AN H-MODE ACCELERATOR WITH PMQ FOCUSING AS A LANSCE DTL REPLACEMENT

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Abstract

High-efficiency normal-conducting RF accelerating structures based on H-mode cavities with a transverse beam focusing by permanent-magnet quadrupoles (PMQ) have been developed for beam velocities in the range of a few percent of the speed of light [1]. At these low beam velocities, an inter-digital H-mode (IH-PMQ) linac is an order of magnitude more efficient than a standard drift-tube linac (DTL). At the Los Alamos Neutron Science Center (LANSCE), upgrades of the proton linac front end are currently under consideration [2]. In view of these plans, we explore a further option of replacing the aging LANSCE DTL by an efficient H-PMQ accelerator. Here we assume that a 201.25-MHz RFQ-based front end up to 750 keV (4% of the speed of light) is followed first by IH-PMQ structures and then by cross-bar H-mode cavities with PMQ focusing (CH-PMQ). Such an H-PMQ linac would bring proton and H- beams to the energy of 100 MeV and transfer them into the existing side-coupled-cavity linac (CCL). Results of the combined electromagnetic and beam-dynamics modeling of the proposed H-PMQ accelerator are presented.

INTRODUCTION

Normal-conducting RF accelerating structures based on H-mode cavities provide very high shunt impedances at beam velocities v in the range from a few to a few tens of percent of the speed of light c [3]. They are widely used in heavy ion accelerators where low-frequency RF (typically, tens of MHz) is required, mostly due to smaller transverse sizes compared to DTLs. We proposed [4] inserting permanent-magnet quadrupoles (PMQ) inside the small drift tubes (DT) of the H-cavities. This approach provides the transverse beam focusing in H-mode structures without any reduction of their accelerating efficiency. Such H-PMQ structures can be very efficient at low beam velocities [1].

The DTL accelerators achieve their best efficiency for particle velocities approximately from 10% to 35% of the speed of light, i.e. $\beta = v/c = 0.1$-0.35. At the Los Alamos Neutron Science Center (LANSCE), the 201.25-MHz DTL covers a wider velocity range, from $\beta = 0.04$ to 0.43 (proton energies 750 keV to 100 MeV), with a decreasing efficiency at the both ends. The beam is further accelerated to 800 MeV in the 805-MHz coupled-cavity linac (CCL). The venerable LANSCE DTL has been in service for ~40 years. In view of recent plans to upgrade the linac front end [2], we explore a potential option of replacing the aging DTL (or some parts of it) by more efficient H-PMQ accelerating structures.

The IH structures are most efficient at β = 0.03-0.1, while for CH the best range is roughly 0.1-0.4 [3, 1]. The effective shunt impedance $Z_{\mathrm{eff}} = ZT^2$ of both decreases as β increases but still remains higher, from an order of magnitude to a few times, than in a typical DTL.

The structure efficiency is only one of many important characteristics. Being a part of a linac, the structure must provide good beam quality to ensure further acceleration without unacceptable beam losses. Proper balance of efficiency and beam quality depends on a particular application. For a compact mobile deuteron linac up to 4 MeV [1], the efficiency was most important since the 4-MeV beam is dumped on a target with little regard for quality. For a DTL replacement, in view of further acceleration, the beam quality becomes more important.

H-PMQ LINAC AS DTL REPLACEMENT

We base our study on a few simple principles. First, the longitudinal and transverse focusing strengths should be smooth along the linac. The DTL parameters in Tab. 1 serve as a good first approximation; the design can be further optimized based on beam dynamics results. Second, the H-PMQ accelerating gradients are chosen close to those in Tab. 1, to keep the DTL length about the same. Finally, the beam quality is more important than the structure efficiency; the latter still should be higher than for the existing DTL. The LANSCE DTL consists of four DTL tanks as listed in Tab. 1.

Table 1: LANSCE DTL parameters [5]

Parameter	**Tank1**	**Tank2**	**Tank3**	**Tank4**
Energy in, W_{in}, MeV	0.75	5.39	41.33	72.72
β, in(-out)	0.04	0.107	0.287	.37-.43
Length L, m	3.26	19.688	18.75	17.92
Aperture r_b, cm	0.75	1-1.5	1.5	1.5
Gradient E_0, MV/m	1.6-2.3	2.4	2.4	2.5
Quad $B'\cdot L_q$, T	2.2-1.9	1.9-1.4	1.5-1.4	≈1.4
Power, P_w, MW	0.31	2.70	2.75	2.67
T-factors	.72-.84	.87-.80	.82-.74	.74-.70
Average ZT^2, MΩ/m	26.8	30.1	23.7	19.2

From the velocity ranges for the individual DTL tanks, a reasonable choice is to replace Tank 1 with IH-PMQ structures, and Tanks 2-4 with CH-PMQ.

IH-PMQ Linac in place of Tank 1

Ideally one should use a single long IH tank instead of DTL tank 1 because additional tank end cells and walls reduce efficiency. However, for long H-tanks the second longitudinal mode TE_{m11}, where $m = 1$ (dipole) for IH and 2 (quadrupole) for CH, can come close in frequency to the working mode $TE_{m1(0)}$. So, it may be more practical to consider two shorter IH tanks. One starts from 0.75 MeV, $\beta = 0.04$, as in the deuteron linac of Ref. [1], except for another velocity profile for protons; the other can continue from 2.5 MeV ($\beta = 0.073$).

The layout of the first IH tank is illustrated in Fig. 1 from CST MicroWave Studio (MWS) [6]; it shows only the IH drift tubes (DTs), supporting stems, and vanes. The vane undercuts near the cavity end walls allow for the magnetic-flux return. The cut dimensions are adjusted to reduce the electric field drop near the tank ends. This tank contains 10 IH "periods," each consisting of two cells. The number of full DTs is 20, and two more half-DTs are located on the end walls. The structure is similar to that developed for deuterons in [1] but the DT sizes are adjusted for protons: DT lengths are from 2.1 to 4.4 cm; DT outer radius is 1.8 cm, see also Tab. 2. The cavity inner radius is 11.4 cm (cf. 47 cm for DTL tank 1).

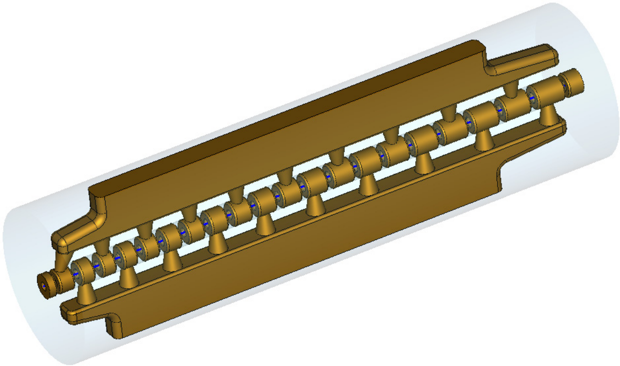

Figure 1: MWS model of IH tank 1. The resonator outer wall is removed; cavity inner volume is in light-blue.

The frequency of the 2nd mode is 16 MHz above 201.25 MHz. The calculated EM parameters are listed in Tab. 2. The Kilpatrick field E_K = 14.8 MV/m at 201.25 MHz [5].

Table 2: IH tanks EM parameters for E_0 = 2.5 MV/m

Parameter (* = 100% duty)	**IH tank 1**	**IH tank 2**
W_{in}, MeV (β_{in})	0.75 (0.04)	2.5 (0.073)
Quality factor Q	9815	12603
Tank length L, m	0.847	1.525
Beam aperture r_b, cm	0.75	0.75
Wall (Cu) RF power, P_w, kW*	34.6	72.8
Electric field E_{max}, MV/m (E_K)	26.2 (1.77)	24.5 (1.65)
T-factors	0.86-0.93	0.93-0.96
Shunt impedance ZT^2, MΩ/m	247.4	231.4

Table 2 also presents parameters of the IH tank 2, which is shown in Fig. 2. Here the cavity is longer, and its radius is 14.4 cm. Two insets show the tank transverse (top) and longitudinal cross sections (without outer wall). The tank contains 22 full DTs with lengths from 4.2 to 6.8 cm. The second mode is ~7 MHz above the working one.

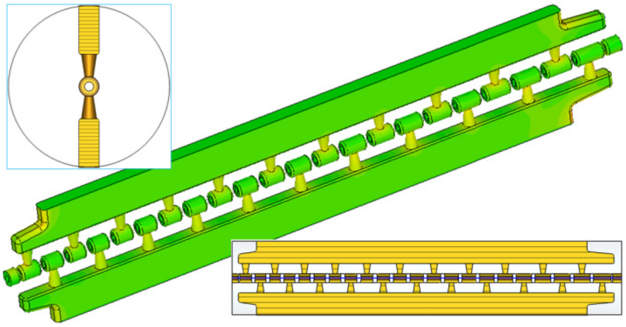

Figure 2: Surface-current magnitude distribution inside the IH tank 2 from 2.5 MeV (red – higher, green – lower).

It is important to notice the power loss distribution inside the IH tanks: in IH T1, 8% is deposited on DTs, 12% on stems, 33% on vanes, and 47% on the outer wall (not shown). For IH T2, the break-down is similar: 8, 16, 28, and 48%, respectively. This means that water cooling using cooling channels in vanes only, as was analyzed in [1], will be sufficient. The LANSCE DTL duty factor is usually below 10% though it may be higher, 15-20%, for future high-power operation. As expected, the effective shunt impedances are significantly higher than in Tab. 1.

One can estimate that even in IH T1, where the DTs are shortest and the transverse focusing needs to be the strongest, the PMQ integral strengths $B'L_q$ = 1.5-2 T are readily achievable with L_q = 1.8 cm. Since the IH period $\beta\lambda$ contains two DTs (in DTL only one), we can have up to 3-4 T per period with FFDD lattice and a PMQ in each DT [1]. This is more than in the LANSCE DTL, cf. Tab. 1; however, the required focusing will be determined by beam dynamics simulations.

The field profile along the tank is tuned to keep the cell gradients nearly constant by adjusting the gap widths between DTs. The end gaps are made shorter to bring up the fields near the tank ends [1]. The gap lengths g are relatively short in both IH tanks: the ratio g/L_c = 0.18-0.33 in IH T1 and 0.17-0.27 in T2, except for the end gaps. Here $L_c = \beta\lambda/2$ is the IH cell length (DT + gap). Having short gaps reduces the vertical E-field component on the beam axis, a known property of IH structures [3].

Using a CH structure instead of IH tank 2 from 2.5 MeV completely eliminates this problem. However, the efficiency is reduced: ZT^2 = 158 MΩ/m for CH with the same DT layout as in Fig. 2, and the wall power is 103 kW. The CH cavity is also larger transversely, r_{cav} = 22.9 cm. One the other hand, the power loss distribution in CH is better: only 2% is deposited on DTs, 13% on stems, 42% on vanes, and 43% on the outer wall.

CH-PMQ Linac in place of Tanks 2-4

From all CH structures required to replace the DTL tanks 2-4, we select only two: one from 5.4 MeV (beginning of tank 2) and the other from 20 MeV (its middle). The first CH tank is shown in Fig. 3. It contains 22 full DTs with lengths from 6.4 to 7.75 cm; the DT outer radius is 2 cm. The ratio g/L_c = 0.17-0.21.The cavity inner radius is 24.15 cm (cf. 45 cm for DTL tank 2).

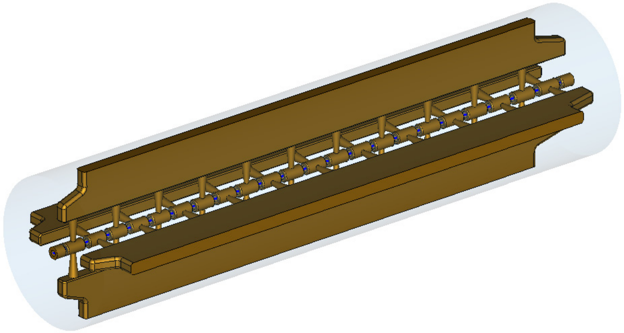

Figure 3: MWS model of CH tank from 5.4 MeV.

The frequency of the second mode is 5.8 MHz above 201.25 MHz. The calculated EM parameters are in Tab. 3.

Table 3: CH tanks EM parameters for $E_0 = 2.5$ MV/m

Parameter (*=100% duty)	CH 5.4 MeV	CH 20 MeV
β_{in}	0.107	0.204
Quality factor Q	15847	20902
Tank length L, m	2.019	4.492
Beam aperture r_b, cm	1.0	1.25
Wall power, P_w, kW*	178.2	763.1
E_{max}, MV/m (E_K)	24.3 (1.64)	22.3 (1.51)
T-factors	0.94-0.97	0.94-0.98
ZT^2, MΩ/m	129.1	66.8

Table 3 also gives the parameters of the CH tank from 20 MeV illustrated in Fig. 4. Two insets show the tank transverse (top) and longitudinal cross sections. The 4.5-m long cavity contains 26 full DTs, from 11 to 13.8-cm long; the DT outer radius is 2.75 cm; the cavity radius is 28.85 cm. The ratio g/L_c ranges from 0.22 to 0.3. The stems are extended longitudinally (cut in the transverse plane and then stretched by 5 cm) to prevent the magnetic field from leaking between them. For such a long cavity, the second mode is only 1.7 MHz above the working one. Even at 20 MeV, the CH shunt impedance is still more than twice that of the LANSCE DTL.

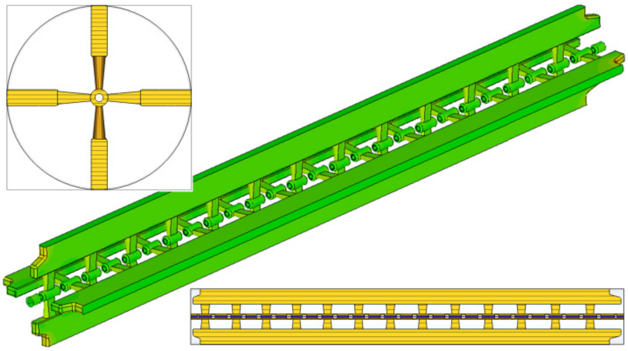

Figure 4: Surface-current magnitude distribution inside the 4.5-m long CH tank from 20 MeV.

The power loss distribution inside the CH tanks is as follows: in CH 5.4, 3% is deposited on DTs, 16% on stems, 39% on vanes, and 42% on the outer wall. For CH 20, the break-down is 1, 12, 37, and 50%, respectively.

For the CH structures near the DTL final energy of 100 MeV, where DTs are long (>20 cm), we consider tanks with smaller numbers of DTs than in Fig. 4, to restrict the tank length. This will keep the higher mode frequencies far enough from the working mode to simplify tuning.

Beam Dynamics Considerations

Preliminary multi-particle beam dynamics simulations with beam parameters typical for the LANSCE DTL do not indicate any problems. However, more detailed simulations with full 3D fields for the whole linac are necessary to evaluate the beam quality. The error studies must follow to estimate the mechanical tolerances.

For the first IH tank, from 0.75 MeV, we used the phase ramp from -45° to -30° to improve the beam capture. For other tanks, both IH and CH, the phase of -30° was used, except the end cells. In the end cells, where the gradients are somewhat lower, the phases are set lower to minimize the focusing changes. The phases are adjusted by changing the gap longitudinal positions [1].

CONCLUSIONS

An option of replacing the aging LANSCE DTL by an efficient proton H-PMQ accelerator has been explored. We assumed 201.25-MHz IH-PMQ structures from 750 keV followed by 201.25-MHz CH-PMQ structures from 5.4 to 100 MeV. Of course, there are other attractive options that are not discussed here, for example, a completely new 402.5-MHz front end followed by a DTL with PMQ focusing like those implemented in the SNS.

IH- and CH-mode 201.25-MHz structures with PMQ focusing have been modeled using the CST MicroWave Studio. As expected, the efficiency of the H-mode linac is significantly higher than that of the existing LANSCE DTL. Beam dynamics results do not indicate any show stoppers. Overall, an H-PMQ linac can be a feasible and efficient replacement for the LANSCE DTL.

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