IH ACCELERATING STRUCTURES WITH PMQ FOCUSING FOR LOW-ENERGY LIGHT IONS*

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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: inter-digital H-mode (IH) 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 proved that such structures provide a very efficient and practical accelerator for light-ion beams of considerable currents. The IH accelerating structures with PMQ focusing 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 in H-structures include well known electric RF quadrupoles in RFQ at very low β and magnetic focusing by quadrupole triplets inserted into the structure [1]. Such 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 continue exploring the IH structures with PMQ beam focusing concentrating on a particular application: a compact deuteron-beam accelerator from 1 to 4 MeV for homeland defense, with the peak current up to 50 mA and duty factor of 10%. Requirements of the system mobility and ease of use favor the room-temperature (RT) option. We will also assume the RF frequency around 200 MHz. Of course, similar structures can be beneficial for other applications, including front ends of ion linacs.

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 rather 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. It can fit into a DT even at the lower end of the IH accelerating structure, with geometrical value β_g=0.034, where L_{DT}=2.16 cm. We consider the transverse focusing structure FnODnO, 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,… Beam dynamics simulations were performed with the envelope code TRACE-3D and its GUI version PBO-Lab [3] for β_g= 0.034 and 0.065. All field-dependent results are calculated assuming the average on-axis field E_0=2.5 MV/m; the RF synchronous phase in the gaps is chosen to be -30°. The results are illustrated in Fig. 1 for IH1-3 (n=2), where a PMQ is inserted in every third DT; the envelopes for 50 mA and zero current are plotted. The rms normalized transverse emittance 0.2π mm·mrad corresponds to $5\cdot0.2/(\beta\gamma)\approx30\pi$ mm·mrad for the un-normalized emittance of the TRACE 3-D equivalent uniform beam at β=0.034.

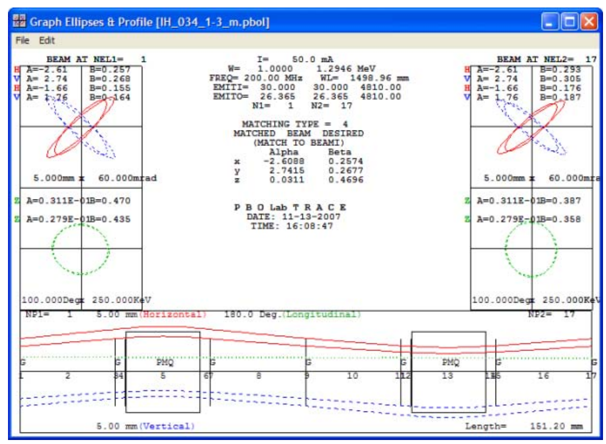

Figure 1: Beam matching results for IH1-3 at β_g = 0.034.

Table 1: Structure comparison for β_g = 0.034.

Focusing Structure	L, cm	x_{max} / y_{max}, mm	x_{min} / y_{min}, mm	r_{max}, mm
IH1-2	10.08	3.75 / 3.71	2.60 / 2.56	4.54
IH1-3	15.12	3.79 / 3.76	2.06 / 2.04	4.30
IH1-4	20.16	4.07 / 4.04	1.72 / 1.67	4.40
IH1-5	25.20	4.55 / 4.56	1.40 / 1.34	4.77

cont.	$\sigma_{x/y}$, deg	$\sigma_{0x/y}$, deg	σ_z/σ_{0z}, deg
IH1-2	17.4 / 17.9	31.7 / 32.1	42.8 / 45.9
IH1-3	33.1 / 34.1	55.6 / 56.4	61.8 / 66.7
IH1-4	51.3 / 53.8	82.4 / 84.5	79.8 / 86.4
IH1-5	75.0 / 79.9	116.7 / 121.5	96.8 / 105.1

Table 1 summarizes our results for the beam sizes and phase advances per focusing period at the low-energy end; L is the focusing period length. For the case IH1-1 200-T/m quads were too weak to keep the beam size within

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the chosen aperture of radius 5 mm. The case IH1-5 should be excluded since its zero-current phase advances $\sigma_{0x/y}$ are above 90°, while the full current advances are below 90°; the beam can be unstable. All configurations IH1-2 to IH1-4 are acceptable, and the differences between them are not very significant; overall, IH 1-3 provides the smallest beam size. However, the beam size is rather large in all these cases, which can lead to undesirable beam losses. The transverse beam size variations along the period are obviously larger for IH1-4, especially compared to IH1-2 where they are minimal. The configuration IH1-2 requires placing a PMQ in every other DT; in IH1-4 the PMQs are placed only in every fourth DT, which gives a significant cost advantage.

Similar calculations were performed for β_g=0.065. Due to longer periods, the zero-current phase advances are above 90° already for IH1-4. However, there are more options at the high-energy end compared to the low-energy end since the DT lengths are longer. We found that using longer PMQ while simultaneously increasing the PMQ and DT apertures to prevent beam losses gives the best results. The modified IH1-3 structure has long PMQs, L_q=3 cm, with weaker gradient, G=150 T/m, which allows to increase the PMQ inner radius to r_{in}= 6 mm, with the outer radius r_{out}=12 mm. The maximal beam size r_{max}= 3.55 mm is small compared to the 6-mm aperture radius, which is especially important to prevent beam losses at the high-energy end, see [4] for details.

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. 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 – to keep or even increase the high accelerating efficiency of the IH structure.

IH STRUCTURE CHARACTERISTICS

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, small cavity transverse size (4-5 times smaller than DTL), and a relatively homogeneous surface loss distribution compared to DTL (no hot spots), which can simplify cooling. Based on the previous results [2], which found the IH structures with DTs supported by two vanes the most effective in this velocity range, we explore the structure characteristics for β=0.033-0.065 using EM modeling with the CST MicroWave Studio (MWS) [5]. The MWS eigensolver finds the modes in one structure period with periodic boundary conditions at the ends.

Structures with Identical DTs and Narrow Gaps

For the IH structures with vanes and narrow gaps, g/L_c = 0.15, the transit-time factor T slowly increases from 0.9 to 0.96 (red circles in Fig. 2), while the shunt impedance Z_{sh} decreases with β. 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 conductivity $5.8\cdot10^7$ $(\Omega\ m)^{-1}$.

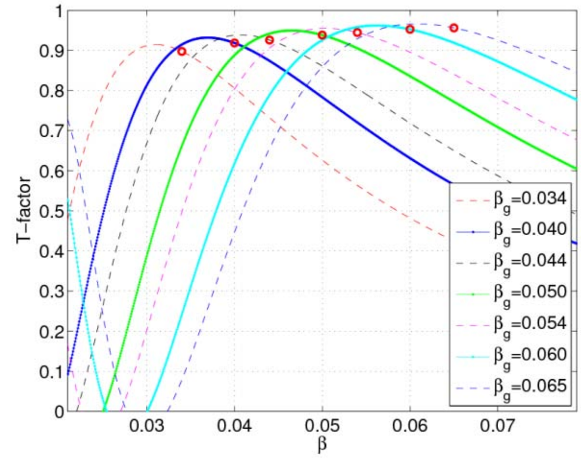

Figure 2: Transit-time factor of different IH structures (defined by β_g) versus beam velocity β.

A few designs of the 1-4 MeV deuteron accelerator based on the regular IH structures with vanes were evaluated [4]. We found only small differences between various designs, from one with gradually increasing cell lengths to the three-step design that includes only cells β_g = 0.04, 0.05, 0.06. In all these cases, the accelerator consists of 19-20 IH periods (38-40 cells) and has the total length 1.45-1.5 m, with the surface-loss power about 25 kW at 100% duty, small compared to the beam power 150 kW at 50 mA CW [4].

One potential concern for the considered IH structures with narrow gaps is that the maximal electric field E_{max} increases with β, exceeding at β_g=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. The surface-loss power per cell P_{loss} and the maximal surface power density $(dP/ds)_{max}$ also increase, see in [4].

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 [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 is shown in Fig. 3. 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 for β_g = 0.04 (Fig. 3); it is above 500 MΩ/m at the high-energy end, β_g = 0.06 [4].

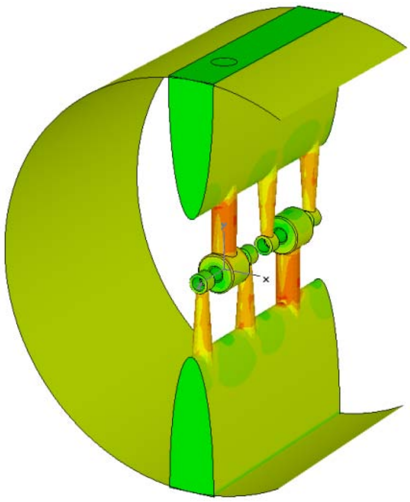

Figure 3: Surface current magnitude in the modified IH1-3 structure (the cavity wall is partially cut).

For wider gaps in IH structures, a noticeable transverse on-axis electric field was observed, the known effect [1]. For its mitigation, asymmetric bulges on DT outer surface were used. The bulges reduce the dipole field but also reduce Z_{sh}, see [4]. We considered an alternative measure – slanted ends of the empty DTs – that compensates 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 should be studied with multi-particle simulations. We plan to perform Parmela 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 due to FE central points located inside the convex metal walls.

Thermal and stress analysis has been performed for the regular IH structures with cooling channels in the vanes. For the nominal 10% duty, the temperature distribution from ANSYS is shown in Fig. 4. Here the water cooling is only in the vanes (2-m/s flow); the maximal temperature (red) is 34.2°C, while the minimal (blue) one is 23.1°C. The outside manifold cooling is not used at 10% duty but can be needed at higher duty factors. This important result – PMQ temperatures can be kept low with the vane cooling – confirms the IH-PMQ RT concept feasibility. The DT vertical displacements for 10% duty are 30 and 40 μm from the support level, which is below the typical manufacturing tolerances.

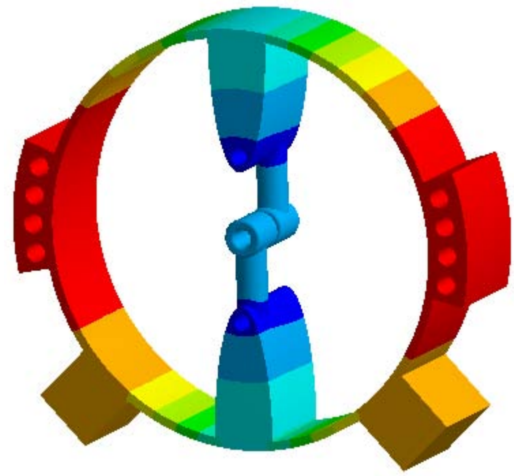

Figure 4: Temperature distribution in regular IH structure.

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 with PMQs 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.

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