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

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Abstract

We report on results of the project 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. The shunt impedance of IH-PMQ structures is 10-20 times higher than that of a conventional drift-tube linac, while the transverse size is 4-5 times smaller. The H-PMQ accelerating structures following a short RFQ can be used both in the front end of ion linacs or in stand-alone applications. Results of the combined 3-D modeling – electromagnetic computations, beam-dynamics simulations with high currents, and thermal-stress analysis – for a full IH-PMQ accelerator tank are presented. The accelerating field profile in the tank is tuned to provide the best propagation of a 50-mA deuteron beam using coupled iterations of EM and beam-dynamics modeling. Multi-particle simulations with Parmela and CST Particle Studio have been used to confirm the design. Measurement results of a cold model of the IH-PMQ tank are presented.

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. [1]. Small sizes of the drift tubes (DTs), 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], can combine both efficient beam acceleration and good transverse focusing. Further studies [3-4], using combined 3D EM modeling, beam-dynamics simulations, and engineering analysis, confirmed feasibility of IH-PMQ accelerating structures. Paper [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 short IH-PMQ tank was designed for the beam velocity range β = 0.0325-0.05. It was analyzed to prove feasibility of high-current beam focusing and thermal management using cooling channels located only in the vanes.

IH-PMQ TANK

The short IH-PMQ tank was redesigned [5] 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 longer DTs allow for longer PMQs that provide stronger transverse focusing. The 3-D EM modeling of the tank was performed with the CST MicroWave Studio (MWS) [6] as before, but now we used iterations of beam-dynamics and EM simulations to adjust the tank layout. The gap widths were tuned so that the electric field strength increases along the tank proportionally to the cell length in order to keep the cell gradient nearly constant. The gap widths vary between 7.1 and 8.3 mm; the first and the last gaps are reduced to 3.6 and 3.9 mm to bring up the cell gradients near the tank ends. The gap locations were adjusted to create a ramp of the synchronous phase along the tank from -45° to -35°. For the first and last cells, with lower fields, the phases were adjusted to -54° and -41°, respectively, to have the same bucket height as the adjacent cells. Such a ramp provided for better beam capture. The modified IH-PMQ tank, IH1m, is shown in Fig. 1. One of the reasons for designing a short tank was to simplify fabrication of its cold model. The cavity total length is 73.51 cm, and its radius is 11.92 cm.

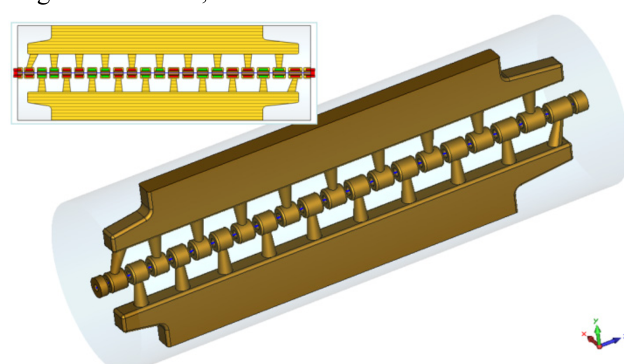

Figure 1: CST Studio model of IH1m tank. The outer wall is removed; the cavity inner volume is in light-blue.

The effective shunt impedance of the tank ZT^2 = 408 MΩ/m, and total RF surface loss at 100% duty is 19.2 kW for the gradient E_0 = 2.5 MV/m, see [5]. The shortest DT is DT3 (23 mm); the longest one is DT20 (34.3 mm). 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 tilt in the tank, as well as its frequency, can be tuned with two pairs of slug tuners.

Two families of 16-segment PMQs are used for beam focusing in IH1m tank: the short ones, 18.89 mm, in the first 12 DTs (0 to 11), and longer ones, 22.67 mm, from DT12 on (12-21). 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; the integrated focusing strength for both PMQ types is the same, 3.2 T. The magnets are arranged in pairs to form an FFDD beam focusing lattice, as schematically illustrated in the inset of Fig. 1 (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 was calculated [5] by the CST Electro-Magnetic Studio (EMS) [6].

The design of the IH1m tank was optimized for high-current beams by iterations of 3-D EM MWS calculations and a specialized linac design code that we developed based on the PARMILA [7] algorithms. The code 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 [5] with PARMELA [7] and CST Particle Studio (PS) [6]. The emittances of the matched input beams to the IH1m tank were estimated using PARMTEQM [7] 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 used the same exact 3-D fields: 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, using up to 100K particles in simulations. The same initial distributions were imported into both PARMELA and PS runs. Results of the beam dynamics simulations for the IH tank indicated no particle losses at the fractional level down to 10^{-5} even at 50 mA, see [5].

IH-PMQ TANK COLD MODEL

A cold model of the IH1m tank has been designed and manufactured. The cold model is a simplified structure made from aluminum for the purpose of making low-power field measurements; it does not have cooling features. The model exploded view is shown in Fig. 2.

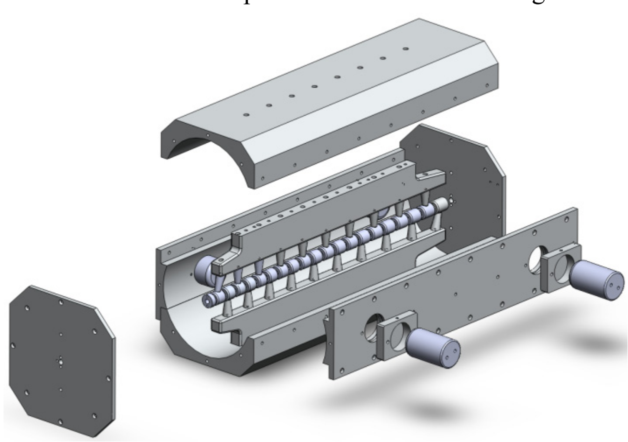

Figure 2: An exploded view of the tank IH1m cold model. Two pairs of slug tuners are located on the side panels.

The outer shell of the tank is comprised of four longitudinal pieces as well as upstream and downstream end walls. Each individual drift tube was machined to finished dimension, and then, using a press-fit technique, was attached to its individual stem. The DT and stem assemblies were bolted to either the top or bottom vane pieces. The assembled vanes were then pinned and bolted to the top and bottom outer-cover pieces respectively.

Because of rather small gaps between the drift tubes, the cold model alignment is very important. Precision Teflon spacers were fabricated and used to set the proper longitudinal gaps between drift tubes. The transverse alignment was set through with a precision alignment fixture that properly oriented the individual drift tubes to each other, and to the vane they were mounted on. A close-up photograph of the drift tubes in the bottom part of the model assembly in Fig. 3 shows also open holes for the tuner slugs on the side wall behind the DTs.

Figure 3: A close-up view of the DTs mounted on the vane in the bottom part of the cold-model assembly.

For the cold model we measured the mode frequency and the electric field profile with a bead-pull technique. The comparison of measured and calculated cell gradients is presented in Fig. 4, where both computed and measured values are scaled to the tank gradient $E_0 = 2.5$ MV/m. The differences are within 2% and indicate a small field tilt from upstream to downstream. A perfect agreement was not expected since the measurements were done with the slug tuners retracted from their nominal positions to bring the frequency down. Later the frequency was adjusted by moving out the side panels with 3-mm-thick shims.

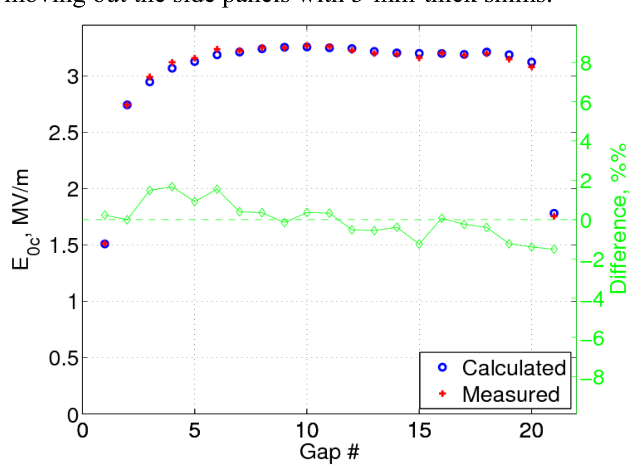

Figure 4: Calculated and measured cell gradients in the IH1m tank cold model (left vertical axis) and differences between them (green, right vertical axis).

Initially the measured frequency of the model with the slug tuners in the nominal position was about 1.35 MHz (0.67%) higher than the calculated design value of 201.25 MHz. Usually the frequencies computed with MWS on reasonably dense meshes are quite accurate. The design [5] was based on the MWS computations that used rather dense meshes up to 8-9 million points covering one half of the model, with account of the tank symmetry.

After this discrepancy was found, the MWS runs were repeated with varying number of mesh points *N*, both with and without adapting meshing. We found an unusual asymptotic behavior: the calculated frequency continued to monotonically increase very slowly as the number of mesh points increased, see Fig. 5. Typically the calculated frequency changes quickly as the number of mesh points *N* increases, and then for large *N* values its value wobbles in a narrow range.

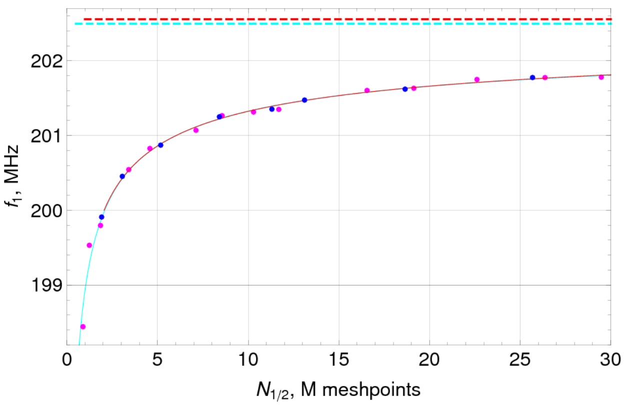

Figure 5: Calculated mode frequency versus the number of mesh points in MWS computations. Blue dots are results w/o adaptive meshes; fitted with red solid curve; dashed red line shows the asymptotic frequency. Magenta dots are for results with adaptive meshing; fitted by cyan solid curve; cyan dashed line is the asymptotic frequency.

The computation results plotted in Fig. 5 suggest fitting the frequency dependence as

$$f(N) = f_o - bN^{-\alpha}, \quad (1)$$

where f_0 is the asymptotic frequency to be found, b and α are two positive constants. One can expect $1/3 < \alpha < 1$, where the lower bound is for spherical symmetry. The fit parameters for the two sets of data in Fig. 5, found with Mathematica, are similar: for meshes without adaptive refinement, f_0 = 202.55 MHz, b = 3.554, and α = 0.461 (red curves); with adaptive meshes, 202.50 MHz, 3.557, and 0.483 (cyan curves). The fit curves in Fig. 5 almost overlap, and the calculated asymptotic frequencies are close to the measured value. We have also performed computations using meshes with different parameters (the ratio of the largest to the smallest cell size, etc). The fit curves change (different b and α) but the asymptotic frequency stays in the range from 202.4 to 202.7 MHz.

One possible explanation for the unusual behavior of the calculated frequency is that in the IH-PMQ structure the electric field is concentrated mostly in the gaps, which are relatively narrow. To calculate the field energy more accurately, one has to resolve the fields in the gaps better. Unfortunately, for the hexahedral meshes this leads to noticeable increases in the mesh size.

SUMMARY

We have demonstrated in [2-5] and above 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 for the IH-PMQ accelerator tank – from combined 3D EM 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 for high currents. Due to the structure efficiency, the thermal management can be simply realized using cooling channels in the vanes. The lessons learned from the cold model fabrication and measurements helped us improve the design process and will serve well for future projects.

Some restrictions of H-PMQ structures at high currents are caused by the limited beam apertures. Increasing the DT bore size forces larger inner radii of PMQs; increasing the inner radius of PMQ 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 have explored a compact efficient deuteron-beam accelerator to 4 MeV. Overall, H-PMQ ion linacs look especially promising for industrial and medical applications.

The authors would like to thank James Witt for the drawings of the cold model, and Claude Conner for its assembly and alignment. This work was supported by the LANL Laboratory-Directed R&D program.

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