Superconducting Radiofrequency Accelerating Structures

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TAS2008
Part II

Largely taken from a lecture by
Jacek Sekutowicz
for SRF 2007, Beijing

Acknowledgement

- The main part is directly from Jacek's Beijing lecture on RF Cavity Design
  - For me this lecture came on rather short notice, therefore I took Jacek's lecture, which I think is excellent
- For the record you will be able to download the full lecture, beside the shortened version included here
  - e.g. omitted Numerical Simulation Methods

Outline of the lectures

- Lecture 1
    - Radiofrequency (RF) cavities
    - Superconductivity basics
    - RF superconductivity
    - Limitations of superconducting RF cavities
- Lecture 2
    - RF Cavity Design
        - By J. Sekutowicz
    - Mechanical Design
        - Lorentz-force Detuning

SRF 2007

Tutorial: Superconducting High ß Cavities

Jacek Sekutowicz, DESY

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

Supe

1908: He
Liquefie

1911: H
Discove

1928-34:
Discove
V, Ti and

RF Acceleration

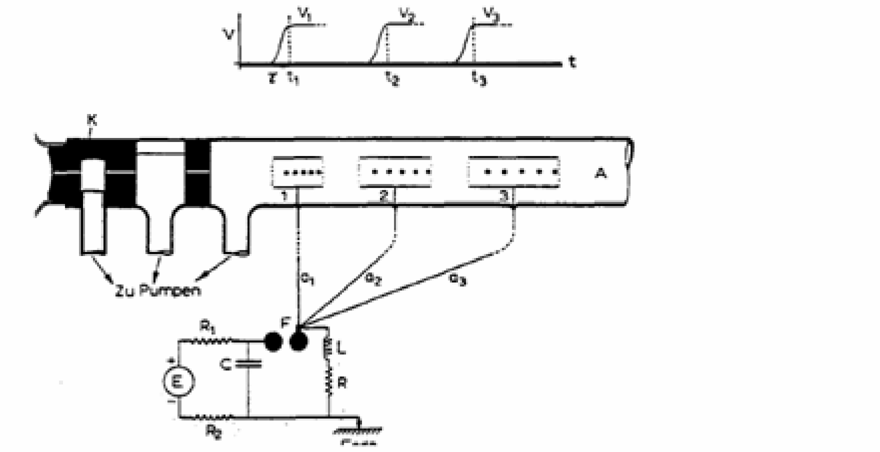


Fig. 1. Diagram of linear accelerator from Professor G. Ising's pioneer publication (1924) of the principle of multiple acceleration of ions.

Invented Klystron.

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

1947: **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.

1. Introduction and History

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)

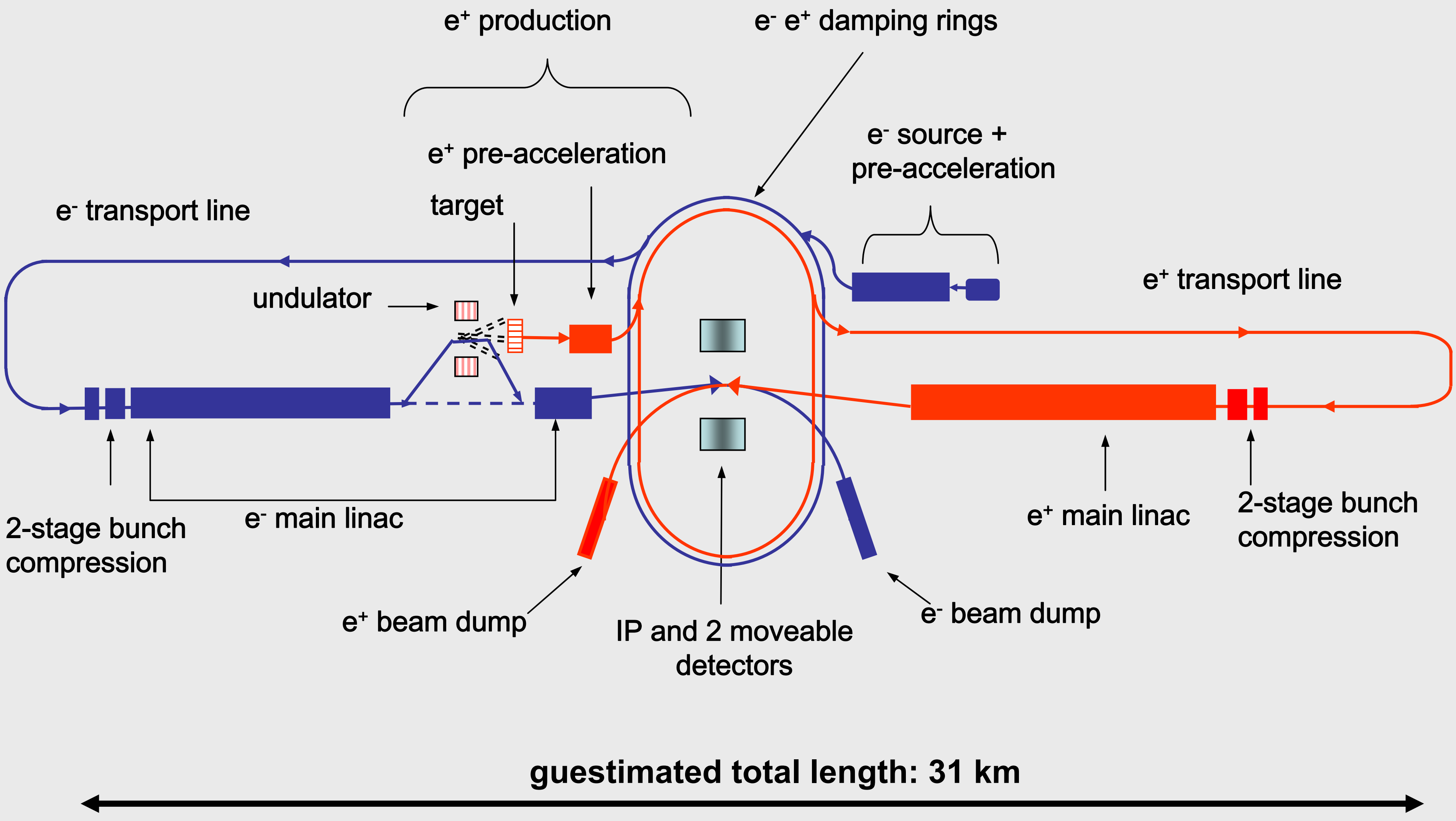
Day after Tomorrow Facilities

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)

1. Introduction and History

ILC (~15764/~16395m)



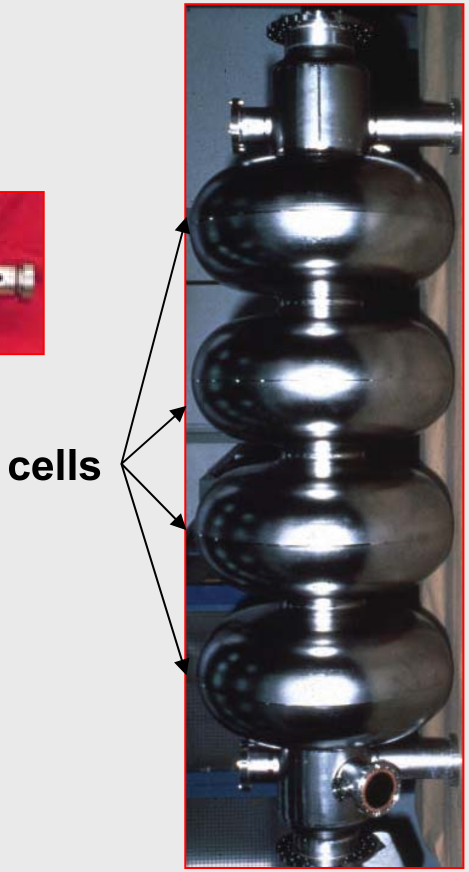
1. Introduction and History

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

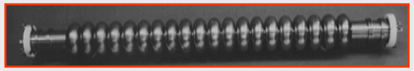
FERMI 3.9 GHz

TESLA/ILC 1.3 GHz

LEP 0.352 GHz

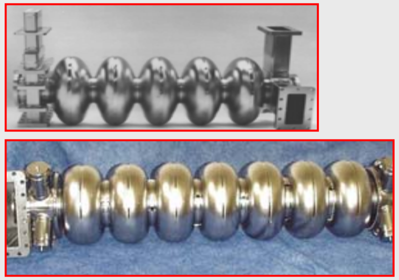


S-DALINAC 3 GHz



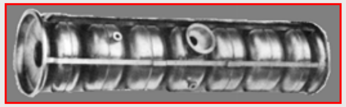
SNS ß=0.61,0.81, 0.805 GHz

CESR/CEBAF 1.5 GHz



HERA 0.5 GHz

HEPL 1.3 GHz



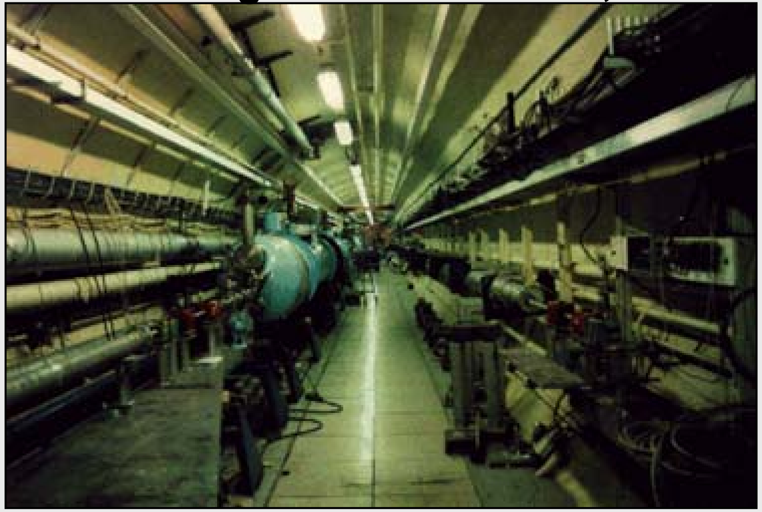
KEK-B 0.5 GHz

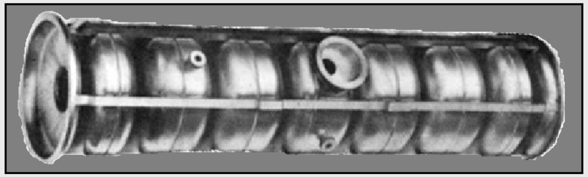
CESR 0.5 GHz

1. Introduction and History

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

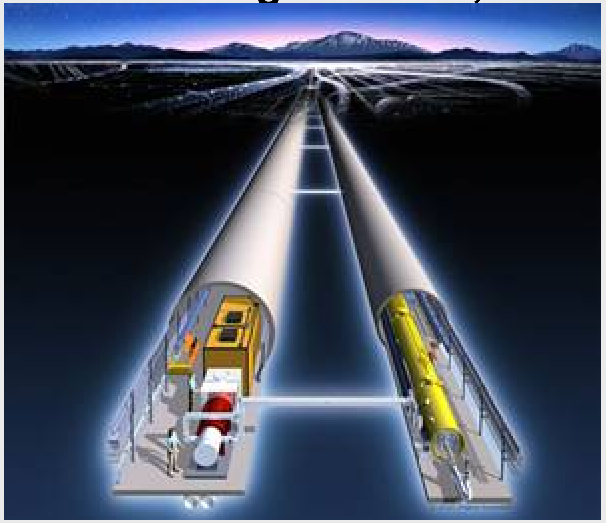
~ 28 m long SCA at Stanford, 1977.





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.

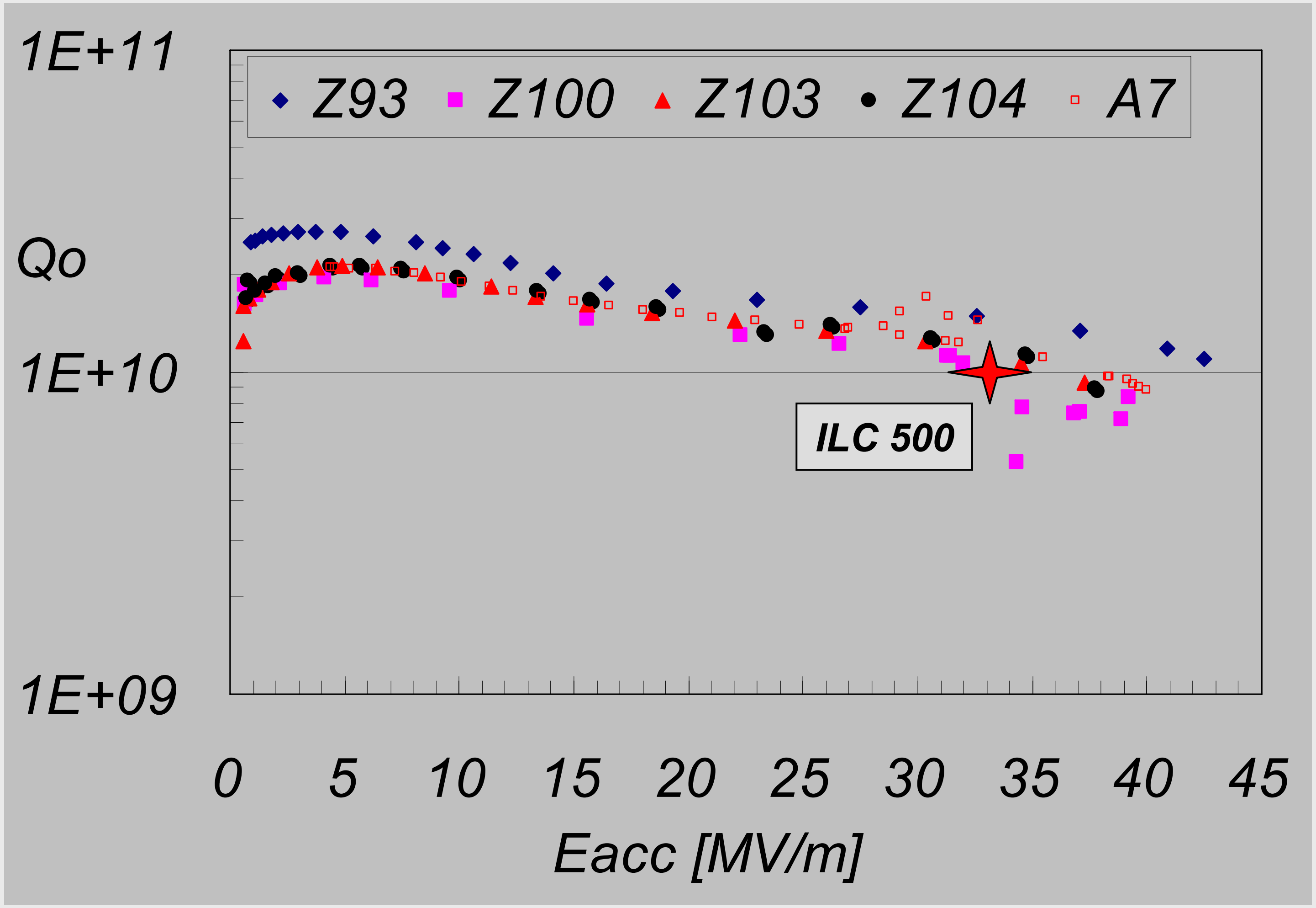
⬇

This gradient is required in all 15764 cavities.

1. Introduction and History

Results at DESY and JLab (2007):

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



2. RF Parameters

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:

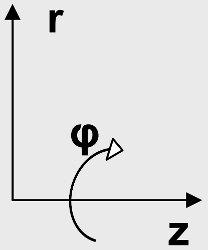
1. Stored E-H fields are harmonic in time.

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.

TM0xx-like monopole **modes have "very strong" E_z component on the symmetry axis.**

Fields of the monopole modes are independent on φ.

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

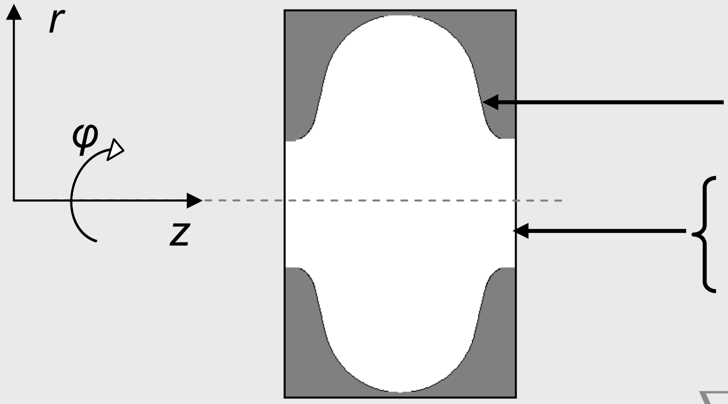
Non monopole (HOM) **modes have component $E_z = 0$ on the symmetry axis.**

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:

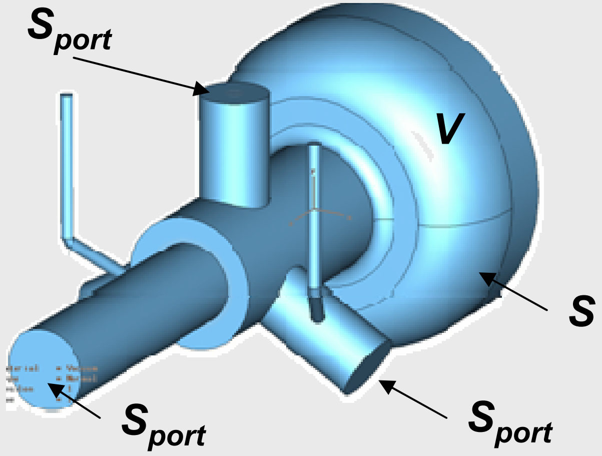
$\mathbf{H_n}(r,z)=[0, H_{\varphi,n}(r,z),0]$,

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

and frequency ω_n .

2. RF Parameters

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



$\boldsymbol{W_n}$ ≡ *stored energy of a mode n* **:** $\{\omega_n, \boldsymbol{E_n}, \boldsymbol{H_n}\}$.

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

Quality Factors

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

Intrinsic $Q \equiv Qo$

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

External $Q \equiv Q_{ext}$

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

2. RF Parameters

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 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:

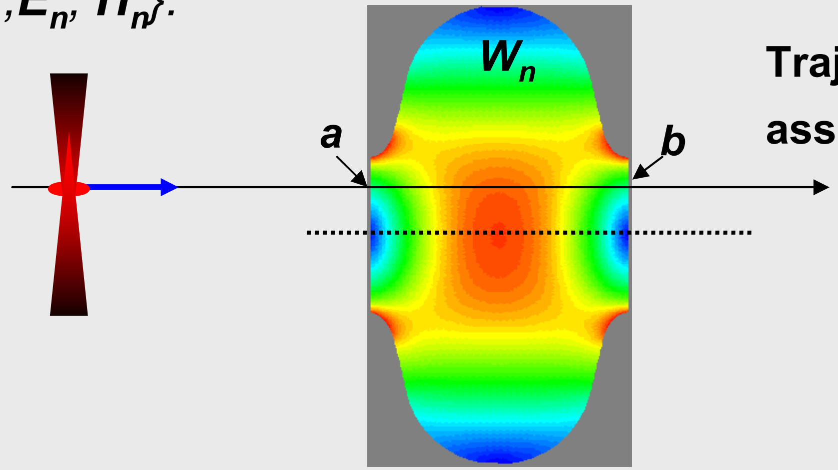
- Acceleration
- Deceleration (ERL)
- HOMs excitation

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

2. RF Parameters

$(R/Q)_n$, 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.

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

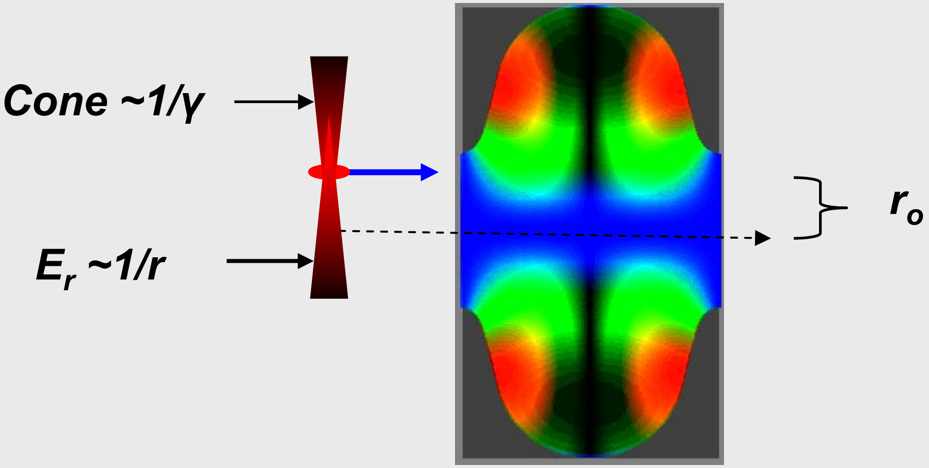
This is due to the surface quality;
Big improvement possible.

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

2. RF Parameters

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 cavity eigenmodes (monopoles and others) having the $E_n(r,\varphi,z)$ field along the trajectory.

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

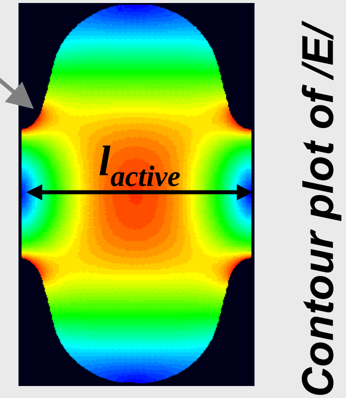
RF parameters of the accelerating mode having more practical background

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

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

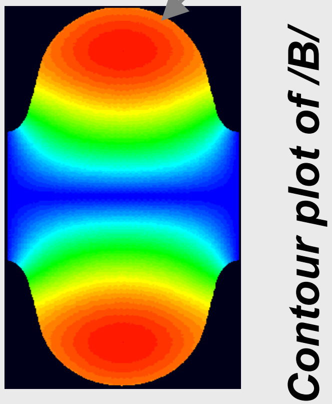
E_{peak} on the surface

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



B_{peak} on the surface

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

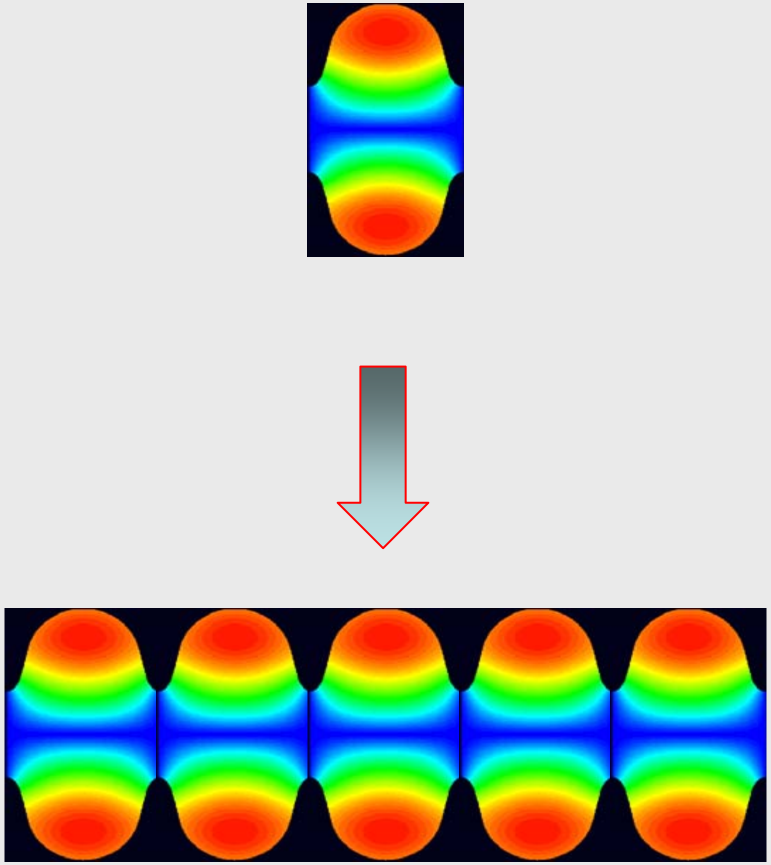


Ratio shows sensitivity of the shape to the field electron emission phenomenon.

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).



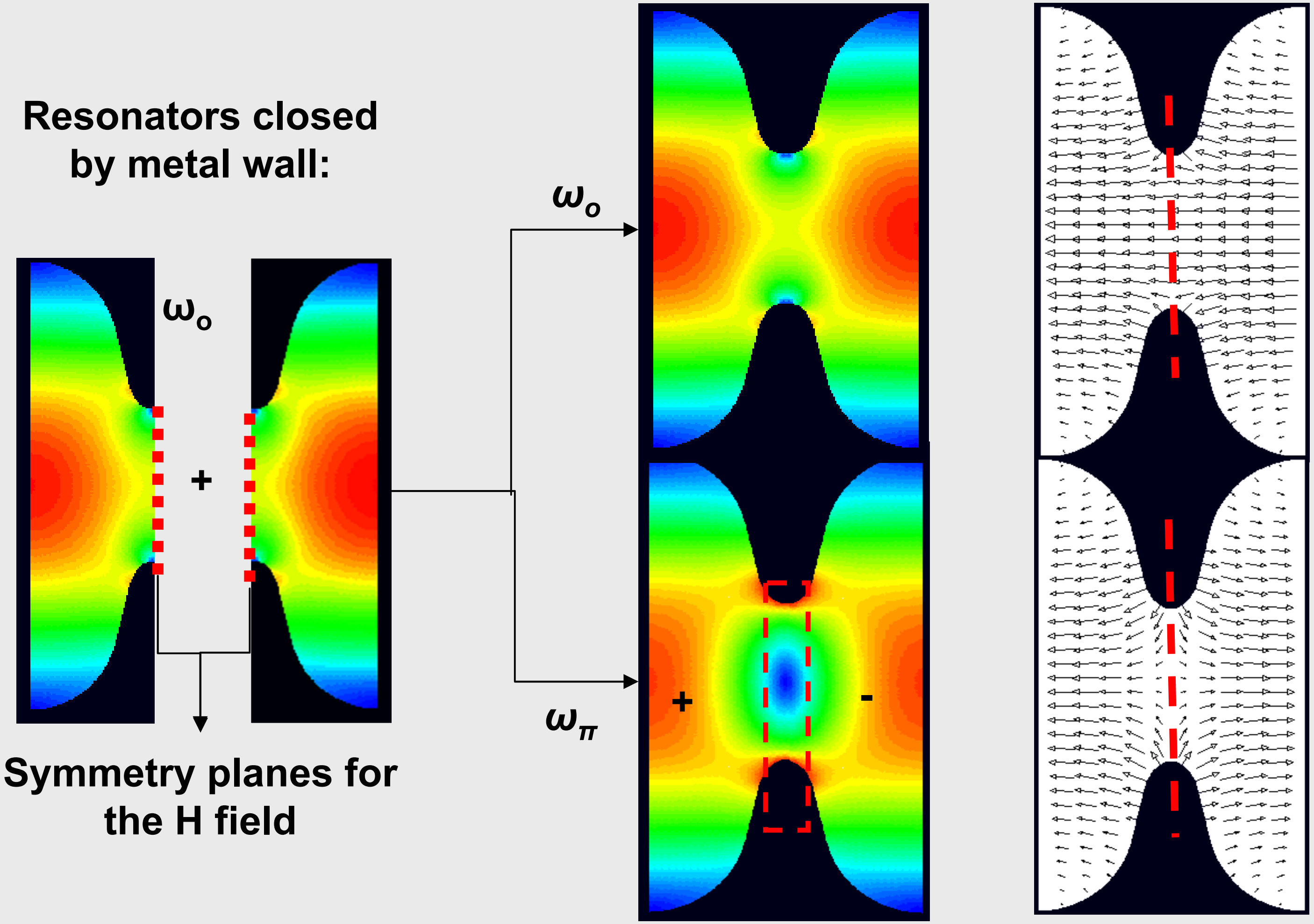
Single-cell structures are attractive from the RF-point of view:

- **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…**

2. RF Parameters



Resonators closed by metal wall:

Symmetry planes for the H field

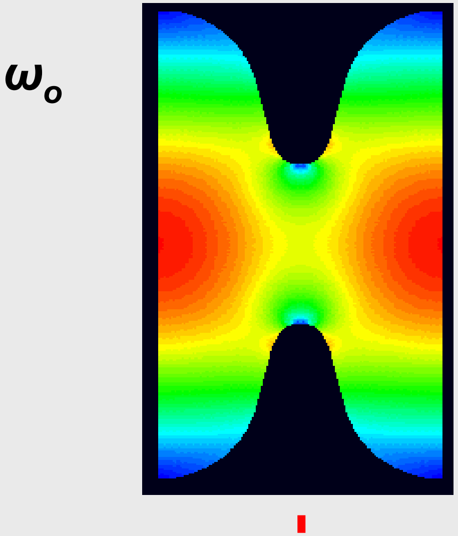
Symmetry plane for the H field

Symmetry plane for the E field

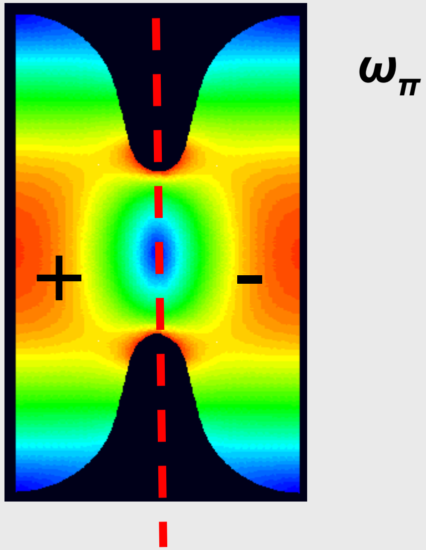
which is an additional solution

2. RF Parameters

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



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

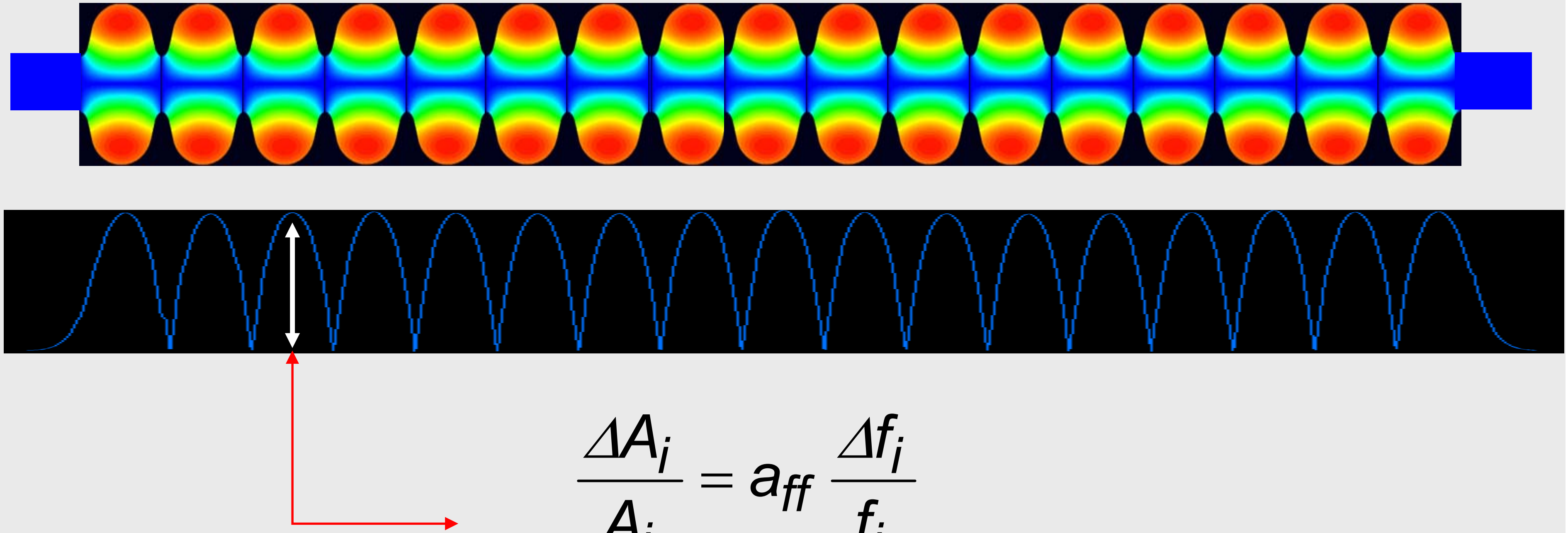


Small H_φ (due to the losses) + strong E_r at the symmetry plane

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

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

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)

3. Criteria for Cavity Design

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

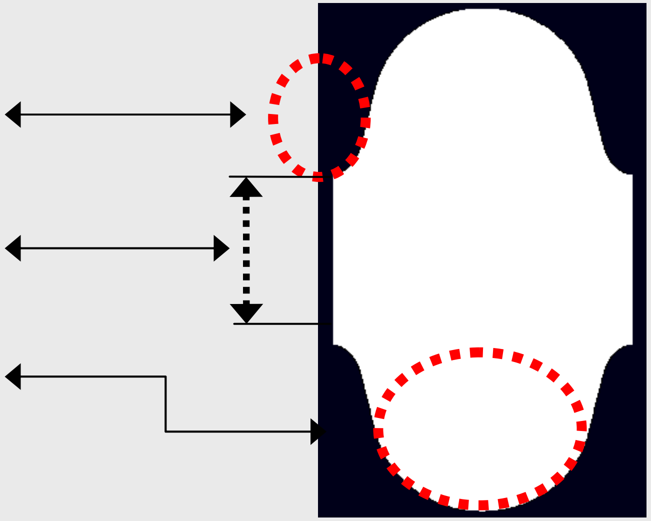
There are 7 parameters we want to optimize for an inner cell

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"**

3. Criteria for Cavity Design

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 $I_{beam} \leftrightarrow$ *Low HOM impedance*	$k_{\perp}, k_{\parallel}$ ↓	r_i ↑	*B-Factory* *RHIC cooling*

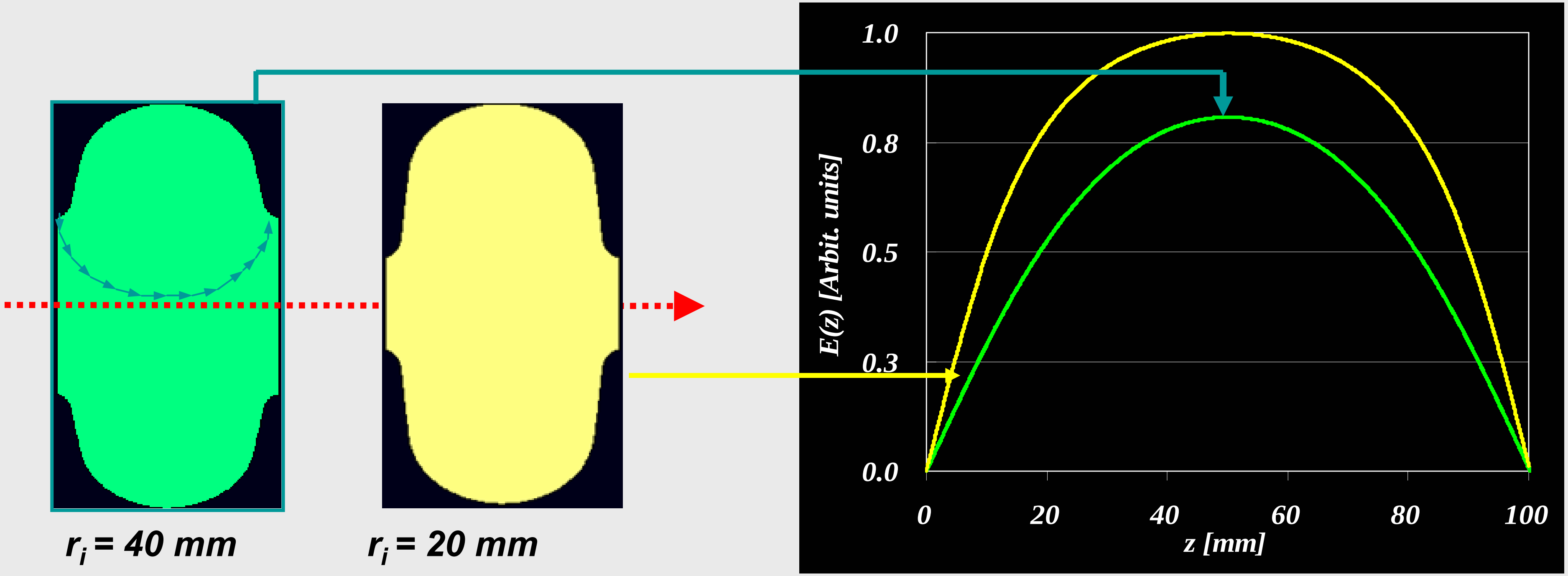
We see here that r_i is a very “powerful variable” to trim the RF-parameters of a cavity.

3. Criteria for Cavity Design

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



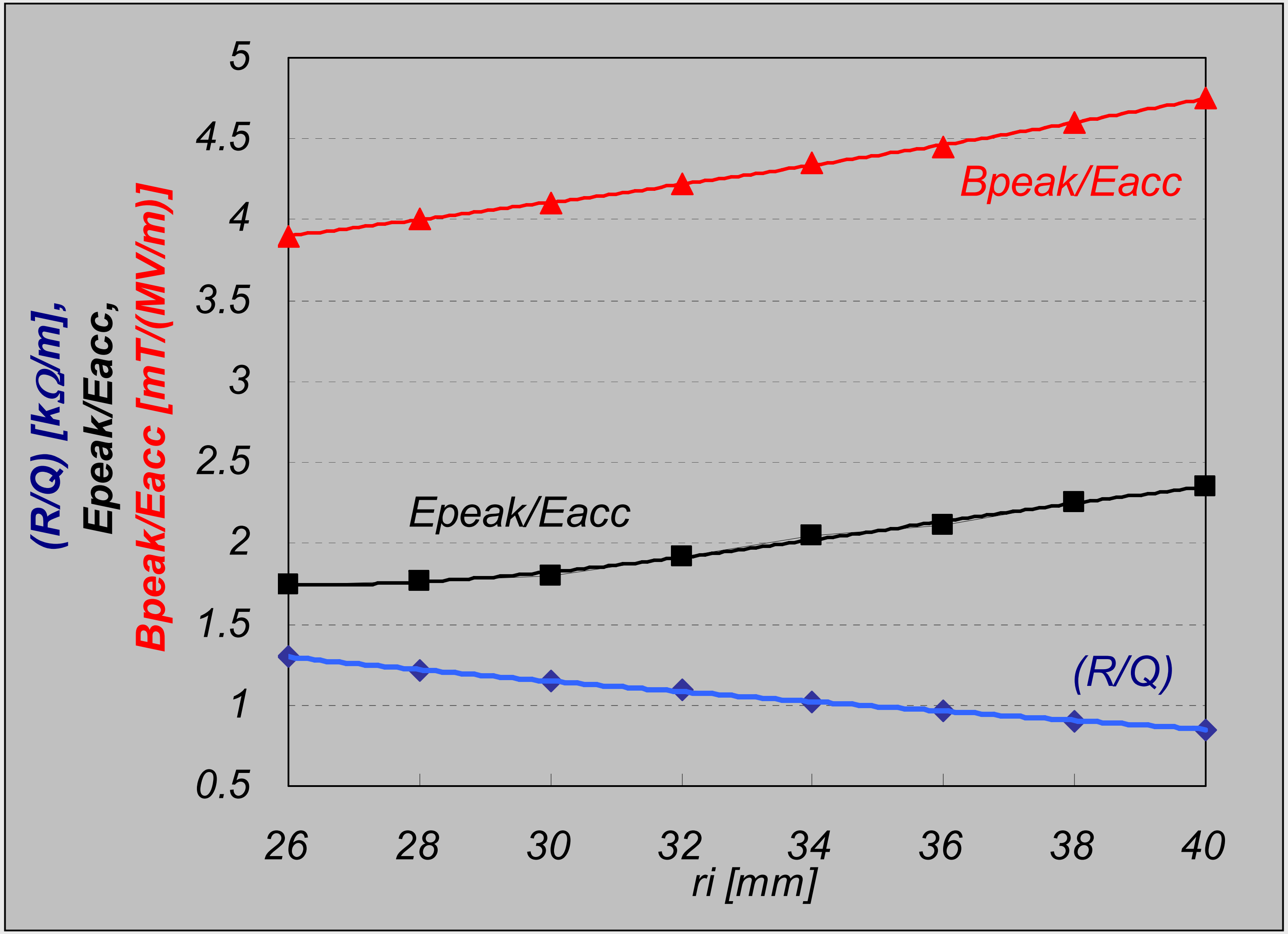
r_i = 40 mm

r_i = 20 mm

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

3. Criteria for Cavity Design

Example:
f = 1.5 GHz

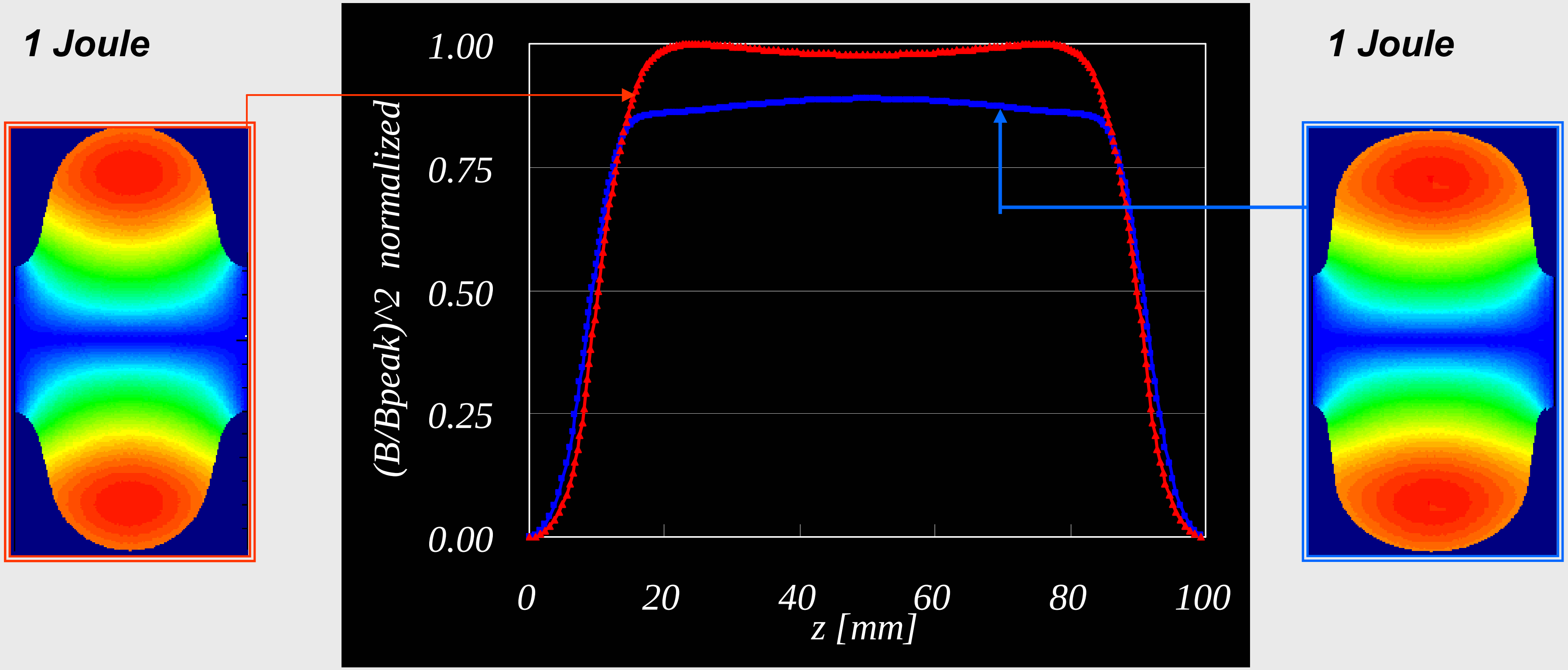


A. Mosnier, E. Haebel, SRF Workshop 1991

3. Criteria for Cavity Design

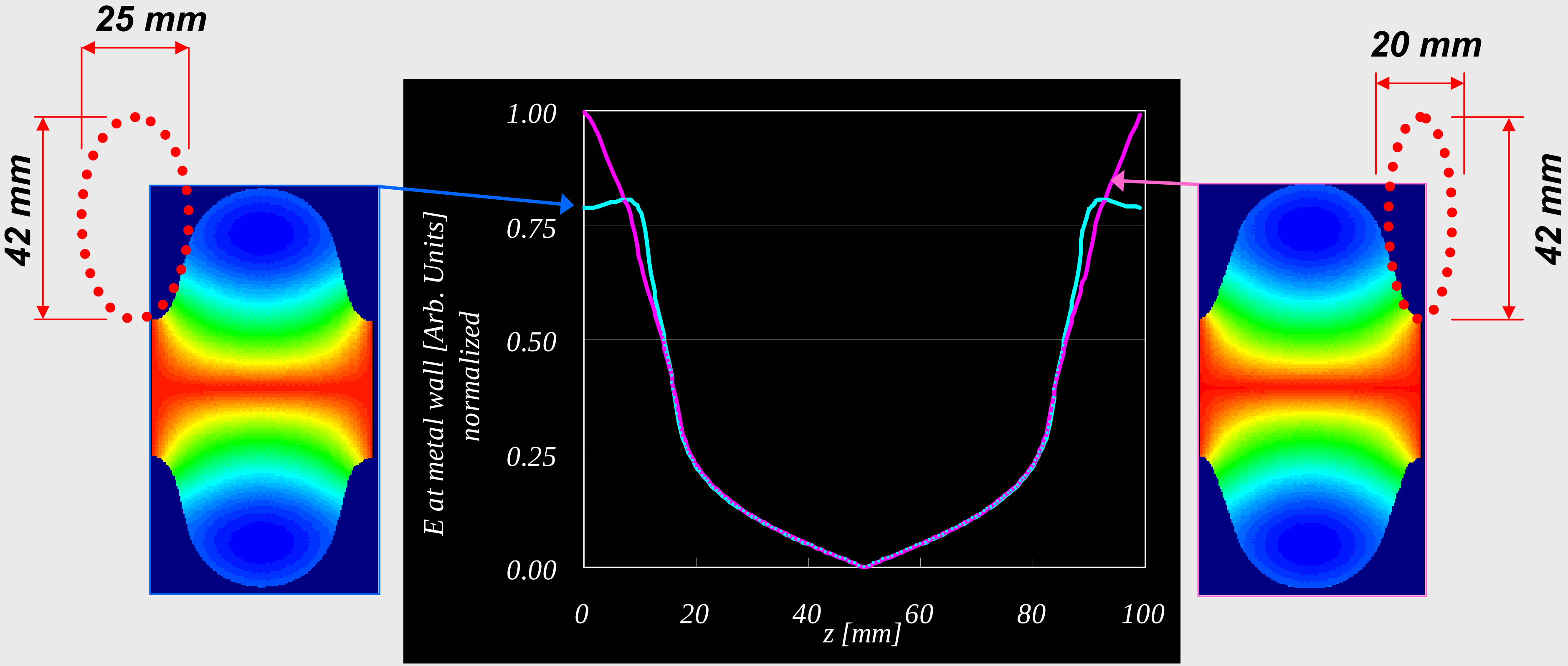
In addition to the iris radius $r_{i\_}$:

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



3. Criteria for Cavity Design

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

We know that a smaller aperture r_i makes FM :

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

(+)

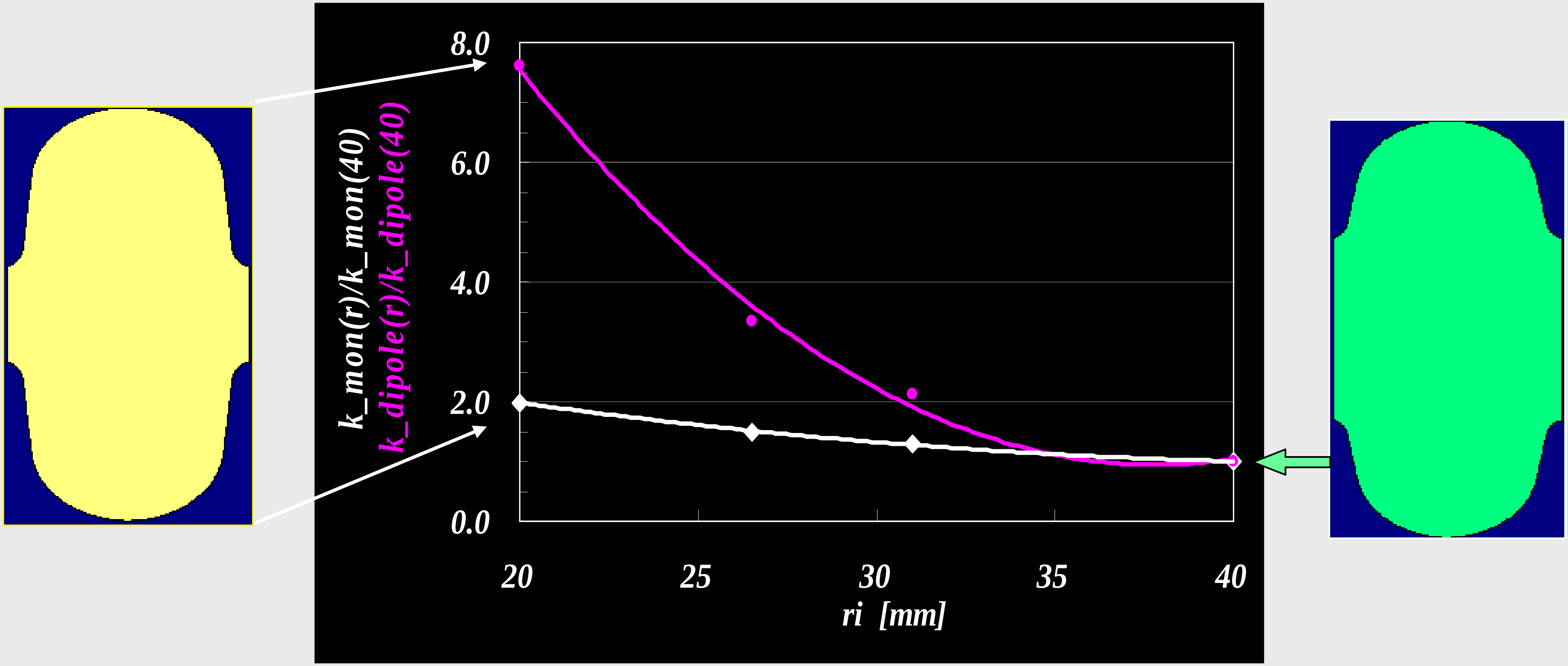
but unfortunately a smaller aperture r_i makes:

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

(-)

3. Criteria for Cavity Design

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

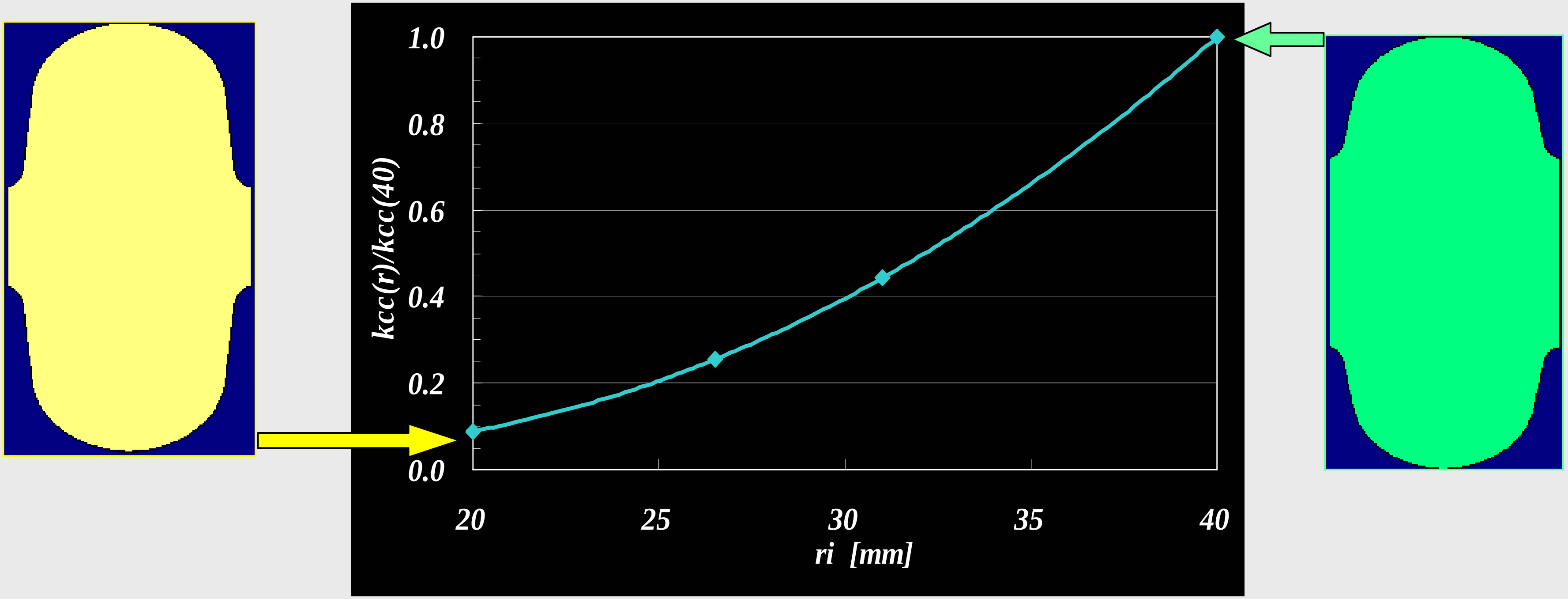
(R/Q) = 86 Ω

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

E_{peak} / E_{acc} = 3.2

3. Criteria for Cavity Design

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

3. Criteria for Cavity Design

What about accelerating mode frequency of a superconducting cavity?

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

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

3. Criteria for Cavity Design

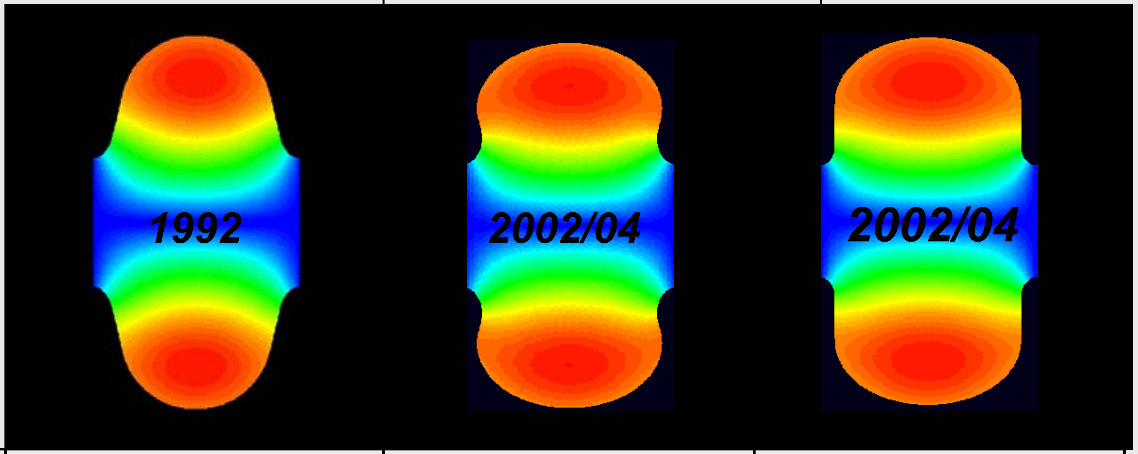
Examples of inner cells

		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/cm^2]	0.22	0.32	0.53	0.23	0.13	0.11	0.15	0.02
$k_\parallel$(σ_z=1mm)	[V/pC]	1.36	1.53	1.71	1.46	1.25	1.27	1.19	0.85

3. Criteria for Cavity Design

Evolution of inner cells proposed for the ILC collider:

TESLA optimized	Re-entrant optimized	LL optimized
E_{peak}/E_{acc}	B_{peak}/E_{acc}	B_{peak}/E_{acc}

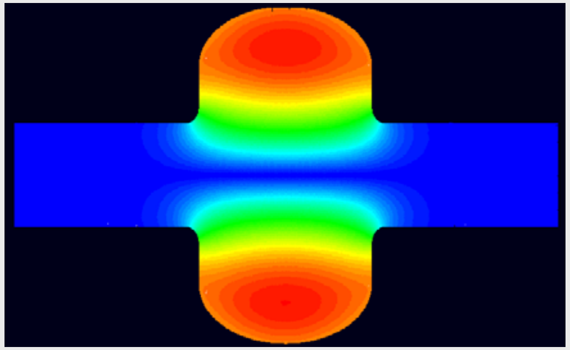


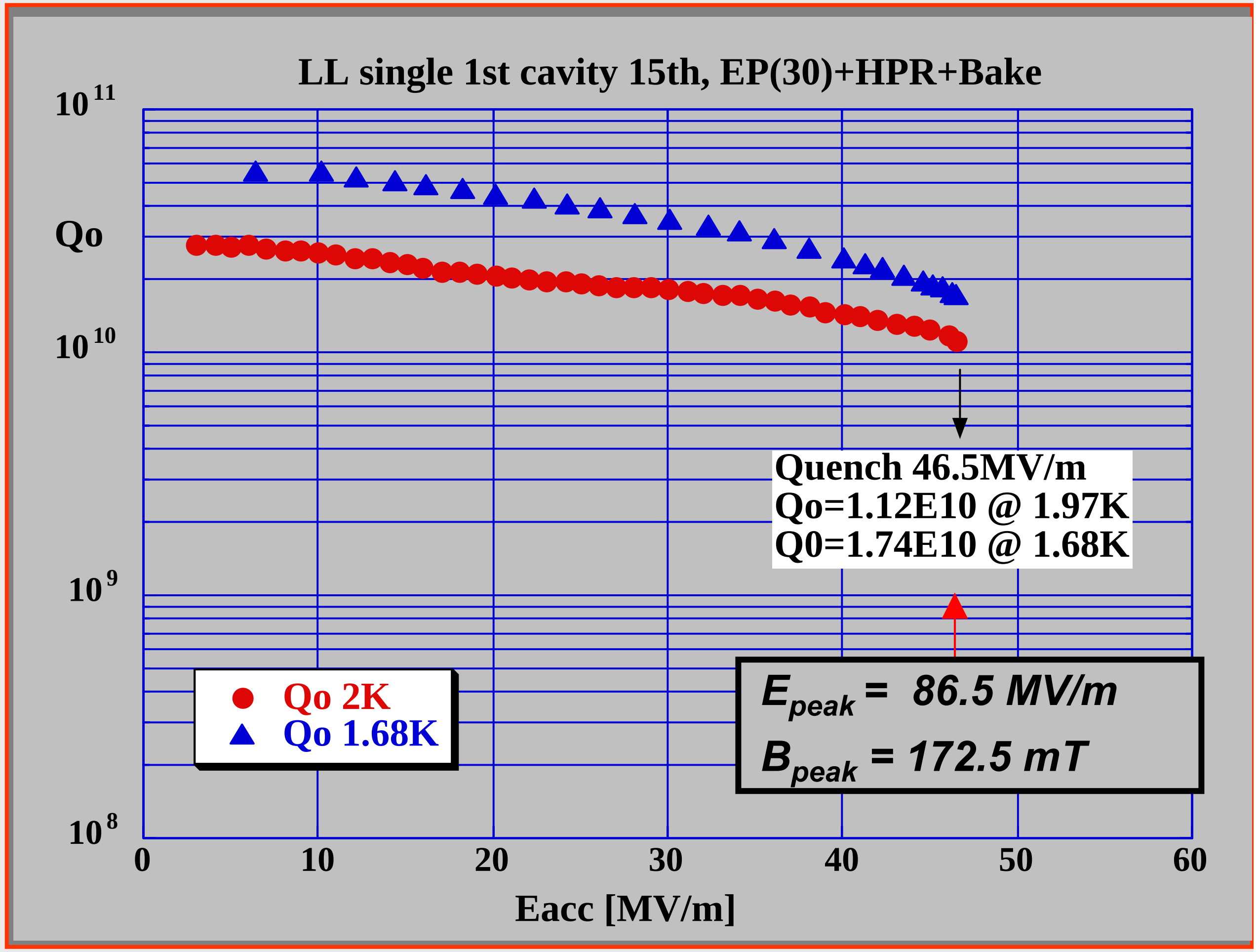
r_i	[mm]	35	30	30
k_{cc}	[%]	1.9	1.56	1.52
E_{peak}/E_{acc}	-	1.98	2.30	2.36
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.57	3.61
R/Q	$[\Omega]$	113.8	135	133.7
G	$[\Omega]$	271	284.3	284
R/Q*G	$[\Omega*\Omega]$	30840	38380	37970
$k_\perp (\sigma_z=1mm)$	$[V/pC/cm^2]$	0.23	0.38	0.38
$k_{//} (\sigma_z=1mm)$	[V/pC]	1.46	1.75	1.72

3. Criteria for Cavity Design

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*

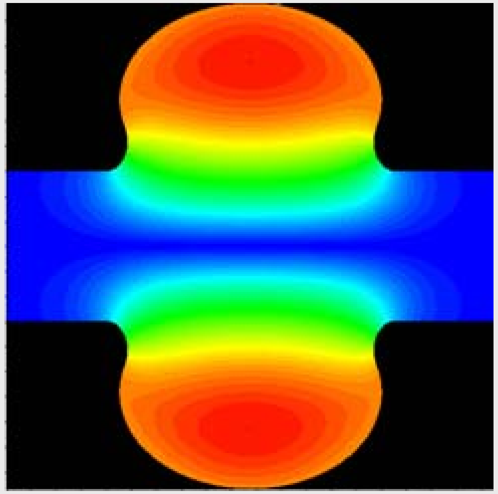


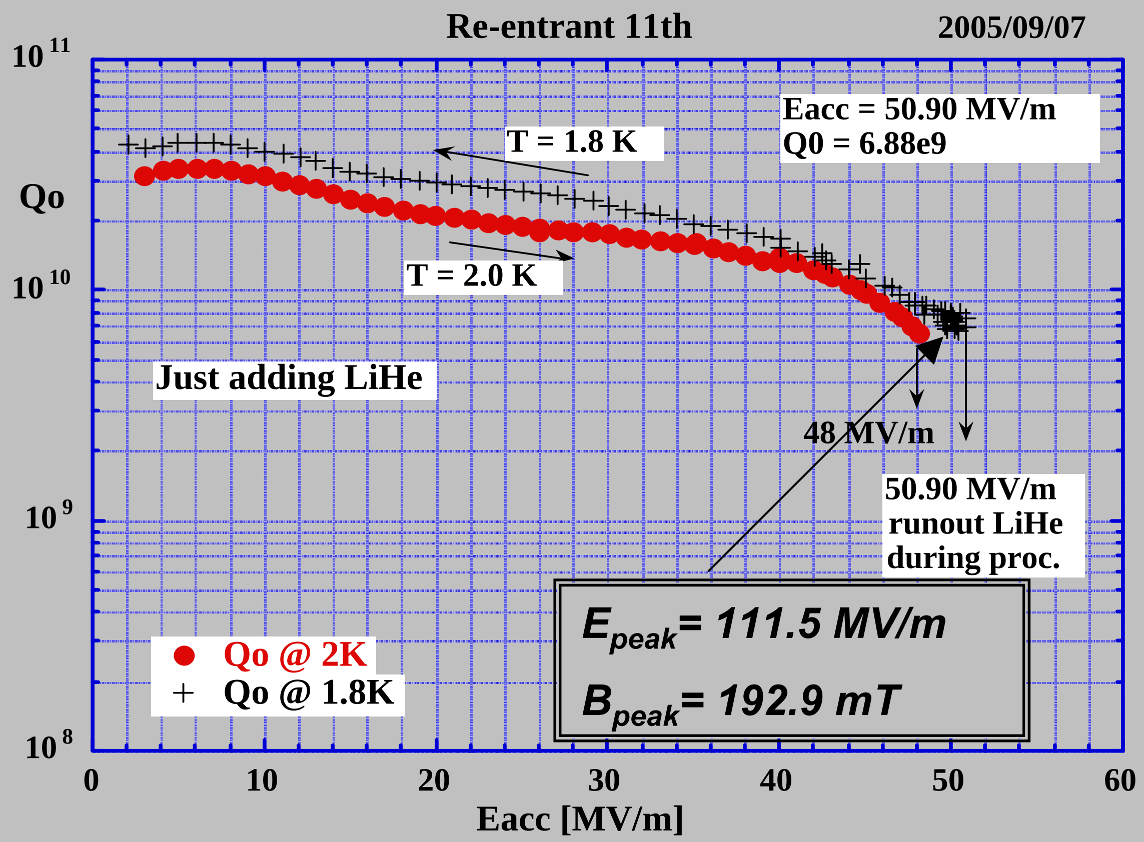


3. Criteria for Cavity Design

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*





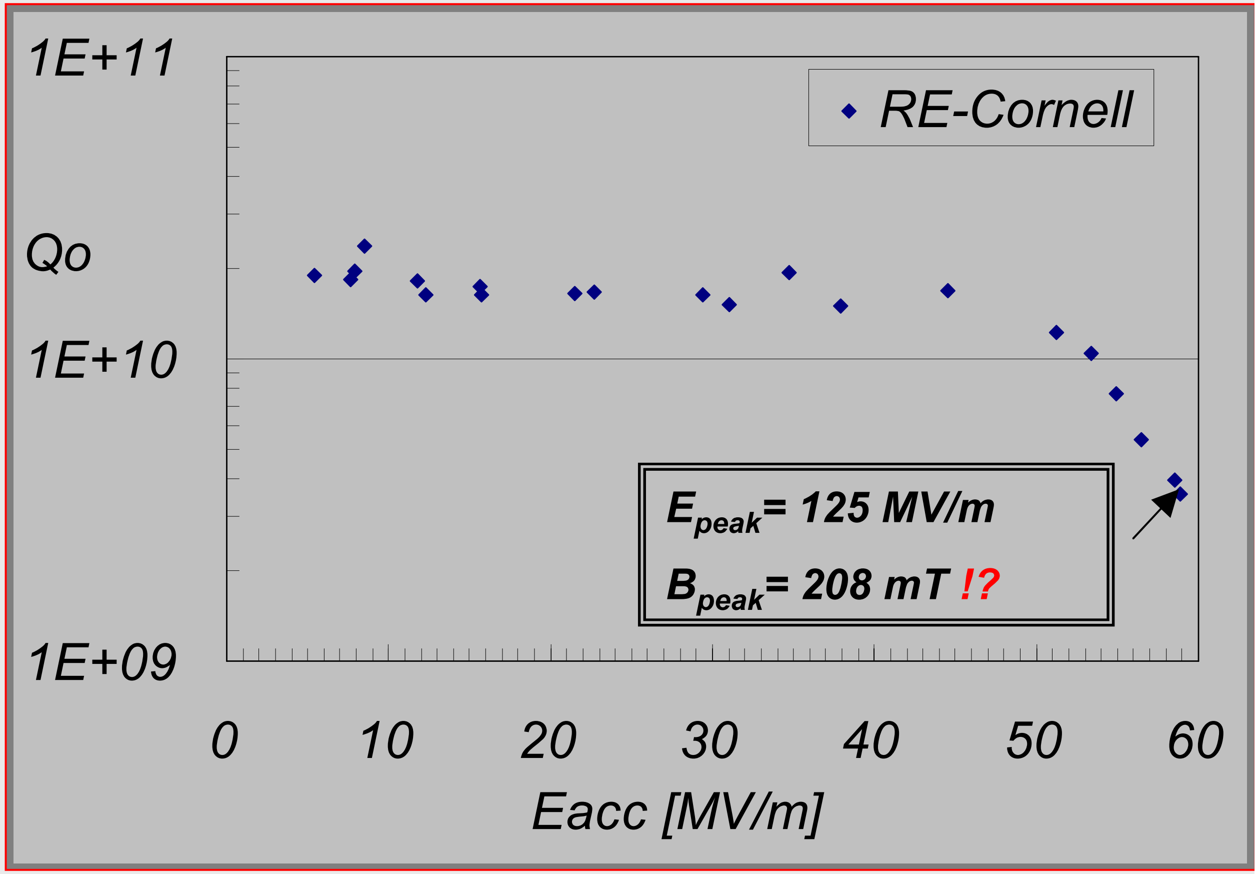
E_{peak}= 111.5 MV/m

B_{peak}= 192.9 mT

3. Criteria for Cavity Design

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



E_{peak}= 125 MV/m

B_{peak}= 208 mT !?

4. Multi-cell Structures and Weakly Coupled Structures

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**

Break

4. Multi-cell Structures and Weakly Coupled Structures

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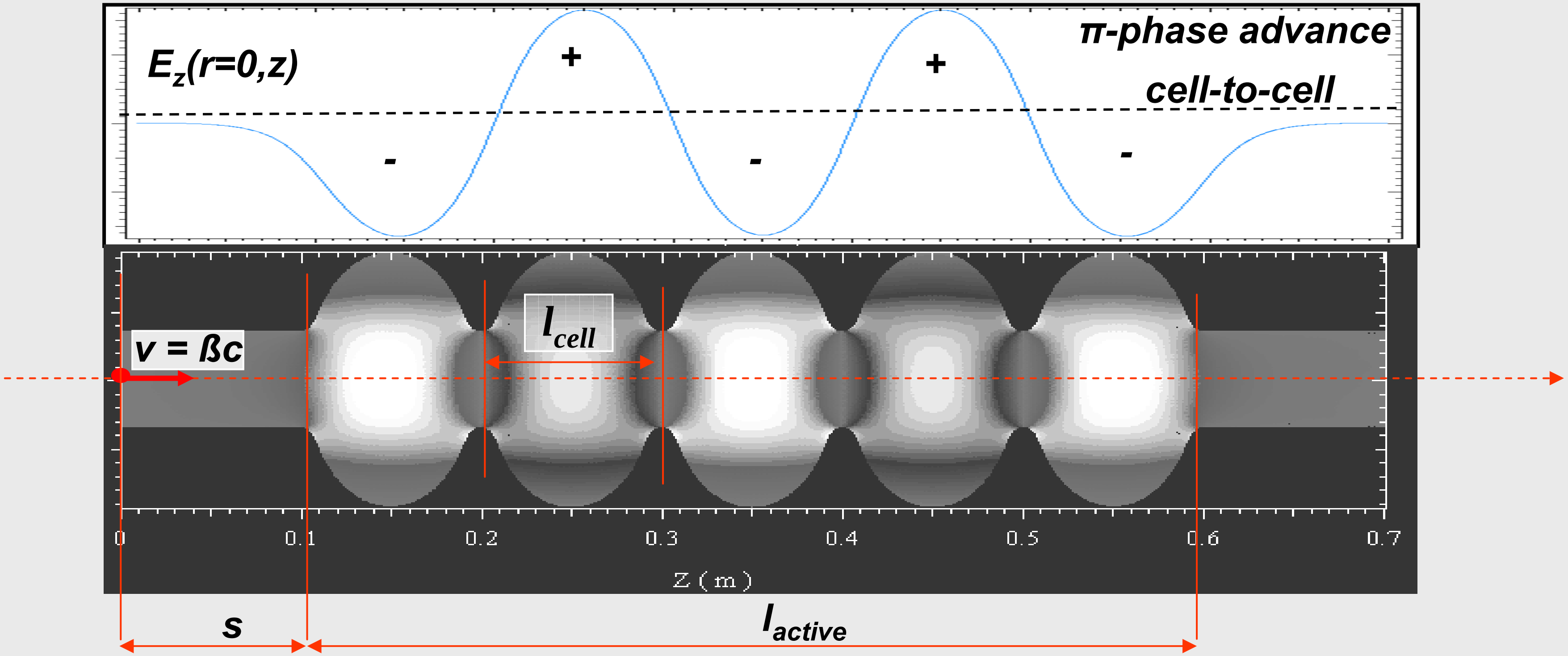
- **The worst performing cell limits whole multi-cell structure**

4. Multi-cell Structures and Weakly Coupled Structures

Accelerating mode in a multi-cell structure



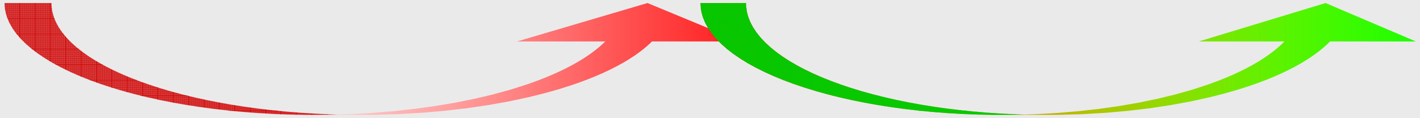
Synchronic acceleration and max of $(R/Q)_{acc}$ when:

1. $l_{active} = Nl_{cell} = Ncß/(2f)$ **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).**

4. Multi-cell Structures and Weakly Coupled Structures

- **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



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

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 %

4. Multi-cell Structures and Weakly Coupled Structures

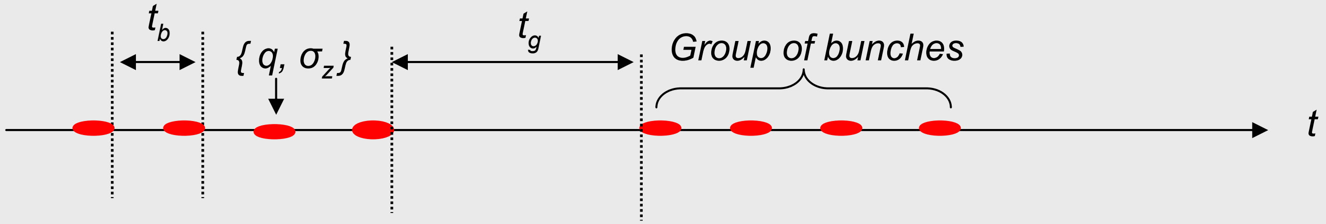
- **HOM trapping in a multi-cell structures**

The excitation of HOMs by the accelerated beam causes:

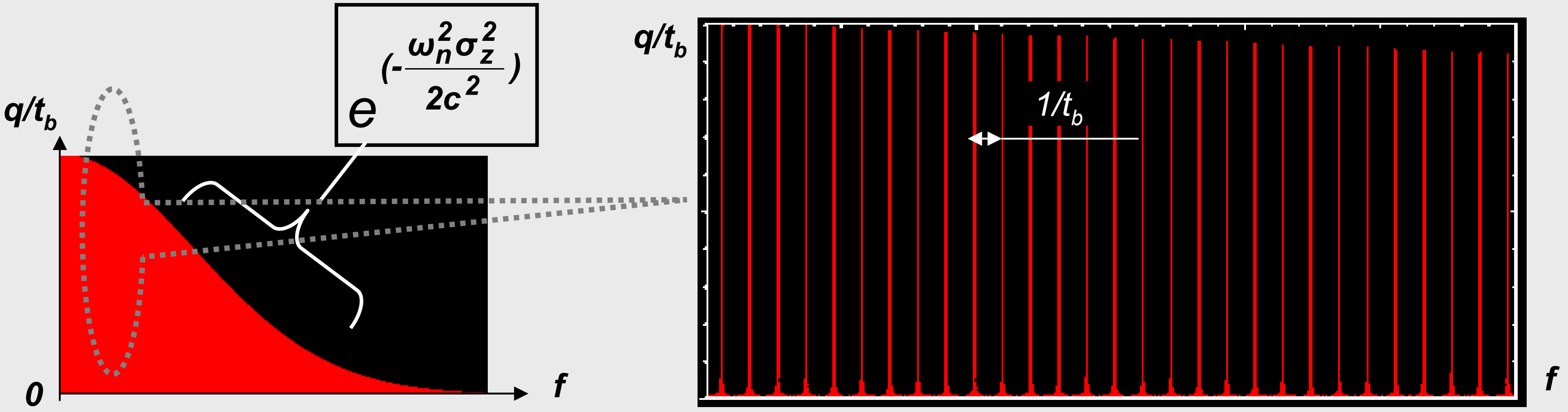
- **Beam instabilities and/or dilution of emittance**
- **Bunch-to-bunch energy modulation**
- **Additional cryogenic loss**

Excitation:

Time structure of the beam

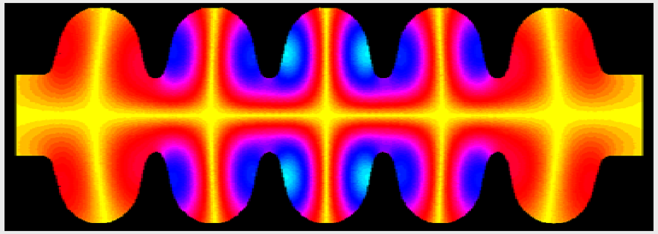


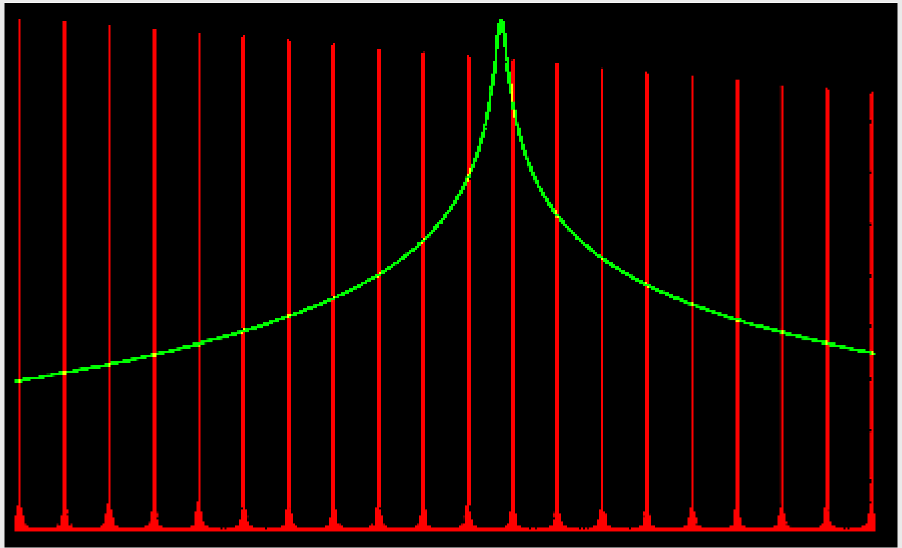
Spectrum of the beam



4. Multi-cell Structures and Weakly Coupled Structures

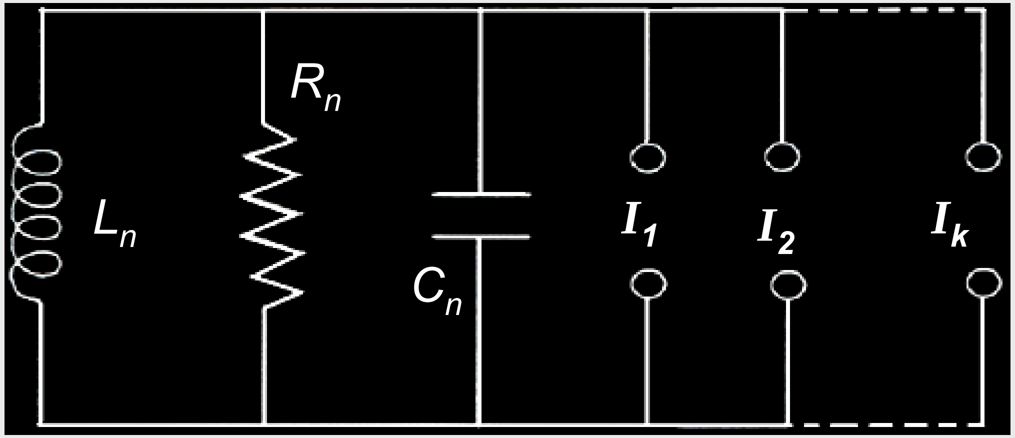
Mode No. *n* : $\{ \omega_n, (R/Q)_n, Ql_n \}$





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

Impedance for the mode n



Multi-source excitation

4. Multi-cell Structures and Weakly Coupled Structures

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

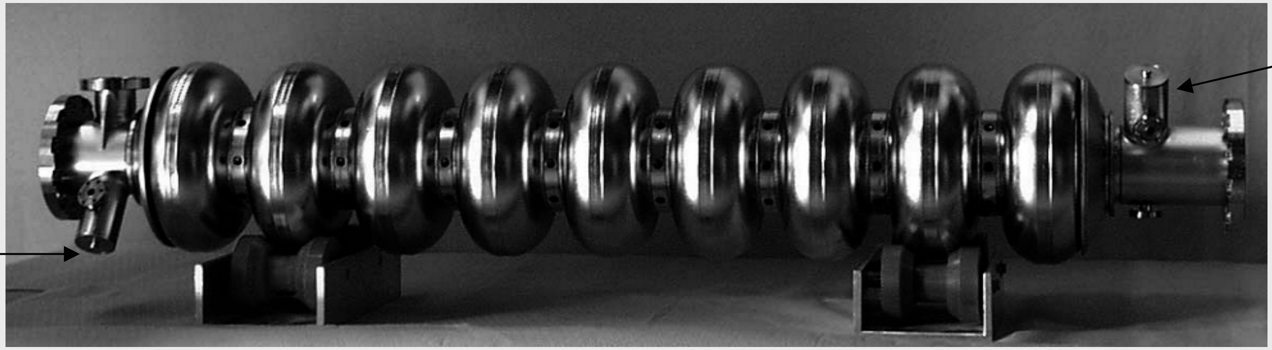
$$P_n = \frac{1}{2}\sum_k Z_n(\omega_k)\cdot I_k^2$$

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

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

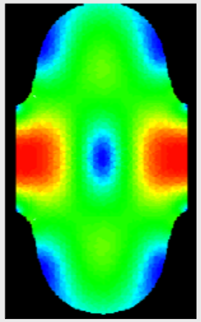
4. Multi-cell Structures and Weakly Coupled Structures

Waveguide HOM ports

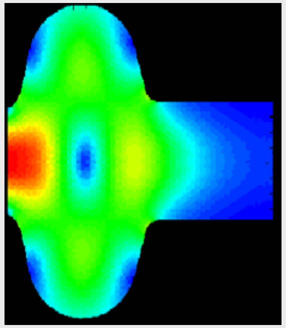
The HOM trapping mechanism is similar to the FM field profile unflatness mechanism:

- **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



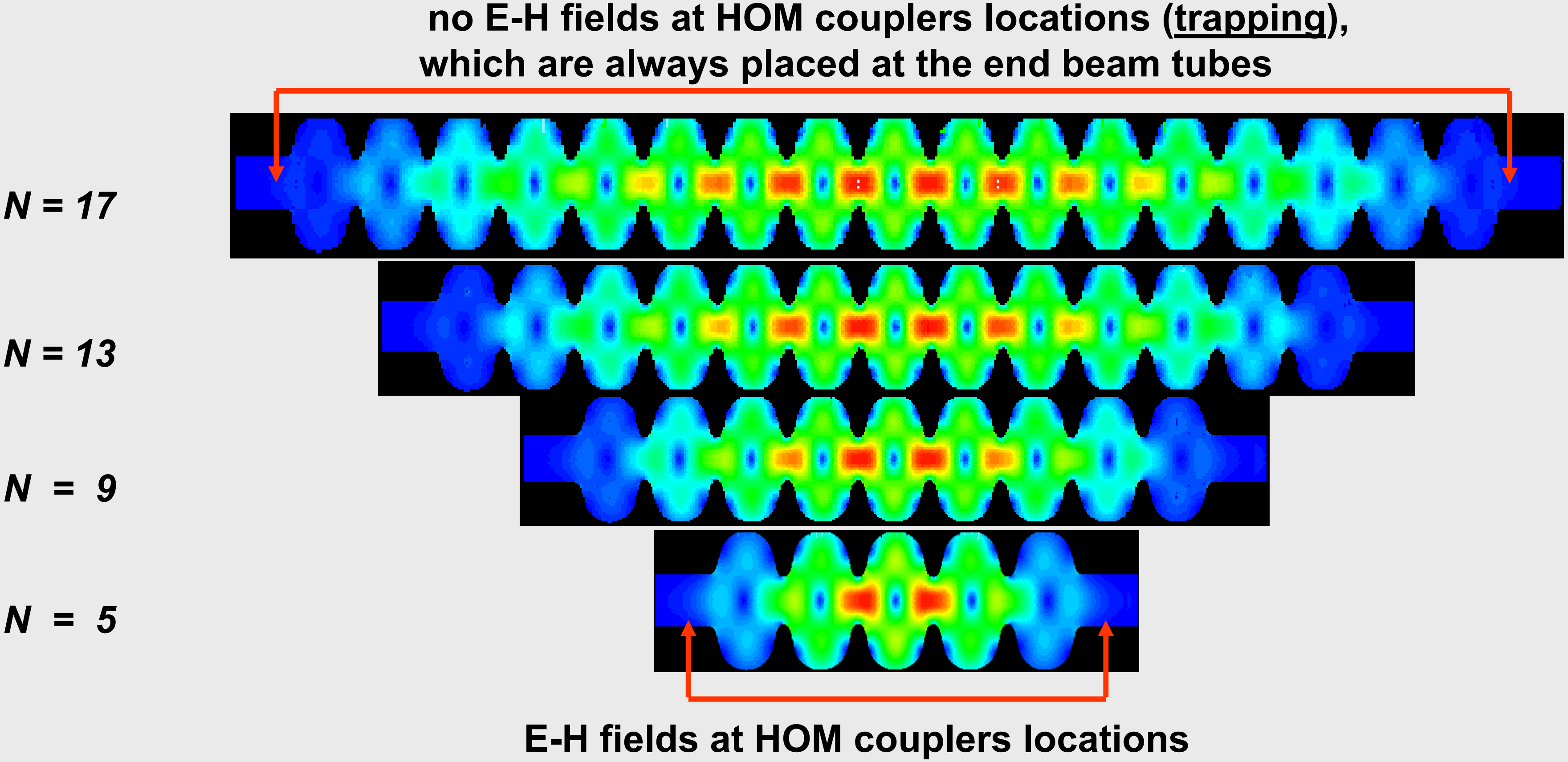
That is why they hardly resonate together



f = 2415 MHz

4. Multi-cell Structures and Weakly Coupled Structures

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



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

4. Multi-cell Structures and Weakly Coupled Structures

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.

4. Multi-cell Structures and Weakly Coupled Structures

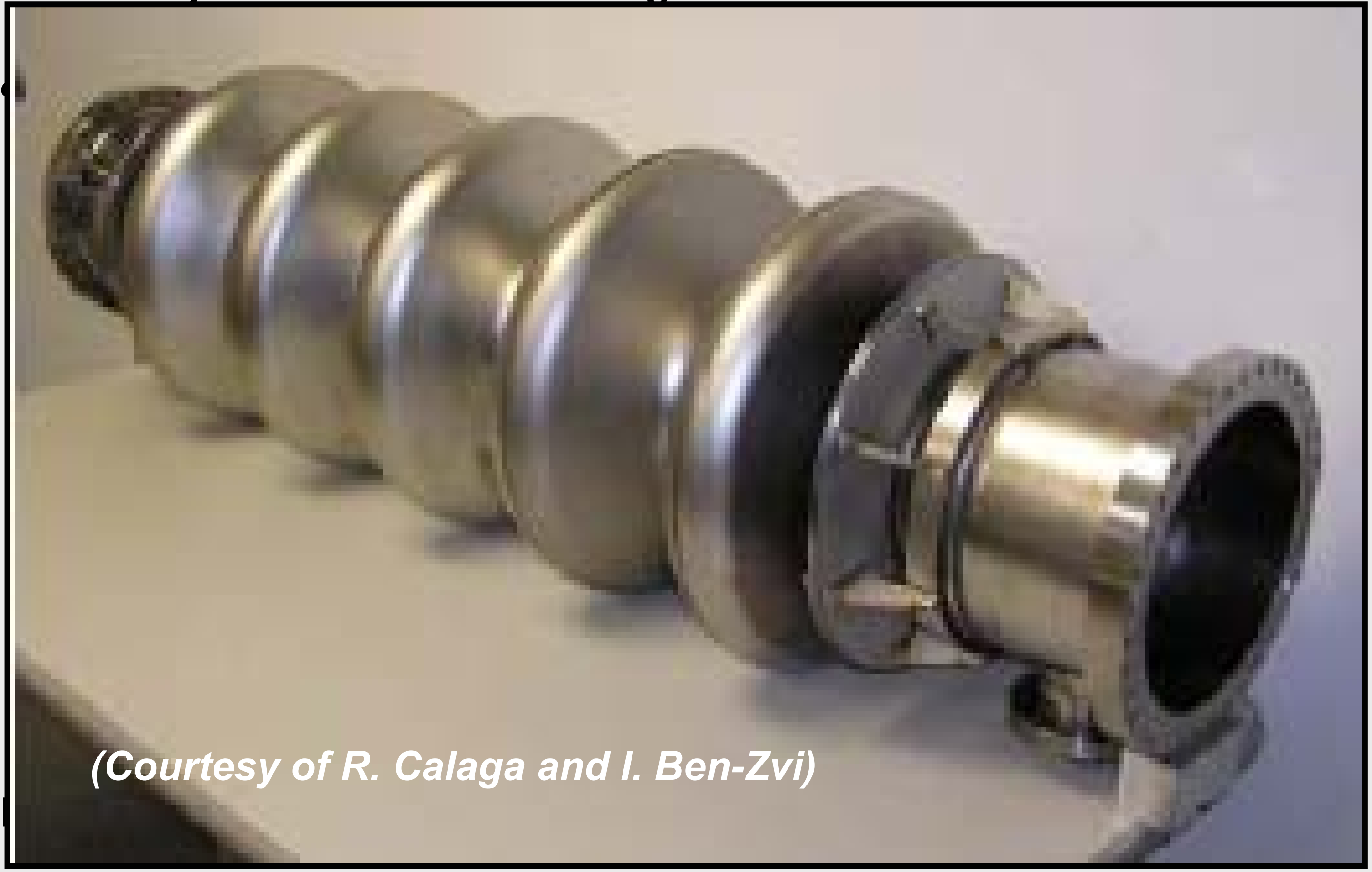
1. **Open irises of the inner cells and end-cells (bigger $k_{cc,HOM}$) and making shape of both very similar**

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

Monopole mode k_{c}

f_{HOM} = 1394 MHz

f_{HOM} = 1403 MHz



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

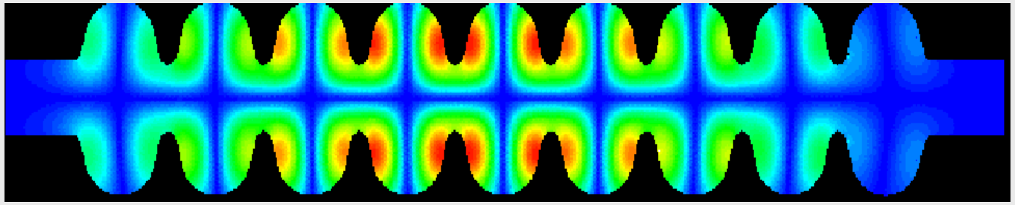
The method causes (
relevant.

4. Multi-cell Structures and Weakly Coupled Structures

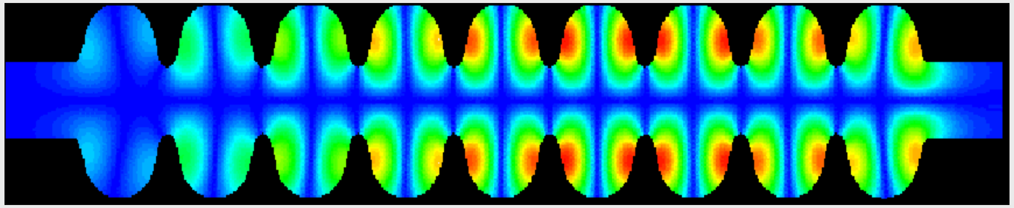
2. Tailor end-cells to equalize HOM frequencies of inner- and end-cells.

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

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

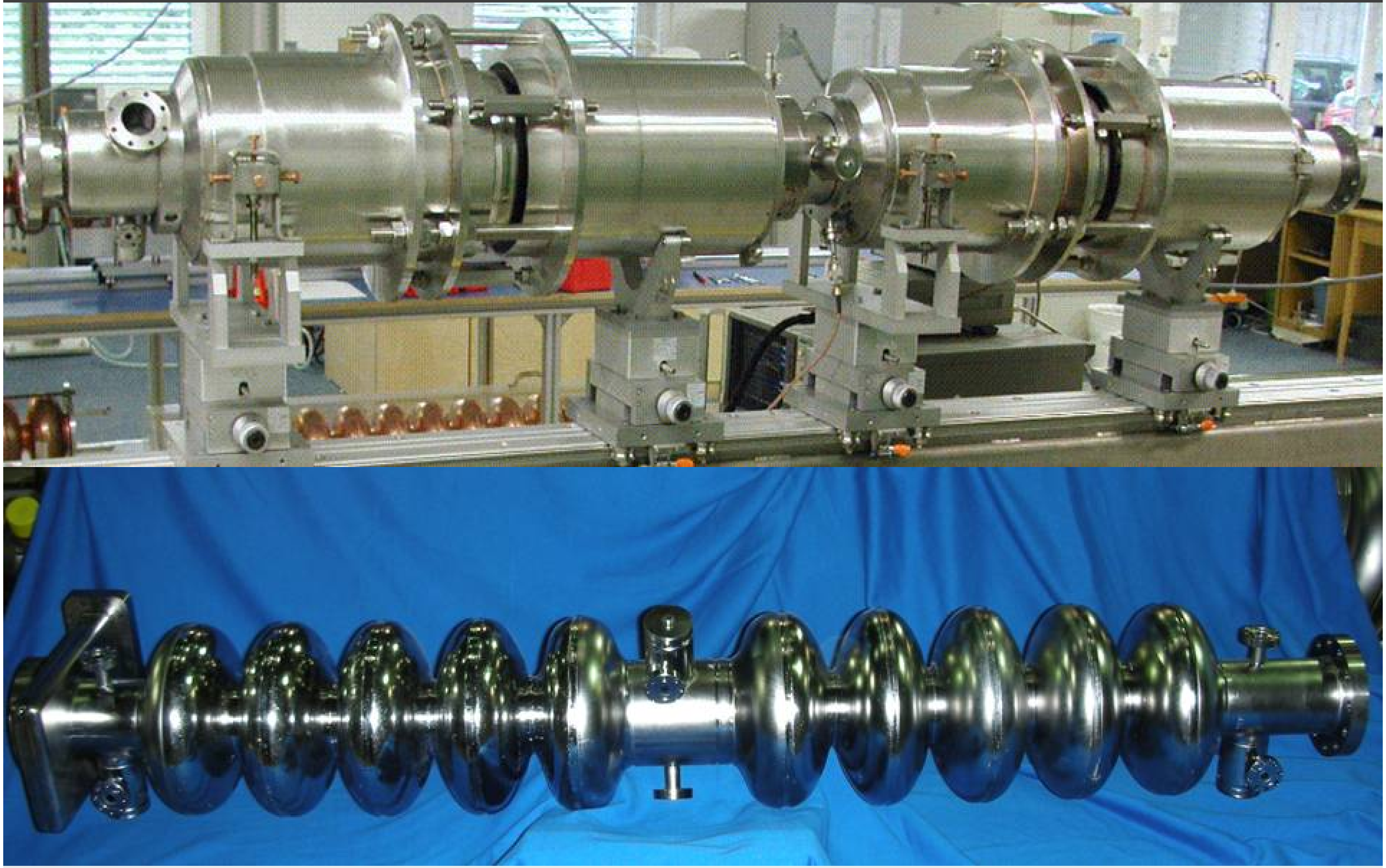


The highest mode in the passband
f_{HOM} = 2458 MHz



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



[...]

- Left out
  - Main coupler power estimation
  - Mode measurement for vertical test

4. Multi-cell Structures and Weakly Coupled Structures

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*

[...]

- Left out
  - – Simulation methods
  - – Vertical Testing

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:

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
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.

Mechanical Design: Detuning

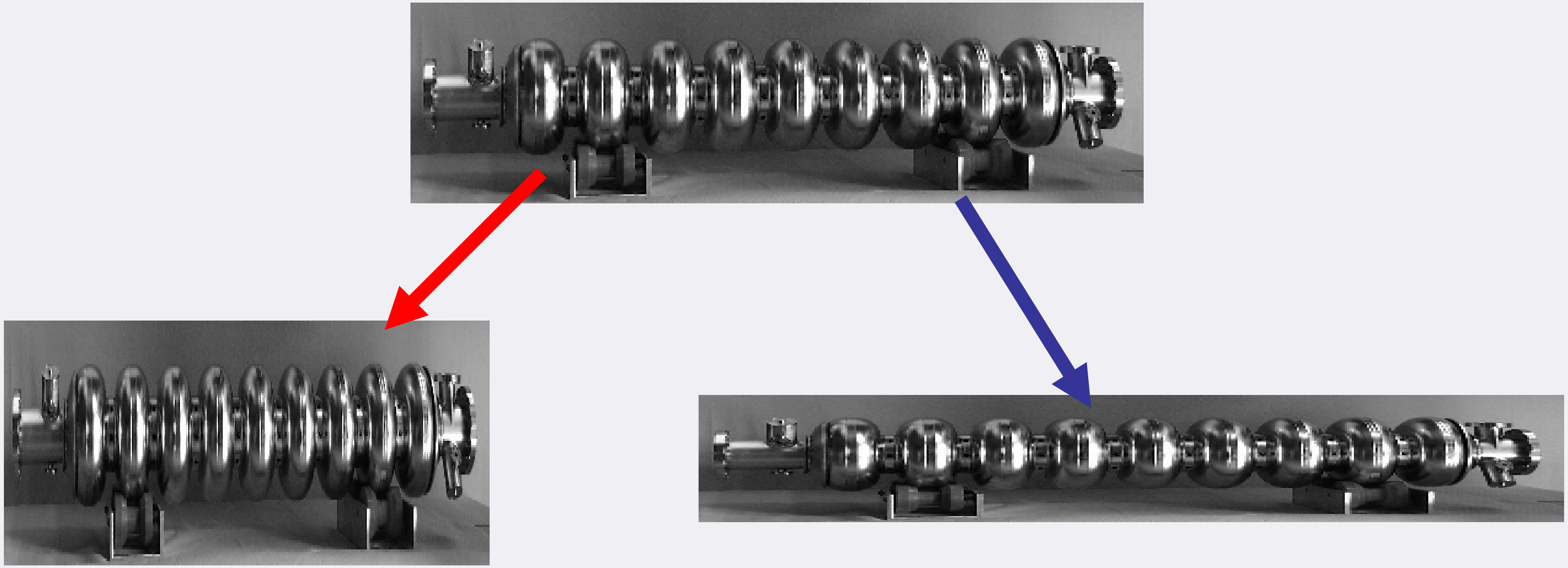
- In many cases a deformation of a cavity leads to frequency change
- Vibrations = ‚Microphonics‘
  - Pumps, ground motion etc.
- Lorentz-force due to RF fields
  - High electromagnetic fields exert a mechanical force on the cavity walls
  - sometimes also called ‚radiation pressure‘
  - For pulsed operation this needs to be compensated for efficient operation

Basic Principle of Frequency Tuning

The frequency of a cavity is determined by the equator diameter: f ~ 1/D

- The simplest way to change the diameter of a cavity is to change its length.

A length change of 3um results in a frequency change of 1kHz



Compression:

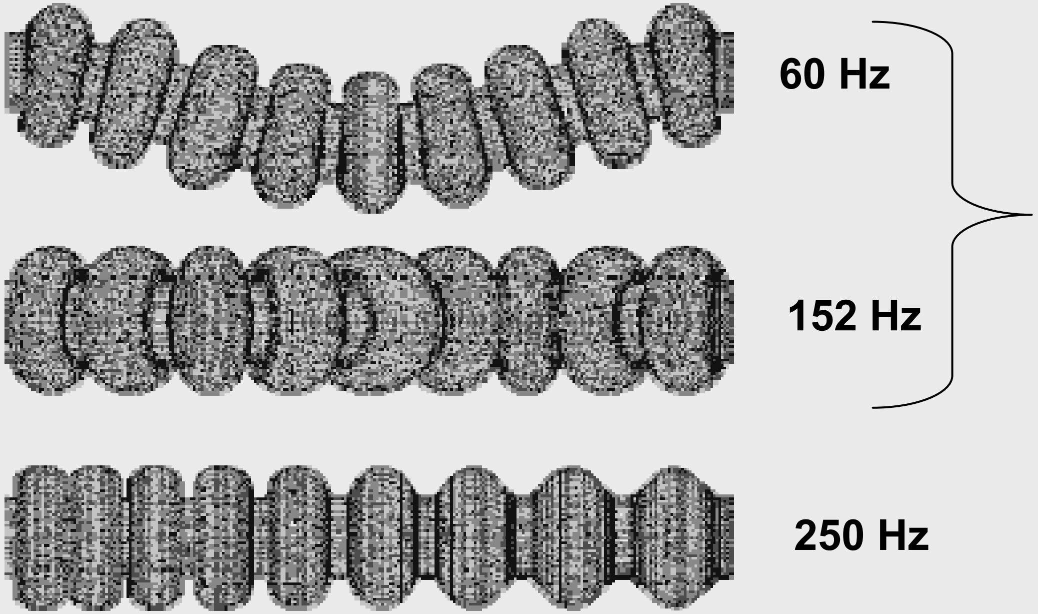
Frequency decreases

Extension:

Frequency increases

8. Mechanical Design

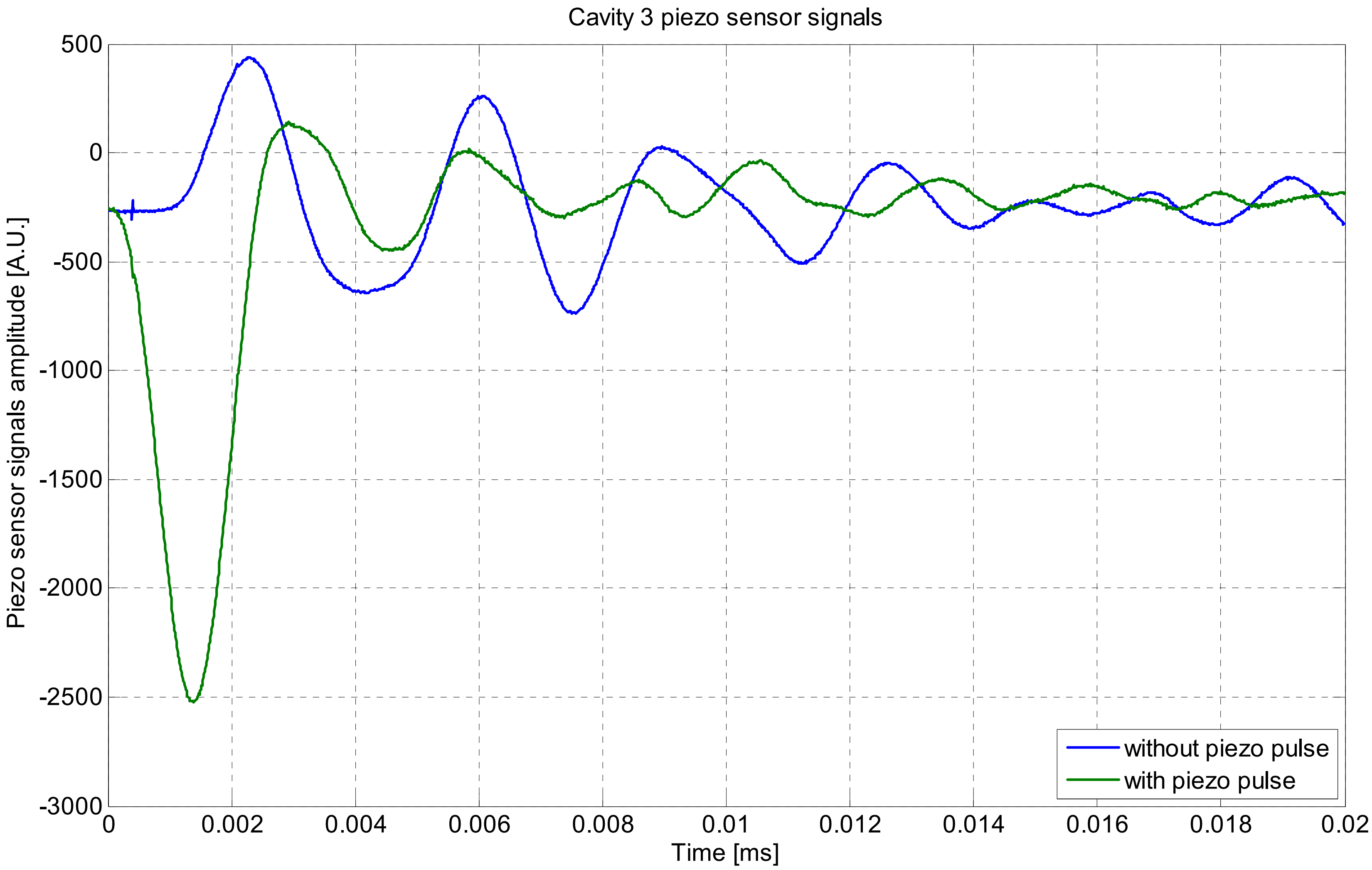
Mechanical Resonances of a multi-cell cavity



TESLA structure

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

Cavity ´Ringing´ excited by RF Pulse

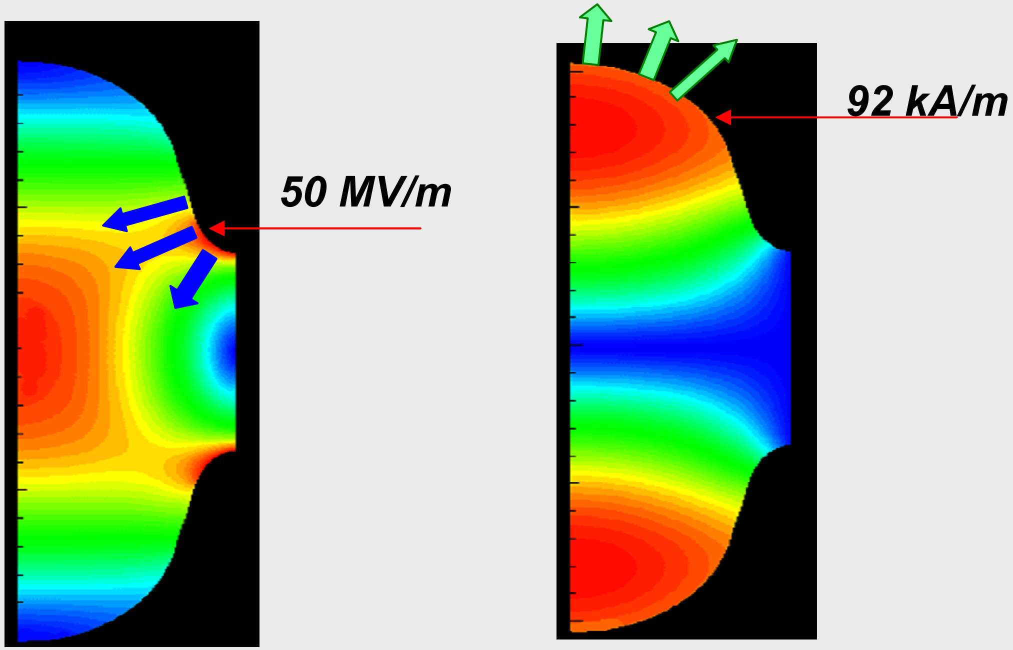


8. Mechanical Design

The mechanical design of a cavity follows its RF design:

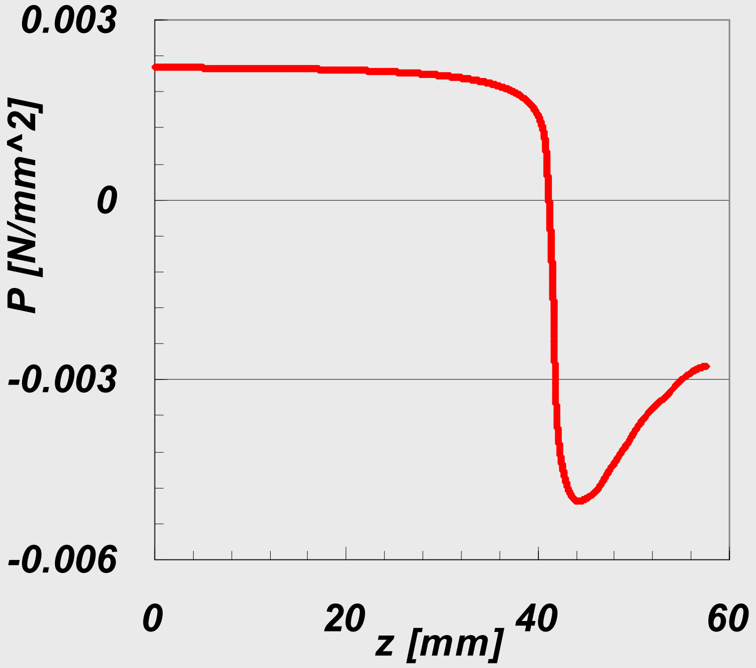
- **Lorentz Force Detuning**
- **Mechanical Resonances**

Lorentz Force Detuning

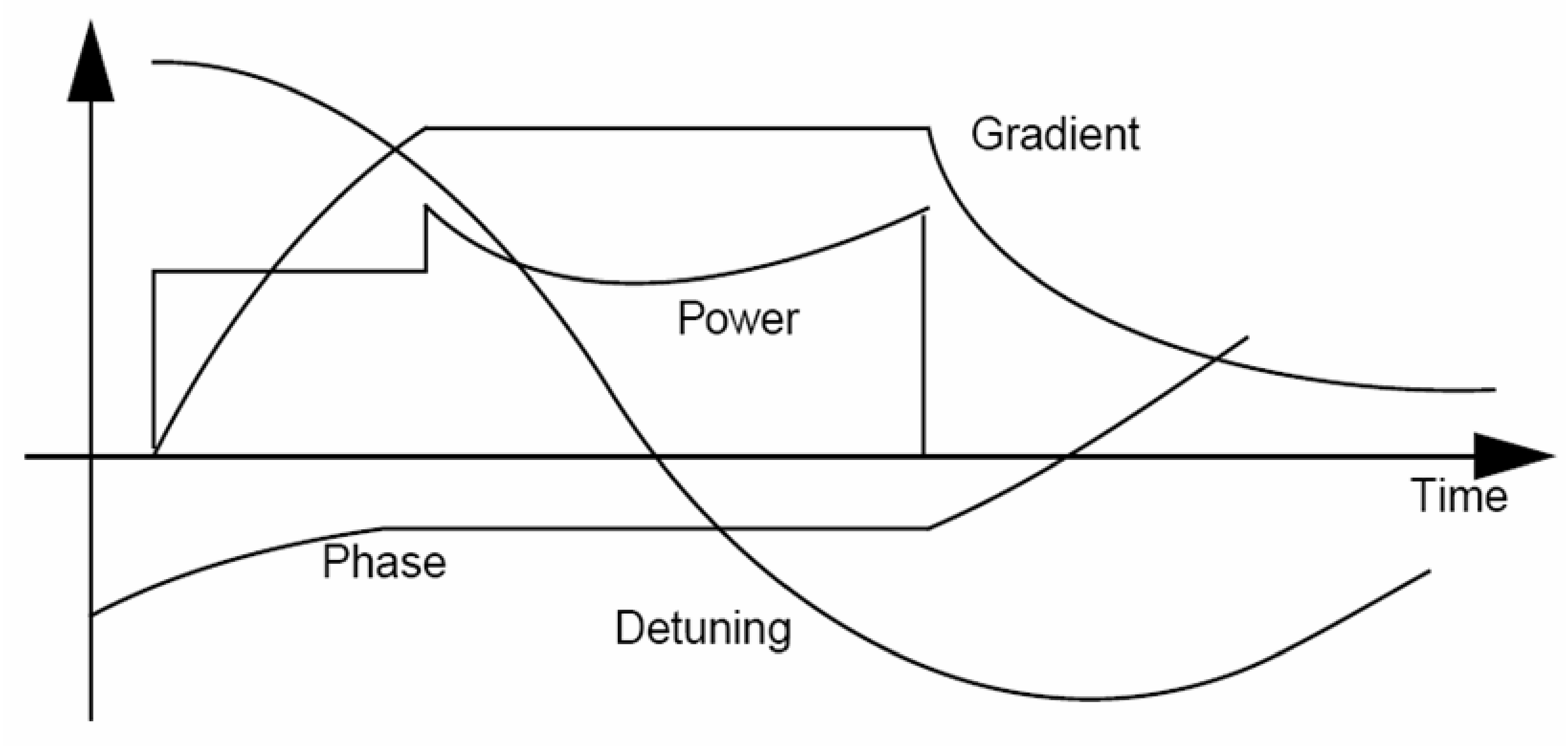


E and H at E_{acc} *= 25 MV/m in TESLA inner-cup*

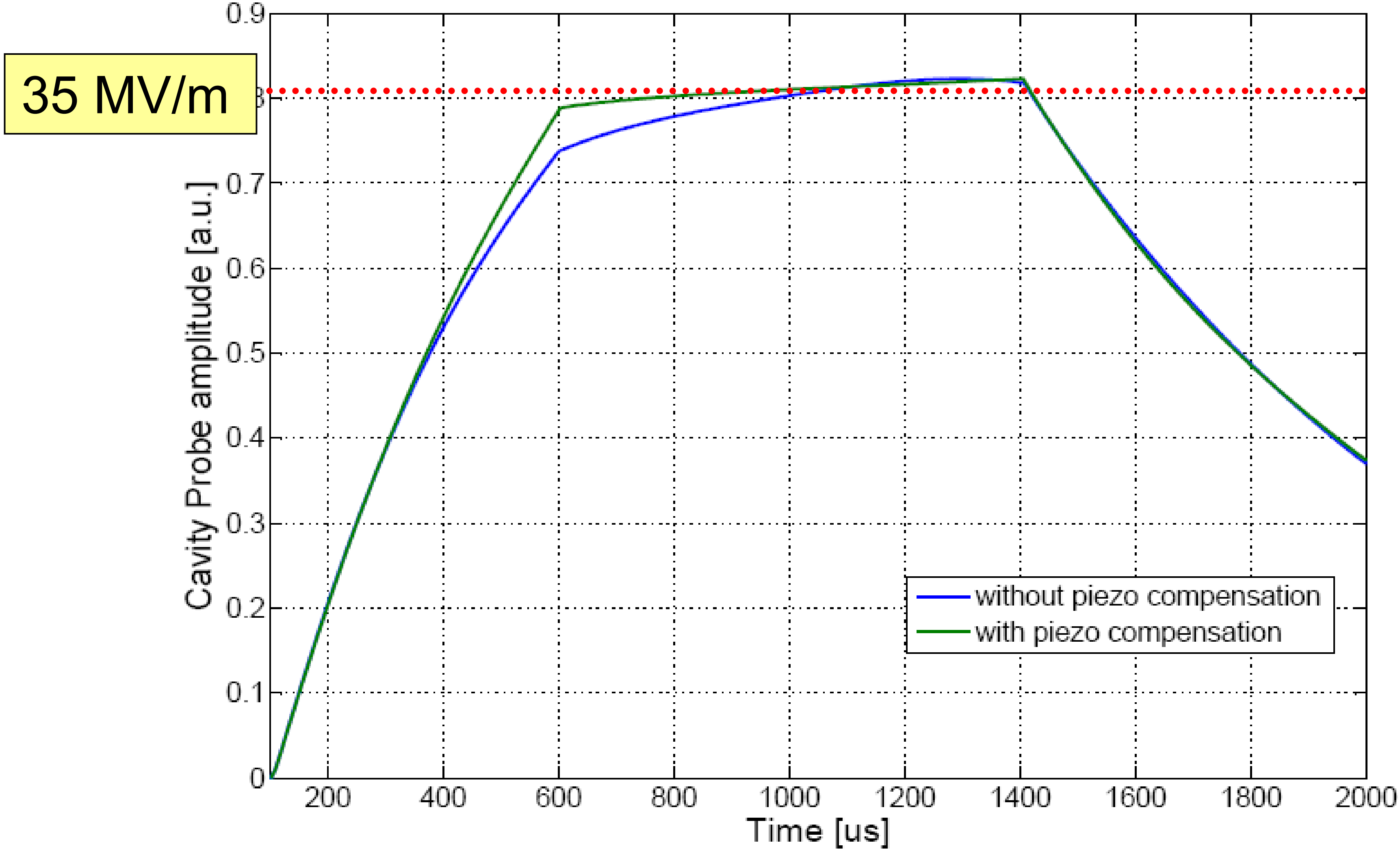
$$P=\frac{\mu_0 H_s^2-\varepsilon_0 E_s^2}{4}$$



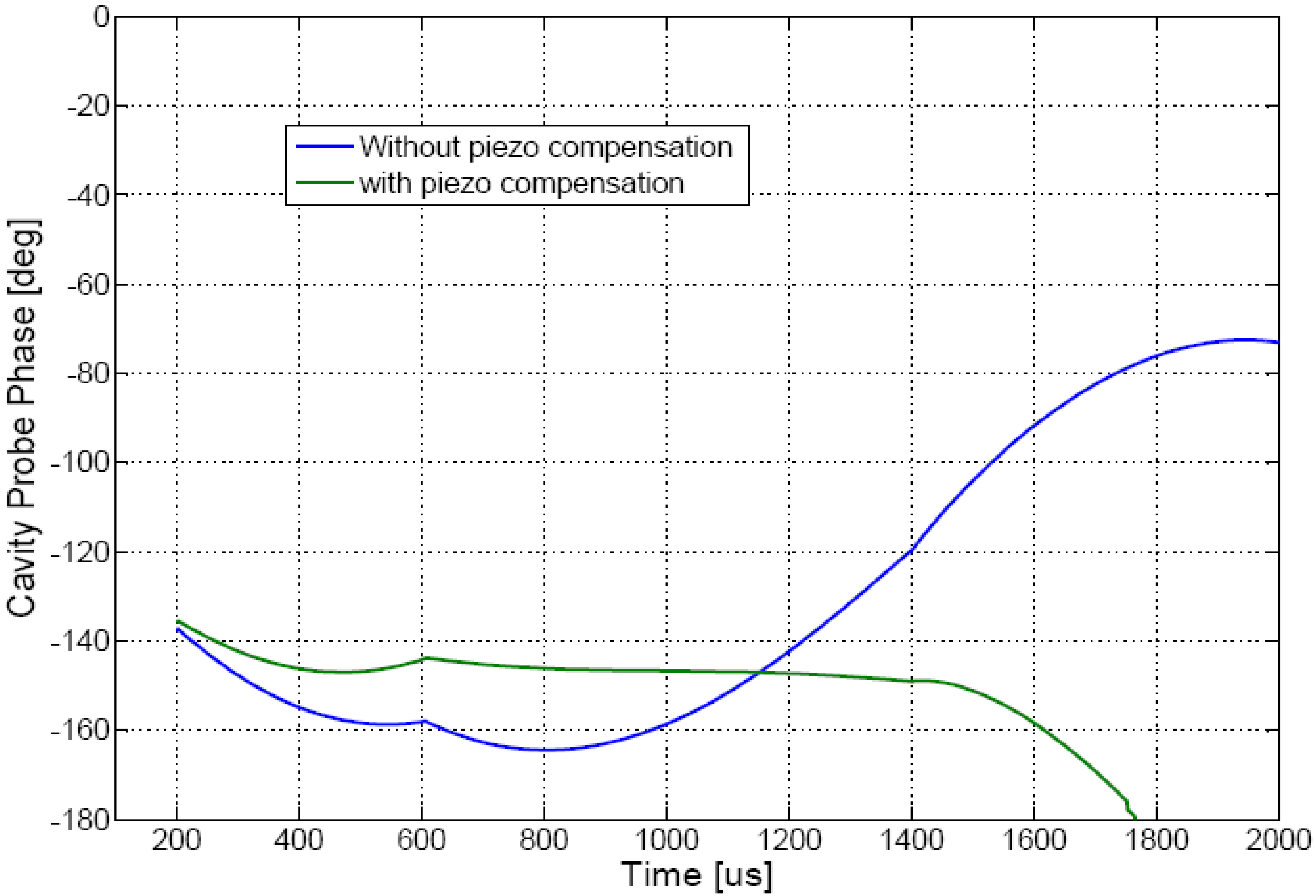
Lorentz-Force Detuning - Scheme



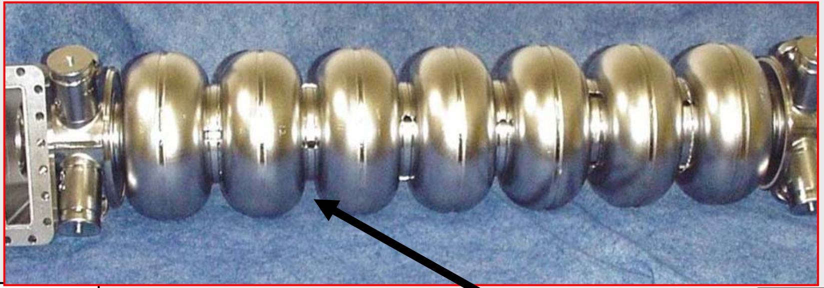
Cavity 3: Gradient

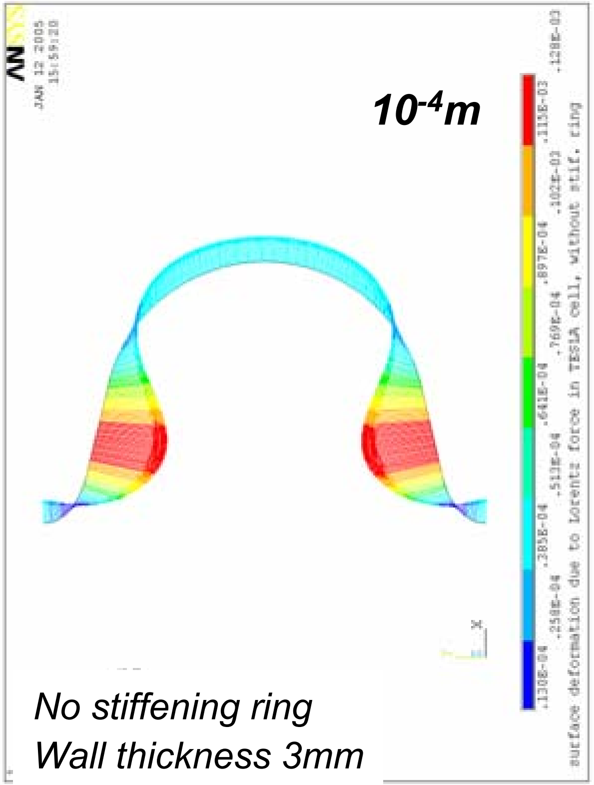

35 MV/m

Cavity 3: Phase



8. Mechanical Design

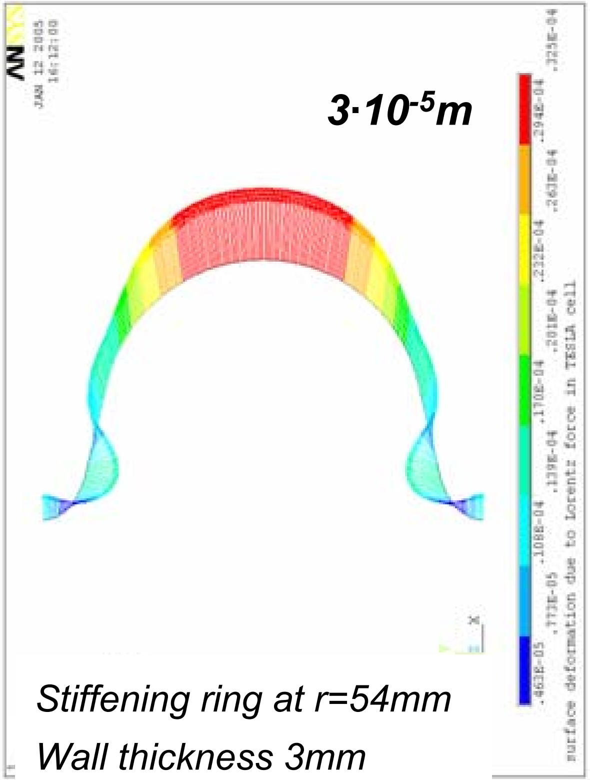




10^{-4}m

No stiffening ring
Wall thickness 3mm

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



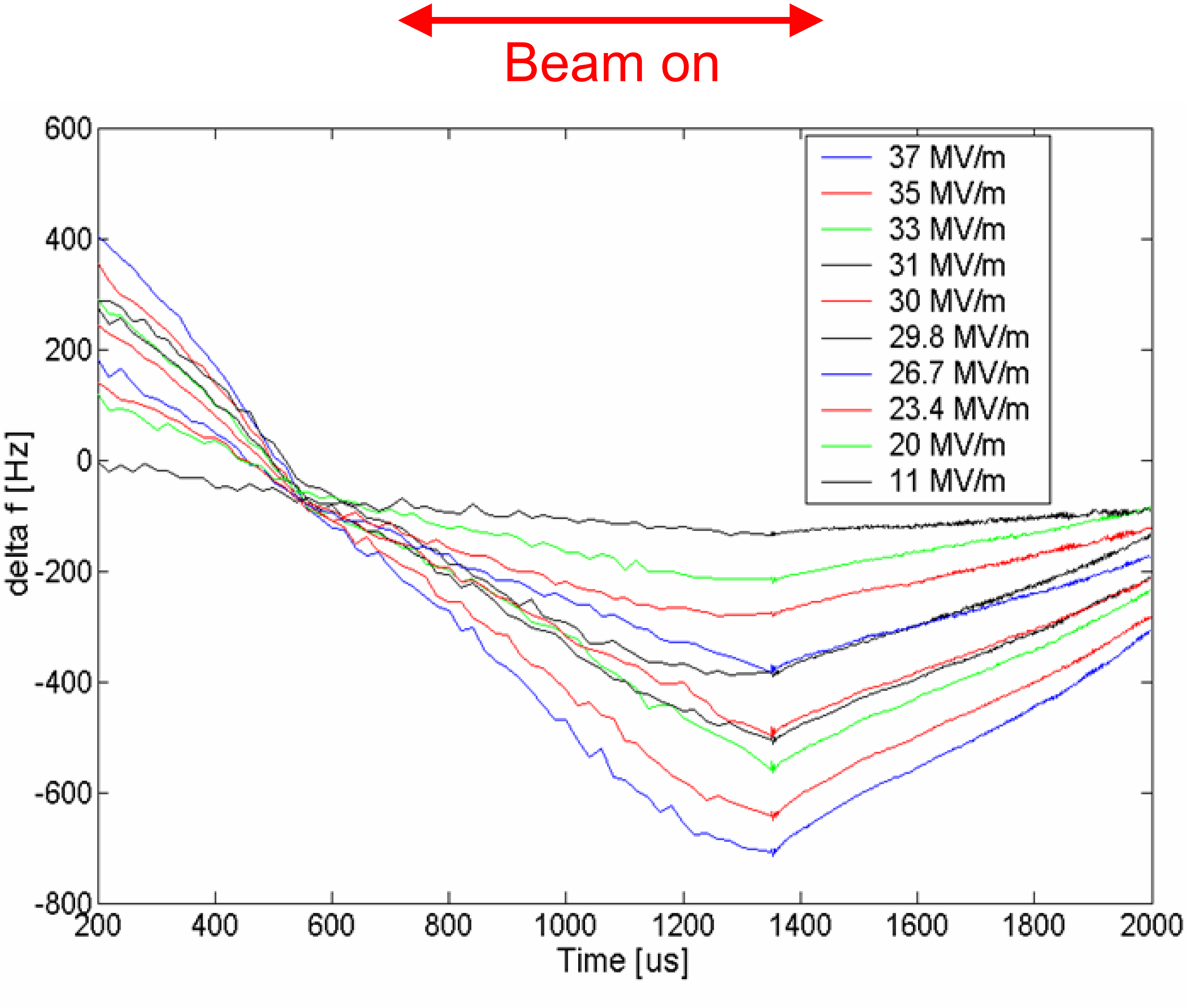
$3 \cdot 10^{-5}$m

Stiffening ring at r=54mm
Wall thickness 3mm

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

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

Frequency detuning during RF pulse



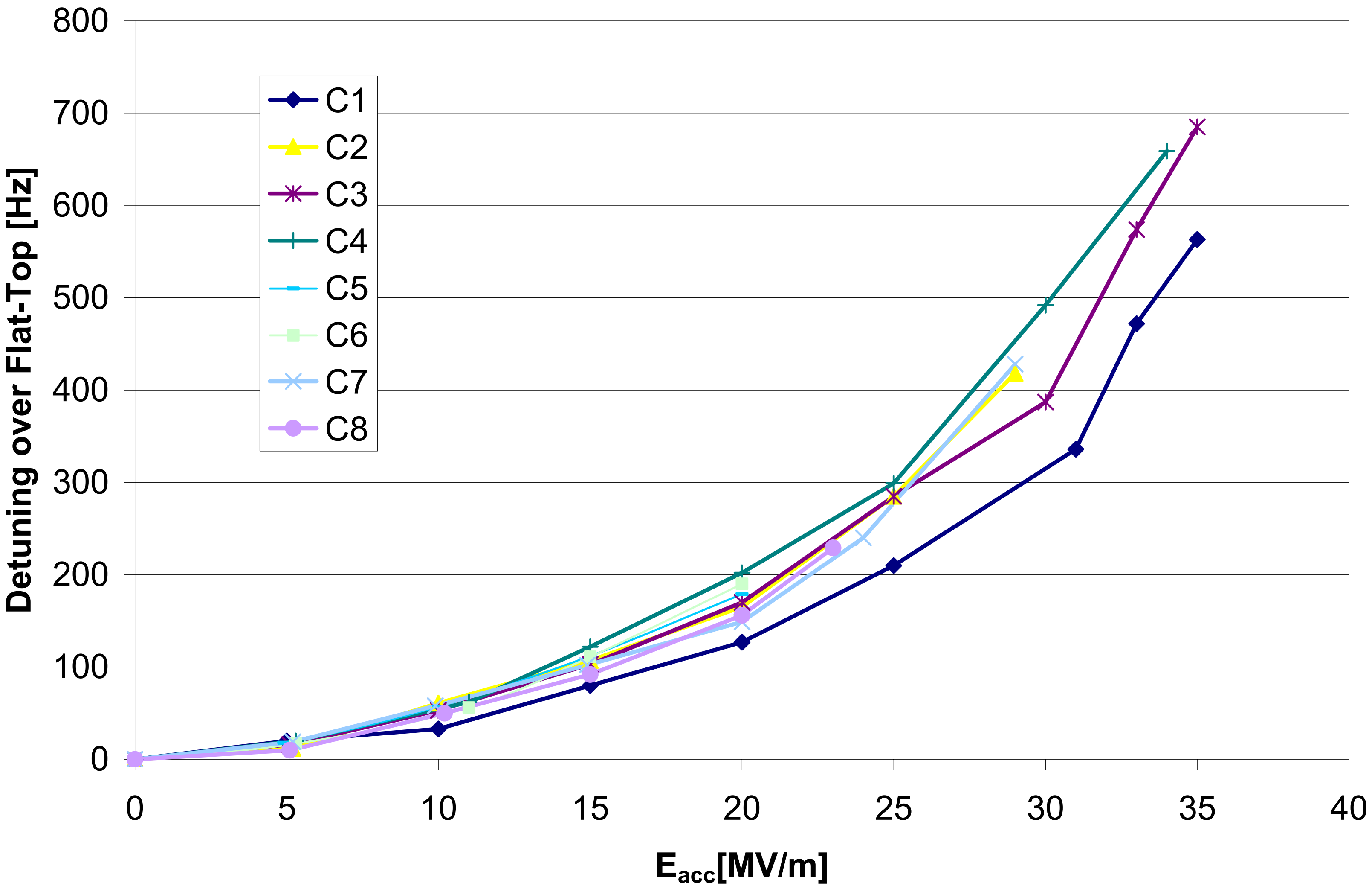
Frequency detuning due Lorentz forces of the electromagnetic field in the cavities:

$\Delta f = K \bullet E_{acc}^2$

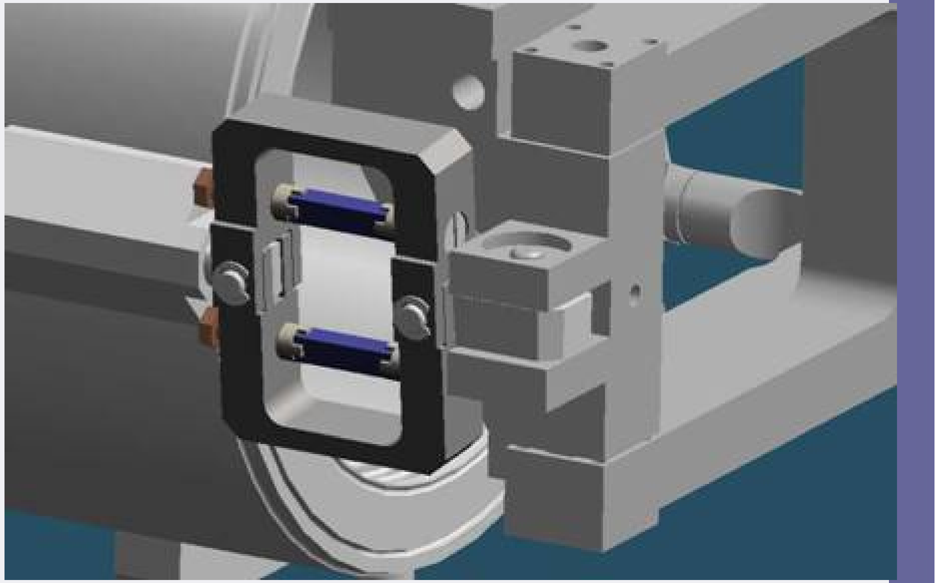
where $K \approx 1$ Hz / $(MV/m)^2$

Remember: Cavity bandwidth with main coupler is ≈ 300 Hz

Lorentz Force Detunings in Module 6



Fast Tuner with Piezos



Maximal load:

- <5 kN

Operating temperature

- 4 -10 K in isolation vacuum
- Stroke (and capacity) reduced to about 10-20% of room temperature stroke

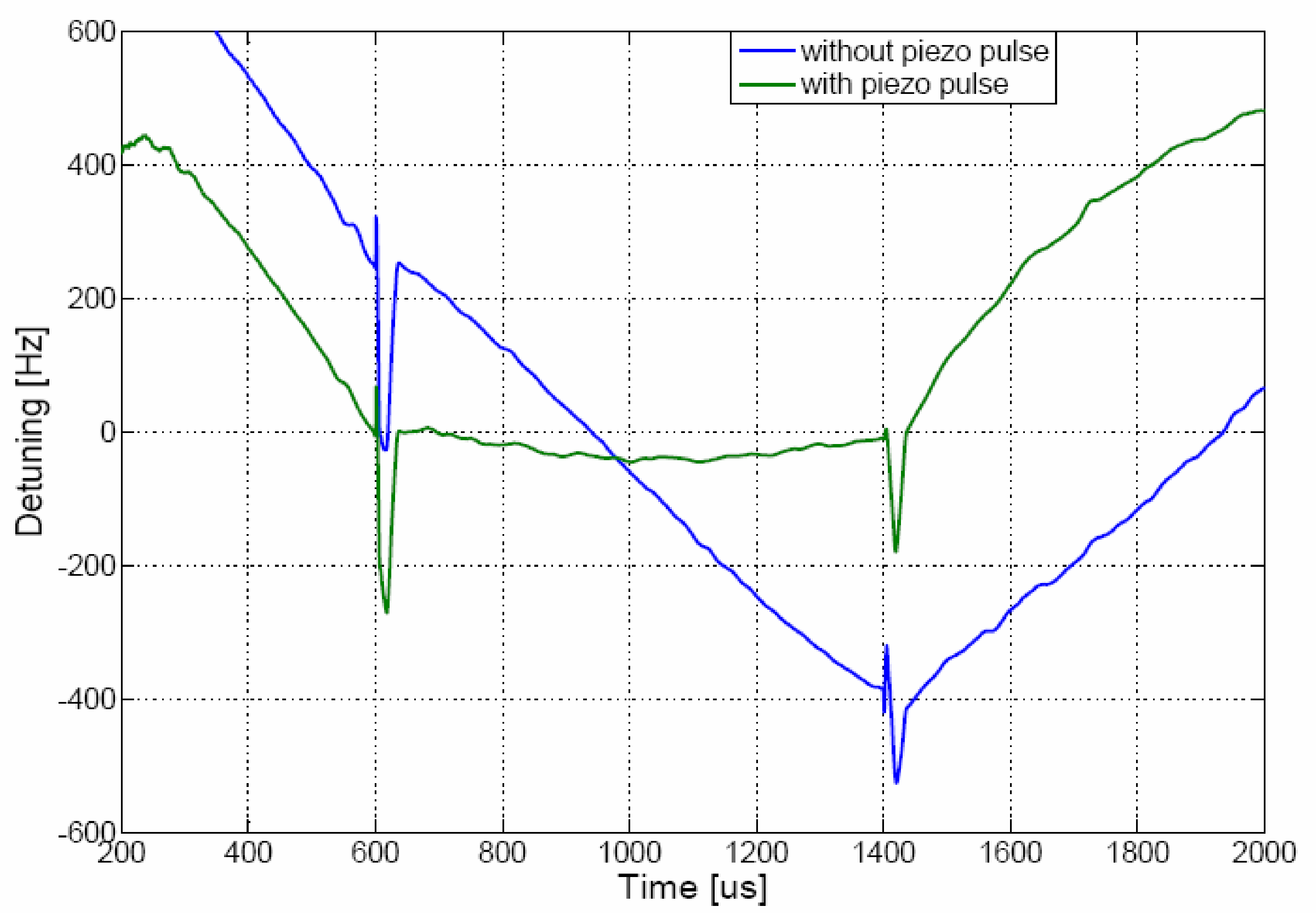
Preload force

- 0,8-1,2 kN/cm^2 for highest lifetime

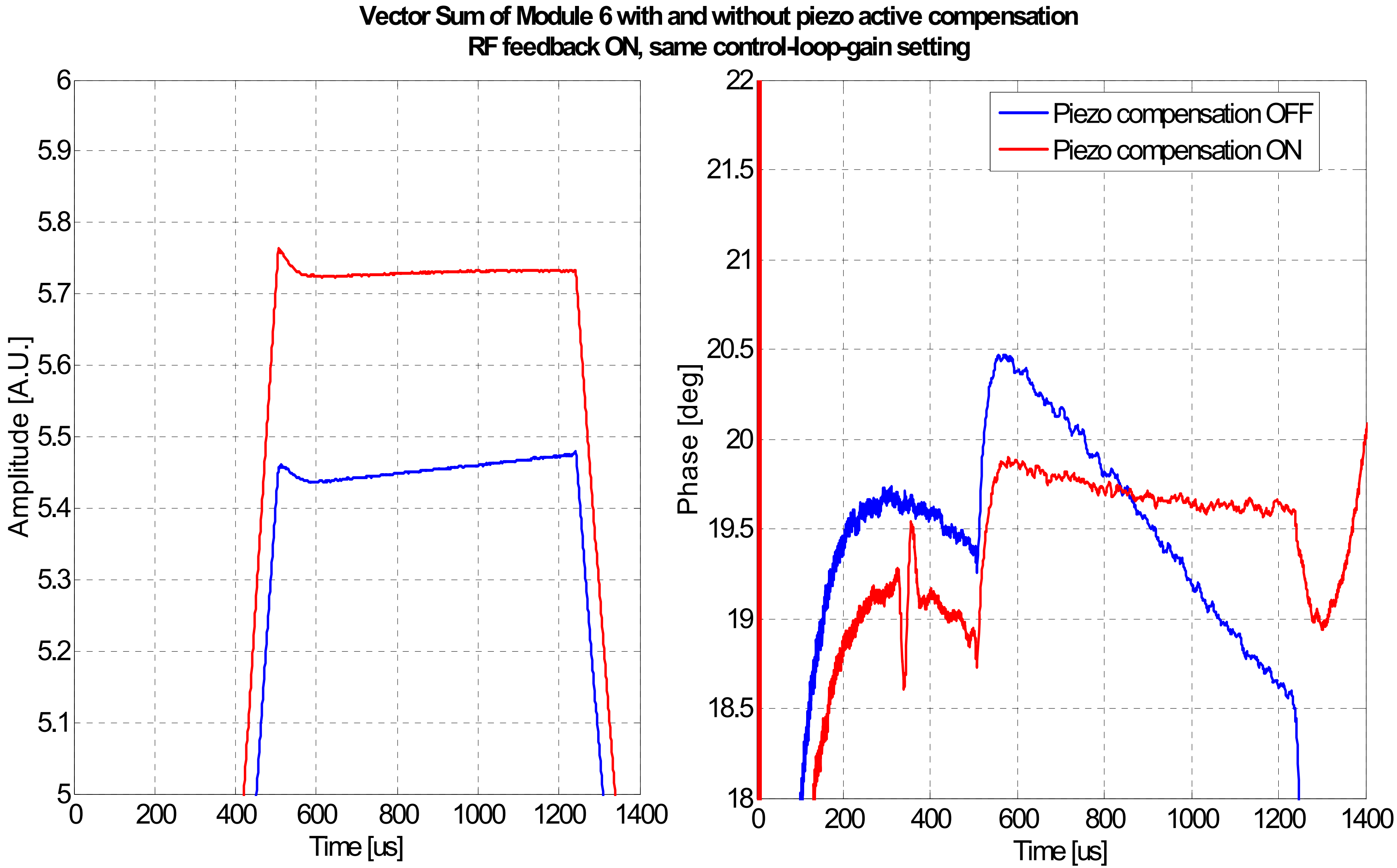
Sensor and actuator configuration

- One active element
- other element as sensor and for redundancy

Cavity 3: Detuning

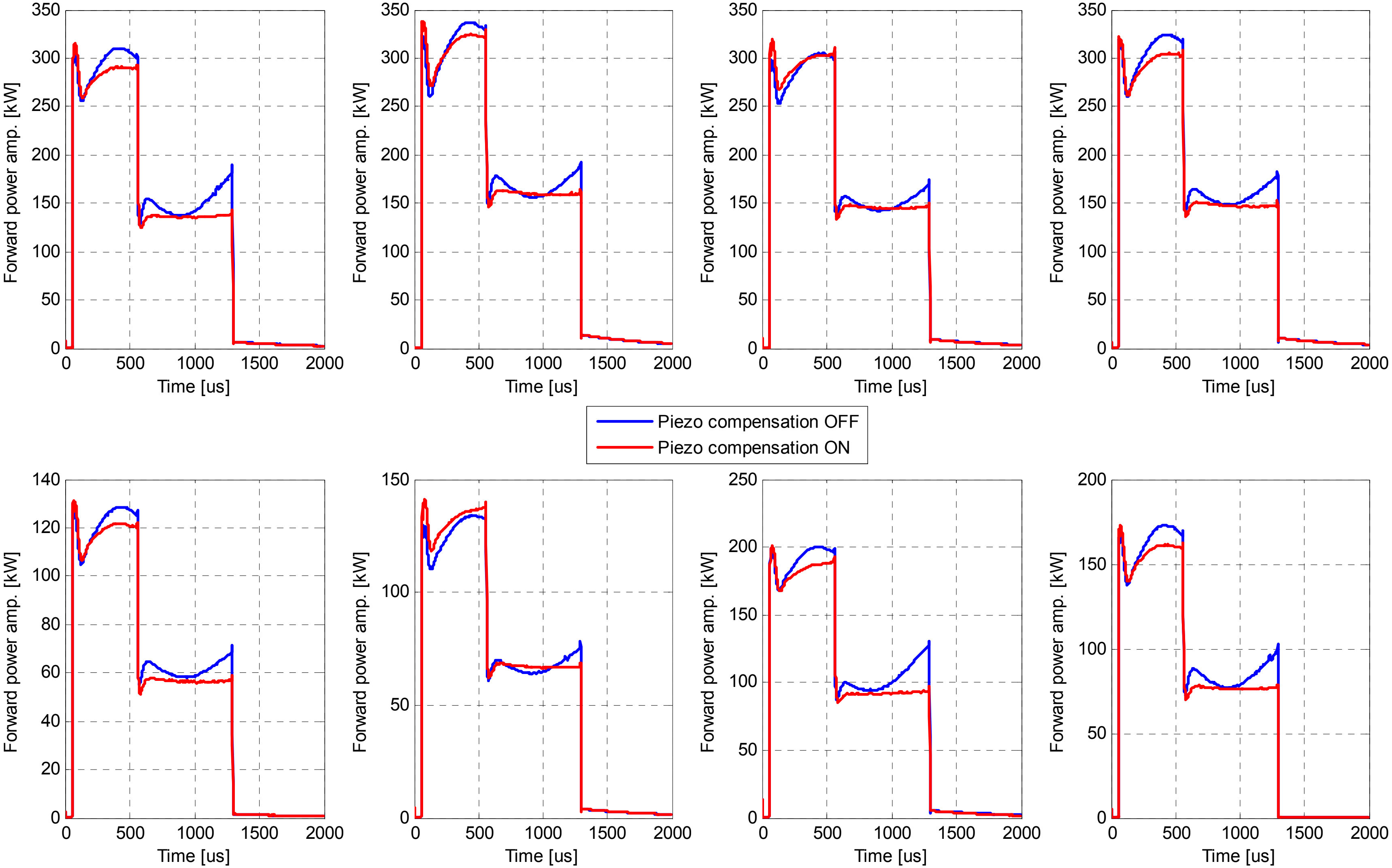


Operation of Full module – Vector-Sum



Operation of Full Module – Forward Power

RF feedback switched ON on module 6 in CMTB. Collection of all amplitude of forward power signals with and without piezo active compensation



Summary Mechanical Design

- Deformations of the cavity due to vibrations or operation need to be taken into account during design
  - E.g. stiffening rings
- For pulsed operation active elements e.g. piezo-stacks can be used to ensure efficient operation at high gradient

Thanks for your attention!