Efficient Accelerating Structures for Low-Energy Light Ions

Sergey Kurennoy, Lawrence Rybarcyk, and Thomas Wangler

LANL, Los Alamos, NM, USA

Thanks to D. Barlow, F. Neri, and J. O'Hara

Room-temperature RF accelerating structures for the beam velocities in the range of a few percent of the speed of light – including H-mode cavities and drift-tube linacs – are considered and compared with respect to their efficiency, compactness, ease of fabrication, and overall cost. Options for the beam transverse focusing in such structures are discussed.

Applications include a compact, mobile deuteron-beam accelerator up to the energy of a few MeV for homeland defense.

Los Alamos NATIONAL LABORATORY

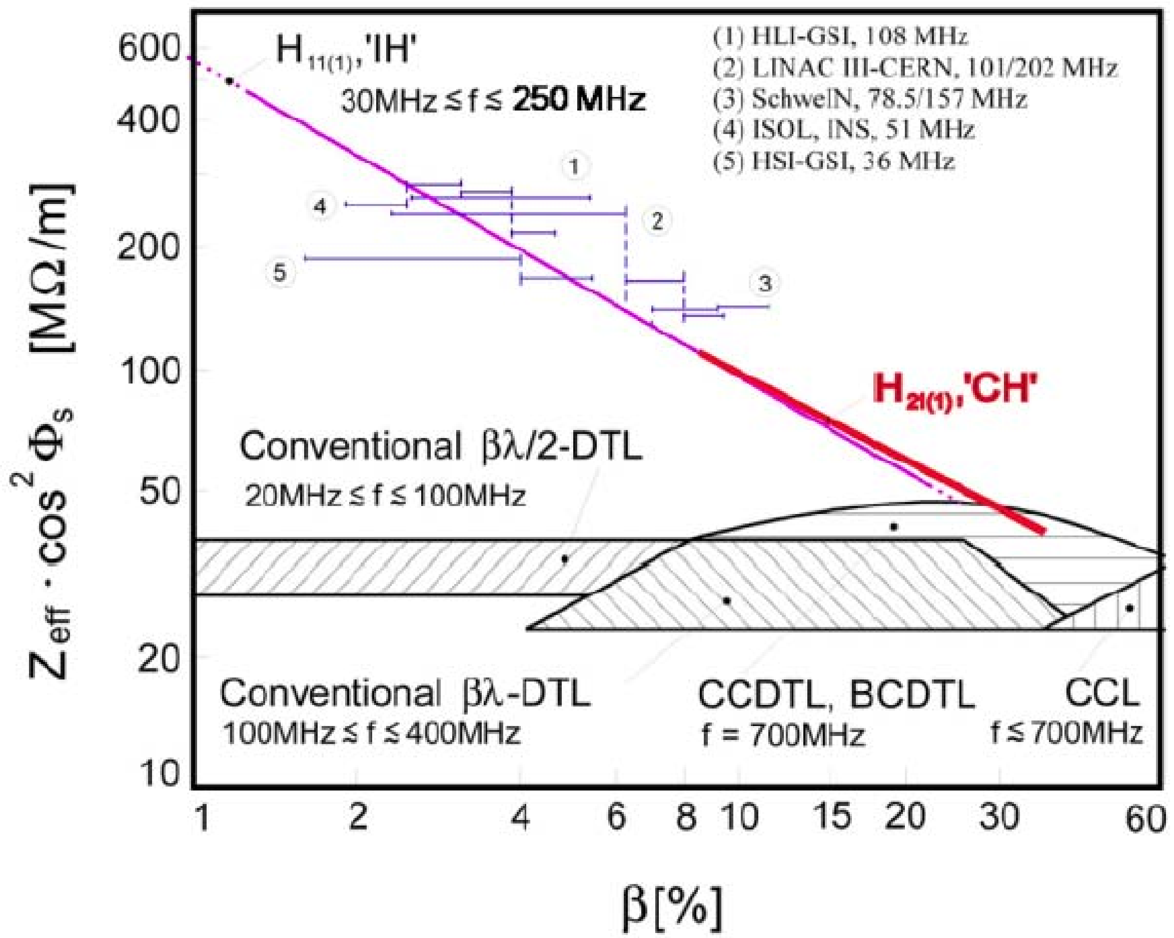
Introduction

- Applications in homeland defense would benefit from deuteron beams of energy 4 MeV with the peak current of 50 mA and duty factor of 10%.
  - Can be done with a 4-MeV RFQ.
  - However, the higher energy part of the RFQ ($\beta \geq 0.03$) is not a very efficient accelerator.
- Alternative accelerating structures for 1 to 4 MeV ($0.034 \leq \beta \leq 0.065$):
  1. IH (Interdigital H-resonator) structure operating in the $TE_{11(0)}$ (dipole) mode.
  2. CH (Cross-bar H-resonator) structure operating in the $TE_{21(0)}$ (quadrupole) mode, same as RFQ. ⟺ Multi-spoke cavities.
  3. DTL (Drift-Tube Linac) – the classical structure for low-energy proton acceleration in TM_{010} (monopole) mode.
  4. Quarter-wave ($\lambda/4$) or half-wave ($\lambda/2$) resonators, independently fed and phased, as used in low-energy superconducting heavy-ion accelerators.

Restrictions:

- Room-temperature structures only (mobile applications).
- Velocity range $0.034 \leq \beta \leq 0.065$ (lower limit - trade-off).
- Frequency ~200 MHz.

Structure comparison



Reference:
H. Podlech,
LINAC04, p.28

Fig.1: Effective shunt impedance of low-energy accelerating structures versus *β*.
The blue horizontal bars represent the existing IH-structures.

Structure comparison

Typical parameters of low-energy accelerating structures.

Structure	"Best" β	f, MHz	ZT^2, MΩ/m	T-factor	Mode
RFQ	$0.005 \leq \beta \leq 0.03$	4-rod: $10 \leq f \leq 200$ 4-vane: $100 \leq f \leq 425$	$\approx$ 1-3†; $\sim \beta^{-2}$	NA	$TE_{21(0)}$
IH	$0.01 \leq \beta \leq 0.10$	$30 \leq f \leq 250$	$300 \rightarrow 150$	≥ 0.85	$TE_{11(0)}$
CH	$0.10 \leq \beta \leq 0.40$	$150 \leq f \leq 800$	$150 \rightarrow 80$	≥ 0.80	$TE_{21(0)}$
DTL	best $0.1 \leq \beta \leq 0.4$ (use $.04 \leq \beta \leq .43$)	$\beta\lambda/2$: $20 \leq f \leq 10$ $\beta\lambda$: $100 \leq f \leq 500$	25 – 50 (26.8 in T1*)	≤ 0.85 .72-.84 T1*	TM_{010}
$\lambda/4$	$\beta \leq 0.15$	$f \leq 160$	15-20	up to 0.95	Coax. $\lambda/4$

† Estimated average value of Z for SNS RFQ is 2.6 MΩ/m; Z decreases as β^{-2} along the RFQ length.
* T1 = LANSCE 201.25-MHz DTL tank 1, proton energy 0.75-5.39 MeV (T. Wangler, *RF Linacs*, p.99).

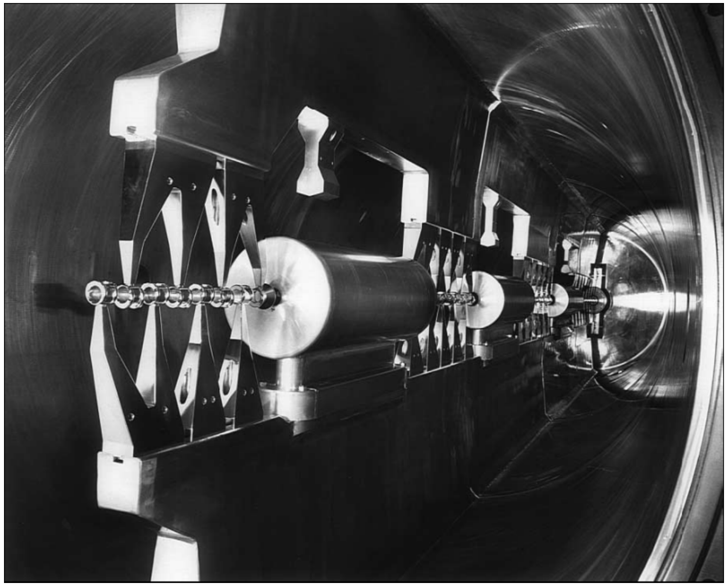
► $\lambda/4$ resonators are good in SC but not competitive with IH/CH at RT (high wall losses).

DTL and especially H-mode accelerating structures are much more efficient than RFQ for β = 0.03-0.1, but, unlike the RFQ, they do not provide the beam focusing. If transverse focusing in H-structures can be achieved without significant reduction of Z_{eff}, they would be the best choice.

Transverse focusing options for H- & DTL-cavities

1. Magnetic quads inside DT, like in DTL, either EM or PMQ. Pro – established. Cons – not efficient at low β; can be difficult for small DTs. Increasing DT reduces Z_{eff}.
2. Split tanks – implement focusing between tanks. Pro – flexible scheme. Cons – reduces Z_{eff}, requires RF power distribution, matching, increases length.
3. Insert quad triplets inside the tank, as done at GSI and CERN. Pro – established. Con – significantly reduces Z_{eff} by increasing the cavity length.
4. Provide transverse electric quadrupole focusing inside the tank. For CH – e.g., 4-vane insertions. For IH and DTL – split electrodes with fingers (V. Teplyakov; D. Swenson: RFID, RFD). Pro – efficient focusing at low β. Con – R&D needed, decreases Z_{eff}.
5. Alternative-phase focusing (APF). Pro – keeps Z_{eff}, cons – low current limit, small longitudinal acceptance.

Fig. 2: GSI IH-cavity with quad triplets (3).
Reference: U. Ratzinger, *NIM* A464 (2001) 636.



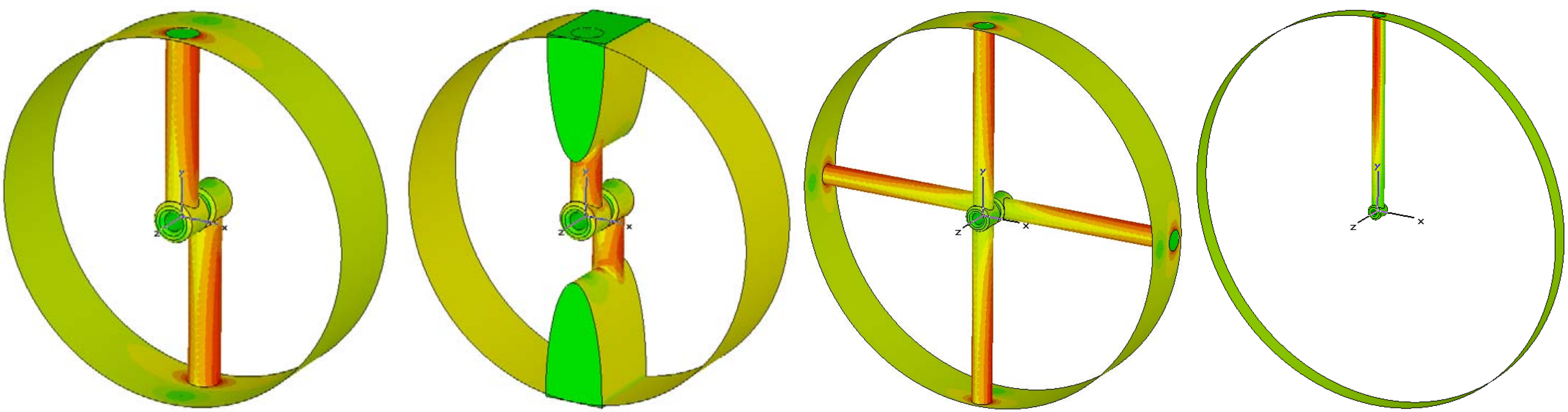
We propose to use PMQ inside the small DT in H-structures to preserve their high accelerating efficiency.

MWS modeling of H- and DTL cavities – 1

Structure comparison at β = 0.034 (r_a = 0.5 cm). E_0 = 2.5 MV/m, f = 201.25 MHz

Structure	L, cm	R, cm	Z_{sh}, MΩ/m	T	$Z_{sh}T^2$, MΩ/m	E_{max}, MV/m	$(dP/ds)_{max}$, W/cm^2	P_{loss}, kW	E_0TL, kV
IH	5.04	9.9	363.8	0.899	294.2	26.7	7.30	0.87	113.4
IH with vanes	5.04	10.4	426.9	0.901	346.2	27.0	5.88	0.74	113.4
CH	5.04	16.4	280.6	0.899	226.7	25.4	4.60	1.13	113.4
DTL	5.04	55	32.3	0.816	21.5	21.1*	31.1*	9.74	102

* no optimization (values can be improved by changing the DT transverse dimensions and shape)



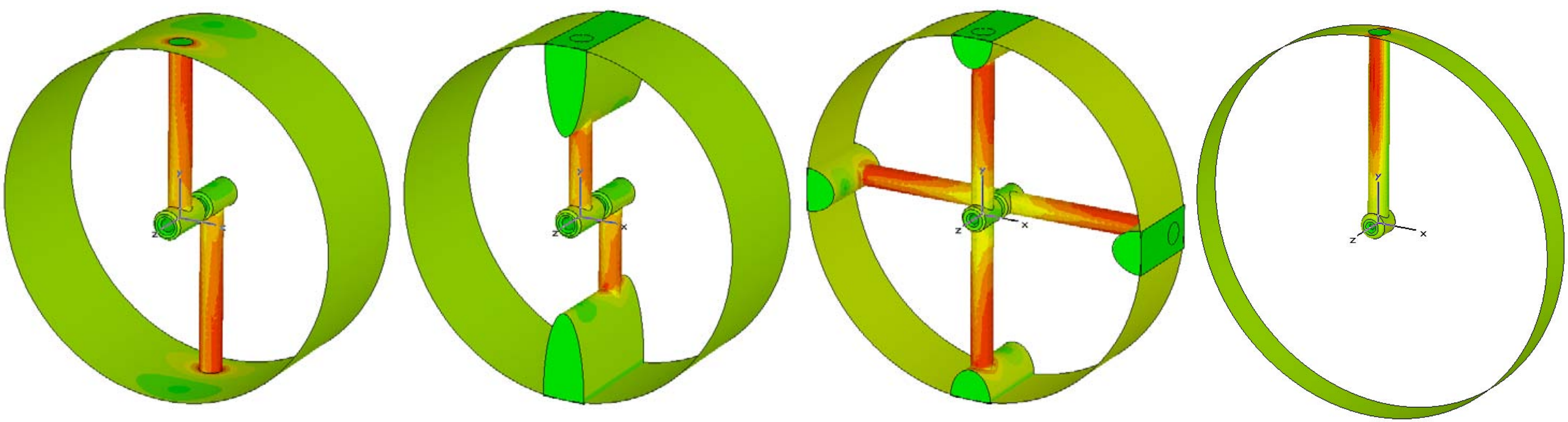
IH — IH with vanes — CH — DTL

MWS modeling of H- and DTL cavities – 2

Structure comparison at β = 0.065 (no optimization). E_0 = 2.5 MV/m, f = 201.25 MHz

Structure	L, cm	R, cm	Z_{sh}, MΩ/m	T	$Z_{sh}T^2$, MΩ/m	E_{max}, MV/m	$(dP/ds)_{max}$, W/cm^2	P_{loss}, kW	E_0TL, kV
IH	4.82	13.4	236.7	0.958	217.1	31.6	17.6	1.27	230.8
IH with vanes	4.82	14.0	294.6	0.956	269.3	31.5	17.7	1.02	115.2
CH with vanes	4.82	20.0	146.0	0.957	133.6	27.3	8.2	2.05	115.3
DTL*	9.64	52.9	45.0	0.867	33.8	20.9	18.8	13.4	209

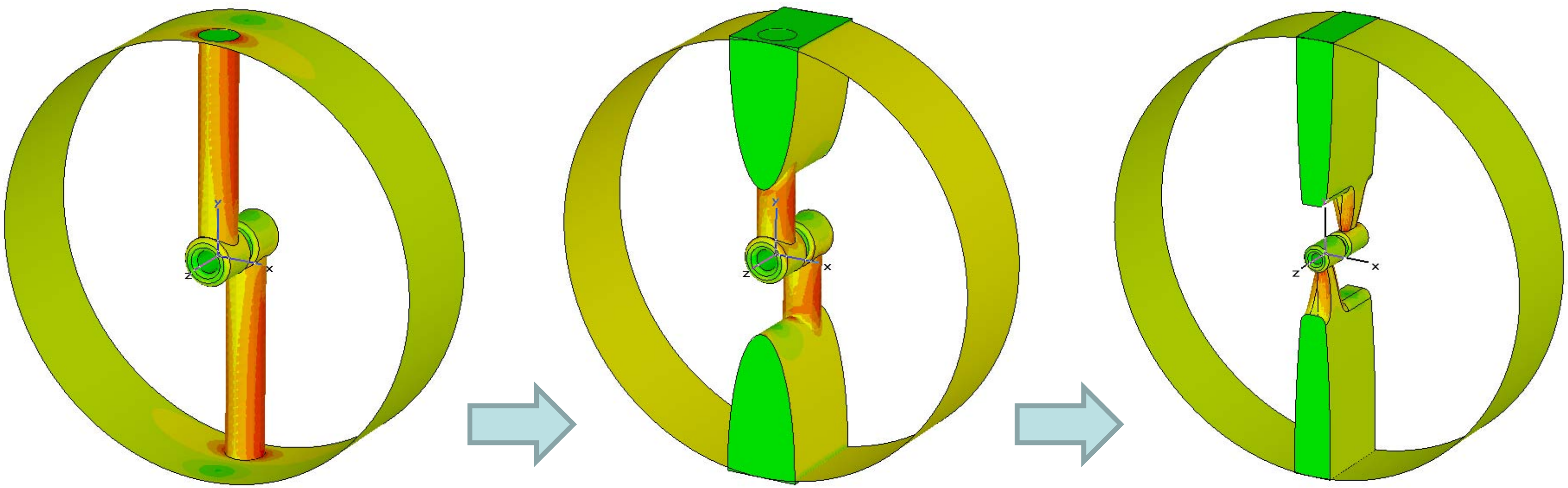
* The aperture radius here is 0.75 cm; the DT dimensions are adjusted to reduce max power density



IH — IH with vanes — CH with small vanes — DTL

MWS modeling - optimizing H-cavities

At $\beta = 0.034$



IH — IH with vanes — IH with mod vanes, small DT diameter

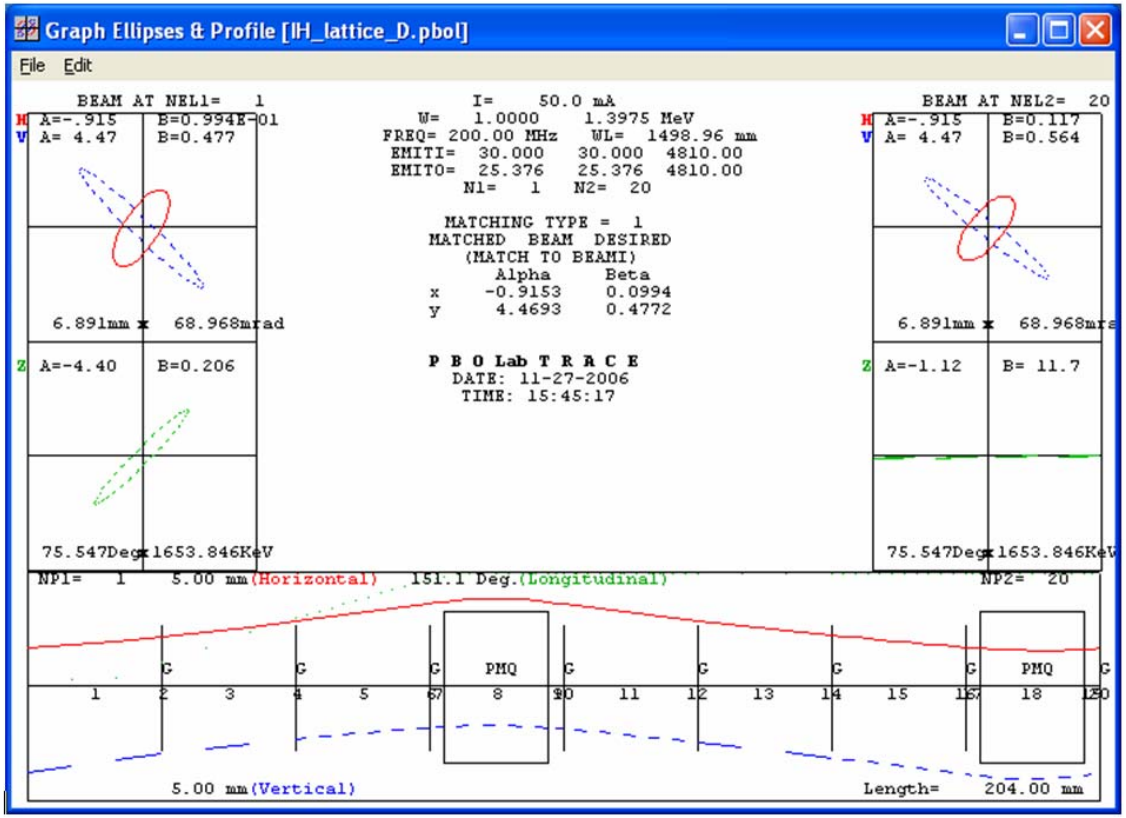
ZT^2 = 294.2 MΩ/m

ZT^2 = 346.2 MΩ/m (+)

ZT^2 = 745.8 MΩ/m (!)

Beam dynamics (preliminary)

TRACE 3-D run (Tom Wangler). Parameters: I = 50 mA, β = 0.034;
PMQ in every 3rd DT (B'=200 T/m, L_q=2 cm); rms ε = 0.2 π mm·mrad.



Phase advance per period x: σ=57°, σ_0=77°; y: σ=54°, σ_0=76°

Such PMQs are feasible!
(Courtesy of Dave Barlow)

N:	2	**1 for dipole or 2 for quad**
ID:	10.00	**mm**
OD:	22.00	**mm**
L:	20.00	**mm**
Br:	1.000	**T**
N-Sgments:	16	**8, 16, 24, ...**
Cn:	0.94	
GL:	**4.0905**	**T-m for Dipoles, T for Quads**
G:	204.52491	T/m for Quads

Reference: K. Halbach, "Physical and optical properties of rare earth colbalt magnets", Nuclear Instruments and Methods, Vol. 187 p 109, (1981).

xyz-matching between RFQ-H and H-DTL is easy
(Fillippo Neri)

IH Deuteron Accelerator 1 to 4 MeV: Estimates.

The total number of IH cells ≤ 40 (20 periods). For example,
16 cells in the low-energy range (β = 0.034), 12 in the medium range, and 10 at the high-energy (β = 0.065).

The cavity active length is below 1.3 m (E_0 = 2.5 MV/m).

Required RF power (201.25 MHz):

CW: ≤ 35 kW cavity loss + (50 mA · 3 MV = 150 kW) in the beam;
at 10% duty: ≤ 4 kW cavity + 15 kW beam ≤ 19 kW average.
⟹ gives IOT option for RF

+ Transverse beam focusing with PMQs inside DTs is feasible.
If PMQs are needed only in 1 out of 3 DTs, the structure effective shunt impedance can be increased even further by making empty DTs smaller.

Cooling with water channels inside vanes (not in DTs!) --
a simple and attractive scheme.

⇨ Compact and efficient RT deuteron accelerator

Low-β RT Accelerating Structures: Summary

- H-mode room-temperature accelerator structures are very efficient at the beam velocities from 0.03c to 0.065c.
- They provide an attractive (compact, efficient) alternative to the RFQ deuteron accelerator from 1 to 4 MeV.
- IH-structures with vanes are the most efficient. They are easy to fabricate and easy to cool.
- Total RF power requirements for an IH-cavity based 50-mA deuteron accelerator from 1 to 4 MeV are below 200 kW peak and 20 kW average.
- Preliminary beam dynamics simulations show that the beam transverse focusing with PMQ is feasible.
- Trade-off study of the whole accelerator configuration (e.g., 1-MeV RFQ + 1-4 MeV IH versus 0.75-MeV RFQ + 0.75-4 MeV IH) is needed to make an optimal choice.
- H-mode structures can be useful for the LANSCE linac upgrade: replace the aging DTL front-end.

Conclusions

The room-temperature RF accelerating structures based on H-mode resonators with the PMQ transverse beam focusing – which would follow a short, low-energy RFQ – appear to be an effective and feasible option for the beam velocities in the range of a few percent of the speed of light.

They compare favorably to the usual DTL and RFQ structures with respect to their efficiency, compactness, ease of fabrication, and, likely, overall cost.

Future plans: more detailed studies of the room-temperature H-mode structures with PMQ focusing to achieve a balance of the structure efficiency, beam quality, and thermal management. It will require multiple iterations of electromagnetic modeling, beam dynamics, and engineering thermal-stress analysis (LDRD proposal).