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PHYSICAL DESIGN OF THE INJECTOR FOR XIPAF-UPGRADING*

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Abstract

This paper describes the physical design of one linac injector for the proton/heavy ion synchrotron, which is under construction for Xi'an 200 MeV Proton Application Facility(XiPAF) heavy ion upgrading project. A heavy ion linac injector will be constructed close to the existing proton linac injector. The heavy ion injector consists of one electron cyclotron resonance(ECR) source, one low energy beam transport(LEBT) section, one radio frequency quadrupole(RFQ) accelerator, one interdigital H-type drift tube linac(IH-DTL), and one linac to ring beam transport(LRBT) section. Heavy ion beams will be accelerated to 2 MeV/u. The unnormalized 99%-particles emittances at the injection point of proton and heavy ion are optimized to be lower than 10 and 16 π mm·mrad, respectively. Besides, low dispersion at the injection point is obtained to minimize the beam offset caused by the dispersion mismatch in the synchrotron. Three scrapers are installed in the LRBT to meet the requirment of emittance and dispersion.

INTRODUCTION

Xi'an 200 MeV proton application facility(XiPAF) is the first facility in China specifically designed to simulate space radiation environments. It was officially launched in 2014 and completed overall beam emission in 2020 [1–3]. XiPAF can currently provide a stable proton beam of 20~200 MeV, and the on-target particle flux can reach an adjustable range of 10^5~10^8 p/cm^2/s [3]. XiPAF is currently composed of a negative hydrogen ion linac, a medium energy beam transport line(MEBT), a proton synchrotron [4], a high energy beam transport line(HEBT), and an experimental target station.

In recent years, the demand of heavy ion single event effect(SEE) experiments is rapidly increasing. The XiPAF-upgrading project has been proposed in order to improve the heavy ion SEE experimental facilities. Based on the proton synchrotron at present, a new heavy ion injector will be constructed to provide heavy ions with a charge-mass ratio in the range of 1/3 ~ 1/6.5, at the energy of 2 MeV/u.

The heavy ion injector consists of an electron cyclotron resonance(ECR) heavy ion source, an low energy beam transport(LEBT), an radio frequency quadrupole(RFQ), an interdigital H-type drift tube linac(IH-DTL), and a linac to ring beam transport(LRBT) section. The RFQ and IH-DTL can accelerate heavy ions to 400 keV/u and 2 MeV/u respectively, which can meet the injection energy requirement of the synchrotron. For the proton injector, existing RFQ and Alvarez-DTL will be reused, and modifications will be mainly made on ECRIS and LRBT.

The overall conceptual design has been completed [5], and this article mainly introduces the physical design of the entire linear injector.

REQUIREMENT OF THE INJECTOR

Because there are various kinds of heavy ions, Bi^{32+} ions with the smallest charge-mass ratio are selected for heavy ion injector optimization design. The type of proton source has changed from the H^- to H^+ due to the change of injection method from stripping injection to multiturn injection. The requirement parameters of the injector are shown in Table 1. The sketch diagram of the whole injector is shown in Fig. 1.

Table 1: Design Parameters of the Linac Injector

Parameter	Proton	Heavy ion
Injected ion	H^+	C^{4+} ~ Bi^{32+}
Charge-mass ratio	1	1/3 ~ 1/6.5
Injection energy	7 MeV	2 MeV/u
Peak current exit of the ECRIS	20 mA(H^+,H_2^+)	50 eμA(Bi^{32+})
Injected current	2~4 mA	≥17 eμA(Bi^{32+})
Unnorm. emit. 99%-particles	≤10π mm·mrad	≤16π mm·mrad
Momentum spread 99%-particles	≤0.3%	≤0.3%
RF Frequency	325 MHz	108 MHz
Repetition rate	0.1 ~ 0.5 Hz	0.1 ~ 0.5 Hz
Beam pulse width	60 ~ 100 us	60 ~ 100 us

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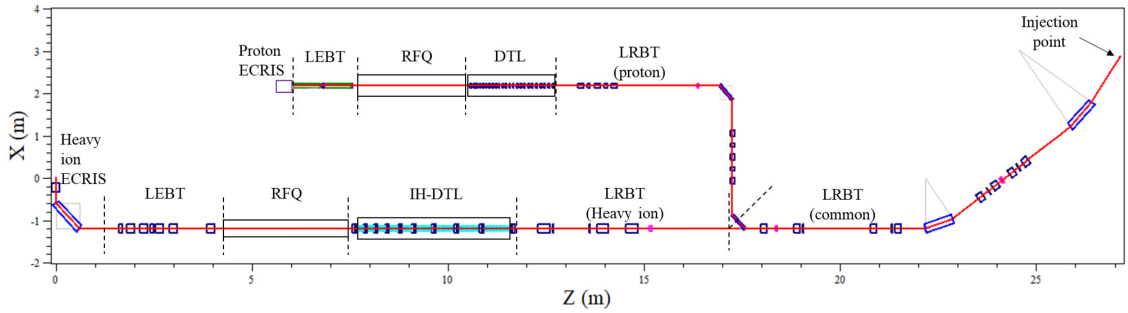

Figure 1: Sketch of the whole injector.

HEAVY ION INJECTOR

For heavy ions, electron cyclotron resonance ion source(ECRIS) [6] is adopted, because it can achieve high current with high charge state. An analytical magnet is needed after the ECRIS to select heavy ions with certain charge states. The ion source system mainly includes the high charge state ECR ion source and ion source beamline system including the analytical magnet.

The phase spaces of the heavy ion beam in x-x' and y-y' planes are different at the exit of the analytical magnet, while the acceptance of RFQ in x-x' and y-y' planes are the same. LEBT is adopted to match the beam between the ion source and RFQ accelerator. Four quadrupole magnets are adopted to make the TWISS parameters in x-x'plane the same as in y-y'plane. A solenoid is used to focus the beam symmetrically into the the RFQ. The sketch diagram of the ion source system and the LEBT is shown in Fig. 2.

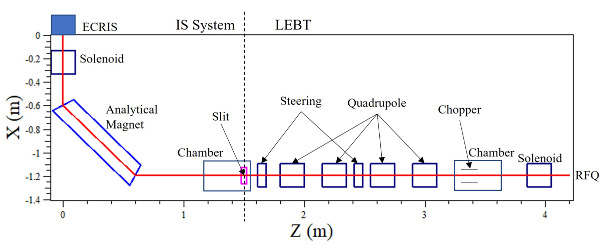

Figure 2: Sketch of the ion source system and the LEBT.

Beam will be accelerated and bunched in a four-vane RFQ after the LEBT. The RFQ has been optimized based on the traditional four-section procedure. In the shaper section, adiabatic shaping [7] is adopted which can improve the particle capture rate. The intervane voltage is ramped in the shaper and buncher sections, and remains constant in the acceleration section. This can increase the acceleration gradient of the RFQ and ensure a low kilpatric factor of 1.8. The beam dynamic parameters of the RFQ are shown in Fig. 3. The dynamic design of the RFQ was carried out with RFQGen [8].

IH-DTL has the advantage of high shunt impedance [9], but its transverse stability is inferior to the Alvarez-DTL. To solve this problem, an IH-DTL with electro-magnet-quadrupole(IH-EMQ) [10] is designed based on the FD lattice, as the main accelerator of XiPAF heavy ion injector.

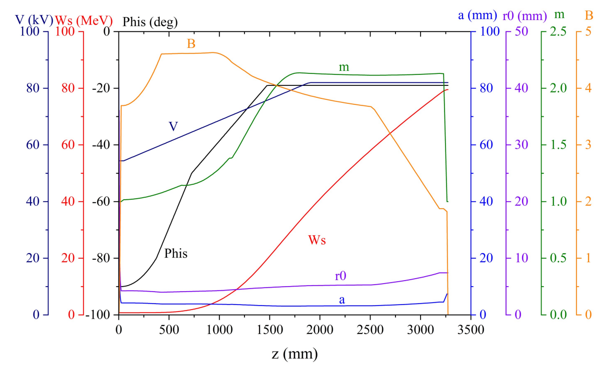

Figure 3: RFQ parameters as a function of length.

The operating frequency of th IH-EMQ is 108 MHz. There are two types of drift tubes in the IH-DTL, one is a small drift tube without a magnet inside, and the other is a large drift tube with EMQ. Drift tube with EMQ is intalled in every 3-6 drift tubes to provide a periodic focusing magnetic field, so the beam loss and emittance growth can be reduced. The total length for the IH-DTL is 3.8 m with an input energy of 0.4 MeV/u and output energy of 2 MeV/u.

Accelerated heavy ion beam is transport by an LRBT to the injection point. Better injection beam parameters should be obtained, including low emittance, low dispersion and high current, to improve injection efficiency and reduce the beam loss in the sychrotron. In the LRBT, 3 scrapers are used to remove particles with large emittance. Two dipole magnets and four quadrupole magnets at the end of LRBT are used to reduce the beam dispersion. The last scraper is located at the position with the maximum dispersion and beam radius, so it can help reduce the dispersion as shown in Fig. 4. The simulation is carried out with TraceWin [11].

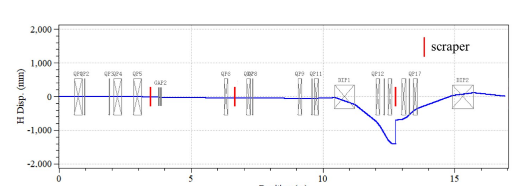

Figure 4: The dispersion of heavy ion in the LRBT simulated with TraceWin.

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The simulated 2.45 times RMS beam envelope in the heavy ion injector is shown in Fig. 5.

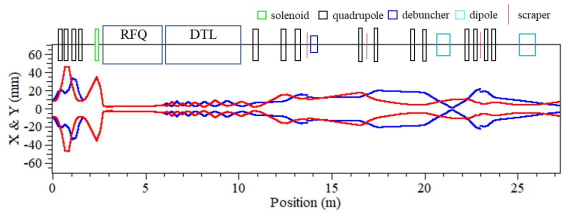

Figure 5: 2.45 times RMS beam envelope in the heavy ion injector simulated with TraceWin.

PROTON INJECTOR

In order to accommodate the heavy ion injection, the injection method of XiPAF synchrotron has been changed from stripping injection to multiturn injection. A new H^+ source is needed to replace the existing H^- ion source. Meanwhile, the required injected current increases due to the decrease of injection gain, and the required current of the ion source has also increased to 20mA(including H^+ and H_2^+). The comparison of two ion sources parameter requirements is shown in Table 2. The LEBT of proton injector mainly consists of 2 solenoids.

Table 2: Comparison of Two Ion Sources Parameter Requirements

Parameter	New	Old
Injected ion	H^+	H^-
Peak current of the ECRIS	20 mA(H^+,H_2^+)	5 mA
Norm. RMS emit.	0.15π mm·mrad	0.2π mm·mrad
Repetition rate	0.1 ~ 0.5 Hz	0.1 ~ 0.5 Hz
Beam pulse width	60 ~ 100 us	60 ~ 100 us

The existing RFQ and Alvarez-DTL are capable of accelerating the H^+. The transverse phase space of beam will be rotated by 90° due to the change in charge state from negative to positive. Therefore, RFQ will be rotated by 90° along the beam axis to counteract this change. DTL does not require any modification.

The proton LRBT has been redesigned with the same design concept as the heavy ion LRBT. The dispersion of the proton in LRBT is shown in Fig. 6. And the 2.45 times RMS beam envelope of the proton injector simulation is shown in Fig. 7.

BEAM AT INJECTION POINT

The main parameters of heavy ions and protons at the injection point are shown in Table 3. All parameters meet the injection requirements. There is an additional beam loss of 30% predicted by the error study. The phase space at the injection point is shown in Fig. 8.

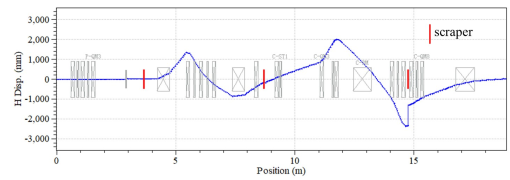

Figure 6: The dispersion of heavy ion in LRBT.

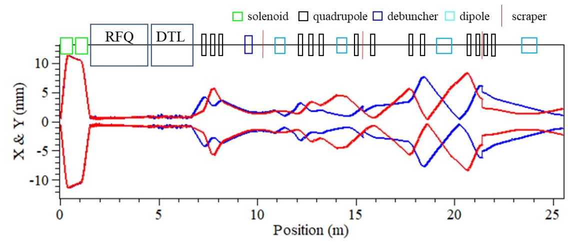

Figure 7: 2.45 times RMS beam envelope in proton injector simulated with TraceWin.

Table 3: Design Parameters of The Linac Injector

Parameter	Proton	Heavy ion
Simulation ion	H^+	Bi^{32+}
Injection energy	7 MeV	2 MeV/u
Total transmission (Additional 30%-loss included)	40.5%	42.3%
Injected current	4 mA	21.1 eμA
Unnorm. emit. 99%-particles	9.3π mm·mrad	15.9π mm·mrad
Momentum spread 99%-particles	≤0.3%	≤0.3%
Dispersion	0.028 m	0.004 m
Dispersion/dz	0.08	-0.069

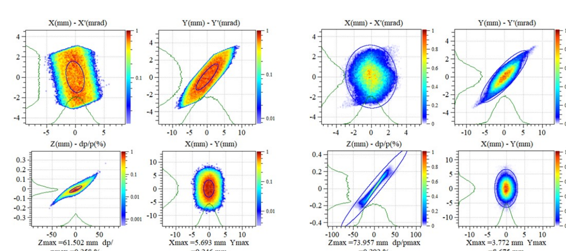

Figure 8: Beam phase spaces at the exit of injection point simulated with TraceWin (left:heavy ion; right: proton).

CONCLUSION AND FUTURE WORK

The heavy ion injector consists of an ECR heavy ion source, an LEBT, an RFQ, an IH-DTL, and an LRBT. The proton injector has been modified based on the existing injector. Three scrapers are used to decrease the emittance and dispersion of the injected beam.

Detailed design of the injector has been completed and components are being machined. It is expected that the beam commissioning of the linac injector will be achieve in 2025.

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