# CAVITY DESIGN

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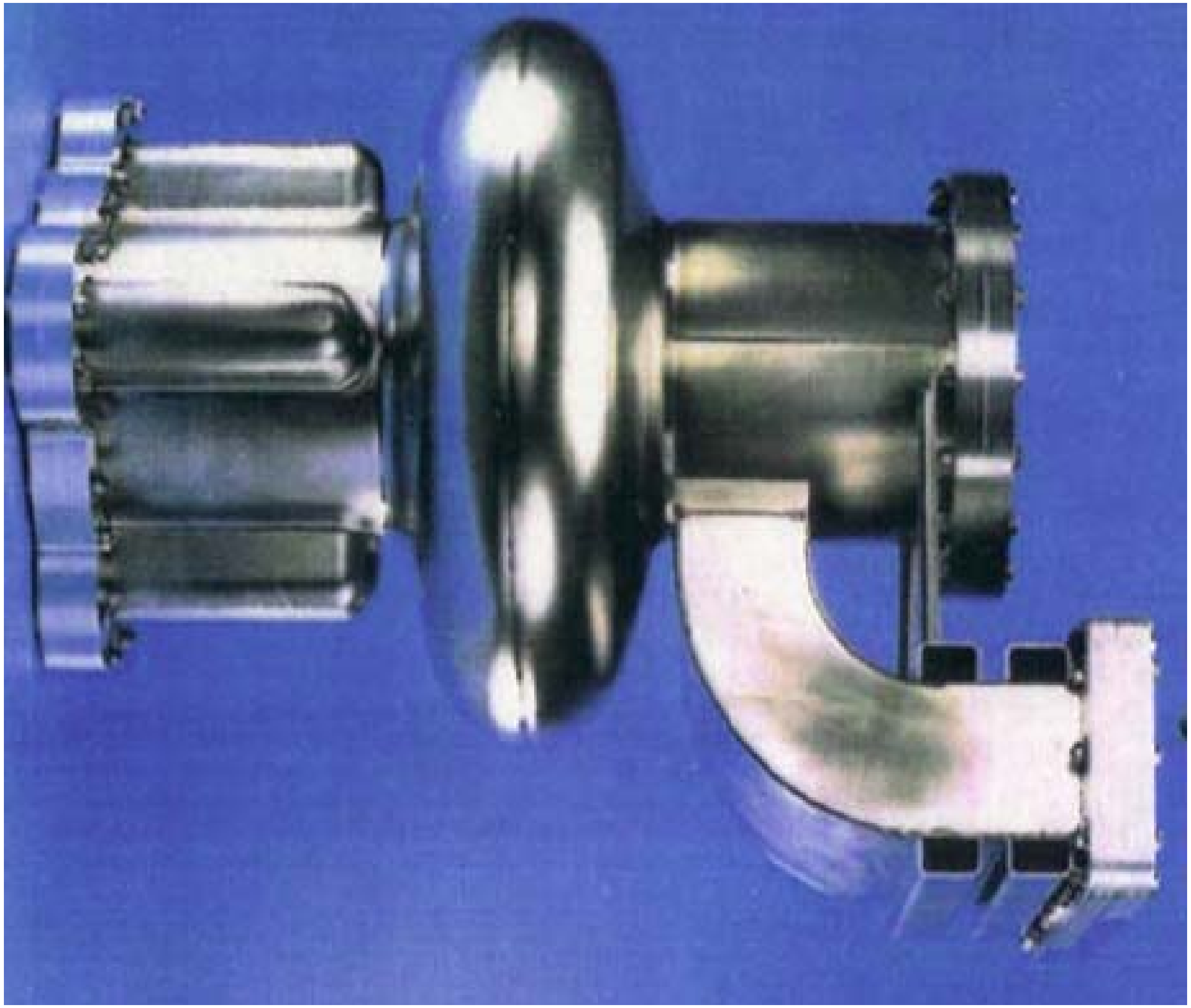
# 500 MHz, Single-cell



# 350 MHz, 4-cell, Nb on Cu

# 1500 MHz, 5-cell

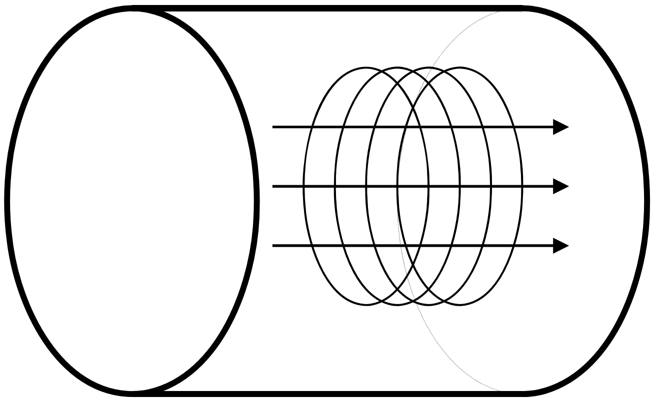
# 1300 MHz 9-cell

# Pill Box Cavity

## Hollow right cylindrical enclosure

## Operated in the $TM_{010}$ mode $\quad H_z = 0$

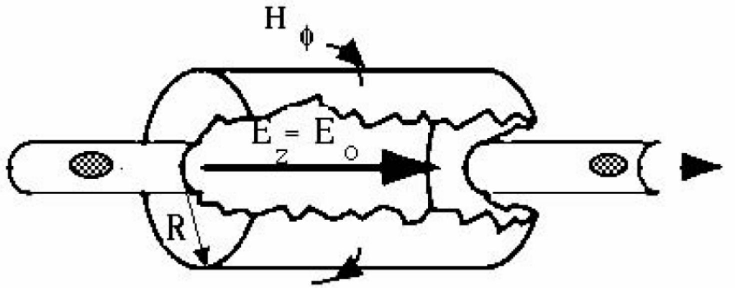
TM$_{010}$ mode



$$\frac{\partial^2 E_z}{\partial^2 r} + \frac{1}{r}\frac{\partial E_z}{\partial r} = \frac{1}{c^2}\frac{\partial^2 E_z}{\partial^2 t} \qquad \omega_0 = \frac{2.405c}{R}$$

$$E_z(r,z,t) = E_0 J_0\left(2.405\frac{r}{R}\right)e^{-i\omega_0 t}$$

$$H_\varphi(r,z,t) = -i\frac{E_0}{\mu_0 c}J_1\left(2.405\frac{r}{R}\right)e^{-i\omega_0 t}$$



# Modes in Pill Box Cavity

- $TM_{010}$
  - Electric field is purely longitudinal
  - Electric and magnetic fields have no angular dependence
  - Frequency depends only on radius, independent on length
- $TM_{0mn}$
  - Monopoles modes that can couple to the beam and exchange energy
- $TM_{1mn}$
  - Dipole modes that can deflect the beam
- TE modes
  - No longitudinal E field
  - Cannot couple to the beam

# TM Modes in a Pill Box Cavity

$$\frac{E_r}{E_0} = -\frac{n\pi}{x_{lm}}\frac{R}{L} J_l'\left(x_{lm}\frac{r}{R}\right)\sin\left(n\pi\frac{z}{L}\right)\cos l\varphi$$

$$\frac{E_\varphi}{E_0} = \frac{ln\pi}{x_{lm}^2}\frac{R^2}{rL} J_l\left(x_{lm}\frac{r}{R}\right)\sin\left(n\pi\frac{z}{L}\right)\sin l\varphi$$

$$\frac{E_z}{E_0} = J_l\left(x_{lm}\frac{r}{R}\right)\sin\left(n\pi\frac{z}{L}\right)\cos l\varphi$$

$$\omega_{lmn} = c\sqrt{\left(\frac{x_{lm}}{R}\right)^2 + \left(\frac{\pi n}{L}\right)^2}$$

$$\frac{H_r}{E_0} = -i\omega\varepsilon\frac{l}{x_{lm}^2}\frac{R^2}{r} J_l\left(x_{lm}\frac{r}{R}\right)\cos\left(n\pi\frac{z}{L}\right)\sin l\varphi$$

$x_{lm}$ is the mth root of $J_l(x)$

$$\frac{H_\varphi}{E_0} = -i\omega\varepsilon\frac{R}{x_{lm}} J_l'\left(x_{lm}\frac{r}{R}\right)\cos\left(n\pi\frac{z}{L}\right)\cos l\varphi$$

$$\frac{H_z}{E_0} = 0$$

# $TM_{010}$ Mode in a Pill Box Cavity

$$E_r = E_\varphi = 0 \qquad E_z = E_0 J_0\left(x_{01}\frac{r}{R}\right)$$

$$H_r = H_z = 0 \qquad H_\varphi = -i\omega\varepsilon E_0 \frac{R}{x_{01}} J_1\left(x_{01}\frac{r}{R}\right)$$

$$\omega = x_{01}\frac{c}{R} \qquad x_{01} = 2.405$$

$$R = \frac{x_{01}}{2\pi}\lambda = 0.383\lambda$$

# $TM_{010}$ Mode in a Pill Box Cavity

## Energy content

$$U = \varepsilon_0 E_0^2 \frac{\pi}{2} J_1^2(x_{01}) L R^2$$

## Power dissipation

$$P = E_0^2 \frac{R_s}{\eta^2} \pi J_1^2(x_{01})(R+L)R$$

$$x_{01} = 2.40483$$

$$J_1(x_{01}) = 0.51915$$

## Geometrical factor

$$G = \eta \frac{x_{01}}{2} \frac{L}{(R+L)}$$

# TM010 Mode in a Pill Box Cavity

## Energy Gain

$$\Delta W = E_0 \frac{\lambda}{\pi} \sin \frac{\pi L}{\lambda}$$

## Gradient

$$E_{acc} = \frac{\Delta W}{\lambda / 2} = E_0 \frac{2}{\pi} \sin \frac{\pi L}{\lambda}$$

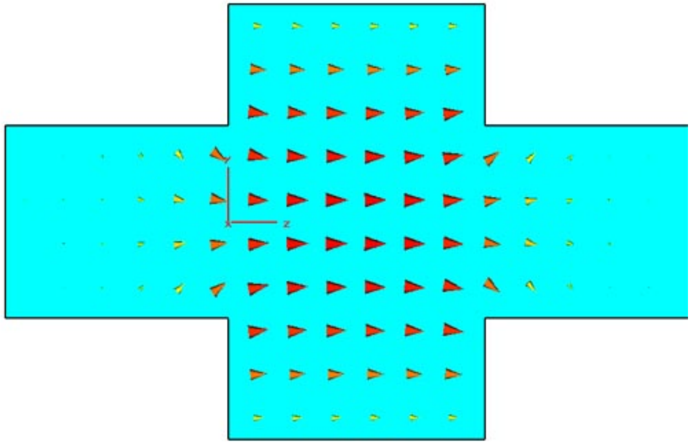
## Shunt impedance

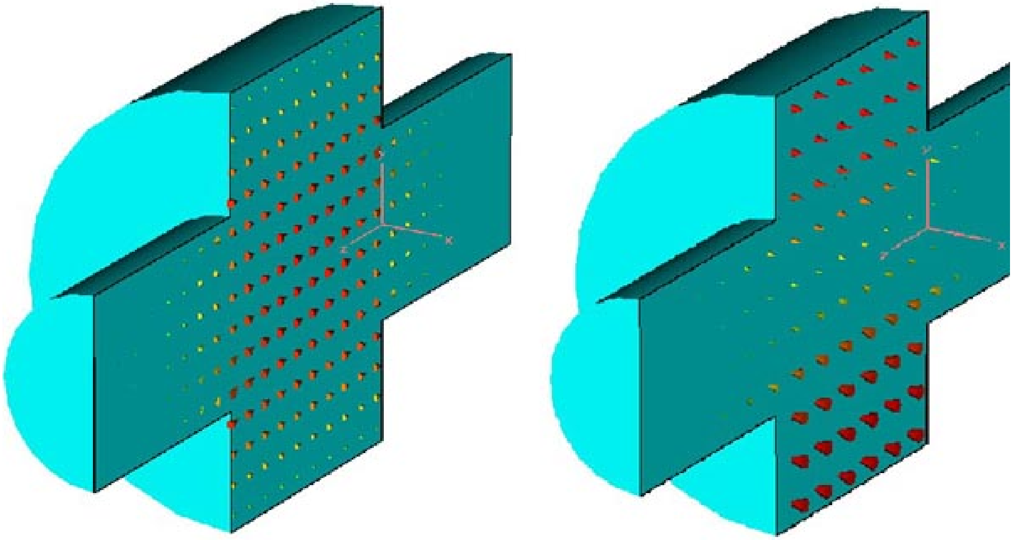
$$R_{sh} = \frac{\eta^2}{R_s} \frac{1}{\pi^3 J_1^2(x_{01})} \frac{\lambda^2}{R(R+L)} \sin^2 \left( \frac{\pi L}{\lambda} \right)$$

# Real Cavities

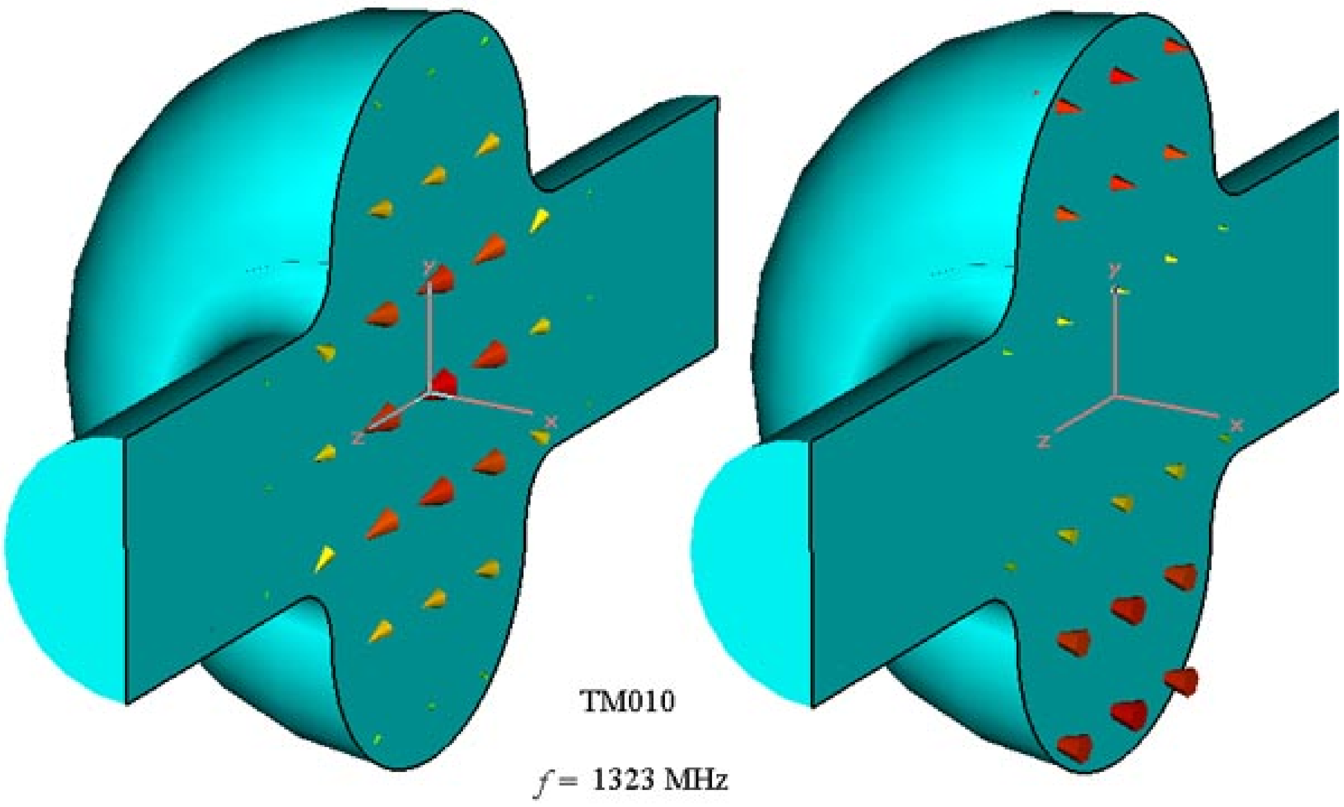
**Beam tubes reduce the electric field on axis**

- **Gradient decreases**
- **Peak fields increase**
- **R/Q decreases**

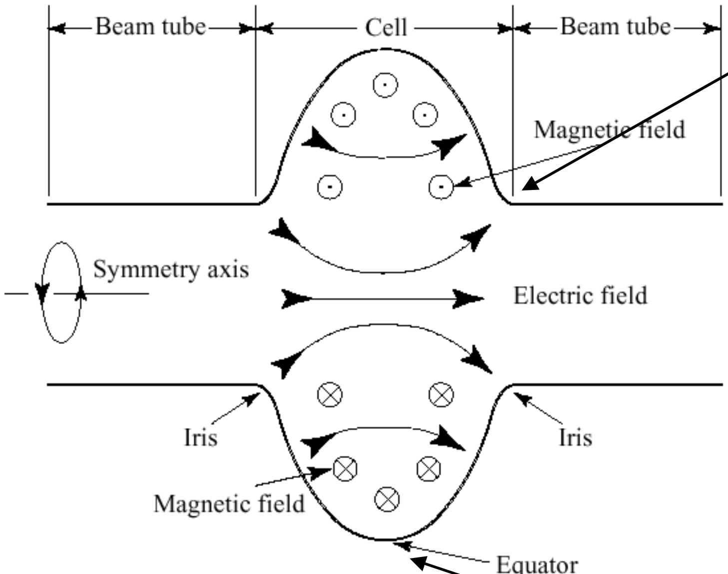




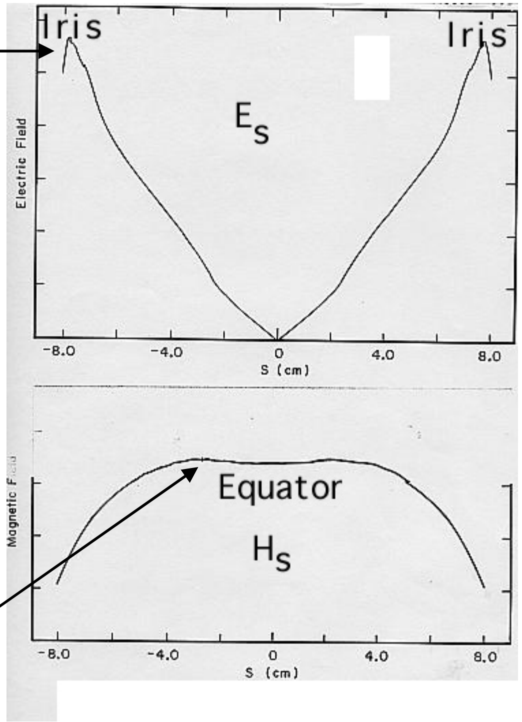
# Real Cavities



# Single Cell Cavities

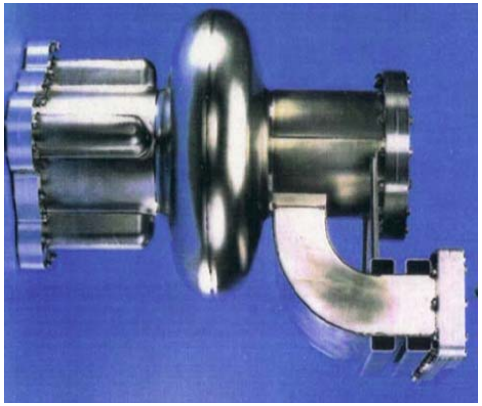


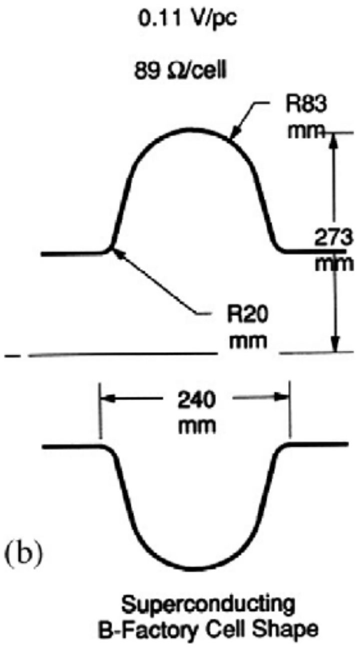

Electric field high at iris




Magnetic field high at equator

# Single Cell Cavities






| Quantity | Cornell SC 500 MHz | Pillbox |
|---|---|---|
| $G$ | 270 ohmΩ | 257 Ω |
| $R_a/Q_0$ | 88 ohm/cell | 196 Ω/cell |
| $E_{pk}/E_{acc}$ | 2.5 | 1.6 |
| $H_{pk}/E_{acc}$ | 52 Oe/MV/m | 30.5 Oe/(MV/m) |

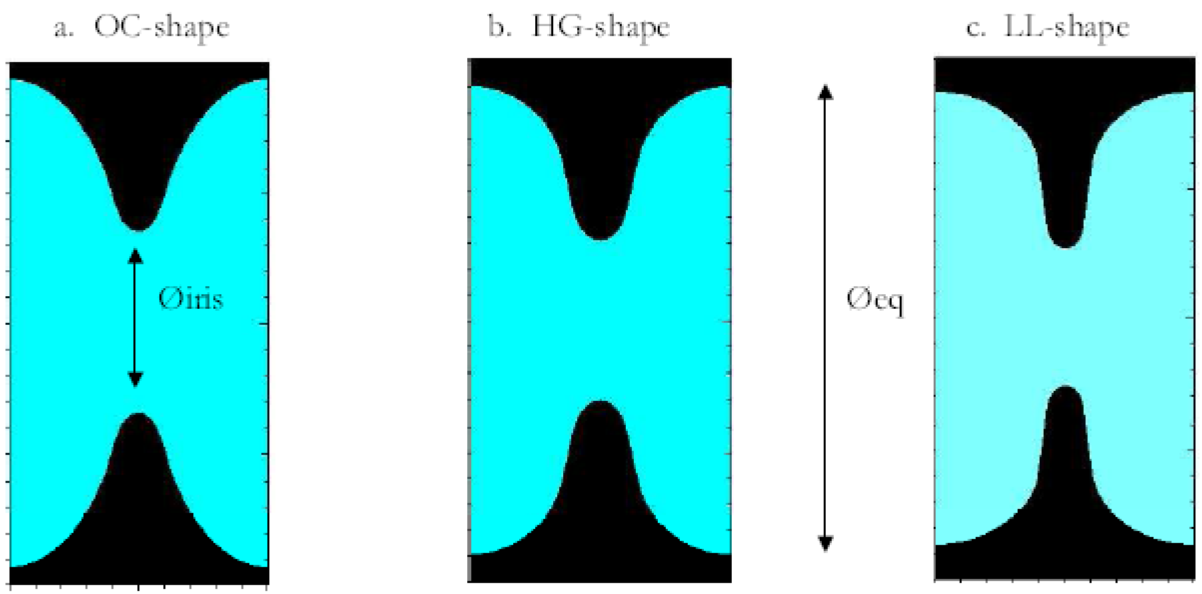
# Cell Shape Design

- What is the purpose of the cavity?
- What EM parameters should be optimized to meet the design specs?

**The “perfect” shape does not exist, it all depends on your application**

# Example: CEBAF Upgrade

- "High Gradient" shape: lowest $E_p/E_{acc}$
- "Low Loss" shape: lowest cryogenic losses G(R/Q)



# CEBAF Upgrade Shape Comparison

Table 1. Parameters of inner dumbbells

| Parameters | Unit | OC-shape | HG-Shape | LL-Shape |
|---|---|---|---|---|
| Øeq | [mm] | 187.03 | 180.50 | 174.00 |
| Øiris | [mm] | 70.00 | 61.40 | 53.00 |
| $k_{cc}$ | [%] | 3.29 | 1.72 | 1.49 |
| $E_{peak}/E_{acc}$ | - | 2.56 | 1.89 | 2.17 |
| $B_{peak}/E_{acc}$ | $[mT \cdot (MV/m)^{-1}]$ | 4.56 | 4.26 | 3.74 |
| Lorentz factor*) $k_L$ | $[Hz \cdot (MV/m)^{-2}]$ | -1.35 | -1.1 | -1.2 |
| R/Q | [Ω] | 96.5 | 111.9 | 128.8 |
| r/q = (R/Q)/length | [Ω/m] | 965 | 1119 | 1288 |
| G | [Ω] | 273.8 | 265.5 | 280.3 |
| R/Q*G | [Ω*Ω] | 26421 | 29709 | 36102 |

**CEBAF Upgrade: cryo-budget limit of 30W/cavity. Higher energy gain can be obtained using LL-shape.**

# New Trend in TM-Cavity Design

- The **field emission is not a hard limit** in the performance of sc cavities if the surface preparation is done in the right way.

- Unlikely this, **magnetic flux on the wall** limits performance of a sc cavity ($Q_0$ decreases or/and quench). Hard limit ~**180 mT** for Nb.

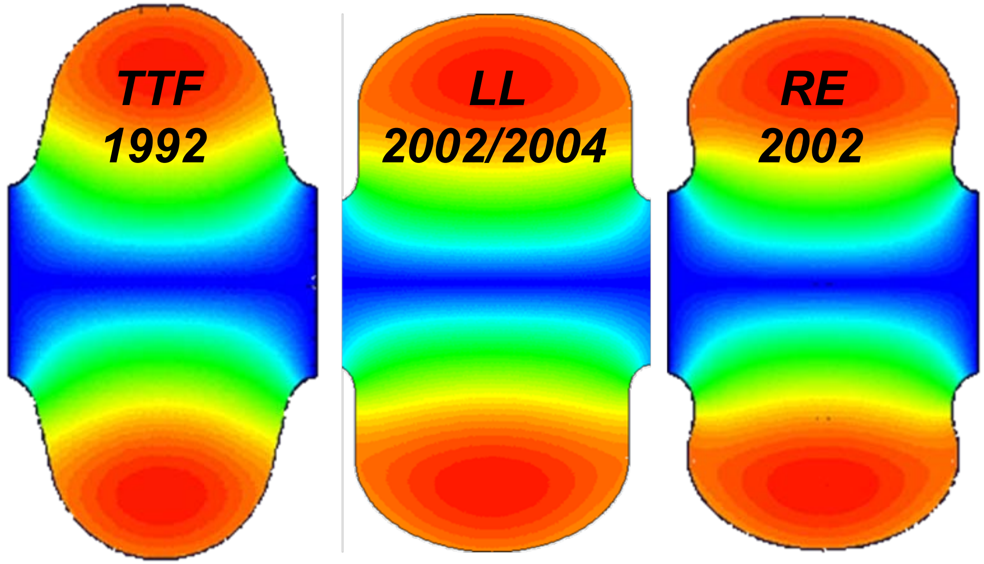
*$B_{peak} / E_{acc}$ should be low*

*1. Cavities may operate at higher gradients.*

*2. Cavities may operate at lower cryogenic load.*

$$\frac{P_{dissipated}}{V_{acc}^2} \equiv \frac{R_s}{G \cdot (R/Q)}$$

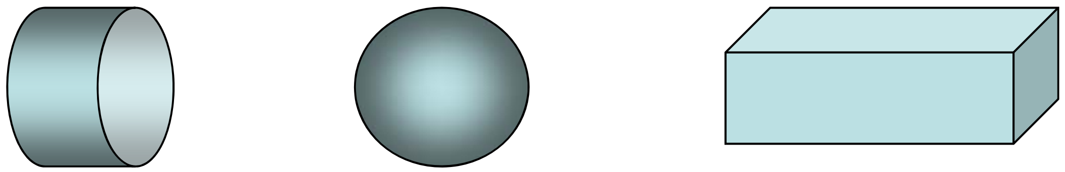
# New Shapes for ILC




| | | | | |
|---|---|---|---|---|
| $r_{iris}$ | [mm] | 35 | 30 | 33 |
| $k_{cc}$ | [%] | 1.9 | 1.52 | 1.8 |
| $E_{peak}/E_{acc}$ | - | 1.98 | 2.36 | 2.21 |
| $B_{peak}/E_{acc}$ | [mT/(MV/m)] | 4.15 | 3.61 | 3.76 |
| R/Q | [Ω] | 113.8 | 133.7 | 126.8 |
| G | [Ω] | 271 | 284 | 277 |
| R/Q*G | [Ω*Ω] | 30840 | 37970 | 35123 |

# RF Simulation Codes for Cavity Design

**The solution to 2D (or 3D) Helmholtz equation can be analytically find only for very few geometries (pillbox, spherical resonators or rectangular resonator).**



***We need numerical methods:***

$$(\nabla^2 + \omega^2 \varepsilon\mu) A = 0$$

***Approximating operator***
***(Finite Difference Methods)***

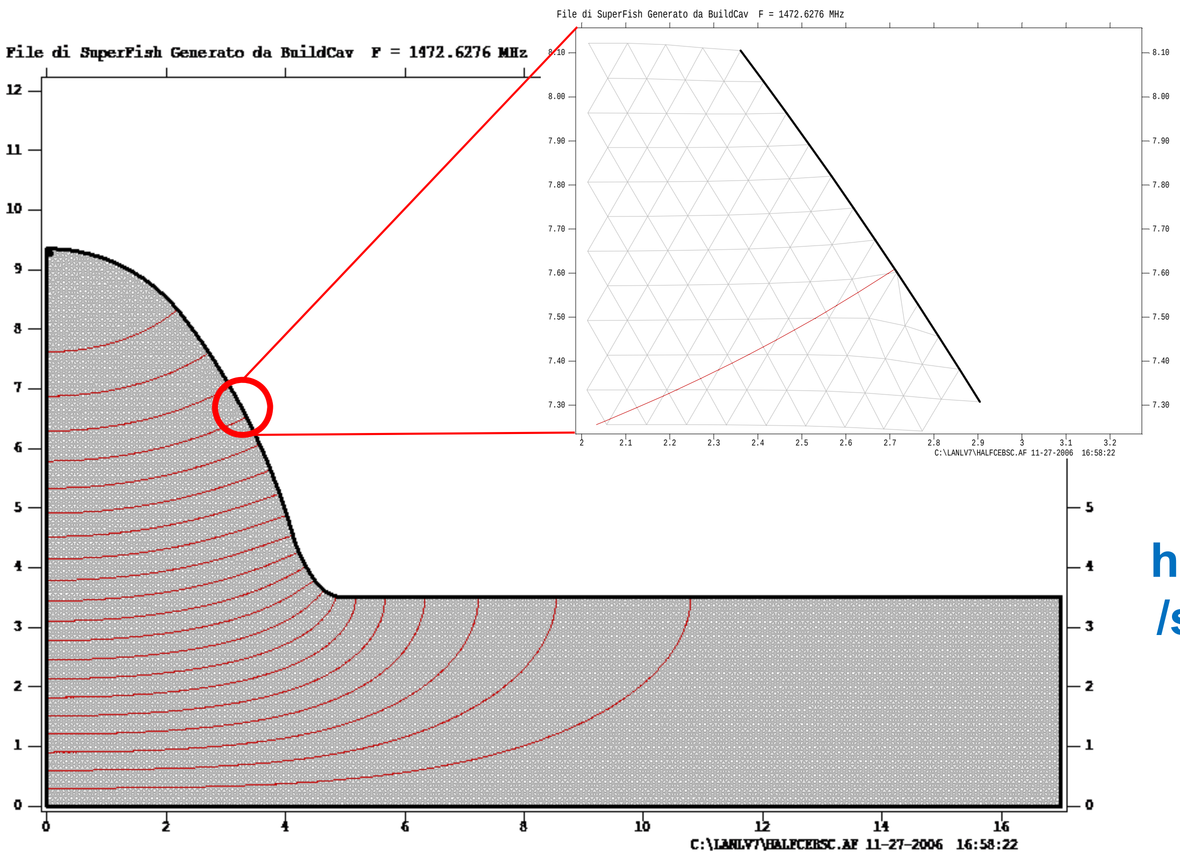
***Approximating function***
***(Finite Element Methods)***

- **2D is fast and allows to define geometry of a cylindrical symmetric body (inner and end-cells) of the cavity.**

- **3D is much more time consuming but necessary for modeling of full equipped cavity with FPC and HOM couplers and if needed to model fabrication errors. Also coupling strength for FPC and damping of HOMs can be modeled only 3D.**

# SUPERFISH

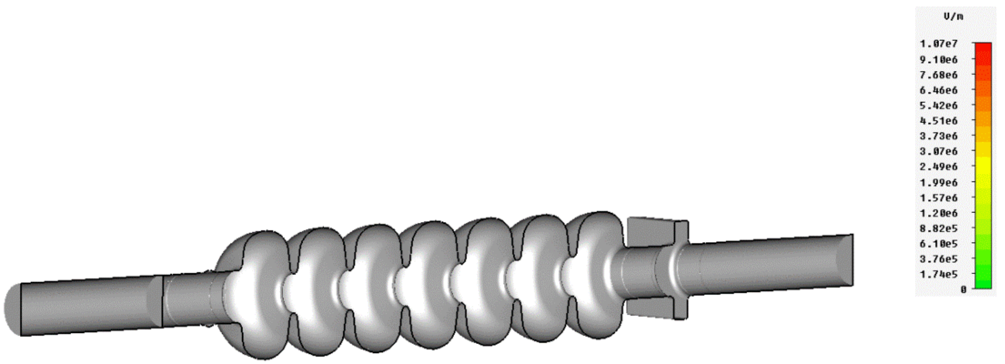
- Free, 2D finite-difference code to design cylindrically symmetric structures (monopole modes only)
- Use symmetry planes to reduce number of mesh points



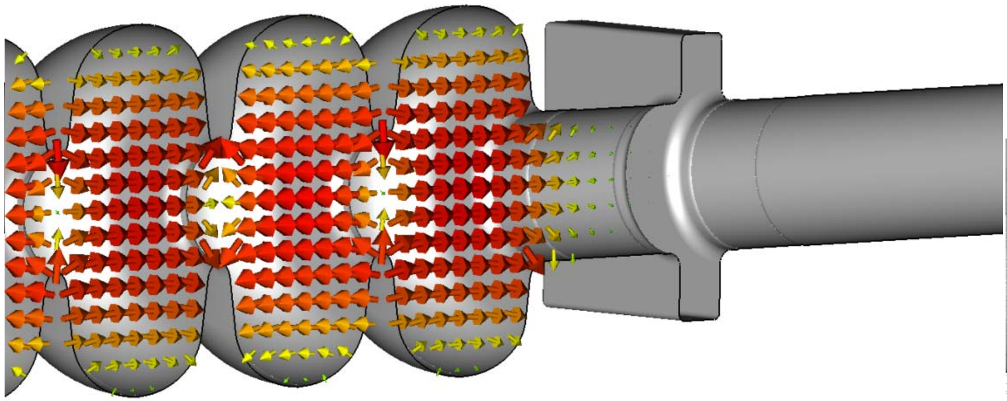

http://laacg1.lanl.gov/laacg/services/download_sf.phtml

# CST Microwave Studio

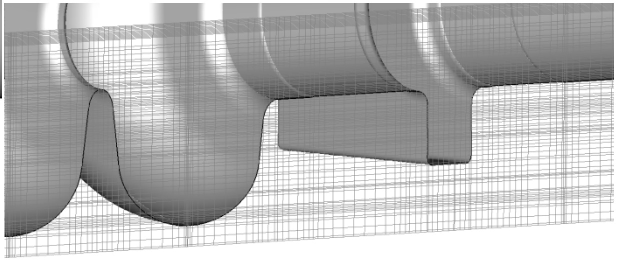
- Expensive, 3D finite-element code, used to design complex RF structure.
  http://www.cst.com/Content/Products/MWS/Overview.aspx




- **Runs on PC**
- **Perfect Boundary Approximation**

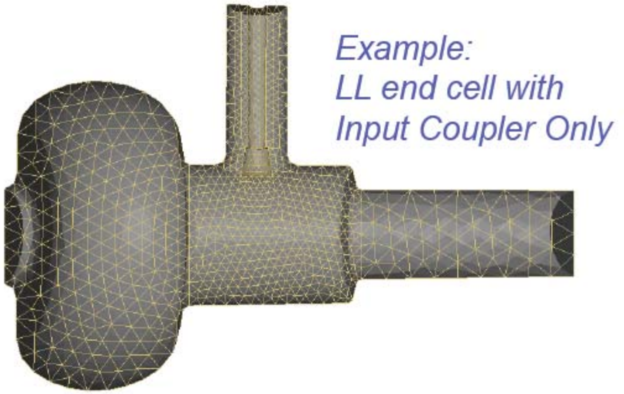


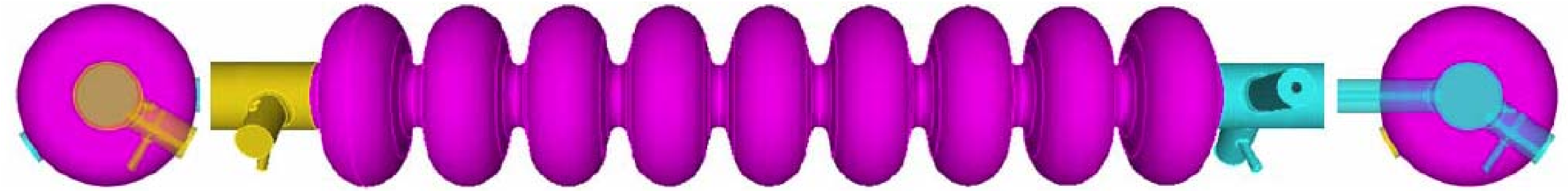
**Hexahedral mesh**



# Omega3P

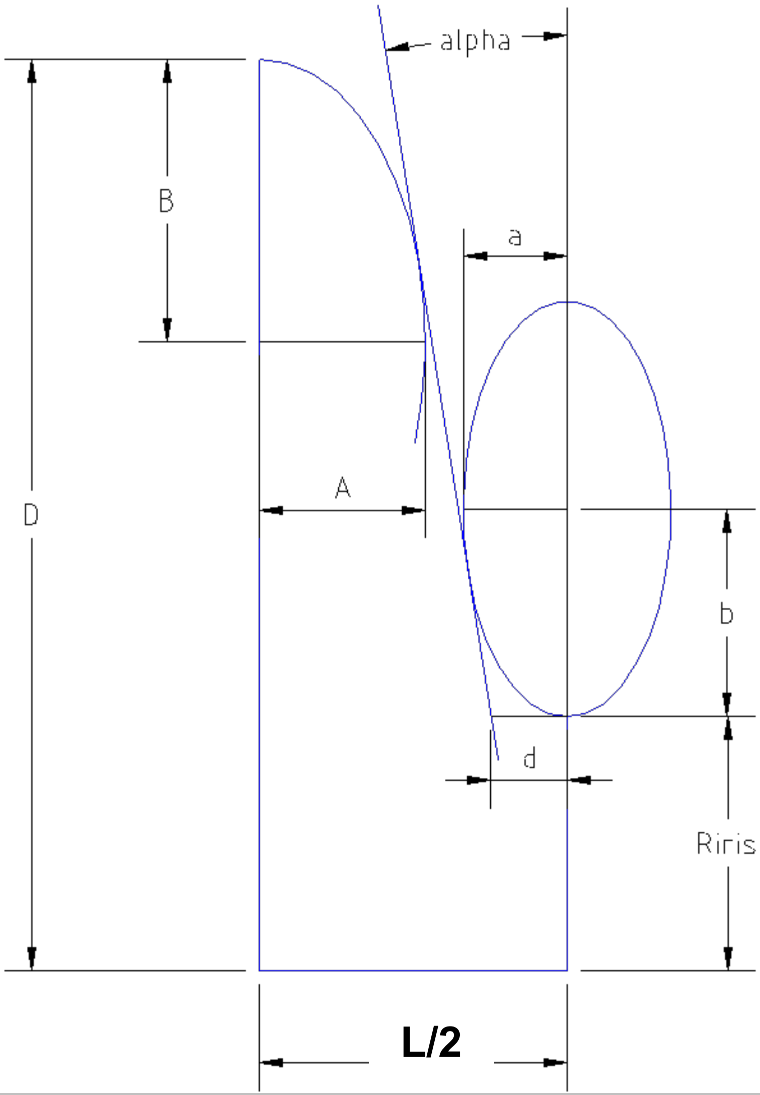
- SLAC, 3D code, high-order Parallel Finite Element (PFE) method
- Runs on Linux
- Tetrahedral conformal mesh
- High order finite elements (basis order p =1 – 6
- Separate software for user interface (CuBit)



# Cell Shape Parametrization

- Full parametric model of the cavity in terms of 7 meaningful geometrical parameters:
  - ✓ Ellipse ratio at the equator (R=B/A)
    ruled by mechanics
  - ✓ Ellipse ratio at the iris (r=b/a)
    $E_{peak}$
  - ✓ Side wall inclination ($\alpha$) and position (d)
    $E_{peak}$ vs. $B_{peak}$ tradeoff and coupling $k_{cc}$
  - ✓ Cavity iris radius $R_{iris}$
    coupling $k_{cc}$
  - ✓ Half-cell Length $L/2=\lambda\beta/4$
    $\beta$
  - ✓ Cavity radius D
    used for frequency tuning
- Behavior of all e.m. and mechanical properties has been found as a function of the above parameters

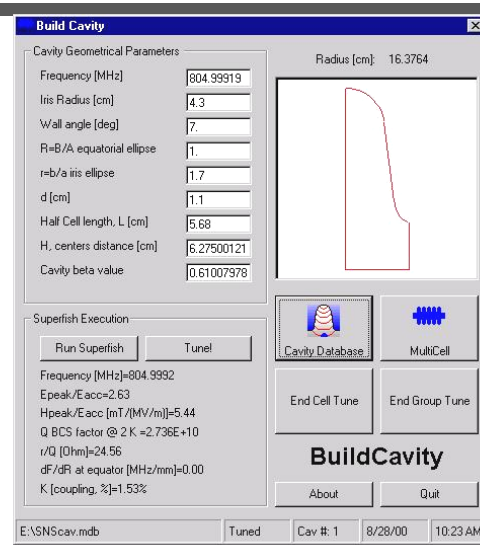


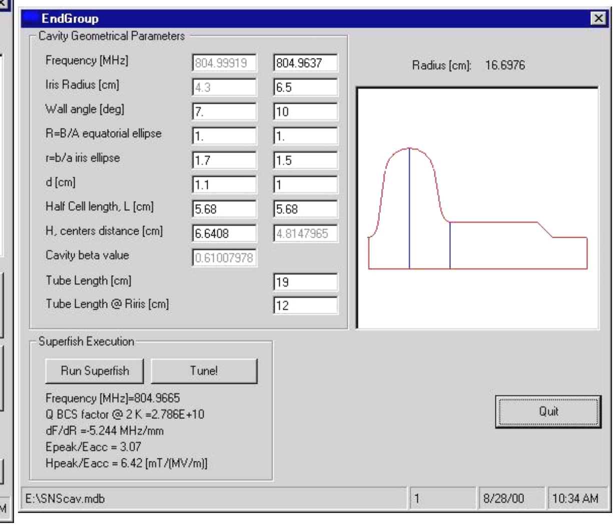
# Tools used for the parametrization

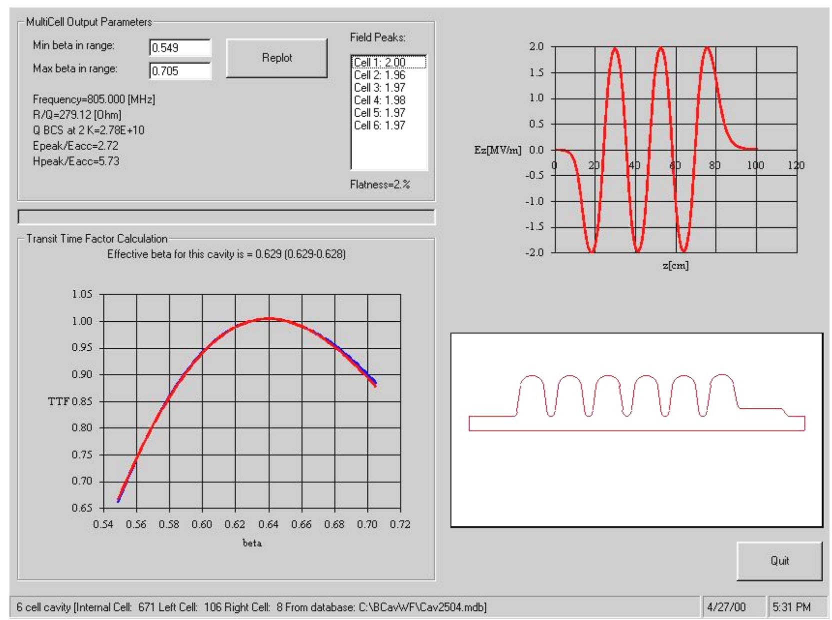
**BuildCavity**: parametric tool for the analysis of the cavity shape on the EM parameters:

- All RF computations are handled by SUPERFISH
- Inner cell tuning is performed through the cell diameter, all the characteristic cell parameters stay constant: R, r, $\alpha$, d, L, $R_{iris}$
- End cell tuning is performed through the wall angle inclination, $\alpha$, or distance, d.

  R, L and $R_{iris}$ are independently settable.
- Multicell cavity is then built to minimize the field unflatness, compute the effective $\beta$ and the final cavity performances.
- A proper file to transfer the cavity geometry to ANSYS is then generated




**Inner cell data**

**L = 56.8 mm**
**R = 1**
**r = 1.7**
**$\alpha$ = 7°**
**d = 11 mm**
**$R_{iris}$ = 43 mm**

# Parameter Choices

- Choose the cavity frequency ⇨ Equator diameter **D**

- Accelerate electrons ($\beta$=1) or protons (several designs with $\beta$ < 1)?

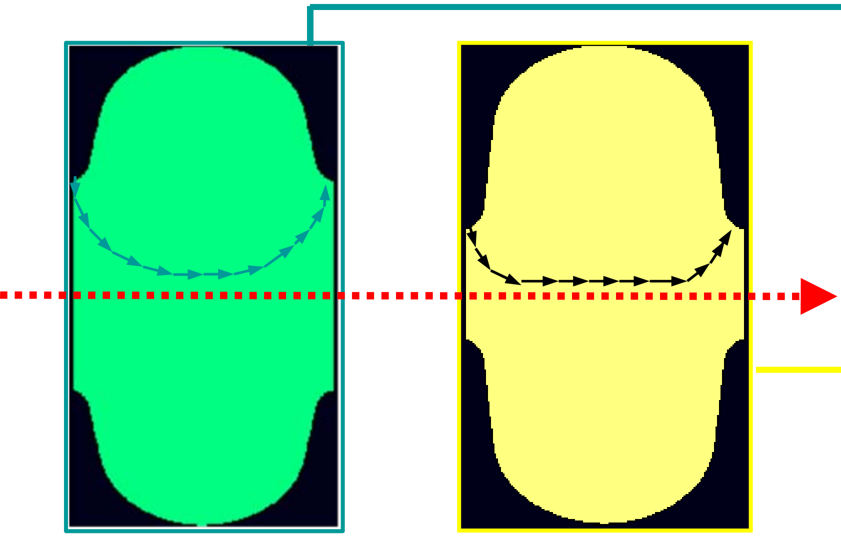
  Cell length, **L = $\lambda\beta$/2**

# One Big “Knob”: $R_{iris}$

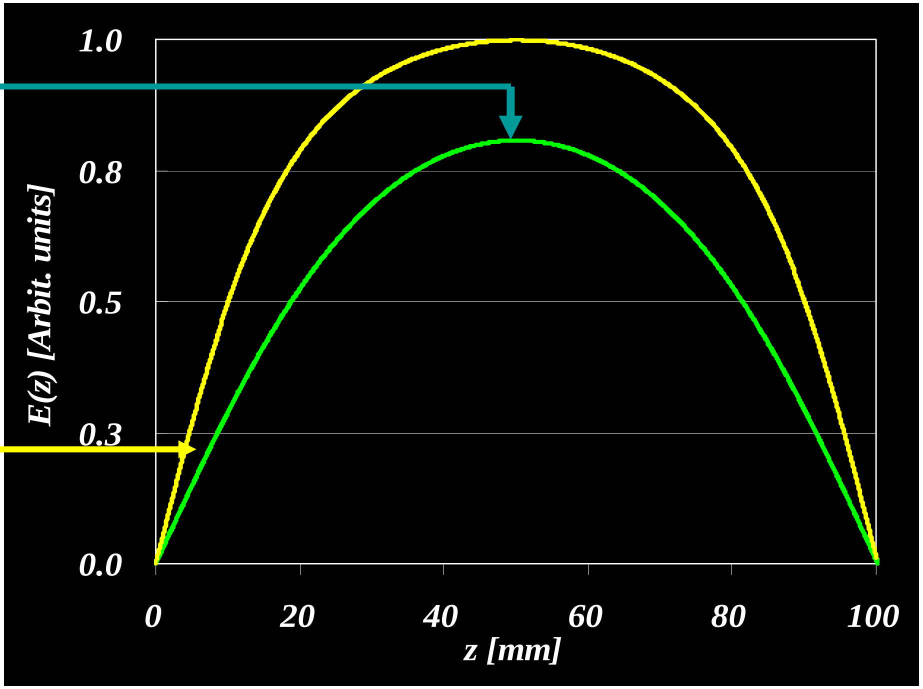
**Why for a smaller aperture ($R_{iris}$)?**

- **(R/Q) is bigger**
- **$E_{peak}/E_{acc}$ , $B_{peak}/E_{acc}$ is lower**

***$E_{acc}$ is higher at the same stored energy in the cell***



***$R_{i\,ris}$= 40 mm*** ***$R_{iris}$ = 20 mm***




***$E_z$ (z) for small and big iris radius***

# More on $R_{iris}$

**We know that a smaller aperture makes:**

- *(R/Q) higher*
- $B_{peak}/E_{acc}$ , $E_{peak}/E_{acc}$ *lower*

**(+)**

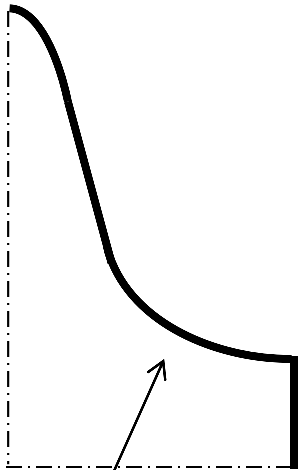
**but unfortunately a smaller aperture makes:**

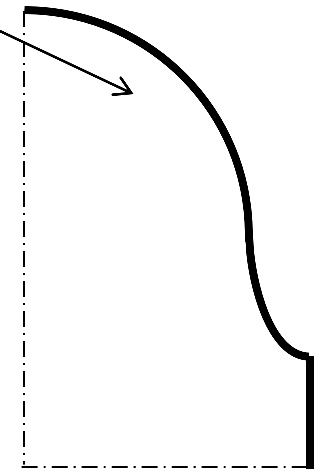
- *HOMs impedances* ($k_{\perp}$ , $k_{\parallel}$) *higher*
- *cell-to-cell coupling* ( $k_{cc}$ ) *weaker*

**(-)**

# "Rule of thumb" for Optimizing Peak Surface Fields

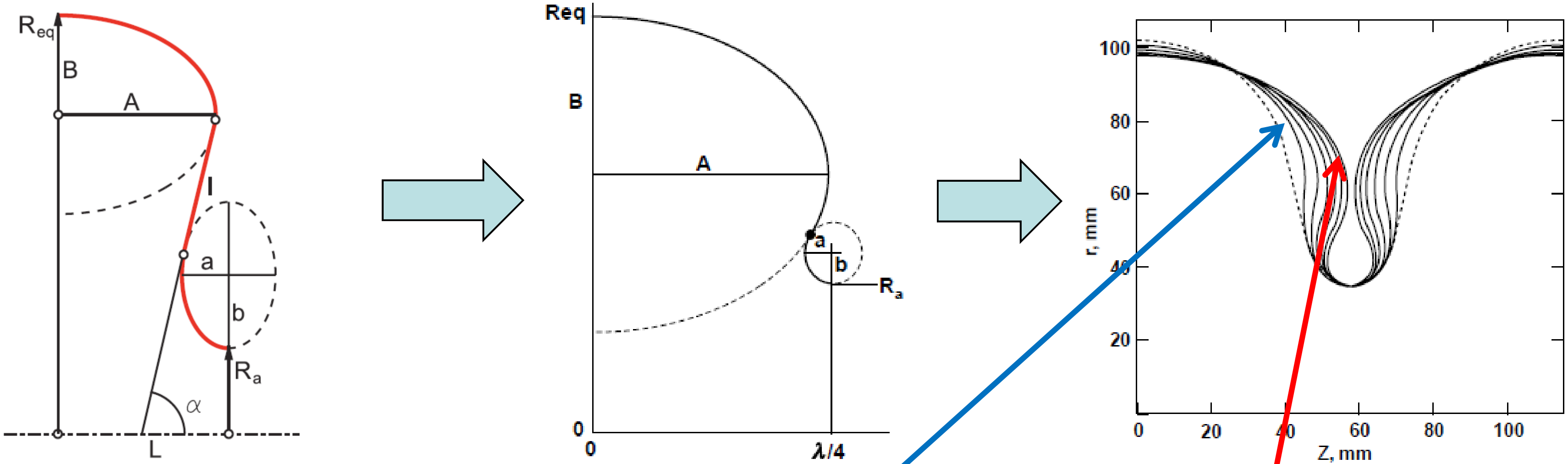
Add "*magnetic volume*" at the equator to reduce $B_{peak}$



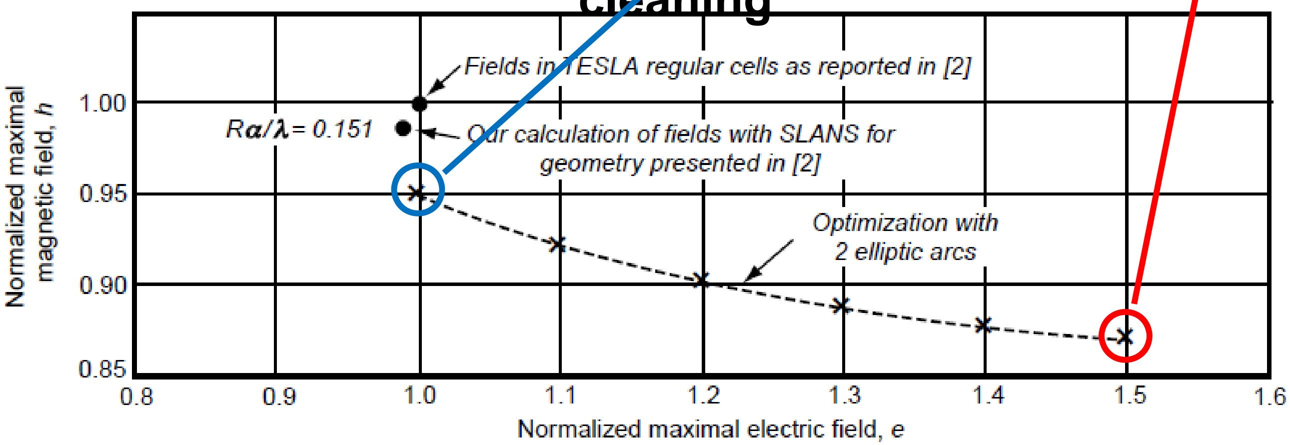


Add "*electric volume*" at the iris to reduce $E_{peak}$

# Pushing the Design: Reentrant cavity

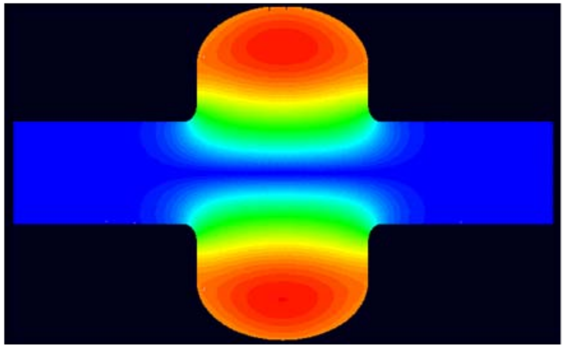


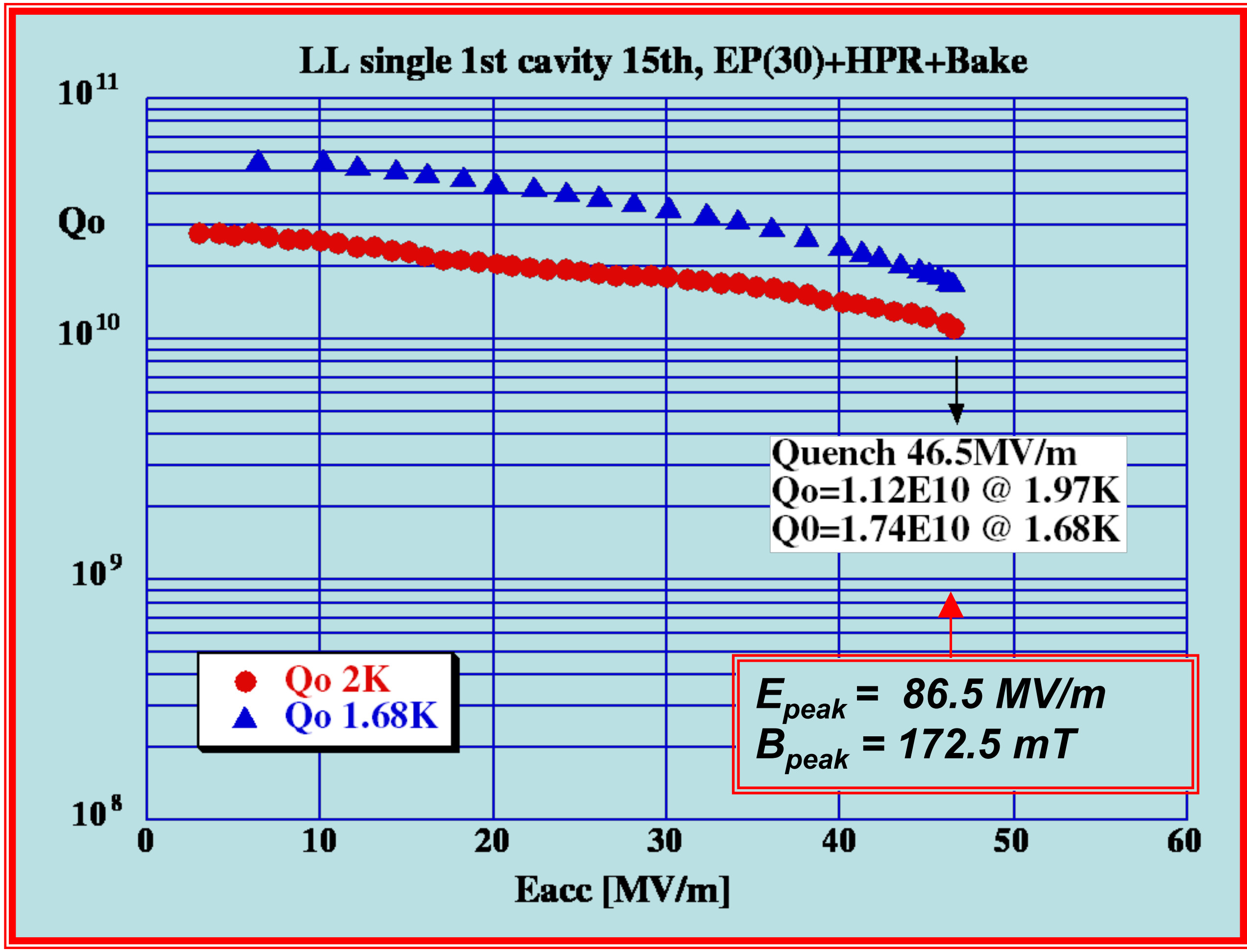

- **3 independent parameters: A, B, a**
- **potential issue with cavity forming and cleaning**



# RF Tests of New Cavity Shapes: LL

| | | LL |
|---|---|---|
| $f_\pi$ | [MHz] | 1286.6 |
| $E_{peak}/E_{acc}$ | - | 1.86 |
| $B_{peak}/E_{acc}$ | [mT/(MV/m)] | 3.71 |
| R/Q | [Ω] | 130.0 |
| G | [Ω] | 279 |
| $Ø_{iris}$ | [mm] | 61 |

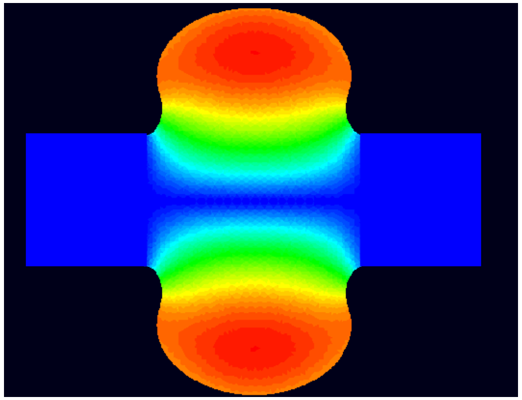


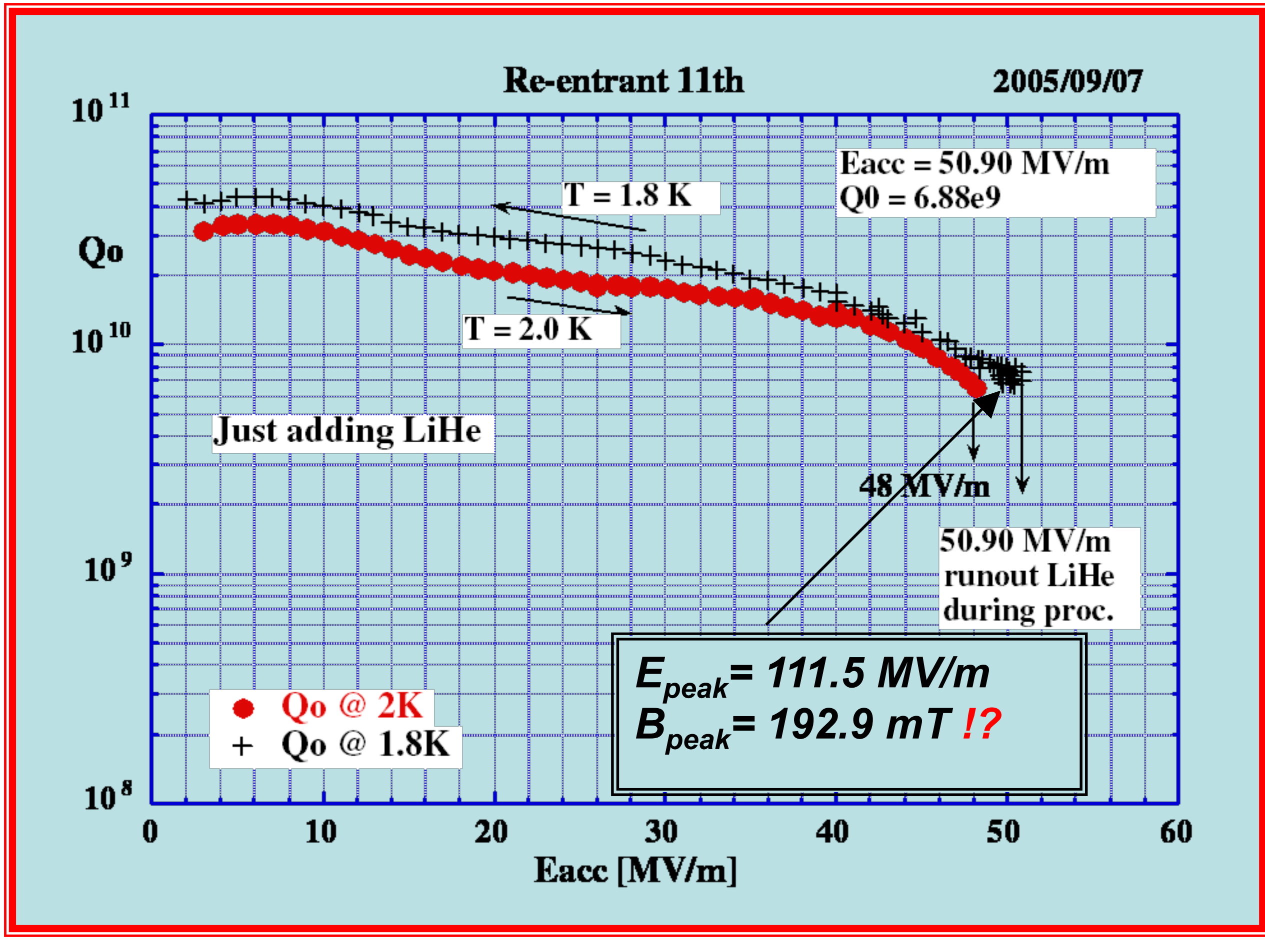



**9-cell LL cavity was tested at JLab up to $E_{acc}$=36MV/m**

# RF Tests of New Cavity Shapes: RE

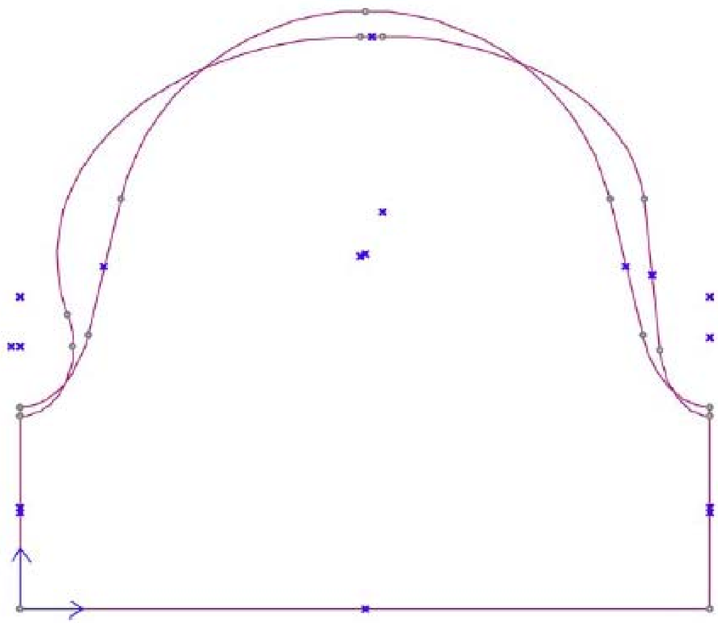
| | | RE |
|---|---|---|
| $f_\pi$ | [MHz] | 1278.6 |
| $E_{peak}/E_{acc}$ | - | 2.19 |
| $B_{peak}/E_{acc}$ | [mT/(MV/m)] | 3.79 |
| R/Q | [Ω] | 126.0 |
| G | [Ω] | 278 |
| $Ø_{iris}$ | [mm] | 68 |

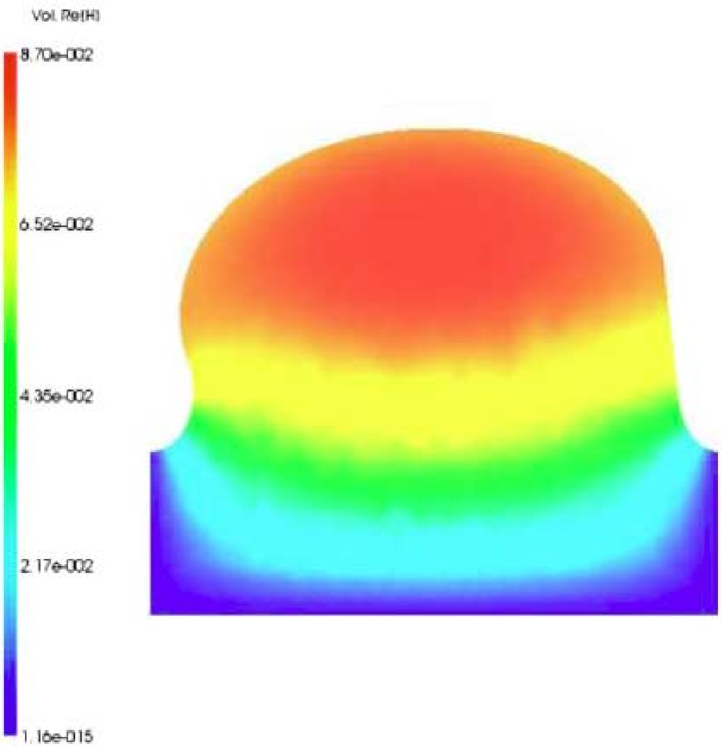





9-cell RE cavity was tested at Cornell up to $E_{acc}$=28MV/m

# Want more?...Half-Reentrant Cavity



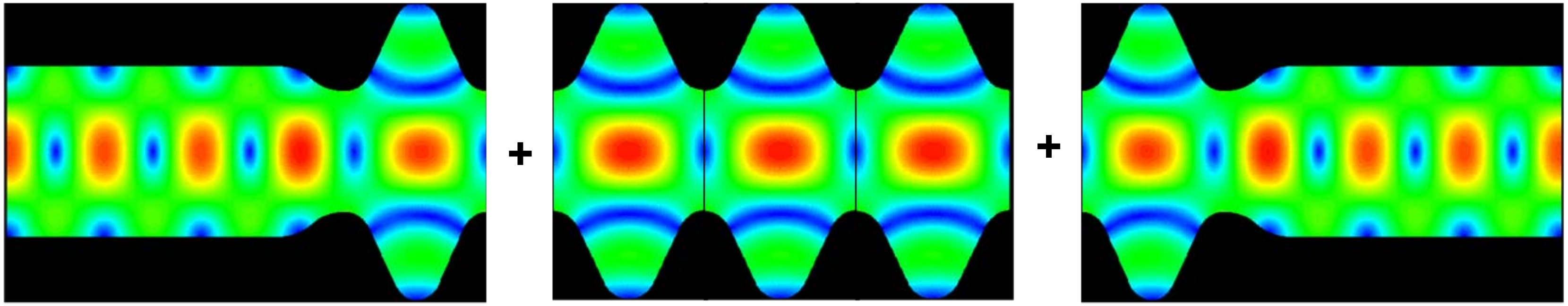



Parameters of the two proposed half-reentrant inner cells compared to the proposed Low Loss ILC geometry

| | High-$k_{cc}$ HR | Low-$k_{cc}$ HR | Low Loss ILC |
|---|---|---|---|
| Frequency (MHz) | 1300 | 1300 | 1300 |
| Wall angle (°) | 6 | 6 | 0.165 |
| $E_{peak}/E_{acc}$ (−) | 2.40 | 2.38 | 2.36 |
| $B_{peak}/E_{acc}$ $\left(\frac{mT}{MV/m}\right)$ | 3.78 | 3.60 | 3.61 |
| $R/Q$ ($\Omega$) | 123 | 135 | 134 |
| $G$ ($\Omega$) | 283 | 283 | 284 |
| $(R/Q)\cdot G$ ($\Omega^2$) | 34,673 | 38,021 | 37,970 |
| $k_{cc}$ (%) | 2.09 | 1.51 | 1.52 |
| $r_i$ (cm) | 3.34 | 2.97 | 3.00 |

# End-Cell Design

**The geometry of end-cells differs from the geometry of inner cells due to the attached beam tubes**



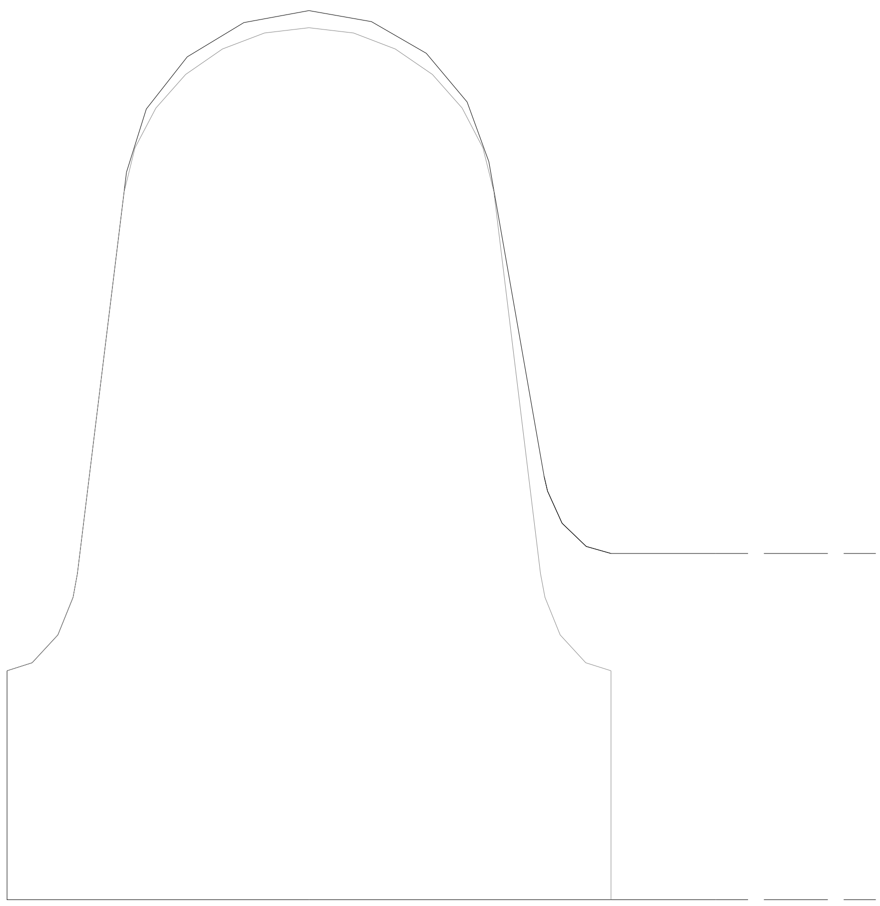
**Their function is multi-folded and their geometry must fulfill three requirements:**

- **field flatness and frequency of the accelerating mode**
- **field strength of the accelerating mode at FPC location enabling operation with matched $Q_{ext}$**
- **fields strength of dangerous HOMs ensuring their required damping by means of HOM couplers or/and beam line absorbers.**

**All three make design of the end-cells more difficult than inner cells.**

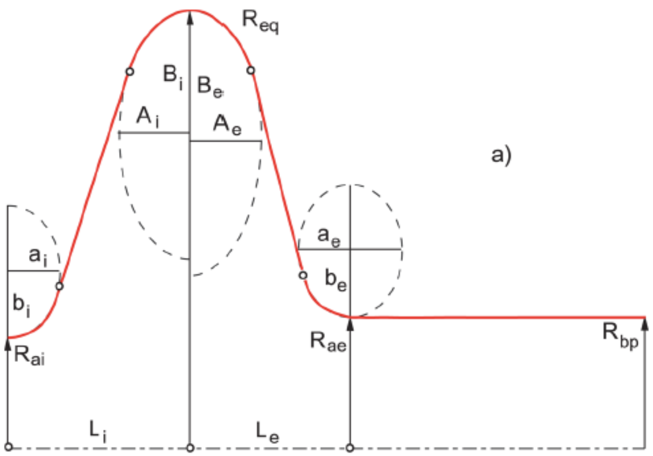
# Example: SNS MB cavity

**Optimization done with BuildCavity**

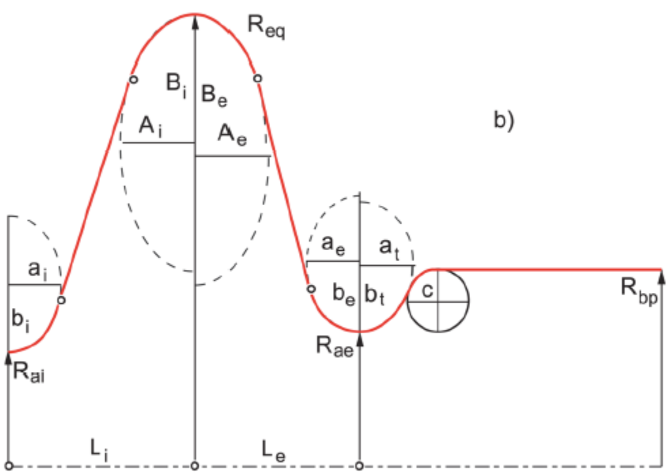


- $R_{iris}$ set to 65 mm to have enough field at the power coupler antenna
- d set 1 mm lower than the in-cell
- optimization of r = b/a at iris
- $\alpha$ set to 10 deg to have the necessary stiffening
- Slater compensation (increase of the magnetic volume) of the cut-off tube (↓f ), d reduction (↓f ), $\alpha$ and $R_{iris}$ increase (↑f ) by increasing the equator radius ⇨ 4 dies
- the frequency of end cell + tube is about 40 kHz lower than the in-cell's due to the asimmetry

# More Examples of End Cell Optimizations

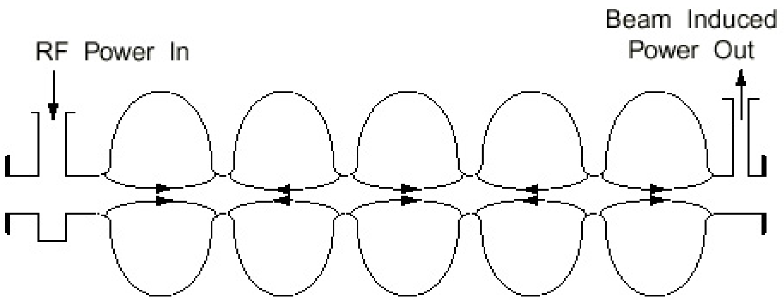



- Same $R_{eq}$ as inner cell, use $L_e$ as parameter to adjust the frequency
- Adjust parameters $A_e$, $B_e$, $a_e$, $b_e$ and $\alpha$ to minimize either $E_{peak}/E_{acc}$ or losses

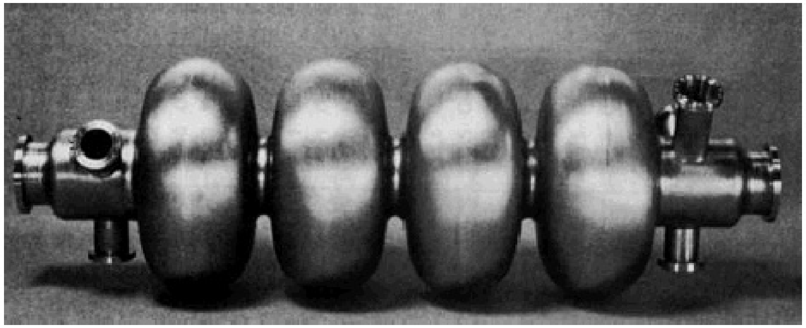



- By adding more parameters ($a_t$, $b_t$, c, $R_{bp}$) it is possible to optimize the propagation of unwanted HOM, without increasing $E_{peak}/E_{acc}$ or losses for the fundamental mode

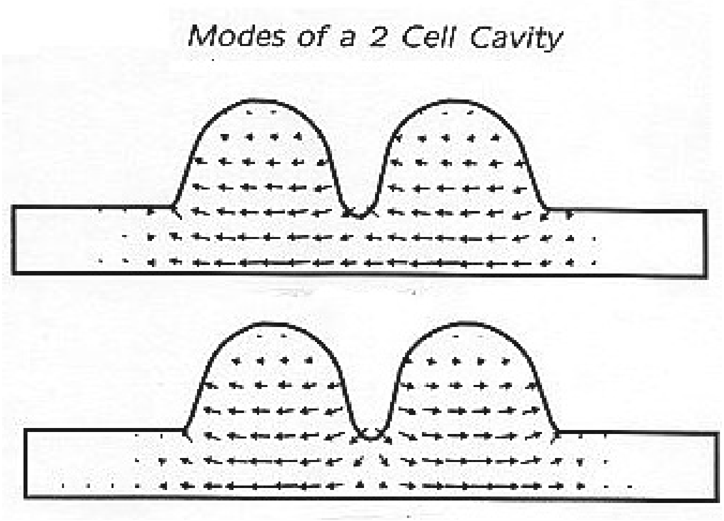
# Multi-Cell Cavities

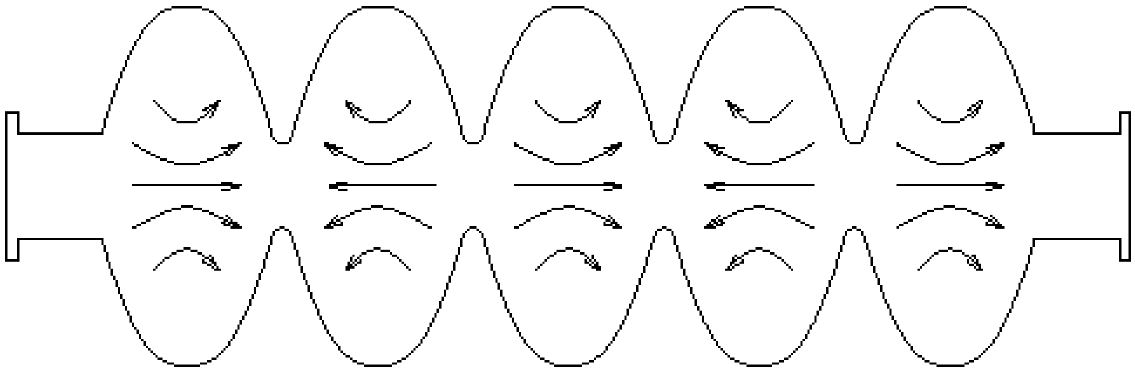



(c)



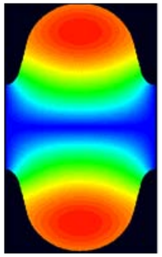
# Multi-Cell Cavities



: Sketch of the electric field lines of the $\pi$-mode of a 5-cell

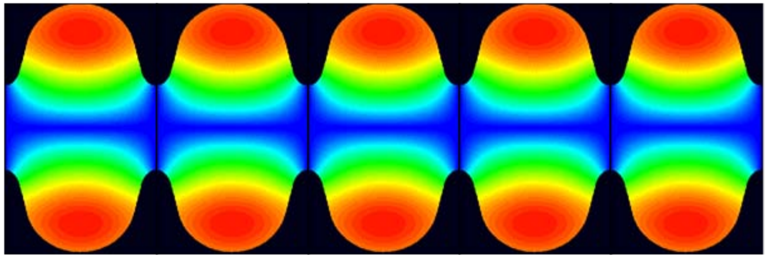
# Multicell Cavities



Single-cell is attractive from the RF-point of view:

- Easier to manage HOM damping
- No field flatness problem.
- Input coupler transfers less power
- Easy for cleaning and preparation

- *But it is expensive to base even a small linear accelerator on the single cell. We do it only for very high beam current machines.*



A multi-cell structure is less expensive and offers higher real-estate gradient but:

*Field flatness (stored energy) in cells becomes sensitive to frequency errors of individual cells*

- *Other problems arise: HOM trapping…*

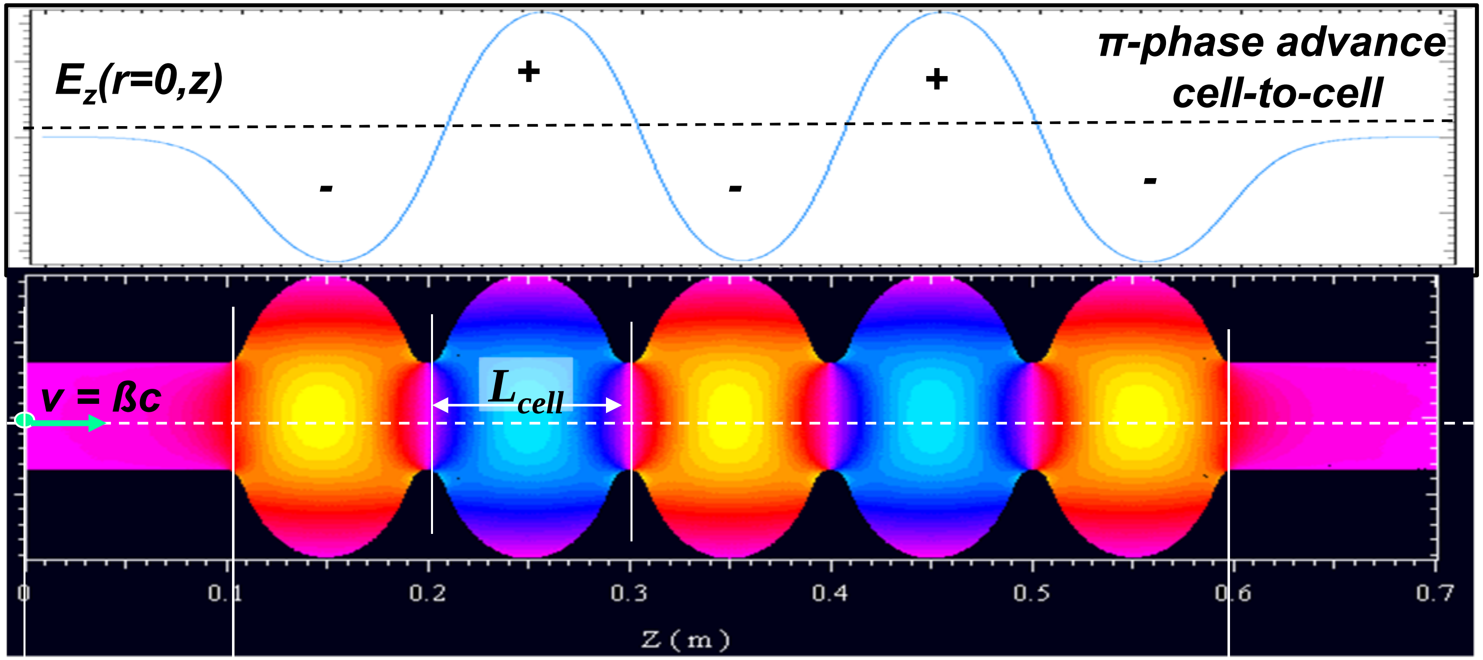
# Pros and Cons of Multicells

- Cost of accelerators are lower (less auxiliaries: LHe vessels, tuners, fundamental power couplers, control electronics)
- Higher real-estate gradient (better fill factor)

- Field flatness vs. N
- HOM trapping vs. N
- Power capability of fundamental power couplers vs. N
- Chemical treatment and final preparation become more complicated
- The worst performing cell limits whole multi-cell structure

# Beam Acceleration

Accelerating mode in a multi-cell structure

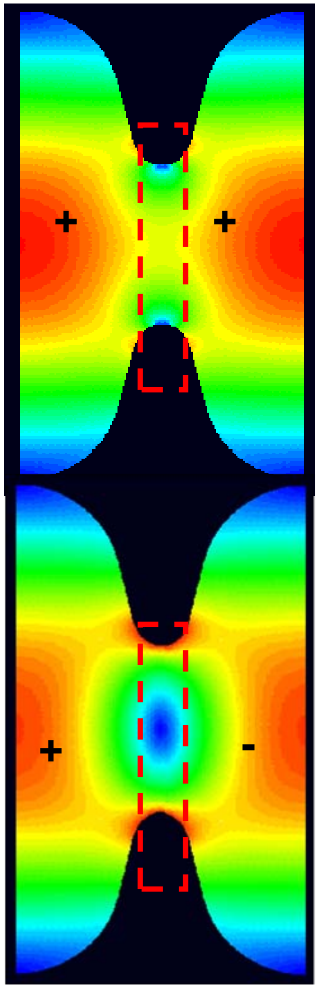



*s* $L_{active}$

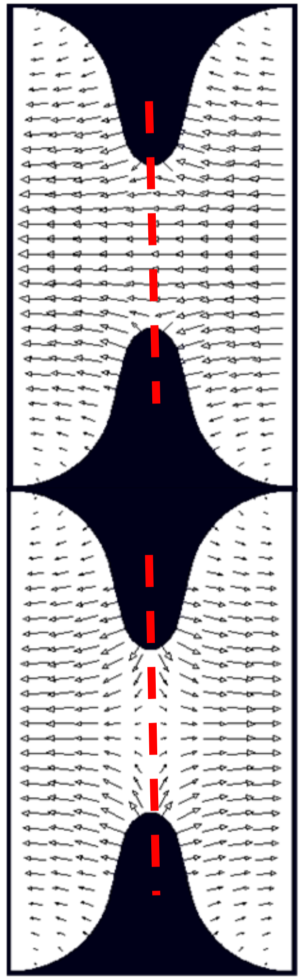
**Synchronic acceleration and max of $(R/Q)_{acc} \leftrightarrow L_{active} = NL_{cell} = Nc\beta/(2f)$ and the injection takes place at an optimum phase $\varphi_{opt}$ which ensures that particles will arrive at the mid-plane of the first cell when $E_{acc}$ reaches its maximum (+q passing to the right) or minimum (-q passing to the right).**

# Coupling between cells

$\omega_o$




$\omega_\pi$



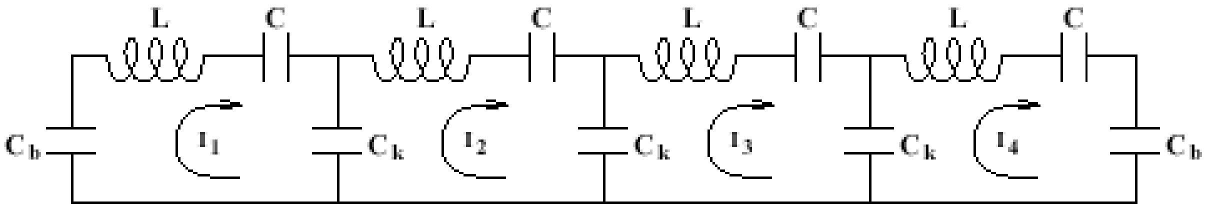
***Symmetry plane for the H field***

***Symmetry plane for the E field which is an additional solution***

**The normalized difference between these frequencies is a measure of the energy flow via the coupling region**

$$k_{cc} = \frac{\omega_\pi - \omega_0}{\frac{\omega_\pi + \omega_0}{2}}$$

# Multi-Cell Cavities




$$k = \frac{C}{C_k} \qquad C_b = C_k / 2$$

**Mode frequencies:**

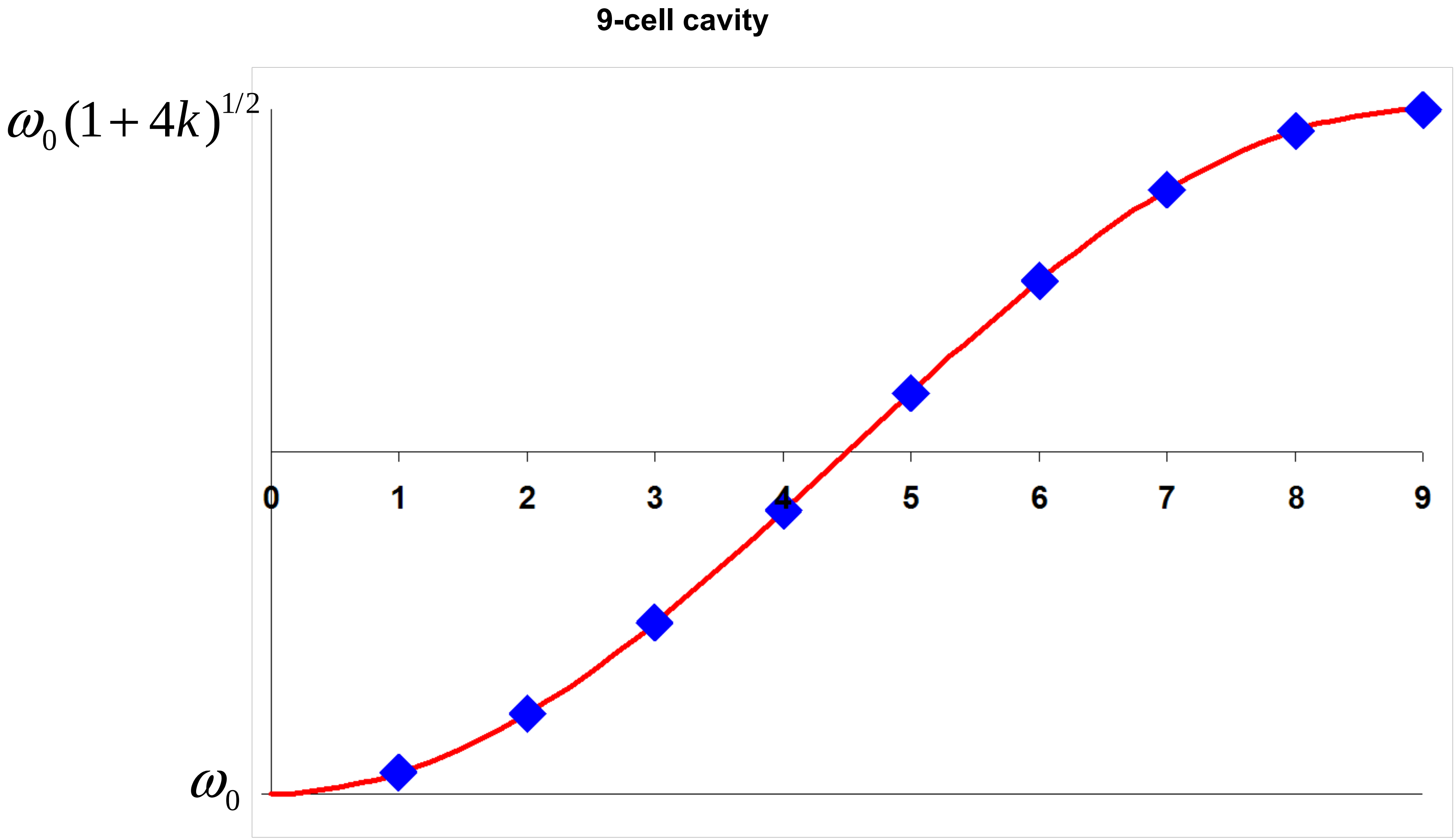
$$\frac{\omega_m^2}{\omega_0^2} = 1 + 2k\left(1 - \cos\frac{\pi m}{n}\right)$$

$$\frac{\omega_n - \omega_{n-1}}{\omega_0} \simeq k\left(1 - \cos\frac{\pi}{n}\right) \simeq \frac{k}{2}\left(\frac{\pi}{n}\right)^2$$

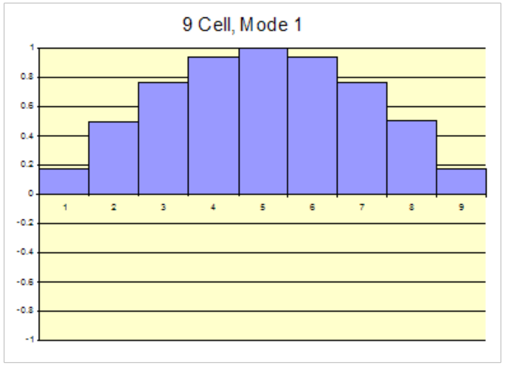
**Voltages in cells:**

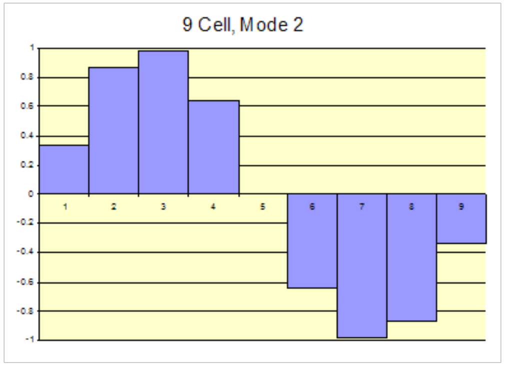
$$V_j^m = \sin\left(\pi m \frac{2j-1}{2n}\right)$$

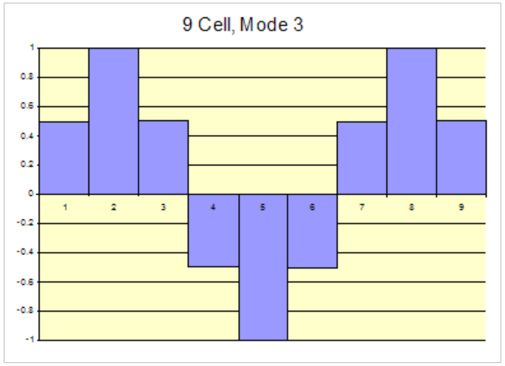
# Pass-Band Modes Frequencies

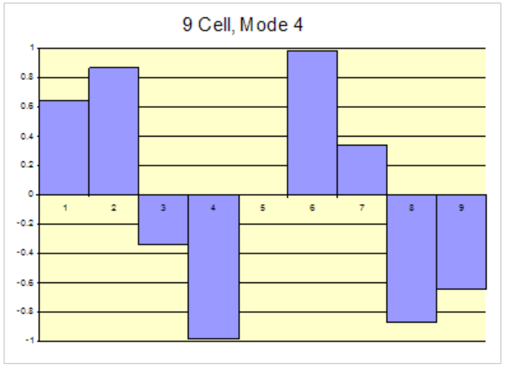


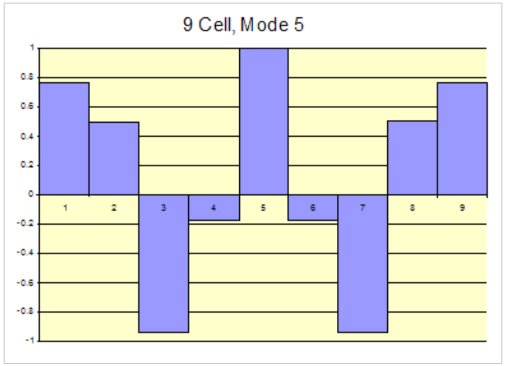
# Cell Excitations in Pass-Band Modes

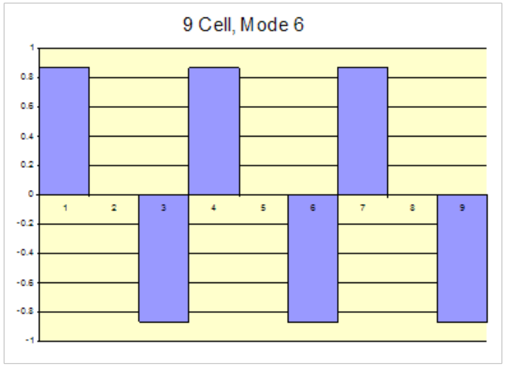


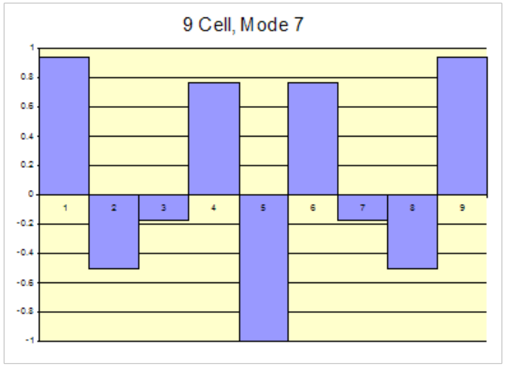



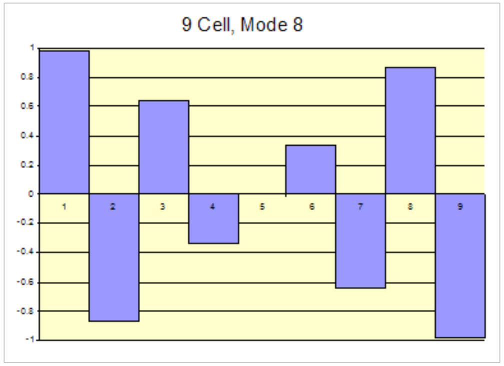



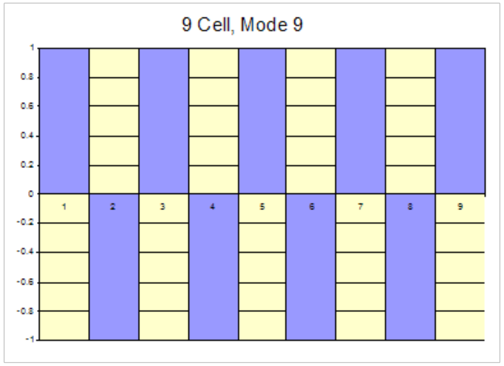



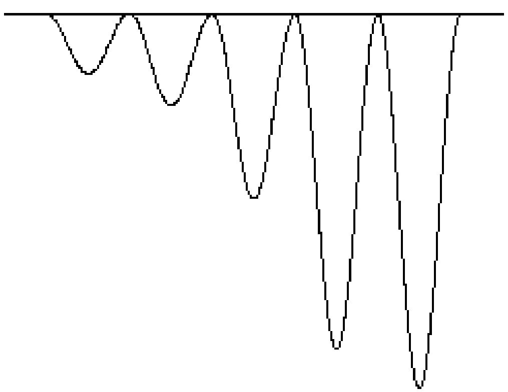



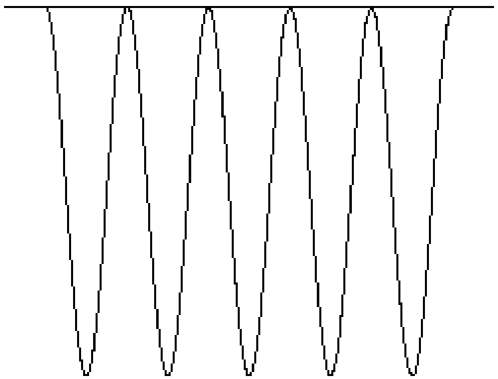
# Field Flatness

**Geometrical differences between cells causes a mixing of the eigenmodes**

**Sensitivity to mechanical deformation depends on mode spacing**

$$\frac{\omega_n - \omega_{n-1}}{\omega_0} \simeq k\left(1 - \cos\frac{\pi}{n}\right) \simeq \frac{k}{2}\left(\frac{\pi}{n}\right)^2$$





# Multipacting Simulations

Once the cavity shape has been designed, multipacting simulations have to be done:

- get the fields on the contour
- electrons are launched from given initial sites at given phases of the RF field
- for a fixed field level the electron trajectories are calculated by integrating the equations of motion, until the electrons hit the wall
- record the location, phase, and impact energy
- the number of secondary electrons is determined, given the SEY function
- the trajectory calculation is continued if the field phase is such as secondary electrons leave the wall
- after a given number of impacts N the No. of free electrons and their avg. impact energy and the No. of secondary electrons is calculated

Counter function

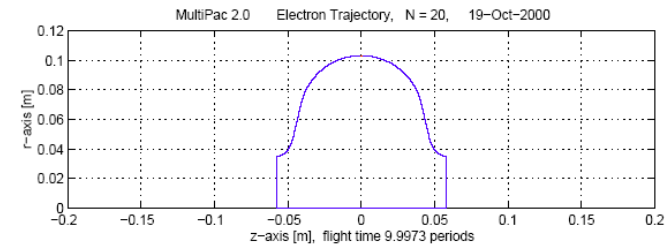
Enhanced counter function

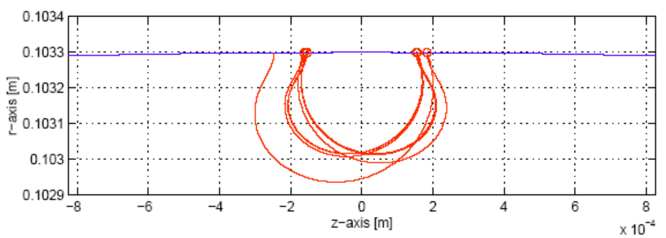
Counter function: field levels at which resonant conditions are satisfied

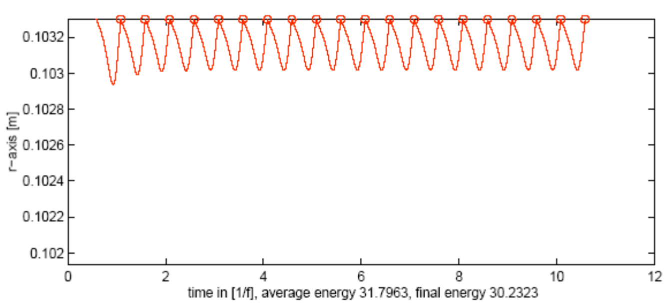
At field levels where Enhanced counter function > No. initial electrons: Multipacting

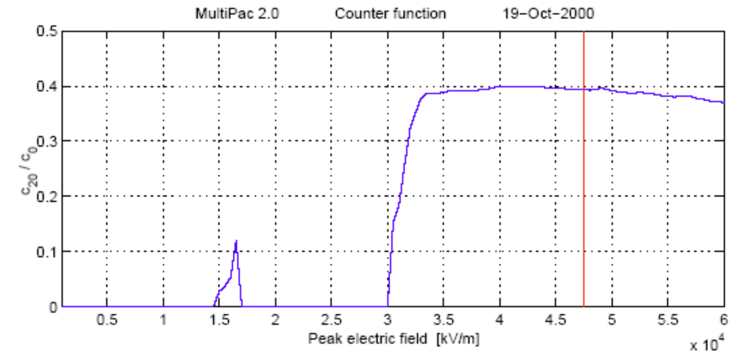
# MultiPac

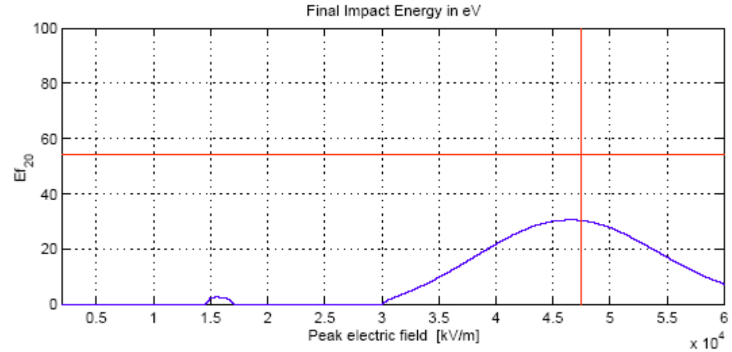
- 2D code, has it's own FEM field solver
- Runs on Linux
- MATLAB user interface

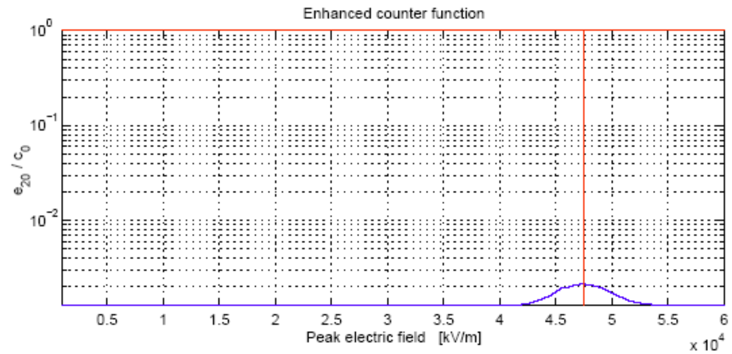


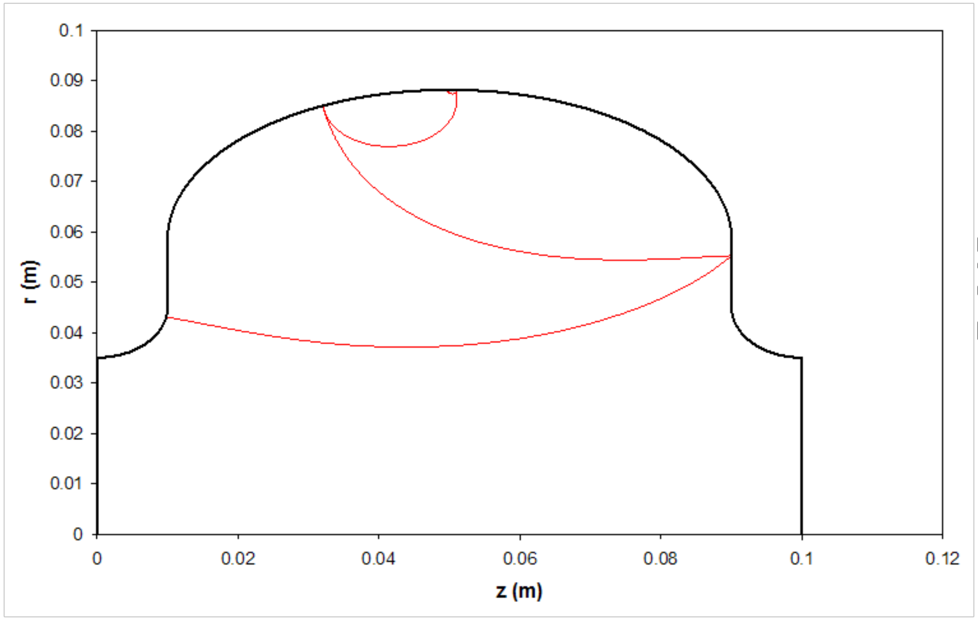



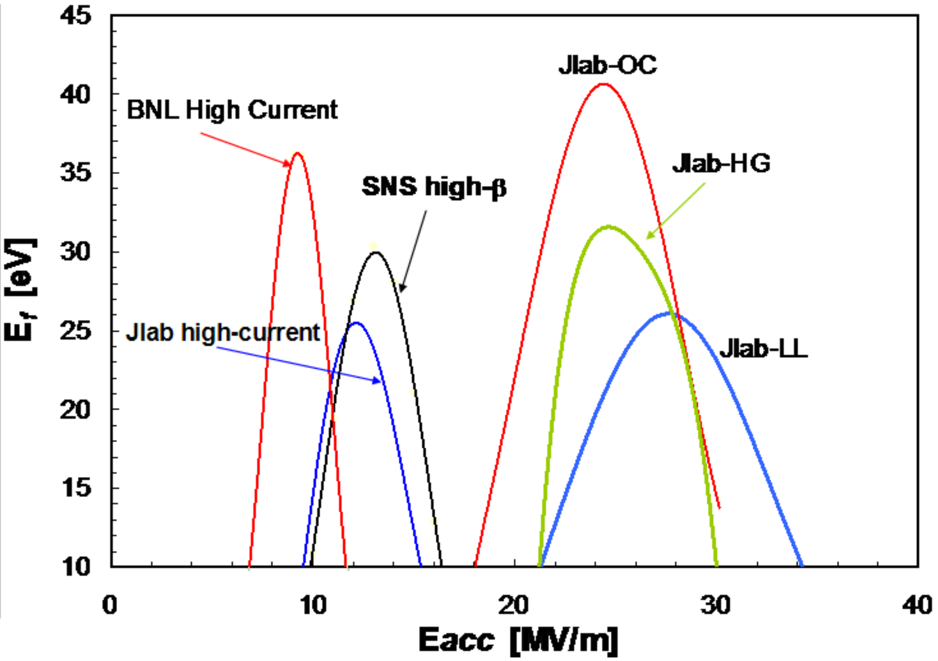



# FishPact

- 2D code, uses SUPERFISH to compute surface fields
- Runs on PC

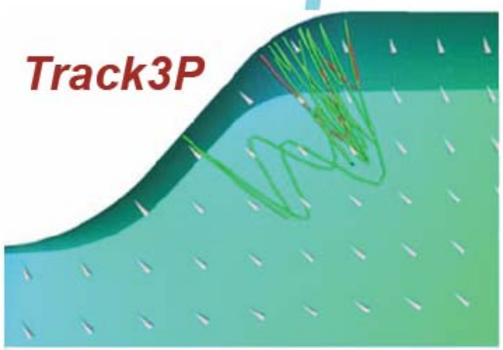


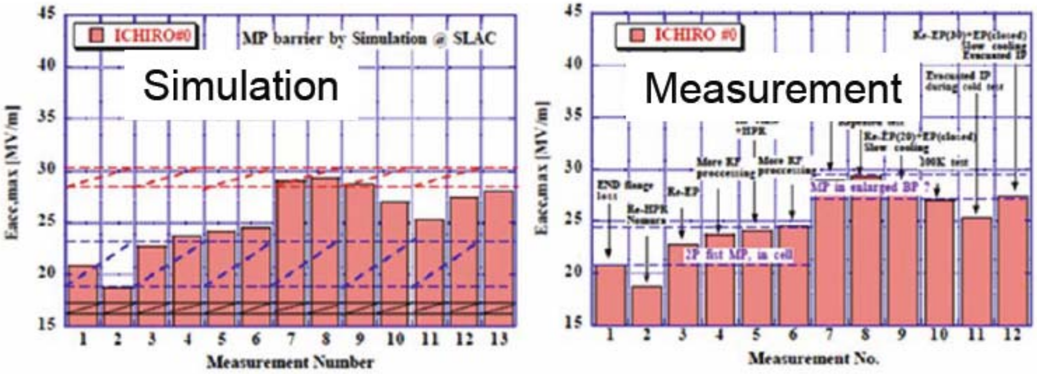



# Track3P

- 3D code, uses Omega3P for field solver
- Runs on Supercomputer, user interface not fully developed

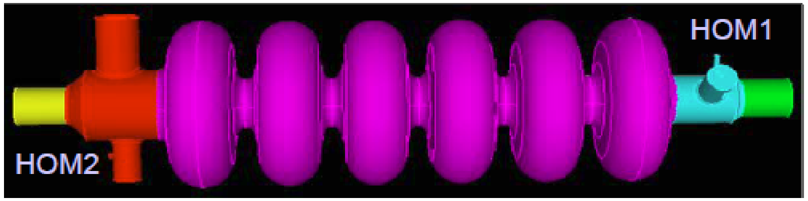
*Example*: Multipacting found in beam pipe step of LL cavity



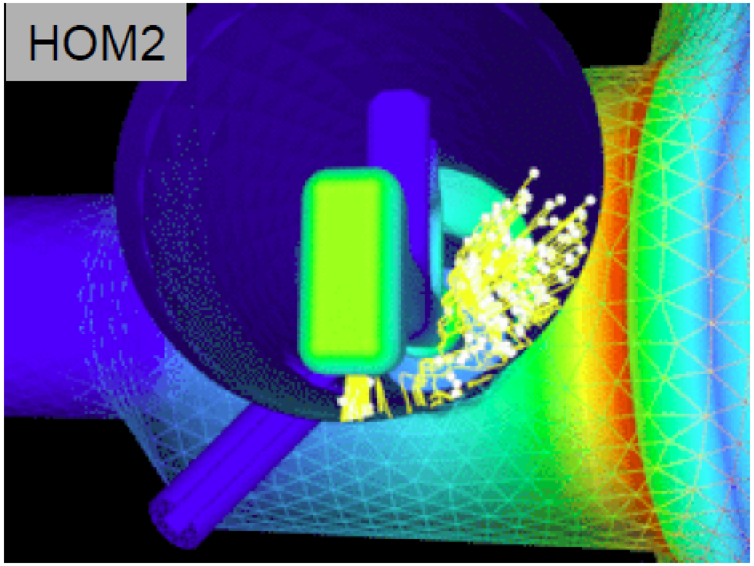



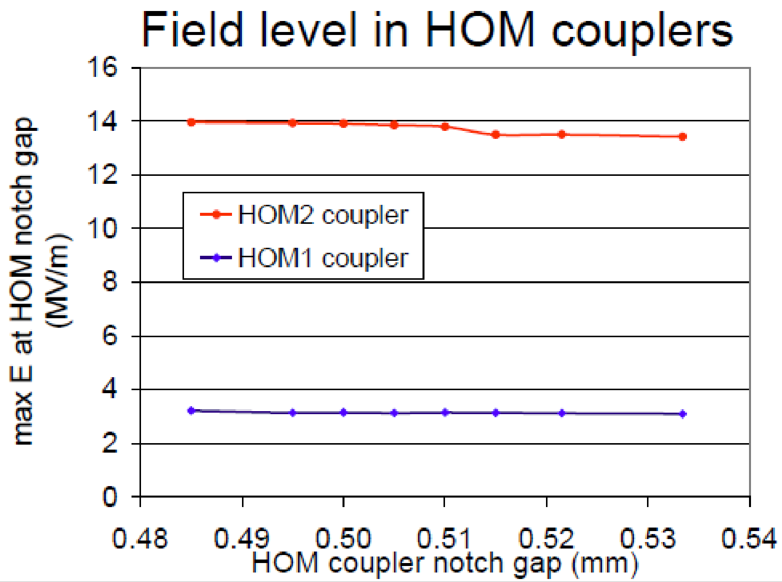

(Left) MP barriers in 9-cell ICHIRO cavity calculated with Track3P, (Right) MP barriers measured on ICHIRO prototype (K.

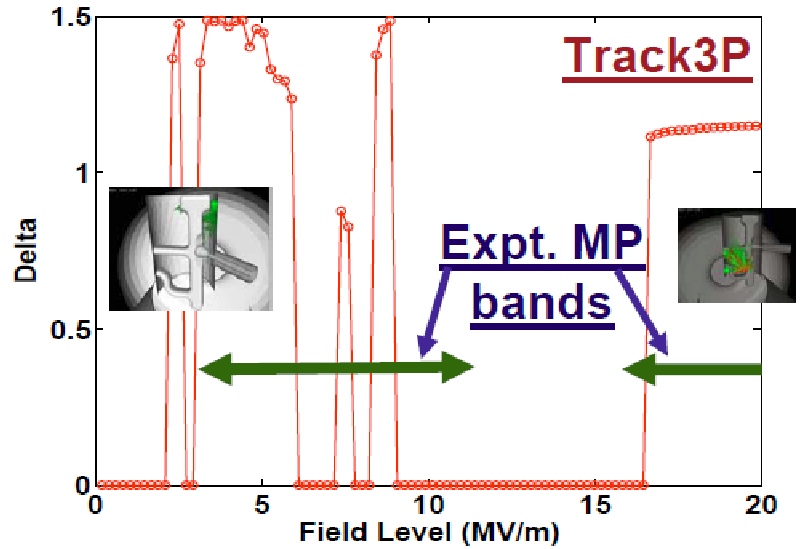
# Example: Multipacting in SNS HOM Coupler




- SNS SCRF cavity experienced RF heating at HOM coupler
- 3D MP simulations showed MP barriers closed to measurements
- Similar analysis are carried out for ILC ICHIRO and crab cavity



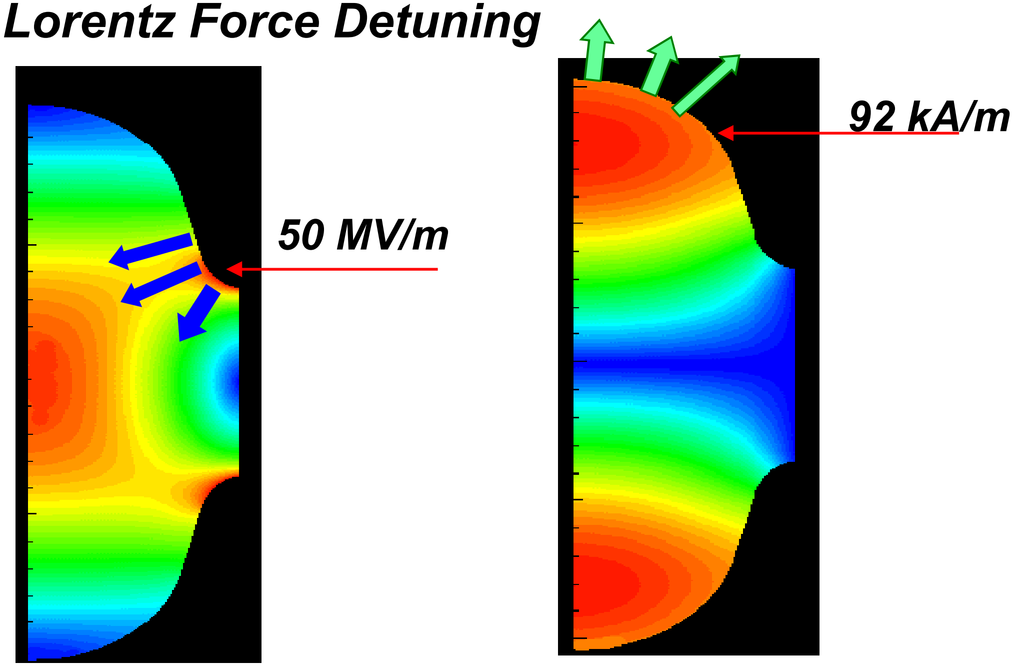
# Mechanical Design

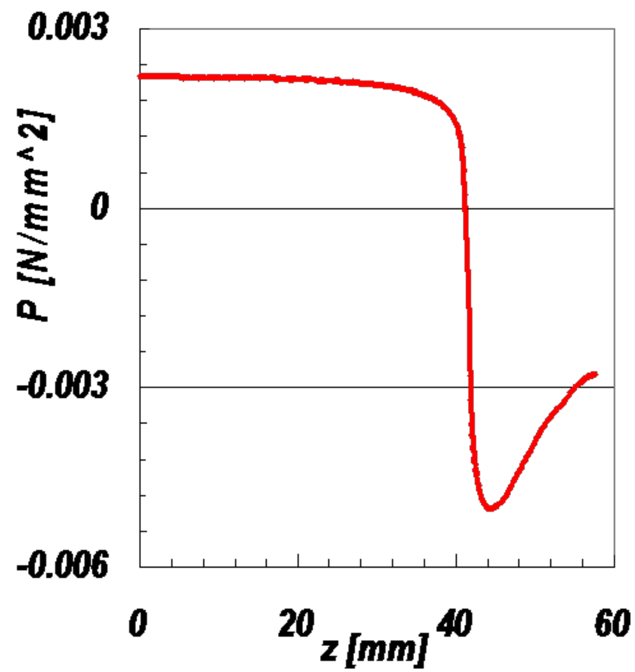
**The mechanical design of a cavity follows its RF design:**

- **Lorentz Force Detuning**
- **Mechanical Resonances**

$$P = \frac{\mu_0 H_s^2 - \varepsilon_0 E_s^2}{4}$$

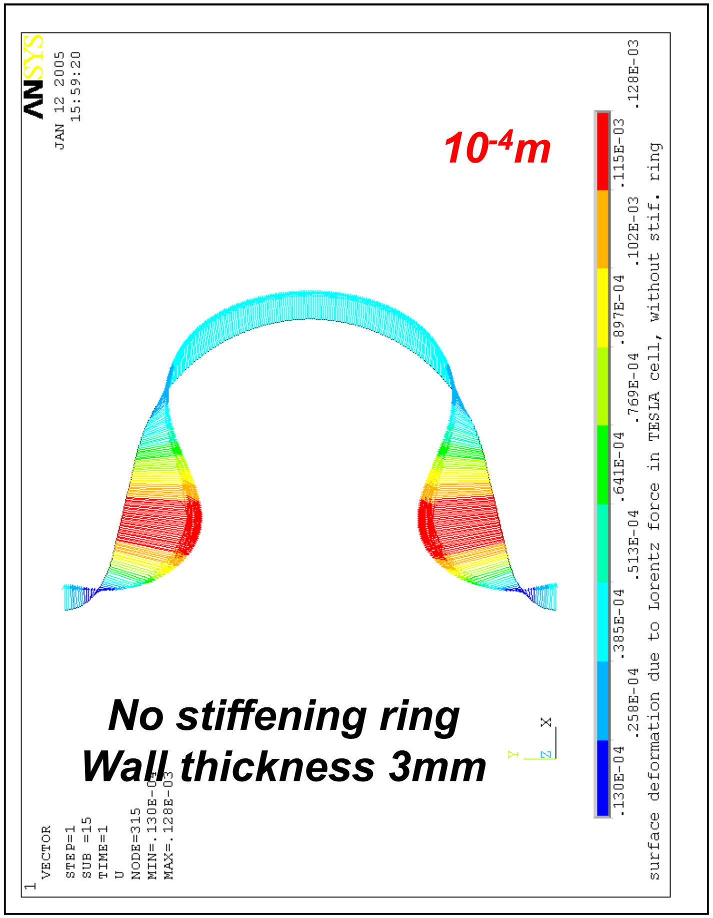
***Lorentz Force Detuning***

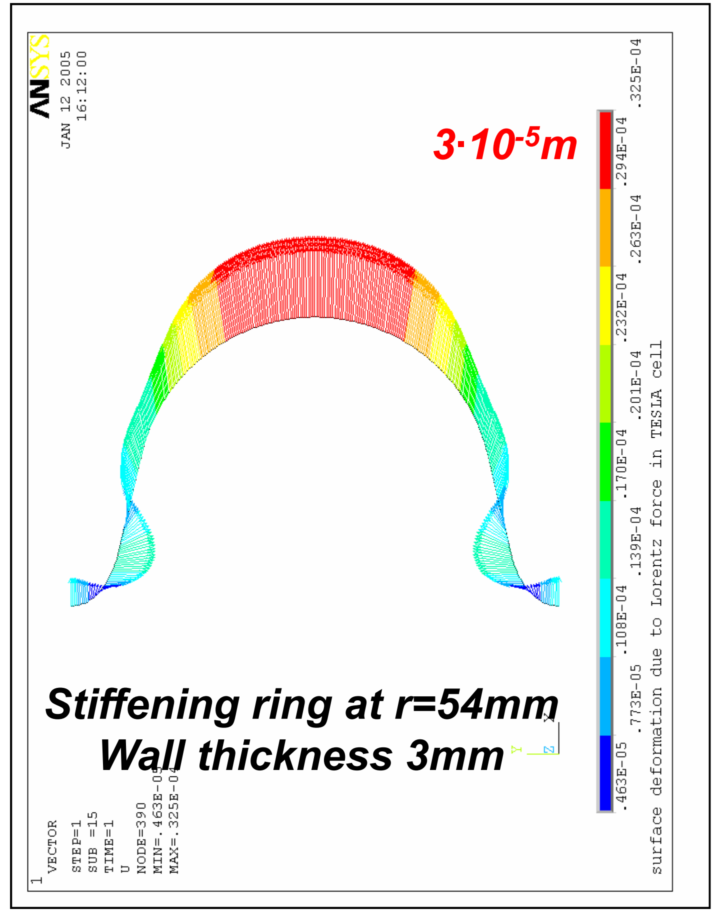



***E and H at $E_{acc}$ = 25 MV/m in TESLA inner-cup***

# Mechanical Design



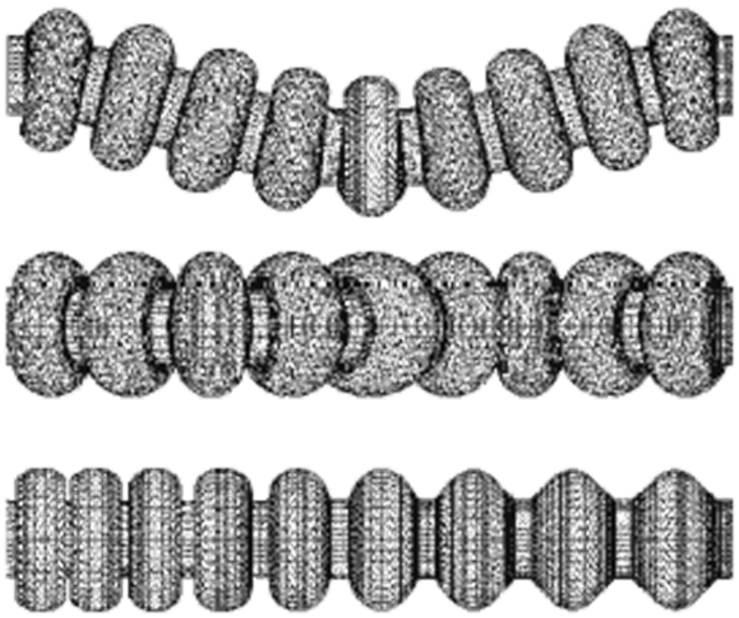

***Essential for the operation of a pulsed accelerator***

$$\Delta f = k_L (E_{acc})^2$$

$$k_L = -1\ \mathrm{Hz/(MV/m)^2}$$

# Mechanical Design

***Mechanical Resonances of a multi-cell cavity***



***60 Hz***

***152 Hz***

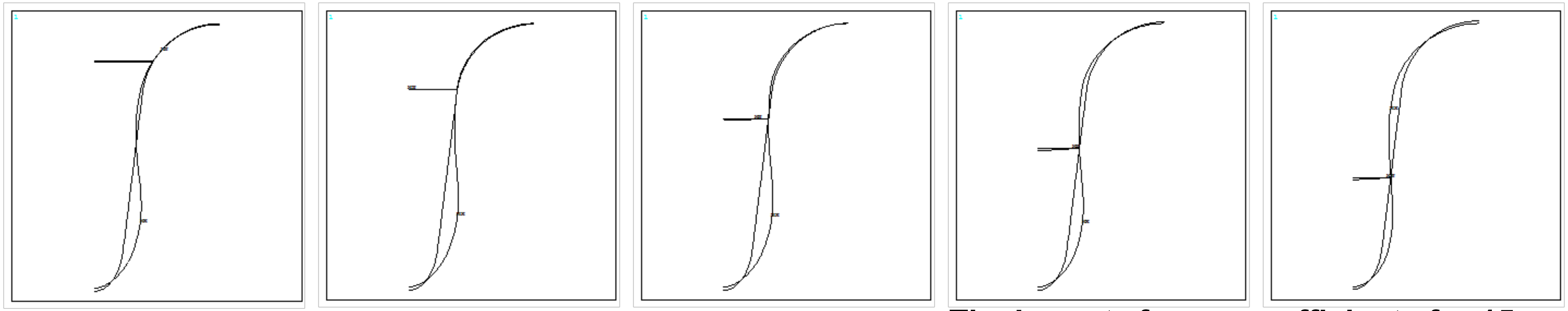
***Transverse modes***

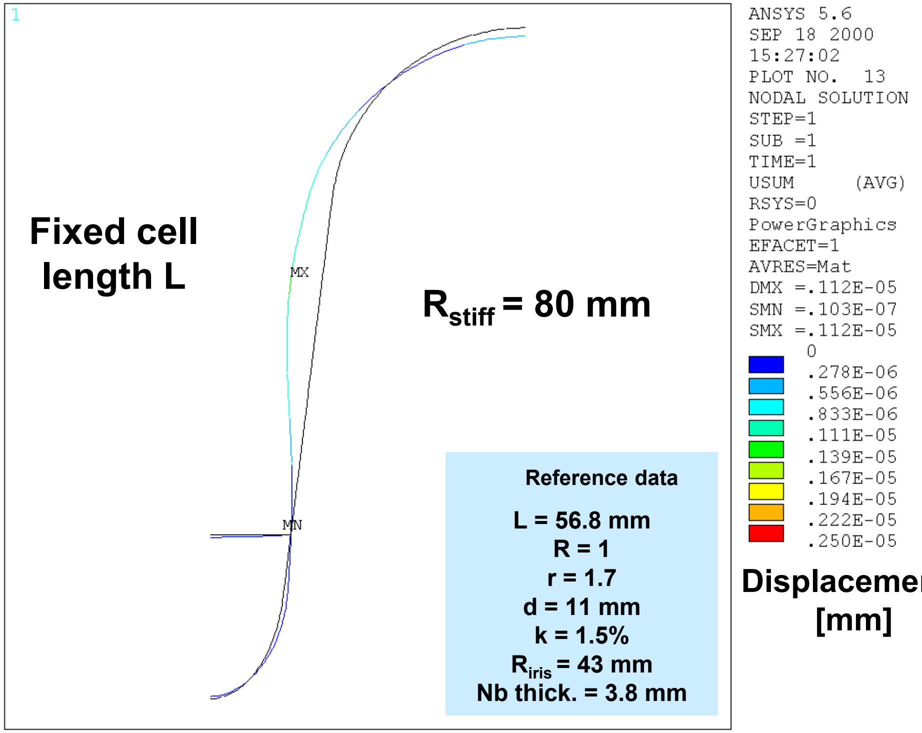
***250 Hz*** ***Longitudinal mode***

***TESLA structure***

***The mechanical resonances modulate frequency of the accelerating mode.***
***Sources of their excitation: vacuum pumps, ground vibrations…***

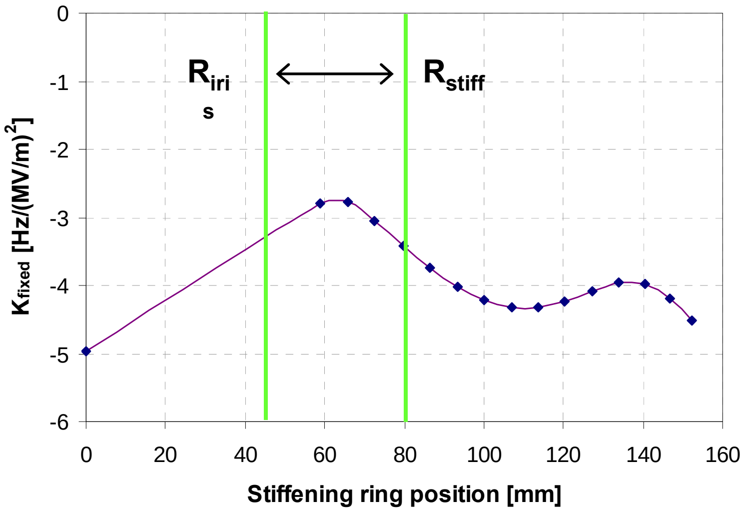
# Optimal stiffening ring position





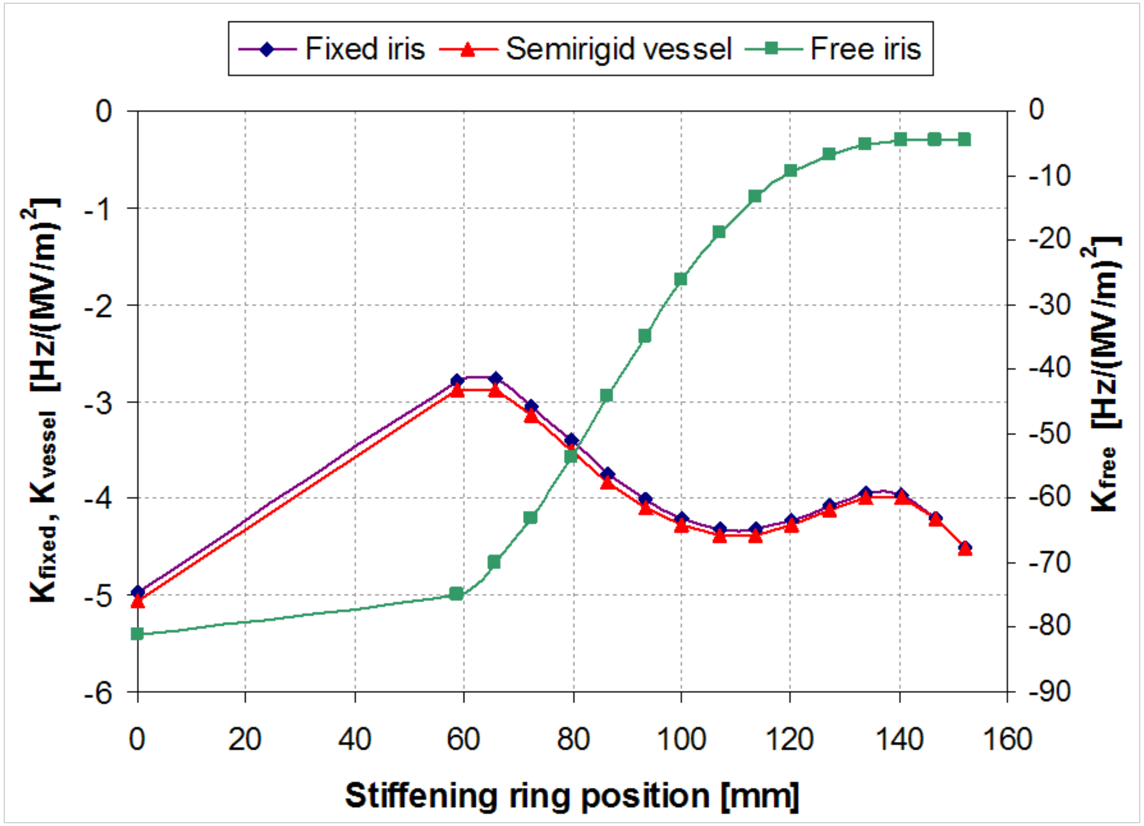

Displacements [mm]

The Lorentz forces coefficients for 15 different stiffening ring positions are evaluated automatically with ANSYS, preparing the geometry and reading the fields from the SFO output from SUPERFISH



# KL for different boundary conditions

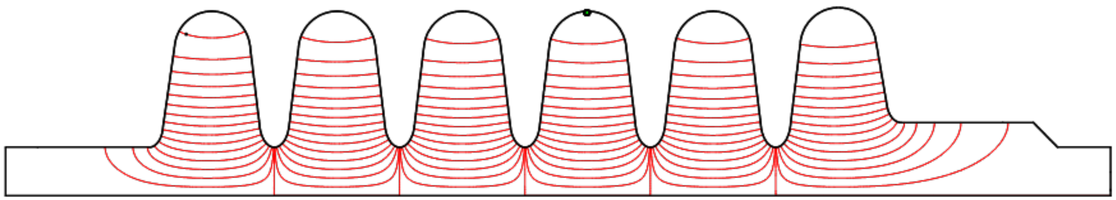
- The estimate for KL strongly depends on the cell boundaries. We compute it for 3 different cases:
  - Fixed cell length
  - Free cell length
  - Helium Vessel/Tuning System (= 3 tubes with diameter 30 mm and thickness 2 mm)



# $\beta_g$ = 0.61 Cavity for SNS

**Effective $\beta$ that matches the TTF curve = 0.630**

| | |
|---|---|
| $E_p/E_{acc}$ | 2.72 (2.63 inner cell) |
| $B_p/E_{acc}$ [mT/(MV/m)] | 5.73 (5.44 inner cell) |
| R/Q [Ω] | 279 |
| G [Ω] | 214 |
| k [%] | 1.53 |
| $Q_{BCS}$ @ 2 K [$10^9$] | 27.8 |
| Frequency [MHz] | 805.000 |
| Field Flatness [%] | 2 |



KL70 = -2.9 [Hz/(MV/m)$^2$]  KL80 = -3.4 [Hz/(MV/m)$^2$]

**Nb thickness = 3.8 mm-**

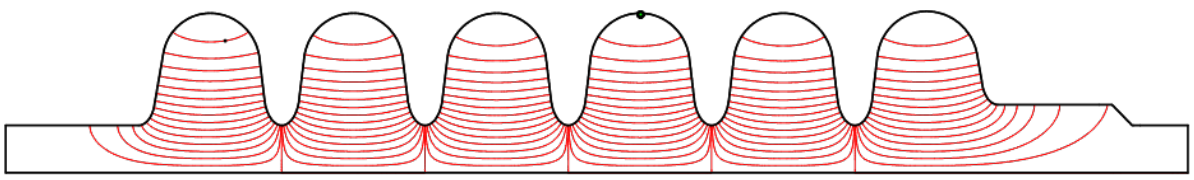
## Geometrical Parameters

| | Inner cell | End Cell Left | End Group (coupler) Left | End Group (coupler) Right |
|---|---|---|---|---|
| L [cm] | 5.68 | 5.68 | 5.68 | |
| $R_{iris}$ [cm] | 4.3 | 4.3 | 4.3 | 6.5 |
| D [cm] | 16.376 | 16.376 | 16.698 | |
| d [cm] | 1.1 | 1.0 | 1.1 | 1.0 |
| r | 1.7 | 1.5 | 1.7 | 1.5 |
| R | 1.0 | 1.0 | 1.0 | |
| α [deg] | 7.0 | 8.36 | 7.0 | 10.0 |

# $\beta_g$ = 0.81 Cavity for SNS

**Effective $\beta$ that matches the TTF curve = 0.832**

| | |
|---|---|
| $E_p/E_{acc}$ | 2.19 (2.14 inner cell) |
| $B_p/E_{acc}$ [mT/(MV/m)] | 4.72 (4.58 inner cell) |
| R/Q [$\Omega$] | 484.8 |
| G [$\Omega$] | 233 |
| k [%] | 1.52 |
| $Q_{BCS}$ @ 2 K [$10^9$] | 36.2 |
| Frequency [MHz] | 805.004 |
| Field Flatness [%] | 1.1 |



**KL70 = -0.7 [Hz/(MV/m)$^2$]** **KL80 = -0.8 [Hz/(MV/m)$^2$]**

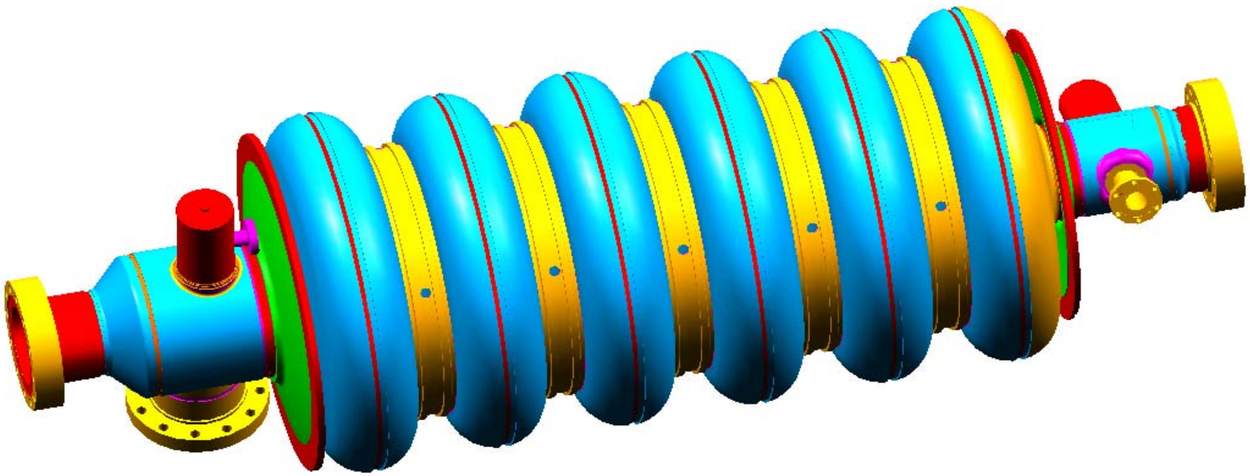
**Nb thickness = 3.8 mm-**

## Geometrical Parameters

| | Inner cell | End Cell Left | End Group (coupler) Left | End Group (coupler) Right |
|---|---|---|---|---|
| L [cm] | 7.55 | 7.55 | 7.55 | |
| $R_{iris}$ [cm] | 4.88 | 4.88 | 4.88 | 7.0 |
| D [cm] | 16.415 | 16.415 | 16.611 | |
| d [cm] | 1.5 | 1.3 | 1.5 | 1.3 |
| r | 1.8 | 1.6 | 1.8 | 1.6 |
| R | 1.0 | 1.0 | 1.0 | |
| $\alpha$ [deg] | 7.0 | 10.072 | 7.0 | 10.0 |

# Stress and Modal Analysis

- Nominal Medium Beta Cavity



# SNS Cavity Modal Analysis

Medium Beta Cavity

| End Condition | Load (atm) | 127 mm Rings (Hz) | 70 mm Rings (Hz) | No Rings (Hz) |
|---|---|---|---|---|
| Fixed-Guided | - | 85 | 48 | 38 |
| Fixed-Fixed | - | 126 (*204) | 57 (*59) | 48 (*42) |
| Fixed-Fixed Mid Supt | - | 149 (*220) | 95 (~*108) | 88 |
| Compressed 0.4mm | 1.65 | 125 | - | 46 |
| Compressed 1.25 mm | 1.65 | 124 | - | 46 |
| | | | | |

(*D. Schrage, LANL)

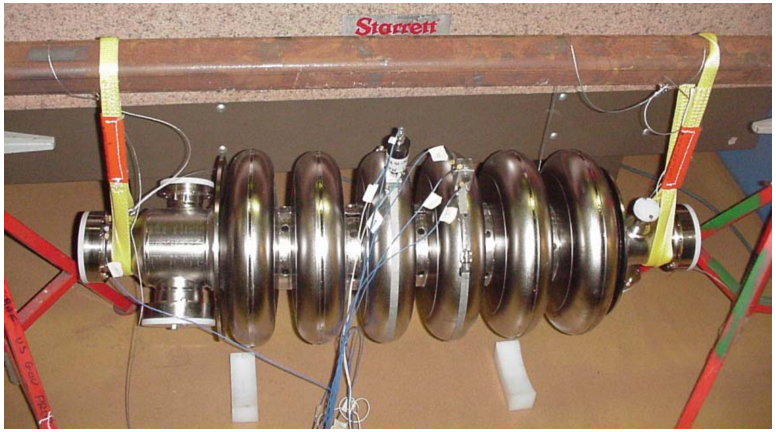
(~ Beta = 0.76)

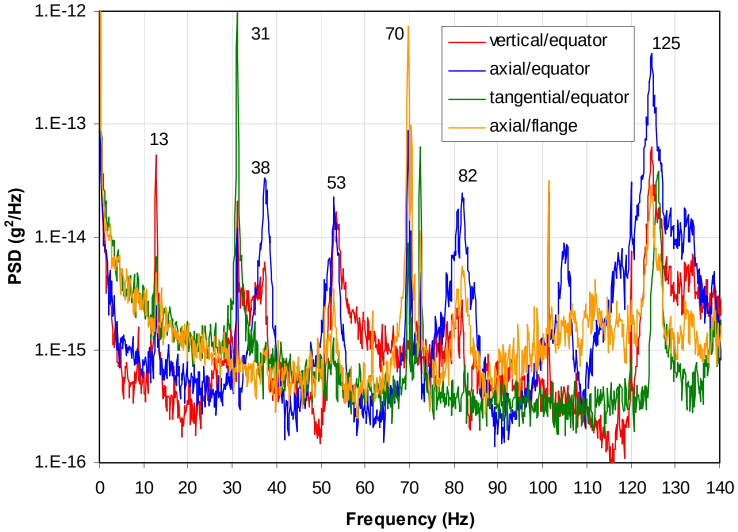
# SNS Cavity Modal Analysis

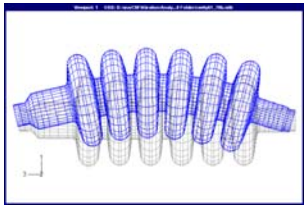
## High Beta Cavity

| End Condition | Load (atm) | 127 mm Rings (Hz) | 70 mm Rings (Hz) | No Rings (Hz) |
|---|---|---|---|---|
| Fixed-Fixed | - | 120 | - | 46 |
| Fixed-Guided | - | 107 | - | 34 |
| Compressed 0.4mm | 1.65 | 120 | - | 44 |
| Compressed 1.25 mm | 1.65 | 119 | - | 44 |
| | | | | |
| | | | | |

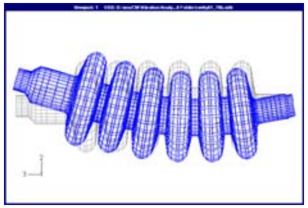
# Mode Analysis, Beta = 0.81



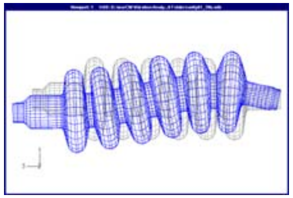



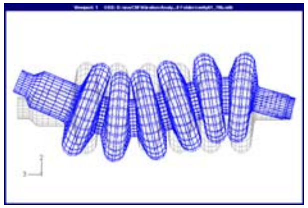
Mode 1 – 14 Hz



Mode 2 – 26 Hz



Mode 3 – 40 Hz



Mode 5 – 72 Hz

| | Natural Frequency (Hz) | |
|---|---|---|
| Mode | Test Data | FE Analysis |
| 1 | 13 | 14 |
| 2 | 31 | 26 |
| 3 | 38 | 40 |
| 4 | 53 | 48 |
| 5 | 70 | 72 |
| 6 | 82 | 83 |
| 7 | 125 | 124 |

# SNS Cavity Mechanical Design Requirements

- Minimize/prevent microphonics
- Withstand loss of vacuum accident up to 5 atm
- Withstand cool down at 1.65 atm
- Adhere to intent of ASME B&P Code
  - Allowable Stress (Sm) = 2/3 Yield Stress
  - Primary Membrane Stress (Pm) <= (Sm)
  - Pm + Bending <= 1.5*Sm
  - Pm + Bending + Secondary Stress <= 3*Sm
    - Allowable Stresses
      - » **Warm Niobium = 4,667 psi**
      - » **Cold Niobium = 53,333 psi**

# Medium Beta Stress Analysis

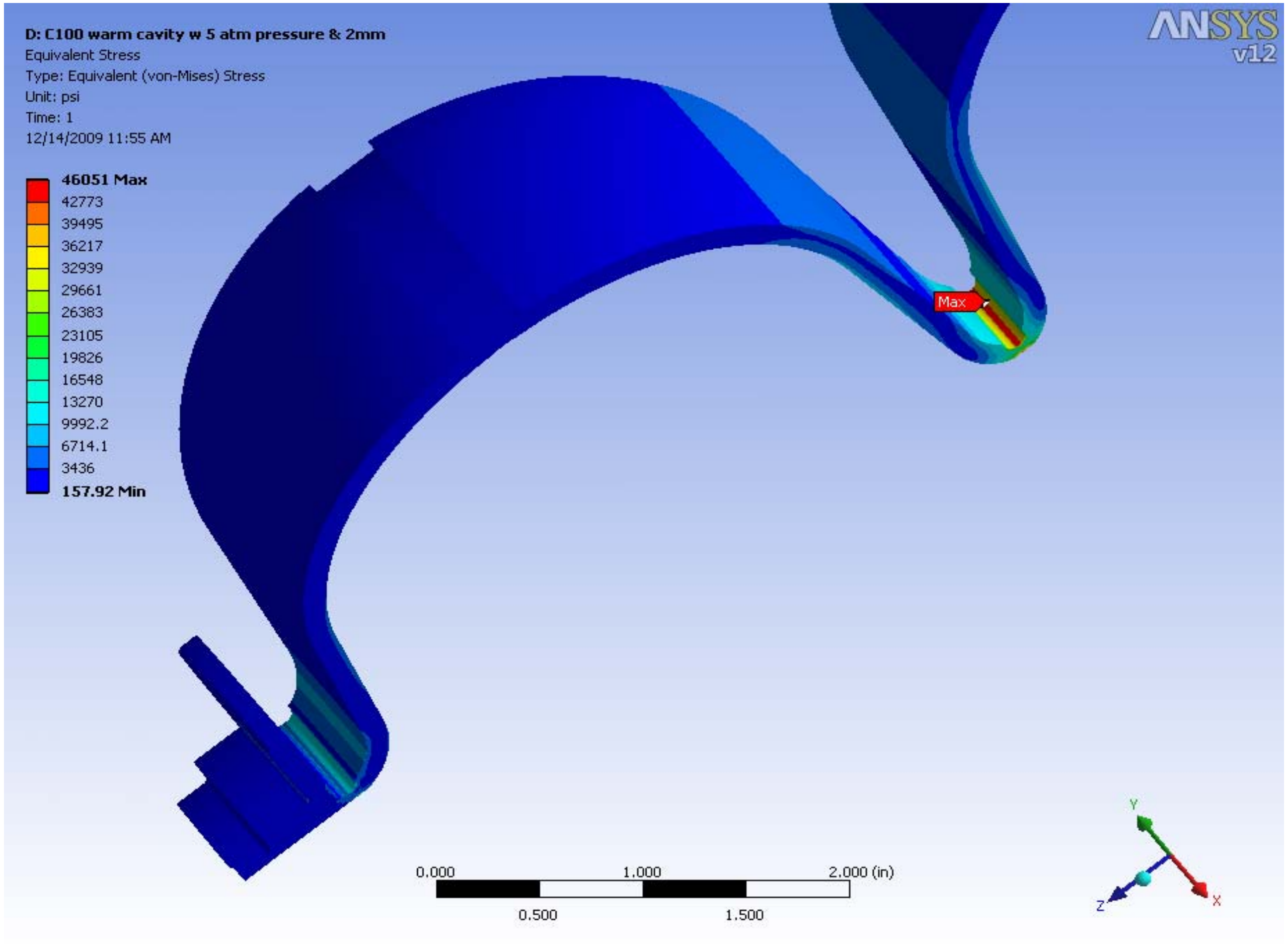
| SNS Medium Beta Cavity Wall Stresses | | | | |
|---|---|---|---|---|
| Compression (mm/end) | Loads (atm) | 127 mm Stiffening Ring Max Stress (psi) | 70 mm Stiffening Ring Max Stress (psi) | No Stiffening Ring Max Stress (psi) |
| 0.2 | 1.65 | - | - | - |
| 0.4 | 1.65 | 3,960 | - | 4,310 |
| 0.5 | 1.65 | 4,610 | - | 4,550 |
| 0.75 | 1.65 | 7,500 | - | 4,670 |
| 1.25 | 1.65 | 17,500 | 5,730 (1.8 atm) | 5,000 |
| 0.75 | 5 | 11,200 | - | 12,900 |
| 1.25 | 5 | 14,300 | 10,100 | 47,100 |

# High Beta Stress Analysis

| SNS High Beta Cavity Wall Stresses | | | | |
|---|---|---|---|---|
| Compression (mm/end) | Loads (atm) | 127 mm Stiffening Ring Max Stress (psi) | 70 mm Stiffening Ring Max Stress (psi) | No Stiffening Ring Max Stress (psi) |
| 0.2 | 1.65 | 3,040 | - | - |
| 0.4 | 1.65 | 6,350 | - | 3,140 |
| 0.5 | 1.65 | 8,070 | - | 3,350 |
| 0.75 | 1.65 | 12,500 | - | 3,940 |
| 1.25 | 1.65 | 21,400 | - | 5,830 |
| 0.75 | 5 | 11,500 | - | 9,130 |
| 1.25 | 5 | 14,300 | - | 9,590 |

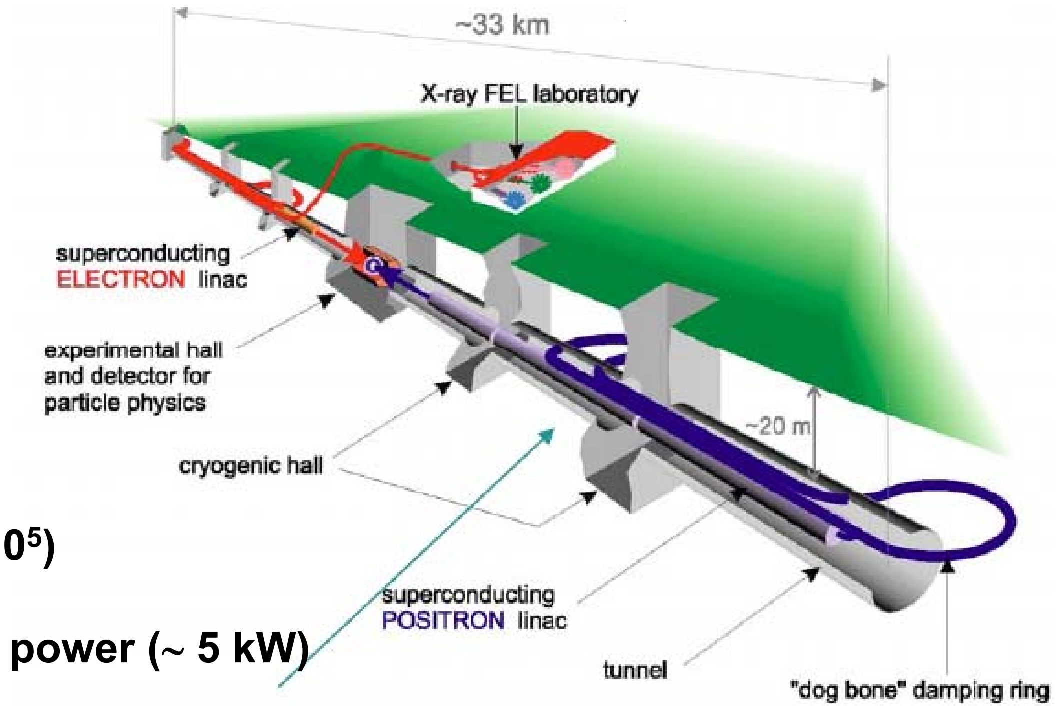
# Mechanical analysis tools

- ANSYS: FEM multiphysics solver




**Peak von Mises stress in cold cavity with 5 atm pressure and 2 mm tuning displacement, calculated on CEBAF LL Upgrade cavity**

# Pulsed LINACs (ILC, XFEL)

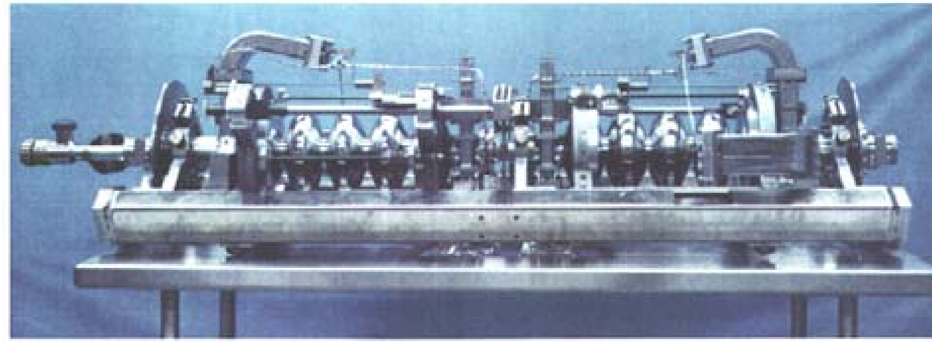



- **High gradient (≥ 25 MV/m)**
- **Moderate HOM damping ($Q_{ext} = 10^4 – 10^5$)**
- **High peak (> 250 kW), low average RF power (~ 5 kW)**

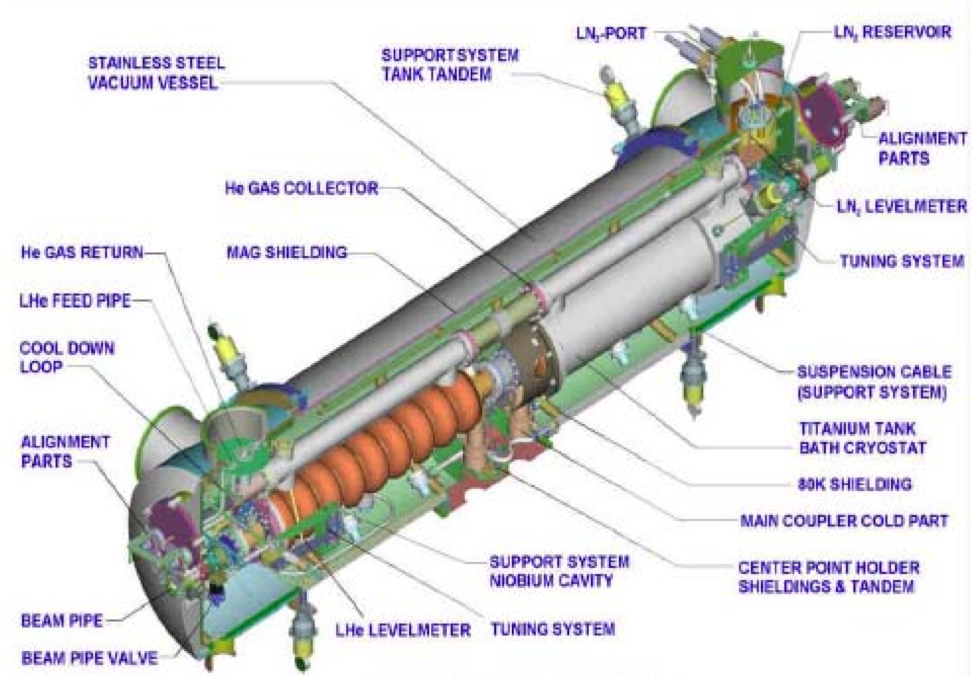
ILC: 21,000 cavities!

# CW Low-Current LINACs (CEBAF, ELBE)

- Moderate to low (8 – 20 MV/m)
- Relaxed HOM damping requirements
- Low average RF power (5 – 13  kW)



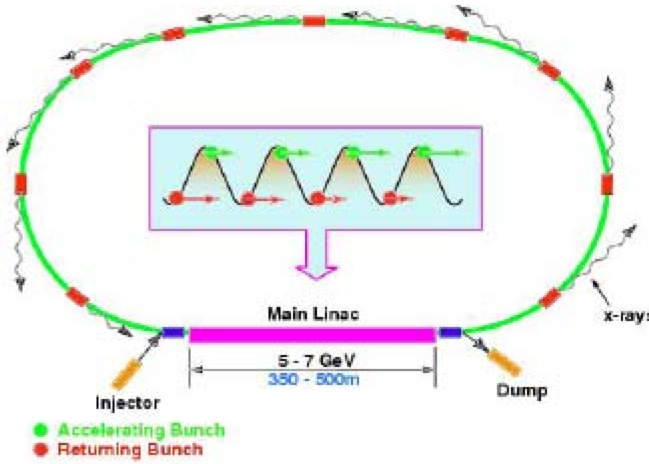
CEBAF cavities

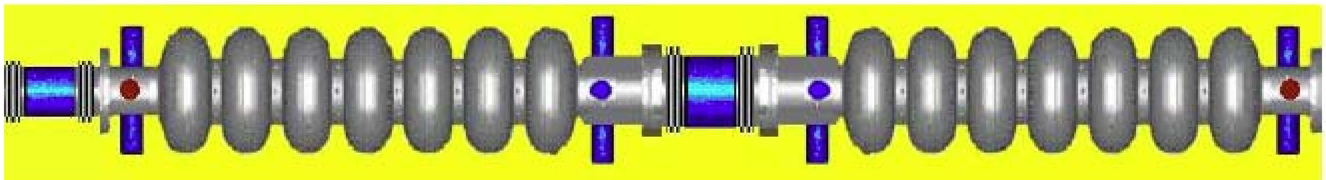



ELBE cryomodule

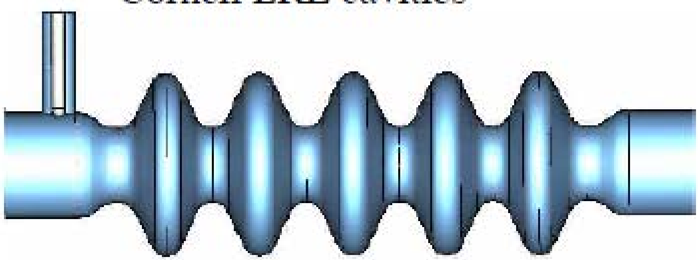
# CW High-Current ERLs

- Moderate gradient (≥ 15 - 20 MV/m)
- Strong HOM damping ($Q_{ext} = 10^2 – 10^4$)
- Low average RF power (few kW)



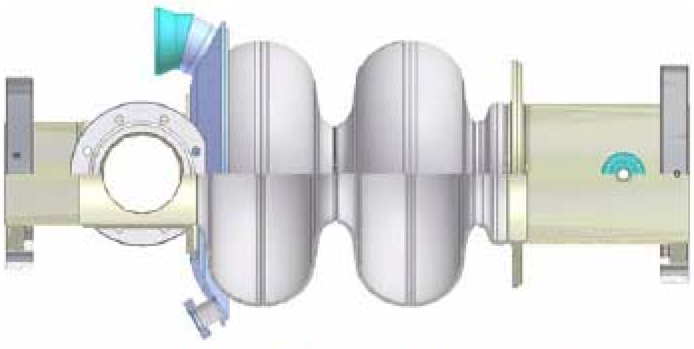
Cornell ERL cavities



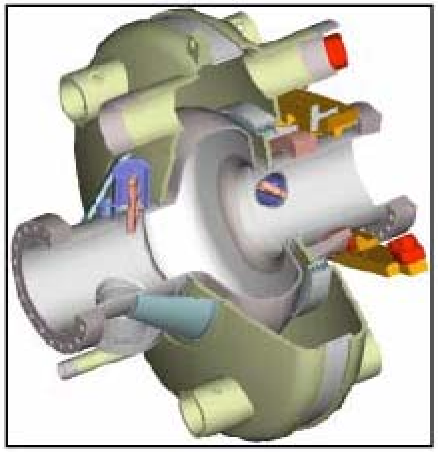
BNL ERL cavity

# CW High-Current Injectors for ERLs

- Moderate to low gradient (5 - 15 MV/m)
- Strong HOM damping ($Q_{ext} = 10^2 – 10^4$)
- High average RF power (50 - 500 kW)



Cornell ERL injector cavity



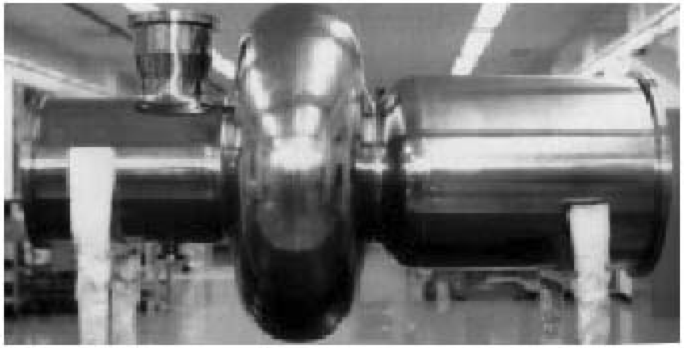
JLab FEL 100 mA injector cavity

# CW High-Current Storage Rings

- Relatively low gradient (5 - 9 MV/m)
- Strong HOM damping ($Q_{ext} \sim 10^2$)
- High average RF power (up to 390 kW)

CESR cavities

LHC cavity



KEK cavity