DESIGN OF THE 7MeV LINAC INJECTOR FOR THE 200MeV SYNCHROTRON OF THE XI'AN PROTON APPLICATION FACILITY*

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Abstract

We present, in this paper, the design result of the 7 MeV linac which will inject the negative hydrogen ion beam to the downsteam synchrotron of the Xi`an Proton Application Facility (XiPAF). This newly designed facility will be located in Xi'an city and provide the proton beam with the maximum energy of 230 MeV for the research of the single event effect. The 7 MeV linac injector is composed of the 50 keV negative hydrogen ion source, Low Energy Beam Transport line (LEBT), 3 MeV four-vane type Radio Frequency Quadrupole (RFQ) accelerator, 7 MeV Alvarez-type Drift Tube Linac (DTL), and the corresponding RF power source system. The output beam of the linac injector is designed with the peak current of 5 mA, maximum repetition frequency of 0.5 Hz, beam pulse width of 10~40 μs and RMS normalized emittance of 0.24 π mm•mard.

INTRODUCTION

To fulfill the need of the experimental simulation of the space radiation environment, especially the investigation of the single event effect, the project of Xi`an Proton Application Facility (XiPAF) is under construction in Xi'an City, China. The facility is mainly composed of one 7 MeV H^- linac injector (Fig. 1), one Middle Energy Beam Transport line (MEBT), one 200 MeV six-fold synchrotron, two High Energy Beam Transport lines (HEBT) and two experimental stations. A flux of 10^5~10^8 p/cm^2/s with the non-uniformity of better than ±10% on the sample in the range of 1 cm×1 cm ~ 10 cm×10 cm is designed. The synchrotron will be operated with the slow-extraction mode to provide the proton beam with the pulse width of 1~10 s. The designed number of the accumulated protons in each pulse in the synchrotron is 1×10^{11}. Injection energy of 7 MeV is therefore determined to both achieve the accumulated particles in the synchrotron and limit the cost of the linac injector. The negative hydrogen ion beam is debunched to reduce the energy spread and strip-injected into the synchrotron. The parameter requirement of the linac injector is presented in Table 1. In this paper, the design result of the 7 MeV linac injector for the 230 MeV synchrotron of the XiPAF project is presented.

Table 1: Requirement of the Linac Injector for XiPAF

Parameter	Value	Unit
Ion type	H^-	
Beam energy	7	MeV
Peak current	5	mA
Maximum repetition rate	0.5	Hz
Beam pulse width	10~40	μs
Normalized RMS emittance	<0.24	π mm•mrad

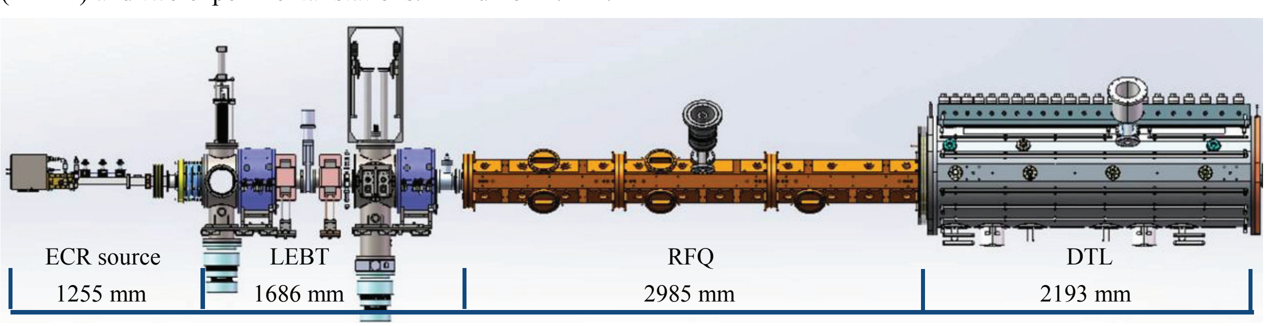

Figure 1: 7 MeV H^- linac injector for the 230 MeV synchrotron of the Xi`an Proton Application Facility (XiPAF).

ECR ION SOURCE

One 2.45 GHz microwave-driven Cesium-free Electron Cyclotron Resonance (ECR) source is to generate the

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negative hydrogen ion beam with enough peak current.The peak current of the extracted H^- beam is expected to be larger than 10 mA, with the output energy of 50 keV and the normalized RMS emittance of less than 0.2 π mm•mrad. One magnetron will be exploited to produce the 2.45 GHz microwave. The minimum pulse width of the RF power needed is 500 µs to produce a stable H^- beam. The layout of the H^- source is shown in Fig. 2.

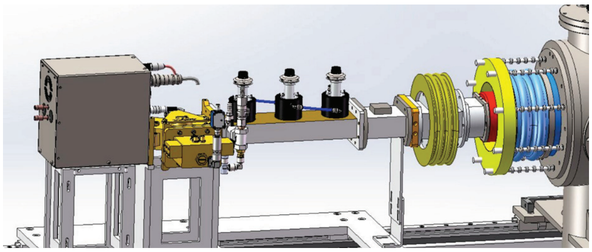

Figure 2: Layout of the 2.45 GHz Electron Cyclotron Resonance (ECR) H^- source.

The discharge chamber has been manufactured and tested successfully at Peking University. The current of the H^- beam was measured by one Faraday cup after the analyzing magnet. With the RF power of 2.8 kW, beam pulse width of 1 ms, repetition rate of 100 Hz, extraction voltage of 50 kV, the current of the H^- beam reached 12.4 mA. The measured normalized RMS emittance was 0.16 π mm•mrad.

LEBT

The H^- current is estimated to be larger than 12.4 mA at the exit of the ion source, considering the H^- stripping loss between the exit of the ion source and the Faraday cup at about 1 meter downstream. Therefore one aperture with adjustable slot size is exploited in the Low Energy Beam

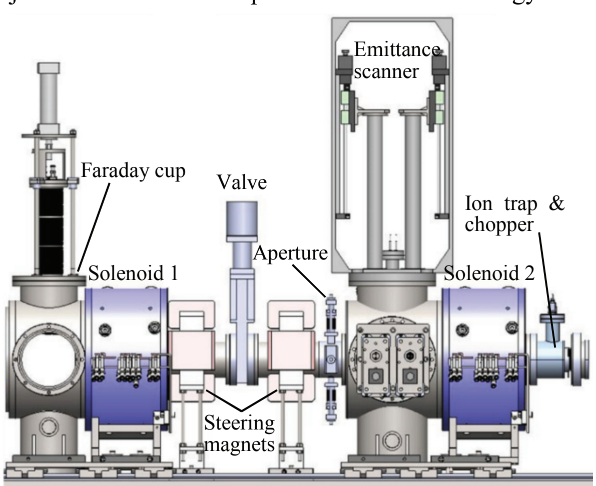

Figure 3: Layout of the Low Energy Beam Transport line (LEBT).

Transport line (LEBT) to obtain the designed current of 6 mA at the entrance of the RFQ accelerator [1]. The matched Twiss parameters (α=1.05, β=4.94 cm/rad) can be achieved by two solenoids. The beam pulse can be shortened to 10~40 µs by one chopper between Solenoid 2 and the RFQ accelerator.

Beam dynamics simulation by the Tracewin code [2] verifies that even with the input current of 10~20 mA, the Space Charge Compensation (SCC) degree of 75%~100% in the LEBT, the desired current of 6 mA at the exit of the LEBT can be acquired by adjusting the aperture size, with the beam phase space ellipse within the acceptance of the RFQ accelerator. Figure 4 shows the beam envelop with the input current of 10 mA, SCC degree of 85% in the LEBT. The current is 6 mA at the entrance of the RFQ with the normalized RMS emittance of 0.14 π mm•mrad.

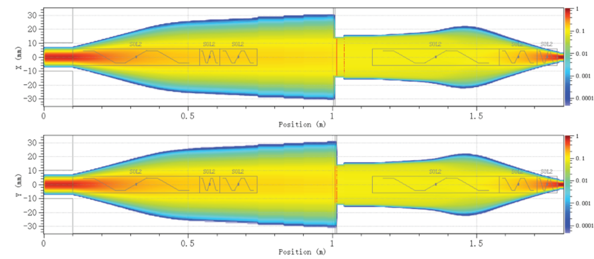

Figure 4: Beam envelop in the LEBT by the Tracewin code, with the input current of 10 mA, SCC degree of 85% (top: x-direction; bottom: y-direction).

RFQ ACCELERATOR

One 3-meter-long four-vane Radio Frequency Quadrupole (RFQ) will accelerate H^- from 50 keV to 3 MeV at an RF frequency of 325 MHz. The value of ρ/r_0 is kept to be 0.8 throughout the structure, where ρ is the transverse curvature of the vane tip and r_0 is the mean bore radius. The design result is shown in Fig. 5, with B the focusing strength, X the focusing parameter, A the acceleration parameter, W the synchronous energy, Φ_s the synchronous phase, m the modulation factor, and a the minimum bore radius.

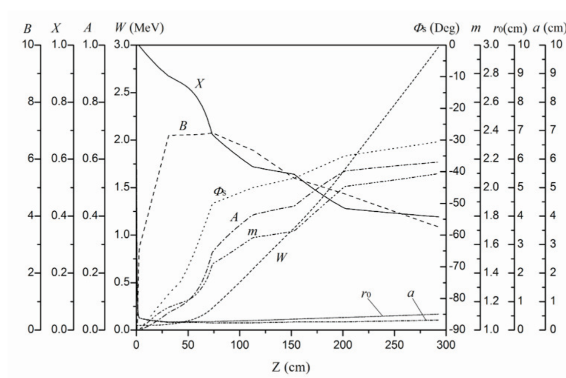

Figure 5: Parameters of the RFQ accelerator versus longitudinal position.

There are undercuts and dipole-mode stabilizer rods at the two ends of the RFQ vanes. The CST code [3] has been used to establish the three-dimensional model. The structure parameters of the undercuts are optimized to keep the calculated frequency of the TE_{210} mode equal to the designed value and the field distribution consistent with the desired curve. The length of the dipole-mode

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stabilizer rods is chosen to be 14.7 cm to maximize the frequency interval between the operating mode and its neighboring dipole modes. The RF peak power of 406 kW is needed including the structure loss of 388 kW and beam power of 18 kW. Two coaxial coupler are adopted to feed the RF power into the RFQ, as shown in Fig. 6.

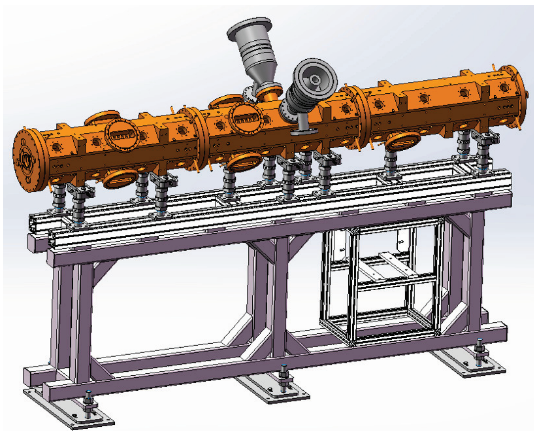

Figure 6: 3D model of the RFQ accelerator.

DRIFT TUBE LINAC

One Alvarez-type Drift Tube Linac (DTL) will accelerate H^- from 3 MeV to 7 MeV at an RF frequency of 325 MHz. Samarium-cobalt permanent magnets are adopted as the transverse focusing quadrupoles for the DTL. The field gradients are designed to be constant (84.6 T/m), except that the gradients of the first four quadrupoles are adjusted to match the RFQ directly. The total length of the DTL is about 2.2 m and the number of the accelerating cells is 23, as shown in Fig. 7.

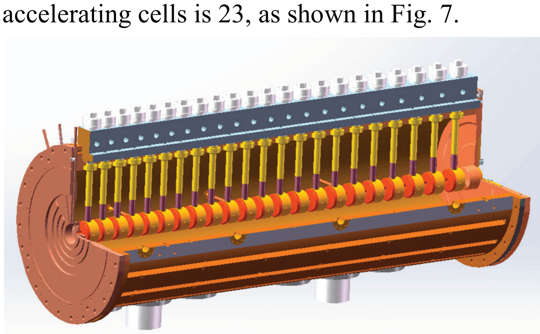

Figure 7: 3D model of the DTL cavity.

The RF peak power of 300 kW is needed including the structure loss of 276 kW and beam power of 24 kW. One coaxial coupler is adopted to feed the RF power into the DTL cavity.

START-TO-END SIMULATION

Figure 8 and Table 2 present the start-to-end simulation result from the exit of the ion source to the exit of the DTL. The particle distribution has been transferred to the dynamics simulation of the following Debuncher in the Middle Energy Beam Transport line (MEBT). It has been verified that the requirement of the momentum spread (<±0.45%) at the injection point can be satisfied.

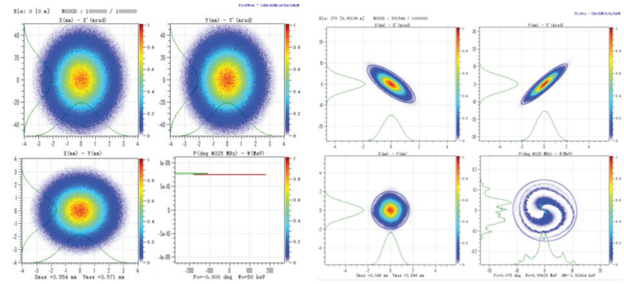

Figure 8: Beam phase space at the exit of the ion source (left) and the exit of the DTL (right).

Table 2: Start-to-end Simulation Result of the Linac Injector for the Synchrotron of the XiPAF Project

Parameter	Exit of the ion source	Exit of the drift tube linac
Beam Energy (MeV)	0.05	7.00
Peak Current (mA)	10	5.92
Energy Spread for 99% Particles (%)	0	2.2
α_x/α_y	0	1.14/-2.19
β_x/β_y (mm/mrad)	0.065	0.287/0.433
$\varepsilon_x/\varepsilon_y$ (π mm•mrad, norm. rms)	0.2	0.145/0.143

CONCLUSION

One 7 MeV linac injector is under construction for the project of Xi`an Proton Application Facility, including one 50 keV ECR H^- source, one LEBT, one 3 MeV four-vane type RFQ accelerator and one 7 MeV Alvarez-type DTL. The RFQ and DTL will be powered by two 4616V4 tetrode amplifiers with the maximum power of 500 kW at 325 MHz. The injector will be cable of delivering the H^- beam with the peak current of 5 mA, maximum repetition rate of 0.5 Hz, and beam pulse width of 10~40 µs.

ACKNOWLEDGMENT

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REFERENCES

[1] R. Tang et al., "Design of the Low Energy Beam Transport Line for Xi`an Proton Application Facility", presented at IPAC'16, Busan, Korea, May 2016, paper TUPMR041, this conference.

[2] D. Uriot, "Tracewin documentation", CEA Saclay, January 2014.

[3] CST Microwave Studio 2012, CST GmbH (Darmstadt, Germany), 2012; http://www.cst.com