher beam current scenarios the last several turns severely overlap. Therefore, it is concluded that for the current design, the beam can be cleanly extracted when the beam power is less than 1.6 MW, which is two times higher than that of the last cyclotron structure version; but for higher beam power operation, more structure optimization and space-charge compensation methods are required..

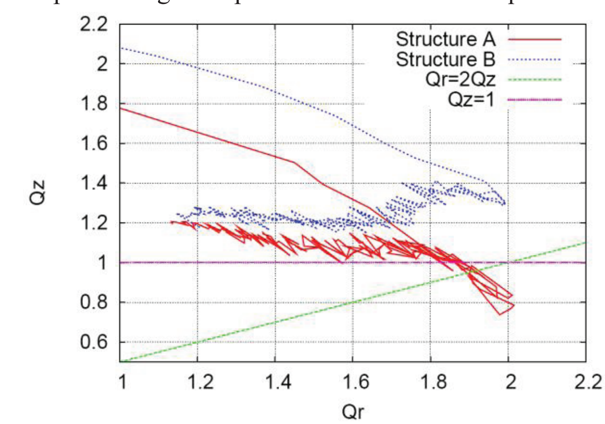

Figure 8: Tune diagram of the structure A(last version) and structure B (current version).

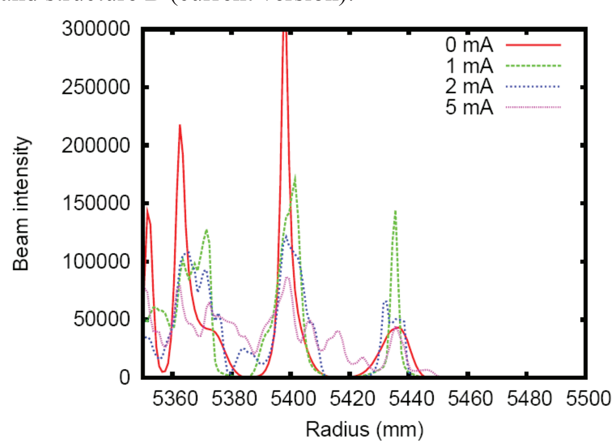

Figure 9: Radial beam profile of the last few turns for different beam current scenarios.

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