DESIGN OF A 750 MHZ IH STRUCTURE FOR MEDICAL APPLICATIONS

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Abstract

Low velocity particles are critical in every hadron accelerator chain. While RFQs nicely cover the first MeV/u range, providing both acceleration and bunching, energies higher than few MeV/u require different structures, depending on the specific application. In the framework of the TULIP project [1], a 750 MHz IH structure was designed, in order to cover the 5-10 MeV/u range. The relatively high operating frequency and small bore aperture radius led the choice towards TE mode structures over more classic DTLs. Hereafter, the RF regular cell and end cell optimization is presented. An innovative solution to compensate dipole kicks is discussed, together with the beam dynamics and the matching with the 5 MeV 750 MHz CERN RFQ [2]. This structure was specifically designed for medical applications with a duty cycle of about 1 ‰, but can easily adapted to duty cycles up to 5 %, typical of PET isotopes production in hospitals.

INTRODUCTION

R&D developments in low beta linear accelerators sparked in the last two decades. Alvarez drift tube linacs (DTL) are usually the preferred solution after the RFQ for pulsed operation. An alternative to DTLs are H-mode linacs, operating in the TE_{110} mode – inter-digital H (IH), or in TE_{210} mode – cross-bar H (CH), as RFQs. Different hybrid solutions – quasi-Alvarez DTL, H-mode linac with PMQ focusing – were studied [3,4]. Ultimately, the choice of the best accelerating structure depends on the application. Medical linear accelerators are characterized by pulsed, low current beam, and have thus a small aperture radius. In addition, a high accelerating gradient is desirable, in order to reduce the overall length of accelerators that have as a final target medical rooms in hospital. This set of parameters – small aperture and high gradient – is unique amongst low beta accelerators, and thus call for a specific design.

COMPARISON BETWEEN STRUCTURES

The 5 MeV 750 MHz CERN proton RFQ represented the starting point of this study. From preliminary beam dynamics considerations, it was decided to use accelerating structures with 2.5 mm aperture radius. The operating frequencies considered were 750 MHz, as the RFQ, and 3 GHz, as the high-beta accelerating structures already designed [5]. The intermediate harmonics were not considered.

RF regular cells with a simplified geometry were optimized in terms of Shunt Impedance (ZTT), considering both DTL and H-mode cavities at the two different frequencies, when applicable (Fig. 1). The results obtained clearly showed the advantage of IH-mode structures in the 5 to 20 MeV/u range. As we will discuss in the following section, the optimization of IH structures is more complex than the optimization of DTL cavities, for which the gap is the most important parameter. As a result, a detailed cavity optimization remarkably increased the ZTT of the 750 MHz IH solution considered (dark red curve in Fig. 1).

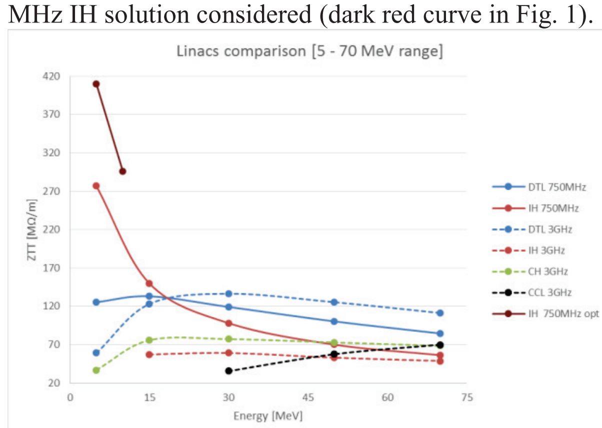

Figure 1: ZTT comparison between different RF cavities.

REGULAR CELL DESIGN

The optimization of TE cavities is more challenging with respect to TM mode ones because of the current flowing in the conductor walls. A DTL RF cell has its ZTT optimum for a given gap, and for stem radius and drift tube thickness the smallest possible. This is not, in absolute terms, the case for IH cavities. For instance, a large stem radius is beneficial because it reduces the Ohmic losses, but it also affects the gap region electric field, thus reducing the ZTT. A careful RF optimization was carried out in order to maximize the ZTT, for a cell length of $\beta\lambda/2$ corresponding to 2.5, 5 and 10 MeV.

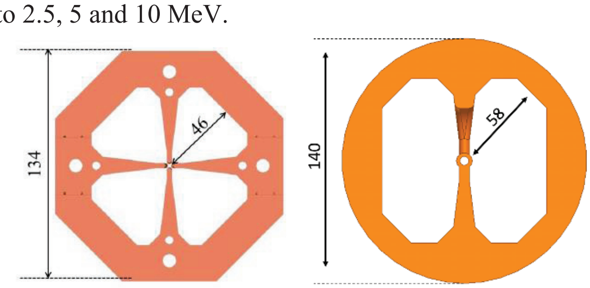

Figure 2: Comparison between the 5 MeV 750 MHz RFQ cell cross section and the IH one.

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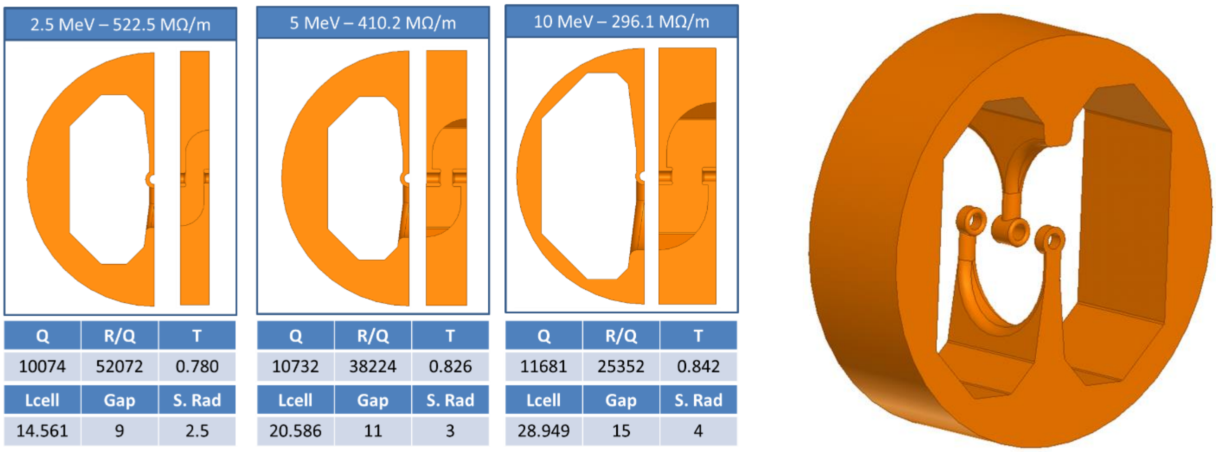

Q	R/Q	T	Q	R/Q	T	Q	R/Q	T
10074	52072	0.780	10732	38224	0.826	11681	25352	0.842
Lcell	**Gap**	**S. Rad**	**Lcell**	**Gap**	**S. Rad**	**Lcell**	**Gap**	**S. Rad**
14.561	9	2.5	20.586	11	3	28.949	15	4

Figure 3: Geometric and main parameters comparison between IH optimized regular cells (left) and structure assembly view (right). Dimensions are in mm, and R upon Q in Ω/m.

The 2.5 MeV regime was investigated in the perspective of further projects with carbon ions. As shown in Fig. 2, the transverse dimension is close to the one of the 750 MHz RFQ. The RF design indeed followed also the goal of having a geometry which is close to the one of the RFQ, in order to maximize the experience gained at CERN in terms of brazing – assembly, and tuning, of structures in these regimes of beta and frequency. The main accelerating and geometric parameters of the optimized cells, together with a view of the structure is reported in Fig. 3.

A thermal and deformation analysis was performed on the optimum geometries found, considering an accelerating gradient of 10 MV/m and a duty cycle typical of medical applications, i.e. 10^{-3} (Fig. 4). It is demonstrated that, at such low DC, cooling of drift tubes is not necessary thanks to the high ZTT. The simulated temperature difference is 1.2 deg, and the maximum temperature induced deformation is 0.5 μm.

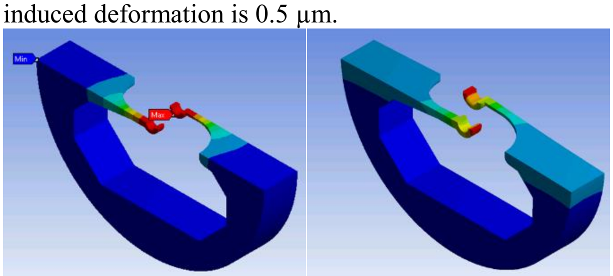

Figure 4: Thermal and deformation analysis for the 5 MeV cell at 10 MV/m accelerating gradient and 10^{-3} duty cycle.

END CELL DESIGN

End-cells are probably the most critical part in the design of an H-mode accelerating structure. The transition from a TE mode to a TM one, due to end-cell walls, forces a strong rupture of the symmetric chain, which can propagates along many regular cells and decrease significantly the overall ZTT. Passing from TE to TM translates into the need of increasing the cavity dimension. The solution adopted is the one presented in [4], though another study proposes a different approach [6]. In this regard, the RF design was completed, but a mechanical study is necessary before validating the proposed solution. The ZTT decrease in the end cells is higher than 50%, thus making this design, as all H-mode cavities, efficient only if the structure is long enough to make the end-cells effect on the overall efficiency negligible.

DIPOLE KICKS

Electrical coupling between drift stems induces a dipole kick component along the stems direction. This effect is a consequence of the small aperture dimension and drift gap, and is not notable in standard low frequency DTLs. While RF defocusing manifests with an imaginary linear component of the transverse voltage over one cell at different transverse axis, dipole kicks are given by the constant real part of the same voltage, as shown in Fig. 5. The slight asymmetry in Fig. 5 comes from higher order terms, sextupoles or octupoles.

Compensation of dipole kicks is usually achieved by modifying the shape of the drift tube, as proposed in [4]. However, authors realized that a simpler solution can be adopted, which is presented in the next section.

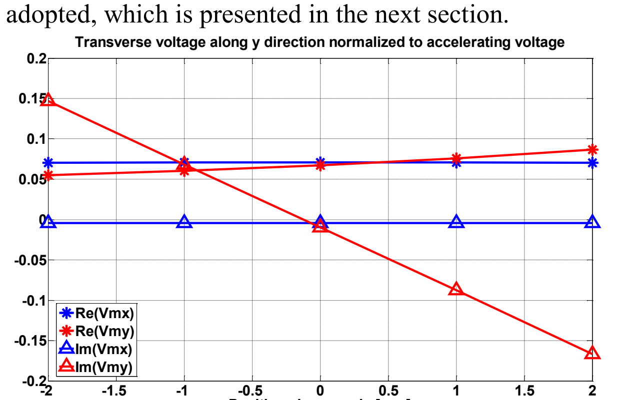

Figure 5: Dipole kicks in a regular cell with drift stems 90 deg rotated.

BEAM DYNAMICS

An accelerating structure approximately 0.9 meter long, length tapered, was designed. The beam dynamics was

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studied considering the structure field map with the code RF-Track [7]. The structure design was driven by the goal of boosting particles from 5 to 10 MeV, assuming as RF power source one 100 kW 750 MHz IOT. For comparison, in the RFQ four 100 kW IOTs are needed. As a result, a 750 MHz RFQ + IH-structure solution would require 500 kW to accelerate protons up to 10 MeV.

Dipole kicks act linearly on particles, thanks to the constant voltage of the IH structures (blue curve in Fig. 6 top). So a compensation as the one proposed in [4] would act as the red or green curve in Fig. 6 top. However, if the kick in the input cell could be reduced, the beam will experience a trajectory similar to the one of a particle in an undulator, because dipole kicks have opposite direction in every gap crossed by the synchronous particle. Quite interestingly, a reduced gap, typical of optimum end-cells design, gives reduced dipole component very close to what is required. In conclusion, the authors have efficiently controlled the beam in simulations simply by a careful design of the end-cells (blue curve in Fig. 6 bottom). The last cell of the structure must also have a reduced dipole component, in order to have zero integrated kick.

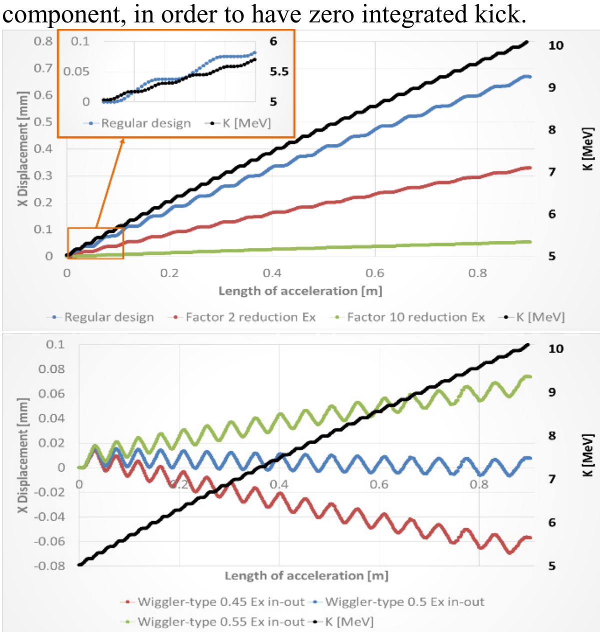

Figure 6: Single particle x-displacement along the IH structure. Transverse component reduced (top) and end-cells compensation (bottom) solutions.

Full beam tracking was then performed, using a triplet focusing between the RFQ output and the IH structure (Fig. 7). The transverse emittance is preserved, while the longitudinal one increases about 50%. It was verified that a modification of the longitudinal phase space at the RFQ output could reduce the longitudinal emittance growth down to 20%.

Though not presented in this paper, it was chosen to accelerate particles from 10 MeV onwards through 3 GHz DTL structures. A relatively high synchronous phase of 20 deg was chosen for the IH structure in order to facilitate the longitudinal matching to the downstream 3 GHz linac acceptance. The transverse matching had to be slightly penalized in order to reach full transmission. However, in the same 5 to 10 MeV energy range, a solution based on 3 GHz DTL, as the one proposed and tested in [8], was studied, and it gives worst performances both in terms of transmission and emittance growth.

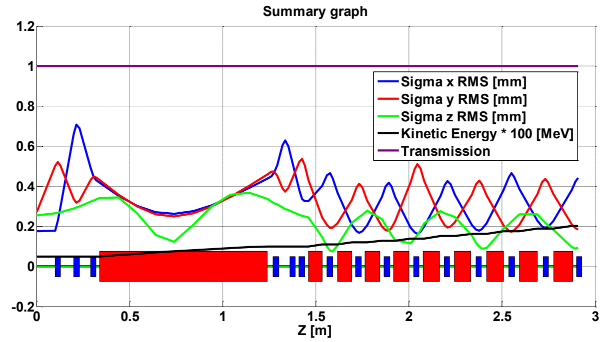

Figure 7: Particles 3D envelopes (1 rms), transmission and kinetic energy from RFQ output to 20 MeV.

SUMMARY

An IH accelerating structure was designed to boost protons from 5 to 10 MeV. This solution represents an ideal continuation of the 750 MHz CERN RFQ to higher beam energies for medical applications, remarkably improving current designs based on high-frequency DTL structures, both from RF and beam dynamics point of view. The longitudinal and transverse matching with a subsequent 3 GHz DTL linac at 10 MeV was studied, and a beam dynamics design from 5 to 20 MeV is presented in this paper.

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