

Computational Needs for the Design of Superconducting Cavities

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- Overlook of SC linac applications
- Specific problems of SC linac design
- SRF cavities overview
- SRF cavity EM design
- Incoherent losses & wakes
- Multipactor & Dark current
- HOM problems
- Beam loading & microphonics
- SRF cavity multiphysics simulations
- Conclusions

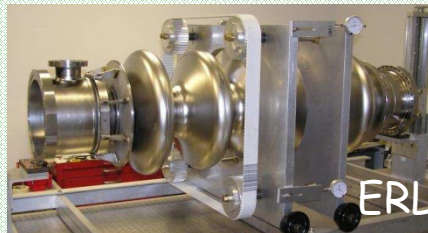
SRF Cavities Applications

- The SRF cavities are widely used for various applications requiring an acceleration of charged particles:

High Energy Physics

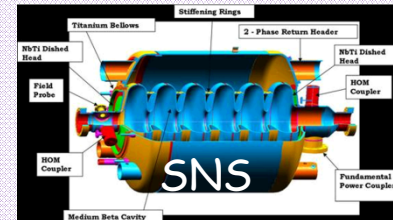
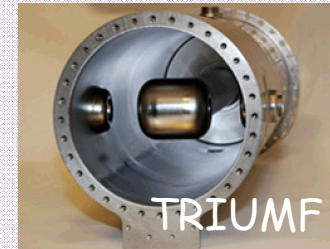
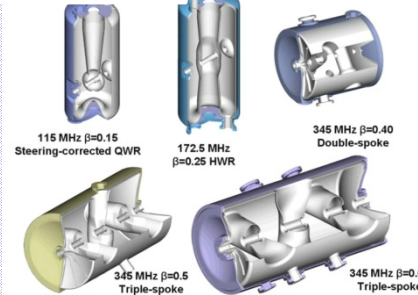


SR Sources

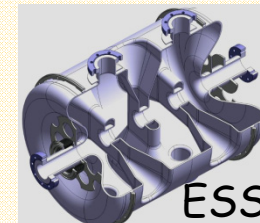
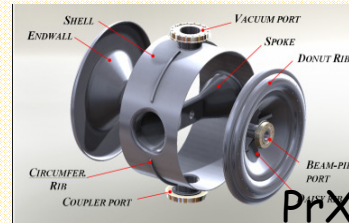


Nuclear Physics

ATLAS



UPCOMING: ADS, ESS, FRIB, ILC, NGLS, Project X, ...



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)

- The following aspects need to be taken into account:

Acceleration efficiency

- cavity R/Q versus beta
- surface field enhancement factors (electric & magnetic)

High Gradient pulsed operation

- Lorentz force detuning

Operation with small beam current

- narrow cavity bandwidth & microphonics
- mechanical stability

High Order Modes (HOMs) dumping

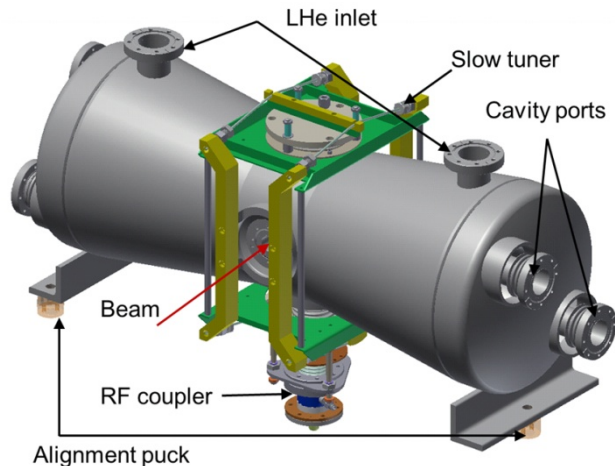
- incoherent effect (loss factors, cryogenic losses)
- coherent effects (emittance dilution, cryo-losses)
- collective effects (transverse & longitudinal beam instabilities)

Field Emission

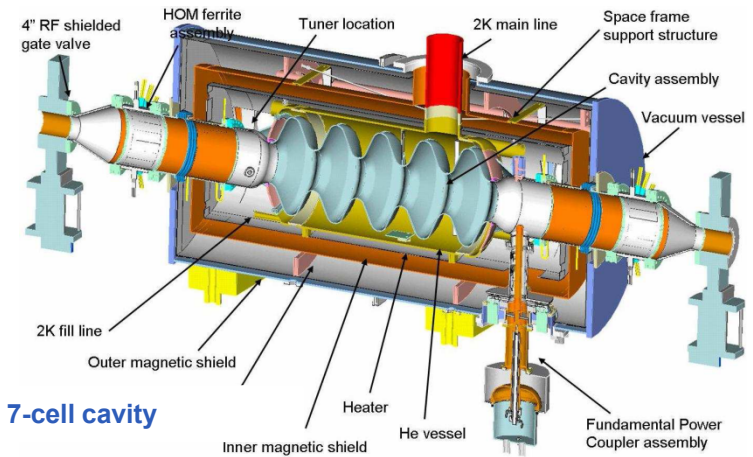
- multipactor
- dark current

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

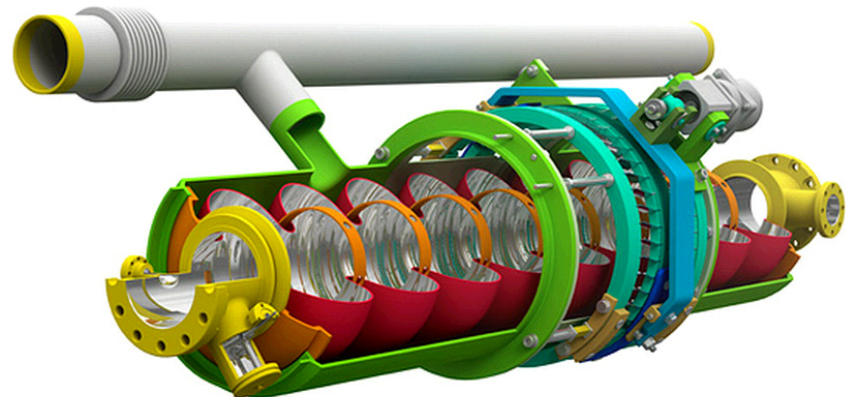
- bare cavity shell with power and HOM couplers
- stiffening elements (ring, bars)
- welded LHe vessel
- Slow and fast frequency tuners
- vacuum ports



HWR 162.5 MHz cavity for Project X



ERL 704 MHz 7-cell cavity



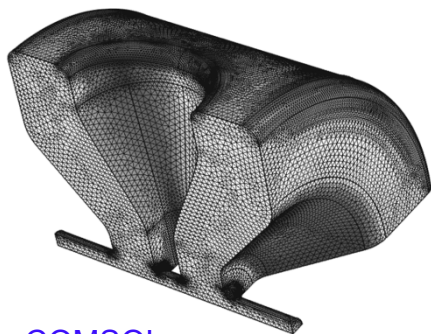
ILC 1.3 GHz 9-cell cavity

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 !

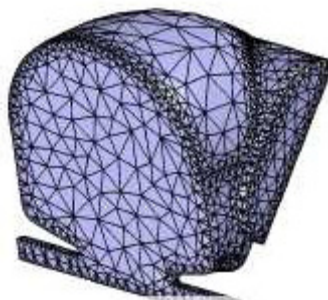
SRF cavity EM design

The SRF cavity EM design requires precise surface electromagnetic fields computation in order to optimize the cavity shape and achieve a maximum accelerating gradient.

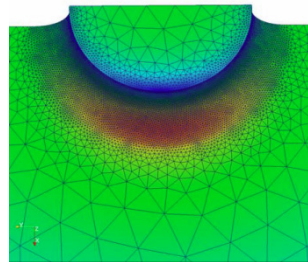
Mesh examples of modern EM codes



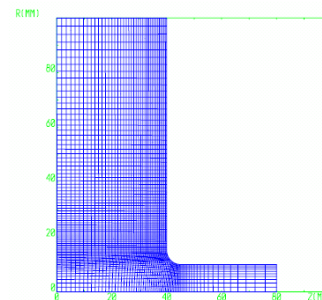
COMSOL



CST

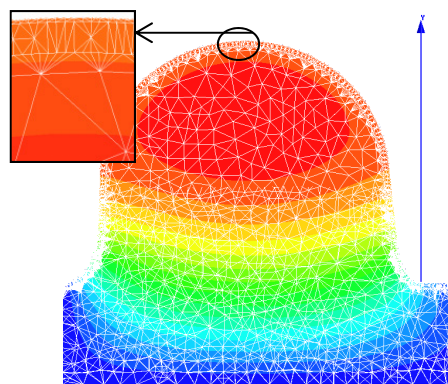
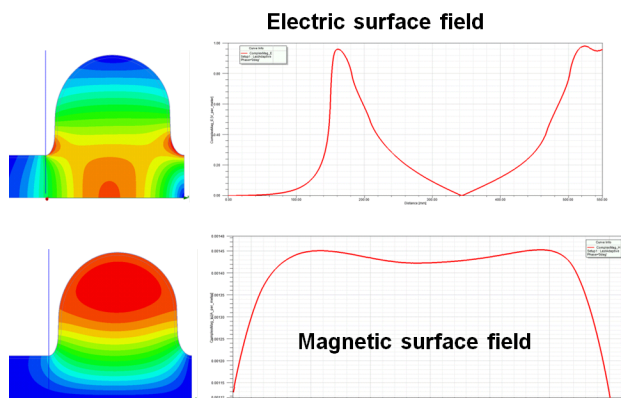


OMEGA3P



SLANS (2D)

HFSS artificial surface mesh

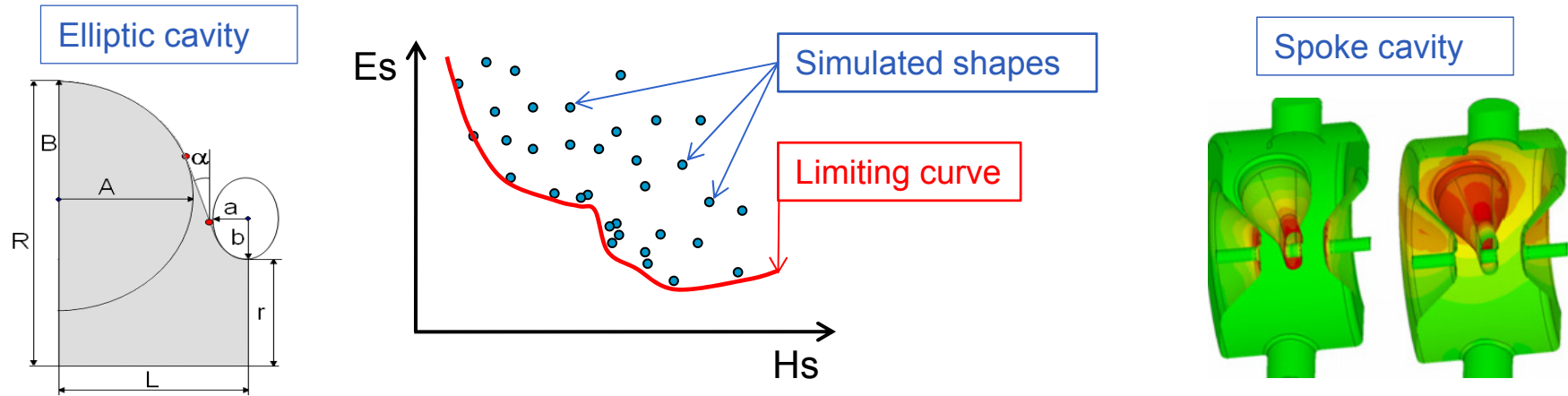


Important factors:

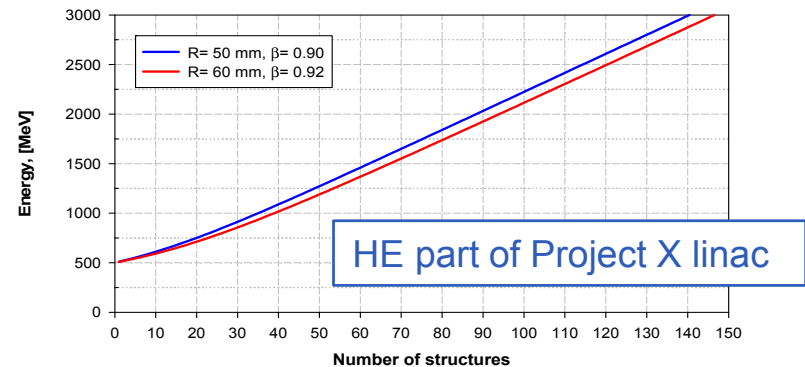
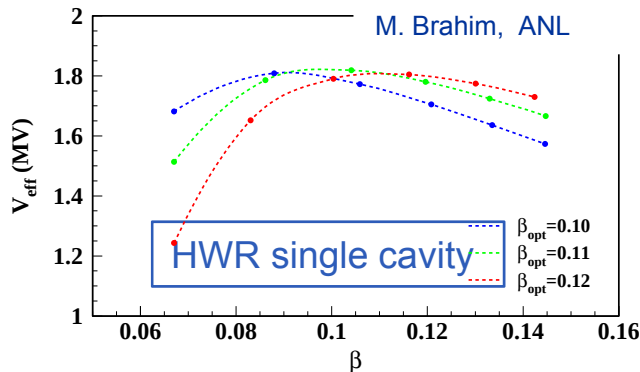
- quality of surface mesh
- type of mesh (hex-, tetra-)
- curved surface elements
- space domain (2D, 3D)

The desirable accuracy of surface electromagnetic fields is $< 1\%$!

1. Cavity shape optimization to minimize both surface E_s and H_s fields and maximize R/Q.



2. Beta optimization (optimal beta for linac sections to minimize total cost of the linac).



3. The further choice is a trade-offs between the requirements on cavity mechanical stability and surface processing.

Software for eigenmode EM simulation.

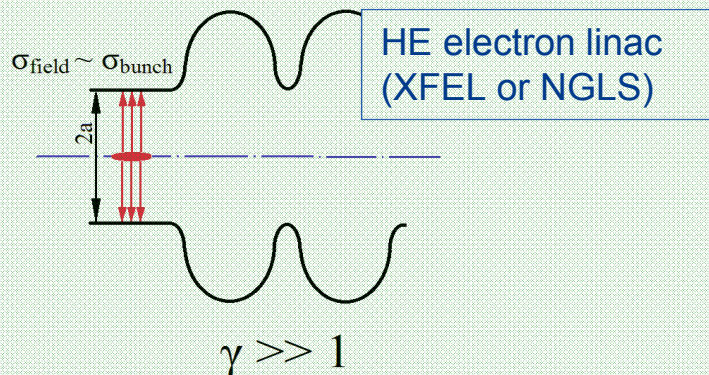
	OMEGA3P	COMSOL*	CST*		SLANS	HFSS*
Domain	3D	2D, 3D	3D		2D	3D
Curved elements	√	√	-	√	√	√
Mesh type	Tetra	Tetra	Hex	Tetra	Quad	Tetra
Complex solver	√	√	√	-	-	√
Parallel computing	√	√	-	√	-	√
H-field enhancement**	?	?	-		√	-

* commercial software

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

Incoherent Losses & Wakes Simulation

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



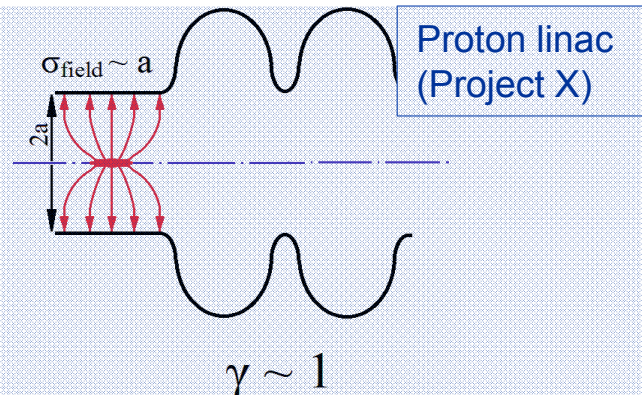
- $f_{\text{max}} \sim c/\sigma_{\text{bunch}}$
- for $\sigma_{\text{bunch}} = 50\mu$, $f_{\text{max}} < 6$ THz

Loss factor depends strongly on the σ_{field} !



Solve in TD

- computing wakefields and wake potentials



- $f_{\text{max}} \sim c/a$
- for $a = 50\text{mm}$, $f_{\text{max}} < 6$ GHz



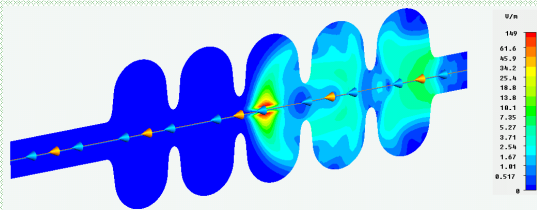
Solve in FD

- loss factors calculation of individual cavity modes

Incoherent Losses & Wakes Simulation

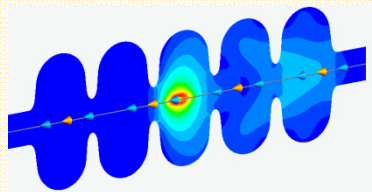
Loss Factor Calculation Challenges (high- β structure for Project X)

Time Domain



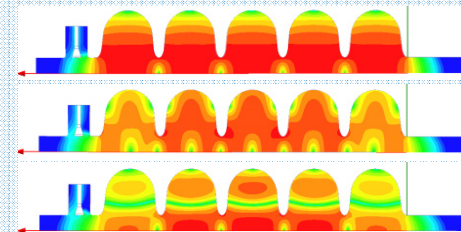
Ultra-relativistic beam ($\beta=1$)

Time Domain



Highly-relativistic beam ($\beta>0.9$)

Frequency Domain

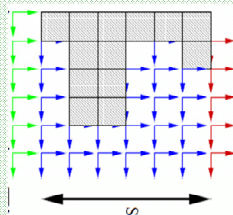


Weakly-relativistic beam ($\beta<0.9$)

Short bunches ($\sigma_z < 1\text{mm}$)

- required memory $\sim (a/\sigma_z)^3$
- computation time $\sim (a/\sigma_z)^4$

Solution: moving mesh



W. Bruns, GdfidL

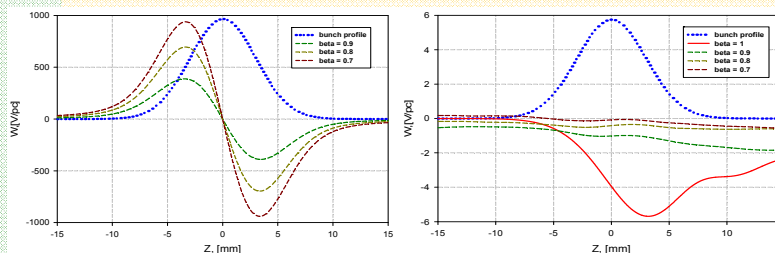
- long catch up distance $\sim a^2/2\sigma_z$

Solution: Indirect methods

Static Coulomb forces

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

Solution: Two simulations to exclude E_s



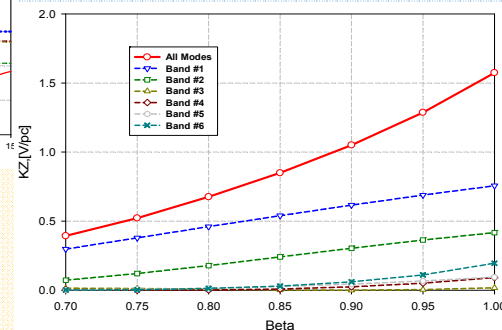
- Direct solver require large mesh size

Solution: parallel computation

HOM modes

- HOM spectrum above beam pipe cut-off freq.

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



Tools for a short range wakefield simulation.

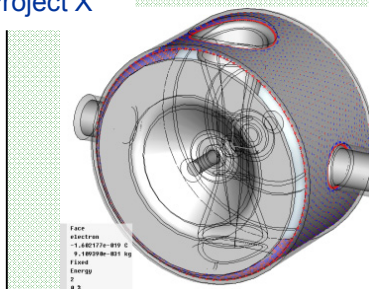
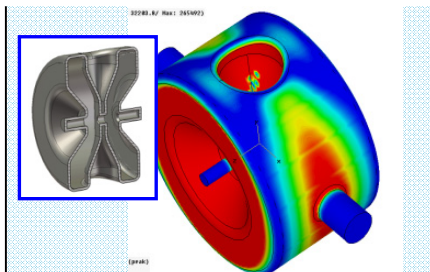
	ABCI	ACE3P	CST*	GdfidL*	ECHO
Domain	2.5D	3D	3D	3D	2D, 3D
Indirect methods	√	√	√	√	√
Moving mesh	√	√	-	√	√
Beta <1	-	-	√	-	-
Parallel computing	√	√	√	√	√

* Commercial software

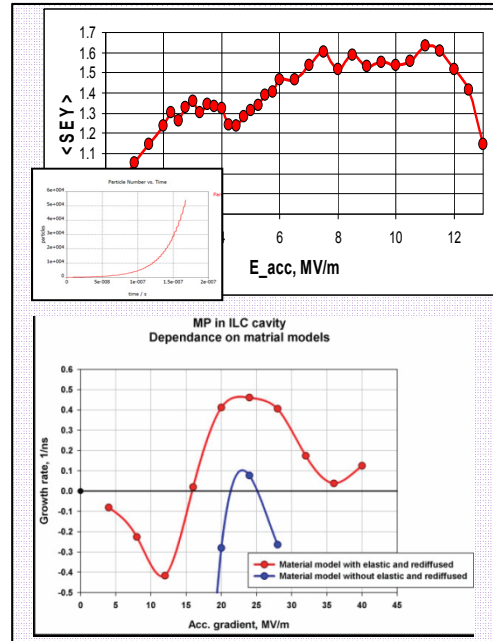
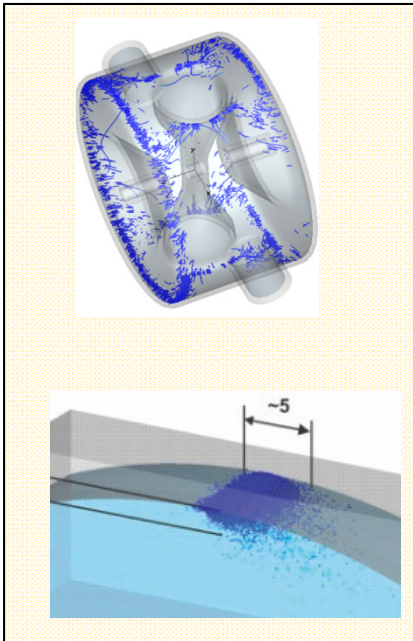
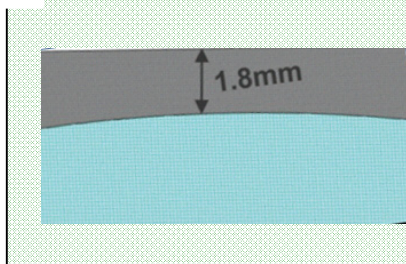
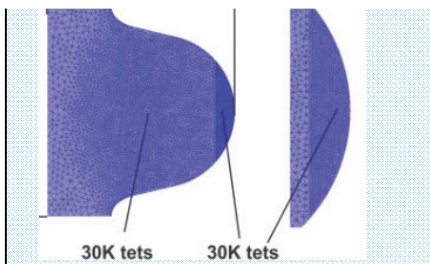
Multipactor & Dark Current Simulations (CST)

Secondary electron emission RF discharge or multipactor (MP) might be a serious obstacle for normal operation of SC cavities and couplers

G. Romanov, FNAL, SSR1 cavity for Project X



S. Kazakov, FNAL, ILC 9-cell cavity



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
- vs.
- Counter Function (CF) method

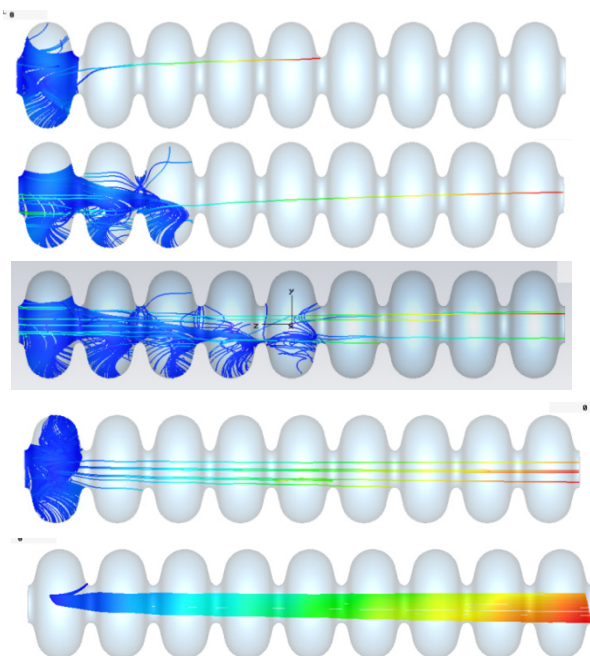
- Advanced statistics on particles
 - numbers
 - collisions
 - sec. emissions
 - dissipations
 - trajectories

High gradient SC cavity may produce electrons emitted from the surface, captured and accelerated along the linac.

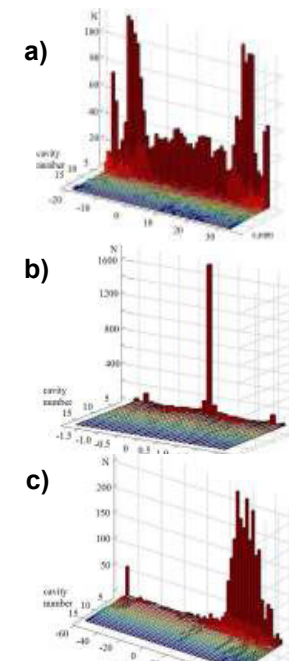
Effect of dark current

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

Particles trajectories depending on RF phase



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



N. Solyak et al., FNAL

Challenges of dark current simulations:

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

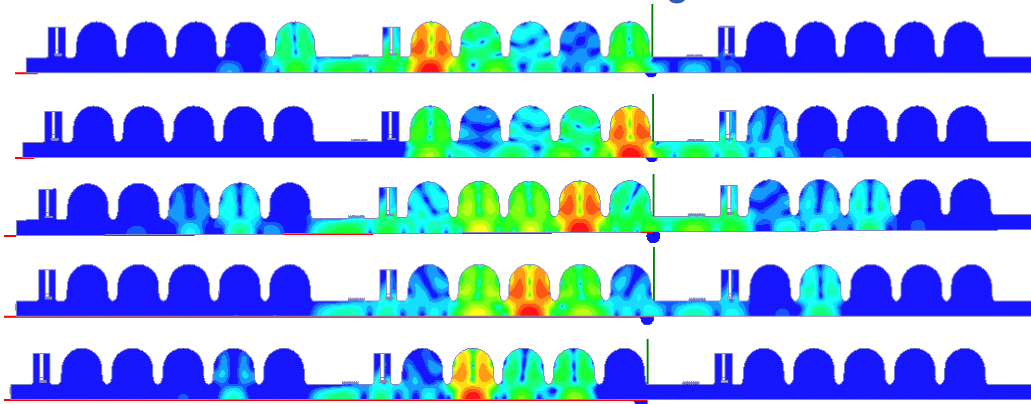
Multipactor & Dark Current Simulations

Software for a multipactor & dark current simulation.

	ACE3P	Analyst*	CST*	COMSOL*	MultiPack
Domain	3D	3D	3D	3D	2D
Emission model	DC Fowler-Nord.	DC	DC Fowler-Nord. Explosive	DC	DC
Secondary emission	True	True	Furman-Pivi (True & Elastic & Rediffused)	True	True
Multipactor model	Impact function	Counter function	Stochastic multi-particles	-	Counter function
Parallel computing	√	√	√	-	√
Space charge	√	-	√	√	-
Visualization	3D traject., space filtering	3D traject.	3D traject., space&time filtering	3D traject, space filtering	2D

* Commercial software

- Because of the fabricating tolerances and further surface processing the actual cavity shape never matches with the theoretical shape.
- There are a natural spreads of the HOMs parameters (freq., R/Q-s and Q_{ext}) from cavity to cavity. We can reproduce it in the simulations using the following procedure:
 - Apply tolerances to the cell dimensions.
 - Calculating the frequency derivation (for operating mode) of each geometrical dimension for the regular and end cells.
 - Tune the individual cell frequency by changing its period (exactly how the tuning machine is working !) at the stage of the full structure geometry creation.
 - Simulate the derived 5-cell structure (check the operating mode flatness !). Repeat the simulation 30-50 times to get the statistics.

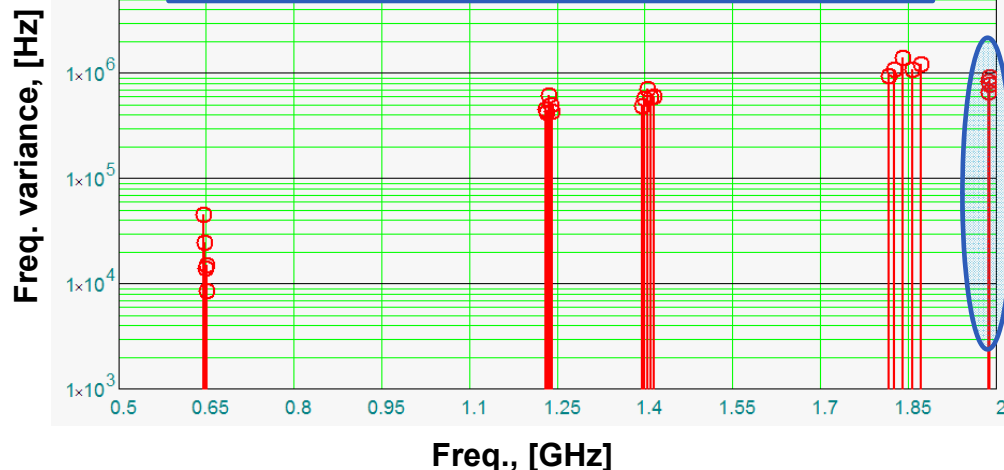


- There are trapped HOM exist in the cavity spectrum above the cut-off frequency on a beam pipe !
- For the accurate result one has to simulate the chain of at least 3 randomly generated structures with mechanical tolerances and take into account the stainless steel bellows between the structures.

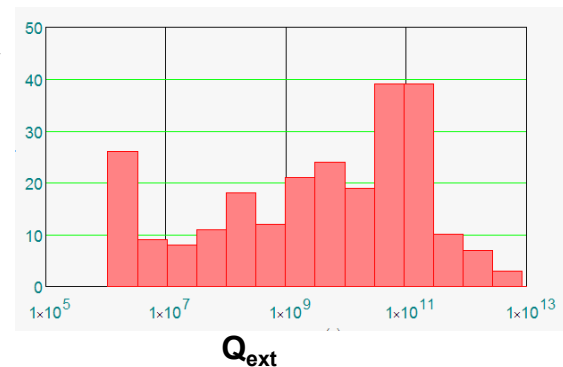
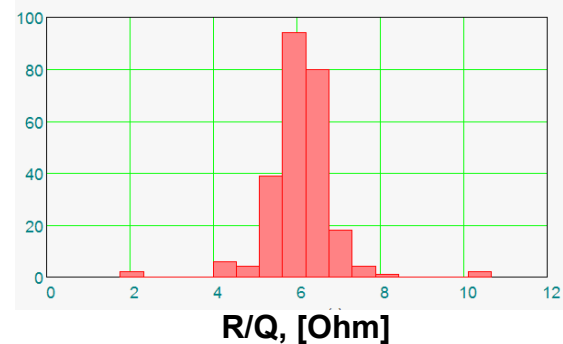
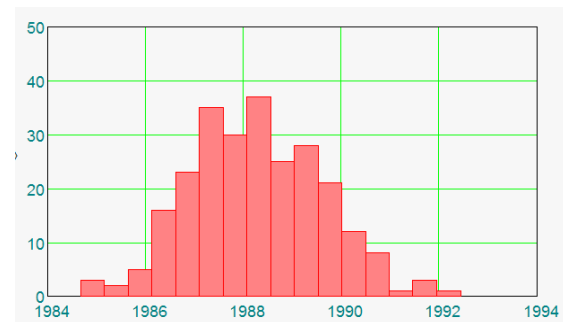
Map of the electric fields in the chain of 3 structures connected with bellows

HOMs Properties Statistical Analysis

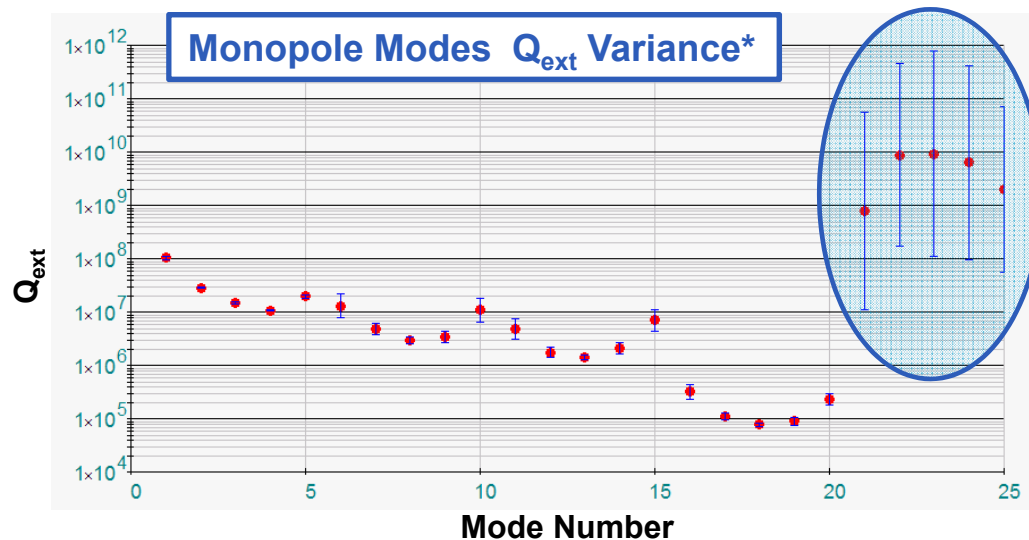
Monopole Modes Frequencies Variance*



5th Monopole Passband Histograms*



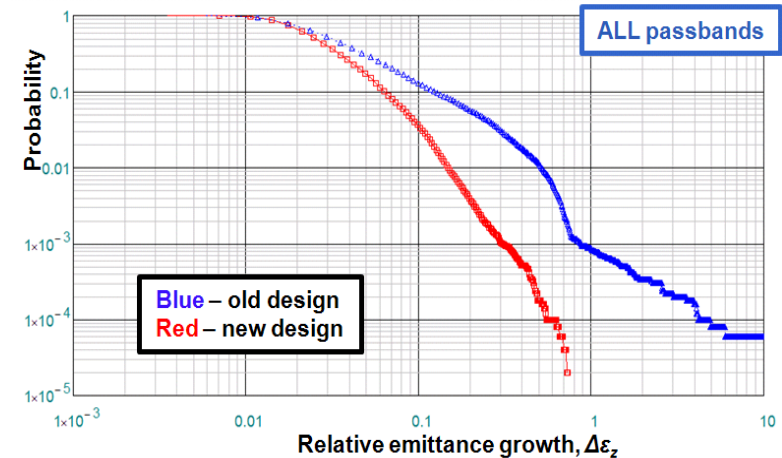
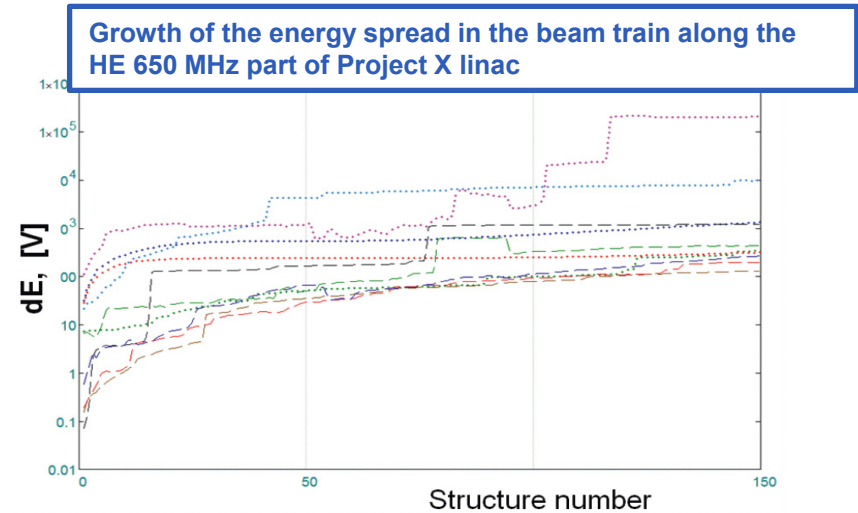
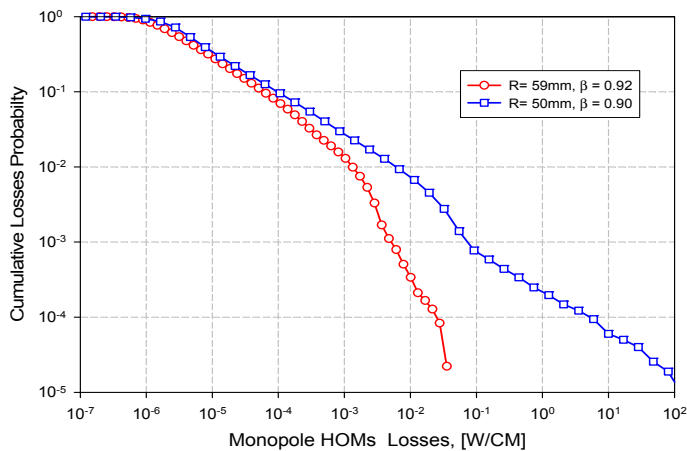
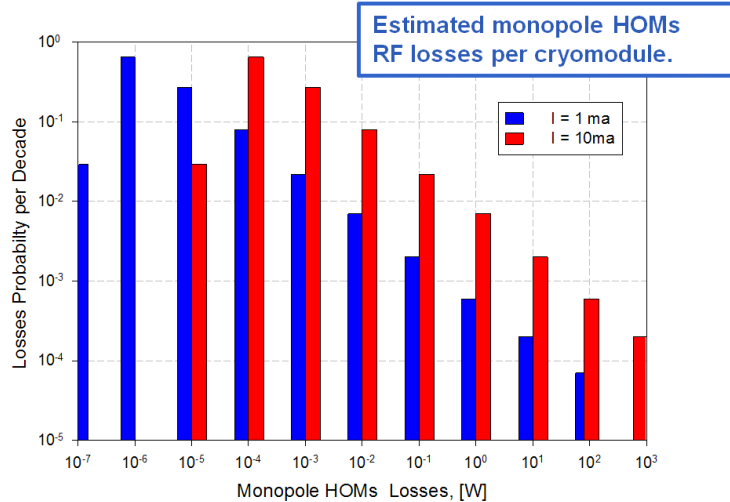
Monopole Modes Q_{ext} Variance*



* 650 MHz, beta= 0.90 Project X structure with ± 0.2 mm tolerance applied

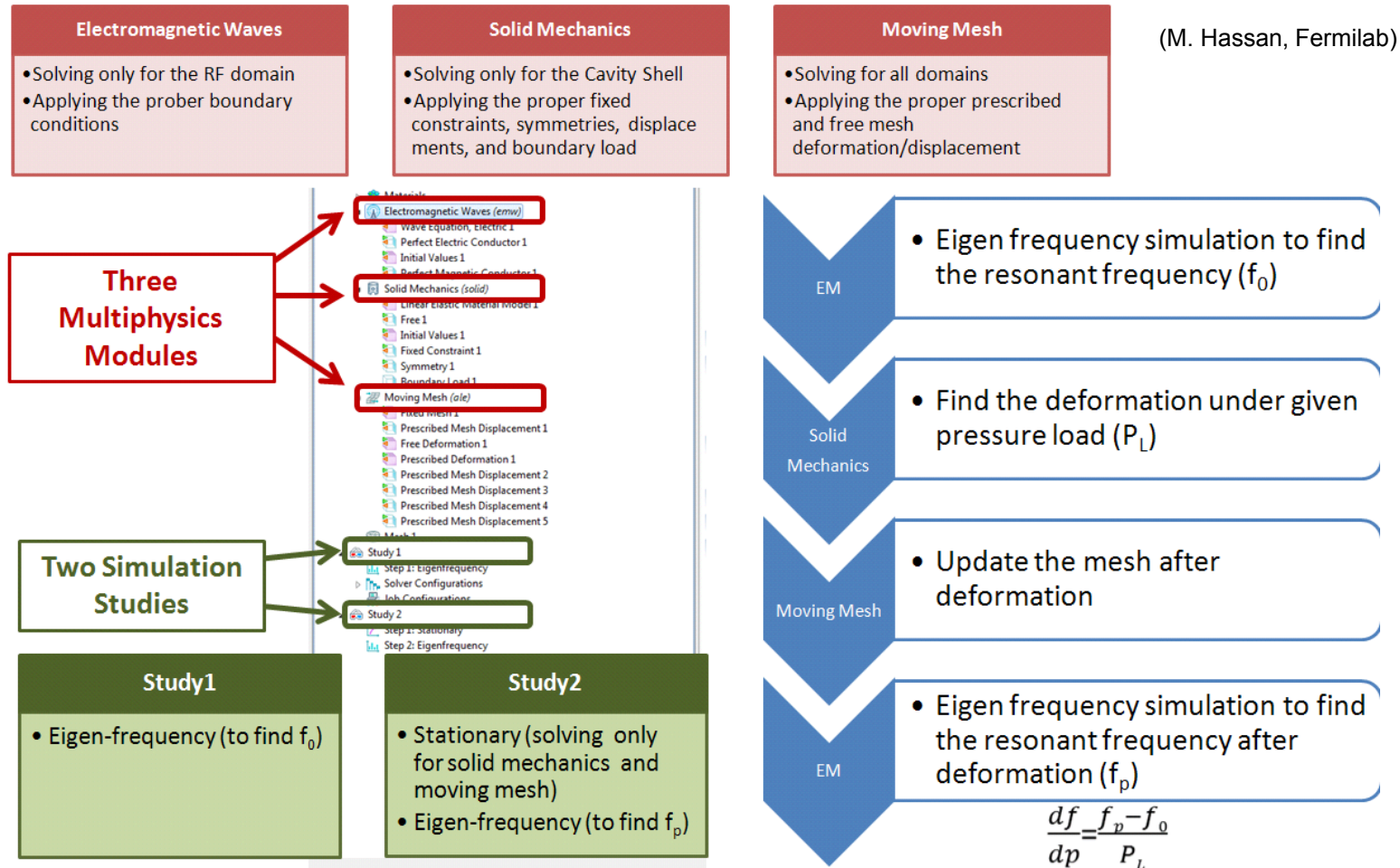
HOMs Properties Statistical Analysis

Based on the predicted deviations of monopole HOMs frequency, Q_{ext} and R/Q , we used 10^7 random cavities in order to estimate the probability of RF losses per cryomodule and the effect of longitudinal emittance growth in Project X linac.



The results of HOMs study allow to exclude HOM couplers/dampers!

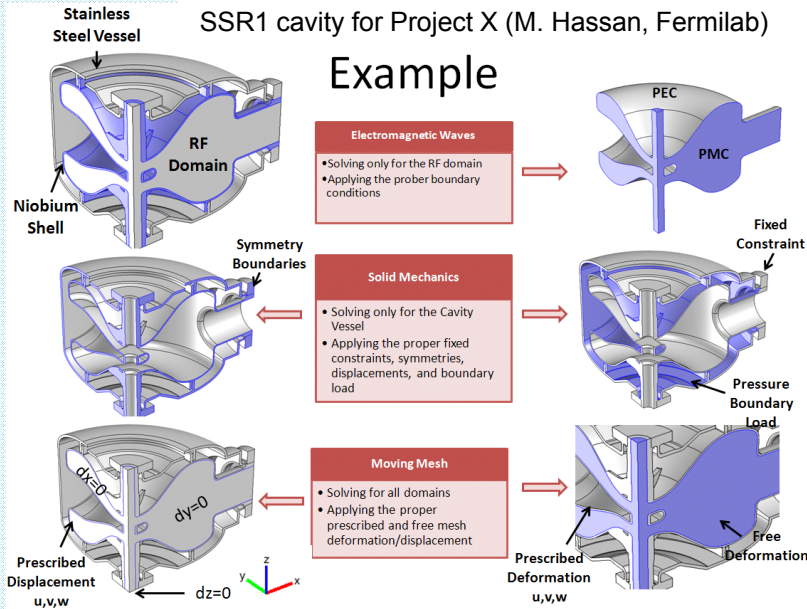
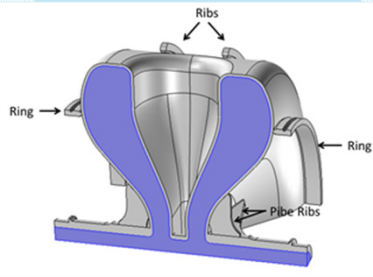
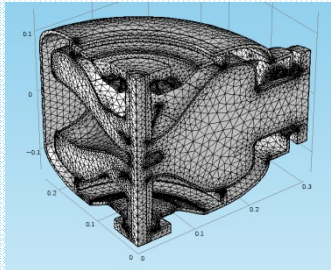
Microphonics is a cavity mechanical deformations driven by external forces such as the pressure fluctuations in a He-vessel and result unfavorable RF phase errors.



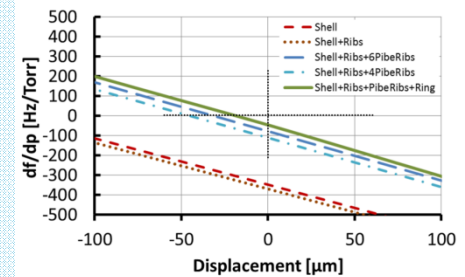
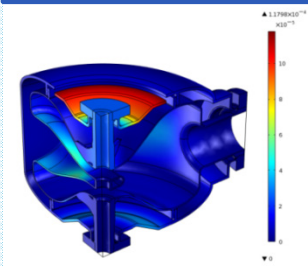
Microphonics study requires self consistent electro-mechanical simulations !

Microphonics in the SRF Cavity

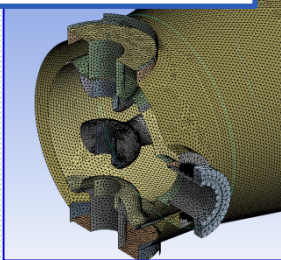
COMSOL moving mesh



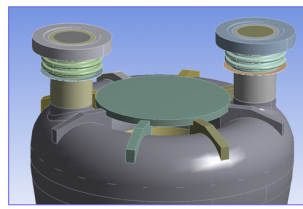
Cavity deformation & df/dp



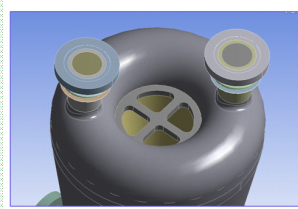
ANSYS mesh



HWR cavity for Project X, (R. Fisher, ANL)

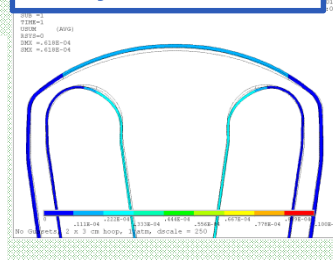


Basic Gussets

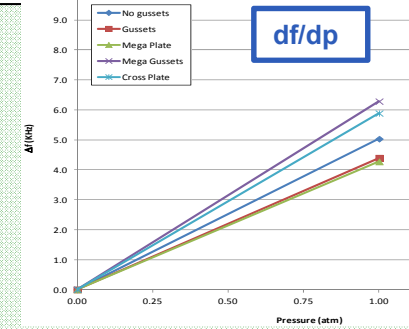


Cross Plate

Cavity deformation



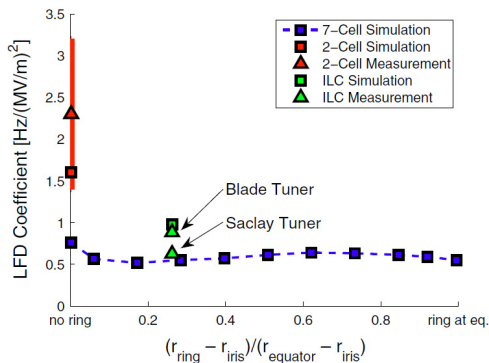
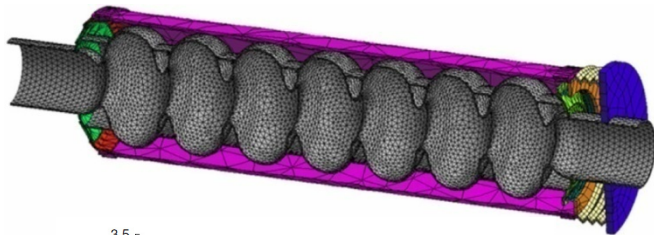
df/dp



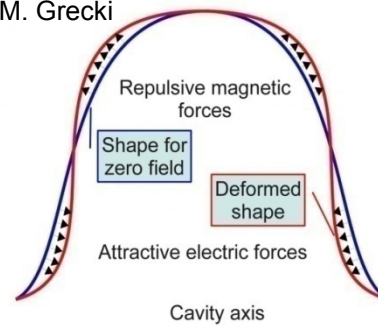
- The conception of moving mesh allows to exclude the mesh errors and achieve excellent accuracy ($\sim 1\text{Hz/Torr}$) in df/dp analysis !
- Using reinforcing and stiffening elements are very important to reduce df/dp

Lorentz Force Detuning (LFD) is the cavity mechanical deformations caused by a pressure load of the Lorentz forces from EM-fields in the cavity. It significantly distort the pulsed operation of SC cavity at high accelerating gradient.

ANSYS mesh of the ERL 7-cell cavity
(S. Posen, Cornell)



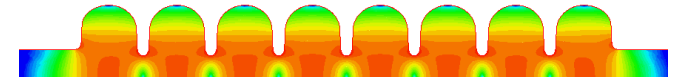
M. Grecki



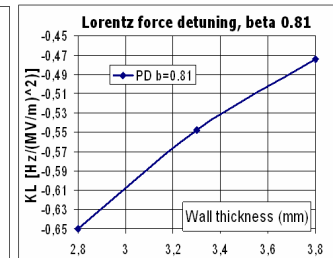
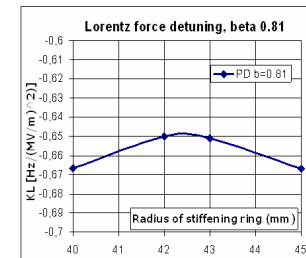
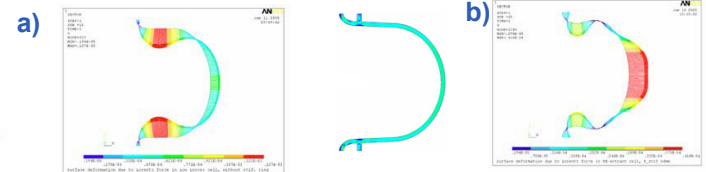
$$P_s = \frac{1}{4} (\mu |\vec{H}|^2 - \epsilon_0 |\vec{E}|^2)$$

$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K E_{acc}^2$$

SCRF b=0.81 elliptical 9-cell cavity
(I. Gonin, Fermilab)

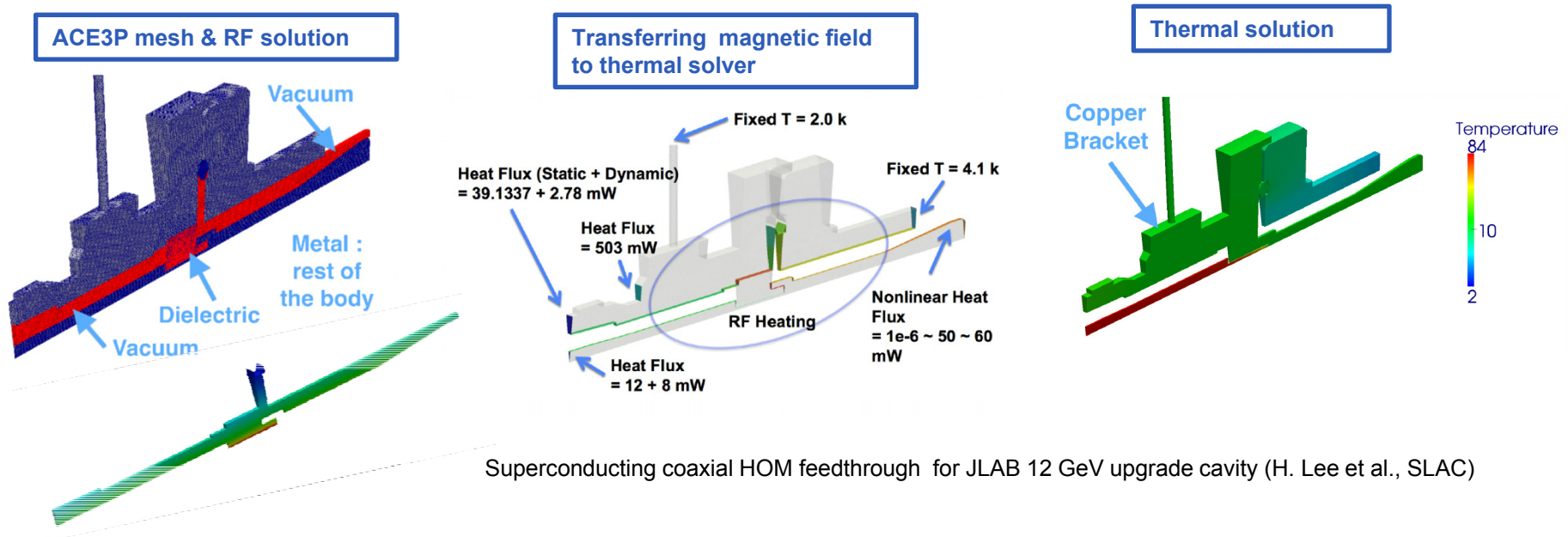


Cavity wall deformations: a) no ring, b) with ring



- The LFD analysis require transferring the solution for EM-fields to mechanical solver.
- The stiffening rings allow to compensate deformations of electric and magnetic fields and, thus, give a low LFD coefficient.
- The accurate LFD simulation require complete mechanical model including He-vessel and slow tuner

The thermal impedance of HOM coupler may cause a thermal instabilities (quench) in the superconducting cavity



- The RF-thermal analysis require transferring the solution for EM-fields to thermal solver.
- The multiphysics effects include nonlinear material properties at the superconducting temperature.
- The parallel RF & thermal solvers implementation allows to perform accurate and fast analysis

Software for a coupled multiphysics problems analysis

	ACE3P	COMSOL*	CST*	ANSYS*
Domain	3D	2D, 3D	3D	3D
Coupled RF & mechanical (df/dp)	✓	✓	✓	✓
LFD	✓	✓	-	✓
Coupled RF & Thermal	✓	✓	✓	✓
Parallel Computing	✓	✓	✓	✓
Moving Mesh	-	✓	-	-
Nonlinear effects	✓	✓	-	✓

* Commercial software

- The design of SRF cavity has to satisfy a complex relationship between the accelerator requirements, cryogenic effects and the cryomodule structure.
- Modern state of the art software for multiphysics analysis allow to simulate various problems related to the design of SRF cavity and find reliable engineering solutions.
- The study of these effects leads to specification of SC cavity and cryomodule and can significantly impact on the efficiency and reliability of the superconducting linac operation.

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