ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPR20

DESIGN OF IH-DTL WITH PMQ FOCUSING FOR MEDICAL RI PRODUCTION

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Abstract

A conceptual design of an accelerator system for medical radioisotope (RI) production has been conducted. The main accelerator of the system is Interdigital H-mode Drift-Tube Linac (IH-DTL) with permanent-magnet quadrupole (PMQ). For Astatine-211 (^{211}At) production, a helium beam should be accelerated over 7.25 MeV/u. The lattice of the PMQs inside the IH-DTL was designed as FFOODDOO so that the maximum gradient of PMQ was lower. The cell parameters were designed with considering the periodical structure of the PMQ lattice and the specifications of the commercially available semiconductor RF power amplifier. After designing the cell parameters, we evaluated the beam dynamics with the space-charge effect by 2D/3D design of cavity and beam tracking. With 2D design of three DTL tanks, the helium beam is accelerated over 7.25 MeV/u with a beam transmission of over 90%. 3D design of the first tank cavity was also finished. After precise optimization of the cavity geometry, the beam transmission achieved over 95% with 3D cavity model of the first tank. The details will be shown in this paper.

INTRODUCTION

In recent years, plans for cancer treatment using medical RI have been progressing worldwide. In Japan, supply of RI is strongly depending on imports from abroad due to the aging of small nuclear reactors. Manufacturing using accelerators could realize a stable supply. The production of an alpha-ray drug requires helium nuclei of 7.25 MeV/u or more. We have conducted the conceptual design of an accelerator system with the aim of accelerating helium ions with a peak current value of 30mA and a duty cycle of 5%.

IH-DTL, which has the H-mode accelerator interdigitate structure operated with TE-110-mode, has been studied for the fundamental science of muon and the injector of the heavy ion therapy in Japan [1-3]. A three-piece design in which two cylindrical shells are attached to a center shell contributes the stable operation and the lower cost for the fabrication [2,4]. Because the alternative-phase focusing (APF) method is difficult to focus the several 10-mA beam, IH-DTL with PMQ focusing (PMQ-IH) are being considered as the candidate for the RI production system with linac. PMQ-IH was also studied with a deuteron beam of the 50-mA peak current for the LANSCE DTL replacement [5,6].

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Figure 1 shows the outline of RI production system with linac. The PMQ-IH section is located after an Radio Frequency Quadrupole Linac (RFQ) which accelerates He+ ions up to 0.6 MeV/u. The resonant frequency and the maximum RF input power of the PMQ-IHs is designed to be 200MHz and 600kW, respectively. Each tank will be driven with two of a commercially available semiconductor RF power amplifier which can operate with the duty factor of 5%. The synchronous phase is selected at -30 degrees for the stable operation because of the suppression of the loss from the longitudinal distribution spread. Following sections in this paper describes the conceptual design procedures of PMQ-IH for RI production system.

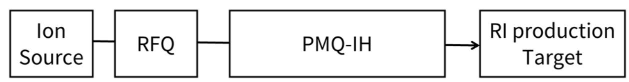

Figure 1: Outline of RI production system with linac.

Table 1: Main parameters of PMQ-IH.

Parameter	Value
Species	Ion (He^+)
Charge-mass ratio (Q/A)	1/4
Injection beam current	30 mA
Resonant frequency	200 MHz
RF power	< 600 kW/tank
RF duty factor	5%
Injection energy	0.6 MeV/u
Extraction energy	> 7.25 MeV/u
Synchronous phase	-30 deg.

DESIGN OF BEAM AND CELL

Design of Beam Dynamics with TRACE3-D

To determine the cell parameters, we first conducted a beam dynamics design within PMQ-IH. This design involved calculations for beam convergence due to PMQ, for which we performed beam envelope calculations using TRACE3-D [7]. The required magnetic field gradients to keep the beam size within a drift tube bore radius of 6 mm was investigated with the FODO and FFOODDOO lattices. It is expected that emittance growth, which cannot be considered in the TRACE3-D calculation, will appear in the particle tracking. Therefore, to account for margins, TRACE3-D calculations were performed with a 5 mm radius aperture, which is smaller than the actual 6 mm bore radius. Figure 2 shows the results for the magnetic field

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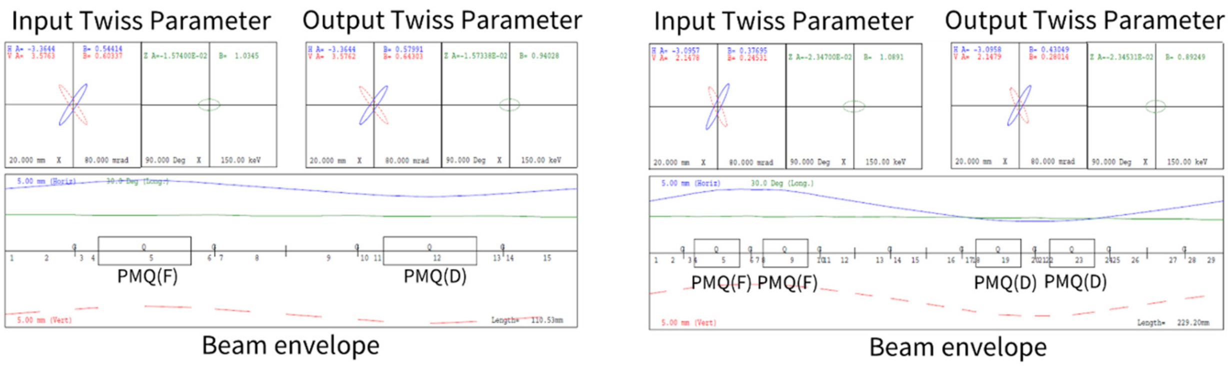

Figure 2: Beam envelope calculation with TRACE: FODO lattice with 300 T/m gradient (left) and FFOODDOO lattice with 200 T/m gradient(right).

gradients in the FODO and FFOODDOO lattices that meet the 5mm criteria. For FODO, a gradient of 300 T/m was required, but for FFOODDOO, the gradient could be reduced to 200 T/m. As the magnetic field gradient of PMQ increases, the outer diameter of the drift tube becomes greater. The larger outer diameter of the drift tube shall lower the shunt impedance of the IH-DTL. Therefore, we chose FFOODDOO lattice for this design.

Design of Cell Parameters

We designed the design of the cell parameters based on the main specifications from Tab. 1. The commercial semiconductor RF power amplifier that we are considering can deliver a maximum RF output of 300 kW with a duty factor of 5%. We are planning to use a multi-coupler configuration with two power supplies per tank. The goal is to ensure that the maximum required RF power per tank remains below 600 kW.

When determining cell parameters for the design, we calculate the energy gain of each cell using the approximate formula of the radial dependence of transit-time factor [8]. The accelerating fields were adjusted so that the RF power was suppressed below 600 kW. And the number of cell was designed to be a multiple of eight due to the lattice of FFOODDOO. Table 2 shows the results of the cell parameters of the PMQ-IHs. Three tanks of PMQ-IH are necessary to achieve the energy of over 7.25 MeV/u. The averages of the axial accelerating field were optimized at each tank.

BEAM TRACKING AND CAVITY DESIGN

Beam Tracking with 2D Cavity Design

Beam tracking had been conducted with 2D cavity design calculated by POISSON. This 2D cavity design and tracking was performed to evaluate the beam loss in the accelerator system before the precise design and calculation of 3D cavity model. The example of the cell configuration with Poisson is shown in Fig. 3. From this calculation, we evaluated the 2D electric field distribution to import the beam tracking and the maximum surface field of this model. Table2 also shows the maximum surface electric fields normalized with the Kilpatrick unit [9] are less than 1.9 which is almost same with previous designs of linacs [2, 5].

With the evaluated electric field from POISSON, the beam dynamics was calculated with General Particle Tracer (GPT) [10]. In the beam dynamics calculation, the space-charge was considered with the Particle-In-Cell (PIC) method implemented to GPT. The beam trajectories with all three tanks and profile at exit of PMQ-IH3 are shown in Fig. 4 and Fig. 5. The trajectories are focused by PMQs, and the transmission was evaluated as over 90 %.

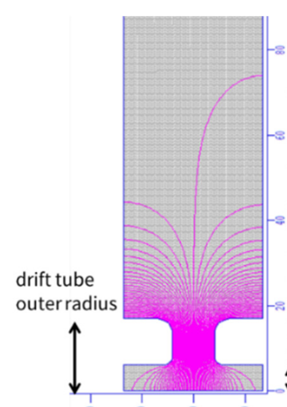

Figure 3: Cell geometry and electrical field by POSSON.

Table 2: Main cell parameters of PMQ-IHs.

Parameter	PMQ-IH1	PMQ-IH2	PMQ-IH3	Unit
Number of cells	64	40	40	#
Extraction energy	3.047	5.283	7.371	MeV/u
Extraction velocity	8.07%	10.60%	12.50%	
Accelerating field	4.5	4.0	3.0	MV/m
Maximum surface field	1.75	1.90	1.53	Kilp.

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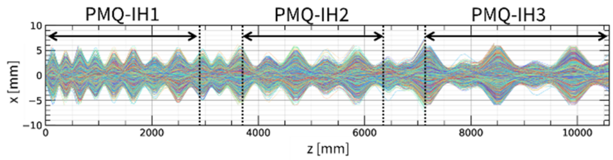

Figure 4: Beam dynamics inside PMQ-IH section.

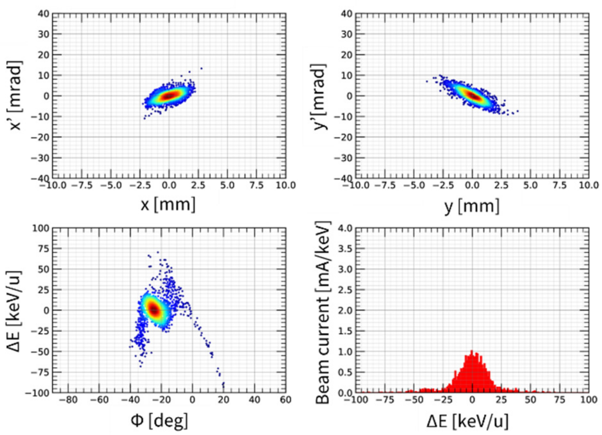

Figure 5: Beam profile at exit of PMQ-IH3.

Cavity Design and Beam Tracking

Beam tracking calculation with the 3D cavity design of PMQ-IH1 had been conducted by CST Studio Suite [11] and GPT. Figure 6 shows the 3D model design of PMQ-IH1. When the design of the cavity configuration, end ridge-cuts in top and bottom ridges (ridge tuners) and the tapered inner radius in the down- to upstream direction (cavity taper) were optimized with periodic models. As Fig. 7 shows the beam dynamics simulation with the optimized electric field distribution in the PMQ-IH1, the beam transmission was over 95%. This transmission rate is consistent with the results of the beam tracking with the 2D cavity design.

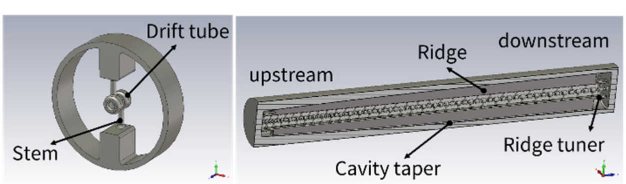

Figure 6: 3D model of PMQ-IH1: Periodic model (left) and tank model of PMQ-IH1 (right).

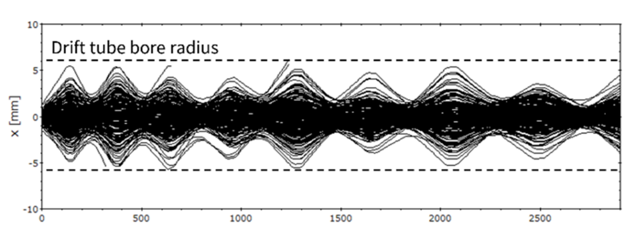

Figure 7: Beam trajectory with the electric field by 3D cavity model of PMQ-IH1.

CONCLUSION

We have conducted the conceptual design of the PMQ-IH for the medical RI production system. The PMQ-IH section to accelerate a helium beam up to 7.25 MeV/u needs the three tanks of PMQ-IH and six 300kW-duty 5% semiconductor RF power amplifiers. From the 2D cavity design and beam tracking with 2D designed electrical field, the maximum surface electric field is comparable with previous designs of linacs and the beam transmission is over 90%. The beam focusing under the space-charge effect is confirmed with 2D cavity design.Therefore the 3D cavity design of PMQ-IH1 was conducted. The ridge tuners and cavity taper were optimized with periodic models. With the optimized the electrical field, the beam transmission of PMQ-IH1 is over 95% which is almost consistent with the beam tracking results with 2D cavity design. The 3D cavity designs of other two tanks is in progress. And we are also planning to approach other RIs production with linac system.

ACKNOWLEDGMENT

The authors are grateful to Dr. M. Yamamoto from Omega solutions Inc. for his cooperation on this work.

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