TM - Class Cavity Design

Tutorial

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Topics

1. Introduction and History
2. RF Parameters
3. Criteria for Cavity Design
    a. Accelerating Cavities
    b. Deflecting Cavities
4. Multi-cell Structures and Weakly Coupled Structures
5. Tools for RF-design
6. LEC and Transient state
7. Mechanical Design
8. Final Remarks and References

Milestones that led to accelerators based on SRF

Superconductivity

1908: Heike Kamerlingh Onnes (Holland)
Liquefied Helium for the first time.

1911: Heike Kamerlingh Onnes
Discovered Superconductivity.

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

RF Acceleration

1924: Gustaf Ising (Sweden)
The First Publication on RF Acceleration
Arkiv för Matematik, Astronomi och Fysik.

1928: Rolf Wideröe (Norway, Germany)
Built the first RF Accelerator,
Arch. für Elektrotechnik 21, vol.18.

1947: Luis Alvarez (USA)
Built first DTL (32 MeV protons).

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

Superconductivity | RF Acceleration

↓

<u>1961:</u> W. Fairbank (Stanford Univ.)

Presented the first proposal for a superconducting accelerator for electrons

A. Banford and G. Stafford (Rutherford Appleton Lab.)

Presented the first proposal for a superconducting accelerator for protons

↓

<u>1964:</u> W. Fairbank, A. Schwettman, P. Wilson (Stanford Univ.)

First acceleration of electrons with sc lead cavity

↓

<u>1970:</u> J. Turneaure (Stanford Univ.)

E_{peak} =70 MV/m and Q~10^{10} in 8.5 GHz cavity !

↓

<u>1968-1981:</u> M. McAshan, A. Schwettman, T. Smith, J. Turneaure, P. Wilson (Stanford Univ.)

Developed and Constructed the Superconducting Accelerator SCA

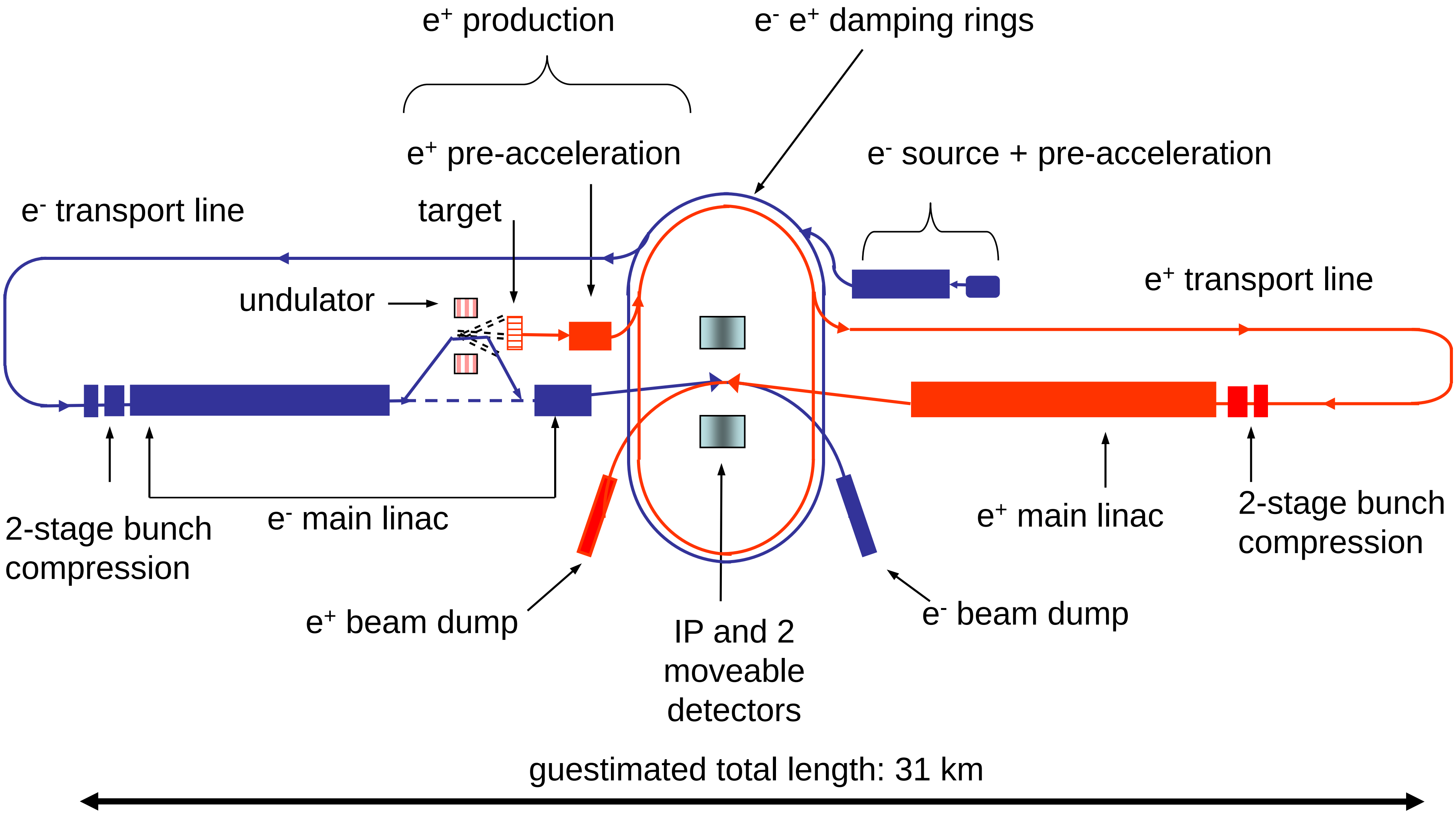
Since then, many sc accelerators were built and we are constructing and making plans for many new facilities.

1. Introduction and History

Accelerator	Country	No. of Cavities	SRF Active Length [m]	Status
TRISTAN	Japan	32	49	dismantled
LEP	**Switzerland**	**288**	**490**	**dismantled**
HERA	Germany	16	19	dismantled
SCA	USA	4	28	shutdown
S-DALINAC	Germany	10	10	operational
CESR	USA	4	1.2	operational
CEBAF	**USA**	**320**	**160**	**operational**
KEK-B	Japan	8	2.4	operational
Taiwan LS	Taiwan	2	0.6	operational
Canadian LS	Canada	2	0.6	operational
DIAMOND	UK	3	0.9	operational
SOLEIL	France	4	1.7	operational
FLASH	Germany	56	58	operational
SNS	USA	81	65	operational
JLab-FEL	USA	24	14	operational
LHC	Switzerland	16	6	operational
ELBE	Germany	6	6	operational
CEBAF 12GeV	USA	+80	56	construction
European XFEL	**Germany**	**648 (808)**	**674 (840)**	**construction**
SNS-Upgrade	USA	+36	33	R&D
ERL Cornell	USA	384	310	R&D
RHIC Cooling	USA	1	1	R&D
BEPC II	China	2	0.6	R&D
Project X	USA	Option 352	Option 360	R&D
ILC	**Option USA**	**15764**	**16395**	**R&D**

1. Introduction and History

ILC (~15764/~16395m)



1. Introduction and History

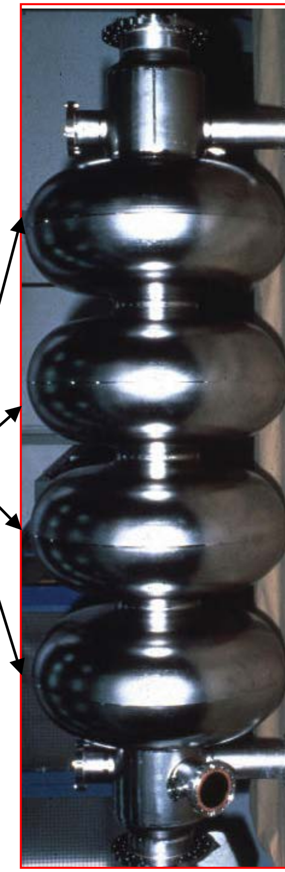
The "core elements" of all mentioned facilities were, are or will be sc standing wave accelerating structures.

Photographs of TM-class (elliptical) accelerating structures with ß ≥ 0.61.

FERMI 3.9 GHz

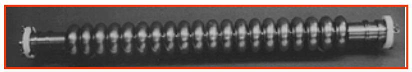
TESLA/ILC 1.3 GHz

LEP 0.352 GHz



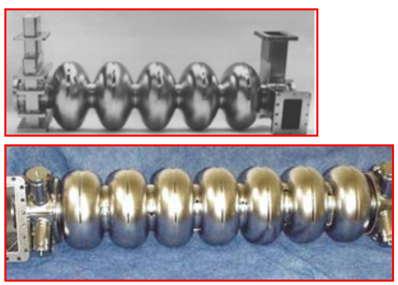
cells

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

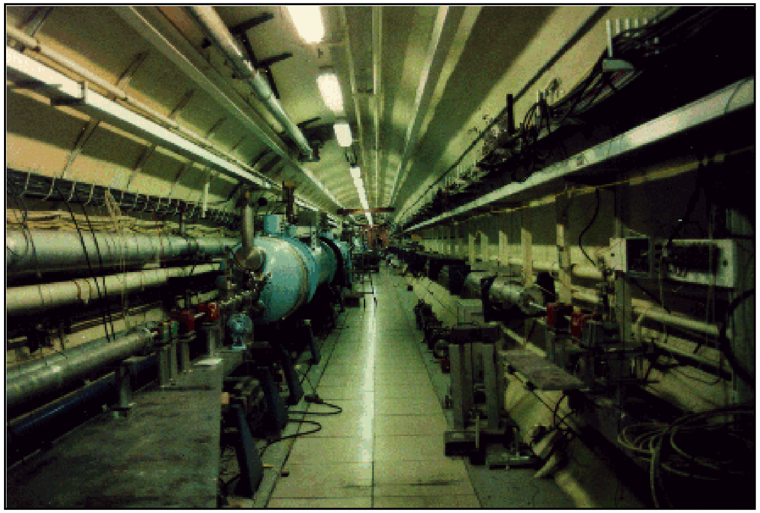
KEK-B 0.5 GHz

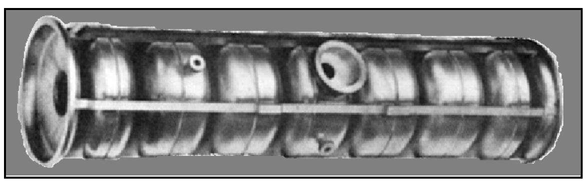
CESR 0.5 GHz

1. Introduction and History

The progress in last 34 years and what do we need in the next 10 years?

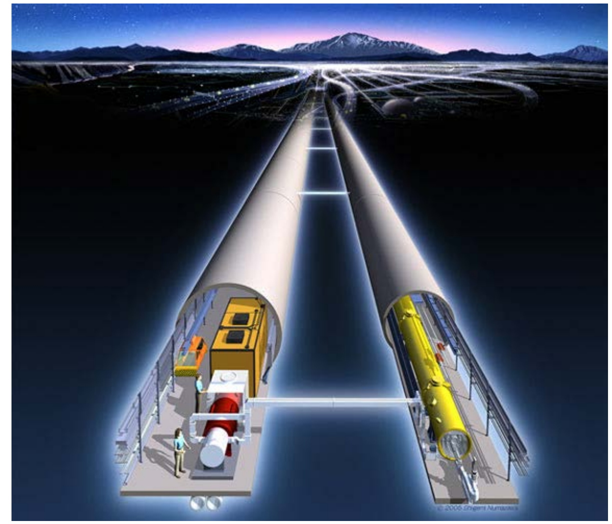
~ 28 m long SCA at Stanford, 1977.





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

~ 21.6 km long ILC linac, 2020+



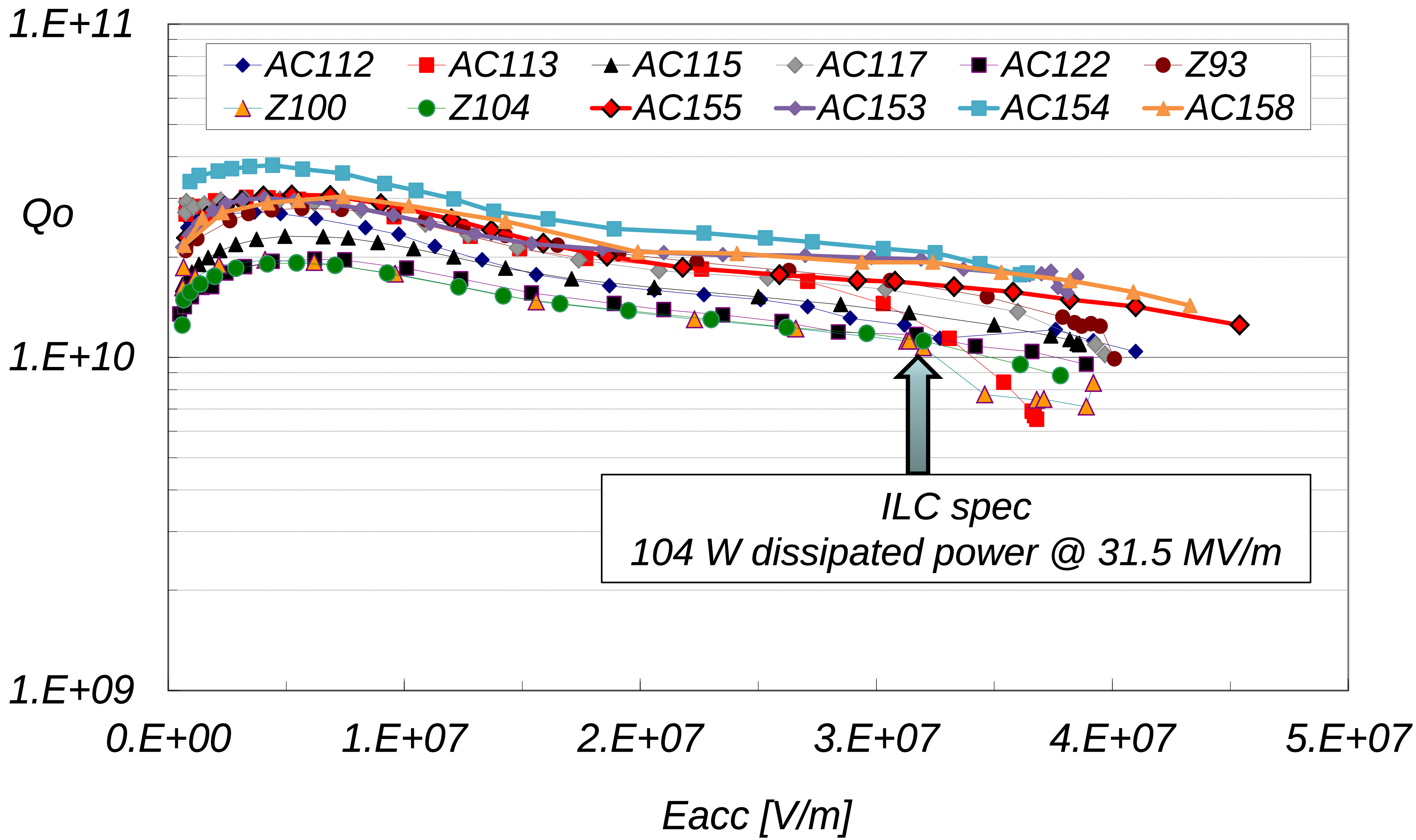
E_{acc} > 35 MV/m was demonstrated in many 9-cell cavities in the cw test.

⬇

The $\langle E_{acc} \rangle$ = 31.5 MV/m is required in all ILC 15764 cavities.

1. Introduction and History

Results at DESY (status July 2011) for 12 electropolished TESLA cavities tested at 2K:



2.1. Cavities and their Eigenmodes

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

We will make 3 assumptions, to continue here with a simple example:

1. Stored *E-H* fields **are harmonic** in time.
2. **Cylindrical symmetry** (good approximation for body of an accelerating cavity).

   Cylindrical *(r, φ, z)* coordinates, with *z* as the symmetry axis and direction of acceleration

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

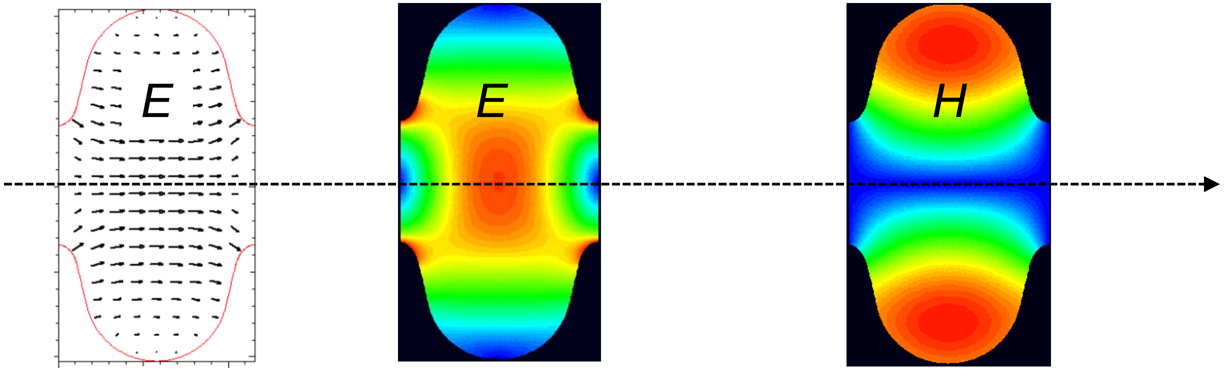
3. Modes suitable for **acceleration have strong *E*** along the beam trajectory.

   This enables, by a proper phasing, an efficient energy exchange between a cavity and beam.

TM0xx-like monopole modes have “very strong” E_z component on the symmetry axis. Their e-m fields do not depend on φ.

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

The lowest frequency mode with **TM010-like** field pattern is suitable for the acceleration



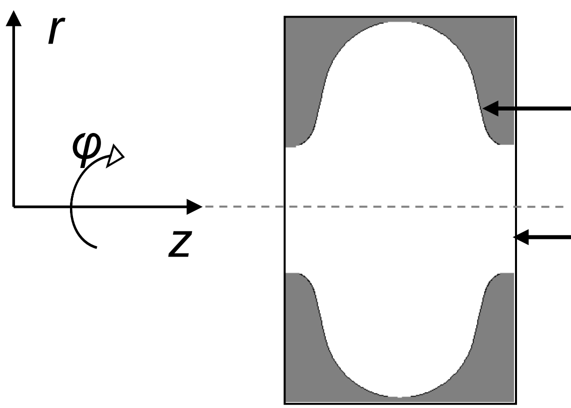
Non monopole modes (HOM) have component $E_z = 0$ on the symmetry axis. Their fields dependent on φ.

TM110-like mode is used in crab-cavities for bunch rotation.

2. RF Parameters

Maxwell equations + boundary conditions for *E* and *H* 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

$H = 0$, $n \cdot H = 0$ optionally on non metal boundary

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

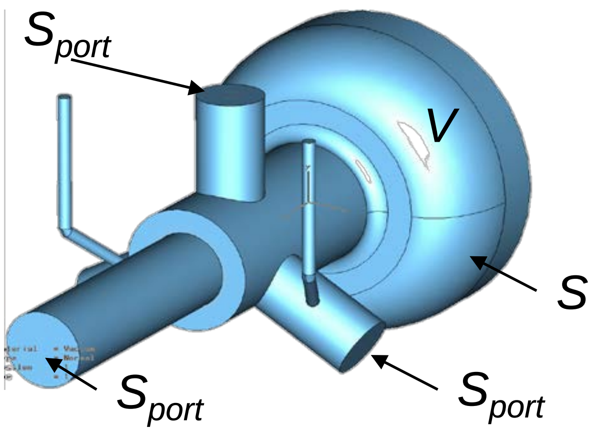
There is infinity number of TM0xx solutions (modes) to the Helmholtz equation.

All modes are determine by:

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

and by frequency ω_n *(n is here the index of a mode).*

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



W_n ≡ *stored energy of a mode n : {ω_n, E_n, 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 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 $R_{s,n}$=1Ω

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

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

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

This interaction which is:

- Acceleration
- Deceleration (ERL)
- HOMs excitation

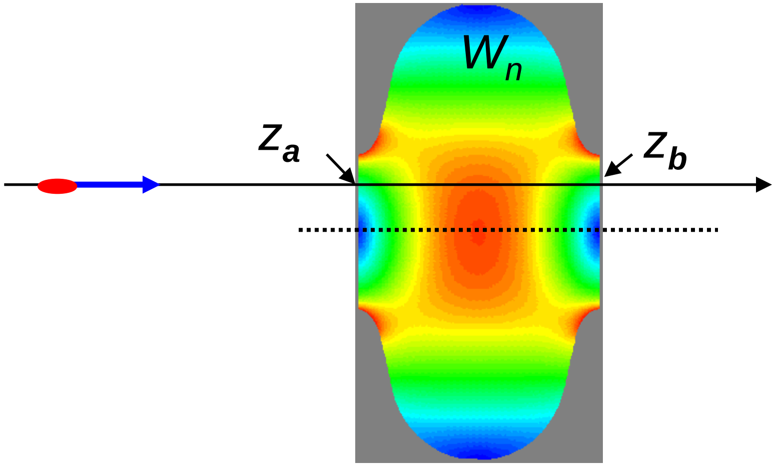
can be described in the Frequency Domain (FD) or/and in Time Domain (TD).

2. RF Parameters

$(R/Q)_n$; beam impedance

It is 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 is a straight line.

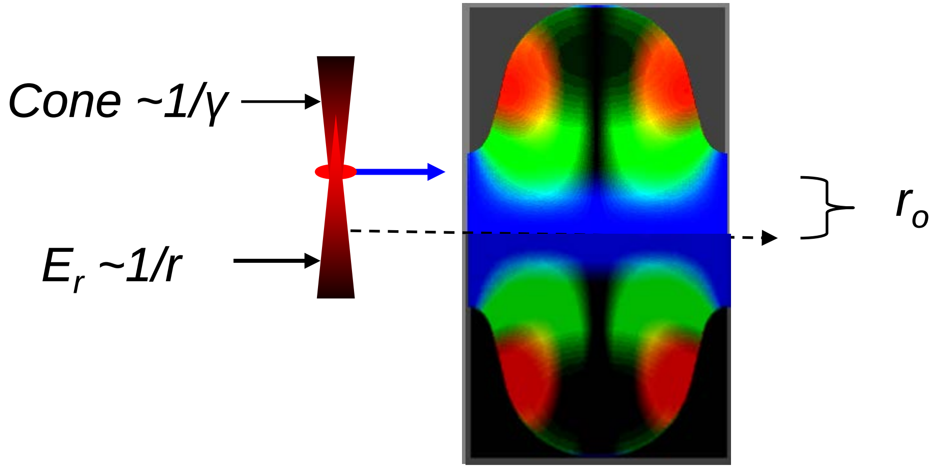
$$V_n = \sqrt{\left(\int_{z_a}^{z_b} E_{n,z} \sin\left(\frac{\omega_n}{\beta c}(z - z_a)\right)dz\right)^2 + \left(\int_{z_a}^{z_b} E_{n,z} \cos\left(\frac{\omega_n}{\beta c}(z - z_a)\right)dz\right)^2}$$

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

Linac convention for *(R/Q)* definition.

Longitudinal and Transverse Loss Factors (TD)
(Excitation of cavity modes)

Ultra relativistic point charge *q* passes empty cavity



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

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

2. RF Parameters

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

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

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

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

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

Both description methods FD and TD are equivalent.

For an individual mode n and point-like charge:

$$k_{\|,n}^{p} = \frac{\omega_n \cdot (R/Q)_n}{4}$$

Similar for other loss factors…….

2.4. Some "practical" RF parameters for the accelerating mode

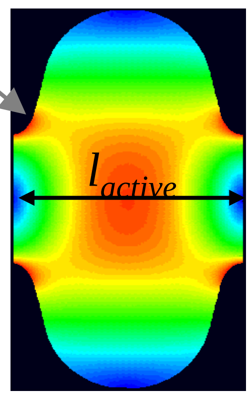
For the stored energy W_{acc} mean value of the accelerating gradient is:

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

E_{peak} on the wall

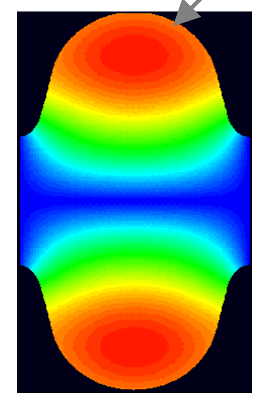
B_{peak} on the wall

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



Contour plot of /E/

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



Contour plot of /B/

The ratio shows sensitivity of the shape to the field electron emission phenomenon.

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

2. RF Parameters

$$G_{acc} \cdot (R/Q)_{acc}$$

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

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

Big improvement is possible:

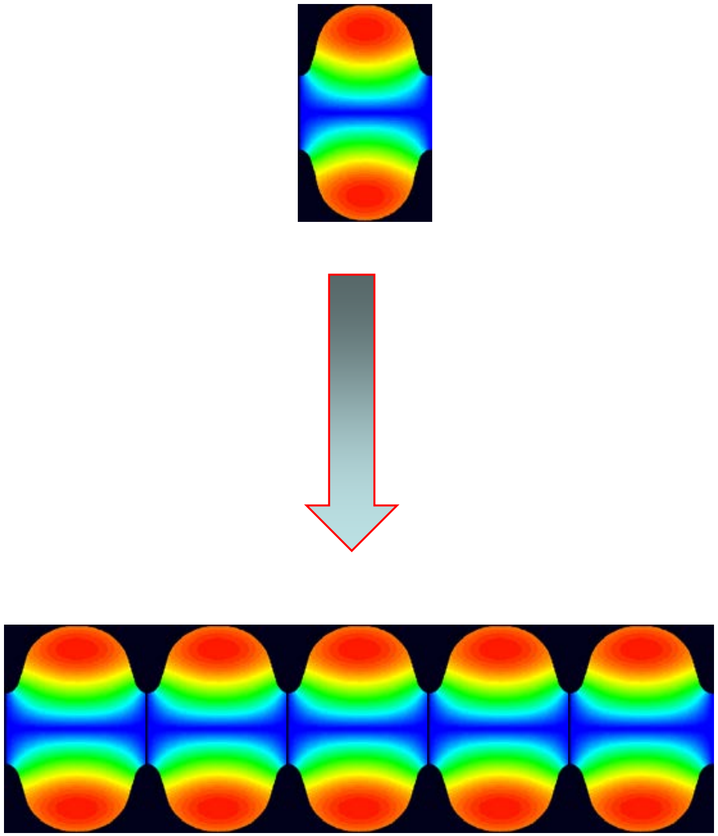
- Due to superconductivity
- Due to the surface quality.

This is due to the geometry of cells (brace under $G_{acc} \cdot (R/Q)_{acc}$)

Moderate improvement possible.

cell-to-cell coupling k_{cc}

The k_{cc} is relevant for the accelerating mode passband of multi-cell structures



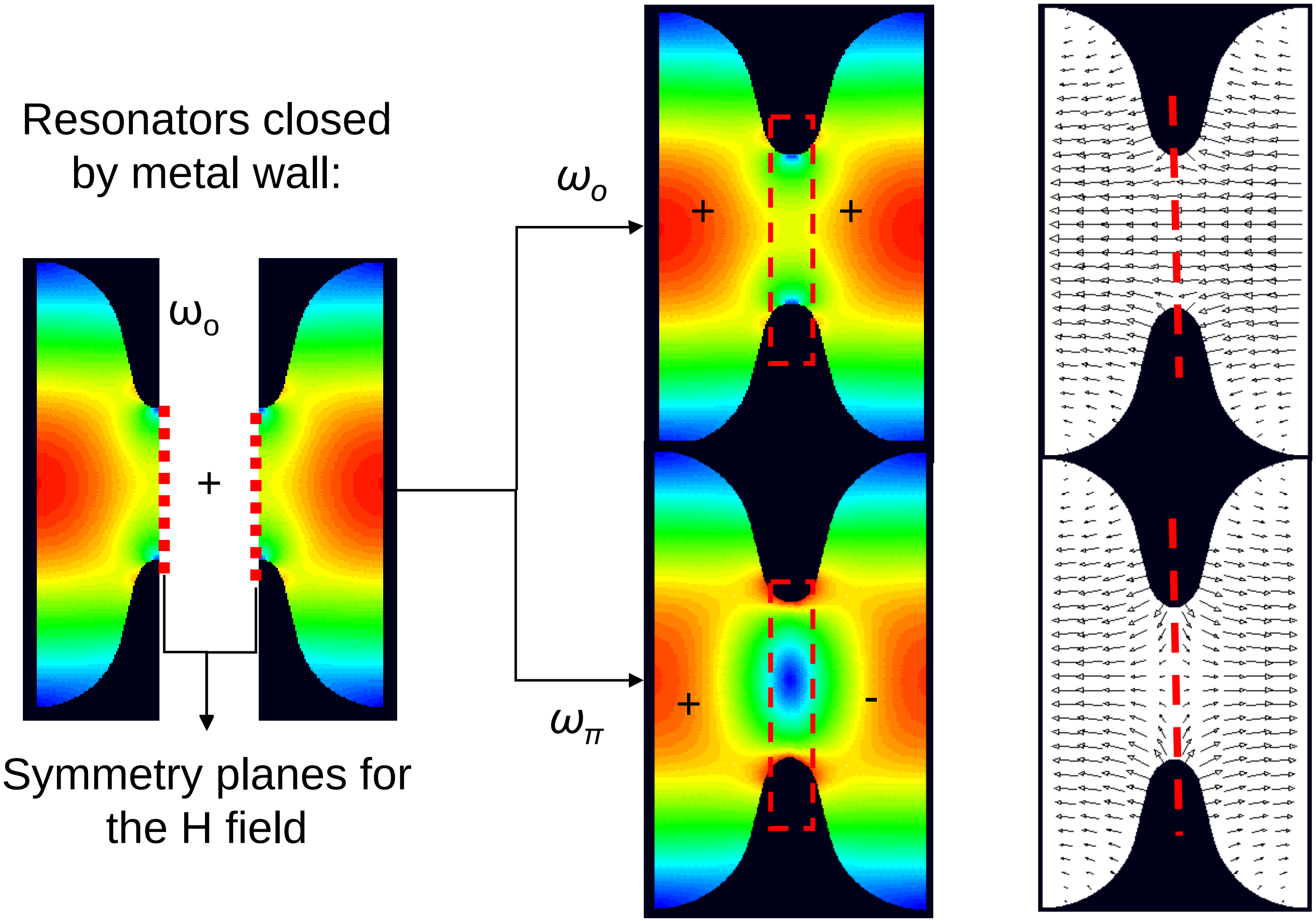
Single-cell structures are attractive because:

- It is easier to manage HOM damping
- There is no field flatness problem.
- Input coupler transfers less power
- They are easy for cleaning and preparation
- But it is expensive to base even a small linear accelerator on the single cells. We do it only for very high beam current machines.

- Multi-cell structures are less expensive/m and allow for higher real-estate gradient.

2. RF Parameters

Resonators closed by metal wall:



Symmetry planes for the H field

Symmetry plane for the H field

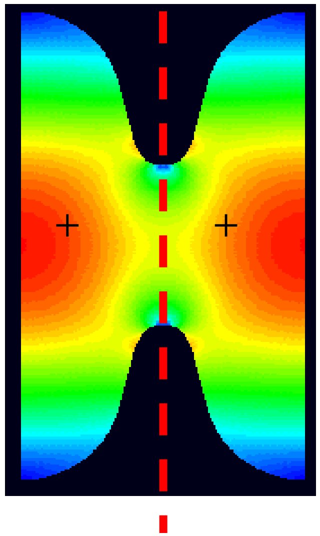
Symmetry plane for the E field,

which is an additional solution

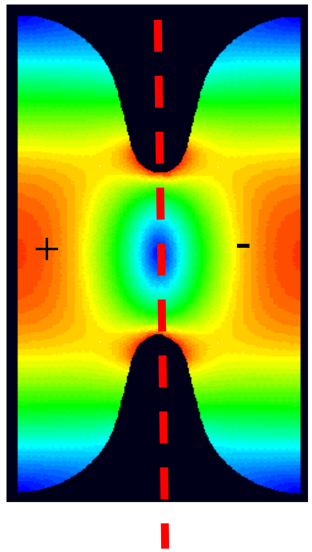
2. RF Parameters

The energy flux across the coupling region, refills dissipated energy in cells.
It is proportional to the transverse components: H_φ and E_r

ω_o



ω_π



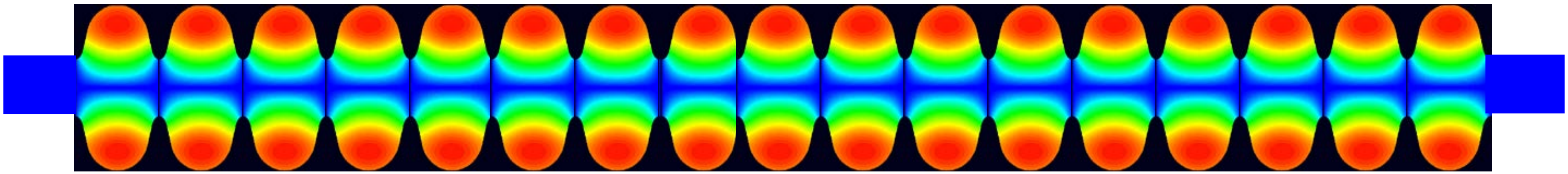
Small E_r (due to the losses) + strong H_φ at the symmetry plane

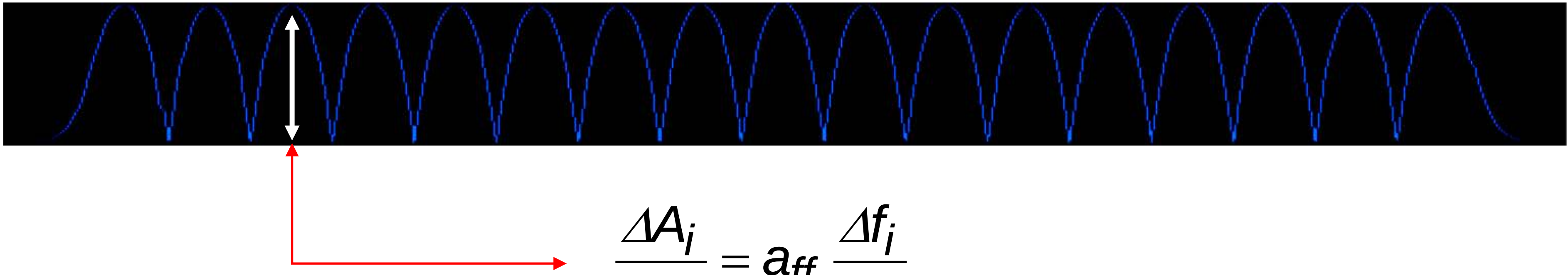
Small H_φ (due to the losses) + strong E_r at the symmetry plane

The normalized difference between ω_o and ω_π 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 a_{ff} for structure made of N cells and the coupling factor k_{cc}

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

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

3. Criteria for Cavity Design; accelerating cells

We will discuss here design of inner cells because they "dominate" the RF properties of multi-cell structures.

RF parameters summary:

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

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

The elliptical shape, which we will focus on, used since late 60's, has two major and indispensible features:

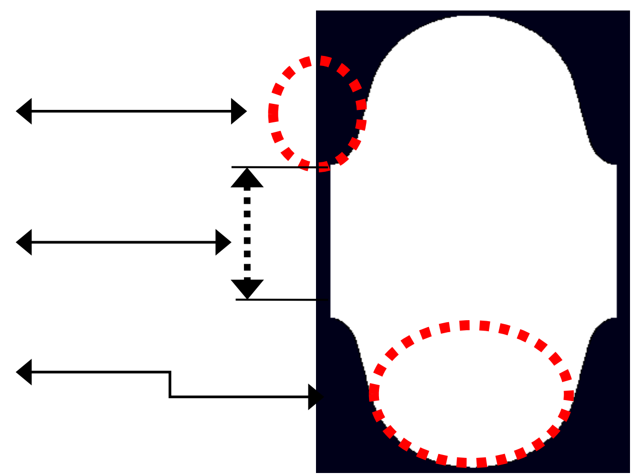
- It is easy to clean
- It demonstrates very little and usually conditionable multipacting.

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".

3. Criteria for Cavity Design: accelerating cells

Criterion	*RF-parameter*	*Improve(s) 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*
High I_{beam} ↔ *Low HOM impedance*	$k_\perp, k_\parallel$ ↓	r_i ↑	*B-Factory RHIC cooling*

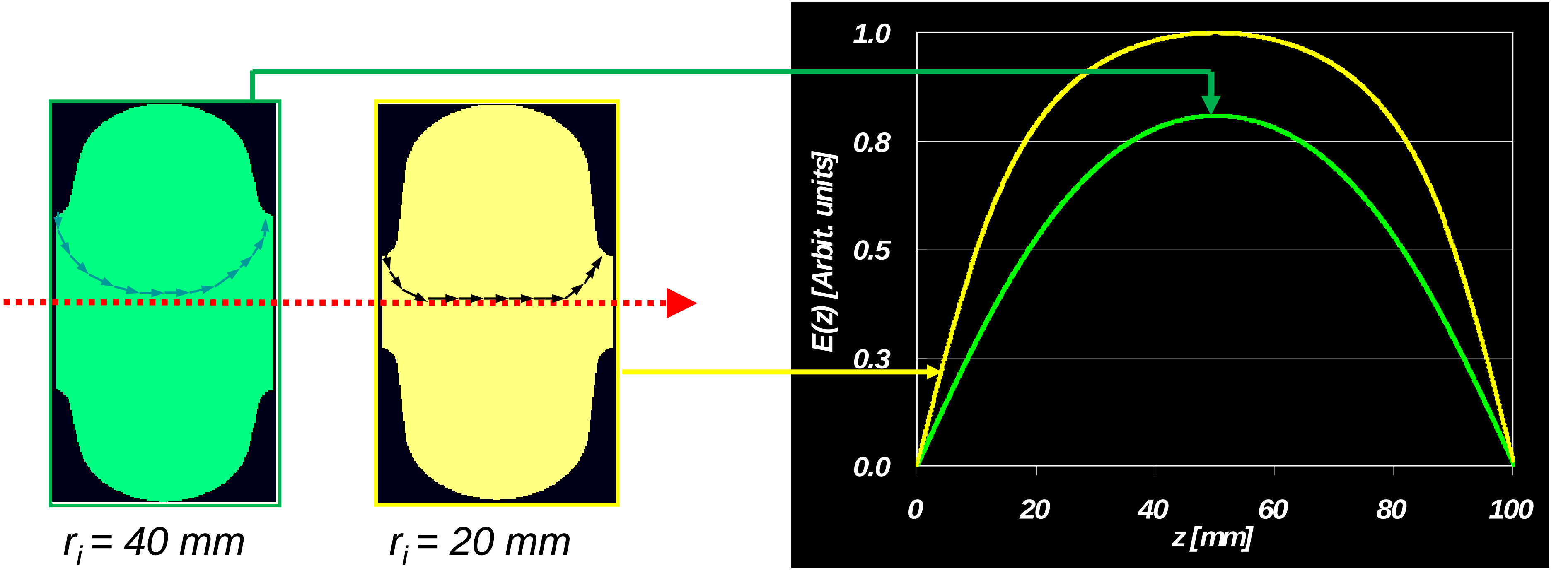
We see here that r_i is a very “powerful variable” to trim the RF-parameters of a cavity.

3. Criteria for Cavity Design: accelerating cells

Why for a smaller aperture (r_i)

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

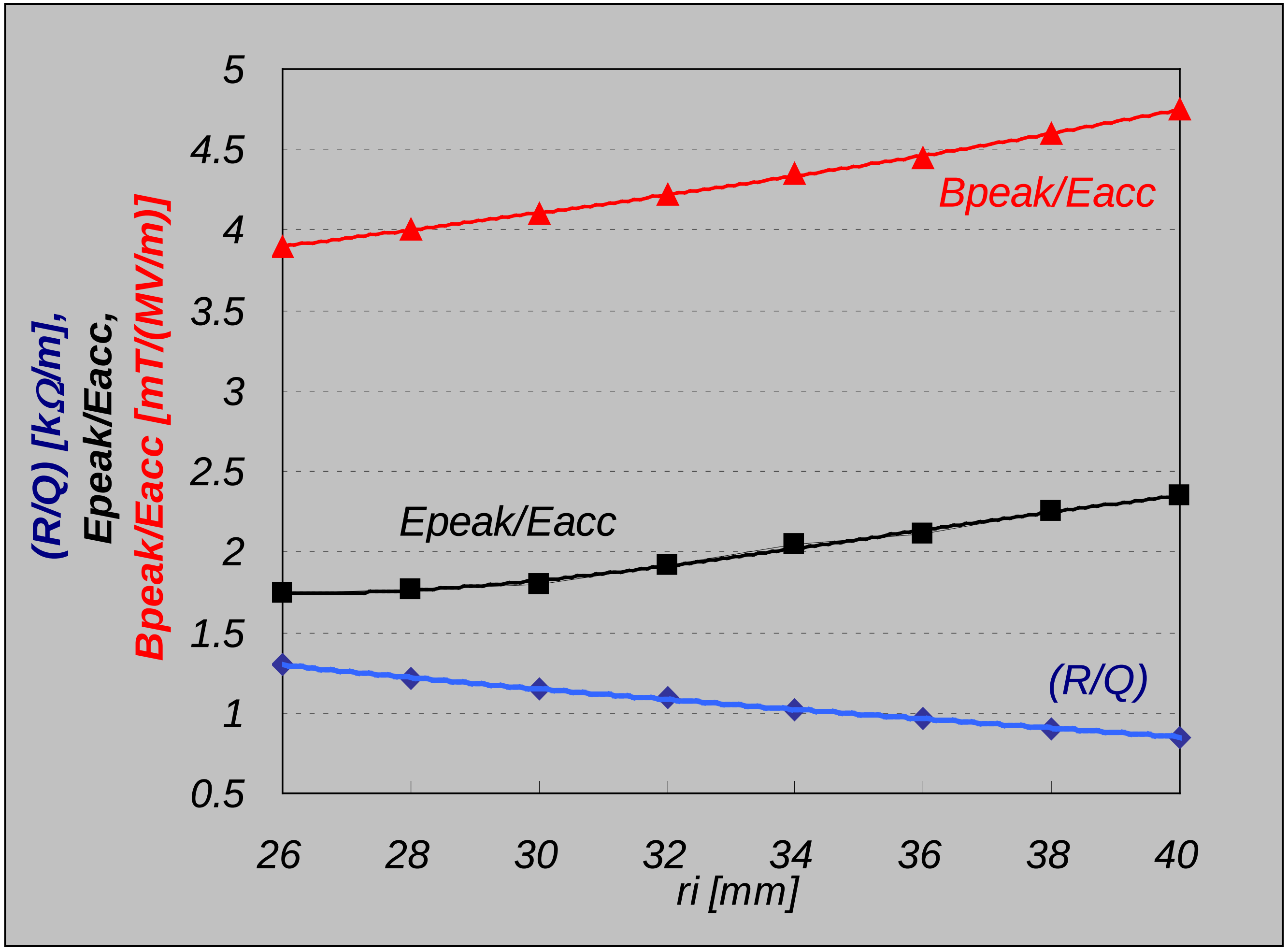
E_{acc} is higher at the same stored energy in the cell with smaller aperture.



E_z (z) for small and big iris radius

Example:

{ (R/Q), E_{peak}/E_{acc} , B_{peak}/E_{acc} } vs. r_i for cell at f = 1.5 GHz

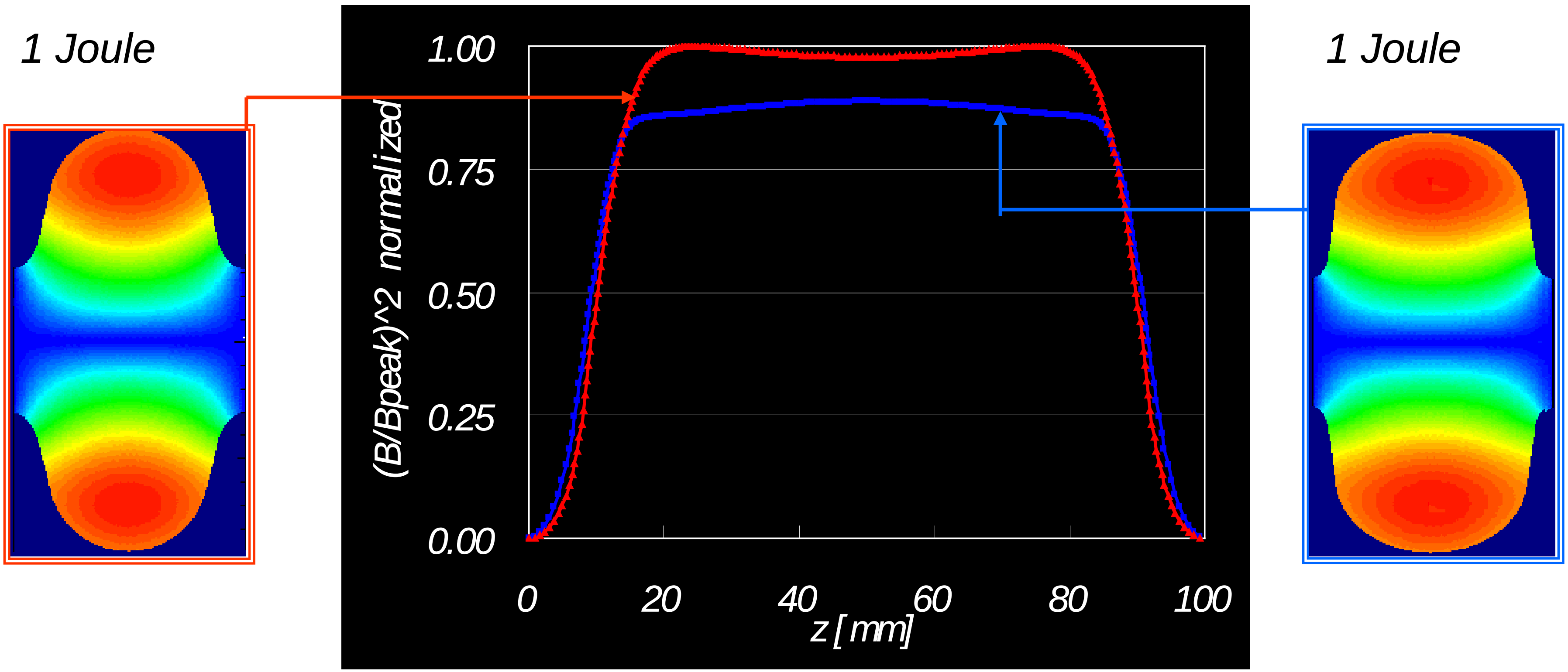


A. Mosnier, E. Haebel, SRF Workshop 1991

3. Criteria for Cavity Design: accelerating cells

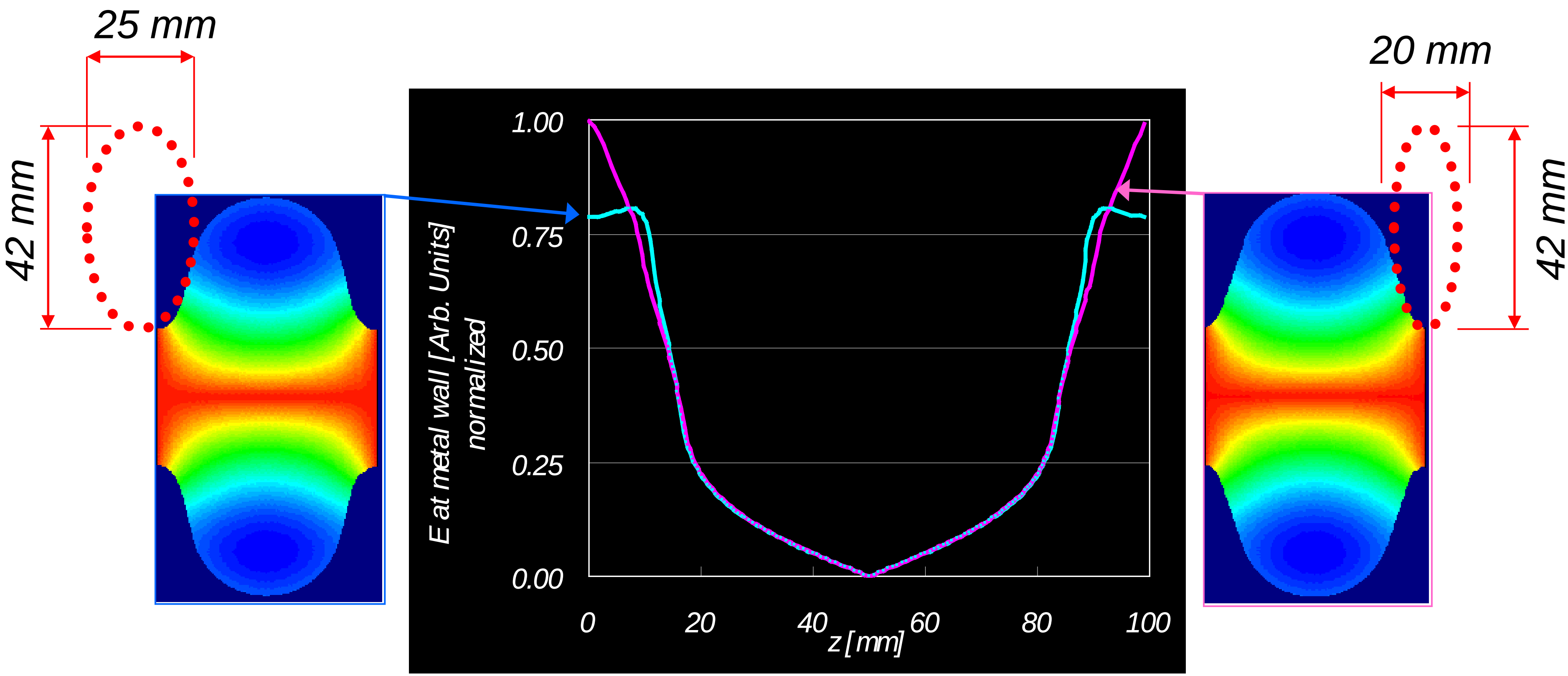
In addition to the iris radius r_i:

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



3. Criteria for Cavity Design: accelerating cells

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



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

3. Criteria for Cavity Design: accelerating cells

We know that a smaller aperture r_i makes FM :

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

} (+)

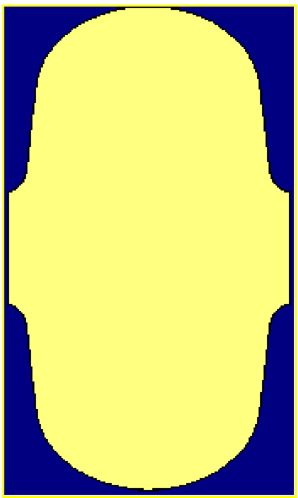
but unfortunately a smaller aperture r_i makes:

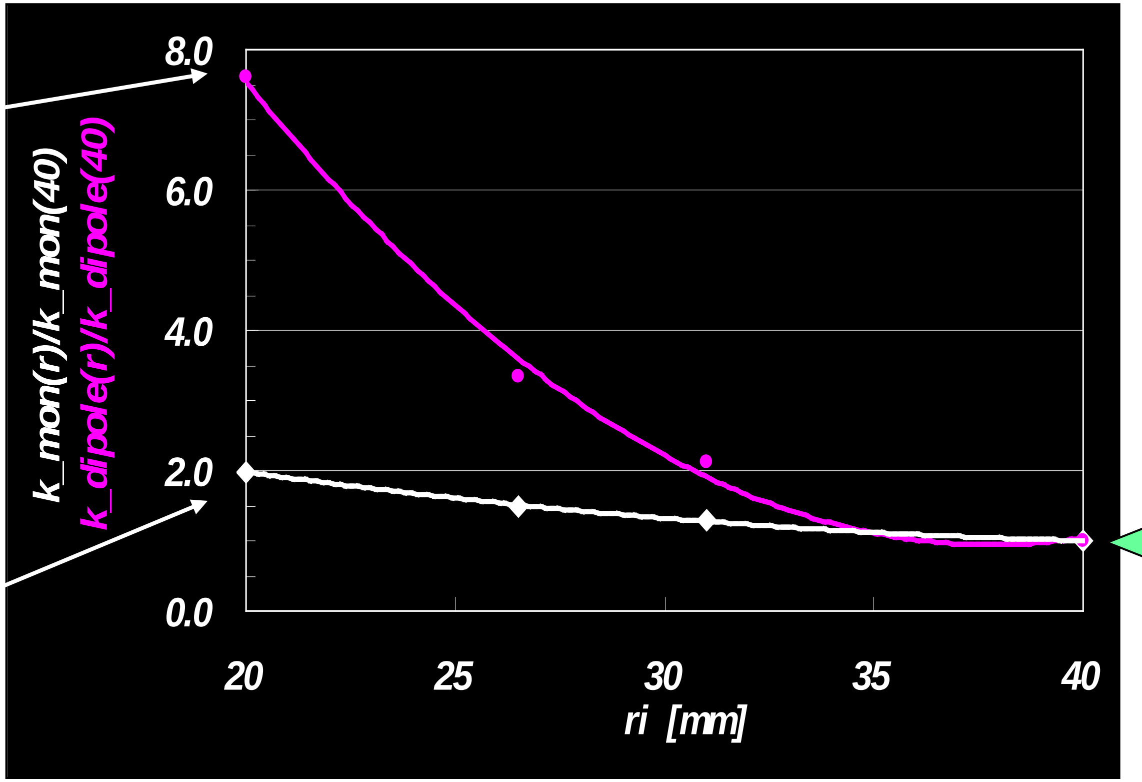
- HOMs impedances $k_{\perp}$ and $k_{\parallel}$ higher
- cell-to-cell coupling k_{cc} weaker

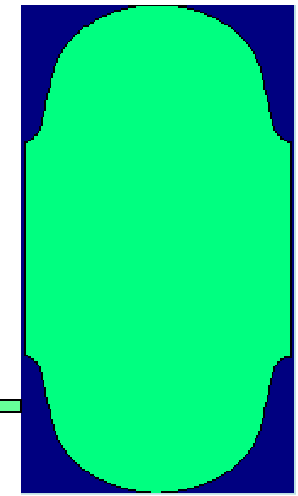
} (-)

3. Criteria for Cavity Design: accelerating cells

HOMs loss factors ($k_{\perp}$, $k_{\parallel}$)







(R/Q) = 152 Ω

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

E_{peak} / E_{acc} = 1.9

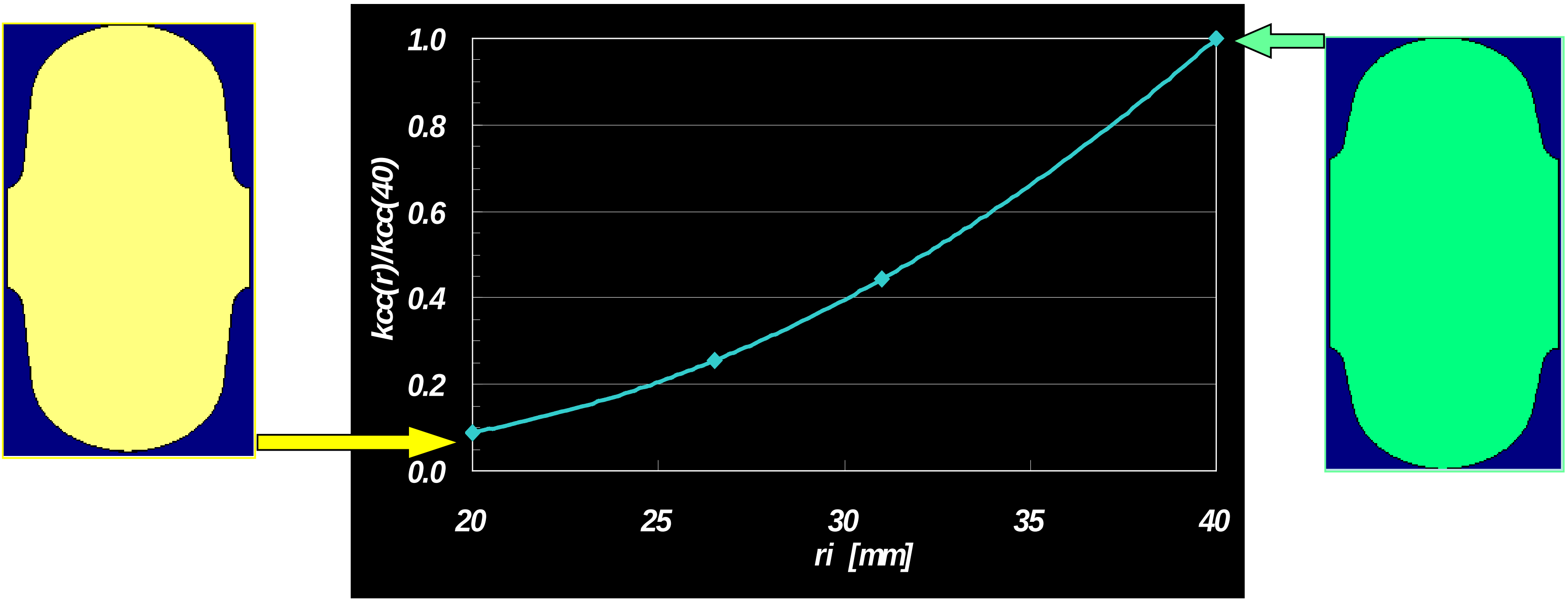
(R/Q) = 86 Ω

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

E_{peak} / E_{acc} = 3.2

3. Criteria for Cavity Design: accelerating cells

Cell-to-cell coupling, k_{cc}



$(R/Q) = 152\ \Omega$

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

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

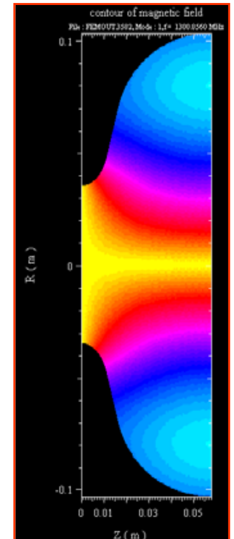
$(R/Q) = 86\ \Omega$

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

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

Frequency of the accelerating mode

x 2 =



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

f_π	[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: accelerating cells

From the formula, we learned before, one obtains:

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

Higher f_π would be a good choice to minimize 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 $R_s(f) \sim (f)^{1/2}$.

For superconductors, like Nb:

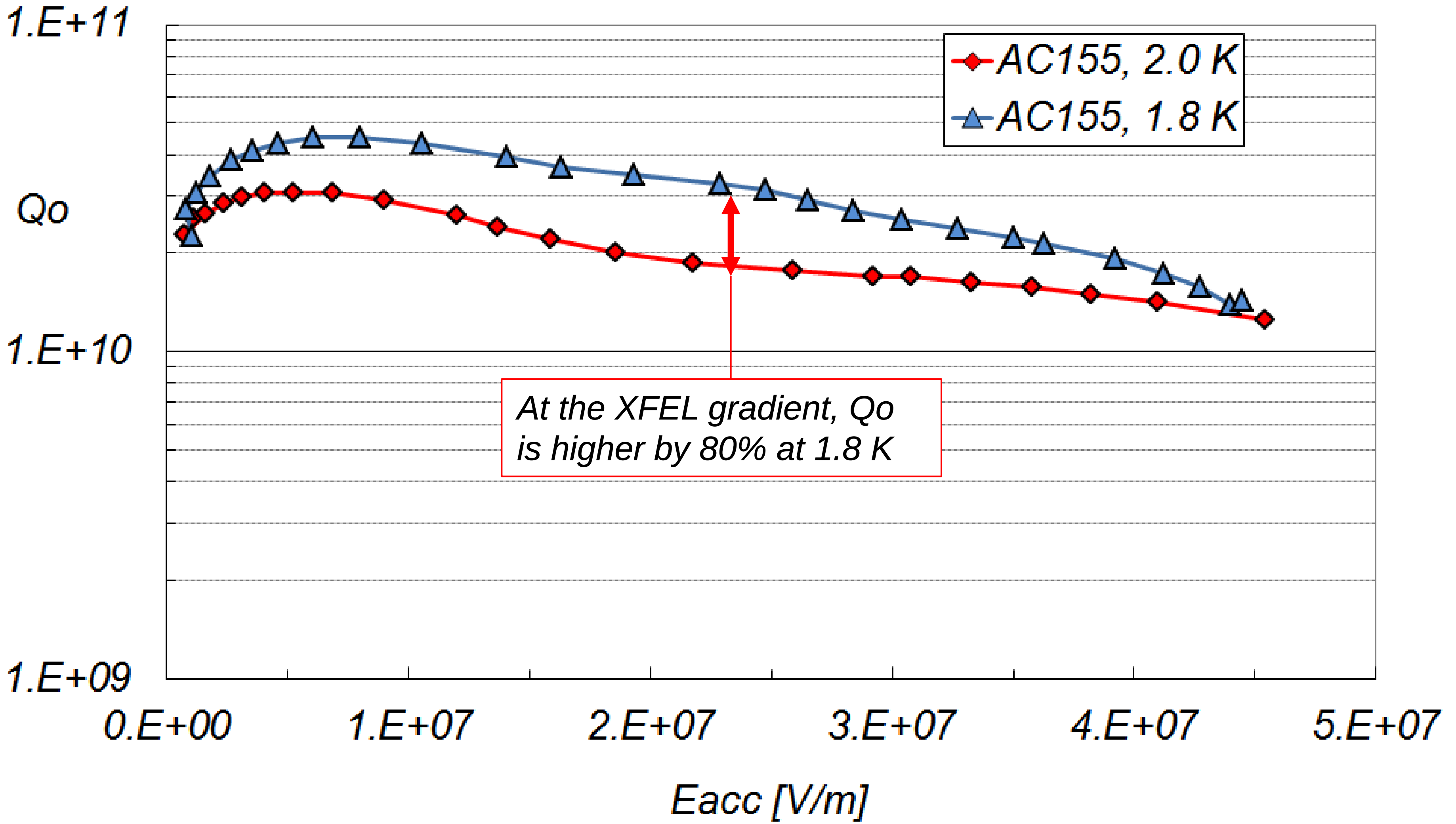
$$R_s(f) = R_{res} + R_{BCS} = R_{res} + 0.0002 \cdot \frac{1}{T} \cdot \left(\frac{f[GHz]}{1.5}\right)^2 \cdot exp\left(-\frac{17.67}{T}\right)$$

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

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

3. Criteria for Cavity Design: accelerating cells

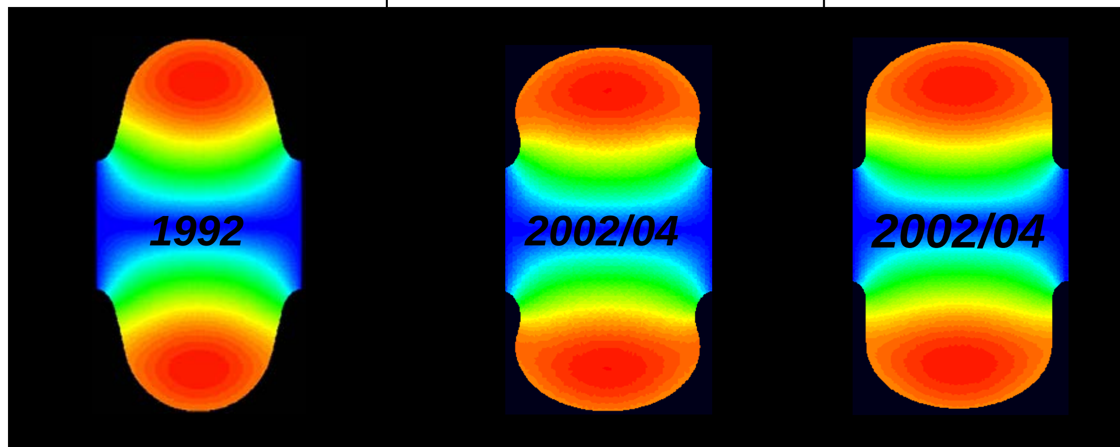
The operation temperature plays a role, especially for high purity Nb:



Examples of inner cells

		CEBAF Original Cornell ß=1	CEBAF -12 Low Loss ß=1	TESLA ß=1	RHIC Cooler ß=1
f_π	[MHz]	1497.0	1497.0	1300.0	703.7
k_{cc}	[%]	3.29	1.49	1.9	2.94
E_{peak}/E_{acc}	-	2.56	2.17	1.98	1.98
B_{peak}/E_{acc}	[mT/(MV/m)]	4.56	3.74	4.15	5.78
R/Q	[Ω]	96.5	128.8	113.8	80.2
G	[Ω]	273.8	280	271	225
R/Q*G	[Ω*Ω]	26421	36064	30840	18045
$k_\perp$ (σ_z=1mm)	[V/pC/cm²]	0.22	0.53	0.23	0.02
$k_\parallel$ (σ_z=1mm)	[V/pC]	1.36	1.71	1.46	0.85

Evolution of inner cells proposed for ILC



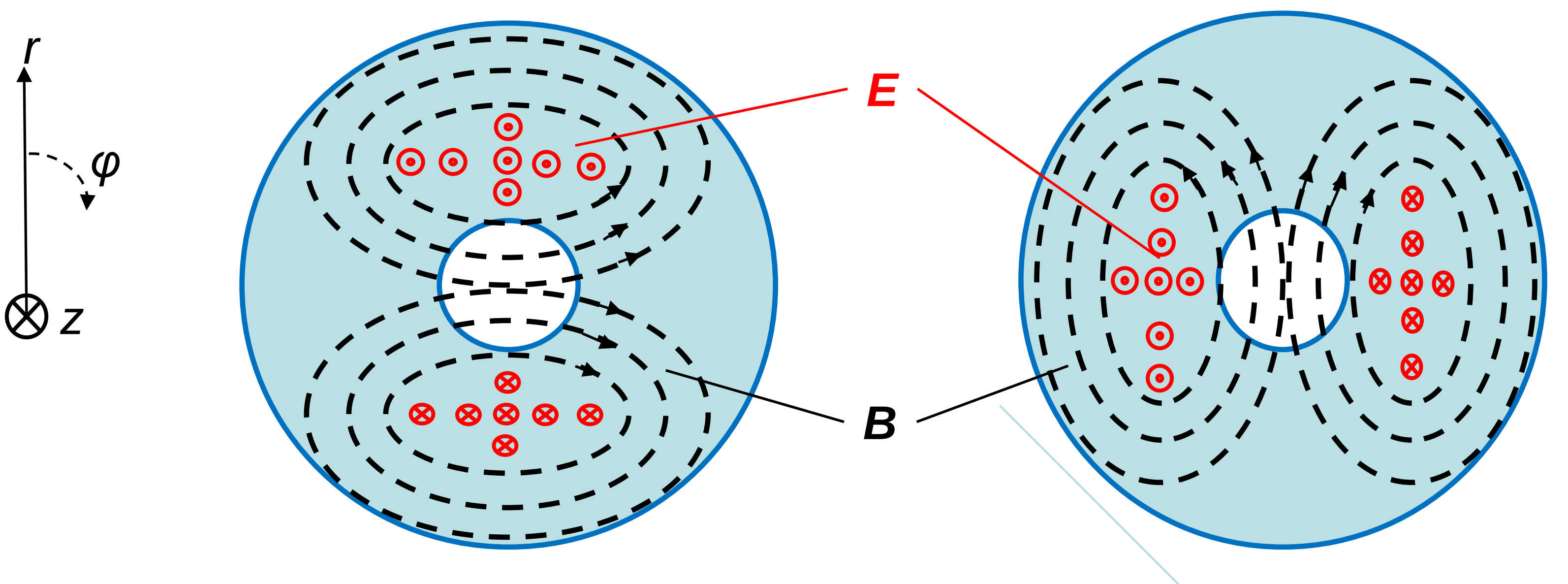
		TESLA optimized E_{peak}/E_{acc}	Re-entrant optimized B_{peak}/E_{acc}	LL optimized B_{peak}/E_{acc}
r_i	[mm]	35	30	30
k_{cc}	[%]	1.9	1.56	1.52
E_{peak}/E_{acc}	-	1.98	2.30	2.36
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.57	3.61
R/Q	[Ω]	113.8	135	133.7
G	[Ω]	271	284.3	284
R/Q*G	[Ω*Ω]	30840	38380	37970
$k_{\perp}$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

3. Criteria for Cavity Design: deflecting cells

As already mentioned deflecting (crab) TM cavities operate in TM_{110}-like dipole mode.

For cylindrical (or close to cylindrical) symmetry, all non-monopole modes; dipoles quadrupoles … are split in two polarizations (two modes shifted by 90°).

TM110 dipole

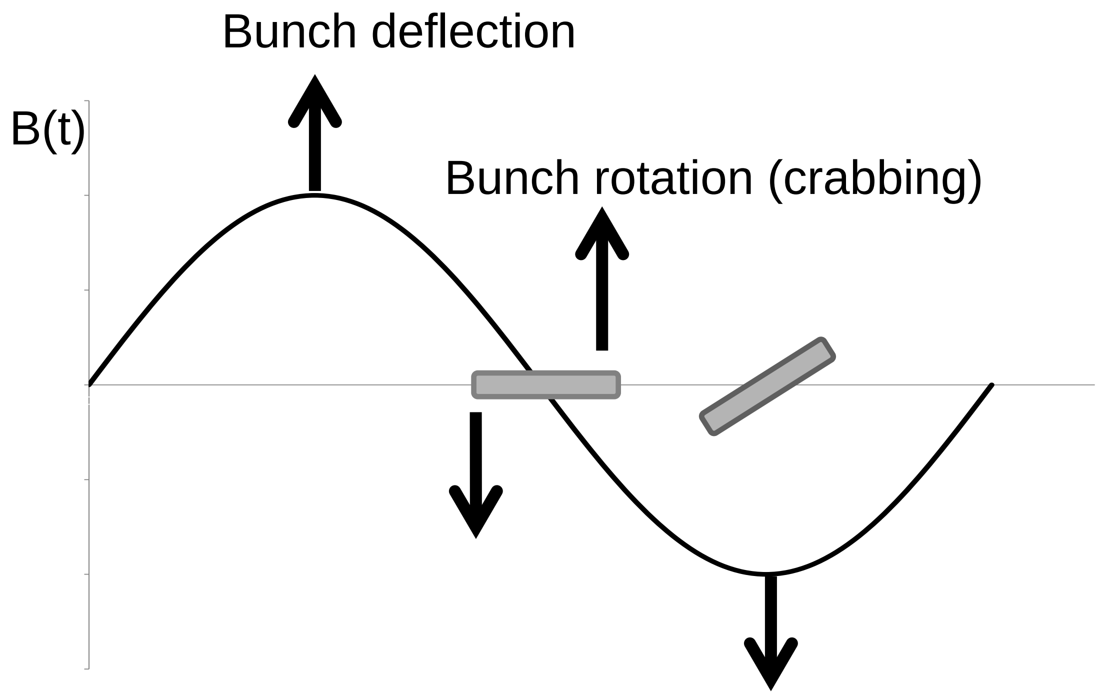


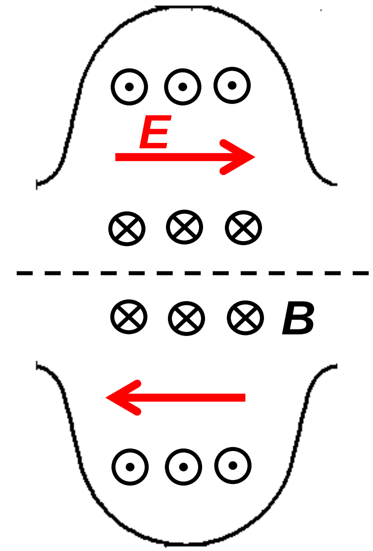
For a cavity having perfect cylindrical symmetry polarizations have the same frequency.

For a cavity having perturbed cylindrical symmetry the frequencies differ, more for more deformed shapes.

3. Criteria for Cavity Design: deflecting cells

Bunch rotation (crabbing) and/or deflection



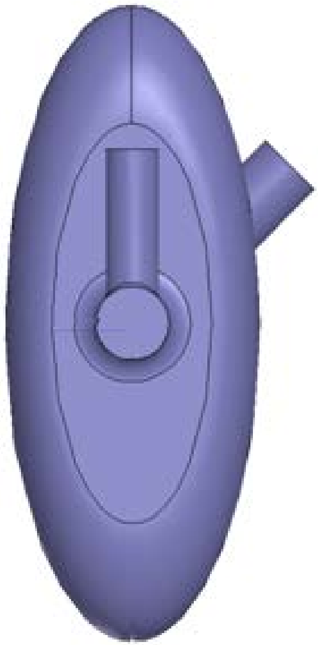


For a crab cavity additional criteria need to be taken into account:

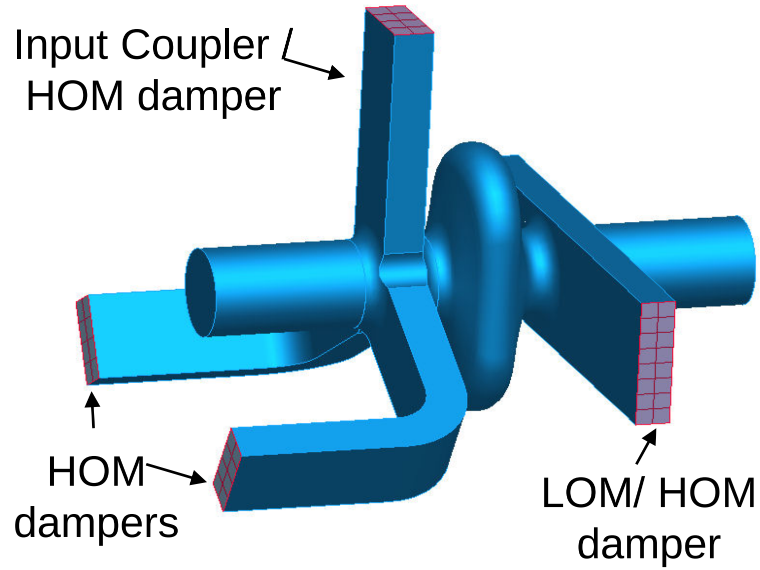
1. Angular position of the deflecting mode must be fixed.
2. Frequency of the second polarization must be apart from the deflecting frequency.
3. Lower-, Same- and Higher order modes must be well damped.

3. Criteria for Cavity Design: deflecting cells

Both fixing position of the deflecting mode and frequency difference is often achieved by per purpose deformation of cells.



800 MHz CC for LHC
L. Ficcadenti, J. Tuckmantel et al.

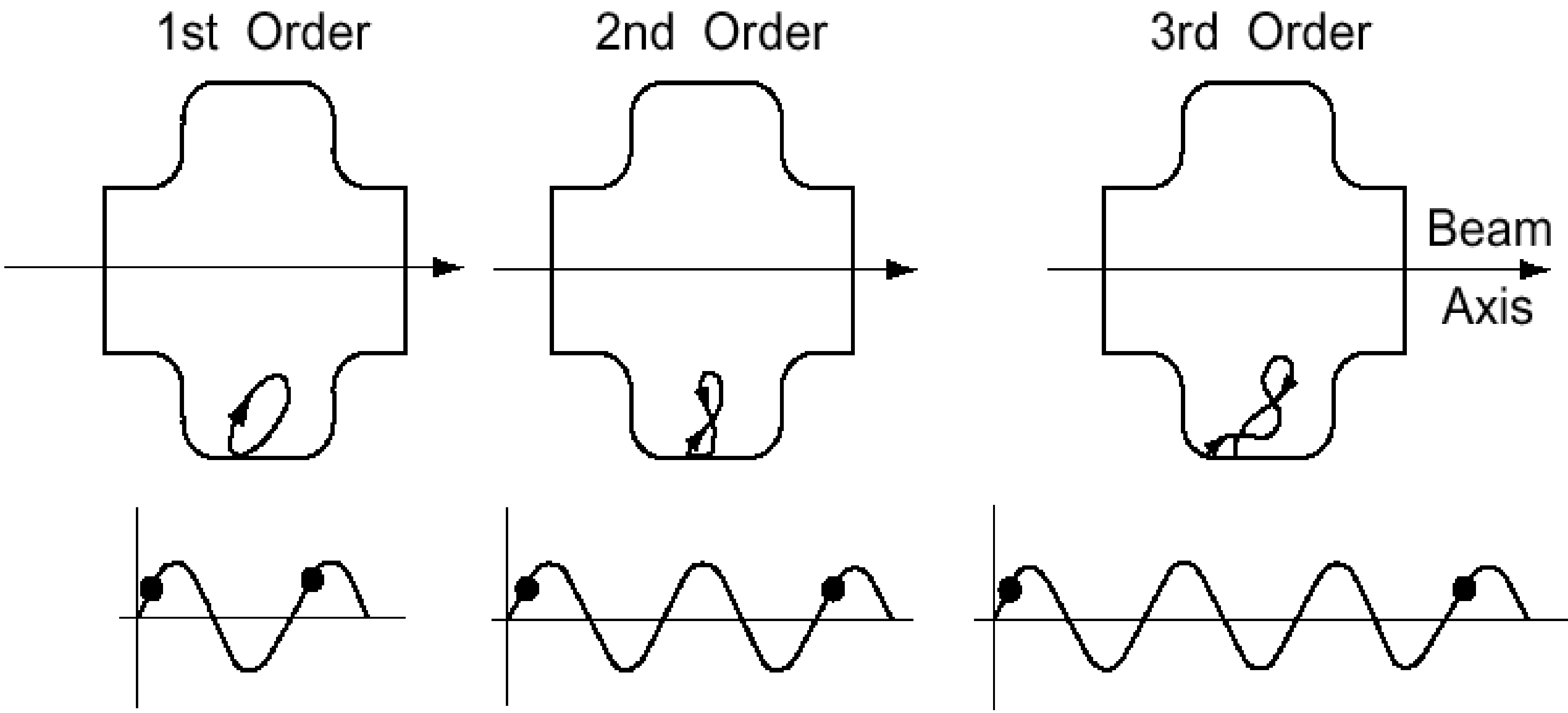


2.8 GHz CC for APS
H. Wang/A. Nassiri et al. ANL/JLab/LBL

As we can see, the LOM, SOM and HOM damping is rather demanding for C-cavities

Multipacting

It is a phenomenon of resonant electron emission and multiplication.

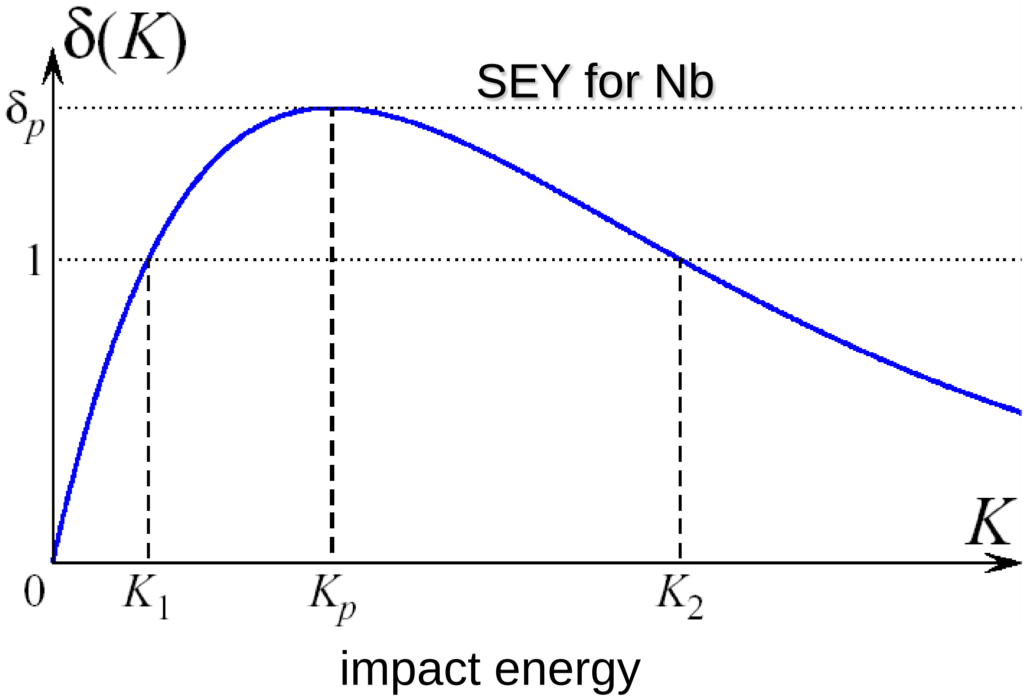


Curtsey W. Hartung

Impacting electron might create more than one secondary electron. This depends on the impact energy *K* and secondary emission yield *δ(K)* .

3. Criteria for Cavity Design

SEY is function of the impact energy *K* and depends on the surface cleanness.



Condition	K_1	K_2
high SEY	$\sim$ 27 eV	$\gtrsim$ 2000 eV
typical SEY	$\sim$ 40 eV	$\sim$ 1000 eV
low SEY	$\sim$ 150 eV	$\sim$ 750 eV

When happens, multipacting is barrier in rising the accelerating field in cavities and usually leads to quench.

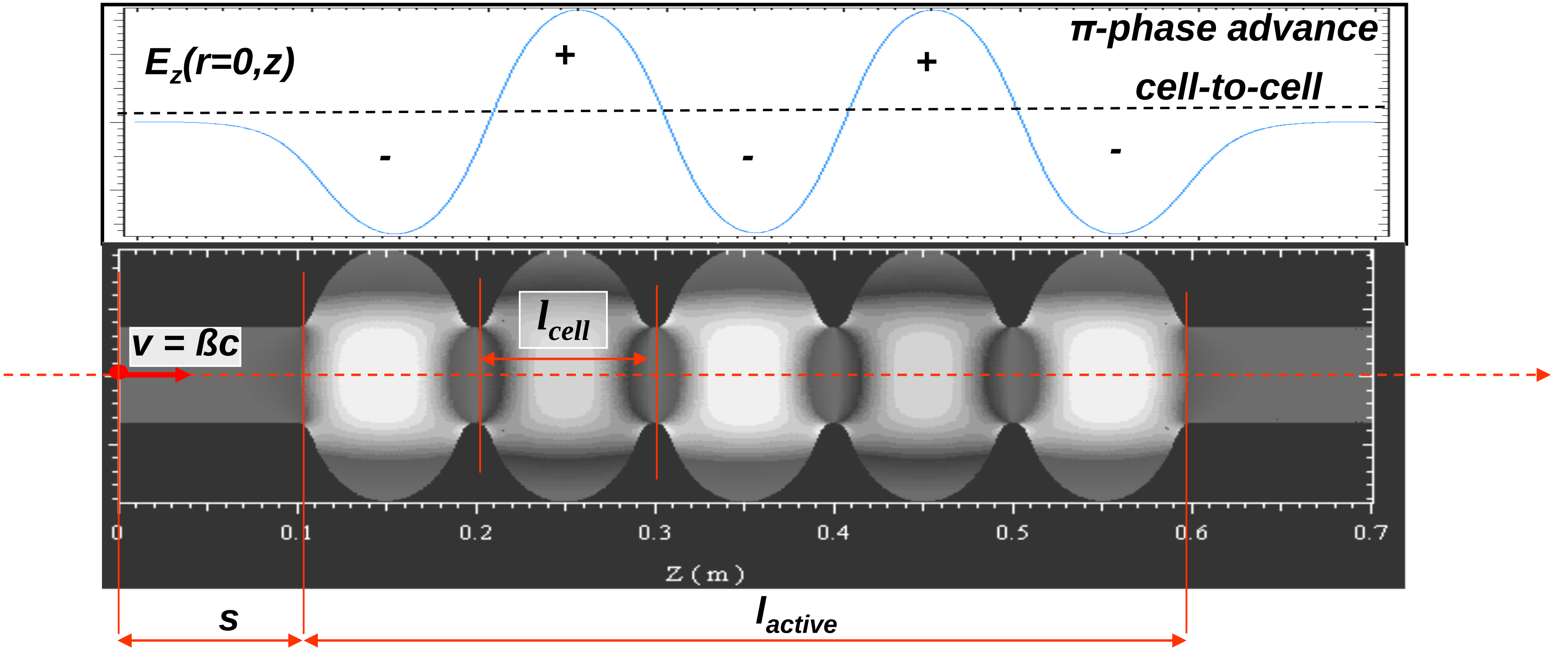
In the design process we need to prove whether or not the shape of cell allows for multipacting.

4. Multi-cell Structures and Weakly Coupled Structures

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

- Cost of accelerators is lower (less auxiliaries: LHe vessels, tuners, fundamental power couplers, control electronics………)
- Higher real-estate gradient (better fill factor)
- Field flatness vs. N
- HOM excitation and trapping vs. N
- Power capability of fundamental power couplers vs. N
- Surface cleaning procedures become more complicated
- The worst performing cell limits whole multi-cell structure

Accelerating mode in multi-cell structures



Synchronic acceleration of relativistic particles in a multi-cell structure takes place 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.

Field flatness in 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*	*Low Loss N =9*	*RHIC N=5*
year	*1982*	*2001*	*2002*	*1992*	*2000*	*2000*	*2003*	*2003*
a_{ff}	*1489*	*2592*	*3288*	*4091*	*3883*	*2924*	*5435*	*850*

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

Decades of experience with: heat and chemical treatment, handling and assembly allow to maintain good field profile, even in cavities with bigger *N* and weaker k_{cc}.

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

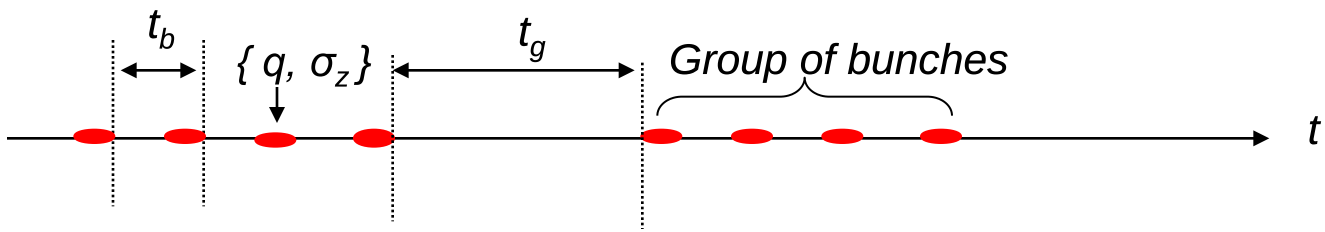
HOM excitation and HOM trapping in multi-cell structures

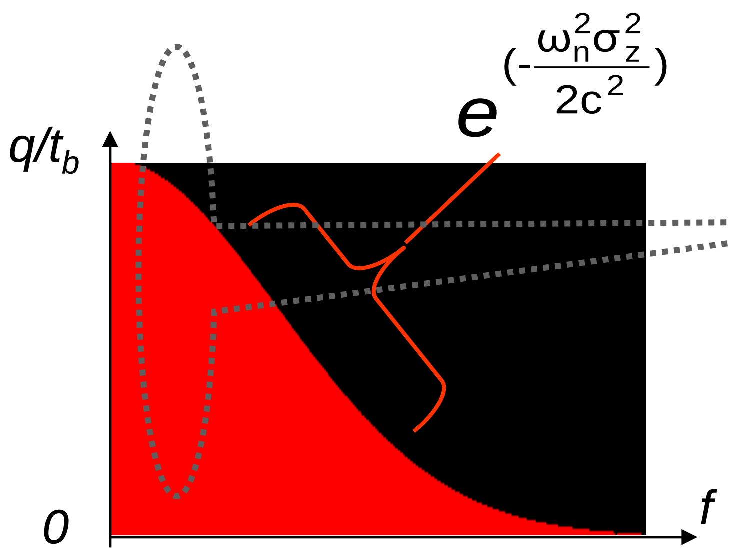
HOM excitation causes:

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

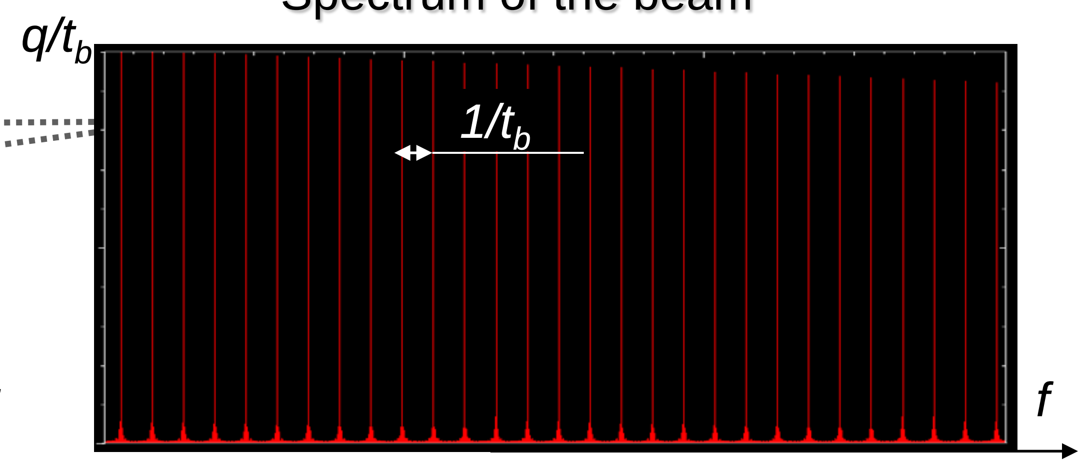
HOM excitation:

Time structure of the beam

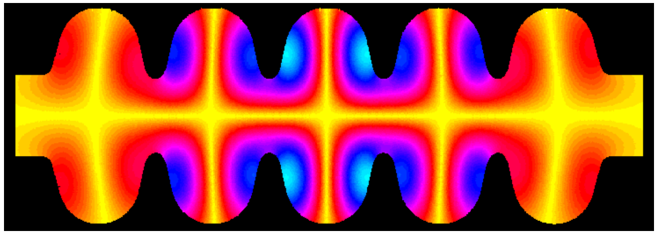


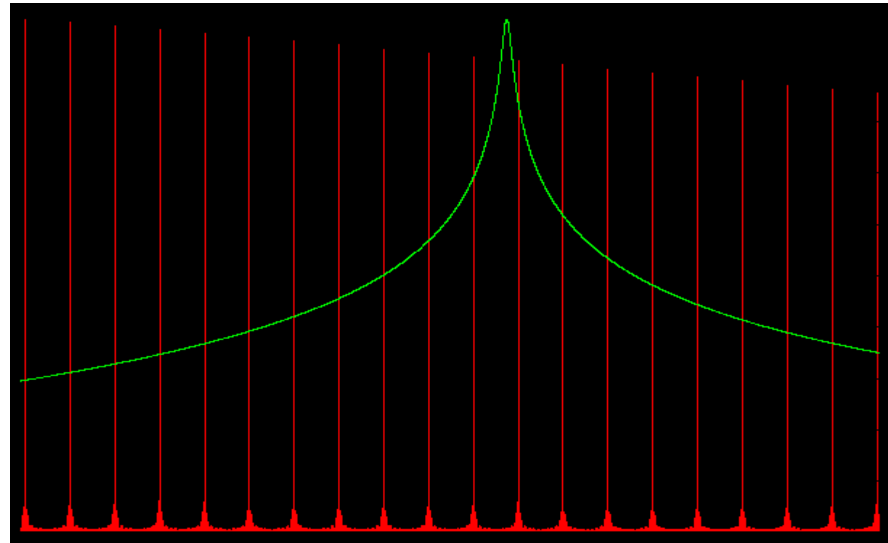


Spectrum of the beam



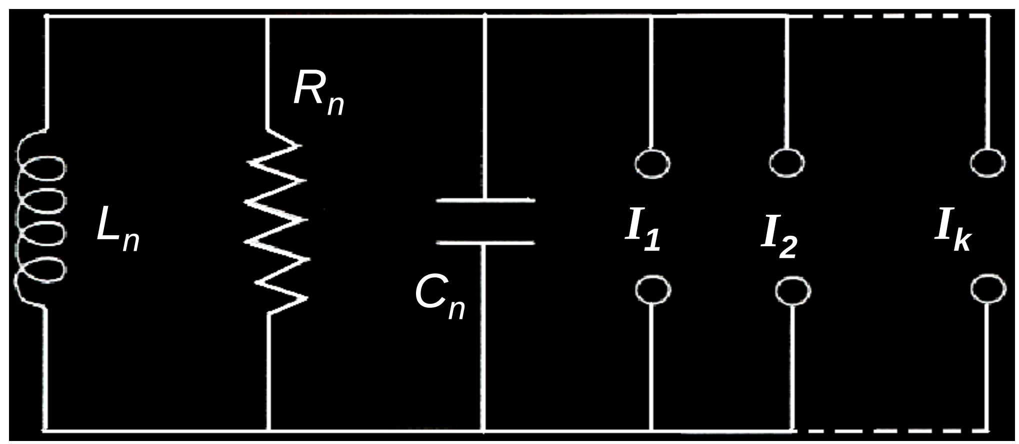
Mode No. *n* : $\{ \omega_n, (R/Q)_n, Q_{L,n} \}$





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

Impedance of the *n*-mode



Multi-source excitation

4. Multi-cell Structures and Weakly Coupled Structures

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

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

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

where:

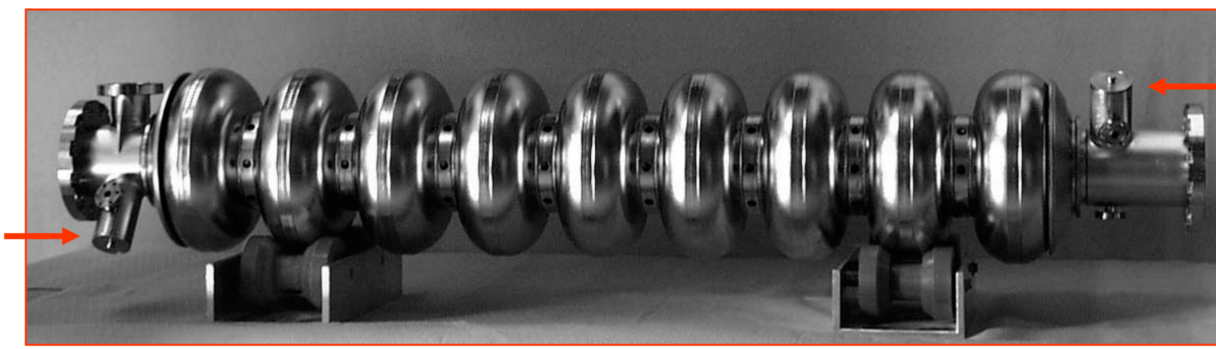
$$\frac{1}{Q_{L,n}} = \frac{1}{Q_{0,n}} + \frac{1}{Q_{ext,n}}$$

← Measure of the extracted power

The HOM couplers, devices extracting the energy from parasitic modes, are attached to cavities for mitigation of high and harmful *E-M* fields of HOM .

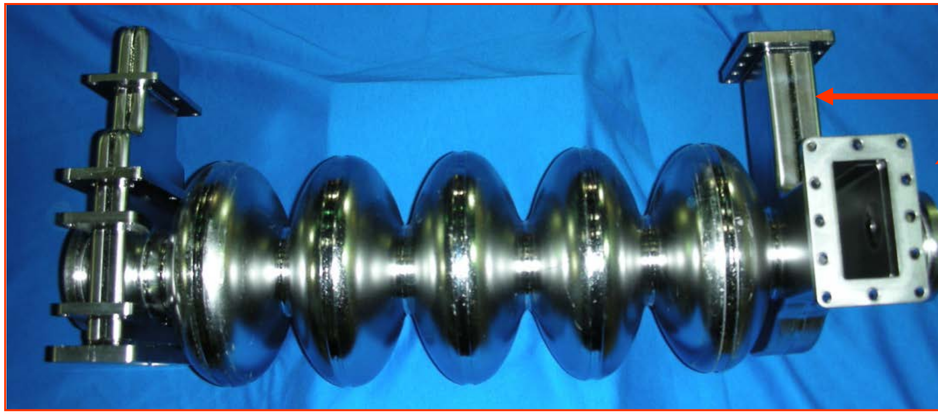
The experience is that, the HOM couplers can be attached to the beam tubes and must not be located at cells because this leads to the performance degradation.

Coaxial HOM coupler



Coaxial HOM coupler

4. Multi-cell Structures and Weakly Coupled Structures

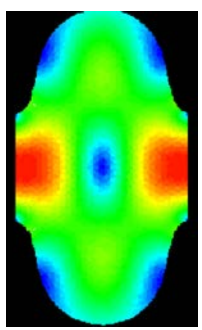


Waveguide HOM ports

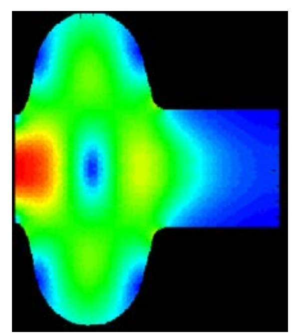
The HOM trapping is similar to the FM field profile unflatness mechanism:

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

f = 2385 MHz



That is why they hardly resonate together



f = 2415 MHz

4. Multi-cell Structures and Weakly Coupled Structures

Example of the trapping and how *N* influences strength of the *E-H* fields at the HOM couplers locations

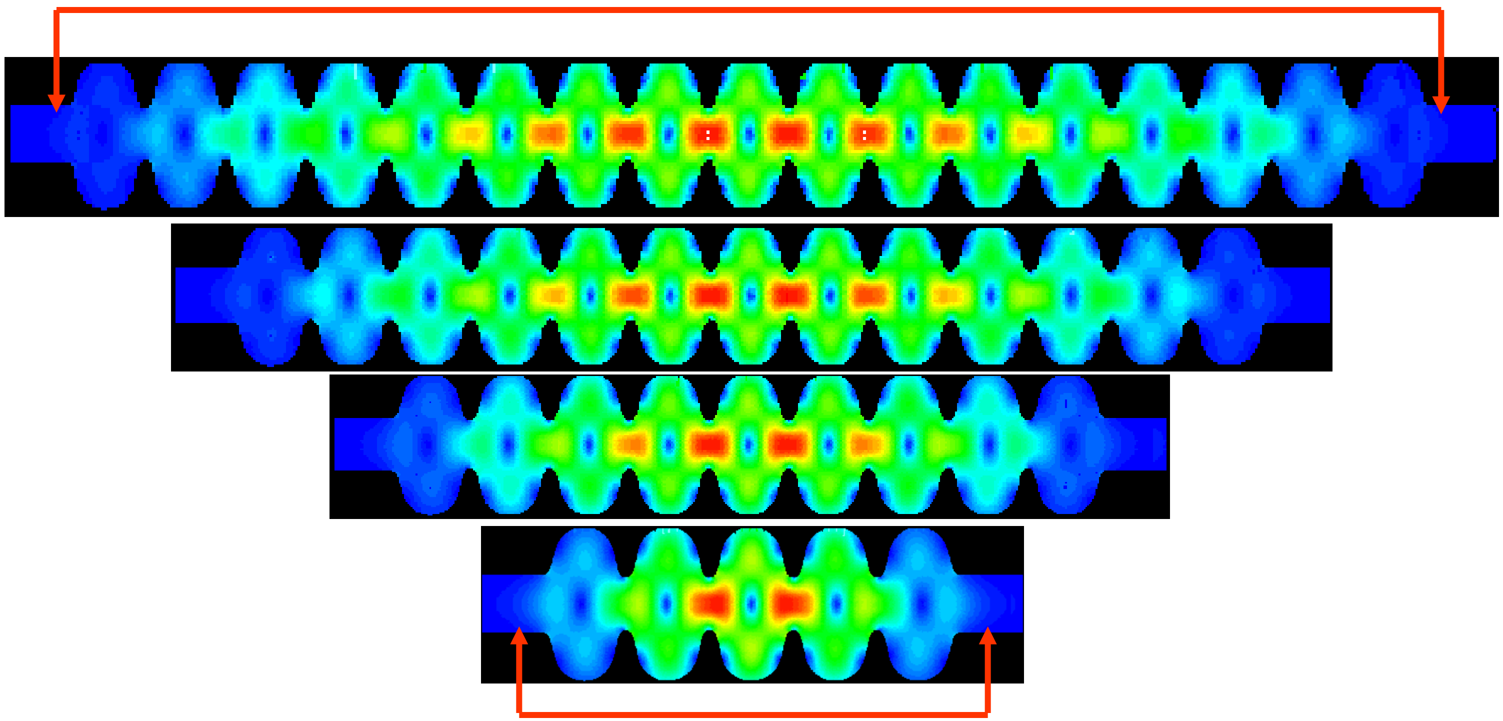
no *E-H* fields at HOM couplers locations (trapping), which are always placed at the end beam tubes

N = 17

N = 13

N = 9

N = 5



E-H fields at HOM couplers locations

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

What else can help 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 must enable matching of Qext of FPC
- field strength of the dangerous HOMs must ensure required damping.

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

4. Multi-cell Structures and Weakly Coupled Structures

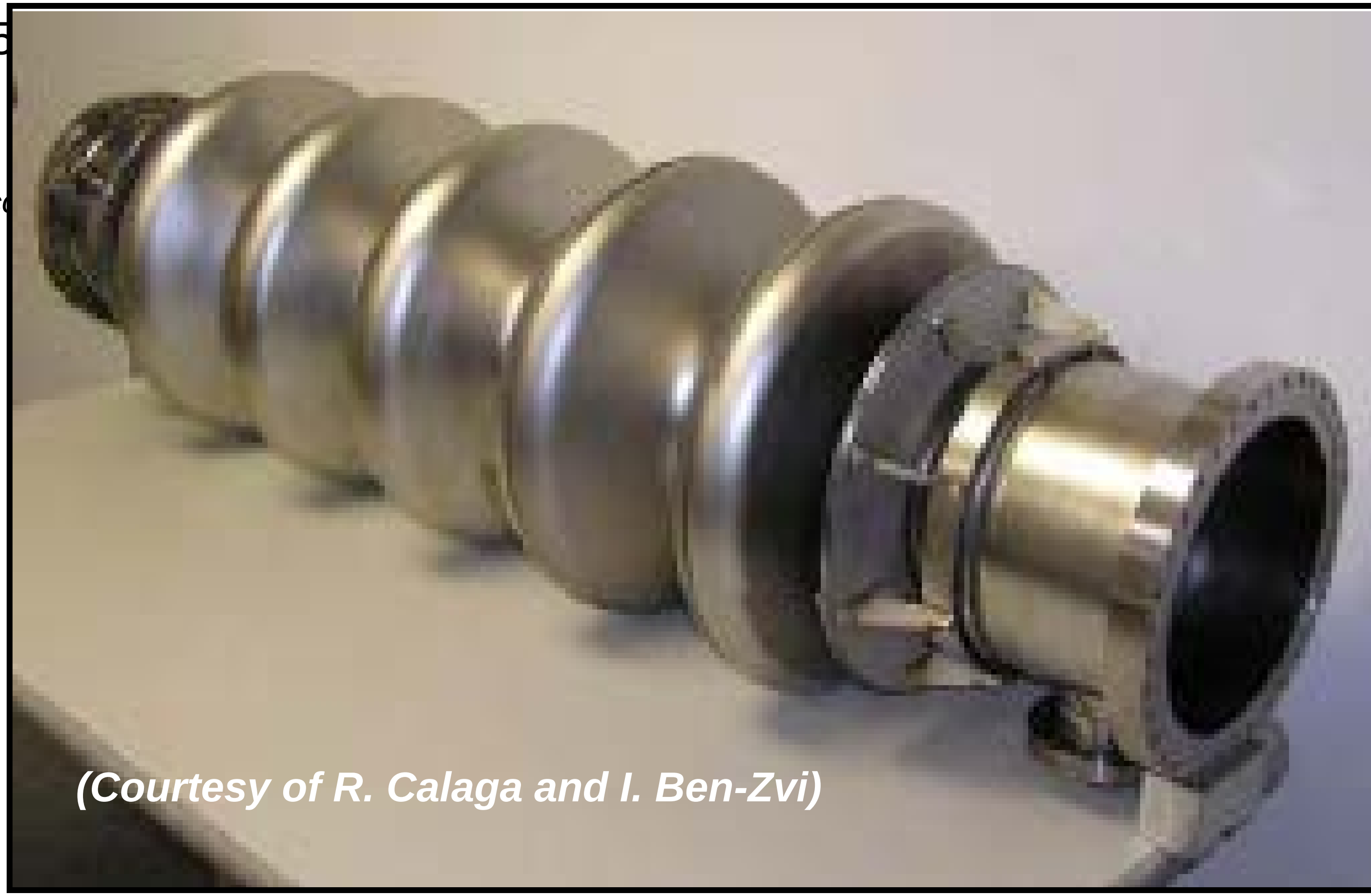
1. Open irises of the inner- and end-cells (bigger $k_{cc,HOM}$) and shaping them similarly.

Example: RHIC 5

Monopole mode k_{c}

f_{HOM} = 1394 MHz

f_{HOM} = 1403 MHz



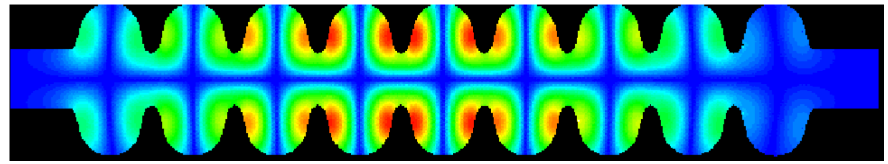
(Courtesy of R. Calaga and I. Ben-Zvi)

The method causes (R/Q) reduction of fundamental mode, which in this application is less relevant.

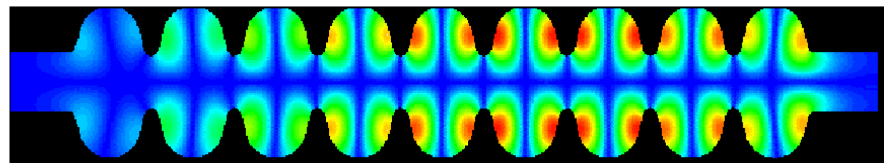
2. Tailoring the end-cells to equalize HOM frequencies of the inner- and end-cells.

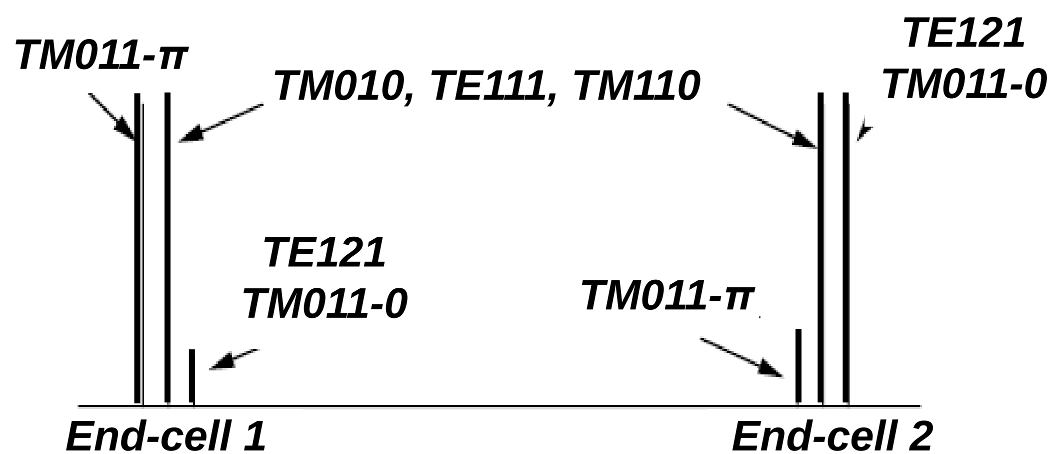
Example: TESLA 9-cell cavity, which has two different end-cells (asymmetric cavity)

The lowest mode in the passband
f_{HOM} = 2382 MHz ***TM011-π***



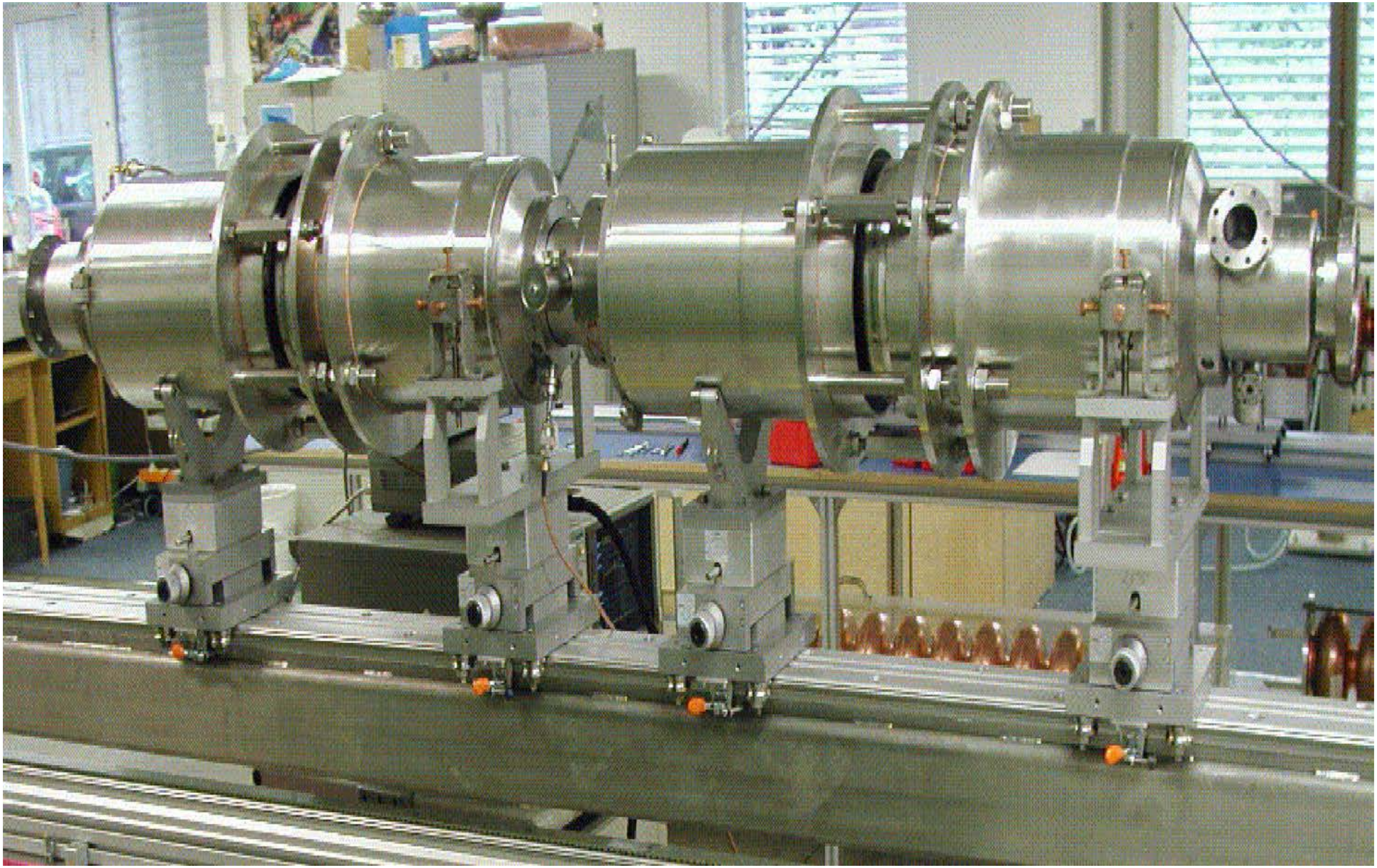
The highest mode in the passband
f_{HOM} = 2458 MHz ***TM011-0***





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

4. Multi-cell Structures and Weakly Coupled Structures



Power capability of the FPC for multi-cell structures

When I_{beam} and E_{acc} are specified and for a superconducting multi-cell structure :

$$P_{in} \sim N$$

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

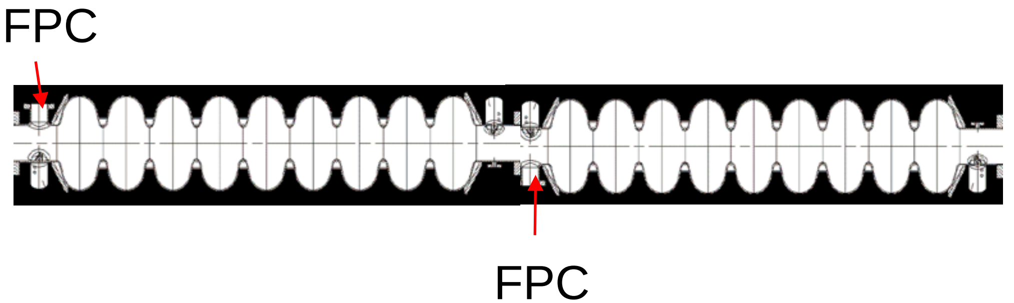
$$\int_{s_{inputport}} E_{acc} \times H_{acc} ds$$

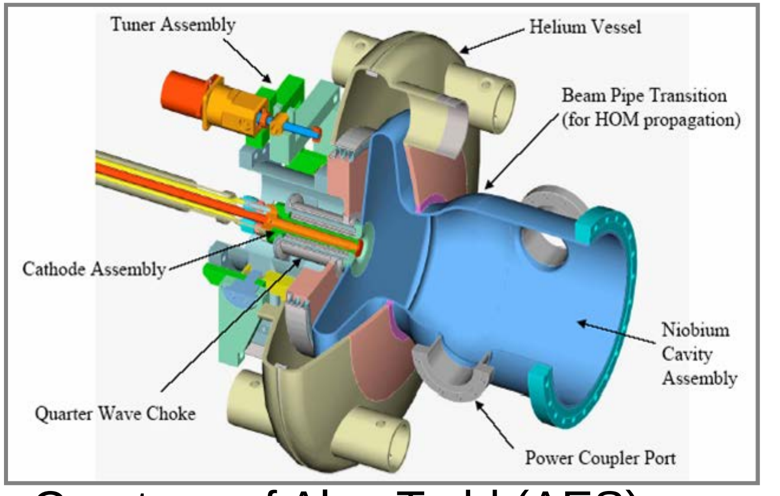
Coupler must penetrate deeper in the beam tube or/and is placed closer to the end cell

Opening for the coupler must be bigger

Each method causes perturbation of the symmetry and increases kick to the beam.

The remedies are: alternating positions of couplers or double couplers





Courtesy of Alan Todd (AES)

Surface cleaning procedures are more complicated

Few words on Nb and on the surface preparation procedures

All high gradient cavities are made of the pure metallic bulk Nb (II-type sc, *Tc* = 9.2 K):

- We use poly-crystal Nb from the very beginning.
- Recently, as proposed by P. Kneisel (JLab) we use also large-grain Nb.

Surface preparation has several steps with three major procedures:

- Chemical treatment: can be Buffered Chemical Polishing or Electro-Polishing
- Heat treatment
- High Pressure Water rinsing

Buffered Chemical Polishing (BCP)

Acids: HF (49%), HNO_3 (65%), H_3PO_4 (85%)

Mixture: 1:1:1 or 1:1:2 by volume

Electro-Polishing (EP)

Electrolyte:

1 part HF(49%), 9 parts H_2SO_4 (96%)

Al-cathode, Nb-anode, J~ 50 mA/cm^2

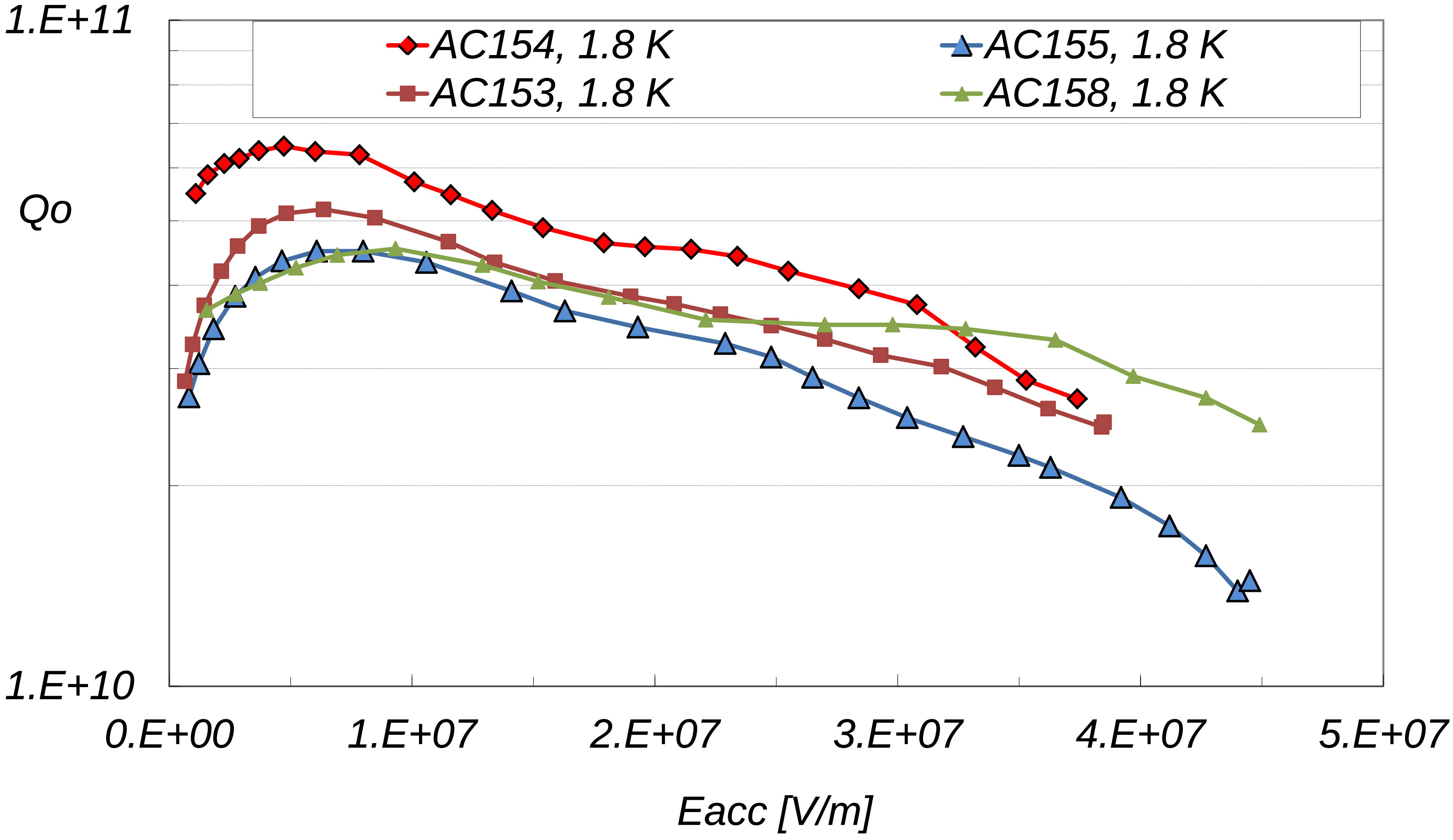
4. Multi-cell Structures and Weakly Coupled Structures

The sequence in the surface preparation is:

- Heavy chemical etch (EP or BCP)
  - Removal of damaged surface layer (100-150um) caused by fabrication and handling
- Removal of surface contamination
  - Ultrasonic cleaning of surface with detergent and DI water, or Alcohol rinse
- Heat treatment (600-800C in vacuum furnace)
  - Removes hydrogen from the bulk niobium to reduce the risk of Q-disease
- RF tuning and mechanical inspection
  - Field profile, calibration of test probes, check mechanical structure
- Removal of surface contamination
  - Ultrasonic cleaning of surface with detergent and DI water,
- Light chemical etch (EP or BCP)
  - Remove any risk from damage during handling and furnace contamination
- High pressure rinse (UPW @100 Bar) + Class 10 drying of cavity
  - Reduction of field emission sources, surface particulates
  - At least two passes over entire surface

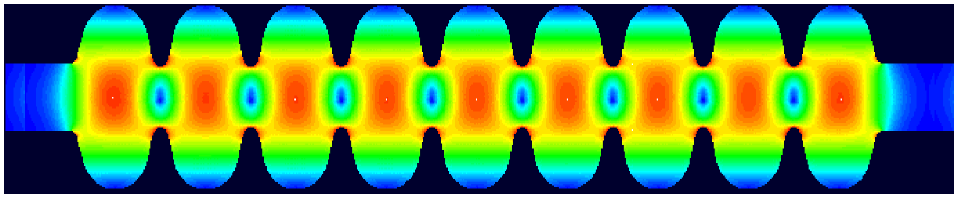
Courtesy J. Mammosser

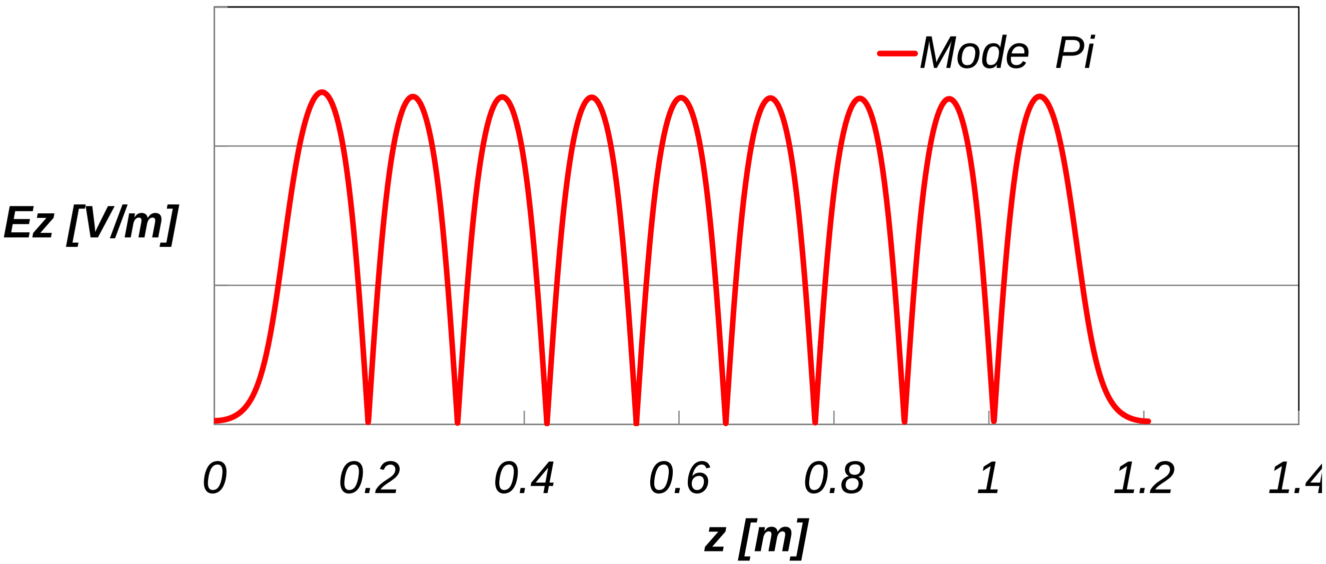
But, when you use Large Grain Nb, make proper cleaning and operate cavities at 1.8K the result can be very nice:



The worst performing cell limits whole multi-cell structure

After the pre-tuning all cells have the same amplitude





We can find out which cell has the worst performance with temperature mapping.

Testing all modes in the FM passband we can find out which pair of cells has the worst performance. For the TESLA cavity the pairs are 1&9, 2&8, 3&7, 4&6. Performance of the cell No 5 can be defined directly.

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

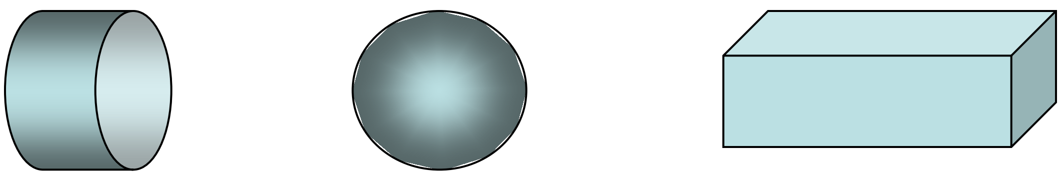
Criterion	Structure	Best parameter	Weakest parameter (point)	Comments
E_{acc}	*HG: 1.5 GHz, N=7* *TESLA: 1.3 GHz, N=9* *ILC-LL: 1.3 GHz, N=9* *ILC-RE 1.3 GHz, N=9*	*Epeak/Eacc= 1.96* *Epeak/Eacc= 1.98* *Bpeak/Eacc= 3.61* *Bpeak/Eacc= 3.57*	*maximum -Eacc* *maximum -Eacc* *Epeak/Eacc* *Epeak/Eacc*	*Designed for I_{beam} < 10 mA, Pulse operation*
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 cavity for $I_{beam} \approx 2$ A*

5. Tools for RF-design

Design of an elliptical cavity is usually 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.
  Also coupling strength for FPC and damping of HOMs can be modeled only in 3D.

Solutions to 2D (or 3D) Helmholtz equation can be found analytically only for very few geometries (pillbox, spherical- and rectangular resonator)



We need numerical methods: $$(\nabla^2 + \omega^2 \varepsilon \mu) A = 0$$

Approximating operator
(Finite Difference Methods)

Approximating function
(Finite Element Methods)

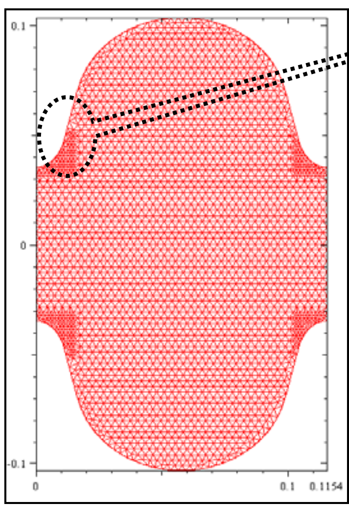
5. Tools for RF-design

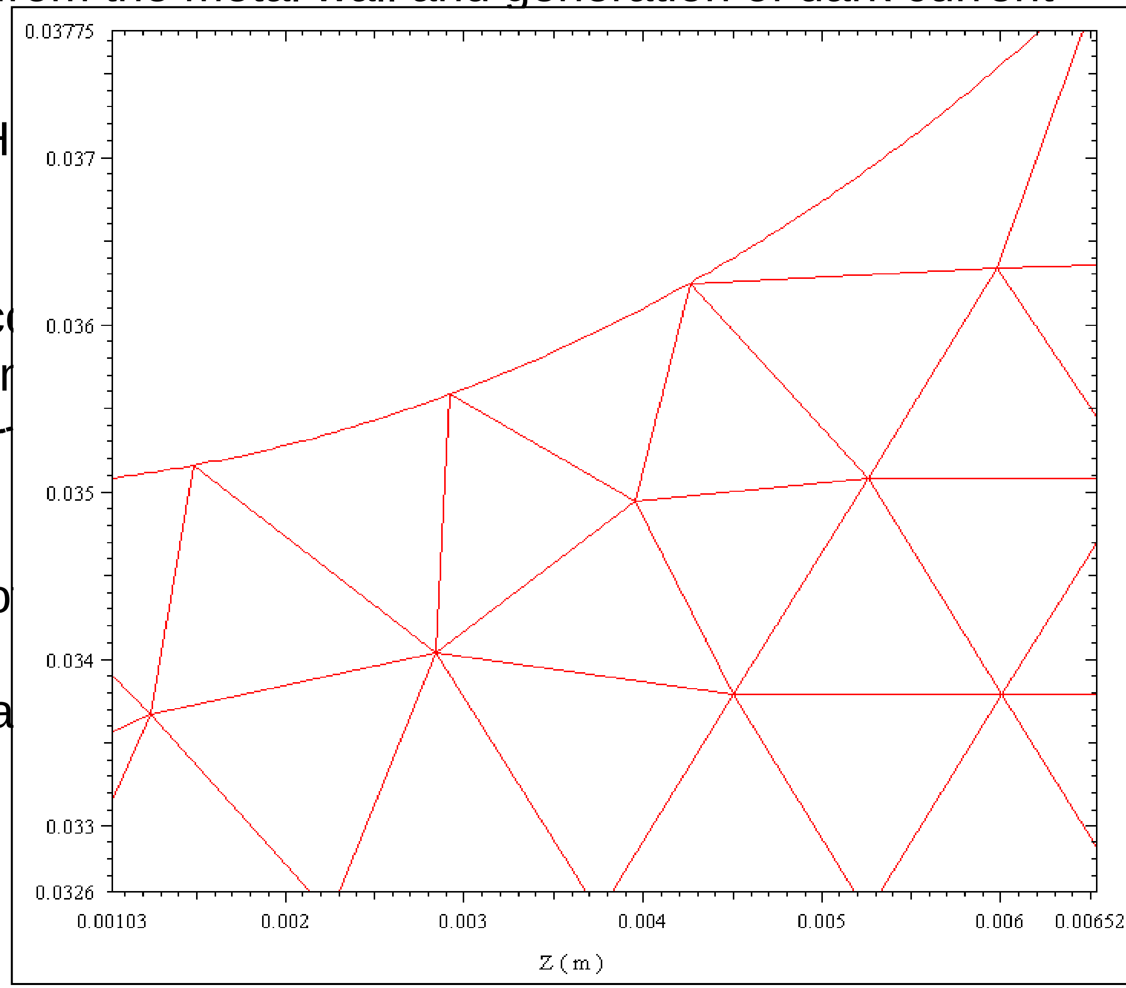
The FEM is superior in mapping of curvilinear boundary. This is essential for modeling of:

- Multipacting
- Electron emission from the metal wall and generation of dark current
- Frequency change … µm)

2D codes like SUPERFISH … ry
approx.) or FEM-code (3rd …

Example from the FEM c… kage
MultiPac by P. Yla-Oijala ar…





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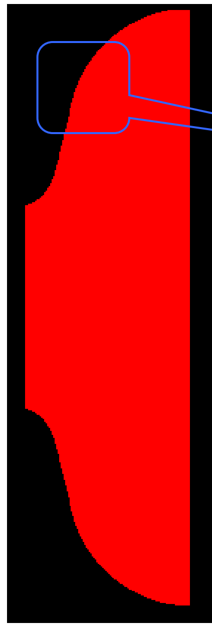
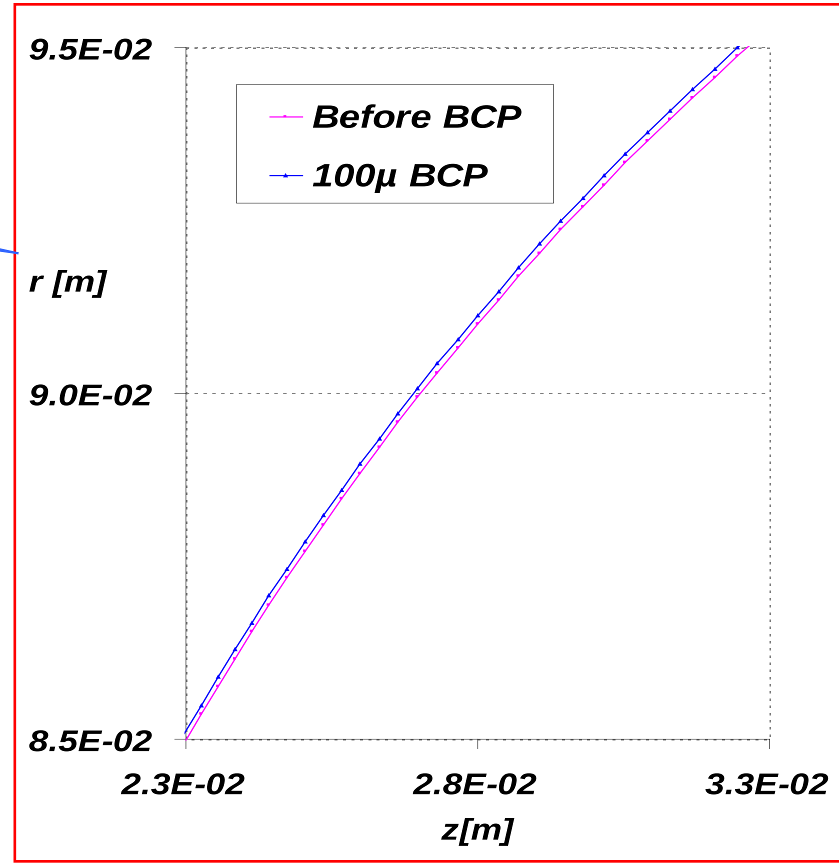
5. Tools for RF-design

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





2D Modeling takes ~2min

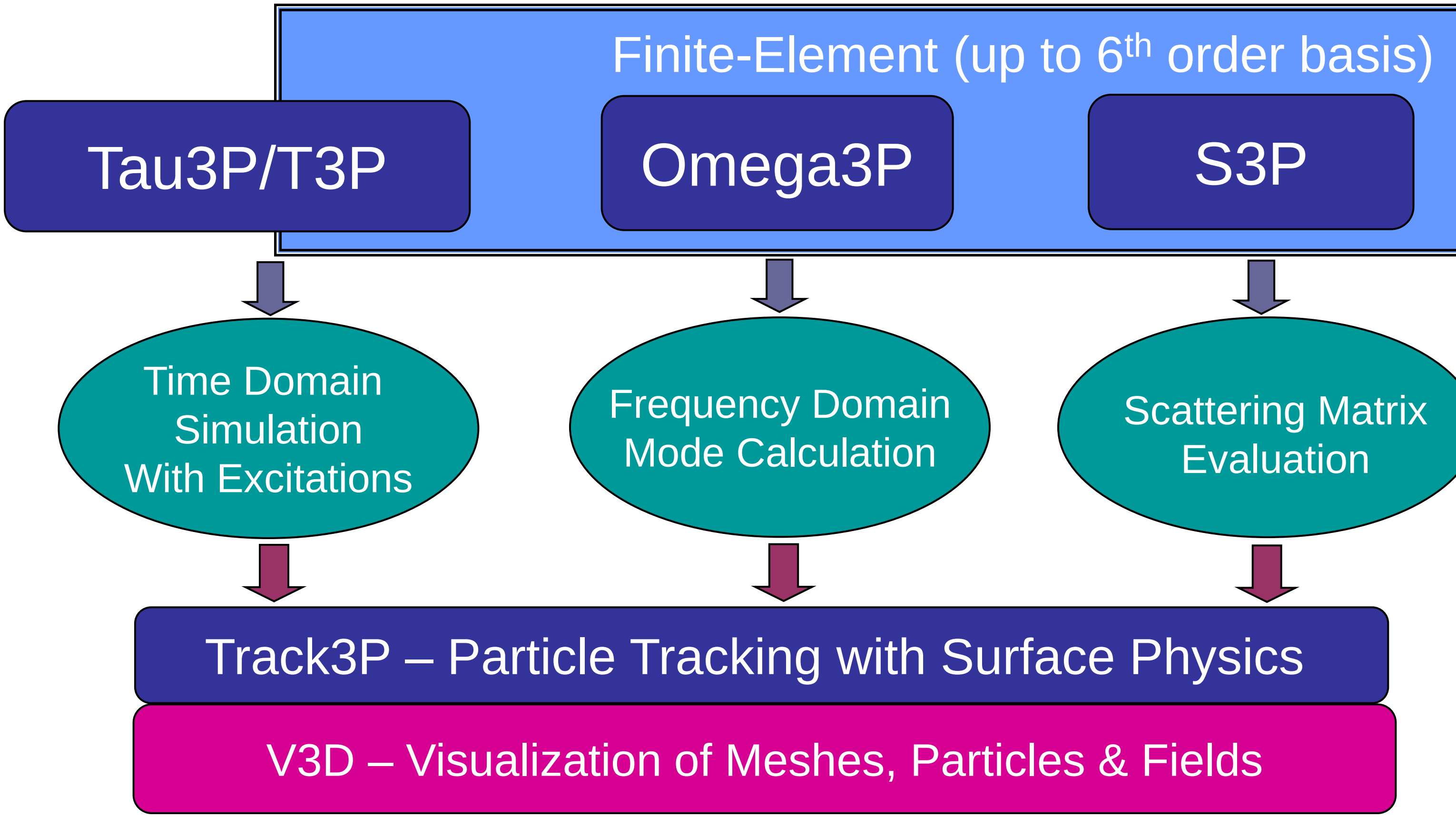
$$\frac{\partial f}{100\,\mu m} = -10kHz\,/\,\mu m$$

which was measured for the uniform removal

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

Electromagnetic Code Development at SLAC by ACD

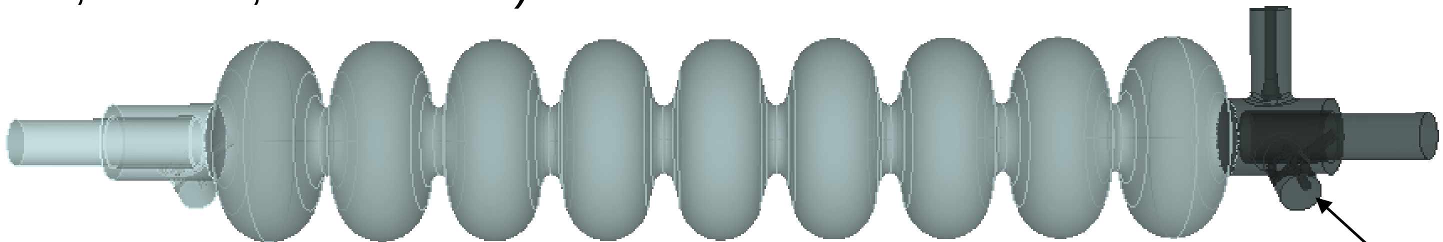
Solves Maxwell's equations with particles in TD & FD

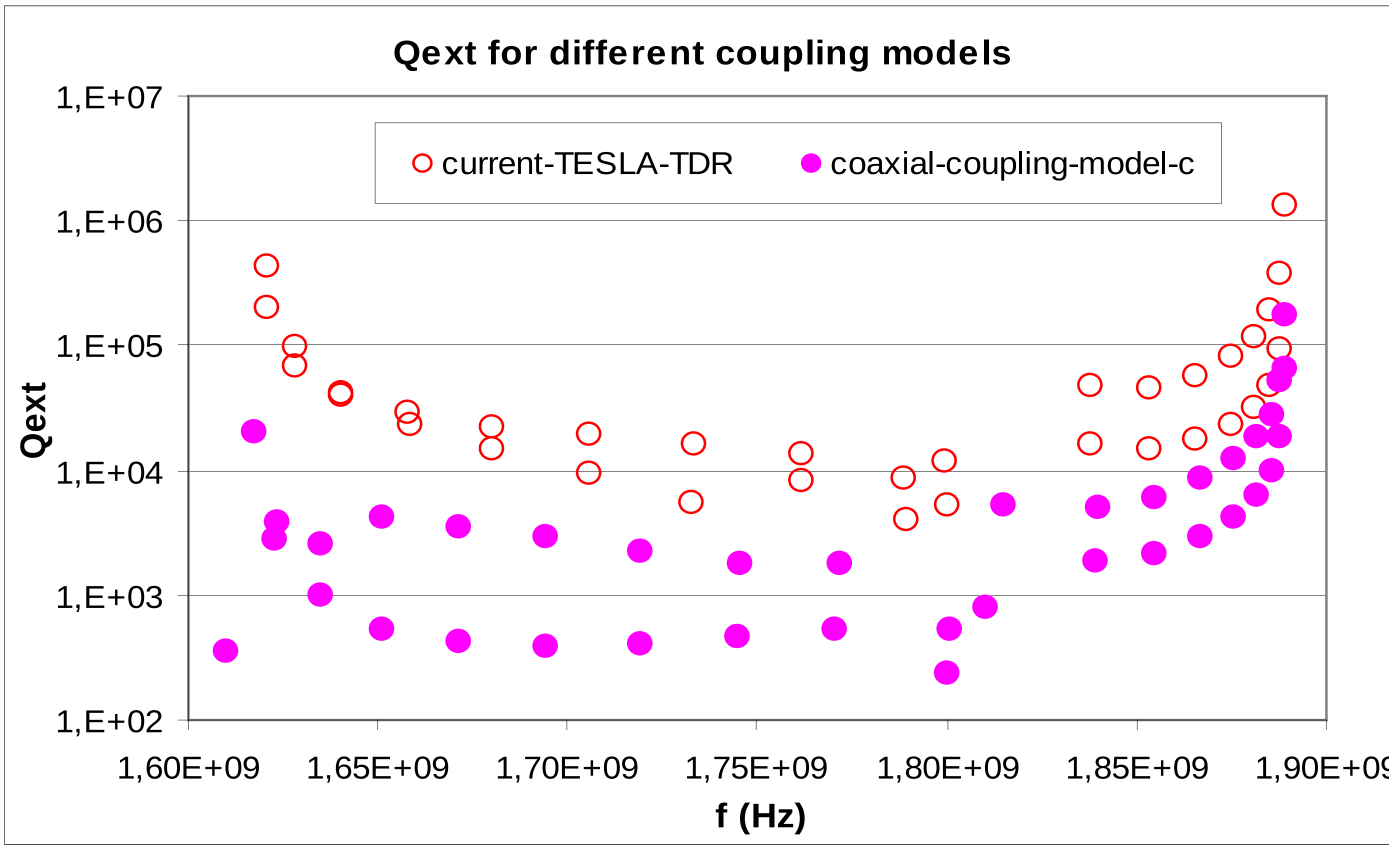


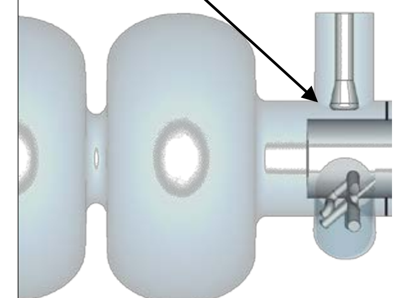
(Courtesy of Kwok Ko and ACD Members)

5. Tools for RF-design

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

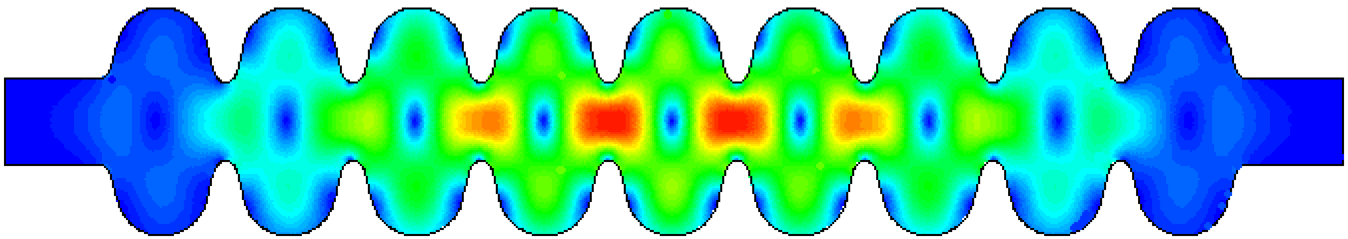


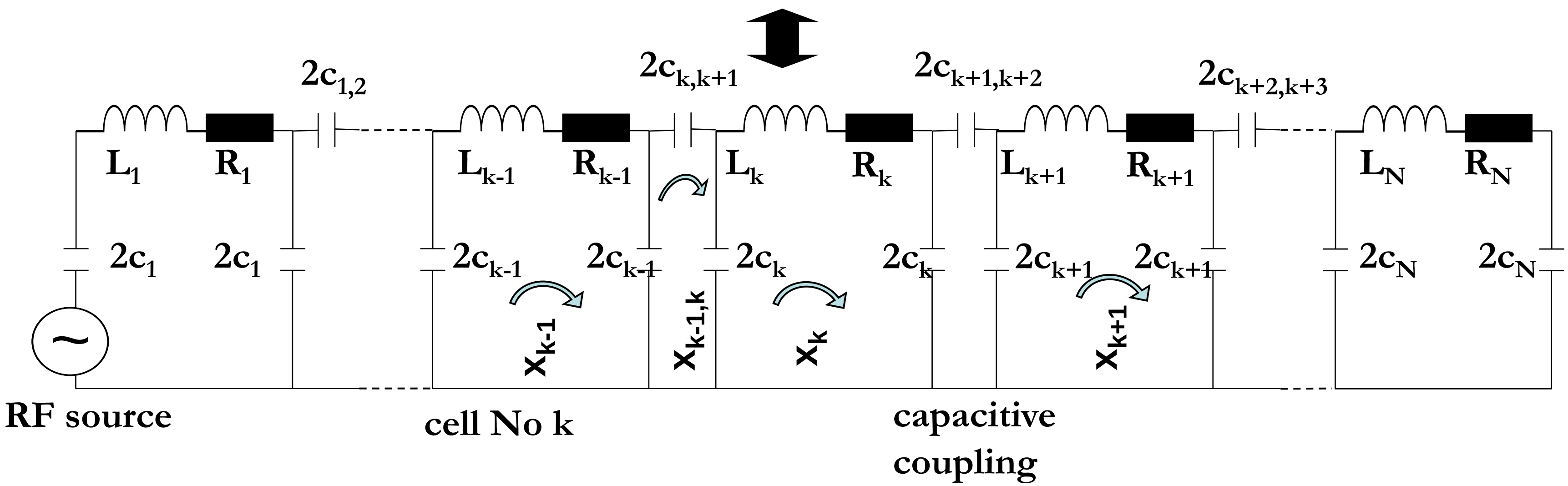




6. LEC and Transient State

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





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

6. LEC and Transient State

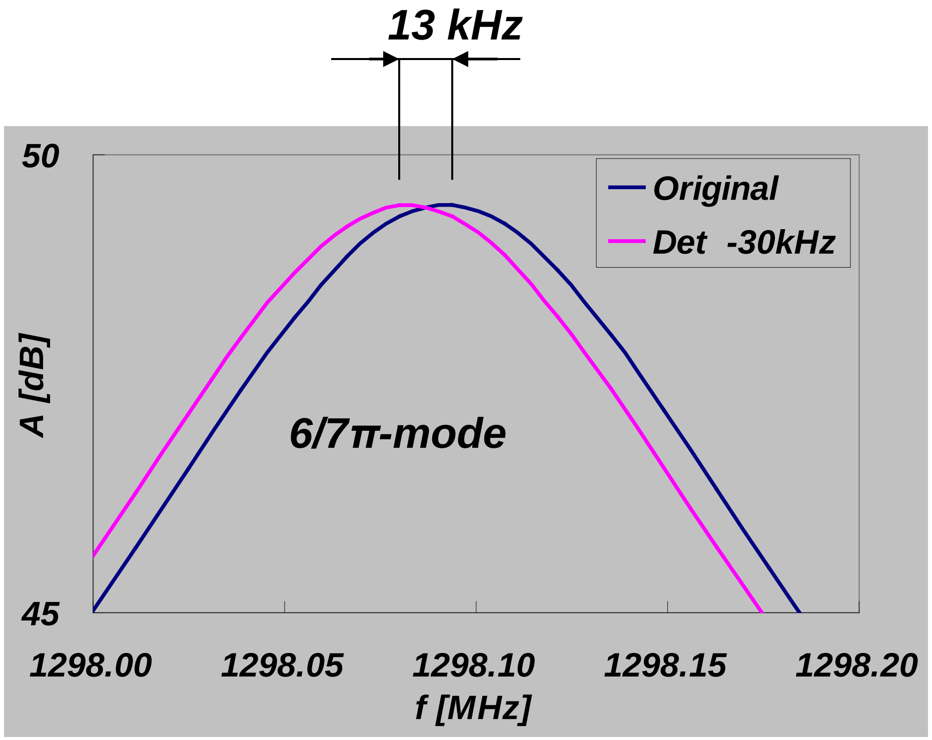
What can be done by means of the LEC:

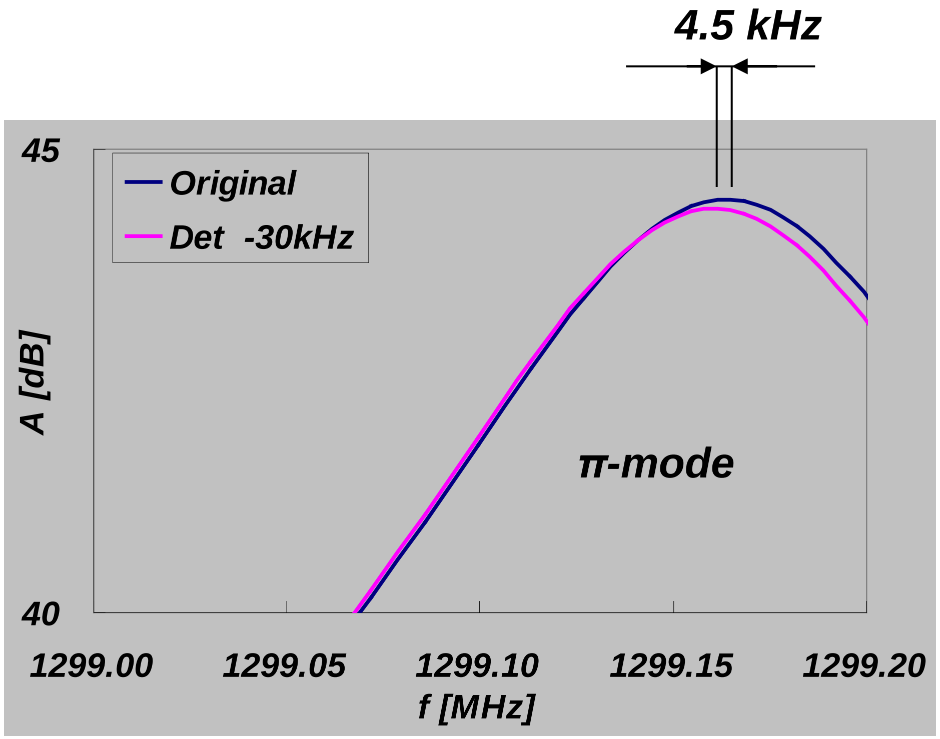
- Cavity pre-tuning after the fabrication and bulk chemical treatment
- Investigation how the field profile in cells depends on their frequency errors ($\partial f/f<10^{-4}$)
- Investigation how passband frequencies depend on cell frequency errors ($\partial f/f<10^{-4}$)
- Modeling of the transient state (mode beating)
- Modeling of the voltage stability during acceleration

blue marked examples of the implementation are shown on next slides

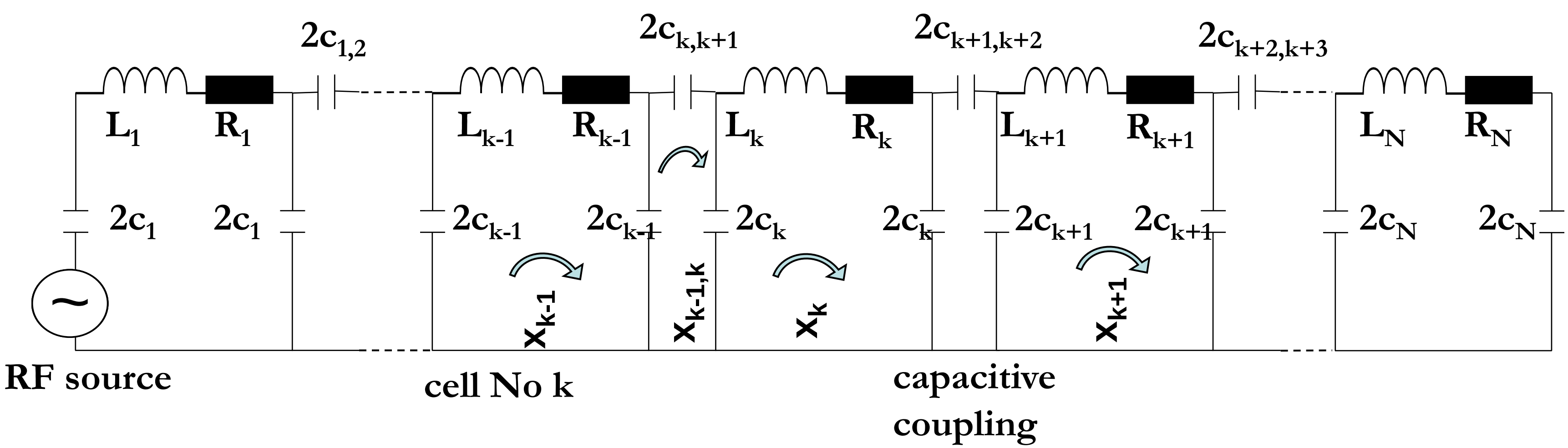
Investigation of the FM passband frequencies sensitivity to cell frequency errors *($\partial f/f<10^{-4}$)*

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





Transient State: Mode beating in the pulse operation



Solving the set of Kirchoff equations:

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

....

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

....

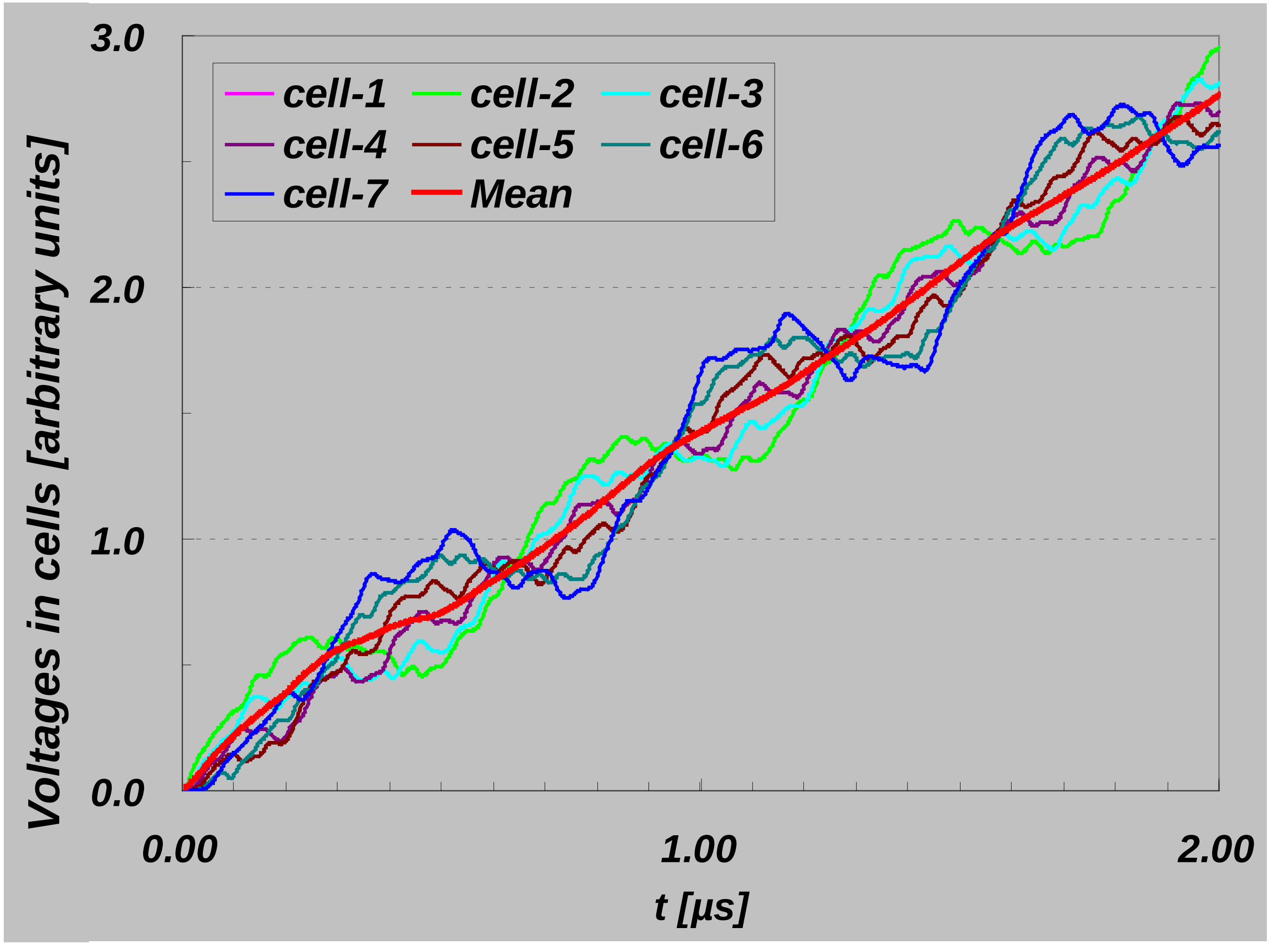
$$-\frac{1}{c_N} \cdot \int_0^t x_{N-1,N}(\tau) d\tau + R_N \cdot x_N(t) + L_N \cdot \dot{x}_N(t) + \frac{1}{c_N} \cdot \int_0^t x_N(\tau) d\tau = 0$$

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

6. LEC and Transient State

Modeling of the transient state (mode beating)

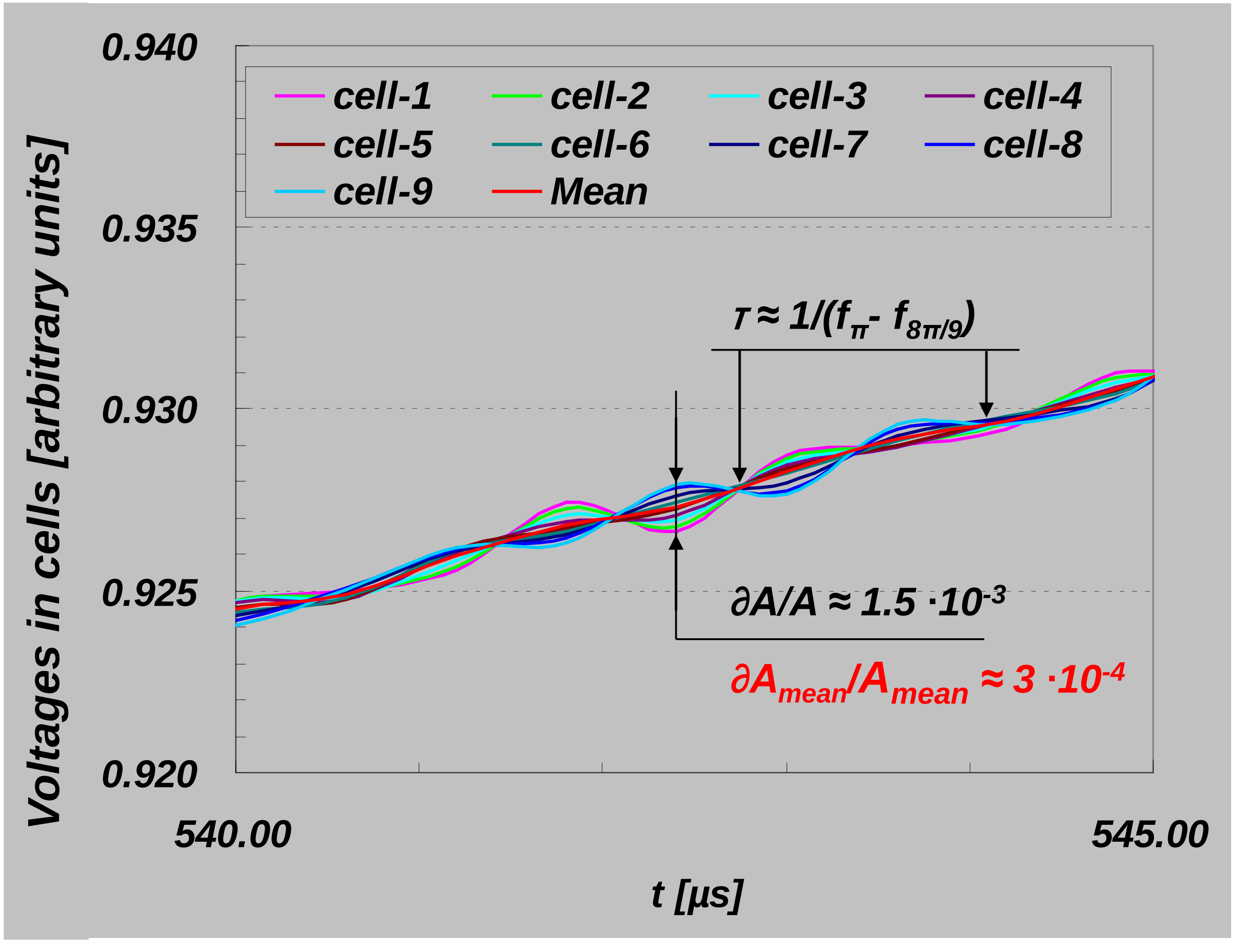
Example: 7-cells, k_{cc}=1.85%, Q_L=3.4 10^6



6. LEC and Transient State

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

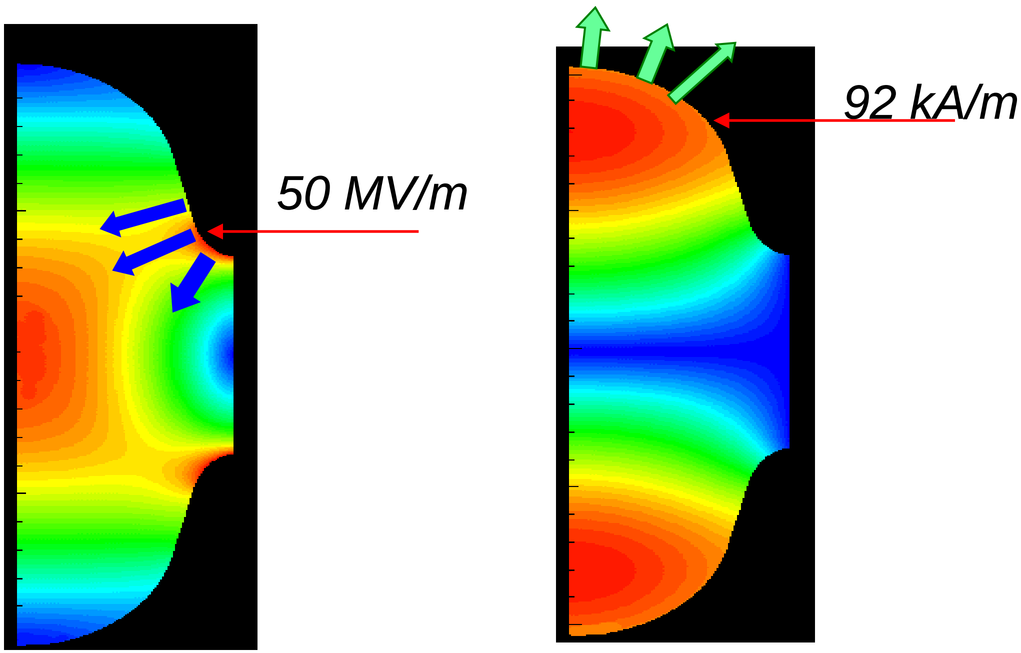


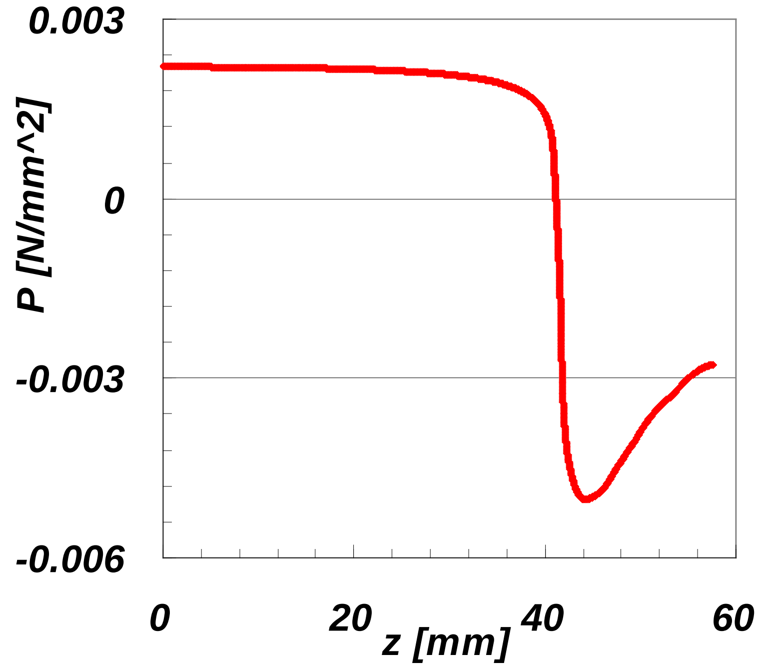
The mechanical design of a cavity follows its RF design:

- Lorentz Force Detuning
- Mechanical Resonances

Lorentz Force Detuning

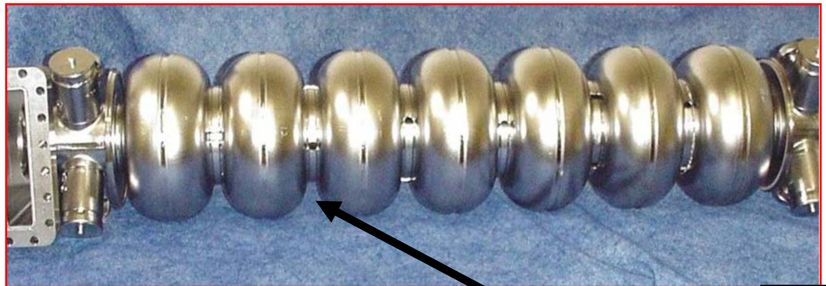
$$P = \frac{\mu_0 H_s^2 - \varepsilon_0 E_s^2}{4}$$

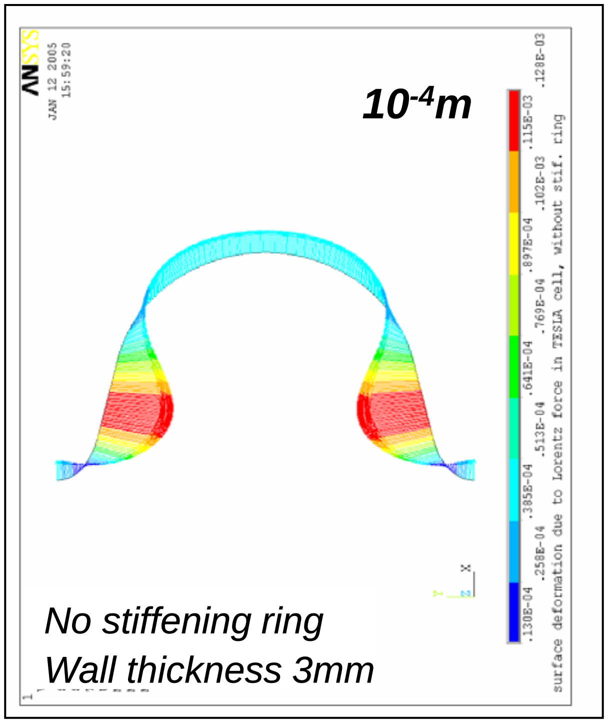




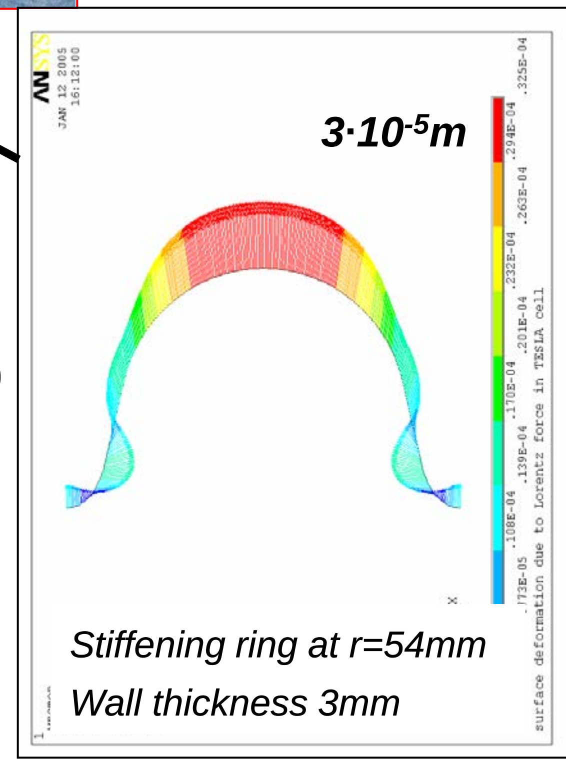
E and H at E_{acc} = 25 MV/m in the TESLA inner-cup

7. Mechanical Design





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



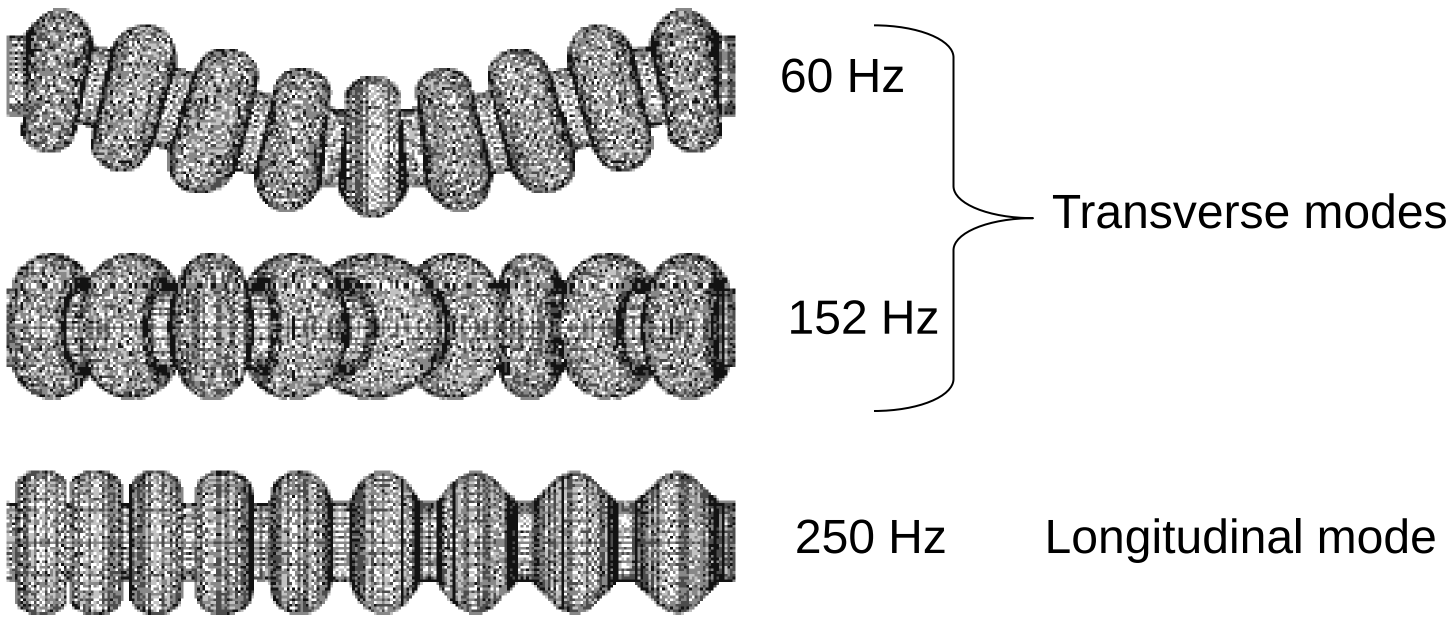
Lorentz force deformation is critical for the operation of a pulsed accelerator

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

For TESLA cavity: $k_L = -1\ Hz/(MV/m)^2$

7. Mechanical Design

Mechanical Resonances of a multi-cell cavity



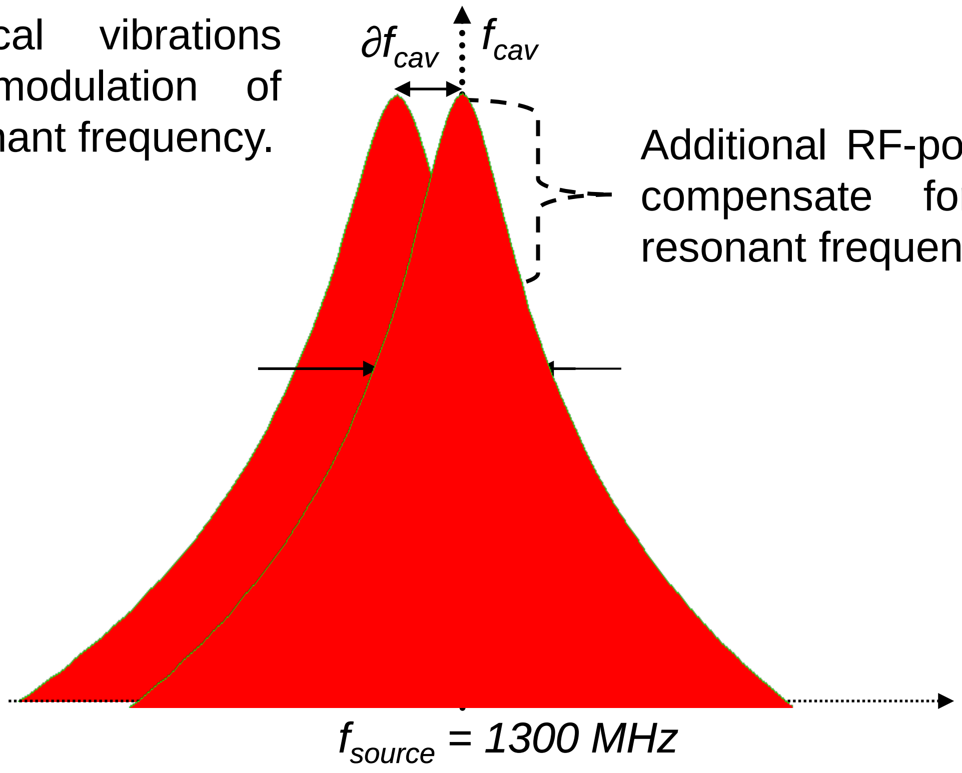
TESLA structure

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

7. Mechanical Design

$$\Delta f_{3db} \equiv \frac{1.3 \cdot 10^{9} Hz}{2 \cdot 10^{7}} = 65 Hz$$

Mechanical vibrations cause modulation of the resonant frequency.



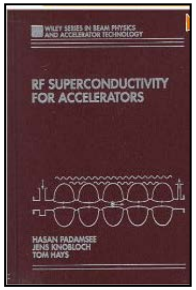
Additional RF-power is needed to compensate for the shift of resonant frequency from 1.3GHz.

8. Final Remarks and References

Not discussed topics:

1. HOM dampers: loop couplers, waveguide couplers, beam line absorbers
2. Input couplers design
3. Cold frequency tuners design
4. Design of LHe vessels
5. ………

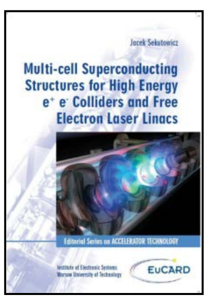
8. Final Remarks and References



1. **H. Padamsee, J. Knobloch, T. Hays, *"RF-Superconductivity for Accelerators"*, Wiley Series in Beam Physics and Accelerator Technology, 1998.**

2. **Proceedings of all SRF Workshops; http://accelconf.web.cern.ch/accelconf/**

3. **TESLA TDR, DESY-Report 2003**



4. **J.S. "Multi-cell Superconducting Structures for High Energy e^+e^- colliders and Free electron Laser Linacs", CERN/FP7; http://eucard.web.cern.ch/eucard/**