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Engineering for Particle Accelerators

Timergali Khabiboulline

U.S. Particle Accelerator School (USPAS)

SRF cavity design, RF measurements and tuning

20 June 2017

Engineering for Particle Accelerators

Instructors: *Vyacheslav Yakovlev, Timergali Khabiboulline, Thomas Nicol and Vladimir Kashikhin, Fermilab, Batavia*
One-week course at USPAS 2017, Lisle, Il
June 19-23, 2017

Daily Schedule

Monday 6/19
9:00-12:00 Yakovlev, Lectures: The fundamentals of large scale accelerator engineering.
14:00 -17:00 Yakovlev, Continuation

19:00-24:00 Study and tutoring

Tuesday 6/20
9:00-12:00 Khabiboulline, lectures: SRF cavity EM and mechanical design, RF measurements and tuning
14:00-17:00 Khabiboulline, Continuation

19:00-24:00 Study and tutoring

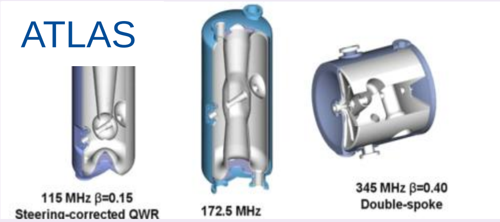
Engineering for Particle Accelerators

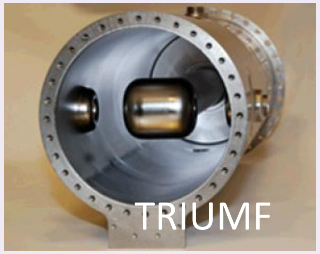
Albright, Robert	Lawrence Berkeley National Lab
Alonso, Inigo	European Spallation Source
Alvarez, Henry	SLAC
Antonini, Piergiorgio	INFN
Baketz, Sherry	Fermilab
Berry, Robert	RadiaBeam Technologies
Contreras, Crispin	Michigan State University
Di Ciocchis, Franco	Fermilab and University of Pisa
Gao, Jiani	EPFL and Paul Scherrer Institut
Gurung, Ujir	Cosmos International College
Kiemschies, Oliver	Fermilab
Kutsaev, Sergey	RadiaBeam Technologies
Liu, Zunping	Argonne National Lab
Martin, Brian	Brookhaven National Lab
Patel, Niral	Fermilab and Indiana University
Zhang, Bo	Dexter Magnetic Technologies

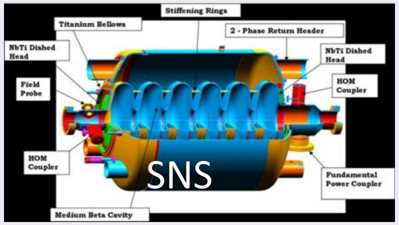
SRF Cavities Applications

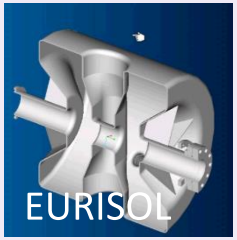
High Energy Physics

Nuclear Physics

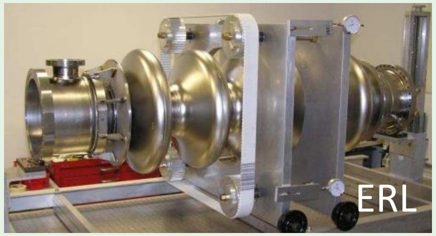




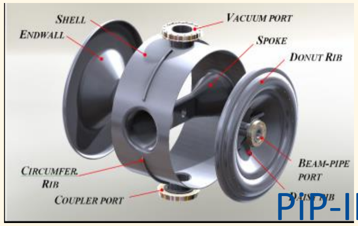


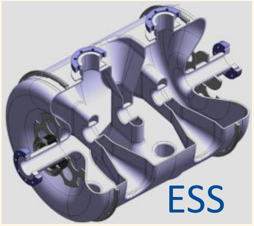


Radiation Sources



UPCOMING: ESS, FRIB, PIP-II, …



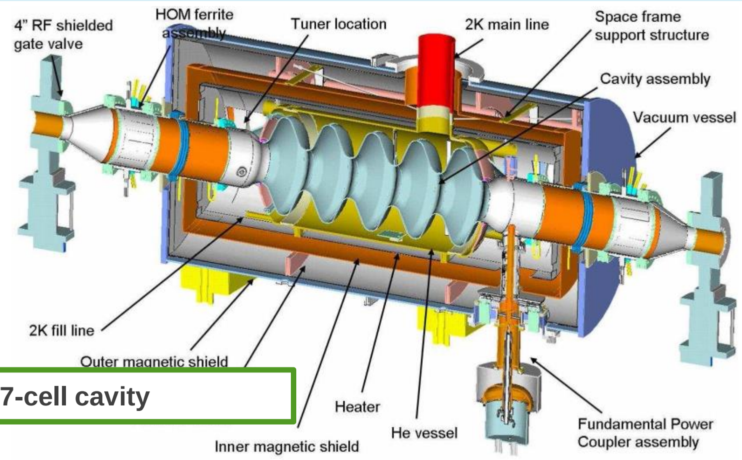


Modern SRF cavities cover wide diapasons of particles beta (0.05..1), operating frequencies (0.072..4 GHz) and beam currents (1mA..100mA, CW & Pulsed)

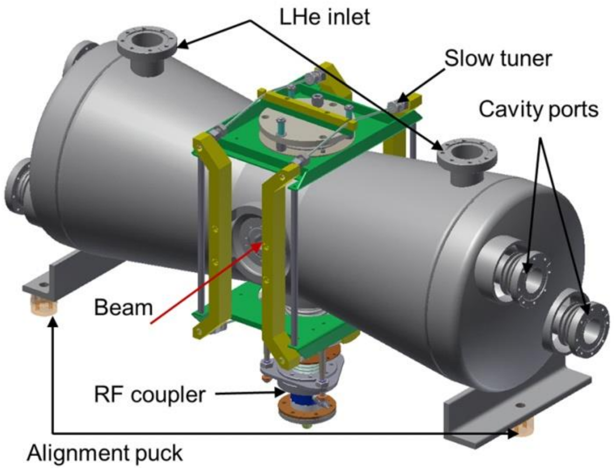
SRF cavity design

SRF cavity is a complicated electro-mechanical assembly and consist of:

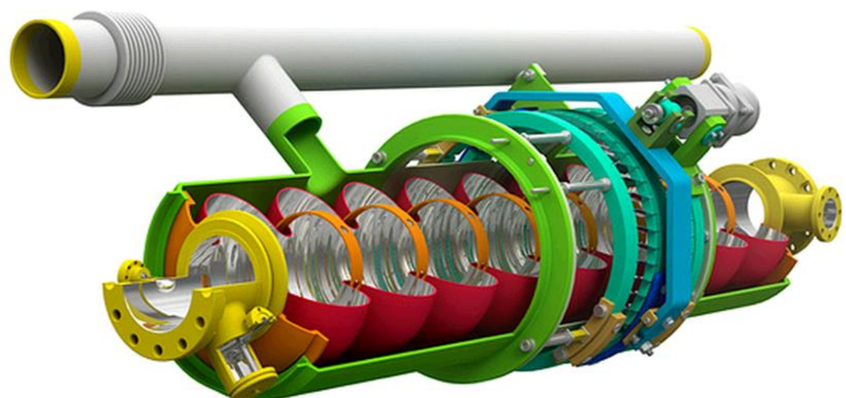
- bare cavity shell with power and HOM couplers
- stiffening elements (ring, bars)
- welded LHe vessel
- Slow and fast frequency tuners
- vacuum ports



ERL 704 MHz 7-cell cavity



HWR 162.5 MHz cavity for PIP-II



ILC 1.3 GHz 9-cell cavity

The design of SRF cavity requires a complex, self consistent electro-mechanical analysis in order to minimize microphonics and/or Lorentz force detuning phenomena and preserving a good cavity tenability simultaneously !

Problems of Superconducting Particle Accelerators

- 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)

Main characteristics of SC acceleration structure

- *(r/Q)* determines the relation ship between the acceleration gradient and energy stored in the acceleration structure *W* per unit length:

$$\left(\frac{r}{Q}\right)=\frac{E^2}{\omega W}$$

- Coupling to the feeding line:

$$\beta=\frac{P_{rad}}{P_{Ohm}}$$

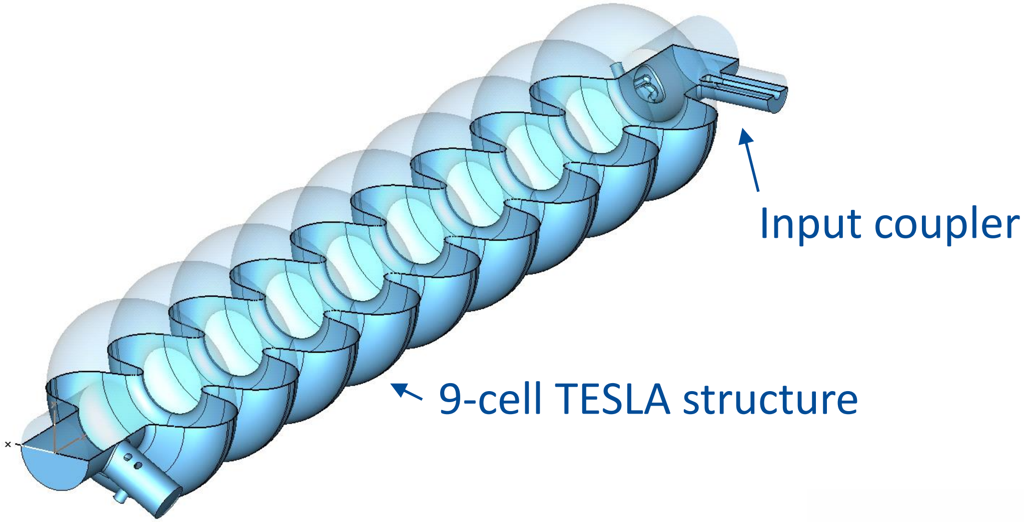
- Loaded *Q*:

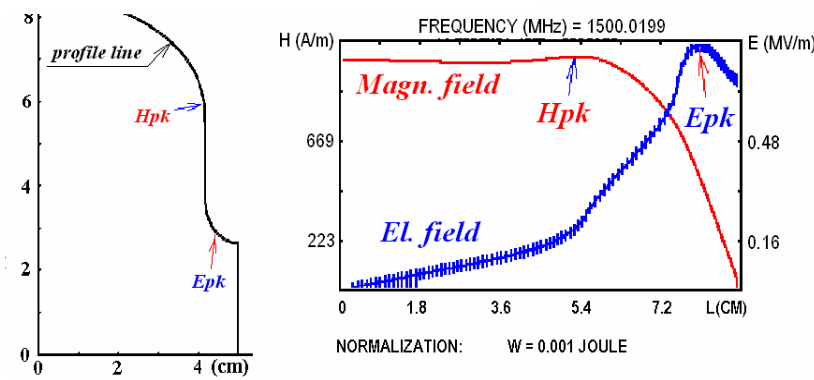
$$Q=\frac{\omega W}{P}=\frac{Q_0}{1+\beta}$$

- Field enhancement factors:

a) Electric: $$k_e=\frac{E_{surf\,pk}}{E};$$

b) Magnetic: $$k_m=\frac{B_{surf\,pk}}{E};$$





Geometry of an inner half-cell of a multicell cavity and field distribution along the profile line.

Main characteristics of SC acceleration structure

- Coupling coefficient: $$k_c = 2\frac{f_\pi - f_0}{f_\pi + f_0};$$

- High Order Modes (HOM):

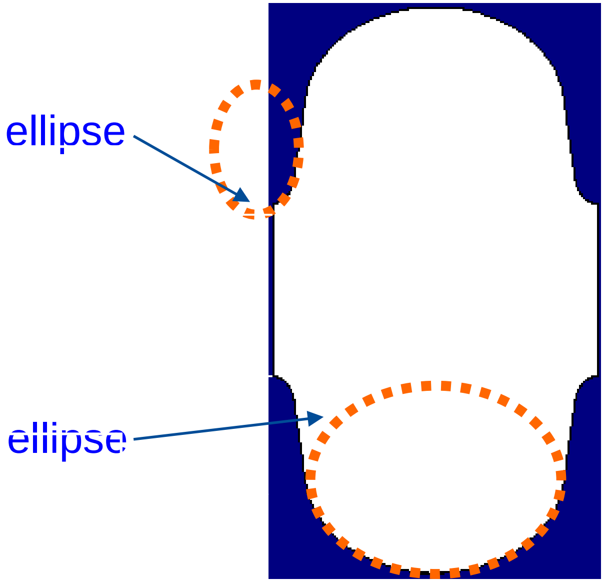
a) Monopole HOM spectrum – losses, bunch-to-bunch energy spread;
b) Dipole HOM spectrum – transverse kick, beam emittance dilution.

HOM frequencies, (r/Q)s and loaded Q-factors are critical, and are the subject of the structure optimization.

- The structure cell geometry:

Constrains:
-low field enhancement factors;
-no multipactoring.
Elliptical shape for the cell and the iris.

Examples:
-TESLA structure;
-Low Loss structure;
-Re-Entrant structure.



Main characteristics of SC acceleration structure

- Resonance frequency of the operating mode f_0;

- Acceleration gradient E;

- Shunt impedance r per unit length; Shunt impedance is relationship between the acceleration gradient and dissipated power P per unit length of the structure. P is the sum of Ohmic losses in the structure P_{Ohm} and the power radiated through the coupling ports P_{rad}.

$$r = \frac{E^2}{P}$$

- Unloaded quality factor Q_0 and geometry factor:

$$Q_0 = \frac{\omega W}{P_{Ohm}} = \frac{\omega\mu_0 \int_V |H|^2 \, dV}{R_s \int_S |H|^2 \, dS} \equiv \frac{G}{R_s},$$

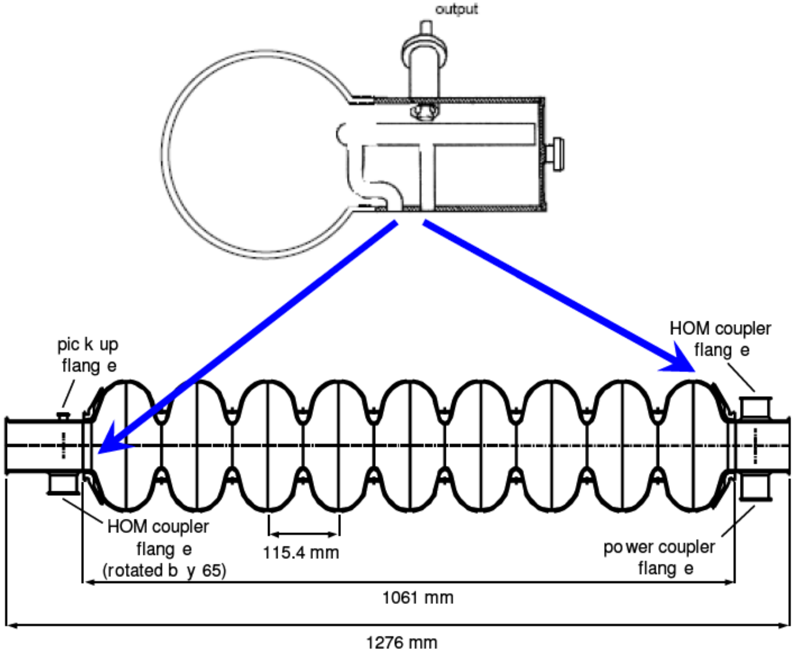
$$\frac{\omega\mu_0 \int_V |H|^2 \, dV}{\int_S |H|^2 \, dS} -$$

geometry factor G (R_s is the surface impedance, W is the energy stored in the structure per unit length).

High Order modes

- HOM extraction/damping.

Criteria:
•Transverse modes: beam emittance dilution;
•Longitudinal modes: power losses, field enhancement, bunch-to-bunch energy spread.

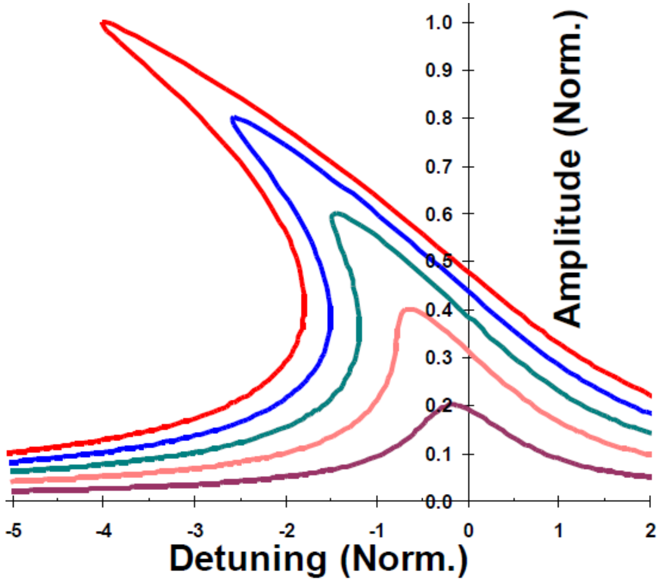


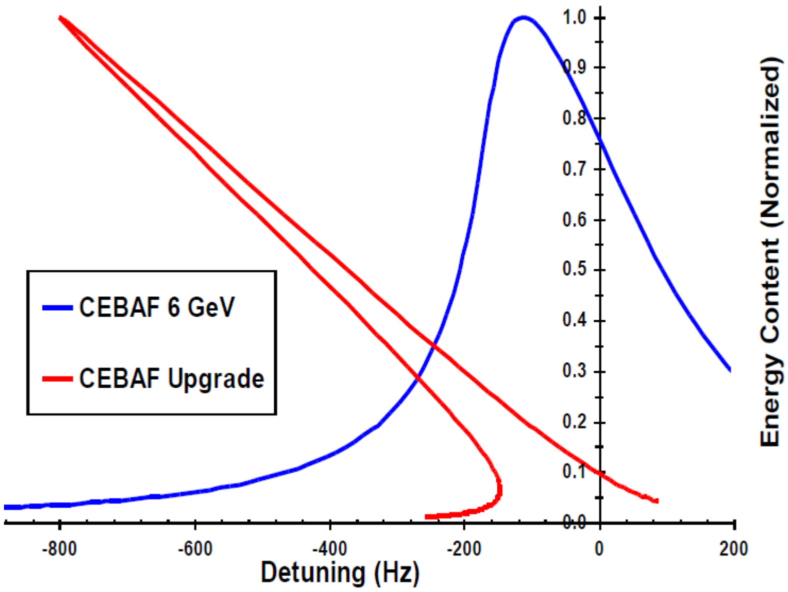
Coaxial loop coupler for superconducting TESLA cavities

- Trapped modes.

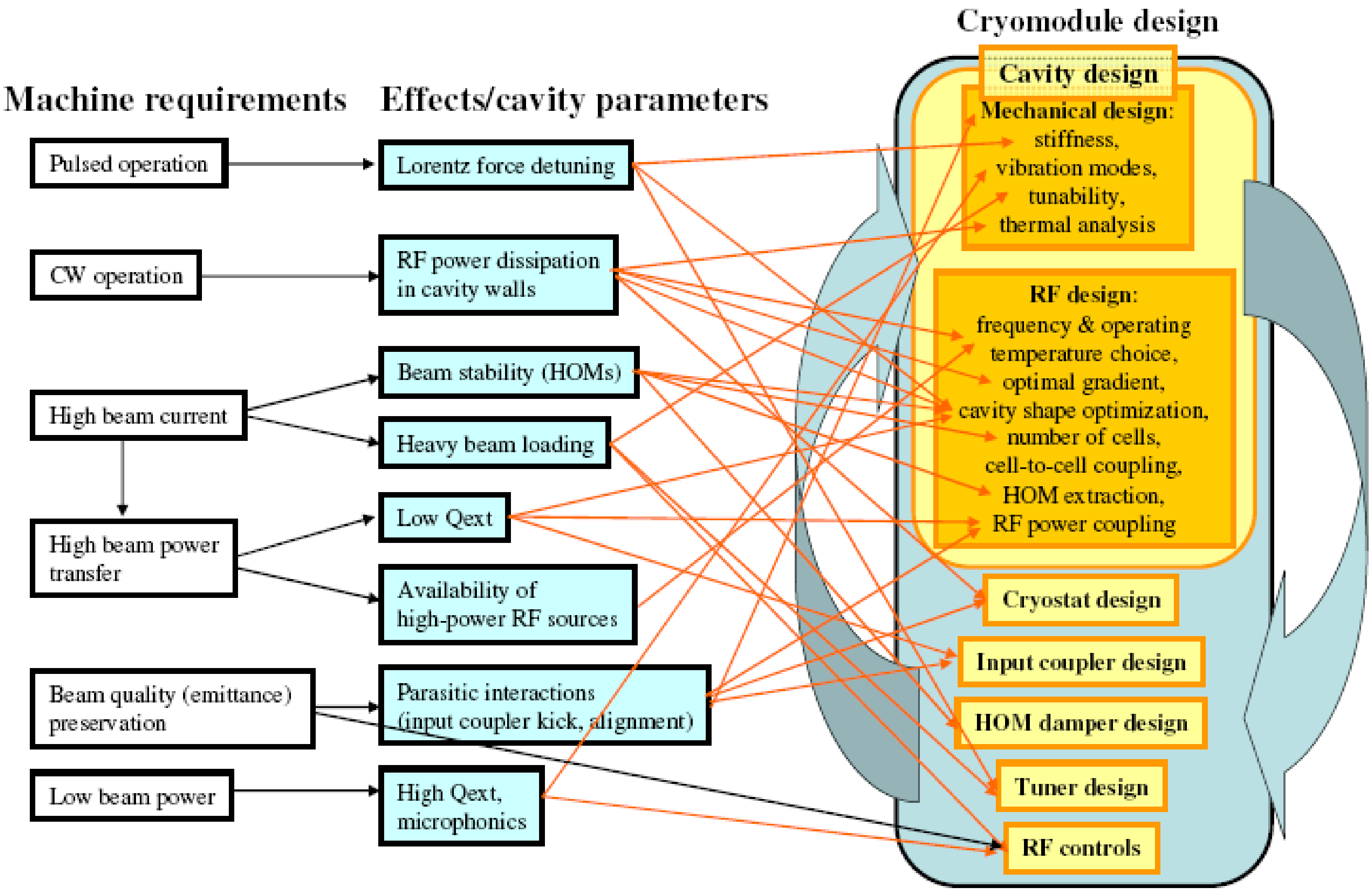
The end cells are to be optimized in order to prevent the field distribution for HOMs having small field in the end cavities, so-called trapped modes. For the trapped modes it is a problem to reduce the loaded Q-factor to acceptable level.

Lorentz Force Detuning





Development of SC accelerating structures



Tools for SC structure simulations

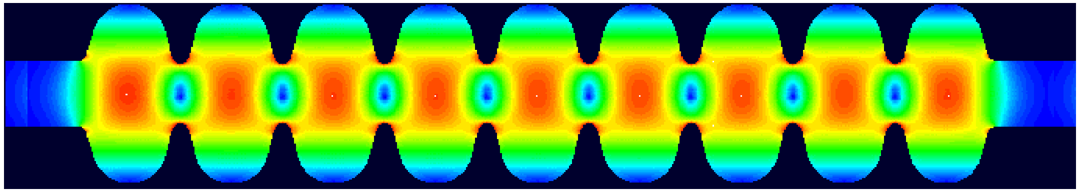
I. **Field calculations:**
   -Spectrum, (r/Q), G, β
   -Field enhancement factors
   - HFSS (3D);
   - CST(3D);
   - Omega-3P (3D);
   - Analyst (3D)
   - COMSOL (3D)

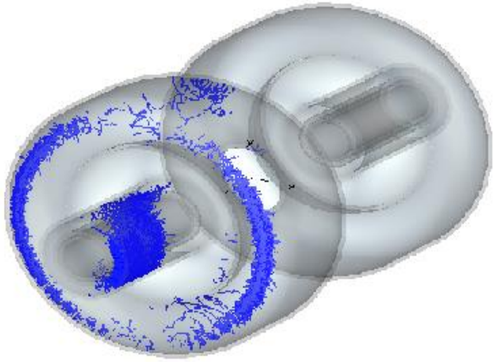
II. **Multipactoring (2D, 3D)**
   - Analyst;
   - CST (3D);
   - Omega-3P

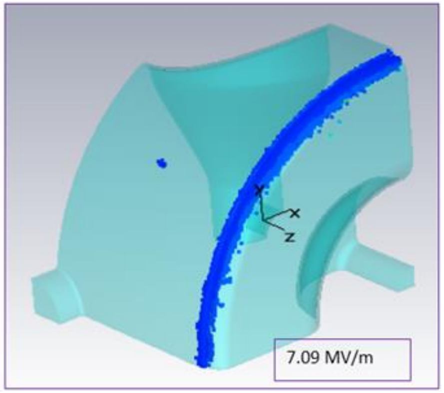
III. **Wakefield simulations (2D, 3D):**
   - GdfidL;
   - PBCI;
   - ECHO.

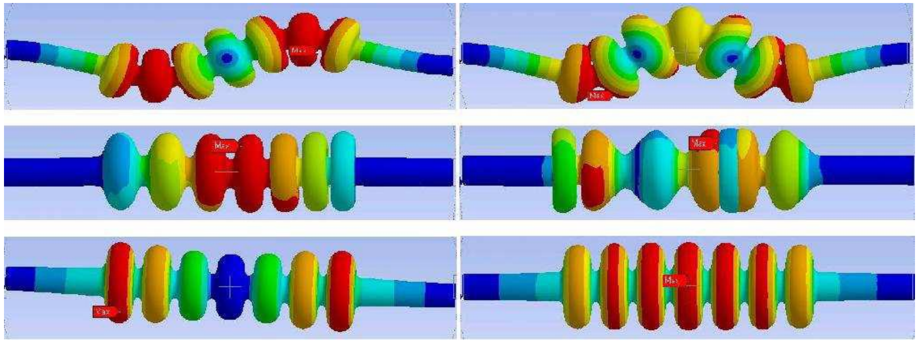
IV. **Mechanical simulations:**
   Lorenz force and Lorenz factor,
   Vibrations,
   Thermal deformations.

a. ANSYS
b. COMSOL









Software packages for SRF cavity design

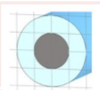
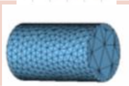
Software for eigenmode EM simulation.

	OMEGA3P	COMSOL*	CST*		SLANS	HFSS*
Domain	3D	2D, 3D	3D		2D	3D
Curved elements	√	√	-	√	√	√
Mesh type	Tetra	Tetra	Hex	Tetra	Quad	Tetra
Complex solver	√	√	√	-	-	√
Parallel computing	√	√	√	√	-	√
H-field enhancement**	-	-	-		√	-

* commercial software

** weighted residual method is applied in order to improve field calculations.

CST Studio Suit Solvers

	CST PARTICLE STUDIO® PIC Solver Gun Solver & Particle Tracking Wakefield Solver	CST MPHYSICS® STUDIO Thermal Stationary Solver Thermal Transient Solver Structural Mechanical Solver	CST MICROWAVE STUDIO® Time Domain Solver Frequency Domain Solver Eigenmode Solver
Mesh Type			
HEX 	X	X	X
TET 		X	X
Sub-solvers			
	$\beta = 1$ $\beta < 1$	-	Lossless: AKS, TET Complex: JDM
Solver Type			
Direct	X	X	X
Iterative		X	X

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CST – Computer Simulation Technology

???????

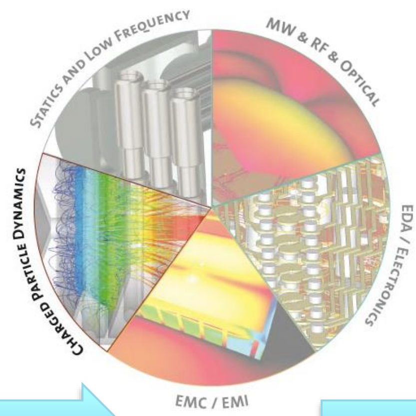
Licensed features:

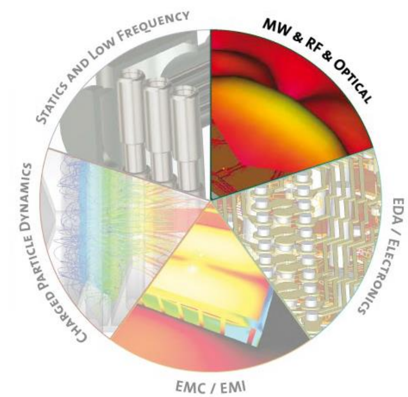
Feature

- Frontend
- Simulation Process
- Solvers
  - Time Domain
  - Frequency Domain
  - Eigenmode
  - Integral Equation
  - Multilayer
  - Asymptotic
  - Printed Circuit Board
  - Rule Check EMC
  - Rule Check SI
  - Rule Check Custom
  - Cable Harness
  - Static
  - Low Frequency
  - Tracking
  - Wakefield
  - Particle In Cell
  - Thermal
  - Structural Mechanics
  - Circuit Simulator
  - Filter Designer (2D)
  - Filter Designer (3D)
- Optimizer
- Acceleration Token

1. What we are doing?
2. What tool do we need?
3. How to use the tool?

Applications





Templates

- Accelerator Components
- Vacuum Electronic Devices
- Space Applications
- Beam Optics

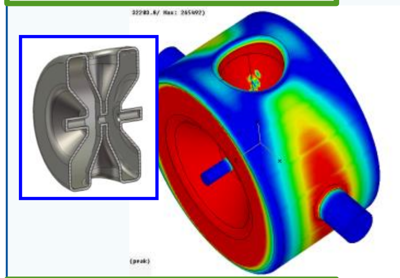
- Antennas
- Circuit & Components
- Radar Cross Section
- Biomedical, Exposure, SAR
- Optical Applications
- Periodic Structures

CST Simulation Workflow

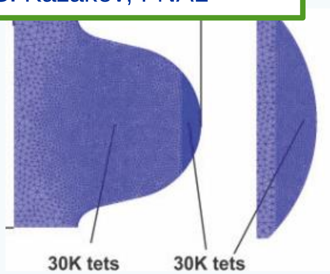
1. Creation of the project 3D model
   - drawing in the CST GUI (takes time, full-parametrization, easy modification)
   - geometry import from 3rd parties CADs (quick, need special license, limited parametrization, potential mesh problem)
2. Choosing a proper solver
   - depends on the problem, available 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

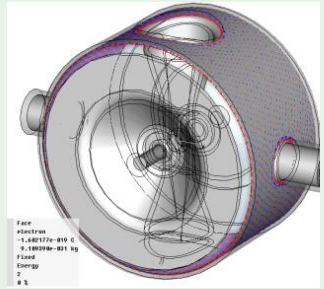
CST Particle Studio Multipactor Simulation

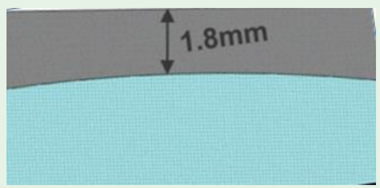
G. Romanov, FNAL

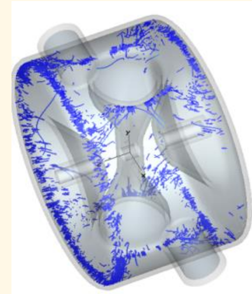


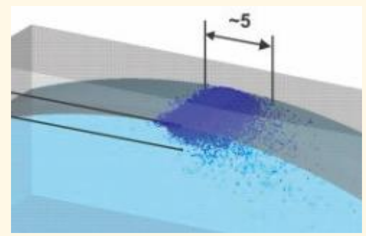
S. Kazakov, FNAL

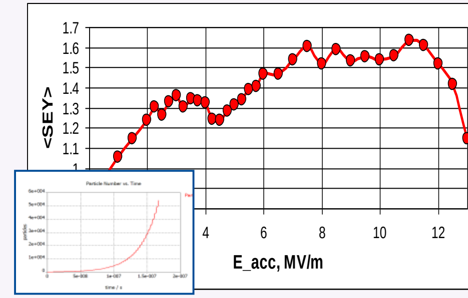


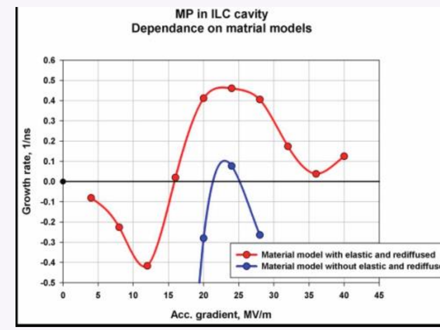








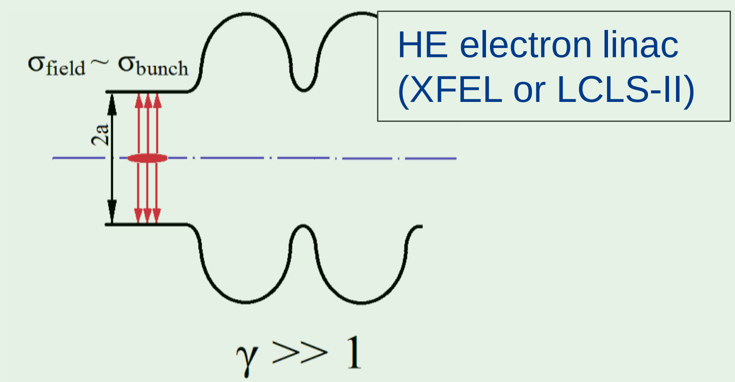




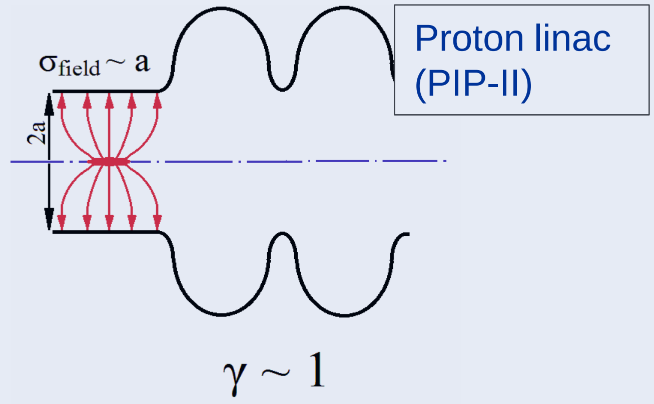
Cavity EM simulation	Setup particle sources	Particle tracking	Post processing
• Complex 3D multi-sections cavity model • Precise surface fields • SW&TW solutions • Mesh matching with tracking module	• Advanced field emission model • Emitters locations, numbers and phases • Material properties	• Multi-particles approach & stochastic SE emission	• Advanced statistics - numbers - collisions - sec. emissions - dissipations - trajectories

Secondary electron emission RF discharge or multipactor (MP) might be a serious obstacle for normal operation of SC cavities and couplers (simulation of SSR1 cavity for PIP-II).

CST PS Incoherent Losses & Wakes Simulations



- fmax ~ c/σ_{bunch}
- for σ_{bunch} = 50μ, fmax < 6 THz



- fmax ~ c/a
- for a = 50mm, fmax < 6 GHz

Loss factor depends strongly on the σ_{field} !

Solve in TD

- computing wakefield and wake potentials

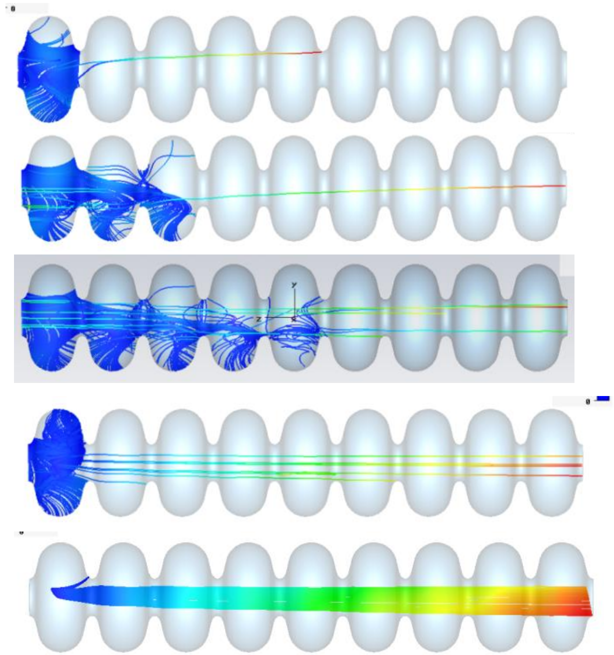
Solve in FD

- loss factors calculation of individual cavity modes

Incoherent losses introduced by radiated wakefield might be an essential part of the total cryolosses in the SC accelerating structure.

CST Particle Studio Dark Current Simulation

Particle trajectories vs RF phase

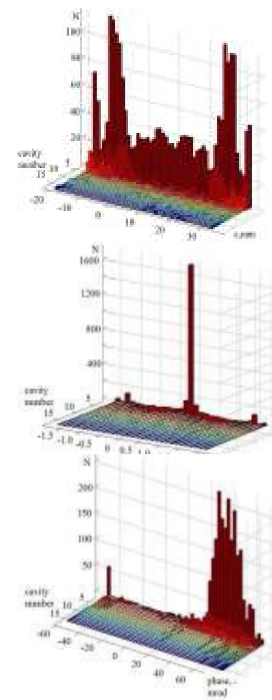


Gun Solver & Particle Tracking

Effect of dark current

- heat and RF loading of the cavity
- production of avalanches of secondary electrons
- accelerating to hundreds of MeV before being kicked out by down stream quadrupoles
- originating electromagnetic cascade showers in the surrounding materials

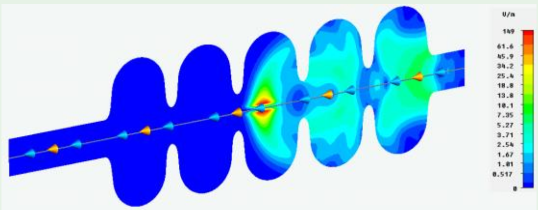
Particles distributions:
a) radial , b) angular and c) phase



Challenges of dark current simulations:
- initial broad angular, space and phase distribution
- realistic model of emitters (Uniform, Gaussian, Fouler-Nord.)
- influence of SE emission
- detailed statistics on lost and accelerated particles

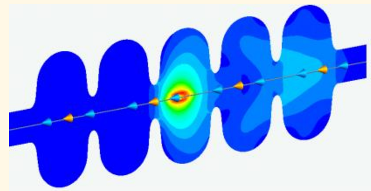
CST PS Loss Factor Simulation

Time Domain



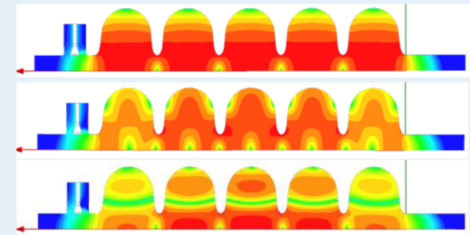
Ultra-relativistic beam (β=1)

Time Domain



Highly-relativistic beam (β>0.9)

Frequency Domain



Weakly-relativistic beam (β<0.9)

Short bunches (σ_z < 1mm)

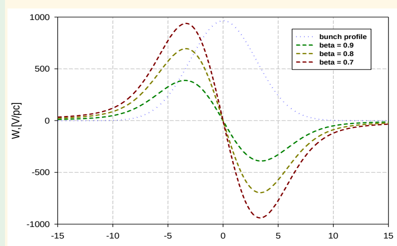
- required memory ~ $(a/\sigma_z)^3$
- computation time ~ $(a/\sigma_z)^4$
- long catch up distance ~ $a^2/2\sigma_z$

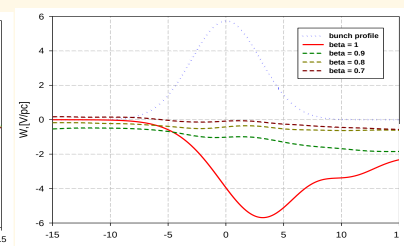
Solution: Indirect methods

Static Coulomb forces

- $E_{static} >> W_z$
- Wrong convolution: $\int (E_s + W_z)\sigma_z dz$

Solution: Two simulations to exclude E_{static}*



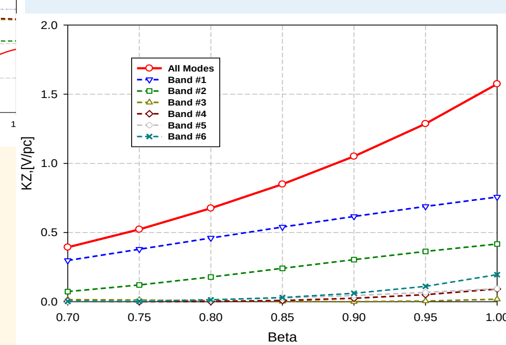


* Andrei Lunin et al., "Cavity Loss Factors for Non-Relativistic Beam in the Project X Linac," PAC2011, New York, March 28, 2011, TUP075

HOM modes

- HOM spectrum above beam pipe cut-off freq.

Solution:
Take modes with max R/Q,
Multi-cavity simulation



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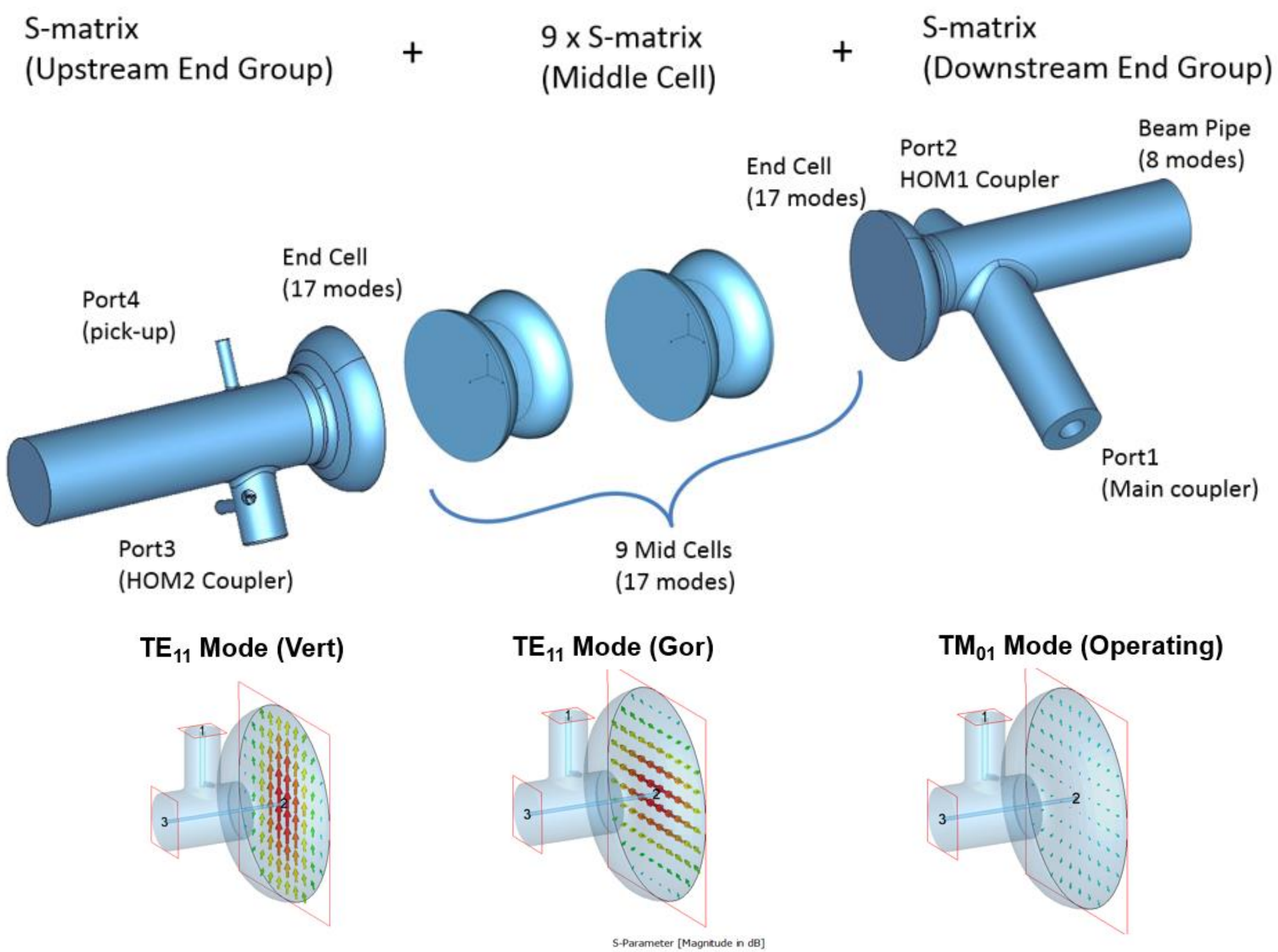
CST Design Studio Scattering Matrix Analysis

ILC 9-cell Structure Decomposition



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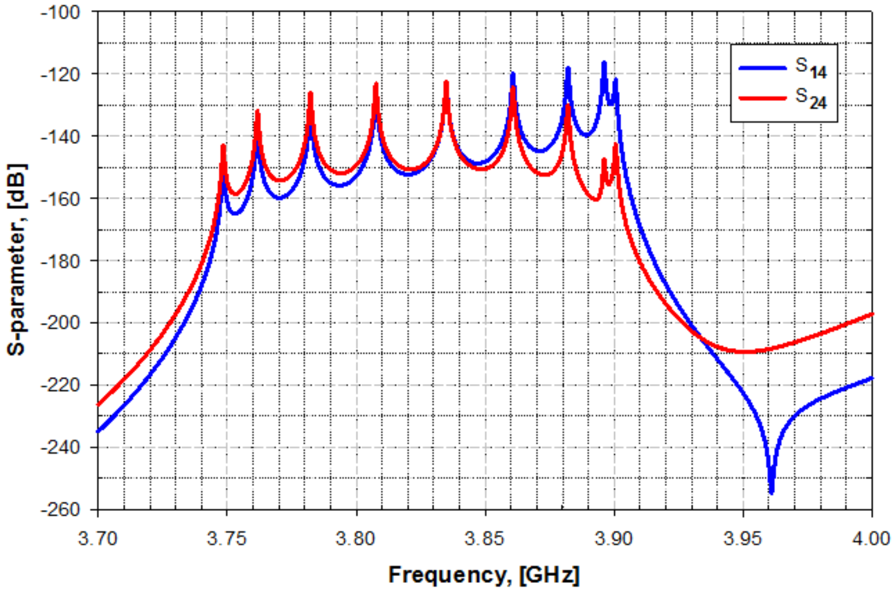
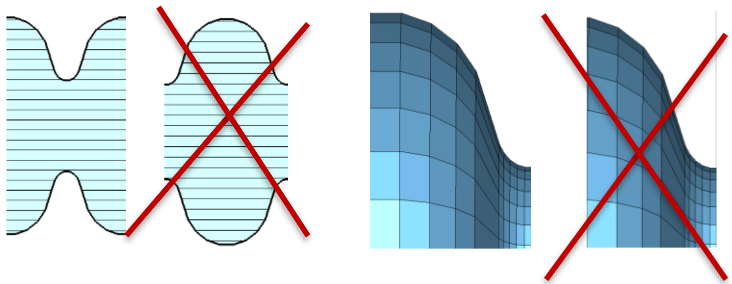
CST Design Studio Scattering Matrix Analysis

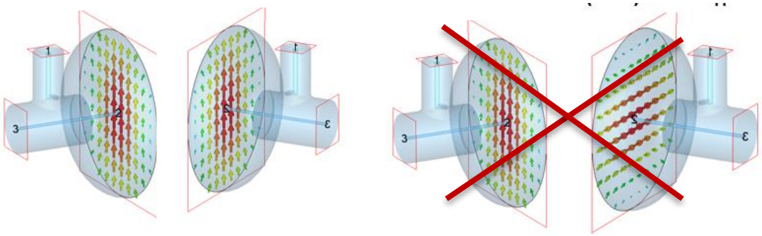
Full Structure S-matrix



Key features

- Fast analysis
- Precise frequency resolution
- Easy phase manipulation
- Multi-structure chain simulation



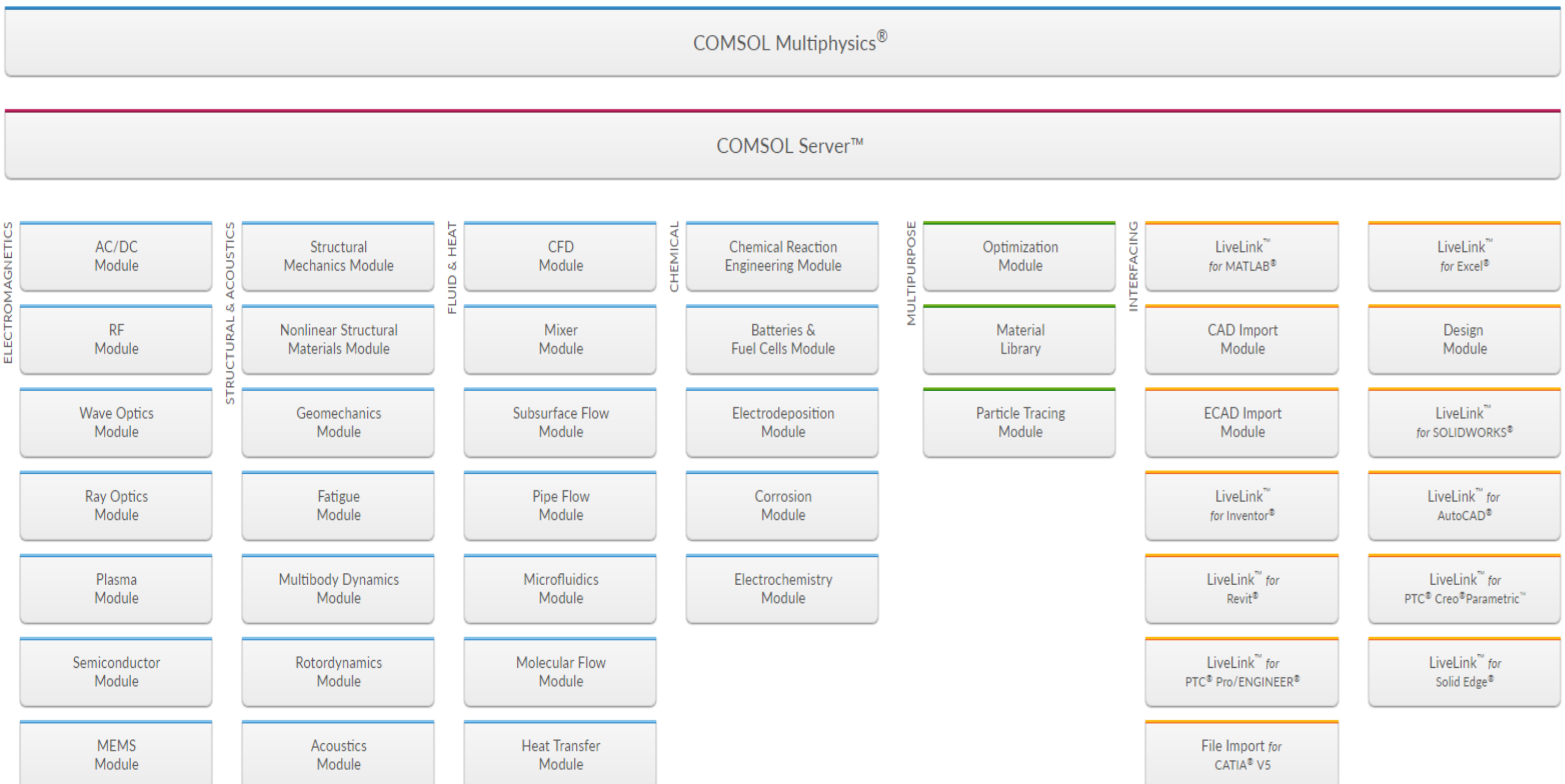


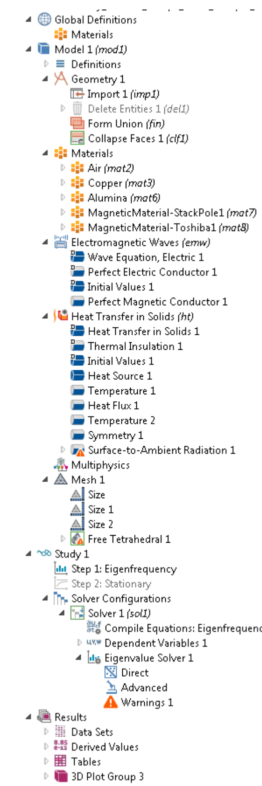
Tips:

- The components have to be non-resonant!
- Leave the regular waveguide section!
- Use proper mode alignment!

Comsol Multiphysics

Multiphysics Software Product Suite

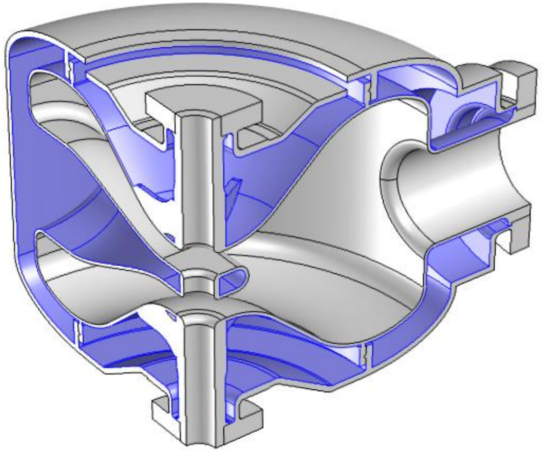


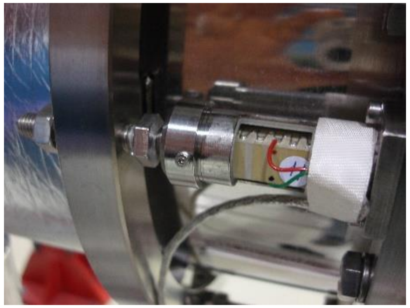


COMSOL. Frequency Sensitivity to Pressure in SSR

- Frequency shifts due helium pressure fluctuations (~few mbar) df/dp is a major issue in superconducting RF cavities
- Narrow BW cavities with high microphonics levels require more RF power
- Beam can be lost if sufficient reserve RF power to compensate for detuning is not available

Helium Vessel pressure surface





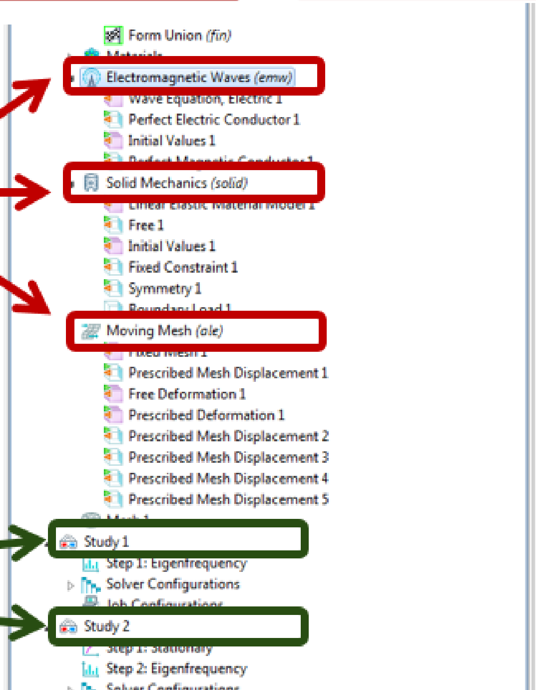
Piezos are used for fast tuning

Fermilab

COMSOL. Frequency Sensitivity to Pressure in SSR

Electromagnetic Waves	Solid Mechanics	Moving Mesh
•Solving only for the RF domain •Applying the prober boundary conditions	•Solving only for the Cavity Vessel •Applying the proper fixed constraints, symmetries, displacements, and boundary load	•Solving for all domains •Applying the proper prescribed and free mesh deformation/displacement

Three Multiphysic Modules



Two Simulation Studies

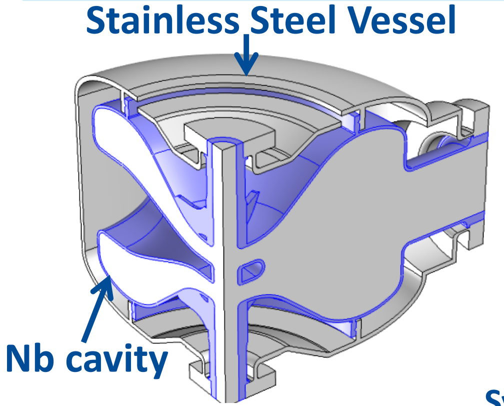
$Study_1$	$Study_2$
• Eigen-frequency (to find f_0)	• Stationary (solving only for solid mechanics and moving mesh) • Eigen-frequency (to find f_p)

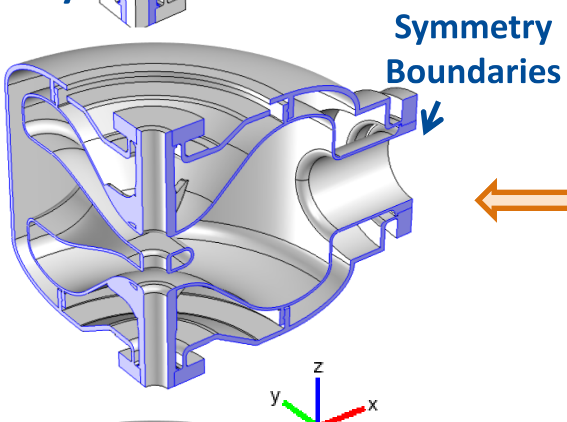
- **EM**: Eigen frequency simulation to find the resonant frequency (f_0)
- **Solid Mechanics**: Find the deformation under given pressure load (P_L)
- **Moving Mesh**: Update the mesh after deformation
- **EM**: Eigen frequency simulation to find the resonant frequency after deformation (f_p)

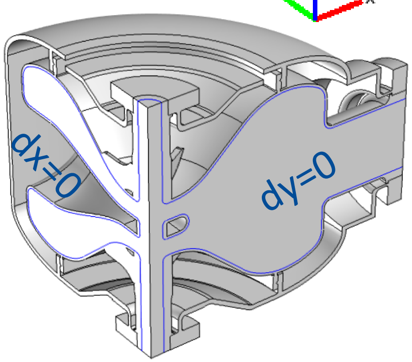
$$\frac{df}{dp} = \frac{f_p - f_0}{P_L}$$

Fermilab

Frequency Sensitivity to Pressure in SSR







Electromagnetic Waves

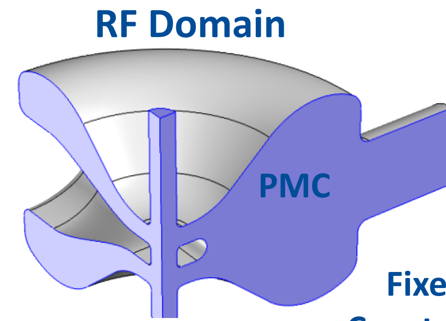
- Solving only for the RF domain
- Applying the prober boundary conditions

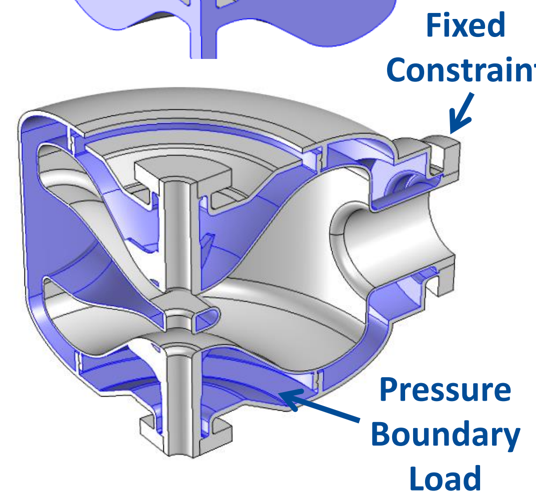
Solid Mechanics

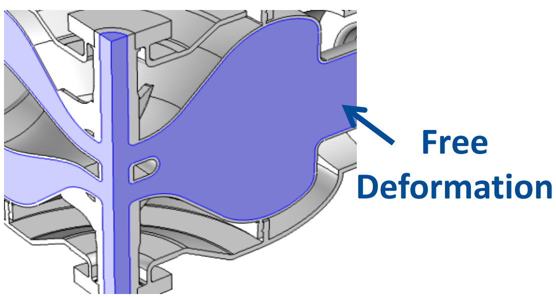
- Solving only for the Cavity Vessel
- Applying the proper fixed constraints, symmetries, displacements, and boundary load

Moving Mesh

- Solving for all domains
- Applying the proper prescribed and free mesh deformation/displacement





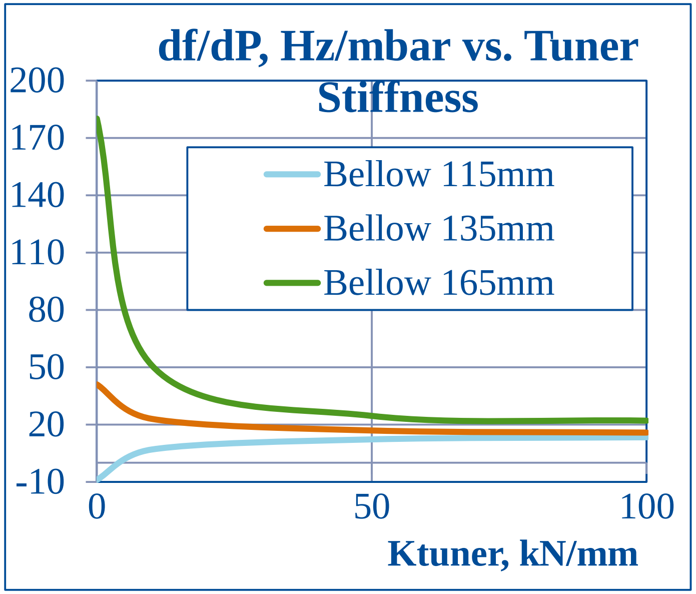


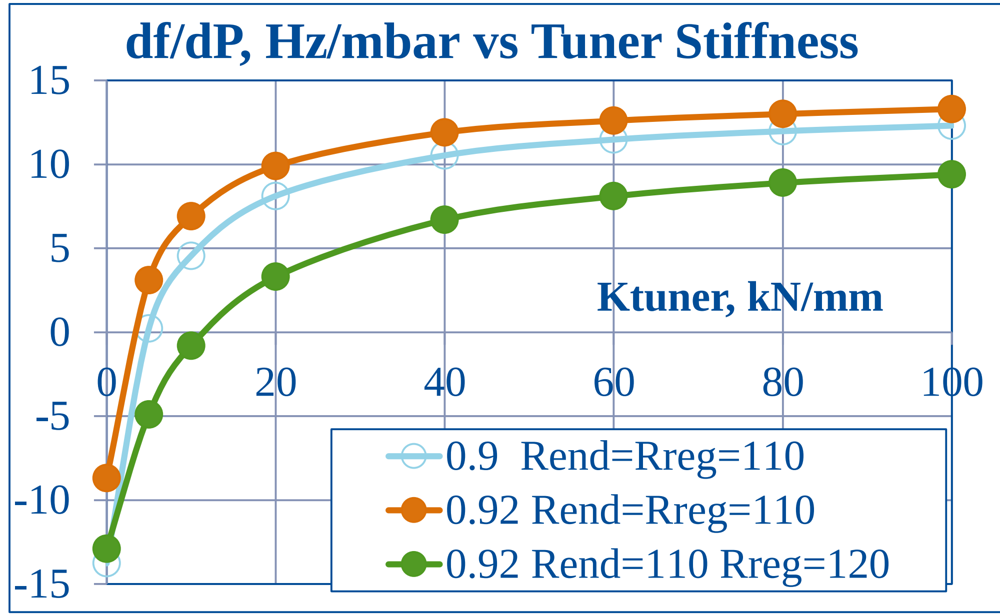
Fermilab

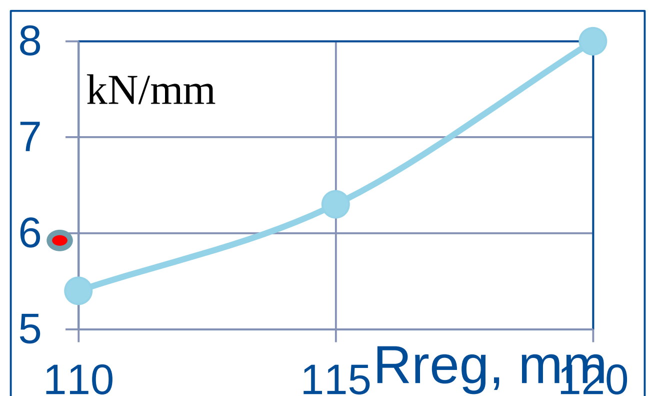
Elliptical cavity design

df/dP optimizations of new design for end lever tuner

HB650 MHz cavity







Stiffness of β=0.92 cavity kN/mm vs. Radius of the Regular stiffening ring

- Stiffness of β=0.9 cavity

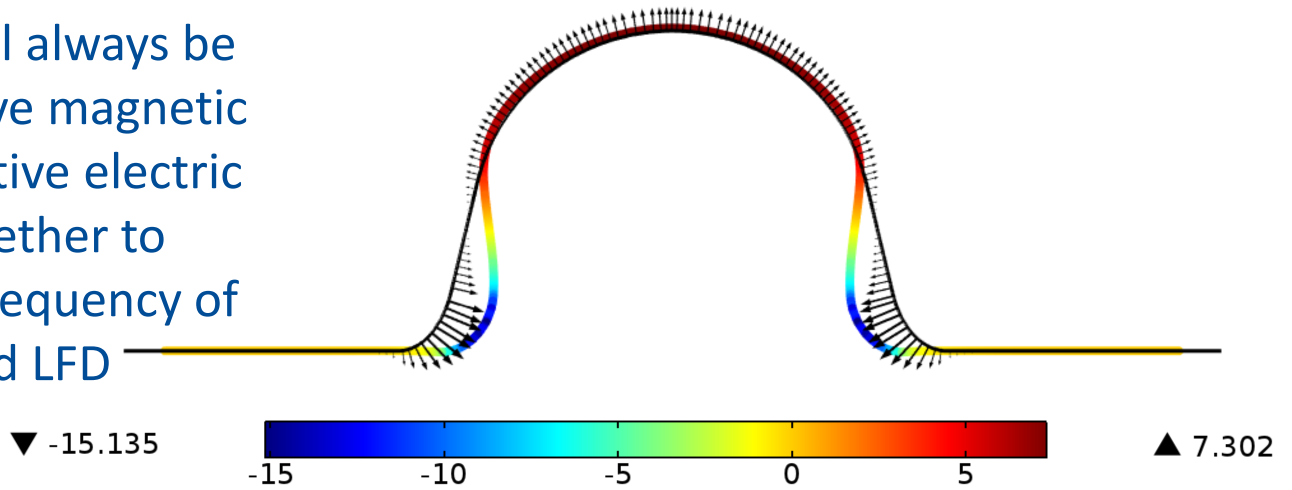
COMSOL. LFD simulations

Electromagnetic fields inside the cavity develop pressure on the cavity inside walls that is defined as

$$P_{rad} = \frac{1}{4}\left(\mu\left|H\right|^2 - \varepsilon\left|E\right|^2\right)$$

Pressure exerted by the magnetic field is positive (push) pressure, while it is negative (pull) for the electric field

Overall frequency shift will always be negative since the repulsive magnetic field forces and the attractive electric field forces both work together to decrease the resonance frequency of the deformed cavity, called LFD



Lorentz forces exerted on the 650 MHz β=0.9 single cell cavity ahead with the radiation pressure values in mbar at the 3.5 MV cavity voltage. Deformation is exaggerated by 20000 times

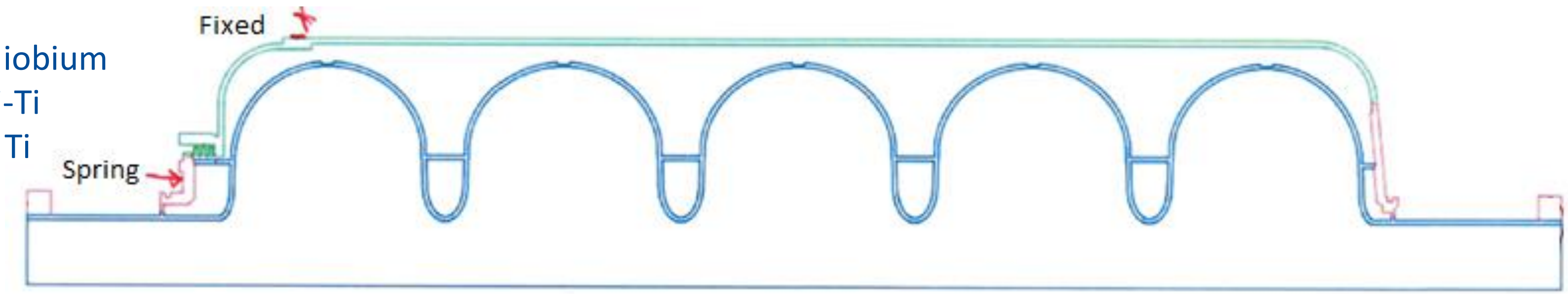
COMSOL. LFD simulations

Radiation pressure

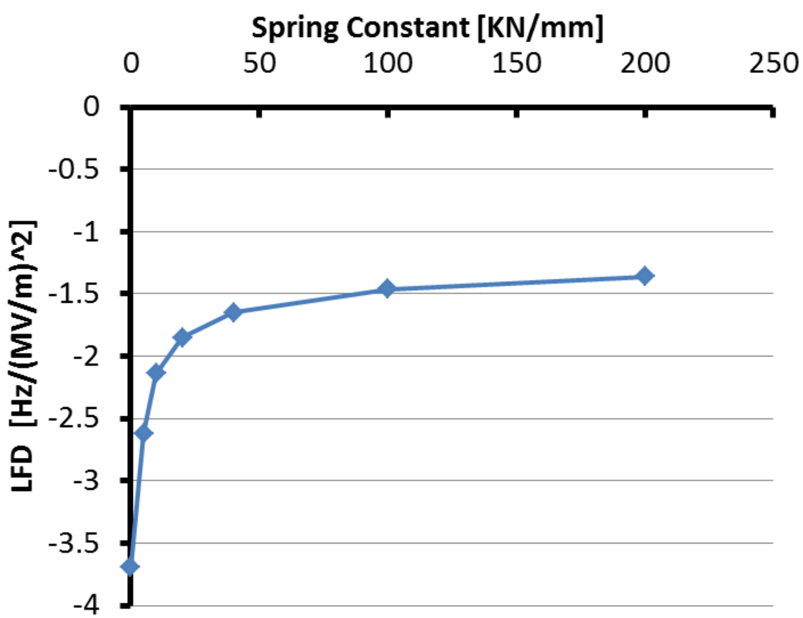
$$P = \frac{1}{4}\left(\mu_0 |H|^2 - \varepsilon_0 |E|^2\right)$$

$$\Delta f = Kl|E_{acc}|^2$$

Blue: Niobium
Red: Ni-Ti
Green: Ti



	Spring Const [KN/mm]	LFD [Hz/(MV/m)^2]
Fixed		**-1.26**
	200	-1.36
	100	-1.46
	40	-1.65
	20	-1.85
	10	-2.14
	5	-2.62
Free	**0**	**-3.69**



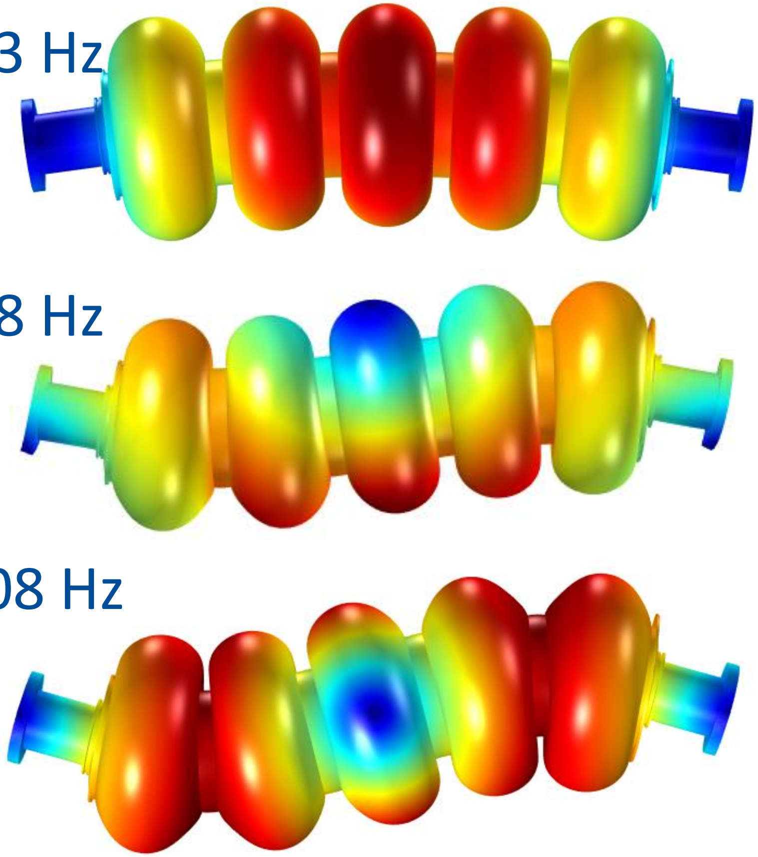
COMSOL. Modal Analysis

- Modal eigen-frequencies of each cavity structure can be numerically calculated using a solid mechanics solver
- Any modification on the cavity structure would necessarily change the modal frequencies.
- The frequency shift in the electromagnetic resonance frequency due to the excitation of a certain modal eigen-frequency could be computed knowing the energy of that eigen-frequency.
- Moreover, we believe that the modal frequency will be affected by the liquid Helium filling the cavity during operation

33 Hz

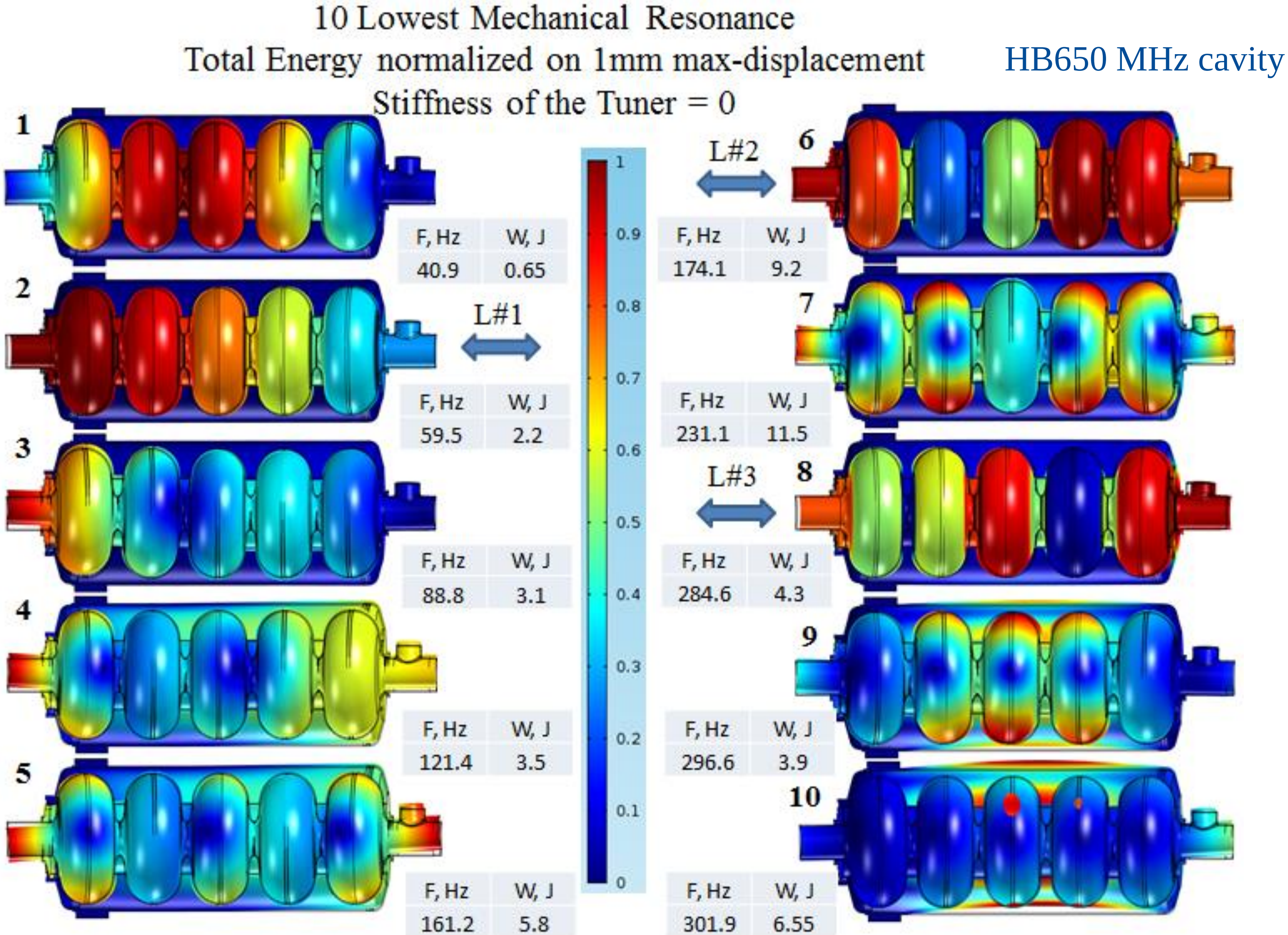
88 Hz

108 Hz



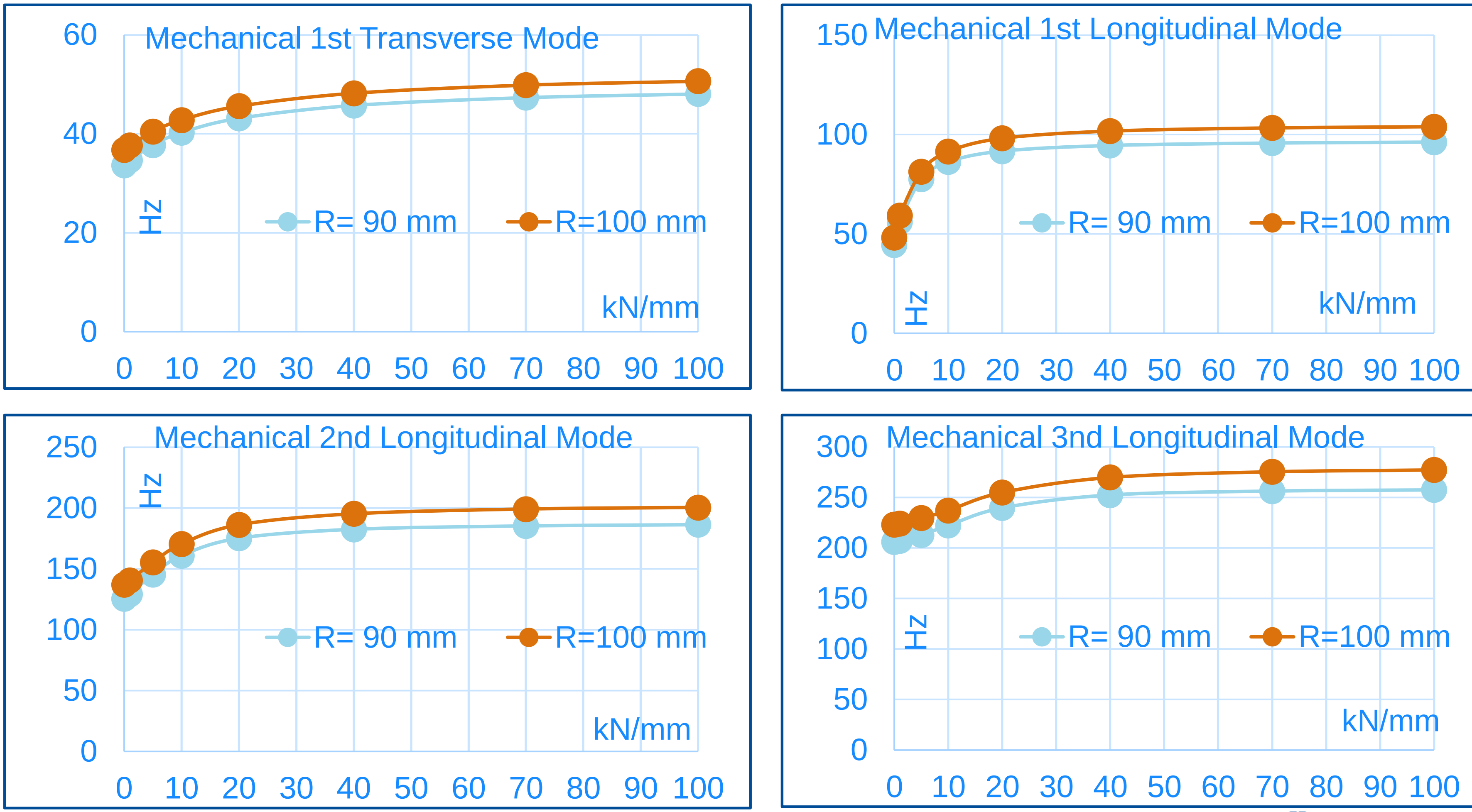
Modal frequencies of the 650 MHz β=0.9 cavity

COMSOL. Modal Analysis

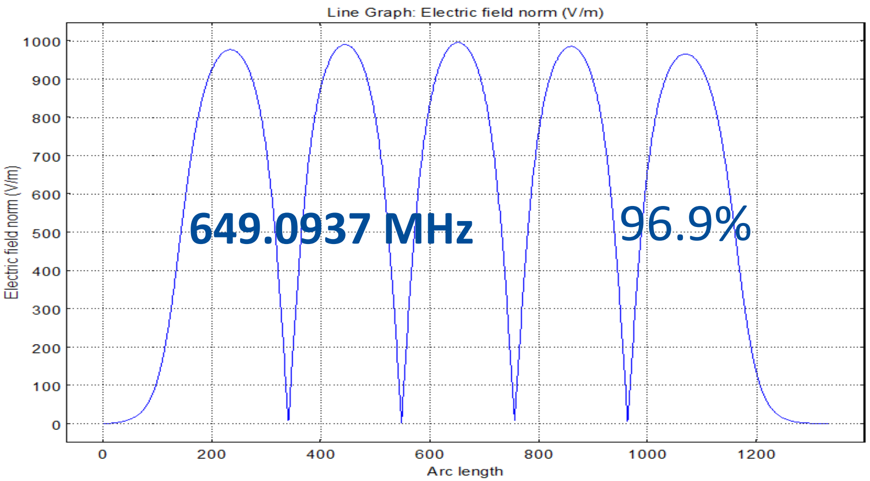


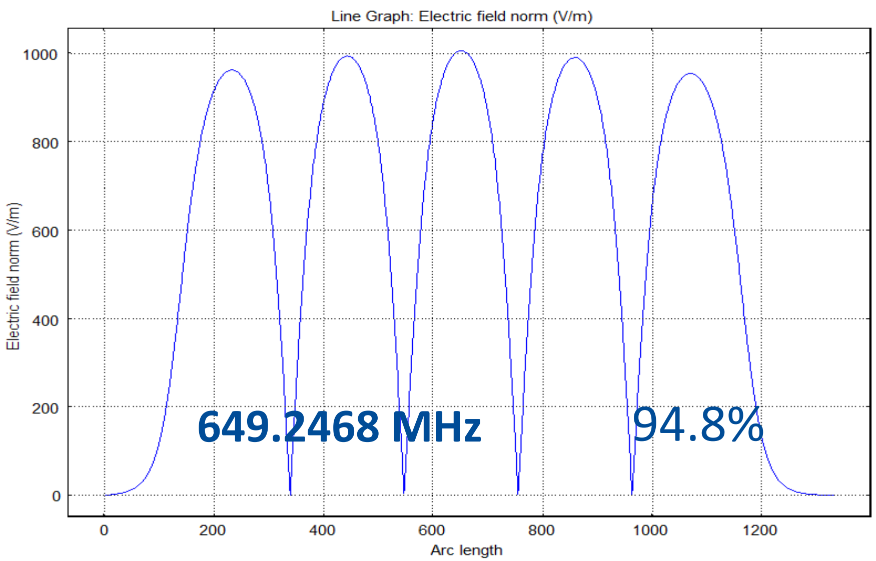
COMSOL. Modal Analysis

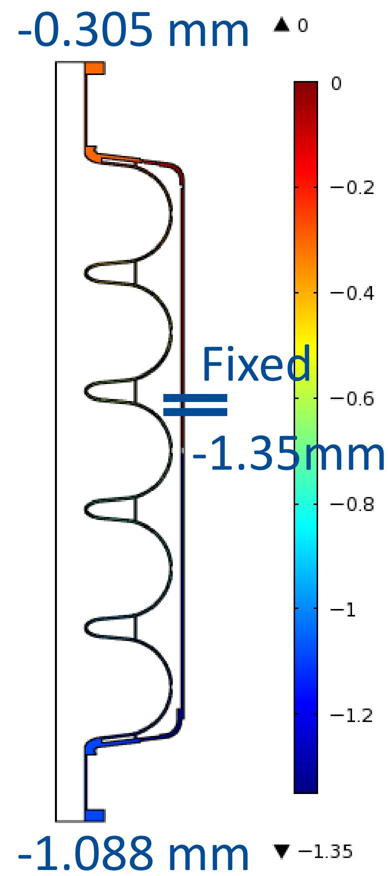
Mechanical resonances HB650 MHz dressed cavity with tuner



COMSOL. Frequency tuning simulations







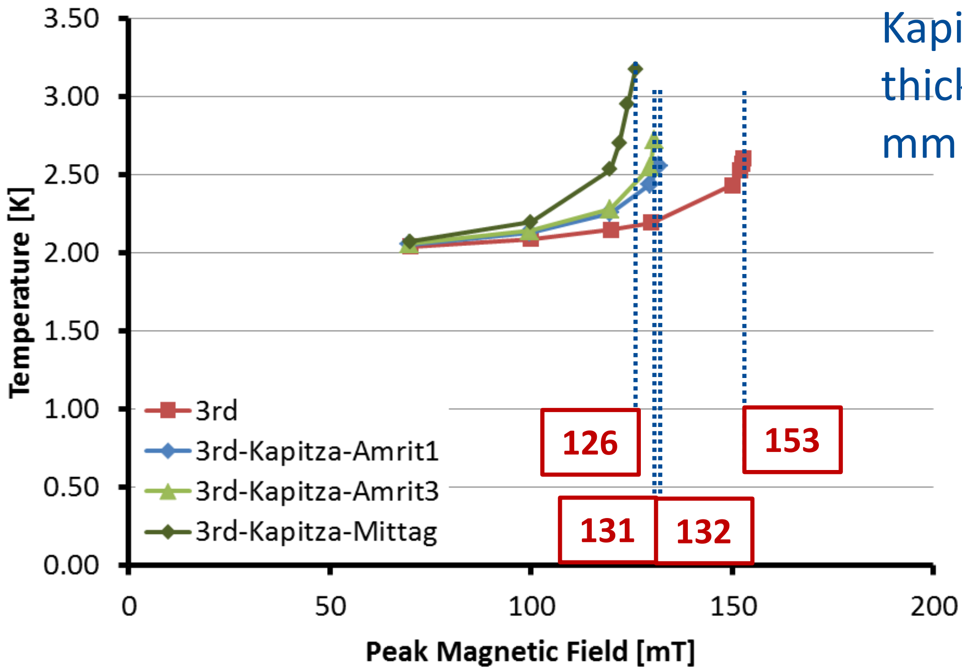
ΔL=0.783 mm, η=58%

ΔF ~ 153.100 KHz

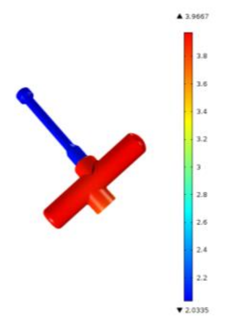
Fermilab

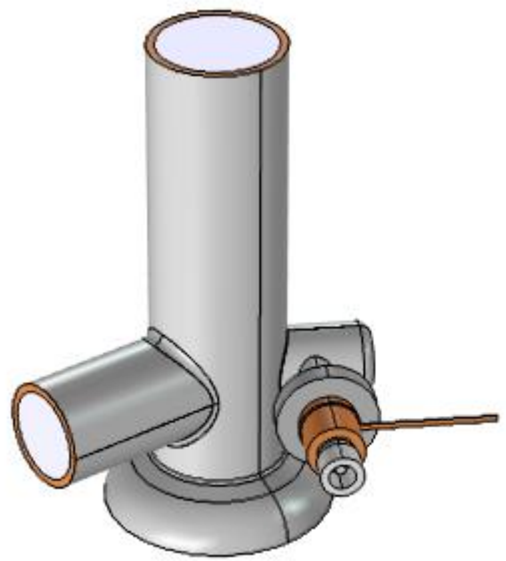
COMSOL. Thermal Analysis

- Given the several models of Kapitza Resistance, we tried to use our experience with the third harmonic cavity to check which one is closer to measurements
- Mittag model looks the closest with quench field 126mT vs 120mT observed in measurements, thus it will be adopted



Kapitza Layer thickness is 0.5 mm





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

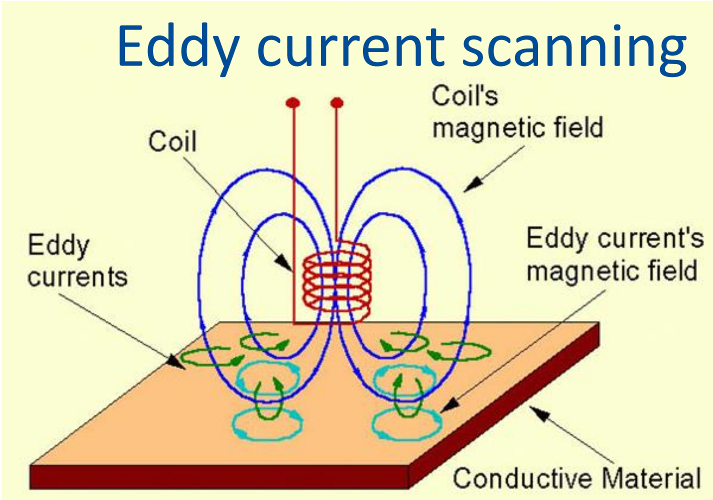
Material quality control

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<σ0,2<100 N/mm² (Mpa)
Fe	≤ 30	C	≤ 10	Tensile strength	> 100 N/mm² (Mpa)
Mo	≤ 50			Elongation at break	30 %
Ni	≤ 30			Vickers hardness HV 10	≤ 60

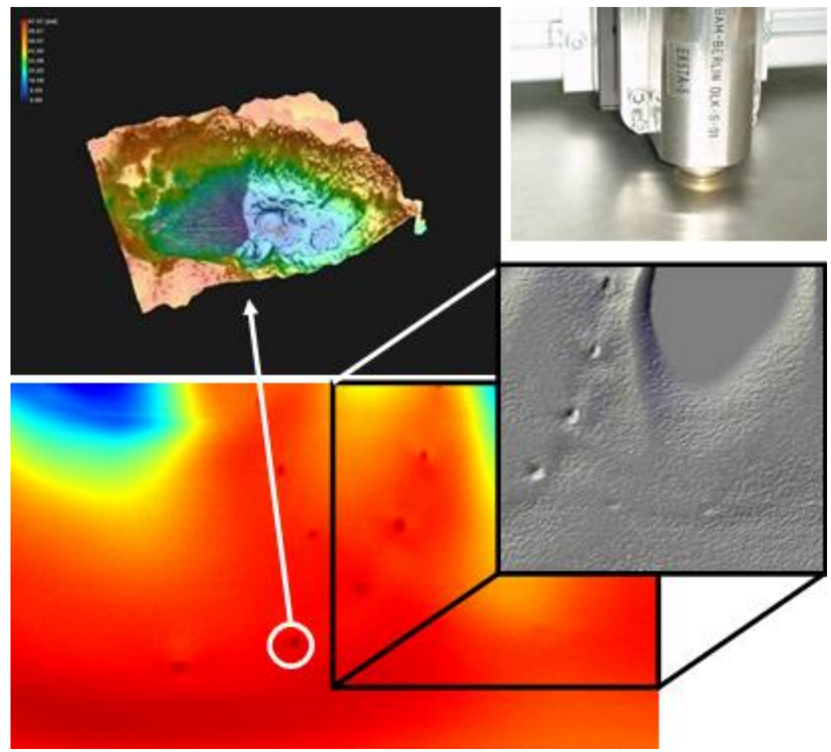
No texture: The difference in mechanical properties (Rm, Rp0,2, AL30) orthogonal and parallel to main rolling direction < 20% (cross rolling).

Material quality control

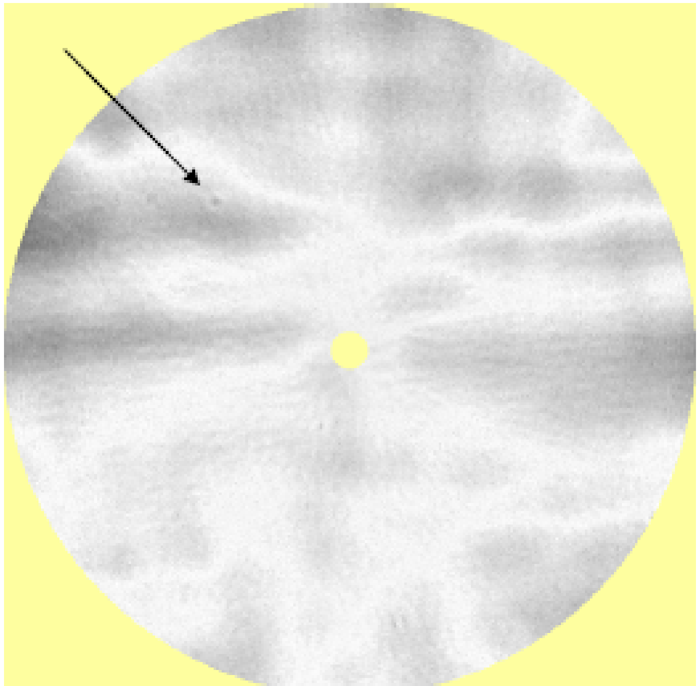


Disks are cut from high purity niobium sheet and eddy current scanned for pits, scratches or inclusions of foreign materials

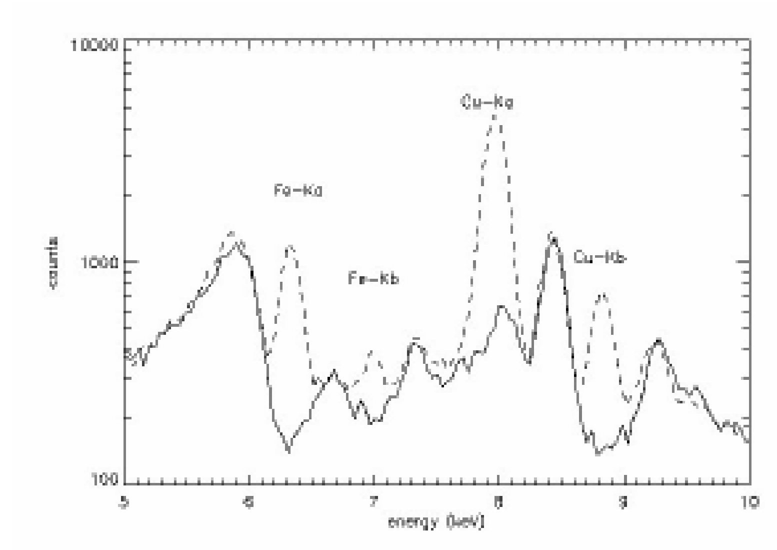
Discs with inclusions of foreign materials or damage are rejected



Material quality control



Example of the Nb sheet eddy current scanning test. Arrow indicates the suspicious spot.

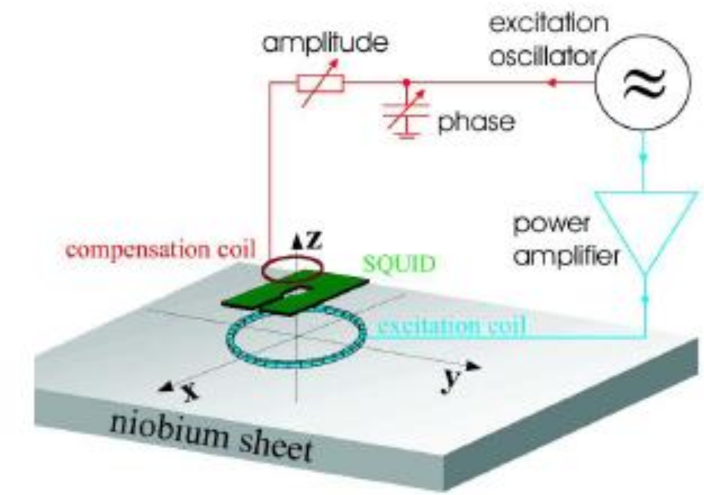


SURFA (Synchrotron Radiation Fluorescence Analysis). Spectrum of K-lines at the spot area (dashed line) in comparison with spot free area (full line).

The spot was identified as an inclusion of foreign material. Cu and Fe signal has been observed in the SURFA spectrum in the spot area.

Material quality control

Development of SQUID based scanning system for testing of niobium sheets

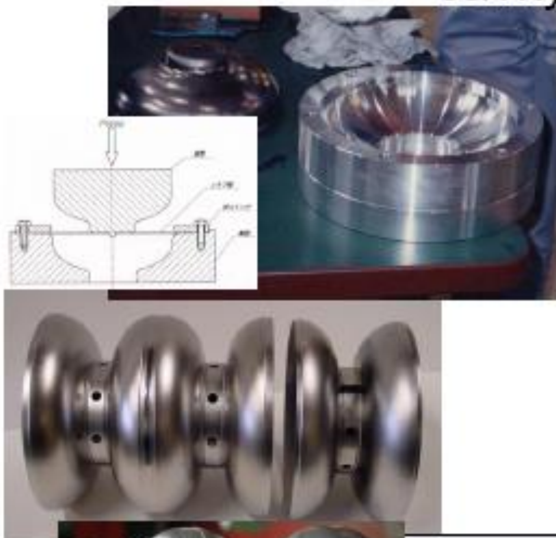


An excitation coil produces eddy currents in the sample, whose magnetic field is detected by the SQUID.

Prototype of SQUID based scanning system for niobium sheets (in work)

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.

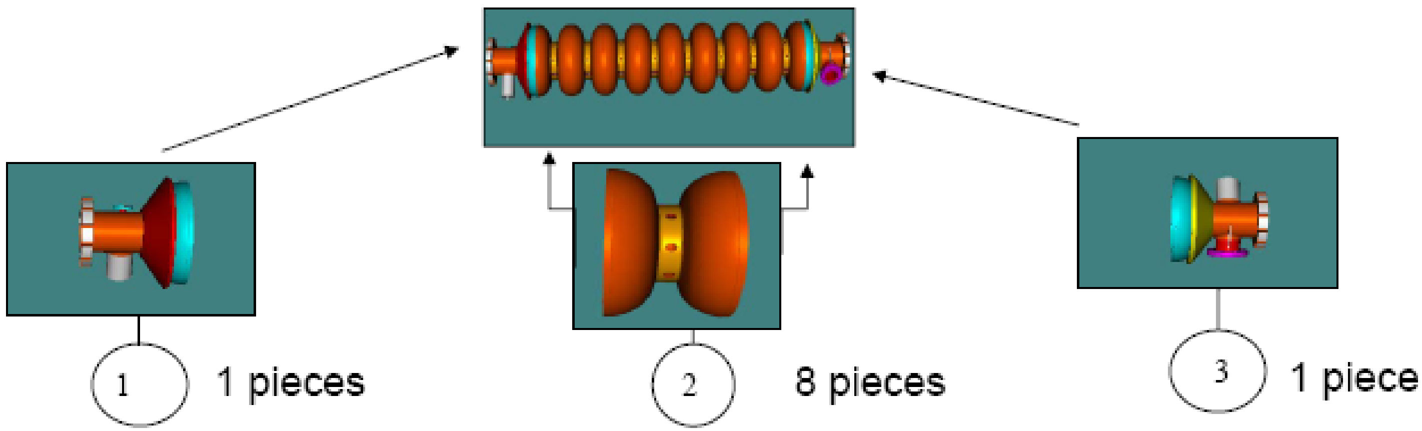
After proper cleaning eight dumb bells and two end group sections welded by electron beam together

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

Fermilab

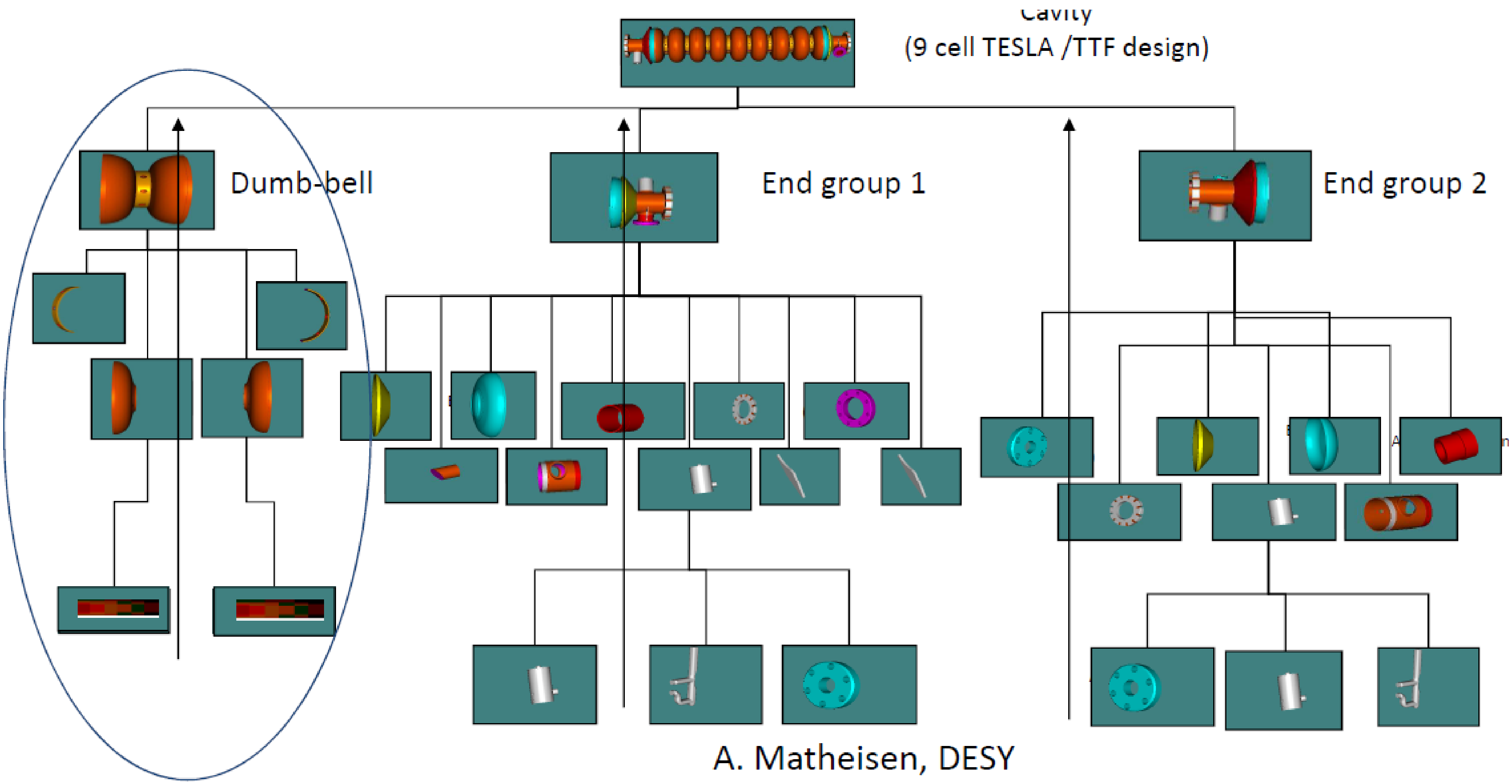
Elliptical cavity production

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



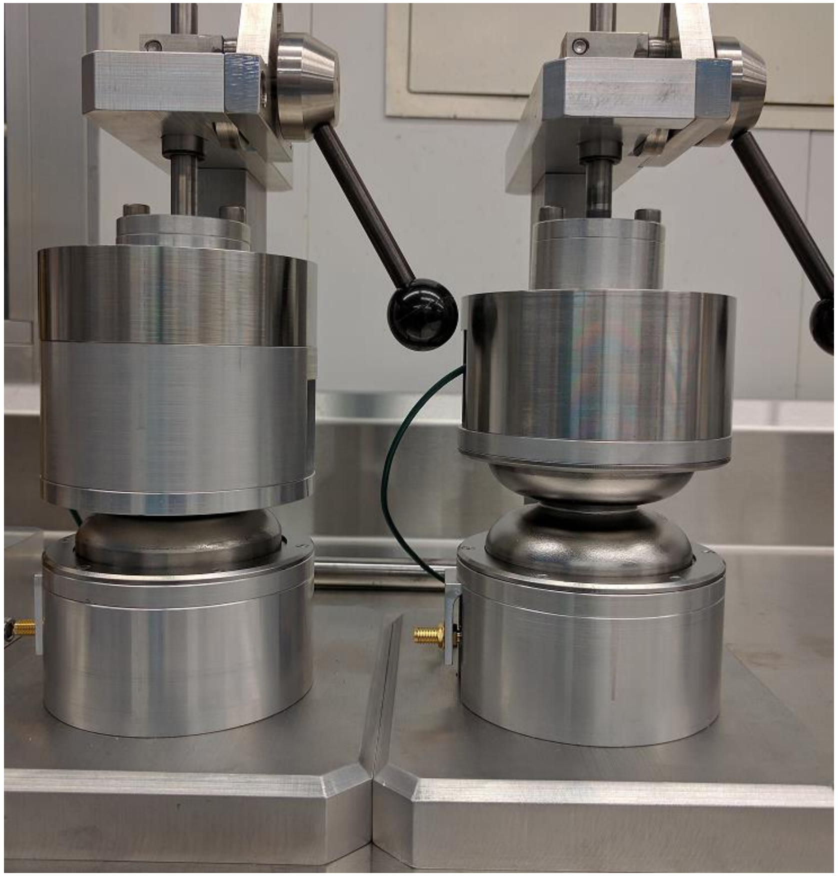
1. Degreasing and rinsing of parts
2. Drying under clean condition
3. Chemical etching at the welding area (Equator)
4. Careful and intensive rinsing with ultra pure water
5. Dry under clean conditions
6. Install parts to fixture under clean conditions
7. Install parts into electron beam (eb) welding 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

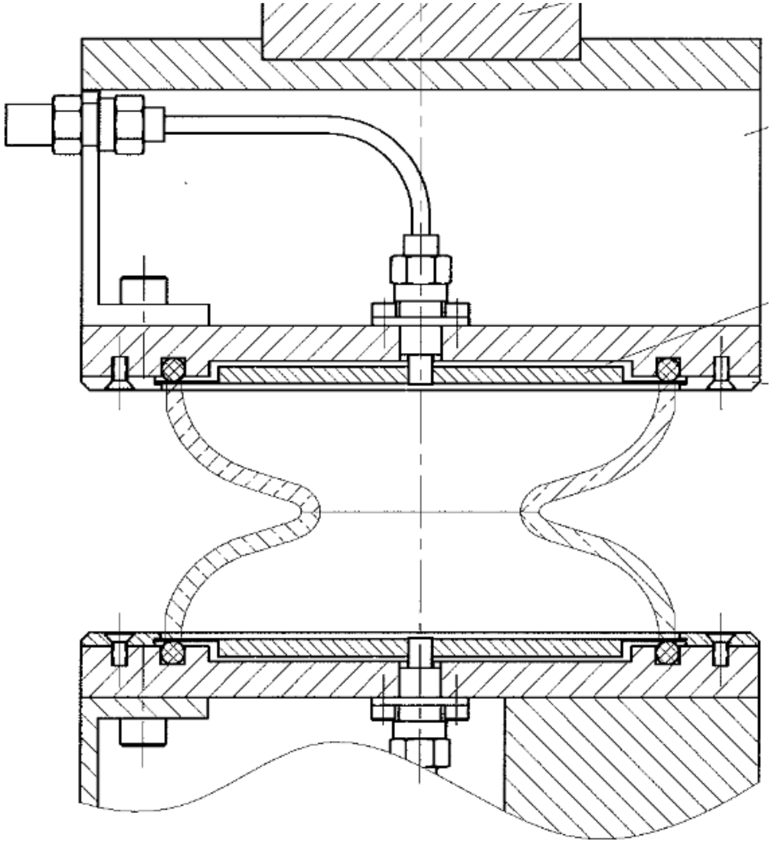
Elliptical cavity production



A. Matheisen, DESY

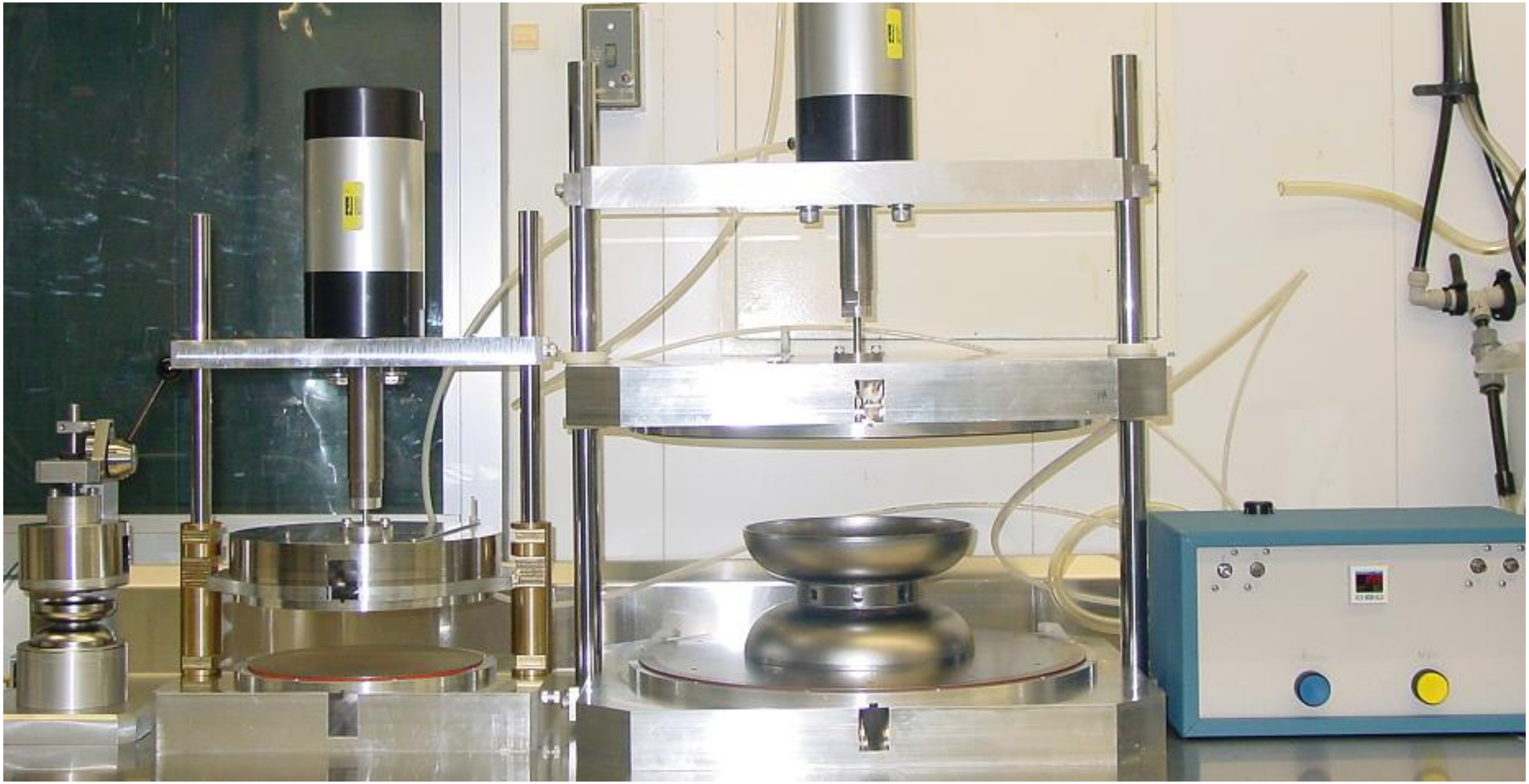
Elliptical cavity production





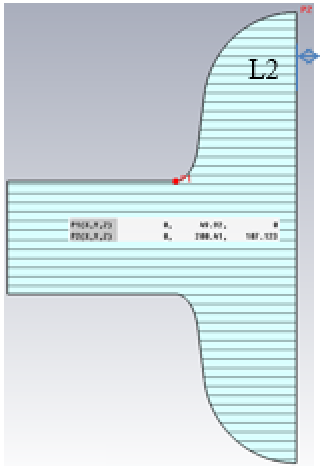
3.9 GHz half cells and dumbbell measurement fixture

Elliptical cavity production



3.9 GHz, 1.3 GHz and 650 MHz dumbbell measurement fixtures

Elliptical cavity production



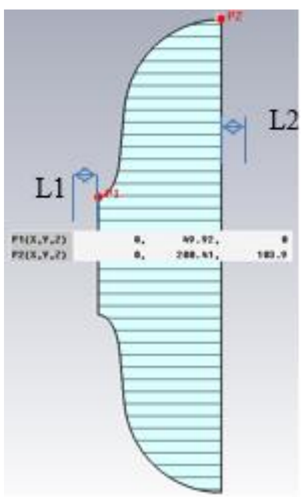
L2	f, MHz
0	649.542
2	647.325
4	645.224

dF/dL2, MHz/mm
-1.123

Frequency vs. L2 length
Magnetic BC on iris side

L2	0	2	4
F, MHz	649.493	647.273	645.169

dF/dL2 ,MHz/mm
-1.125

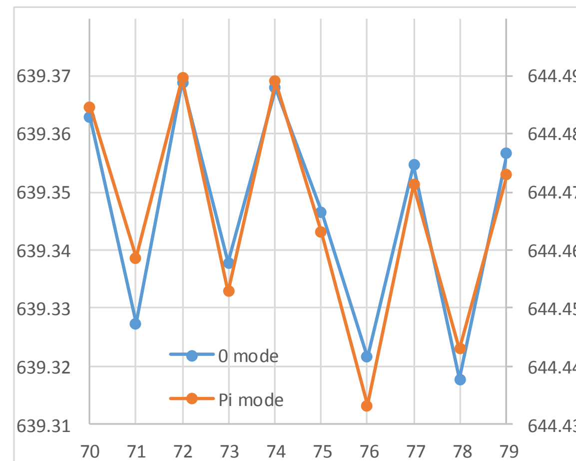


Electrical BC on both sides

	0	2	4
0	644.194	642.14	640.193
2	644.62	642.552	640.593
4	644.972	642.894	640.924

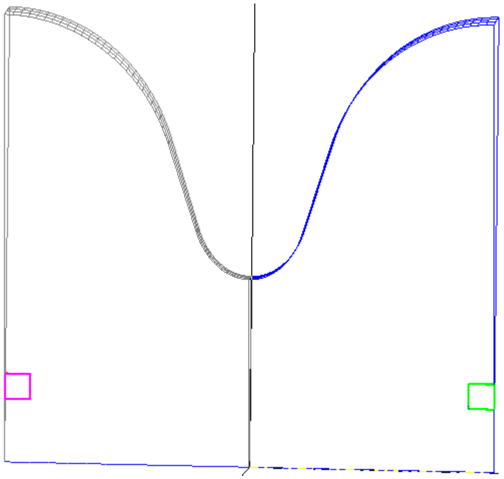
	0	2	4
0	0.000	-2.054	-4.001
2	0.426	-1.642	-3.601
4	0.778	-1.300	-3.270

dF/dL1	dF/dL2
0.223	-1.04



650 MHz beta 0.90 copper dumbbell				
	L, mm	F0, MHz	F1, MHz	dF, MHz
Measured	213.05	639.37	644.47	5.1
Expected	213.8	641.167	646.206	5.039
dF, MHz		-1.797	-1.736	

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 :

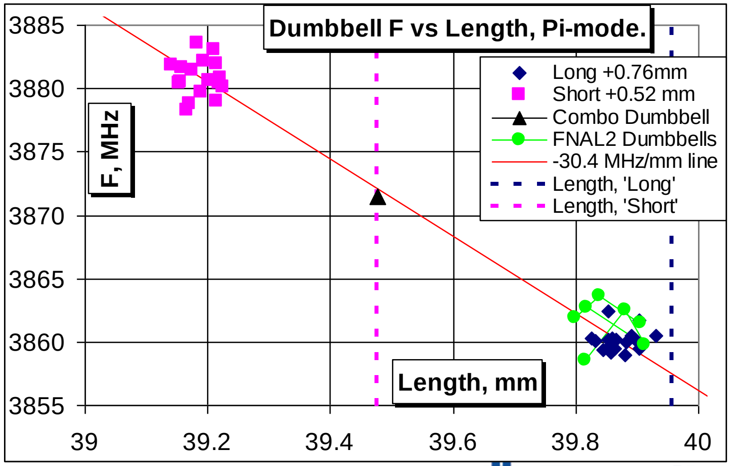
-Frequency and length measurements. Sensitivity of the frequency to extra length is 14 MHz/mm at iris and -55 MHz/mm at equator.

-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 $k \sim 4(F_{pi} - F_0)/(F_{pi} + F_0)$, for a 3rd harmonic cavity k~0.08 MHz



-Trimming calculations:

-Equator trimming

-Equator welding

-Mechanical and RF QC of the new cavity.

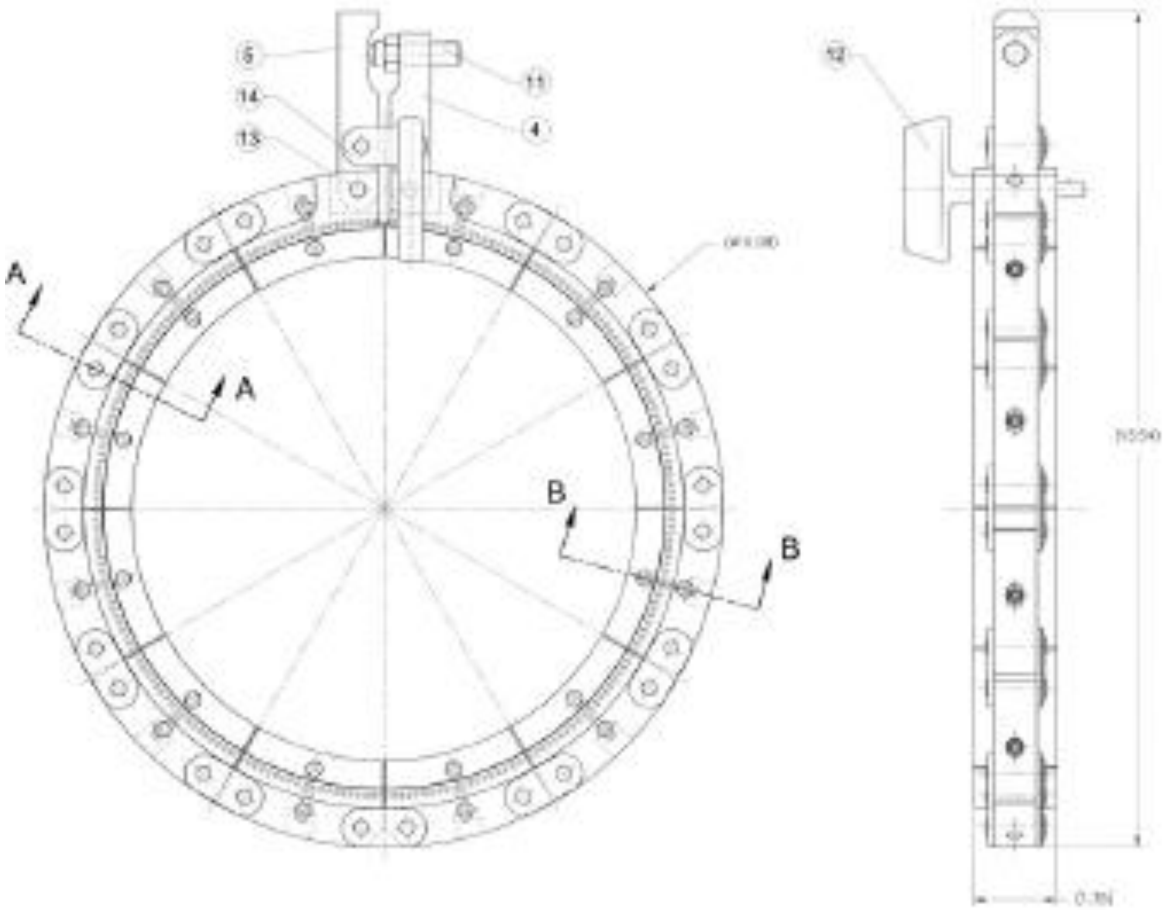
-Bulk BCP and 800C baking,

-RF tuning of the cavity

Multi-cell cavity field flatness tuning

"Iris", axial tuning fixture

"Equator", radial tuning fixture



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 dFn=1 kHz field distribution will change by dAi.

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

Perturbation of frequency of each will change field distribution:

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

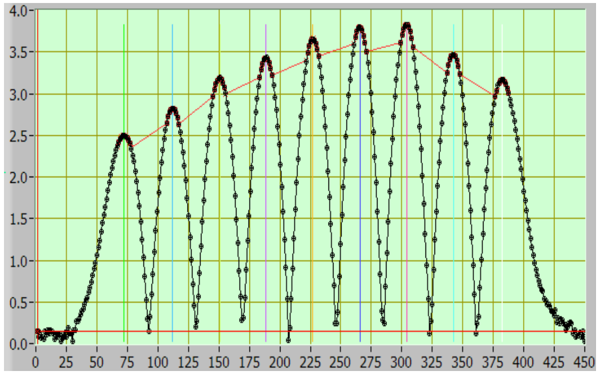
$$dA = K * dF \Rightarrow K^{-1} * dA = K^{-1} K * dF = dF$$

Where sensitivity coefficients matrix K calculated from HFSS simulations.

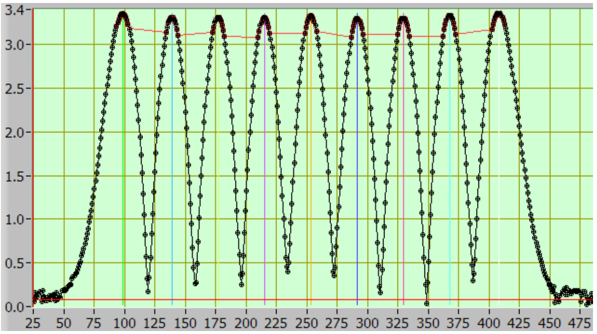
During RF tuning of the cavity we need to tune its operating mode frequency F_9. Also we can not measure individual cell frequency but can measure F_9. Tuning of cell #n by dFn shifts also cavity frequency by dF_9~dFn/9. If design frequency is $F_9 0$ tuning of the cell should be done by shifting operating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



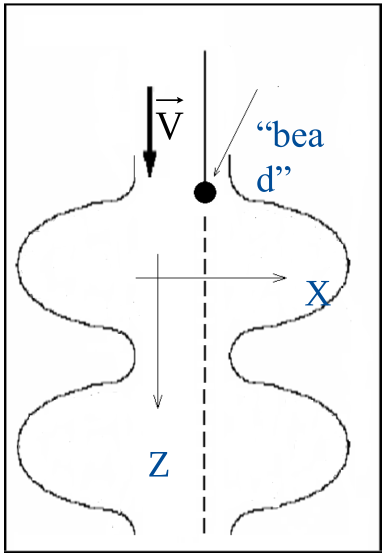
After tuning. FF 98%, slope +0.64 %

Cavity cell centers measurements technique based on bead-pull

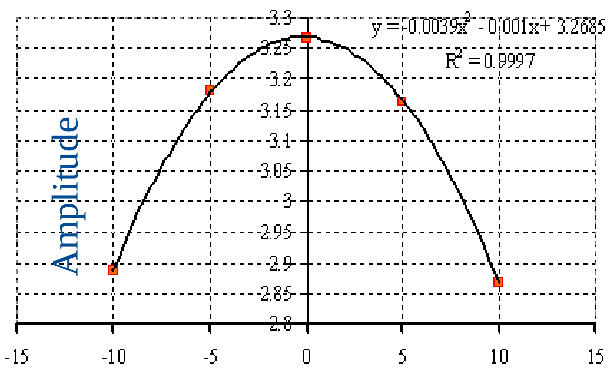
We need to measure cavity alignment. Usually people measure it mechanically on the outside surface of the cavity. This measurements time consuming, needs additional equipment and not possible for a cavity welded to He vessel.

Calculations of the electrical center of the each cell of the cavity based on bead pull measurements. It includes next steps:

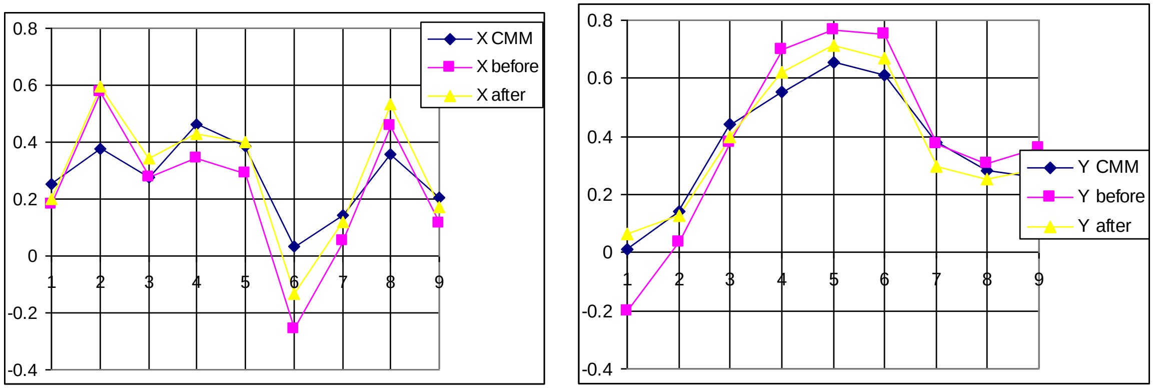
- Bead pull measurements setup allows positioning of the fishing line in the plane perpendicular to cavity axes Z. Initial position of the line is go through centers of beam flanges
- Field distribution measurements in several positions shifted in XZ plane on line parallel to cavity axes. Usually 5 measurements with displacements -2d, -d, 0, d, 2d.
- Calculations of field Anm maximum in each cell #n center and measurement #m.
- Calculations of electric cell center Xn for each cell #n as a position of 2nd order best fit line maximum. $An(x)=A0-k(X-Xn)^2$.
- Similar calculations for YZ plane.
- At the end we have coordinates (Xn,Yn) of electric centers for each cell of the cavity.
- Cavity rotates by 180 degree around beam pipe flanges and measurements and calculations repeated. Combination of these two measurements allow us exclude error of initial positioning of fishing line.



$$\Delta\varphi = k_H \mu_0 H^2 - k_E \varepsilon_0 E^2)$$



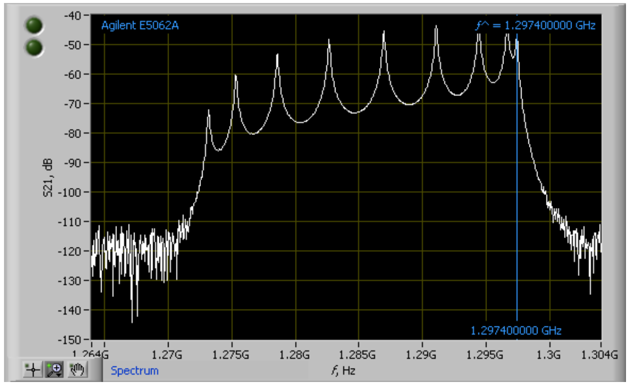
Coordinate at axis X, mm

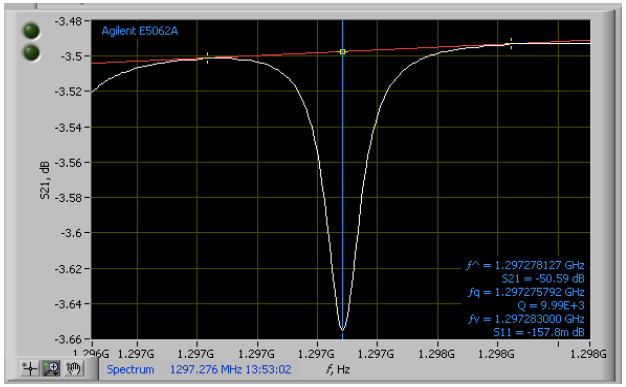


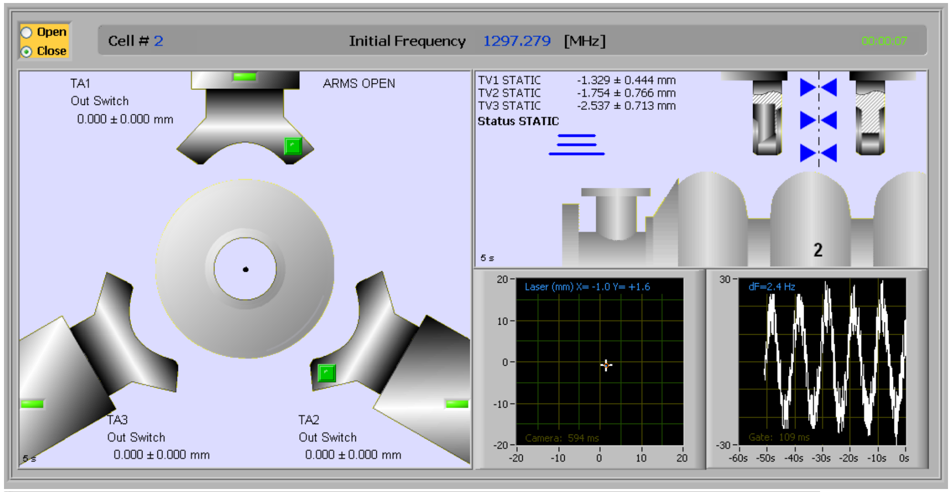
CMM and bead-pull cell center measurements.

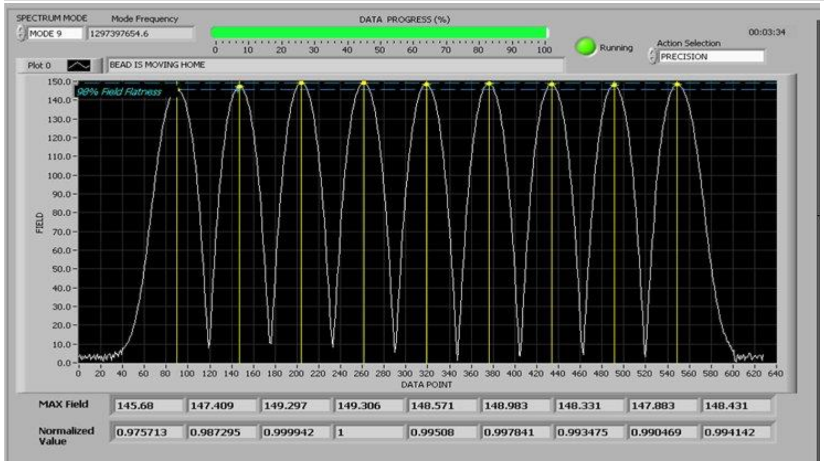
ICL Cavity Tuning Machine

ICL Cavity Tuning Machine







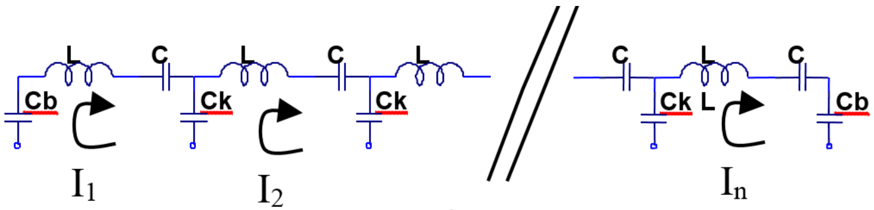


$$\frac{\Delta\omega}{\omega_0} = \frac{\Delta U}{U} = -\frac{\pi r^3}{U}\left[\varepsilon_0\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right)E_0^{\,2} + \mu_0\left(\frac{\mu_r - 1}{\mu_r + 2}\right)H_0^{\,2}\right]$$

$$\frac{\Delta\omega}{\omega_0} = \frac{1}{2Q_L}\tan\Phi$$

ICL Cavity Tuning Machine

Electrical Tuning Model



$$C_b = C_k / 2$$

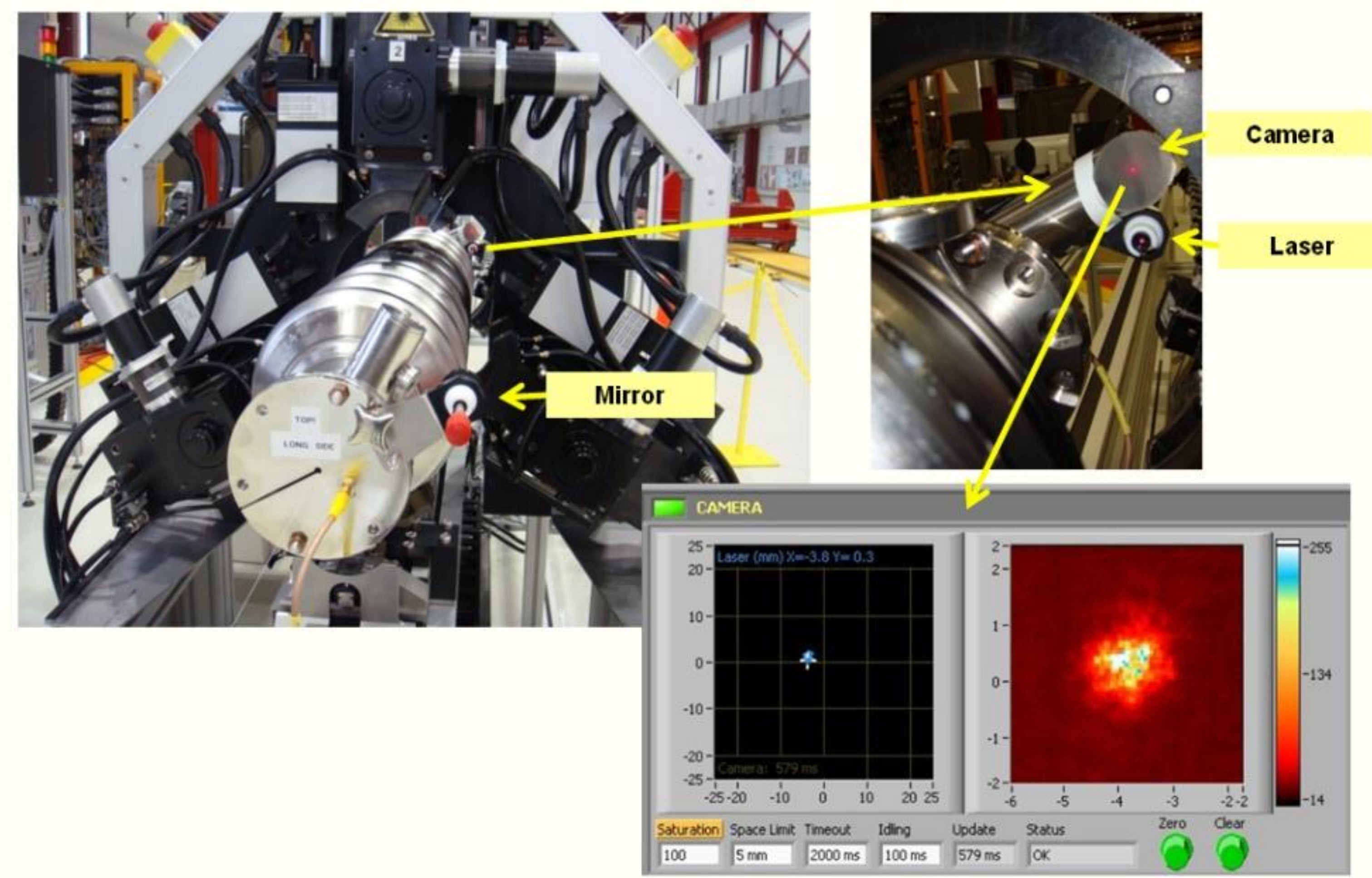
$$\frac{\omega_m^2}{\omega_0^2} = 1 + 2k\left(1 - \cos\frac{\pi m}{n}\right)$$

Perturbed Cell	Mode								
	π/9	2π/9	3π/9	4π/9	5π/9	6π/9	7π/9	8π/9	π
None	1272962627	1274957050	1278058814	1282360406	1286719290	1291034246	1294192355	1296275920	1297214369
1	1272959699	1274949285	1278047078	1282343291	1286695334	1290996581	1294136536	1296224176	1297205203
2	1272939491	1274907939	1278012098	1282330706	1286709481	1291034246	1294177869	1296239536	1297205472
3	1272924645	1274916603	1278054186	1282348121	1286674373	1291000233	1294191942	1296245084	1297200897
4	1272915218	1274947447	1278037944	1282313655	1286718116	1290998462	1294169950	1296259744	1297196374
5	1272912506	1274954947	1278008131	1282359819	1286670529	1291034241	1294151821	1296272762	1297192563
6	1272923849	1274929386	1278051897	1282310247	1286716636	1290998492	1294164774	1296275168	1297185955
7	1272938364	1274907219	1278040820	1282355751	1286676137	1291000182	1294190354	1296265922	1297181903
8	1272952642	1274921183	1278006846	1282322376	1286706288	1291034210	1294182137	1296251275	1297179711
9	1272961664	1274951633	1278046252	1282339175	1286688707	1290997073	1294153570	1296241250	1297179205
None	1272962524	1274957210	1278058803	1282360435	1286719319	1291034246	1294192366	1296275951	1297214419

Example Bead-Pull Frequency Data from a 9-Cell Tesla Style Cavity

ICL Cavity Tuning Machine

Cavity Alignment



ICL Cavity Tuning Machine

Laser based alignment correction

Frequency tuning of the cavity cell in the Cavity Tuning Machine based on deformation of the cell in axial direction. Deformation provided by three motorized Arms located around the cell in the plane perpendicular to cavity axes uniformly every 120 degrees. Arm #1 is located on the top of the cell. Arm #2 is in the right side of the cavity, when we look from power coupler end of the cavity. Arm #3 is in the left side of the cavity in same view.

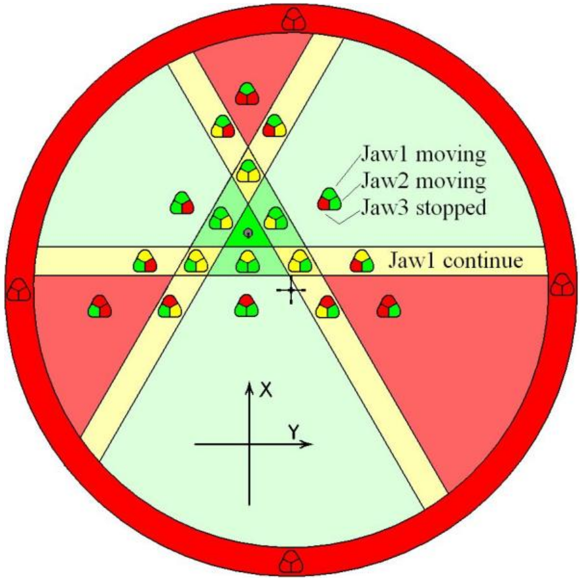
Each Arm ends with Jaw each side located in plane of one (of two) Irises of the cell. Jaw distance can be changed by stepper motor with gear box independently for each Jaw.

During the tuning Jaw distances change causing axial deformation of the cell. Frequency of the cell and cavity drops when distances decrease and the frequency goes up when distances increases. Note: for safe operation Jaws can not move in opposite direction.

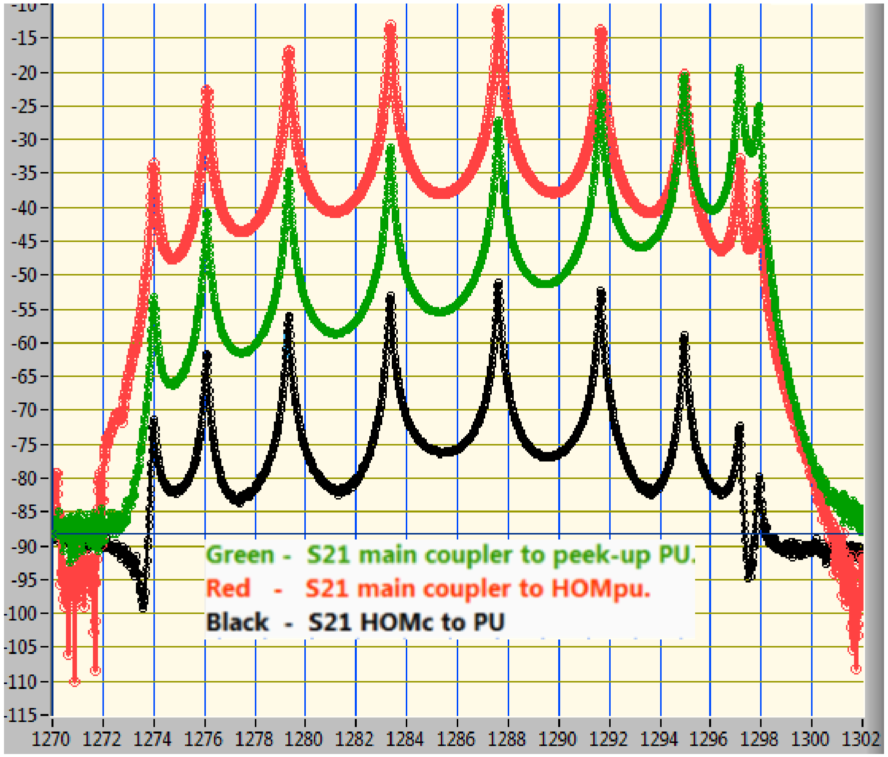
We need to redistribute Jaws motions to imptove cavity alignment. Laser based Cavity Alignment Control System is used for this purpose. Beam emitted from Laser installed on Cavity Coupler end Beam Pipe Flange reflects from mirror installed on another end Beam Pipe Flange. Retuned laser beam image detected by camera installed on same flange as Laser. Any angular change between two Beam pipe flanges cause change of laser beam image spot position. Alignment conservation technique is based on keeping laser beam image spot position as close as possible to the initial position during cell tuning.

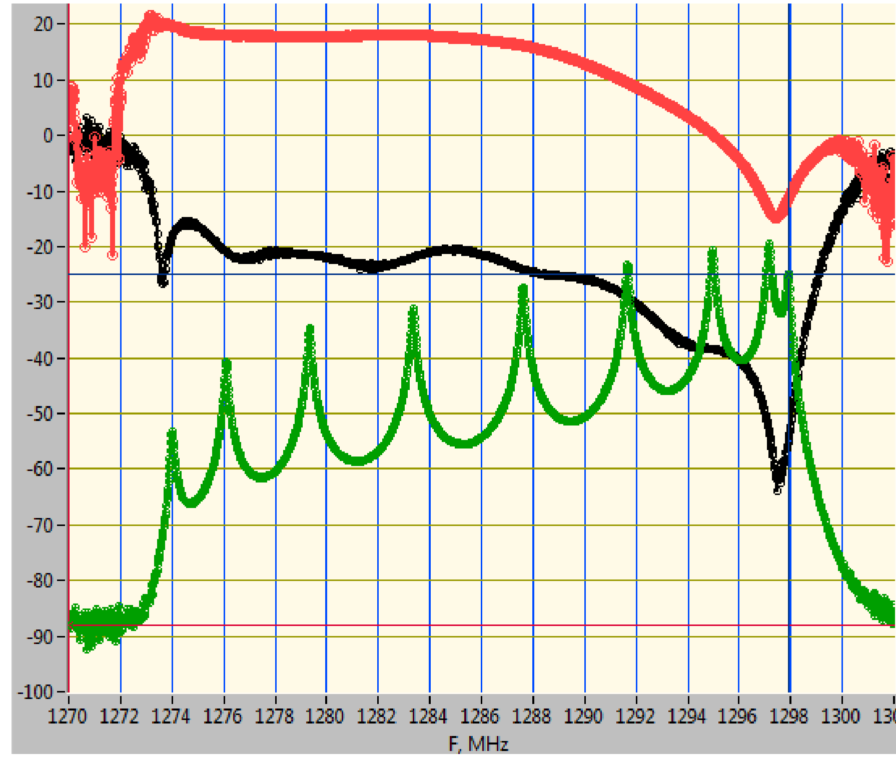
Another advantage of laser based Cavity Alignment Control System is possibility to perform control during aligning of the cavity. It is necessary for a cavity with bad alignment originally, before tuning.

So we need a technique to control cavity alignment during frequency tuning. It will allow us to keep cavity alignment and even improve it.



HOM notch frequency tuning





S21 power coupler to PU

S21 power coupler to HOMpu

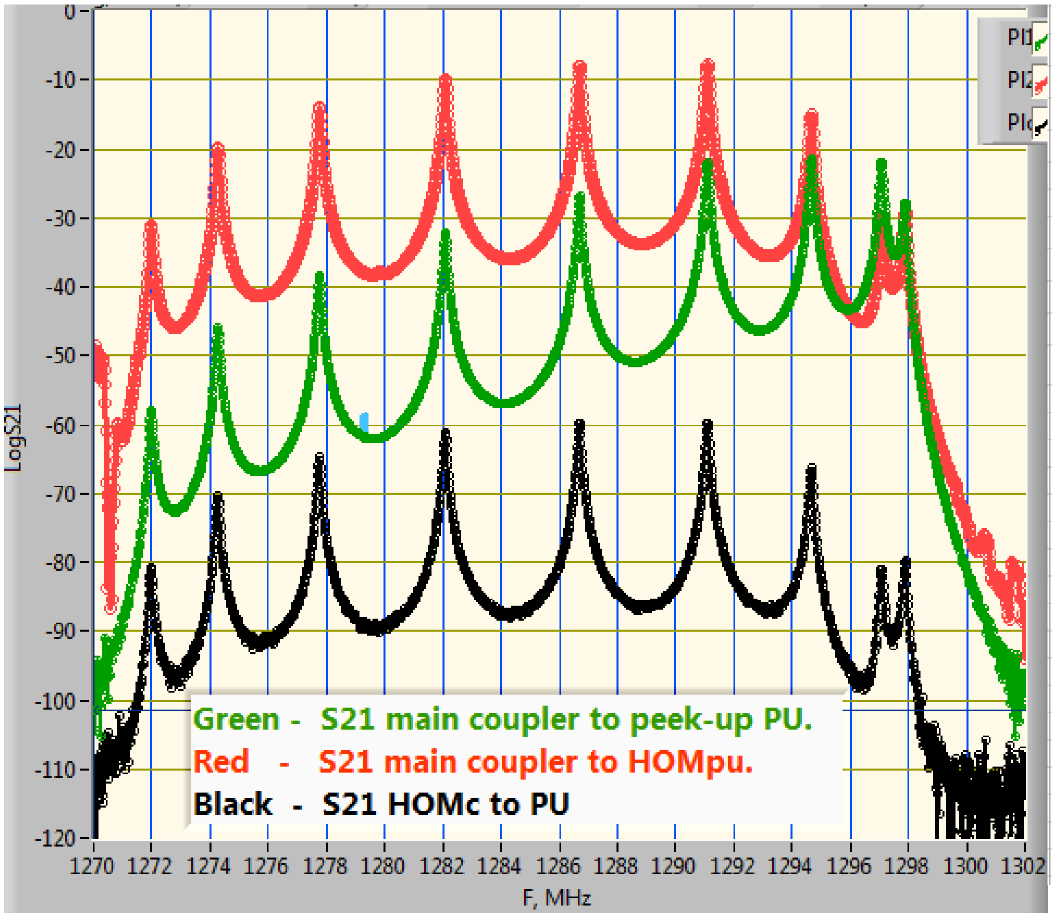
S21 HOMc to PU

S21 power coupler to PU

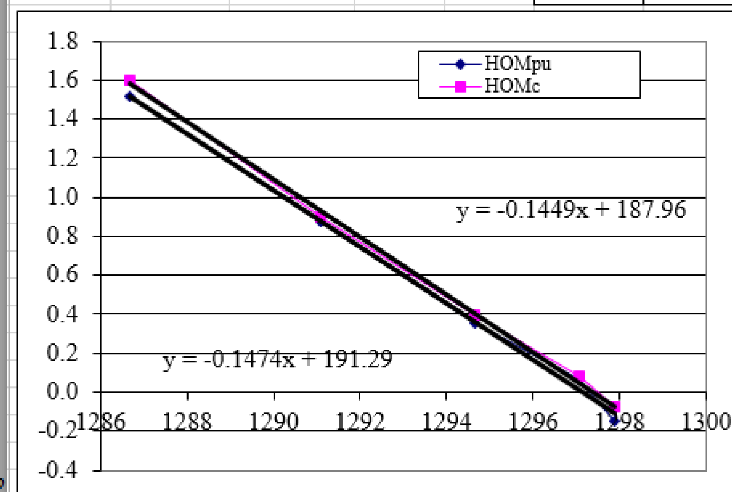
Red curve |S21/S21|

Black curve|S21/S21|

HOM notch frequency tuning

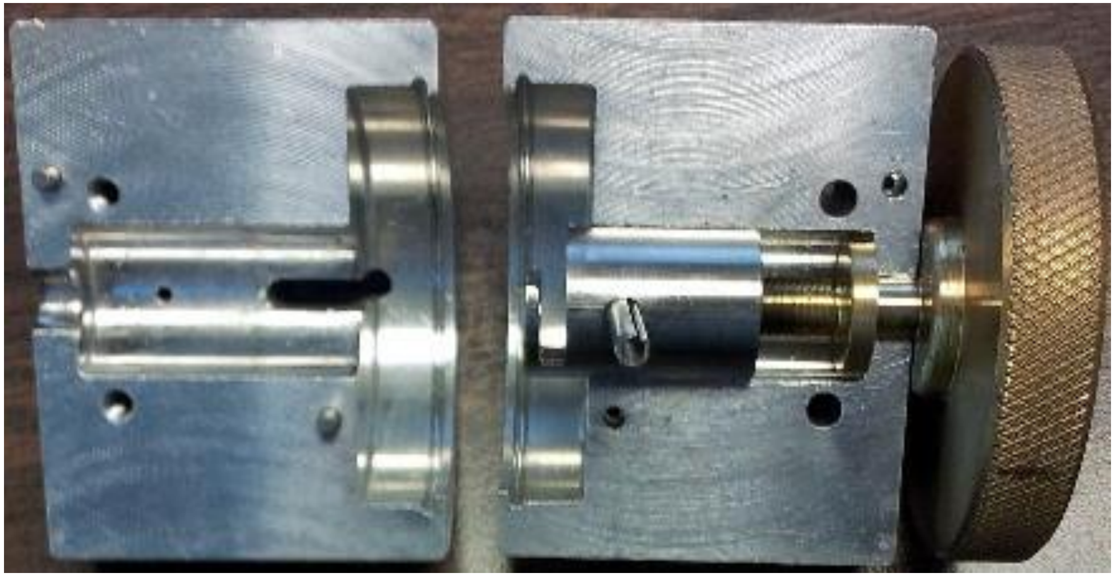


F, MHz	Q	PU	HOMpu	HOMc		
1271.98	9771	1.26E+00	2.77E+01	8.99E-02	3.749	5.005
1274.27	9897	5.08E+00	1.01E+02	3.05E-01	3.379	4.202
1277.76	9860	1.20E+01	2.01E+02	5.70E-01	2.851	3.324
1282.08	9869	2.43E+01	3.15E+02	8.71E-01	2.207	2.513
1286.69	9820	4.47E+01	4.00E+02	1.02E+00	1.519	1.599
1291.09	9826	7.93E+01	4.08E+02	1.02E+00	0.873	0.900
1294.66	9865	8.42E+01	1.75E+02	4.75E-01	0.353	0.395
1297.07	9697	8.01E+01	3.14E+01	8.95E-02	0.067	0.078
1297.89	9429	4.01E+01	3.45E+01	1.01E-01	-0.146	-0.078
					HOMpu	HOMc
					1297.2	1297.0



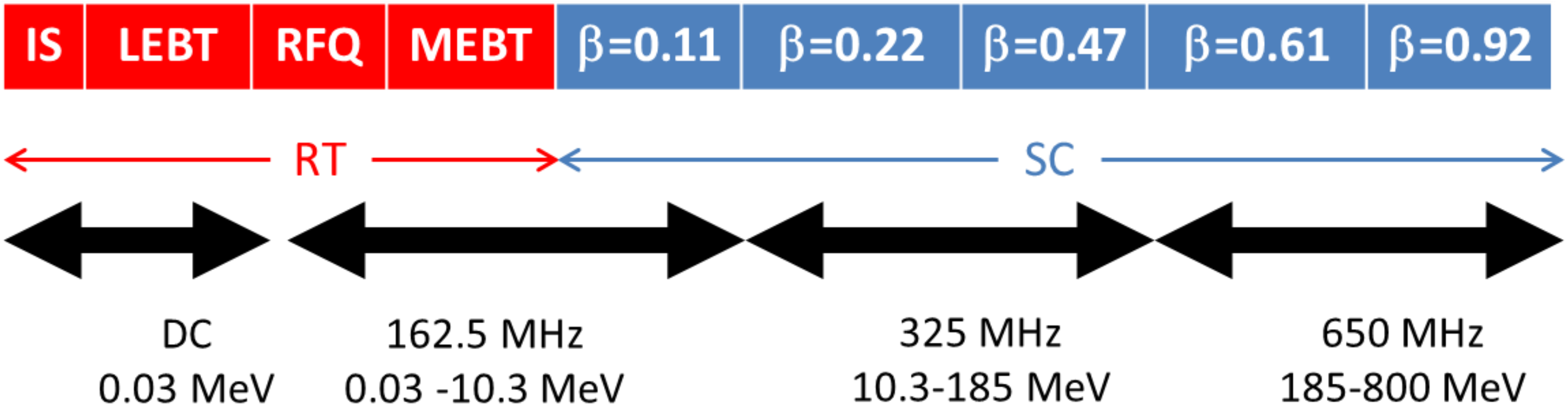
HOM notch frequency tuning

Notch frequency tuning tool



HB650 β=0.9/0.92 cavity for PIP-II design

PIP-II Layout



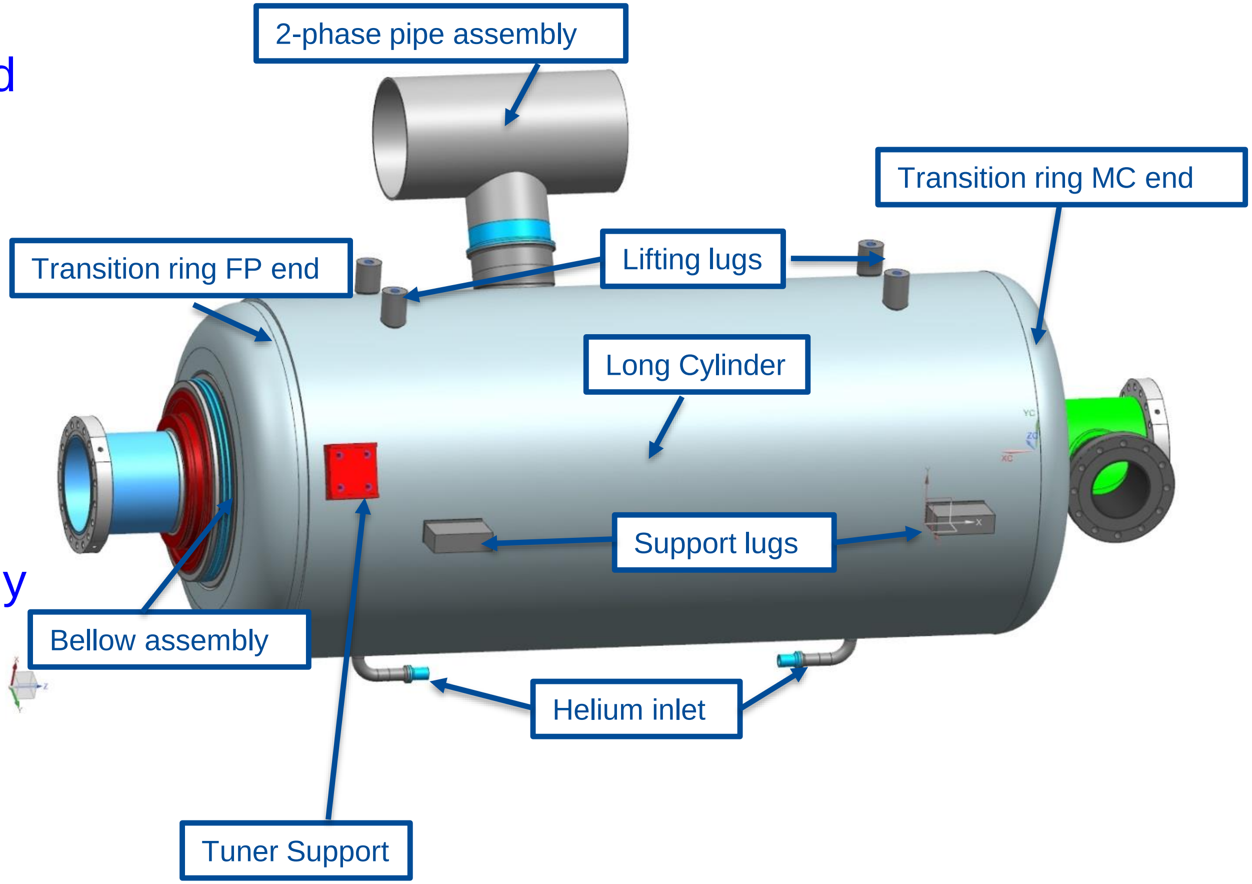
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet

HB 650 MHz Cavity Helium Vessel

components:

1. Long Cylinder
2. Transition ring MC end
3. Transition ring FP end
4. Bellow assembly
5. Support lugs
6. Lifting lugs
7. Helium inlet
8. 2-phase pipe assembly
9. Tuner mounting lugs
10. Bellow restrains

11. Magnetic shielding (external)

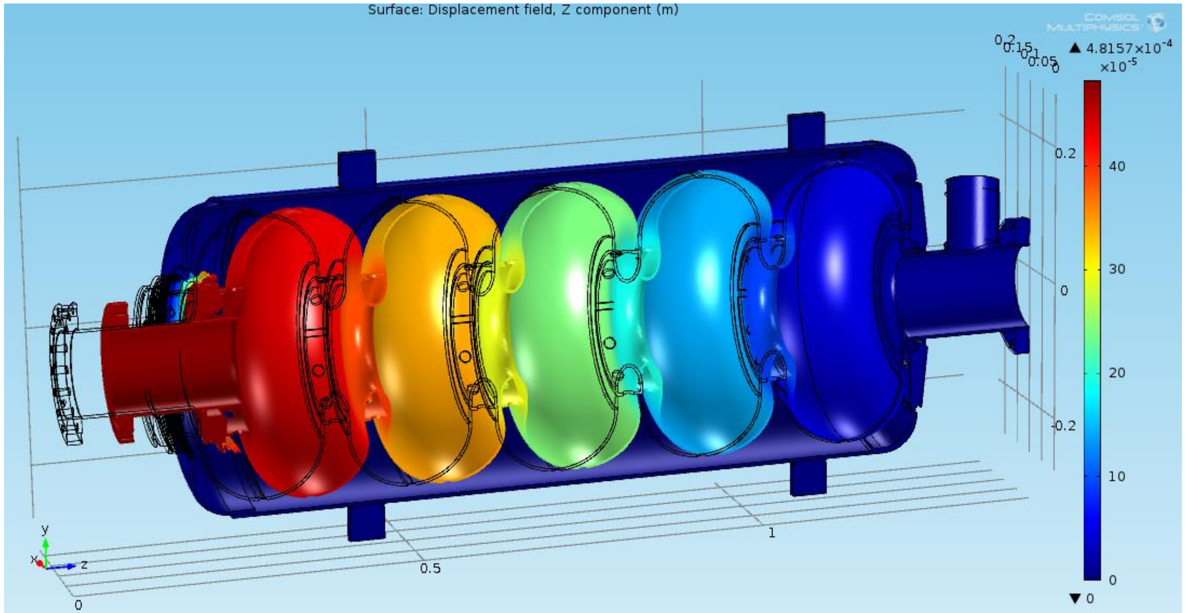


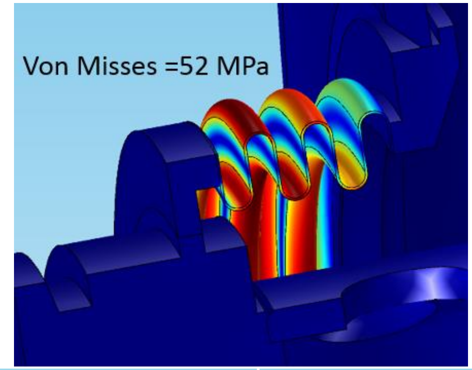
The Scope of EM-Mechanical Design

- 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

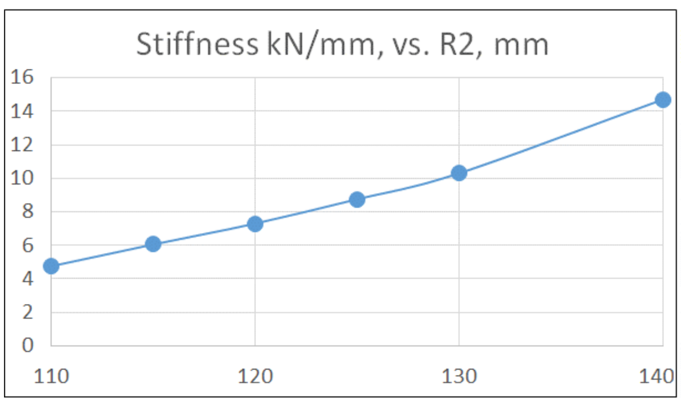
1. Warm Pressurization
2. Cold operation at maximum pressure
3. Cool down and tuner extension
4. Cold operation at maximum pressure and LHe weight
5. Upset condition – Insulating and beam vacuum failure

Cavity stiffness simulations





F, N	1000
x1, mm	0.295
x2, mm	0.016
σ bellow, MPa	52
σ cavity, MPa	10



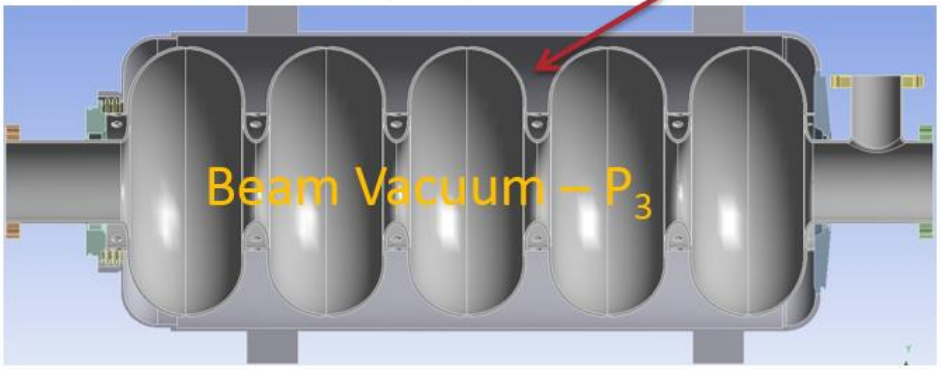
R2,mm	Stiffness kN/mm
110	4.75
115	6.2
120	7.3
125	8.75
130	10.3
140	14.7

	Young's modulus 293K/2K	Poisson ratio 293K/2K
Niobium	105/118	0.38
Titanium	106/117	0.37
Niobium-Titanium	62/68	0.33

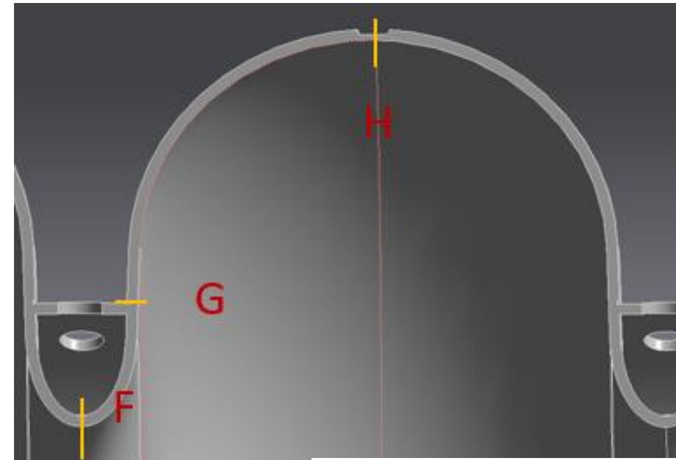
Stress analysis

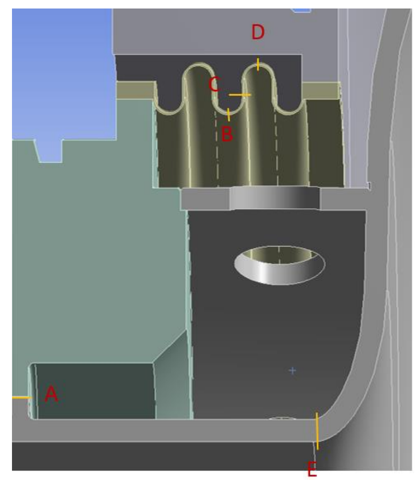
Insulating vacuum – P_2

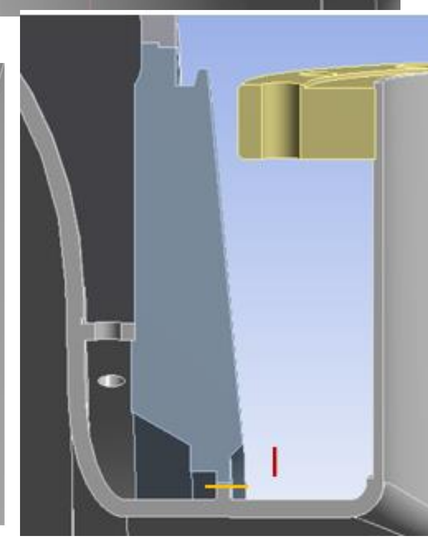
Pressure in LHe volume – P_1



Load Case	Loads	Condition Simulated	Applicable Temperature	Applicable Stress Categories
1	1. Gravity 2. $P_1 = 0.2$ MPa 3. $P_2 = P_3 = 0$	Warm Pressurization	293 K	Pm, P_L, Q, Pm + P_b , P_L + Q
2	1. Gravity 2. Liquid Helium head 3. $P_1 = 0.4$ MPa 4. $P_2 = P_3 = 0$	Cold operation, full LHe, maximum pressure – no thermal contraction	2 K	Pm, P_L, Q, Pm + P_b , P_L + Q
3	1. Cool down to 1.88 K 2. Tuner extension of 2 mm	Cool down and tuner extension, no primary loads	2 K	Q
4	1. Gravity 2. Liquid Helium head 3. Cool down to 1.88 K 4. Tuner extension of 2 mm 5. $P_1 = 0.4$ MPa 6. $P_2 = P_3 = 0$	Cold operation, full LHe inventory, maximum pressure – primary and secondary loads	2 K	Q
5	1. Gravity 2. $P_1 = 0$ 3. $P_2 = P_3 = 0.1$ MPa	Insulating and beam vacuum upset, helium volume evacuated	293 K	Pm, P_L, Q, Pm + P_b , P_L + Q







Stress analysis. Allowable Stresses (MPa)

	Allowable Stress (S) for materials		Allowable Stress (0.6xS) for weld joints	
Material	2 K	293 K	2 K	293 K
Nb	171	25	102.6	15
Ti-45Nb	156	156	93.6	93.6
Gr. 2Ti	319	99	191.4	59.4

	Stress Category							
	Pm		P_L		P_m (or P_L) + P_b		P_m (or P_L) + P_b + Q	
Material	2 K	293K	2 K	293K	2 K	293K	2 K	293K
Nb	171	25	256.5	37.5	256.5	37.5	513	75
Ti-45Nb	156	156	234	234	234	234	468	468
Gr. 2Ti	319	99	478.5	148.5	478.5	148.5	957	297
Nb Welds	102.6	15	154	22.5	154	22.5	308	45
Ti-45Nb Welds	93.6	93.6	140.4	140.4	140.4	140.4	280.8	280.8
Gr. 2Ti Welds	191.4	59.4	287	89	287	89	574	574

Note : The allowable stresses have not been reduced by 0.8 (recommended by point 3.4.1.10 of TD-09-005, confirmed by Tom Peterson). For welds it has been reduced by factor of 0.6.

Pm = primary membrane stress; P_L = primary local membrane stress P_b = primary bending stress
Q = secondary stress

Stress analysis. Linearized Stress Table (MPa)

Location	P_m	S_a	$P_m + P_b$	S_a
A (Nb-Ti weld tuner end)	1.08	93.6	2.05	140.4
B (Bellow lower weld)	36	59.4	60	89
C (Bellow weld)	36.8	59.4	69.82	89
D (Bellow upper weld)	28.8	59.4	54.87	89
E (Nb weld at end cell)	4.46	15	5.53	30
F (Nb weld at Iris)	4.28	15	7	22.5
G (Nb material near stiffening ring)	5.66	25	12.4	37.5
H (Nb weld at equator)	6.33	15	11.62	22.5
I (Nb-Ti weld coupler end)	4.92	93.6	7.1	140.4

Simulation of stresses during production

Temperature	*Protection*	*The steps during cavity assembly or operations*		Insulated Vacuum, bar	Cavity Beamline, bar	He Vessel, bar	Forces on the cavity flange for fully constrained cavity, kN	Cavity length changes, for non-constrained cavity, mm
Tcavity=300K	Safety Brackets	1	Cavity after dressing	1	1	1	0	0.00
		2	Cavity leak check at the clean room	1	0	1	-3.83	-1.10
		3	He Vessel leak check during CM assembly	1	1	0	0.014	-0.03
		4	He Vessel pressure test during CM assembly	1	1	3.3	-0.03	0.06
	Tuner Installed	5	He Vessel leak check during CM testing	1	0	0	-4.4	-1.10
		6	He Vessel pressure test during CM assembly	1	0	3.3	-3.87	-1.01
5K		7	Start of cooling down CM or HTS	0	0	1.5	-0.02	0.04
2K		8	Operating condition	0	0	0.03	0	0.00
5K		9	Cold loss of vacuum accident	0	0	4	-0.05	0.10

LCLS-II Tuner Electro-Mechanical Design

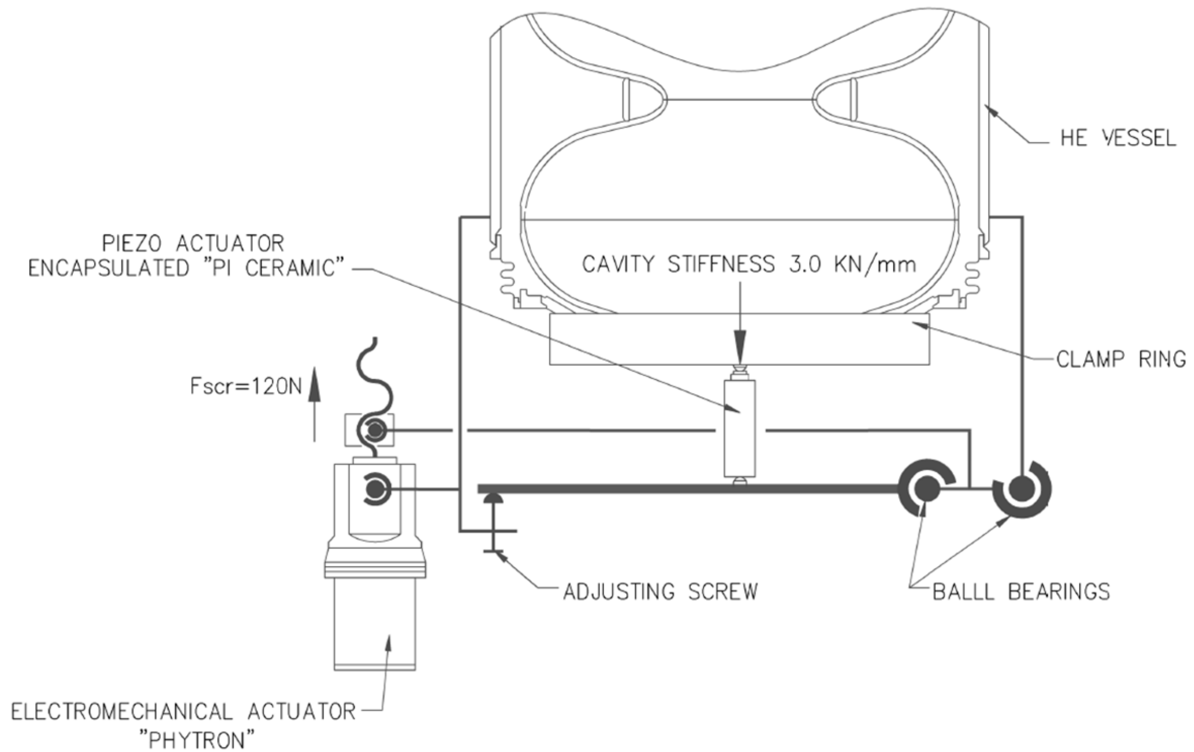
- *Tuner must tune cavity (slow and fast) and protect cavity/He Vessel system during CM production cycle and operation of the accelerator*
- *Tuner needs to fit the existing inventory of cavities at FNAL. ..”short-short” (cavity built for slim blade tuner for CM3/4/5…).*
- *Active tuner components (electromechanical actuator& piezo-stack) need to be replaceable through special ports;*
- *High reliability of tuner components (electromechanical actuator and piezo-actuator);*
- *Tight requirements for slow/coarse & fast/fine tuning resolution → cavity has narrow bandwidth ($F_{1/2}$~15Hz) and resonance control requirements ΔF_{peak}=10Hz (or σ=1.5Hz))*

LCLS-II Tuner Electro-Mechanical Design

Slow Tuner frequency range	nominal	250kHz
	maximum	450kHz
Slow Tuner dimensional range	nominal	0.75mm
	maximum	1.3mm
Slow Tuner sensitivity		1-2Hz/step
Fast Tuner frequency range		1kHz
Fast Tuner dimensional range		3um
Fast Tuner tuning resolution		1Hz
Fast Tuner stroke resolution		3nm
Fast Tuner response bandwidth		5kHz
Min. tuner stiffness		30kN/mm
Min. tuner mechanical resonance		5kHz
Tuner operating condition		insulated vacuum T=20-60K
Slow Tuner/ electromechanical actuator lifetime (20 years)		1000 spindle rotation
Fast Tuner/ electromechanical actuator lifetime (20 years)		$4*10^9$ pulses

LCLS II Tuner Schematics

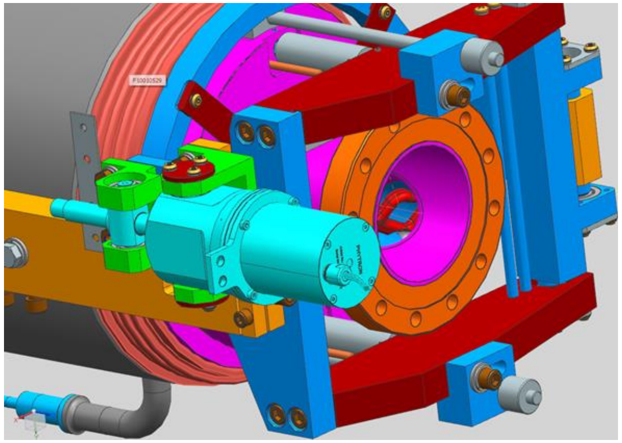
- Slow/Coarse Tuner is double lever tuner (close to design of the SACLAY 1)
- Coarse Tuner ration 1/20 (Saclay 1 ~ 1/17)
- Fast Tuner - two piezo installed close to flange of cavity /translation of the **stroke from piezo directly** to the cavity

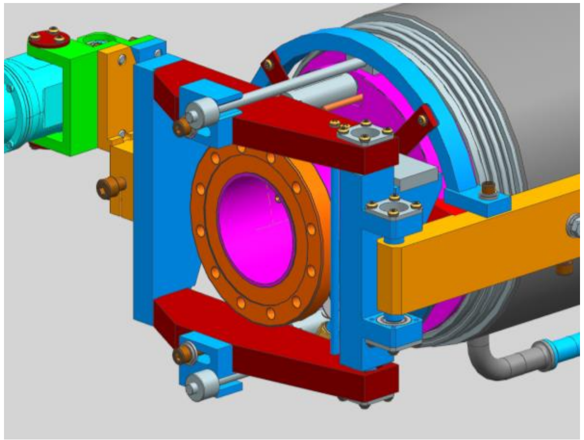


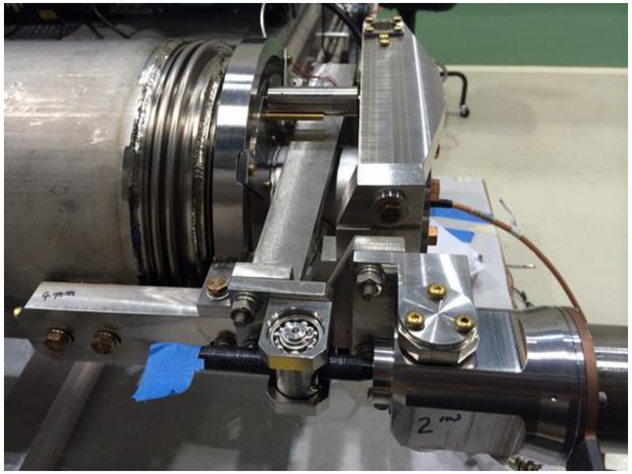
LCLS–II CAVITY SIDE TUNER SCHEMATIC

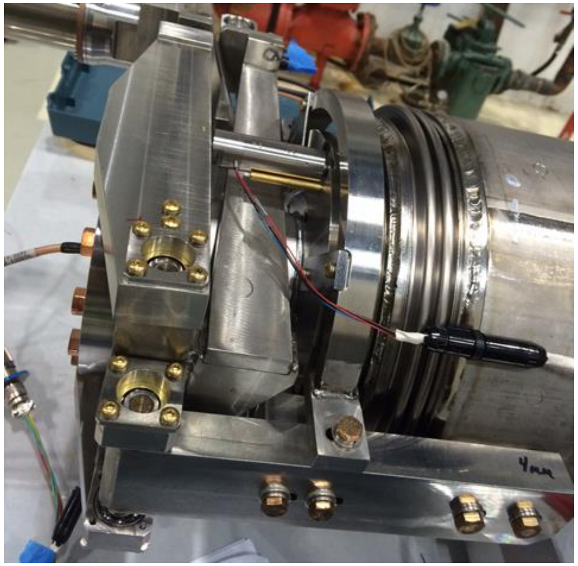
Design of the LCLS II Tuner

design included several features specific to requirements that electromechanical actuator and piezo-elements replaceable through special designated port

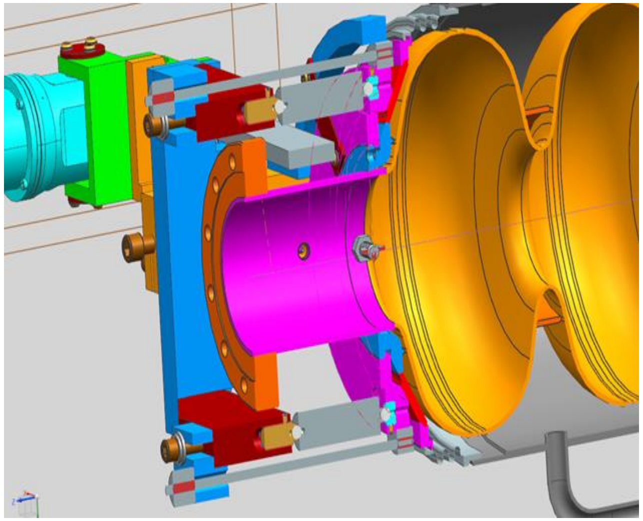


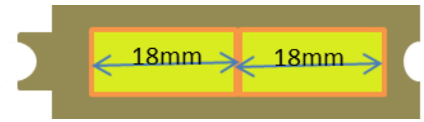


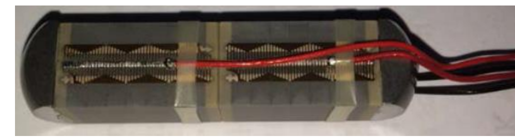


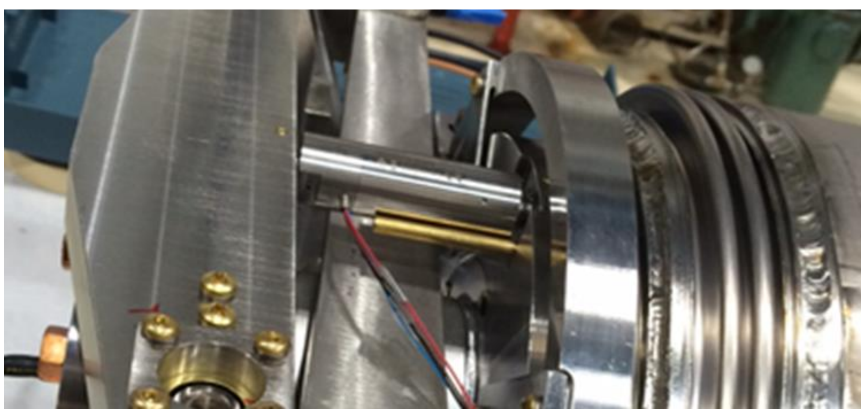


Details of FAST (piezo) Tuner design







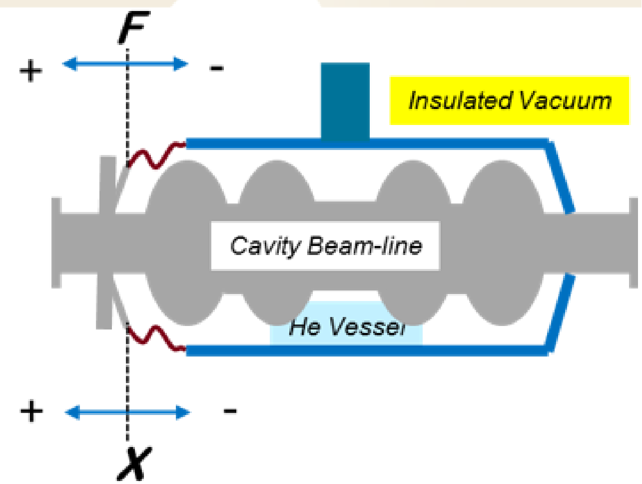


Encapsulated piezo designed and manufactured by Physik Instrumente (PI) per FNAL specifications.

Each capsule has inside two 18*10*10mm PICMA piezos. Piezo preloaded with 800N.

Forces/stroke on the cavity/He vessel system

TEMPERATURE	PROTECTION		***The step*** during cavity assembly or operations	Insulated Vacuum, bar abs	Cavity Beamline, bar abs	Helium Vessel, bar abs	Forces on cavity flange with absolutely restrained cavity, kN	Cavity length will changes if flange non-restrained, mm
T_{cav}=300K	RESTRAIN BRACKETS	*0*	Cavity is relaxed after HV welding	1	1	1	*0*	*0*
		1	Cavity/He Vessel Leak Checkt at MP9	1	1	0		
		2	Cavity/He Vessel Pressure test at MP9	1	1	3.3		1.4
		3	Cavity/He Vessel Leak Check in CM	1	0	0		-0.8
		4	Cavity/He Vessel leak check in Clean Room	1	0	1		
	TUNER INSTALLED ON CAVITY	*5*	He Vessel pressure test in CM	1	0	3.3		1.1
		6	Start of cooling down CM	0	0	1.5		0.8
		7	Linac maintenance (e.g., tuner or interconnect access)	1	0	1.4		
		8a	Tuner access and disconnect (e.g., replace piezo), what is max cryo system pressure	1	0	0		-0.8
		8b		1	0	2.5		
5K		*9*	End of cooling down	0	0	1.5		
2K		*10*	Operating condition	0	0.03	0		
5K		*11*	Worst case cold loss of vacuum accident. Will piezo and tuner survive?	0	0	4	10.4	



Requirements: $|X_{T=300K}| < 0.6$mm

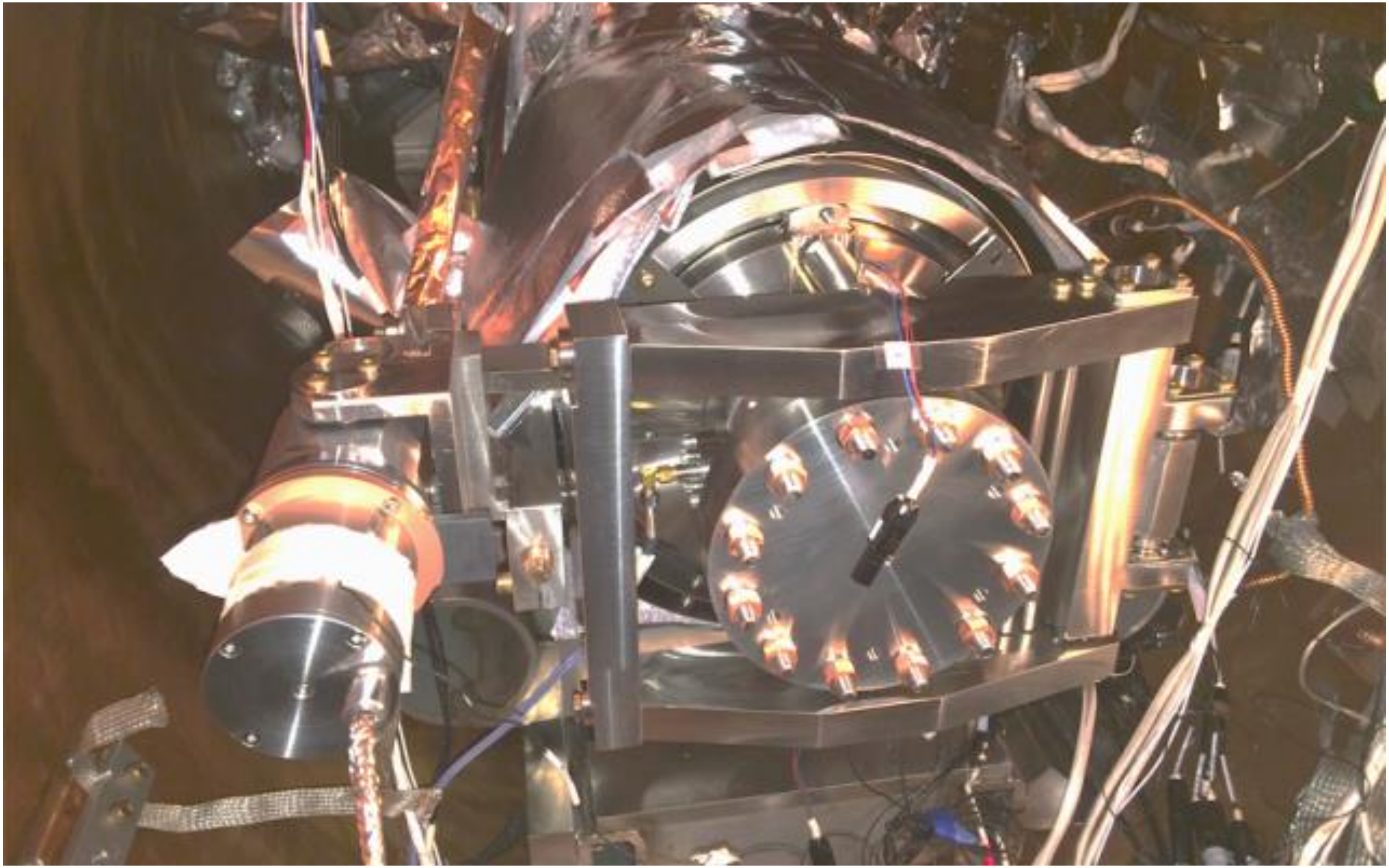
To preserve cavity in elastic region

Final design of the Tuner and restrained brackets included requirements to protect cavity during all steps.
Cavity will be always in elastic region

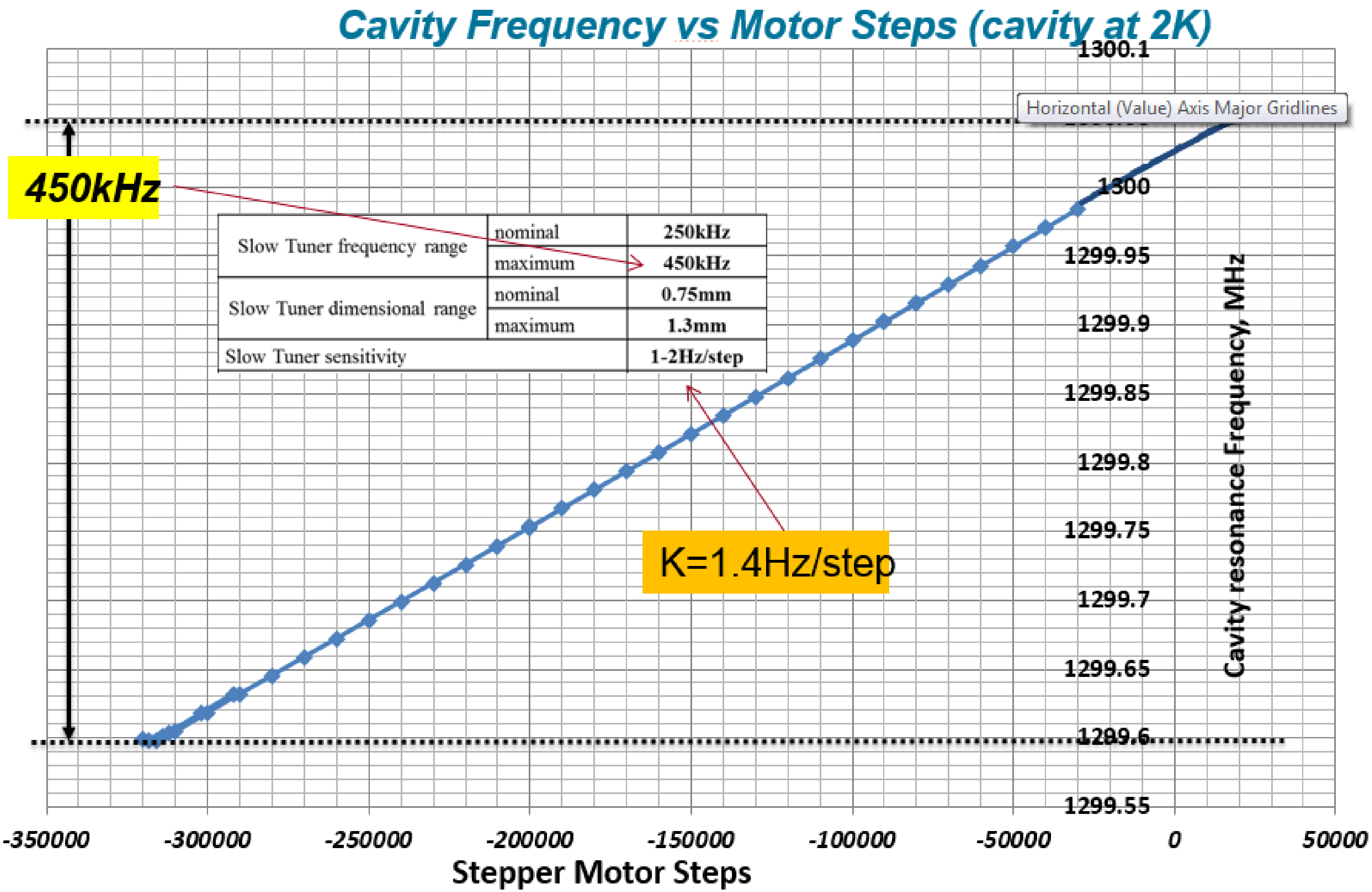
Piezo-stack will handle these forces

_S-II Director's Review, February 17-19, 2015

Tuner Test results at HTS



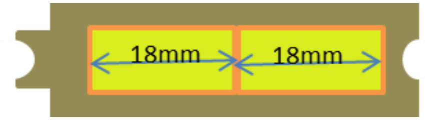
Tuner Test results at HTS

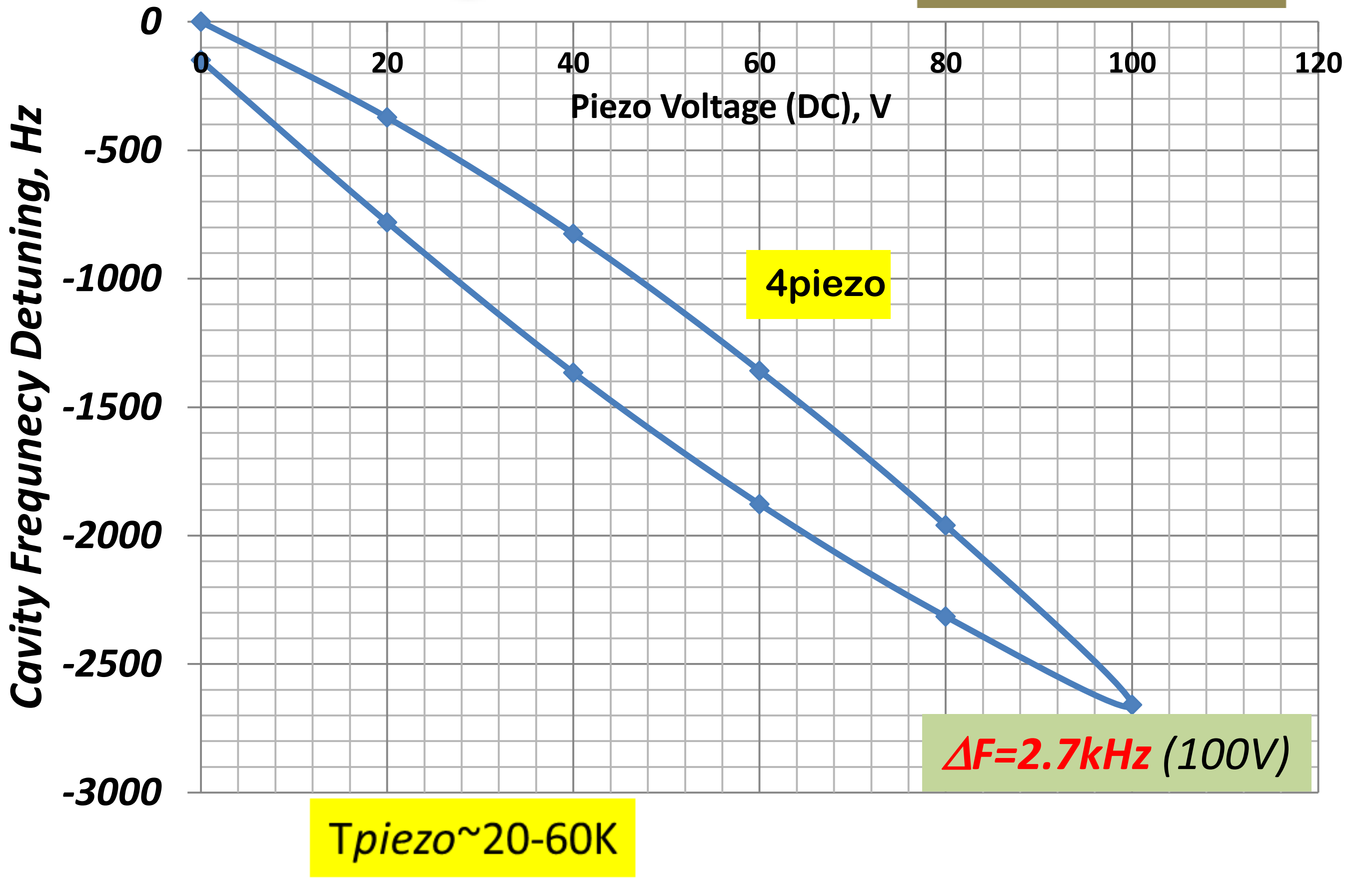


Slow Tuner frequency range	nominal	250kHz
	maximum	450kHz
Slow Tuner dimensional range	nominal	0.75mm
	maximum	1.3mm
Slow Tuner sensitivity		1-2Hz/step

Piezo Tuner Range

Fast Tuner frequency range	1kHz
Fast Tuner dimensional range	3um

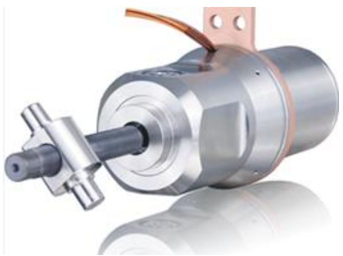




High reliability of tuner components

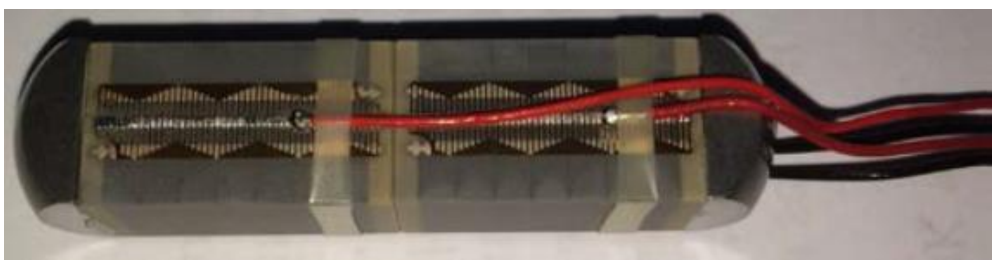
1. Phytron electromechanical Actuator (stepper motor/planetary gear/Ti spindle) *(designed per FNAL specs in the frame of the Project X.)*

Joint test (JLAB/FNAL) of production unit is underway at JLAB

Picture	Name	Motor	Gear Box	Spindle/Nut	Forces	Longevity tested
	LCLS II	Phytron 1.2A	planetary gear (ration 1:50)	Titanium & SS M12*1	+/-1300N	tested in ins. vacuum at HTS for 5000 turns **(5 XFEL lifetimes).** In the force range +/-1500N. Motor run with current 0.7A

2. Piezo actuator – encapsulated piezo made at PI Ceramics per FNAL specification for LCLS II project

(Designated piezo lifetime program is underway at FNAL)



Fermilab

LCLS-II Tuner Summary

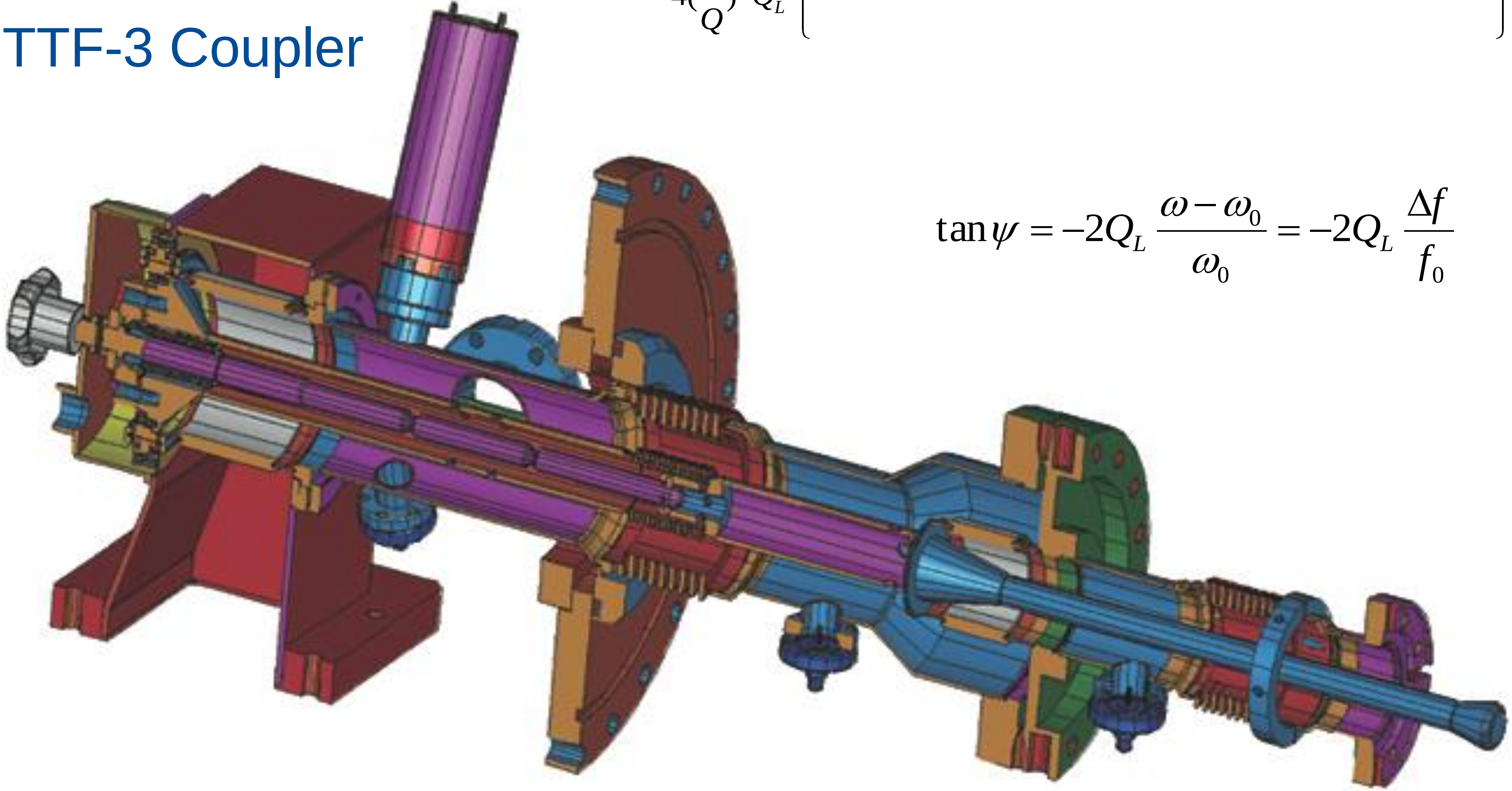
- Design of the LCLS II prototype cryomodule Tuner is mature. Several small issues found during prototype assembly and testing were corrected. Questions/comments from previous reviews were addressed.
- Tuner parameters, measured during tuner test at HTS, meet/exceed technical requirements specifications.
- Reliability of the tuner is addressed by two measures: tuner is accessible through designated ports and the active components (electromechanical actuator& piezo-actuator) illustrated reasonable longevity
- Preservation of the cavity Q0 with tuner (remnant magnetic field) will be tested in mid-March
- Procurement of long (~3 months) lead components (stepper motor and piezo-actuators) can be started

Power coupler design

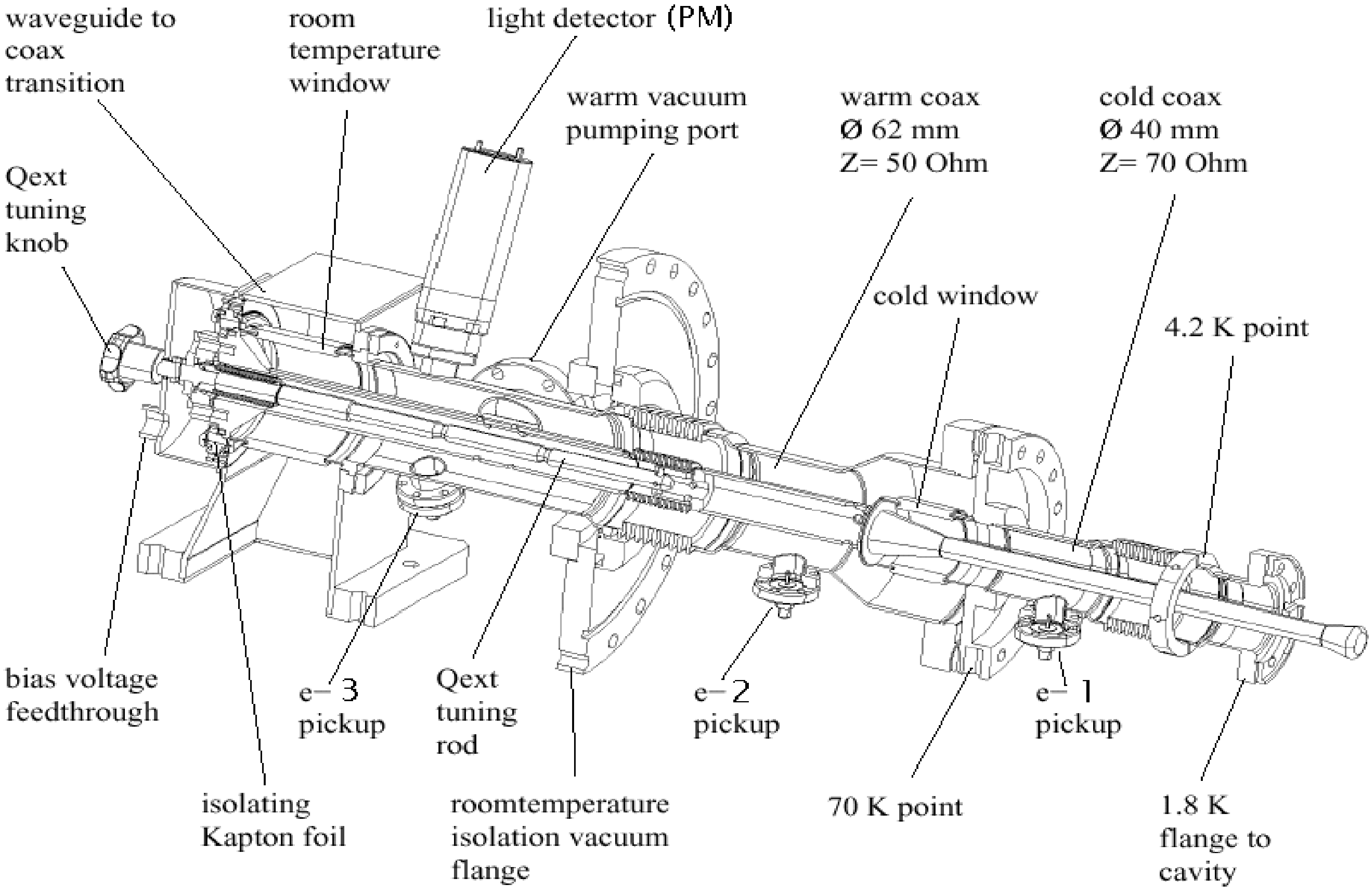
$$P_g = \frac{V_{cav}^2}{4(\frac{R}{Q})\cdot Q_L}\left\{(1+\frac{(\frac{R}{Q})\cdot Q_L I_{b0}}{V_{cav}}\cos\phi_b)^2 + (\tan\psi + \frac{(\frac{R}{Q})\cdot Q_L \cdot I_{b0}}{V_{cav}}\sin\phi_b)^2\right\}$$

TTF-3 Coupler

$$\tan\psi = -2Q_L\frac{\omega-\omega_0}{\omega_0} = -2Q_L\frac{\Delta f}{f_0}$$

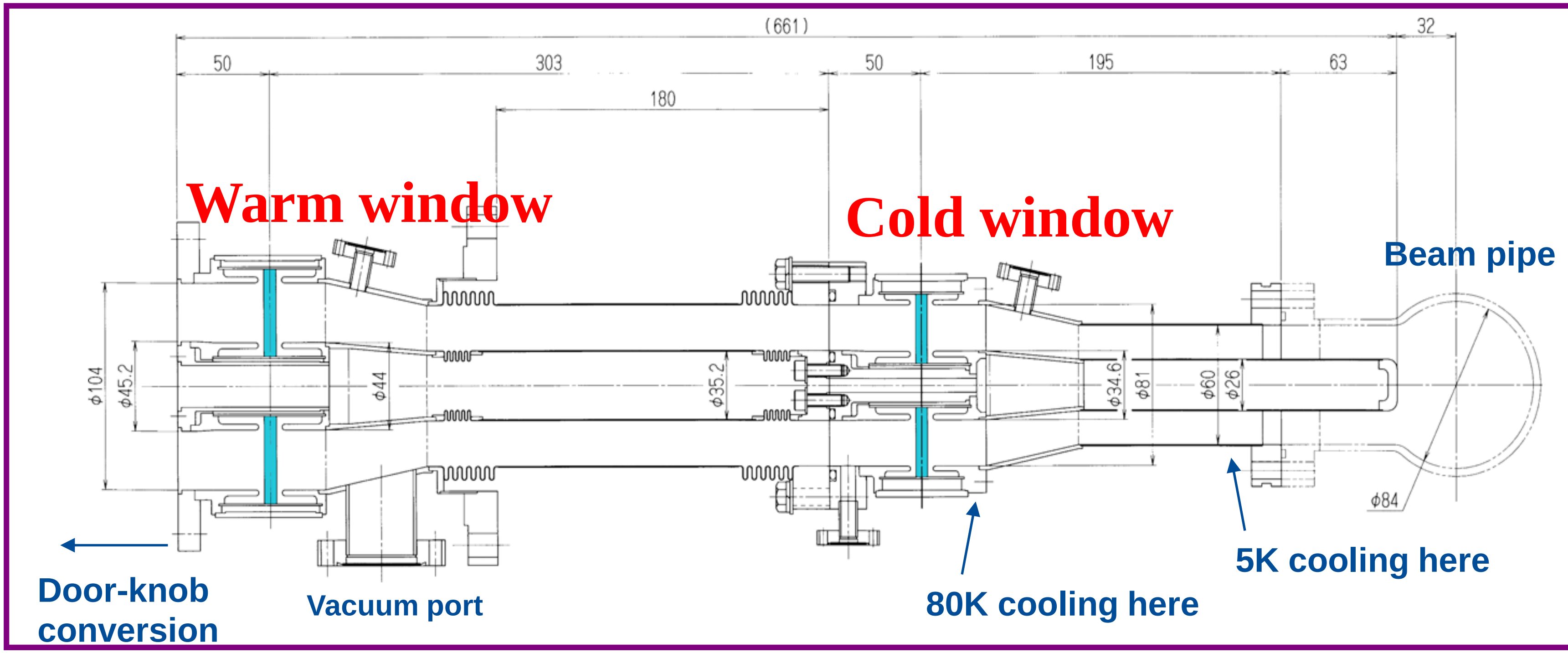


Power coupler design



Power coupler design

TRISTAN Type Coaxial Disk Ceramic



$Q_{ext} = 2.0 \times 10^6$

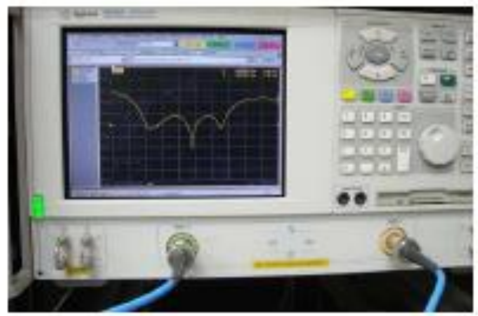
$P_{rf} = 350$ kW

	80 K	5 K	2 K
Static Loss	5 W	1.1 W	0.05 W
Dynamic Loss	3 W	0.2 W	0.03 W

Power coupler design

Cold measurement.

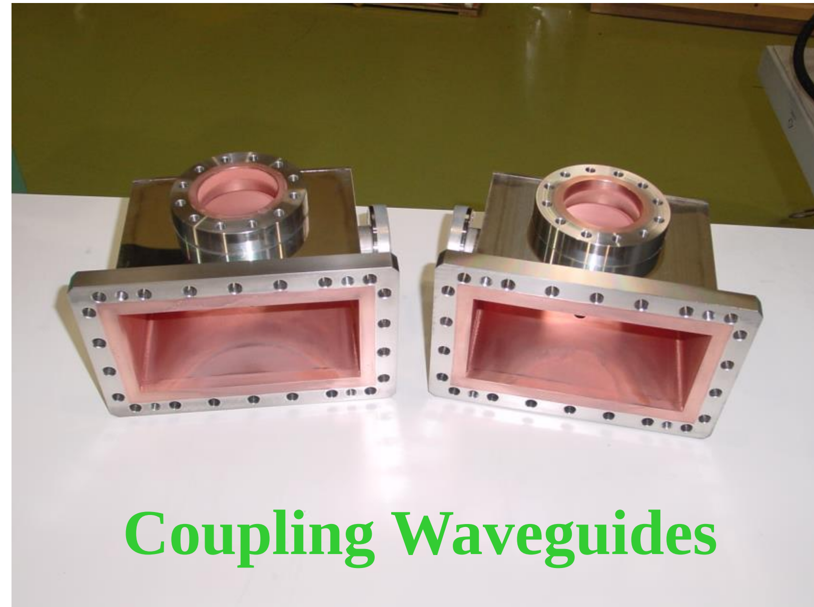
TOSHIBA did mechanical job perfectly! These rather complicated devices was built without any single preliminary RF cold measurements. But we got good SWR instantly just after assembling! It was a big relief.



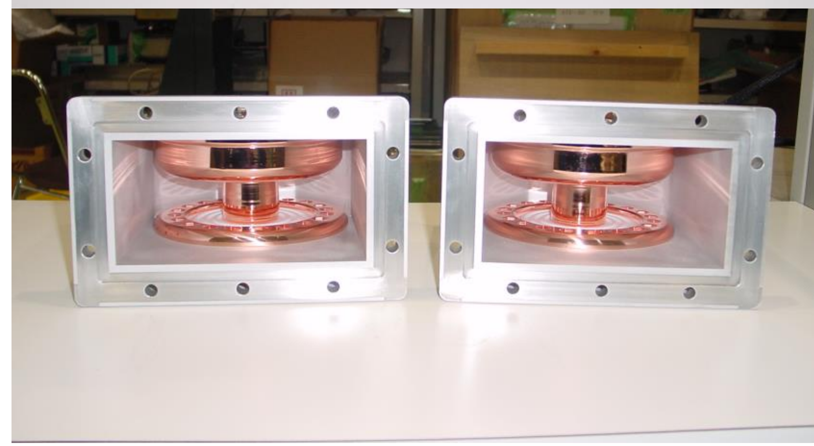
Power coupler design

Components for
High Power Test Stand

Input Couplers



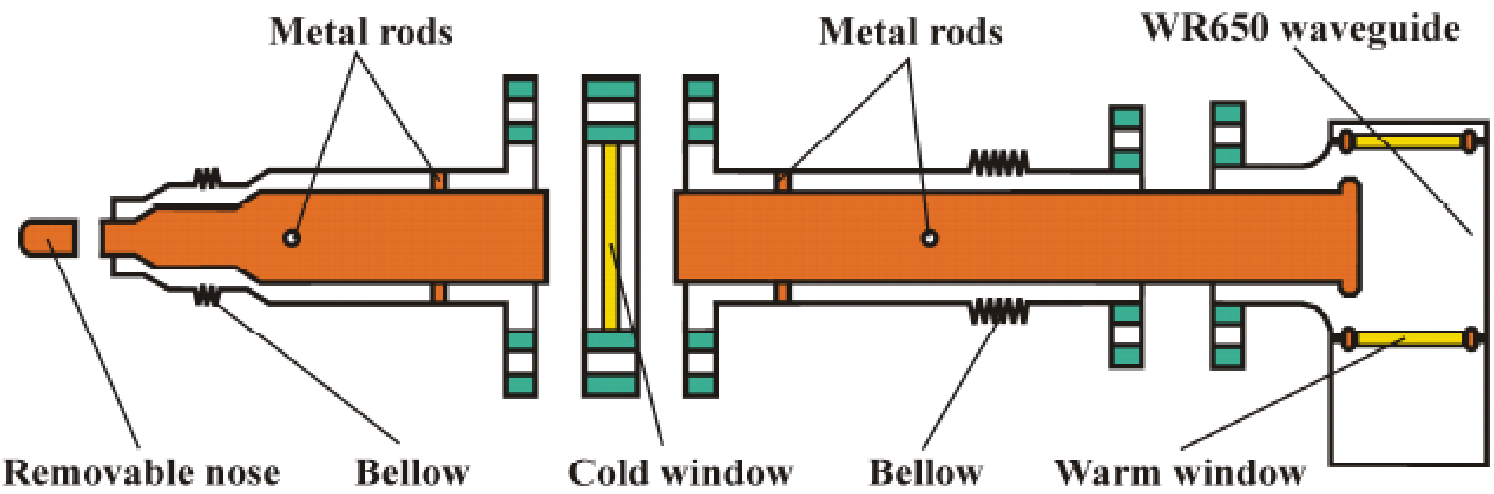
Coupling Waveguides



Doorknobs

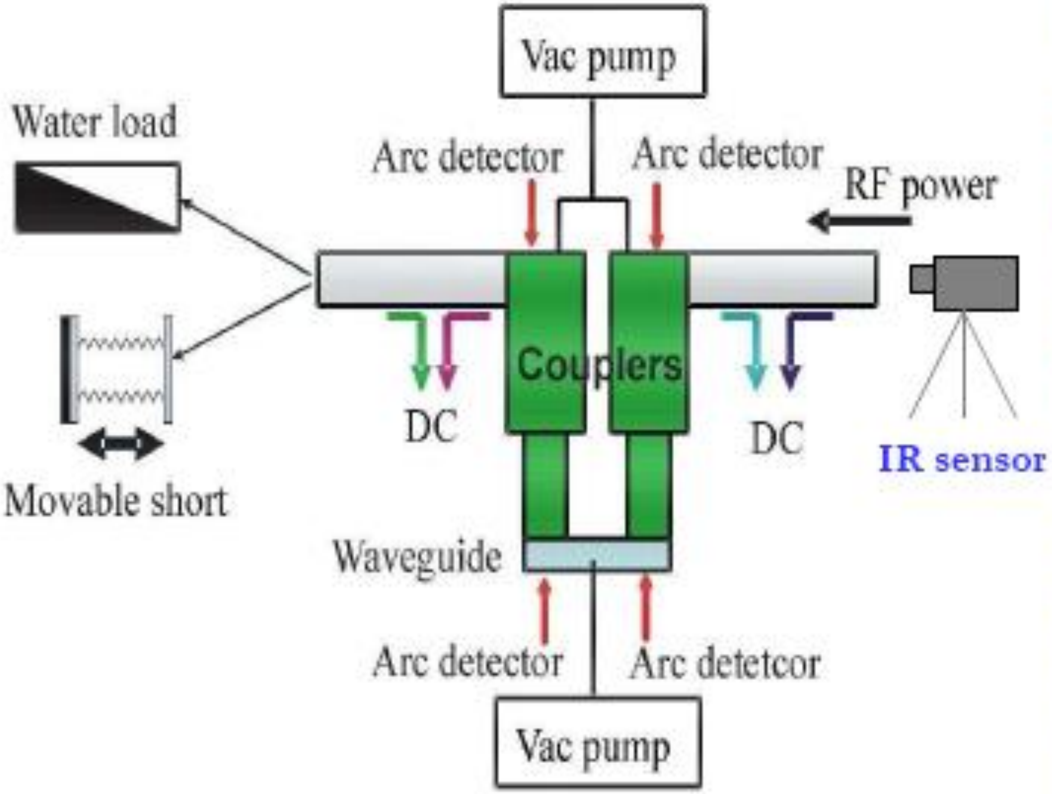
Power coupler design

Capacitive-coupling Coupler

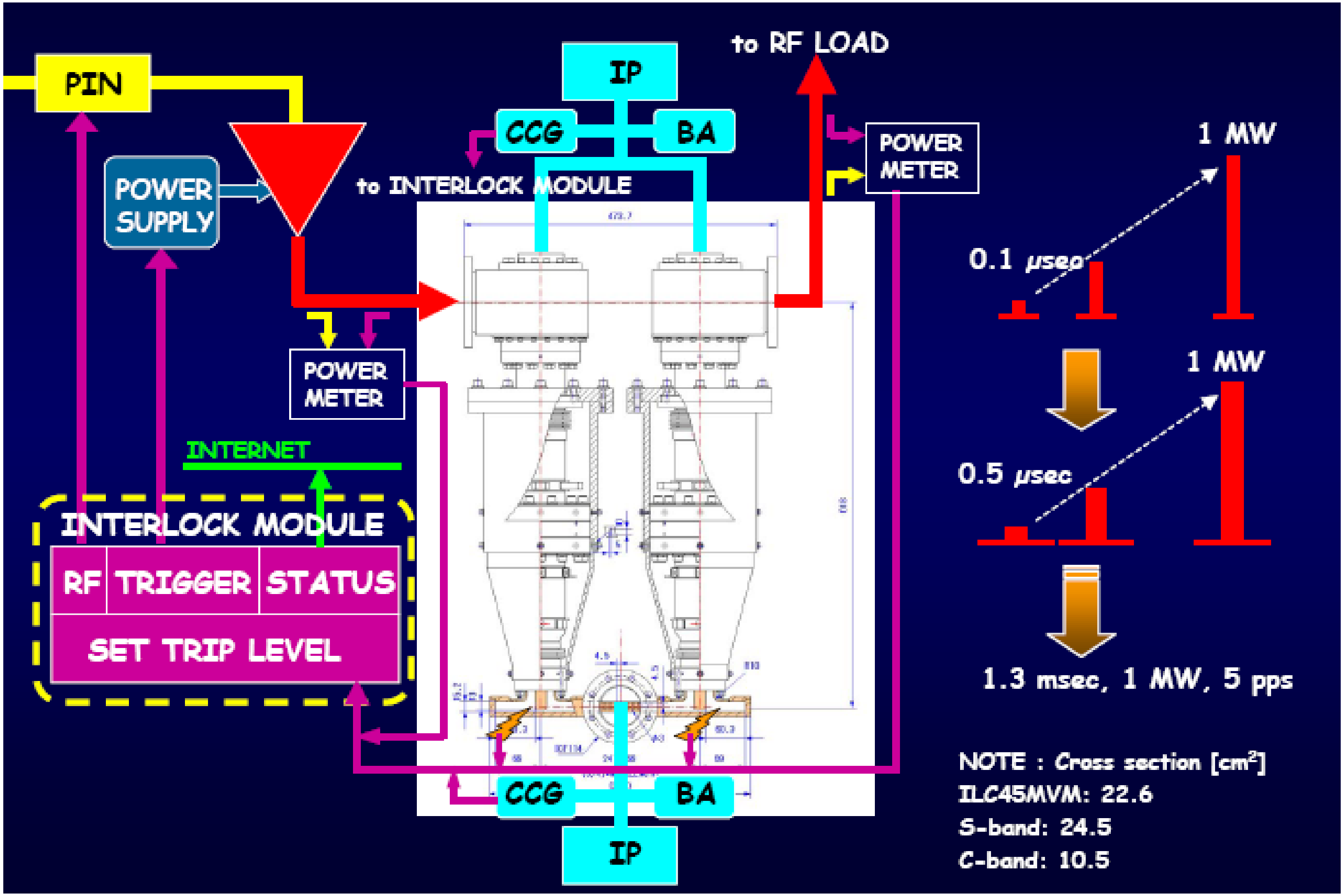


Coupler can be modified to have changeable coupling.
Two bellows allow to move middle part of coupler with antenna.

Power coupler high power tests

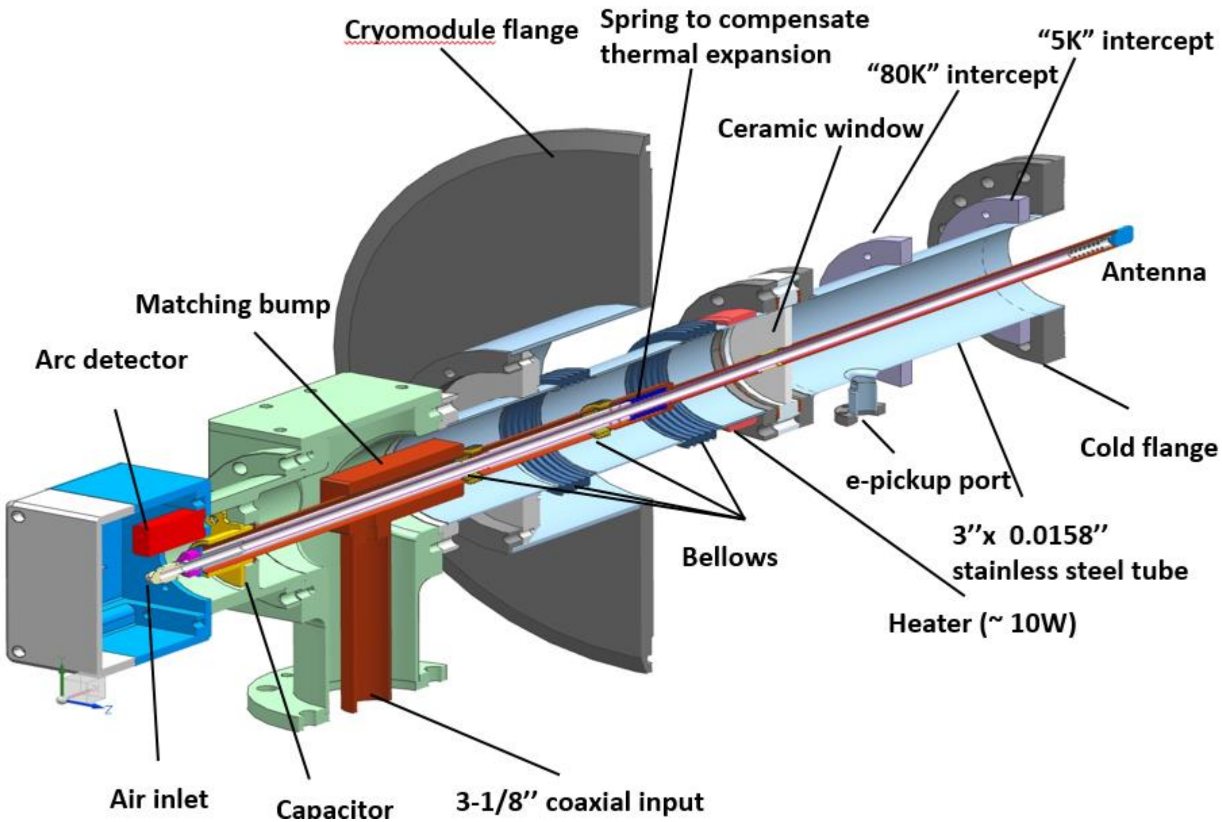


Power coupler high power tests



Fermilab

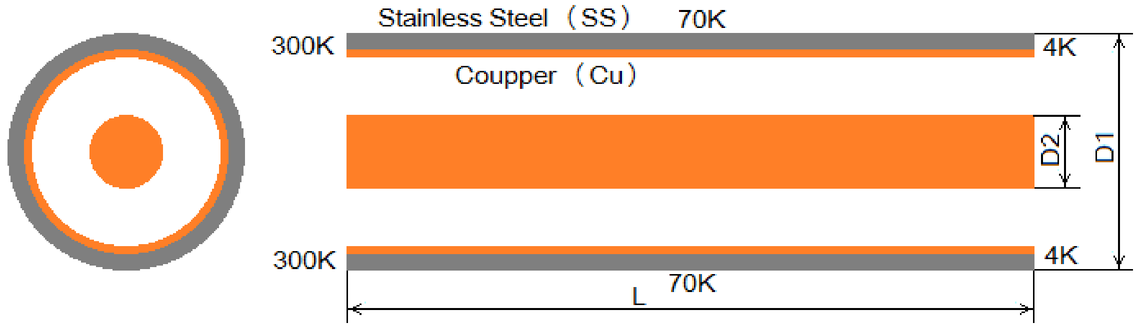
325 MHz coupler



Parameter	Value
Frequency	325 MHz
Pass band (S_{11}<0.1)	> 1 MHz
Operating power (CW)	25 kW
HV bias	~ 2 kV

P, kW	2K / Pl, W	15K / Pl, W	125K / Pl, W
0	0.06 / 52	0.58 / 151	2.02 / 40
3	0.10 / 86	0.81 / 211	2.35 / 47
6	0.15 / 129	1.03 / 268	2.68 / 54
20	0.35 / 301	2.07 / 538	4.25 / 85
30	0.50 / 430	2.82 / 733	5.36 / 107

Homework



Coaxial power coupler

1. Given:
   1. External conductor with outer diameter D1, SS wall thickness d1, Cu coating thickness d2
   2. Length L, internal conductor diameter D2
   3. RF power P in TW regime.
   4. One end temperature 300K other end 4K. 70K heat sink in the middle
   5. Thermal conductivity p1 for SS and p2 for copper not depend on temperature.
   6. Electrical surface resistance SS Rs1 for and Cu Rs2
   7. Thermal radiation is negligible. Attenuation of RF power is negligible
   8. Efficiency of 70 K cooler is 5%, efficiency of 4K cooler is 0.5%

2. Assumptions:
   1. Thermal radiation is negligible. Vacuum.
   2. Attenuation of RF power is negligible.

$$P_t = \frac{\partial Q}{\partial t} = p \oiint_S \nabla T \cdot dS = p \cdot \Delta T / L \cdot S$$

1. Questions:
   1. What heat power flow at 70K and 4K intercepts at P=0 W?
   2. What is power consumption at cryoplant at P=0 W?