TM-CLASS CAVITY DESIGN

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Outline

- "Pill-box" cavity
- Cell shape design
  - EM design
  - Multipacting analysis
- Multi-cell cavity design
  - HOM analysis
  - Mechanical analysis

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Simplest case: "Pill-box" cavity
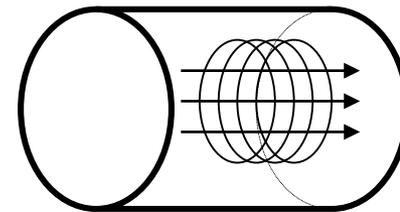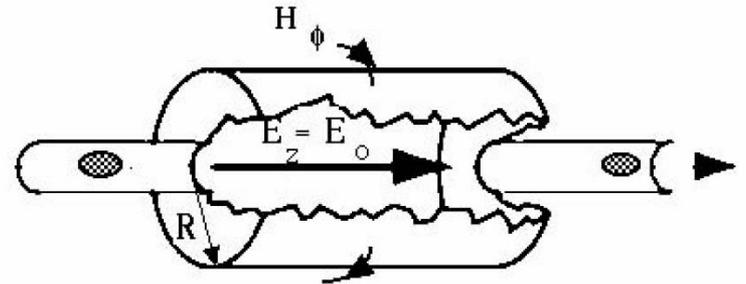
Hollow right cylindrical enclosure

Operated in the TM$_{010}$ mode

TM$_{010}$ mode

$$E_z = E_0 J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}$$

$$H_\phi = -i\frac{E_0}{\eta} J_1\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}$$

$$\omega_{010} = \frac{2.405c}{R} \qquad \eta = \sqrt{\frac{\mu_0}{\epsilon_0}}$$

Modes in Pill Box Cavity

- **E.m. field in the cavity is solution to the wave equation**

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \begin{Bmatrix} \mathbf{E} \\ \mathbf{H} \end{Bmatrix} = 0 \qquad \hat{n} \times \mathbf{E} = 0, \quad \hat{n} \cdot \mathbf{H} = 0$$

- **TM_{010}**
  - **Electric field is purely longitudinal**
  - **Electric and magnetic fields have no angular dependence**
  - **Frequency depends only on radius, independent on length**
- **TM_{0np}**
  - **Monopoles modes that can couple to the beam and exchange energy**
- **TM_{1np}**
  - **Dipole modes that can deflect the beam**
- **TE modes**
  - **No longitudinal E field**
  - **Can be used to deflect beam**

TM Modes in a Pill Box Cavity

The TM solution to the wave equation in cylindrical coordinates has the form:
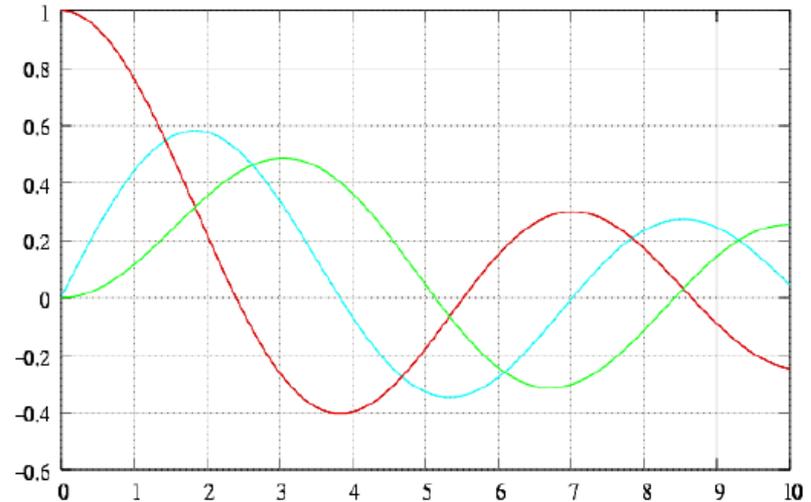
$$E_z \propto J_m(k_{mn}r) \quad \cos m\theta \quad \cos k_z z$$
$$E_r \propto p\, J'_m(k_{mn}r) \quad \cos m\theta \quad \sin k_z z$$
$$E_\theta \propto \frac{p}{r} J_m(k_{mn}r) \quad \sin m\theta \quad \sin k_z z$$

$$B_z = 0$$
$$B_r \propto -\frac{i}{r} J_m(k_{mn}r) \quad \sin m\theta \quad \cos k_z z$$
$$B_\theta \propto -i\, J'_m(k_{mn}r) \quad \cos m\theta \quad \cos k_z z$$

m, n, p are integers that describe the mode of the solution.
The J_m are Bessel functions of the first kind. J'_m is the derivative of the Bessel function.

$$k_z = \frac{\pi p}{L_{cav}}, \qquad \frac{\omega^2}{c^2} = k_{mn}^2 + k_z^2 \qquad J'_0(z) = -J_1(z), \quad J'_1(z) = J_0(z) - \frac{1}{z}J_1(z), \ldots$$
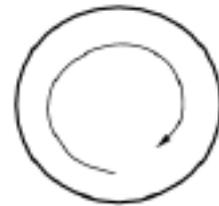
$k_{mn} = u_{mn}/R$, where u_{mn} is the nth root of $J_m(x)$

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TM mode indices *mnp*

The modes are described by three indices.

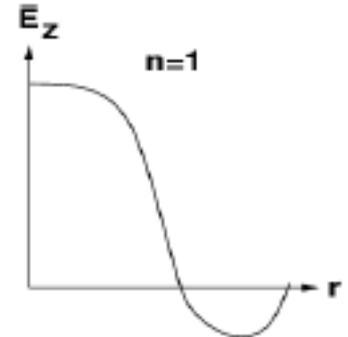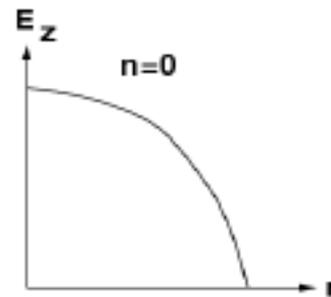m is the number of variation of field of the azimuthal variable ϕ:
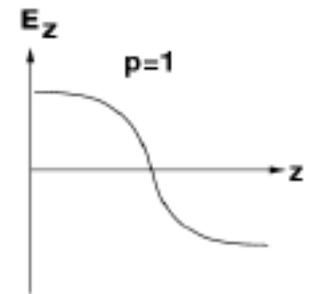
m = 0, 1, 2, ...

m = 0   m = 1

n is the number of nulls in E_z along the radial direction

n = 1, 2, 3, ...

E_z n=0 E_z n=1

p is the number of nodes of E_z along the z-axis.

p = 0, 1, 2, ...

E_z p=0 E_z p=1

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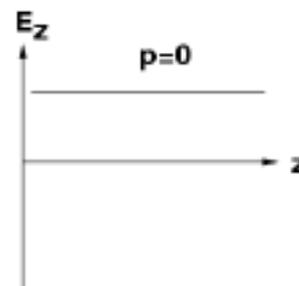
TM$_{010}$ Mode in a Pill Box Cavity

Energy content

$$U = \frac{1}{2}\varepsilon_0 E_0^2 \pi J_1^2(x_{01}) L R^2$$

Power dissipation

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

$x_{01} = 2.40483$

$J_1(x_{01}) = 0.51915$

Geometrical factor

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

TM$_{010}$ Mode in a Pill Box Cavity

Voltage Gain

$$V_c = LE_0 \frac{\sin\left(\frac{\pi L}{\lambda}\right)}{\frac{\pi L}{\lambda}}$$

Gradient

$$E_{acc} = \frac{V_c}{L}$$

Shunt impedance

$$R_a = \frac{4\eta^2 L^2}{\pi^3 R_s J_1^2(x_{01}) R(R+L)} \qquad\qquad R_a/Q_0 \text{ is independent of } R_s$$
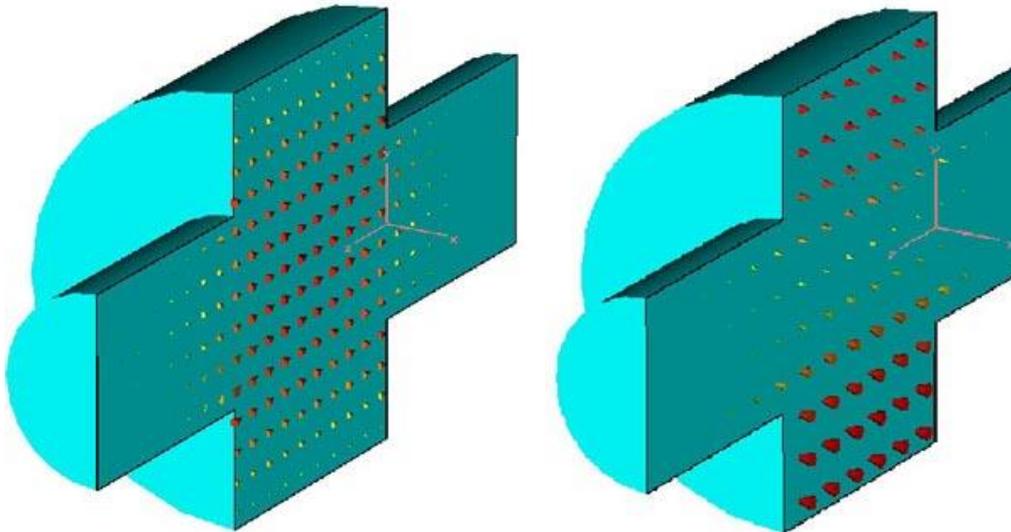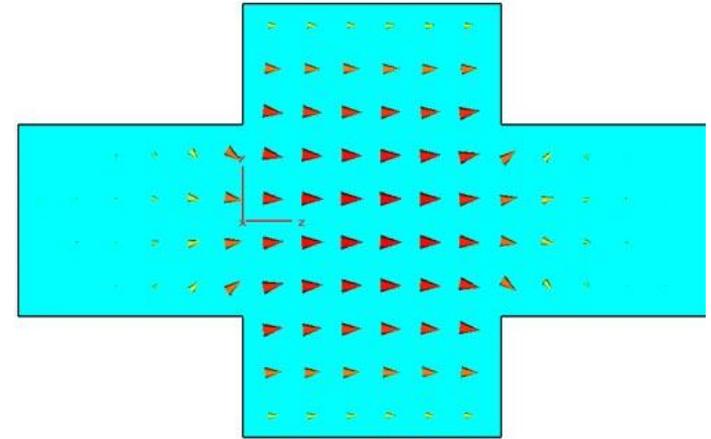
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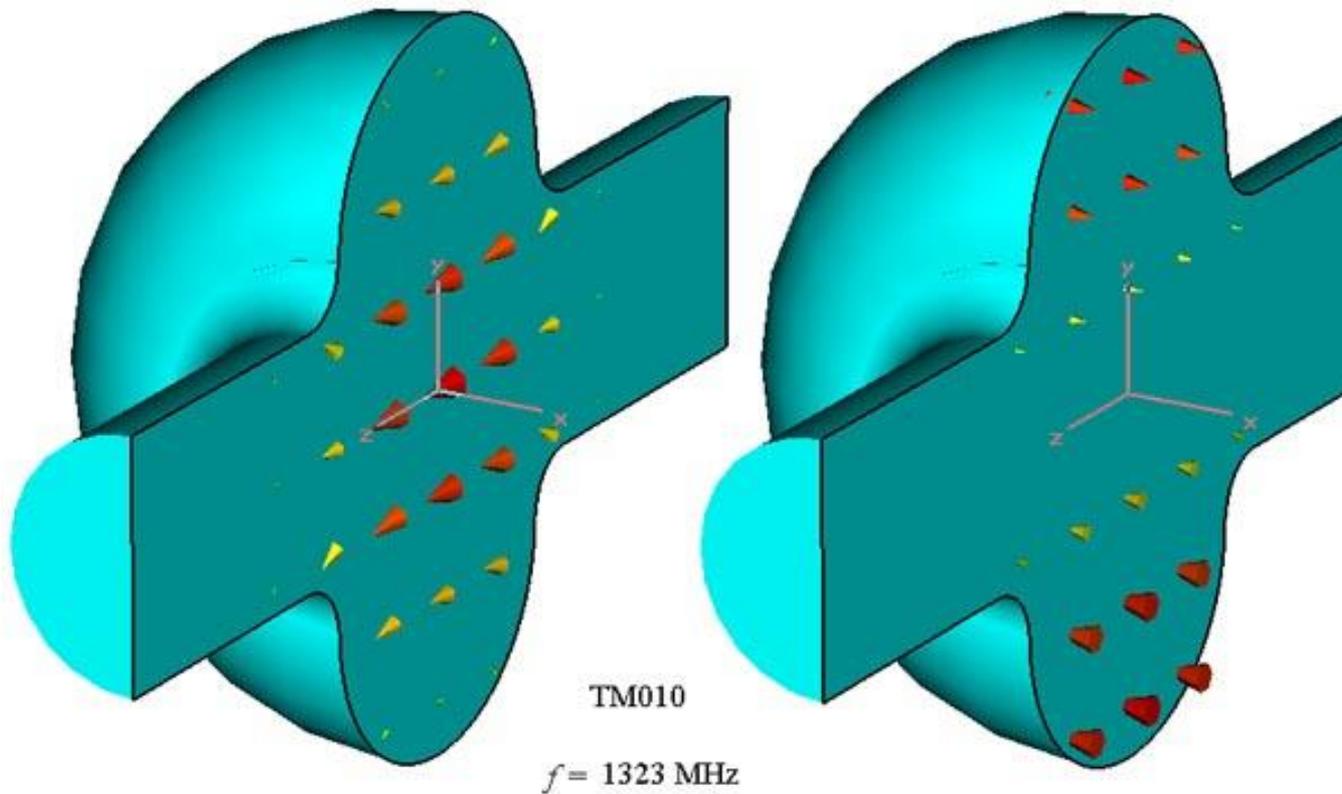
Real Cavities

Beam tubes reduce the electric field on axis
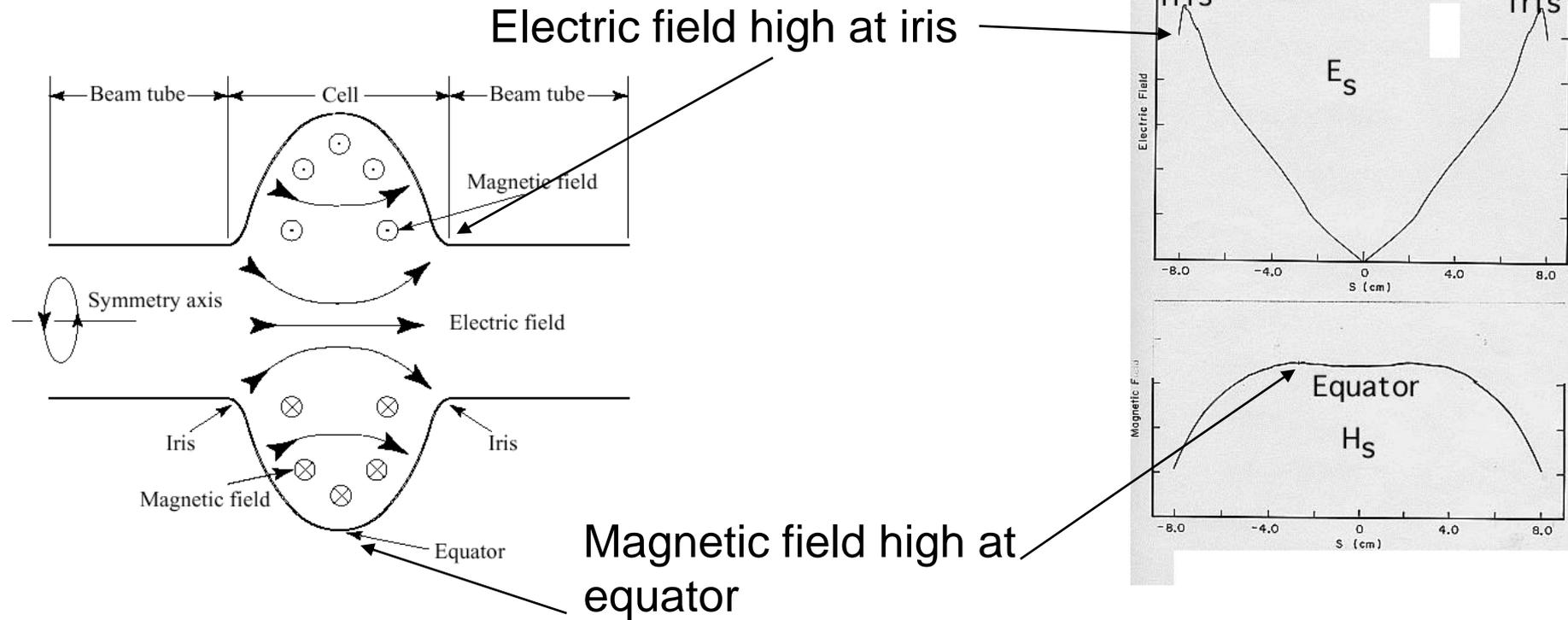
Gradient decreases

Peak fields increase

R/Q decreases

Real Cavities

TM010

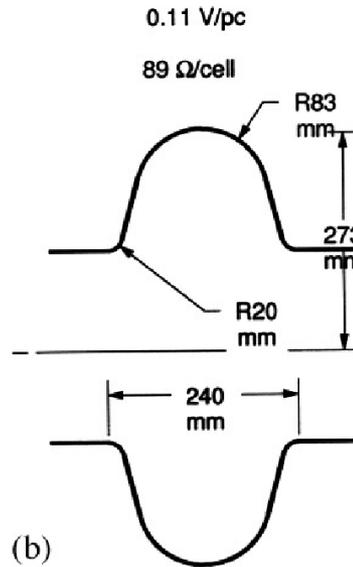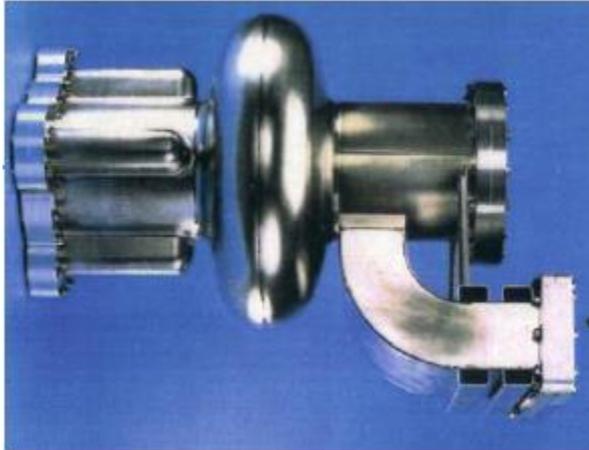$f = 1323$ MHz

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Single Cell Cavities

Electric field high at iris

Magnetic field high at equator

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Single Cell Cavities

0.11 V/pc

89 Ω/cell

R83 mm

273 mm

R20 mm

240 mm

(b)

Superconducting
B-Factory Cell Shape

| Quantity	Cornell SC 500 MHz	Pillbox
G	270 Ω	257 Ω
R_{a}/Q_0	88 ohm/cell	196 Ω/cell
$E_{\mathrm{pk}}/E_{\mathrm{acc}}$	2.5	1.6
$H_{\mathrm{pk}}/E_{\mathrm{acc}}$	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

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Example: CEBAF Upgrade

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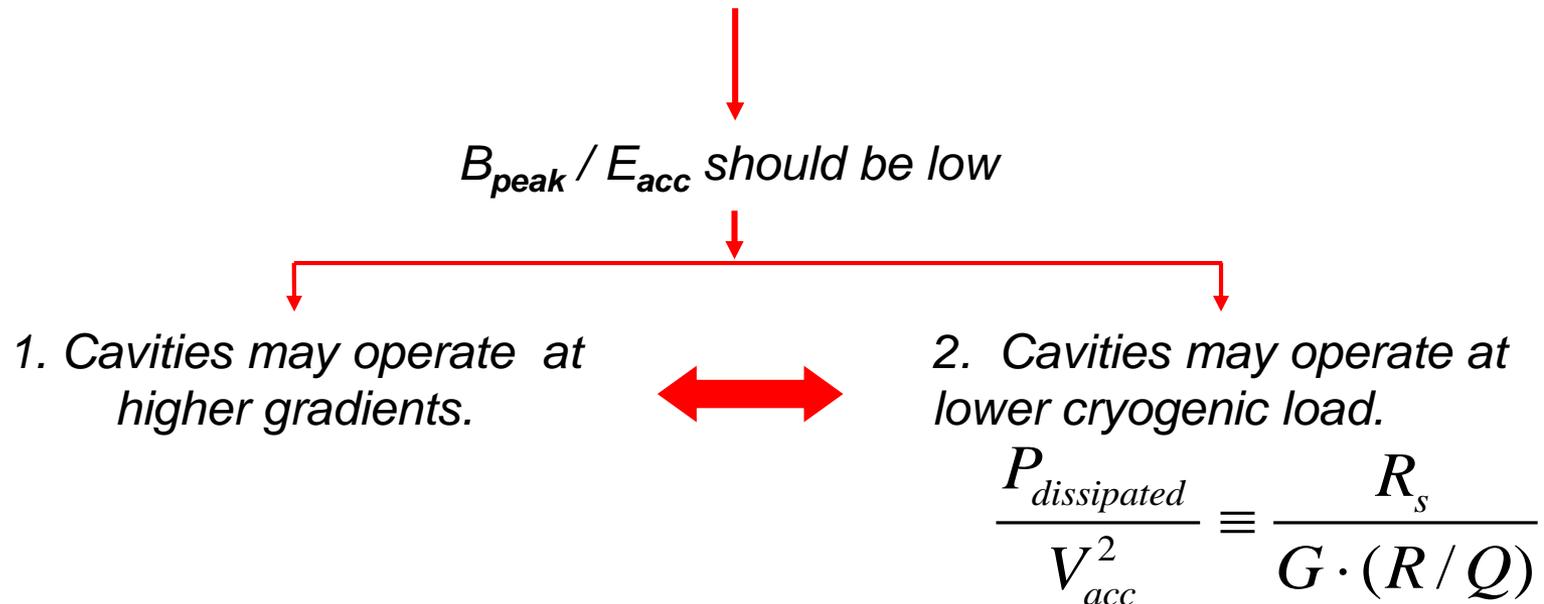- "Low Loss" shape: lowest cryogenic losses, maximize $G(R/Q)$

a. OC-shape   b. HG-shape   c. LL-shape

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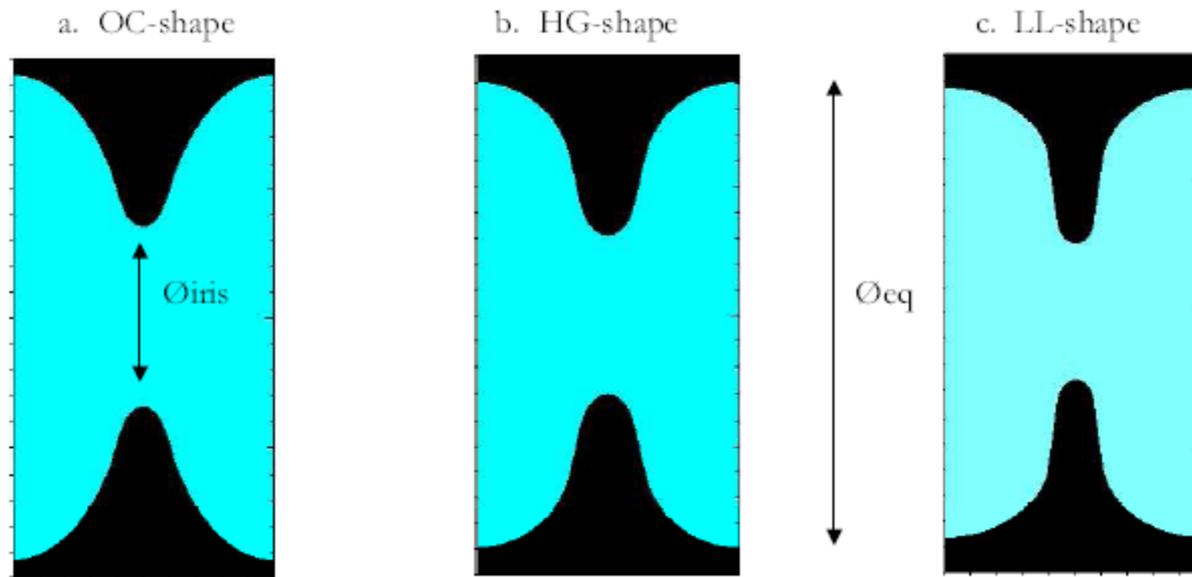
CEBAF Upgrade Shape Comparison

Table 1. Parameters of inner dumbbells

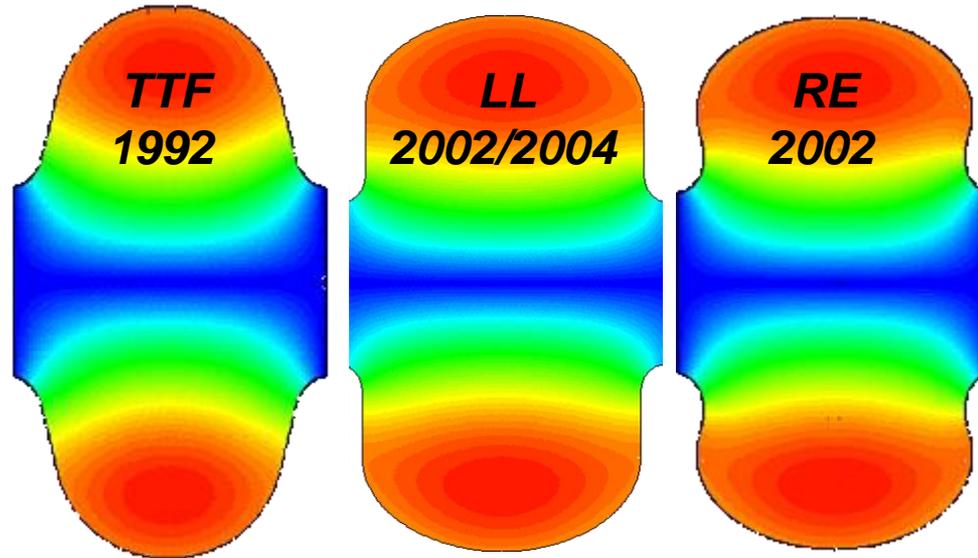| Parameters	Unit	OC-shape	HG-Shape	LL-Shape
$\varnothing$eq	[mm]	187.03	180.50	174.00
$\varnothing$iris	[mm]	70.00	61.40	53.00
k_{cc}	[%]	3.29	1.72	1.49
E_{peak}/E_{acc}	-	2.56	1.89	2.17
B_{peak}/E_{acc}	[mT·(MV/m)$^{-2}$]	4.56	4.26	3.74
Lorentz factor[*] k_L	[Hz·(MV/m)$^{-2}$]	-1.35	-1.1	-1.2
R/Q	[Ω]	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.

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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.

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

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New Shapes for ILC

		TTF 1992	LL 2002/2004	RE 2002
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
$R/Q*G$	[$\Omega*\Omega$]	30840	37970	35123

RF Simulation Codes for Cavity Design

The solution to 2D (or 3D) Helmholtz equation can be analytically found only for very few geometries (pillbox,   spherical resonators or rectangular resonator).
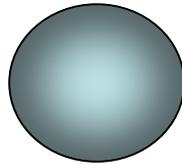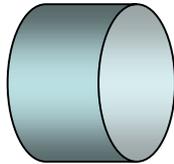
We need numerical methods:

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

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)
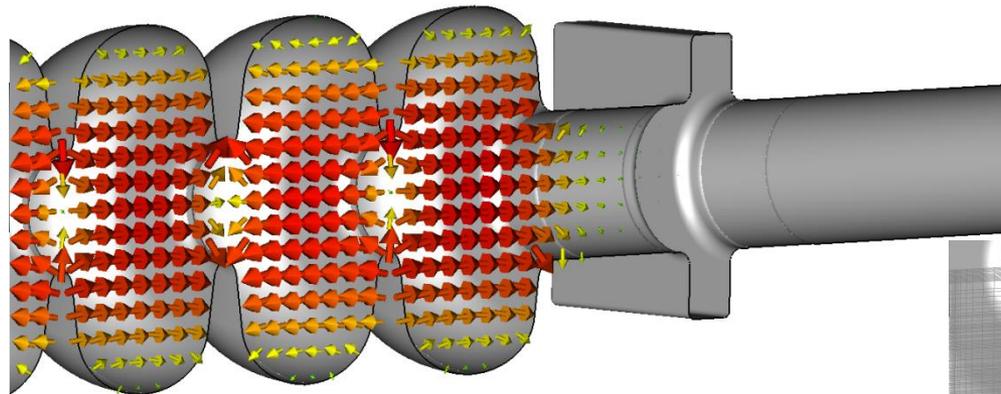- Use symmetry planes to reduce number of mesh points
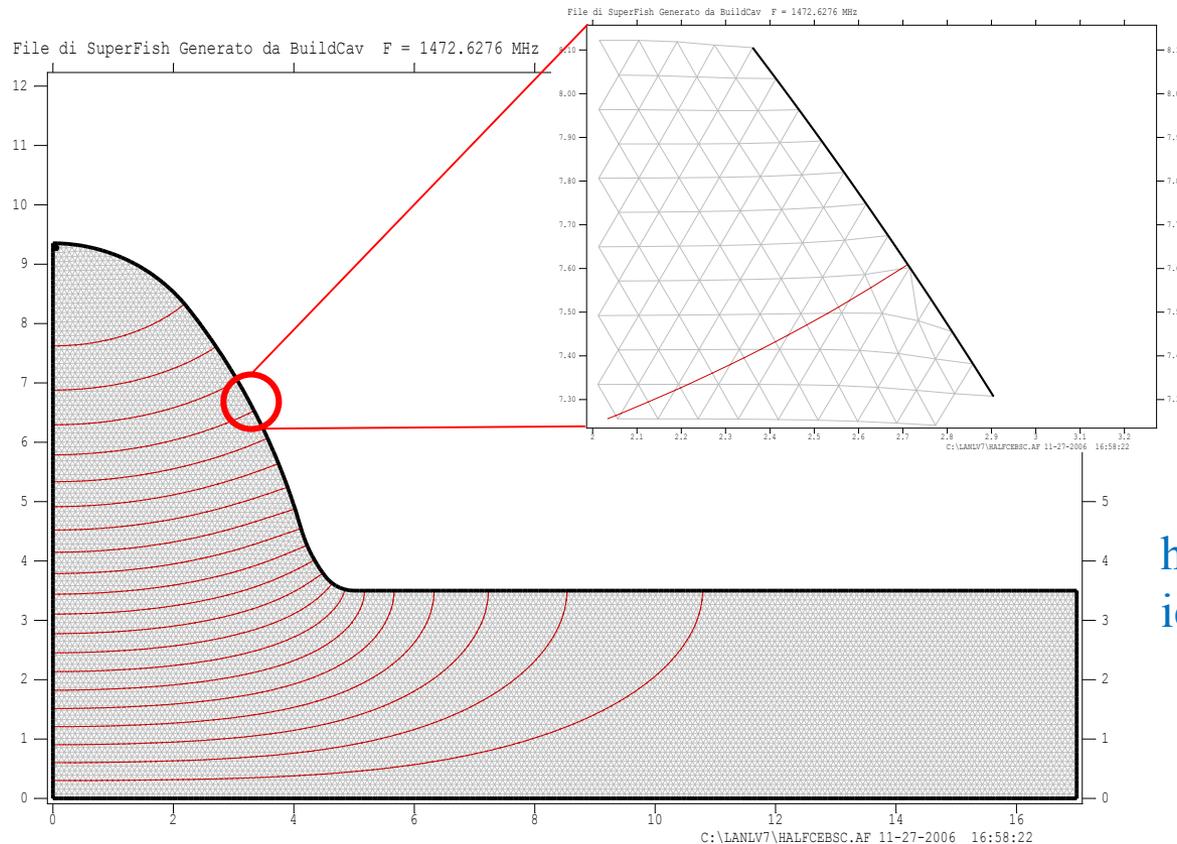
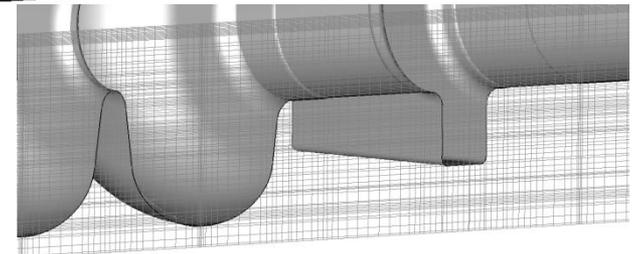http://laacg1.lanl.gov/laacg/services/download_sf.phtml

CST Microwave Studio

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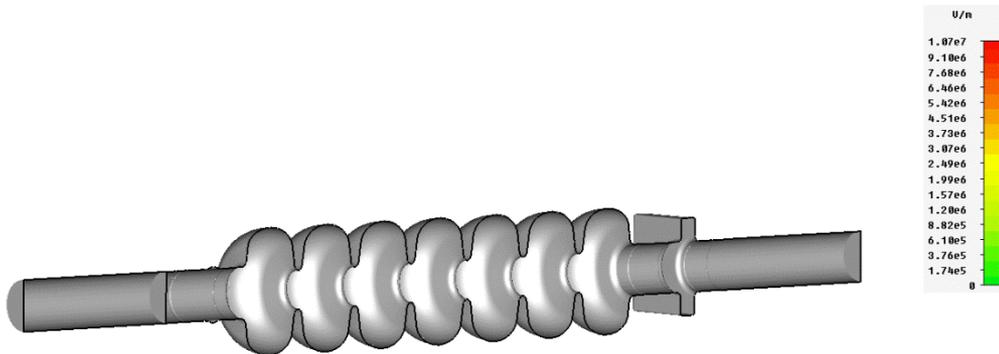
- Runs on PC
- Perfect Boundary Approximation

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

- Separate software for user interface (CuBit)

Example:
LL end cell with
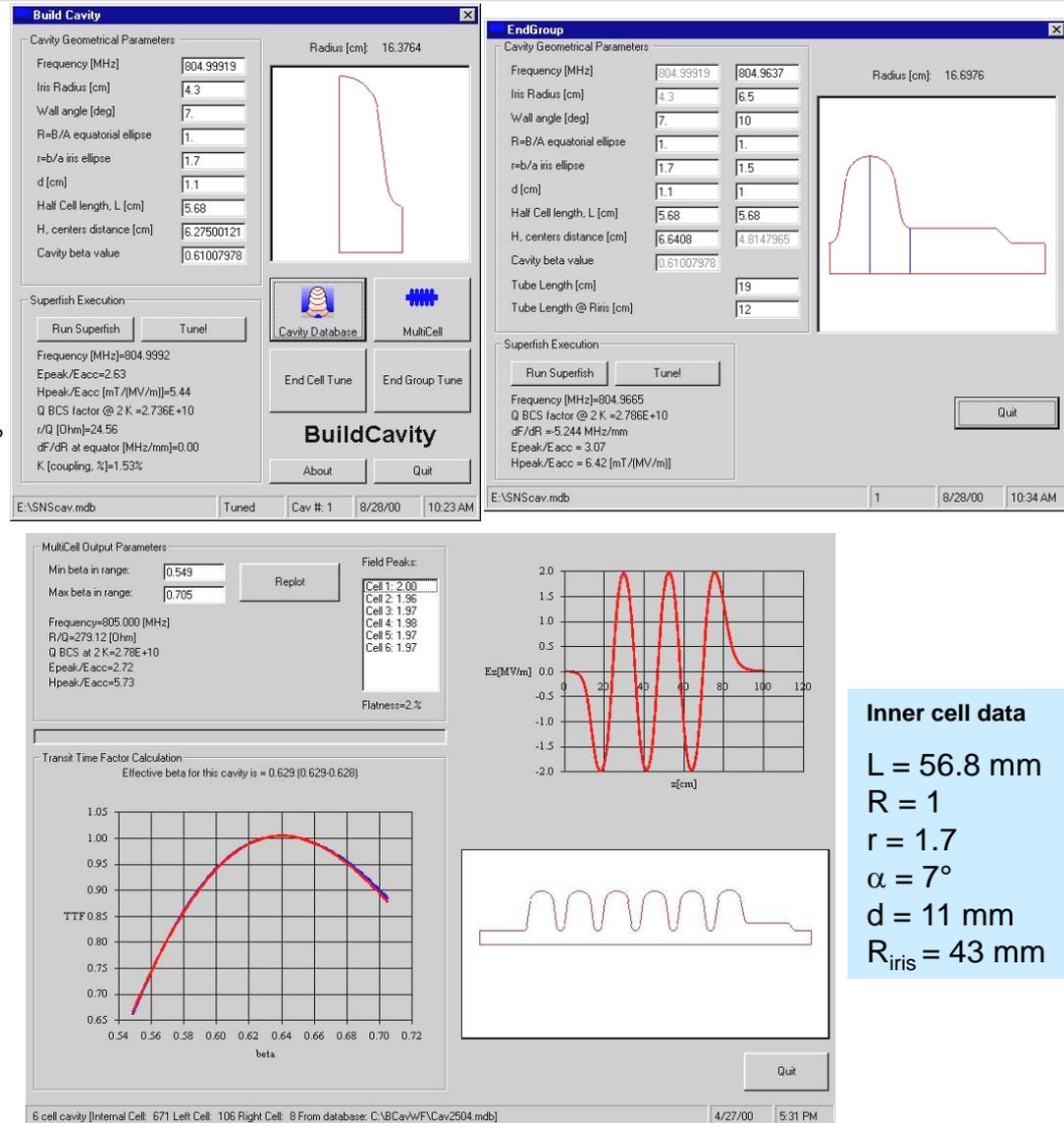*Input Coupler Only*

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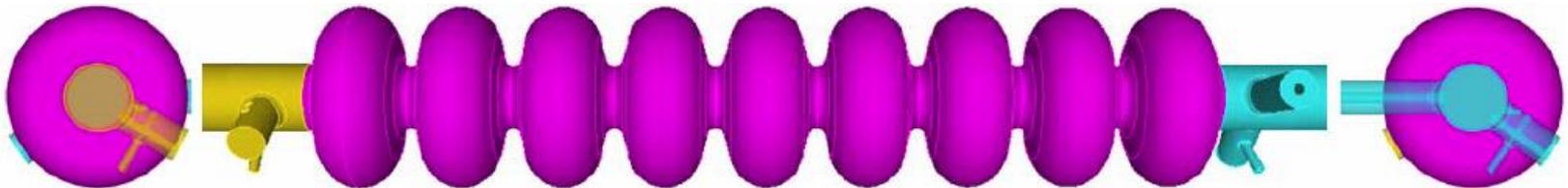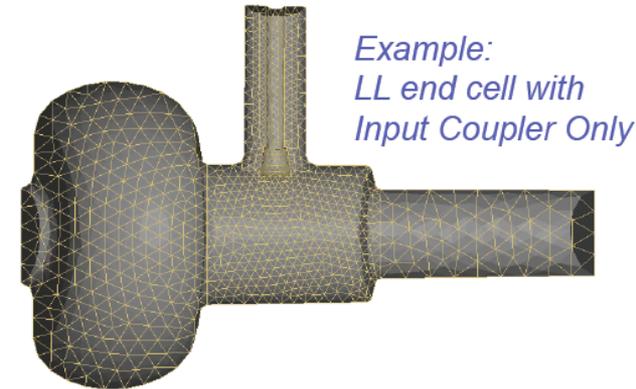
Cell Shape Parametrization

- 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 (α)
    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=λβ/4
    β
  - ✓ 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
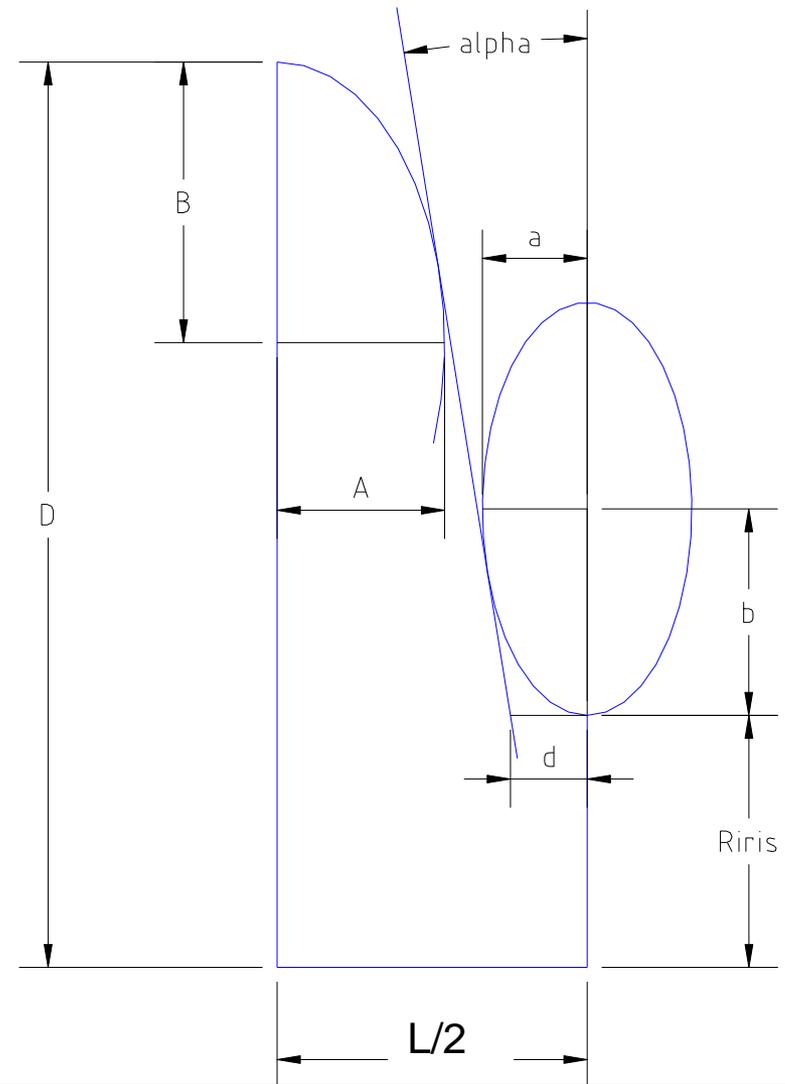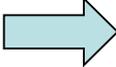
BuildCavity: parametric tool for the analysis of the cavity shape on the EM parameters:

– 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, α, d, L, R_{iris}

– End cell tuning is performed through the wall angle inclination, α, or distance, d.

R, L and R_{iris} are independently settable.

– Multicell cavity is then built to minimize the field unflatness, compute the effective β and the final cavity performances.

– A proper file to transfer the cavity geometry to ANSYS is then generated

Build Cavity

Cavity Geometrical Parameters

Frequency [MHz]	804.99919
Iris Radius [cm]	4.3
Wall angle [deg]	7.
R=B/A equatorial ellipse	1.
r=b/a iris ellipse	1.7
d [cm]	1.1
Half Cell length, L [cm]	5.68
H, centers distance [cm]	6.27500121
Cavity beta value	0.61007978

Radius [cm]: 16.3764

Superfish Execution

Run Superfish | Tune!

Frequency [MHz]=804.9992
Epeak/Eacc=2.63
Hpeak/Eacc [mT/(MV/m)]=5.44
Q BCS factor @ 2 K =2.736E+10
r/Q [Ohm]=24.56
dF/dR at equator [MHz/mm]=0.00
K [coupling, %]=1.53%

Cavity Database | MultiCell
End Cell Tune | End Group Tune

BuildCavity

About | Quit

E:\SNScav.mdb | Tuned | Cav #: 1 | 8/28/00 | 10:23 AM

EndGroup

Cavity Geometrical Parameters

Frequency [MHz]	804.99919	804.9637
Iris Radius [cm]	4.3	6.5
Wall angle [deg]	7.	10
R=B/A equatorial ellipse	1.	1.
r=b/a iris ellipse	1.7	1.5
d [cm]	1.1	1
Half Cell length, L [cm]	5.68	5.68
H, centers distance [cm]	6.6408	4.8147965
Cavity beta value	0.61007978	
Tube Length [cm]		19
Tube Length @ Riris [cm]		12

Radius [cm]: 16.6976

Superfish Execution

Run Superfish | Tune!

Frequency [MHz]=804.9665
Q BCS factor @ 2 K =2.786E+10
dF/dR =-5.244 MHz/mm
Epeak/Eacc = 3.07
Hpeak/Eacc = 6.42 [mT/(MV/m)]

Quit

E:\SNScav.mdb | 1 | 8/28/00 | 10:34 AM

MultiCell Output Parameters

Min beta in range: 0.549
Max beta in range: 0.705

Replot

Field Peaks:
Cell 1: 2.00
Cell 2: 1.96
Cell 3: 1.97
Cell 4: 1.98
Cell 5: 1.97
Cell 6: 1.97

Frequency=805.000 [MHz]
R/Q=279.12 [Ohm]
Q BCS at 2 K=2.78E+10
Epeak/Eacc=2.72
Hpeak/Eacc=5.73

Flatness=2%

Transit Time Factor Calculation
Effective beta for this cavity is = 0.629 (0.629-0.628)

6 cell cavity [Internal Cell: 671 Left Cell: 106 Right Cell: 8 From database: C:\BCavWF\Cav2504.mdb] | 4/27/00 | 5:31 PM

Inner cell data

L = 56.8 mm
R = 1
r = 1.7
α = 7°
d = 11 mm
R_{iris} = 43 mm

Parameter Choices

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

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Beam Acceleration: cell length

Accelerating mode in a multi-cell structure

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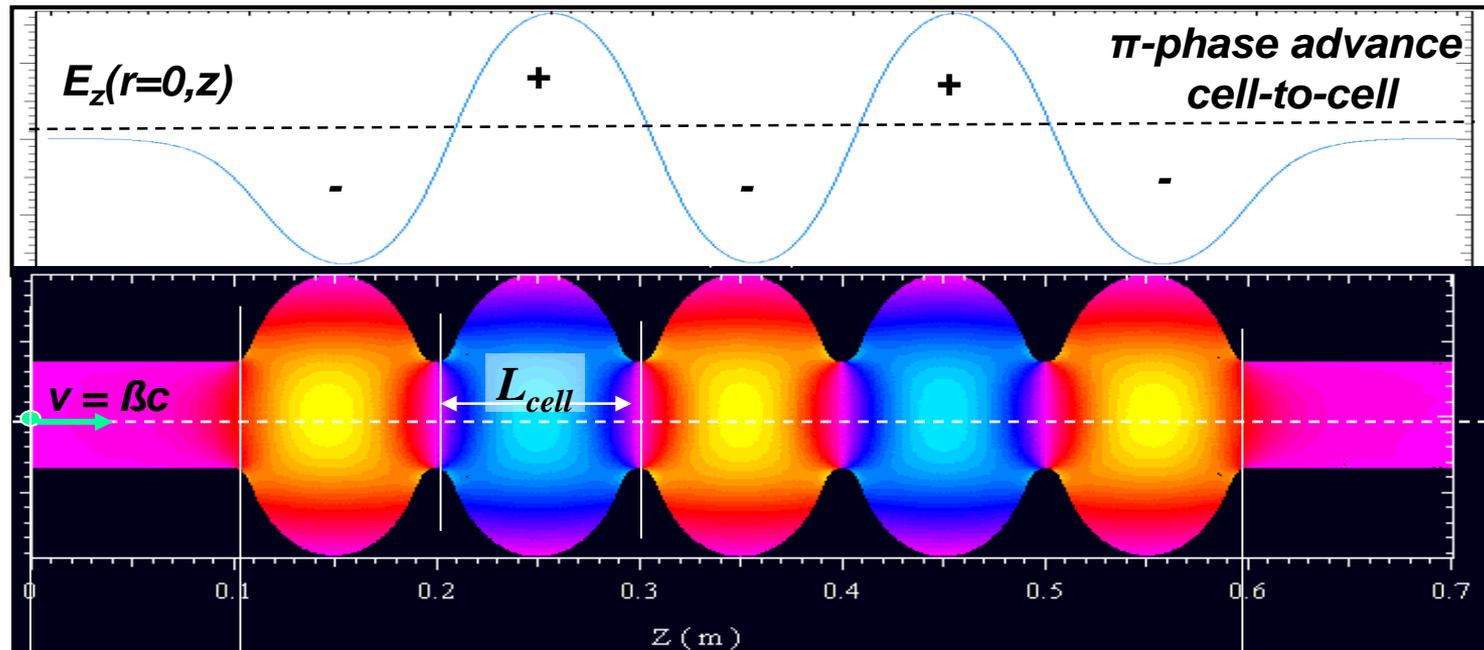
Synchronic acceleration and max of $(R/Q)_{acc} \leftrightarrow L_{active} = NL_{cell} = Nc\beta/(2f)$ and the injection takes place at an optimum phase φ_{opt} which ensures that particles will arrive at the mid-plane of the first cell when E_{acc} reaches its maximum (+q passing to the right) or minimum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

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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
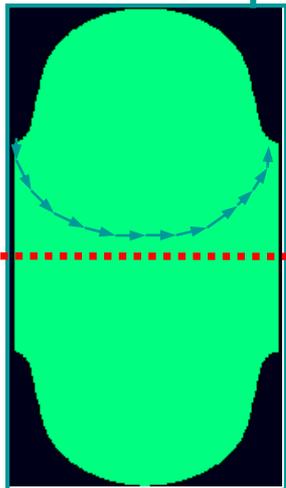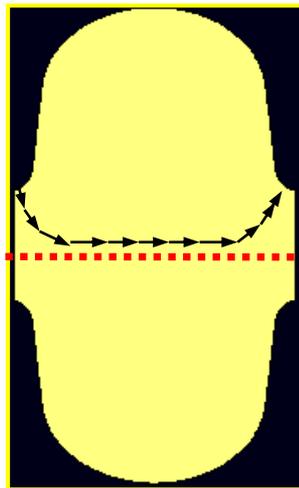
$R_{i\,ris}$ = 40 mm   **R_{iris} = 20 mm**
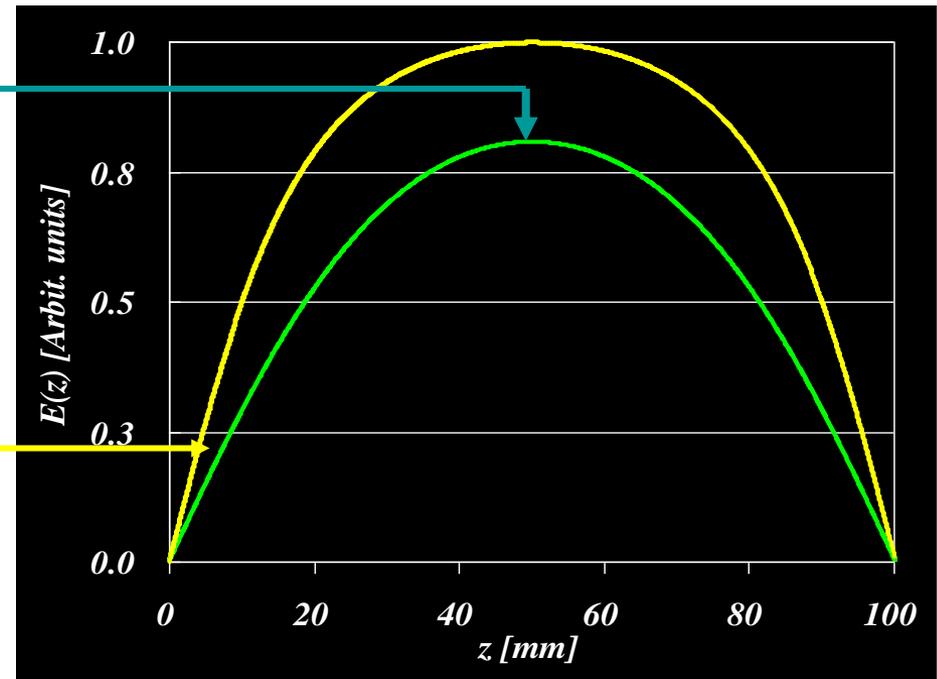
E_z (z) for small and big iris radius

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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*

(-)

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"Rule of thumb" for Optimizing Peak Surface Fields

Add "*magnetic volume*" at the equator to reduce B_{peak}
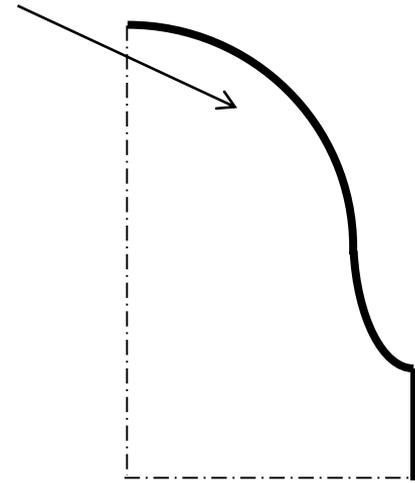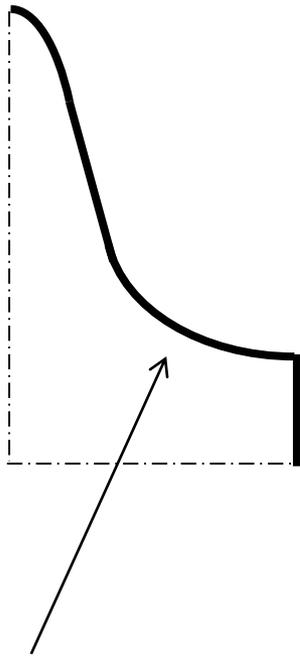
Add "*electric volume*" at the iris to reduce E_{peak}

Pushing the Design: Reentrant cavity
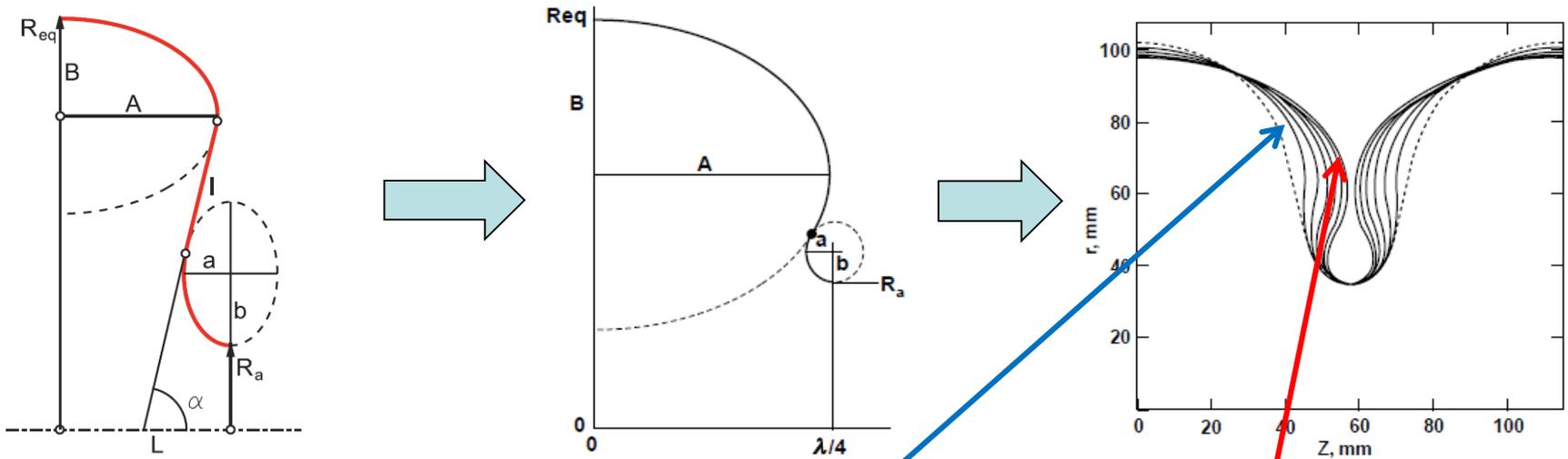
• 3 independent parameters: A, B, a
• potential issue with cavity forming and cleaning
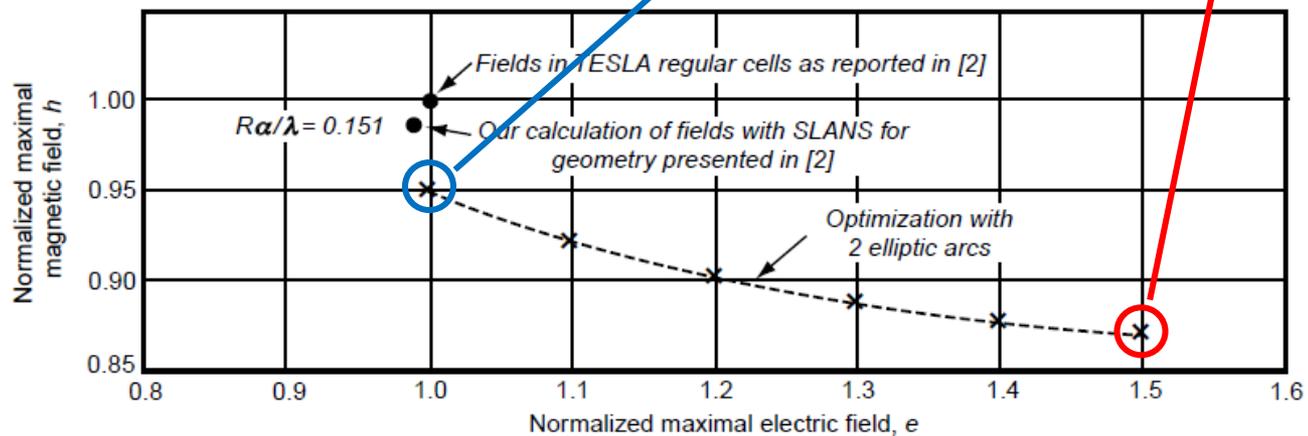
RF Tests of New Cavity Shapes: LL

		LL
f_{π}	[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
$\varnothing_{iris}$	[mm]	61

LL single 1st cavity 15th, EP(30)+HPR+Bake

Quench 46.5MV/m
Qo=1.12E10 @ 1.97K
Q0=1.74E10 @ 1.68K

- ● Qo 2K
- ▲ Qo 1.68K

E_{peak} = 86.5 MV/m
B_{peak} = 172.5 mT

Qo

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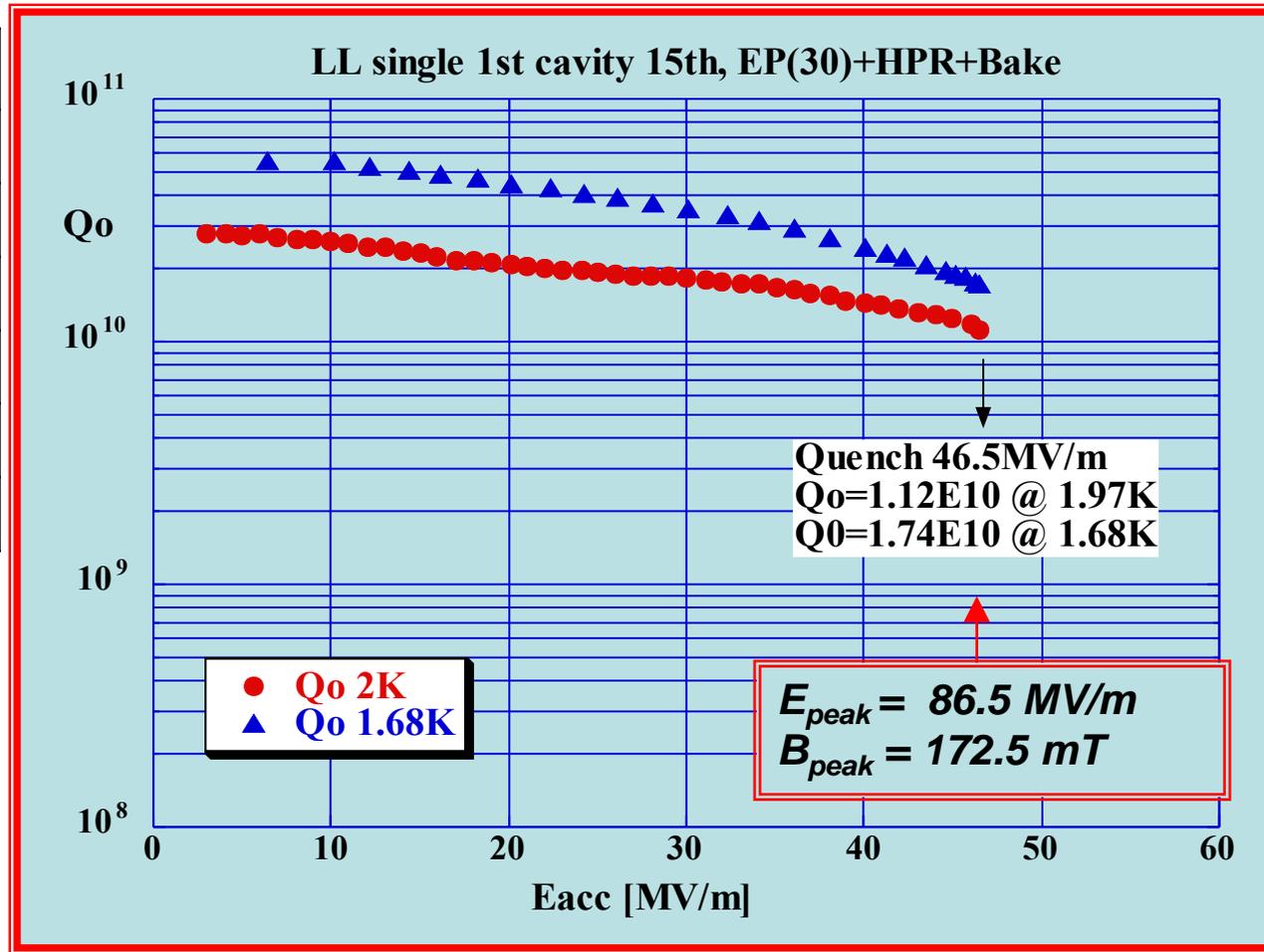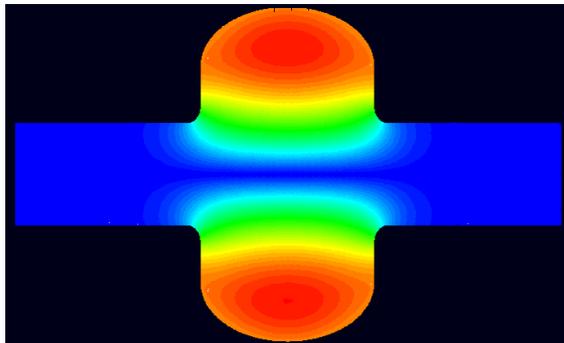
9-cell LL cavity was tested at JLab up to E_{acc}=36MV/m

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RF Tests of New Cavity Shapes: RE

		RE
f_π	[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
$\emptyset_{iris}$	[mm]	68

Re-entrant 11th   2005/09/07

Eacc = 50.90 MV/m
Q0 = 6.88e9

T = 1.8 K

Qo

T = 2.0 K

Just adding LiHe

48 MV/m

50.90 MV/m
runout LiHe
during proc.

E_{peak}= 111.5 MV/m
B_{peak}= 192.9 mT !?

● Qo @ 2K
+ Qo @ 1.8K

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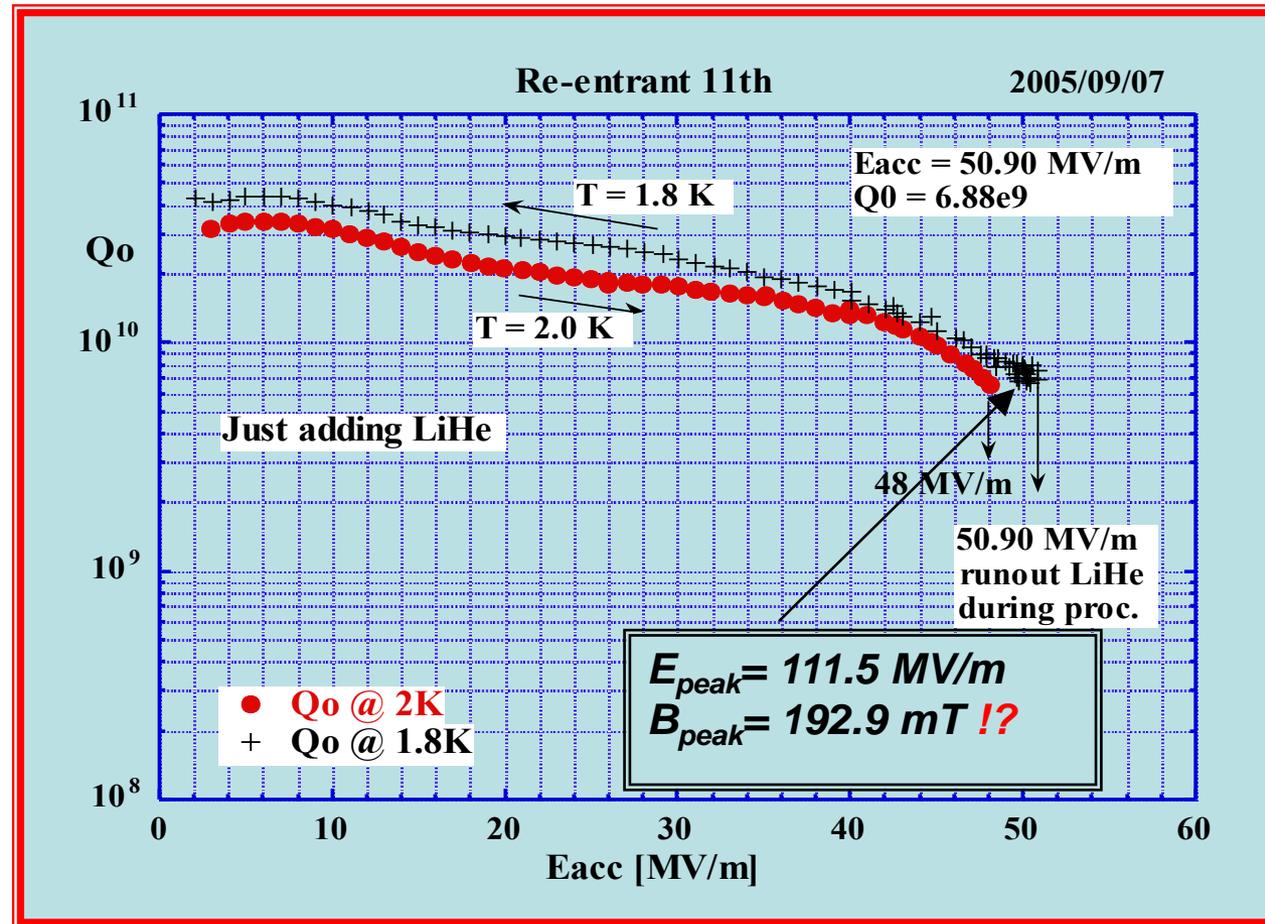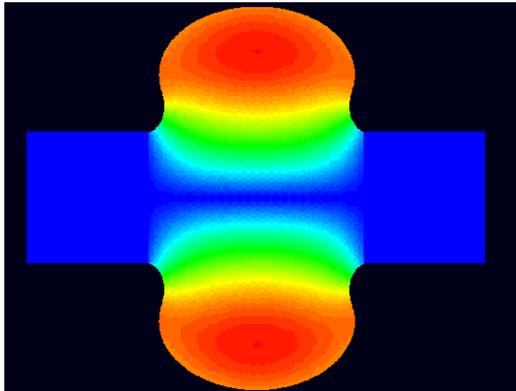
9-cell RE cavity was tested at Cornell up to E_{acc}=28MV/m

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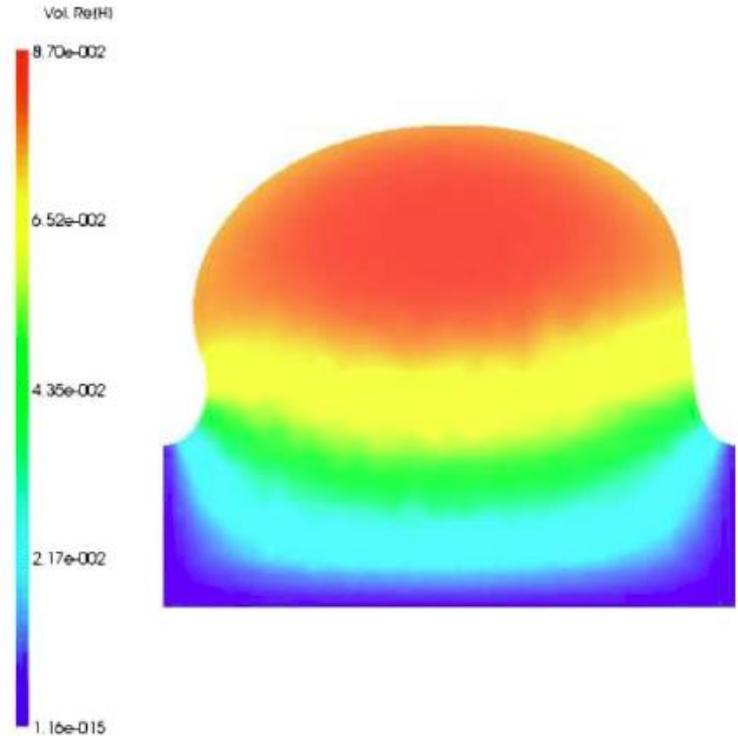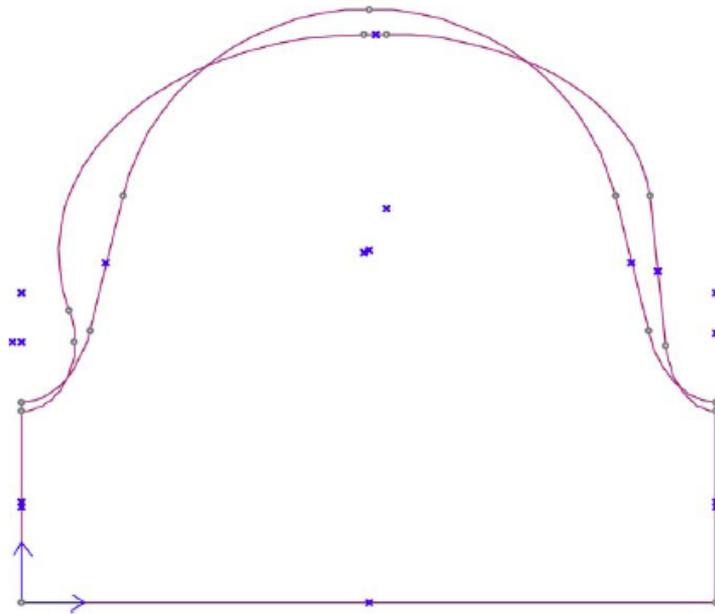
Parameters of the two proposed half-reentrant inner cells compared to the proposed Low Loss ILC geometry

	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 (Ω)	123	135	134
G (Ω)	283	283	284
$(R/Q) \cdot G$ (Ω²)	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
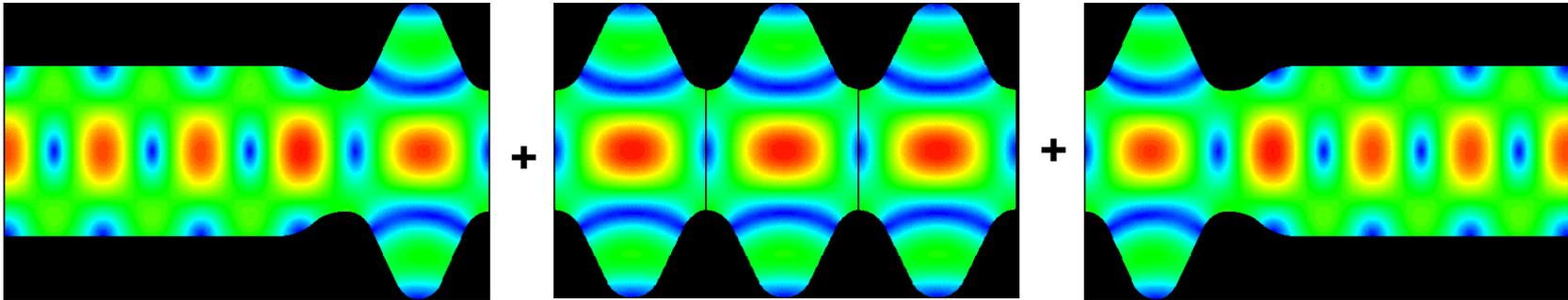
Their function is multi-folded and their geometry must fulfill three requirements:

- 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.

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Optimization done with BuildCavity

$$\frac{\Delta f}{f_0} = -\frac{1}{4U} \iiint_{\Delta V} \left(\mu_0 H^2 - \varepsilon_0 E^2 \right) dV$$
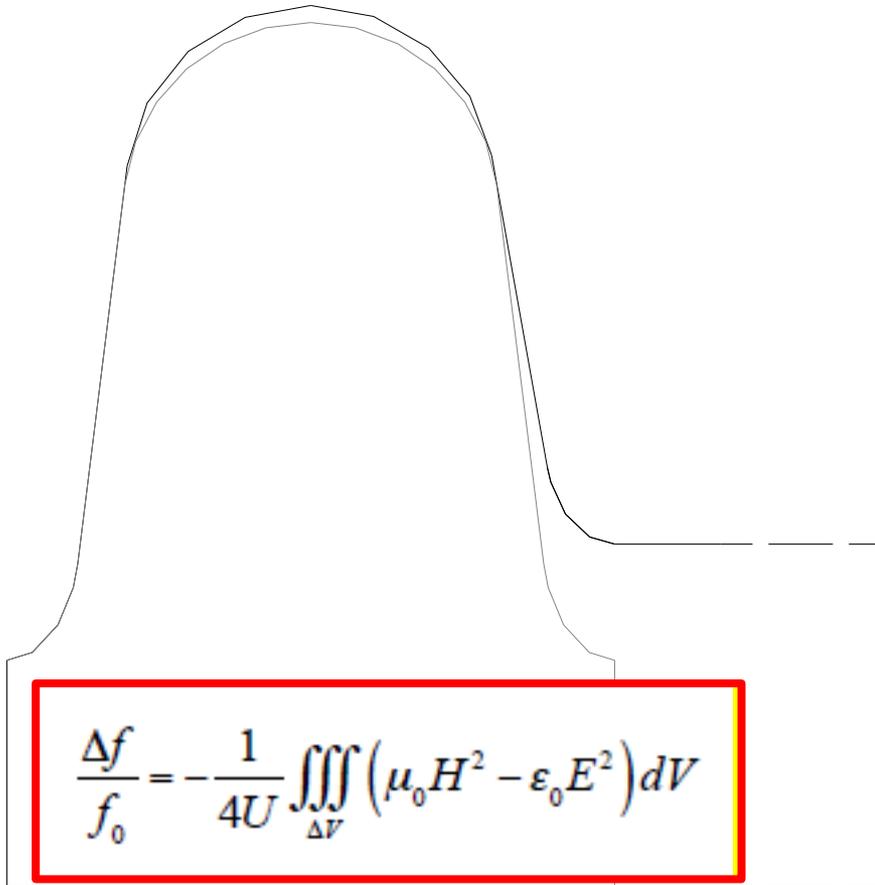
- R_{iris} set to 65 mm to have enough field at the power coupler antenna

- d set 1 mm lower than the in-cell

- optimization of r = b/a at iris

- α set to 10 deg to have the necessary stiffening

- Slater compensation (increase of the magnetic volume) of the cut-off tube ($\downarrow$f), d reduction ($\downarrow$f), α and R_{iris} increase ($\uparrow$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
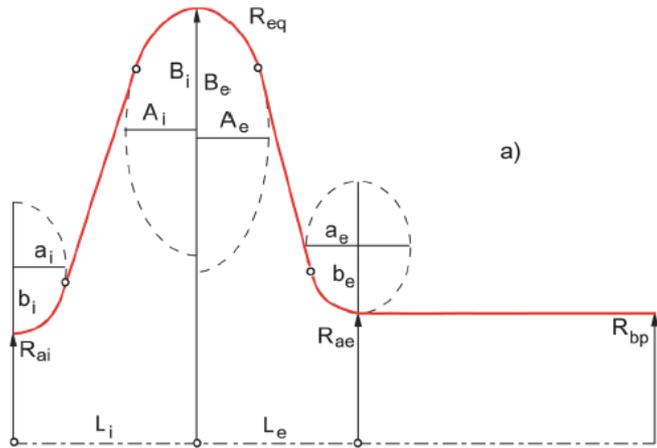
- Same R_{eq} as inner cell, use L_e as parameter to adjust the frequency
- Adjust parameters A_e, B_e, a_e, b_e and α to minimize either E_{peak}/E_{acc} or losses
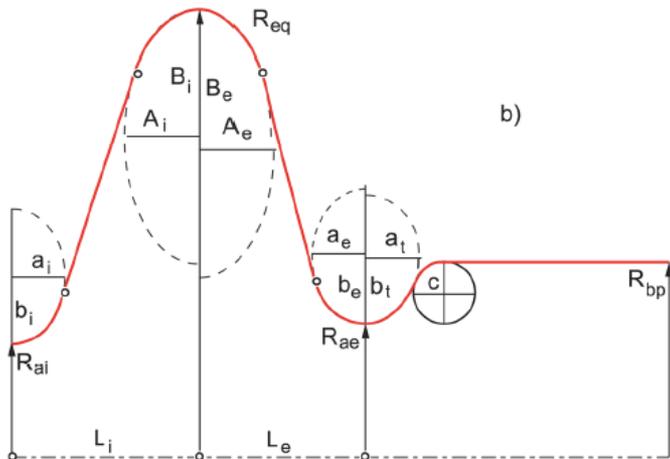
- By adding more parameters (a_t, b_t, c, R_{bp}) it is possible to optimize the propagation of unwanted HOM, without increasing E_{peak}/E_{acc} or losses for the fundamental mode

Multicell Cavities
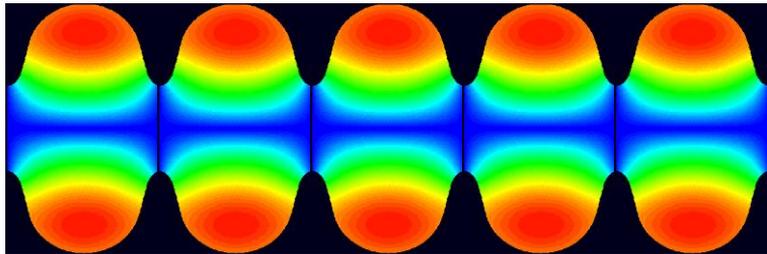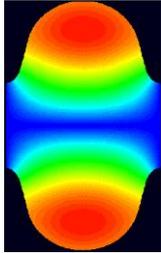
Single-cell is attractive from the RF-point of view:
- Easier to manage HOM damping
- No field flatness problem.
- Input coupler transfers less power
- Easy for cleaning and preparation

- ***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…*

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Coupling between cells

ω_o

ω_π
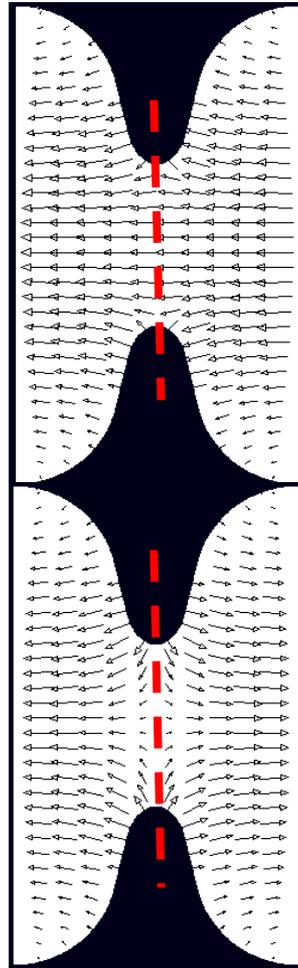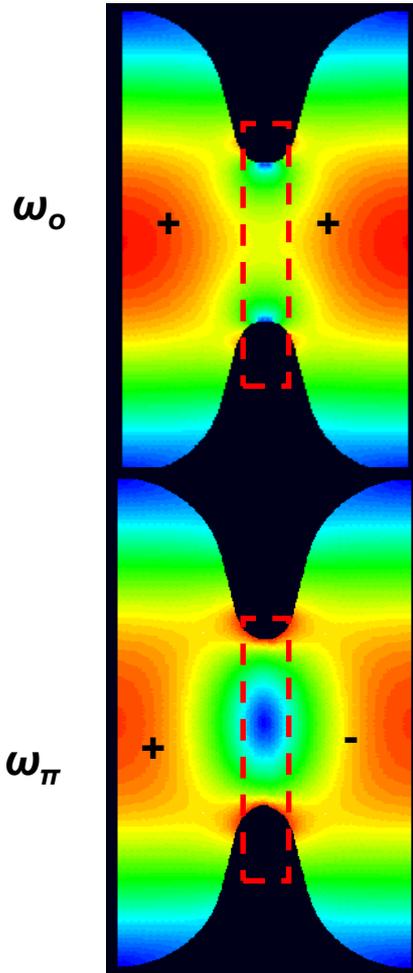
Symmetry plane for the H field

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

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

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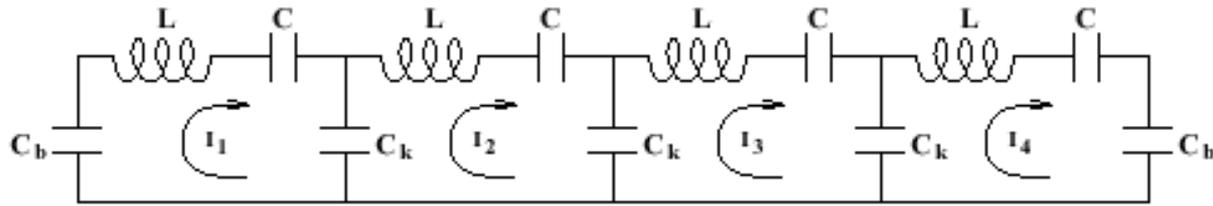
$$k = \frac{C}{C_k} \qquad C_b = C_k / 2$$

Mode frequencies:

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

$$\frac{\omega_N - \omega_{N-1}}{\omega_0} \sim k\left(1 - \cos\frac{\pi}{N}\right) \cong \frac{k}{2}\left(\frac{\pi}{N}\right)^2$$

Voltages in cells:

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

Pass-Band Modes Frequencies

9-cell cavity

Jefferson Lab
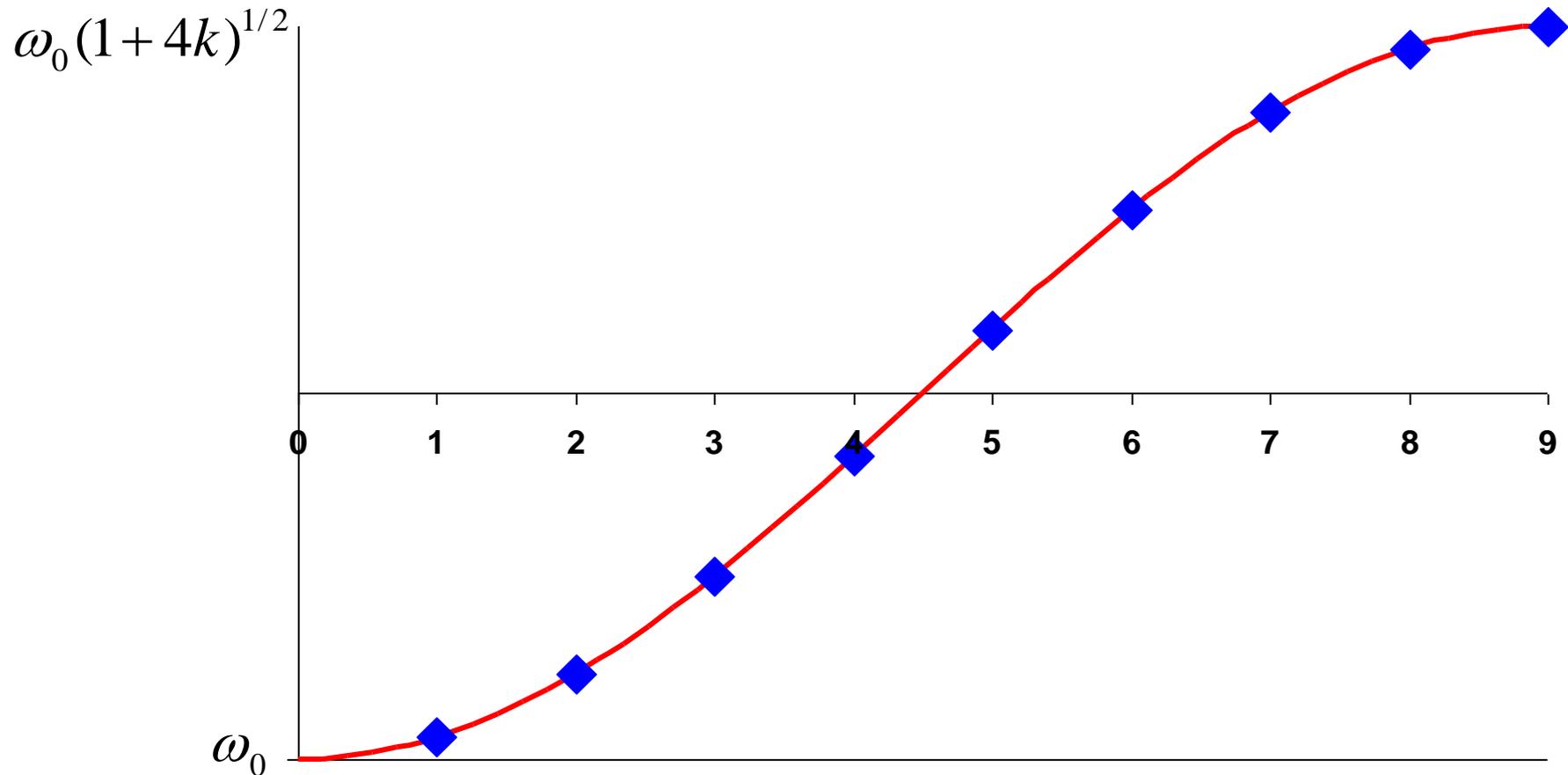
Cell Excitations in Pass-Band Modes
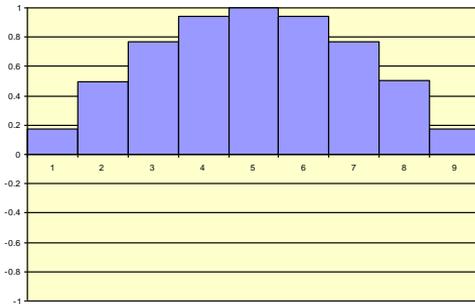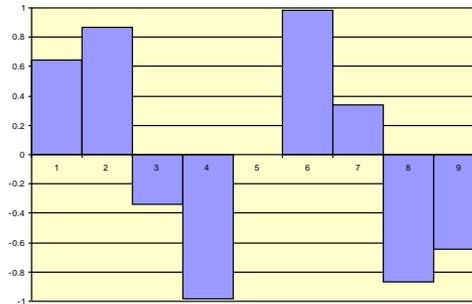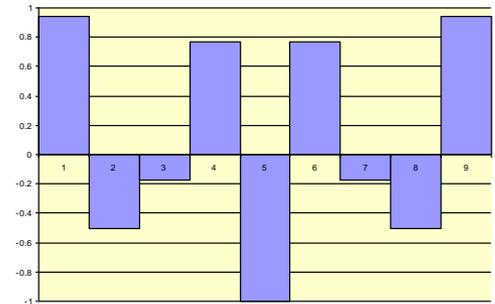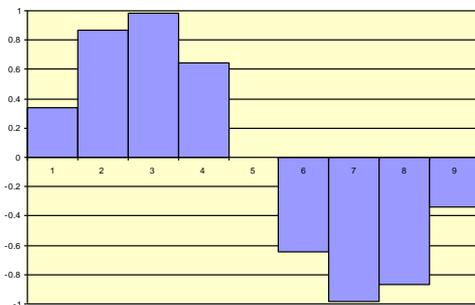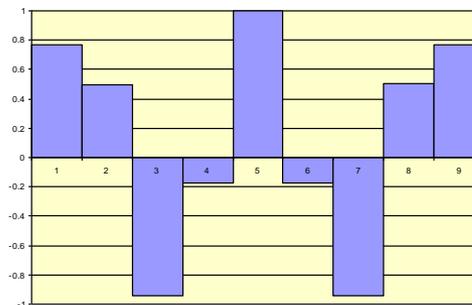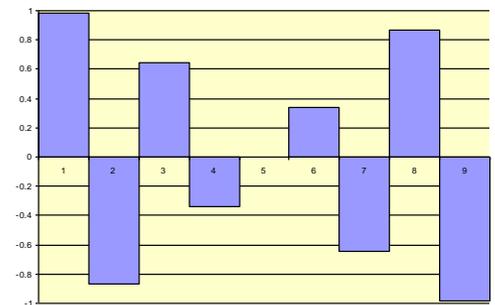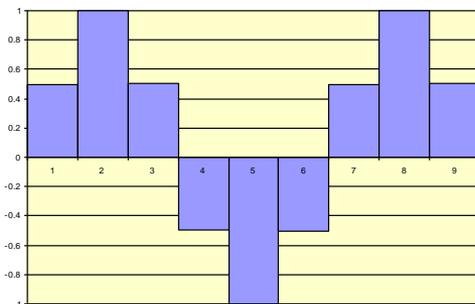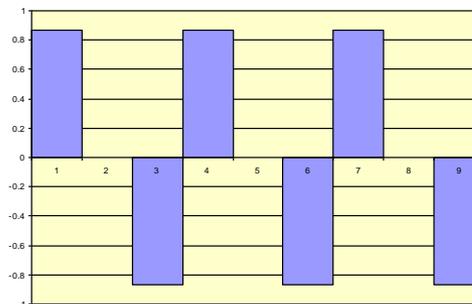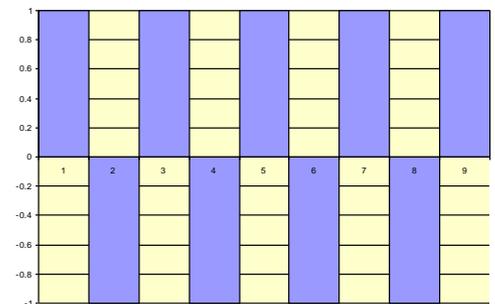
Field Flatness

Geometrical differences between cells causes a mixing of the eigenmodes

Sensitivity to mechanical deformation depends on mode spacing

Tune to
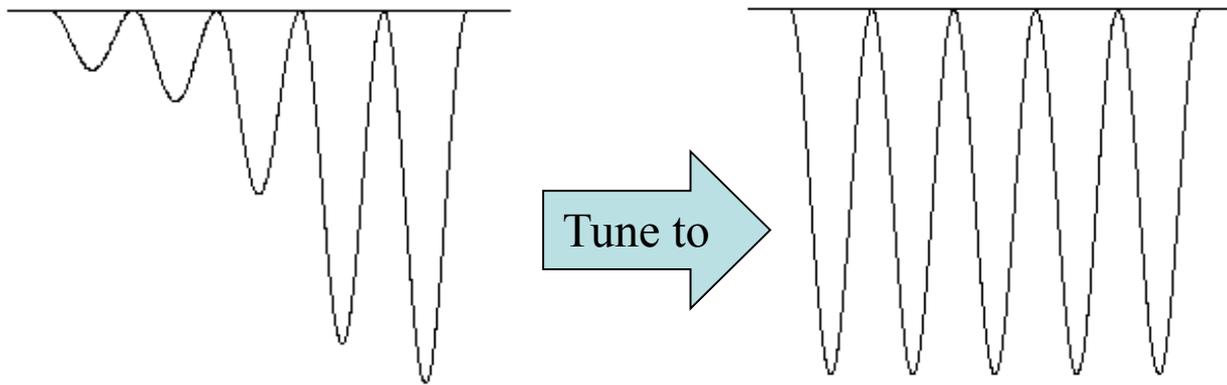
Field flatness factor for elliptical cavities with arbitrary ß=v/c

$$a_{ff} = \frac{N^2}{k_{cc} \cdot \text{ß}}$$

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

β<1 Cavities: Transit Time Factor
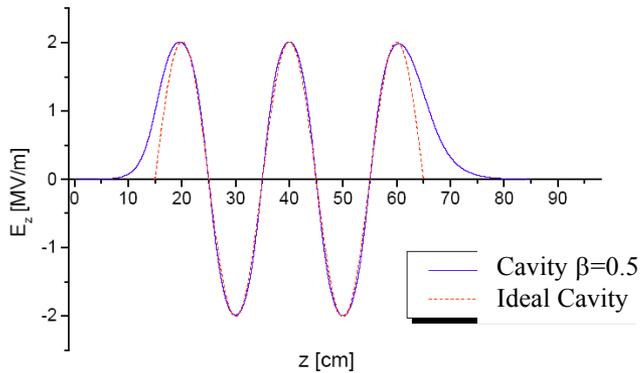
LINAC design is made assuming "ideal" cavity with sinusoidal field on-axis

$$E_{z,ideal}(z) = E_0 \sin\left(\frac{2\pi}{\lambda \beta_g} z\right) \qquad \beta_g = \frac{2L}{\lambda}$$

The "real" β, β_c, of a multi-cell cavity is defined as the β_g of an ideal cavity that has an the energy gain curve for the synchronous particle closest to the one of the real cavity

$$\delta W(\beta, \beta_c) = q \int_0^{L_{tot}} E_z(z) \cos\left[\frac{\omega}{\beta c}(z - z_c)\right] dz$$

$$T^{(N)}(\beta, \beta_c) = \frac{\delta W(\beta, \beta_c)}{\delta W(\beta = \beta_c, \beta_c)}$$

$$\delta W = q\Delta V = q E_{acc} L_{att} T^{(N)}(\beta, \beta_c) \cos\phi_S$$

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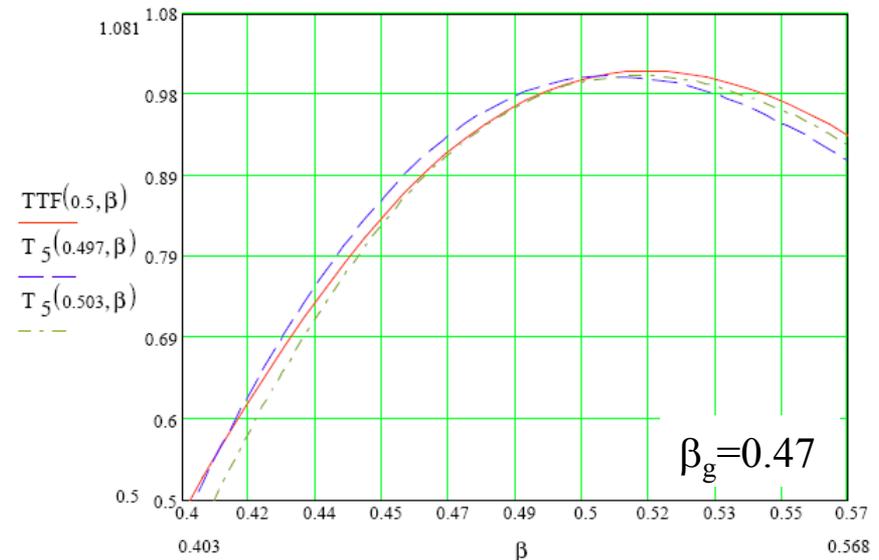
$\beta_g = 0.61$ Cavity for SNS

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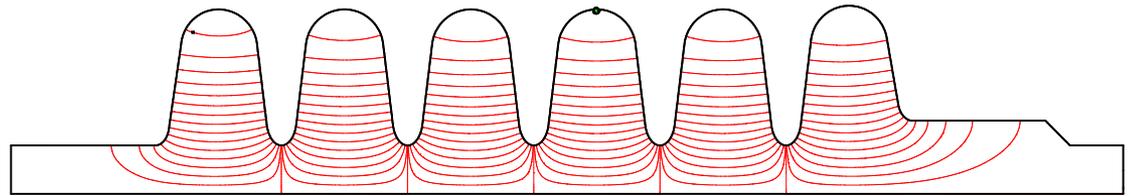
KL70 = -2.9 [Hz/(MV/m)^2]   KL80 = -3.4 [Hz/(MV/m)^2]

Nb thickness = 3.8 mm-

Geometrical Parameters

	Inner cell	End Cell Left	End Group (coupler)	
			Left	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

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$\beta_g = 0.81$ Cavity for SNS

Effective β 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 [Ω]   484.8

G [Ω]   233

k [%]   1.52

Q_{BCS} @ 2 K [10^9] 36.2

Frequency [MHz]   805.004

Field Flatness [%]   1.1
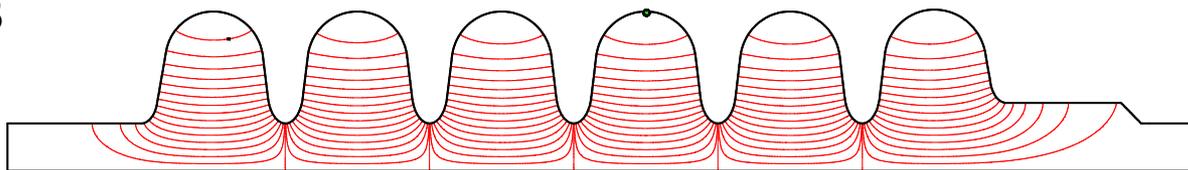
KL70 = -0.7 [Hz/(MV/m)^2]   KL80 = -0.8 [Hz/(MV/m)^2]

Nb thickness = 3.8 mm-

Geometrical Parameters

	Inner cell	End Cell Left	End Group (coupler)	
			Left	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	
α [deg]	7.0	10.072	7.0	10.0

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

Enhanced counter function

Counter function

Counter function: field levels at which resonant conditions are satisfied

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

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MultiPac

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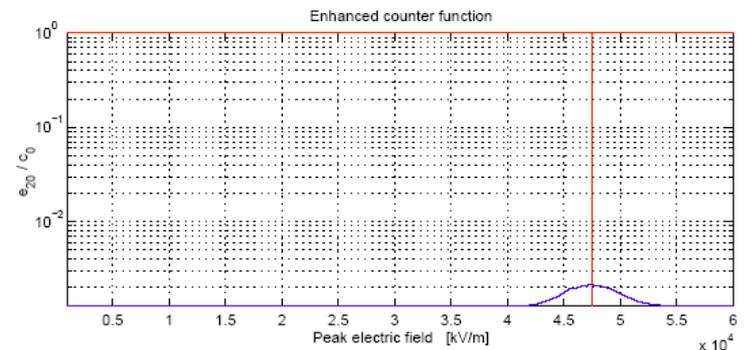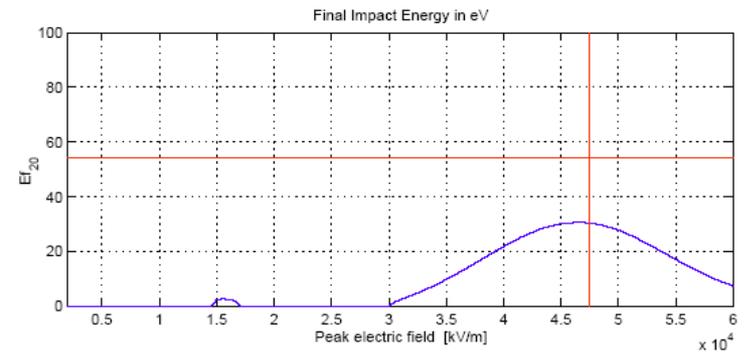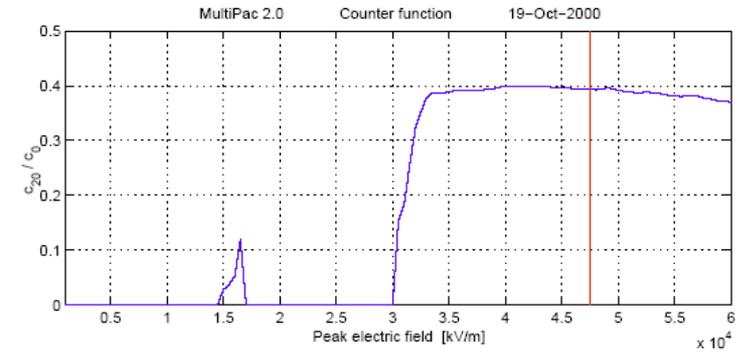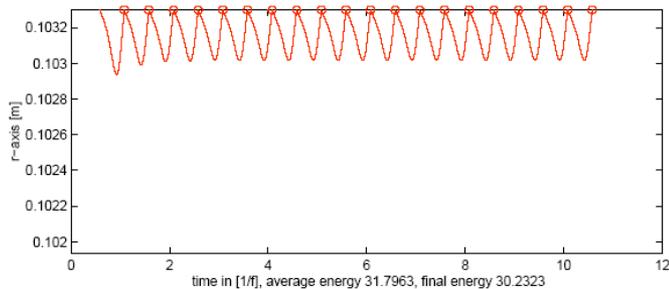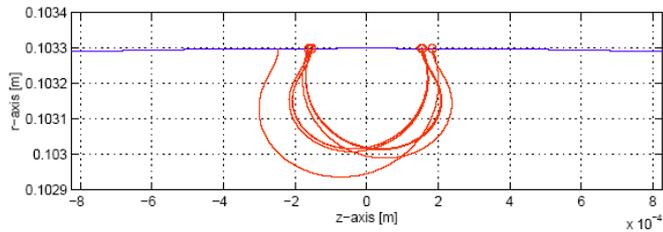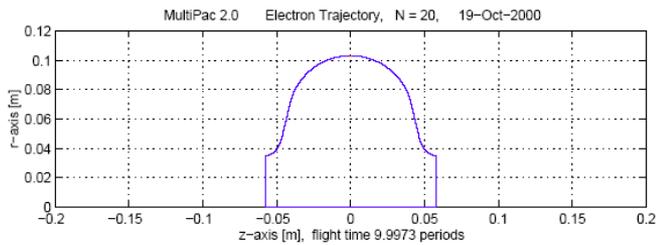
FishPact

- 2D code, uses SUPERFISH to compute surface fields
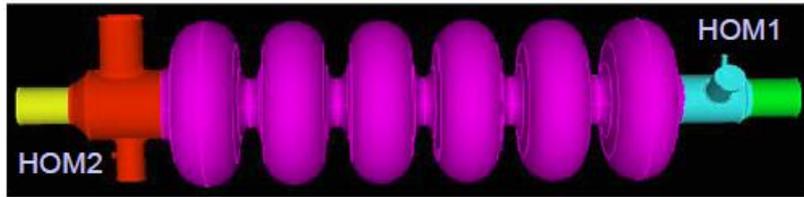- Runs on PC
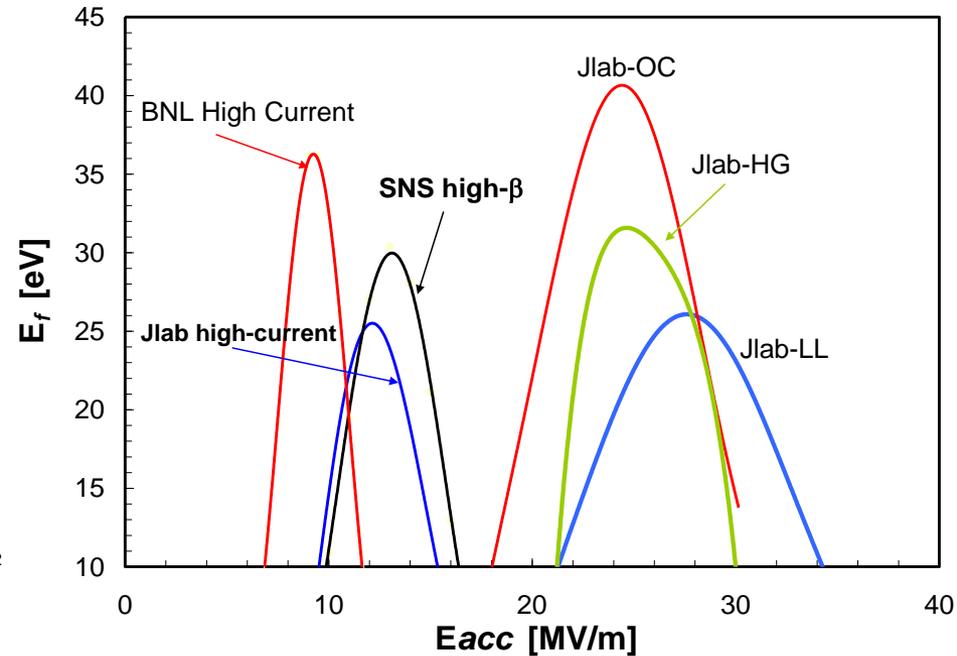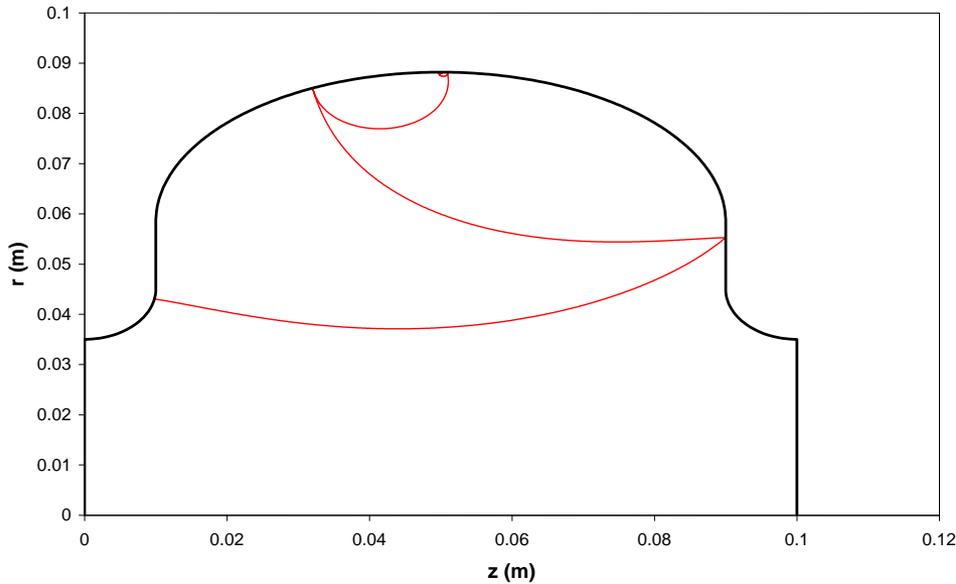
Track3P

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

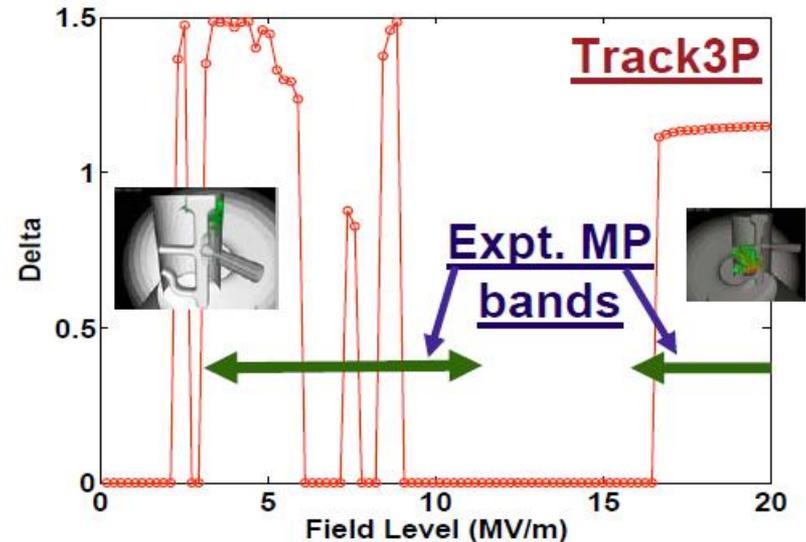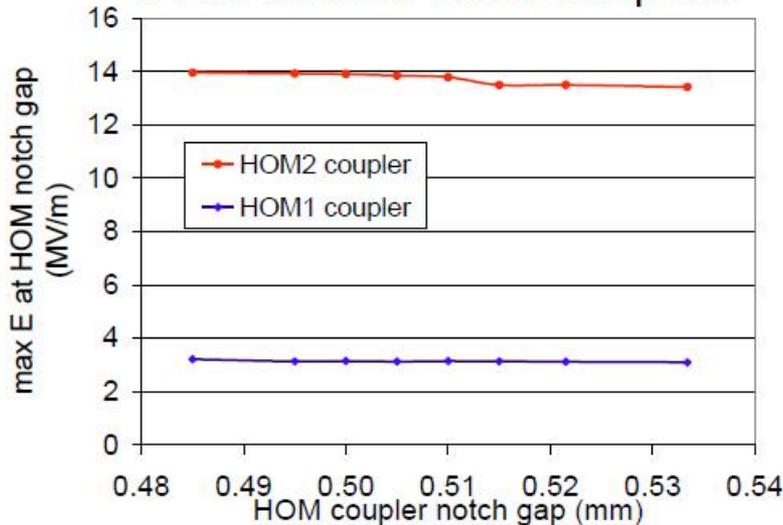*Example*: Multipacting found in beam pipe step of LL cavity
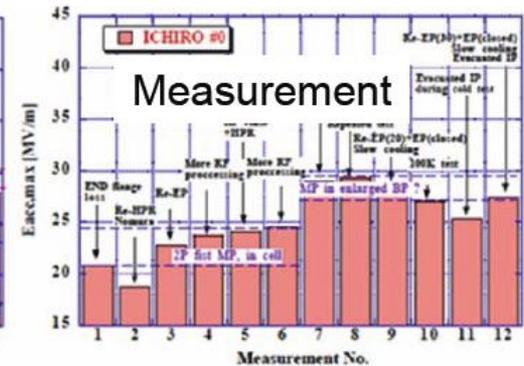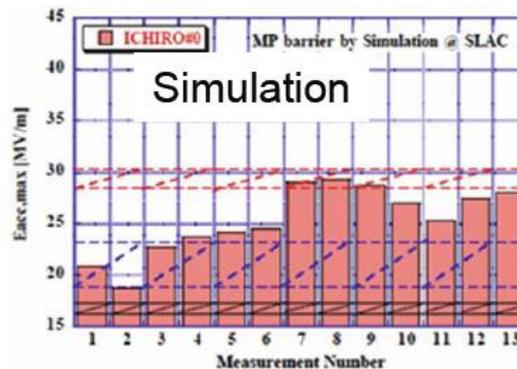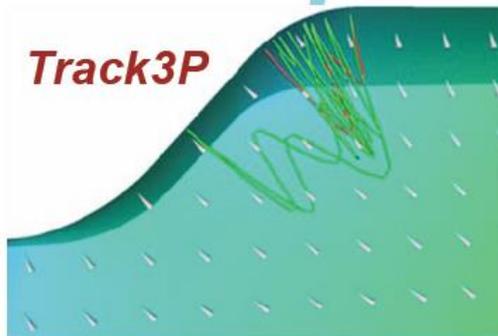
(Left) MP barriers in 9-cell ICHIRO cavity calculated with
Track3P, (Right) MP barriers measured on ICHIRO prototype (K.

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Example: Multipacting in SNS HOM Coupler

HOM1
HOM2
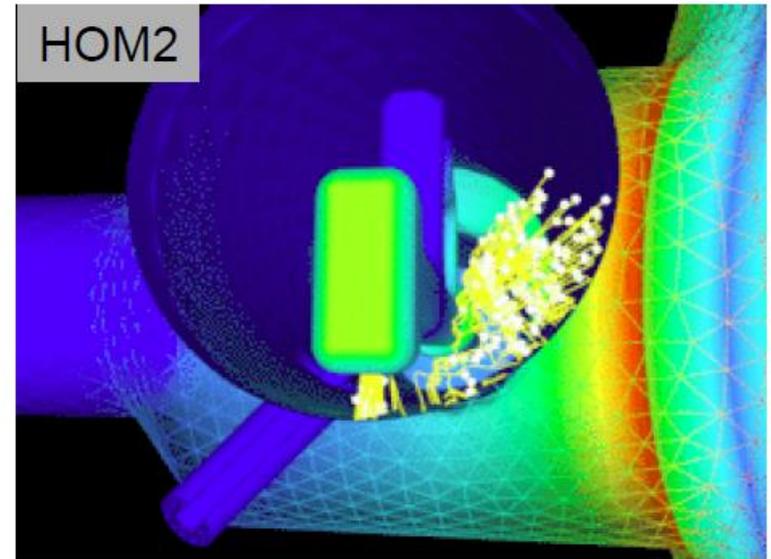
- SNS SCRF cavity experienced RF heating at HOM coupler
- 3D MP simulations showed MP barriers closed to measurements
- Similar analysis are carried out for ILC ICHIRO and crab cavity

HOM2

Field level in HOM couplers

max E at HOM notch gap (MV/m) vs HOM coupler notch gap (mm)

- HOM2 coupler
- HOM1 coupler

Track3P

Delta vs Field Level (MV/m)

Expt. MP bands

Mechanical Analysis

The mechanical design of a cavity follows its RF design:

- Lorentz Force Detuning
- Mechanical Resonances
- Structural stability under different load conditions

Lorentz Force Detuning

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

92 kA/m

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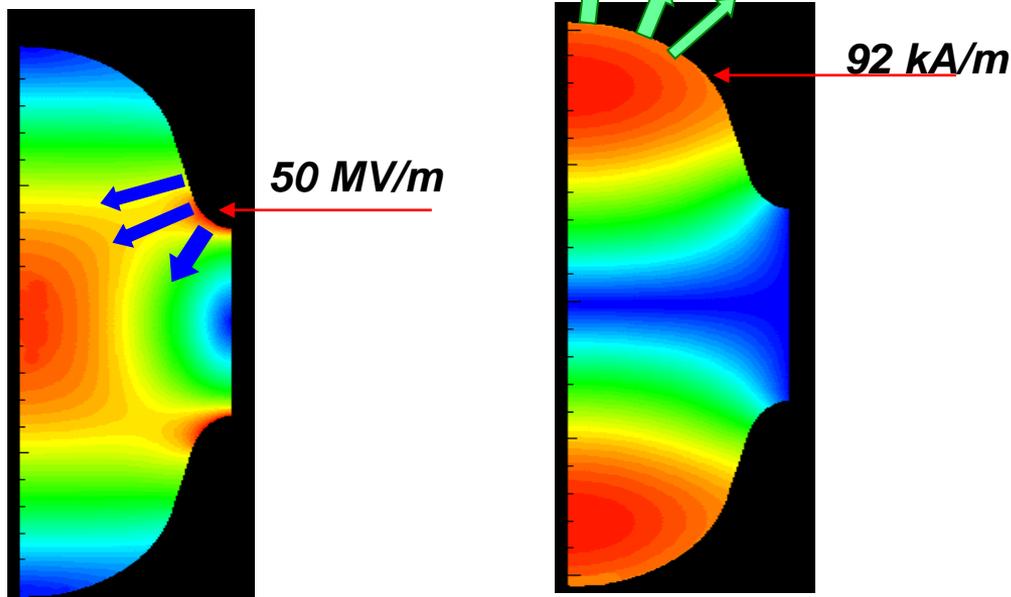
E and H at E_{acc} = 25 MV/m in TESLA inner-cup
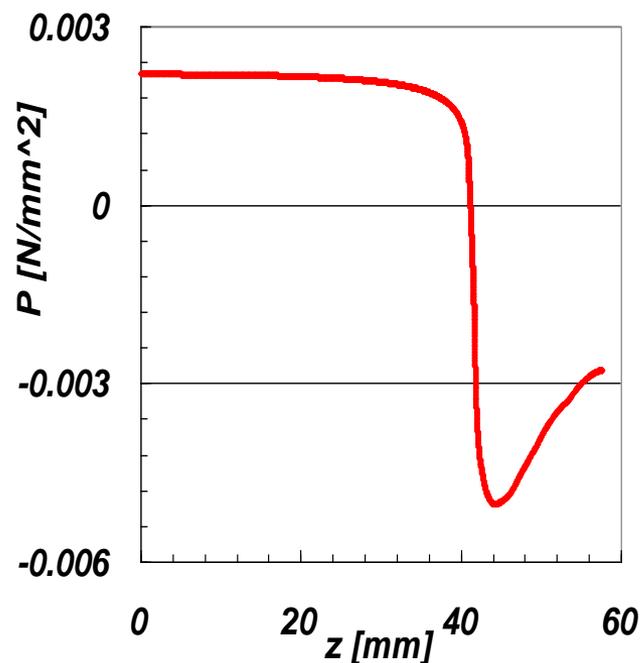
Stiffening

Surface deformation without and with stiffening ring

$10^{-4}m$

No stiffening ring
Wall thickness 3mm

$3\cdot10^{-5}m$

Stiffening ring at r=54mm
Wall thickness 3mm
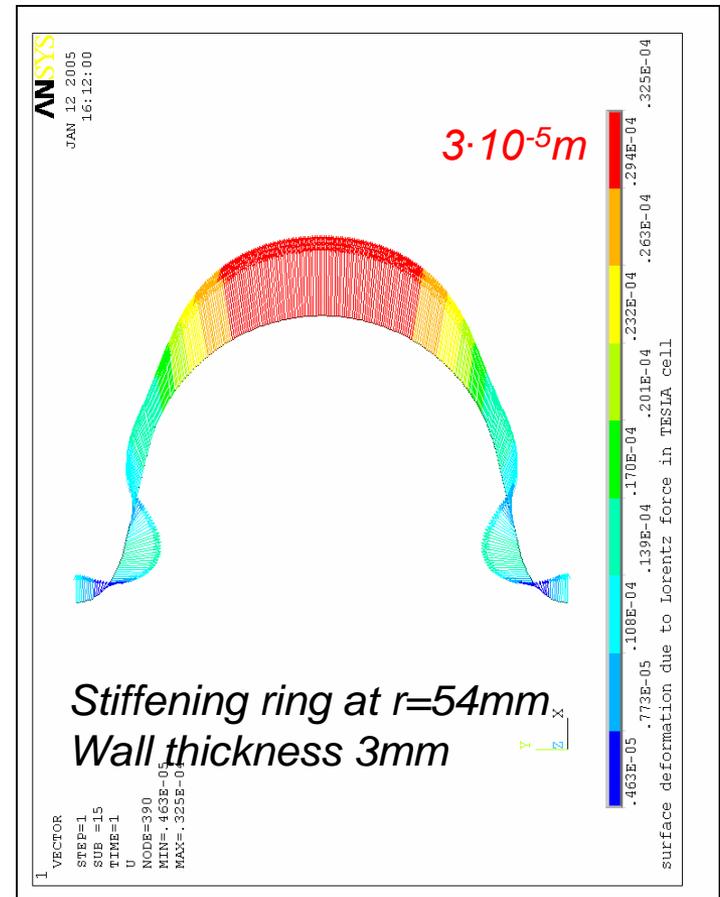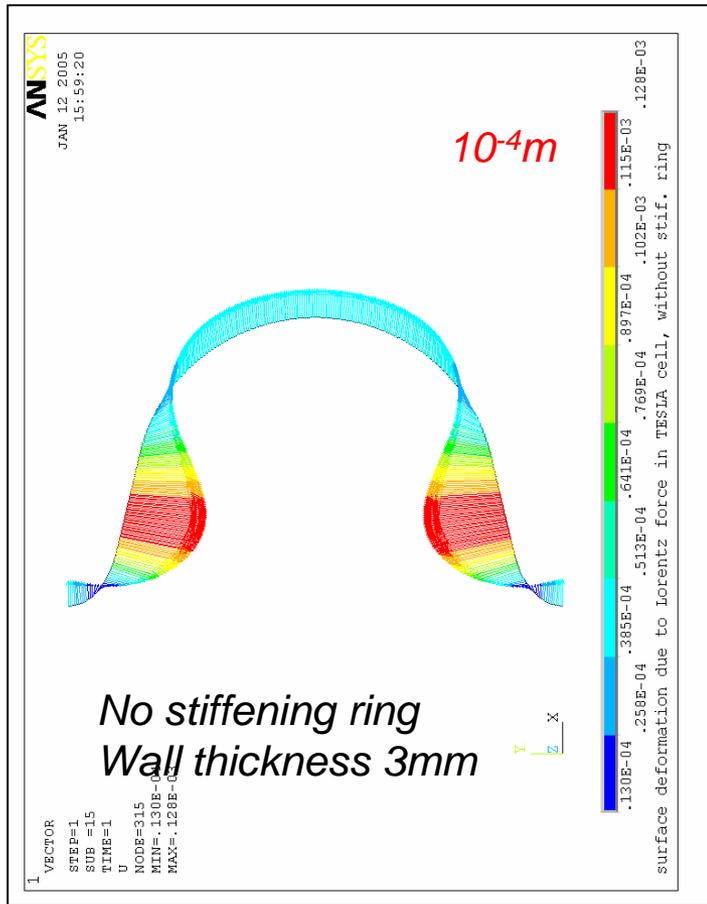
Essential for the operation of a pulsed accelerator
$$\Delta f = k_L(E_{acc})^2$$

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

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Optimal stiffening ring position

Fixed cell
length L

R_{stiff} = 80 mm
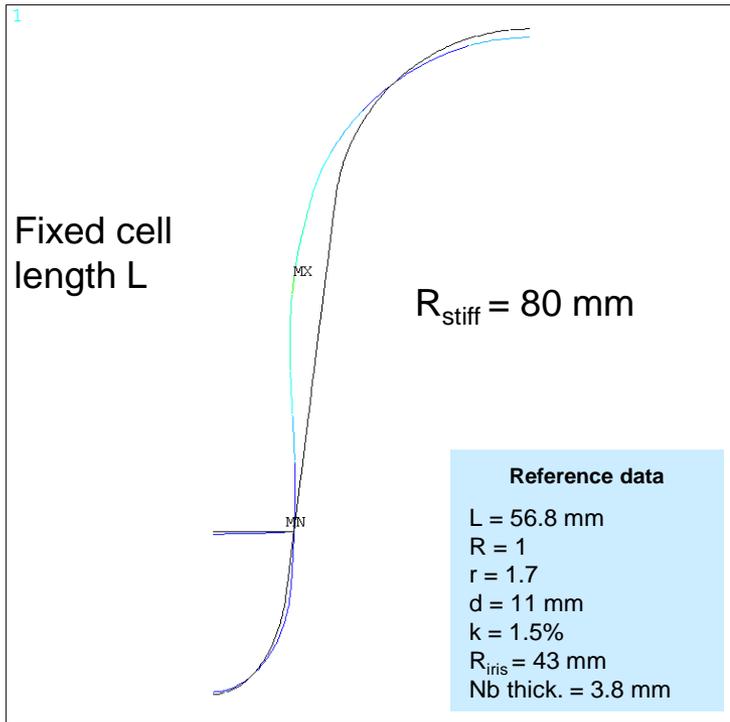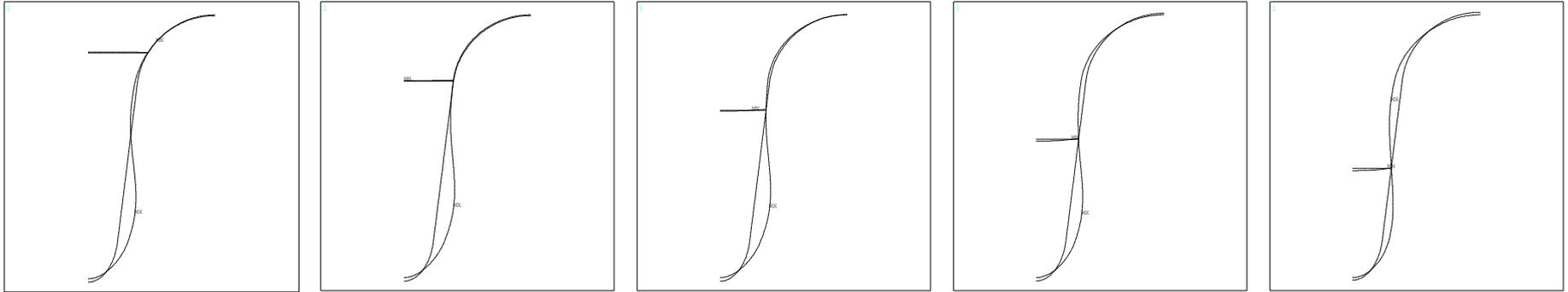
ANSYS 5.6
SEP 18 2000
15:27:02
PLOT NO. 13
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
USUM   (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.112E-05
SMN =.103E-07
SMX =.112E-05
         0
         .278E-06
         .556E-06
         .833E-06
         .111E-05
         .139E-05
         .167E-05
         .194E-05
         .222E-05
         .250E-05

Displacements
[mm]

Reference data

L = 56.8 mm
R = 1
r = 1.7
d = 11 mm
k = 1.5%
R_{iris} = 43 mm
Nb thick. = 3.8 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

R_{iris} ⟷ R_{stiff}

K_{fixed} [Hz/(MV/m)²]

Stiffening ring position [mm]

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JSA
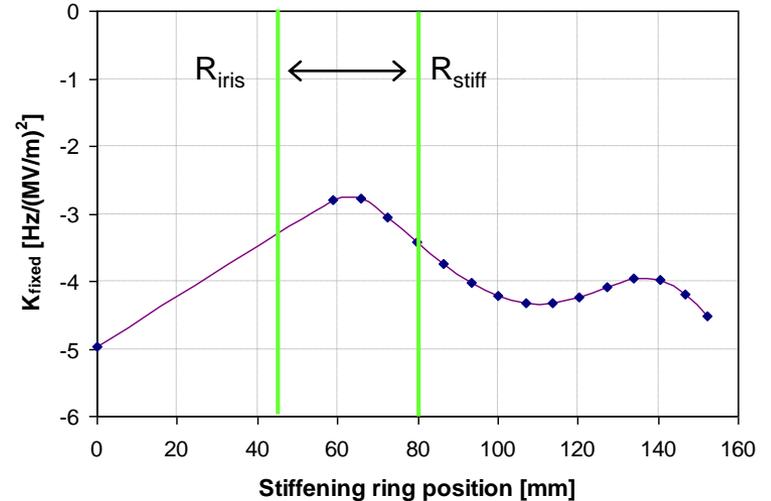
K_L for different boundary conditions

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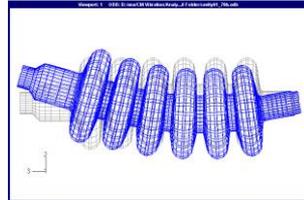 - Helium Vessel/Tuning System (= 3 tubes with diameter 30 mm and thickness 2 mm)
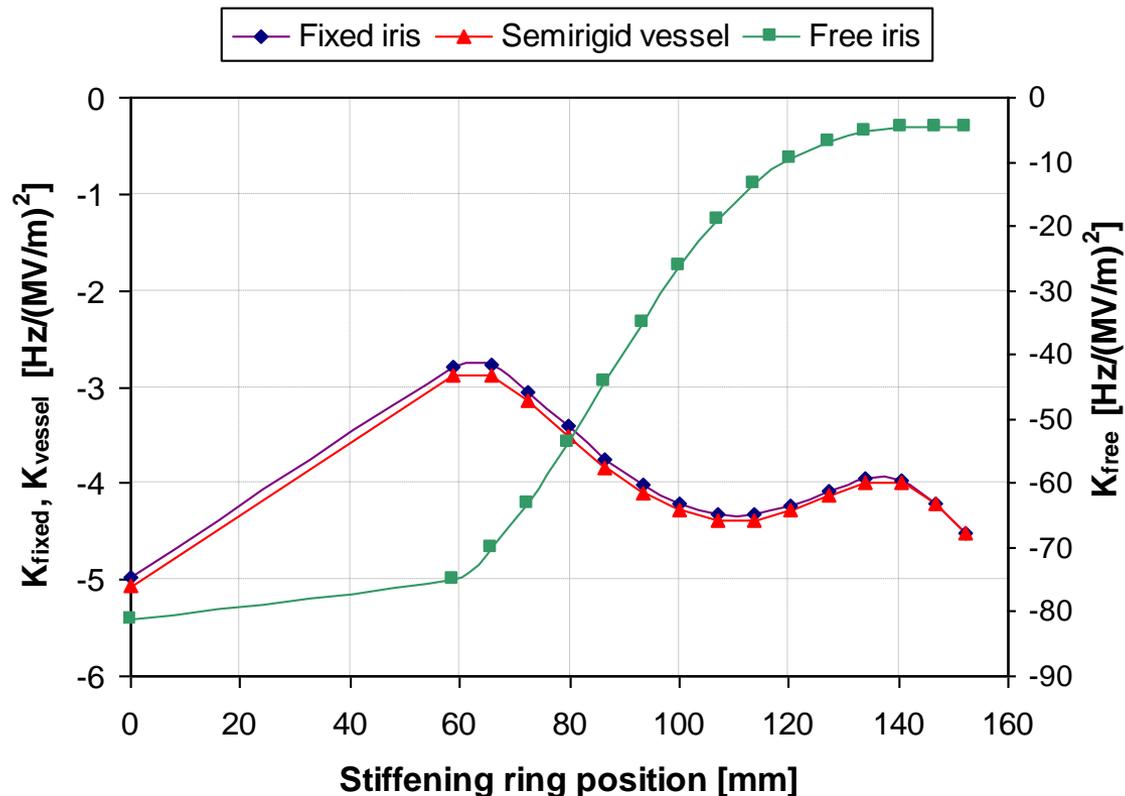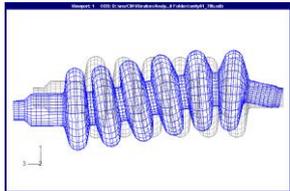
Mode Analysis

Calculate mechanical resonances of a multi-cell cavity as they modulate frequency of the accelerating mode. Sources of their excitation: vacuum pumps, ground vibrations…
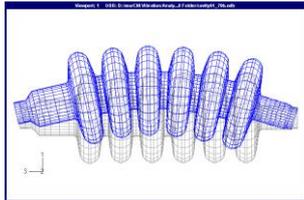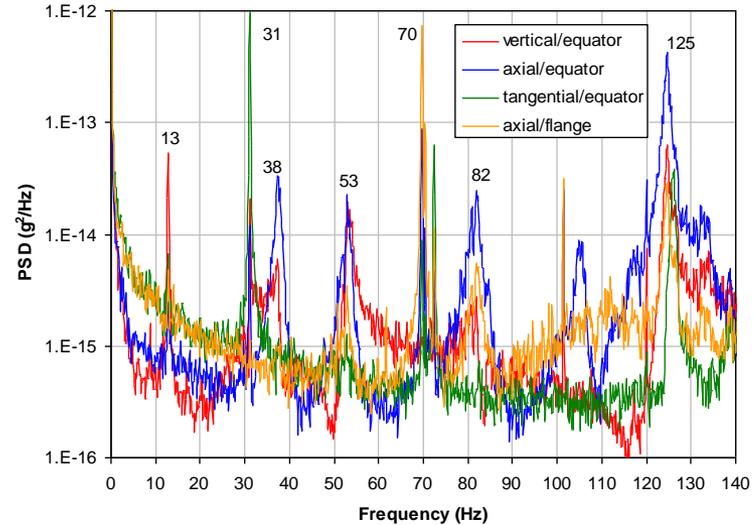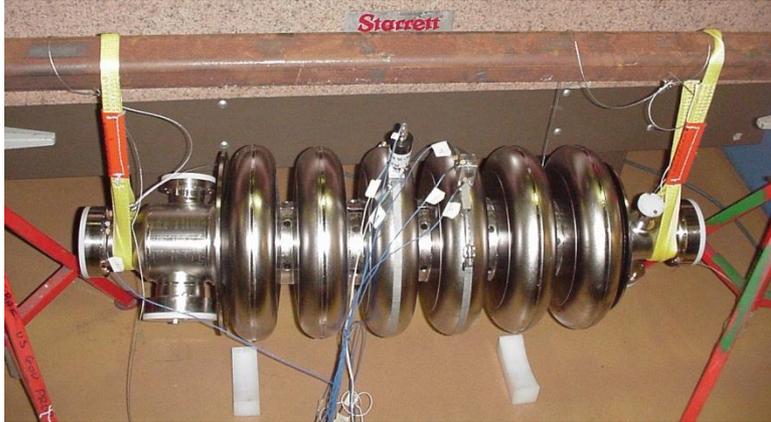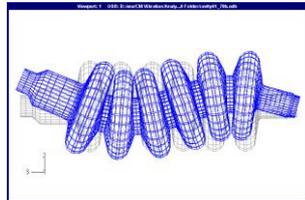

Mode 1 – 14 Hz

Mode 2 – 26 Hz

Mode 3 – 40 Hz

Mode 5 – 72 Hz

Mode	Natural Frequency (Hz)	
	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

Typical 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
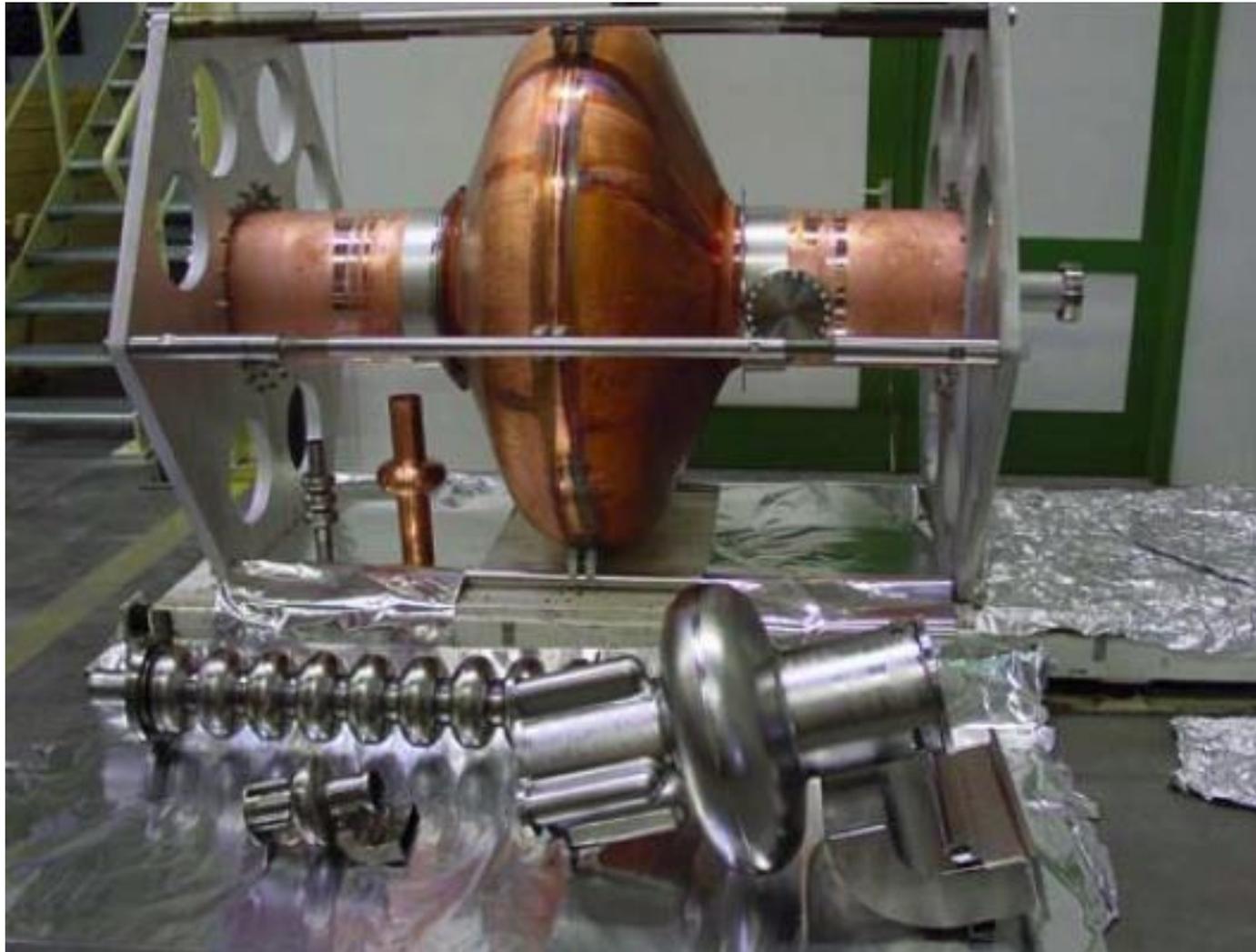   - **Warm Niobium = 4,667 psi**
      - **Cold Niobium = 53,333 psi**

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Mechanical analysis tools

- ANSYS: FEM multiphysics solver
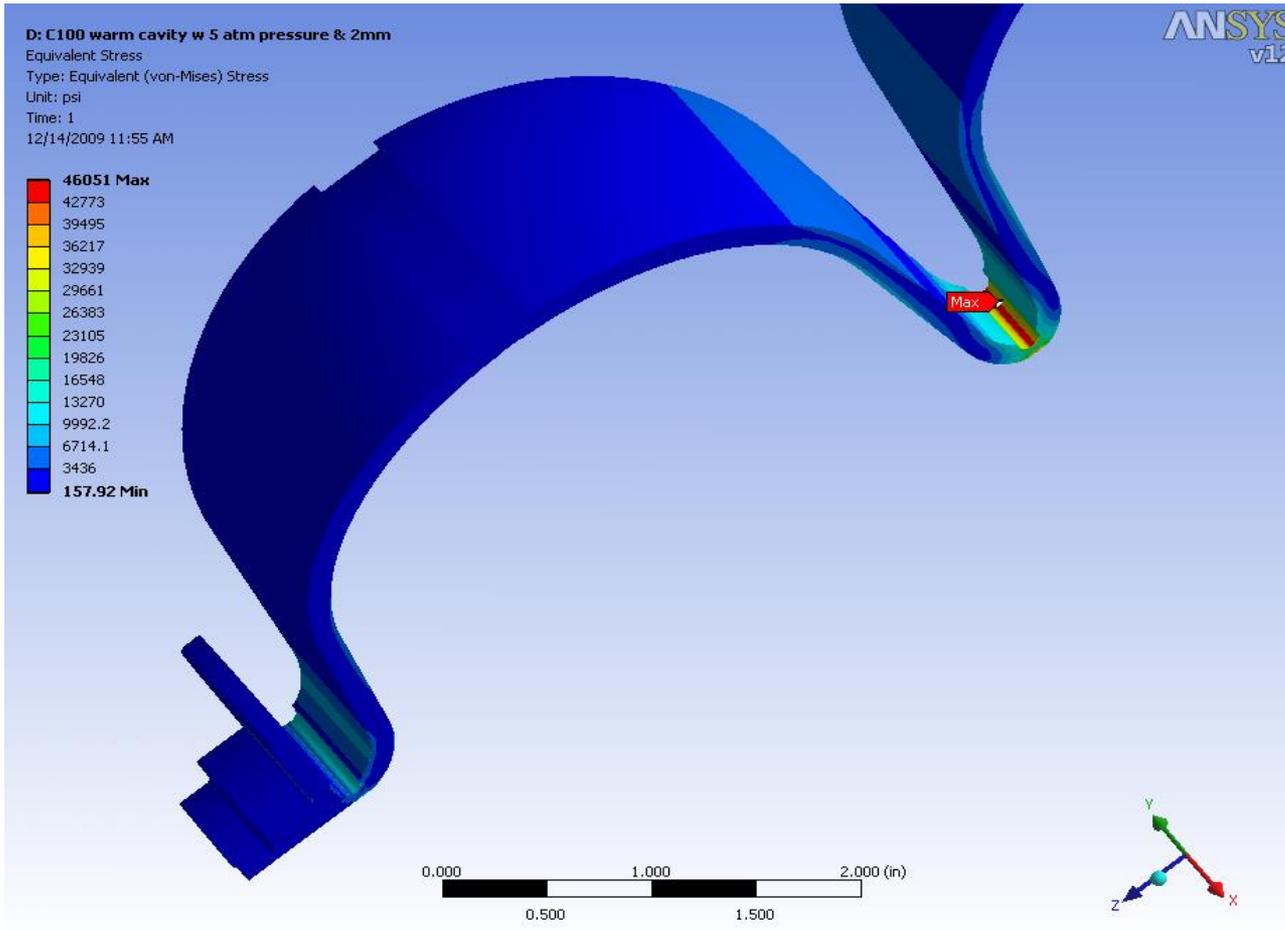
Peak von Mises stress in cold cavity with 5 atm pressure and 2 mm tuning displacement, calculated on CEBAF LL Upgrade cavity
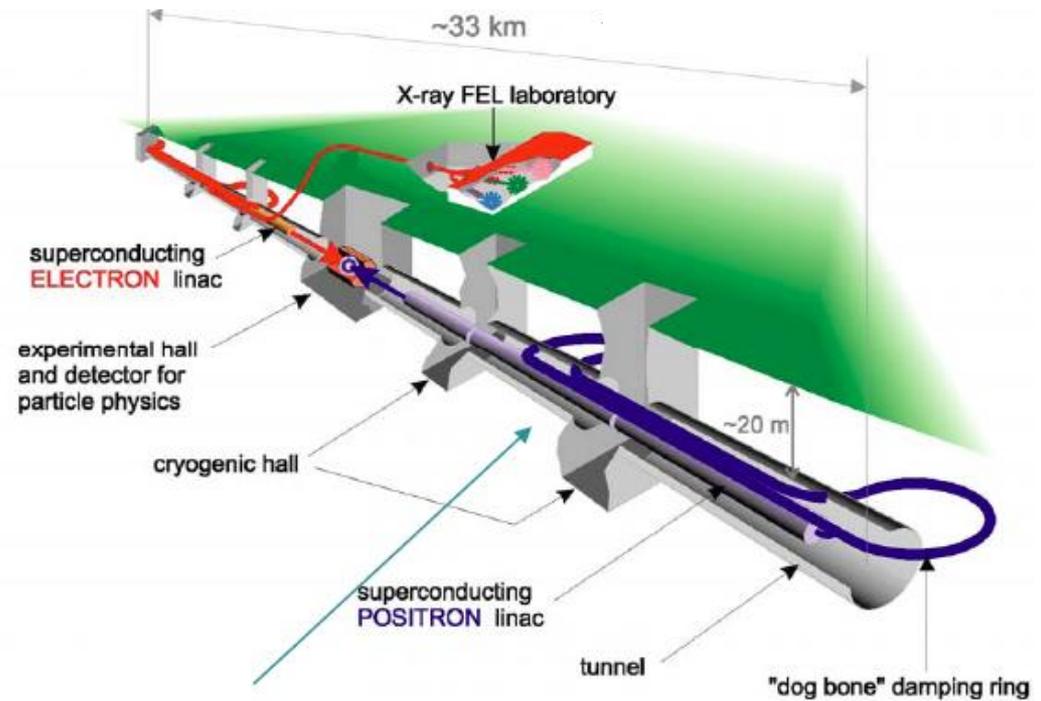
Cavities, large and small…

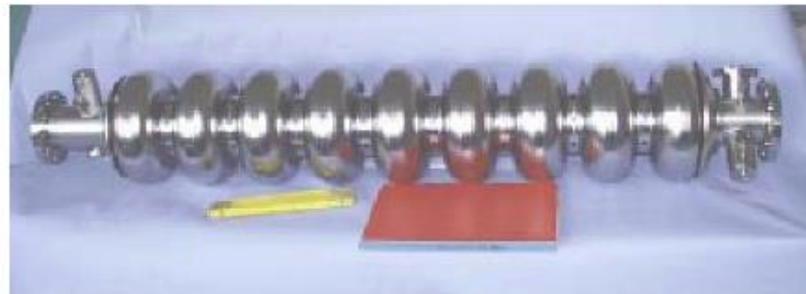Jefferson Lab   JSA

500 MHz, Single-cell
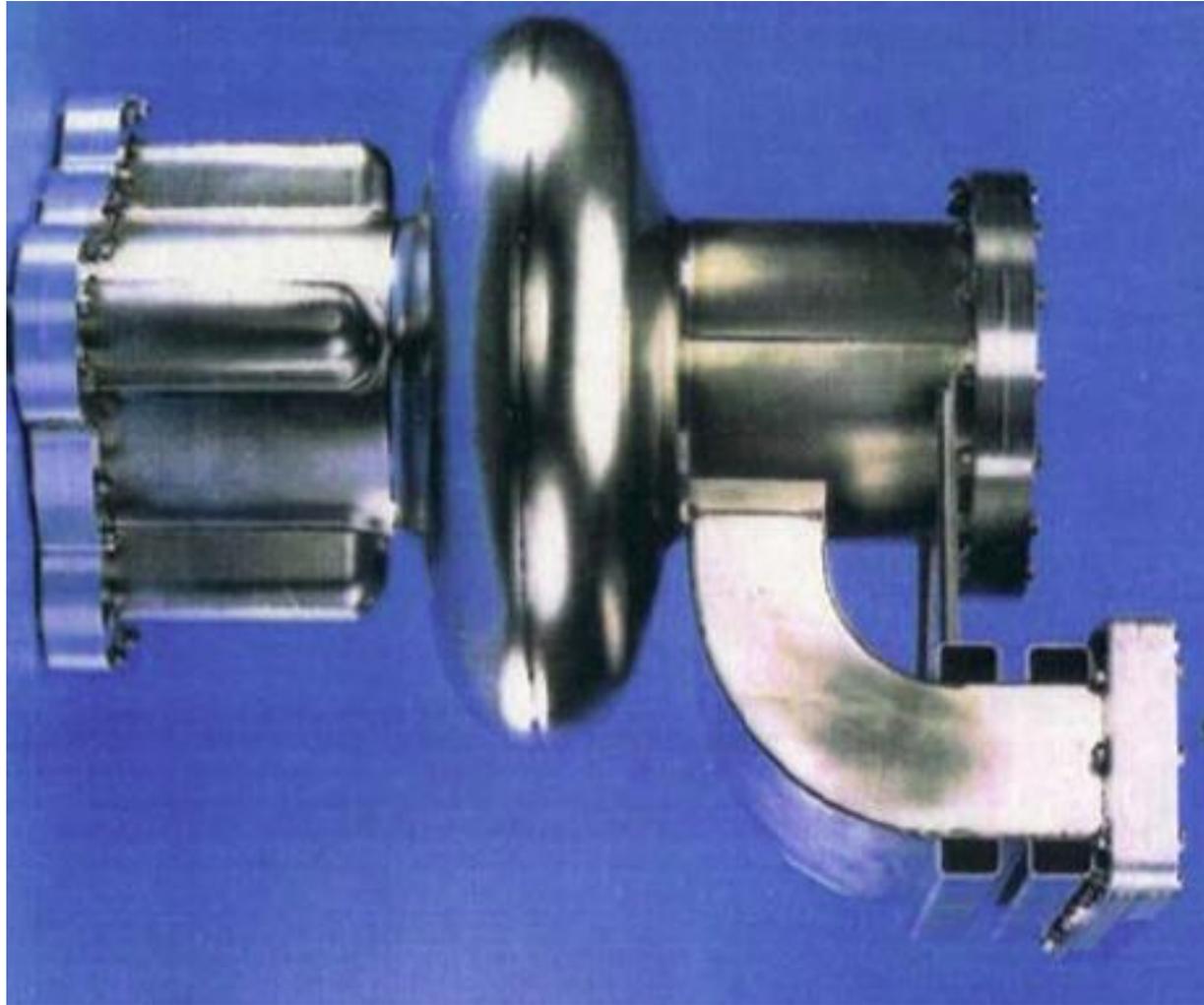
Pulsed LINACs (ILC, XFEL)

- High gradient ($\geq$ 25 MV/m)

- Moderate HOM damping ($Q_{ext} = 10^4 - 10^5$)
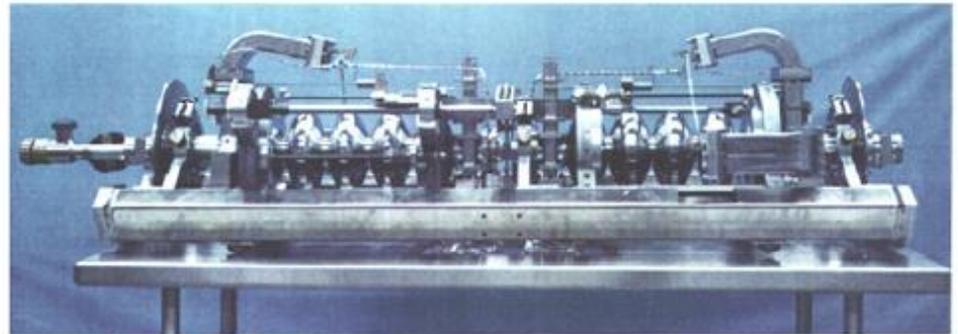
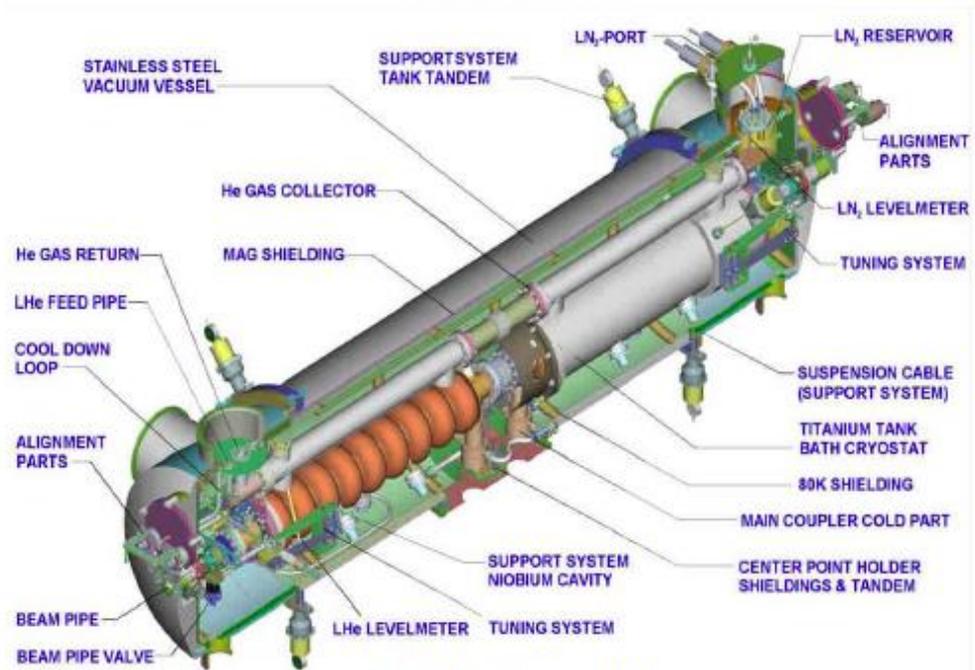- High peak (> 250 kW), low average RF power (~ 5 kW)

ILC: 21,000 cavities!

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CW Low-Current LINACs (CEBAF, ELBE)

• Moderate to low (8 – 20 MV/m)

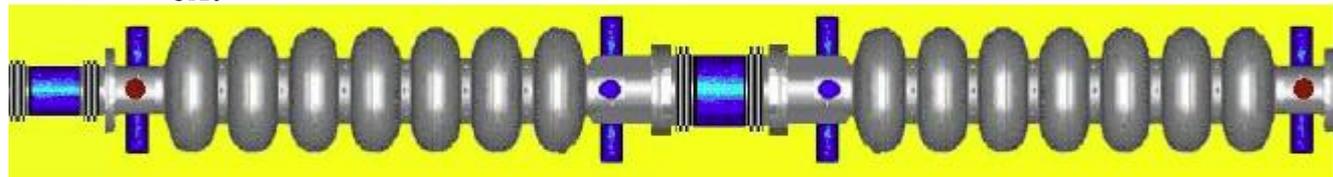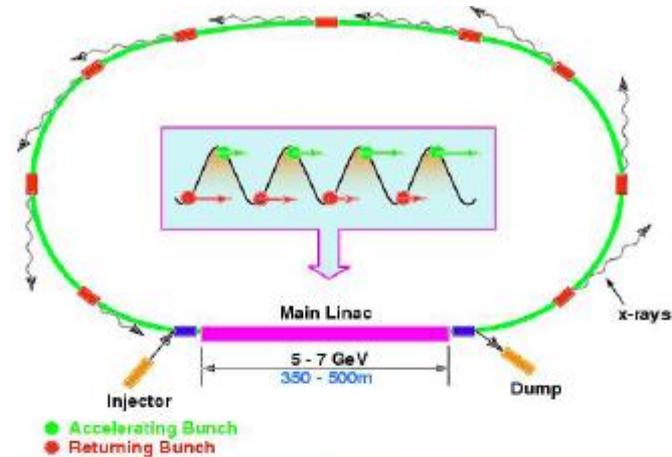• Relaxed HOM damping requirements

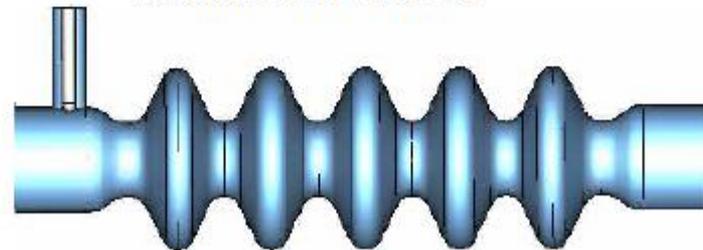• Low average RF power (5 – 13 kW)

CEBAF cavities

ELBE cryomodule

CW High-Current ERLs

• Moderate gradient (≥ 15 - 20 MV/m)

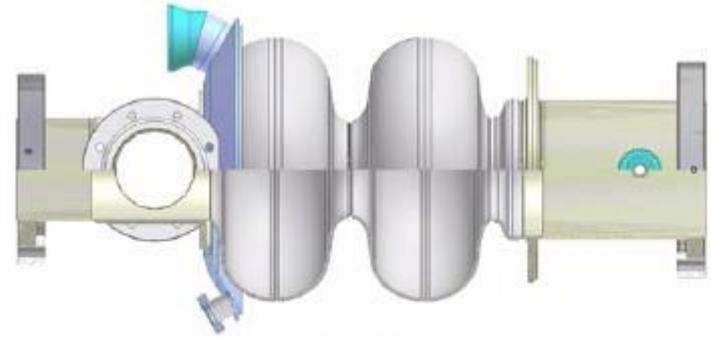• Strong HOM damping (Q_{ext} = $10^2 - 10^4$)

• Low average RF power (few kW)
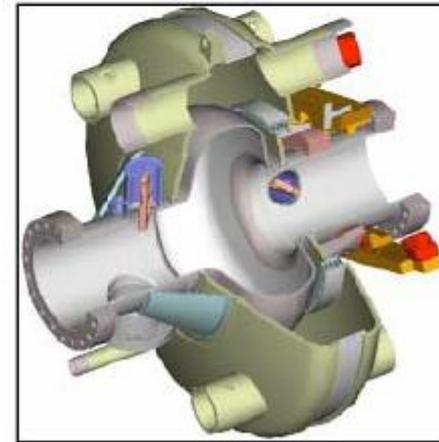

Cornell ERL cavities

BNL ERL cavity

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CW High-Current Injectors for ERLs

Cornell ERL injector cavity

- Moderate to low gradient (5 - 15 MV/m)

- Strong HOM damping ($Q_{ext} = 10^2 - 10^4$)

- High average RF power (50 - 500 kW)

JLab FEL 100 mA injector cavity

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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

Summary

Cavity DESIGN: be creative *and have fun with it!*

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