Proton and Ion Linear Accelerators

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U.S. Particle Accelerator School

June 7 – July 2, 2021

Proton and Ion Linear Accelerators

13. RF accelerating structures, Lecture 4

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U.S. Particle Accelerator School (USPAS)

Education in Beam Physics and Accelerator Technology

June 24, 2021

RF accelerating structures

Outline:

- Beam-cavity interaction.
- SRF Cavity Design Approaches for Linear Accelerators

Chapter 8.

Beam-cavity Interaction

a. Beam loading;
b. Optimal coupling;
c. Wake potential;
d. HOM excitation effects.

Beam Loading

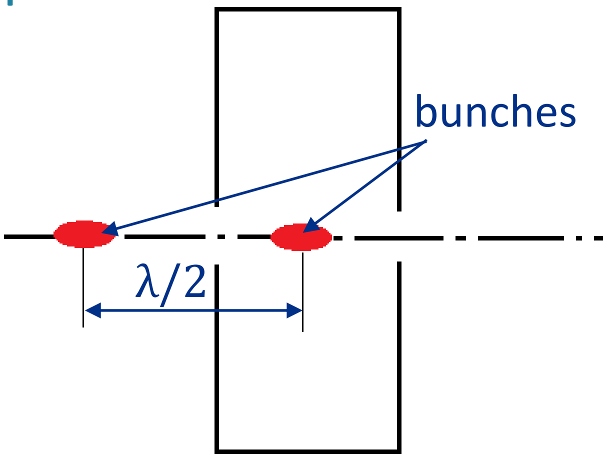
Wilson's Theorems:

Perry B. Wilson
1927-2013

1. The bunch exiting the empty cavity, decelerates by $V_i/2$, where V_i is the voltage left in the cavity.

Two bunches with the distance between them of $\lambda/2$ excite total zero voltage.
If on bunches "sees" fraction α of V, one has:

$$q_b(V_i - \alpha V_i) = q_b \alpha V_i \rightarrow \alpha = 1/2.$$



Beam Loading

Wilson's theorems:

2. The voltage V exited by the bunch with the charge q_b is

$$V_i = 1/2 \cdot R/Q \cdot \omega \cdot q_b$$

Energy conservation law:

$$1/2 \cdot V_i \cdot q_b = V_i^2/(R/Q \cdot \omega) \rightarrow V_i = 1/2 \cdot R/Q \cdot \omega \cdot q_b$$

The energy loss of the bunch is equal to

$$U = 1/2 \cdot V_i \cdot q_b = 1/4 \cdot R/Q \cdot \omega \cdot q_b^2 = k \cdot q_b^2$$

here k is loss factor,

$$k = 1/4 \cdot R/Q \cdot \omega.$$

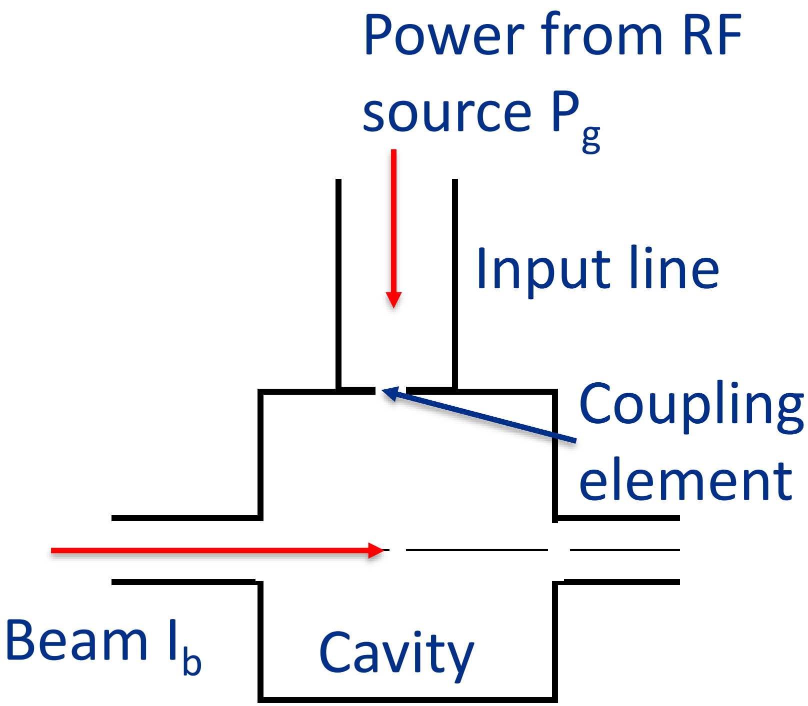
If the beam pulse is short compared to time constant τ (field decay time),

$$V_I = 1/2 \cdot R/Q \cdot \omega \cdot q$$

is a total voltage induced by the beam pulse in the cavity,

q is a total charge, $q = \Sigma q_b = I \cdot t_{beam}$.

Beam Loading

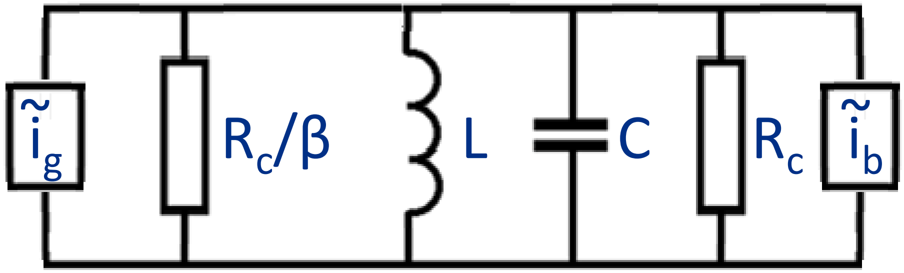


- RF source and beam $\omega_g = \omega_b = \omega$;
- Cavity: ω_0
- Cavity voltage : V_c
- Shunt impedance: R_{sh}
- Losses: $P_c = V_c^2/R_{sh} = V_c^2/(Q_0 \cdot R/Q)$
- Radiation to the line: $V_c^2/(Q_{ext} \cdot R/Q)$
- Coupling: $\beta = Q_0/ Q_{ext}$
- Loaded Q: $Q_L = Q_0/(1+ \beta)$
- Average beam current: I_b
- Synchronous phase: φ
- Power consumed by the beam: $P_b = I_b V_c \cos\varphi$
- Input power P_g
- Reflected power: $P_r = P_g - P_c - P_b$

Details are in Appendix 8

Beam Loading

Equivalent circuit for the beam-loaded cavity transformed to the resonance circuit:



$L=R/Q/(2\omega_0)$
$C=2/(R/Q\cdot\,\omega_0)$
$R_c=R/Q\cdot Q_0/2$
$\tilde{i}_b=-2I_b$

From this equivalent circuit we have:

$$P_g=\frac{V_c^2(1+\beta)^2}{4\beta Q_0(R/Q)}\left[\left(1+\frac{I_{\mathrm{Re}}(R/Q)Q_0}{V_c(1+\beta)}\right)^2+\left(\frac{Q_0}{1+\beta}\frac{\left(\omega^2-\omega_0^2\right)}{\omega_0^2}+\frac{I_{\mathrm{Im}}(R/Q)Q_0}{V(1+\beta)}\right)^2\right]$$

where $I_{Re}=I_b cos\varphi$ and $I_{Im}=I_b sin\varphi$

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Beam Loading

If the cavity is detuned by Δf versus the RF source frequency and r.m.s. microphonics amplitude is δf, the required power is the following :

$$P_g = \frac{V_c^2(1+\beta)^2}{4\beta Q_0 (R/Q)}\left[\left(1+\frac{I_{\rm Re}(R/Q)Q_0}{V_c(1+\beta)}\right)^2 + \left(\frac{Q_0}{1+\beta}\frac{2\delta f}{f} + \left|\frac{Q_0}{1+\beta}\frac{2\Delta f}{f} + \frac{I_{\rm Im}(r/Q)Q_0}{V_c(1+\beta)}\right|\right)^2\right]$$

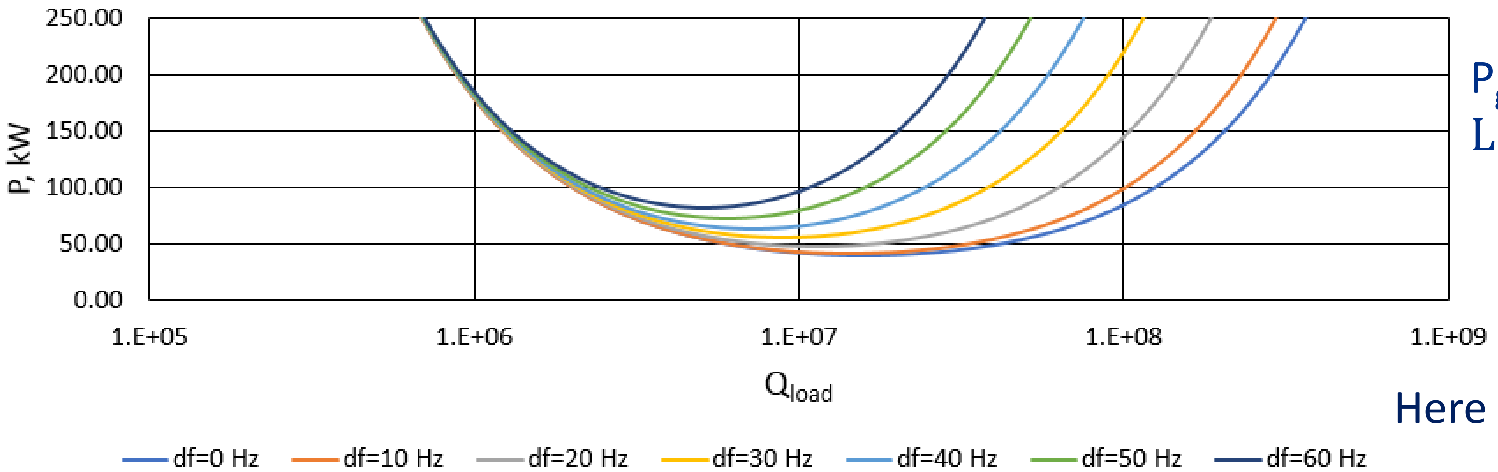
Typically, the cavity has "static detune":

$$\Delta f = -f\frac{I_{\rm Im}(R/Q)}{2V_c}$$

In this case.

$$P_g = \frac{V_c^2(1+\beta)^2}{4\beta Q_0 (R/Q)}\left[\left(1+\frac{I_{\rm Re}(R/Q)Q_0}{V_c(1+\beta)}\right)^2 + \left(\frac{Q_0}{1+\beta}\frac{2\delta f}{f}\right)^2\right]$$

The optimal coupling providing minimal power: $\beta_{opt} = \left[\left(1+\frac{I_{\rm Re}(R/Q)Q_0}{V_c}\right)^2 + \left(\frac{2\delta f Q_0}{f}\right)^2\right]^{1/2}$



$P_g(\delta f)$ for LB 650 (PIP II)

$$Q_{load} = \frac{Q_0}{1+\beta}$$

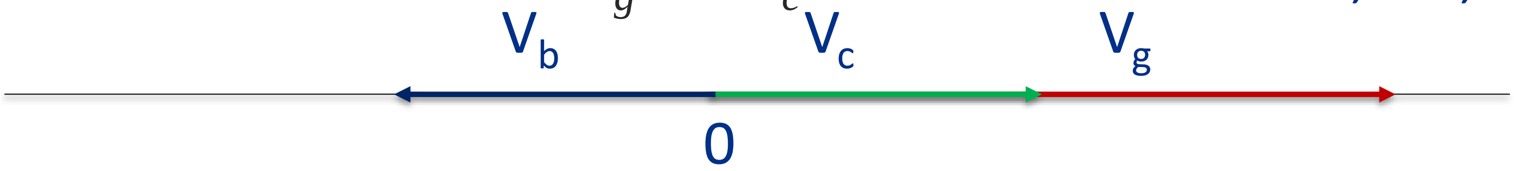
$$df = \frac{f}{Q_{load}},$$

Here df-cavity bandwidth

Beam Loading

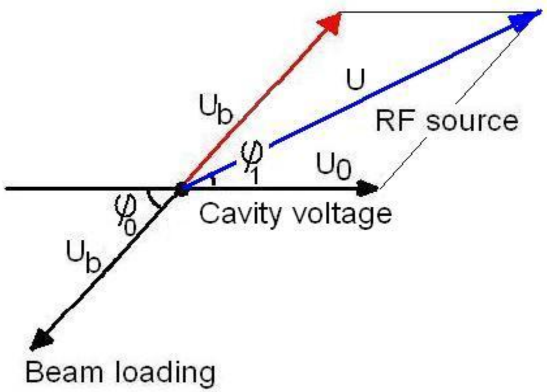
- In resonance for a SRF cavity $\beta_{opt} >> 1$ and $\beta_{opt} = I_b \cdot R/Q \cdot Q_0/V_c$ and $Q_L = V_c/(I_b \cdot R/Q)$. The cavity bandwidth $\Delta f = f/Q_L = f \cdot I_b \cdot (R/Q)/V_c$.

- for optimal coupling for the SRF cavity $V_b = -V_c$ and $P_g = |V_c \cdot I_b|$ Note that in this case $V_g = 2V_c$ and reflection is zero, i.e., $P_r = 0$.



- Without the beam in order to maintain the same voltage in the SRF cavity at the same coupling $P_{g0} = 1/4 \cdot P_a$. For SRF cavity reflection in this case is ~100%.

- Phase shift between the bunch and the cavity voltage

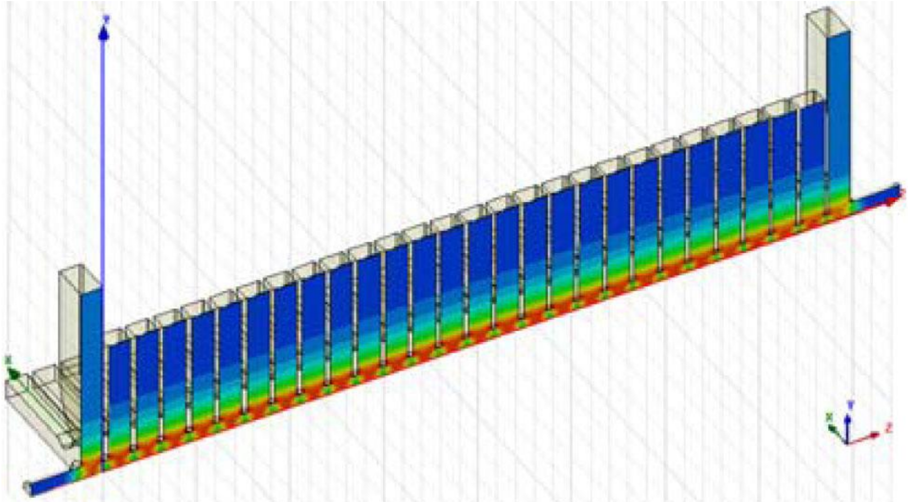


Beam Loading, Travelling Wave

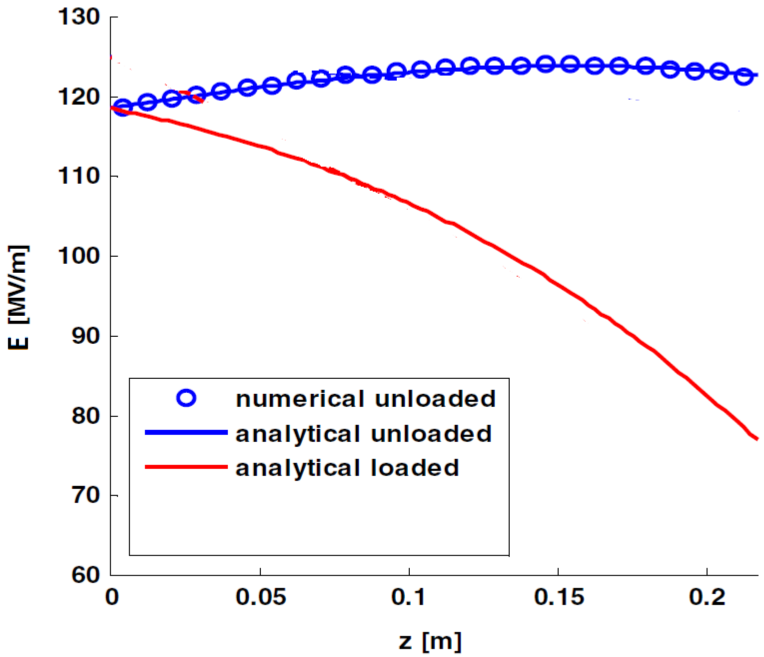
In presence of a beam (see slide 79):

$$\frac{dW_{0,j}}{dt} = -P_j + P_{j-1} - \frac{\omega_0 W_{0,j}}{Q_0} - V_c I_b, \qquad (1)$$

Beam loading changes the field distribution along the structure.



CLIC 12 GHz structure



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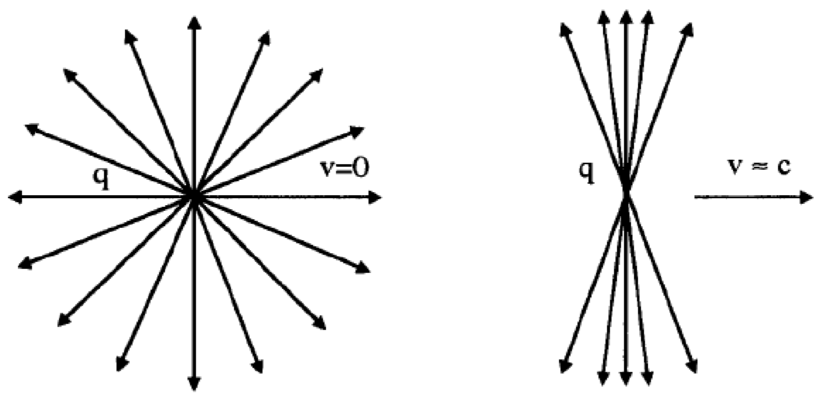
Wake potentials

1. Fields of a moving charge in free apace:

$$\mathbf{E} = \frac{q\hat{r}}{4\pi\varepsilon_0 r^2\gamma^2(1-\beta^2\sin^2\psi)^{3/2}}$$

For $\gamma \to \infty$ $\quad E_r = \frac{q\delta(z-ct)}{2\pi\varepsilon_0 r} \qquad B_\theta = \frac{\mu_0 c q\delta(z-ct)}{2\pi r}$



$$F_r = q'(E_r - cB_\theta) = \frac{q'q\delta(z-ct)}{2\pi\varepsilon_0 r} - \frac{q'q\mu_0 c^2\delta(z-ct)}{2\pi r} = 0$$

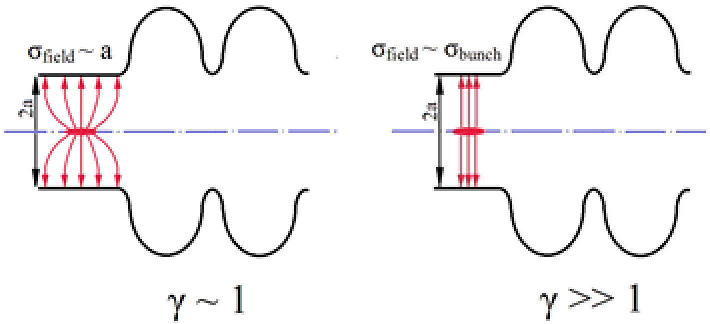
Fermilab

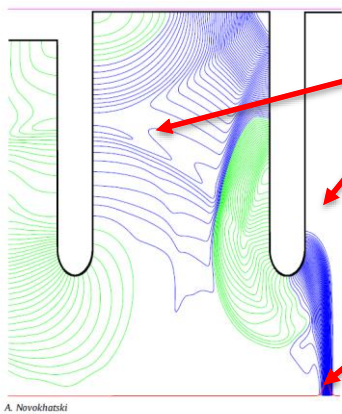
Wake potentials

1. Fields in the smooth waveguide with ideally conducting walls:
   No radiation (lack of synchronism: $v_{ph}>c$)
   Coulomb forces (including image):
   $F_r = q(E_r - vB_\phi) \sim 1/\gamma^2$
   $F_z \sim 1/\gamma^2$ (static field is compensated by eddy field).

2. In presence of obstacle radiation takes place
   - change of cross section,
   - finite conductivity
   - dielectric wall

Wake potentials





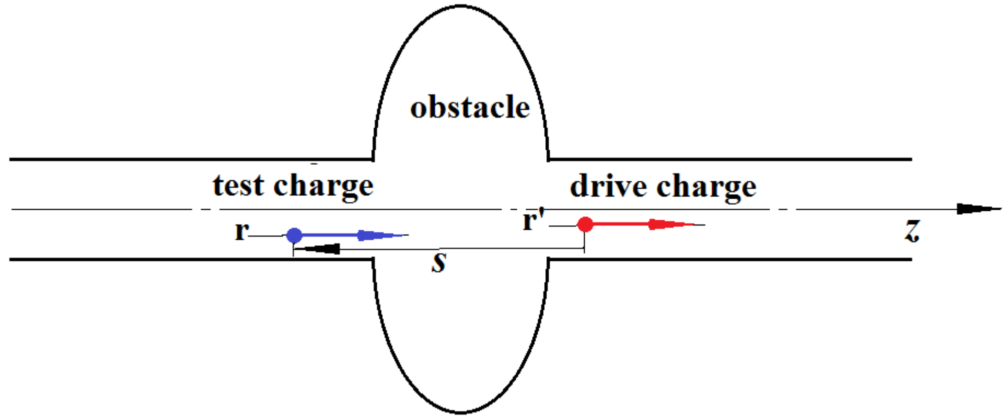
Acceleration cells

bunch

Blue – deceleration, green – acceleration

- Energy lost by the bunch:
  $W = kq^2$
  k is the loss factor.
- Transverse momentum kick:
  $\Delta p_\perp c = rq^2 k_\perp$
  $k_\perp$ is a kick factor

Radiation fields in the TW acceleration structure



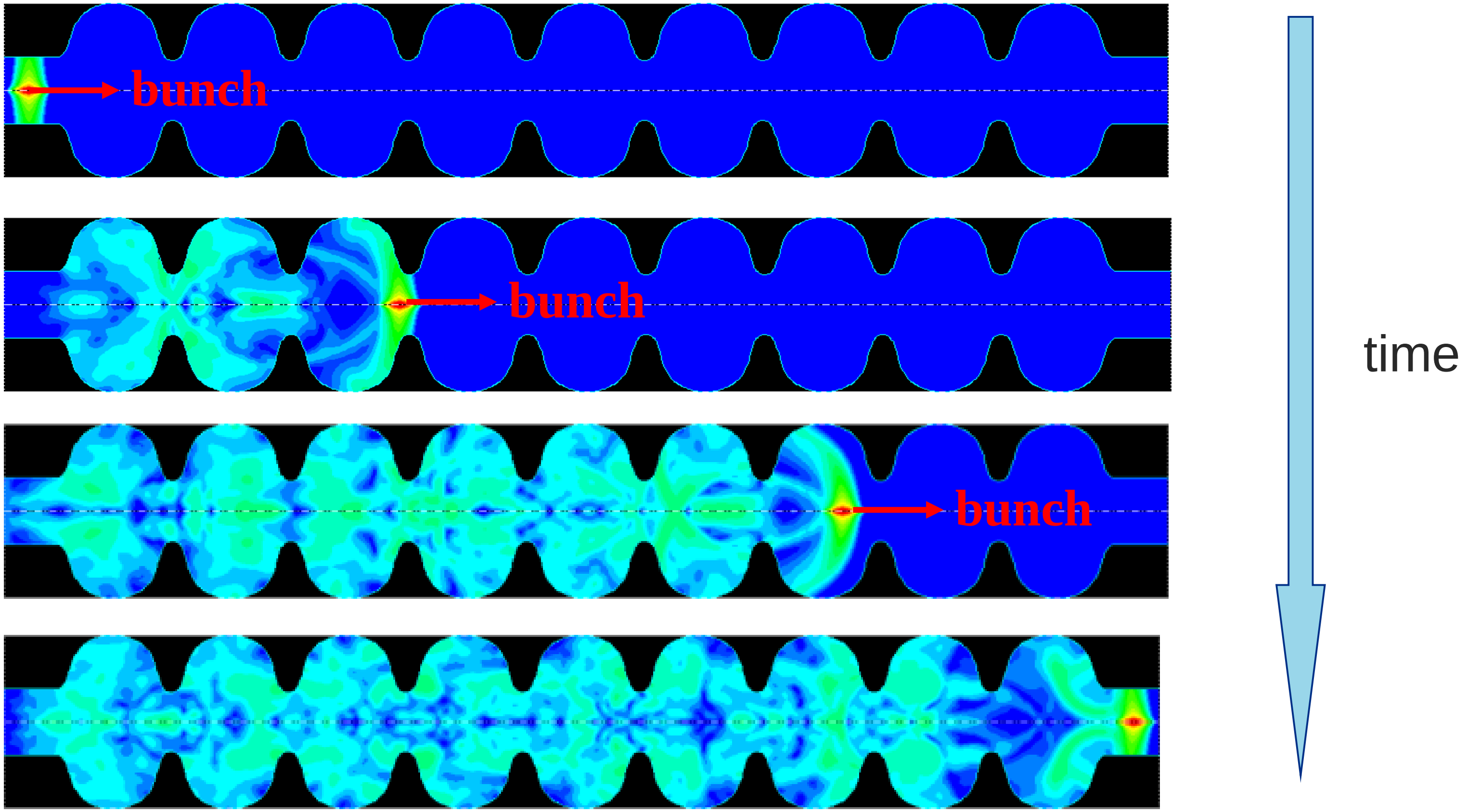
$$W_z(\vec{r},\vec{r}',s) = -\frac{1}{q}\int_{z_1}^{z_2} dz\,[E_z(\vec{r},z,t)]_{t=(z+s)/c},$$

$$\vec{W}_\perp(\vec{r},\vec{r}',s) = \frac{1}{q}\int_{z_1}^{z_2} dz\left[\vec{E}_\perp + c(\hat{z}\times\vec{B})\right]_{t=(z+s)/c}.$$

$W_z=0$, $W_\perp=0$ for $s<0$

More details: Appendix 13

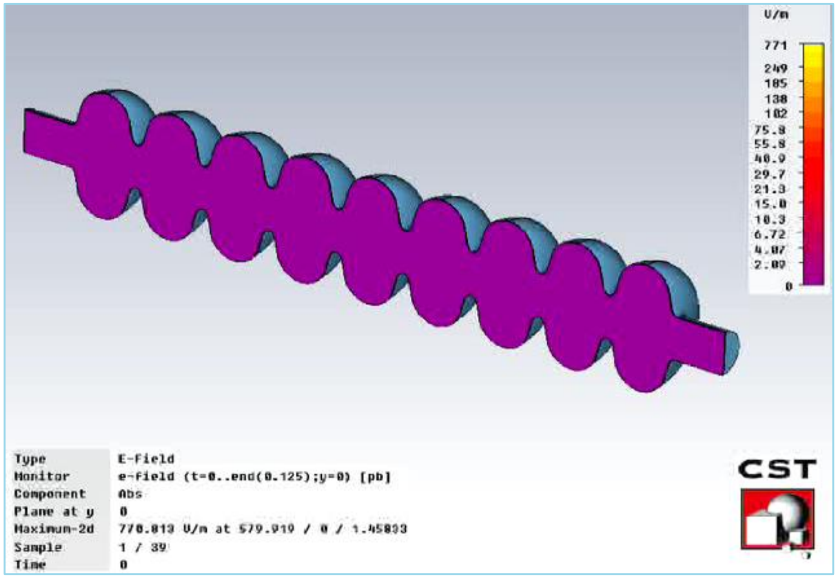
Electromagnetic field excited by bunch



The bunched beam excites electromagnetic field inside an originally empty cavity.

Short- and long-range wakefields

- Short range wake-field → Fields along the bunch and just behind it:
  - Cause bunch energy loss and energy spread along the bunch
  - Single bunch break up instability
  - Cooper pair breaking in the case of extremely short bunches
- Long range wakes (HOMs):
  - Monopole modes: Longitudinal coupled bunch instabilities; RF heating; Longitudinal emittance dilution …
  - Dipole modes: Transverse transverse coupled bunch instabilities; Emittance dilution; beam break-up instabilities …

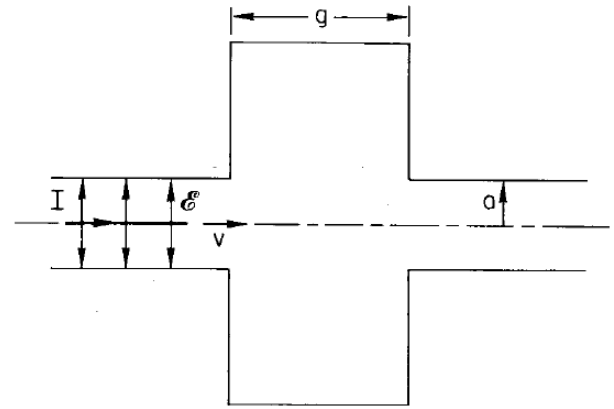


Wake potentials

Pillbox with the holes:

$$k_\ell(\sigma) = \frac{Z_0 c}{\pi^{5/2} a}\sqrt{\frac{g}{\sigma}}\left[\Gamma(1/4)/4 - \left(\frac{\omega_c \sigma}{c}\right)^{1/2}\right]$$

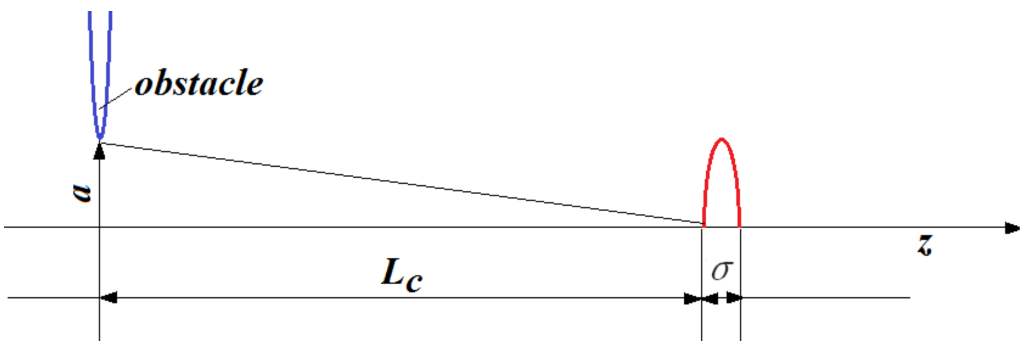
$$k_\perp(\sigma) = (4.36..)\frac{Z_0 c}{\pi^3 a^3}\sqrt{g\sigma}$$



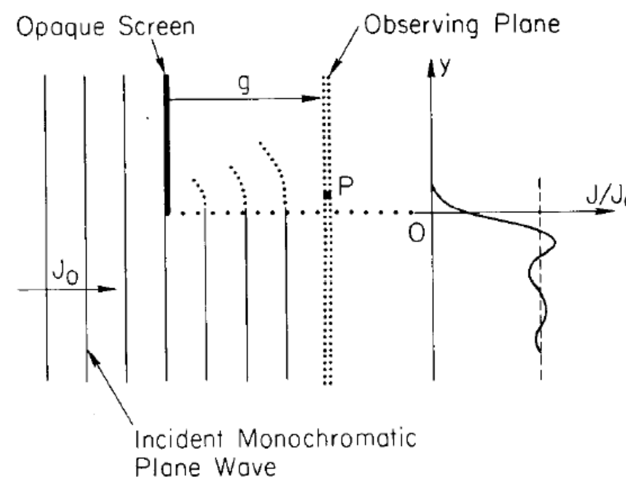
For Gaussian bunch, $\Gamma(1/4)/4 = 0.908..$

Loss and kick factors depend on the cavity geometry and the bunch Length.

Catch-up problem:



$(L_c^2+a^2)^{1/2} = L_c+\sigma \qquad L_c \approx a^2/2\sigma$

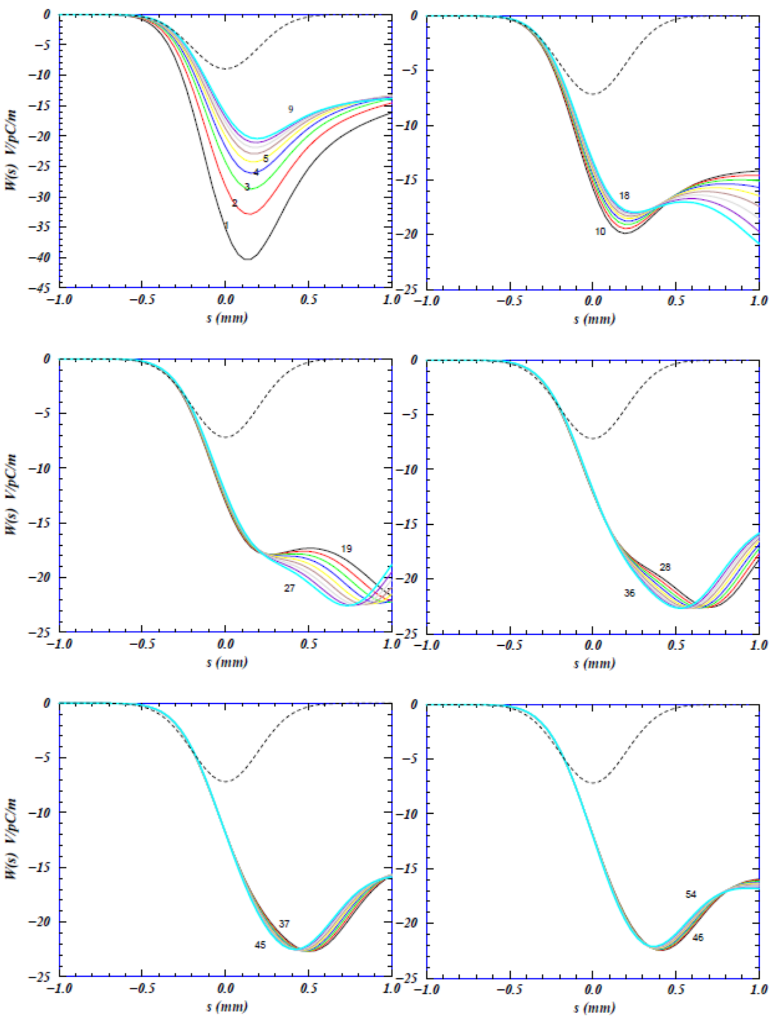


Diffraction model:

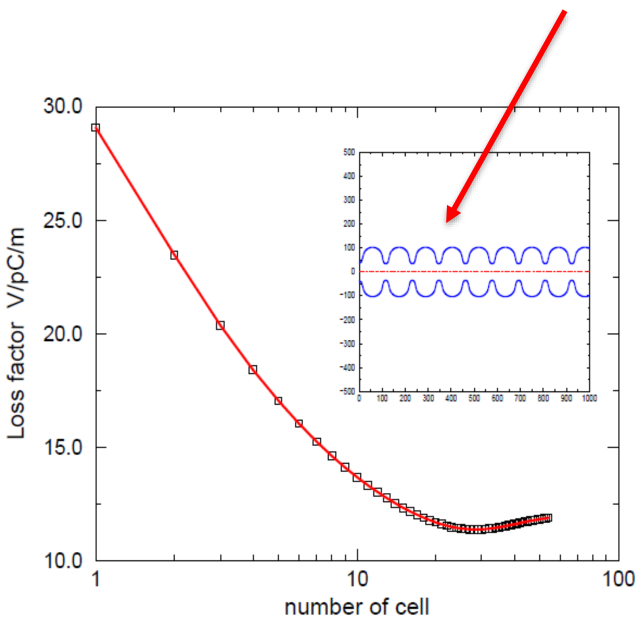
Wake potentials

Transition of the wakefield in semi-infinite periodic structure:

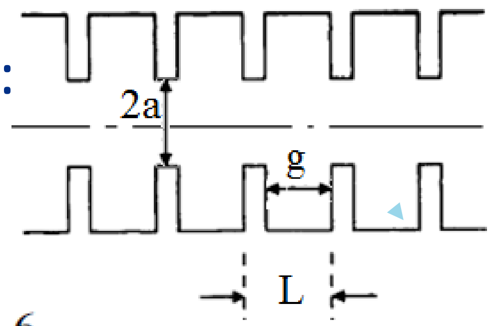
- Calculations of the loos distribution for a chain of TESLA cells. The loss factor and wake amplitude decrease with the cell number. The shape of the wake does not change significantly after the bunch exceeds the catch-up distance, which is ~3 m (27 TESLA cells) for this case (σ = 0.2 mm, a = 35 mm)



$$L = \frac{a^2}{2\sigma_z}$$



Wake potentials



Semi-Infinite periodic structure (steady-state wake):
→wakes per unit length.

- Karl Bane model (KB) :

$$W_L(s,s_0)=\frac{Z_0 c}{\pi a^2}\exp\left(-\sqrt{s/s_0}\right);\ \text{where}\ s_0=0.41\frac{a^{1.8}g^{1.6}}{L^{2.4}},$$

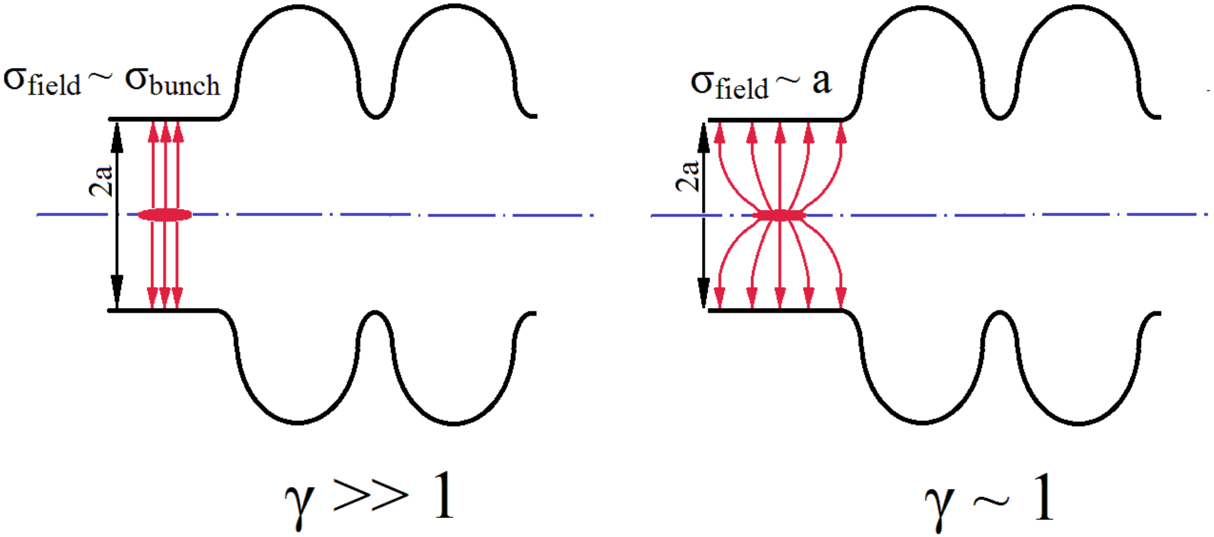
when $\sigma \to 0,\ k_l=\frac{Z_0 c}{\pi a^2}$

Steady-state wake – when the structure length > catch-up distance.

❖ Wake potentials limit the cavity aperture and therefore, determine the cavity design, especially for SRF electron linacs for FELs, where the bunch length is small.

Wake potentials

Wakefiled for non-relativistic bunch:



HE electron linac
(ILC, XFEL or LCLS II)

$f_{max} \sim c/\sigma_{bunch}$

Proton linac

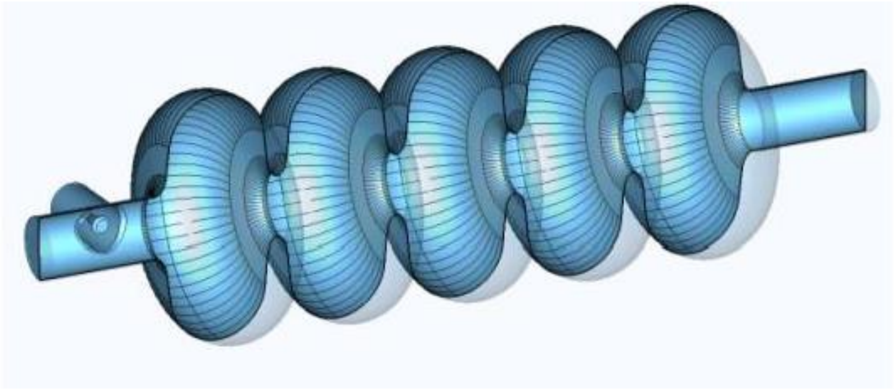
$f_{max} \sim c/a$

for $\sigma_{bunch} = 50\mu$, $f_{max} < 6$ THz for $a = 50mm$, $f_{max} < 6$ GHz

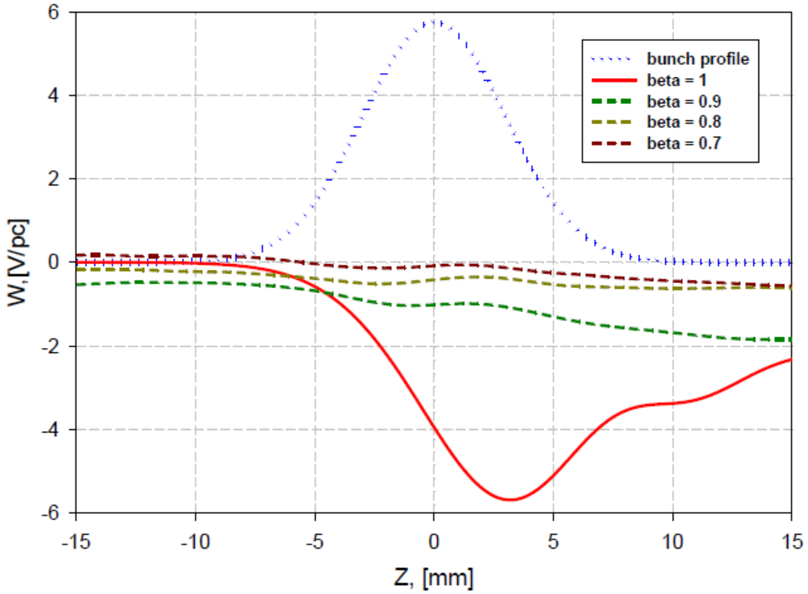
Diffraction losses are determined by σ_{field}, $P \sim (\sigma_{field})^{-1/2}$

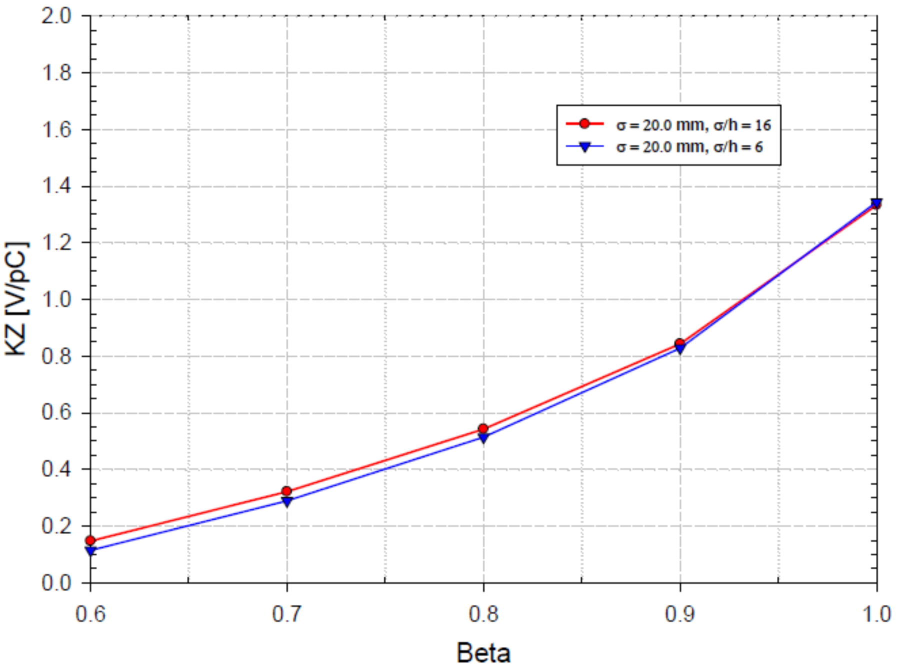
Wake potentials

Wakefiled for non-relativistic bunch:



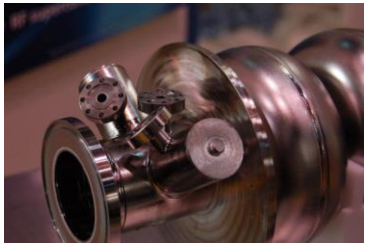
The 650 MHz, β=0.9 elliptical accelerating cavity for ProjectX





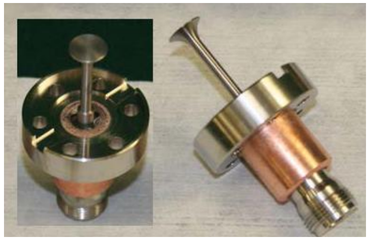
High-Order Modes in elliptical SRF cavities (long-range wakes)

- Possible issues:
- Trapped modes;
- Resonance excitation of HOMs;
- Collective effects – transverse (BBU) and longitudinal (klystron-type instability);



- Additional cryo-losses;
- Emittance dilution (longitudinal and transverse).

- HOM damper is a vulnerable, expensive and complicated part of SC acceleration cavity (problems – heating, multipacting, etc; additional hardware – cables, feed-through, connectors, loads). HOM dampers may limit a cavity performance and reduce operation reliability;



"To damp, or not to damp?"

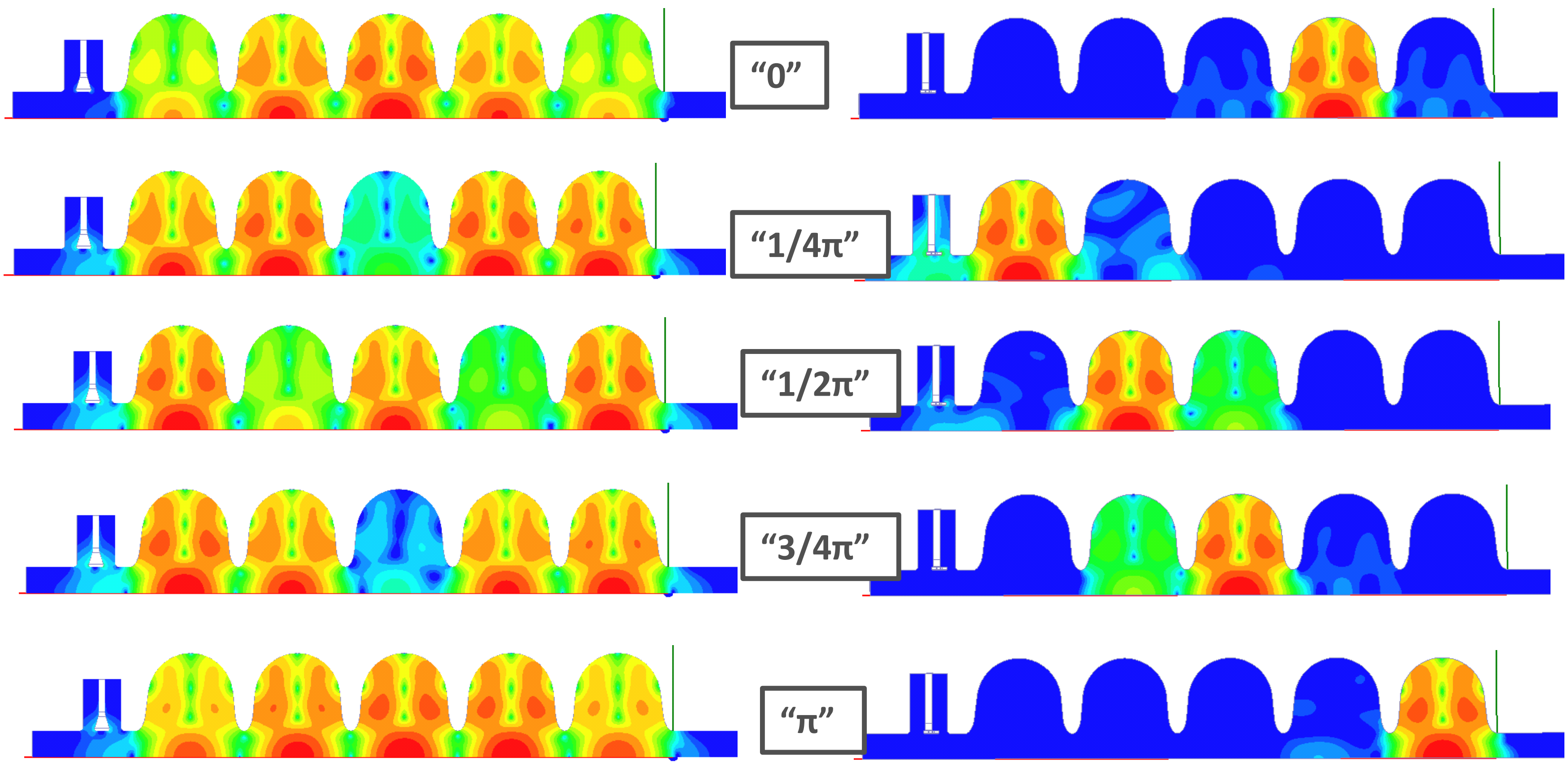
High-Order Modes in elliptical SRF cavities (long-range wakes)

- Specifics of Higher Order Mode effects in the elliptical cavities of proton linacs:
  - Non-relativistic beam;
  - Small current and small bunch population;
  - No feedback (linac);
  - Complicated beam timing structure (dense frequency spectrum).

Trapped Modes in elliptical SRF cavities

For some modes *k (coupling)* may be very small (electric coupling is compensated by magnetic coupling). Because of manufacturing errors the field distribution may change, the mode will not be coupled to the FC or beam pipe, and have high Q_{load} – so called trapped modes.

An example of a bad cavity design containing a trapped mode:

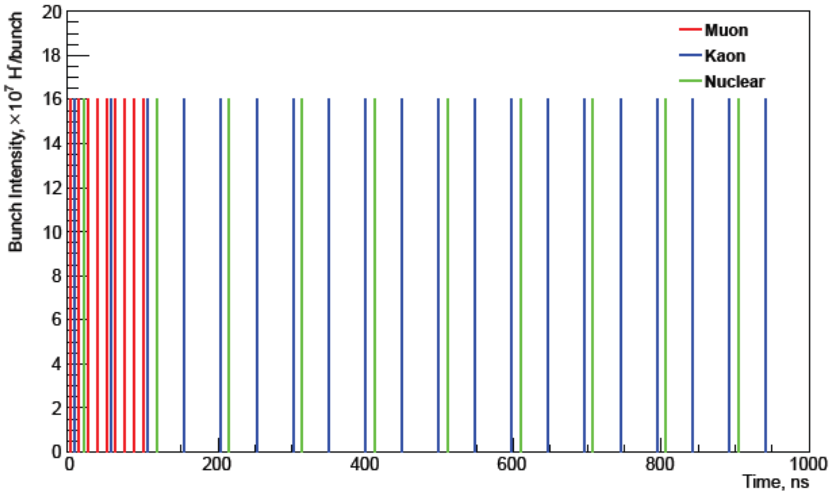


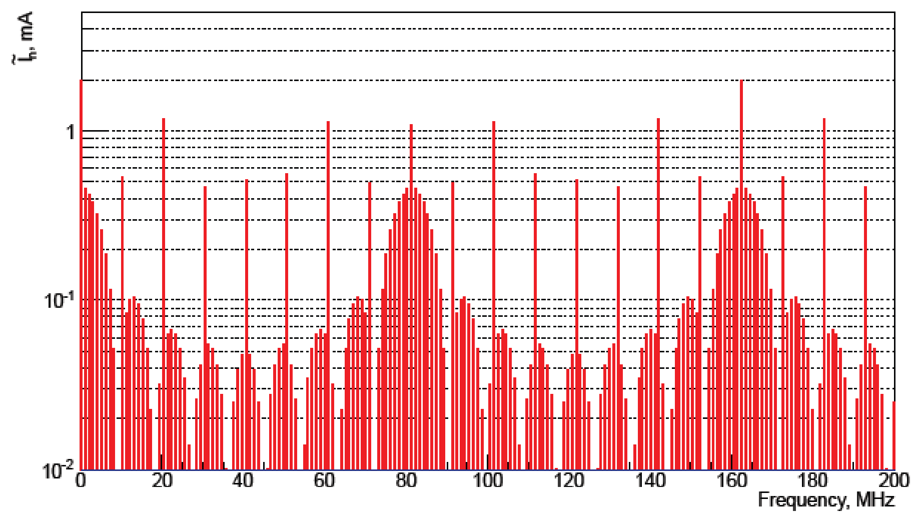
HOMs in an ideal cavity.

HOMs in a “realistic” cavity, i.e., in presence of misalignments.

In both cases the operating mode is tuned to correct frequency and field flatness.

Resonance excitation of HOMs in elliptical SRF cavities



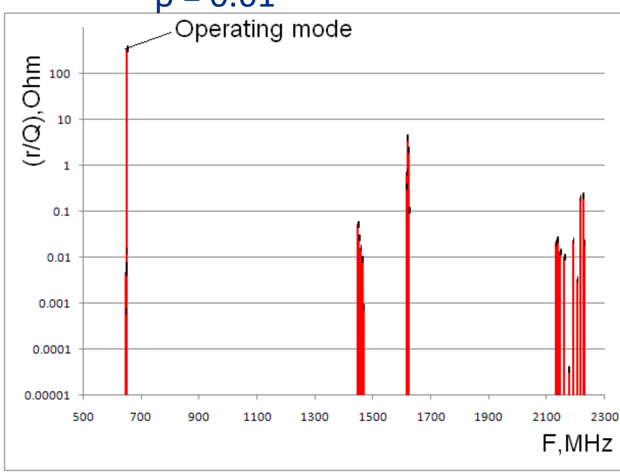


Example of the beam structure for multi-experimental proton driver (Project X)

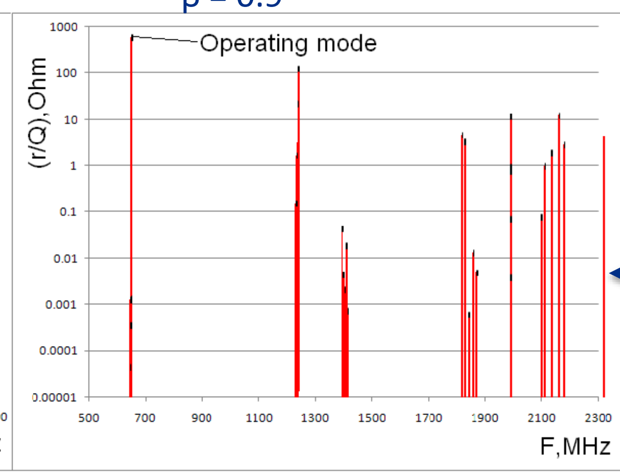
The beam current spectrum may be dense: for PX it contains

- ● harmonics of the bunch sequence frequency of 10.15 MHz and
- ● sidebands of the harmonics of 81.25 MHz separated by 1 MHz.

$\beta = 0.61$



$\beta = 0.9$



← R/Q spectrum of the cavities

Resonance excitation of HOMs in elliptical SRF cavities

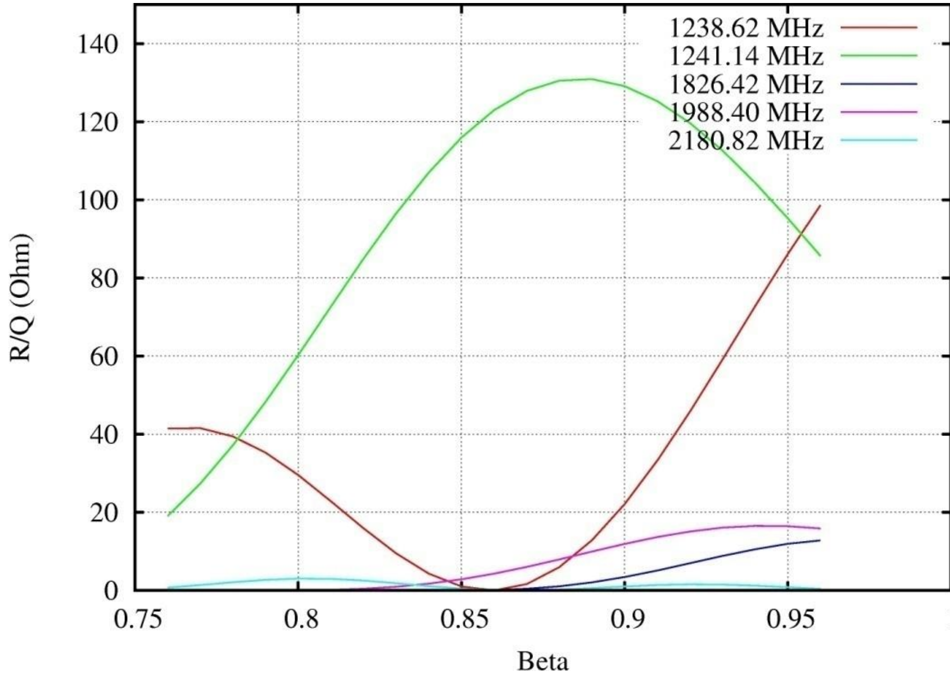
HOM have frequency spread caused by manufacturing errors:

❖For 1.3 GHz ILC cavity r.m.s. spread σ_f of the resonance frequencies is 6-9 MHz depending on the pass band;

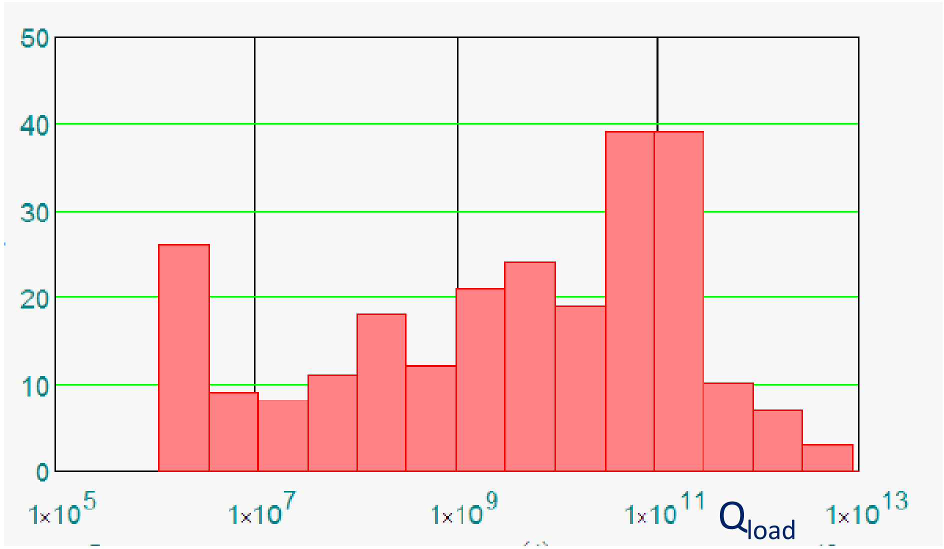
❖Cornell: $\sigma_f \approx 10.9 \cdot 10^{-4} \times (f_{HOM} - f_0)$,

❖SNS: $\sigma_f \approx (9.6 \cdot 10^{-4} - 13.4 \cdot 10^{-4}) \times (f_{HOM} - f_0)$;

$\Delta f_{max} = |f_{HOM,calculated} - f_{HOM,measured}| \sim \sigma_f$



(R/Q) for HOM modes depends on the particle velocity β (650 MHz, β=0.9 cavity)



Variation of Q_{load} for 5th passband (650 MHz, β=0.9 cavity)

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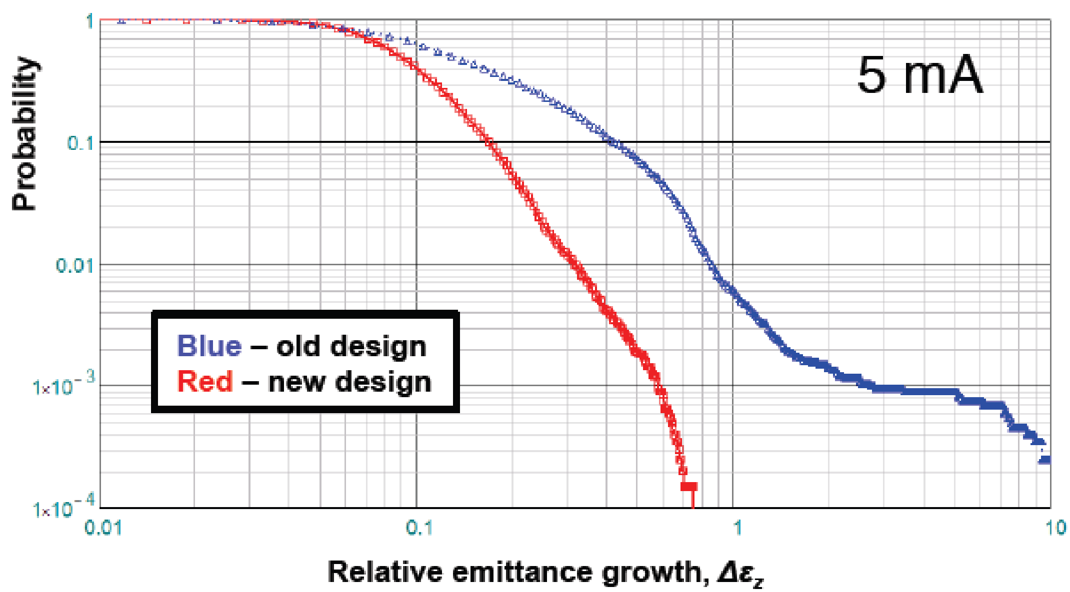
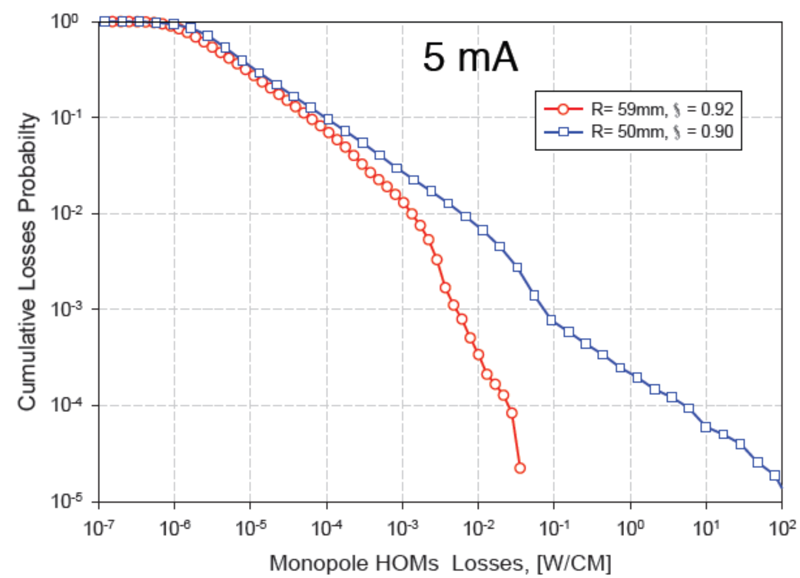
Resonance excitation of HOMs in elliptical SRF cavities (cont)

- Longitudinal emittance dilution does not take place if $\delta f \gg f\,\dfrac{\tilde{I}(R/Q)\sigma_t}{4\sqrt{2}\varepsilon_z}$
  For typical parameters for proton linacs $\delta f \gg$ 10-100 Hz.

- Transverse emittance dilution does not take place if $\delta f \ll \dfrac{c x_0 \tilde{I}(R/Q)_1}{8\sqrt{2}\pi\beta\gamma U_0\sqrt{\varepsilon/\beta_f}}$ Not an issue!
  For typical parameters for proton linacs $\delta f \gg$ 1-10 Hz.



PIP II SRF linac



Cryo load caused by HOMS

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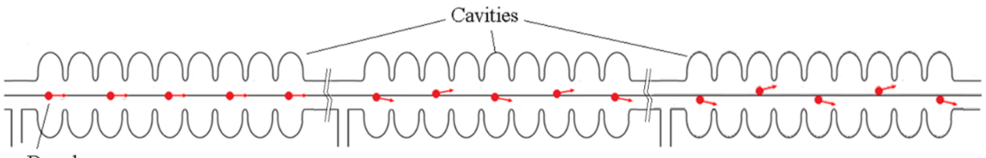
Resonance excitation of HOMs in elliptical SRF cavities (cont)

Collective effects:

- Beam break –up (BBU) , transverse
- “Klystron-type” , longitudinal.



Mechanism of cumulative beam break-up instability.

Why collective effects is not an issue for SRF proton linacs with elliptical cavities:

- No feedback as in ERLs (or CEBAF);
- Different cavity types with different frequencies and different HOM spectrum are used;
- Frequency spread of HOMs in each cavity type, caused by manufacturing errors;
- Velocity dependence of the (R/Q);
- Small – compared to electron linacs -beam current.

- No HOM dampers in SNS upgrade cavities (I_{beam} =26 mA);
- No HOM dampers in ESS cavities (I_{beam} =50 mA);
- No HOM dampers in PIP II cavities (I_{beam} up to 5 mA);
- Probably, HOM dampers will be necessary for future high – current drivers for ADS.

$$U_{kick} = i x_0 I_0 Q_{ext} \left(\frac{r_\perp}{Q}\right)$$

- Alignment!

Summary:

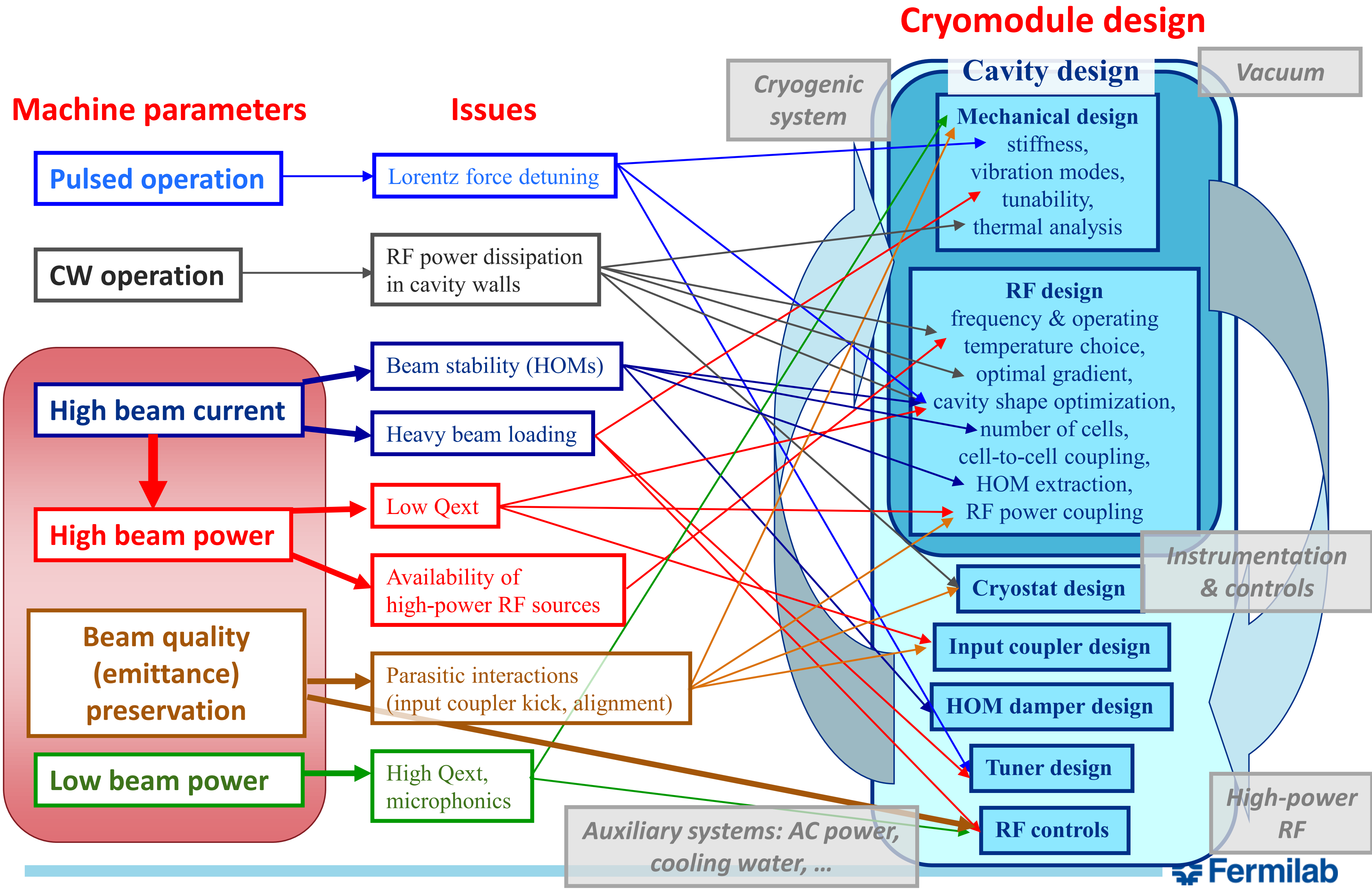
- Accelerated beam excites RF field in the cavity, which should be compensated by the RF source'
- The required power is determined by the beam current, voltage, cavities R/Q, loaded Q, cavity detune and the synchronous phase. There is the optimal coupling which provides minimal input power.
- Ultra-relativistic bunch radiates the field in the cavity, which may cause energy spread and transverse instability. Short-range wake changes the beam dynamics in the same bunch.
- Loss factor and kick factor limit the cavity aperture, that should be taken into account during the cavity design.
- Long-range wakes (= HOMs) may affect the beam dynamics (cumulative instabilities). The cavity should be optimized to get rid of trapped modes, and modes with high R/Q and Q_{load}. For proton linacs (pulsed and CW) HOMs typically are not the issue; for electron SRF linacs HOMs should be damped.
- Proper cavity alignment should be provided to mitigate or get rid of cumulative instabilities.

Chapter 9.

SRF Cavity Design Approaches for Linear Accelerators.

a. The cavity RF design: approaches, tools;
b. SRF cavity mechanical design;
c. The cavity component design – RF couplers and tuners;
d. Cryo-module design: issues and approaches.

SRF system design interdependences



SRF cavities design issues:

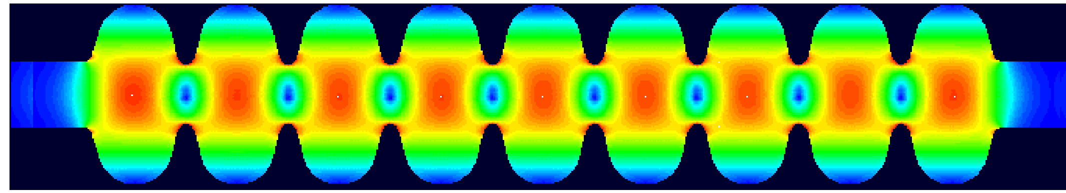
- Acceleration efficiency
  - max R/Q & min surface field enhancement factors (electric & magnetic)
- High Order Modes (HOMs) dumping
  - incoherent effect (loss factors, cryogenic losses)
  - coherent effects (emittance dilution, cryo-losses)
  - collective effects (transverse & longitudinal beam instabilities)
- Operation with small beam current
  - narrow cavity bandwidth & microphonics
- Field Emission
  - multipactor & dark current
- High Gradient pulsed operation
  - Lorentz force detuning
- Input Power Coupler
  - CW operation (min RF loss & static heat load)
- Beam Instrumentation
  - Cold Beam Position Monitor (low & high relativistic beam)

Tools for RF cavity simulations:

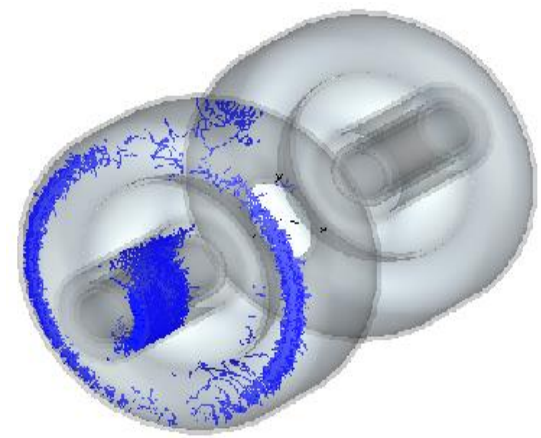
I. Field calculations:

-Spectrum, (r/Q), G, β (coupling)

-Field enhancement factors



- HFSS (3D);
- CST (3D);
- Omega-3P (3D);
- Analyst (3D);
- Superfish (2D)
- SLANS (2D, high precision of the field calculation).

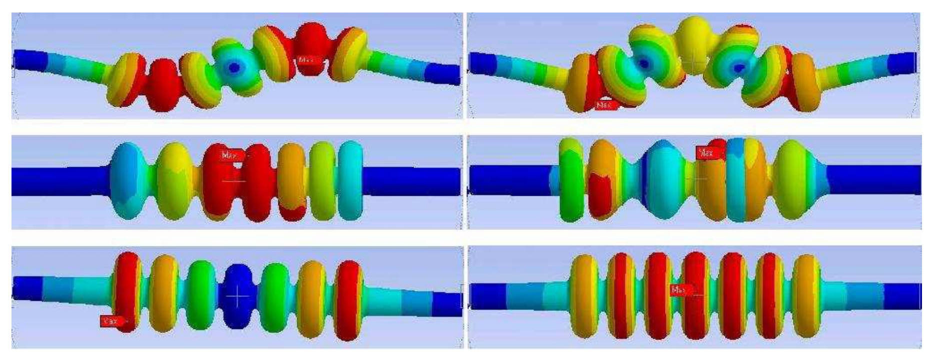


II. Multipactoring (2D, 3D)

- Analyst;
- CST (3D);
- Omega-3P

III. Wakefield simulations (2D, 3D):

- GdfidL;
- PBCI;
- ECHO.



IV. Mechanical simulations:

Lorenz force and Lorenz factor,
Vibrations,
Thermal deformations.

a. ANSYS

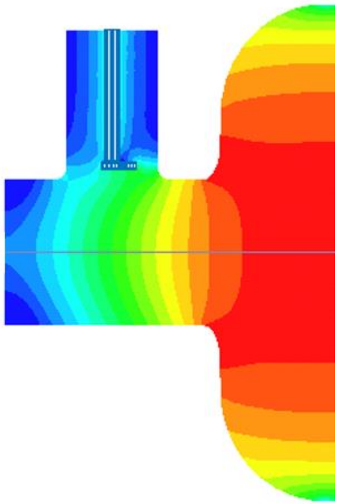
Fermilab

Cavity Simulation Workflow

1. Creation of the project 3D model
   - drawing in the CST GUI (takes time, full-parametrization, easy modification)
   - geometry import from 3rd parties CADs (quick, need special license, limited parametrization, potential mesh problem)
2. Choosing a proper solver
   - depends on the problem, available hardware, simulation time …
3. Setting boundary conditions
   - frequency, symmetries, ports, materials, beam excitation, temperature, …
4. Checking the mesh quality
   - generate and visualize the mesh, set initial mesh size, create sub-volumes and modify models if needed, mesh fine-tuning (curvature order, surface approximation)
5. Solver fine-tuning
   - direct or iterative, parallelization, special settings, …
6. Running first simulation
   - check the results, set postprocessing steps, tune & modify the mesh, …
7. Setting optimization
   - set parameters sweep, define the goal function, simplify the model

Design approaches

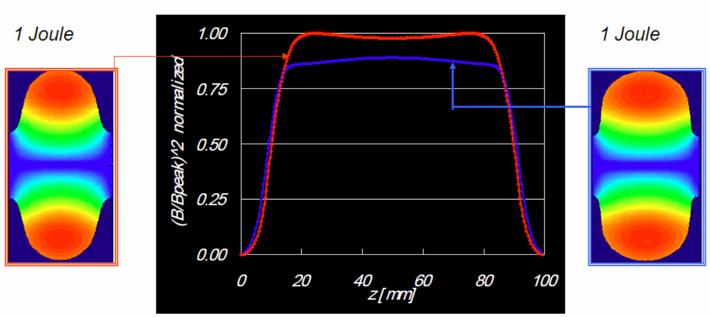
- **Aperture choice:**
- Smaller aperture → smaller field enhancement factors, higher R/Q;
- Limitations:
  - beam losses,
  - field flatness,
  - mechanical stability,
  - surface processing,
  - Q_{load} (coupling to the main coupler)
  - HOMs (trapped modes)
  - Wakes (electron accelerators)

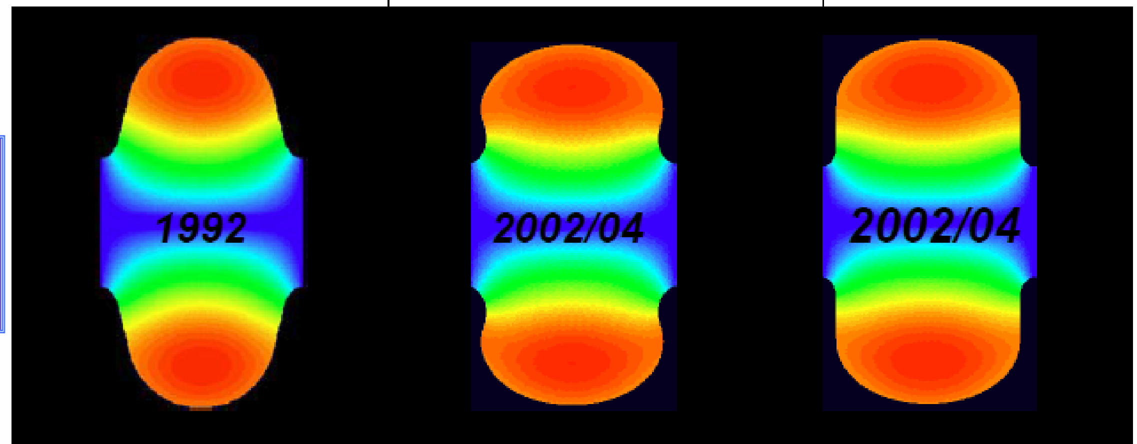


SNS (805 MHz): 2a=86mm (β=0.61), 2a/λ = 0.23
2a=98mm (β=0.81), 2a/λ = 0.26
HIPPI (704 MHz): 2a=80mm (β=0.47), 2a/λ = 0.19
PIP II (650 MHz): 2a=83mm (β=0.61), 2a/λ = 0.18
2a=100 mm (β=0.9), 2a/λ = 0.22

Design approaches

Cavity shape:





		TESLA optimized E_{peak}/E_{acc}	Re-entrant optimized B_{peak}/E_{acc}	LL optimized B_{peak}/E_{acc}
r_i	[mm]	35	30	30
k_{cc}	[%]	1.9	1.56	1.52
E_{peak}/E_{acc}	-	1.98	2.30	2.36
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.57	3.61
R/Q	[Ω]	113.8	135	133.7
G	[Ω]	271	284.3	284
R/Q*G	[Ω*Ω]	30840	38380	37970
$k_{\perp}$ (σ_z=1mm)	[V/pC/cm^2]	0.23	0.38	0.38
$k_{\parallel}$ (σ_z=1mm)	[V/pC]	1.46	1.75	1.72

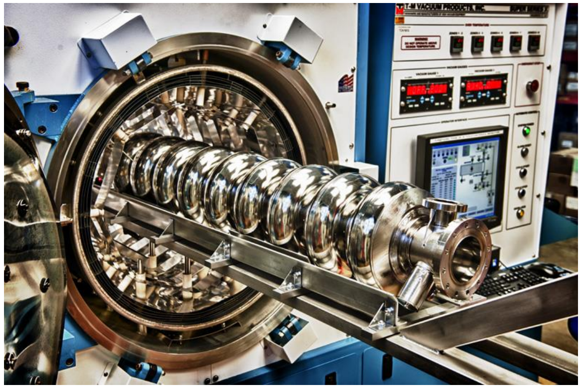
Electromagnetic optimization

The Scope of EM-Mechanical Design (a cavity +He vessel)

- Minimize a sensitivity to microphonics due to He pressure fluctuations (df/dP) and mechanical vibrations
- Minimize a Lorentz Force Detuning (LFD) coefficient
- To keep the stiffness and tuning sensitivity at suitable level to allow for tuning.
- Keep provision for slow and fast tuner integration.
- Enough strength to withstand atmospheric pressure
- “Dressed” cavity has to be qualified in 5 different load conditions by stress analysis

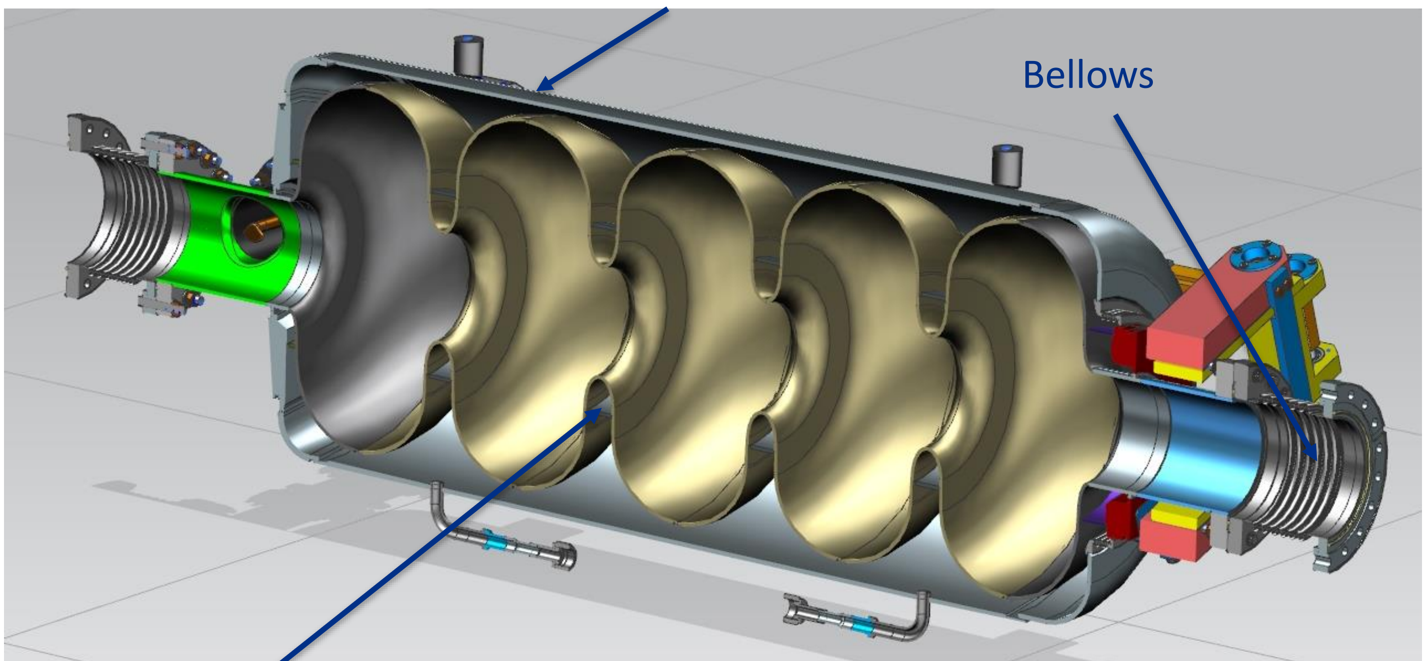
1. Warm Pressurization
2. Cold operation at maximum pressure
3. Cool down and tuner extension
4. Cold operation at maximum pressure and LHe weight
5. Upset condition – Insulating and beam vacuum failure

Design approaches. Mechanical stiffness

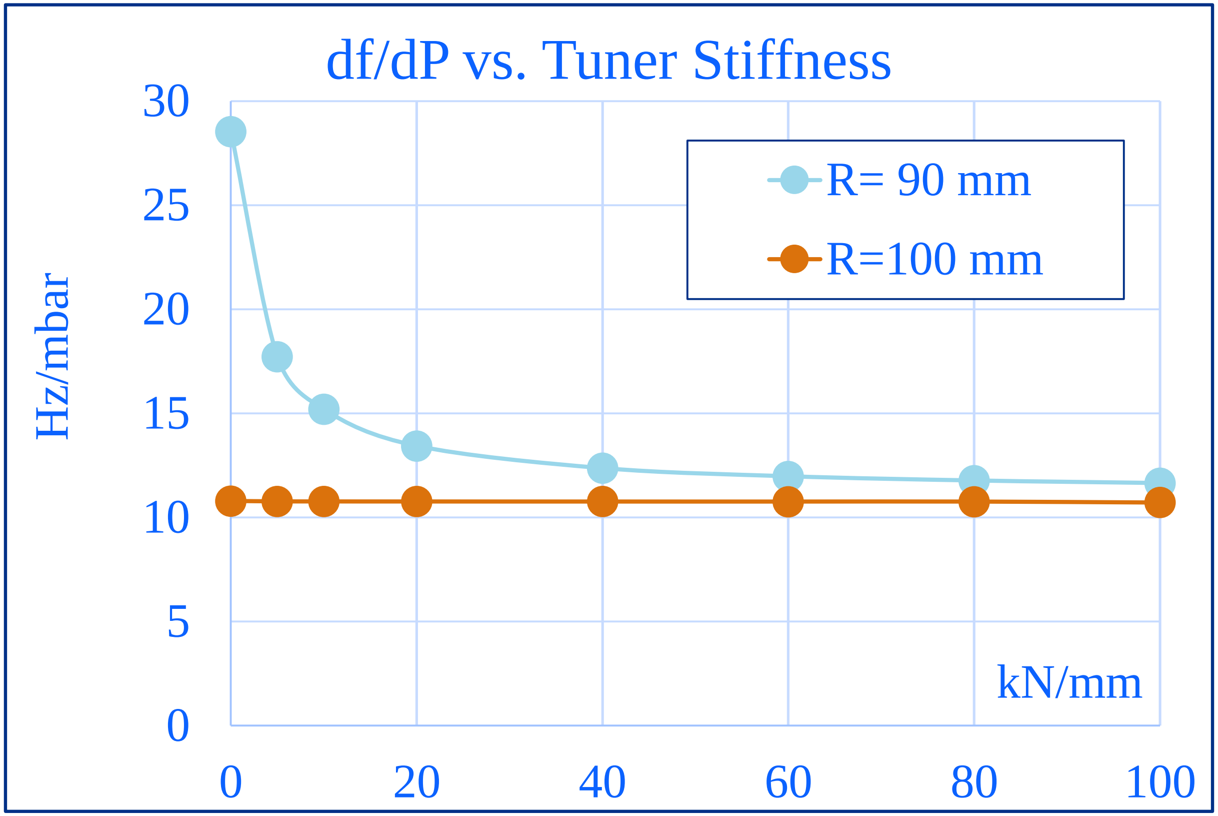


Bare cavity

Dressed cavity



Design approaches, df/dP optimization



df/dP for stiffening ring R = 90 mm vs. 100 mm
Bellows radius of OD=125 mm

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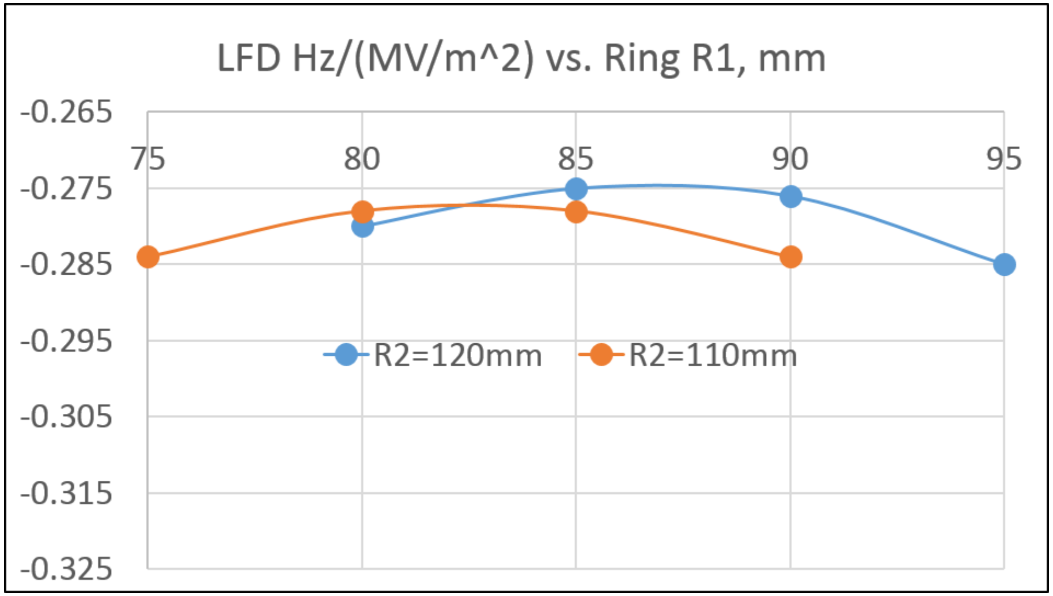
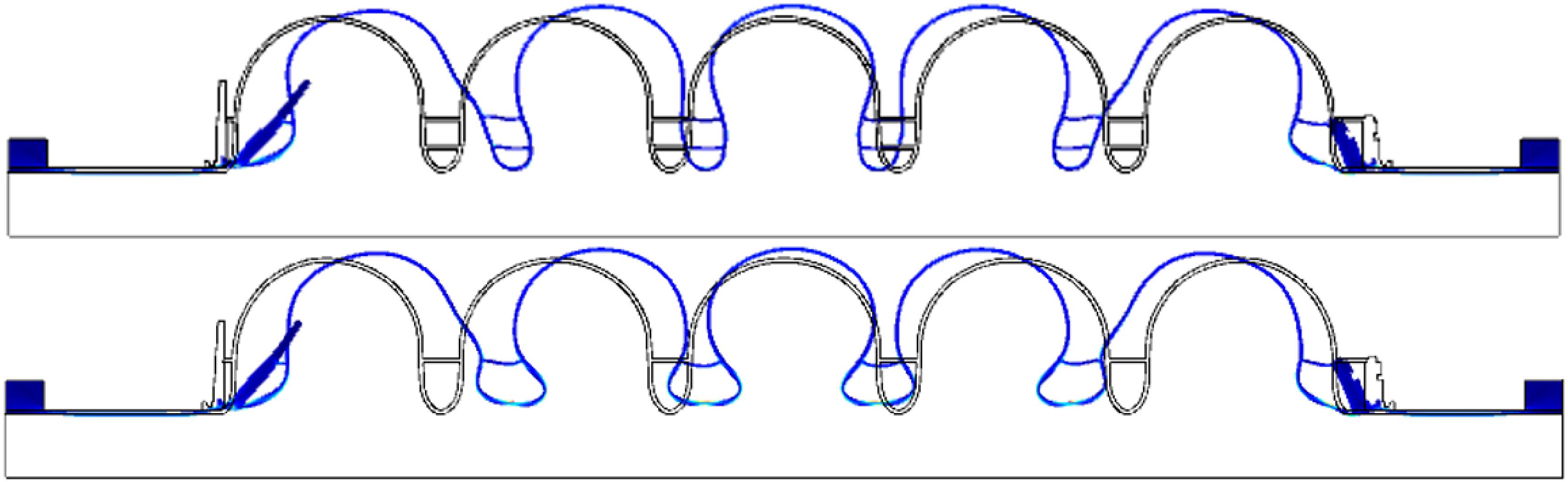
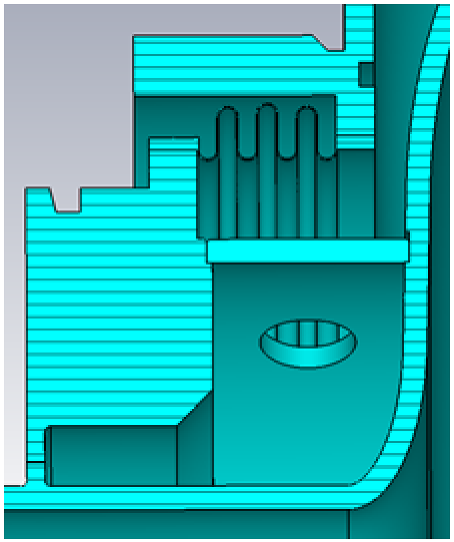
Design approaches, LFD minimization.

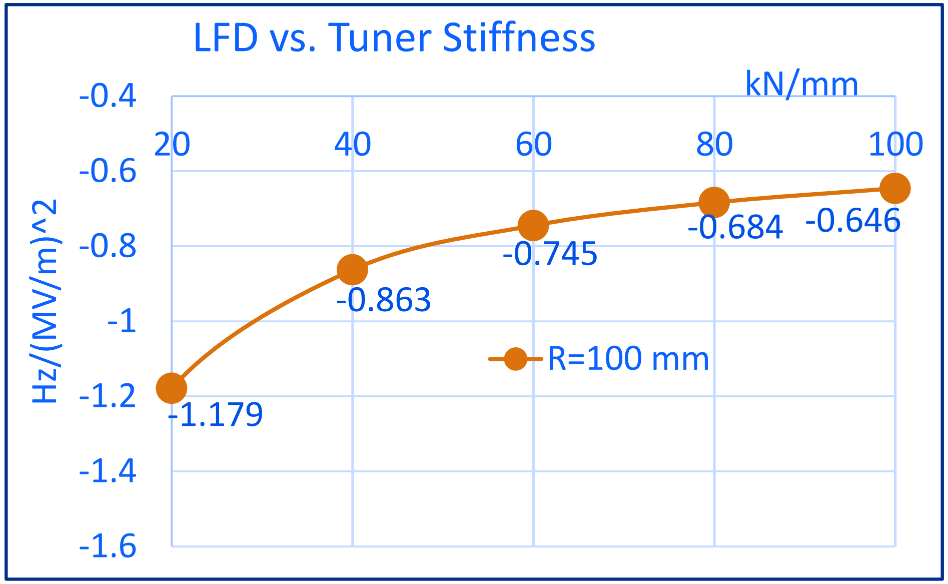


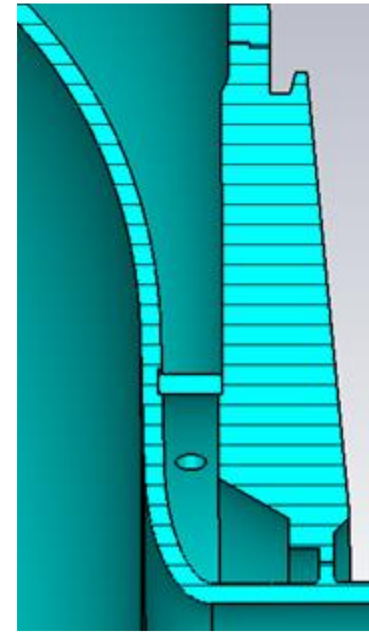
For 2 rings LFD~-0.275 Hz/(MV/m)^2
For 1 ring LFD~-0.38 Hz/(MV/m)^2.



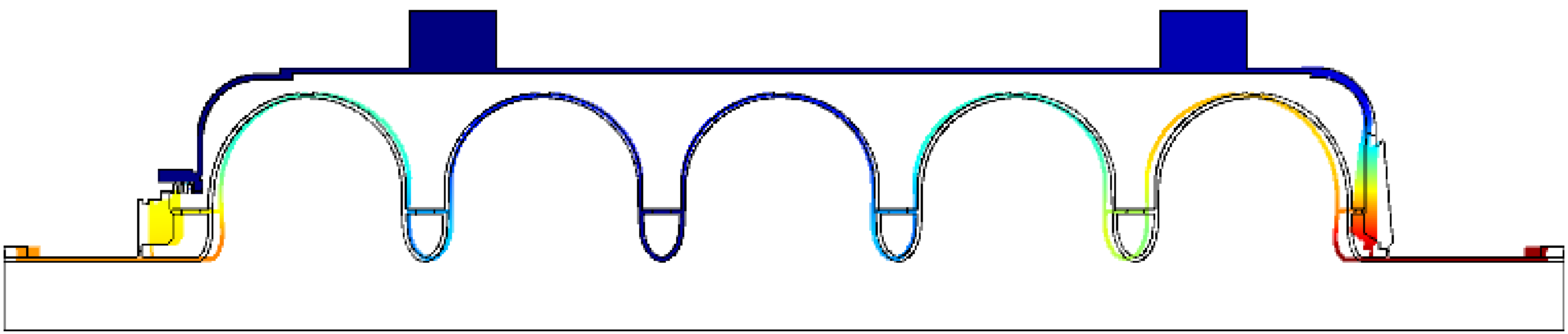
Design approaches, LFD optimization



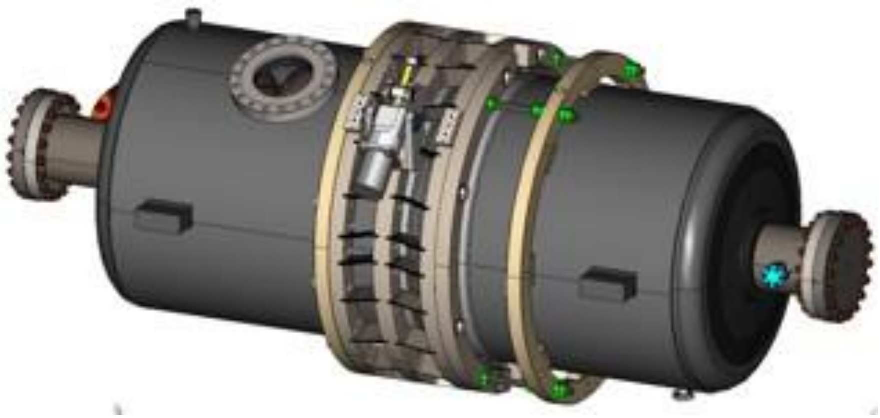


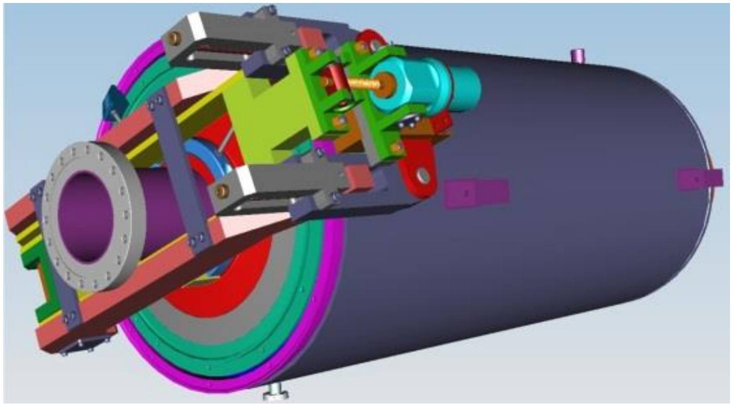


LFD for dressed cavity with R=100 mm stiffening rings



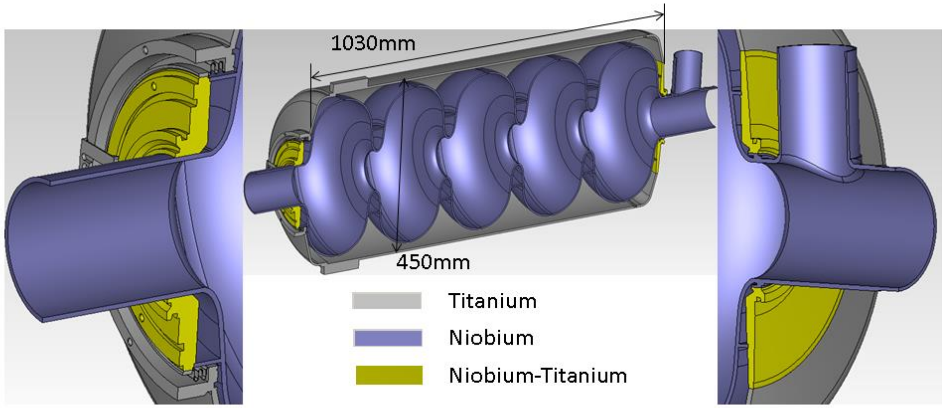
Design approaches, an elliptical cavity tuner options





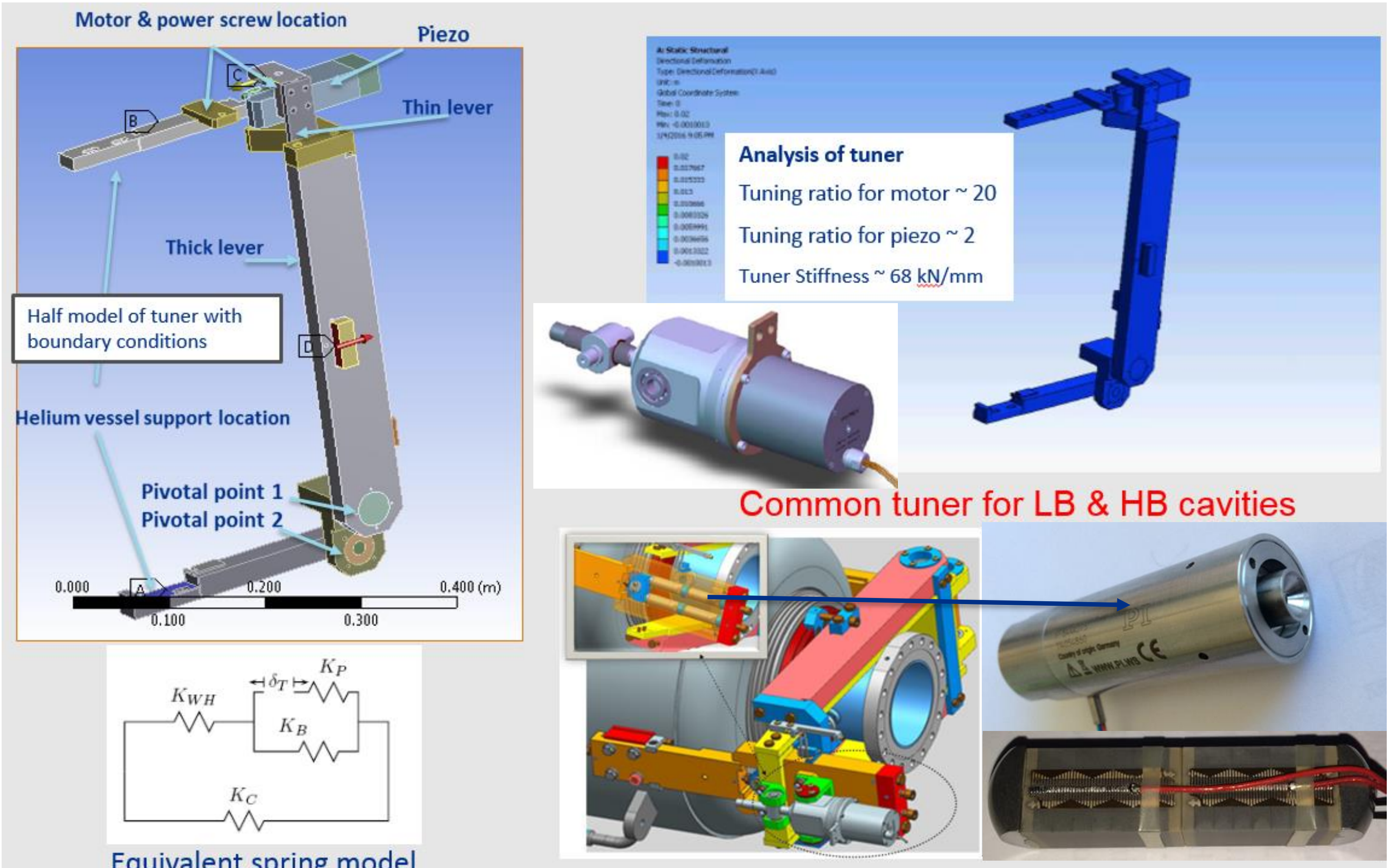
Lever Tuner design:
- Low df/dP,
- Mechanical resonances > 60 Hz;
- Good tunability;
- Less expensive.

Blade Tuner – scaled ILC:
- High df/dP,
- Insufficient tuning efficiency;



Design approaches, the tuner

- Coarse tuner (step motor) – for the cavity tuning after cooldown, range ~100 kHz
- Fine tuner (piezo) – for microphonics and LFD compensation, range ~ 1kHz

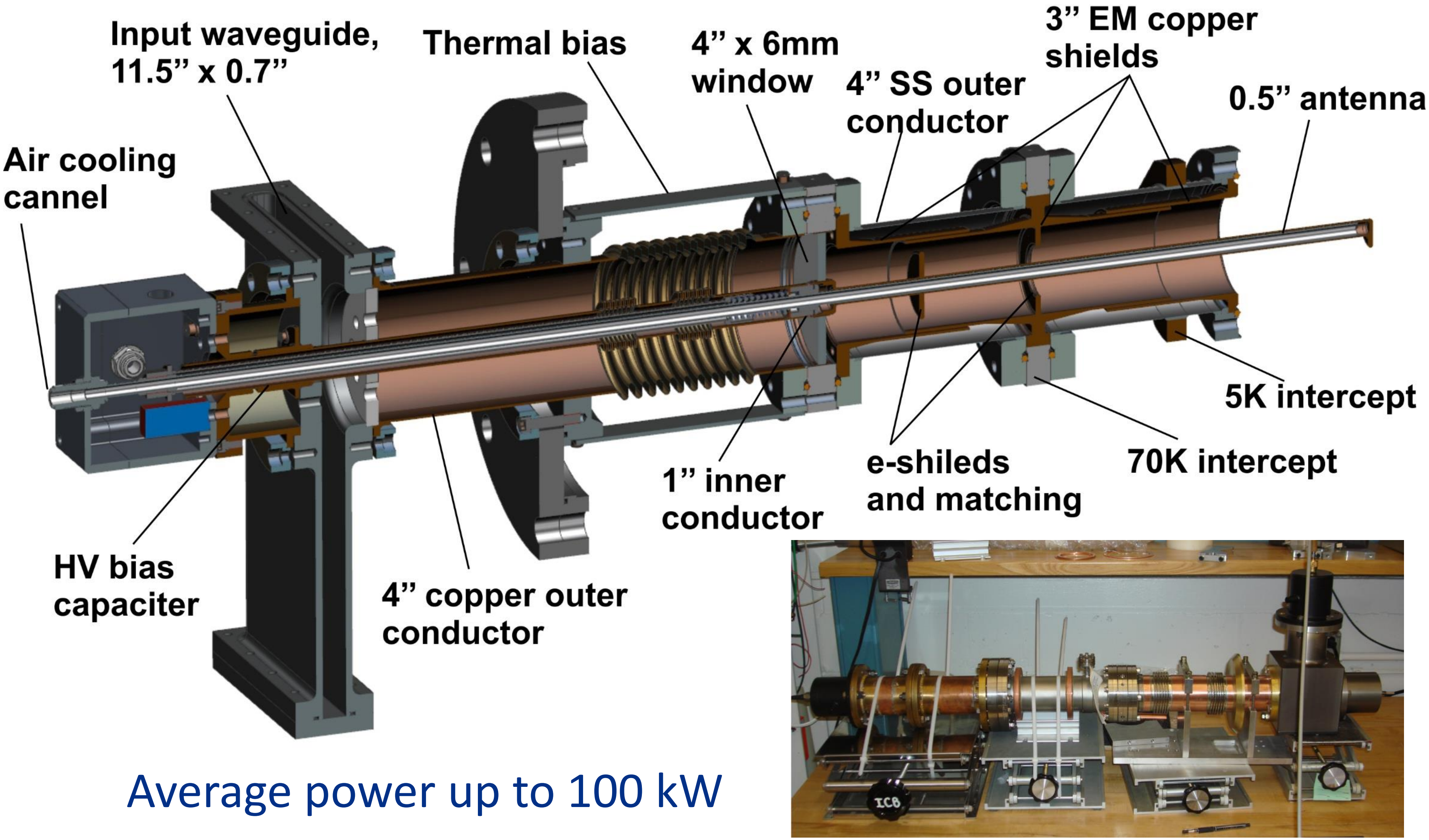


Couplers for SRF cavities:

- ❑ The couplers should transfer RF power to the cavity operating at cryo temperature
- \- High pulsed power (hundreds of kW for pulsed operation - SNS, ESS) → good electric strength
- \- High average power (up to 100 kW in CW – PIP II) → low dynamic losses, sufficient cooling (air, He)
- \- Low static losses
- \- Good vacuum properties
- ❑ Issues:
- \- MP in the vacuum part → DC bias
- \- Copper plating (chips)
- ❑ Design choices:
- \- One window versus two windows
- \- Type of cooling

Couplers for SRF cavities:

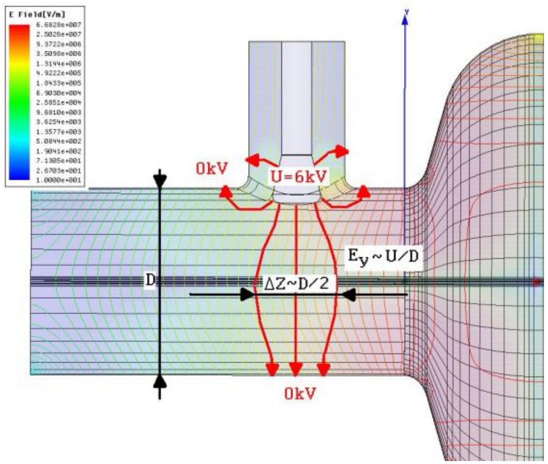
Coupler for PIP II LB/HB 650

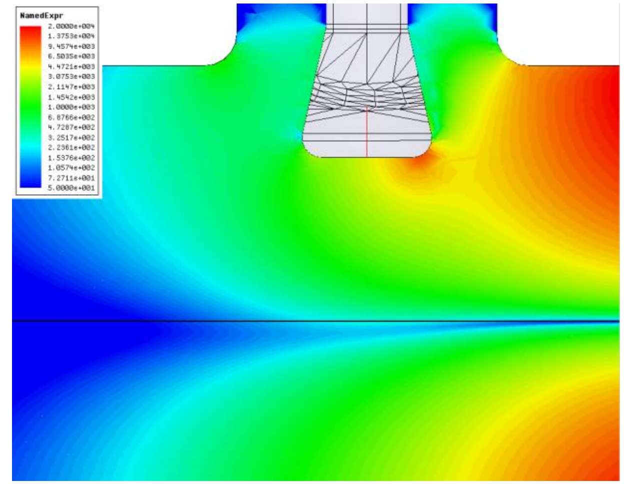


Average power up to 100 kW

RF kick caused by the input and HOM couplers.

Simple estimations of the transverse fields caused by the main coupler:





RF voltage*:*

U=(2PZ)$^{1/2}$, *Z*–coax impedance;

for *P*=300 kW and *Z*≈70 Ohms

U ≈ 6 kV

Transverse kick:

$$\nu = \frac{\Delta p_y c}{\Delta U_{acc}} \approx \frac{U}{2U_{acc}} = \frac{6kV}{2\times 30MV} = 10^{-4}$$

Transverse kick caused by the couplers acts on a bunch the same direction for all the RF cavities of the linac.

Real part may be compensated by the linac feedback system;

Imaginary part dives the beam emittance dilution (here β is beta-function, σ is the bunch length, and U_0 is the initial beam energy):

$$\gamma\varepsilon \approx \gamma(z_{\max}) y_{\max} y'_{\max} = \frac{\pi^2 \nu^2 E^2 \sigma^2 \beta^3 \gamma_0}{\lambda_{RF}^2 U_0^2}$$

SRF cavity production technology

Parts: sheets, tubes → Parts QC → Half cell forming → Iris welding → Dumbbell, end ass. RF QC → Equator welding → QC

Fabrication → Quality Control → Chemical Processing → Heat Treatment → Frequency Tuning → Light Chemistry → Baking → VTS Testing

Vessel Welding → Light Chemistry → Quality Control → HTS Testing

String Assembly → Quality Control → Cryomodule Assembly → Cryomodule Testing

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Typical Technical Specification to Niobium Sheets (For XFEL Cavities)

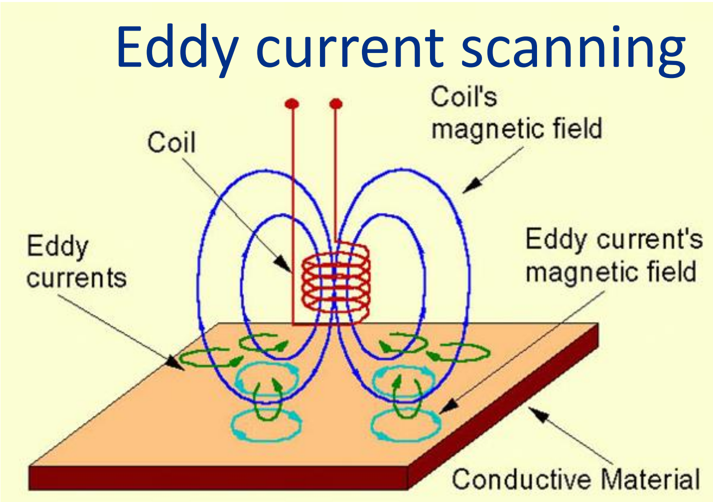
Concentration of impurities in ppm*				Mechanical properties	
Ta	≤ 500	H	≤ 2	RRR**	≥ 300
W	≤ 70	N	≤ 10	Grain size	≈ 50 µm
Ti	≤ 50	O	≤ 10	Yield strength, $\sigma_{0.2}$	$50<\sigma 0{,}2<100$ N/mm^2 (Mpa)
Fe	≤ 30	C	≤ 10	Tensile strength	> 100 N/mm^2 (Mpa)
Mo	≤ 50			Elongation at break	30 %
Ni	≤ 30			Vickers hardness HV 10	≤ 60

*ppm=Parts per Million

**The Residual Resistance Ratio "RRR" is the ratio of resistance at 300K (room temperature) to the resistance at 10K.

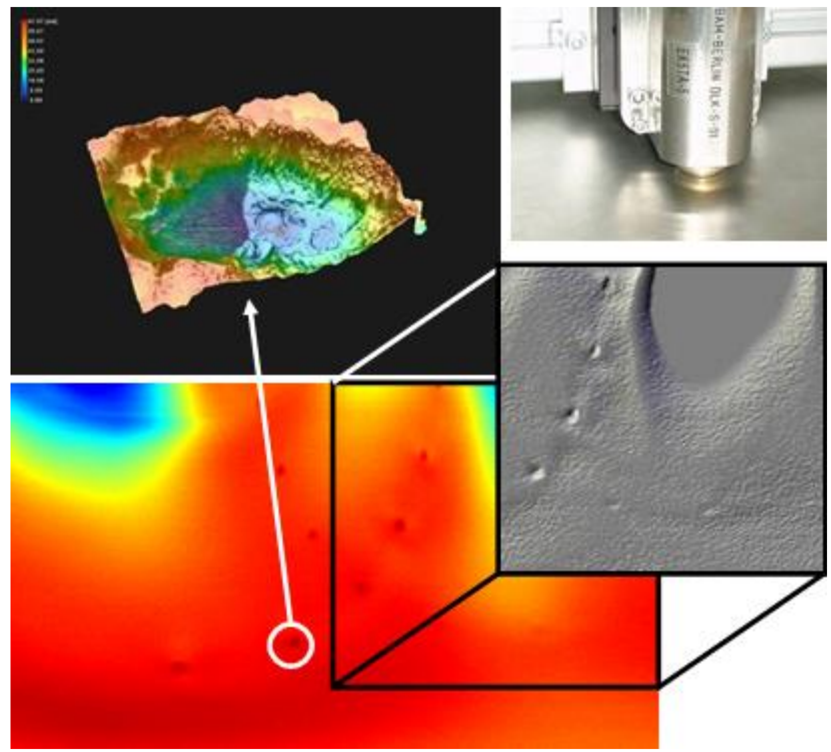
Fermilab

Material quality control



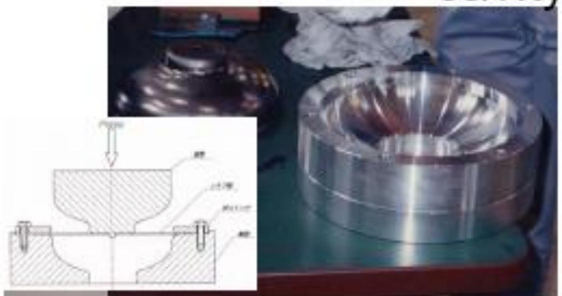
Disks are cut from high purity niobium sheet and eddy current scanned for pits, scratches or inclusions of foreign materials

Discs with inclusions of foreign materials or damage are rejected



Elliptical cavity production

Fabrication: Conventional fabrication (deep drawing and EB welding of fine grain Nb). Experiences of ca. 20 years of industrial cavity fabrication are available



Half cells are produced by deep drawing.

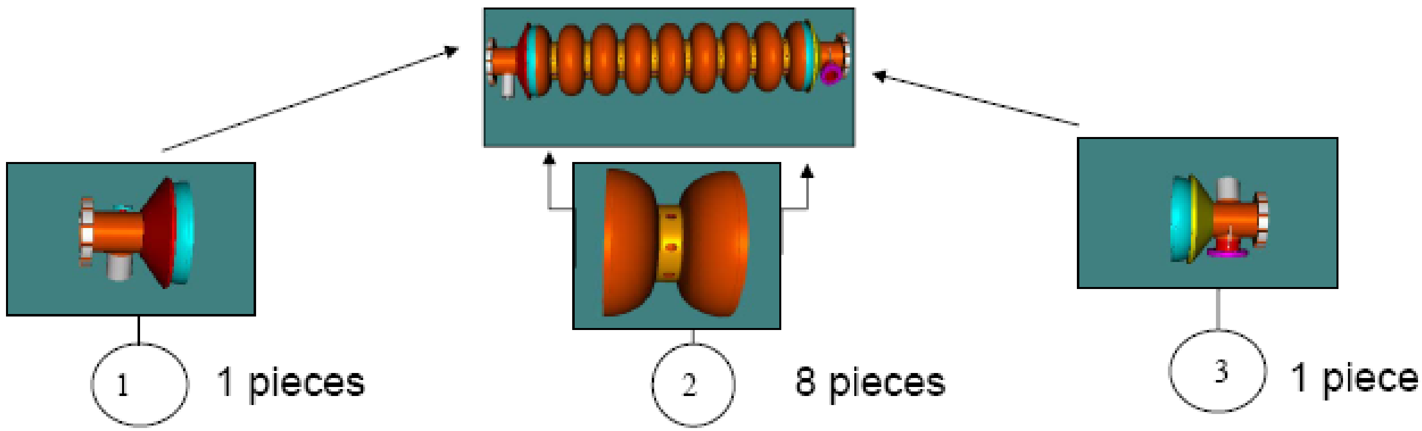
Dumb bells are formed by electron beam welding.

After proper cleaning eight dumb bells and two end group sections welded by electron beam together

Important: clean conditions on all steps
shape accuracy, preparation and EB welding

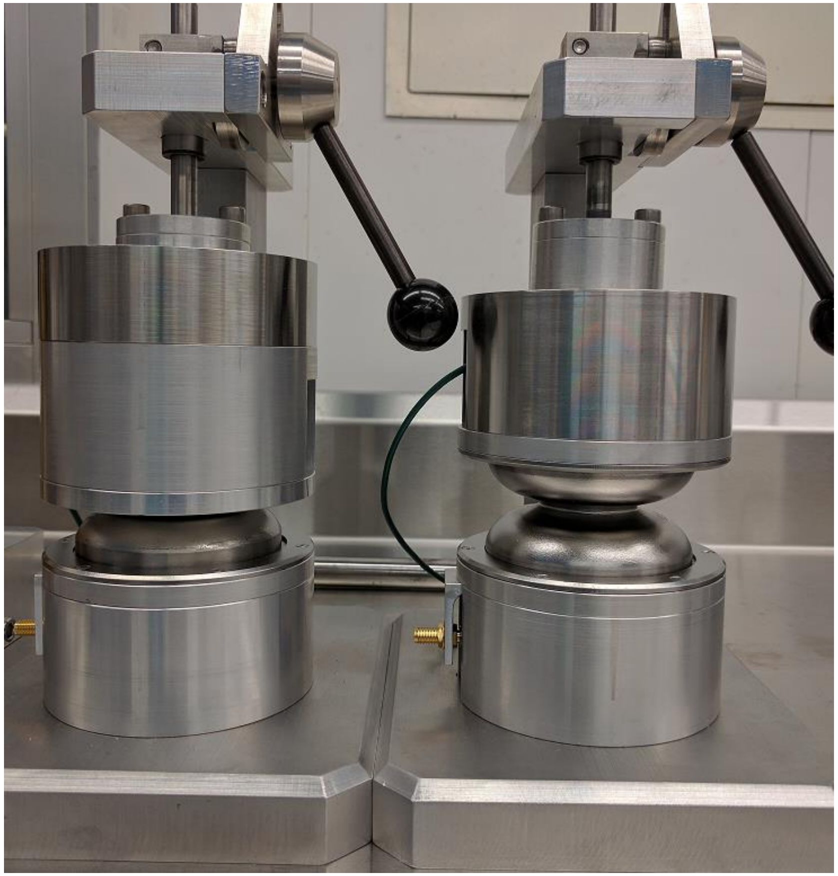
Elliptical cavity production

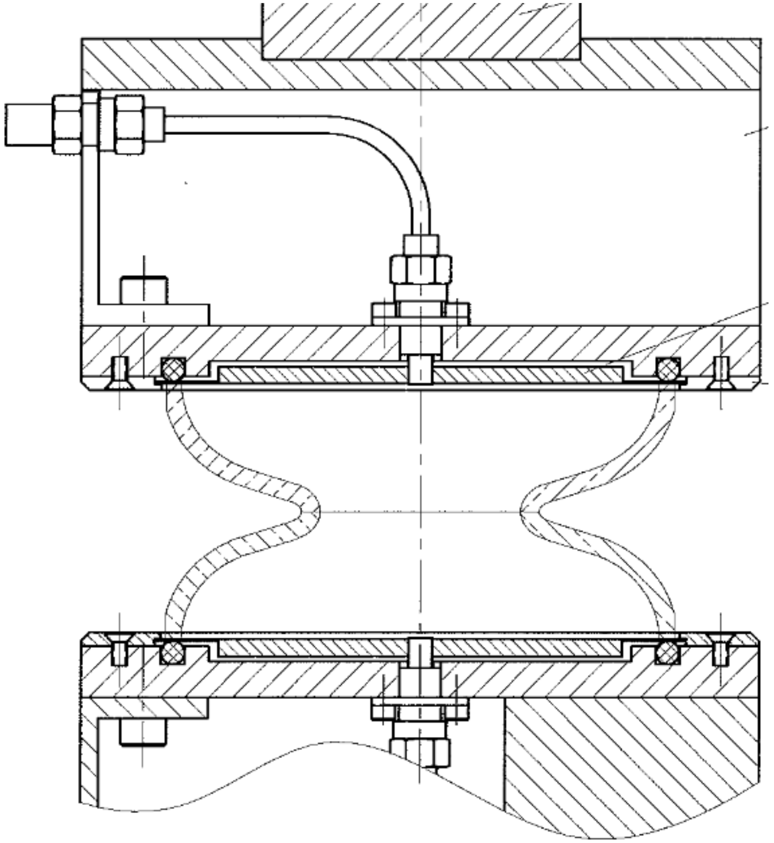
Cavity welding: the general way
There are differences of welding processes in industry



1. Degreasing and rinsing of parts
2. Drying under clean condition
3. Chemical etching at the welding area (Equator)
4. Careful and intensive rinsing with ultra pure water
5. Dry under clean conditions
6. Install parts to fixture under clean conditions
7. Install parts into electron beam (eb) welding chamber
   (no contamination on the weld area allowed)
8. Install vacuum in the eb welding chamber <= 1E-5 mbar
9. Welding and cool down of Nb to T< 60 C before venting
10. Leak check of weld

Elliptical cavity production





MEASURING OF DUMBELL

3.9 GHz half cells and dumbbell measurement fixture

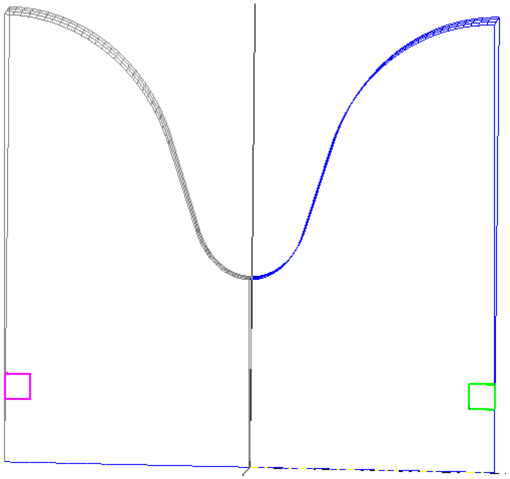
Elliptical cavity production

Cavity production steps:

-Eddy current scanning of Nb shits.

-Cut disk blanks with hole in the center

-Flow forming of half cell and trimming iris and equator area with extra length for tuning and welding shrinkage compensation. No extra length for a tuning in mid-cells. If pass visual inspection :



-Frequency and length measurements. Sensitivity of the frequency to extra length is 14 MHz/mm at iris and -55 MHz/mm at equator.

-EB welding of two half cell at iris to form dumbbell. Partual penetration welding from both sides. If pass visual inspection :

-Frequency and length measurements of the dumbbells. Both mode frequencies F_0 and F_{pi} measured 3 times: 1) without perturbation F0 and F1, 2) with perturbation in 1st half cell F_{01} and F_{11} 3) with perturbation in 2nd half cell F_{02} and F_{12}. Difference of the frequencies of two half cell can be calculated from these data:

$$dF=F_2-F_1=(F_{01} - F_{11} +F_{12} - F_{02})/(F_{01} +F_{11}- F_{02} -F_{12}))*k*F0$$

Where $k\sim4(F_{pi} - F_0)/(F_{pi} + F_0)$, for a 3rd harmonic cavity k~0.08 MHz

-Trimming calculations:

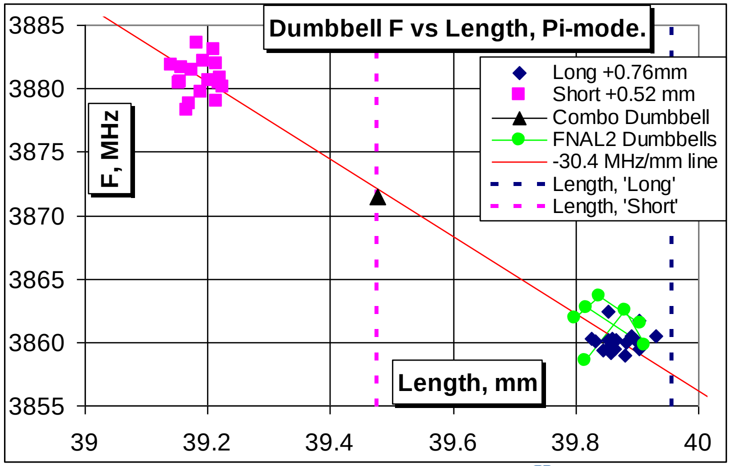
-Equator trimming

-Equator welding

-Mechanical and RF QC of the new cavity.

-Bulk BCP and 800C baking,

-RF tuning of the cavity



Multi-cell cavity field flatness tuning

FNAL elliptical 9 cell cavity tuning procedure. This technique based on bead-pull measurements of field distribution on operating (pi-mode). Amplitudes of E-field in the center of each cell used for frequency of individual cells.

Normalized field distribution is uniform, Ai=1 for i=1,2, … 8, 9, if frequency of each cell are same. When frequency of the cell #n is shifted by dF_n field distribution will change by dA_i.

$$dA_i = K_{in} * dF_n$$

Perturbation of frequency of each will change field distribution:

Let us solve this equation to find frequency perturbation from field distribution:

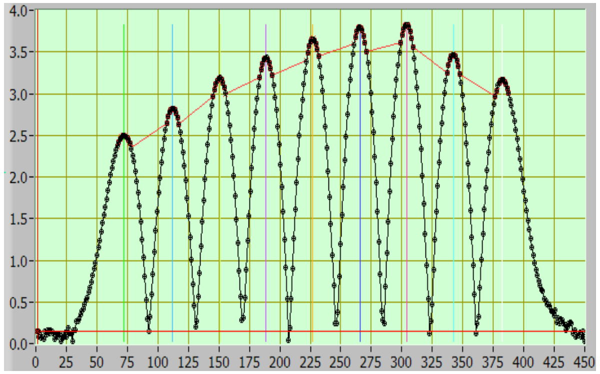
$$dA = K * dF \Rightarrow K^{-1} * dA = K^{-1} K * dF = dF$$

Where sensitivity coefficients matrix *K* calculated from HFSS simulations.

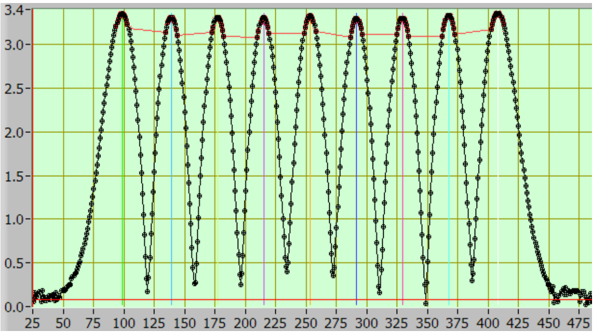
During RF tuning of the cavity we need to tune its operating mode frequency F_9. Also we can not measure individual cell frequency but can measure F_9. Tuning of cell #n by dF_n shifts also cavity frequency by $dF_9 \sim dF_n/9$. If design frequency is $F_9 0$ tuning of the cell should be done by shifting operating mode frequency by:

$$dF_9 = (F_9 0 - F_9 - dF_n)/9$$

This technique works best when field flatness of the cavity is close to ideal. Because it linear and based on small perturbations. Tuning is better to start with most perturbed cell. If field flatness still not acceptable the additional tuning cycle should be done.



Before tuning. FF 65%, slope +28 %

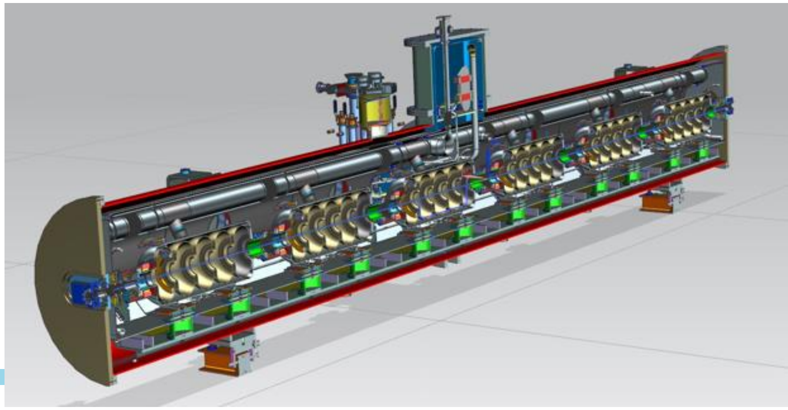


After tuning. FF 98%, slope +0.64 %

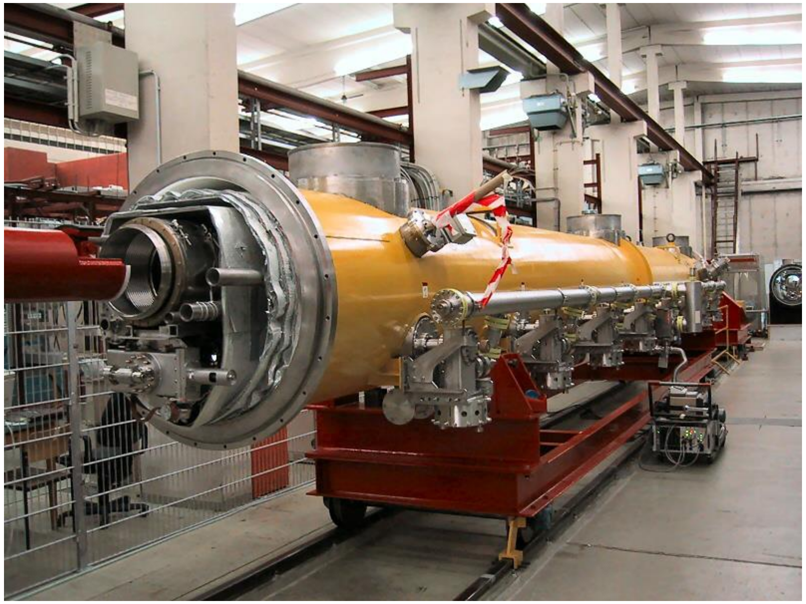
ICL Cavity Tuning Machine

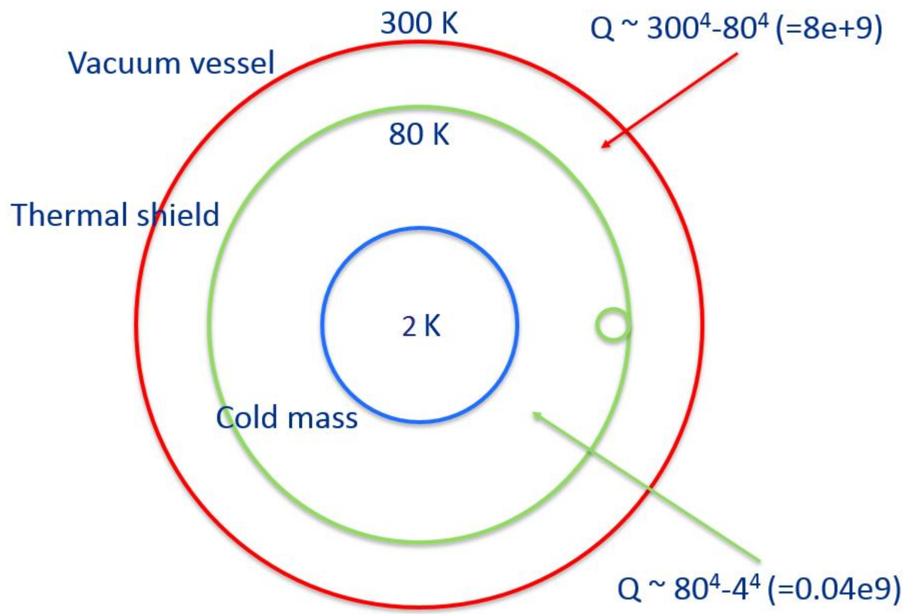
Vacuum vessels

- The outermost cryostat component that:
  - Contains the insulating vacuum.
  - Serves as the major structural element to which all other systems are attached to the accelerator tunnel floor.
  - Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.
- The design for internal and external pressure are addressed by the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2 and specific workplace codes.
- Insulating vacuum is generally in the 1e10^{-6} torr range, but can be as low as 1e10^{-4}. The lower the better.



Vacuum vessel and thermal shields

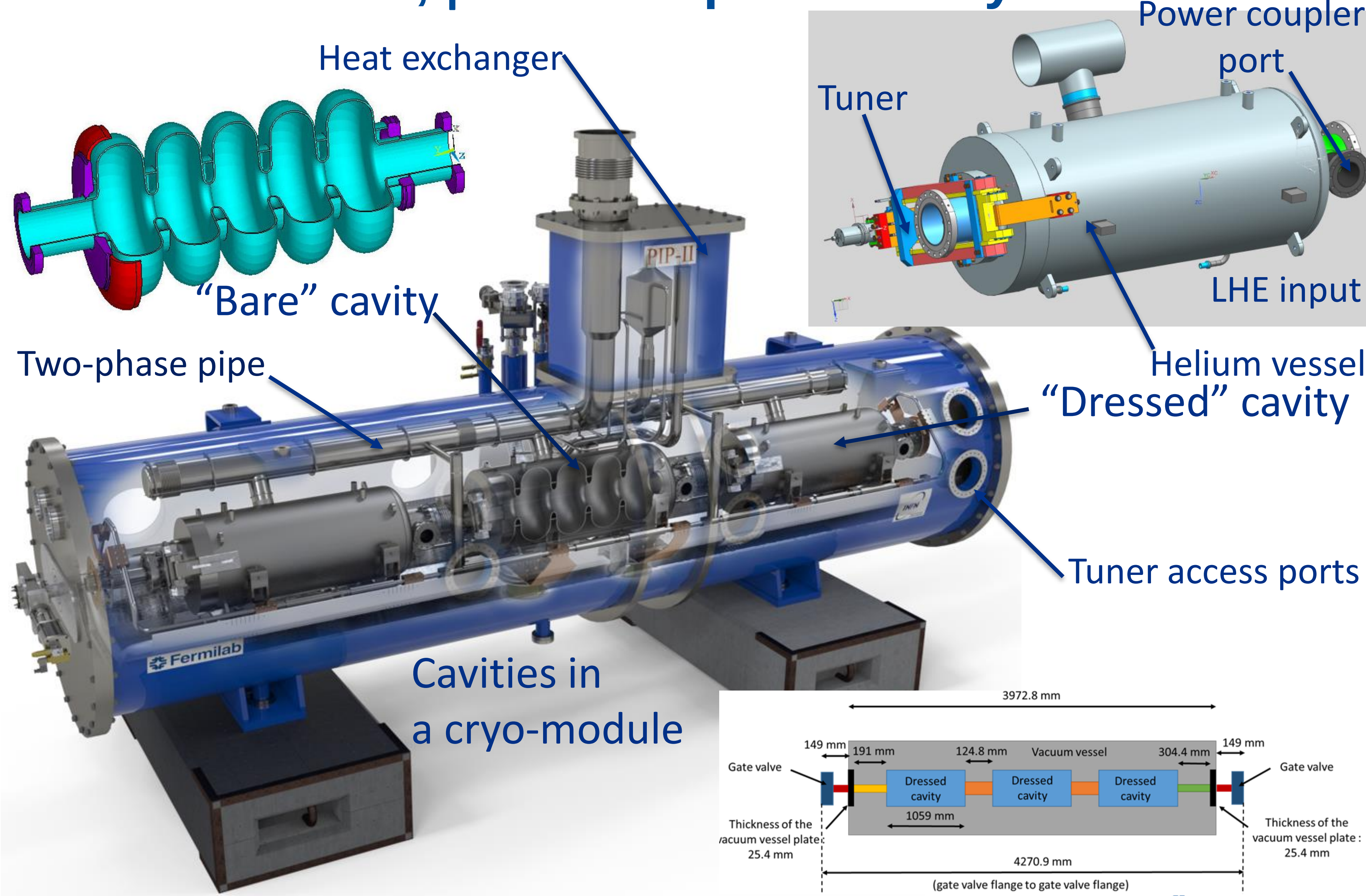




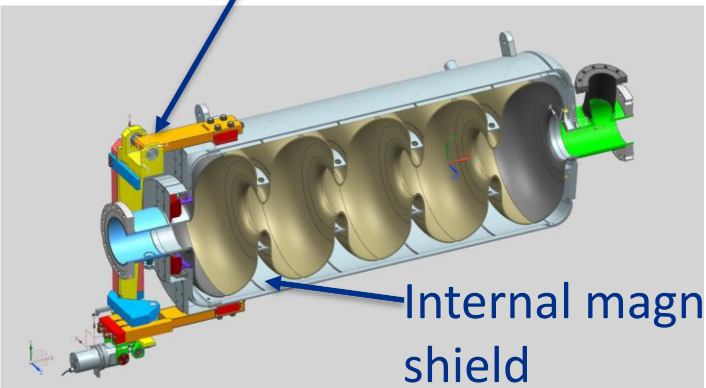
Insulation

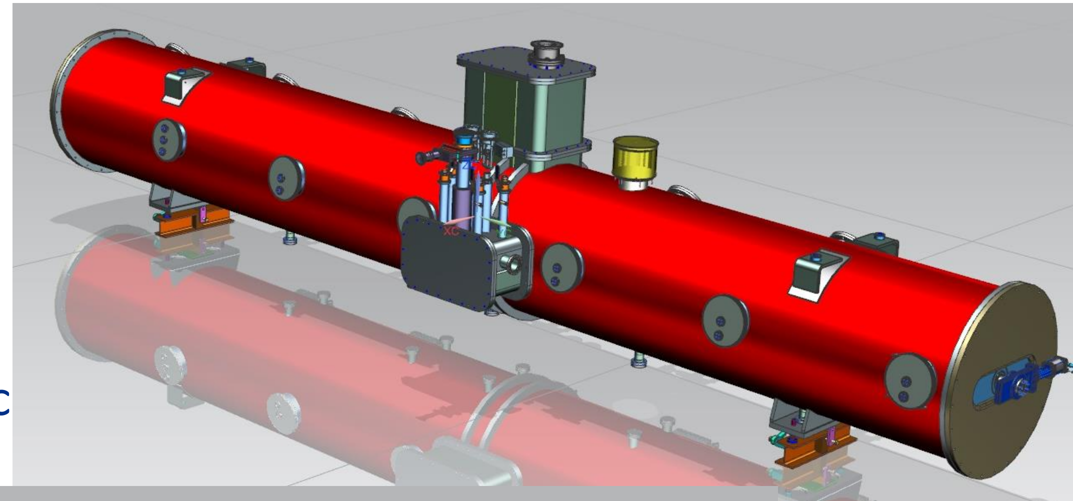
- Multi-layer insulation (MLI) reflects radiation heat transfer back toward its source.
- Usually mounted on the outside of the colder surface, e.g. the thermal shield or cold mass.
- Consists of alternating layers of reflector and spacer material:
  - Reflector is usually double-aluminized mylar sheets 6-12 μm thick aluminum-coated on both sides with a minimum of 300 Å.
  - Spacer is usually a polyester net, fiberglass net or other similar material compatible with the environment.
  - The reflector can be perforated to facilitate pumpout.
- The number of layers varies, but is usually from 30-60 layers on a thermal shield nominally at 80 K and 10-15 layers on a lower temperature shield or cold mass.
- It must be in vacuum – $1e10^{-4}$ torr or lower.
- To estimate the total heat load due to radiation and residual gas conduction, realistic values are ~1.5 W/m^2 at 80 K and ~0.15 W/m^2 at 4.5 K.

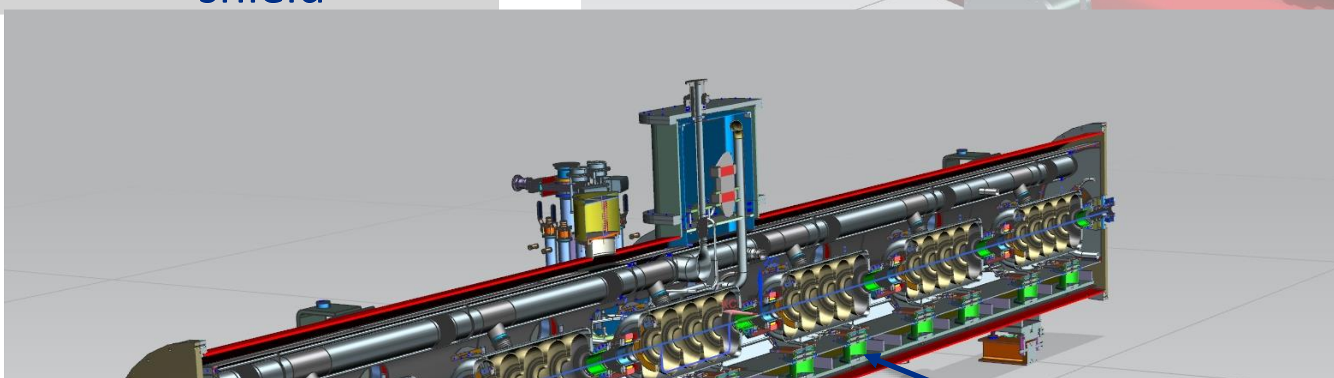
CM for 650 MHz, β=0.61 elliptical cavity for PIP II



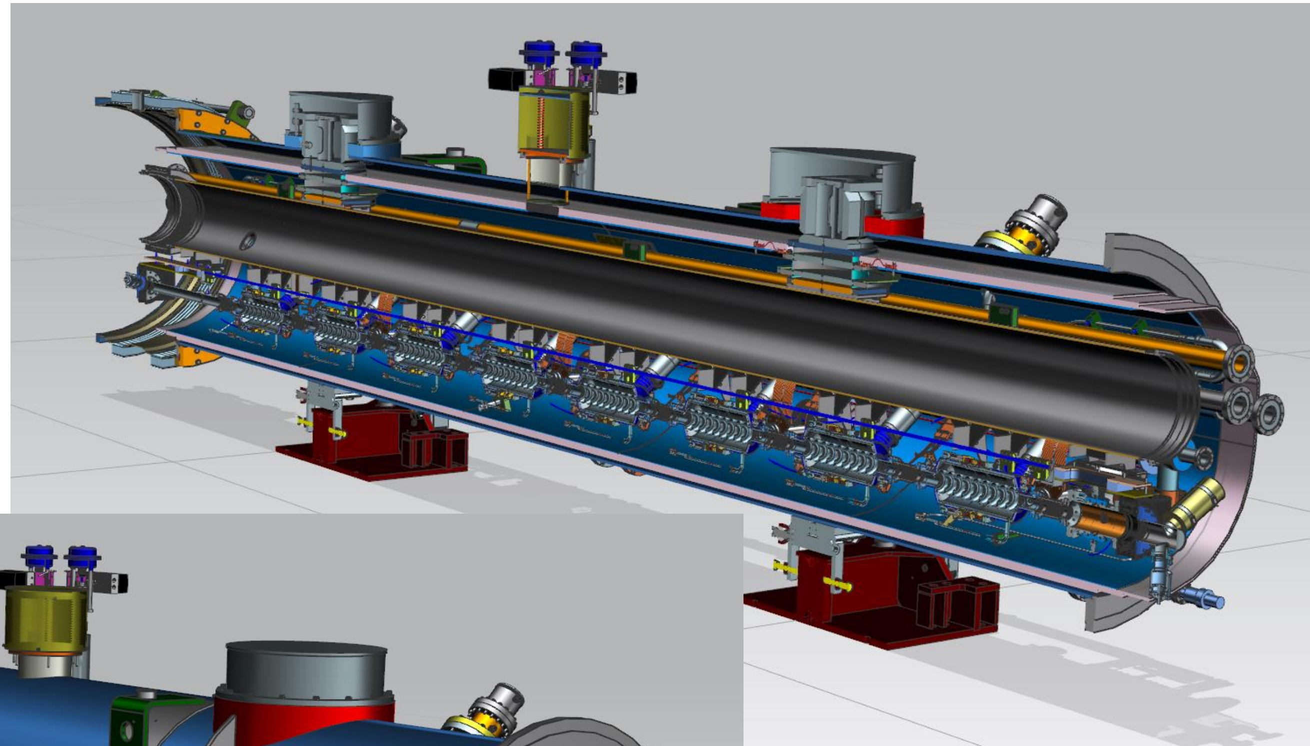
CM for 650 MHz, β=0.9 elliptical cavity for PIP II

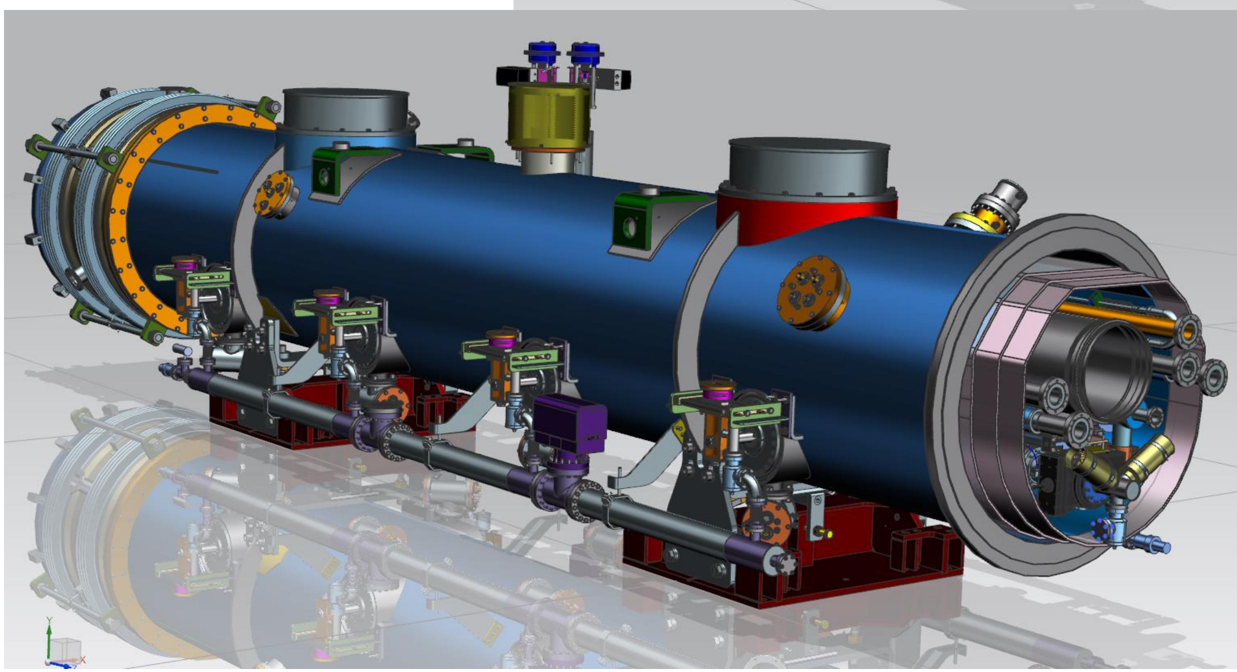




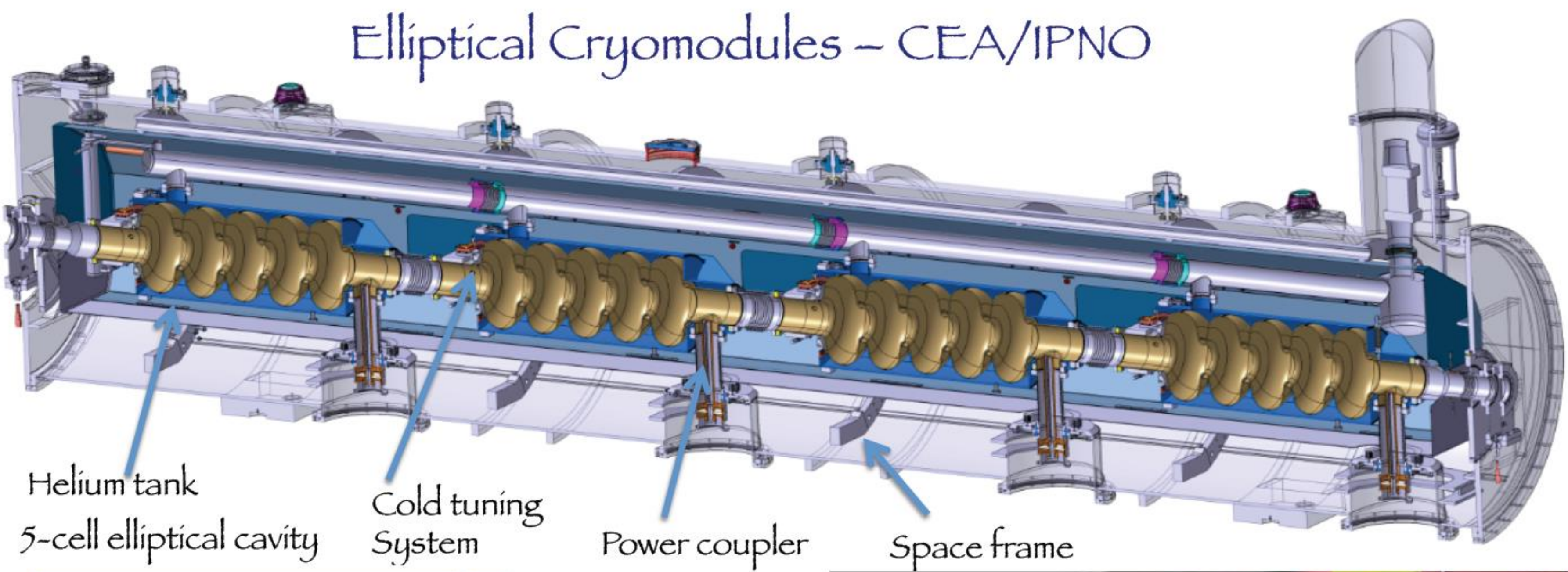


CM for 3.9 GHz elliptical cavity for LCLS II





Cavities supported by High-power couplers



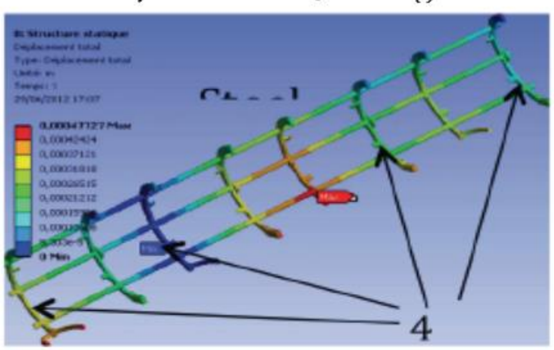
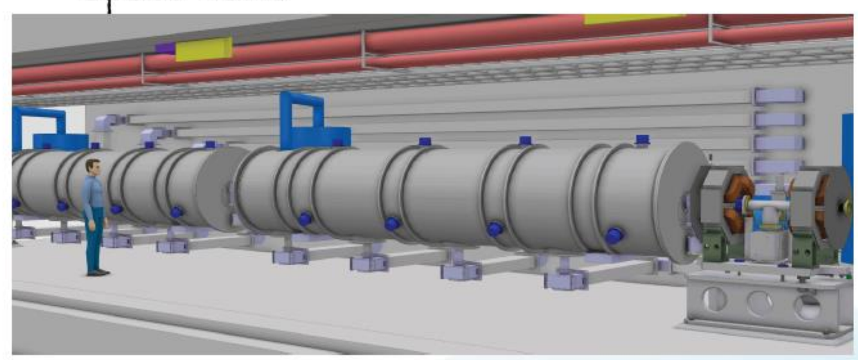
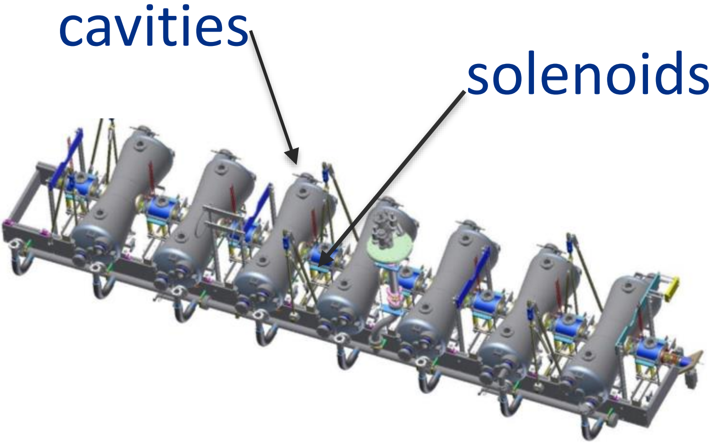


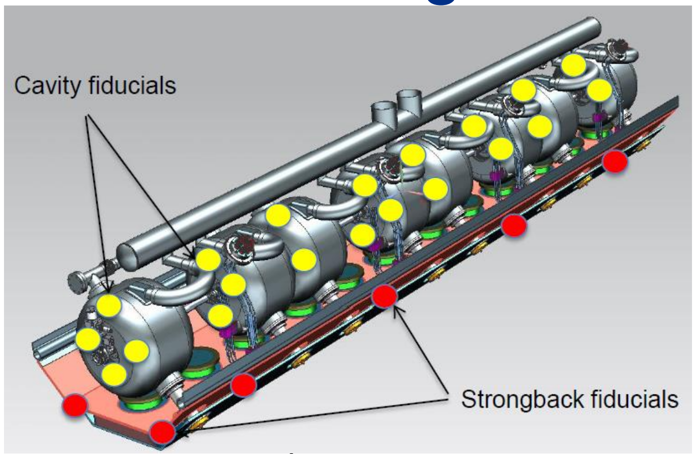
Figure 4.120: Helium vessel with hanging rod



CM for 325 MHz HWR cavities for PIP II (developed by ANL)



Cavities alignment



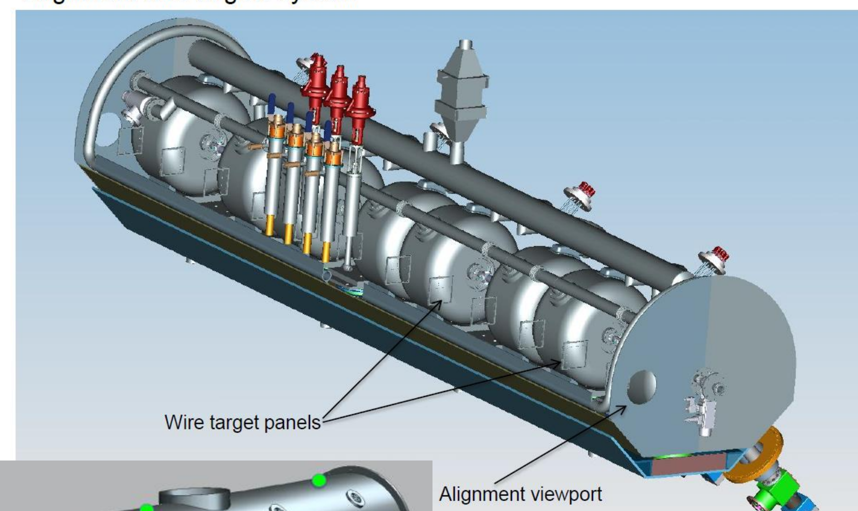
Transverse cavity alignment, mm RMS <±1
Angular alignment, mrad RMS ≤±10

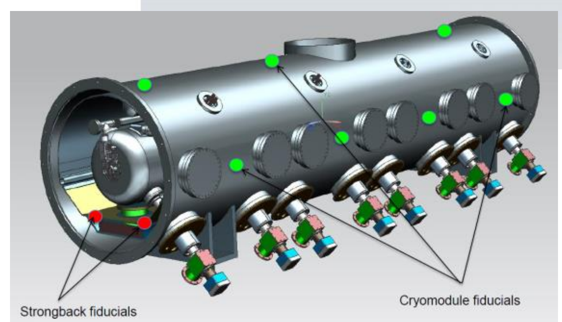
- The cavity string is aligned in warm state with an offset to compensate for thermal shrinking.
- Laser Trackers and precision optical and electronic levels is used as instrumentation for the alignment of cavity string
- After completion of cavity string alignment and transfer to the strongback referencing points, the cavities and solenoids temporary fiducials, as well as the fiducials on both sides of the strongback, can be removed

❑ Beam – base alignment (BPM, HOMs)

- Special alignment wire target panels (4 per each component, 1 upstream and 1 downstream on each left-right side) – used for relative optical measurement with respect to external reference points
- Each panel has two intersecting wires forming a crosshair along the diagonal, creating 24 configurations

Alignment wire targets system





Fermilab

Cryogenics and thermoacoustic oscillations

- LCLS-II is a low-beam-current SRF linac → cavities have very narrow bandwidth, ~10 Hz.
- During acceptance testing of the prototype LCLS-II cryomodule, unexpectedly high level of microphonics was encountered preventing stable operation of the cavities in a GDR mode.
- The problem was traced to thermoacoustic oscillations in the supply JT valves.
- Thermoacoustic oscillations generally occur in long gas-filled tubes with a large temperature gradient.
- Acoustic modes couple to mass transport up and down column especially well when gas density is strongly tied to temperature. E.g. warm gas from the top of a valve column moving to the cold bottom contracts, reducing pressure at warm region, driving the now cold gas back.
- These oscillations are generally important for the tremendous heat leaks they can represent, not microphonics.

- Low pressure operation consistently eliminated icing on the supply valves (JT, bypass)
- **Indicates *suppression* of thermo-acoustic oscillations**

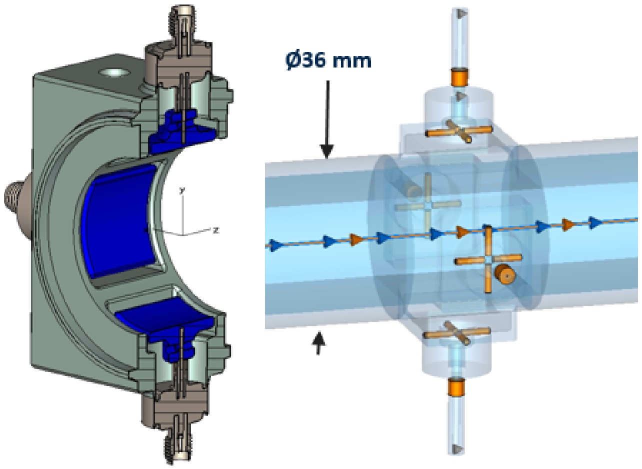
J. Holzbauer, "1.3 GHz Microphonics measurement and mitigations," MRCW18

Beam Diagnostics

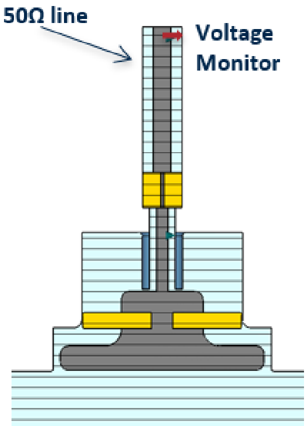
- *Beam Position and Phase Measurement System (button –type or stripline BPMs)*
- *Beam Loss Measurement System (ionization chambers).*
- *Beam Intensity Measurement System (DC current transformers and beam toroids*)
- *Beam Transverse Profile Measurement System (traditional wire scanner or photo-disassociation of H^- by laser radiation)*
- *Beam Transverse Emittance Measurements (Allison-Type Emittance Scanners or Laser-Based Emittance Scanners)*

"Don't try to save on the beam diagnostics!"

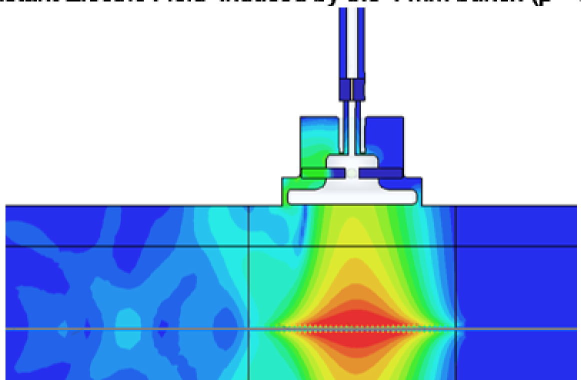
Beam Diagnostics in CM, beam position monitors (BPM)



BPM signals produced by the 4 mm rms bunch

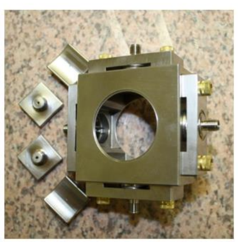


Instant Electric Field induced by the 4 mm bunch (β =1)



BPM signals spectral densities for various bunch lengths

- Hermetic feedthrough welding is finished.
- Next step = fit the electrodes and electron beam weld them into position.



BPMs for HWR cryomodule, prototype (top) and production (bottom) units

BPMs for SSR1 cryomodule

P.Ostroumov, PIP-II MAC meeting, 03/10/15 1

BPMs are mounted to the focusing elements:

ring pickup

Summary:

- ❑ RF design of the cavity is based on
- the accelerator operation regime – pulsed or CW;
- the beam power and energy;
- the beam quality requirements.
- ❑ RF cavity parameter optimization includes:
- frequency,
- RT versus SRF
- operating temperature choice for SRF,
- optimal gradient,
- cavity shape optimization,
- number of cells,
- cell-to-cell coupling,
- HOM extraction,
- RF power coupling
- ❑ RF linac is self-consistent system and its subsystem are interconnected; therefore, the RF cavity design is an iterative process.
- ❑ RF cavity design includes:
- RF parameter optimization;
- MP analysis
- Mechanical optimization.

Summary (cont):

- The SRF cavity component design includes:
  - the input power design;
  - the cavity tuner design;
  - The He vessel design.
- The SRF cavity manufacturing process contains a lot of operations and requires high technological culture:
  - material quality control;
  - cell manufacturing and pre-tune;
  - final assembly;
  - surface processing;
  - welding into the He vessel;
  - component assembly;
  - Cavity string assembly;
  - cryo-module assembly;
  - alignment
- The cryo-module:
  - Contains the insulating vacuum.
  - Serves as the major structural element to which all other systems are attached to the accelerator tunnel floor.
  - Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.