New Geometries Overview

(elliptical cavities)

J. Sekutowicz, DESY

1. Criteria for the inner-cell optimization
2. Multi-cell structures; Number of cells
3. Elliptical cavities ß=1
4. Elliptical cavities ß<1
5. Summary

In this presentation I will report about the work of many colleagues. I want to express my thanks to:

- D. Barni
- I. Ben-Zvi
- R. Calaga
- E. Chiavieri
- G. Ciovati
- E. Haebel
- W. Hartung
- P. Kneisel
- S. Li
- A. Mosnier
- S. Noguchi
- H. Padamsee
- C. Pagani
- P. Pierini
- D. Proch
- K. Saito
- V. Shemelin
- O. Takeda
- T. Tajima
- B. Visentin
- E. Zaplatin

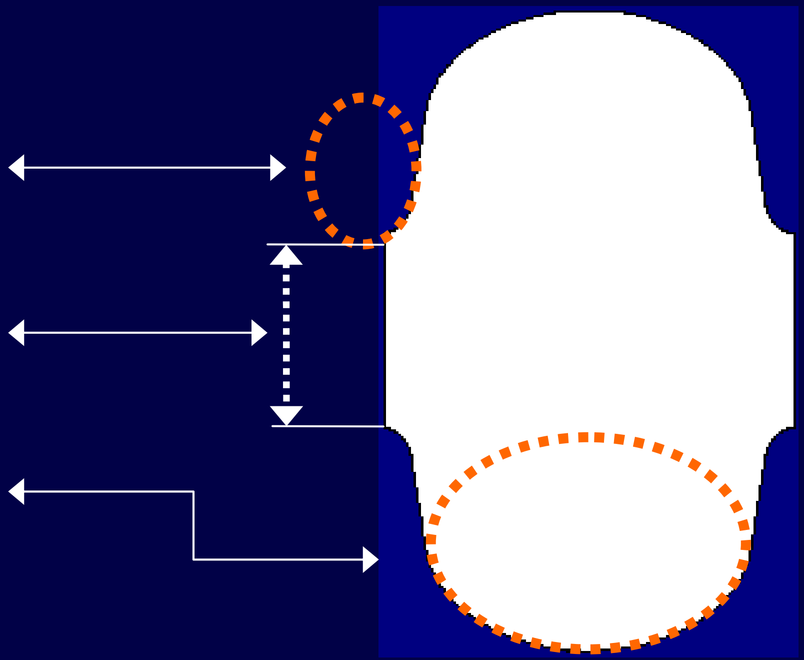
1. Criteria for the inner-cell optimization

RF parameters :

- FM : (R/Q), G, E_{peak}/E_{acc} , B_{peak}/E_{acc} , k_{cc}
- HOM : $k_{\perp}$, $k_{\parallel}$

Geometry :

- iris ellipsis : half-axis h_r , h_z
- iris radius : r_i
- equator ellipsis : half-axis h_r , h_z



1. Criteria for the inner-cell optimization, cont.

Criteria	RF-parameter	Improves when	Cavity example
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
Low HOM impedance	$k_\perp$, $k_\parallel$ ↓	r_i ↑	B-Factory RHIC cooling

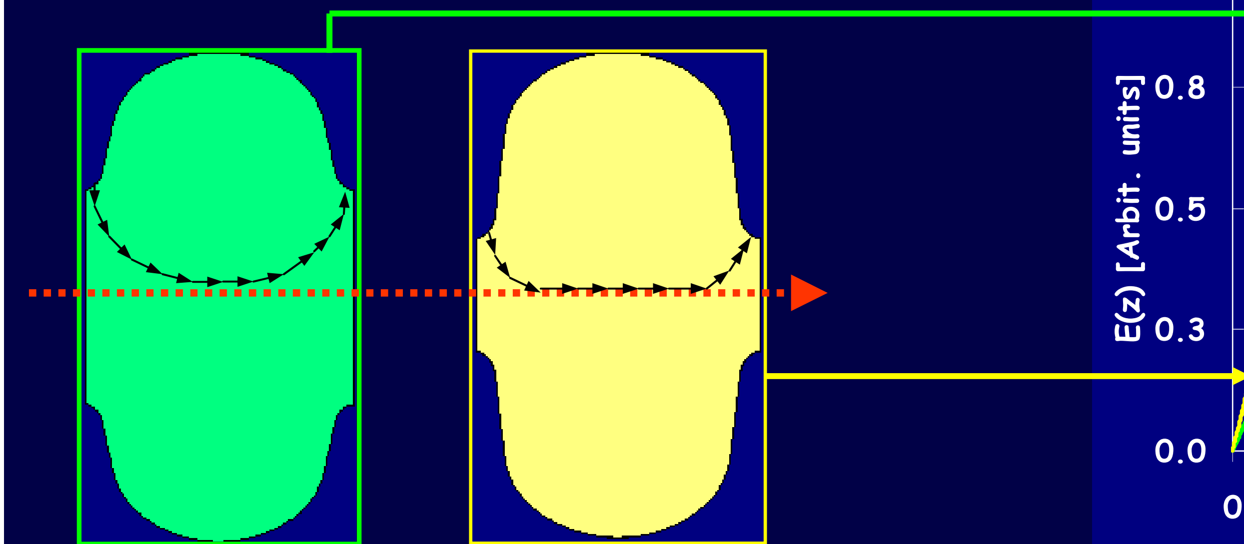
We see here that r_i is a "powerful knob" to trim the RF-parameters

1. Criteria for the inner-cell optimization, cont.

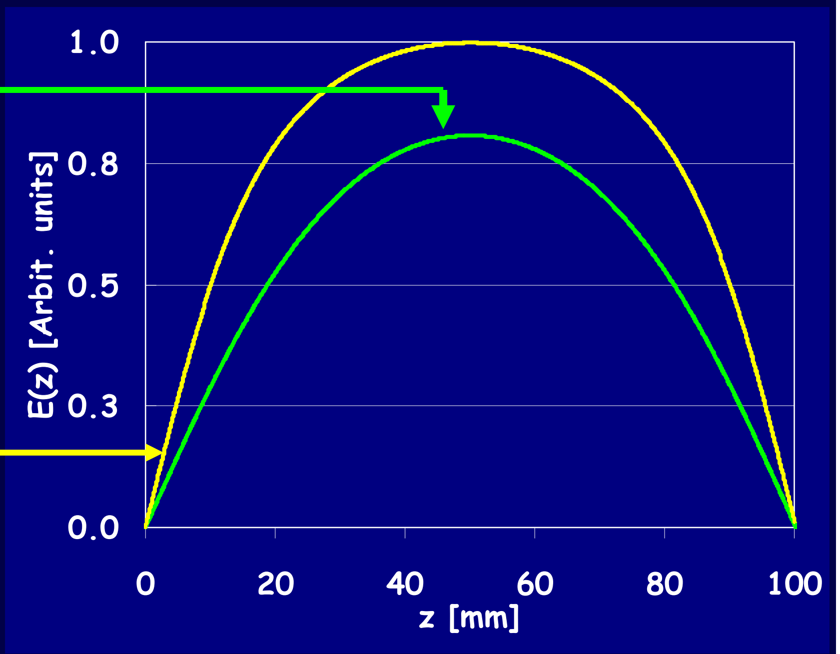
Why for smaller aperture (r_i)

- (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



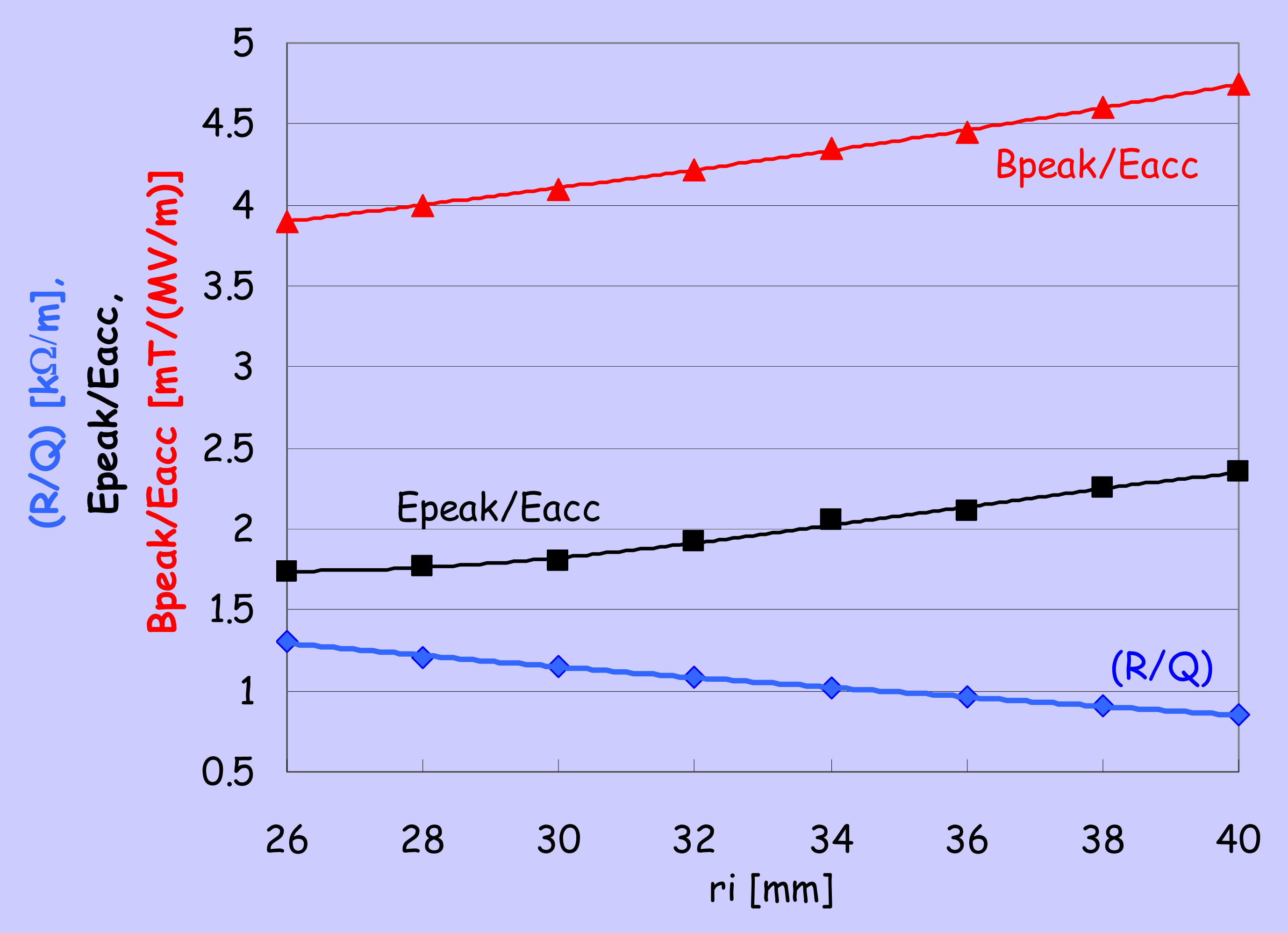
r_i = 40 mm r_i = 20 mm



E_z (z) for small and big iris radius

1. Criteria for the inner-cell optimization, cont.

Example:
f = 1.5 GHz



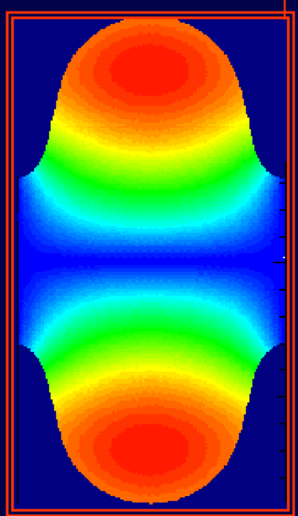
A. Mosnier, E. Haebel, SRF Workshop 1991

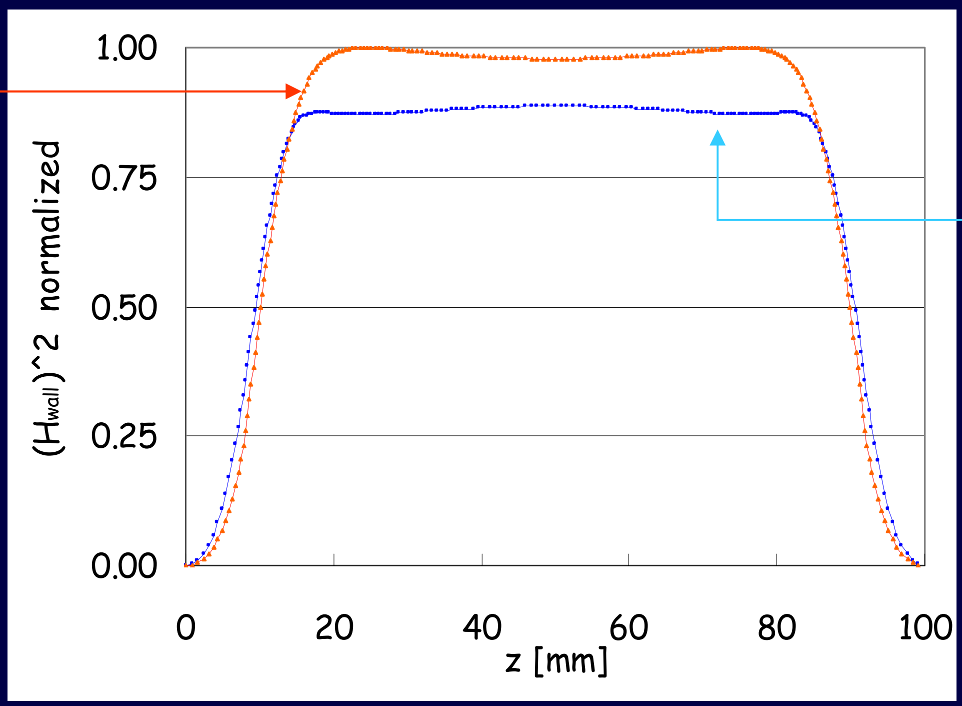
1. Criteria for the inner-cell optimization, cont.

In addition to the iris radius :

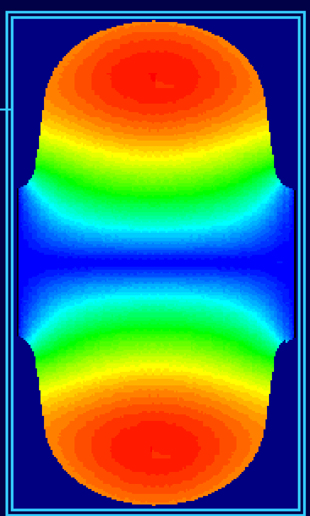
- B_{peak}/E_{acc} (and G) changes vs. Equator shape

1 Joule

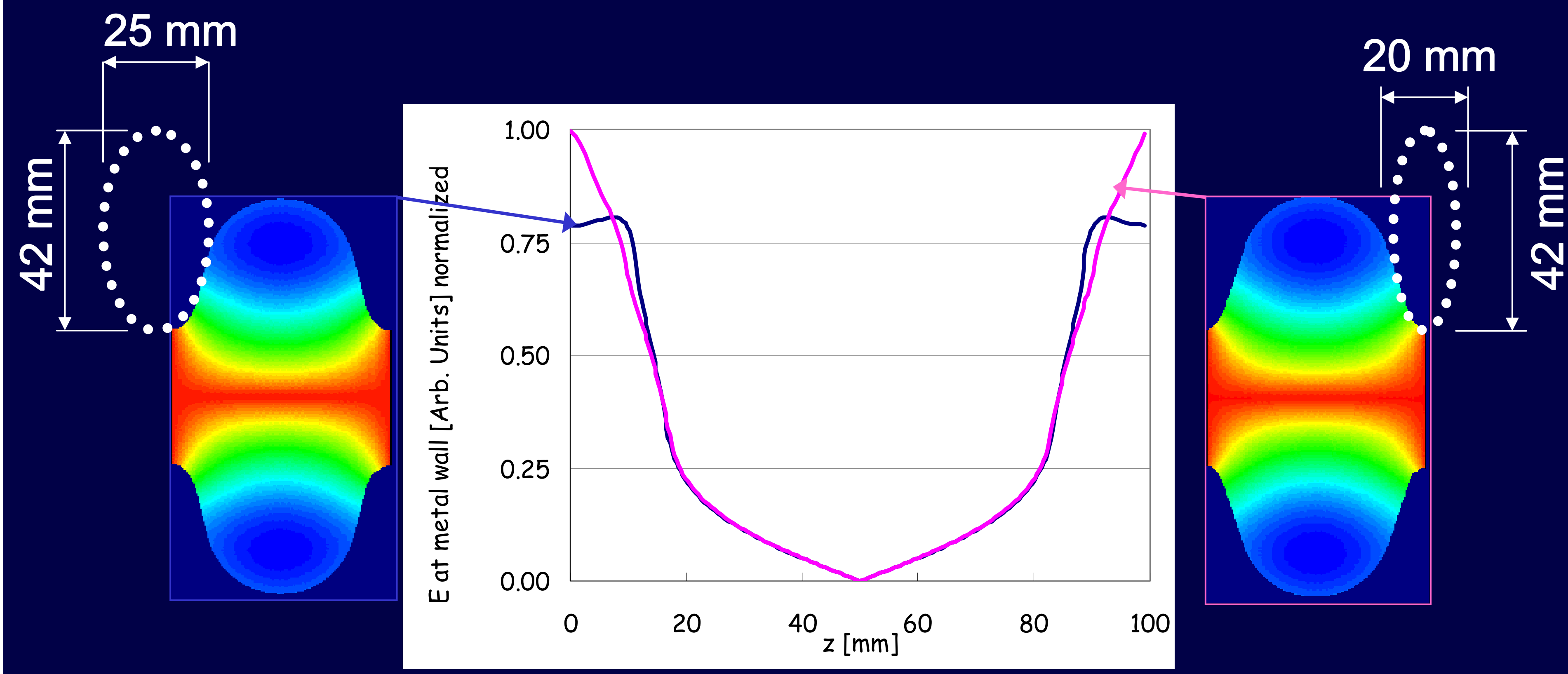




1 Joule



Similar : E_{peak}/E_{acc} changes vs. Iris shape



Both cells have the same: f, (R/Q), and iris radius

1. Criteria for the inner-cell optimization, cont.

We know that a smaller aperture makes FM :

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

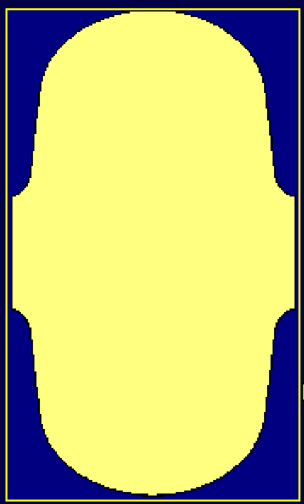
} (+)

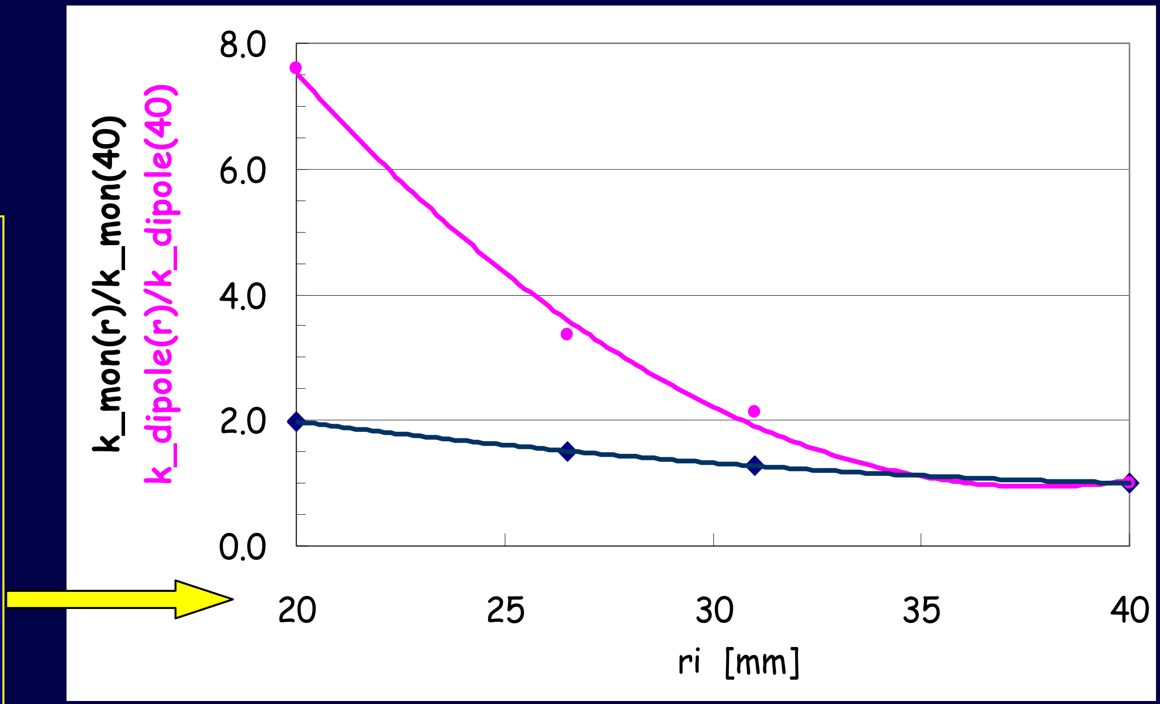
but unfortunately a smaller aperture makes:

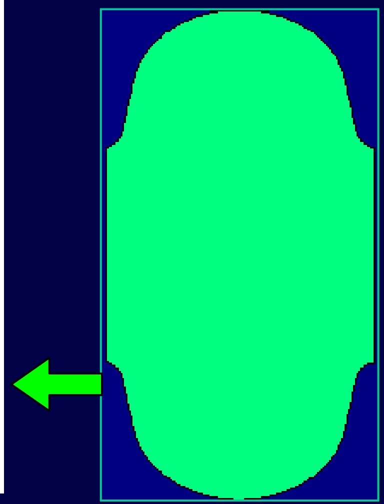
- HOMs impedances ($k_\perp$, $k_\parallel$) higher
- cell-to-cell coupling (k_{cc}) weaker

} (-)

1. Criteria for the inner-cell optimization, cont.







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

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

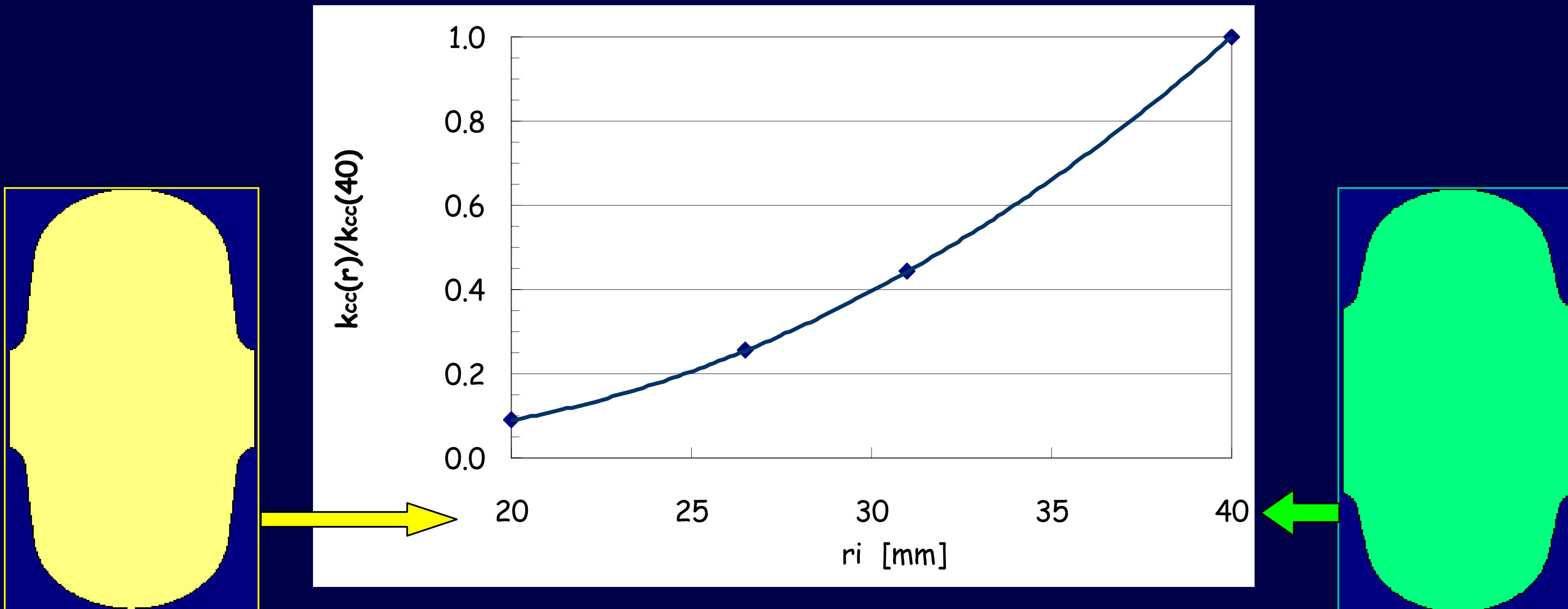
$E_{peak} / E_{acc} = 1.9$

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

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

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

1. Criteria for the inner-cell optimization, cont.



(R/Q) = 152 Ω	(R/Q) = 86 Ω
B_{peak} / E_{acc} = 3.5 mT/(MV/m)	B_{peak} / E_{acc} = 4.6 mT/(MV/m)
E_{peak} / E_{acc} = 1.9	E_{peak} / E_{acc} = 3.2

1. Criteria for the inner-cell optimization, cont.

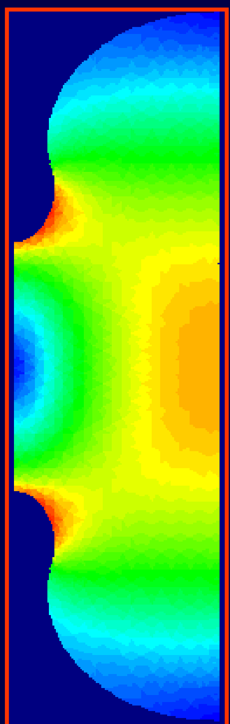
Inner cells parameter

		CEBAF Original Cornell ß=1	new: CEBAF -12 High Gradient ß=1	new: CEBAF -12 Low Loss ß=1	TESLA ß=1	SNS ß=0.61	SNS ß=0.81	new: RIA ß=0.47	new: 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
$k_\parallel$ (σ_z=1mm)	[V/pC]	1.36	1.53	1.71	1.46	1.25	1.27	1.19	0.85

1. Criteria for the inner-cell optimization, cont.

There are two new cavities proposed recently as a replacement for the TESLA 9-cell structures (no model has been built, further optimization will follow):

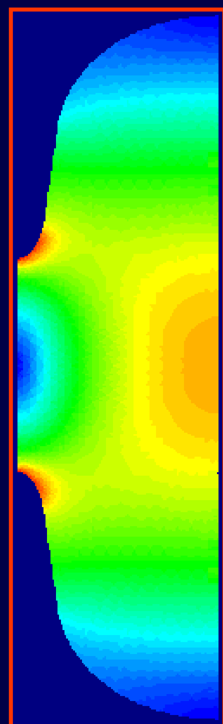
Re-entrant



Optimized for:

B_{peak}/E_{acc}

LL-ILC



Optimized for:

B_{peak}/E_{acc} & (R/Q)*G

		Re-entrant Cornell ß=1	Low Loss DESY/KEK ß=1
f_o	[MHz]	1273.0	1281.5
f_π	[MHz]	1300.0	1300.0
k_{cc}	[%]	2.08	1.43
E_{peak}/E_{acc}	-	2.20	2.17
B_{peak}/E_{acc}	[mT/(MV/m)]	3.9	3.7
R/Q	[Ω]	120	130
G	[Ω]	277	280
R/Q*G	[Ω*Ω]	33240	36400
$k_\perp$ (σ_z=1mm)	[V/pC/cm^2]	0.23	0.38
$k_\parallel$ (σ_z=1mm)	[V/pC]	1.45	1.72

2. Multi-cell structures; Number of cells

Why do we need to use multi-cell structures ?

- To increase real estate gradient (better filling factor)
- To reduce costs (less auxiliaries: vessels, tuners, FPCs)

There are 3 limitations in N / structure :

- Field flatness of the FM : N vs. k_{cc}
- Trapping of HOMs : N vs. achievable HOMs Q_{ext}
- FPC capability : N vs. P_{input}
  (relaxed for some ER operations)

2. Multi-cell structures; Number of cells

Field flatness of the FM : N vs. k_{cc}

The measure of the field flatness sensitivity to frequency errors in a multi-cell cavity is: $a_f = (N)^2 / (ß \cdot k_{cc})$

	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
a_f	1489	2592	3288	4091	3883	2924	5040	850

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

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

2. Multi-cell structures; Number of cells, cont.

Trapping of HOMs: N vs. achievable HOMs Qext

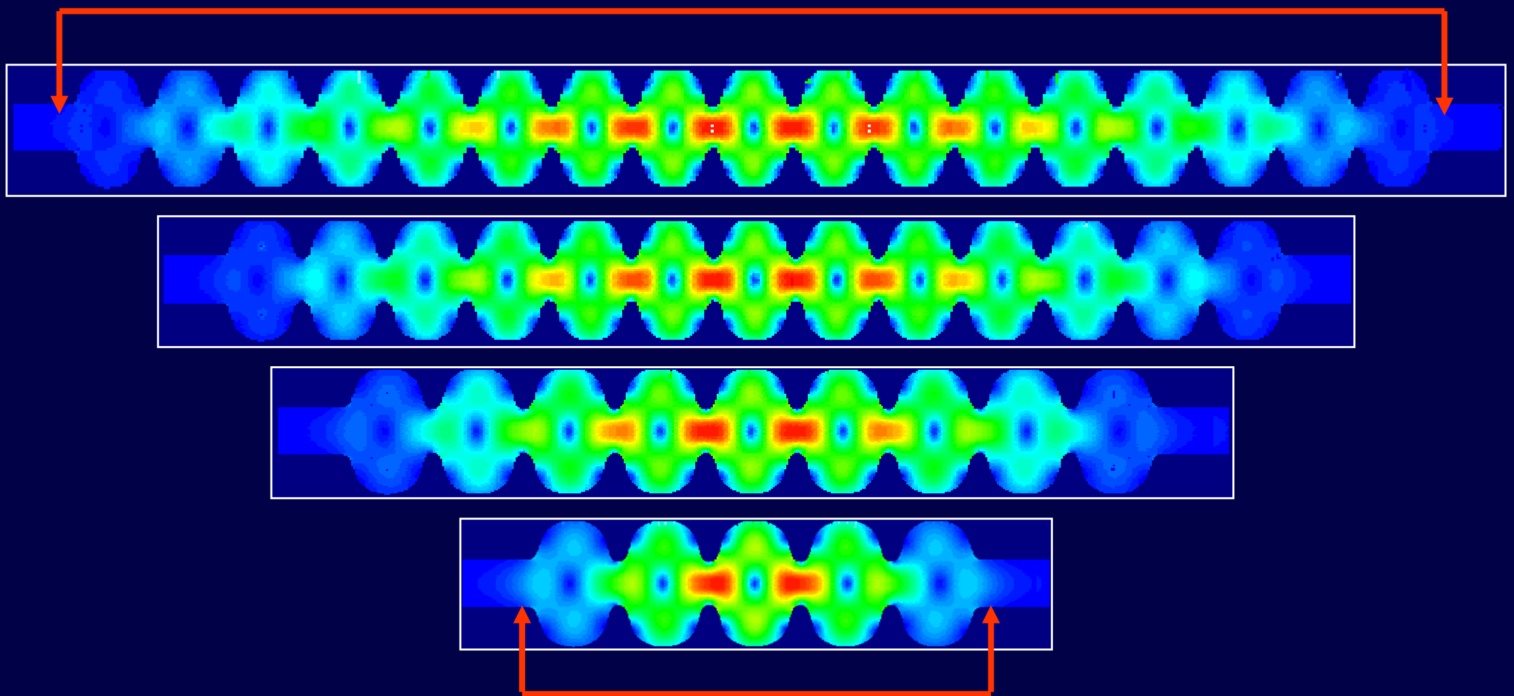
no e-m fields at HOM couplers positions

N = 17

N = 13

N = 9

N = 5



e-m fields at HOM couplers positions

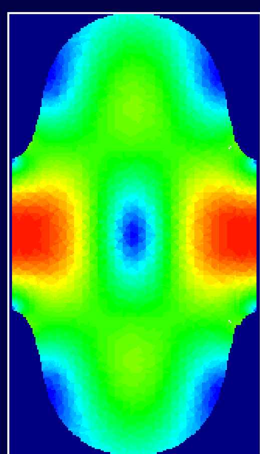
2. Multi-cell structures; Number of cells, cont.

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

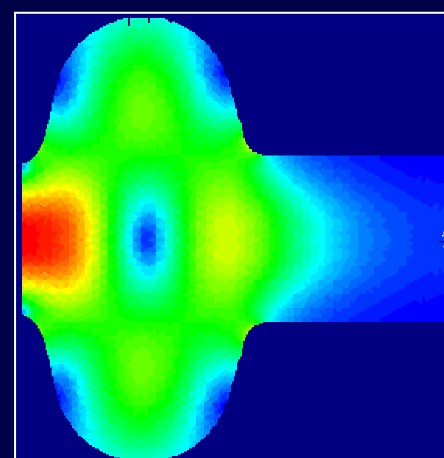
- weak HOM cell-to-cell $k_{cc,HOM}$ coupling
- difference in HOM frequency of end-cell and inner-cell

In the example from the previous slide:

f = 2385 MHz



That is why they hardly resonate together



f = 2415 MHz

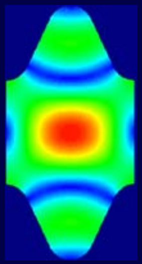
To untrapp HOMs we can:

- open both irises of inner cells and end-cells (bigger $k_{cc,HOM}$)

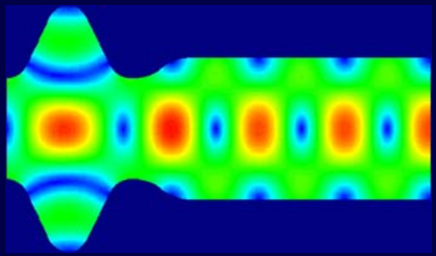
Example: the RHIC cavity for the cooling:

Monopole mode $k_{cc,HOM}$ = 6.7 %

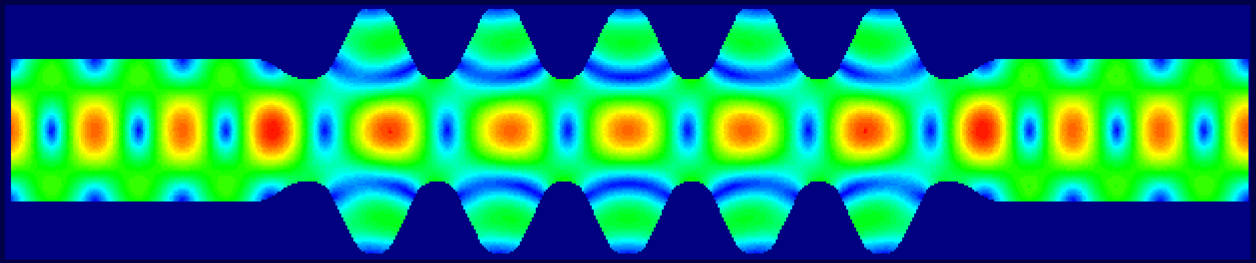
f_{HOM} = 1394 MHz



f_{HOM} = 1407 MHz



f_{HOM} = 1403 MHz

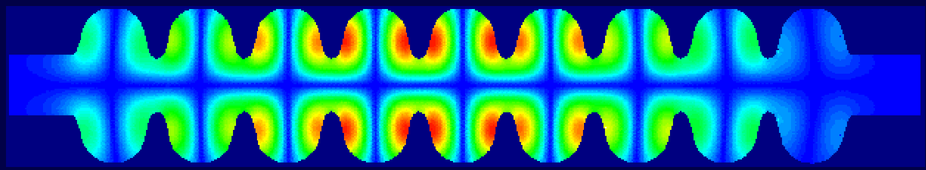


2. Multi-cell structures; Number of cells, cont.

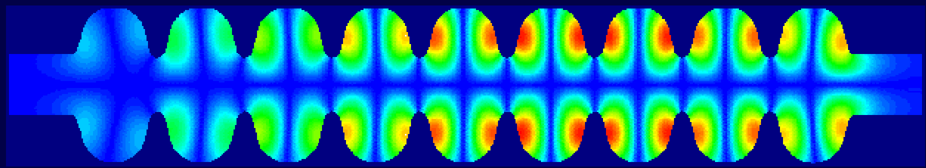
- tailor end-cells to equalize HOM frequencies of inner- and end-cells (works for very few modes)

Example: TESLA cavity, which has two different end-cells

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



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

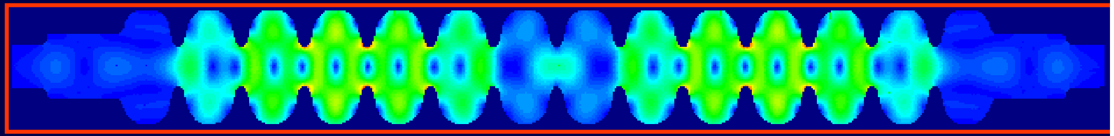


2. Multi-cell structures; Number of cells, cont.

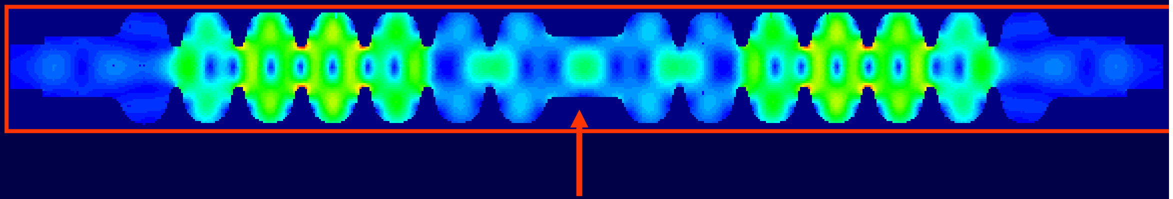
- we can also split a long structure in weakly coupled subsections to have space for HOM couplers in mid of a long structure

Example: 2x7-cell instead of 14-cell structure

2453 MHz, (R/Q) = 230 Ω



2451 MHz, (R/Q) = 212 Ω



e-m fields at HOM couplers positions

- less cells in a structure helps always to reach low Qs of HOMs

2. Multi-cell structures; Interconnection

Towards the higher real estate gradient

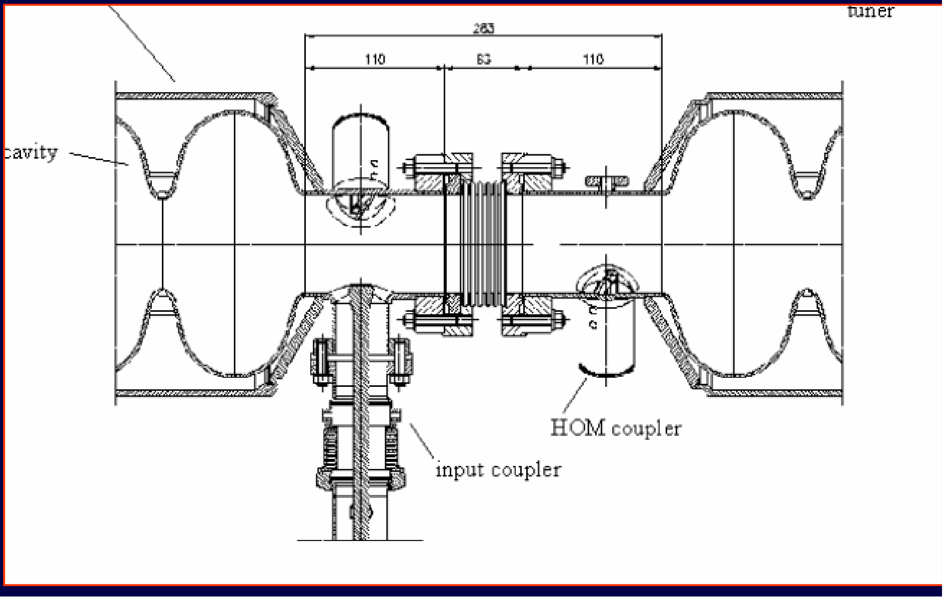
- It is an important issue for long machines based on SRF: ILC
- It is related to the end-groups (end-cells) geometry
- We are approaching limit of 40 MV/m in multi-cell cavities
- Each “MV/m ” near this limit is very expensive

Example: TESLA 800 TDR2001

Active length: 1036 mm

Interconnection: 283 mm

The effective gradient drops by 21.5% from 35 MV/m to 27.5 MV/m



2. Multi-cell structures; Interconnection, cont.

How can one improve the filling factor ?

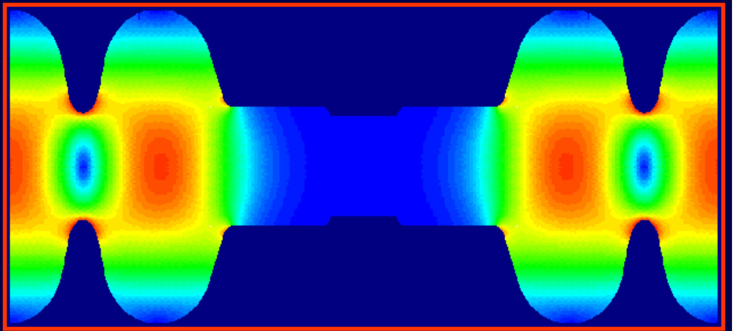
- By using short interconnections with “step” in diameter:
  - a) no FM coupling between neighboring cavities
  - b) fixed standing wave position of the dangerous dipoles (3-rd passband) at HOM coupler location.

Example cont.: TESLA 800 TDR2001

Active length: 1036 mm

Here, the effective gradient drops by 16.2 % from 35 MV/m to 29.3 MV/m

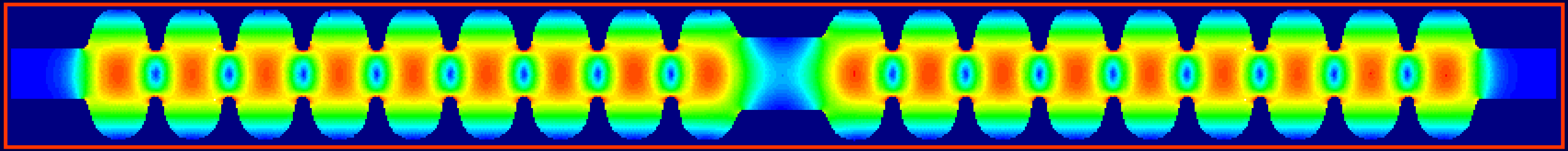
and TESLA can be shorter by **1.8 km !!!!!!**



Interconnection: 200 mm

2. Multi-cell structures; Interconnection, cont.

- we can go one step further and use weakly coupled pairs of 9-cell structures



Interconnection: 115 mm

Example cont.: TESLA800 TDR2001

When we apply both interconnections modification:

the effective gradient drops by 13.2 % from 35 MV/m to 30.4 MV/m

and

TESLA800 can be shorter by 2.7 km !!!!!!

3. Elliptical cavities ß=1

"Ranking list" of multi-cell cavities ß=1

Criterion	Structure	Best parameter	Weakest parameter	Comments
E_{acc}	HG: 1.5 GHz, N=7 TESLA: 1.3 GHz, N=9	E_{peak}/E_{acc}= 1.96 E_{peak}/E_{acc}= 1.98	Filling factor	Designed for I_{beam} < 10 mA, *Cornell 100 mA*
RE E_{acc}	2x9 TESLA: 1.3 GHz, N= 18	Filling factor E_{peak}/E_{acc}= 2.0	Field flatness preservation	New FPC design: 0.8 MW
P_{loss}	LL: 1.5 GHz, N= 7	B_{peak}/E_{acc}= 3.7 (R/Q)*G	Not easy to clean, HOM damping	Designed for I_{beam} < 1 mA
Z_{HOM}	RHIC: 0.7 GHz, N= 5	Very low: $k_{\perp}$, $k_{\parallel}$ E_{peak}/E_{acc}= 1.98	Cryogenic losses	First multi-cell for I_{beam} ≈ 2 A

(only in the list when Cu or Nb model has been built). New designs marked in yellow

4. Elliptical cavities ß<1

These cavities are not operated at the limits of the Nb properties.

The cell-geometry makes some of them difficult to pre-tune and sensitive to the Lorentz force.

		JAERI KEK	APT LANL	JAERI KEK	TRASCO INFN	SNS JLAB	SNS JLAB	RIA MSU/JLAB	ASH Saclay / Orsay
f_{π}	[MHz]	600	700	972	704	805	805.0	805.0	700
ß	-	0.604	0.64	0.6	0.85	0.61	0.81	0.47	0.65
N	-	5	5	9	5	6	6	6	5

They are very often an alternative to non-elliptic cavities (spoke). The advantage one can see here is usually big aperture (~2 x spoke aperture) for the proton and ion beams.

4. Summary

- The process of cavity design is well understood
- The new geometries are helpful to push the performance. However when we improve one chosen parameter (by 10-20%) some of them degrade more or less by the same amount
- For the ILC linac we should not waste MV/m's having poor filling factor.
- If the limitation is not E_{peak} (not all of us agree with this statement) then new cell geometry should have B_{peak}/E_{acc} as low as possible. We have two candidates (re-entrant and LL, others new shapes are welcome)
- I think, that there is much more potential to push the SRF performance in using better Nb and better preparation methods (see progress in the performance of the TESLA cavities)