SRF 2007

Tutorial: Superconducting High ß Cavities

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Topics

1. Introduction and History (in brief)
2. RF Parameters
3. Criteria for Cavity Design
4. Multi-cell Structures and Weakly Coupled Structures
5. Tools for RF-design
6. LEC and Transient state
7. Performance tests
8. Mechanical Design
9. Final Remarks

1. Introduction and History

Milestones that led to accelerators based on SRF

Superconductivity

<u>1908:</u> Heike Kamerlingh Onnes (Holland)
Liquefied Helium.

<u>1911:</u> Heike Kamerlingh Onnes
Discovered Superconductivity.

<u>1928-34:</u> Walther Meissner (Germany)
Discovered Superconductivity of Ta, V, Ti and Nb.

RF Acceleration

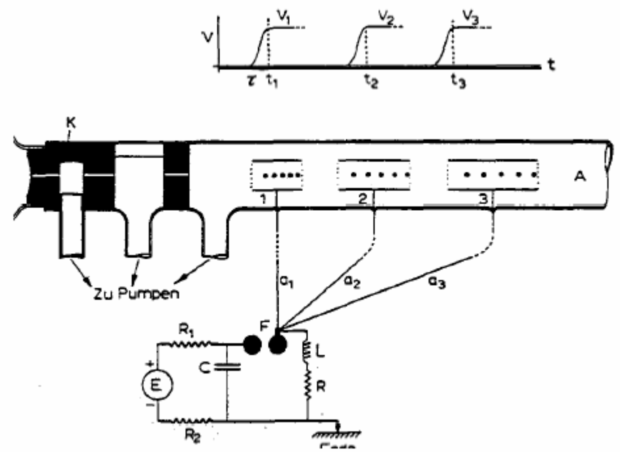


Fig. 1. Diagram of linear accelerator from Professor G. Ising's pioneer publication (1924) of the principle of multiple acceleration of ions.

Invented Klystron.

<u>1947:</u> Luis Alvarez (USA)
Built first DTL (32 MeV protons).

<u>1947:</u> W. Hansen (USA)
Built first 6 MeV e-accelerator, Mark I (TW-structure).

1. Introduction and History

Superconductivity **RF Acceleration**

<u>1961:</u> Bill Fairbank (Stanford Univ.) presented the first proposal for a superconducting accelerator.

<u>1964:</u> Bill Fairbank, Alan Schwettman and Perry Wilson (Stanford University)
First acceleration of electrons with sc lead cavity.

<u>1967:</u> John Turneaure (Stanford University)
Epeak =70 MV/m and Q~10^{10} in 8.5 GHz cavity !!

<u>1968-1981:</u> Mike McAshan, Alan Schwettman, Todd Smith, John Turneaure and Perry Wilson (Stanford University)
Development and Construction of the Superconducting Accelerator SCA.

Dismantled Facilities

1. TRISTAN (32/49m)*
2. LEP (288/490m)
3. HERA (16/19m)

Operating Facilities

1. SCA (4/28m)
2. S-DALINAC (10/10m)
3. CESR (4/1.2 m)
4. CEBAF (320/160m)
5. KEK B-Factory (8/2.4m)
6. Taiwan LS (1+1/0.3m)
7. Canadian LS (1+1/0.3m)
8. DIAMOND (3/0.9m)
9. SOLEIL (4/1.7m)
10. TTF II (56/58m)
11. SNS (81/65m)
12. JLab-FEL (24/14m)
13. LHC (16/6m)
14. ELBE (6/6m)

*(Number of cavities/total active length)

Tomorrow Facilities

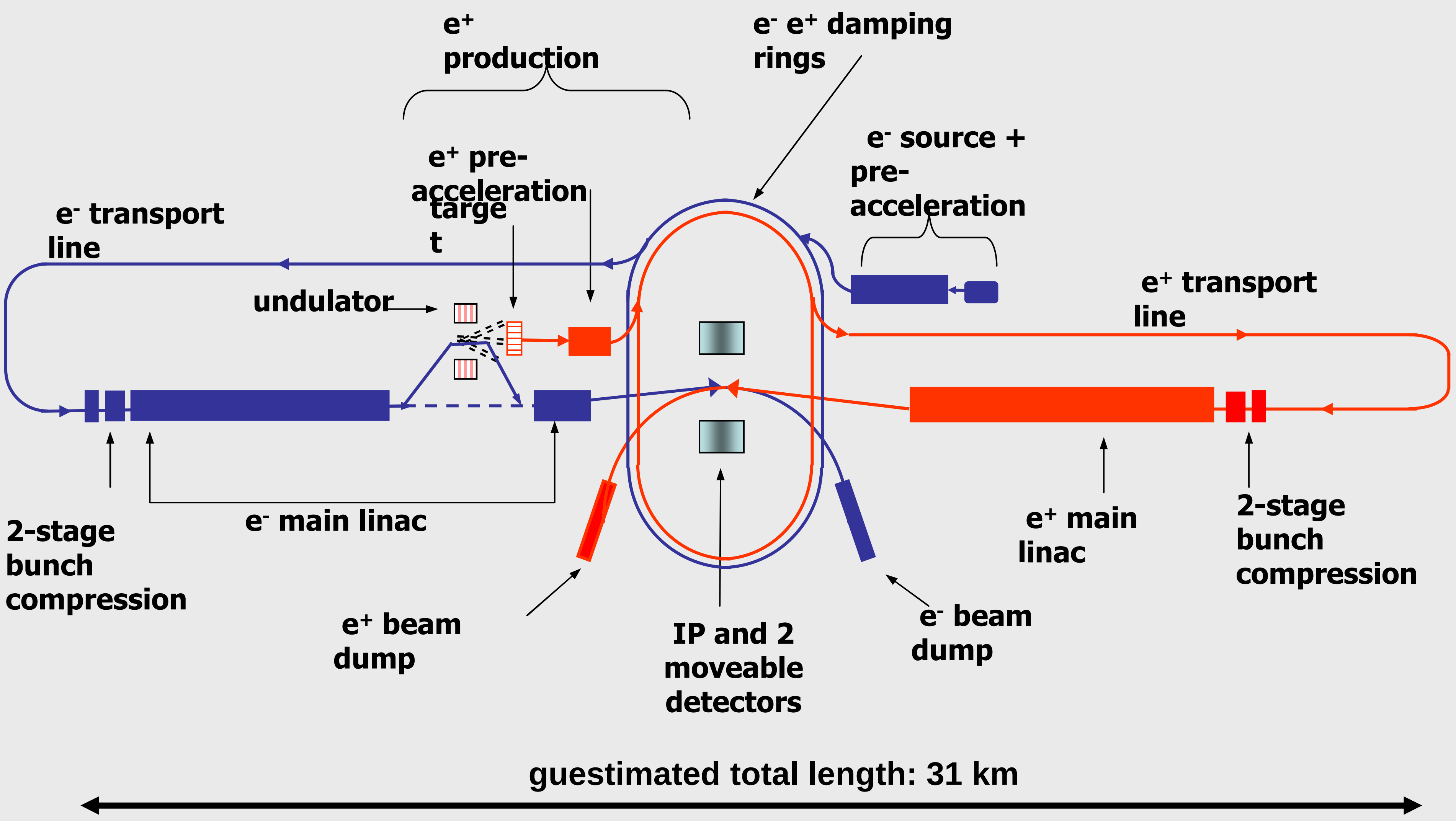
1. **CEBAF-12GeV (400/216m)**
2. **SNS-upgrade (117/ 98m)**
3. **XFEL (800/832m)**
4. **ERL-Cornell (310/250m)**
5. **BESSY (144+7$_{3\text{-Harm}}$ /152m)**
6. **4GLS (~40/~42m)**
7. **RHIC-cooling (4/4 m)**
8. **Shanghai LS…….**
9. **BEPC II (2/0.6m)**

Day after Tomorrow Facilities

1. **RIA (option 180/122m)**
2. **X-Ray MIT (option 176/184m)**
3. **LUX (~40/~50m)**
4. **FERMI Proton Linac (384/370m)**
5. **ERHIC………**
6. **ELIC …..**
7. **ARC-EN-CIEL (48/50m)**

8. ILC (~15764/~16395m)

ILC (~15764/~16395m)

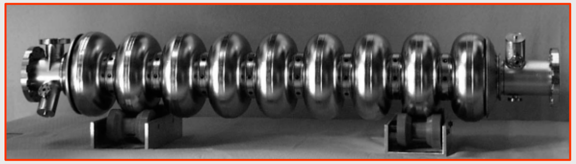


1. Introduction and History

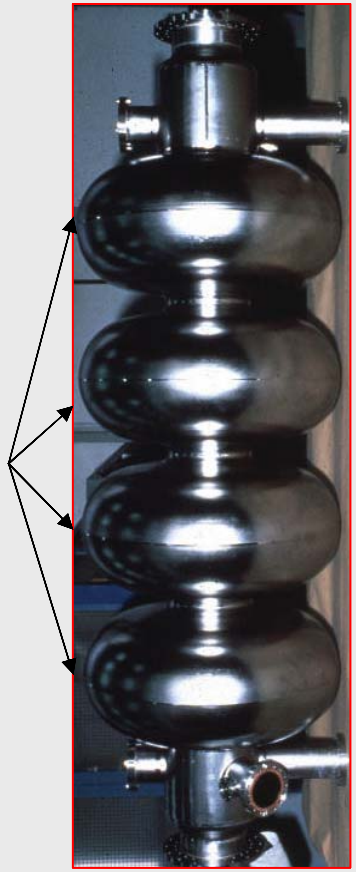
The "heart" of all mentioned facilities are sc standing wave (usually multi-cell) accelerating structures.

FERMI 3.9 GHz

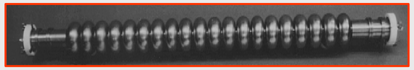
TESLA/ILC 1.3 GHz



LEP 0.352 GHz

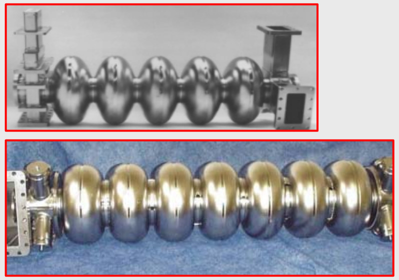


S-DALINAC 3 GHz



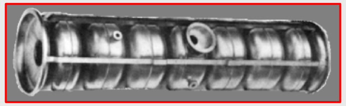
SNS ß=0.61,0.81, 0.805 GHz

CESR/CEBAF 1.5 GHz

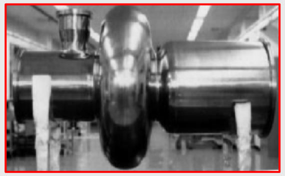


HERA 0.5 GHz

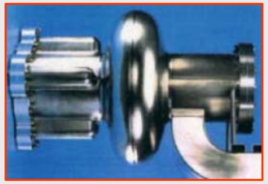
HEPL 1.3 GHz



KEK-B 0.5 GHz

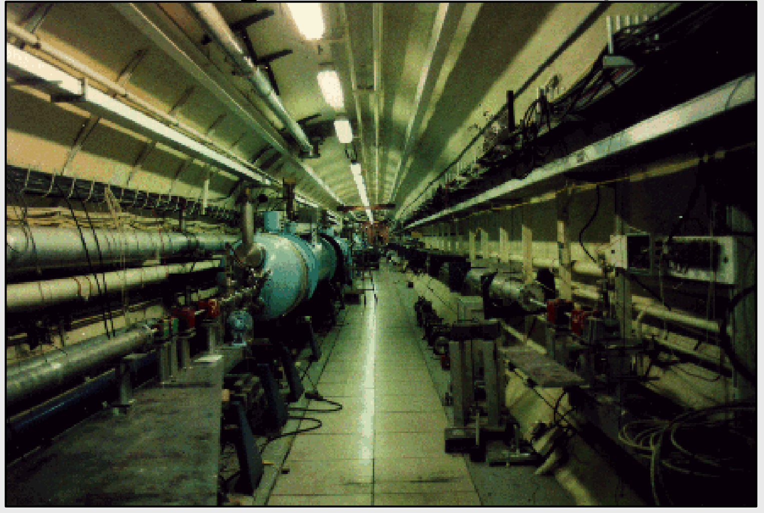


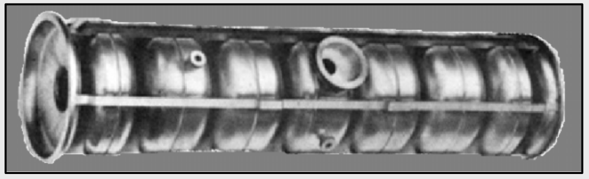
CESR 0.5 GHz



What is the progress in the 30 years and what do we need in the next 10 years?

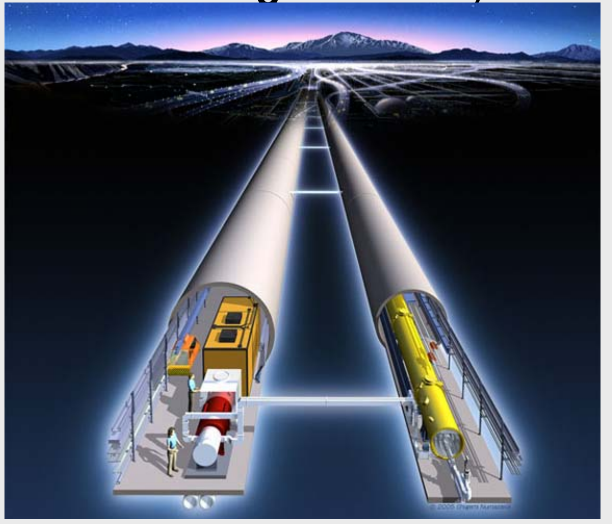
~ 28 m long SCA at Stanford, 1977.

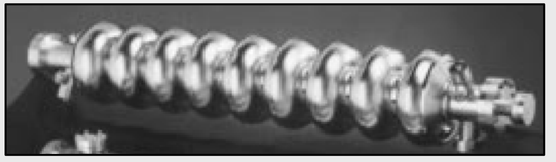




E_{acc} ~2 (2.5) MV/m in cw (10% DF).
4 Structures 5.65m + capture + pre-accelerator.

~ 21.6 km long ILC linac, 2015+





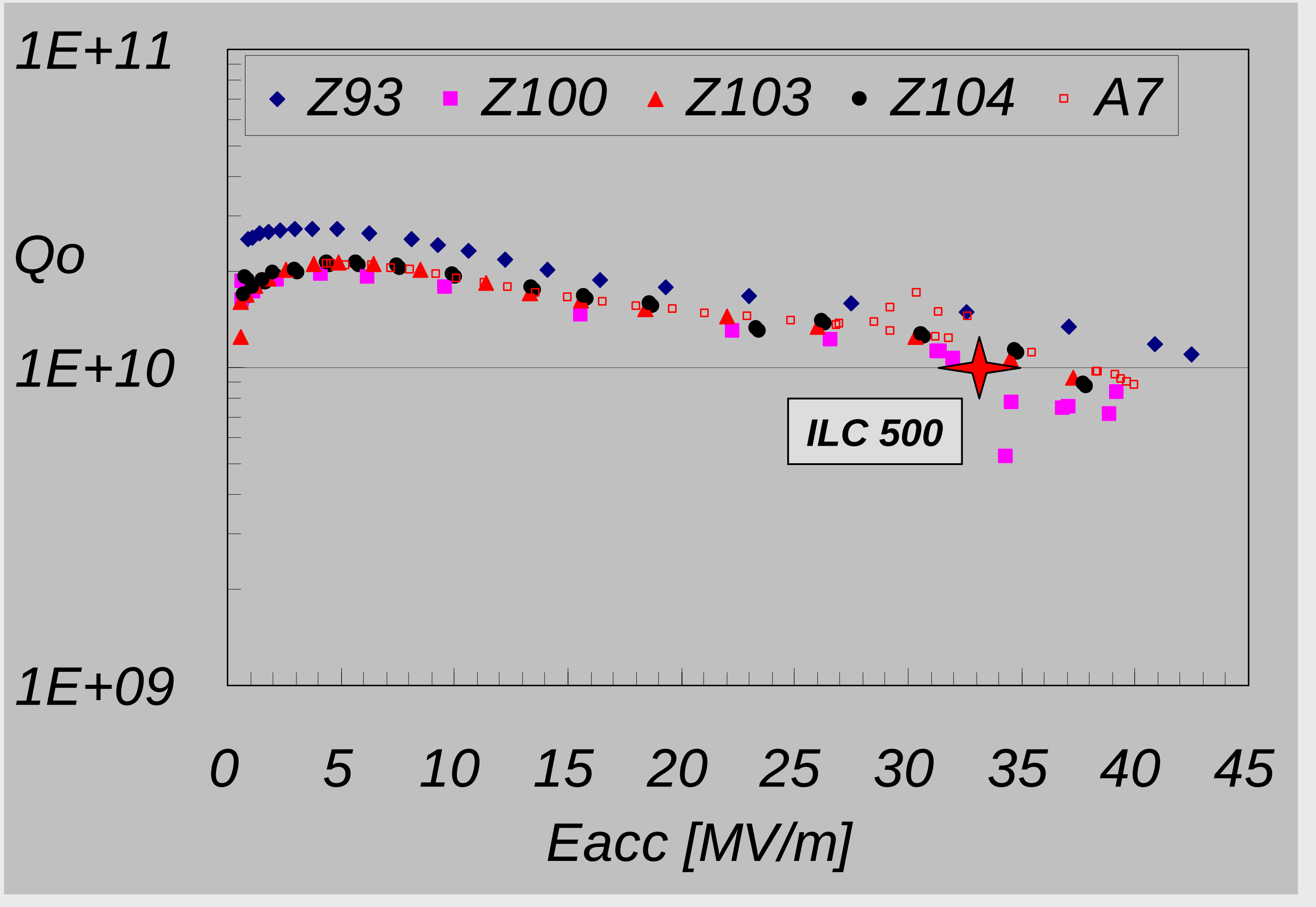
E_{acc} > 34 MV/m shown in several 9-cells in the cw test.

⬇

This gradient is required in all 15764 cavities.

Results at DESY and JLab (2007):

cw test result at 2K for 5 electropolished 9-cell TESLA cavities.



2.1 Cavities and their Eigenmodes

Cavity≡ an arbitrary volume, partially closed by the metal wall, capable to store the E-H energy

~ 3.95 GHz is the lowest frequency

First assumption:

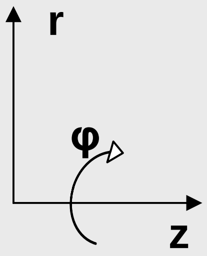
1. **Stored E-H fields are harmonic in time.**

Maxwell equations for the harmonic, lossless case with no free charge in the volume

$$\begin{cases} \nabla \times H = i\omega\varepsilon E \\ \nabla \times E = -i\omega\mu H \\ \nabla \cdot E = 0 \\ \nabla \cdot H = 0 \end{cases}$$

Second assumption (good approximation for the elliptical cavities):

2. The volume is cylindrically symmetric. We commonly use the (r, φ, z) coordinates.



z is conventional direction of the acceleration and symmetry axis

$$\begin{cases} \nabla_c \times H = i\omega\varepsilon E \\ \nabla_c \times E = -i\omega\mu H \\ \nabla_c \cdot E = 0 \\ \nabla_c \cdot H = 0 \end{cases}$$

$$\nabla_c \times A = \vec{i}_r \left(\frac{1}{r}\frac{\partial A_z}{\partial \varphi} - \frac{\partial A_\varphi}{\partial z} \right) + \vec{i}_\varphi \left(\frac{\partial A_r}{\partial z} - \frac{\partial A_z}{\partial r} \right) + \vec{i}_z \left(\frac{1}{r}\frac{\partial (rA_\varphi)}{\partial r} - \frac{1}{r}\frac{\partial A_r}{\partial \varphi} \right)$$

$$\nabla_c \cdot A = \frac{1}{r}\frac{\partial (rA_r)}{\partial r} + \frac{1}{r}\frac{\partial A_\varphi}{\partial \varphi} + \frac{\partial A_z}{\partial z}$$

2. RF Parameters

Third assumption

3. For the acceleration are suitable field patterns with strong E along the beam trajectory.

This ensures, by the proper phasing, maximal energy exchange between the cavity and beam.

<u>TM0xx-like monopole</u> modes have "very strong" E_z component on the symmetry axis.

Fields of the monopole modes are independent on φ.

$$\frac{\partial E}{\partial \varphi} = 0 \qquad \frac{\partial H}{\partial \varphi} = 0$$

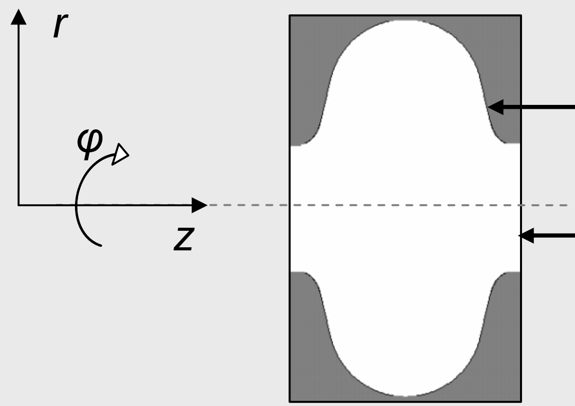
<u>Non monopole (HOM)</u> modes have component $E_z = 0$ on the symmetry axis.

Their fields dependent on φ.

2. RF Parameters

Maxwell equations + boundary conditions for E and H fields lead to the Helmholtz equation, which is an eigenvalue problem.

For H(r,z) field of a monopole mode the equation is:



$$(\nabla_c^2 + \omega^2 \varepsilon\mu)H = 0$$

$n \cdot H = 0$ **on metal wall**

$\begin{cases} H = 0 \\ n \cdot H = 0 \end{cases}$ **optionally on non metal boundary**

$$\nabla_c^2 A = \nabla_c(\nabla_c \cdot A) - \nabla_c \times \nabla_c \times A$$

There is infinity number of TM0xx solutions (modes) to the Helmholtz equation.

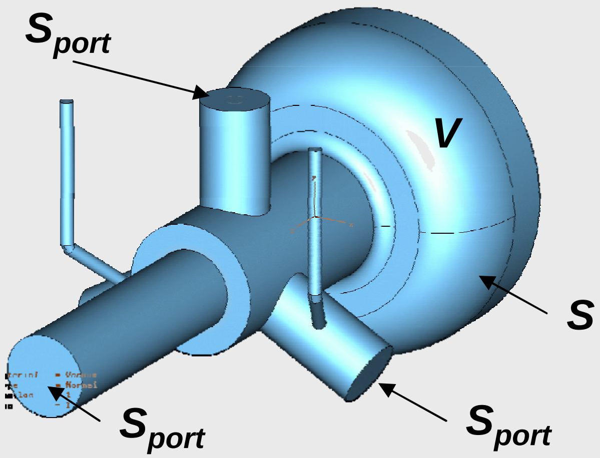
All modes are determine by:

$\boldsymbol{H_n}(r,z)=[0, H_{\varphi,n}(r,z),0]$,

$\boldsymbol{E_n}(r,z)=[E_{r,n}(r,z),0, E_{z,n}(r,z)]$

and frequency $\boldsymbol{\omega_n}$.

2.2 What are figures of merit for a cavity storing E-H energy?



***W_n* ≡ *stored energy of a mode n* : {ω_n, $\mathbf{E}_n$, $\mathbf{H}_n$}.**

$$W_n \equiv 2\mu \int_V \frac{H_n^2}{4} dV = 2\varepsilon \int_V \frac{E_n^2}{4} dV$$

Quality Factors

The measure of the energy loss in the metal wall and due to the radiation via open ports:

Intrinsic *Q* ≡ *Qo*

$$Q_{0,n} \equiv \frac{\omega_n \cdot W_n}{P_n} = \frac{\omega_n \cdot W_n}{\frac{R_{s,n}}{2} \int_S H_n^2 ds}$$

External *Q* ≡ Q_{ext}

$$Q_{ext,n} \equiv \frac{\omega_n \cdot W_n}{P_{rad,n}} = \frac{\omega_n \cdot W_n}{\frac{1}{2} \int_{S_{port}} E_n \times H_n ds}$$

Geometric Factor

The measure of the energy loss in the metal wall for the surface resistance $R_{s,n}=1\Omega$

$$G_n \equiv Q_{0,n} \cdot R_{s,n} = \frac{\omega_n \cdot W_n \cdot R_{s,n}}{P_n} = \frac{\omega_n \cdot W_n}{\frac{1}{2}\int_S H_n^2 ds}$$

It is the ratio of the stored energy to the integral of $(H_n)^2$ **on the metal surface.**

2.3 What are figures of merit for the beam-cavity interaction?

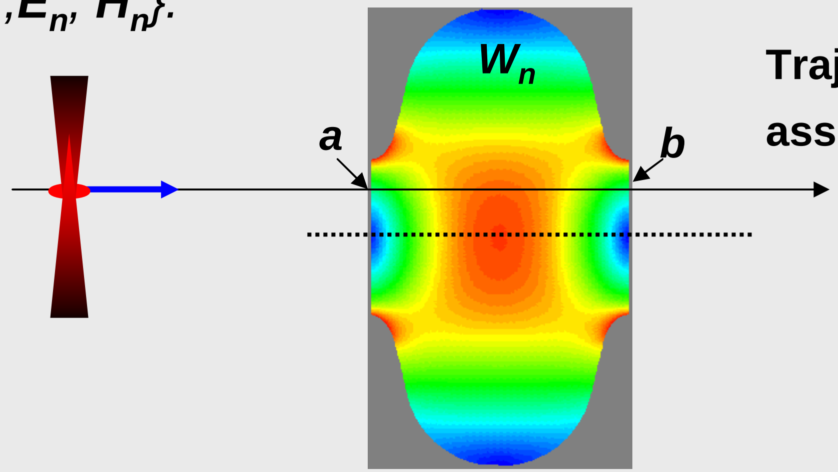
This interaction which is:

- **Acceleration**
- **Deceleration (ERL)**
- **HOMs excitation**

can be described in the Frequency Domain (FD) or/and in Time Domain (TD).

$(R/Q)_n$, a “measure” of the energy exchange between point charge and mode n (FD).

mode n : $\{\omega_n, E_n, H_n\}$.



Trajectory of the point charge q, assumed here to be a straight line.

$$V_n = \sqrt{\left(\int_{z_a}^{z_b} E_{n,z} \sin\left(\frac{\omega_n}{\beta c}(z - z_a)\right)dz\right)^2 + \left(\int_{z_a}^{z_b} E_{n,z} \cos\left(\frac{\omega_n}{\beta c}(z - z_a)\right)dz\right)^2}$$

$$(R/Q)_n \equiv \frac{V_n^2}{\omega_n W_n}$$

2. RF Parameters

For the accelerating mode we often use the product of $G_{acc} \cdot (R/Q)_{acc}$, as a "measure" of the power P dissipated in the metal wall at the given accelerating voltage V_{acc} and the given surface resistance R_s.

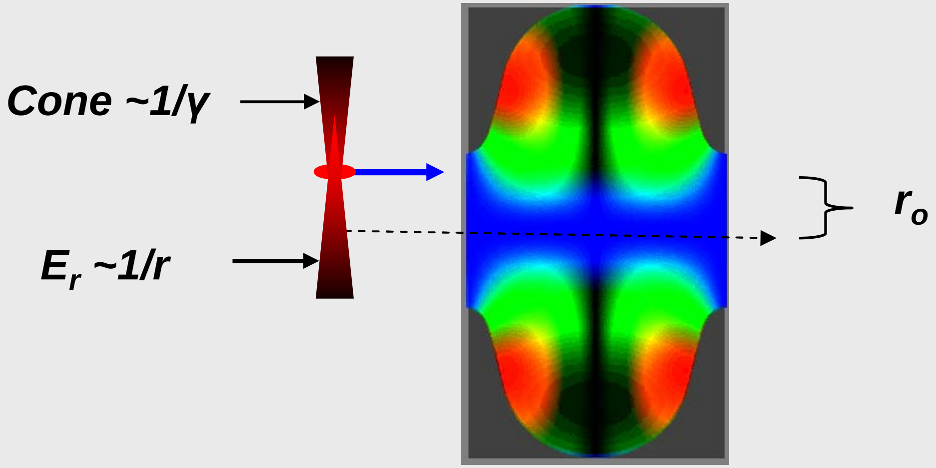
$$\frac{P_{dissipated}}{V_{acc}^2} \equiv \frac{R_s}{G_{acc} \cdot (R/Q)_{acc}}$$

This is due to the surface quality;
Big improvement possible.

This is due to the geometry of cells;
Moderate improvement possible.

Longitudinal and Transverse Loss Factors (TD)

Ultra relativistic point charge *q* passes empty cavity



a. Density of the inducted charge on the wall depends on the distance to the beam trajectory.

b. The non uniform charge density on the metal wall causes the current flow on the surface.

2. RF Parameters

The amount of energy lost by charge q to the cavity is:

$\Delta U_q = k_{\parallel} \cdot q^2$ **for monopole modes (max. on axis)**

$\Delta U_q = k_{\perp} \cdot q^2$ **for non monopole modes (off axis)**

where $k_{\parallel}$ and $k_{\perp}(r)$ are loss factors for the monopole and transverse modes respectively.

The induced *E-H* field (wake) is a superposition of <u>cavity eigenmodes</u> (monopoles and others) having the $E_n(r,\varphi,z)$ field <u>along the trajectory</u>.

Both description methods FD and TD are equivalent.

For individual mode n and point-like charge:

$$k^{\mathbf{p}}_{\parallel,n} = \frac{\omega_n \cdot (R/Q)_n}{4}$$

Note the linac convention for (R/Q) definition.

Similar for other loss factors…….

2. RF Parameters

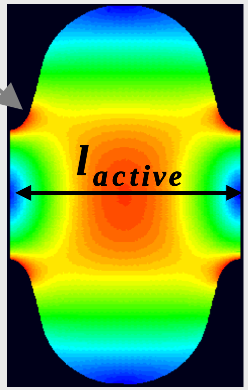
RF parameters of the accelerating mode having more practical background

At stored energy W_{acc} the mean value of the accelerating gradient is:

$$E_{acc} = \frac{\sqrt{\omega_{acc} \cdot W_{acc} \cdot (R/Q)_{acc}}}{l_{active}}$$

E_{peak} on the surface

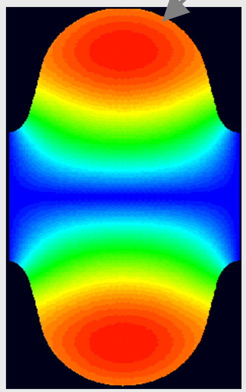
$$\frac{E_{peak}}{E_{acc}}$$



Contour plot of /E/

B_{peak} on the surface

$$\frac{B_{peak}}{E_{acc}}$$



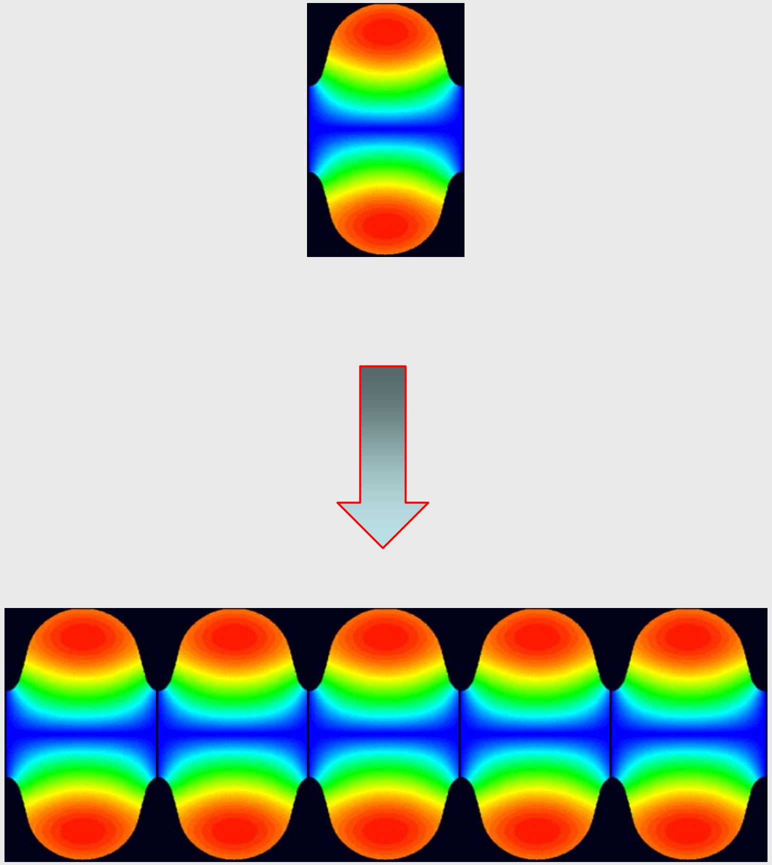
Contour plot of /B/

Ratio shows sensitivity of the shape to the field electron emission phenomenon.

Ratio shows limit in E_{acc} due to the break-down of superconductivity (Nb ~190mT).

2. RF Parameters

The last parameter, relevant for multi-cell accelerating structures, is the coupling k_{cc} between cells for the accelerating mode passband (Fundamental Mode passband).



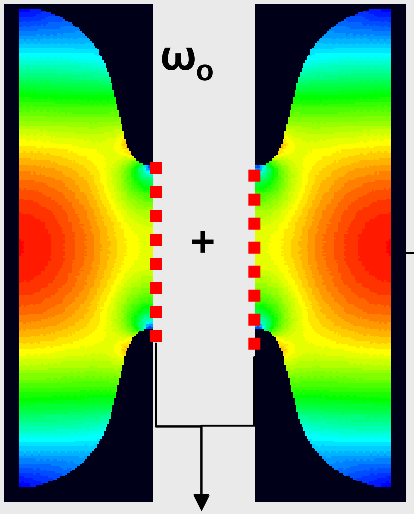
Single-cell structures are attractive from the RF-point of view:

- **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.**

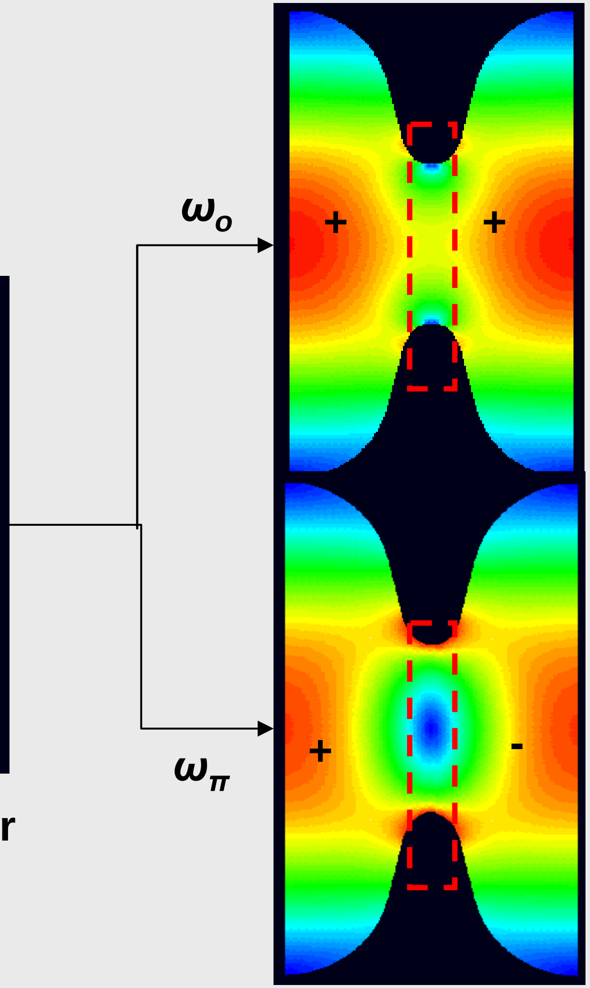
Multi-cell structures are less expensive and offers higher real-estate gradient but:

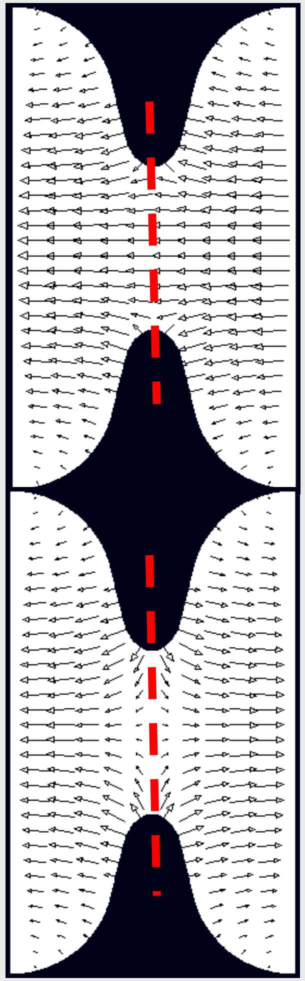
- **Field flatness (stored energy) in cells becomes sensitive to frequency errors of individual cells**
- **Other problems arise: HOM trapping…**

Resonators closed by metal wall:



Symmetry planes for the H field





Symmetry plane for the H field

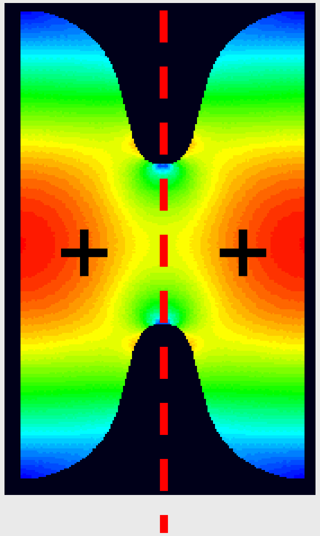
Symmetry plane for the E field

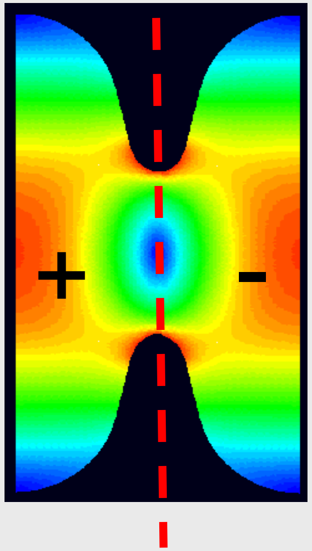
which is an additional solution

2. RF Parameters

The energy flux across the coupling region, refilling energy loss is proportional to the transverse components: H_φ and E_r

ω_o





ω_π

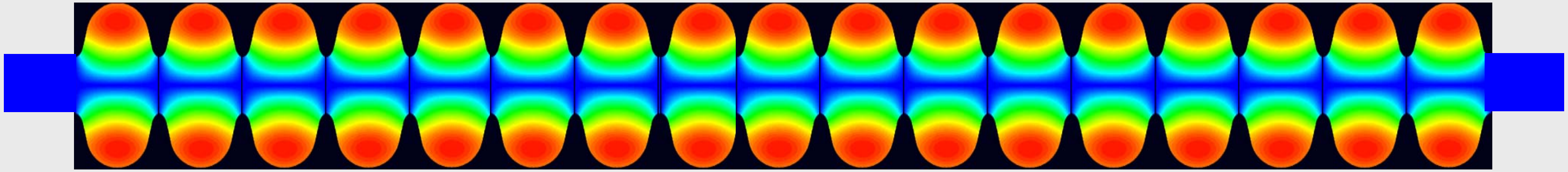
Small E_r (due to the losses) + strong H_φ at the symmetry plane

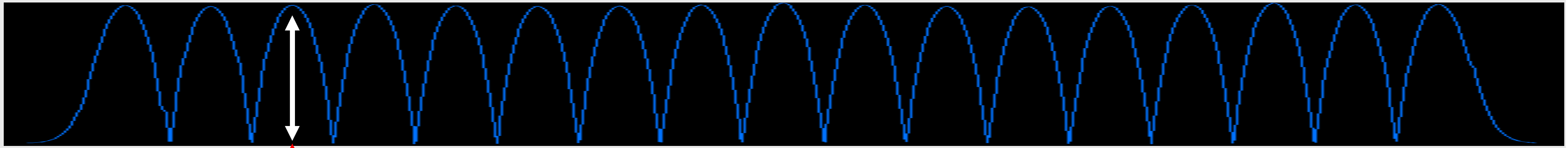
Small H_φ (due to the losses) + strong E_r at the symmetry plane

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

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

2. RF Parameters





$$\frac{\Delta A_i}{A_i} = a_{ff}\,\frac{\Delta f_i}{f_i}$$

Field flatness factor for a structure made of *N* cells and coupling factor k_{cc}

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

The above formulae estimate sensitivity of a multi-cell field profile to frequency errors of an individual cell for the accelerating mode (π-mode)

We will talk here about inner cells design because these cells “dominate” parameters of a multi-cell superconducting accelerating structure.

RF parameters summary:

FM ***: (R/Q), G,*** E_{peak}/E_{acc}, B_{peak}/E_{acc}, k_{cc}

HOM : $k_{\perp}$, $k_{\parallel}$.

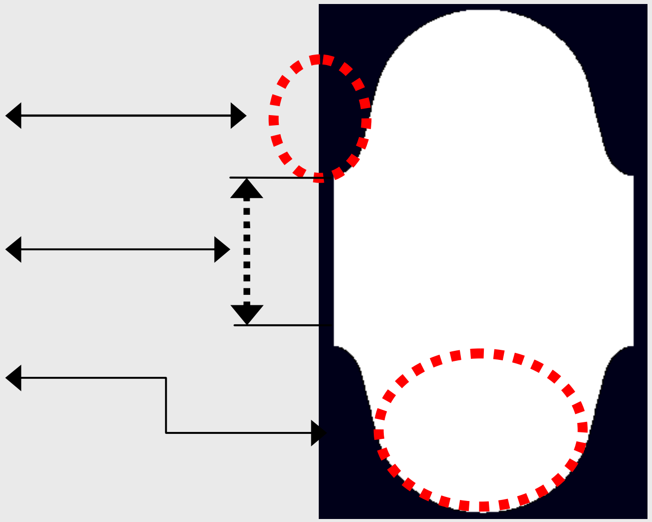
There are 7 parameters we want to optimize for an inner cell

Geometry :

iris ellipsis : *half-axis* h_r, h_z

iris radius : r_i

equator ellipsis : *half-axis* h_r, h_z



There is some kind of conflict *7 parameters* and only *5 variables* to “tune”

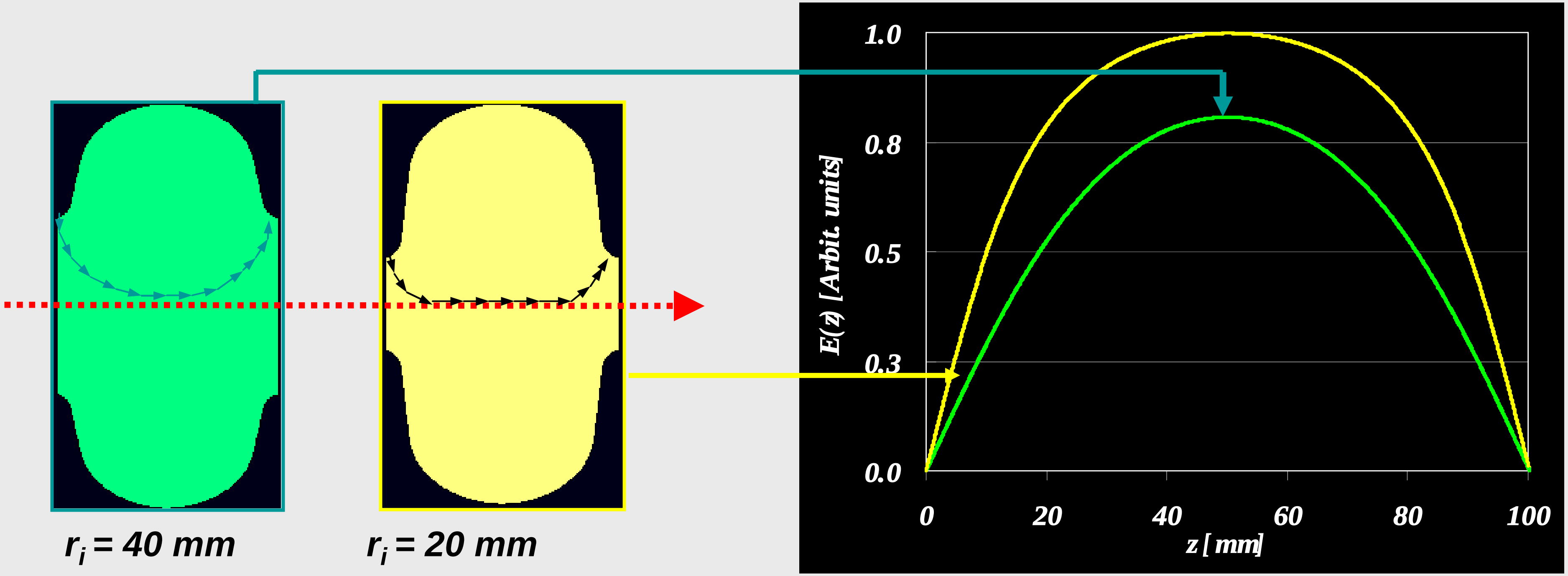
Criteria	RF-parameter	Improves when	Cavity examples
Operation at high gradient	E_{peak} / E_{acc} B_{peak} / E_{acc} ↓	r_i ↓ Iris, Equator shape	TESLA, HG CEBAF-12 GeV
Low cryogenic losses	$(R/Q) \cdot G$ ↑	r_i ↓ Equator shape	LL CEBAF-12 GeV LL- ILC cavity
High I_{beam} ↔ Low HOM impedance	$k_{\perp}, k_{\parallel}$ ↓	r_i ↑	B-Factory RHIC cooling

We see here that r_i is a very “powerful variable” to trim the RF-parameters of a cavity.

Why for a smaller aperture (r_i)

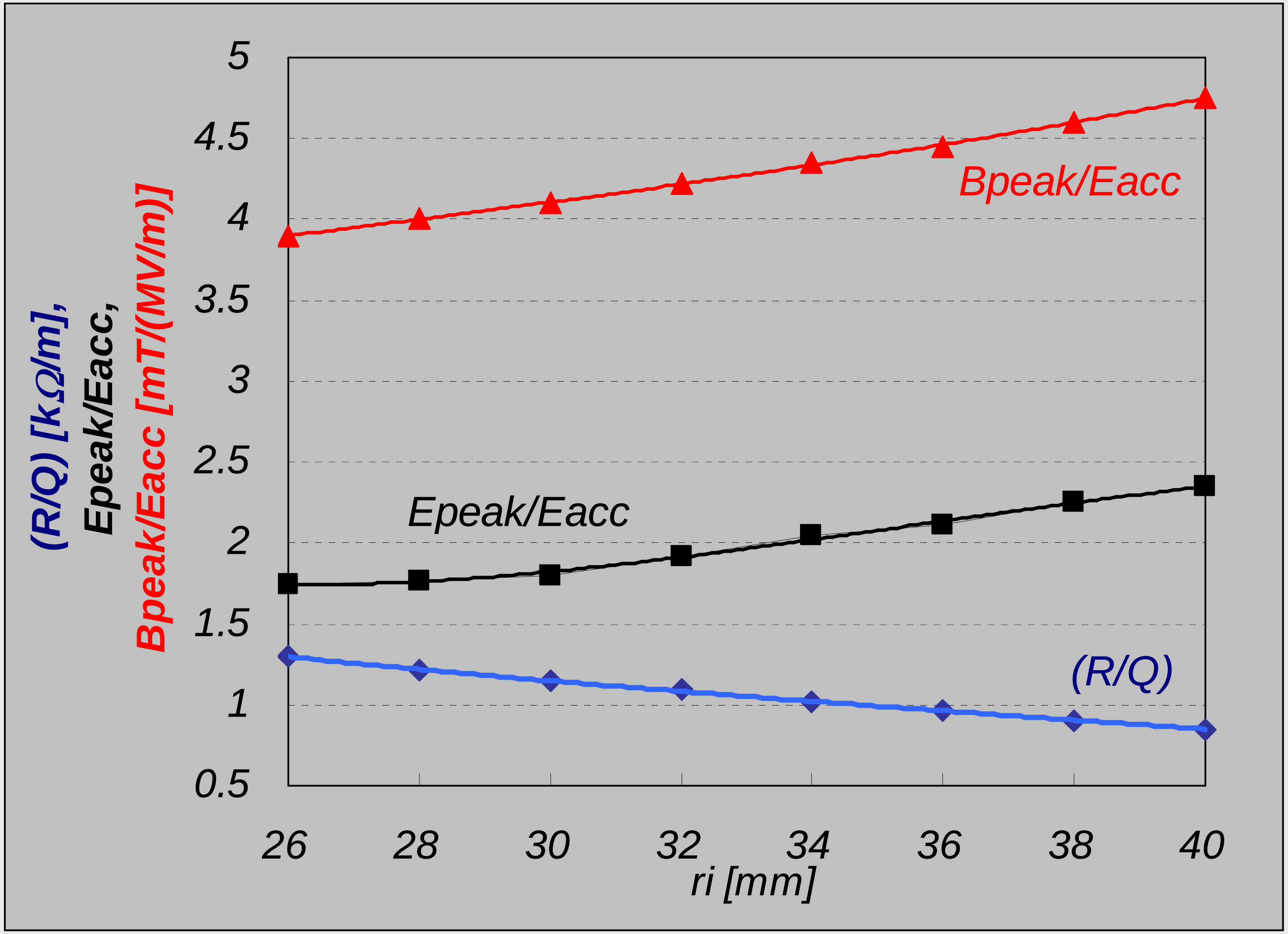
- ***(R/Q)* is bigger**
- **E_{peak}/E_{acc} , B_{peak}/E_{acc} is lower ?**

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



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

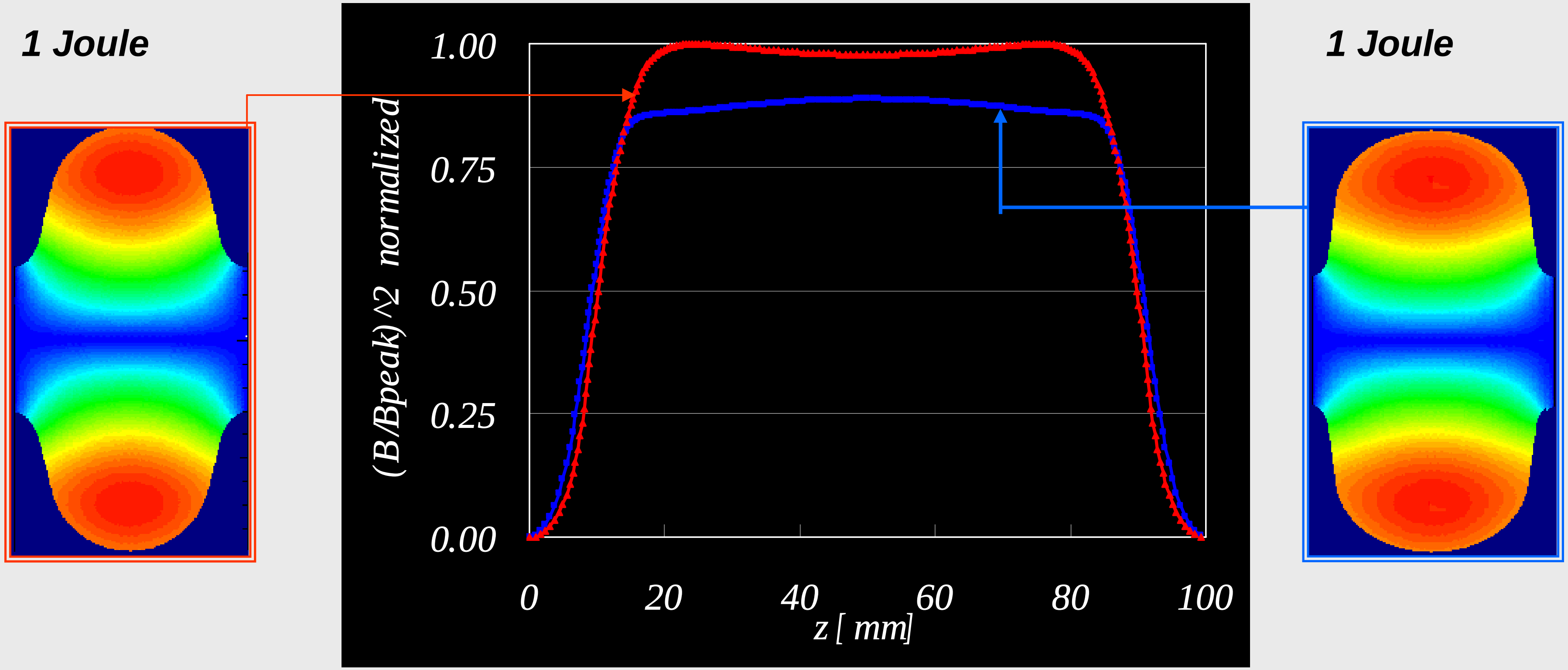
Example:
f = 1.5 GHz



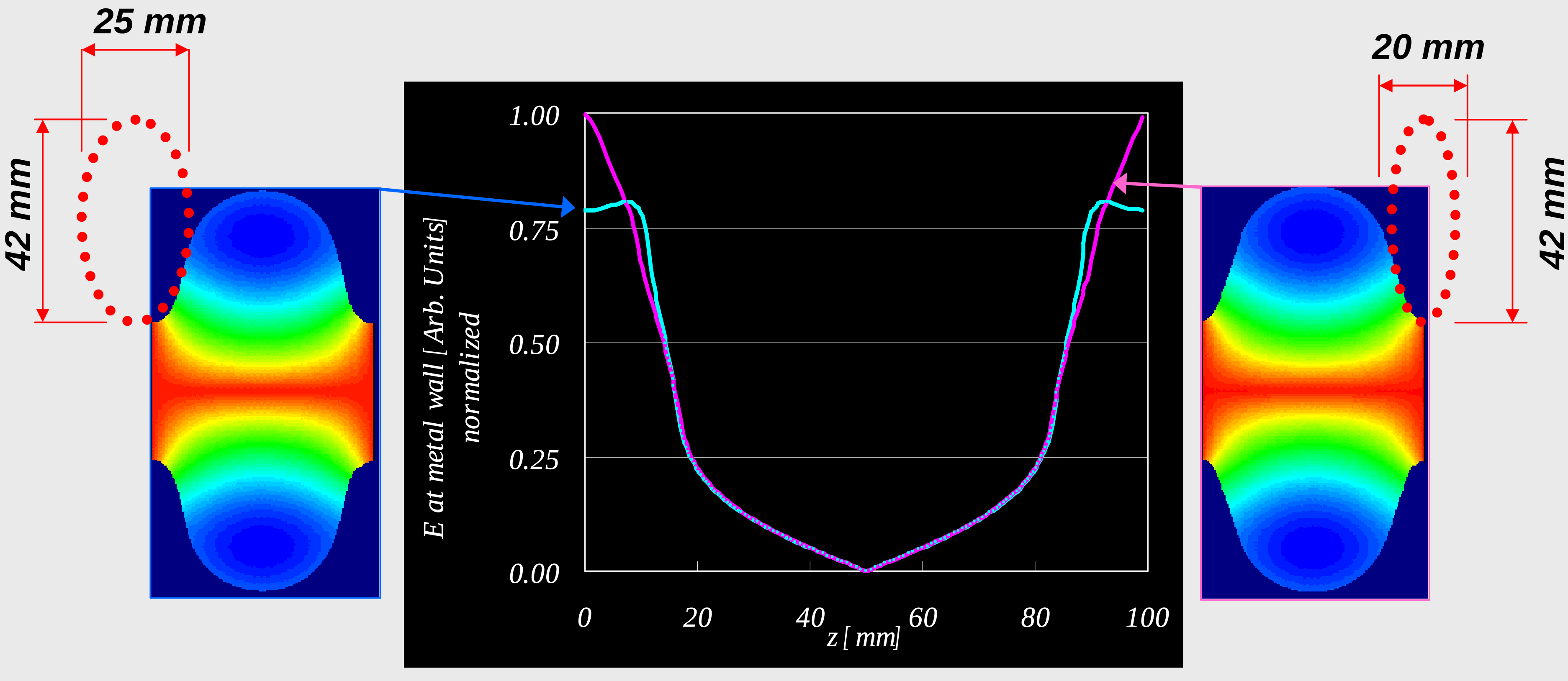
A. Mosnier, E. Haebel, SRF Workshop 1991

In addition to the iris radius *r_{i}*:

- ***B_{peak}/E_{acc}*** (and ***G***) changes vs. the equator shape



Similarly : E_{peak}/E_{acc} **changes vs. the iris shape**



Both cells have the same: *f, (R/Q)* and r_i

We know that a smaller aperture r_i makes FM :

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

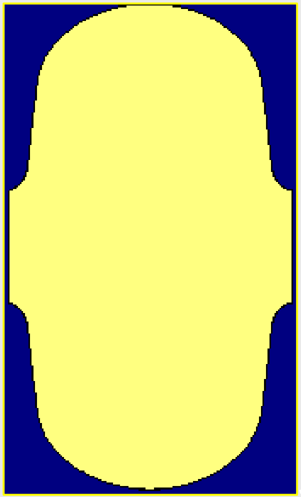
(+)

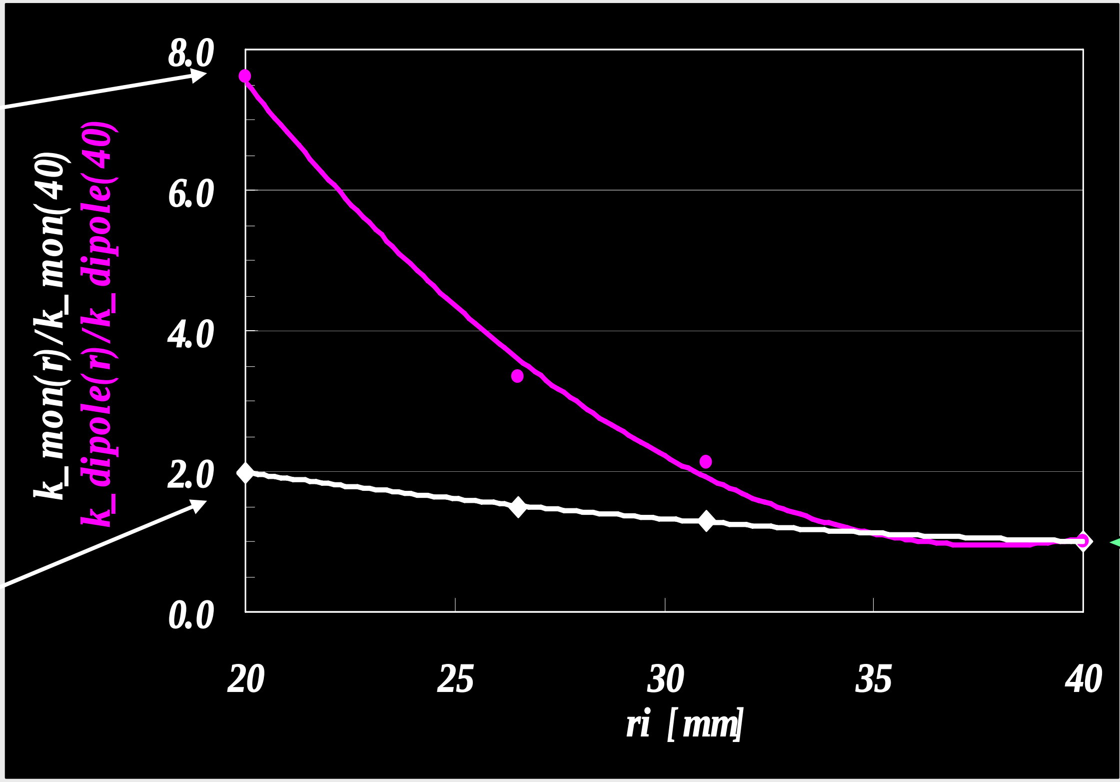
but unfortunately a smaller aperture r_i makes:

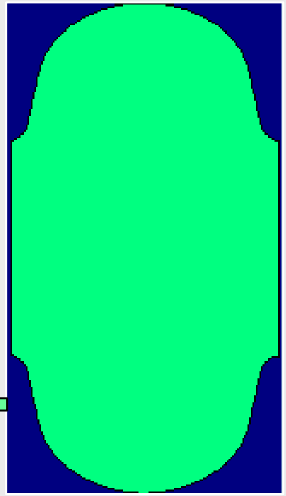
- **HOMs impedances $(k_\perp , k_\parallel)$ higher**
- **cell-to-cell coupling (k_{cc}) weaker**

(-)

HOMs impedances ($k_{\perp}$, $k_{\parallel}$)







(R/Q) = 152 Ω

B_{peak} / E_{acc} = 3.5 mT/(MV/m)

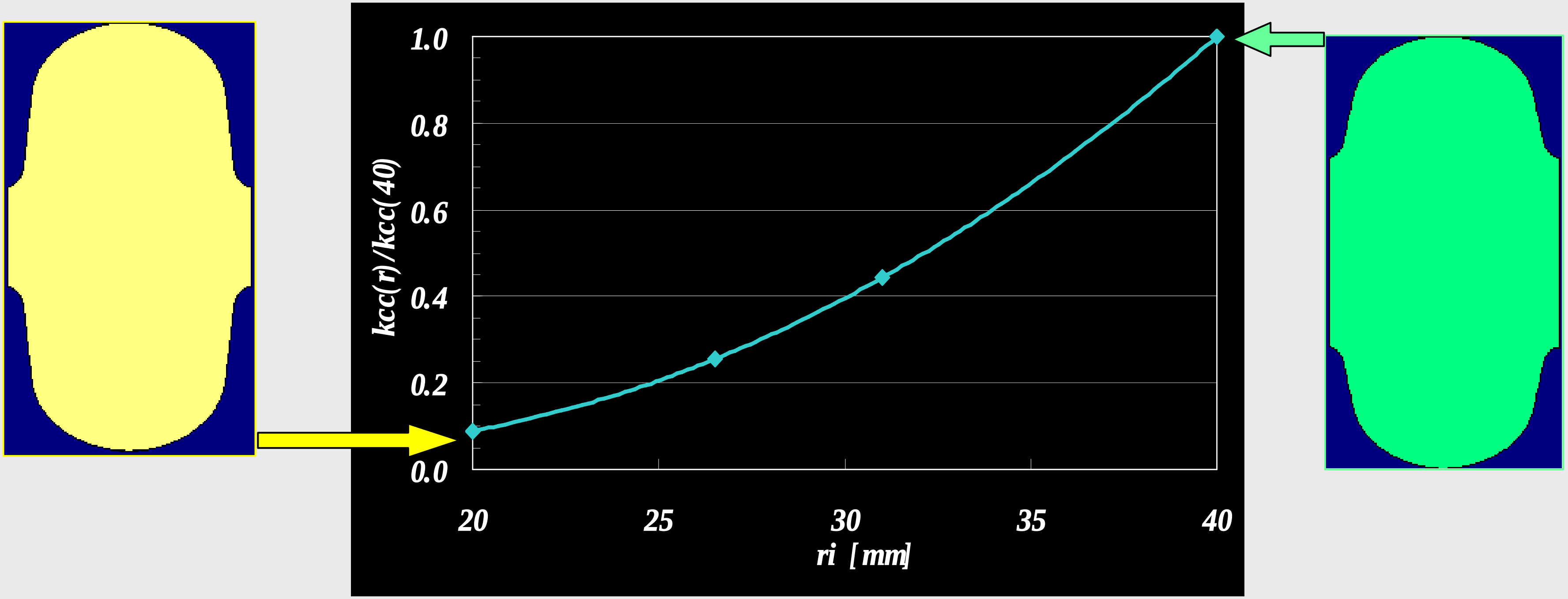
E_{peak} / E_{acc} = 1.9

(R/Q) = 86 Ω

B_{peak} / E_{acc} = 4.6 mT/(MV/m)

E_{peak} / E_{acc} = 3.2

Cell-to-cell coupling *(kcc)*



(R/Q) = 152 Ω

B_{peak} / E_{acc} ***= 3.5 mT/(MV/m)***

E_{peak} / E_{acc} ***= 1.9***

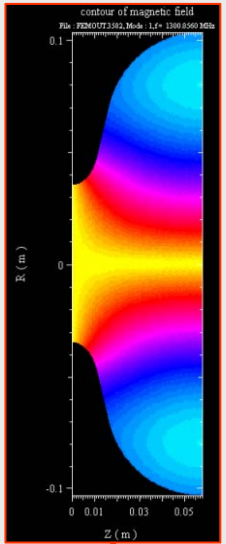
(R/Q) = 86 Ω

B_{peak} / E_{acc} ***= 4.6 mT/(MV/m)***

E_{peak} / E_{acc} ***= 3.2***

What about accelerating mode frequency of a superconducting cavity?

x 2 =



f_n	[MHz]	2600
R/Q	[Ω]	57
r/q=(R/Q)/l	[Ω/m]	2000
G	[Ω]	271

f_n	[MHz]	1300
R/Q	[Ω]	57
r/q=(R/Q)/l	[Ω/m]	1000
G	[Ω]	271

$r/q = (R/Q)/l \sim f$

3. Criteria for Cavity Design

From the formula, we learned before:

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

one obtains:

$$P_{dissipated} = \frac{R_s \cdot V_{acc}^2}{G_{acc} \cdot (r/q)_{acc} \cdot l_{active}}$$

A higher frequency would be a good choice to minimize power dissipation in the metal wall when the length l_{active} and final energy V_{acc} are fixed.

Unfortunately this applies only to room temperature structures made of Cu, which $R_s \sim (f)^{1/2}$.

For superconductors like Nb:

$$R_s(f) = R_{res} + R_{BCS} = R_{res} + 0.0002 \cdot \frac{1}{T} \cdot \left(\frac{f[GHz]}{1.5}\right)^2 \cdot exp\left(-\frac{17.67}{T}\right)$$

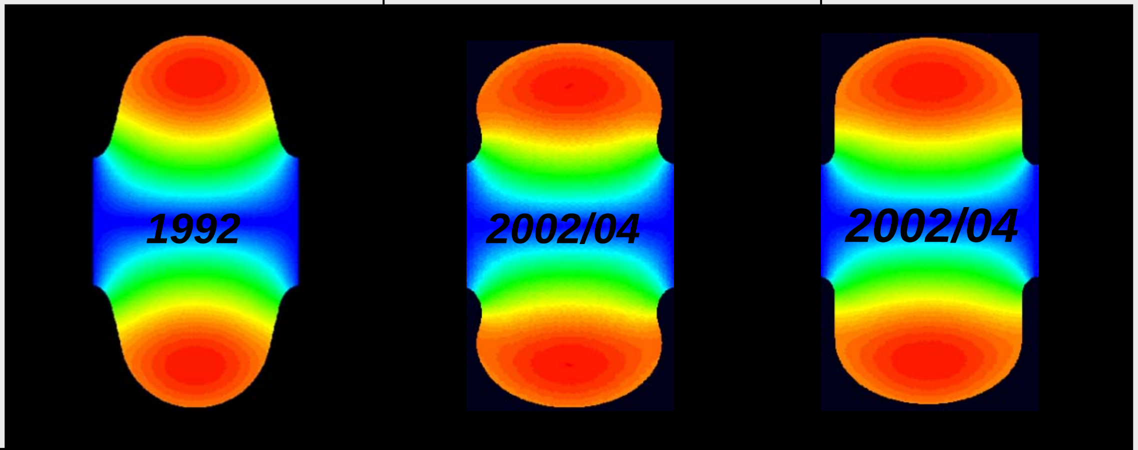
and increase of $R_s \sim (f)^2$ for higher f must be compensated with lower temperature T.

This is why ILC (1.3GHz) will operate at 2K (1.8K), and HERA (0.5GHz) and LEP (0.352GHz) could operate at 4.2 K

Examples of inner cells

		CEBAF Original Cornell ß=1	CEBAF -12 High Gradient ß=1	CEBAF -12 Low Loss ß=1	TESLA ß=1	SNS ß=0.61	SNS ß=0.81	RIA ß=0.47	RHIC Cooler ß=1
f_o	[MHz]	1448.3	1468.9	1475.1	1278.0	792.8	792.8	793.0	683.0
f_π	[MHz]	1497.0	1497.0	1497.0	1300.0	805.0	805.0	805.0	703.7
k_{cc}	[%]	3.29	1.89	1.49	1.9	1.52	1.52	1.52	2.94
E_{peak}/E_{acc}	-	2.56	1.96	2.17	1.98	2.66	2.14	3.28	1.98
B_{peak}/E_{acc}	[mT/(MV/m)]	4.56	4.15	3.74	4.15	5.44	4.58	6.51	5.78
R/Q	[Ω]	96.5	112	128.8	113.8	49.2	83.8	28.5	80.2
G	[Ω]	273.8	266	280	271	176	226	136	225
R/Q*G	[Ω*Ω]	26421	29792	36064	30840	8659	18939	3876	18045
$k_\perp$ (σ_z=1mm)	[V/pC/cm²]	0.22	0.32	0.53	0.23	0.13	0.11	0.15	0.02
$k_{//}$ (σ_z=1mm)	[V/pC]	1.36	1.53	1.71	1.46	1.25	1.27	1.19	0.85

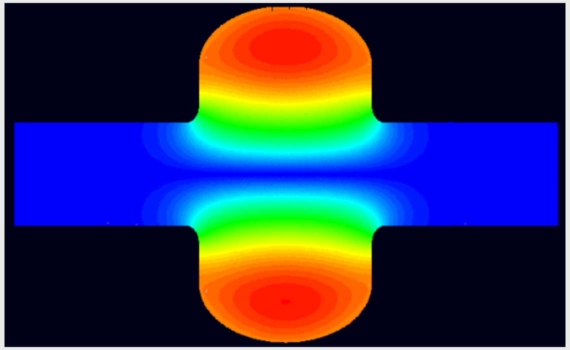
Evolution of inner cells proposed for the ILC collider:

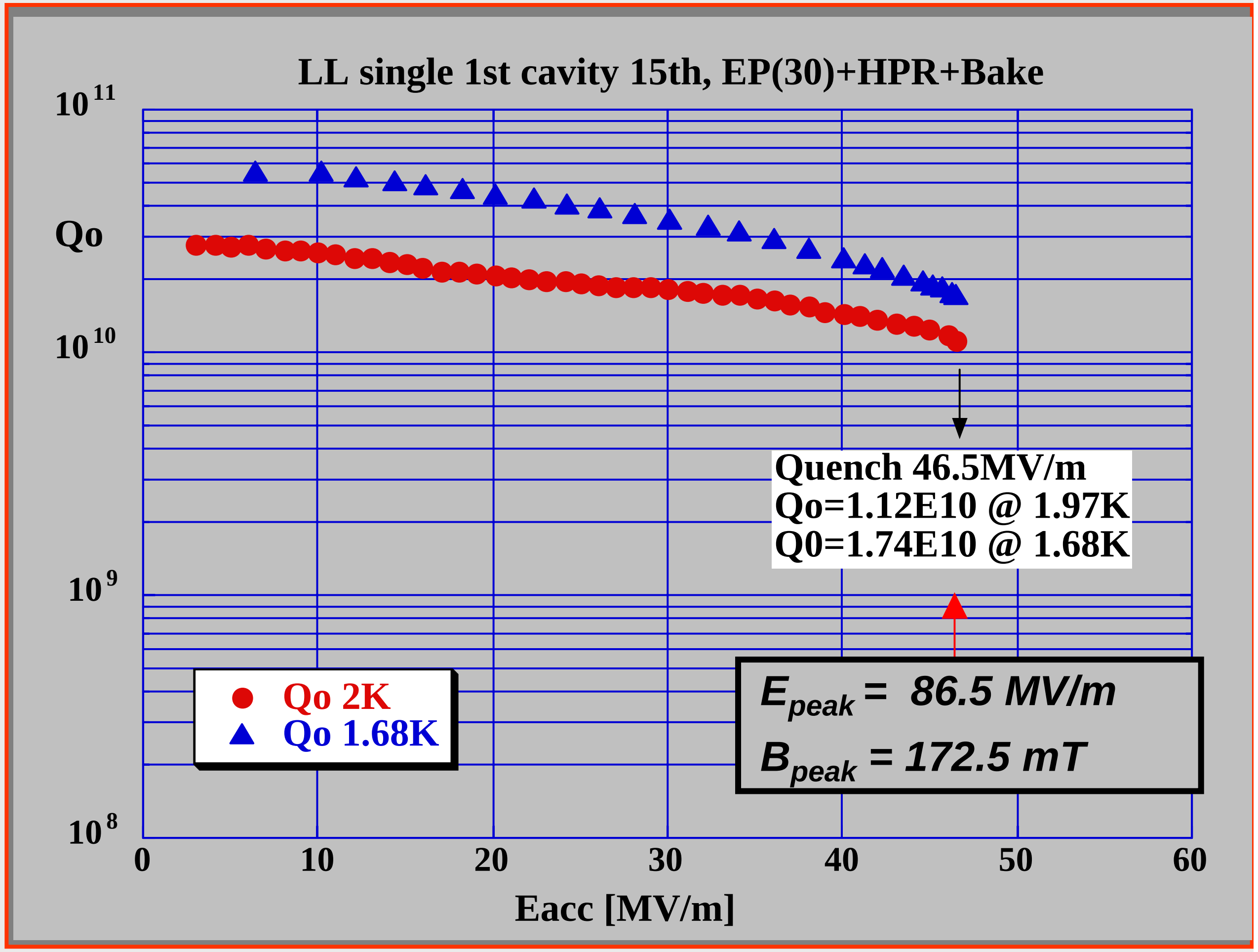


		TESLA optimized E_{peak}/E_{acc}	Re-entrant optimized B_{peak}/E_{acc}	LL optimized B_{peak}/E_{acc}
r_i	[mm]	35	30	30
k_{cc}	[%]	1.9	1.56	1.52
E_{peak}/E_{acc}	-	1.98	2.30	2.36
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.57	3.61
R/Q	[Ω]	113.8	135	133.7
G	[Ω]	271	284.3	284
R/Q*G	[Ω*Ω]	30840	38380	37970
$k_{\perp}$ (σ_z=1mm)	[V/pC/cm²]	0.23	0.38	0.38
$k_{\parallel}$ (σ_z=1mm)	[V/pC]	1.46	1.75	1.72

KEK test September 2005 !!!!!!!

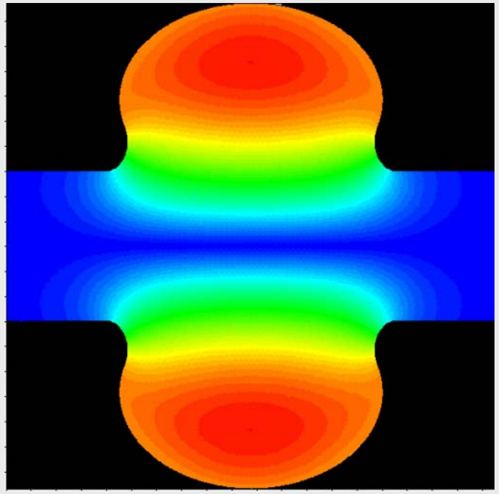
		LL
f	*[MHz]*	*1286.6*
E_{peak}/E_{acc}	-	*1.86*
B_{peak}/E_{acc}	*[mT/(MV/m)]*	*3.71*
R/Q	*[Ω]*	*130.0*
G	*[Ω]*	*279*
$Ø_{iris}$	*[mm]*	*61*

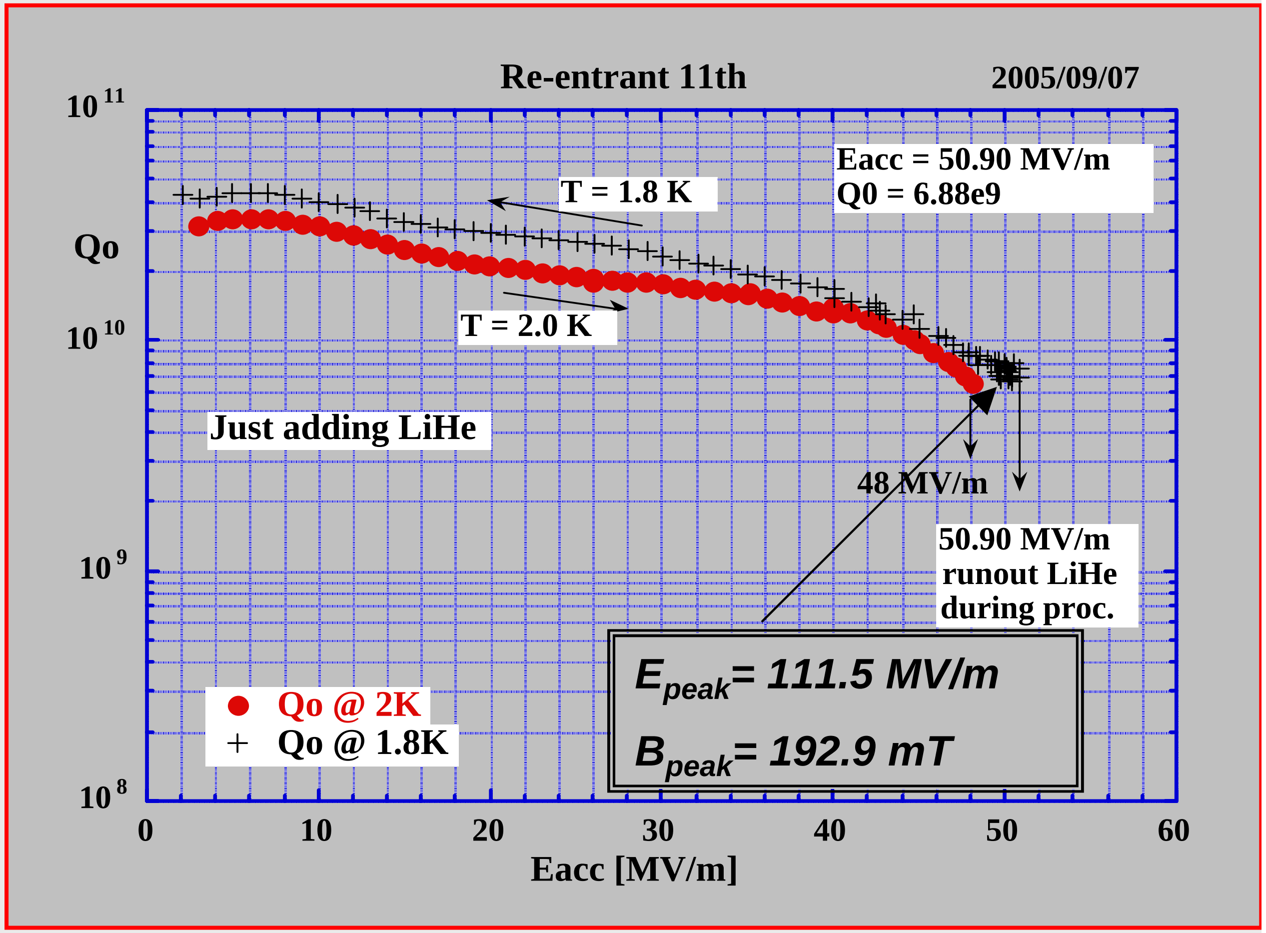




KEK tests September 2005

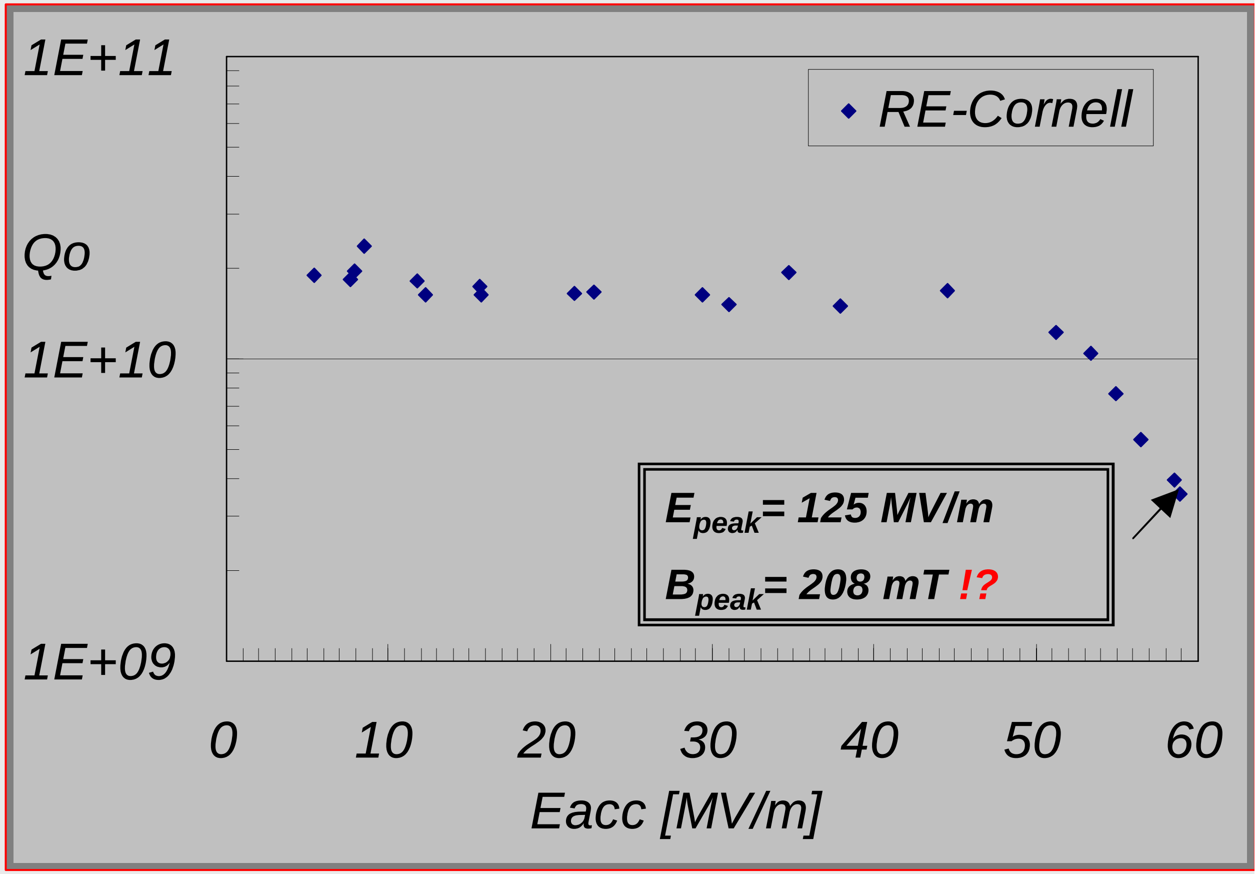
		RE
f	*[MHz]*	*1278.6*
E_{peak}/E_{acc}	-	*2.19*
B_{peak}/E_{acc}	*[mT/(MV/m)]*	*3.79*
R/Q	*[Ω]*	*126.0*
G	*[Ω]*	*278*
$Ø_{iris}$	*[mm]*	*68*





Cornell, test in March 2007 !!!!

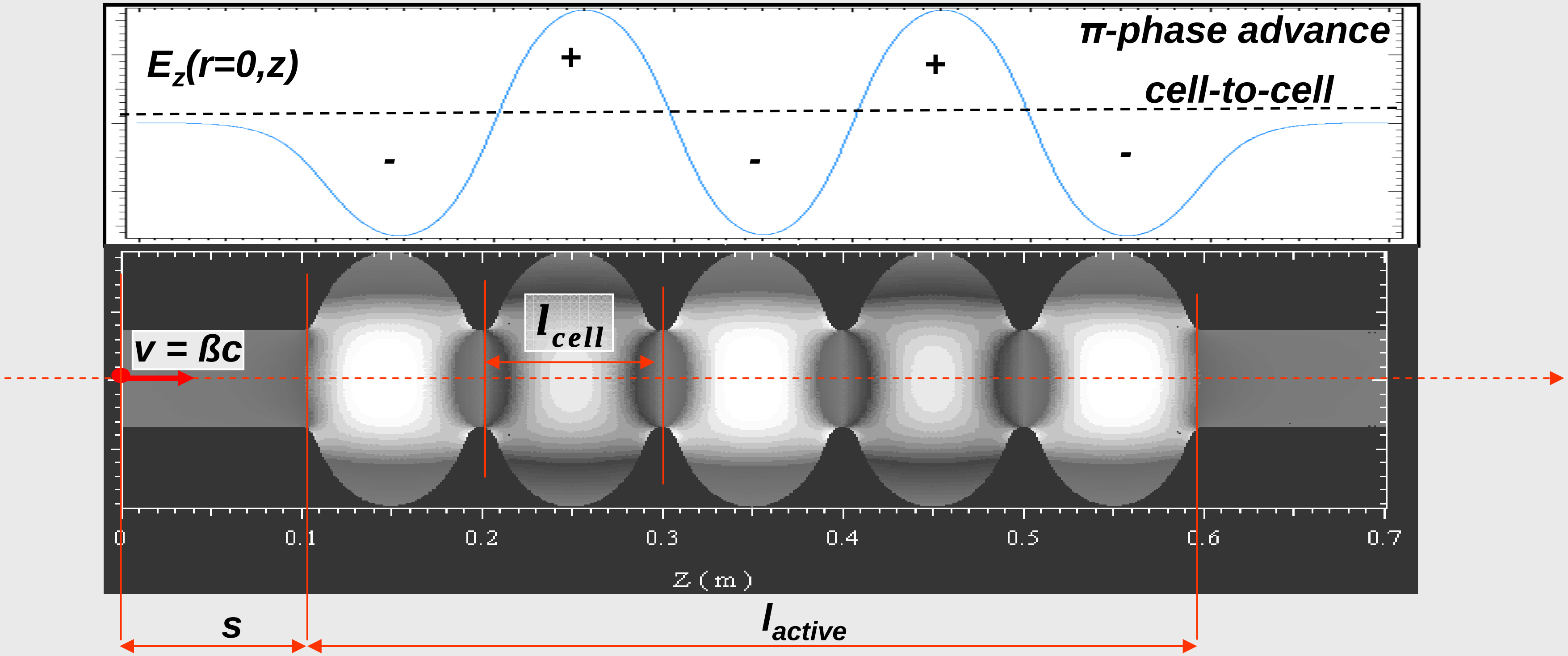
		RE+Tubes
f	[MHz]	1300.3
E_{peak}/E_{acc}	-	2.11
B_{peak}/E_{acc}	[mT/(MV/m)]	3.53
R/Q	[Ω]	126.0
G	[Ω]	283.3
$Ø_{iris}$	[mm]	60



We re-call pros and cons for a multi-cell structure

- **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**

Accelerating mode in a multi-cell structure



Synchronic acceleration and max of $(R/Q)_{acc}$ when:

1. $l_{active} = Nl_{cell} = Nc\beta/(2f)$ **and**
2. **the injection takes place at an optimum phase φ_{opt} which ensures that particles 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).**

- **Field flatness in a multi-cell structures**

	Original Cornell N = 5	High Gradient N =7	Low Loss N =7	TESLA N=9	SNS ß=0.61 N=6	SNS ß=0.81 N=6	RIA ß=0.47 N=6	RHIC N=5
year	1982	2001	2002	1992	2000	2000	2003	2003
a_{ff}	1489	2592	3288	4091	3883	2924	5040	850

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

Many years of experience with: heat treatment, chemical treatment, handling and assembly allows one to preserve field profile, even in cavities with bigger *N* and weaker k_{cc}

For the TESLA cavities: field flatness is better than 95 %

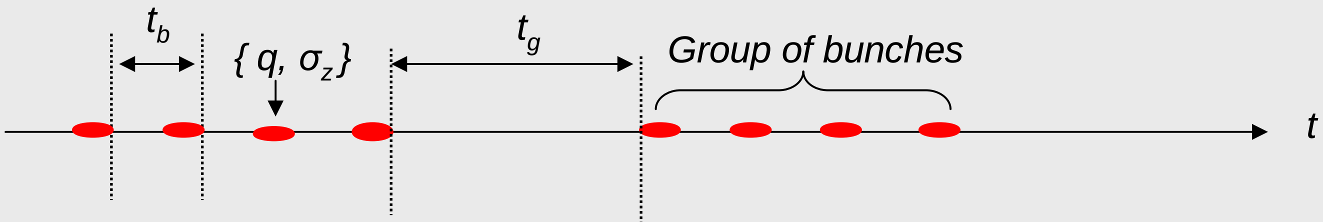
- **HOM trapping in a multi-cell structures**

The excitation of HOMs by the accelerated beam causes:

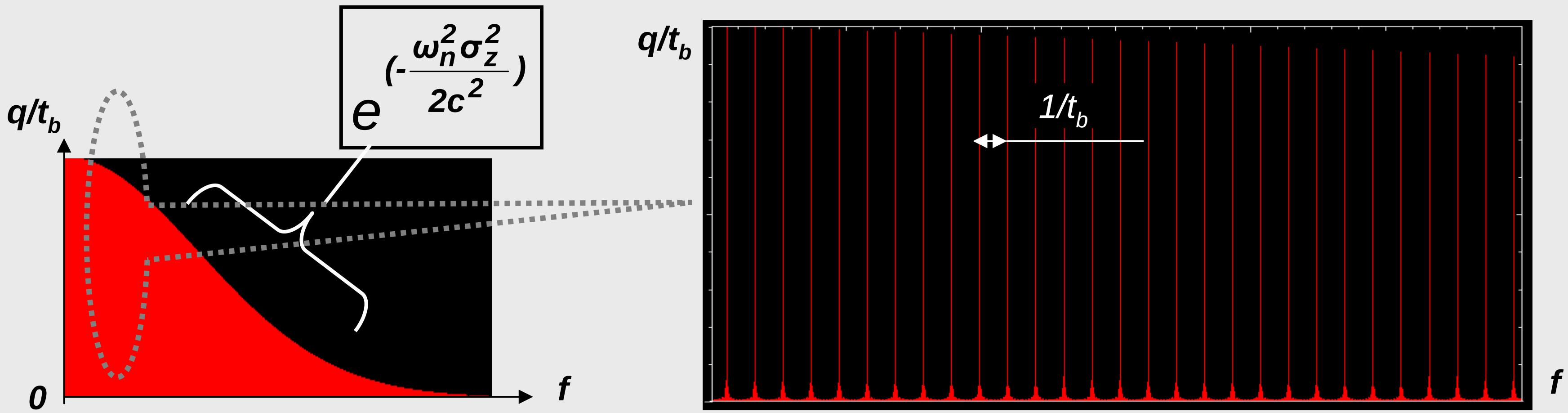
- **Beam instabilities and/or dilution of emittance**
- **Bunch-to-bunch energy modulation**
- **Additional cryogenic loss**

Excitation:

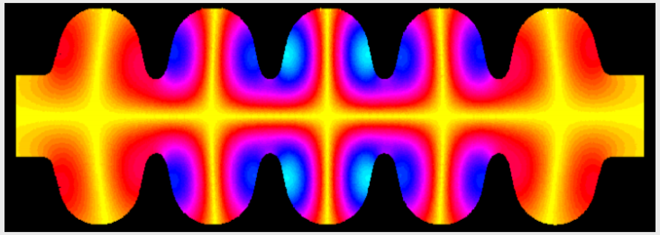
Time structure of the beam

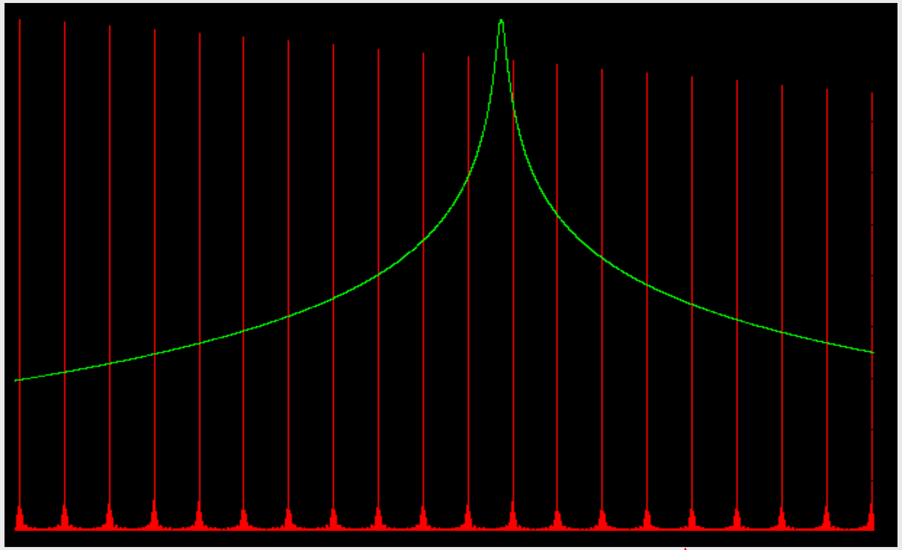


Spectrum of the beam



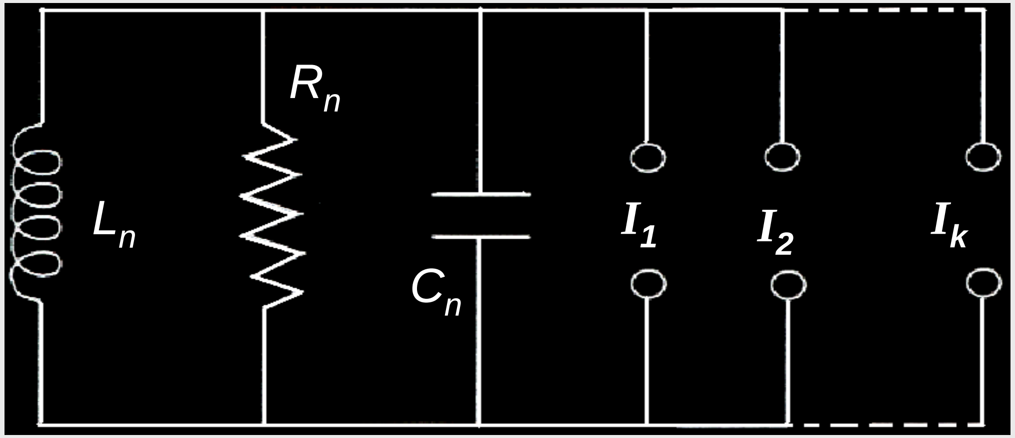
Mode No. *n* : { ω_n, $(R/Q)_n$, Ql_n }





$$Z_n(\omega) = \frac{(R/Q)_n \cdot Q_{L,n}}{1 + jQ_{L,n}\left(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}\right)}$$

Impedance for the mode n



Multi-source excitation

The power induced by "all" spectral lines (current sources) in mode No. n:

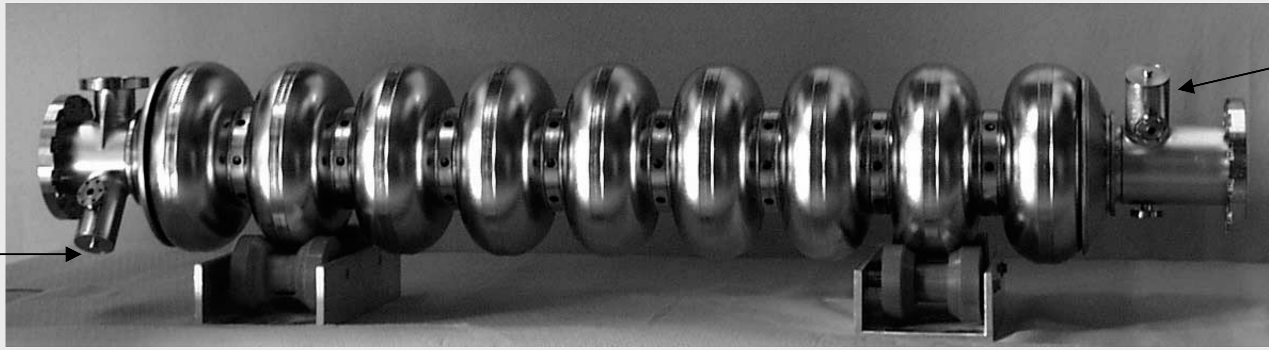
$$P_n = \frac{1}{2}\sum_k Z_n(\omega_k)\cdot I_k^2$$

$$Z_n(\omega) = \frac{(R/Q)_n \cdot Q_{L,n}}{1 + jQ_{L,n}\left(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}\right)} \quad \text{and} \quad \frac{1}{Q_{L,n}} = \frac{1}{Q_{0,n}} + \frac{1}{Q_{ext,n}}$$

Measure of the extracted power

The HOM couplers, devices extracting the energy from the parasitic modes, are attached to cavities to mitigate these phenomenon.

The experience shows that, the HOM couplers and FM couplers can be attached to the beam tubes and must not be located at cells because this leads to the performance degradation.



Coaxial HOM coupler

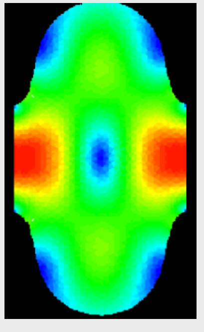
Coaxial HOM coupler

Waveguide HOM ports

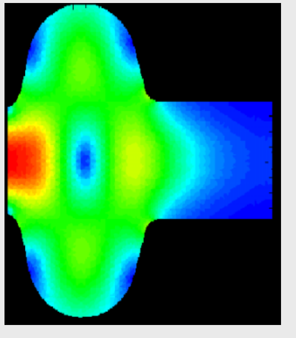
The HOM trapping mechanism is similar to the FM field profile unflatness mechanism:

- **weak $k_{cc,HOM}$, cell-to-cell coupling for HOM**
- **difference in the HOM frequency between the end-cell and inner-cell**

f = 2385 MHz



That is why they hardly resonate together



f = 2415 MHz

Example: how N influences strength of the E-H fields at HOM couplers locations

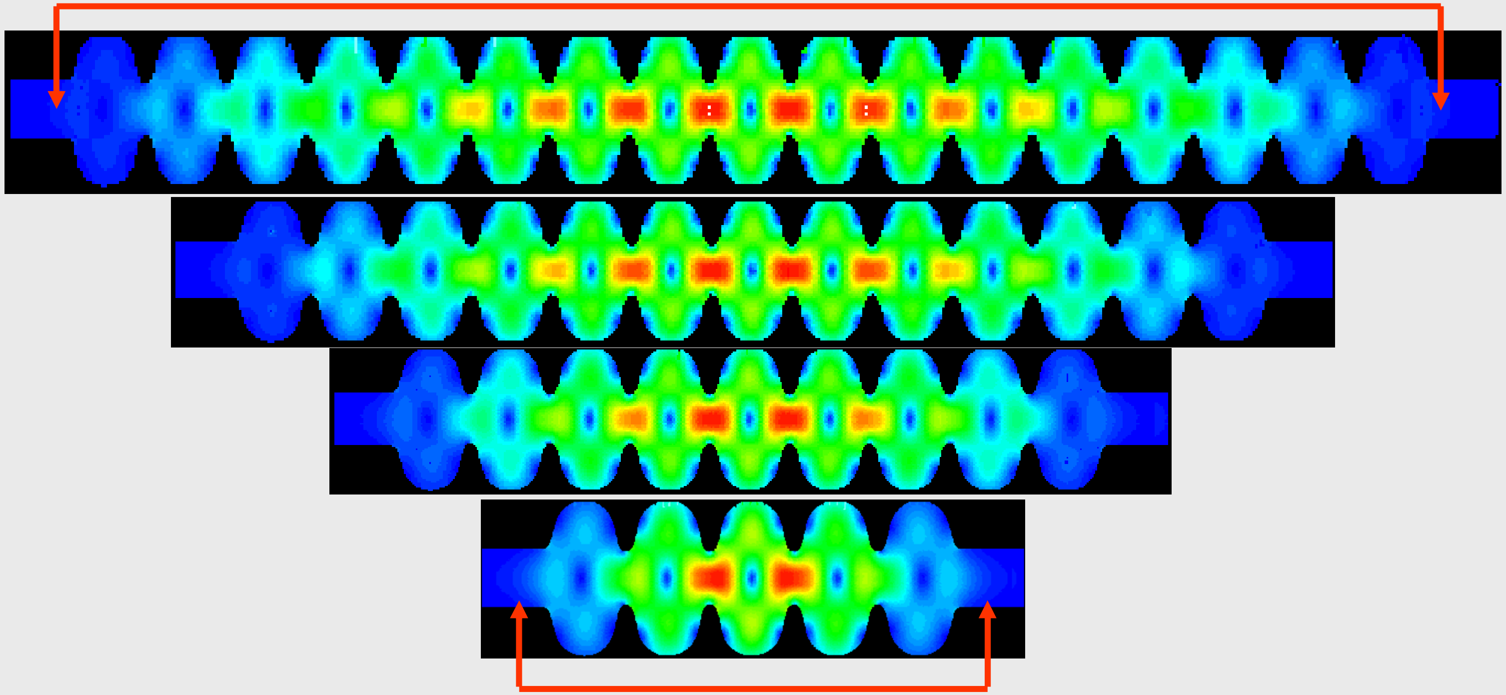
no E-H fields at HOM couplers locations (<u>trapping</u>), which are always placed at the end beam tubes

N = 17

N = 13

N = 9

N = 5



E-H fields at HOM couplers locations

Less cells in a structure helps always to reach low Qs of HOMs.

What additional to reducing N can we do to avoid the trapping?

Adjustment of end-cells

The geometry of end-cells differs from the geometry of inner cells due to the attached beam tubes, HOM- and input couplers.

Their function is multifold and their geometry must fulfill three requirements:

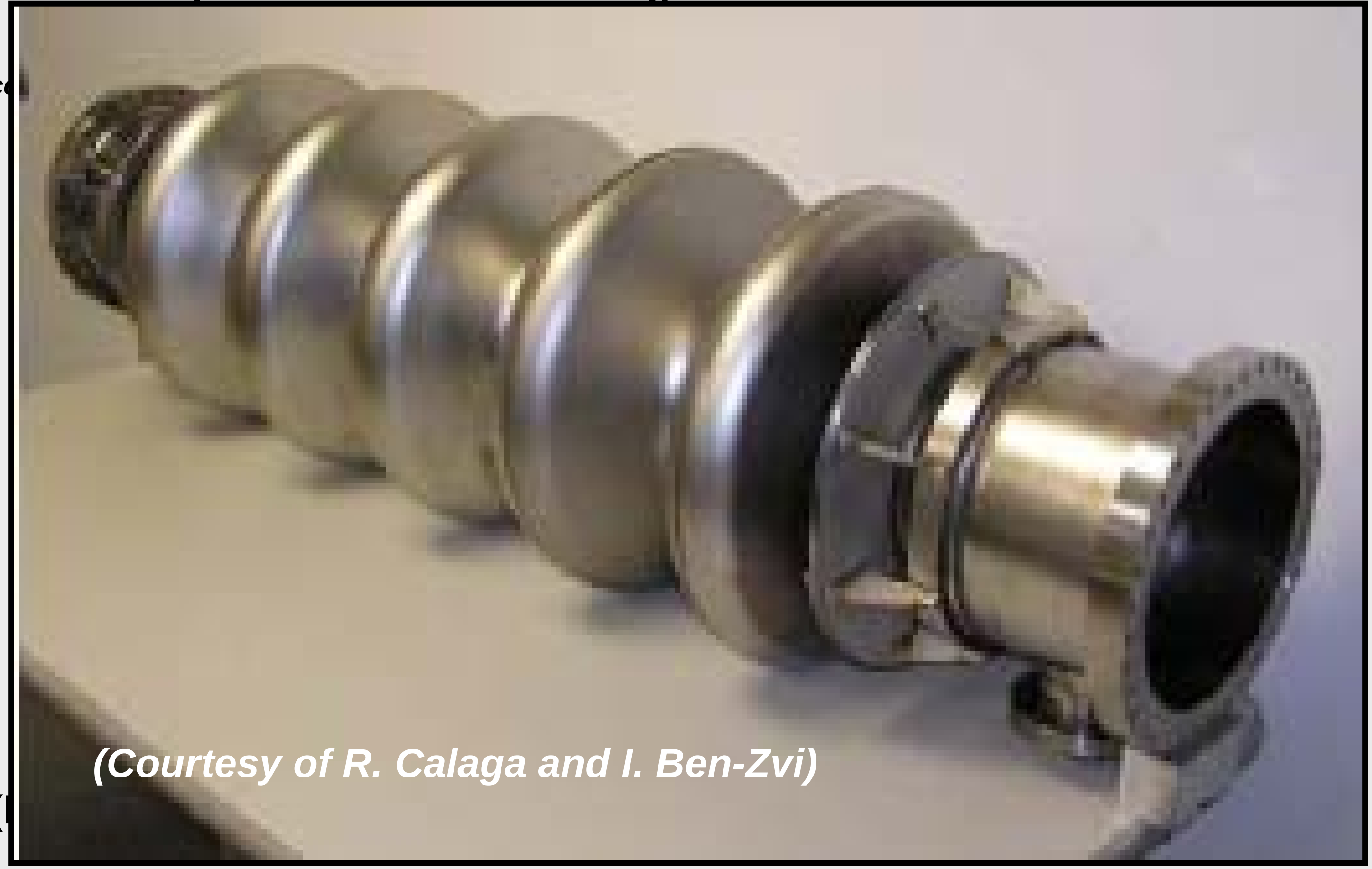
- **field flatness and frequency of the accelerating mode**
- **field strength of the accelerating mode at FPC location enabling operation with matched Qext**
- **fields strength of dangerous HOMs ensuring their required damping by means of HOM couplers or/and beam line absorbers.**

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

1. Open irises of the inner cells and end-cells (bigger $k_{cc,HOM}$) and making shape of both very similar

Example: RHIC 5-cell cavity for the electron cooling:

Monopole mode k_{c}


(Courtesy of R. Calaga and I. Ben-Zvi)

f_{HOM} = 1394 MHz

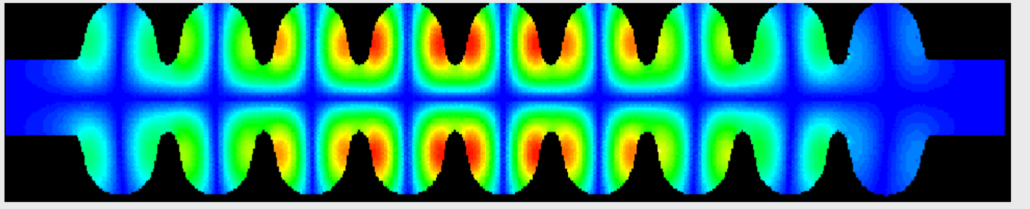
f_{HOM} = 1403 MHz

The method causes (
relevant.

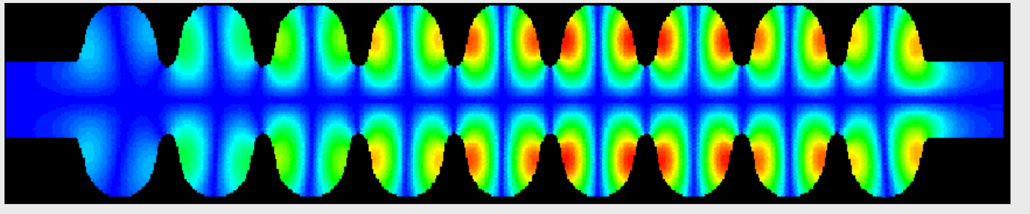
2. Tailor end-cells to equalize HOM frequencies of inner- and end-cells.

Example: TESLA 9-cell cavity, which has two different end-cells (asymmetric cavity)

The lowest mode in the passband
f_{HOM} = 2382 MHz

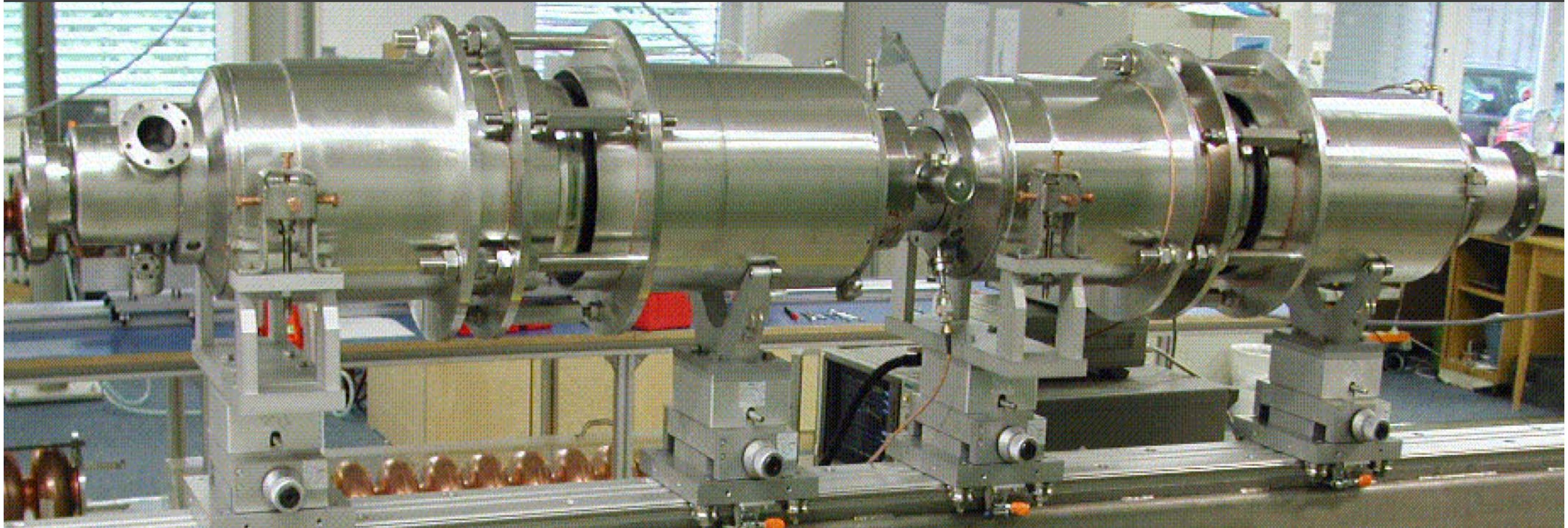


The highest mode in the passband
f_{HOM} = 2458 MHz



The method works for very few modes but keeps the (R/Q) value high of the fundamental mode.

4. Multi-cell Structures and Weakly Coupled Structures



- **Power capability of fundamental power couplers in a multi-cell structures**

When I_{beam} and E_{acc} are specified and a superconducting multi-cell structure does not operate in the energy recovery mode:

$$P_{in} \sim N$$

Q_{ext} of the FPC, which usually is << than intrinsic *Qo*, is:

$$Q_{ext} \cong \frac{E_{acc} \cdot ß \cdot \lambda \cdot N}{I_{beam} \cdot (R/Q)_{cell} \cdot N} = \frac{E_{acc} \cdot ß \cdot \lambda}{I_{beam} \cdot (R/Q)_{cell}} = \frac{\omega_{acc} \cdot W_{onecell} \cdot N}{\frac{1}{2} \int_{S_{inputport}} E_{acc} \times H_{acc} \, ds}$$

Independent of N

It must be ~ N to keep the ratio constant

$$\int_{S_{inputport}} E_{acc} \times H_{acc}\, ds$$

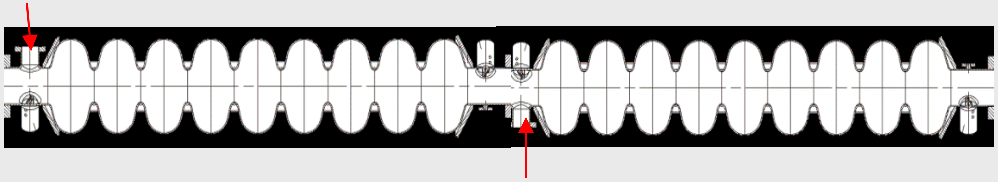
Coupler must penetrate deeper in the beam tube or/and will be placed closer to the end cell

Opening for the coupler must be bigger

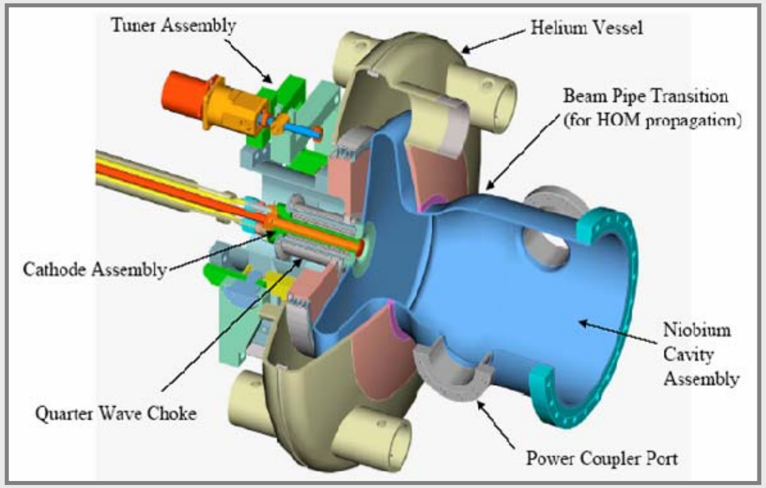
Both perturb cylindrical symmetry of the end tube and increase kick to the beam

The remedies are: alternating positions of couplers or double couplers

FPC

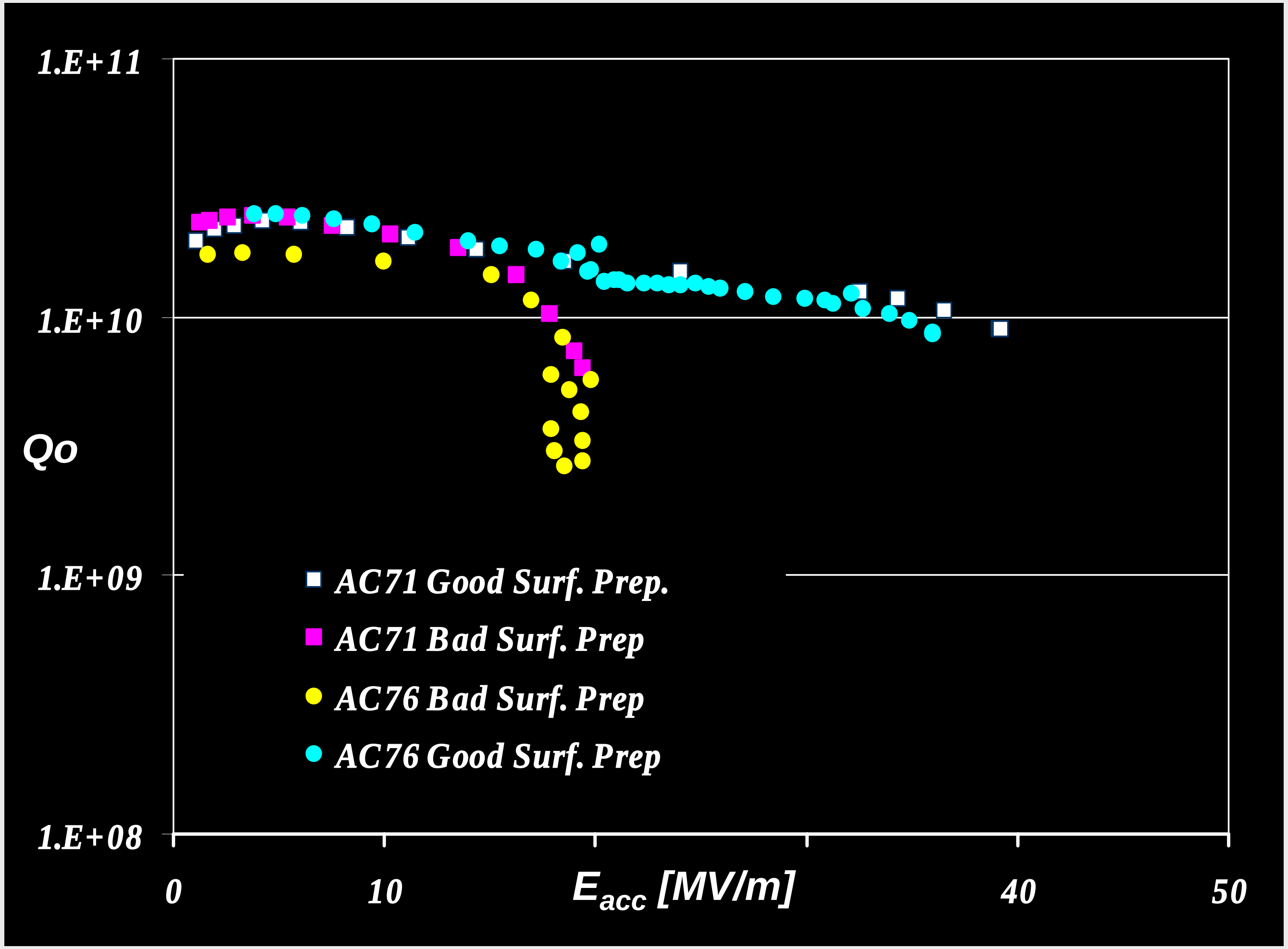


FPC



Courtesy of Alan Todd (AES)

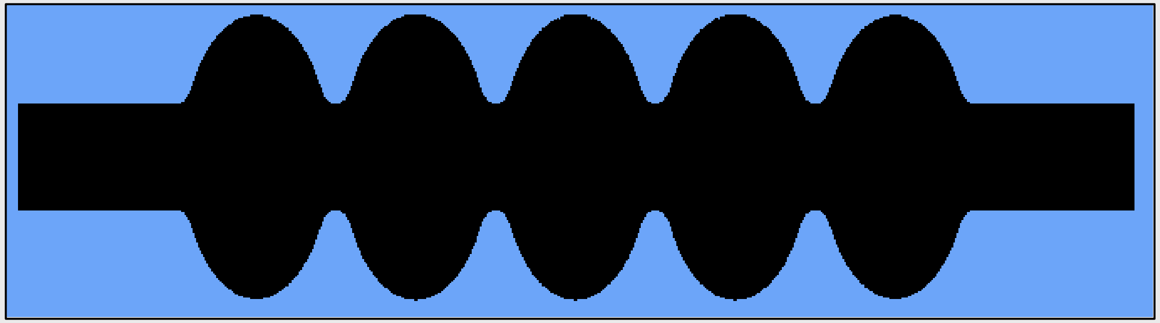
- **Chemical treatment and final preparation become more complicated**

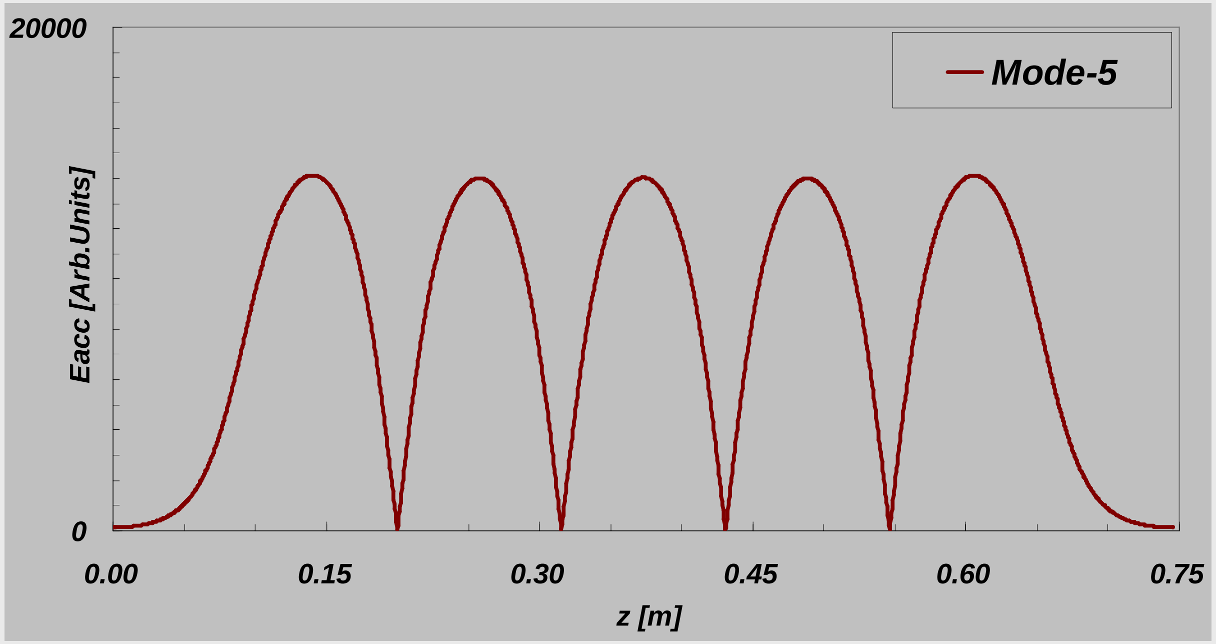


The best performance is still difficult to reach. The preparation procedures must be repeated several times. Our ultimate goal of 35 MV/m @ 5·10^{9} is still very "expensive"

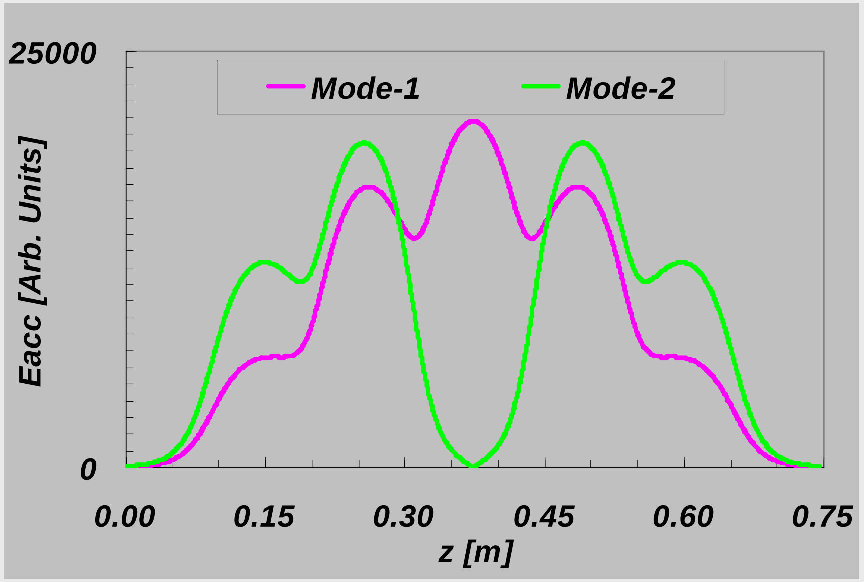
- **The worst performing cell limits whole multi-cell structure**

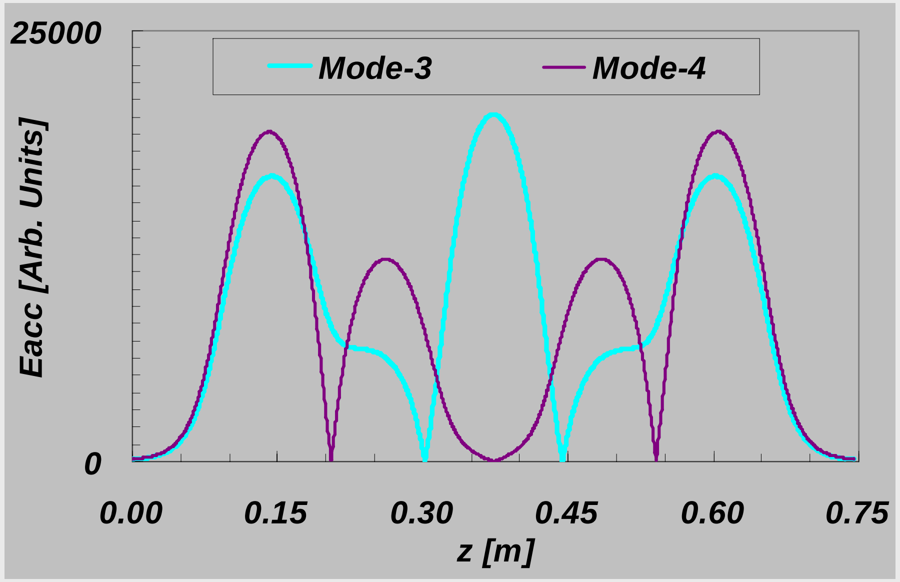
Example: 1.3 GHz, k_{cc} = 1.85%, 5-cells:





Max. achievable E_{acc} for all FM passband modes allows to find limiting cells. The values E_{max1} … E_{max5} tell us which cell, 3 or pairs (2,4) or (1,5), limits the performance in the accelerating mode (5th).





Norm. E_i / E_5 in modes of 5 –cells at the same stored energy

Cell	π/5	2π/5	3π/5	4π/5	π
3	$1.48E_5$	0	$1.41E_5$	0	E_5
2&4	$1.18E_5$	$1.35E_5$	$0.51E_5$	$0.82E_5$	E_5
1&5	$0.52E_5$	$0.88E_5$	$1.18E_5$	$1.35E_5$	E_5

List of multi-cell cavities ß=1 optimized for various criteria.

Criterion	Structure	Best parameter	Weakest parameter (point)	Comments
E_{acc}	HG: 1.5 GHz, N=7 TESLA: 1.3 GHz, N=9 ILC-LL: 1.3 GHz, N=9 ILC-RE 1.3 GHz, N=9	Epeak/Eacc= 1.96 Epeak/Eacc= 1.98 Bpeak/Eacc= 3.61 Bpeak/Eacc= 3.57	Real estate -Eacc Real estate -Eacc Real estate-Eacc, Epeak/Eacc Real estate-Eacc, Epeak/Eacc	Designed for I_{beam} < 10 mA, Pulse operation
Real estate E_{acc}	2x9 TESLA: 1.3 GHz, N= 18	Real estate-Eacc Epeak/Eacc= 2.0	Field flatness preservation Cleaning	New FPC design for 0.8 MW, Difficult to clean
P_{loss}	LL: 1.5 GHz, N= 7	Bpeak/Eacc= 3.7 (R/Q)·G	Not easy to clean, HOM damping	Designed for I_{beam} < 1 mA First LL-type cavity
Z_{HOM}	RHIC: 0.7 GHz, N= 5	Very low: $k_\perp$, $k_\parallel$ Epeak/Eacc= 1.98	Cryogenic losses	First multi-cell for $I_{beam} \approx 2$ A

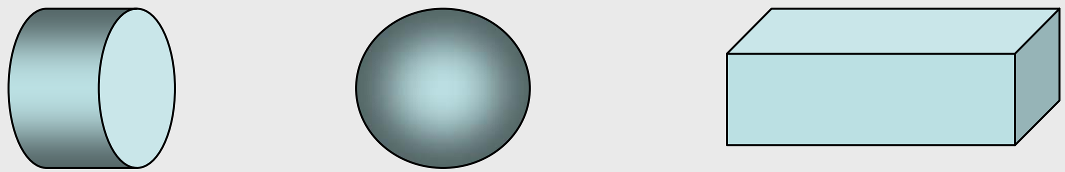
5. Tools for RF-design

Usually the design of an elliptical cavity is performed in two steps "2D" and "3D" :

- **"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.**

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)

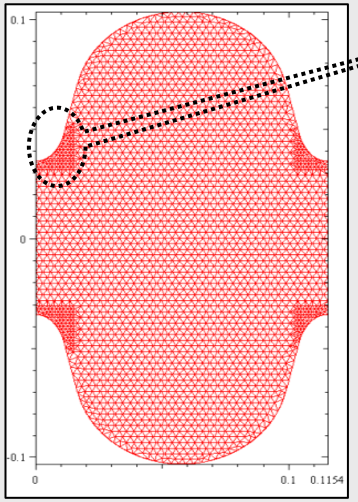
Approximating function (Finite Element Methods)

The FEM is superior in mapping of curvilinear boundary, which is essential for modeling of:

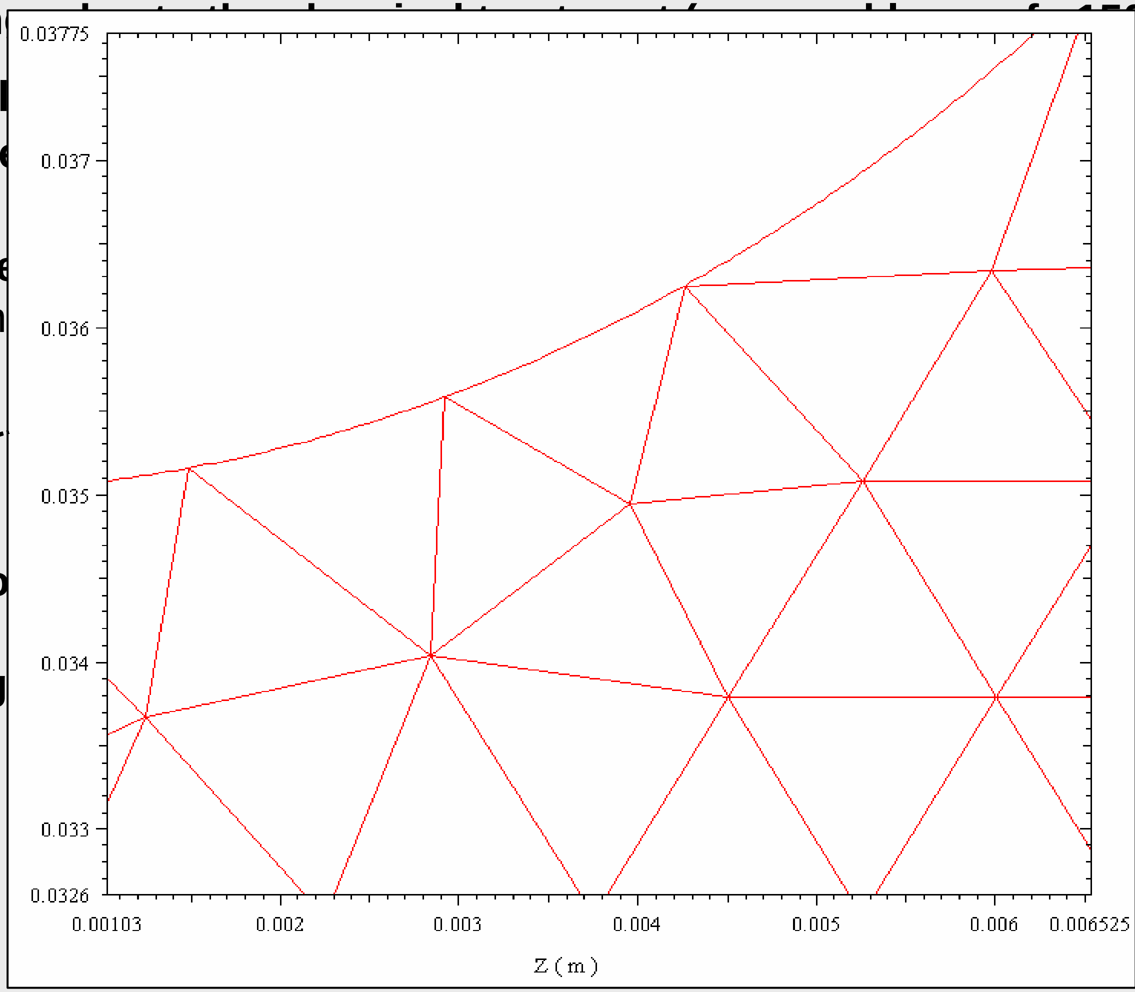
- **Multipacting**
- **Electron emission from the metal wall and generation of dark current**
- **Frequency chan**... **µm)**

2D codes like SUPERFISH (I... **dary approximation) or FEM-code**... **ed.**

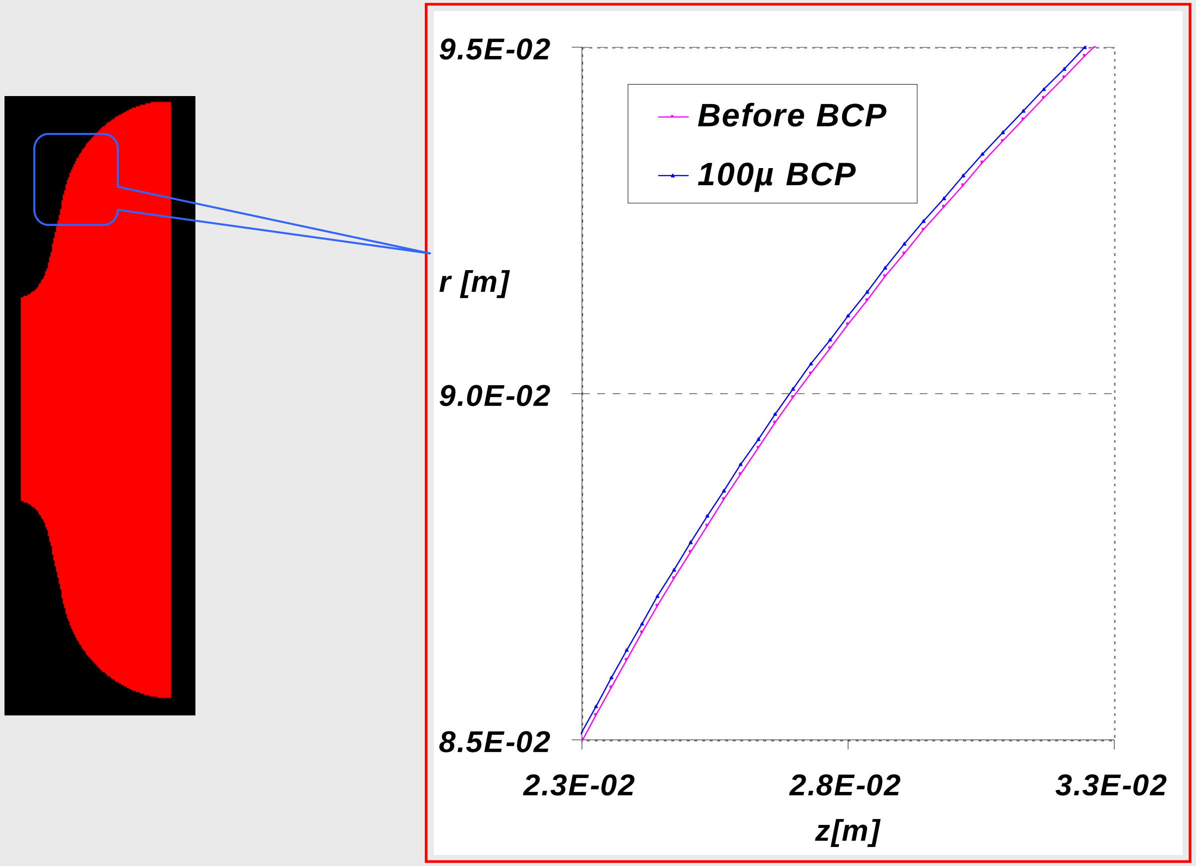
Example from the FEM code... **tiPac by** P. Yla-Oijala and D. Proch...



Smoo...
force...
a "zig...



Example: FEM-code modeling of the frequency change due to the chemical treatment (removed layer of 100µm)



Zoomed difference in shape of the TESLA mid cup after 100µm BCP

2D Modeling takes ~2min

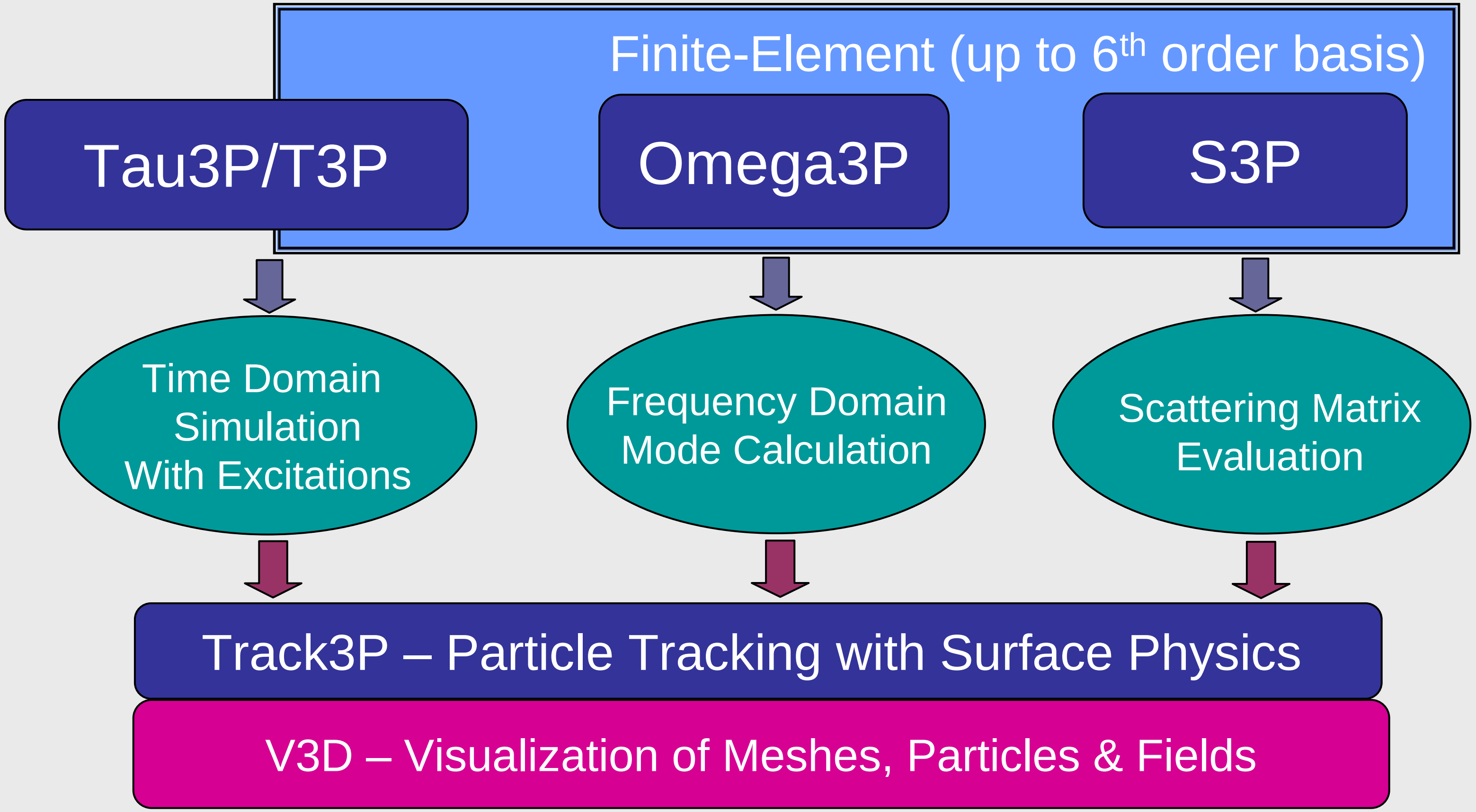
$$\frac{\partial f}{100\,\mu m} = -10 kHz / \mu m$$

which was measured for the uniform removal

5. Tools for RF-design

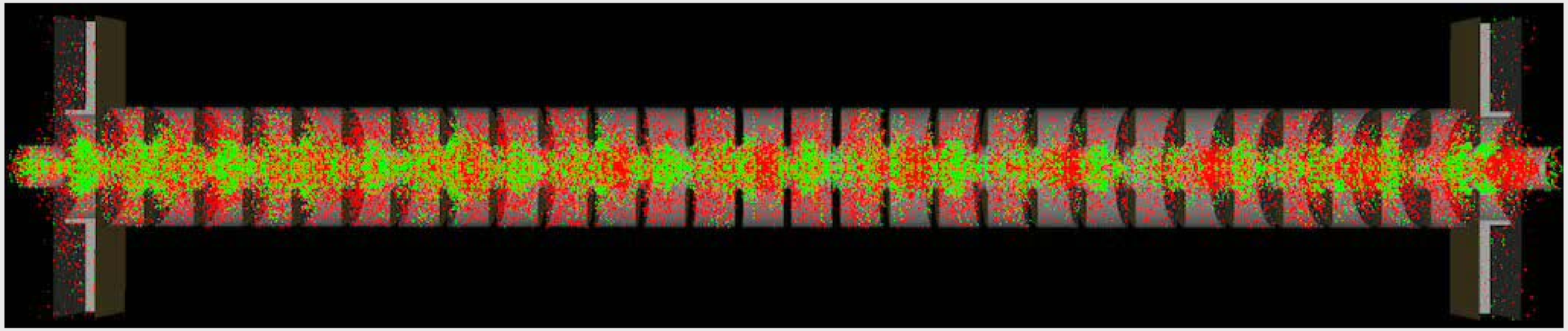
Electromagnetic Code Development at SLAC by ACD

Solves Maxwell's equations with particles in time & frequency domains using High Resolution modeling and End-to-end simulation.



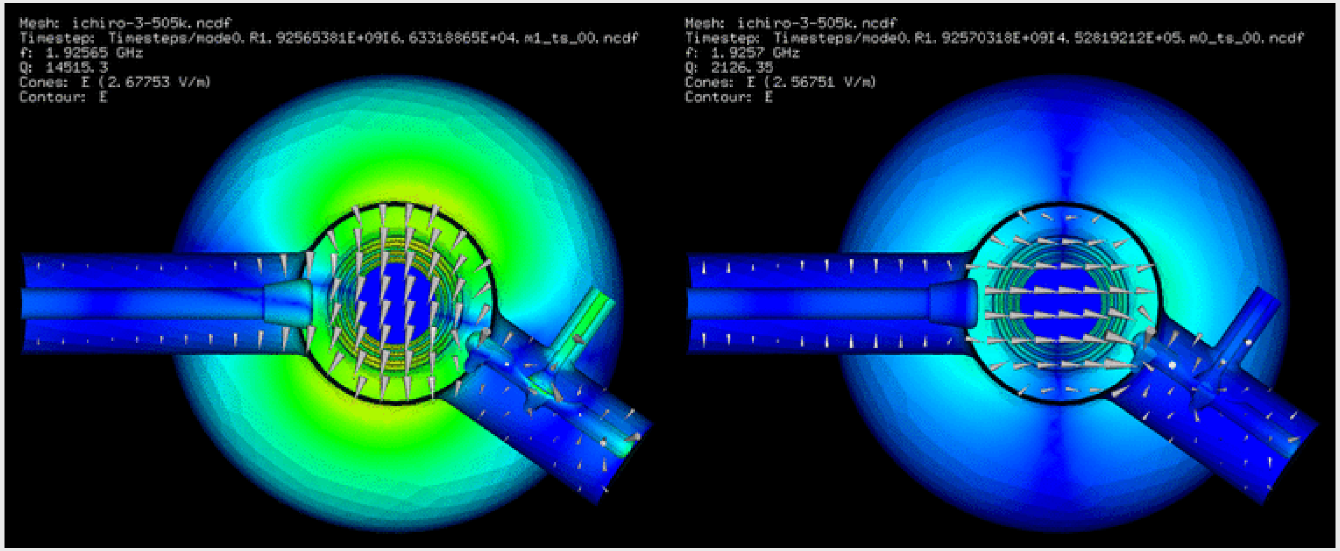
(Courtesy of Kwok Ko and ACD Members)

Example of 3D Dark current simulation in the NLC structure (Track3P)



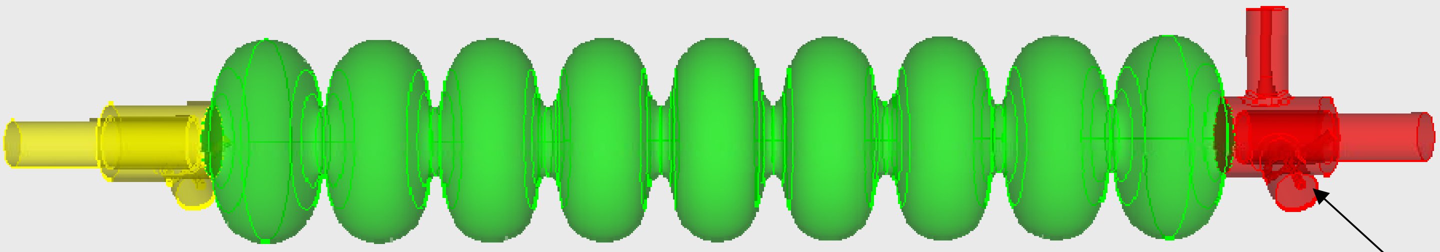
Red – Primary particles, Green – Secondary particles

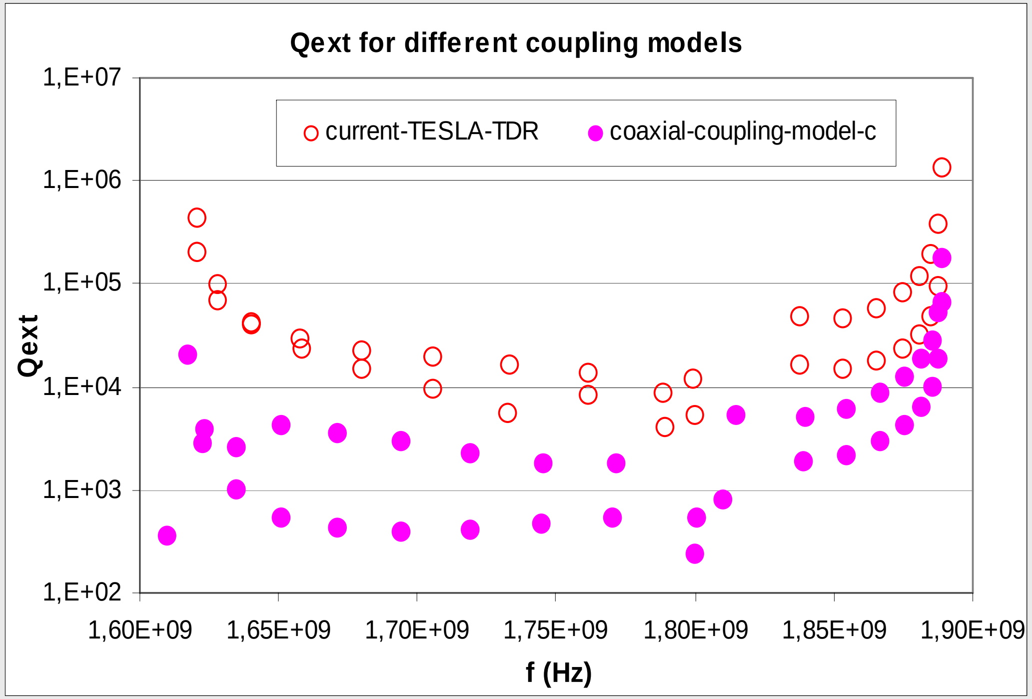
Example of 3D two dipoles overlapping modeling in the TESLA cavity with Omega3P

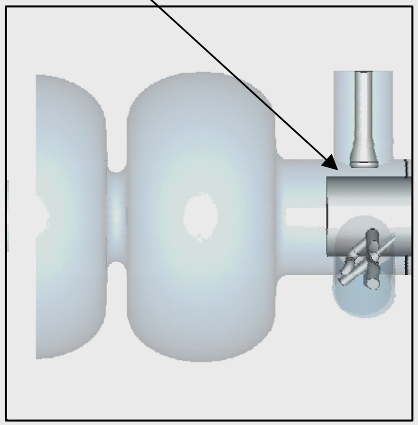


(Courtesy of Kwok Ko and ACD Members)

Example of 3D dipole damping modeling for the TESLA cavity with the coaxial beam tube coupling (Omega3P, L. Xiao, ACD SLAC)

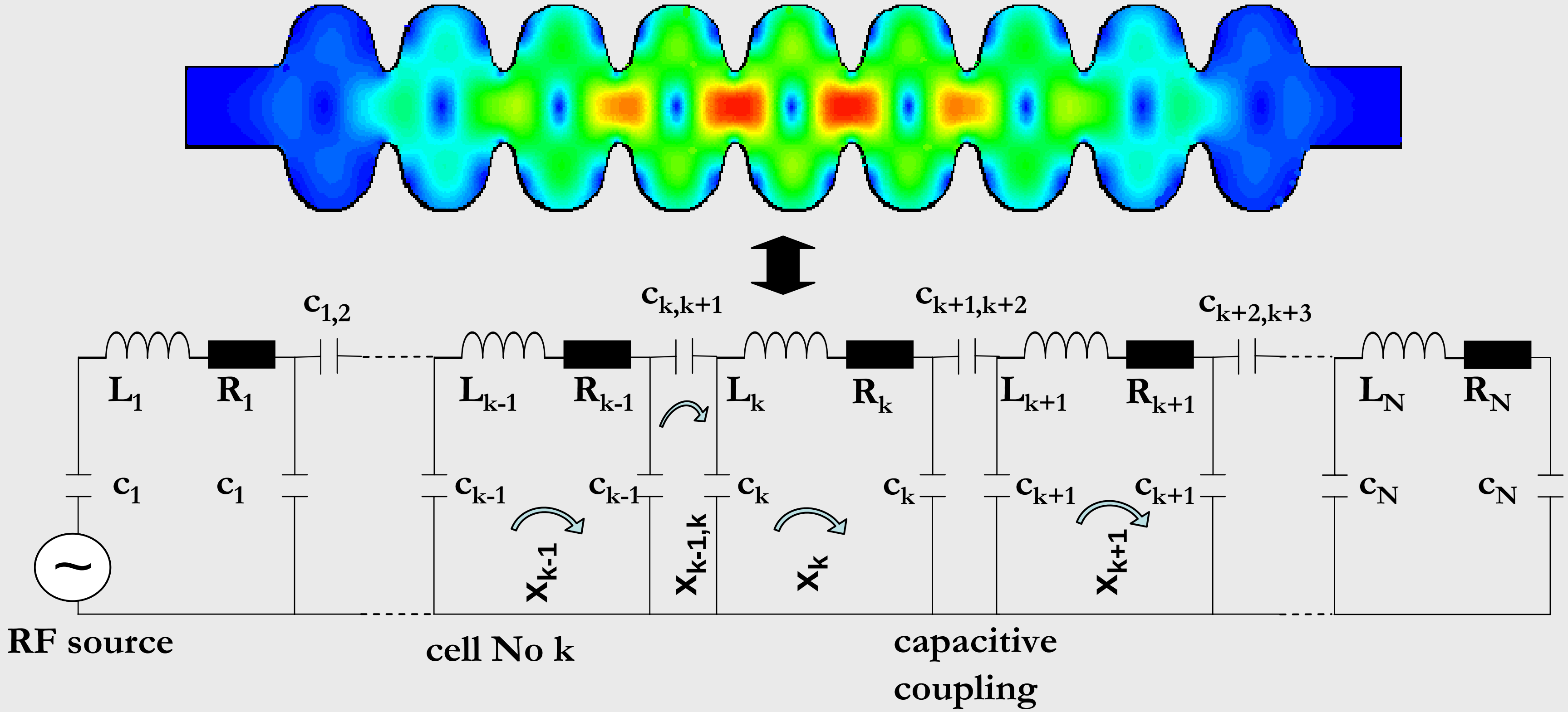






4th order multipacting was found in the coupler at 26 MV/m, not necessary dangerous one

In the RF design process we use 2D-codes (SUPERFISH, SLANS, FEM..) and 3D-codes (Microwave Studio, HFSS, MAFIA and OMEGA-3P) but still the Lumped Element replacement Circuit can be helpful to investigate some RF properties.



Where: $2\pi f_{FM} = (L_k \cdot c_k)^{-0.5}$; $(R/Q)_{FM} = (L_k/c_k)^{0.5}$; $R=(R/Q)_{FM} \cdot Q_{L,FM}$;

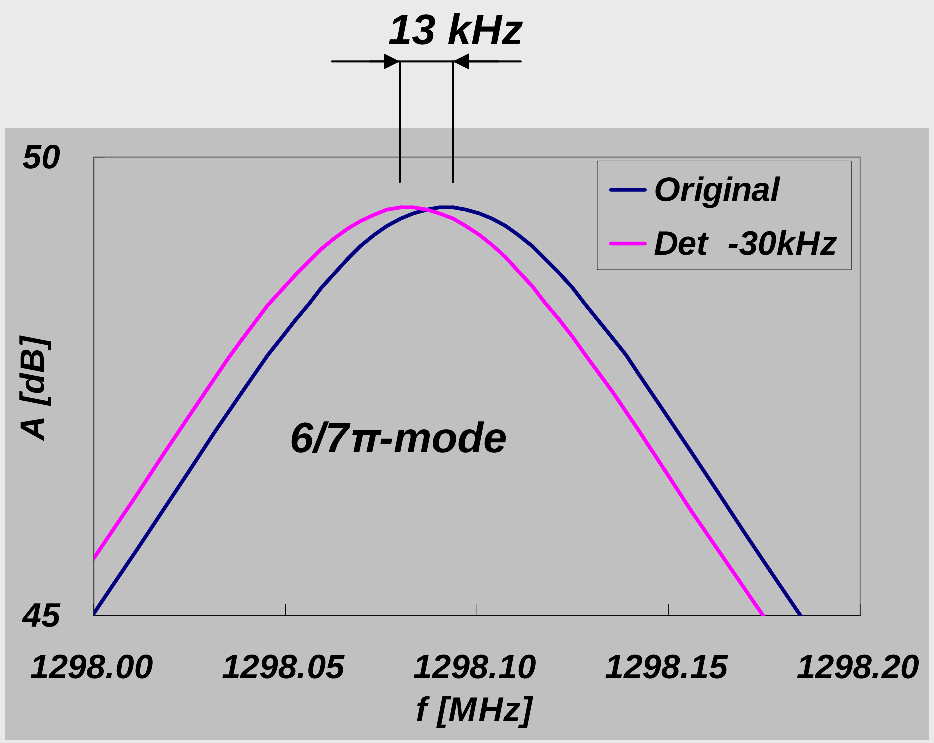
What makes sense to be done by means of the LEC:

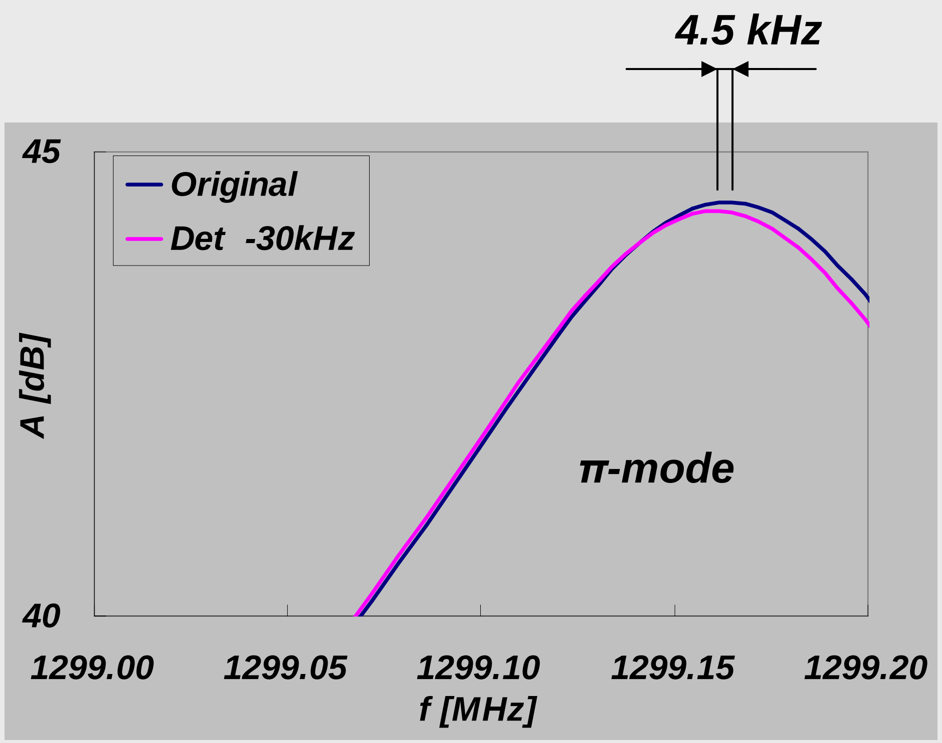
- **Cavity tuning after the fabrication and main chemical treatment**
- **Investigation of the field profiles sensitivity to cell frequency errors ($\partial f/f<10^{-4}$) for the FM passband**
- **Investigation of the FM passband frequency sensitivity to cell frequency errors ($\partial f/f<10^{-4}$)**
- **Modeling of the transient state (mode beating)**
- **Modeling of the voltage stability during acceleration**

***for blue marked implementations examples are shown on next slides**

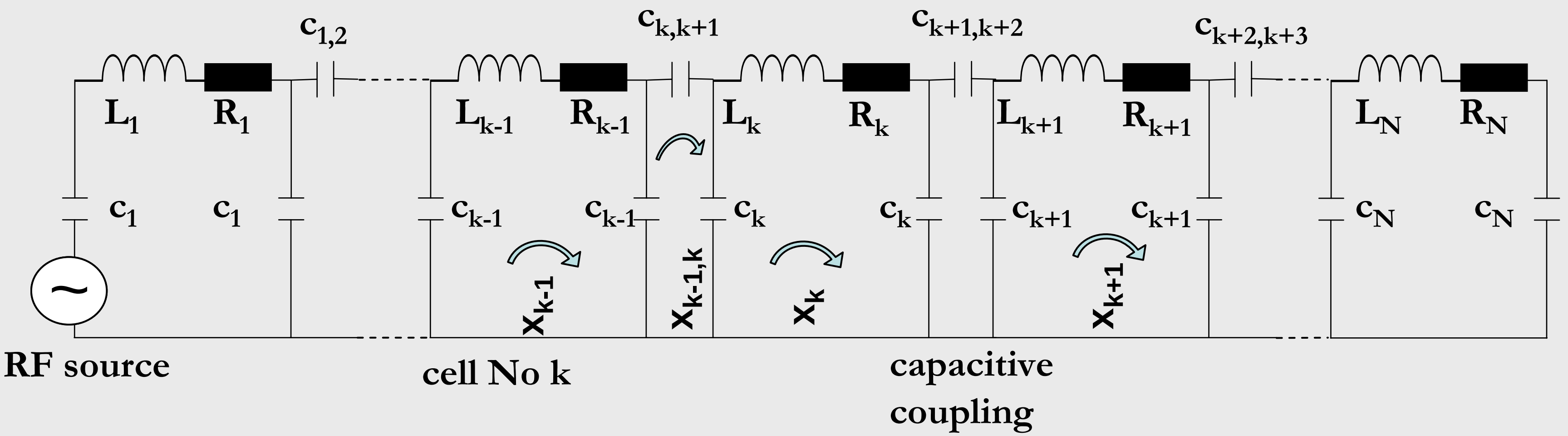
- **Investigation of the FM passband frequencies sensitivity to cell frequency errors *($\partial f/f<10^{-4}$)***

Example: 7-cells, k_{cc}=*1.85%*, 1st cell detuned by *-30kHz* (= the cell length change -11 µm !!, hard to model for 2D and 3D codes)





Transient State: Mode beating in pulse operation



Solving the set of Kirchoff equations:

$$R_1 \cdot x_1(t) + L_1 \cdot \dot{x}_1(t) + \frac{1}{c_1} \cdot \int_0^t x_1(\tau)d\tau - \frac{1}{c_1} \cdot \int_0^t x_{1,2}(\tau)d\tau = U_{-1}(t) \cdot e(t)$$

……..

$$-\frac{1}{c_k} \cdot \int_0^t x_{k-1,k}(\tau)d\tau + R_k \cdot x_k(t) + L_k \cdot \dot{x}_k(t) + \frac{1}{c_k} \cdot \int_0^t x_k(\tau)d\tau - \frac{1}{c_k} \cdot \int_0^t x_{k,k+1}(\tau)d\tau = 0$$

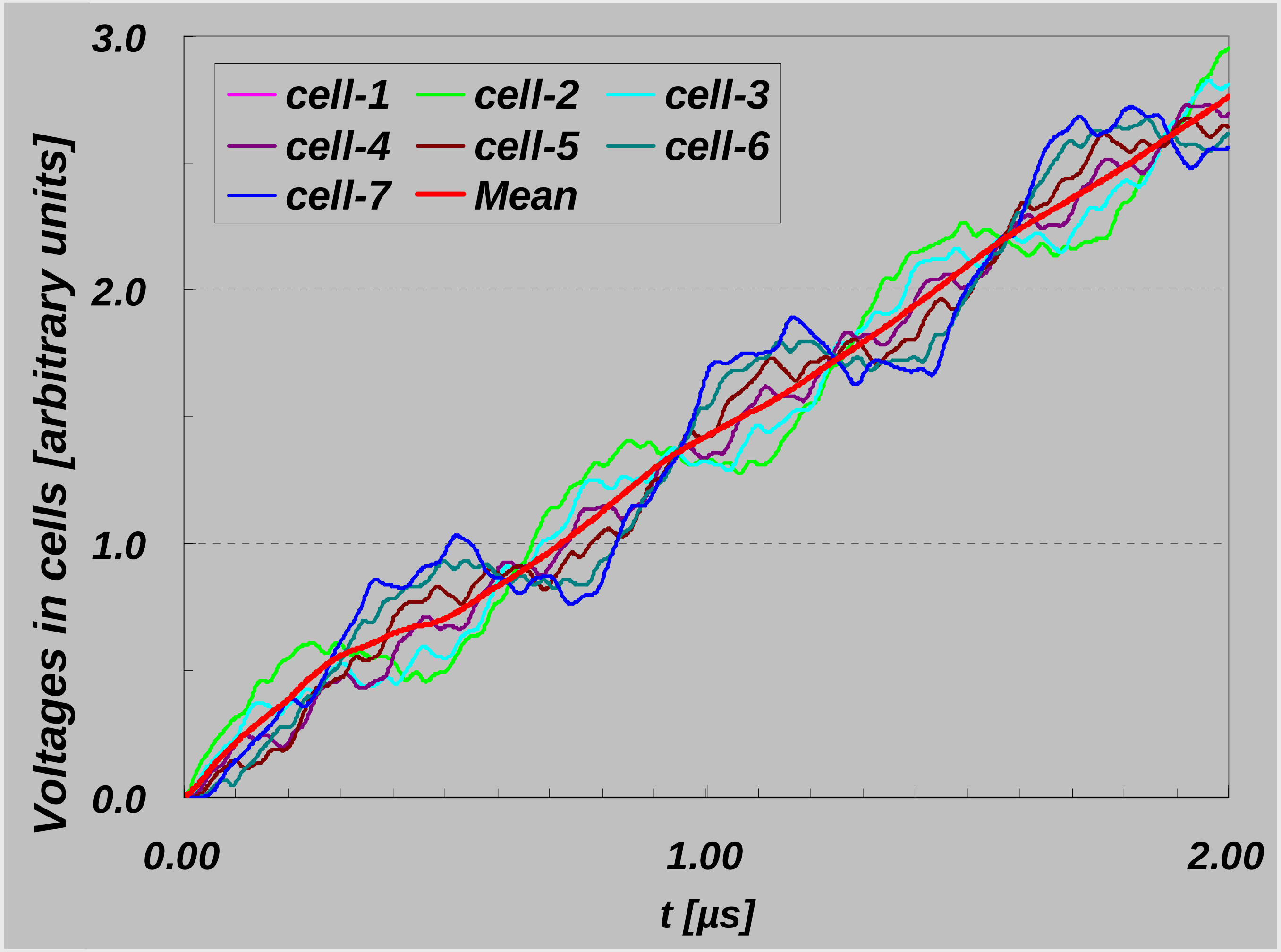
……..

$$-\frac{1}{c_N} \cdot \int_0^t x_{N-1,N}(\tau)d\tau + R_N \cdot x_N(t) + L_N \cdot \dot{x}_N(t) + \frac{1}{c_N} \cdot \int_0^t x_N(\tau)d\tau = 0$$

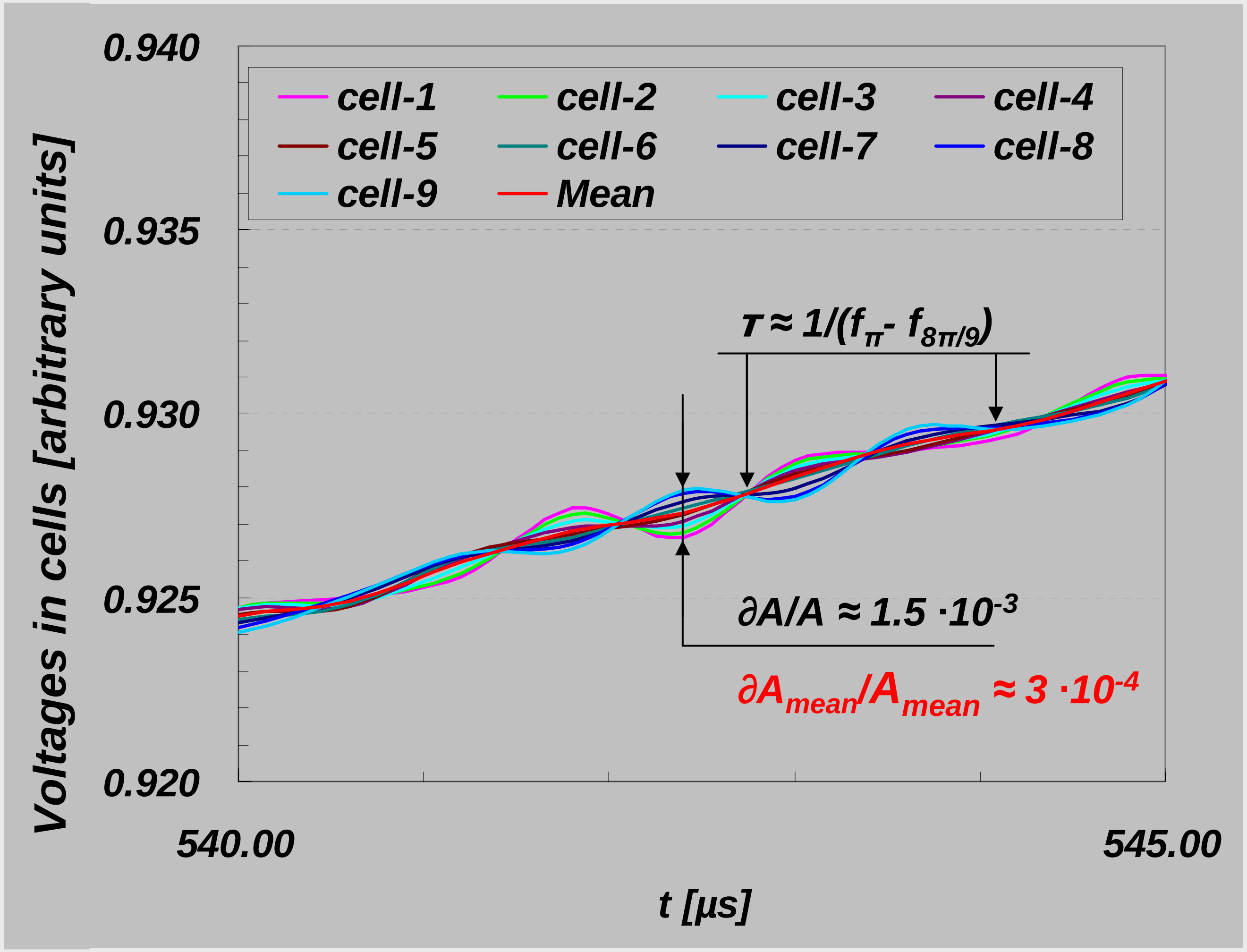
one can find voltages right after the RF-source is switched on and during the acceleration

- **Modeling of the transient state (mode beating)**

Example: 7-cells, k_{cc}=1.85%, Q_L=3.4 10^6



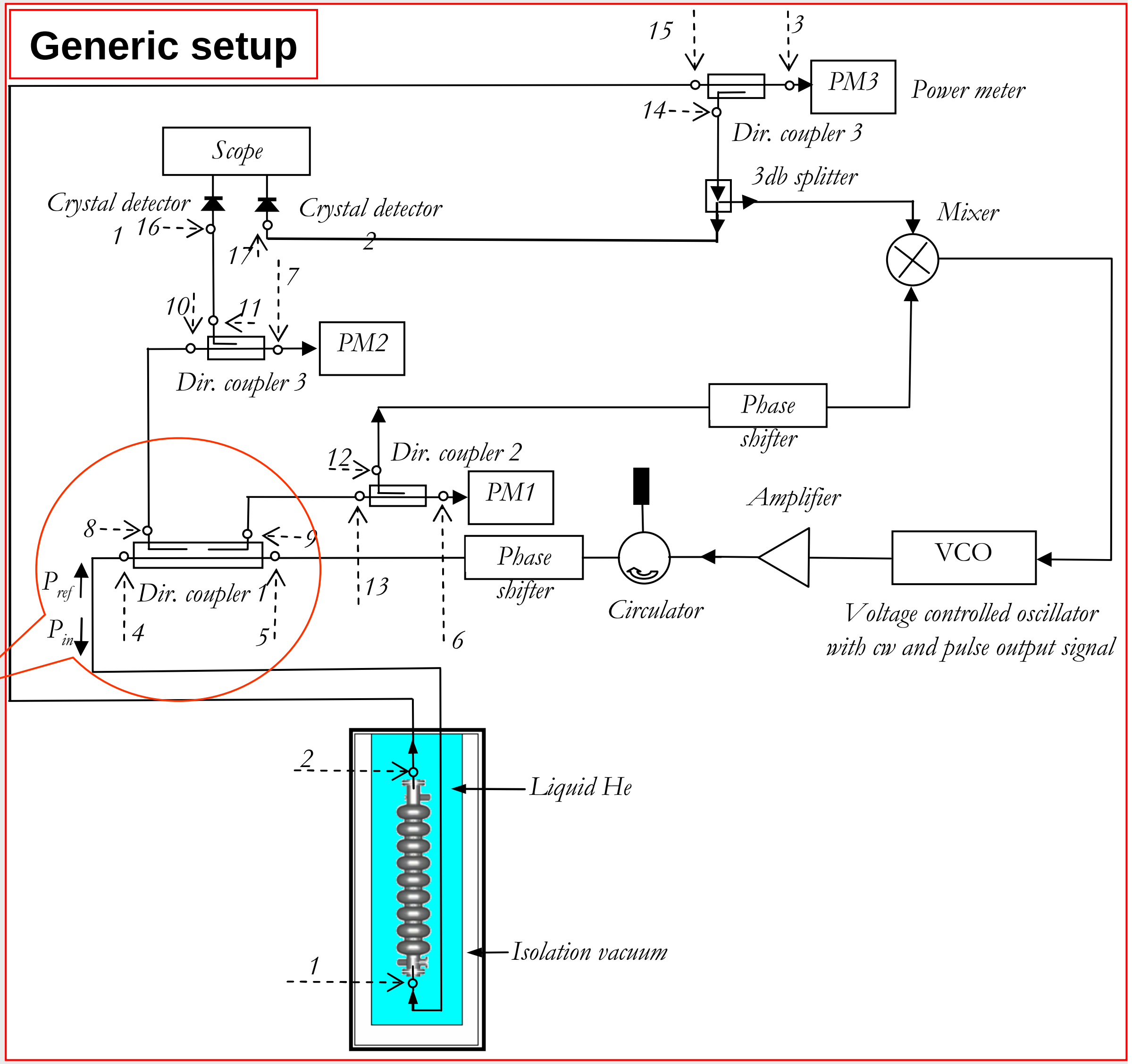
- **Modeling of the transient state (mode beating at the beam arrival time)**
  Example: 9-cell TESLA structure, k_{cc}=1.85%, Q_L=3.8 10^6



"Vertical test" at T<Tc (usually ≤ 2K): **The goal is: Q_o vs. E_{acc} (E_{peak})**

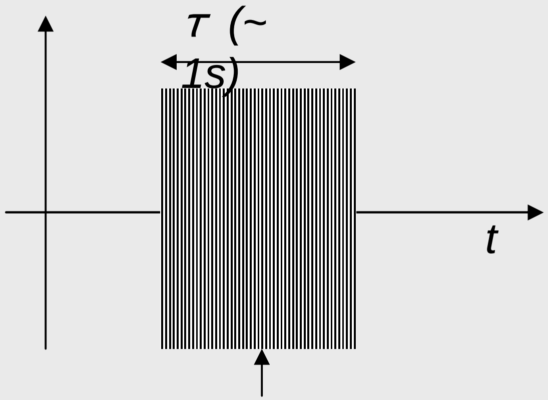
Two remarks:

- Half width of the resonance is<1Hz, VCO follows the frequency of the tested cavity
- The main error is due to the limited directivity of the directional coupler (~ 30dB)

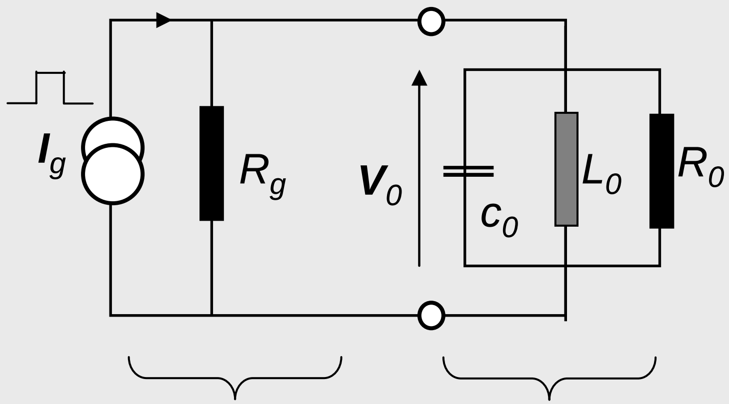


At first, in these tests one measures the coupling strength $ß_L$ and $ß_{out}$ of the input and output antennae.

Step 1. Response (shape of the reflected wave amplitude) of the cavity to the rectangular RF-pulse



~10^9 RF oscillations at the resonant frequency



Replacement LEC for the RF-source

Replacement LEC for the tested cavity

$$f1(t) = -\frac{1-\beta_L}{1+\beta_L} - \frac{2\beta_L}{1+\beta_L} e^{-\frac{\omega_0 t}{2Q_L}} S(t) \quad \text{for} \quad t \in \langle 0, \tau_p - \rangle$$

$$f2(t) = f1(t) + f1(t-\tau_p) S(t-\tau_p) \quad \text{for} \quad t \in \langle \tau_p, \infty \rangle$$

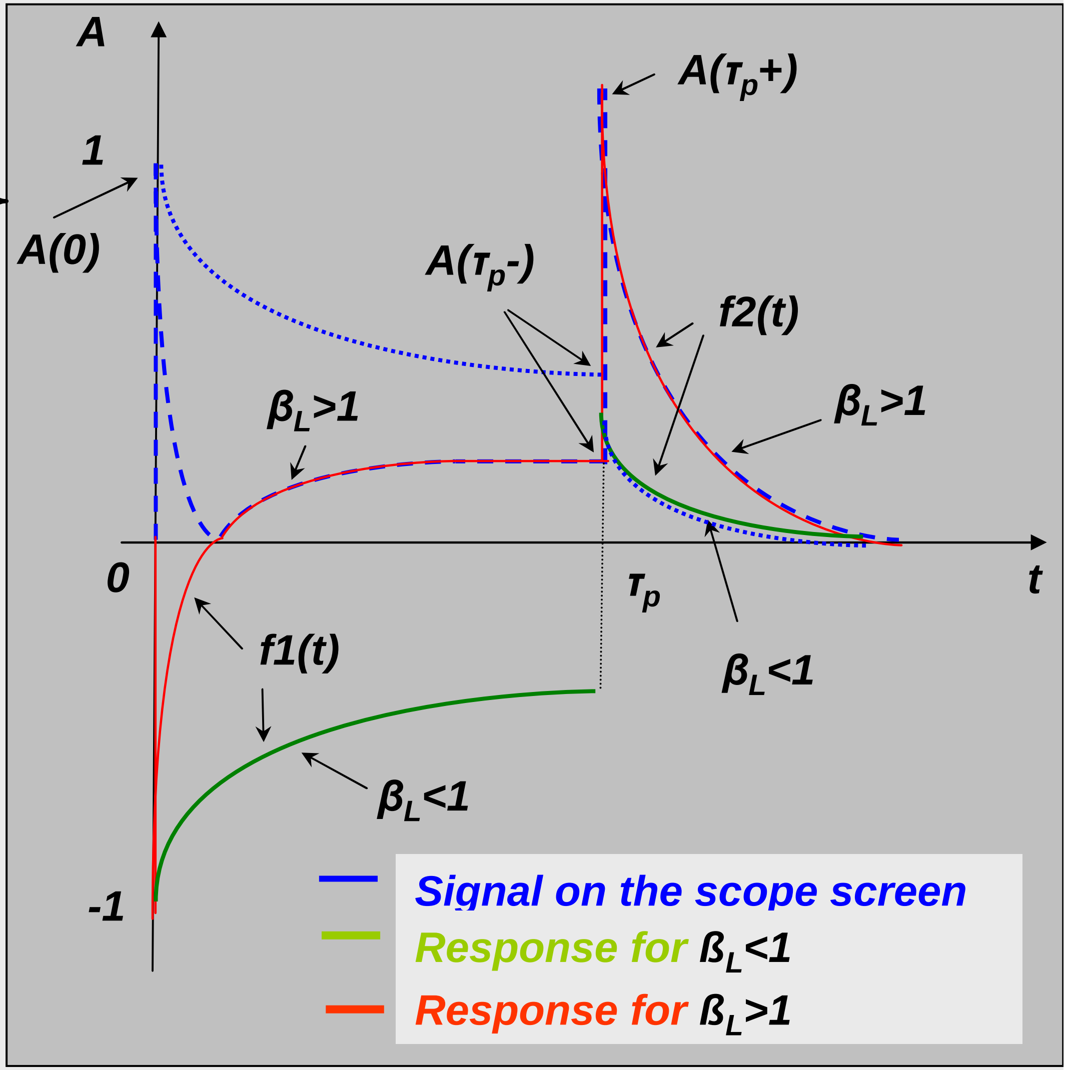
where $S(t)$ **is the step function**.

β_L **can be computed with there formulas**:

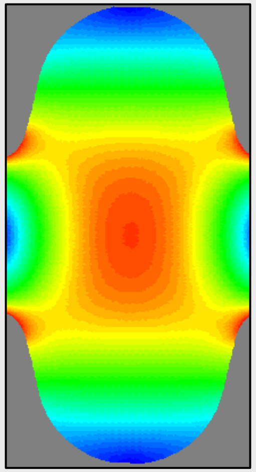
$$\beta_L = \frac{A(0) - A(\tau_p -)}{A(0) + A(\tau_p -)}$$

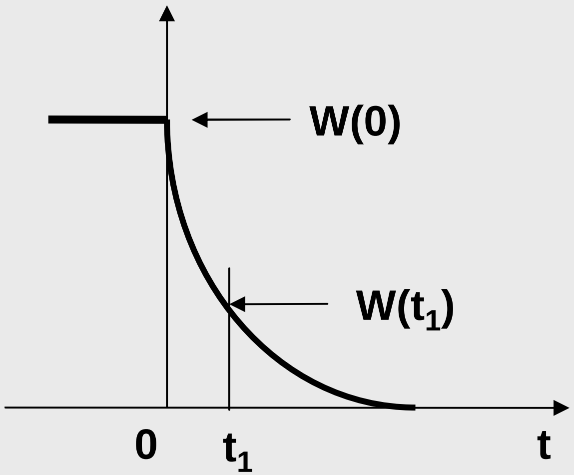
$$\beta_L = \frac{A(\tau_p +)}{2A(0) - A(\tau_p +)}$$

$$\beta_L = \frac{A(\tau_p +)}{2A(\tau_p -) + A(\tau_p +)}$$



Step 2. Energy decay right after the RF-pulse is switched off





$$W(t) = W(\tau_p +) e^{-\frac{\omega_0 (t - \tau_p +)}{Q_L}}$$

and measuring the input and transmitted power (*P_{in}* and *P_{tran}*), one obtains:

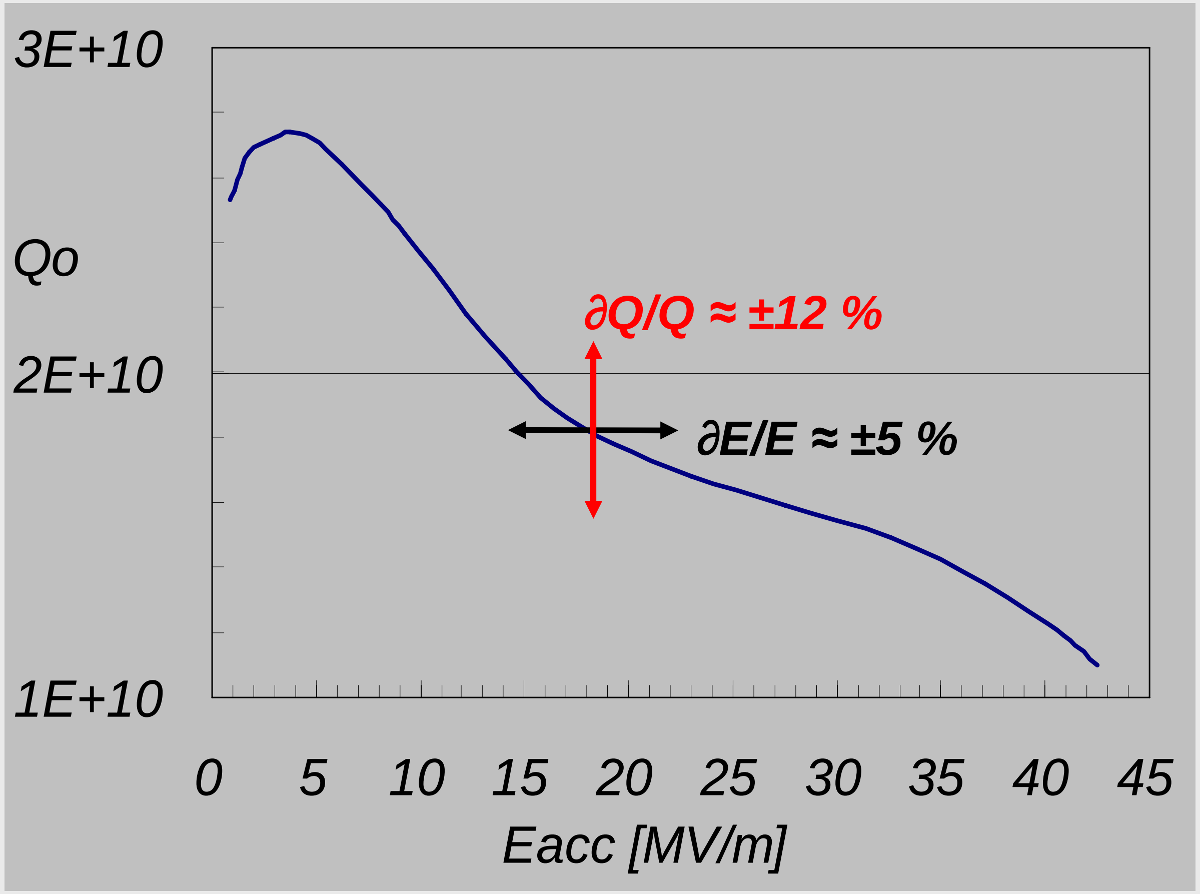
$$Q_0 = Q_L (1 + ß_L)(1 + \frac{P_{tran}}{P_{in} - P_{tran}})$$

$$Q_{out} = Q_0 \frac{P_{in} - P_{tran}}{P_{tran}}$$

The directivity of the directional coupler in the input line is ~ 30 dB (commercially available best double directional couplers).

The measurement of $ß_L$ has error due to the interference of the forwards and reflected wave.

With no other errors, the directivity makes following uncertainties in the measured data.

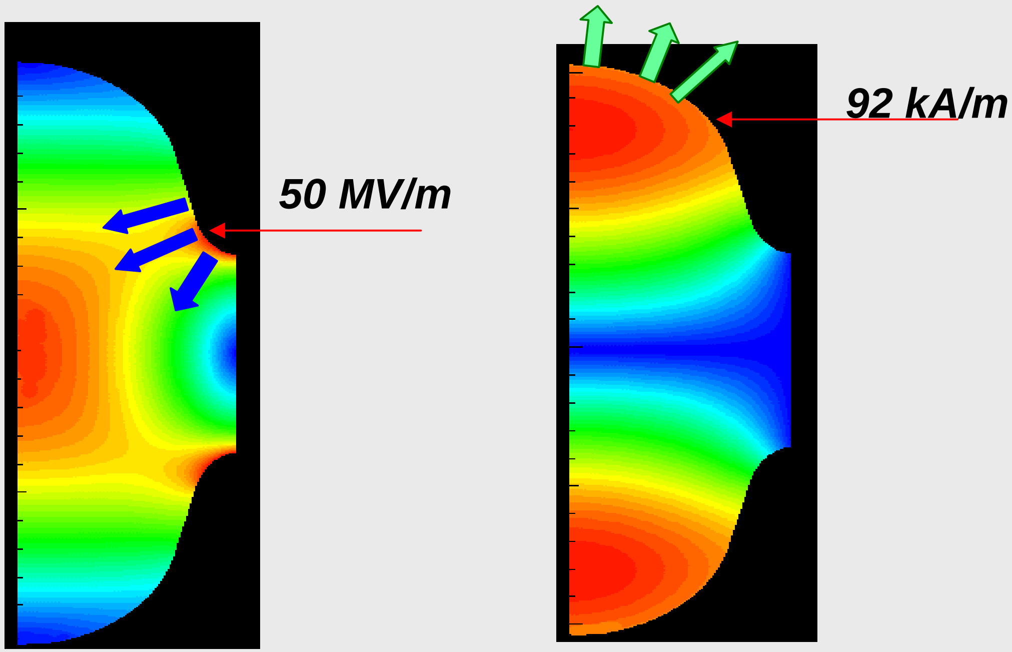


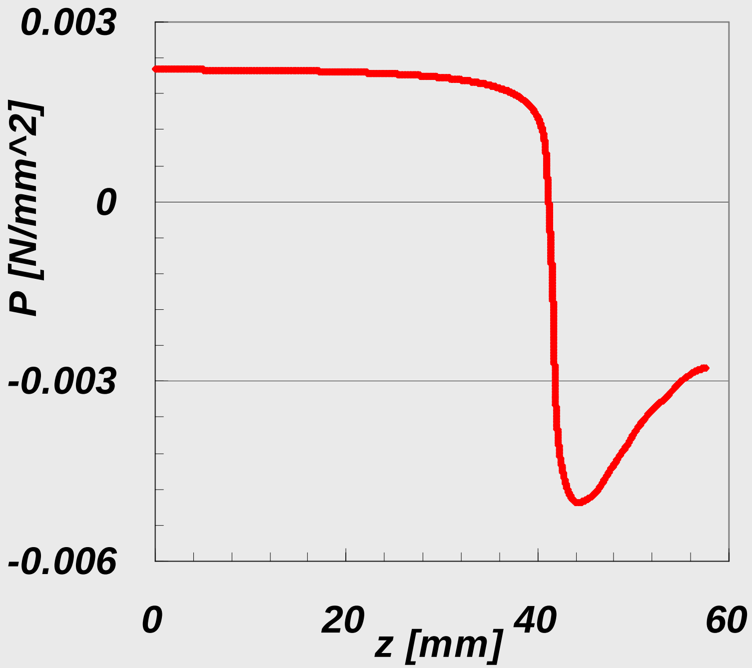
The mechanical design of a cavity follows its RF design:

- Lorentz Force Detuning
- Mechanical Resonances

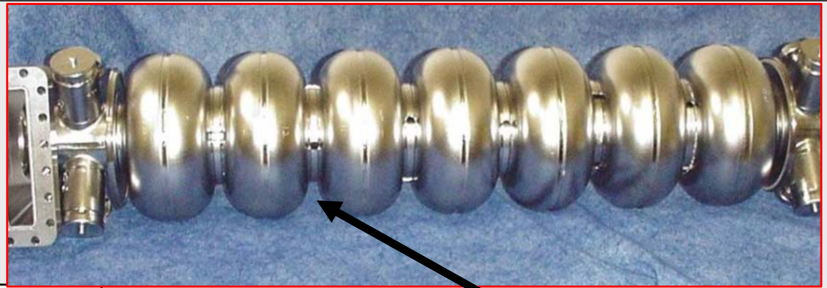
Lorentz Force Detuning

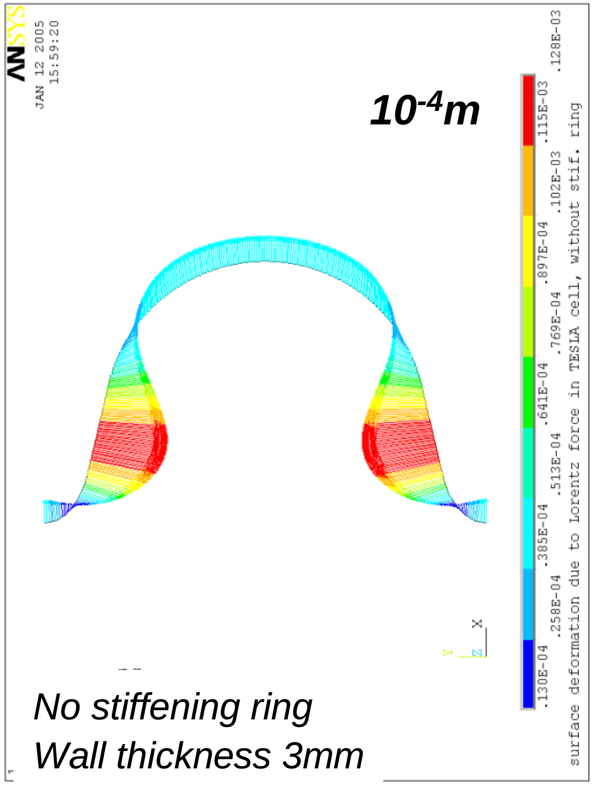
$$P = \frac{\mu_0 H_s^2 - \varepsilon_0 E_s^2}{4}$$



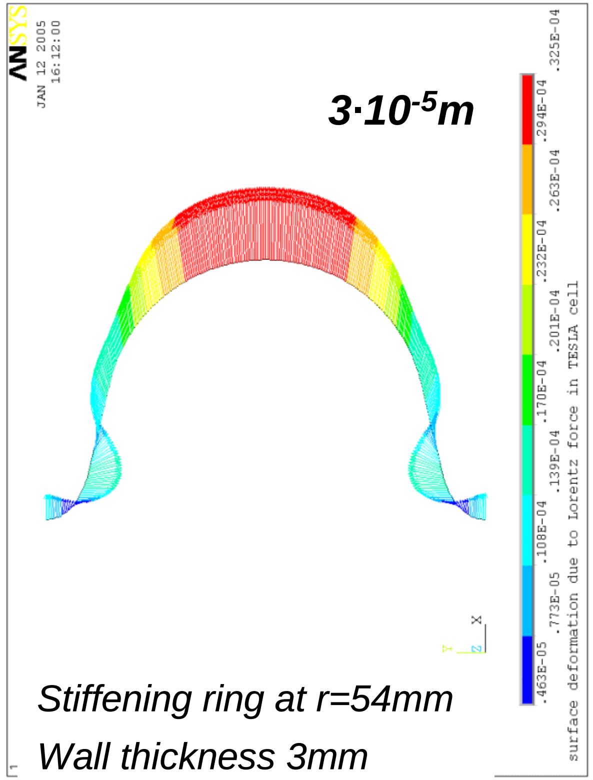


E and H at E_{acc} = 25 MV/m in TESLA inner-cup





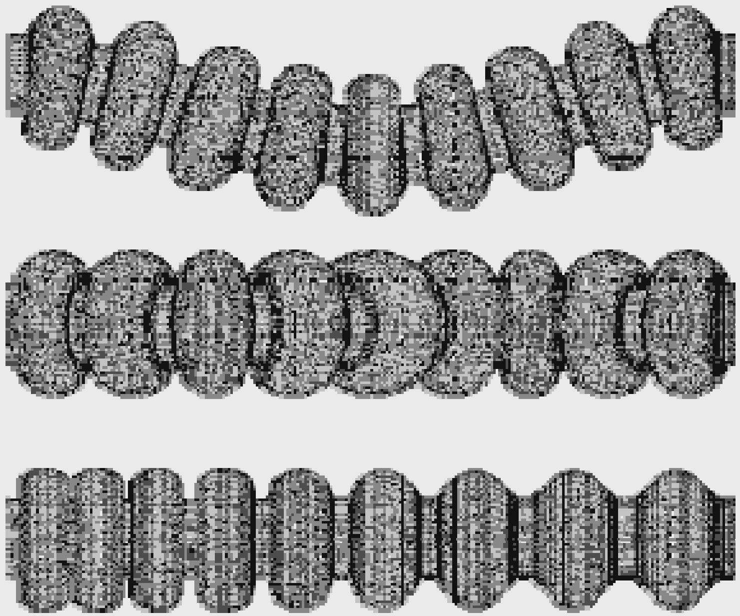
Surface deformation without and with stiffening ring (courtesy of I. Bonin, FERMI)



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

Essential for the operation of a pulsed accelerator $\Delta f = k_L(E_{acc})^2$

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…

9. Final Remarks

- Both RF- and Mechanical design are well understood
- We have day by day better tools for designing of accelerating cavities
- There is not a “golden” cavity suitable for all applications
- Not all requirements can be fulfilled at once and cavities must be tailored to their applications.

References:

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2. Proceedings of all SRF Workshops
3. TESLA TDR, DESY-Report 2003.
4. J.S. , “TESLA Superconducting Accelerating Structures” Institute of Physics, Journal of Measurement Science and Technology, 18 (2007) 2285-2292.