EFFICIENT LOW-BETA H-MODE ACCELERATING STRUCTURES WITH PMQ FOCUSING

S.S. Kurennoy, J.F. O'Hara, E.R. Olivas, L.J. Rybarcyk, LANL, Los Alamos, NM 87545, U.S.A.

Abstract

We are developing high-efficiency room-temperature RF accelerating structures for beam velocities in the range of a few percent of the speed of light by merging two well-known ideas: H-mode cavities and the transverse beam focusing with permanent-magnet quadrupoles (PMQ). Combining electromagnetic 3-D modeling with beam dynamics simulations and thermal-stress analysis, we have found that the H-mode structures with PMQ focusing provide a very efficient and practical accelerator for light-ion beams of considerable currents. Such accelerating structures following a short RFQ can be used in the front end of ion linacs or in stand-alone applications such as a compact deuteron-beam accelerator up to the energy of a few MeV.

INTRODUCTION

Room-temperature H-mode resonators – inter-digital (IH) or cross-bar (CH) – provide effective acceleration at low beam velocities, $\beta=v/c<0.3$-0.4, e.g. [1]. IH structures are especially efficient at very low velocities, $\beta<0.1$. Transverse focusing options used in H-structures include electric RF quadrupoles in RFQ at very low β and magnetic focusing by quadrupole triplets inserted into the structure [1]. The triplet insertions interrupt the structure reducing its acceleration efficiency. On the other hand, small sizes of the drift tubes (DTs) required to achieve high shunt impedances in H-structures prevent placing usual electromagnetic quadrupoles inside DTs. Using permanent-magnet quadrupoles (PMQs) placed inside H-structure small DTs was suggested [2], which promises both efficient beam acceleration and beam focusing.

Here we focus on a particular application: using IH structures with PMQ beam focusing for a compact deuteron-beam accelerator from 1 to 4 MeV at the RF frequency around 200 MHz, with the peak current up to 50 mA and duty factor of 10%. Such an accelerator can serve in a mobile intense neutron and gamma source for interrogation of special nuclear materials for homeland defense. Requirements of the system mobility and ease of use favor the room-temperature (RT) option. For higher energies and/or higher RF frequencies using CH-PMQ structures can be beneficial.

PMQ FOCUSING IN IH STRUCTURES

Deuteron kinetic energies from 1 to 4 MeV correspond to the beam velocity range of $\beta=0.033$-0.065. The cell length $L_c=\beta\lambda/2$ – equal to a half-period in IH structures – is very short at the low-energy end, only about 2.5 cm. To keep the DT length L_{DT} as long as possible, we consider first the IH structure with narrow gaps g between DTs by fixing the ratio $g/L_c=0.15$. A 2-cm long PMQ with the bore radius 5 mm can readily provide the field gradient G=200 T/m, even if the PMQ outer radius is only 11 mm. Such PMQs fit into DTs even at the lower end of the IH accelerating structure, with geometrical value $\beta_g=0.034$, where the DT length is L_{DT}=2.16 cm. In Ref. [3, 4] we explored the beam transverse focusing structure F*n*OD*n*O, where the focusing period consists of one focusing (F) and one defocusing (D) PMQ separated and followed by n empty DTs, n=0,1,2,… We denote such structures as IH 1-(n+1), with one PMQ per (n+1) cells. Initial beam dynamics calculations were performed with the envelope code TRACE-3D; the results for the beam sizes and phase advances are summarized in [3, 4]. Long focusing periods are excluded because of large phase advances $\sigma_{0x/y}$ per focusing period, above 90°. All configurations IH1-2 to IH1-4 were found acceptable, and the differences between them were not very significant. Overall, IH1-3 (n=2), cf. Fig. 1, where PMQs are inserted in every third DT, provided the smallest beam size.

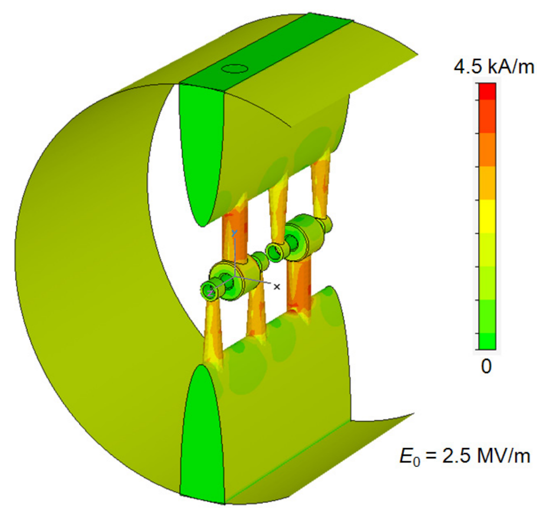

Figure 1: Surface current magnitude in the modified IH1-3 structure for β_g = 0.04 (the cavity wall is partially cut).

Still, the beam size was rather large in all the cases, which can lead to undesirable beam losses. We plan to perform multi-particle beam-dynamics simulations next. Should they indicate significant beam losses, we will apply stronger transverse focusing using PMQ pairing, e.g. FFODDO (IH2-3); the structure is illustrated in Fig. 2. Such focusing schemes make the matched beam size smaller and reduce losses. TRACE-3D envelope calculations were performed also for the high energy end, β_g=0.065. There are more options there since the DT lengths are longer. For example, using longer PMQ while simultaneously increasing the PMQ and DT apertures to prevent beam losses gives good results [3]. Preventing beam losses is especially important at the high-energy end of the deuteron linac.

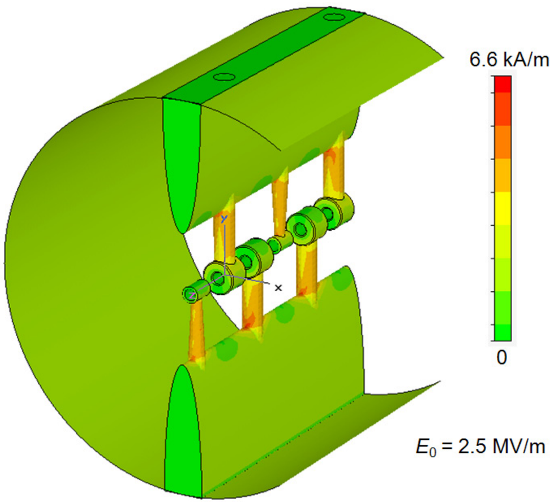

Figure 2: Surface current magnitude in the modified IH2-3 structure for $\beta_g = 0.06$ (the cavity wall is partially cut).

Overall, the transverse focusing structure IH1-3 (FOODOO, n=2), where PMQs are inserted only in every third DT, appears to be the best choice. It provides an acceptable beam transverse size while reducing the number of the required PMQs by a factor of three compared to the maximum equal to the number of DTs – a significant cost saving. It also gives us an opportunity to use DTs of different sizes – increasing the transverse size of DTs with PMQ while reducing the sizes of empty DT, as shown in Fig. 1 – to keep or even increase the high accelerating efficiency of the IH structure.

IH STRUCTURE CHARACTERISTICS

It is known that IH room-temperature structures have high accelerating efficiency, an order of magnitude higher than the DTL structures, in the beam velocity range β = 0.033-0.065, and small cavity transverse size (3-4 times smaller than DTL) [1]. Relatively homogeneous surface loss distributions compared to DTL (no hot spots) can simplify cooling. Our previous results [2] found the IH structures with DTs supported by stems on two vanes the most effective in this velocity range. We explore the characteristics of such IH structures for β = 0.033-0.065 using EM modeling with the CST MicroWave Studio (MWS) [5]. The MWS eigensolver finds the modes in one period of the structure with periodic boundary conditions imposed at the ends.

Structures with Identical DTs and Narrow Gaps

For the regular IH structures (identical DTs) with vanes and narrow gaps, g/L_c = 0.15, the transit-time factor T slowly increases from 0.9 to 0.96, while the shunt impedance Z_{sh} decreases with β [3]. The effective shunt impedance $Z_{sh}T^2$ ranges from 360 at low β to 300 MΩ/m at high β, well above $Z_{sh}T^2$ of the DTL structure, which increases from 22 to 34 MΩ/m in this velocity range. Here we assume the copper surface with $\sigma = 5.8\cdot10^7$ $(\Omega\ \mathrm{m})^{-1}$.

A few designs of the 1 to 4 MeV deuteron accelerator based on the regular IH structures with vanes were evaluated [4]. We found only small differences between various design options, from one with gradually increasing cell lengths to the three-step design that includes only three types of cells, with β_g = 0.04, 0.05, 0.06. In all these cases, assuming the average on-axis electric field E_0=2.5 MV/m and the RF synchronous phase -30°, the accelerator consists of 19-20 IH periods (38-40 cells) and has the total length 1.45-1.5 m. The surface-loss power is about 25 kW at 100% duty, small compared to the beam power 150 kW at 50 mA CW. Using a phase ramp to better capture the RFQ beam longitudinally would slightly increase the linac length.

One potential concern for the considered IH structures with narrow gaps was the maximal electric field E_{max} exceeding for $\beta_g \geq 0.05$ the conservative safe level of $1.8E_K$, where E_K=14.8 MV/m is the Kilpatrick field at 201.25 MHz. In fact, the RF breakdown level can be even lower due to high magnetic fields near the PMQ surface. The surface loss per cell P_{loss} and the maximal surface power density $(dP/ds)_{max}$ also increase as β increases.

Structure Improvement Options

One possible way to reduce E_{max} for a fixed gradient is increasing the gap length between DTs by making the DTs shorter. This is an attractive option at $\beta_g \geq 0.05$, since the DTs are relatively long and can accommodate PMQs even with reduced DT length. For regular IH structures L_{DT} should remain longer than the PMQ length, L_q=2 cm, which limits the gap width by g/L_c= 0.25, 0.35, 0.45 for β_g =0.04, 0.05, 0.06, respectively. Apart from a small drop in the T-factor values (3-8%), the structure parameters improve significantly with the gap width increase: the effective shunt impedance $Z_{sh}T^2$ increases by ~50%, from 300-360 MΩ/m to ~500 MΩ/m; E_{max} is reduced to safe levels around 20 MV/m with wider gaps [3, 4].

Another option for the IH structure improvement is to use DTs of different transverse sizes depending on whether they house PMQ inside or not. In IH1-3 structure, the transverse size of the DT with PMQ can be increased to facilitate the PMQ placement inside it, while the outer diameter of empty DTs can be reduced to keep the shunt impedance high. One can go a step further and reduce also the lengths of empty DTs to have wider gaps. One period of the modified IH1-3 structure for β_g = 0.04 is shown in Fig. 1. The DTs with PMQ have large r_{out} = 14 mm and length 24 mm; the empty DTs are short and slim, r_{out} = 7 mm and length near 12 mm; the aperture radius is 5 mm. The resulting $Z_{sh}T^2$ is 712 MΩ/m; it decreases at the high-energy end but still is above 500 MΩ/m for β_g = 0.06 [4].

For wider gaps in IH structures, a noticeable transverse on-axis electric field was observed, the known effect [1]. Asymmetric bulges on DT outer surface were used for its mitigation. The bulges reduce the dipole field but also reduce Z_{sh}. We considered an alternative measure – slanted ends of the empty DTs – that can compensate the integral transverse kick completely [4]. It keeps Z_{sh} high but increases E_{max} more than the bulges. The effects of the transverse on-axis electric field on the beam will be studied using Parmela multi-particle beam dynamics simulations with the MWS calculated 3-D fields for the modified IH structures.

ENGINEERING ANALYSIS

We have developed a procedure [6] to transfer surface-loss power data calculated by MWS to finite-element (FE) engineering codes COSMOS and ANSYS. The important feature is that the MWS fields are extracted not exactly at the cavity surface points but with a small offset into the cavity along the normal to each FE out of the FE center point. This helps avoiding errors in the surface fields due to hexahedral MWS meshes as well as in the cases when the FE central points are located inside convex metal walls. Thermal and stress analysis was performed for the regular IH structures with cooling channels in the vanes.

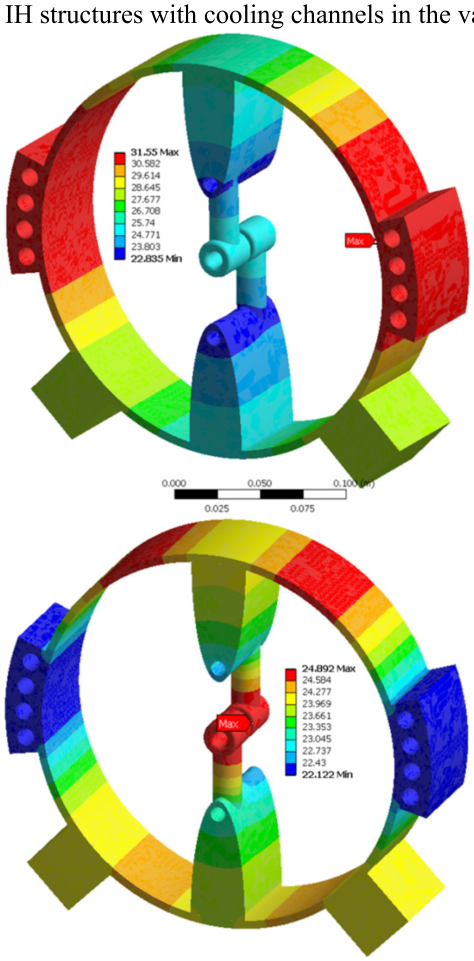

Figure 3: Temperature distribution in regular IH structure.

For the nominal 10% duty, the temperature distributions calculated by ANSYS are shown in Fig. 3. In the top picture, the water cooling is only in the vanes (4.4-m/s flow, 22°C inlet temperature); the maximal temperature (red) is 31.6°C, while the minimal (blue) one is 22.8°C. With the side-wall manifold cooling added at 10% duty (Fig. 3, bottom), the temperature range is from 22.1°C to 24.9°C. This option may be needed at higher duty factors. This important result – PMQ temperatures can be kept low by cooling only the vanes – confirms the IH-PMQ RT concept feasibility. The DT relative vertical displacements for 10% duty are between 15 and 35 μm depending on the cooling scheme, below typical manufacturing tolerances. The stresses at 10% duty are practically the same as in the cold state due to the atmospheric pressure, below 8 MPa, and even at 100% duty they do not exceed 28 MPa, which is still very far from the copper yield stress of 57 MPa. The transient thermal-stress analysis did not show any stresses above the static ones.

SUMMARY

We are developing RT IH accelerating structures with PMQ beam focusing for low beam velocities using 3-D electromagnetic modeling combined with beam dynamics simulations and thermal-stress analysis. The modified IH1-3 structures, like the one shown in Fig. 1, where PMQs are inserted in every third (larger) DT followed by two short and slim empty DTs, provide both high accelerating efficiency – $Z_{sh}T^2$ from 700 to 500 MΩ/m in the beam velocity range β = 0.033-0.065 – and good transverse beam focusing. Detailed multi-particle beam dynamics simulations are planned next. Should they indicate noticeable beam losses, we will switch to stronger focusing by pairing PMQs – see an example of the modified IH2-3 structure in Fig. 2 – and/or increase the DT apertures.

A compact 1-4 MeV deuteron linac based on IH-PMQ structure with the accelerating gradient E_0=2.5 MV/m has the total length of about 1.5 m. The surface-loss power in the accelerator is below 3 kW at the nominal 10% duty, which is less than 20% of the power delivered to the 50-mA deuteron beam, 15 kW. High efficiency of the described compact deuteron linac opens new options for RF. One of them is using inductive output tubes (IOT) instead of expensive custom grid tubes or klystrons as RF power sources; it would lead to both cost savings and an increased mobility of the system.

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