H-MODE ACCELERATING STRUCTURES WITH PMQ FOCUSING FOR LOW-BETA ION BEAMS

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Abstract

We are developing high-efficiency normal-conducting RF accelerating structures based on inter-digital H-mode (IH) cavities and the transverse beam focusing with permanent-magnet quadrupoles (PMQ), for beam velocities in the range of a few percent of the speed of light. Such IH-PMQ accelerating structures following a short RFQ can be used in the front end of ion linacs or in stand-alone applications, e.g. a compact deuteron-beam accelerator up to the energy of several MeV. Results of combined 3-D modeling for a full IH-PMQ accelerator tank – electromagnetic computations, beam-dynamics simulations with high currents, and thermal-stress analysis – are presented. The accelerating field profile in the tank is tuned to provide the best beam propagation using coupled iterations of electromagnetic and beam-dynamics modeling. A cold model of the IH-PMQ tank is being manufactured.

INTRODUCTION

Room-temperature accelerating structures based on inter-digital H-mode (IH) resonators are very efficient at very low beam velocities, $\beta = v/c < 0.1$, e.g. see [1]. Small sizes of the drift tubes (DTs), which are required for achieving high shunt impedances in the H-resonators, usually prevent placing conventional electromagnetic quadrupoles inside DTs. Inserting permanent-magnet quadrupoles (PMQs) inside small DTs of the H-structure, as was suggested in [2], promises both efficient beam acceleration and good transverse focusing. Further studies of this approach [3] based on EM 3-D modeling, beam-dynamics simulations, and engineering analysis, confirmed that IH-PMQ accelerating structures are feasible. Papers [3] studied only one or a few periods of the IH structures in the beam velocity range β = 0.0325-0.065, corresponding to the deuteron beam energies from 1 to 4 MeV. In [4] a complete short tank containing the IH-PMQ accelerating structures with vanes was designed. The beam velocity range was chosen to be β = 0.0325-0.05, so that the tank can serve as the first of two tanks in a 1-4 MeV compact deuteron (D^+) accelerator. We mostly concentrated on the end-cell design and the means to tune the electric field profile along the beam axis, as well as the frequency of the working mode to 201.25 MHz. This IH-PMQ tank was also used to analyze and prove feasibility of the thermal management with cooling channels in vanes, even at high duty factors.

MODIFIED IH-PMQ TANK DESIGN

The IH-PMQ tank [4] was designed with equal gaps between DTs, which leads to equal magnitudes of the on-axis electric field in (and voltages across) the gaps except the two end ones, cf. Fig. 1. The cell length L_c increases along the structure as $L_c = \beta_g\lambda/2$, where β_g is the design beam velocity and λ is the RF wavelength, so the average accelerating gradient per cell decreases along the tank. Beam dynamics simulations for the IH tank indicated no problems at low or moderate currents but for high currents (~50 mA) the beam particles can be lost at the DT walls. Due to small DT lengths in that design, from 1.8 cm, short PMQs inside DTs were not strong enough to focus high-current beams.

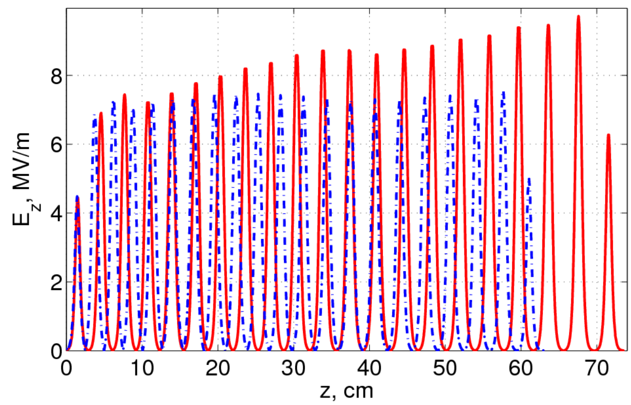

Figure 1: Magnitude of the on-axis electric field in the IH-PMQ tank [4] (dot-dashed) and in the modified tank of Fig. 2 (solid). E_0 = 2.5 MV/m in both cases.

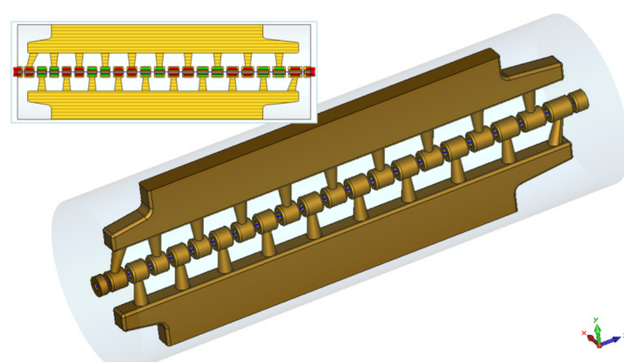

Figure 2: CST Studio model of the IH-PMQ tank for β = 0.04-0.0543. The tank outer wall is removed, and the cavity inner volume is shown in light-blue.

The IH-PMQ tank was redesigned to have a higher injection energy (β_{in} = 0.04, 1.5-MeV D^+ energy; β_{out} = 0.0543, ~2.8 MeV) so that its DTs are longer. The 3-D EM modeling of the tank was performed with the CST MicroWave Studio (MWS) [5] as in [2-4], but this time we used iterations of beam-dynamics and EM simulations to adjust the tank layout. The gap widths were tuned for the electric field strength to increase along the tank proportionally to the cell length, cf. Fig. 1, to keep the cell gradient nearly constant. The gap positions were also adjusted to create a ramp of the synchronous phase along the tank from -45° to -35°, except -54° in the first gap and -41° in the last. The ramp maintains a constant RF-bucket height and provides better beam capture. The modified IH-PMQ tank is shown in Fig. 2. The cavity total length is 73.51 cm, and its radius is 11.92 cm. The EM parameters of the tank for E_0 = 2.5 MV/m are listed in Tab. 1.

Table 1: EM parameters of IH-PMQ tank.

Parameter (* = at 100% duty factor)	**Value**
Quality factor Q	9973
Transit-time factors T, for 21 gaps	0.91-0.95
Effective shunt impedance ZT^2, MΩ/m	408
Surface (Cu) RF power loss P_{surf}, kW*	19.2
Maximal electric field E_{max}, MV/m	23.3 (1.58E_K)
Maximal surface loss density, W/cm^2*	113

In this design, the shortest DT is DT3 (23 mm); the longest one is DT20 (34.3 mm). The gap widths vary between 7.1 and 8.3 mm, except the very first and the last gap, which were reduced to 3.6 and 3.9 mm, respectively, to bring up the electric fields near the tank ends. All drift tubes up to DT11 have the bore radius of 5 mm, and from DT12 they all have a larger bore radius of 5.5 mm. The outer radius of all DTs is the same, 14 mm. The field profile in the tank, as well as its frequency, can be tuned with two pairs of slug tuners in the side walls, one pair near the tank entrance and the other near its end. The slug tuners are not shown in Fig. 2 but can be seen in Fig. 6 of the IH-PMQ tank cold model.

PMQ Fields

Two families of the 16-segment PMQs are used for beam focusing in this tank: the short ones, 18.89 mm, in the first 12 DTs (0 to 11), and longer ones, 22.67 mm, from DT12 on (12-22). The remanent magnetic flux density for the PMQ SmCo segments is 1.0 T, a conservative value. The inner PMQ radius is 5.5 mm for the first PMQ family, and 6 mm for the second; the outer radius is 11 mm for both. The quadrupole gradients of the 16-segment PMQs are 170 and 142 T/m, but the integrated focusing strengths for both PMQ types are the same, 3.2 T. The PMQ magnets are arranged in pairs to form an FFDD beam focusing lattice, as schematically illustrated in the inset of Fig. 2 (F in red, D in green).

To take into account the PMQ field overlaps, the static magnetic field for the whole array of 22 PMQs, cf. Fig. 3, was calculated by the CST Electro-Magnetic Studio (EMS) [5]. The computation was performed with a very fine mesh, 24M points for one quarter of the structure, with account of symmetry, but took only about 10 min on a PC with dual quad-core Intel W5590 3.33-GHz processors. The red segments in Fig. 3 were used in EMS computation. The field overlaps are clearly seen in the left inset of Fig. 3, which shows the vertical field component at the aperture of the smaller DTs in the horizontal plane (x = 5 mm, y = 0). The right inset shows B-field arrows in the middle of PMQ in DT10 (log scale, max 1.05 T).

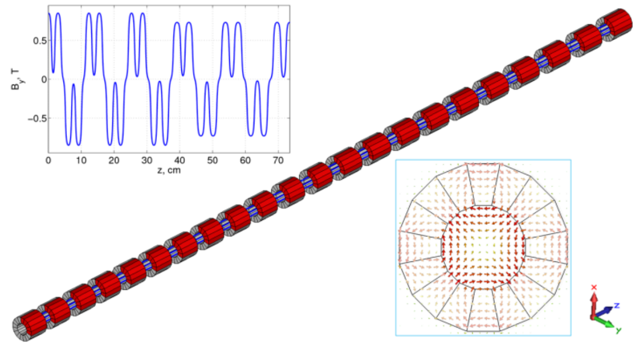

Figure 3: Array of 22 PMQs in the IH-PMQ tank and their magnetic fields calculated by CST EMS.

BEAM DYNAMICS

The design of the IH-PMQ tank in Fig. 2 was optimized for high-current beams using iterations of 3-D EM MWS calculations and a specialized linac design code that we have developed based on the PARMILA [6] algorithms. It applies the transit-time factors calculated for individual cells from MWS results to fine-tune the beam velocity profile along the tank. After that we employed 3-D multi-particle beam dynamics simulations with PARMELA [6] and CST Particle Studio (PS) [5] to confirm the design. The emittances of the matched input beams to the IH tank were estimated using PARMTEQM [6] for a generic RFQ with the deuteron output energy 1.5 MeV and current 50 mA. The initial normalized transverse rms emittance in the RFQ was 0.13 π mm·mrad at 62 keV and 55 mA. Both PARMELA and PS multi-particle simulations have used the same exact 3-D fields from the CST Studio codes [5]: RF fields from MWS and static magnetic field from EMS.

We explored both "water-bag" and Gaussian initial distributions of the bunch particles generated by the PARMILA code, with up to 100K particles used in simulations. The same initial distributions were imported into both PARMELA and PS runs. Results of the beam dynamics simulations for the IH tank indicate no particle loss at the fractional level down to 10^{-5} even at 50 mA, as illustrated in Figs. 4-5.

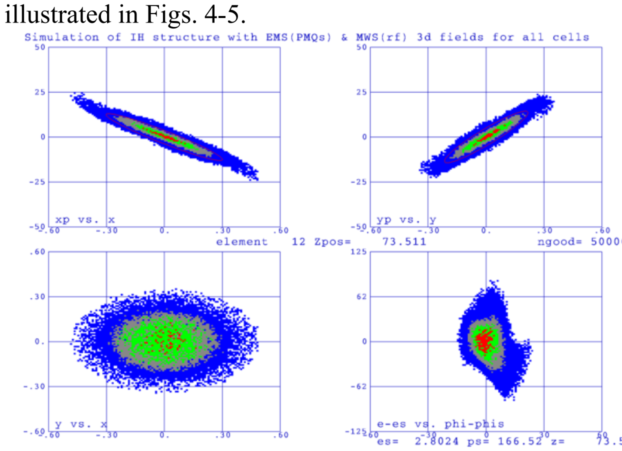

Figure 4: PARMELA phase-space plots of a Gaussian bunch with 50K particles at the IH-PMQ tank exit.

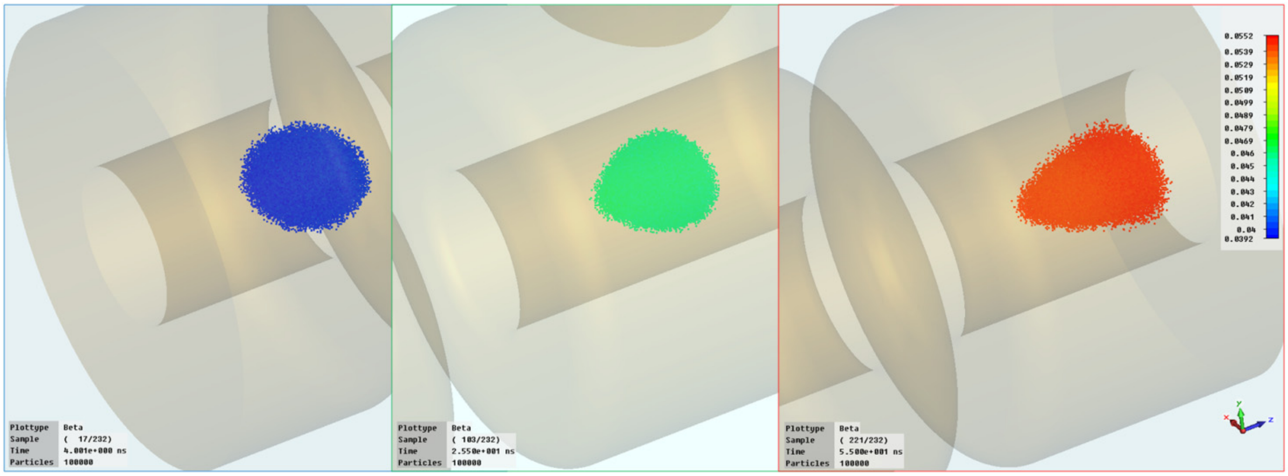

Figure 5: Evolution of a Gaussian bunch with 100K particles in the IH-PMQ tank computed by the CST Particle Studio: near the entrance, in the middle, and near the exit. Color changes indicate the particle-energy increase (β-scale shown).

IH-CAVITY COLD MODEL

A cold model of the IH-PMQ tank – a simple aluminum model without cooling for low-power field measurements – is being manufactured. Its 3-D drawing is in Fig. 6, where the slug tuners are also shown. Measurements of the mode frequency and the electric field profile with a bead pull are planned.

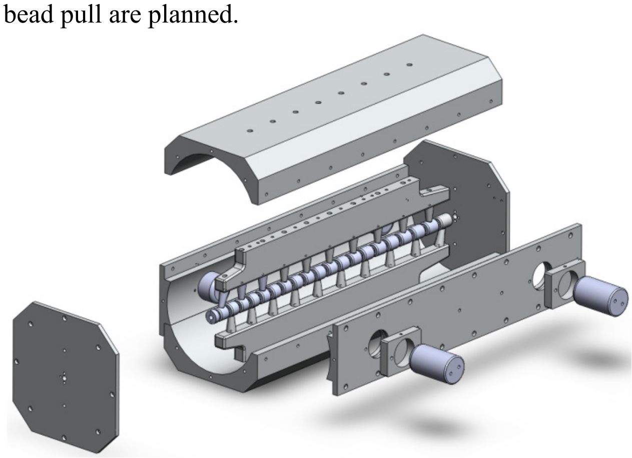

Figure 6: Explosion view of the tank cold model.

SUMMARY

We have demonstrated that normal-conducting IH-PMQ accelerating structures are feasible and very efficient for beam velocities in the range of a few percent of the speed of light. Results of combined 3-D modeling for the IH-PMQ accelerator tank – electromagnetic computations, beam-dynamics simulations, and thermal-stress analysis – prove that H-mode structures (IH-, and the higher-mode CH-, etc) with PMQ focusing can work even at high currents. Due to the structure efficiency, the thermal management is simple and can be realized with cooling channels in vanes [4]. The accelerating field profile in the IH-PMQ tank was tuned to provide the best beam propagation using coupled iterations of electromagnetic and beam-dynamics modeling.

One inherent limitation of all H-mode structures is a fixed velocity profile. Our study indicates also that some restrictions of H-PMQ structures at high currents can be caused by limited beam apertures. This conclusion is due to the fact that increasing the DT bore size leads to larger inner radii of PMQs, and increasing the inner radius of PMQ quickly weakens its focusing strength.

IH-PMQ accelerating structures following a short RFQ can be used in the front end of ion linacs or in stand-alone applications. In particular, we explored a compact efficient deuteron-beam accelerator to 4 MeV. Overall, H-PMQ ion linacs look especially promising for industrial and medical applications.

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