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PRIMARY BEAM DYNAMICS DESIGN OF A HEAVY-ION IH-DTL WITH ELECTROMAGNETIC QUADRUPOLES

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Abstract

A new IH-DTL beam dynamics scheme, IH-EMQ (ElectroMagnetic Quadrupole) is presented to obtain a large longitudinal acceptance. In this scheme, electromagnetic quadrupoles are installed inside the drift tubes of IH-DTL. A large-longitudinal-acceptance heavy-ion IH-DTL design is described in this paper. With the limit current of 25 mA, the 90% normalized longitudinal acceptance reaches 87.8π deg·MeV for the 60 MeV $^{197}Au^{30+}$, which is 8 times of the input emittance.

INTRODUCTION

Interdigital H-mode Drift Tube Linacs (IH-DTLs) are widely used in heavy-ion accelerators, especially as injectors for synchrotron-based heavy-ion facilities. Compared with the Alvarez-type DTL, the IH-DTL has higher shunt impedance and higher accelerating gradient for β <0.1 [1]. Less power and length are required to accelerate the same particle to the same energy at the same resonant frequency.

At present, the Combined Zero-Degree Structure (KONUS) [2] and Alternating Phase-Focused (APF) [3,4] are commonly adopted in the beam dynamics schemes of IH-DTLs. In the KONUS design, triplets are used as transverse focusing elements in the cavity or between the cavities. As for APF, the RF phase array needs to be carefully designed to focus the beam in the transverse plane.

Different transverse focusing strengths should be obtained to accelerate particles with different charge-mass ratios and the same velocity in one accelerator. Therefore, it is necessary to provide different transverse focusing by adjustable magnets, solenoids or RFQ segments for heavy-ion IH-DTLs. S.S. Kurennoy proposed a method by installing permanent magnet quadrupoles in the drift tubes of the IH-DTL cavity to enhance the transverse focusing [5]. By adopting Kurennoy's idea, we present a new IH-DTL beam dynamics scheme, IH-EMQ (ElectroMagnetic Quadrupole), for the purpose of a large longitudinal acceptance. In this scheme, the electromagnetic quadrupoles are installed inside the drift tubes of the IH-DTL. The longitudinal acceptances for APF and KONUS are not large, which lead to tight longitudinal tolerances (the stable phase widths are about 10° for APF [6], and 20° for KONUS [7]). The longitudinal tolerances can be loose and beam commissioning processes can be easy with a large longitudinal acceptance. IH-EMQ can enlarge the longitudinal acceptance by adopting the conventional synchronous phase design.

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REQUIREMENT OF IH-EMQ

An IH-EMQ is proposed for a synchrotron-based space irradiation facility [8], aiming at providing carbon, aluminum, gold, silver and other elements with high energy. The heavy-ion beam from the exit of RFQ is accelerated by the IH-EMQ and then injected into the synchrotron. The IH-EMQ aims to accelerate different heavy-ion particles from 0.3 MeV/u to 1 MeV/u, with charge-mass ratios of 1/2-1/6.5. The RF frequency is chosen to be 108.48MHz. Requirement parameters of the IH-EMQ are listed in Table 1.

Table 1: IH-EMQ Requirement Parameters

Parameter	Value
Ion type	$^{12}C^{6+}$-$^{197}Au^{30+}$
Charge-mass ratio	1/2-1/6.5
Input beam energy	0.3 MeV/u
Output beam energy	1 MeV/u
Peak current ($^{197}Au^{30+}$)	50 eμA
Peak current ($^{12}C^{6+}$)	100 eμA
RF frequency	108.48 MHz
Pulse length	60-100 μs
Pulse repetition rate	0.1-0.5 Hz

IH-EMQ SCHEME

The key point of the IH-EMQ beam dynamics scheme is to place electromagnetic quadrupoles inside the drift tubes of the IH-DTL to provide the transverse focusing.

For transverse beam dynamics, electromagnetic quadrupoles are mounted inside every few drift tubes. One periodic structure of the lattice of the IH-EMQ is shown in Fig. 1 from the first half EMQ to the second. To install the quadrupoles, the outer radius of the drift tubes should be large, which will lead to a significant decline in the shunt impedance of the cell. The less number of the quadrupoles installed, the less degradation of the shunt impedance of the cavity.

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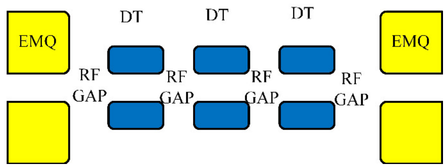

Figure 1: Sketch diagram of the typical IH-EMQ lattice.

For longitudinal beam dynamics, the RF field is designed to fulfill the need for acceleration. It is not necessary to provide transverse focusing as APF beam dynamics does.

The process of IH-EMQ design is described as follows [9]. First, the choice of transverse lattice, RF phase, and RF field are proposed. Then the transit time factor (T) and the normalized peak surface field (E_p/E_0, E_p and E_0 are the peak surface field and accelerating gradient, respectively) of single cells are given by the RF simulation of single-cell models. According to the beam dynamics design result, the model of the IH-EMQ cavity is built for RF simulation to check the effective voltages with the beam dynamics design values. The simulated effective voltages are used to give a updated beam dynamics design. At last, when the effective voltages converge through the iterative optimization, the design can be terminated.

SINGLE-CELL RF SIMULATION

Single-cell RF simulation is to provide effective voltages for the beam dynamics design. The effective voltages are calculated using T and E_0. RF optimization of single cells mainly aims at minimizing E_p/E_0, thus high acceleration gradient can be achieved.

Cost saving is attractive for an accelerator. One way to be economic is saving the machining-cost, and another way is saving power. To reach the demand of short accelerator and low power-cost, high accelerating gradient and high shunt impedance in the RF design are needed. As the IH-DTL cavities have higher shunt impedance compared with the Alvarez-type DTL cavities for β<0.1, the IH-DTLs are more attractive for saving power.

The single-cell and drift-tube models are shown in Fig. 2.

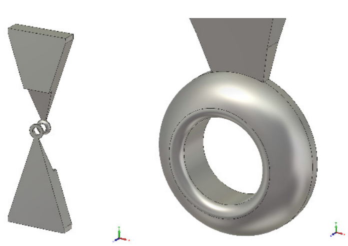
Figure 2: Model of the single cell and drift tube of IH-EMQ.

By optimizing the parameters of the drift tubes, E_p/E_0 can be reduced to less than 4.8. E_0 is designed as 5 MV/m, and the Kilpatrick factor is 2.05.

T and shunt impedance per meter (Z) of the single cell with different particle velocities are given in Fig. 3. T increases while Z decreases rapidly with the beam velocity.

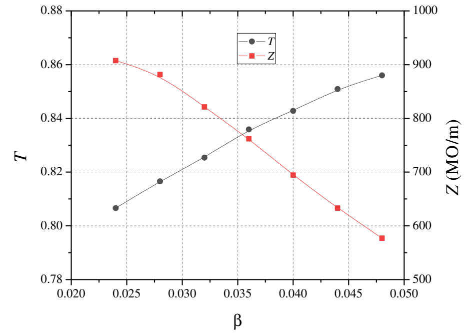

Figure 3: RF results of a single cell with different particle velocities.

BEAM DYNAMICS

Beam Dynamics Design

EMQs are placed every 3 or 4 cells to provide the transverse focusing, with the total number of EMQs and cells are 7 and 26, respectively. First four quadrupoles are used to match DTL with the beam distribution at the exit of the RFQ. FD lattice is chosen as the quadrupole law.

An RFQ is designed for heavy-ion beams, including the Au^{30+} and C^{6+}. The Au^{30+} particle distribution from the RFQ exit is used as the input distribution at the entrance of the DTL, which is shown in Fig. 4. The beam distribution of Au^{30+} and C^{6+} output from the RFQ are similar, so only the Au^{30+} beam is considered in the following discussions.

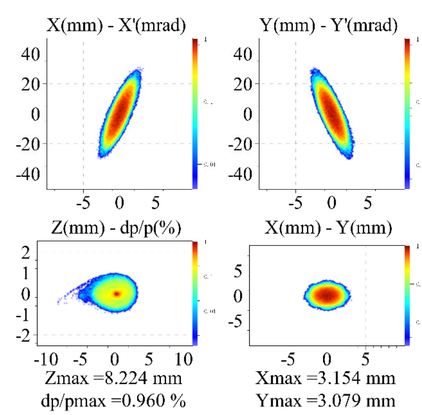

Figure 4: Phase spaces at the exit of the RFQ (Au^{30+}).

The transverse matching result is presented in Fig. 5. Also, to decrease the envelope in the DTL, the exit part of the RFQ can also be re-designed to match with the entrance of the IH-DTL by decreasing the phase advance per meter in the further design [10].

The RF phase and accelerating gradient are important in the longitudinal beam dynamics design. The constant accelerating gradient per meter is adopted in the cavity. If E_p/E_0 in each cell are known, higher E_0 can be employed by keeping the Kilpatrick factor to 2. The main synchrotron phase is chosen as -20°, with high bunching ability and acceleration efficiency. The gap voltage and synchrotron phase in each cell are shown in Fig. 6.

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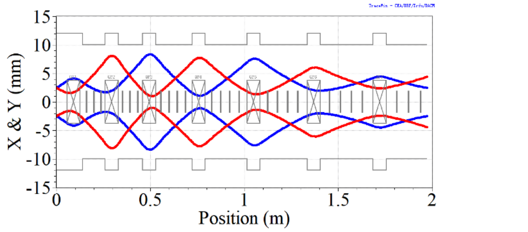

Figure 5: 2.45 times RMS beam envelope inside the IH-EMQ (blue: x-direction; red: y-direction).

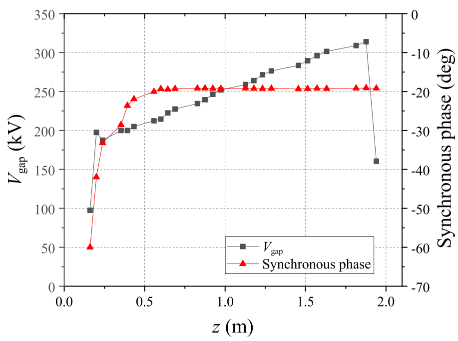

Figure 6: Gap voltage and synchrotron phase of IH-EMQ.

Beam Dynamics Design Result

The multi-particle beam simulation is performed by the TraceWin code [11]. The transmission of the IH-EMQ given by TraceWin is 99%. The phase spaces at the exit of the DTL are given in Fig. 7.

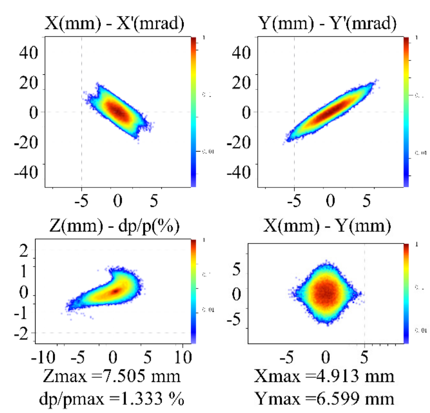

Figure 7: Phase spaces at the exit of the IH-EMQ (Au^{30+}).

The beam dynamics design result of the IH-EMQ is shown in Table 2.

Longitudinal Acceptance and Current Limit

The main characteristics of the IH-EMQ beam dynamics scheme are its large longitudinal acceptance and high current limit.

The longitudinal normalized 90% acceptance of 60 MeV Au^{30+} is 87.8π deg·MeV, which is 8 times of the input emittance. The tolerance of the longitudinal dynamics can be loose. The acceptance is presented in Fig. 8. The phase width of the stable region is suggested to be 40°.

Table 2: IH-EMQ Beam Dynamics Result

Parameter	$^{12}C^{6+}$	$^{197}Au^{30+}$
Input beam energy	0.3 MeV/u	
Input Norm. RMS emittance	0.16π mm·mrad	
Output beam energy	1 MeV/u	
Output Norm. RMS emittance	0.18π mm·mrad	
Output energy spread (90%)	±1.2%	
Peak current	100 eμA	50 eμA
Average accelerating gradient	1.5 MV/m	5 MV/m
Transmission	99%	
Total length	1.97 m	

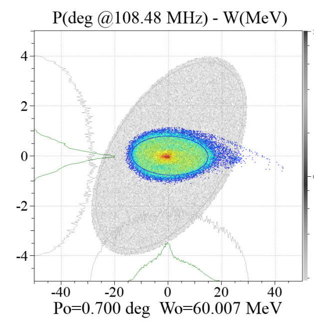

Figure 8: Longitudinal ellipse acceptance (shadow) of 60 MeV Au^{30+} and emittance output from the RFQ (color).

The output current against the input beam current is shown in Fig. 9. The transmission of IH-EMQ is above 95% up to about 22 mA, and the current limit is supposed to be 25mA.

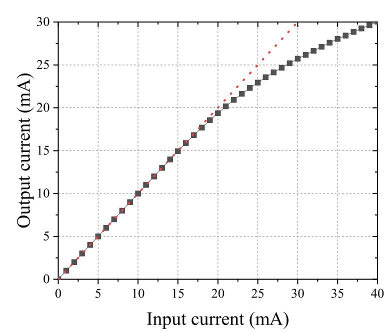

Figure 9: Current transmission for IH-EMQ.

CONCLUSION

A new IH-DTL beam dynamics scheme, IH-EMQ, is proposed, with an enhanced transverse focusing and an enlarged longitudinal acceptance. The primary RF and beam dynamics designs of the heavy-ion IH-DTL have been presented. The longitudinal acceptance is 8 times the input emittance with the stable phase width of 40° and the current limit of 25 mA. The further RF simulation of the whole IH-EMQ cavity will be carried out in the future.

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