Proton and Ion Linear Accelerators

Yuri Batygin[1], Sergey Kurennoy[1], Sebastian Szustkowski[1], Salvador Sosa Guitron[1], Vyacheslav Yakovlev [2]

[1]Los Alamos National Laboratory
[2]Fermi National Accelerator Laboratory

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Proton and Ion Linear Accelerators
RF linacs: cavities, structures, EM design

Sergey Kurennoy, LANL

USPAS, July 19, 2024

Lecture 10

LA-UR-17-24573

Content

- Why linacs & RF together?
- Reminder: basics of linacs
- RF cavities
- Accelerating structures: RFQ, DTL, CCL, etc.
- Electromagnetic (EM) design of accelerating structures. Tools.

Sources:

T.P. Wangler. *RF linear accelerators*, Wiley-VCH, 2nd Ed., 2008.

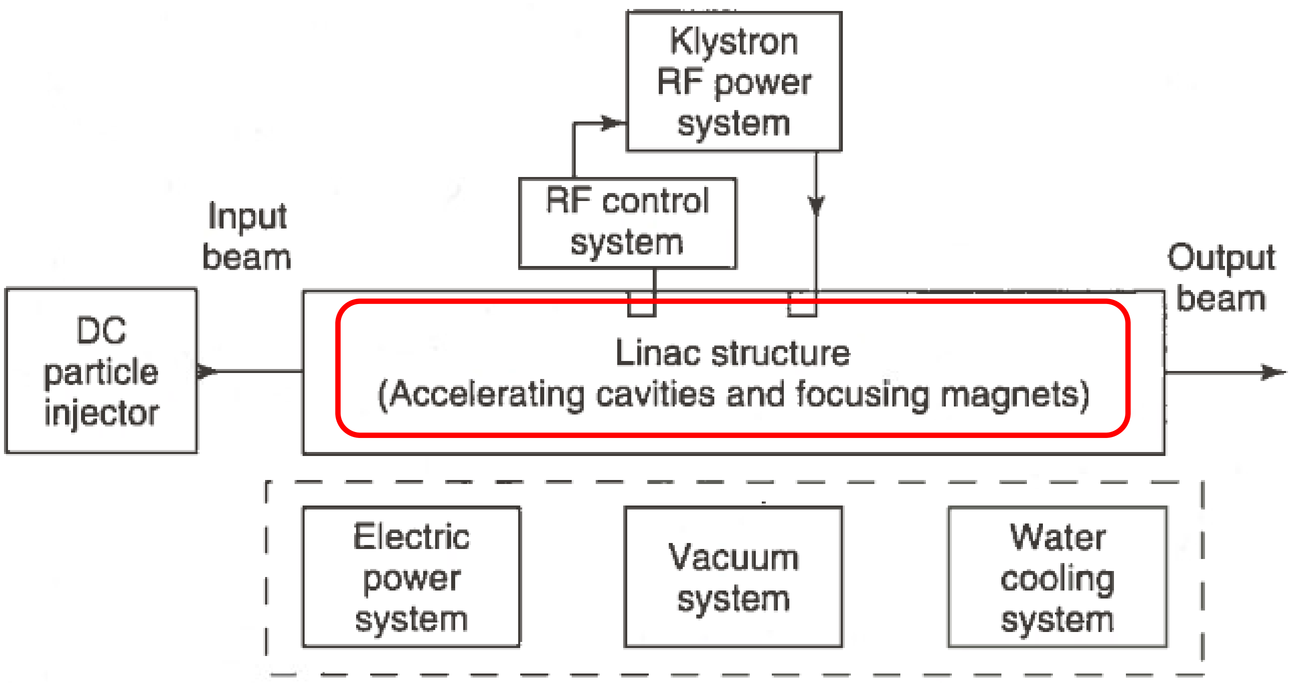
Handbook of Accelerator Physics and Engineering. 3rd Ed., Eds. A. Chao *et al*. World Scientific, 2023.

Linacs

Linear accelerator (linac) – a device that accelerates charged particles in a straight line.

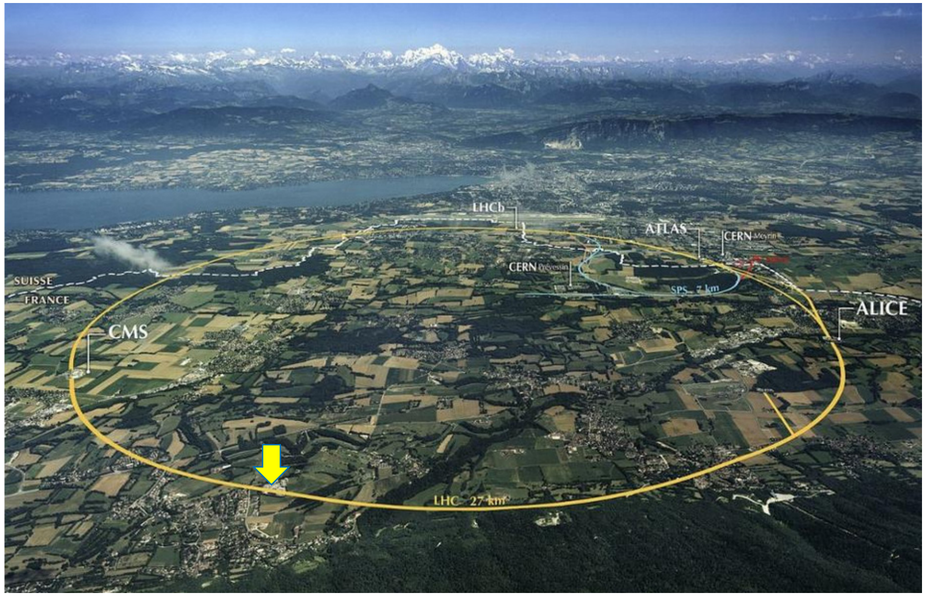
Linac types:

- **Electrostatic** – electric field is produced by a fixed voltage (e.g., old TV tubes)
- **Induction** – electric field is produced by changing magnetic flux
- **Radio-Frequency (RF)** – fields are produced by external sources of RF power



RF linac schematics

Why linacs & RF together?



LHC – circular p-p collider (2008): 27 km, but RF acceleration section <100 m. 8 SC 400.8-MHz RF cavities per ring; 8-16 MV; each cavity is only ~2 m long and powered by one klystron (16 klystrons total).

LHC RF section = 2 short linacs!

SLAC – electron linac (1968): 3 km, & RF acceleration "section" ~3 km.

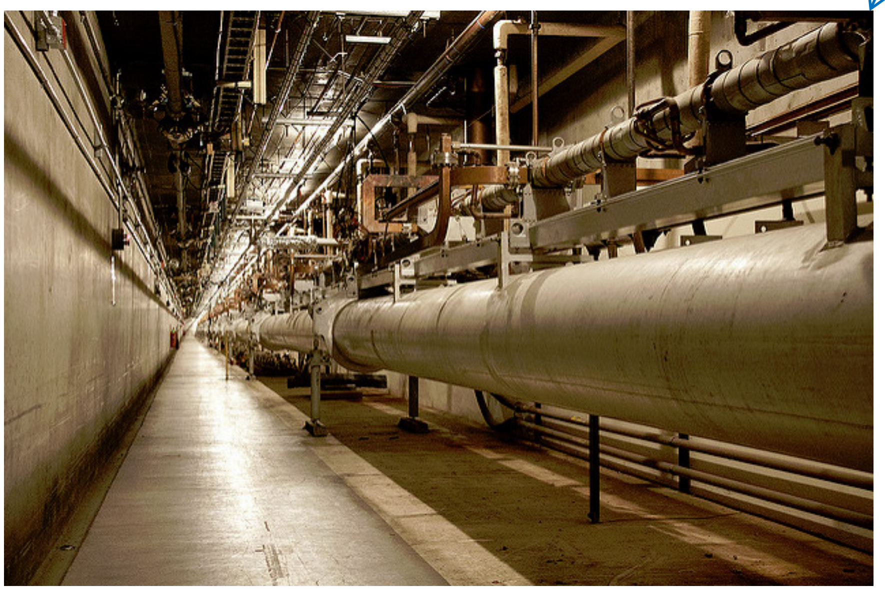
240 2856-MHz klystrons (design - 960), each with 50-MW peak power (x2 with pulse compression), provide total voltage up to ~50 GV (SLC, 1989).

Why linacs & RF together?

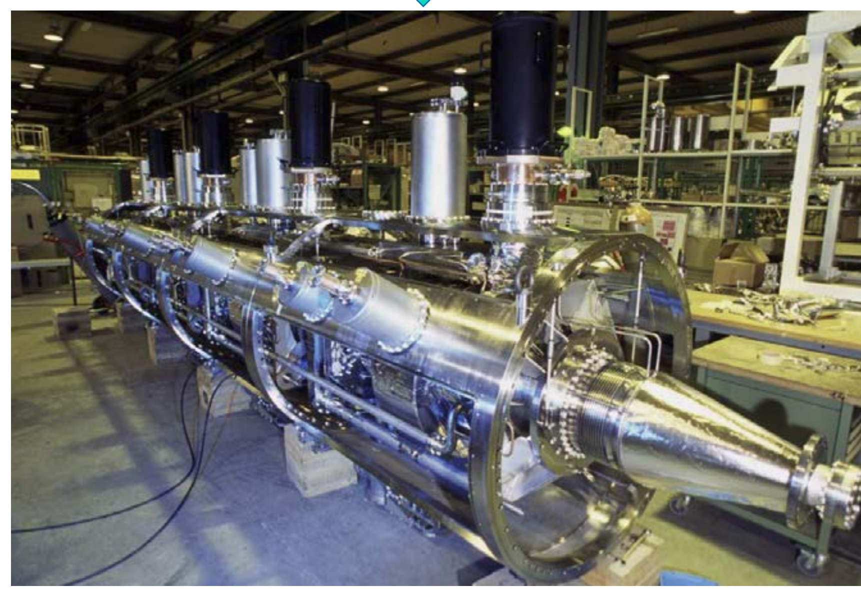
SLAC klystron gallery

SLAC linac (30’ below)

960 traveling-wave structures (x3m)



LHC 4 RF cavities in cryo-module



Why linacs & RF together?

LANSCE (LAMPF) linac (1972)

800 m, 800 MeV

Protons (p) and hydrogen ions (H^-)

Drift-tube linac (DTL)

62 m, 0.75-100 MeV

$\beta = v/c = 0.04\text{-}0.43$

4 201.25-MHz tubes (≤3 MW)

Coupled-cavity linac (CCL)

731 m, 100-800 MeV

$\beta = v/c = 0.43\text{-}0.84$

44 805-MHz klystrons (1 MW)

Induction Accelerator

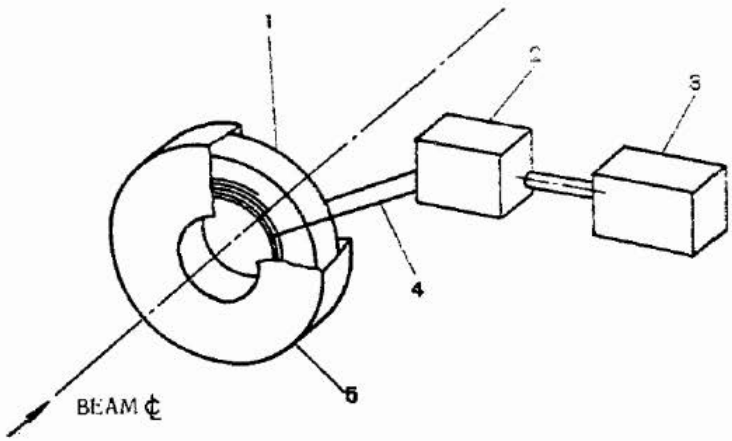
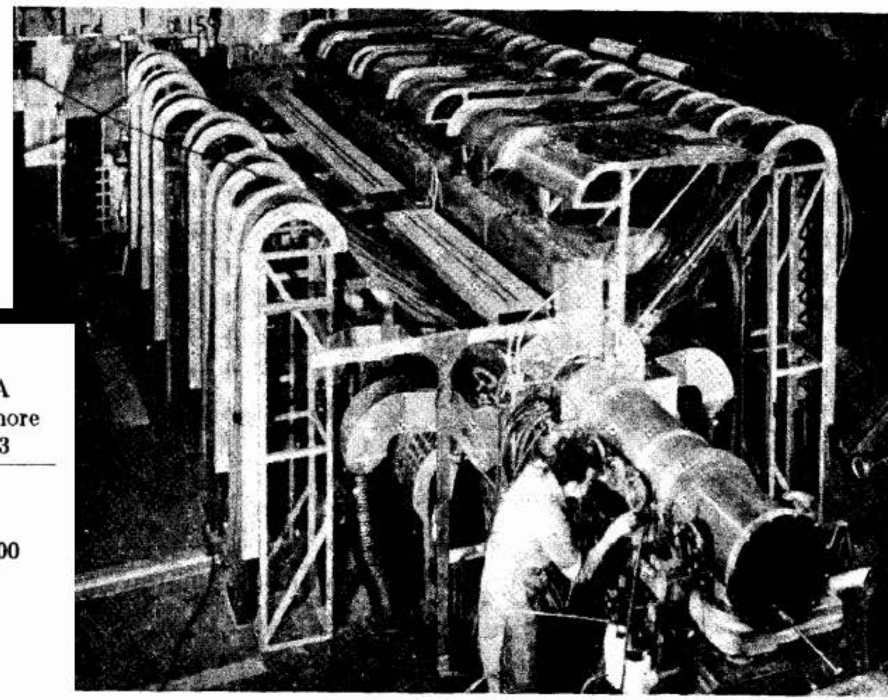


Fig. 1. Induction accelerator principle:
1 — laminated iron core; *2* — switch; *3* — pulse forming network; *4* — primary loop; *5* — secondary (case).

$$\oint \vec{E}\cdot\vec{dl} = -\frac{1}{c}\int_s \frac{\vec{dB}}{dt}\cdot\vec{ds},$$

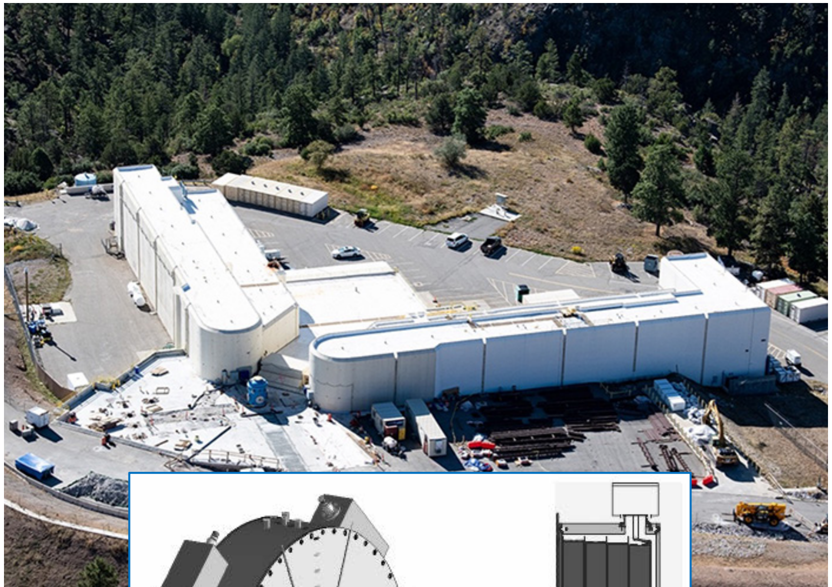
Table 3. Parameters for Typical Induction Accelerators

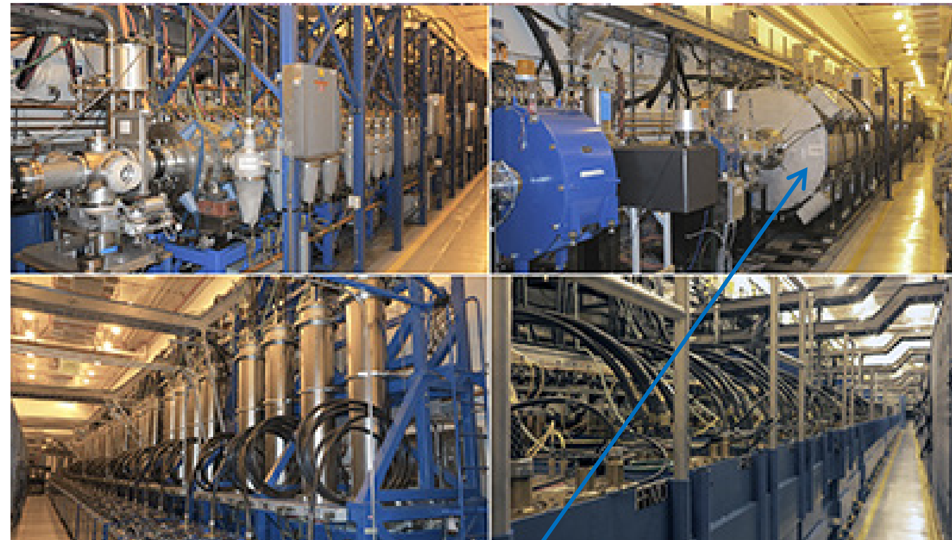
Accelerator	Astron Injector Livermore 1963	ERA Injector Berkeley 1971	NEP 2 Injector Dubna 1971	ATA Livermore 1983
Kinetic energy, MeV	3.7	4.0	30	50
Beam current on target, A	350	900	250	10,000
Pulse duration, ns	300	2-45	500	50
Pulse energy, kJ	0.4	0.1	3.8	25
Rep rate, pps	0-60	0-5	50	5
Number of switch modules	300	17	750	200

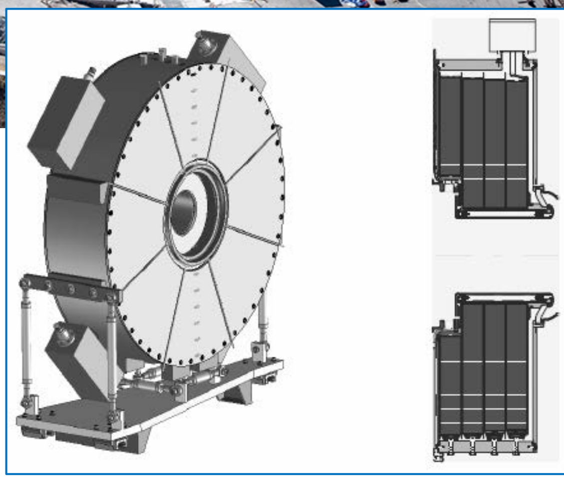


Overhead view of the Astron accelerator as it appeared when first put into operation.

DARHT at LANL – two linear induction accelerators







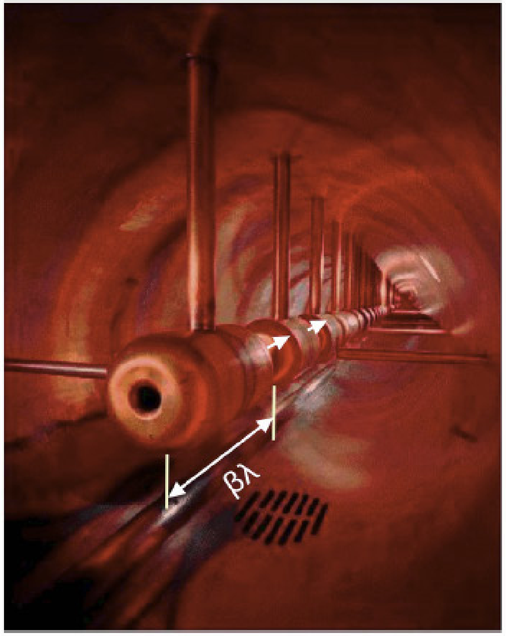
Induction cells of Axis 2:

Beam pipe diameter 12" (8 cells) and 10" (66 cells)

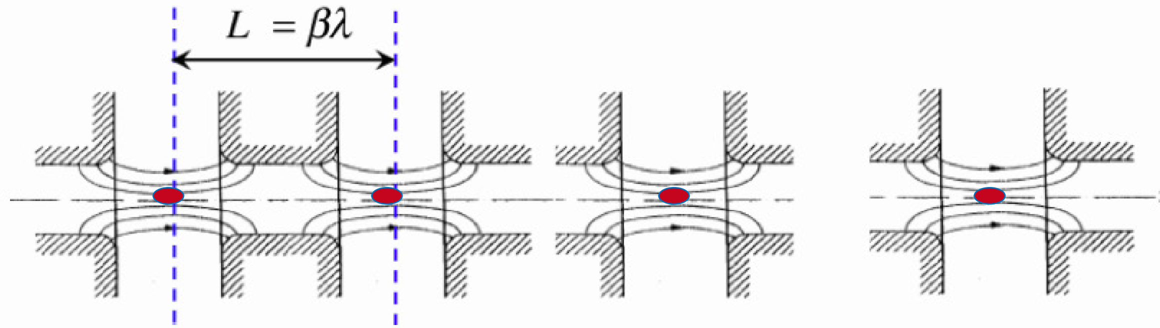
Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility:

- Axis 1 (1999): 60-ns pulse, 2 kA, 20 MeV e-beam → high-Z target → X-rays (64 cells)
- Axis 2 (2008): 1.6-μs long flat-top pulse (4 short pieces cut), 2 kA, 17 MeV (74 cells)

Resonance acceleration principle



Alvarez accelerating structure



Field distribution in RF structure: $E_z(z,r,t) = E_g(z,r)\cos(\omega t)$

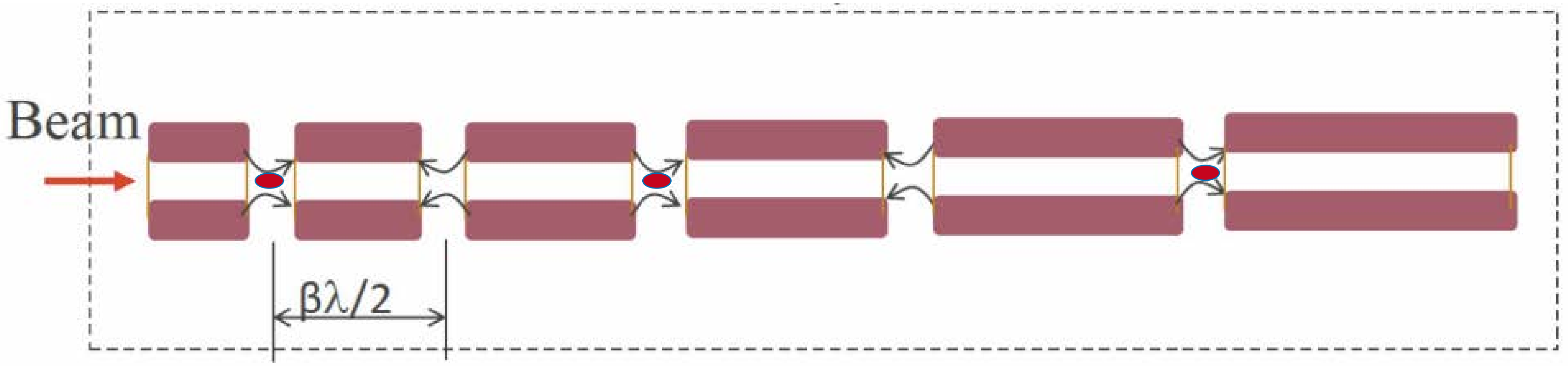
Time of flight between RF gaps $t_{flight} = T_{RF\ period} = \dfrac{1}{f}$

Distance between RF gaps $L = n\beta c T_{RF\ period} = n\beta\lambda$

RF Frequency f

- <u>Synchronism</u> between the accelerating field and particles is due to the linac spatial structure: particles arrive at the gaps when the electric field is in the accelerating phase, and are hidden from the field inside drift tubes during the decelerating phase.
- The above example is a 0-mode accelerating structure (Alvarez DTL): the gap fields work in phase, $\Delta\varphi = 0$. BTW, $t_{flight} = mT_{RF}$, where $m = 2,3,\ldots$ will work too ($m\beta\lambda$-mode).
- Note: all these tricks are for ions at β <(<) 1; for electrons, things are much simpler.

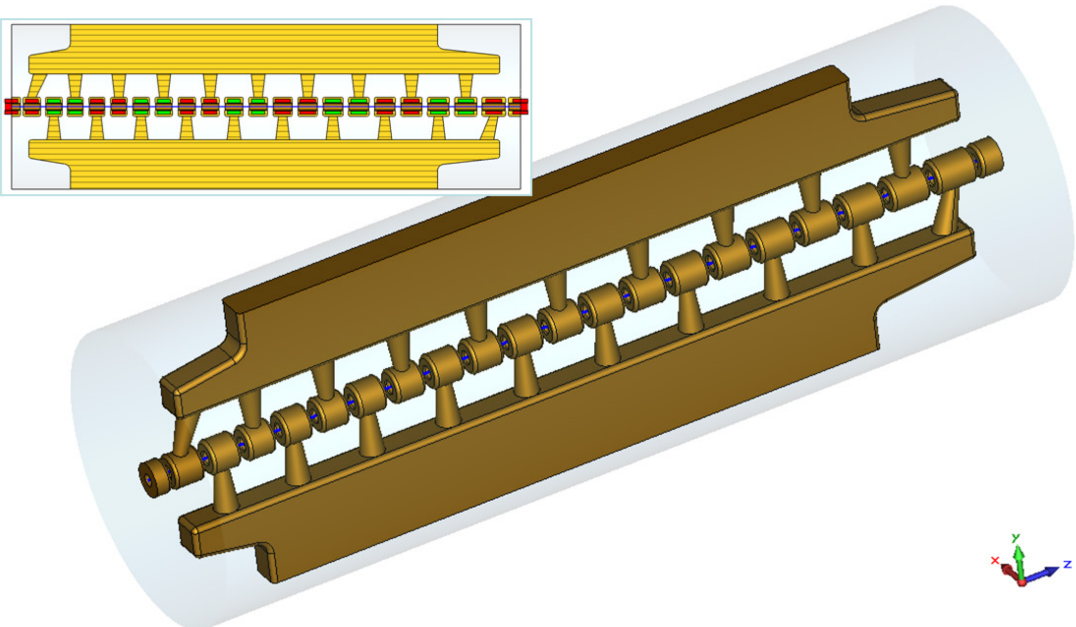
Resonance acceleration: π-mode



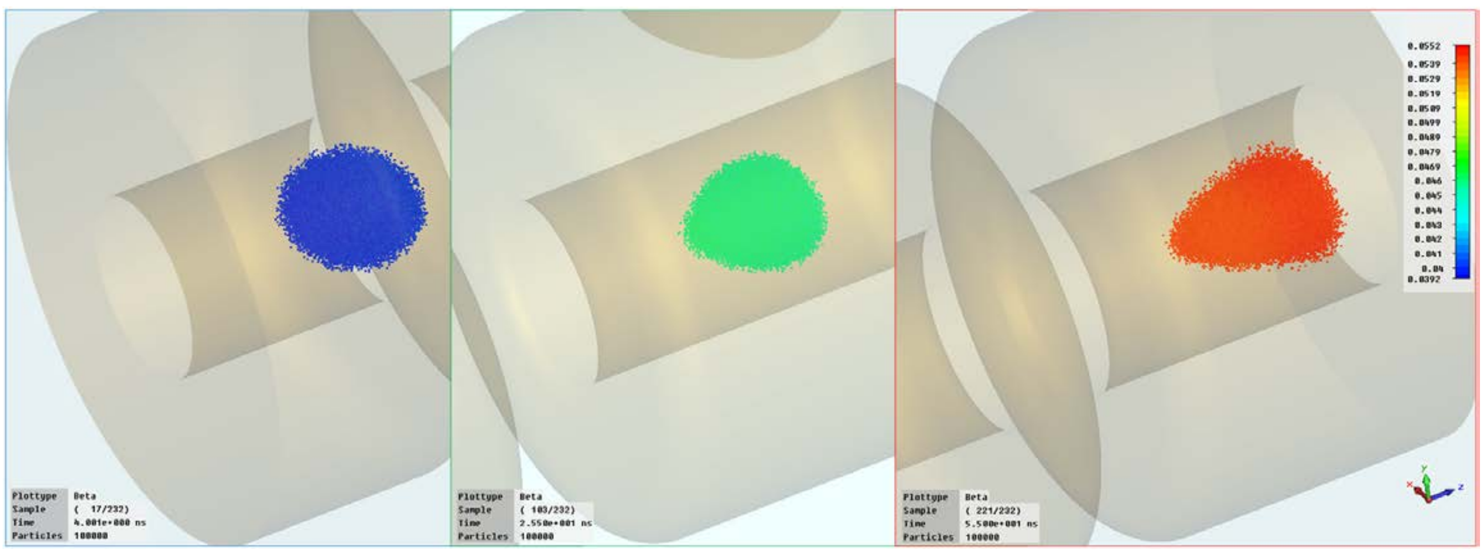
Accelerating structure with π - type standing wave.

- This is a π-mode accelerating structure (e.g., Wideroe DTL): the fields in the adjacent gaps are in opposite phases, $\Delta\varphi = \pi$.
- Particles accelerated in a gap should arrive to the next gap in one half of the RF period (strictly speaking, $(n+1/2)T_{RF}$) so that its electric field changes to the accelerating phase.
- Still there is a “synchronism” between the RF field and the linac spatial structure.
- In principle, one can accelerate simultaneously a beam of opposite charge (with the same particle mass) with its bunches shifted by π in phase.

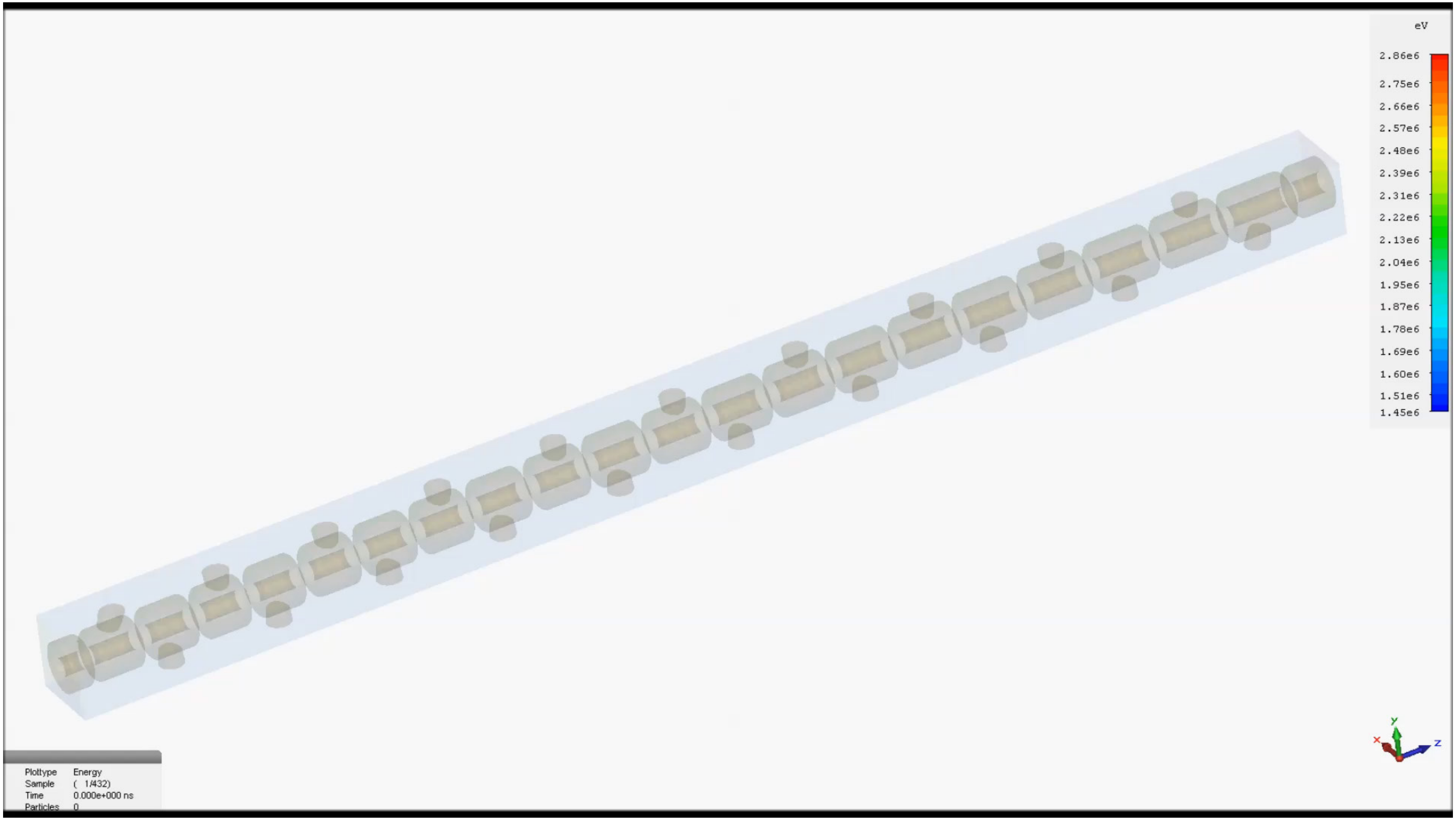
Example: Inter-digital H-mode (IH) structure



IH-PMQ structure for deuterons from $\beta=v/c=0.04$ to 0.055:
 $f=201.25$ MHz, $I=50$ mA
 $L=73.5$ cm, $a=0.5$-0.55 cm.
CST Studio simulations: RF fields (MWS), PM quadrupole fields (EMS), and beam dynamics (Particle Studio).

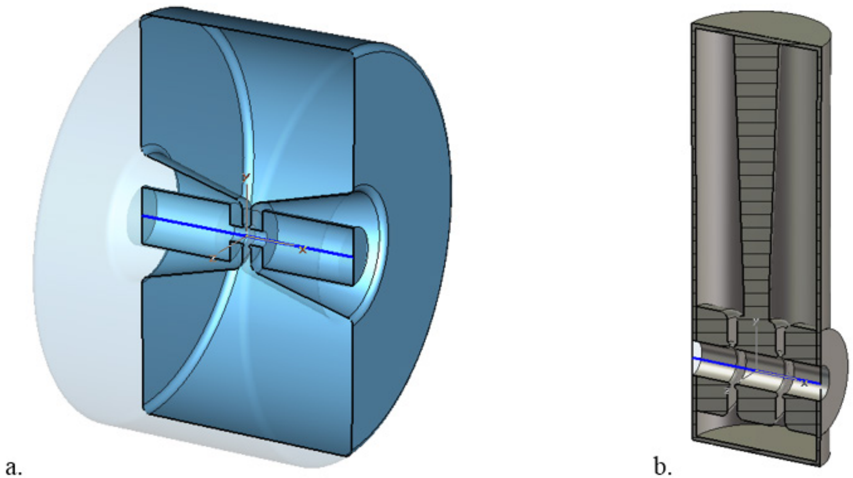


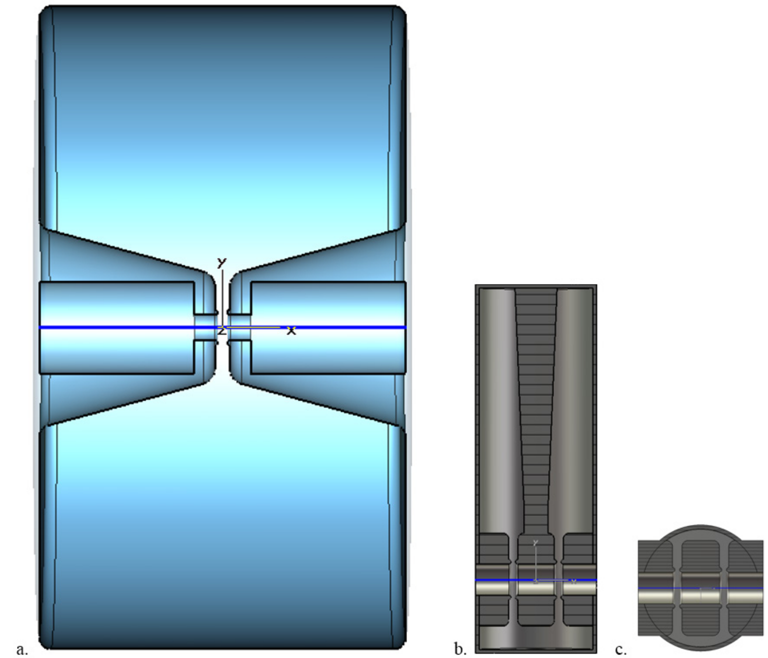
Inter-digital H-mode (IH) structure



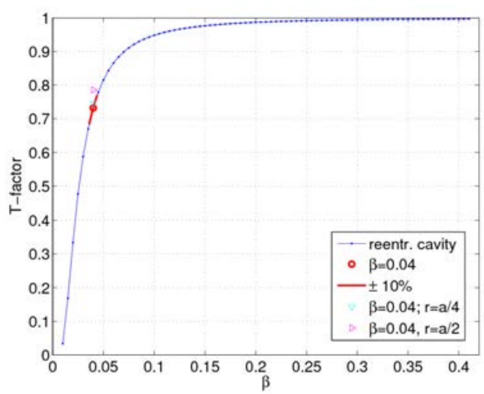
10 bunches of 10K particles (*d*) are accelerated in the cavity

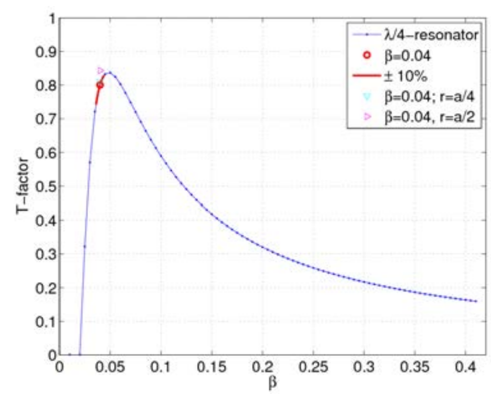
Buncher cavities





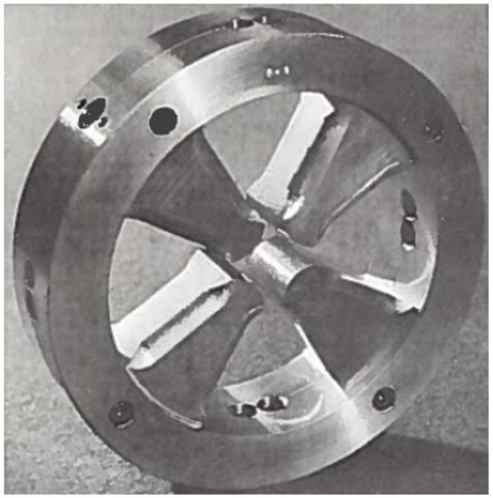
Two buncher cavities: (a) re-entrant and
(b) coaxial quarter-wave (λ/4) types.
Right – on the same scale.





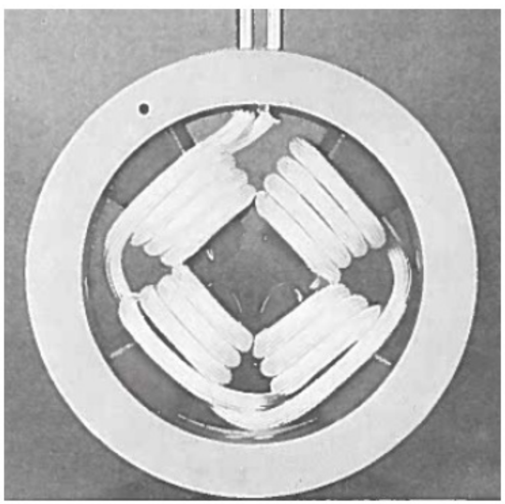
Transit-time factors for two cavities vs velocity

Linac electromagnetic quadrupoles – LANSCE DTL

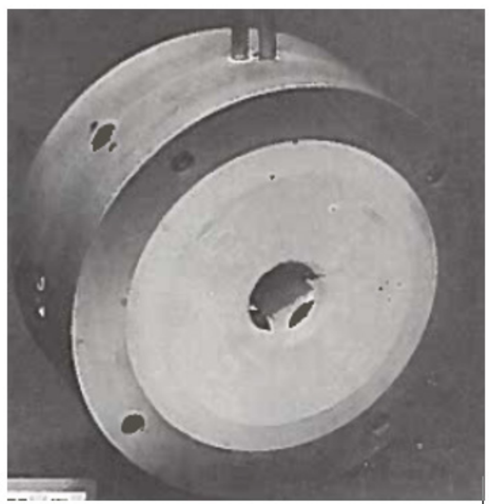


(a)

(b)



(c)

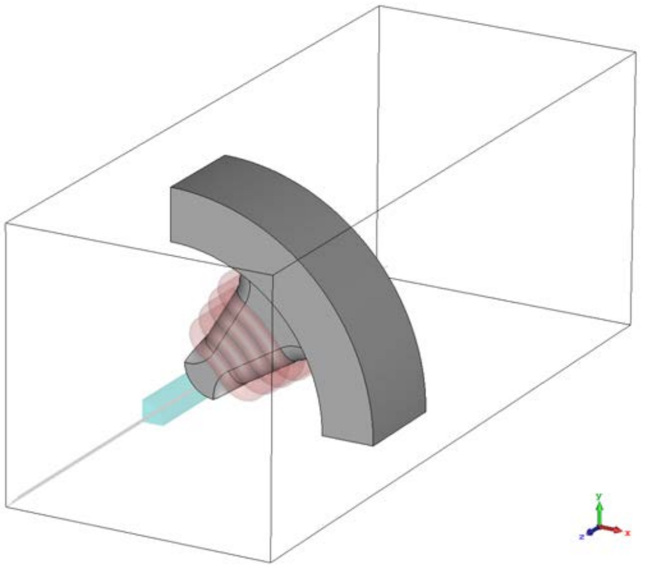


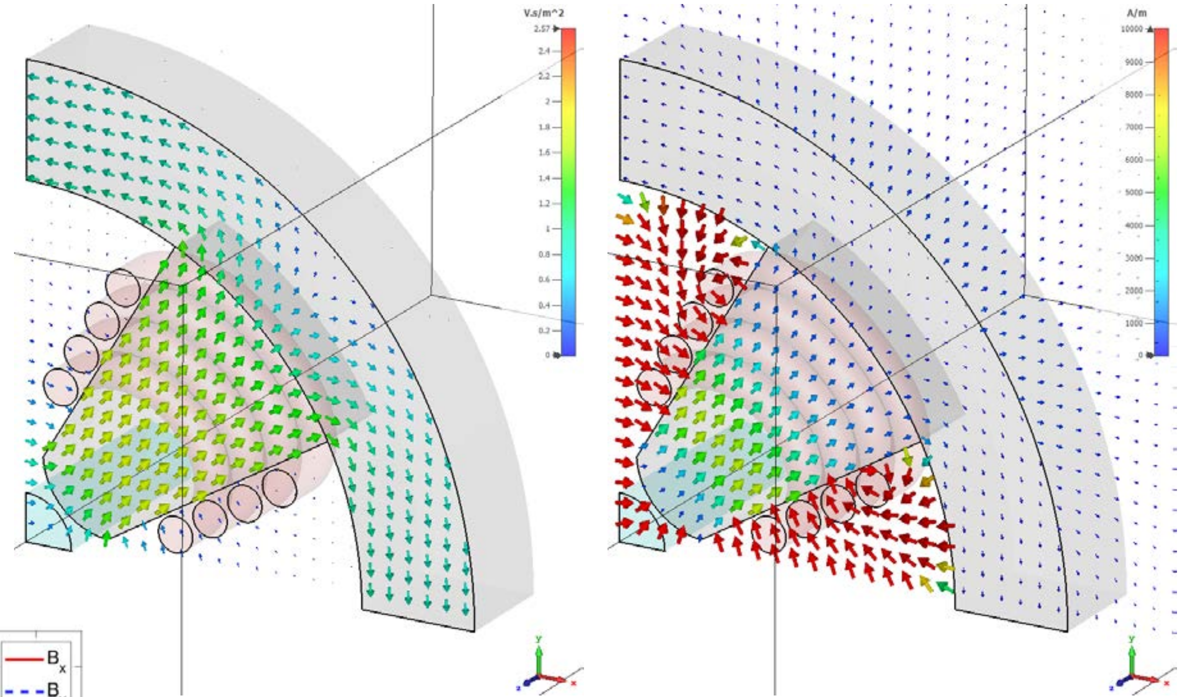
(d)

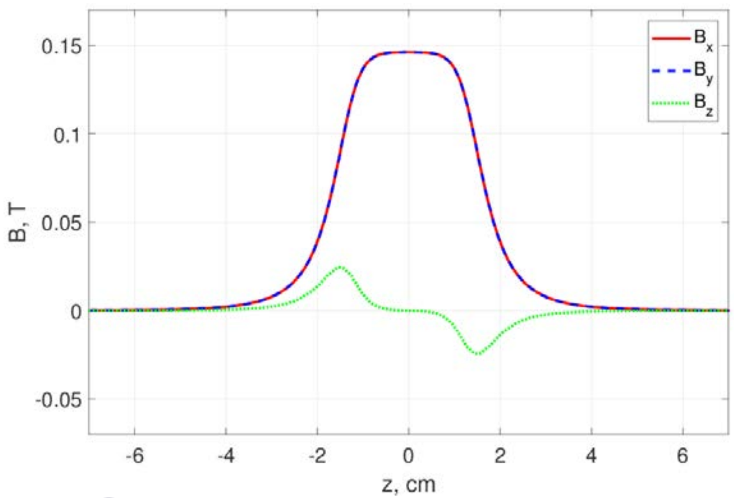
DTL tank 1 EM quadrupoles are installed inside drift tubes:
(a) yoke and pole pieces (iron);
(b) current coil (copper, hollow);
(c) coil assembled with iron;
(d) quadrupole fully assembled.

EM quadrupole gradients are adjusted by changing current: gradient G=73.5 T/m at ~562 A. GL = 2.59 T in Q1.

LANSCE DTL EM quadrupoles – material replacement

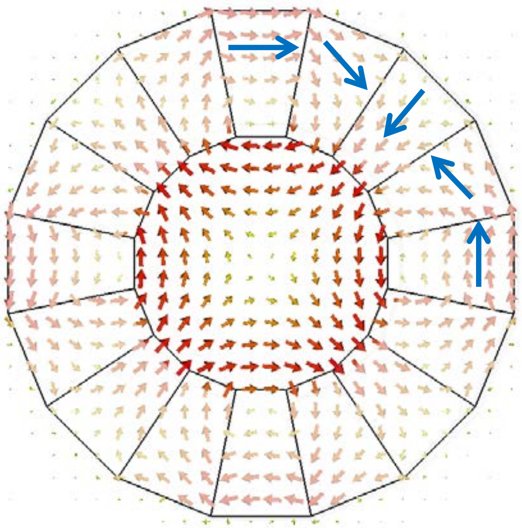






The design strength in Q1 with C1006 steel is achieved at higher current, ~586 A.

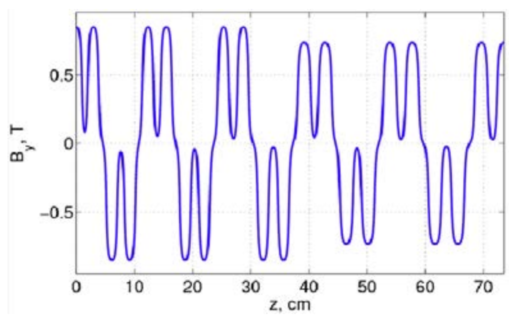
Permanent-magnet quadrupoles

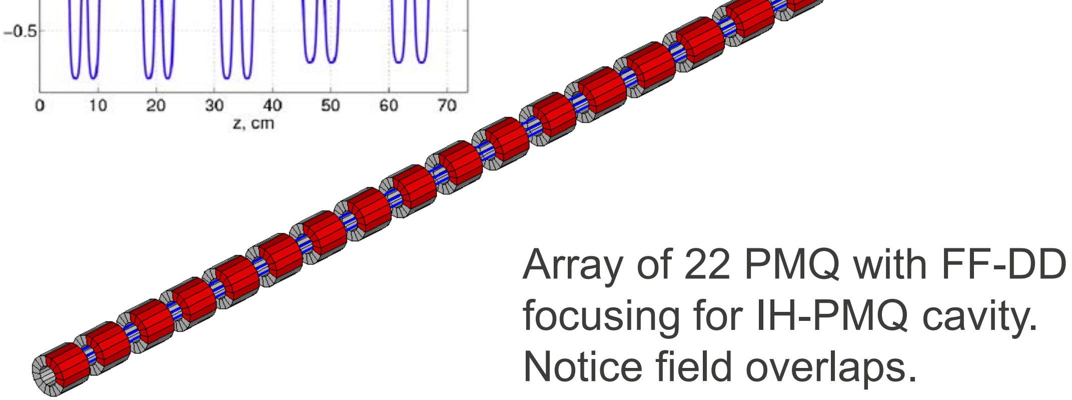


Magnetic field in the cross section of M=16 PMQ calculated with CST EM Studio. For r_{in} = 5.5 mm, r_{out} = 11 mm, G= 170 T/m; length L=19 mm.

Permanent-magnet quadrupoles are assembled from segments of PM materials, usually SmCo or NdFeB, with properly oriented magnetization vectors in segments. The gradient of such a quadrupole with M = 16 segments (typically M = 12, 16), the remnant field B_r (~1 T), and radii r_{in} and r_{out}, is

$$G = 2B_r\left(\frac{1}{r_{in}} - \frac{1}{r_{out}}\right)K_2; \quad K_2 = \cos^2\frac{\pi}{M}\,\frac{\sin(2\pi/M)}{2\pi/M} \cong 0.937.$$

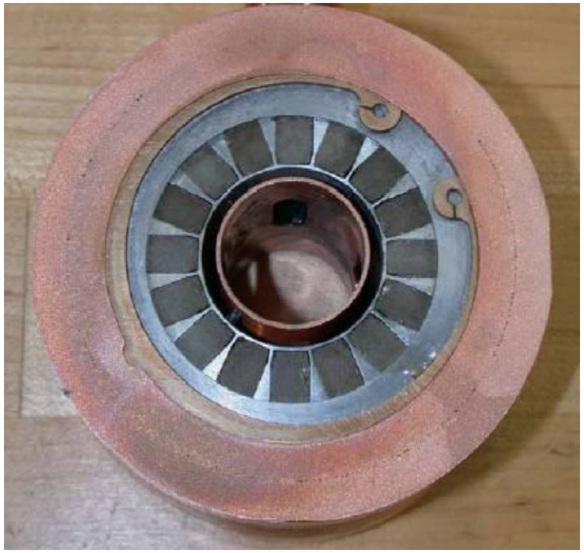




Array of 22 PMQ with FF-DD focusing for IH-PMQ cavity. Notice field overlaps.

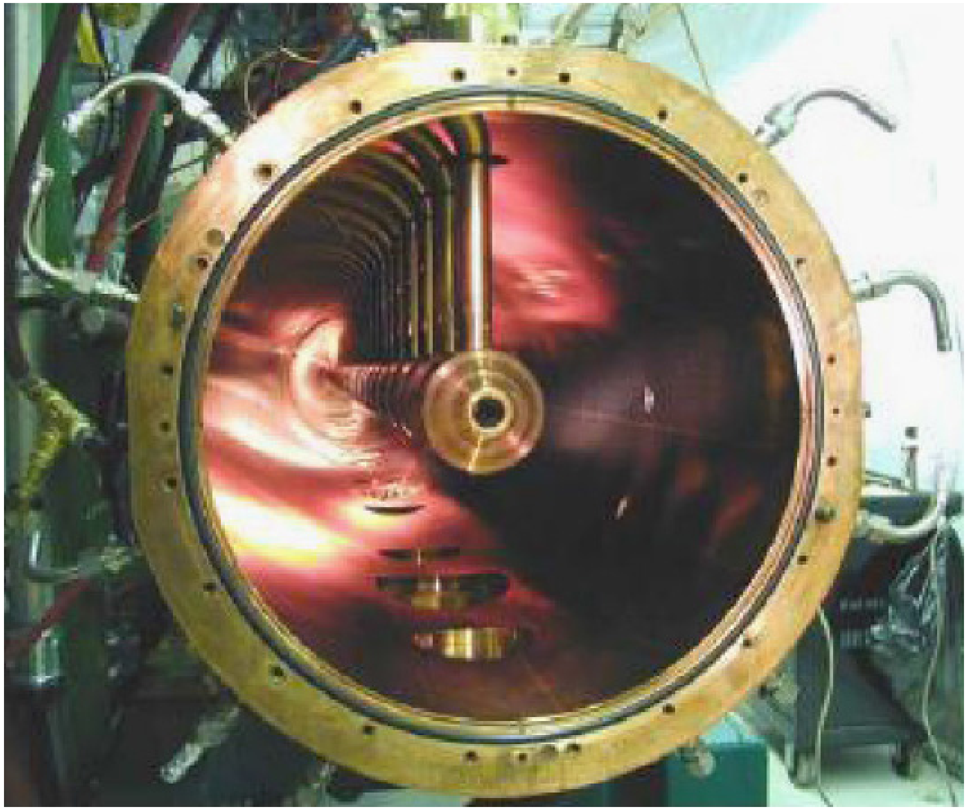
Permanent-magnet quadrupoles are installed in the DTL of the Spallation Neutron Source (SNS).

Permanent-magnet quadrupoles in SNS



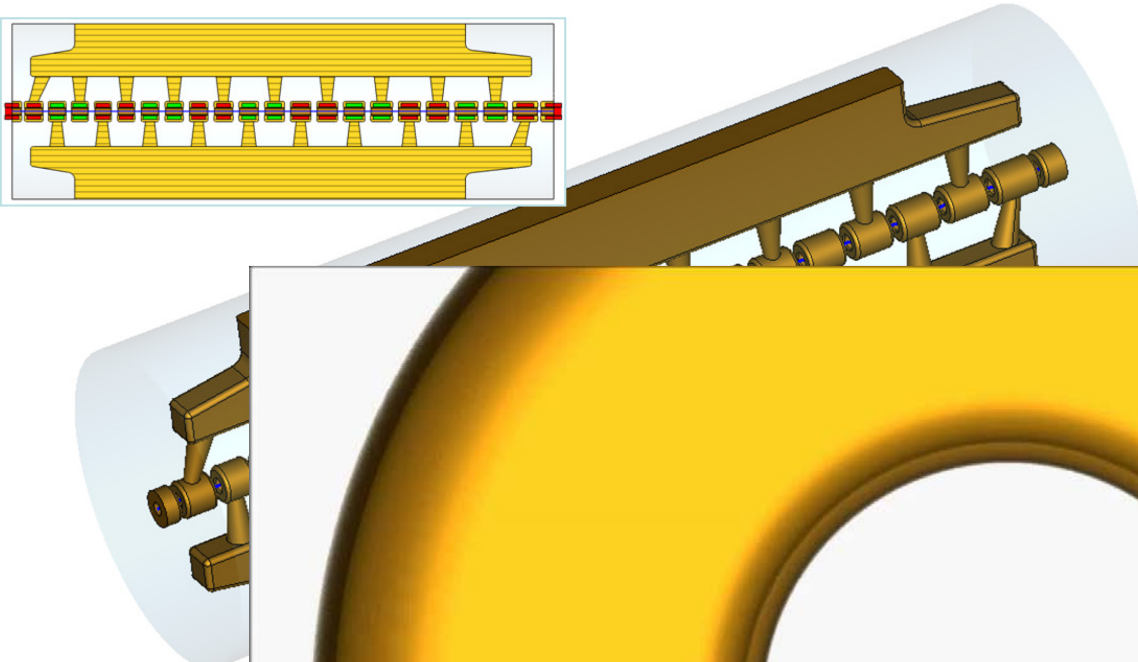
Cut of the SNS DTL drift tube with PMQ. The bore aperture diameter is 2.5 cm.

Permanent-magnet quadrupoles (PMQ) are installed in the DTL of the Spallation Neutron Source (SNS, Oak Ridge). Now PMQ are also installed in Linac 4 at CERN.



SNS DTL tank 3 with PMQs inside drift tubes (DTs). Some DTs contain beam position monitors (BPM). FFODDO focusing structure.

Example: Inter-digital H-mode (IH) structure with PMQ



IH-PMQ structure for deuterons from $\beta = v/c = 0.04$ to 0.055. Focusing structure FOFODODO. CST Particle Studio simulations.

Summary 1

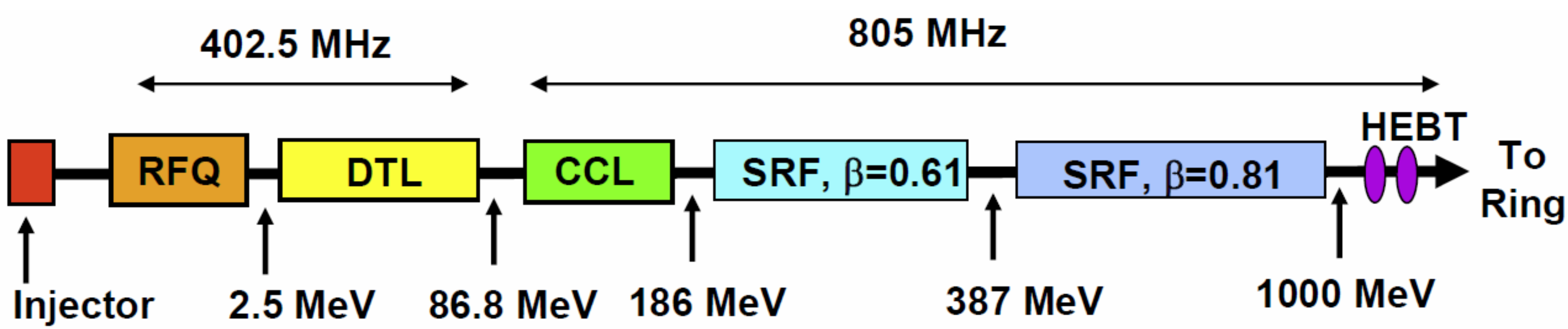
- Linacs and RF are closely related.
- In ion linacs synchronism between accelerated particles and RF is achieved by designing a spatial structure with $L_c \sim \beta\lambda$. Fixed velocity profile! Independent-cavity structures can also used, e.g., in heavy-ion linacs, for more flexibility.
- Longitudinal and transverse beam focusing cannot be achieved simultaneously in RF fields. External transverse beam focusing is usually added.

Linac parts

Linac scheme: particle source + accelerating structure(s)

Electron linacs: electron gun + linac (TW or SW β=1 structure); with some tricks.

Ion linacs: ion source (injector) + various structures for different values of β.



Scheme of SNS linac:

- RFQ = RF Quadrupole accelerator
- DTL = Drift-Tube Linac
- CCL = Coupled-Cavity Linac
- SRF = SC RF linac
- HEBT = High-Energy Beam Transport

Typical RF linac structures

Front end

- Ion source
- RFQ

Medium-energy section

- DTL
- SDTL
- IH-structure
- SC cavities

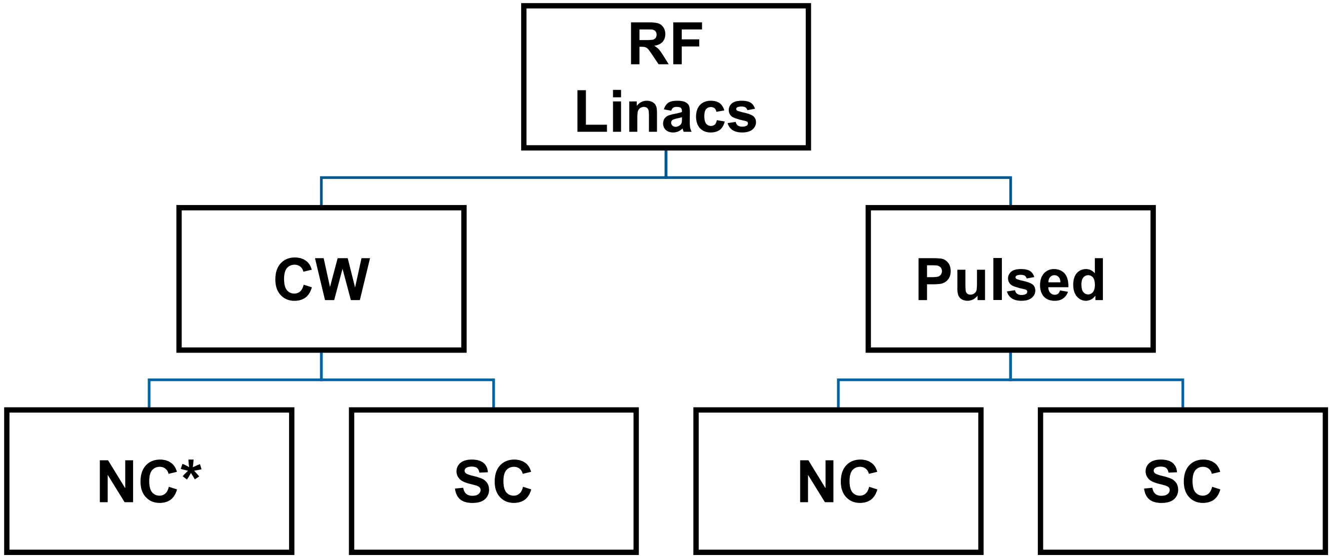
Frequency jump
Lattice transition

High-energy section

Coupled Cavity Linac
(Side coupled structure
Disk-and Washer Structure
Annular Coupled Structure)
SC Cavities
(Elliptical
Spoke-loaded TEM-class)

From P. Ostroumov (2012)

RF Linac Types



CW – NC*

- **ISAC-I**
- **RIKEN inj.**
- **LEDA RFQ**
- **SARAF RFQ**

*Low-energy, several MeV/u Heavy-ions

CW – SC

- **ATLAS**
- **ISAC-II**
- **INFN**
- **SARAF**
- **SPIRAL-2**
- **FRIB**
- Project X
- EURISOL
- ADS projects

Pulsed – NC

- **LANSCE**
- **Synchrotron Injectors (FNAL,KEK, CERN, IHEP….)**
- **MMF (Moscow)**
- **SNS**

Pulsed – SC

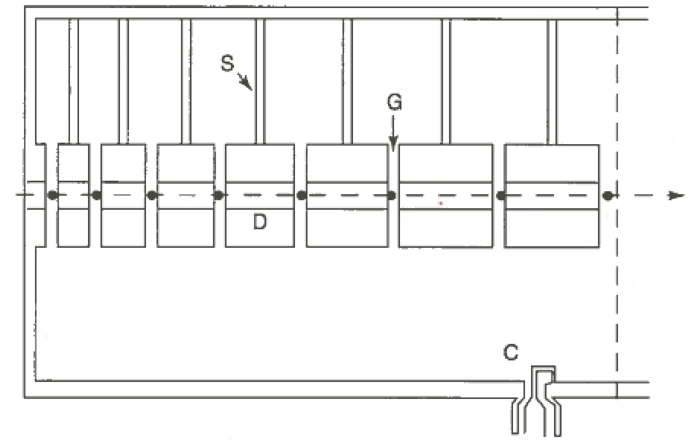
- **SNS**
- ~~CERN SPL~~
- ESS

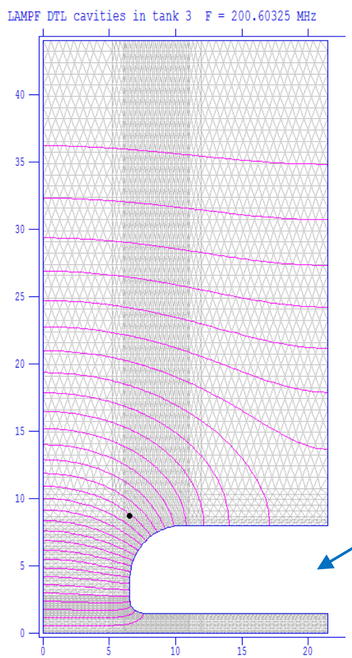
From P. Ostroumov (2012)

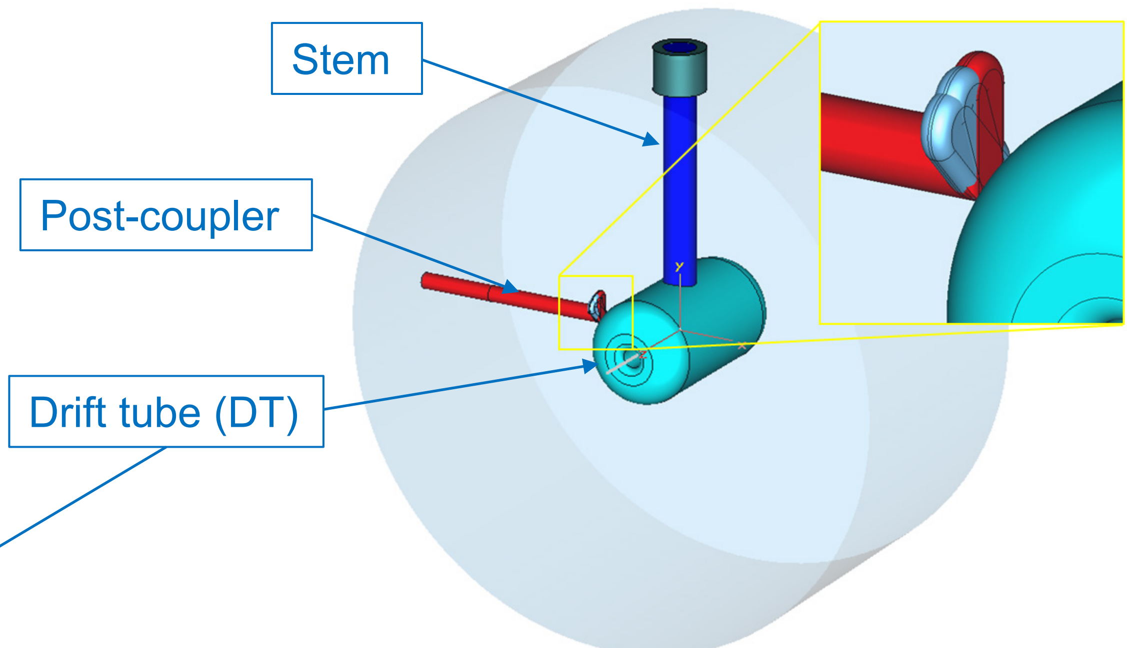
Drift-Tube Linac (DTL)

Alvarez DTL structure (1946):

- TM_{010}-like mode (E_z, E_r, B_θ)
- DTs hide the beam bunches during the decelerating phase of electric field
- cell length $L_c = \beta\lambda$
- long cavities (tanks) are more efficient
- field stabilization by post-couplers in long tanks

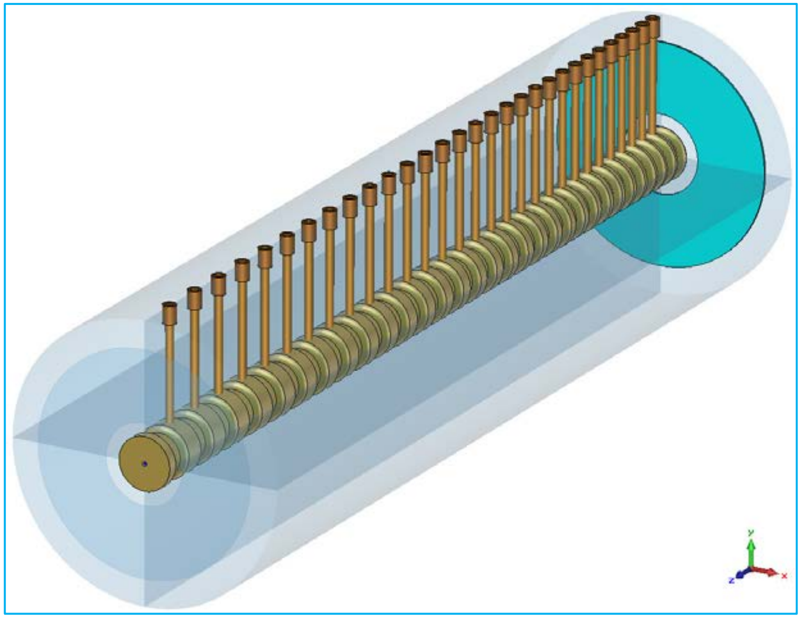






Electric field lines (Superfish, left) and CST model of cell 98 (1^{st} in T3) of the LANSCE DTL.

LANSCE DTL (1968)



CST model of Tank 1

Usually, the average longitudinal field E_0 is constant (flat) along the tank length but in T1 it is ramped (increasing). Tilt tuners.

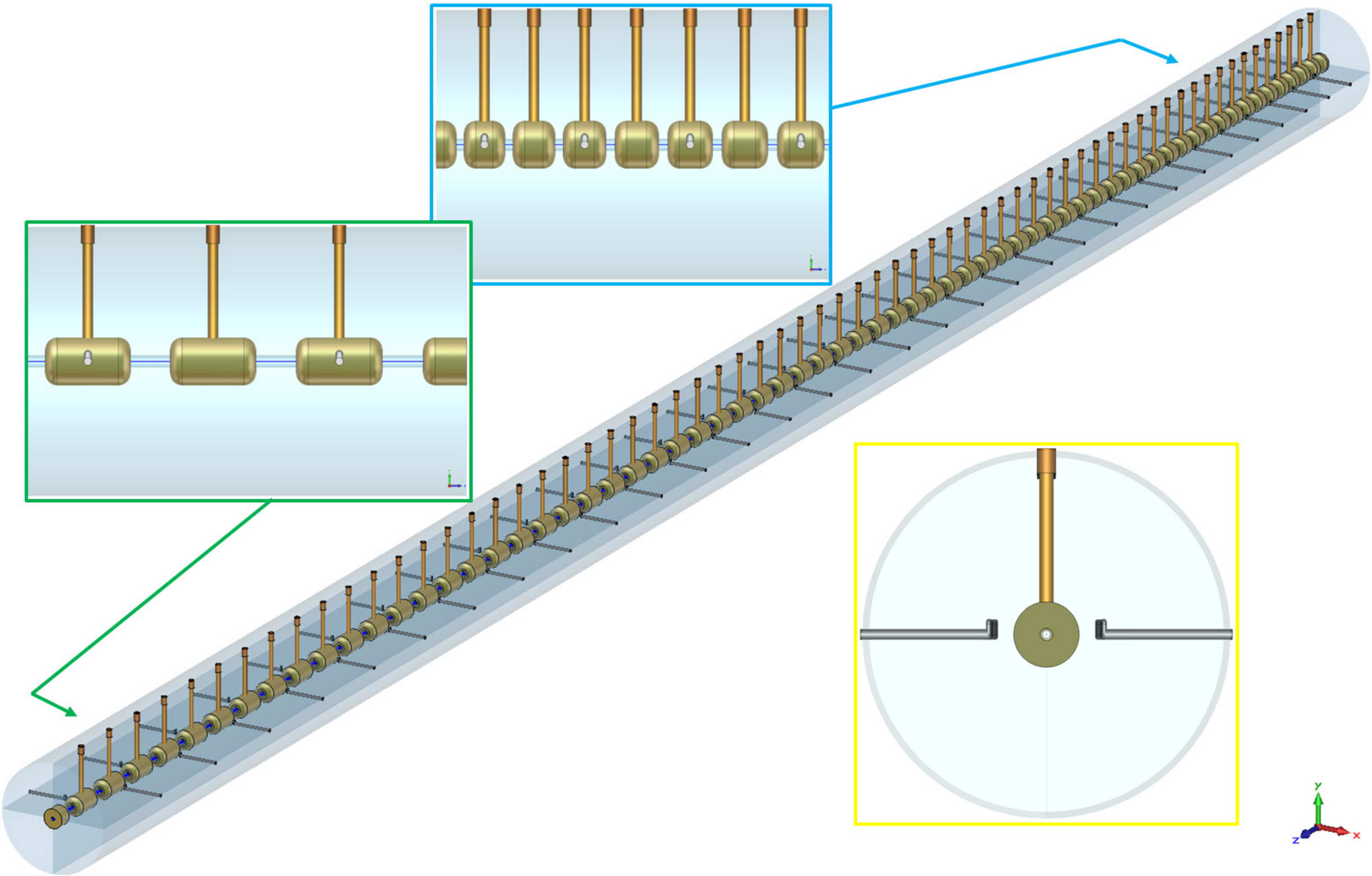
Table 4.1 DTL parameters for the LANSCE proton accelerator.

	Tank 1	Tank 2		Tank 3	Tank 4
Cell number	1 to 31	32 to 59	60 to 97	98 to 135	136 to 165
Energy in (MeV) β	0.75 0.04	5.39 0.107		41.33	72.72
Energy out (MeV) β	5.39	41.33 0.287		72.72 0.37	100.00
Energy gain (MeV)	4.64	35.94		31.39	27.28
Tank length (cm)	326.0	1968.8		1875.0	1792.0
Tank diameter (cm)	94.0	90.0		88.0	88.0
Drift-tube diameter (cm)	18.0	16.0		16.0	16.0
Drift-tube corner radius (cm)	2.0	4.0		4.0	4.0
Bore radius (cm)	0.75	1.0	1.5	1.5	1.5
Bore corner radius (cm)	0.5	1.0		1.0	1.0
g/L	0.21–0.27	0.16–0.32		0.30–0.37	0.37–0.41
Number of cells	31	66		38	30
Number of quads	32	29	38	20	16
Quad gradient (kG/cm)	8.34–2.46	2.44–1.89	1.01–0.87	0.90–0.84	0.84–0.83
Quad length (cm)	2.62–7.88	7.88	16.29	16.29	16.29
E_0 (MV/m)	1.60–2.30	2.40		2.40	2.50
ϕ_s (°)	−26	−26		−26	−26
Power (MW)	0.305	2.697		2.745	2.674
Intertank space (cm)	15.90	85.62		110.95	–
Transit-time factor, T	0.72–0.84	0.87–0.80		0.82–0.74	0.74–0.68
Mean ZT^2 (MΩ/m)	26.8	30.1		23.7	19.2

Total length including intertank spaces = 61.7 m

The best efficiency (higher effective shunt impedance) for DTL is achieved in the beam velocity range β = 0.1-0.3. At LANSCE it is used for wider range, β = 0.04-0.43.

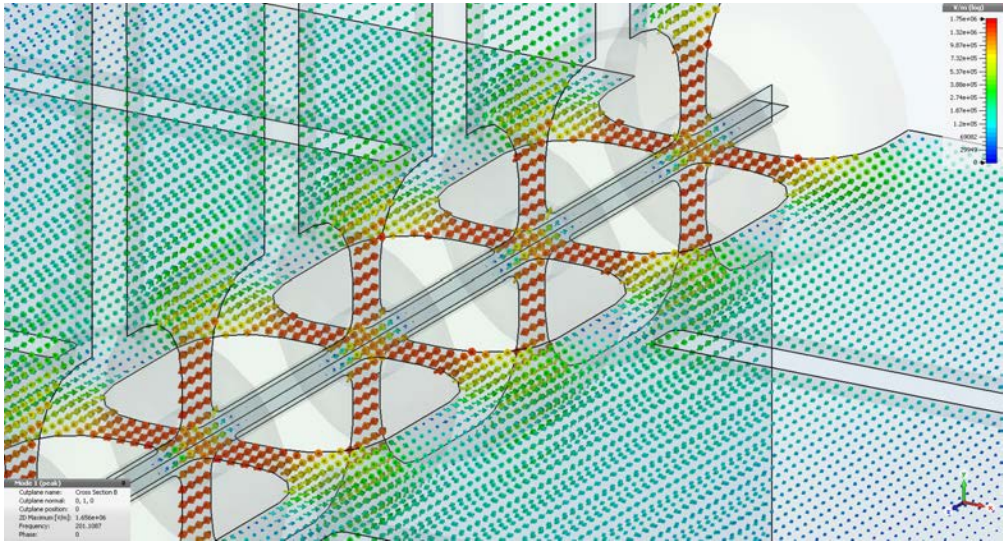
LANSCE DTL tank models

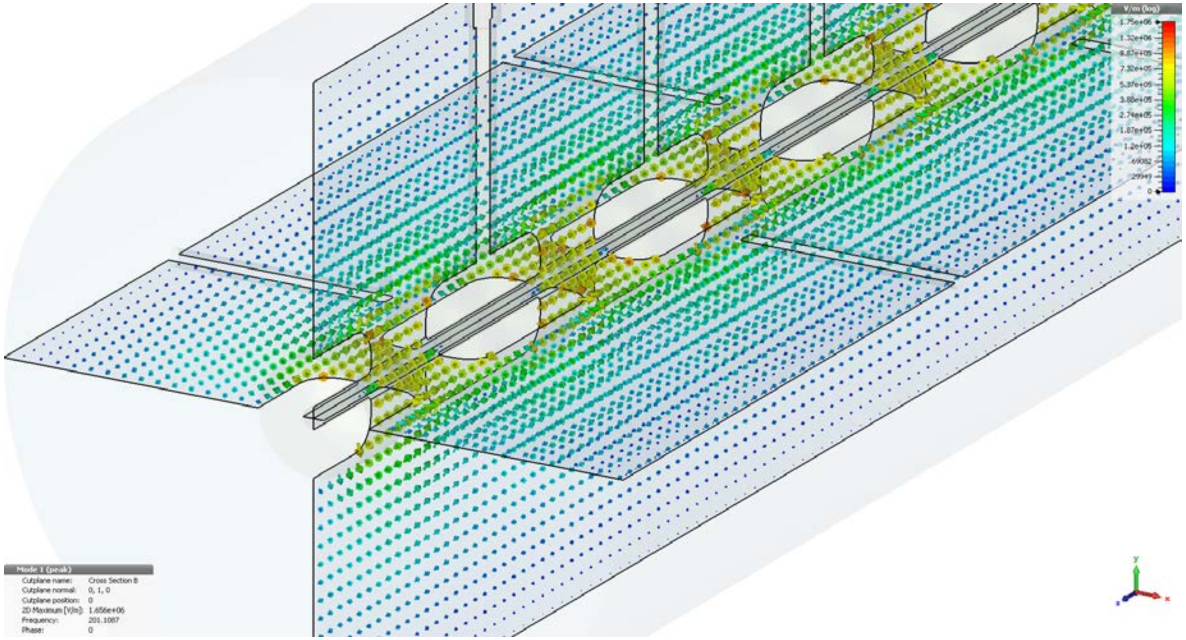


CST model of the LANSCE DTL tank 2: 66 cells, 19.68-m long, β = 0.107-0.287

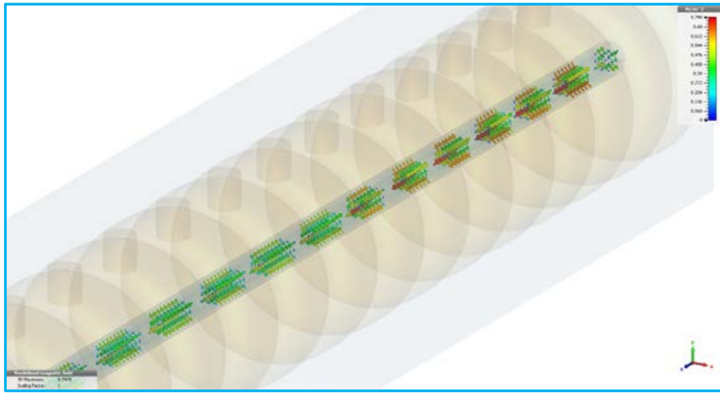
Fields in DTL tanks

Electric field arrows (MWS norm.) in *x* & *y*-planes near the entrance (right) and exit (bottom) of DTL tank 2.

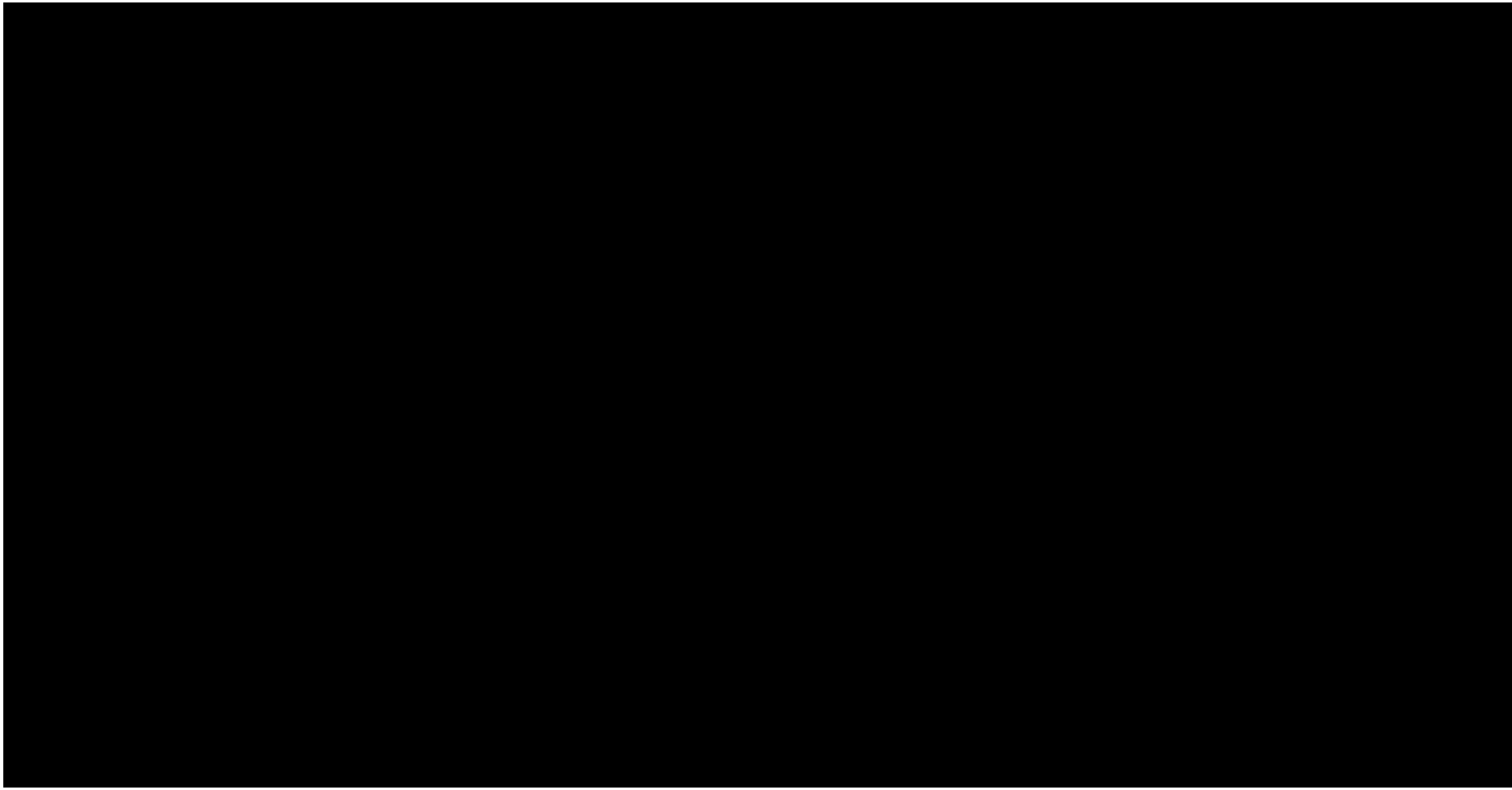




Magnetic fields of quadrupoles near the entrance of DTL tank 1 (imported in PS).

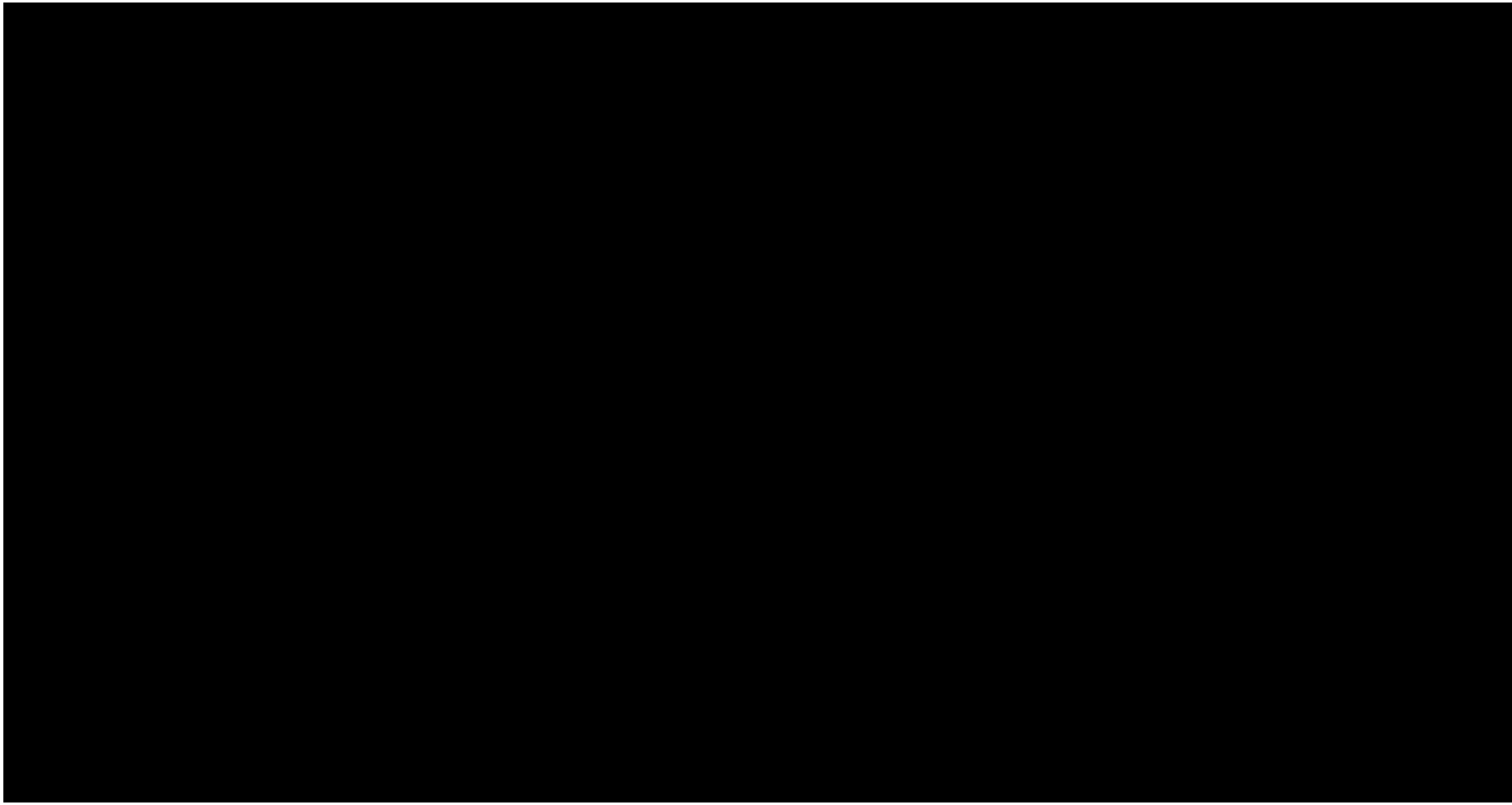


DTL – PS simulations in LANSCE DTL tanks



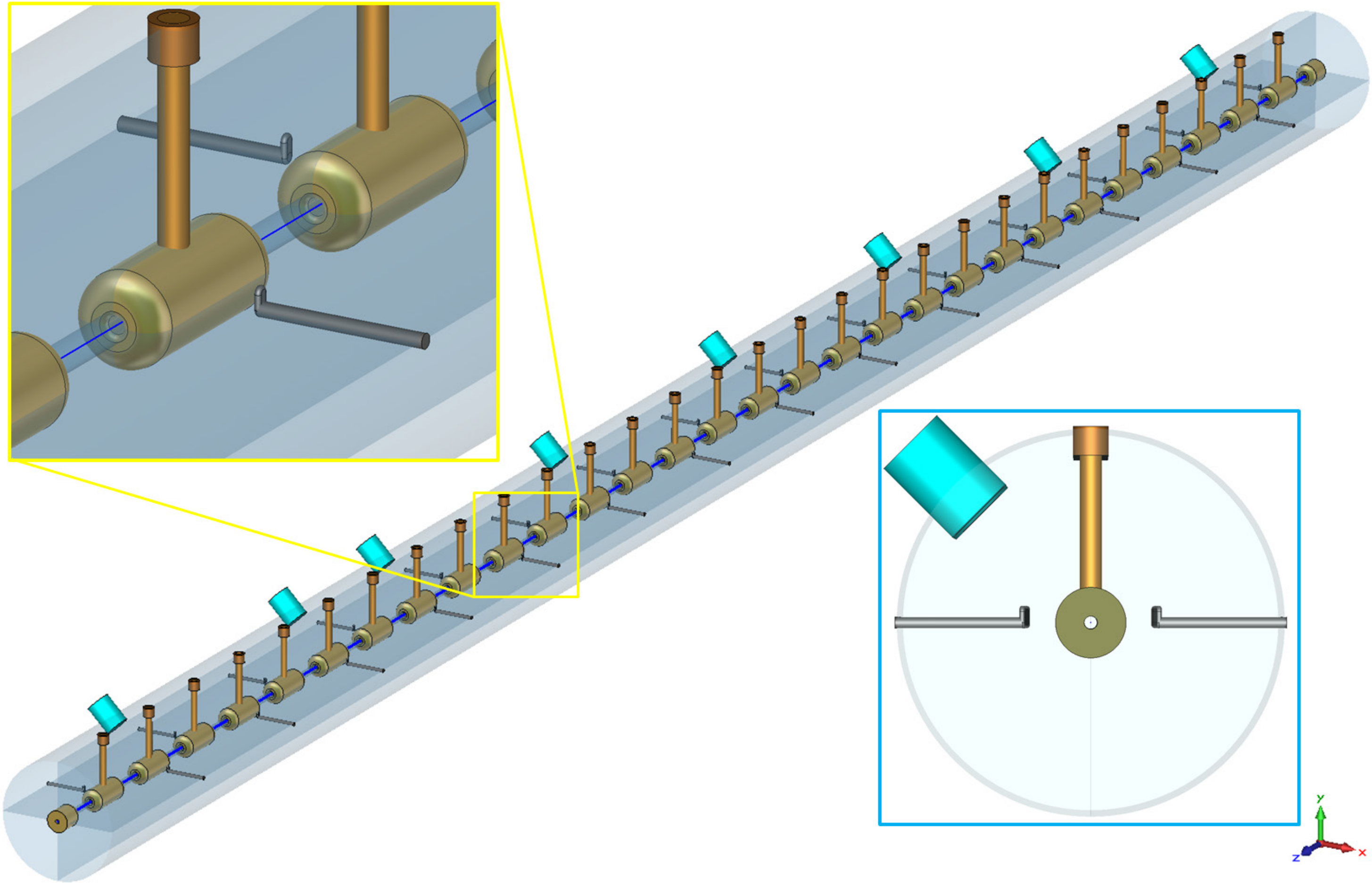
Particle Studio simulations of 10 RF periods (10x10K) of 18-mA proton beam injected into DTL tank 1. Transmission 85% (80.6% in bunches, 4.4% in the tail).

DTL – PS simulations in LANSCE DTL tanks



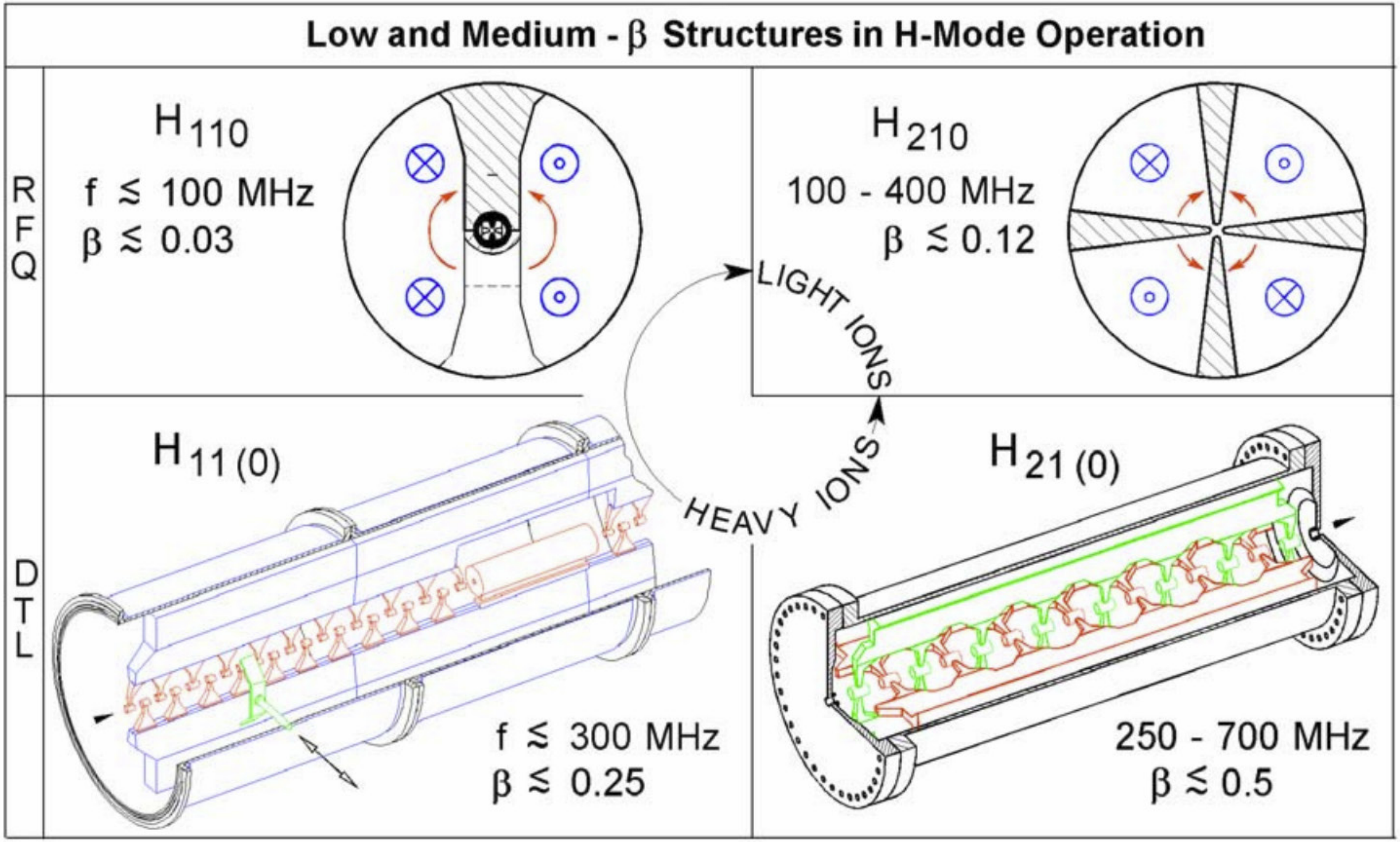
Particle Studio simulations of 10 RF periods (10x10K) of 18-mA proton beam injected into DTL tank 1 – end-tank view. Transmission 85% (bunches 80.6%, tail 4.4%).

DTL cavities: tuning



Frequency and field profile slug tuners in the DTL tank 4 model

H-mode DTL – another type of DTL

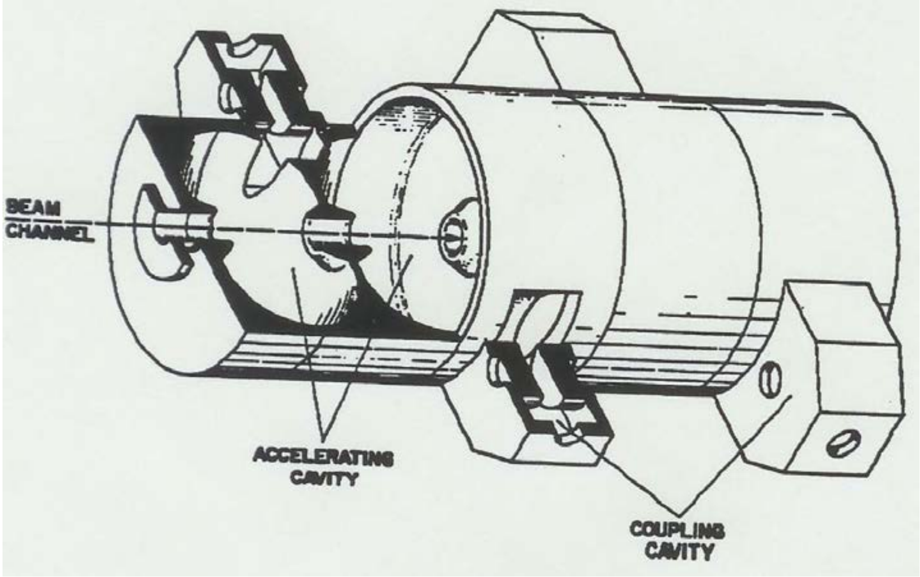


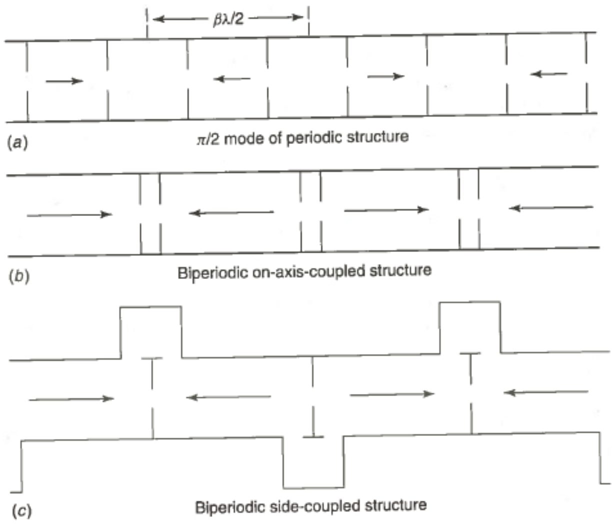
TE-mode DTL cavities: interdigital H_{110} (IH) and cross-bar H_{210} (CH)

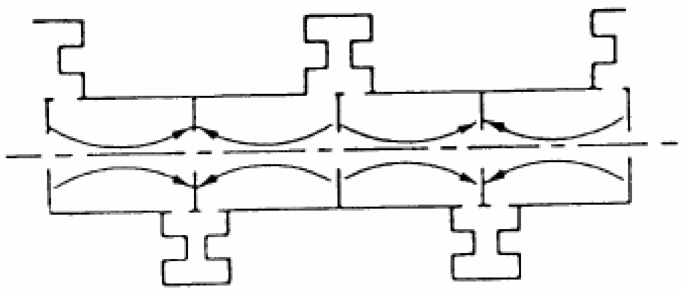
Coupled-Cavity Linac (CCL)

The coupling cells are not excited when the structure is tuned.

Various types of CCL (see below) are used at relatively high velocities, typically for $\beta \geq 0.4$.





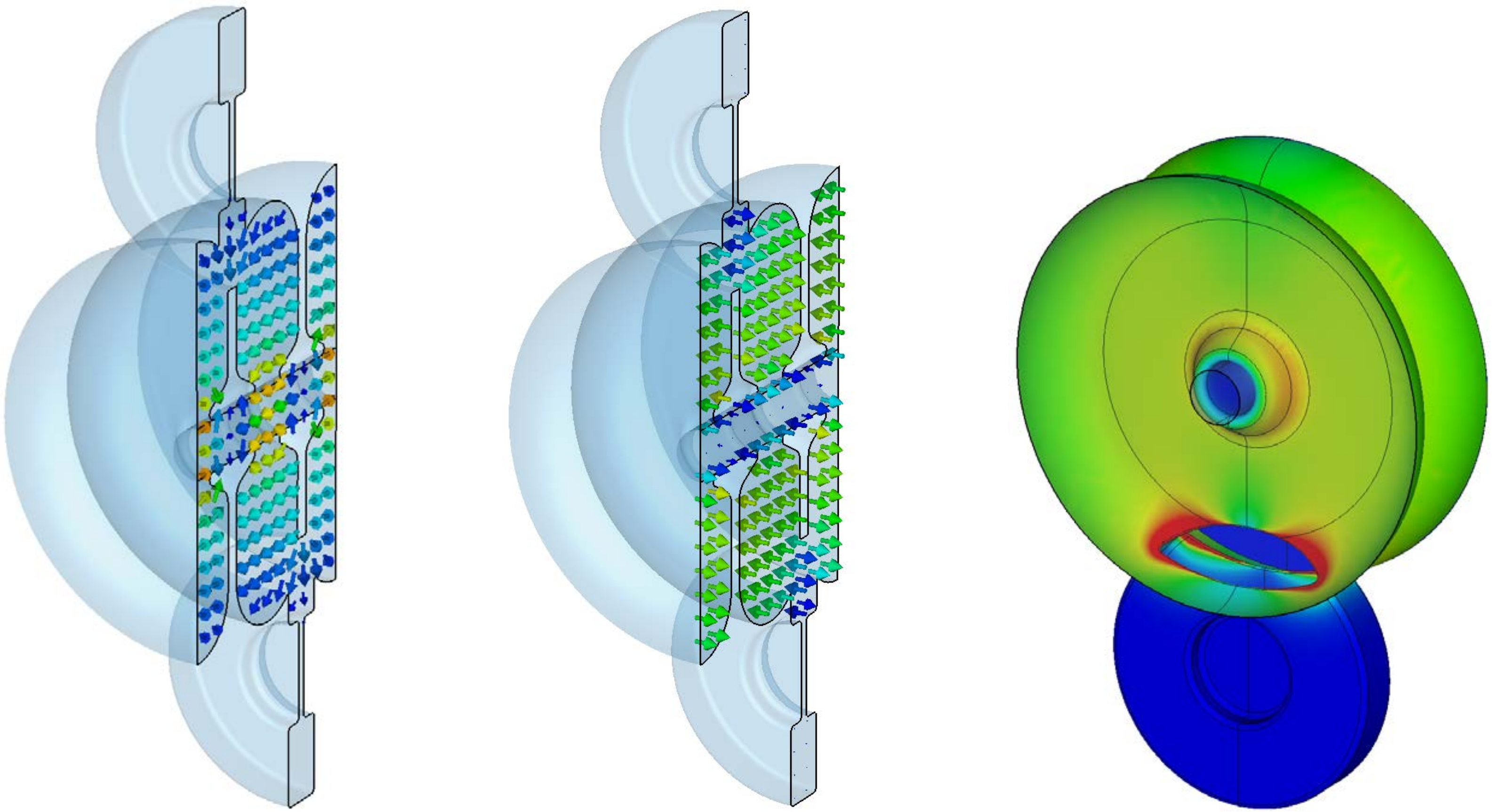


Energy range 100-800 MeV
High shunt impedance: up to 50 MΩ/m

Los Alamos Side Coupled Structure (1968)

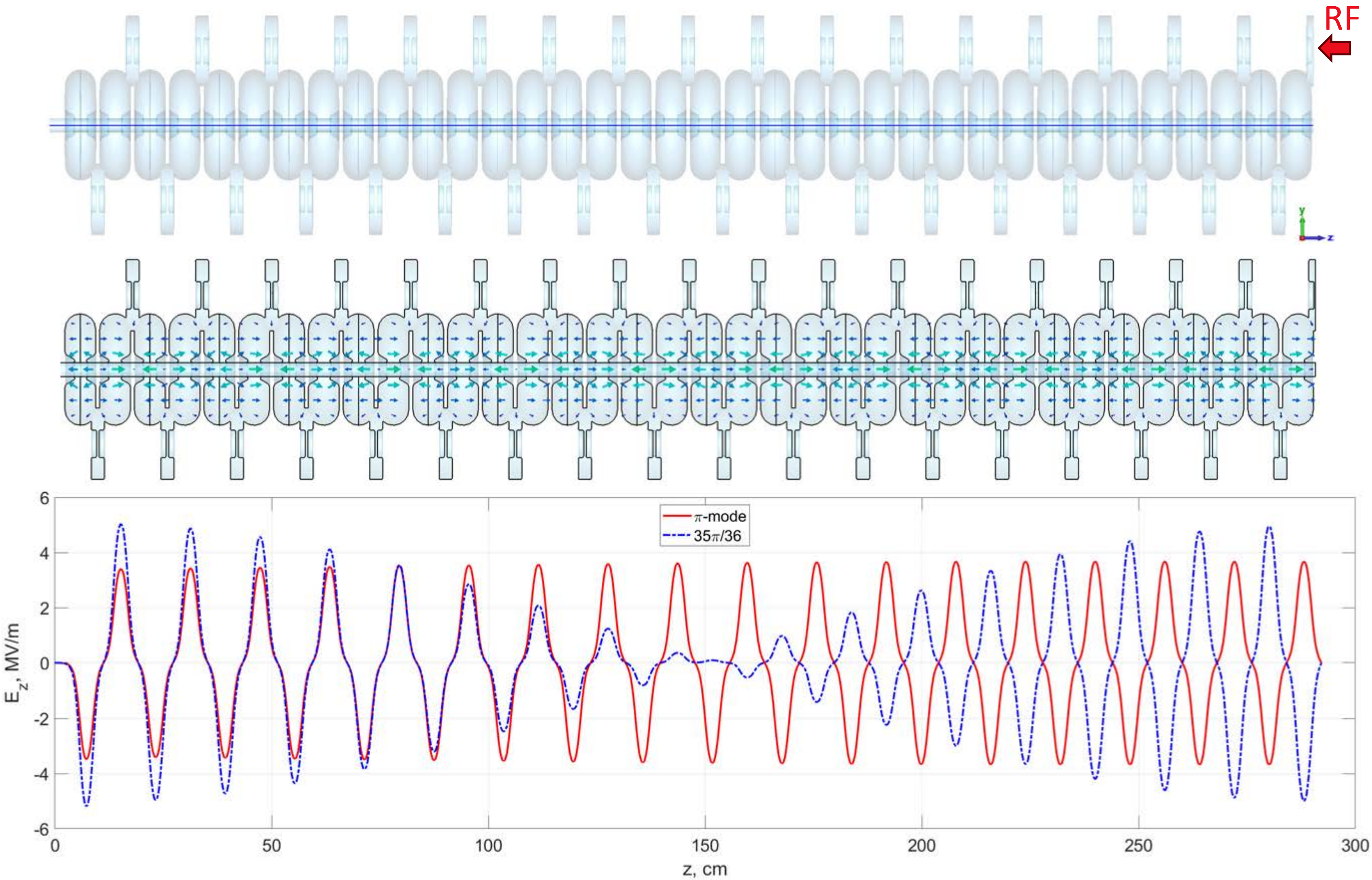
LANSCE CCL – Module 5 Tank 1 (M5T1)

M5T1: 36 accelerating cells with 35 coupling cells (18 periods); length 2.89 m + 72-cm drift.
- Effective shunt impedance ZT^2 = 31.5 MΩ/m.
- Energy in 100 MeV (β = 0.43), out 103.4 MeV.



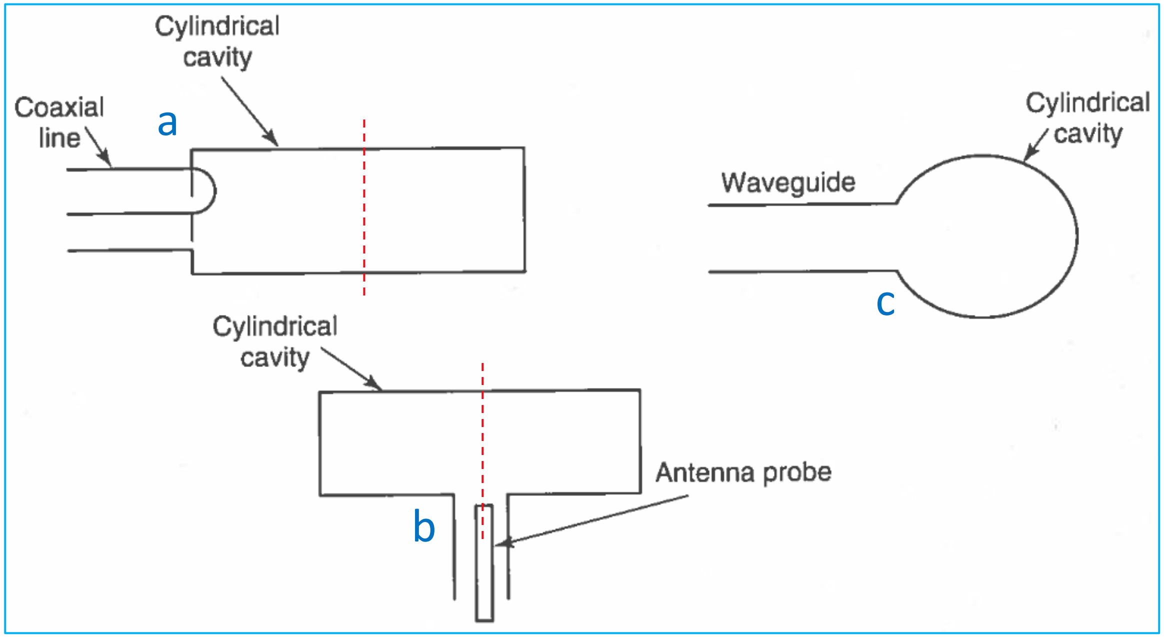
Electric (left) and magnetic (middle) fields and surface-current magnitude (right) in one period of M5T1

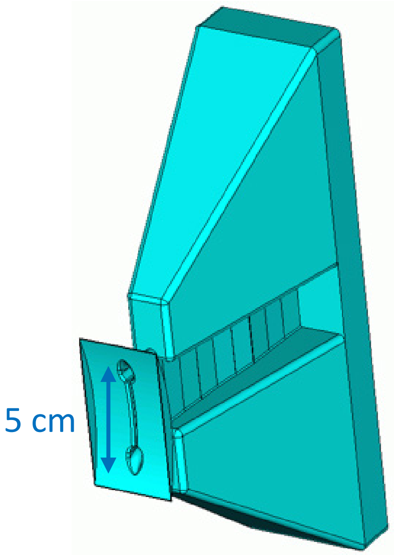
LANSCE CCL – Module 5 Tank 1



M5T1 cavity (top); electric field of the operating π-mode (middle); on-axis longitudinal electric fields of the two lowest modes: π-mode (red) and mode 35/36 π per AC (blue dashed)

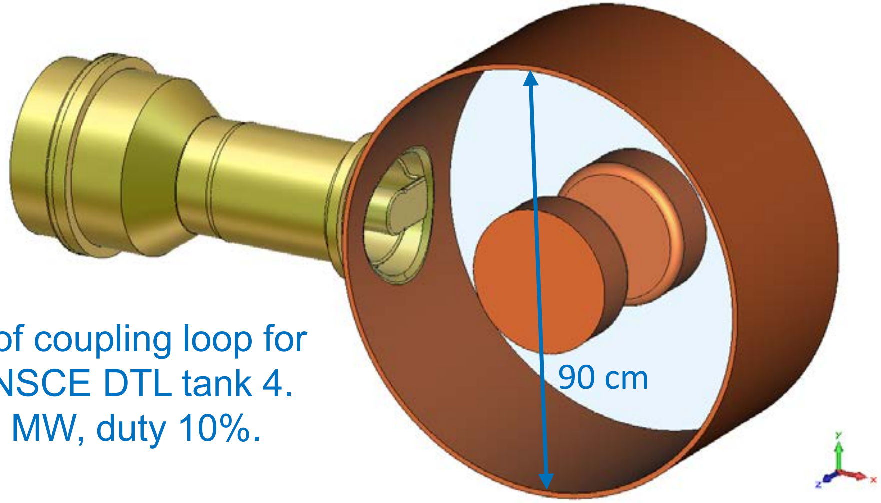
Coupling RF power to cavities





“Dog-bone” coupling iris for high-power FEL photoinjector. Up to 0.5 MW at 100% duty.

Methods of coupling to RF cavities:
(a) magnetic – current loop;
(b) electric – antenna;
(c) magnetic – iris WG-cavity



Model of coupling loop for the LANSCE DTL tank 4. Up to 3 MW, duty 10%.

Summary 2

- RF cavities and some common accelerating structures (DTL, CCL) are reviewed.

Figures of merit for accelerating structures

Quality factor (stored energy U, averaged power loss P) $$Q = \frac{\omega U}{P}$$

Shunt impedance (total cavity voltage V_0) $$R_{sh} = \frac{V_0^2}{P}$$

Effective shunt impedance (effective voltage $V_0 T$) $$R_{eff} = R_{sh} T^2$$

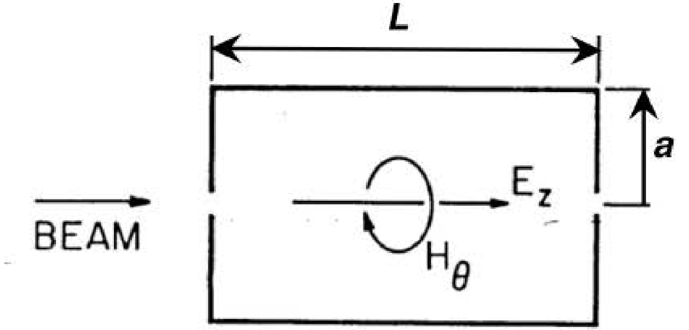
Shunt impedance per unit length (voltage $V_0 = E_0 L$) $$Z = \frac{E_0^2}{P/L}$$

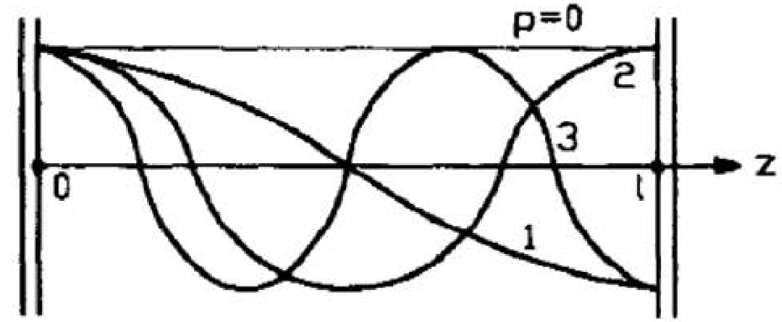
Effective shunt impedance per unit length (Z_{eff}) $$ZT^2 = \frac{(E_0 T)^2}{P/L}$$

Ratio R_{eff}/Q is independent of surface losses and depends only on the cavity (structure) geometry $$\frac{R_{eff}}{Q} = \frac{(V_0 T)^2}{\omega U}$$

Ratios $E_{\text{max}}/E_{\text{acc}}$ ($E_{\text{acc}} = E_0 T$) and $B_{\text{max}}/E_{\text{acc}}$ – lower is better. The latter is very important for SC cavities.

RF cavities: cylindrical resonator (pillbox)





Longitudinally integer number of half-variations can be excited

$$k_z = \frac{\pi p}{L}$$

Transverse boundary condition:

$$E_z(a) = 0 \qquad J_n(k_r a) = 0 \quad k_r = \frac{\upsilon_{nm}}{a}$$

$$\frac{\omega_o^2}{c^2} - k_z^2 = \frac{\upsilon_{nm}^2}{a^2}$$

Frequency of oscillation mode is

$$\boxed{\omega_o = c\sqrt{\frac{\upsilon_{nm}^2}{a^2} + \left(\frac{\pi p}{L}\right)^2}}$$

Longitudinal component

$$E_z = E_o J_n\left(\upsilon_{nm}\frac{r}{a}\right)\cos n\theta \cos\frac{\pi p z}{L}$$

mode TM_{nmp}

Example: TM_{010} mode

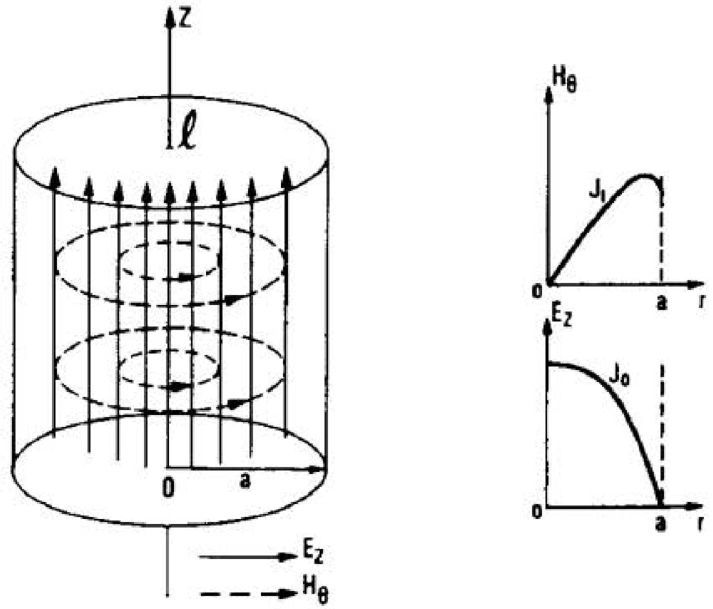
$J_1'(x) = 0 \quad x_1 = 1.841 \quad J_1(x_1) = 0.5819$

$J_1(2.405) = 0.5191$

Field components
$$E_z = E_o J_o(\upsilon_{01}\frac{r}{a})\cos\omega_o t$$
$$B_\theta = -\frac{E_o}{c} J_1(\upsilon_{01}\frac{r}{a})\sin\omega_o t$$

Boundary condition
$$E_z(a) = 0$$
$$\upsilon_{01} = 2.405$$

Frequency of resonator
$$k_z = 0$$
$$\omega_o = 2\pi f = \frac{c\,\upsilon_{01}}{a}$$
$$\boxed{f = \frac{2.405\,c}{2\pi a}}$$



TM010 mode in a pill-box cavity.

Example: radius of resonator for *f* = 201.25 MHz:
$$a = \frac{2.405\,c}{2\pi f} = 0.57m$$

Note:
$$B = \mu_0 H; \quad [B] = \mathrm{T}; [H] = \mathrm{A/m}; Z_0 = \sqrt{\mu_0/\varepsilon_0} = 376.7\,\Omega; \quad [E] = [Z_0 H] = \mathrm{V/m};$$
$$c = 1/\sqrt{\mu_0\varepsilon_0}; \quad \mu_0 c = Z_0.$$

Energy dissipation in resonator and Q factor

Dissipated power is a combination of power losses inside cavity and outside cavity

$$P = P_o + P_{ext}$$

Energy stored in cavity

$$W_o = \frac{1}{2}\int_{V_o} \mu H_m^2 dV = \frac{1}{2}\int_{V_o} \varepsilon E_m^2 dV$$

Quality factor

$$Q = \frac{\omega_o W_o}{P}$$

Q-factor is a combination of unloaded quality factor of cavity and external quality (loaded Q factor)

$$\frac{1}{Q} = \frac{1}{Q_o} + \frac{1}{Q_{ext}}$$

External quality factor

$$Q_{ext} = \frac{\omega_o W_o}{P_{ext}}$$

Losses in metal with surface resistance R_s [Ohm]

$$P_o = \frac{R_s}{2}\int_S H_m^2 dS$$

$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$, where σ is the surface conductivity,

and δ is the skin depth $\delta = \sqrt{2/(\mu_0\sigma\omega)}$.

Unloaded quality factor $Q_o = \frac{\omega_o W_o}{P_o}$

$$Q_o = \frac{\omega_o}{R_s}\frac{\int_{V_o} H_m^2 dV}{\int_S H_m^2 dS}$$

Physical meaning: $Q = G\frac{V}{S\delta}$

Quality factor of TM_{010} cavity

Magnetic field

$$H_{m\theta} = -E_o \sqrt{\frac{\varepsilon_o}{\mu_o}} J_1(\upsilon_{01} \frac{r}{a})$$

Amplitude

Energy stored in cavity

$$W_o = \frac{1}{2} \int_{V_o} \mu_o H_{m\theta}^2 dV = \frac{\pi \varepsilon_o E_o^2 L a^2 J_1^2(\upsilon_{01})}{2} = 0.135 \pi \varepsilon_o L a^2 E_o^2$$

Loss power in cavity

$$P_o = \frac{R_s}{2} \int_S H_{m\theta}^2 dS = \pi a R_s E_o^2 \frac{\varepsilon_o}{\mu_o} J_1^2(\upsilon_{01})(L+a)$$

Unloaded quality factor

$$Q_o = \frac{\omega_o W_o}{P} = \frac{\upsilon_{01}}{2R_s} \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{1}{(1+\frac{a}{L})} = 1.2025 \frac{376.7[Ohm]}{R_s} \frac{1}{(1+\frac{a}{L})}$$

For ideal copper surface $\sigma = 5.8 \cdot 10^7$ Sm/m, so that $R_s = 2.6 \cdot 10^{-4} \sqrt{f}$(MHz) Ω. At 201.25 MHz, R_s = 3.7 mΩ, and Q_0 = 66500 for a/L = 1. In practice, typically 10%-20% less.

Surface conductivity in superconducting RF cavities

For RF cavities the power loss depends on the surface resistance: for normal-conducting

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$$ scales with RF frequency as $\sqrt{f}$.

In superconducting (SC) RF cavities the surface resistance is much lower; e.g., for Nb

$$R_s(\Omega) = 9\cdot 10^{-5}\frac{f^2(GHz)}{T(^\circ K)}\exp\left(-\alpha\frac{T_c}{T}\right) + R_{res},$$

where R_{res} is the residual resistance (~1-10 nΩ), α = 1.83, and T_c = 9.2 K is the critical temperature.

SC R_s is ~10^{-5} of that in copper, and so are the cavity surface losses!

RF cavity design

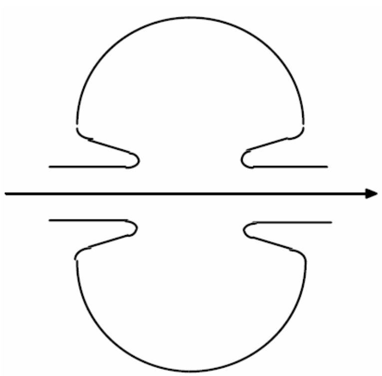
Cavity design goals depend on many factors including the cavity type and its application: maximize accelerating gradient, minimize losses (NC), minimize max surface fields, etc.

Frequency dependence of cavity parameters: *a ~ 1/f*,

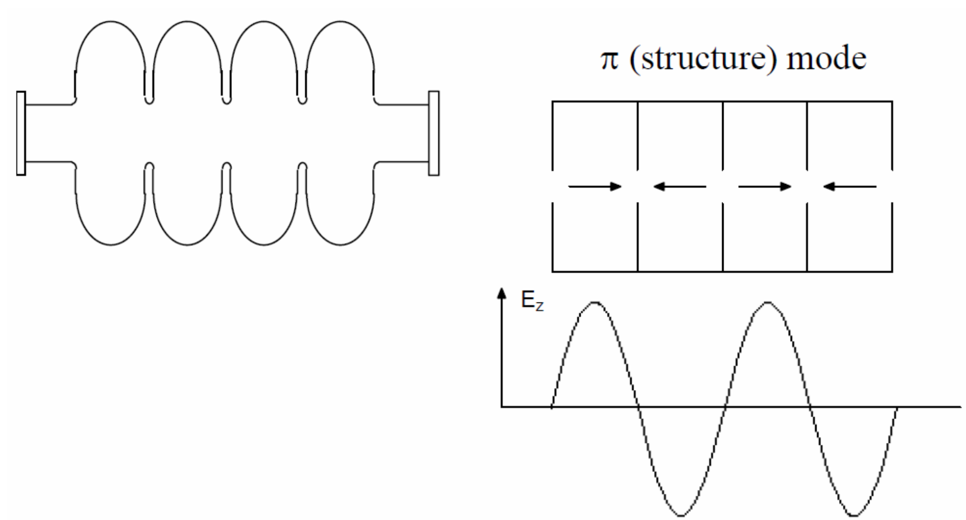
$$P \propto \begin{Bmatrix} f^{-1/2}, & \text{NC} \\ f, & \text{SC} \end{Bmatrix} \qquad Q \propto \begin{Bmatrix} f^{-1/2}, & \text{NC} \\ f^{-2}, & \text{SC} \end{Bmatrix} \qquad ZT^2 \propto \begin{Bmatrix} f^{1/2}, & \text{NC} \\ f^{-1}, & \text{SC} \end{Bmatrix}$$

Frequency choice also depends on available RF sources and beam parameters.

Changing cavity shape is the common way of achieving the design goals. Examples:



Nose-cone cavity



4-cell elliptical cavity (SC)

RF cavity design codes

- Calculation of EM fields in the cavity: frequencies, modes, secondary parameters (losses, *Q*, shunt impedance, surface fields, ...)
- Calculation methods:
  - Analytical (simple cavity shapes) + perturbation theory
  - 2D codes (axisymmetric or flat structures): Superfish, URMEL, …
  - 3D codes: CST, HFSS, Analyst, ACE-3P (Omega-3P), etc.

Los Alamos Accelerator Code Group (LAACG)

Available at laacg.lanl.gov/laacg/services/services.phtml

Poisson / Superfish

- *collection of programs for calculating static magnetic and electric fields and radio-frequency electromagnetic fields in either 2-D Cartesian coordinates or axially symmetric cylindrical coordinates.*
- *triangular mesh*
- *includes plotting and post-processing*

* Poisson / Pandira

- *static electric and magnetic fields*

* Superfish

- *radio-frequency electromagnetic fields*

Windows PC – C:\LANL contains *programs & utilities; \Docs; \Examples; etc.*

LANL Home - LANL Directory - Search LANL Web

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LAACG

Los Alamos Accelerator Code Group *

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->Parmteq
->Trace-2D/3D
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* This work is supported by the U. S. Department of Energy, Office of Science, Division of High Energy Physics.

Los Alamos National Laboratory

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Superfish (SF)

Steps for running SF (from command window or with right click):

- create geo file (test.am); $x \rightarrow z$, $y \rightarrow r$ (cm); define BC and materials
- run Automesh on test.am > test.T35 with geo and mesh
- run Fish on test.T35 > test.T35 with fields
- double-click test.T35 to see field lines
- run post-processing of test.T35 > test.sfo to get cavity parameters

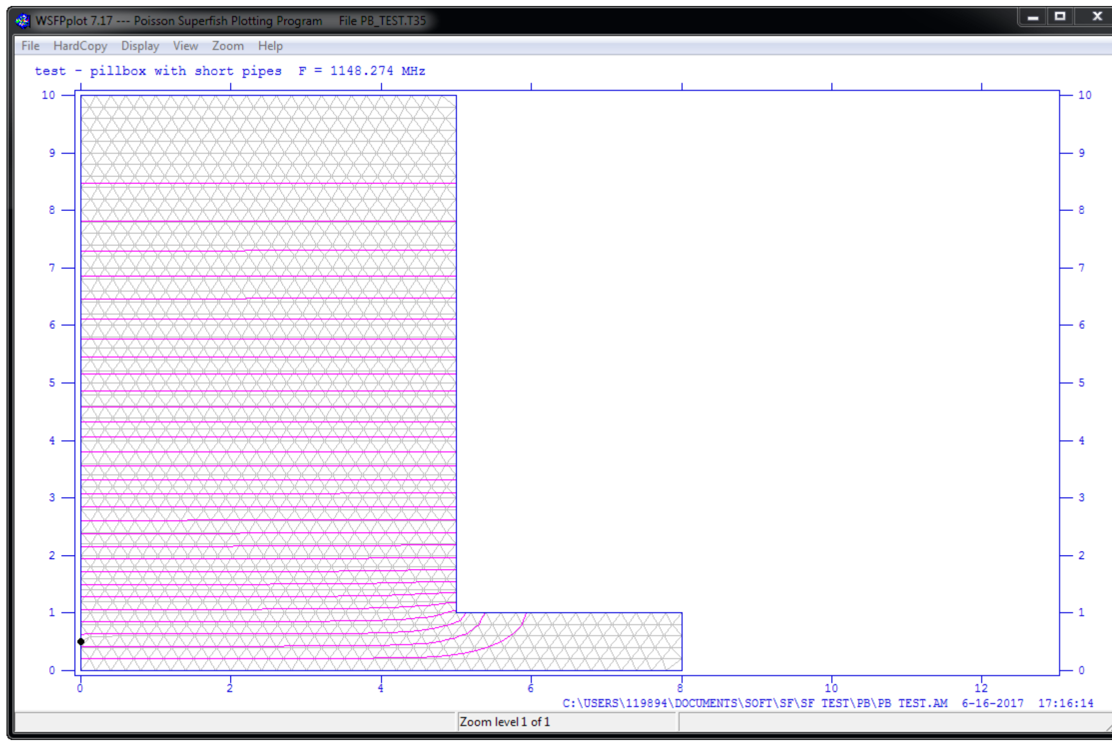
Alternative: run Autofish on test.am

pb_test.am

```
test - pillbox with short pipes

&reg kprob=1,
dx=0.2,dy=0.2,
xdri=0.,ydri=0.5,freq=1500.00,dslope=-1,
npoint=7 &

&po x= 0.0,  y= 0.0 &
&po x= 0.0,  y= 10.0 &
&po x= 5.0, y= 10.0 &
&po x= 5.0, y= 1.0 &
&po x= 8.0, y= 1.0 &
&po x= 8.0, y= 0.0 &
&po x= 0.0,  y= 0.0 &
```



Superfish input file

SF input (*.am or *.af):

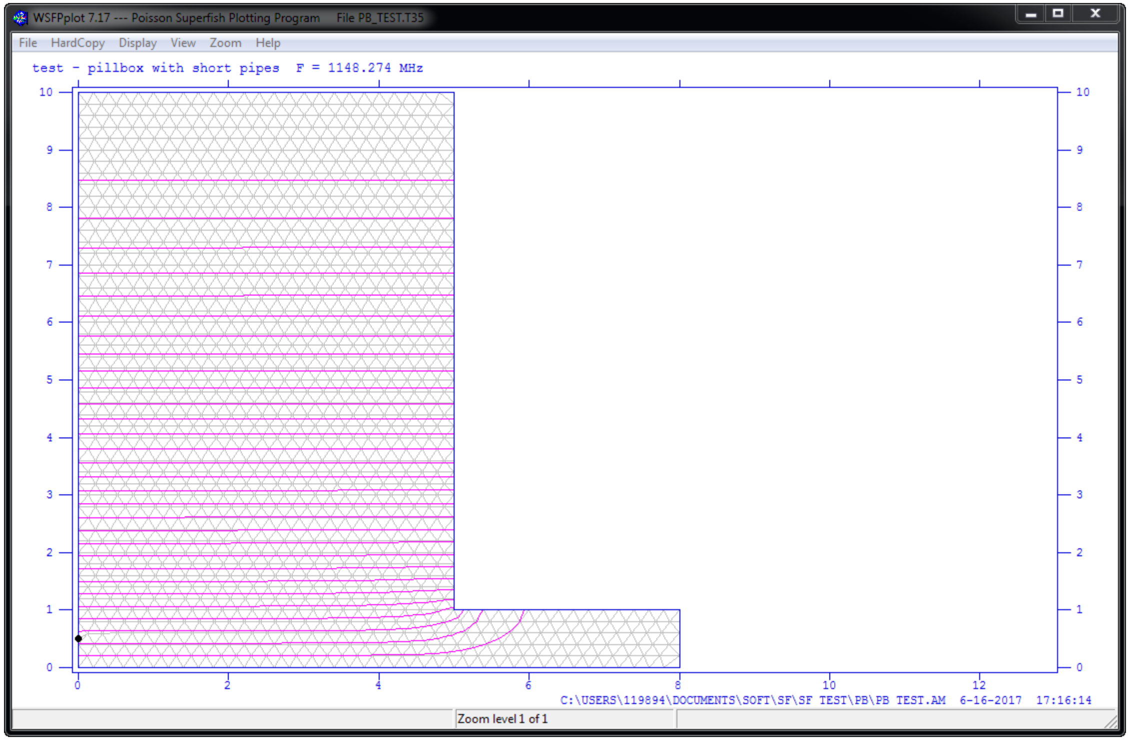
- First line is the problem title (< 80 char) followed by 3 namelists: REG, PO, MT (actually parsing). Delimiters: & or $; comment: ; or !
- $reg: kprob - problem type (1 – SF, 0 – Poisson) – in the 1st $reg, symmetry: e.g., icylin=1 – cylindrical; BCs; approximate frequency (MHz); mat #.
- $po: defines geometry; separate $po list for each material. Note $po … $.
- $mt: mt=2, 3, … - material table defines mat properties (epsilon, mu).

pb_test.am

```
test - pillbox with short pipes

&reg kprob=1,
dx=0.2,dy=0.2,
xdri=0.,ydri=0.5,freq=1500.00,dslope=-1,
npoint=7 &

&po x= 0.0,  y= 0.0 &
&po x= 0.0,  y= 10.0 &
&po x= 5.0, y= 10.0 &
&po x= 5.0, y= 1.0 &
&po x= 8.0, y= 1.0 &
&po x= 8.0, y= 0.0 &
&po x= 0.0,  y= 0.0 &
```



Superfish problem 1. Pillbox cavity.

Design TM_{010} cavity for frequency 201.25 MHz

- Estimate radius *R*, choose length *L* (default units – cm); define BCs or use default BCs (SF: left – symmetry: Dirichlet BC).
- Create cavity geometry file, e.g., pb.am
- run Automesh on pb.am > pb.T35 with geo and mesh
- run Fish on pb.T35 > pb.T35 with fields
- double-click pb.T35 to see field lines
- run SFO post-processing of pb.T35 > pb.sfo

For TM_{nmp} modes in a cylindrical cavity of radius *R* and length *L*, the frequency

$$f_{nmp} = \frac{c}{2\pi}\sqrt{\left(\frac{j_{nm}}{R}\right)^2 + \left(\frac{\pi p}{L}\right)^2},$$

where j_{nm} are the roots of $J_n(j_{nm}) = 0$. The value of j_{01} = 2.4048.

SF problems 1a & 1b. Pillbox cavity with beam pipe.

SF 1a: Design TM_{010} cavity for frequency 201.25 MHz with beam pipe.

- Add beam pipe to the pillbox cavity you already designed. Use pipe radius $a \ll R$, choose pipe length $p > 2a$.
- Will the cavity frequency increase or decrease when you add the pipe?

SF 1b: TM_{010} cavity with rounded edge of cavity-pipe connection: blend the sharp edge by introducing an arc:

Use $po nt=2, x0=11.0, y0=3.5, r=1, theta=270 $ to make an arc.

Slater perturbation theorem relates the cavity frequency change with energy changes due to small deformations of cavity walls:

$$\frac{\Delta f}{f_0} = \frac{\Delta W_m - \Delta W_e}{2W_0}.$$

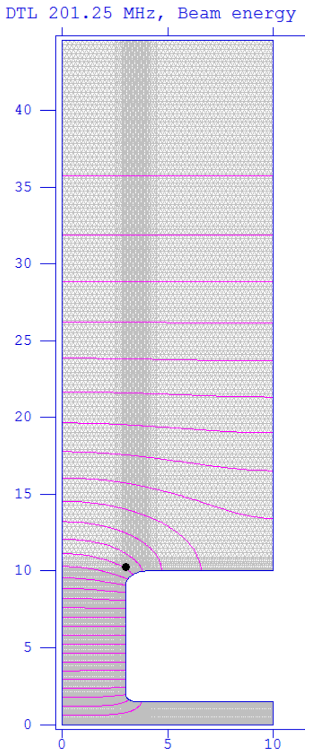
Sometimes it is useful to use *L*-*C* circuit analogy for the cavity frequency:

$$f = \frac{1}{2\pi\sqrt{LC}}.$$

SF problem 2. Pillbox cavity with drift tube

Design TM_{010} cavity for frequency 201.25 MHz with a drift tube.

- Recommended *g*/*L*=0.3, DT outer radius 10 cm. How large is the frequency shift from 201.25 MHz when DT is inserted?
- Adjust cavity radius to get back to 201.25 MHz.



DTL design using DTLfish

Tuning code DTLfish can design and tune a sequence of cells with some required parameters, e.g. frequency, in a given velocity range, e.g. β = 0.1-0.3.

DTL201.dtl

```
; DTLfish control file
; Copyright 1998, by the University of California.

TITLE
DTL 201.25 MHz, Beam energy = 8.5 MeV
ENDTITLE

PARTICLE              H+
FILEname_prefix       DTL
SEQuence_number       1
FREQuency             201.25
;BETA                  0.135
G_OVER_Beta_lambda    0.3
LENGTH                20.
DIAMeter              90.
DRIFT_TUBE_Diameter   20.0
;GAP_Length            5.
E0_Normalization      1.0
CORNER_radius         1.
OUTER_nose_radius     1.
INNER_nose_radius     0.5
BORE_radius           1.5
FLAT_length           0
STEM_Diameter         1.905
STEM_Count            1
PHASE_length          180
DELTA_frequency       0.005
MESH_size             0.05
INCrement             2
START                 2

ENDFILE
```

DTLfish_seq.txt

```
...
START                 -2

; Start codes for DTLfish:
; 1 No tuning
; 2 Adjust tank diameter
; 3 Adjust drift tube diameter (not recommended)
; 4 Adjust gap
; 5 Adjust face angle

SEQuence_number       2       ; Problem 2
BETA                  0.1
LENGTH                7.053940188235
DIAMeter              PREVIOUS
G_OVER_Beta_lambda    0.2042467589655
GAP_Length            1.440744421384
START                 -4

SEQuence_number       3       ; Problem 3
BETA                  0.15
DIAMeter              PREVIOUS
START                 -4
```

SF problem 3. DTL design using DTLfish.

Design DTL cells for frequency 201.25 MHz for β = 0.135.

- Recommended g/L=0.3, DT outer radius 10 cm. Note: *.dtl
- DTLfish can tune the cavity parameters, e.g. cavity radius or gap, to get the required frequency, 201.25 MHz.

DTL201.dtl

```
; DTLfish control file
; Copyright 1998, by the University of California.

TITLE
DTL 201.25 MHz, Beam energy = 8.5 MeV
ENDTITLE

PARTICLE             H+
FILEname_prefix      DTL
SEQuence_number      1
FREQuency            201.25
;BETA                 0.135
G_OVER_Beta_lambda   0.3
LENGTH               20.
DIAMeter             90.
DRIFT_TUBE_Diameter  20.0
;GAP_Length           5.
E0_Normalization     1.0
CORNER_radius        1.
OUTER_nose_radius    1.
INNER_nose_radius    0.5
BORE_radius          1.5
FLAT_length          0
STEM_Diameter        1.905
STEM_Count           1
PHASE_length         180
DELTA_frequency      0.005
MESH_size            0.05
INCrement            2
START                2

ENDFILE
```