Dynamics study of a drift tube linac for both heavy ions and proton

Heng Du\textsuperscript{1,2}, Xuejun Yin\textsuperscript{1,2}, Jancheng Yang\textsuperscript{1}, Youjin Yuan\textsuperscript{1}, Jiawen Xia\textsuperscript{1}, Xiaoni Li\textsuperscript{1,2}, Zhongshan Li\textsuperscript{1,2}, Kedong Wang\textsuperscript{1}, and Qiyu Kong\textsuperscript{1}

\textsuperscript{1} Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China
\textsuperscript{2} Huizhou Research Center of Ion Sciences, 516003 Huizhou, Guangdong, China
E-mail: duheng@impcas.ac.cn

Abstract. An accelerator complex for Space Environment Simulation and Research Infrastructure (SESRI) has been designed by Institute of Modern Physics (IMP) and will be constructed in Harbin Institute of Technology (HIT). This accelerator consists of an ECR ion source, a linac injector, a synchrotron and 3 experiment terminals. As an important part of the complex, the linac injector should provide both proton and different kinds of heavy ions, from helium to bismuth, with energy of 5 MeV and 1 MeV/u respectively for the synchrotron. In order to provide beams with the mass to charge ratio (A/Q) range from 1 to 6.5 (for proton to 209\textsuperscript{Bi}\textsuperscript{32\textsuperscript{+}}) by only one linac injector, a special solution of the main acceleration section DTL is carried out. The relevant dynamics calculations, such as beam matching, stripping process of the hydrogen molecule ion and beam energy spread reducing, are performed by Particle in Cell (PIC) method.

1. Introduction
In order to simulate and research the damage to the electronic equipment and organism on the spacecraft by high energy particles in the universe, Harbin Institute of Technology (HIT) proposed building an accelerator based nuclear irradiation source named Space Environment Simulation and Research Infrastructure (SESRI). The accelerator complex of SESRI has been designed by Institute of Modern Physics (IMP) and will be constructed in Harbin Institute of Technology (HIT). The accelerator consists of an ECR ion source, a linac injector, a synchrotron and 3 experiment terminals. As an important part of the complex, the linac injector should provide both proton and different kinds of heavy ions, from helium to bismuth, with energy of 5 MeV and 1 MeV/u respectively for the synchrotron. In order to provide beams with the mass to charge ratio (A/Q) range from 1 to 6.5 (for proton to 209\textsuperscript{Bi}\textsuperscript{32\textsuperscript{+}}) by only one linac injector, a special solution of the main acceleration section DTL is carried out. The relevant dynamics calculations, such as beam matching, stripping process of the hydrogen molecule ion and beam energy spread reducing, are performed by Particle in Cell (PIC) method.

According to the project requirement, preliminary dynamics design of the DTL has finished. And then, beam dynamics tracking with a PIC simulation code for different operation mode along the main acceleration section is accomplished. The simulation takes beam matching into account and verifies the preliminary design. On the other hand, effects of stripping foil on the
hydrogen molecule ion \((H_2^+)\) are studied. A short beam transport line used for reducing the beam energy spread of proton and heavy ion is also designed in the PIC simulation.

![Figure 1. Integrated layout of SESRI accelerator complex.](image)

### Table 1. Inject beam parameters of the SESRI synchrotron.

| Parameter             | Value                                      |
|-----------------------|--------------------------------------------|
| Beam energy           | 1 MeV/u \((^{209}\text{Bi}^{32+})\), 5 MeV (proton) |
| Beam current          | 30 e\(\mu\)A \((^{209}\text{Bi}^{32+})\), 300 e\(\mu\)A (proton) |
| Duty factor           | 0.1-0.5\%                                 |
| Energy Spread         | ±0.3\%                                    |
| Phase space Acceptance| 200(H), 30(V) \(\pi\) mm-mrad             |
| Transverse emittance  | \(\leq 13 \pi\) mm-mrad                  |

2. Preliminary dynamics design of the DTL

The R/Q of the injected ion into the synchrotron ranges from 1 to 6.5 and it is too large for a normal conducting multicell linac, because the cavity power is proportional to squared of the R/Q. The whole RF system cannot operate stably in such a large power range. So in order to provide proton beam to the synchrotron, \(H_2^+\) is accelerated to 1 MeV/u by RFQ and DTL1 firstly and then be stripped to proton to ulteriorly accelerate by DTL2. In this way, the R/Q range of the RFQ and the first DTL will be only from 2 to 6.5. Beam extraction energy of the RFQ is set to 300 keV/u for \(H_2^+\) and other heavy ions. The RF frequency is 108 MHz for the whole linac injector, and for DTL cavity interdigital H-mode (IH) structure is employed because of its high shunt impedance. So both of the two DTLs are based on \(\pi\)-mode structure.

KONUS beam dynamic concept[2] and LORASR code[3] are adopted to make the preliminary dynamics design of the DTL for the linac injector. On the basis of the injection energy requirements of the synchrotron for proton and heavy ions, this linac injector contains two DTL cavities. All heavy ions including \(H_2^+\) can be accelerated to 1 MeV/u by the DTL1 which
contains an inner focusing quadrupole triplet. There is also an quadrupole triplet between DTL1 and DTL2. DTL2 is only used to accelerate the proton from 1 MeV to 5 MeV. For heavy ions, it is just treated as a drift section. Design parameters of both DTL1 and DTL2 are shown in table 2. The maximum on-axis electric field values of each accelerating gap are optimized to 8.5 MV/m by tuning the gap length and integral voltage. Between the two DTLs, there must be a foil for stripping H$_2^+$ to proton. For simplicity, the effects of stripping foil on the H$_2^+$ are ignored in the preliminary design.

| Parameter               | DTL1        | DTL2        |
|-------------------------|-------------|-------------|
| RF structure            | IH          | IH          |
| Cavity inner length [mm]| 1688.5      | 1385.0      |
| Gap number              | 26          | 13          |
| Gap length [mm]         | 17.37-27.75 | 27.87-36.26 |
| Gap voltage [kV]        | 100-295     | 160-400     |
| Transit time factor     | 0.77-0.86   | 0.84-0.95   |
| Tube inner diameter [mm]| 20.0        | 25.0        |

In the dynamics calculation, the tracking particle is set to be proton, but the maximum values of gap voltage and quadrupole magnet strength about DTL1 must be reasonable when $^{209}$Bi$^{32+}$ is accelerated. The Kilpatrick factor is less than 2.1 and the maximum pole face magnetic field of all quadrupole magnets is not larger than 0.9 T. Beam transverse and longitudinal phase space distribution at the entrance of DTL1 is set to a uniform distribution where the RMS emittance is 0.2 $\mu$m-mrad and 0.45 $\mu$s-keV/u respectively as shown in figure 2. Transverse envelope of 90% beam is shown in figure 3. DTL2 is followed by a quadrupole triplet. Energy spread and bunch length boundary of the beam relative to the synchronous particle can be seen in figure 4. The normalized RMS emittances relative increase is small in the transverse planes but a little larger in the longitudinal plane as shown in figure 5. Nevertheless, the synchrotron cares more about the transverse emittance, especially the horizontal one, and beam energy spread. As shown in figure 6, the minor axis of longitudinal phase ellipse is short and it will benefit us in reducing the beam energy spread which will be discuss later.
3. Beam tracking for $^{209}$Bi$^{32+}$

The preliminary design of the beam dynamics in the RFQ has been finished and the phase space distribution of the extracted beam of the RFQ is shown in figure 7. Water bag distribution is chosen for generating the particle coordinate in each phase space plane. The transverse normalized RMS emittance is 0.15 $\pi$mm-mrad. And longitudinal RMS emittance is 14 $\pi$Deg.-keV/u. Between the RFQ and DTL1, there is a 1.5 meter-long beam transport line including 5 quadrupole magnets and a 2 gap buncher named Buncher1. When doing the simulation of $^{209}$Bi$^{32+}$, DTL2 is treated as a drift section. The second buncher behind DTL2 is used for reducing the beam energy spread of heavy ions extracted from DTL1. The PIC simulation is performed by BEAMPATH code.[4] The transverse beam envelope, bunch length and energy spread along the main acceleration section are shown in figure 8. At the exit of the linac injector, energy spread of $^{209}$Bi$^{32+}$ is less than $\pm$0.3%. In this simulation, transverse normalized RMS emittance increases by about 28% which is larger than preliminary design result. On the basis of the requirement of synchrotron, the normalized RMS emittance of heavy ion beam extracted from RFQ must be less than 0.125 $\pi$mm-mrad.

4. Beam tracking for $H^+_2$/proton

Because the RFQ and DTL1 are designed for $H^+_2$ and the DTL2 is designed for proton beam, a stripping foil is needed to convert $H^+_2$ to proton. It will enlarge the transverse beam emittance.
Figure 7. Beam phase space distribution at the exit of RFQ.

Figure 8. Beam envelope and energy spread along the main acceleration section.

and energy spread. On the other hand, the holistic beam energy would be lower slightly. These trouble must be considered in dynamics tracking. According to literature research[5], a 15 \( \mu g/cm^2 \) carbon foil is chosen, and the stripping efficiency approaches 100% for 1 MeV/u H\(^+\). Its influence on H\(^+\) beam is calculated by LISE++ code[6] as shown in table 3, which will be used in the beam tracking.

| Parameter          | Value     |
|--------------------|-----------|
| Energy loss        | 1.7 keV/u |
| Energy straggle    | 0.6 keV/u (1\(\sigma\)) |
| Angular Straggle   | 1.47 mrad (1\(\sigma\)) |
| Lateral spread     | 1e-5 \(\mu m\) (1\(\sigma\)) |

Table 3. Calculating results for 1 MeV/u H\(^+\) stripping to proton by LISE++.

The beam tracking calculation of 500 \( \mu A \) H\(^+\)/proton is also performed by BEAMPATH code. Monte Carlo method is adopted for the charge stripping process. Buncher3 is placed behind DTL2 with a distance of 2.5 m for reducing the energy spread of proton. The transverse beam envelope, bunch length and energy spread of H\(^+\)/proton can be seen in figure 9. Energy spread of 100% beam is too large for the synchrotron. But after removing the 20% particles having large energy spread, the rest of the beam can satisfy the energy spread requirement of the synchrotron. Transverse emittances of H\(^+\)/proton are shown in figure 10. The local saltation of beam emittance is because of the long bunch not enter into a quadrupole magnet entirely[7]. Because the injection design of synchrotron demands painting in horizontal direction, vertical emittance growth is acceptable. Based on the above beam tracking, proton beam extracted by the linac injector can meet the design requirements.

5. Conclusion
Dynamic design and tracking calculation of the DTL for the linac injector of SESRI complex has been finished which can provide 1 MeV/u heavy ion and 5 MeV proton beam for the synchrotron. Beam matching section between RFQ and DTL1, stripping foil and energy spread...
Reducing section are design and simulated. The transverse emittances of heavy ion and proton beam are both less than 13 $\mu$m-mrad and satisfy the injection demand of the synchrotron. Beam energy spread of extraction beam of this linac injector can also meet the requirements of synchrotron basically. The RF structure design of these two DTLs is in progress.

Acknowledgments
We are grateful to Y.R. Lu at PKU for his constructive suggestions.

References
[1] LIU M, CHAI W P, YANG J CH, RUAN S, LIU J, YAO L P. Injection Design and Simulation Study of Synchrotron in SESRI. Nucl. Phys. Rev., 2017, 34(4): 730-734.
[2] Tiede R, et al., Konus beam dynamics designs using H-mode cavities in Proc. HB08, Nashville, TN, USA, Aug. 2008, paper WGB11, p. 223.
[3] Tiede R, et al., LORASR Code Development, in Proc. 10th European Particle Accelerator Conf. (EPAC06), Edinburgh, UK, Jun. 2006, paper WEPCH118, p. 2194-2196.
[4] Batygin Y K, Particle-in-cell code BEAMPATH for beam dynamics simulations in linear accelerators and beamlines, Nucl. Instr. Meth. A, 2005, 539: 455.
[5] Meggitt B T, et al., Equilibrium charge-fractions for H$^+$ and H$_2^+$ ions transmitted through carbon foils at 60-300 keV, Journal of Physics B Atomic & Molecular Physics, 1973, 6(12): 362-364.
[6] Bazin D, Tarasov O B, Lewitowicz M, Sorlin O, "The code LISE: a new version for 'Windows, Nuclear Physics A 701 (2002) 661-665.
[7] Du H , Yuan Y J , Li Z S , et al. Beam dynamics, RF measurement, and commissioning of a CW heavy ion IH-DTL[J]. Nuclear Science and Techniques, 2018, 29(3):42.