CONCEPTUAL DESIGN OF A NOVEL RFQ FOR MEDICAL ACCELERATORS

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Abstract

At the Heidelberg Ion Beam Therapy Centre HIT we operate a 4-rod RFQ as first stage of a 7 MeV/u injector linac followed by an IH-DTL. During the first years of patient treatment the injector performance was perfectly adequate, even though the transmission of the linac remained below the theoretical expectations. New developments in dose delivery technology already realised or to come in the future increase the demand on higher beam intensities which will finally result in shorter irradiation times. As measurements performed at our test bench have confirmed that there is a margin for higher transmissions especially for the RFQ we are currently preparing for a new RFQ design. While keeping the original design parameters, the new RFQ should be optimised with respect to the transmission of beams from different ion sources such as electron cyclotron resonance or electron beam ion sources. All parts of the RFQ will be put up for discussion including electrodes, stems, tank and the integrated rebuncher. The design work will profit from new concepts that have evolved at our own and other medical heavy ion facilities in operation and from the progress modern simulation tools have run through.

MOTIVATION

As a new field of application radio-frequency-quadrupoles (RFQs) are nowadays used in medicine as part of injectors for subsequent circular accelerators (synchrotrons). One of the world's leading facilities for the treatment of cancer patients with ion beams is the Ion Beam Therapy Centre of the Heidelberg University Hospital (HIT) [1]. It comes along with an ion accelerator designed for carbon ions with a maximum energy of 430 MeV per nucleon. The range of available ion species is not limited to carbon ions. Both heavier elements, such as e.g. oxygen, as well as lighter ions, such as hydrogen or helium, are accelerated. Since patient treatment was established in 2009 the capacity of HIT could be continuously increased up to 750 carbon and proton patients per year. A further rise of the patient number will essentially depend on the achievable beam intensity.

One known source of particle losses is the HIT-RFQ. Its maximum achievable transmission ranges between 30 % and 40 % depending on the ion species and beam intensity. Measurements carried out at other therapy facilities such as the one in Marburg (now Marburg Ion Beam Therapy Centre [2]) obtain consistent results. Obviously it is not possible to achieve higher transmissions with the current RFQ design in combination with beams from the ion sources in operation, the electron cyclotron resonance ion sources (ECRIS). In order to further increase the efficiency of our ion beam therapy facility, it is necessary to increase the transmission of the RFQ accelerator by a factor of about 2.5. This can be achieved by optimising the RFQ in terms of design, fabrication and adjustment. The medium term objective of this work is therefore the design, construction and testing of a highly efficient RFQ structure with high transmission (desirably 90 %) maintaining the parameters of the original RFQ.

RFQ IN OPERATION

The RFQ currently in operation is a 4-rod type RFQ developped at the IAP Frankfurt [3]. It accelerates ions from 8 keV/u to 400 keV/u. Further design parameters can be found in Table 1. The resonant structure, as shown in Fig. 1, consists of four electrodes held by 16 stems which are electrically connected via tuning plates with variable height. As a peculiarity the rebuncher for longitudinal beam focusing into the subsequent IH drift tube linac (IH-DTL) is placed within the RFQ tank and is coupled to the resonant structure. This unique design was chosen for the sake of compactness and cost efficiency but is attended by a loss of variability during operation.

Table 1: RFQ Design Parameters

Parameter	Value
input energy	8 keV/u
output energy	400 keV/u
operating frequency	216.816 MHz
max. power consumption (pulsed)	200 kW
max. mass-to-charge ratio	3

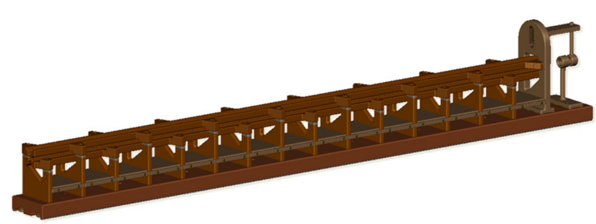

Figure 1: Resonant structure of the 4-rod RFQ with base plate, stems, tuning plates, electrodes and integrated rebuncher (beam direction from left to right).

CONCEPT FOR A NEW RFQ

Based on eight years of operational experience we see room for improvement for all major components of the RFQ.

Tank

The tank of the current RFQ essentially consists of a 250 mm diameter stainless steel tube equipped with sockets

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and flanges for different purposes. The access to the inner structure (electrodes and tuning plates) for field flattening is given by the two vacuum pump sockets which have to be turned upwards. The work through these access openings, consisting of placing the perturbation capacitor and shifting the tuning plates, revealed as very inefficient.

For the new tank we consider a layout with a removable cover plate, as e.g. realised in Ref. [4], that allows direct access to the structure. This will facilitate the tuning procedure considerably and allows a retuning when the RFQ is installed in the beam line. Moreover we will pay special attention on the mechanical rigidity which revealed to be weakly dimensioned.

Rebuncher

As the RFQ is equipped with an integrated two gap rebuncher there is no way to change the amplitude or the phase during operation. The correct phase (RF zero-crossing) is guaranteed by the longitudinal dimensions not providing any adjustability. The appropriate longitudinal focusing strength (RF field amplitude) must be adjusted manually during the commissioning by moving the support of the drift tubes up and down (Lecher line theory). This can only be done after opening the end flange and is a time consuming procedure. A new tank with a cover plate, as described in the previous section, facilitated this action enormously. It would be a further improvement if a newly designed rebuncher provided an adjustability keeping the drift tubes on axis while the support arm is moved.

Although not yet fully discussed, we do currently not consider in detail an upgrade with a separate rebuncher cavity, last but not least because it implied a shift of the IH-DTL downstream the beamline to gain space for the additional cavity, a big effort without guaranteed benefit.

Electrode Stem

In contrast to the 4-vane type the 4-rod type RFQ consists of an arrangement of vertical stems aligned on a base plate. The quadrupole electrodes are mounted at the two upper ends such that each stem holds a pair of opposite electrodes (see Fig. 2). It is a question of the stem design to yield equal voltages at the electrodes when the resonant circuit between neighboured stems is excited. In this context particular attention must be paid on the geometry of the outer stems [5]. The crucial design parameter of the inner stems is the angle of the connection between the two upper ends of the stem (angle α in Fig. 2). By changing this angle the different propagation times towards the two stem ends can be equalised. From electromagnetic field simulations (see below) we know that the original stem design produces a significant dipole component in the quadrupole channel leading to steering effects which can in extreme cases result in particle losses. With the help of an electromagnetic simulation tool and a minimisation algorithm the optimal angle for a new stem design can be determined.

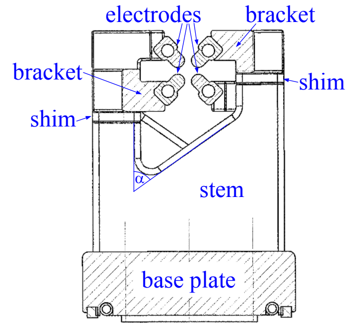

Figure 2: Stems and electrodes of the 4-rod RFQ (sectional view in beam direction).

Electrode Alignment

Longitudinal Alignment The requirements on the longitudinal alignment accuracy of the RFQ electrodes increase with the operating frequency and decrease with input velocity. Compared to other heavy ion RFQs the HIT medical RFQ has a very high operating frequency (216.816 MHz) combined with an input velocity ($\beta = 4.1{\cdot}10^{-3}$) only slightly above typical values, which in sum results in very short RF cell lengths at the low-energy end of the rods ($\beta\lambda/2 = 2.9$ mm). These circumstances impose strong requirements on the longitudinal alignment accuracy.

To get an idea of which accuracies one has to achieve it is reasonable to assume the maximum phase shift between two adjacent RFQ cells (1°) as maximum tolerable alignment error. This assumption leads to longitudinal tolerances in the order of 10 microns.

To achieve this goal two measures have to be taken. First of all the fabrication tolerances for the electrode length has to be defined accordingly. In this context it has to be assured that modulation and electrode coincide perfectly. Secondly one needs a reference surface on each electrode for the alignment process.

Transverse Alignment Concerning the transverse alignment accuracy it has been found that the previous method of brazing the electrode brackets warps the milled electrodes and leads to distortions between the fixed brackets. It is therefore advisable to fabricate the electrodes in one piece without the necessity of brazing.

Furthermore the transverse alignment can be improved by the application of a portal milling machine. With this the upper surfaces of the support stems, the interface to the electrode brackets, can be fly-cut after the stems have been mounted on the base plate.

These methods have first been practised for the RFQ which was foreseen for the therapy facility in Kiel [6], now dismantled.

Electrode Modulation

To yield the highest particle transmission it will be inevitable to design new electrodes (modulation) using realistic beam emittance and particle distributions at the RFQ entrance. In the ideal case modern ion source simulation programmes, such as Ref. [7], will be applied. They examine the 6D particle distribution and deliver all 2D subspaces.

Another access to realistic particle distributions are emittance measurements. At our test bench we performed emittance measurements of EBIS beams using a pepper pot (Ref. [8]) and ECR beams applying the slit-grid method. Even if the latter measurements do not deliver all correlations we are convinced that we get a much more realistic image of the beam than the one used for the original design which was a uniformly filled hyper-ellispoid in the 4D-phase-space (“waterbag distribution”).

To make the emittance measurement usable for beam dynamics simulations we wrote a script (Python) that allows us to generate randomised particle distrubtions representing the measurements. The distribution, containing a user-given number of particles, is based on interpolation and consequently does not show any discretisation. The code offers the possibility to "overwrite" defective channels and has an optional background substraction and cleaning function. We have cross-checked our code by calculating the emittance from the particle distribution applying the statistical definition and got comparable results as from the acquisition software.

As an example we show in Fig. 3 the horizontal emittance of a 200 μA $^{12}C^{4+}$ beam measured at our test bench. After source extraction the beam passes a 90° double focusing dipole and a quadrupole triplet. These conditions are comparable to the ones in the real low energy beam transport system. The irregular ECR beam is well represented by the particle distribution. The area with missing data (around −30 mrad) is filled up with particles by interpolation. The cleaning function assures that there are no particles outside the obvious beam area. The rms-emittance calculated by the emittance software is 59 πmm·mrad which agrees well to the value of 61 πmm·mrad computed from the particle distribution.

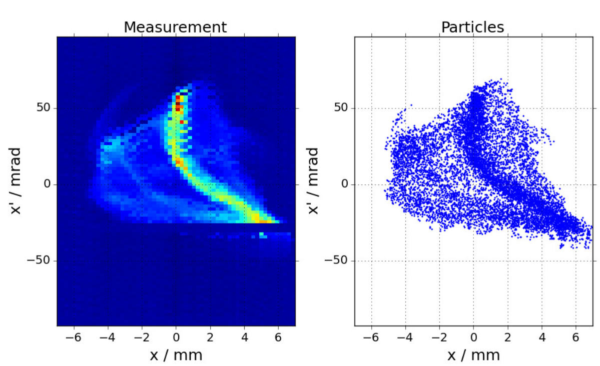

Figure 3: Measured horizontal beam emittance of an ECR beam (I = 200 μA) at the test bench (left) and generated particle distribution (right).

The beam optics of the test bench and the LEBT section are well known and so we can transport the particle distribution hence and forth according to our needs.

ELECTROMAGNETIC FIELD SIMULATIONS

The complete design process should be accompanied by electrodynamics field simulations. The goals of these are:

- definition of the heights of the tuning plates (field flatness)
- definition of the rebuncher geometry
- definition of the stem angle
- verification of the electrode modulation by particle tracking

We have proven in a dedicated study that it is possible to simulate a complete RFQ, including the electrode modulation, with a modern electromagnetic field simulation software. The model shown in Fig. 4 was set up with CST Microwave Studio® [9]. The eigenfrequency of the operating mode (216.816 MHz) could be reproduced within 1 MHz (0,5%) not taking into account the plunger.

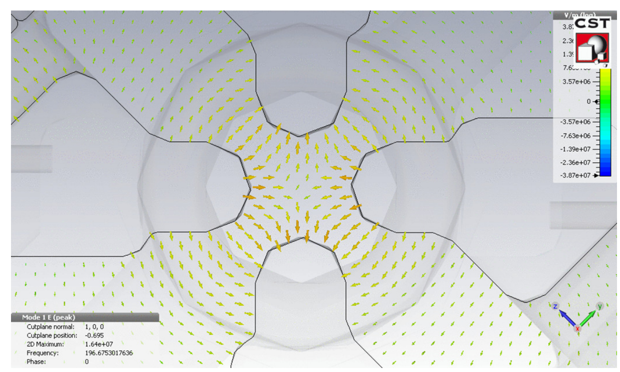

Figure 4: Electric field of the RFQ (original design), including electrode modulation, simulated with CST Microwave Studio®.

CONCLUSION

On the path towards higher beam intensities there is no way around a new RFQ design. The work presented here could serve as a guideline. It is obvious that many details have to be concretised. From the mentioned work packages certainly the ion source simulation and the specification of the electrode modulation are the one to precede the final design engineering which has to be accompanied by the EM field simulations.

Anyway it will be worth the effort, all the more as there will be two facilities which will profit from this development, namely HIT and MIT (Marburg Ion Beam Therapy Centre), both daughters of the Heidelberg University Hospital.

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