Compact Linac for Deuterons
(Based on IH Structures with PMQ Focusing)

S. Kurennoy, J. O'Hara, L. Rybarcyk

LANL, Los Alamos, NM

Thanks to D. Barlow, F. Neri, and T. Wangler

We are developing a compact deuteron-beam accelerator up to the 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.

Supported by LANL LDRD program

Los Alamos
NATIONAL LABORATORY

HB 2008, August 27, 2008

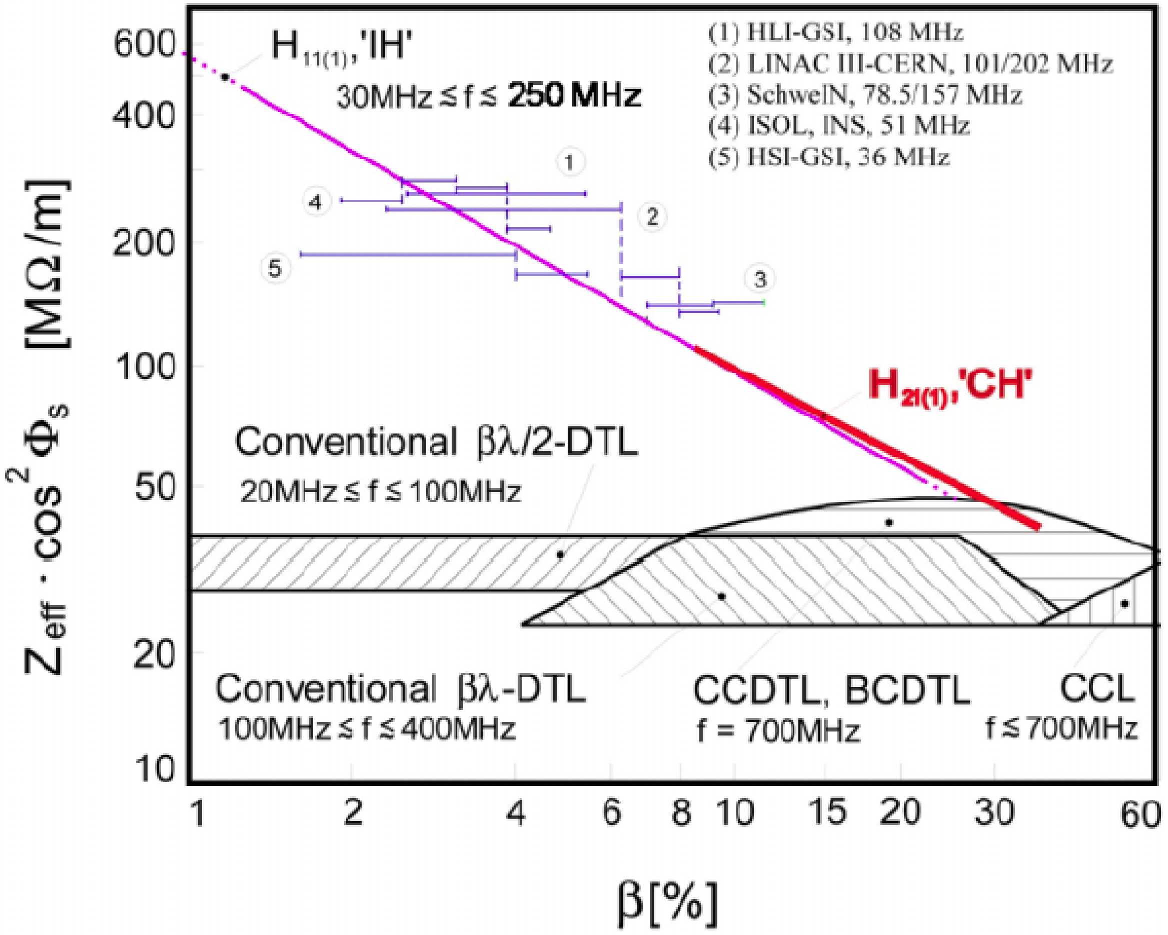
Introduction

- 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.
  - The higher energy part of the RFQ ($\beta \geq 0.03$) is not an efficient accelerator.
- Alternative accelerating structures for 1 to 4 MeV ($0.033 \leq \beta \leq 0.065$):
  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 $0.033 \leq \beta \leq 0.065$ (lower limit - trade-off).
- Frequency ~200 MHz.

Structure comparison



Reference:
H. Podlech,
LINAC04, p.28;
U. Ratzinger,
CAS 2000

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	$0.005 \le \beta \le 0.03$	4-rod: $10 \le f \le 200$ 4-vane: $100 \le f \le 425$	$\approx$ 1-3[†]; ~ β^{-2}	NA	$TE_{21(0)}$
IH	$0.01 \le \beta \le 0.10$	$30 \le f \le 250$	300 → 150	≥ 0.85	$TE_{11(0)}$
CH	$0.10 \le \beta \le 0.40$	$150 \le f \le 800$	150 → 80	≥ 0.80	$TE_{21(0)}$
DTL	best $0.1 \le \beta \le 0.4$ (use $.04 \le \beta \le .43$)	$\beta\lambda/2$: $20 \le f \le 10$ $\beta\lambda$: $100 \le f \le 500$	25 – 50 (26.8 in T1[*])	≤ 0.85 .72-.84 T1[*]	TM_{010}
$\lambda/4$	$\beta \le 0.15$	$f \le 160$	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).

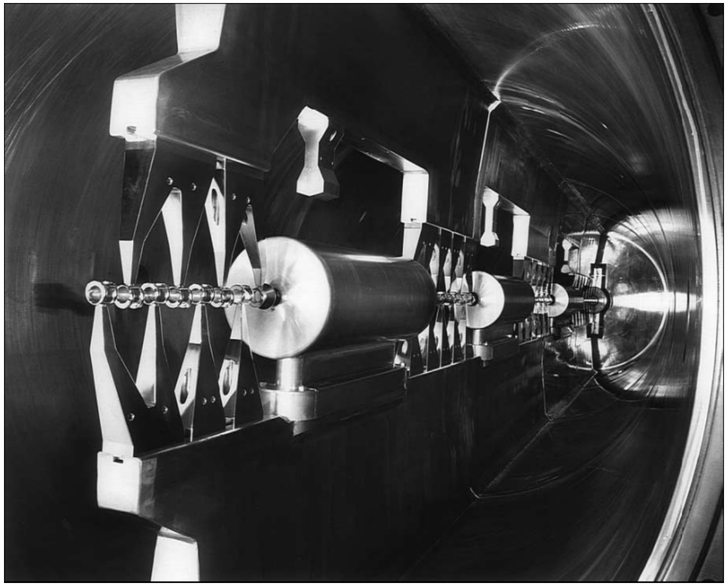
- $\lambda/4$ resonators are good in SC but not competitive with IH/CH at RT (high wall losses).

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 very 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. Pro – established. Con – reduces Z_{eff} due to the increased 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 – Z_{eff} is only slightly reduced, cons – low current limit, small longitudinal acceptance.

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



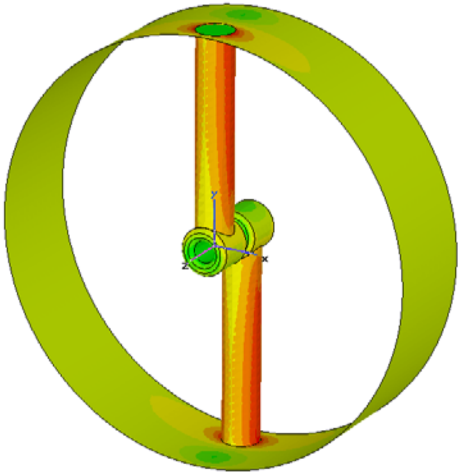
We propose to use PMQ inside the small DT in H-structures to preserve their high accelerating efficiency.

MWS modeling of H- and DTL cavities – 1

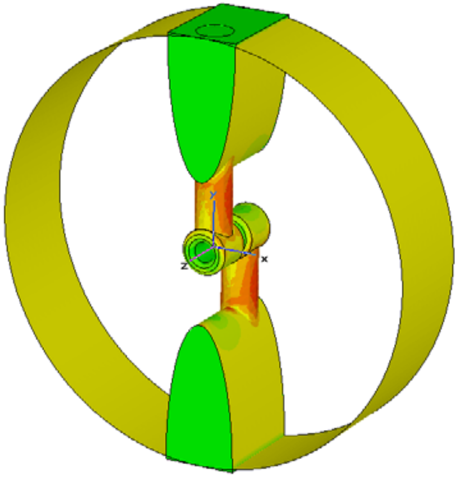
Structure comparison at $\beta = 0.034$ ($r_a = 0.5$ cm). $E_0 = 2.5$ MV/m, $f = 201.25$ MHz

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

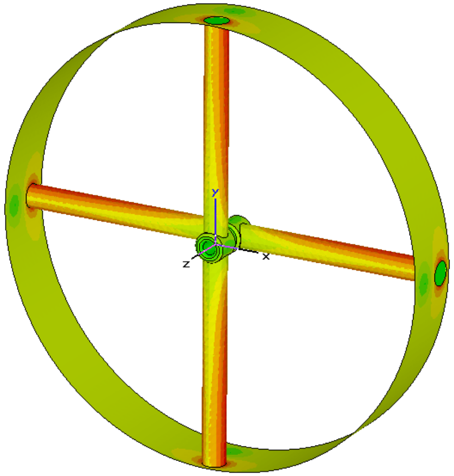
* no optimization (values can be improved by changing the DT transverse dimensions and shape)



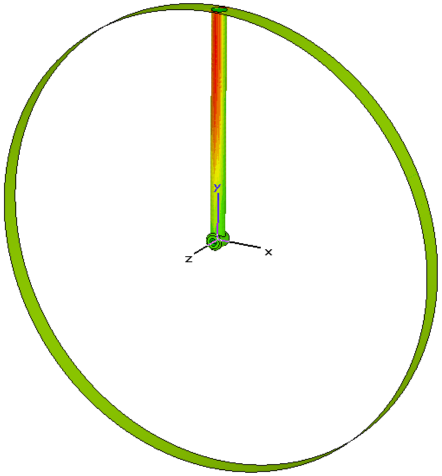
IH



IH with vanes



CH



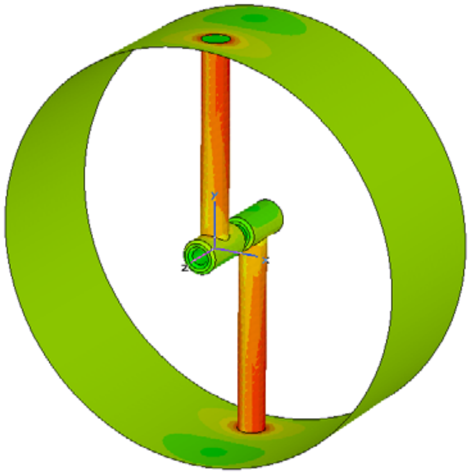
DTL

MWS modeling of H- and DTL cavities – 2

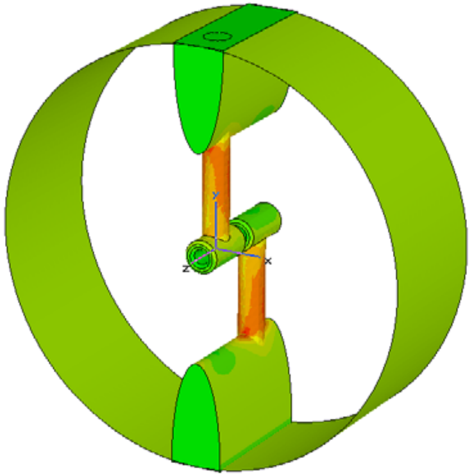
Structure comparison at $\beta = 0.065$ (no optimization). $E_0 = 2.5$ MV/m, $f = 201.25$ MHz

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	9.64	13.4	236.7	0.958	217.1	31.6	17.6	1.27	230.8
IH with vanes	9.64	14.0	294.6	0.956	269.3	31.5	17.7	1.02	230.4
CH with vanes	9.64	20.0	146.0	0.957	133.6	27.3	8.2	2.05	230.6
DTL*	9.64	52.9	45.0	0.867	33.8	20.9	18.8	13.4	209

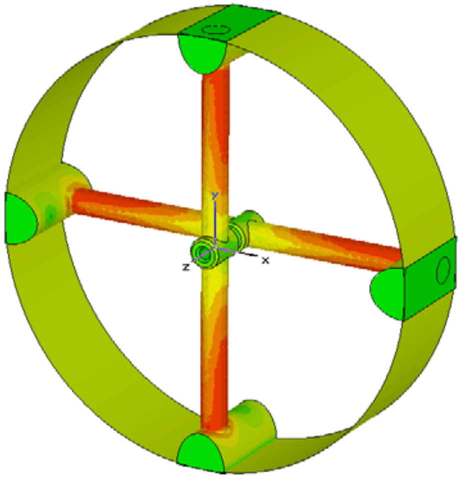
* The aperture radius here is 0.75 cm; the DT dimensions are adjusted to reduce max power density



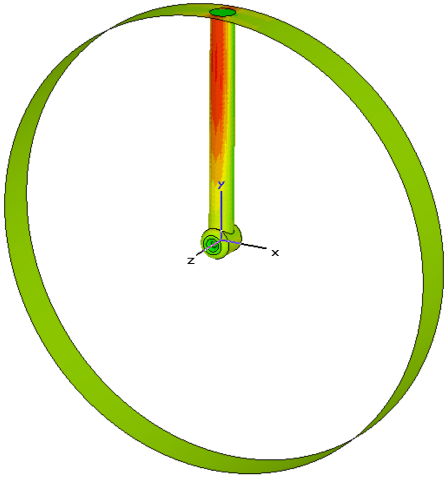
IH



IH with vanes



CH with small vanes

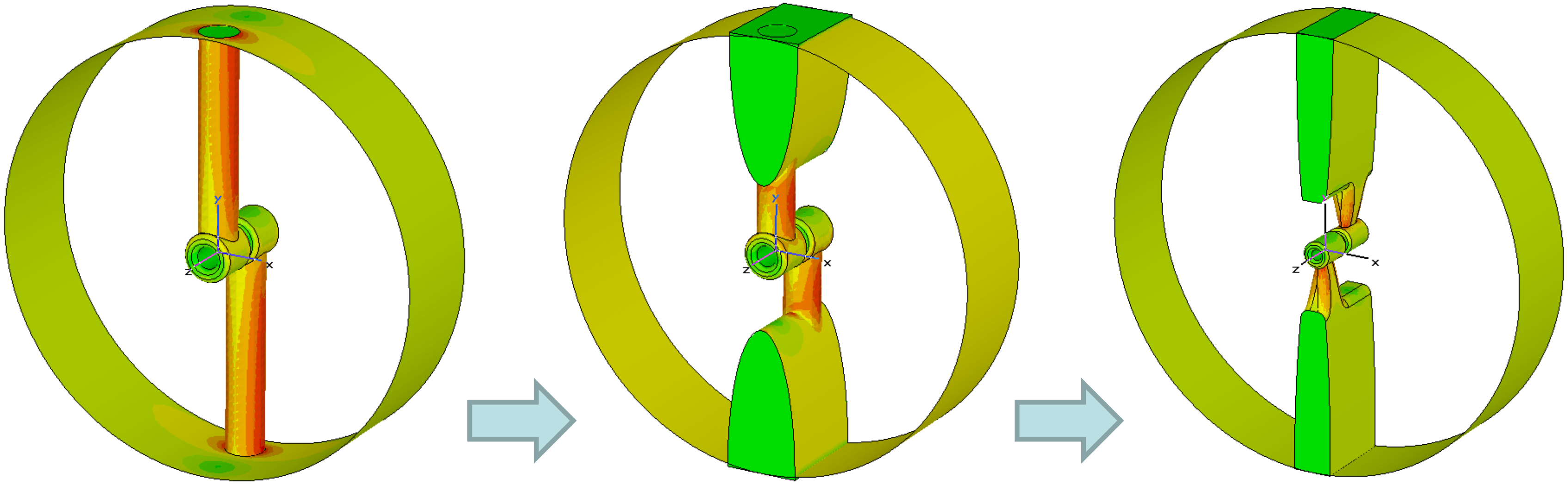


DTL

Los Alamos
NATIONAL LABORATORY

MWS modeling - optimizing H-cavities

At $\beta = 0.034$



IH

IH with vanes

IH with mod vanes, small DT diameter

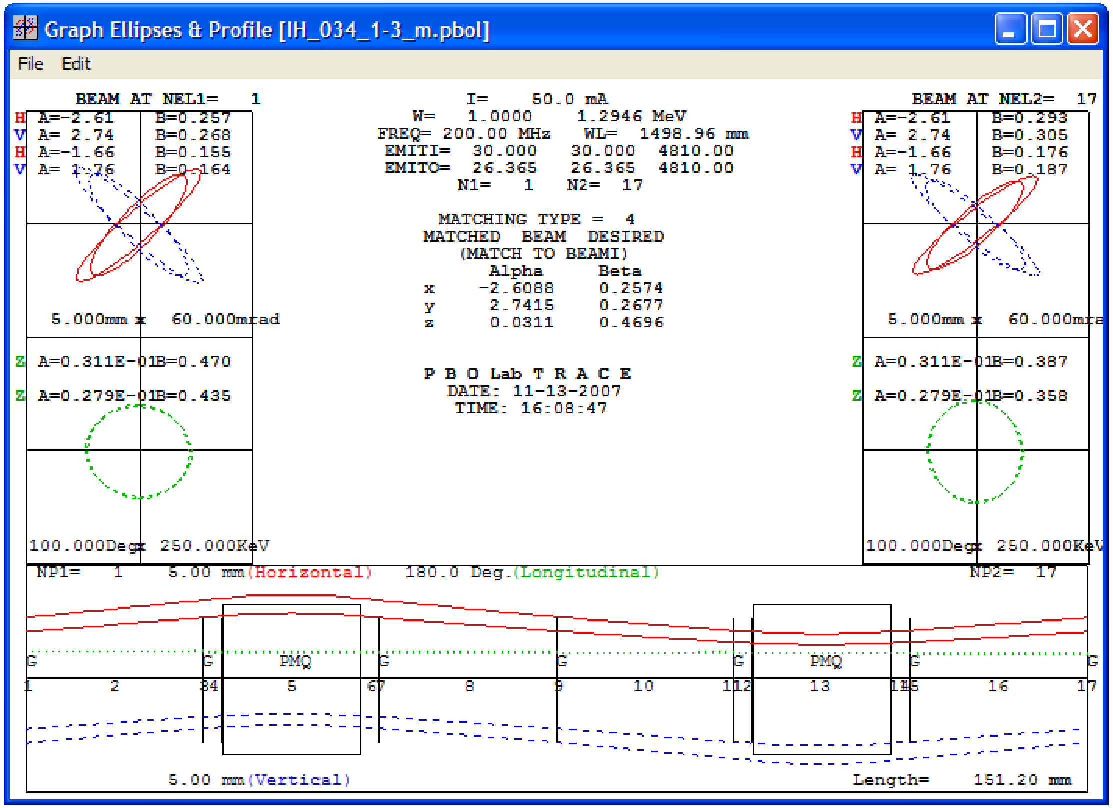
$ZT^2 = 294.2$ MΩ/m

$ZT^2 = 346.2$ MΩ/m (+)

$ZT^2 = 745.8$ MΩ/m (!)

Beam dynamics

TRACE 3-D. Parameters: I = 50 mA, β = 0.034 (1 MeV D)
IH1-3: PMQ in every 3rd DT (B'=200 T/m, L_q=2 cm); rms ε = 0.2 π mm·mrad.



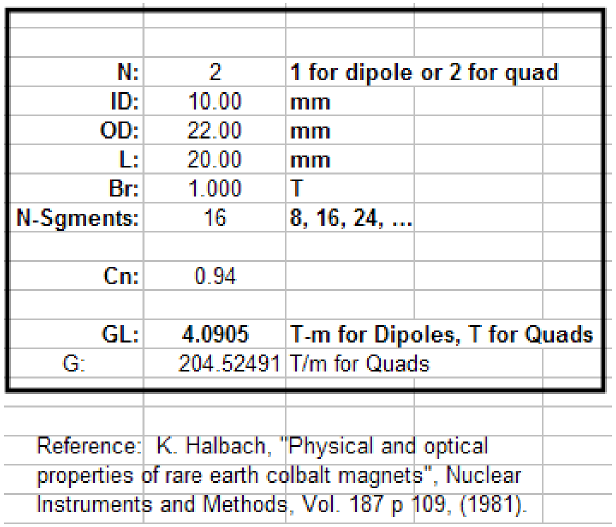
```
BEAM AT NEL1=    1
H A=-2.61    B=0.257
V A= 2.74    B=0.268
H A=-1.66    B=0.155
V A= 1.76    B=0.164
5.000mm x   60.000mrad
Z A=0.311E-01B=0.470
Z A=0.279E-01B=0.435
100.000Degx  250.000KeV
```

```
         I=     50.0 mA
    W=    1.0000     1.2946 MeV
FREQ= 200.00 MHz    WL=  1498.96 mm
 EMITI=  30.000    30.000   4810.00
 EMITO=  26.365    26.365   4810.00
      N1=    1    N2=   17

    MATCHING TYPE =   4
  MATCHED  BEAM  DESIRED
     (MATCH TO BEAMI)
          Alpha     Beta
x       -2.6088     0.2574
y        2.7415     0.2677
z        0.0311     0.4696

  P B O Lab T R A C E
    DATE: 11-13-2007
     TIME: 16:08:47
```

```
BEAM AT NEL2=   17
H A=-2.61    B=0.293
V A= 2.74    B=0.305
H A=-1.66    B=0.176
V A= 1.76    B=0.187
5.000mm x   60.000mra
Z A=0.311E-01B=0.387
Z A=0.279E-01B=0.358
100.000Degx  250.000KeV
```

```
NP1=    1    5.00 mm(Horizontal)   180.0 Deg.(Longitudinal)          NP2=   17
G                G       PMQ       G              G              G       PMQ       G              G
1       2        34       5        67     8       9      10      112     13        1415    16     17
                 5.00 mm(Vertical)                                       Length=     151.20 mm
```

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).

Phase advance per period x: σ=33°, σ_0=56°; y: σ=34°, σ_0=56°
Beam size: r_{max} = 4.3 mm.

xyz-matching between RFQ-H and H-DTL is feasible (F. Neri)

Beam dynamics 2

TRACE 3-D: I = 50 mA; norm ε_{rms} = 0.2 π mm·mrad; PMQ B'=200 T/m, L_q=2 cm.

Focusing structure F*n*OD*n*O: IH1-(n+1) = PMQ in every (n+1)th DT

Table: Phase advances per focusing period and beam sizes for β = 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

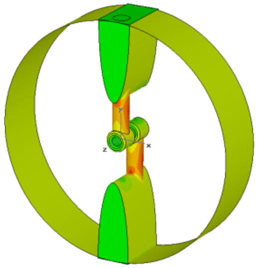
cont.	$\sigma_{x/y}$, deg	$\sigma_{0x/y}$, deg	σ_z/σ_{0z}, deg
IH1-2	17.4 / 17.9	31.7 / 32.1	42.8 / 45.9
IH1-3	33.1 / 34.1	55.6 / 56.4	61.8 / 66.7
IH1-4	51.3 / 53.8	82.4 / 84.5	79.8 / 86.4
IH1-5	75.0 / 79.9	116.7 / 121.5	96.8 / 105.1

IH1-5 should be excluded – beam stability

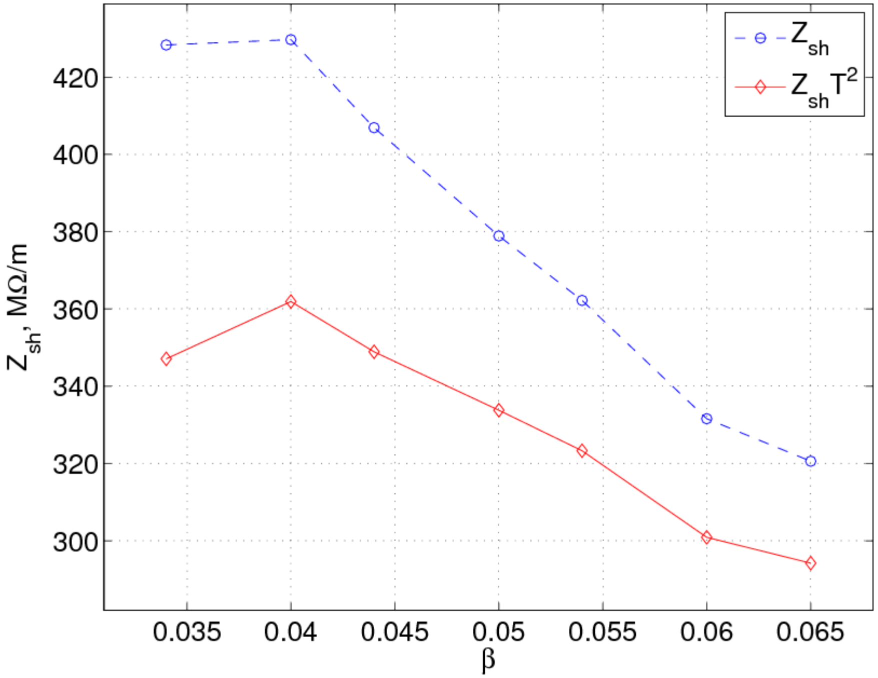
The same exercise for β = 0.065: already IH1-4 is out. Longer DTs – more options.

Overall, IH1-3 appears to be the best choice. N_{PMQ} = 1/3 N_{max} – cost reduction!

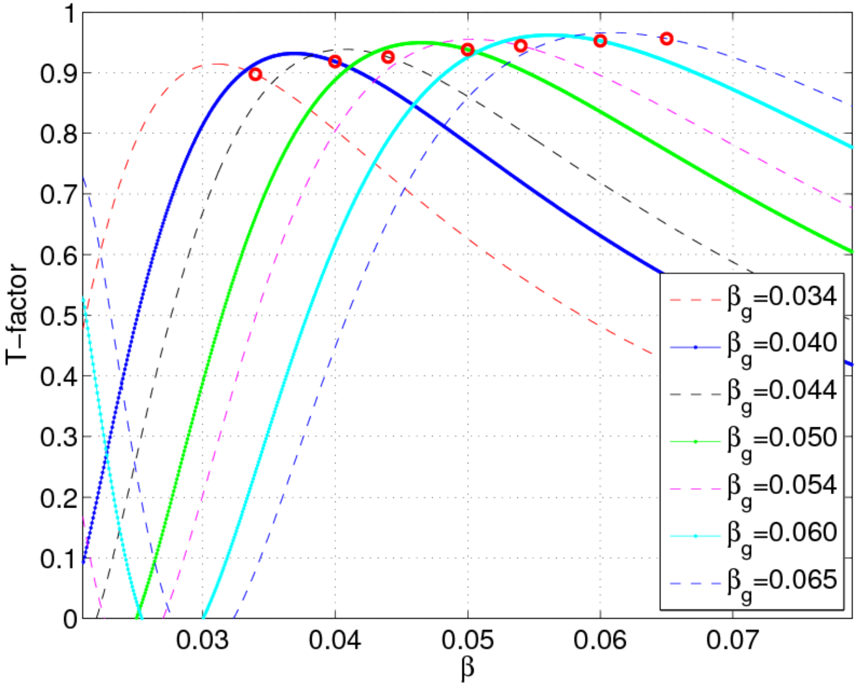
EM properties of IH structures



Regular IH structures with vanes & narrow gaps ($g/L_c = 0.15$).

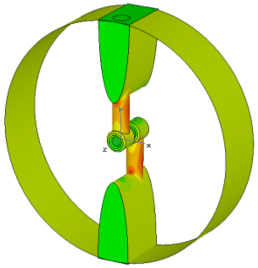


Shunt impedance of regular IH structures with narrow gaps versus β_g.

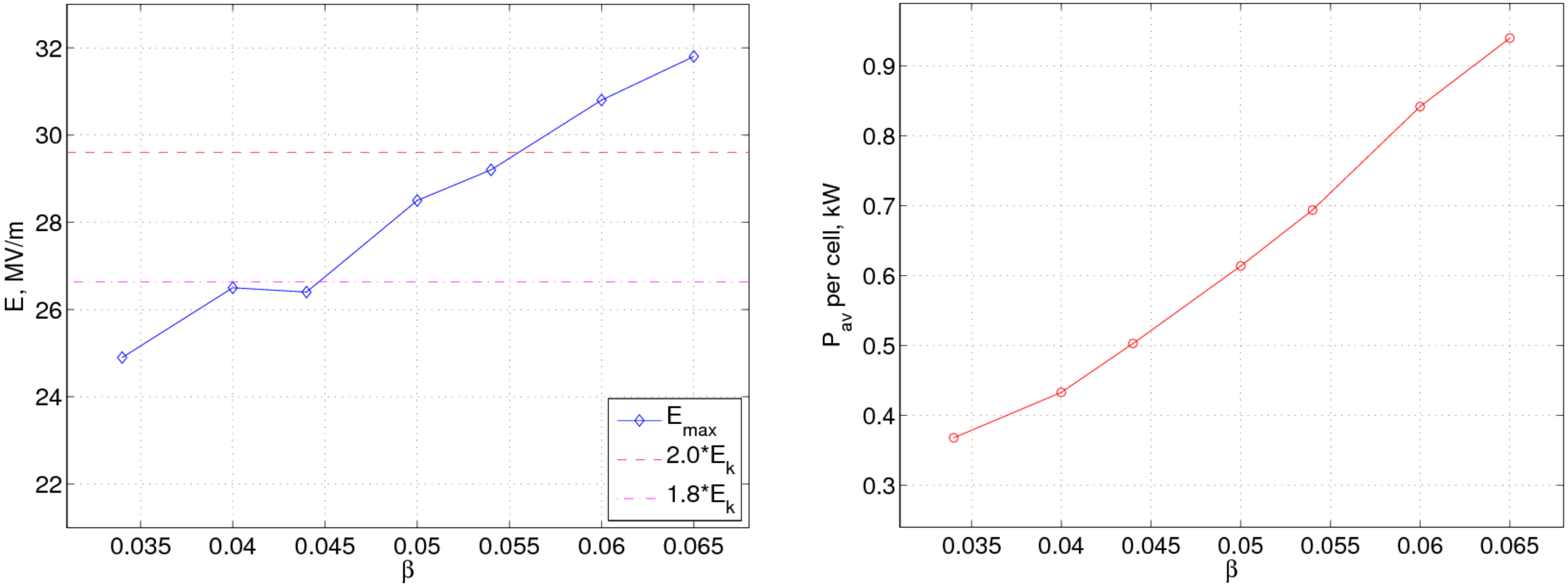


Transit-time factor of regular IH structures (defined by β_g) versus beam velocity β.

EM properties of IH structures - 2



Regular IH structures with vanes & narrow gaps (g/L_c = 0.15):
E_{max} becomes high (> $1.8E_K$) at $\beta_g \geq 0.05$.



Maximal electric field in regular IH structures with narrow gaps versus β_g.

Surface loss power (100% duty) in regular IH structures with narrow gaps versus β_g.

IH Deuteron Accelerator 1 to 4 MeV:

The total number of IH cells ≤ 40 (19-20 periods):

- either gradually increasing cell lengths (the cell length $L_c = \beta\lambda/2$),
- or a three-step design that includes only cells with β_g = 0.04, 0.05, 0.06.

The cavity length is below 1.5 m (E_0 = 2.5 MV/m; φ = -30°).

Required RF power (201.25 MHz):

CW: ≤ 25 kW cavity loss + (50 mA · 3 MV = 150 kW) in the beam;
at 10% duty: ≤ 3 kW cavity + 15 kW beam ≤ 18 kW average.
⟹ gives IOT option for RF

+ Transverse beam focusing with PMQs inside DTs.
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.

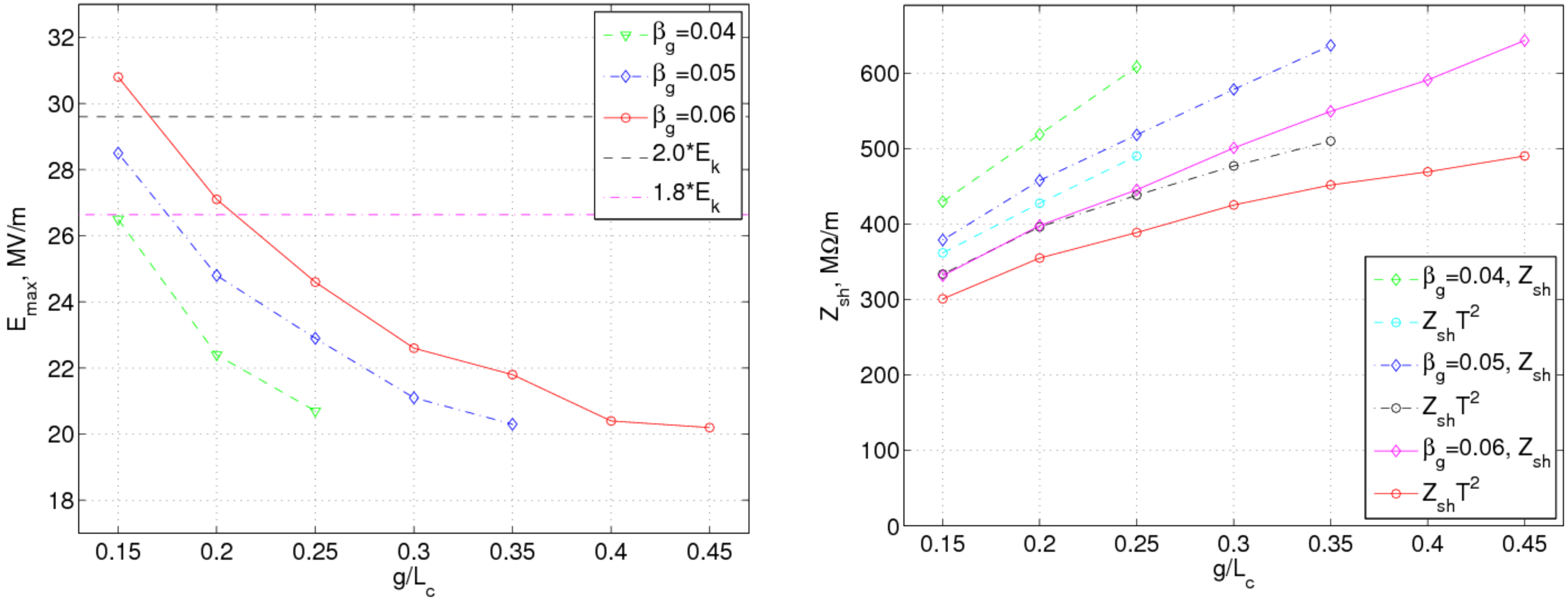
+ Cooling with water channels inside vanes (not in DTs!) --
a simple and attractive scheme.

⇨ Compact and efficient RT deuteron linac

IH-structure improvement options

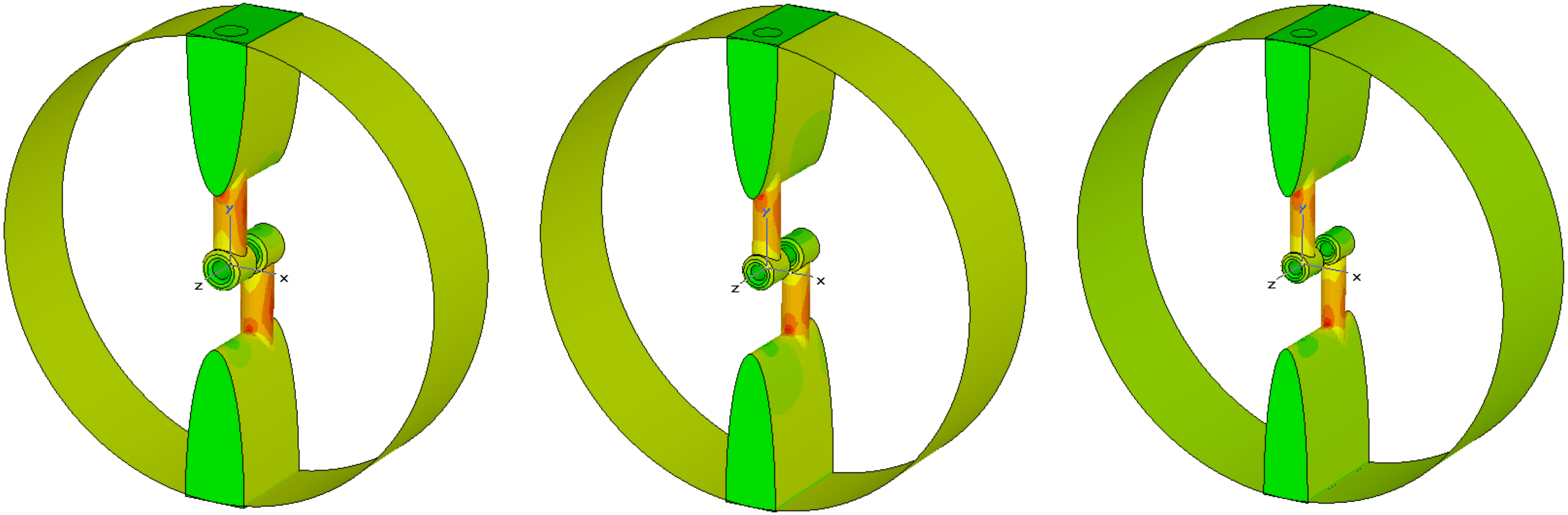
1. Increase the gap length between DTs by making the DTs shorter – reduces E_{max} for a fixed gradient.

   Especially attractive option at $\beta_g \geq 0.05$; $L_{DT} > L_q = 2$ cm limits the gap width: $g/L_c = 0.25, 0.35, 0.45$ for $\beta_g = 0.04, 0.05, 0.06$



Maximal electric field (left) and shunt impedance (right) in regular IH structures versus g/L_c.

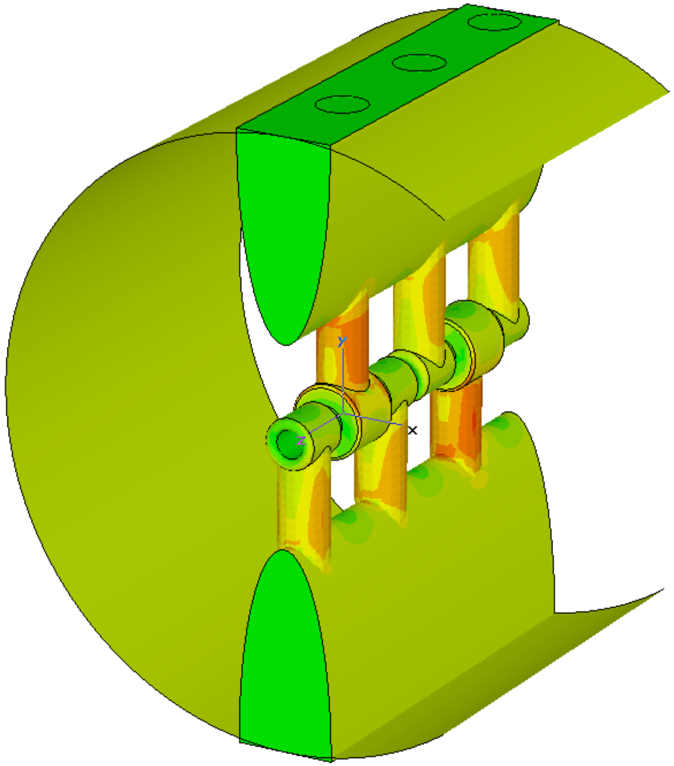
Regular IH structures with wider gaps

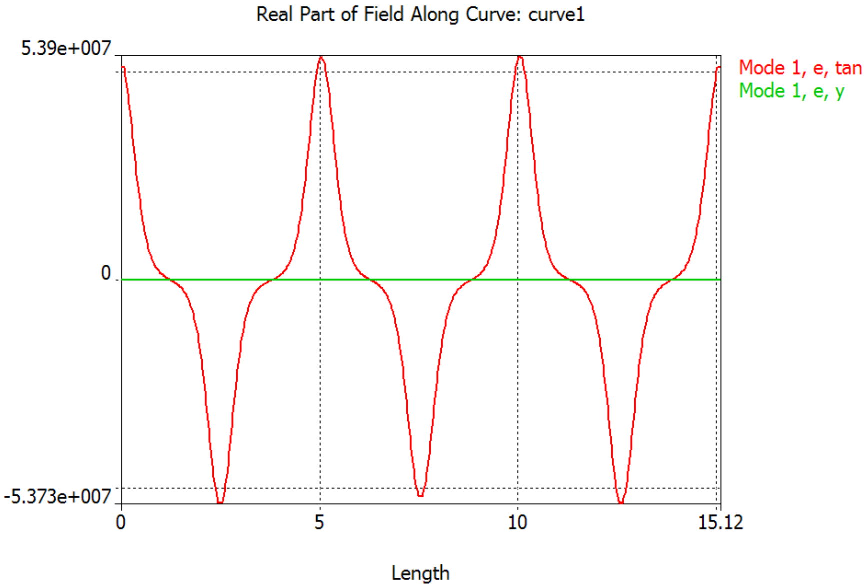


Surface current distribution in the IH structures with identical DTs and wider gaps:
$\beta_g = 0.04$, $g = 0.25L_c$ (left), $\beta_g = 0.05$, $g = 0.35L_c$ (center), and $\beta_g = 0.06$, $g = 0.45L_c$ (right).

IH-structure improvement options

2. Reduce the outer radius of empty DTs in IH1-n structures – increases shunt impedance

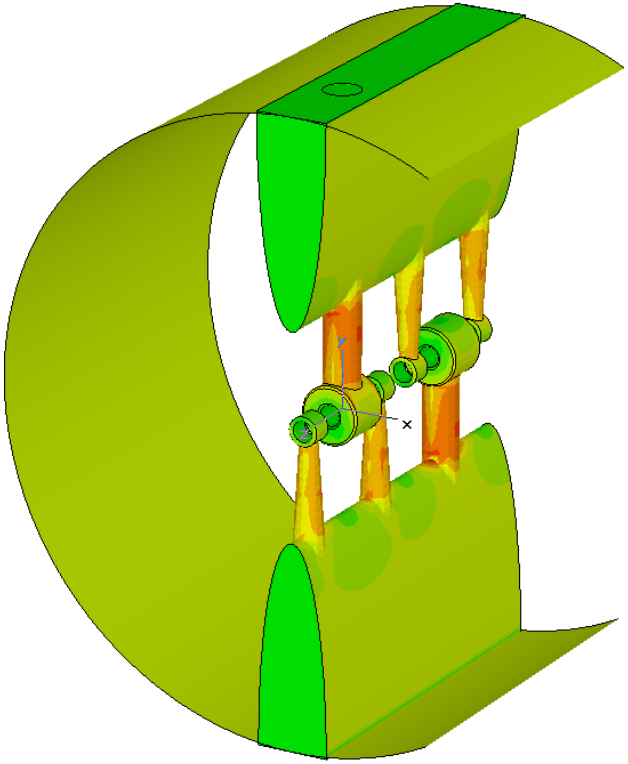


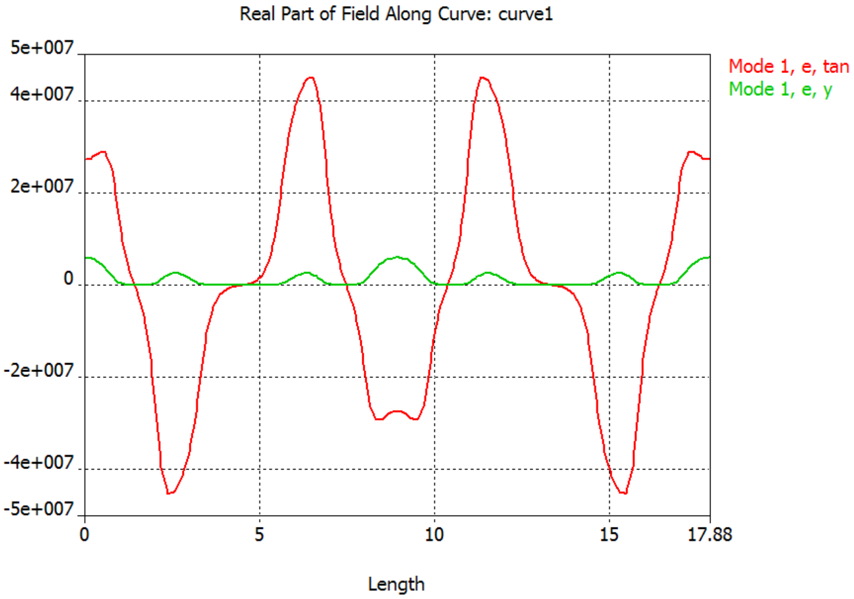


IH1-3 structure for β_g = 0.034 with different transverse sizes for DT with (r_{out} = 13 mm) and without PMQs (r_{out} = 9 mm). Here $g = 0.15L_c$; $Z_{sh}T^2$ = 370 MΩ/m (vs 347), but E_{max}!

IH-structure improvement options

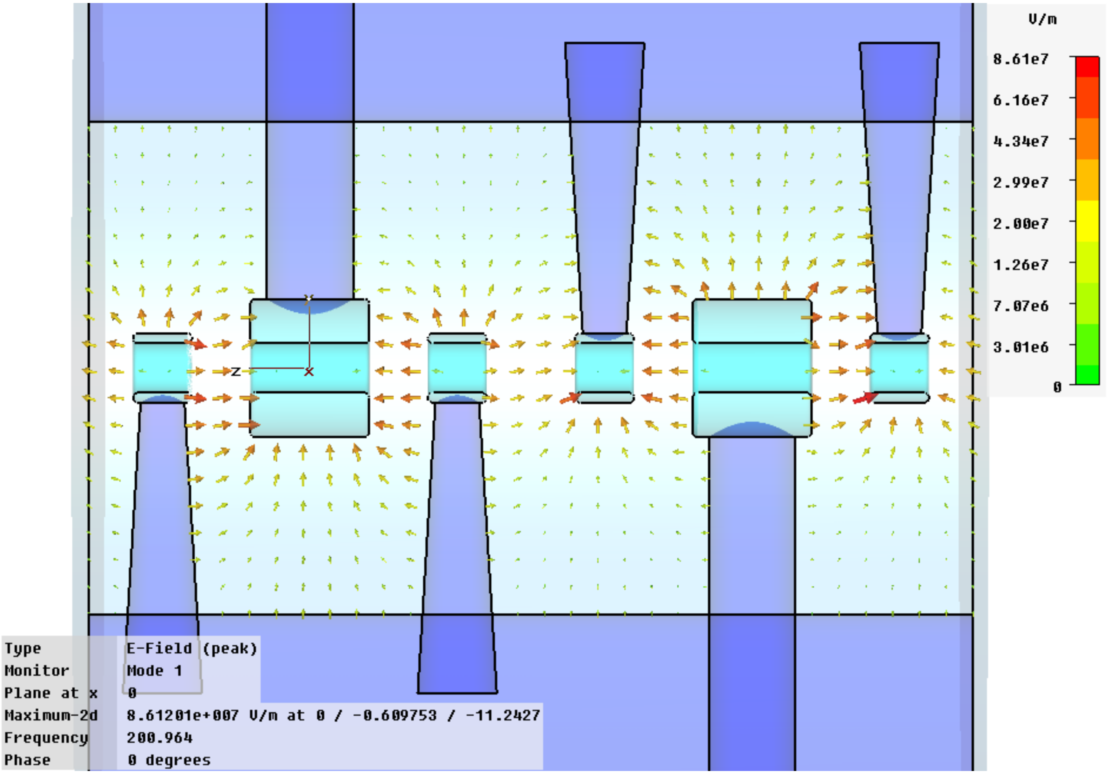
3. Combine 1 & 2: wider gaps and slim empty DTs in IH1-n structures – increases shunt impedance while keeping acceptable E_{max}.





Modified IH1-3 structure for $\beta_g = 0.04$ with large DT with PMQ (r_{out} = 14 mm) and slim DT without PMQ (r_{out} = 7 mm). Here g/L_c = 0.397 & 0.6; $Z_{sh}T^2$ = 712 MΩ/m, E_{max} = 18.5 MV/m.

IH structures with wider gaps – E_{tr} on axis!

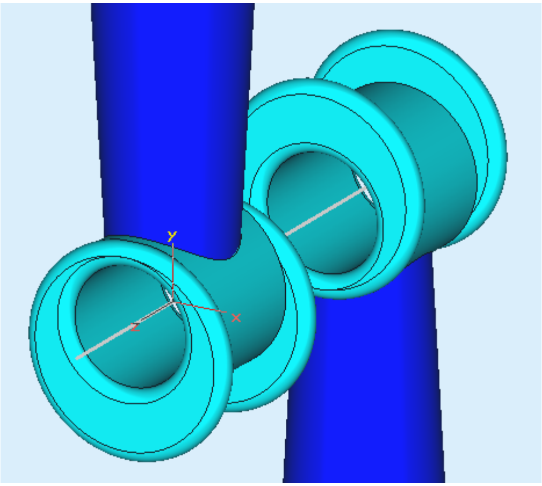


```
Type          E-Field (peak)
Monitor       Mode 1
Plane at x    0
Maximum-2d    8.61201e+007 V/m at 0 / -0.609753 / -11.2427
Frequency     200.964
Phase         0 degrees
```

The field asymmetry in IH was recognized long time ago.

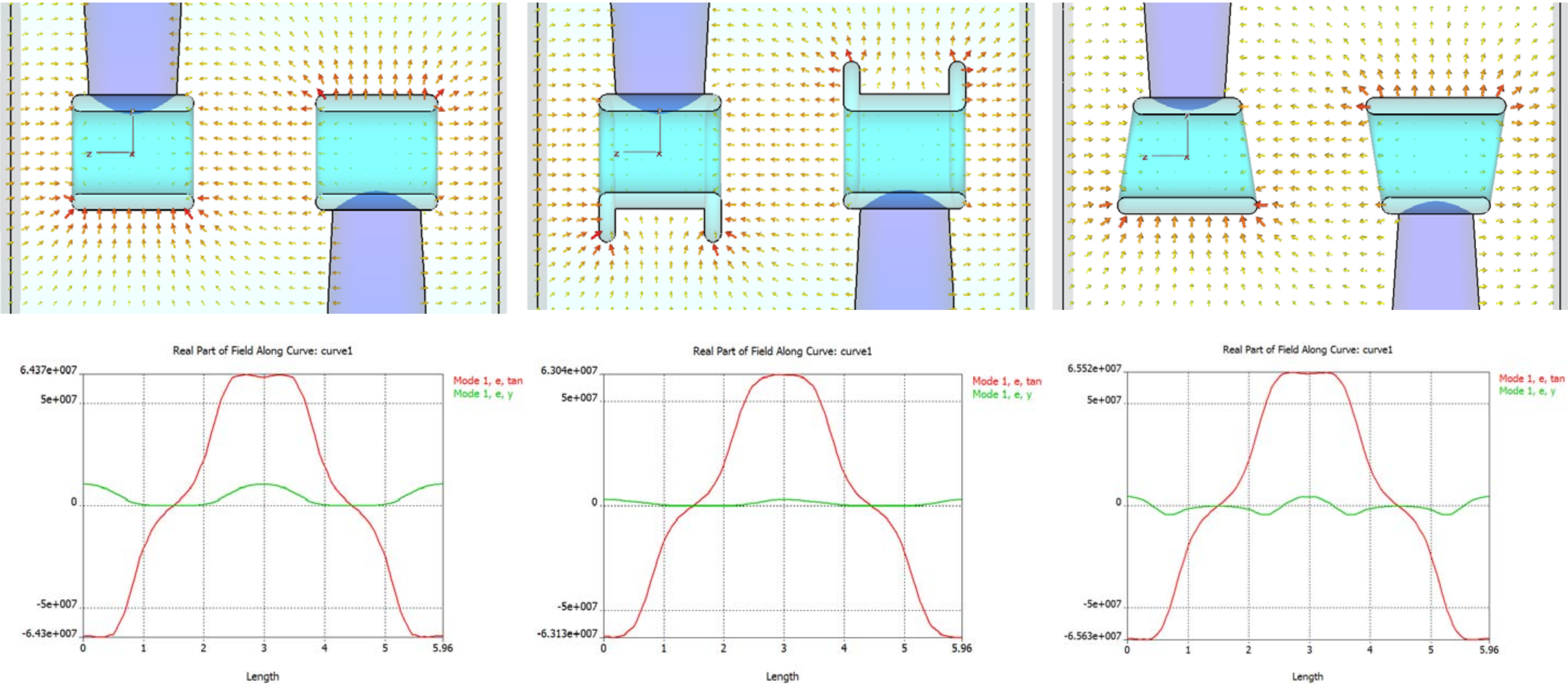
Mitigation – non-concentric bulges on the slim DTs [CERN (LINAC3) and GSI (HLI and HSI)].

Price – reduced Z_{sh} (~15-20%); E_{max} is up by 50%.



Other mitigation options are also possible, e.g. slanted DT ends.

IH structures with wider gaps – E_{tr} mitigation



Electric fields in IH structures (left); with asymmetric bulges (center); with slanted ends (right): field arrows in the vertical symmetry plane (top, log scale), and on-axis fields (bottom). No bulges: reduced Z_{sh} (~15-20%); E_{max} is up by 50%.

No bulges: $\delta = 9.6°$.

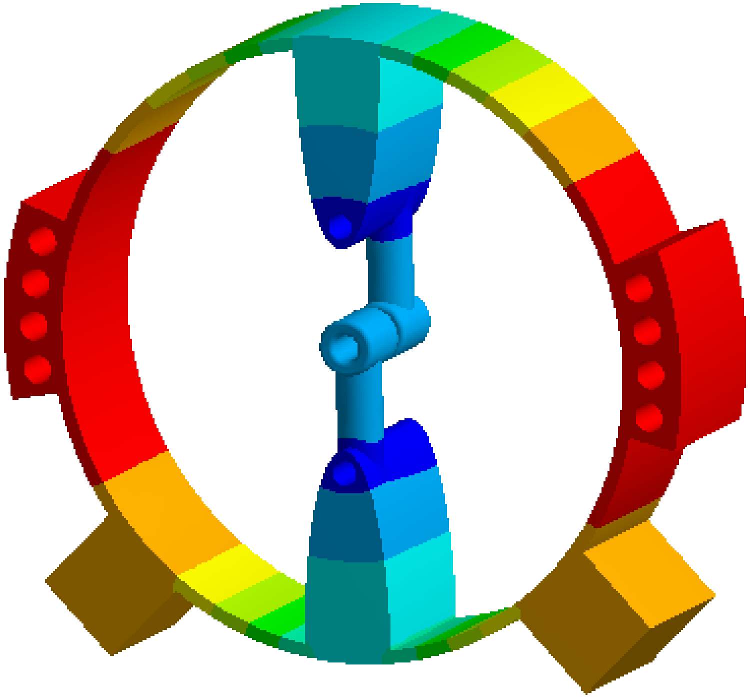
Bulges $\Delta = 2$ mm: $\delta = 3°$.
But $Z_{sh} \downarrow$ 20%; $E_{max} \uparrow$ 50%.

Slanted ends: $\langle\delta\rangle = 0$.
Z_{sh} ~$\uparrow$ but $E_{max} \uparrow > 50\%$.

Engineering analysis

A procedure to transfer surface-loss power data calculated by MWS to finite-element (FE) engineering codes COSMOS and ANSYS:

- 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.



Temperature distribution in regular IH structures with water cooling in vanes for the nominal 10% duty:

- Water 22°C, 2-m/s flow. T_{max} (red) is 34.2°C, T_{max} (blue) is 23.1°C.
- No outside cooling is needed here.
- DT vertical displacements for 10% duty are 30 and 40 μm – below the typical manufacturing tolerances.

The important result – PMQ temperatures can be kept low with the vane cooling – confirms the IH-PMQ RT concept feasibility.

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 appear to be the best: the most efficient, 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.
- Beam dynamics envelope simulations show that the beam transverse focusing with PMQ is feasible.
- 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.

- Continue development of the room-temperature H-mode structures with PMQ focusing to achieve a balance of the structure efficiency, beam quality, and thermal management: iterations of
  - electromagnetic modeling (whole tank, end cells, …),
  - beam dynamics (multi-particle simulations: MWS fields → Parmela),
  - detailed engineering thermal-stress analysis.
- Cold model.
- PMQs (1-2).

References:

1. S. Kurennoy, L. Rybarcyk, and T. Wangler, “Efficient Accelerating Structures for Low-Energy Light Ions,” PAC’07, Albuquerque, NM, p. 3824 (2007).
2. S. Kurennoy, Technical notes AOT-ABS: 07-032, 08-008, 08-017, LA-UR-08-03795, Los Alamos, 2008
3. S. Kurennoy et al, “IH Accelerating Structures with PMQ Focusing for Low-Energy Light Ions,” EPAC08, Genoa, Italy, THPP026, p. 3431 (2008).