COMPACT LINAC FOR DEUTERONS*

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

Abstract

We are developing a compact deuteron-beam accelerator up to the deuteron energy of a few MeV based on room-temperature inter-digital H-mode (IH) accelerating structures with the transverse beam focusing using permanent-magnet quadrupoles (PMQ). Combining electromagnetic 3-D modeling with beam dynamics simulations and thermal-stress analysis, we show that IH-PMQ structures provide very efficient and practical accelerators for light-ion beams of considerable currents at the beam velocities around a few percent of the speed of light. IH-structures with PMQ focusing following a short RFQ can also be beneficial in the front end of ion linacs.

INTRODUCTION

Room-temperature H-mode resonators – inter-digital (IH) or cross-bar (CH) – provide effective acceleration at low beam velocities, β=v/c<0.3-0.4, e.g. [1]. IH structures are especially efficient at very low velocities, β<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 study the IH structures with PMQ beam focusing for a particular application: a compact deuteron-beam accelerator from 1 to 4 MeV, 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. We also assume the RF frequency around 200 MHz. Increasing the frequency to, say, 400 MHz, would make the accelerator even more compact. However, at higher frequencies the IH structure sizes become rather small, and even though using tiny PMQs is not excluded, such structures require additional studies.

PMQ FOCUSING IN IH STRUCTURES

Deuteron kinetic energies from 1 to 4 MeV correspond to the beam velocity range of β=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. Such PMQs can fit into DTs even at the lower end of the IH accelerating structure, with geometrical value β_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,… Beam dynamics calculations were performed with the envelope code TRACE-3D and its GUI version PBO-Lab for β_g= 0.034 and 0.065. All field-dependent results were calculated assuming the average on-axis field E_0=2.5 MV/m; the RF synchronous phase in the gaps was chosen to be -30°. The rms normalized transverse emittance was assumed 0.2π mm·mrad for the 50-mA current that corresponds to 5·0.2/($\beta\gamma$) ≈30π mm·mrad for the un-normalized emittance of the TRACE 3-D equivalent uniform beam at β=0.034.

Within these constrains, it was shown that acceptable beam focusing at the lower energy end can be achieved in the structure IH1-3 (n=2), where a PMQ is inserted in every third DT. Our results for the beam sizes and phase advances per focusing period are summarized in [3]. At the low-energy end, for the case IH1-1 200-T/m quads were too weak to keep the beam size within the chosen aperture of radius 5 mm. The case IH1-5 has to be excluded since its zero-current phase advances $\sigma_{0x/y}$ were above 90°, with the full current advances below 90°, which can make the beam unstable. All configurations IH1-2 to IH1-4 were acceptable, and the differences between them were not very significant; but overall, IH 1-3 provided the smallest beam size. Still the beam size was rather large in all the cases, which can lead to undesirable beam losses. One should note that if multi-particle beam-dynamics simulations indicate significant beam losses with this focusing, we can switch to stronger transverse focusing using PMQ pairing, e.g. FFODDO, etc. Such focusing schemes can make the matched beam size smaller and reduce losses. As one can expect, the transverse beam size variations along the period were larger for IH1-4, while with IH1-2 they were 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 the high energy end, β_g=0.065. Due to longer periods, the zero-current phase advances exceed 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

*This work is supported by DOE NNSA via LANL LDRD program
#kurennoy@lanl.gov

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. Preventing beam losses is especially important at the high-energy end of the deuteron linac.

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. 1), 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 $5.8{\cdot}10^7$ (Ω m)$^{-1}$.

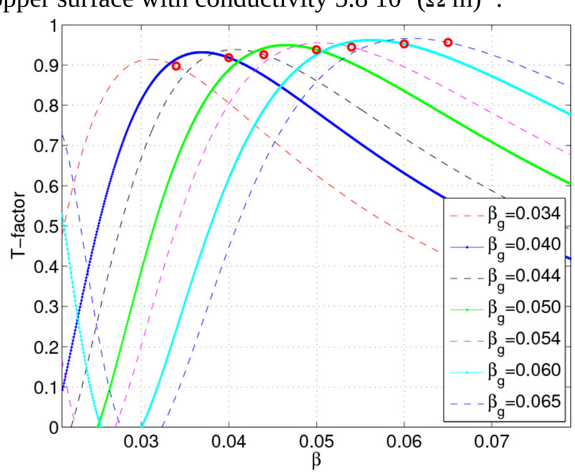

Figure 1: Transit-time factor of different IH structures (defined by β_g) versus beam velocity β.

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, 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. In fact, the RF breakdown level can be even lower due to high magnetic fields near the PMQ surface. 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. 2. 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, and the cavity radius is 149.5 mm. The resulting $Z_{sh}T^2$ is 712 MΩ/m for β_g = 0.04 (Fig. 2); it is still above 500 MΩ/m at the high-energy end, β_g = 0.06 [4].

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.

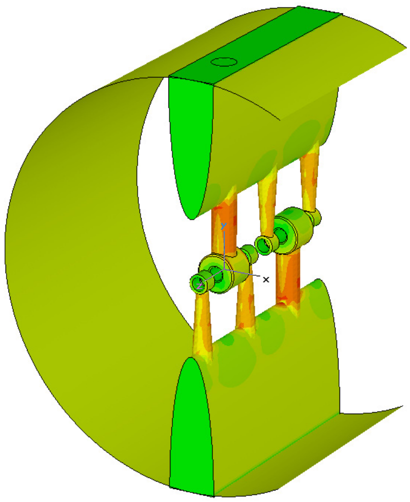

Figure 2: Surface current magnitude in the modified IH1-3 structure (the cavity wall is partially cut).

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 as the next step.

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 convex metal walls. Thermal and stress analysis has been performed for the regular IH structures with cooling channels in the vanes.

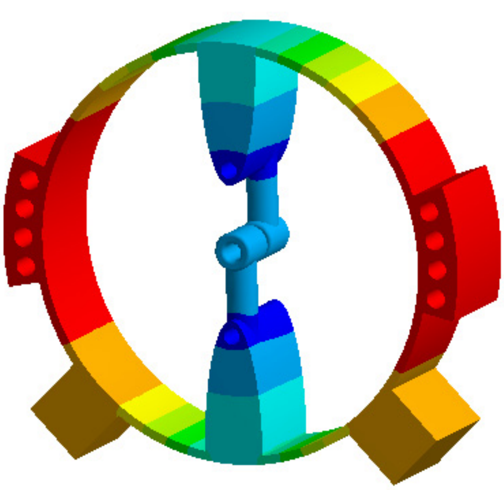

Figure 3: Temperature distribution in regular IH structure.

For the nominal 10% duty, the temperature distribution calculated by ANSYS is shown in Fig. 3. Here the water cooling is only in the vanes (2-m/s flow, 22°C inlet temperature); 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 typical manufacturing tolerances.

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.

A compact 1-4 MeV deuteron linac based on IH-PMQ structure with the accelerating gradient E_0=2.5 MV/m would have the total length 1.45-1.5 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. The transverse size is 3-4 times smaller than for an equivalent DTL, while the wall power loss is more than an order of magnitude lower.

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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REFERENCES

[1] U. Ratzinger, NIM A464 (2001) 636; Proceed. CAS 2000, CERN 2005-003, p. 351 (2005).

[2] S. Kurennoy, L. Rybarcyk, and T. Wangler, “Efficient Accelerating Structures for Low-Energy Light Ions,” PAC’07, Albuquerque, NM, p. 3824 (2007).

[3] S. Kurennoy, S. Konecni, J. O’Hara, & L. Rybarcyk, “IH Accelerating Structures with PMQ Focusing for Low-Energy Light Ions,” EPAC08, Genoa, p. 3428 (2008).

[4] S. Kurennoy, Technical notes AOT-ABS: 07-032, 08-008, 08-017; LA-UR-08-03795, Los Alamos, 2008.

[5] CST MicroWave Studio 2008, http://www.cst.com.

[6] S. Kurennoy, S. Konecni, J. O’Hara, & L. Rybarcyk, “Heating and Stress in the LANSCE Side-Coupled Linac RF Cavities,” EPAC08, Genoa, p. 3431 (2008).