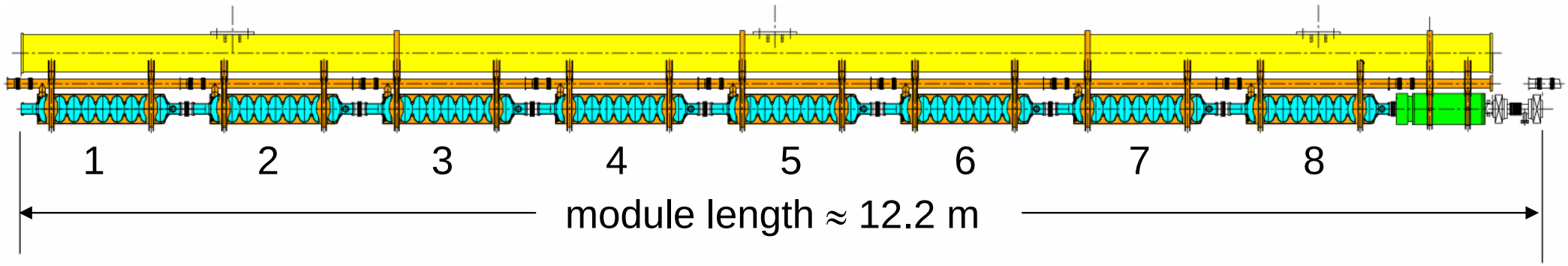
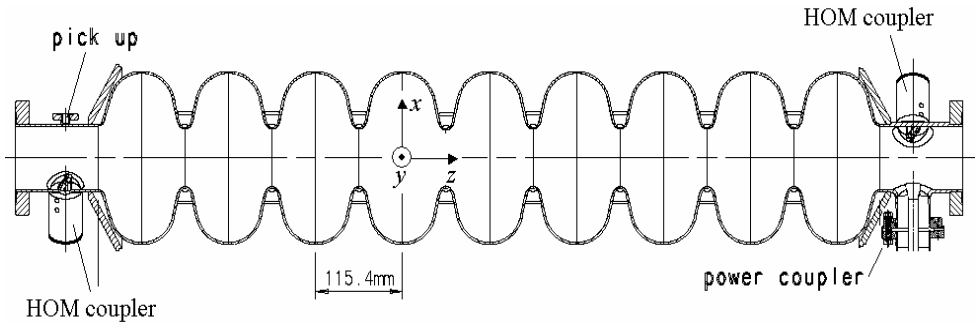
(Higher Order) Modes in Cavity Structures





r_{pipe} = 39 mm

TESLA cavity with main coupler
and two HOM couplers

cutoff frequencies & cavity bands

from R.Wanzenberg, TESLA 2001-33

r_{pipe} = 39 mm, cutoff frequencies:

monopole modes f_c/GHz	dipole modes f_c/GHz	quadrupole modes f_c/GHz
2.942 (TM)	**2.253 (TE)**	**3.737 (TE)**
4.688 (TE)	4.688 (TM)	6.283 (TM)
6.753 (TM)	6.523 (TE)	8.204 (TE)
8.583 (TE)	8.583 (TM)	10.298 (TM)
…	…	…

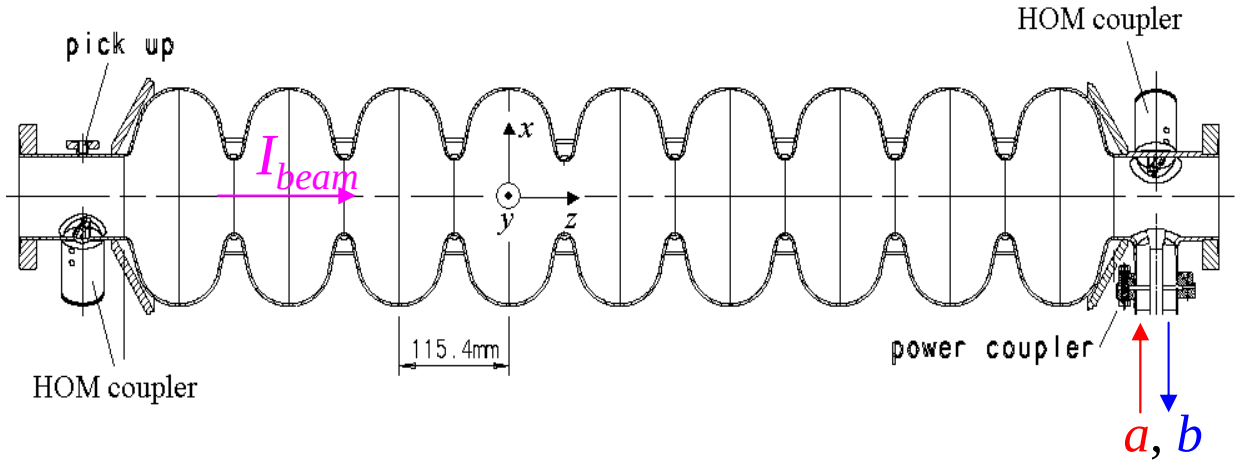
TESLA cavity, bands:

TM monopole modes f/GHz	dipole modes f/GHz	quadrupole modes f/GHz
1.275 … 1.30	1.63 … 1.80	2.30 … 2.32
2.38 … 2.45	1.84 … 1.89	2.47 … 2.49
2.67 … 2.76	2.48 … 2.58	3.21 … 3.46
3.39 … 3.67	2.82 … 3.01	3.56 … 3.62
…	3.08 … 3.12	3.66 … 3.69
	…	3.85 … 3.87
		…

$f < f_c$: calculate cavities

$f > f_c$: coupled cavities → calculate modules (or less? or more?)

below f_c: accelerating mode



forward & reflected wave (klystron)

steady state (after filling):

$$a = I_{beam}\sqrt{\frac{2Qk_{\|}}{\omega}} + V_{acc}\sqrt{\frac{\omega}{2Qk_{\|}}}\left(\frac{1}{2} - j\frac{\delta\omega Q}{\omega}\right)$$

$$b = -I_{beam}\sqrt{\frac{2Qk_{\|}}{\omega}} + V_{acc}\sqrt{\frac{\omega}{2Qk_{\|}}}\left(\frac{1}{2} + j\frac{\delta\omega Q}{\omega}\right)$$

$$(a,b) \leftrightarrow (I_{beam}, V_{acc})$$

with:

Q = external quality

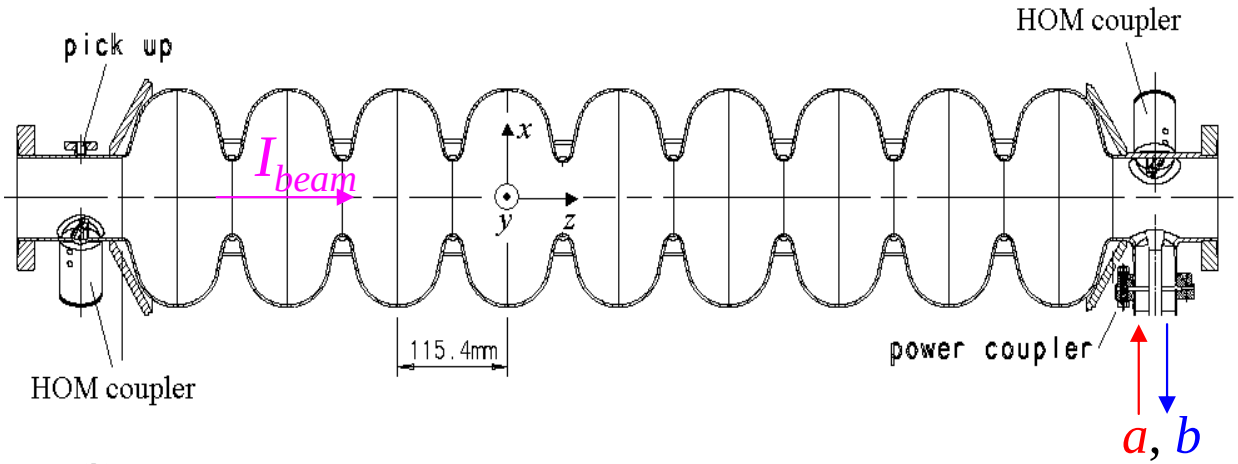
$k_{\|}$ = longitudinal loss parameter

$= |V_{\mathrm{acc}}|^2/4W_{\mathrm{tot}}$

ω = frequency

$\delta\omega$ = detuning

below f_c: accelerating mode
external quality & coupler kick



$$\mathbf{E} = a\mathbf{E}^{(a)} + b\mathbf{E}^{(b)}$$

$$\mathbf{B} = a\mathbf{B}^{(a)} + b\mathbf{B}^{(b)}$$

$$\mathbf{V} = \int \left(\mathbf{E} + c\mathbf{u}_z \times \mathbf{B}\right) \exp\left(j\frac{\omega}{c}z\right) dz = a\mathbf{V}^{(a)} + b\mathbf{V}^{(b)}$$

← coupler kick depends on forward and backward wave!

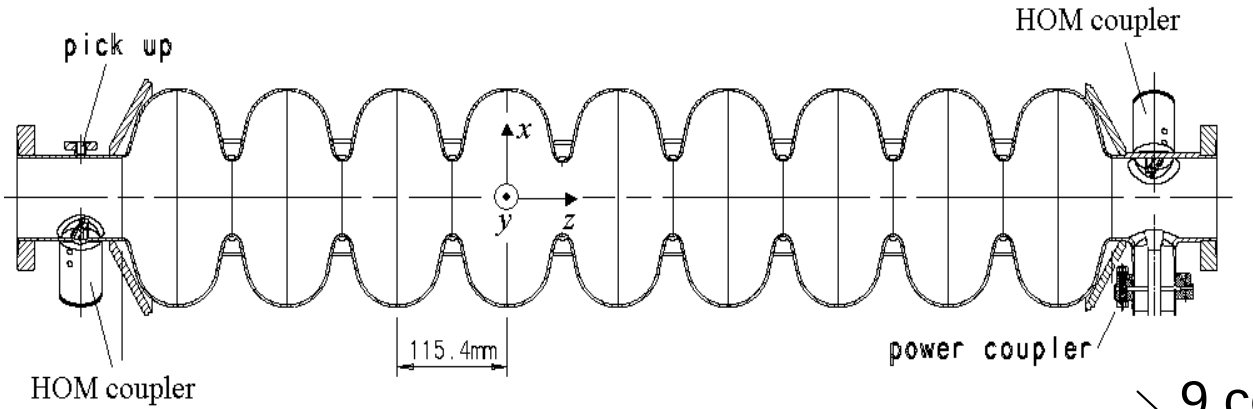
special case: $b = 0$ (matched operation)

$V_{acc} = \mathbf{V} \cdot \mathbf{u}_z$ longitudinal voltage

$V_t = \mathbf{V} \cdot \mathbf{u}_t$ transverse voltage with $\mathbf{u}_t = \mathbf{u}_{x/y}$

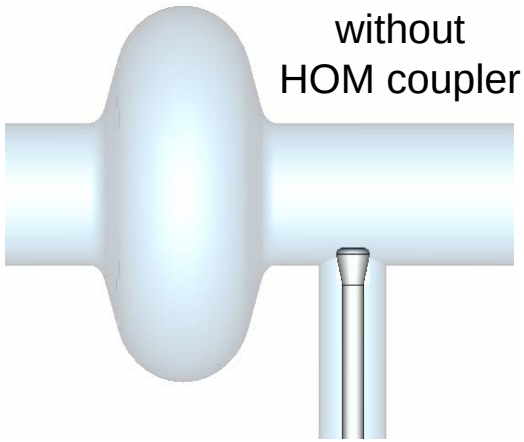
normalized kick: $k_{t,n} = V_t / V_{acc}$

below f_c: accelerating mode
simplifications



9 cells

1 cell



coupler field:

establish energy flow to (or from cavity) !!!
either with beam or by wall losses
or by dW/dt ≠ 0

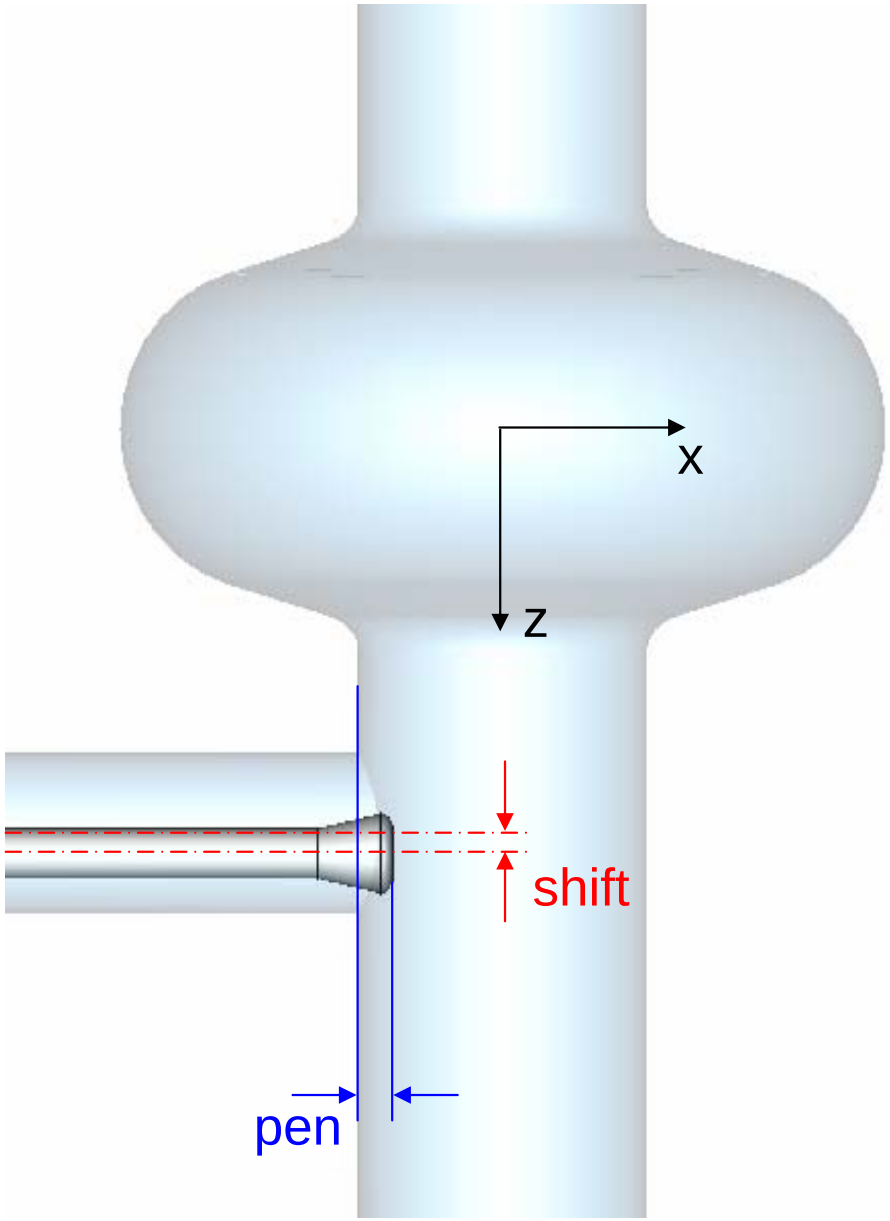
scale field:

energy in 9 cell cavity ≈ 9 x energy in 1 cell cavity for the same input power or the same accelerating field

→ $Q_{ext,9cell} \approx 9 \times Q_{ext,1cell}$

complete documentation (with all tricks):
http://adweb.desy.de/~mpymax/mafia/HOM_Coupler/index.html

below f_c: accelerating mode
external quality & coupler kick



penetration depth & displacement
of inner conductor

scaled to TESLA cavity:

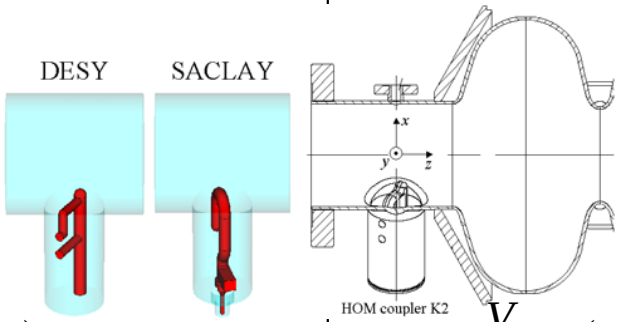
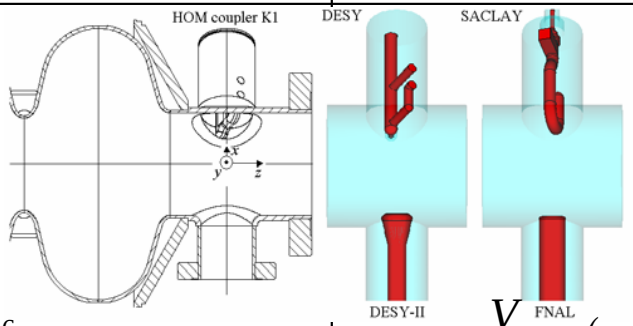
$\frac{Q_{ext}}{10^6}$ $\frac{10^6 \cdot V_x}{V_z}$

MWS-discretization: 30lines@2GHz

pen/mm \ shift/mm	-5	0	5
4.5	3.347 19.9+j35.9	4.490	
6	2.466 47.6+j40.9	3.384 30.6+j54.3	
7.5	1.781 84.5+j50.0	2.4482 58.7+j65.0	3.987 37.4+j68.1
9	1.272 130.3+j56.9	1.940 93.4+j83.3	3.464 65.1+j88.9
10.5	0.9662	1.663	2.583 100.9+j86.5
12		1.351	2.099 141.1+j65.0

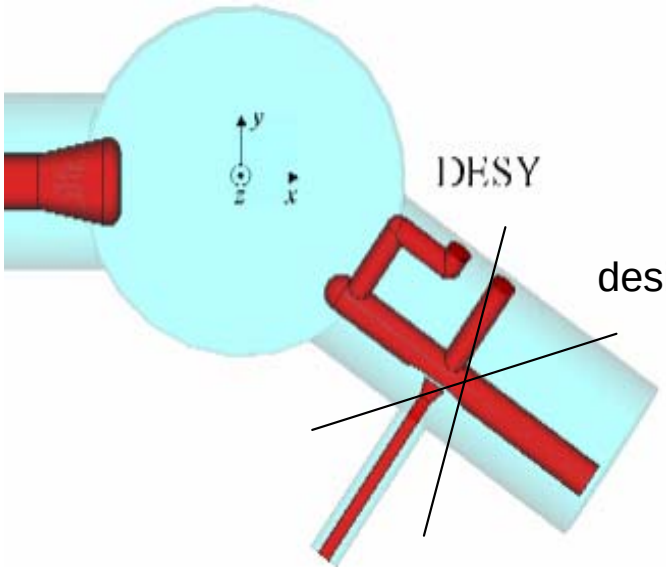
below f_c: accelerating mode

kick by main coupler & HOM couplers:

	desy	saclay
upstream	 $\frac{V_x}{V_\parallel} = (-53.0 + j14.3)\cdot 10^{-6}$ $\frac{V_y}{V_\parallel} = (-33.4 + j2.8)\cdot 10^{-6}$	$\frac{V_x}{V_\parallel} = (-20.1 + j24.5)\cdot 10^{-6}$ $\frac{V_y}{V_\parallel} = (-26.2 + j12.5)\cdot 10^{-6}$
downstream $Q_{ext} \approx 2.5\cdot 10^6$	 $\frac{V_x}{V_\parallel} = (2 + j54)\cdot 10^{-6}$ $\frac{V_y}{V_\parallel} = (32 + j6)\cdot 10^{-6}$	$\frac{V_x}{V_\parallel} = (34 + j45)\cdot 10^{-6}$ $\frac{V_y}{V_\parallel} = (28 + j15)\cdot 10^{-6}$

phase reference is center of cell 1

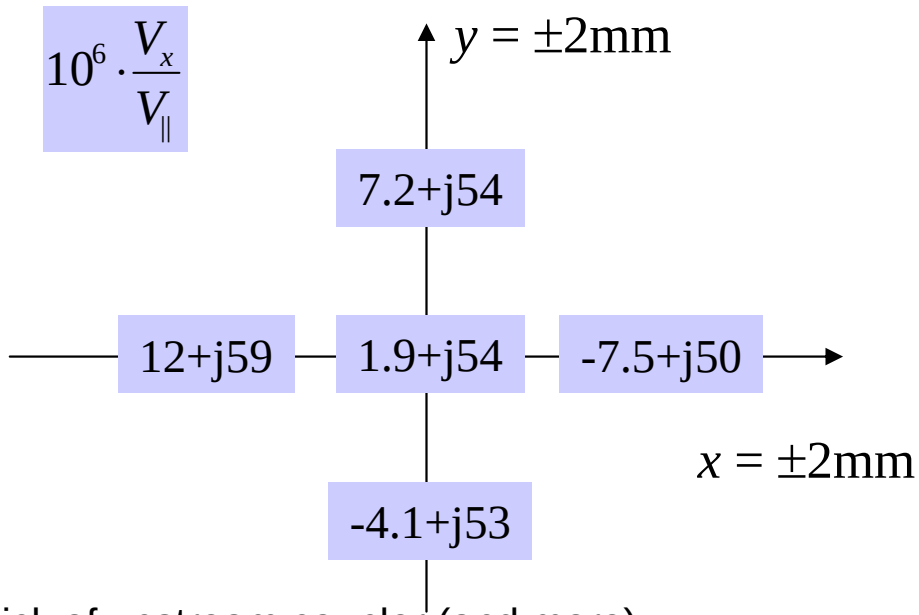
below f_c: accelerating mode
kick by main & HOM couplers



design has been changed
(mirrored coupler)

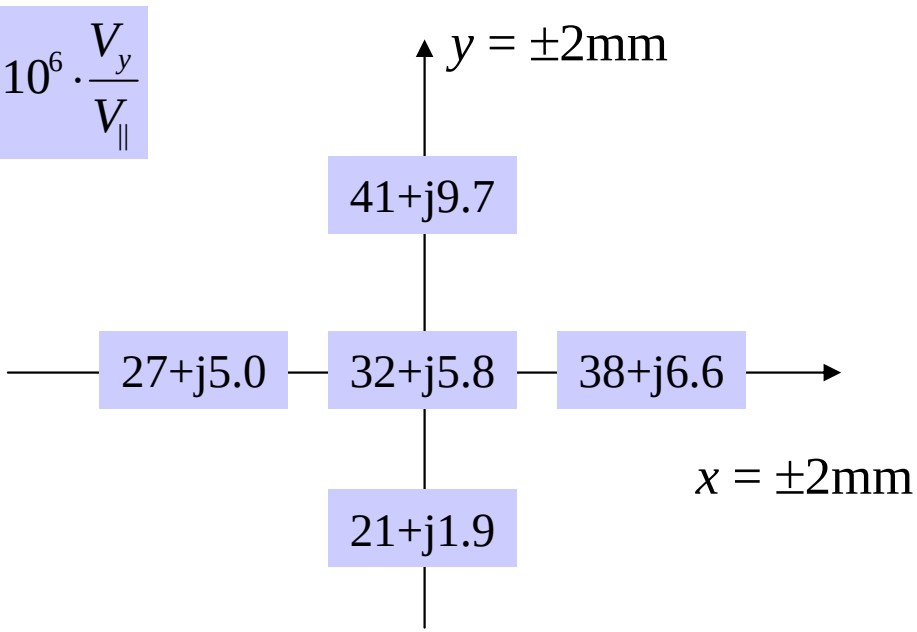
horizontal kick

$10^6 \cdot \frac{V_x}{V_\parallel}$



vertical kick

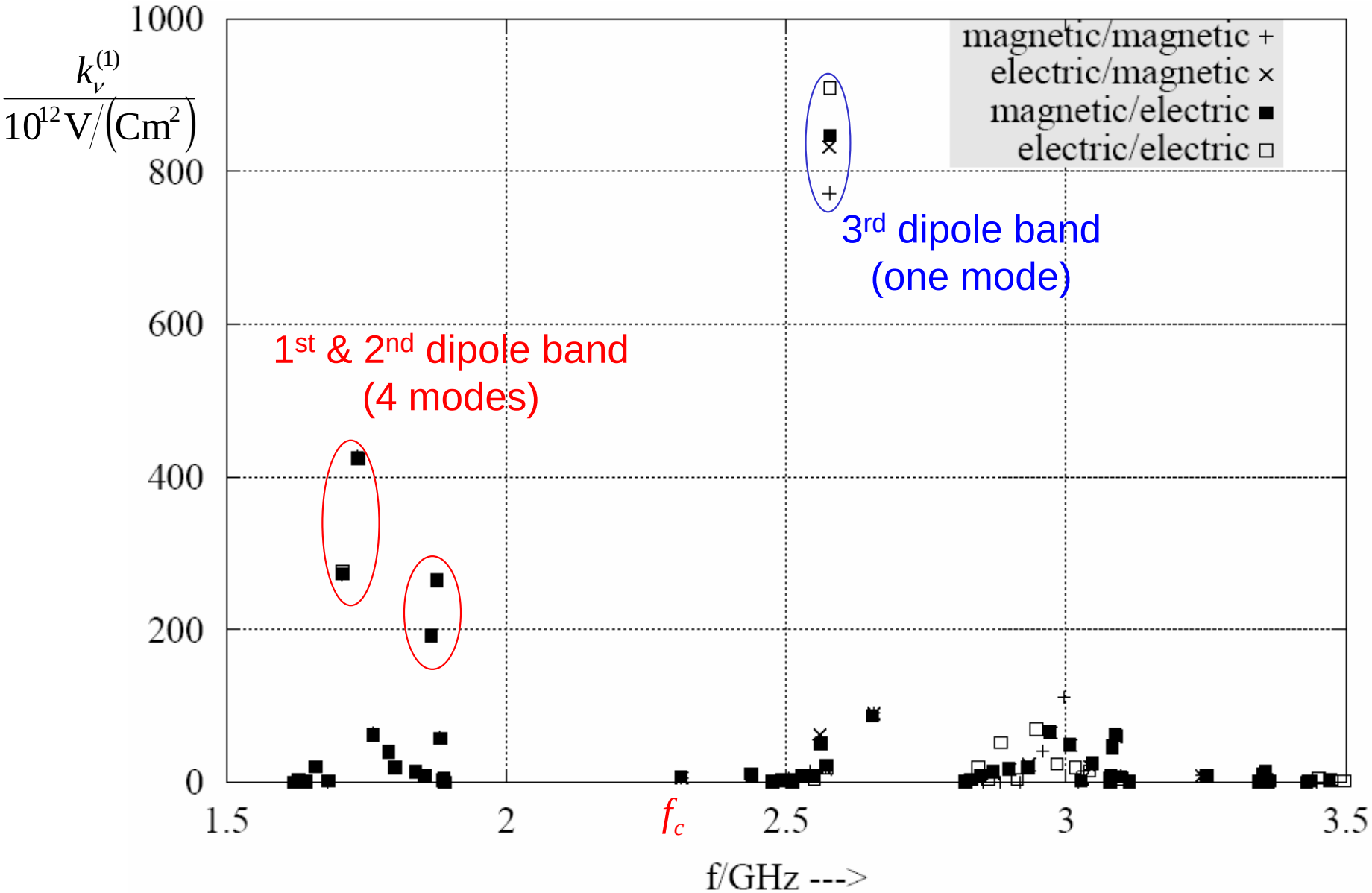
$10^6 \cdot \frac{V_y}{V_\parallel}$



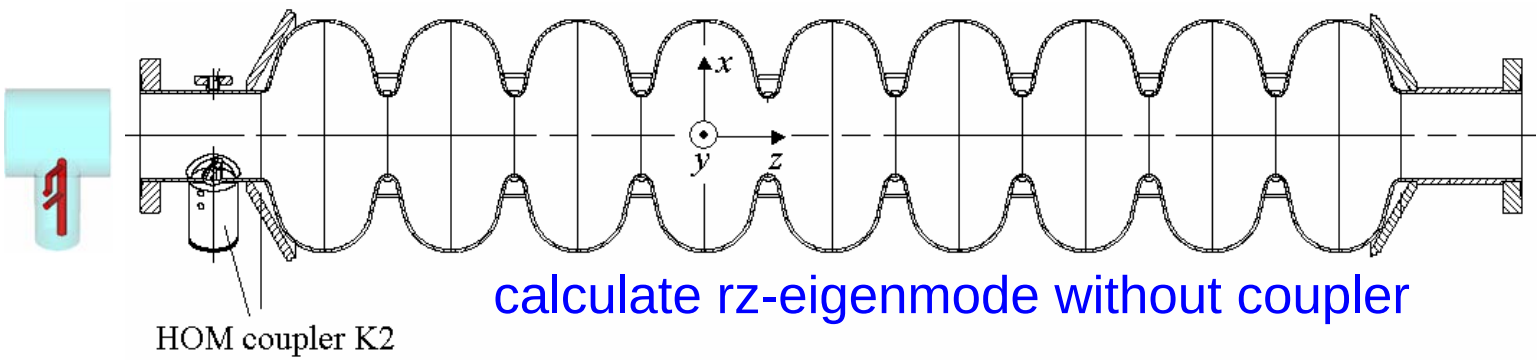
kick of upstream coupler (and more):
http://www.desy.de/~dohlus/2004/2004.09.holgers_seminar/asym&kick_sep2004.pdf

below f_c: dipole modes

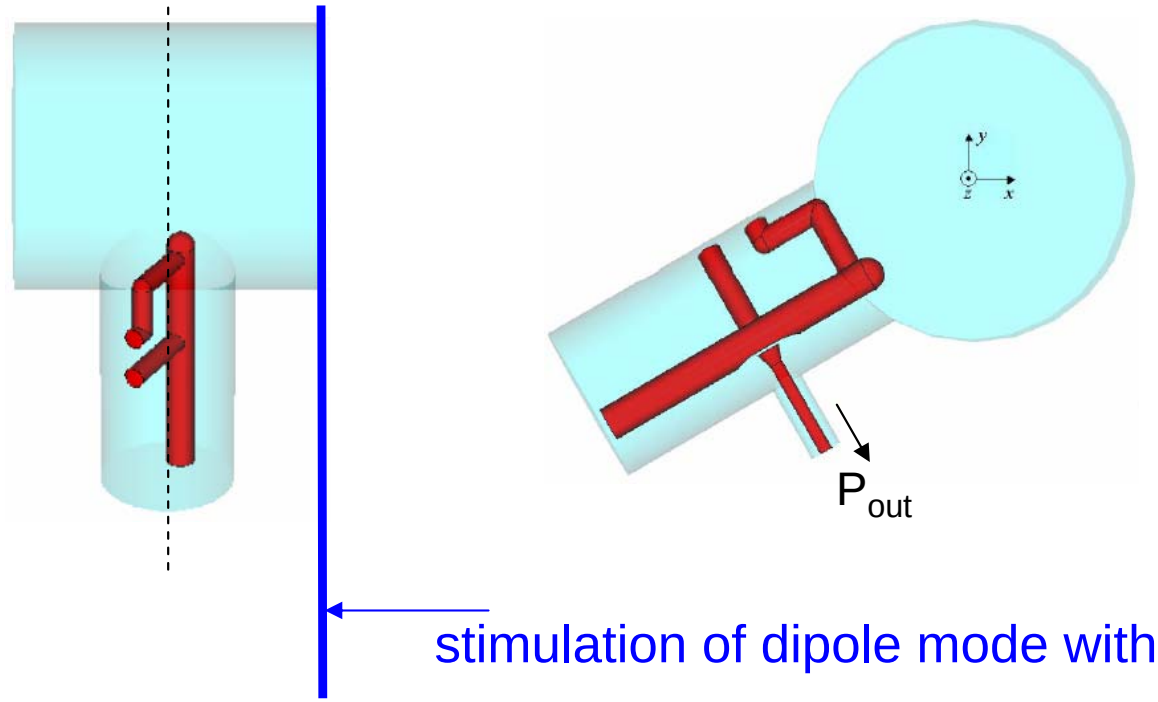
frequencies & loss parameters from rz eigenmode calculation



below f_c: dipole modes
pseudo field matching



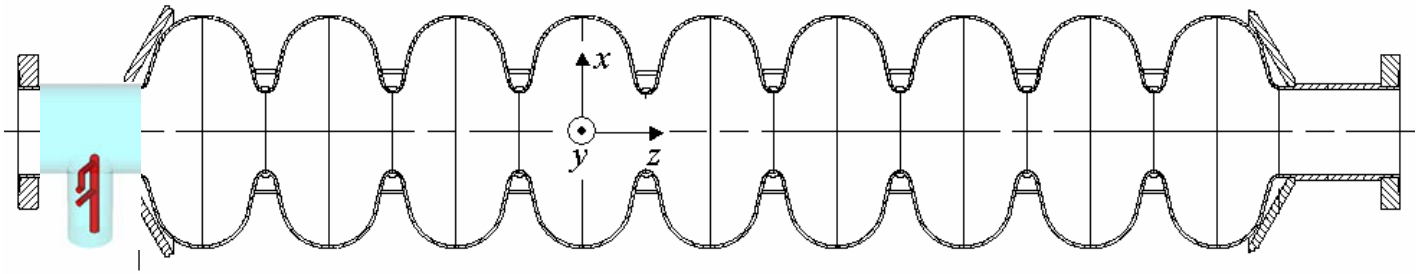
calculate rz-eigenmode without coupler



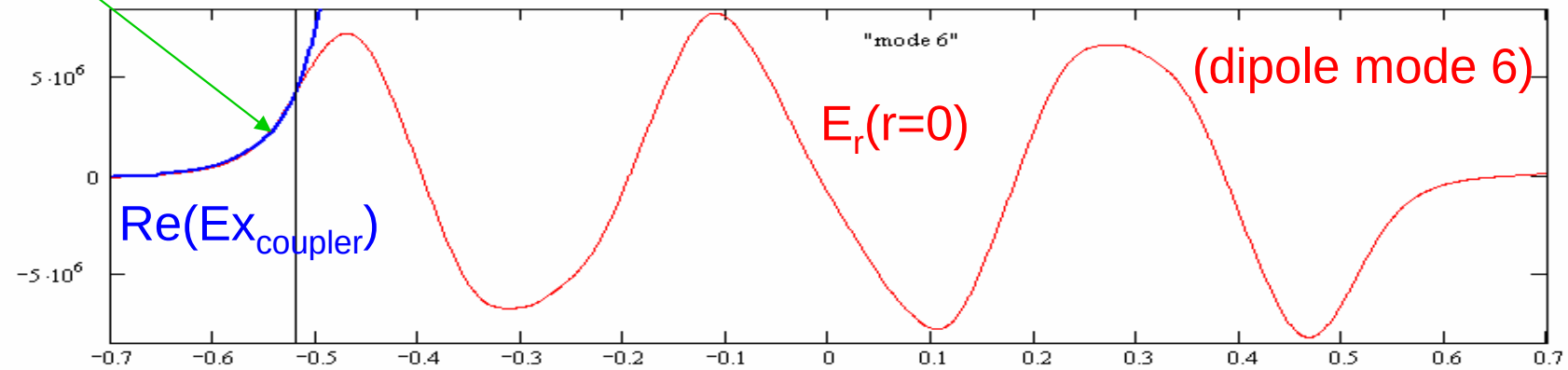
stimulation of dipole mode with horizontal polarization

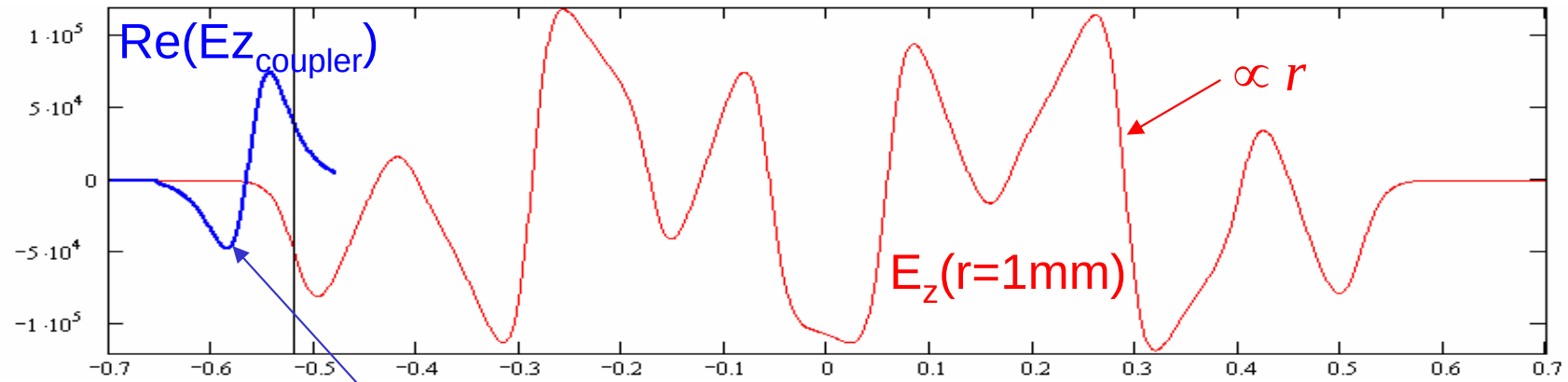
below f_c: dipole modes

pseudo field matching; estimate Qext & field asymmetry



matching

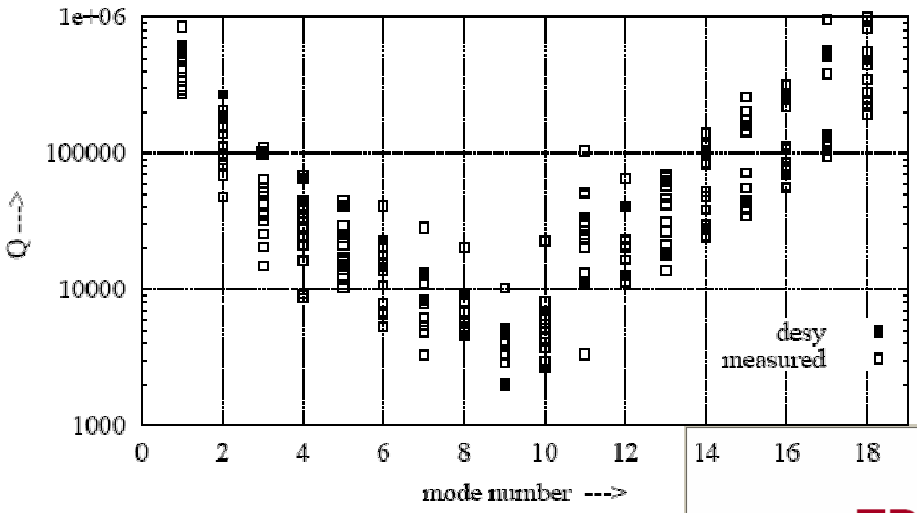




nearly offset independent

→ mode excitation even with beam on axis

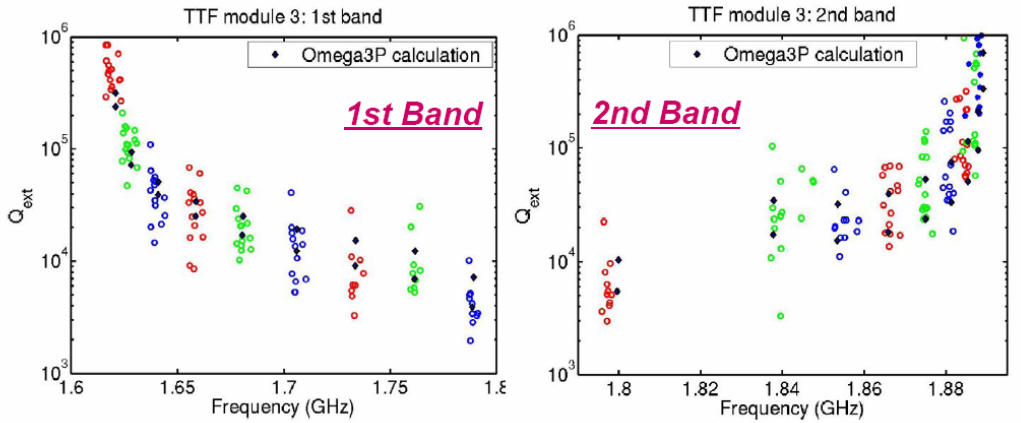
below f_c: dipole modes
estimatet Qext



even with “flagship” supercomputers:

TDR Cavity – HOM Damping (Omega3P)

*Comparing measurements (color) with **Omega3P** (black) complex eigenmode solutions ($Q_{ext}=f_{real}/2f_{imag}$) shows data scatter around ideal cavity results due to shape deformations*



0.53 M quadratic elements, 3.5 M DOFs, 512 CPU with 300 GB on Seaborg, Second Arnoldi with MUMPs, 1 hour per dipole band

from:

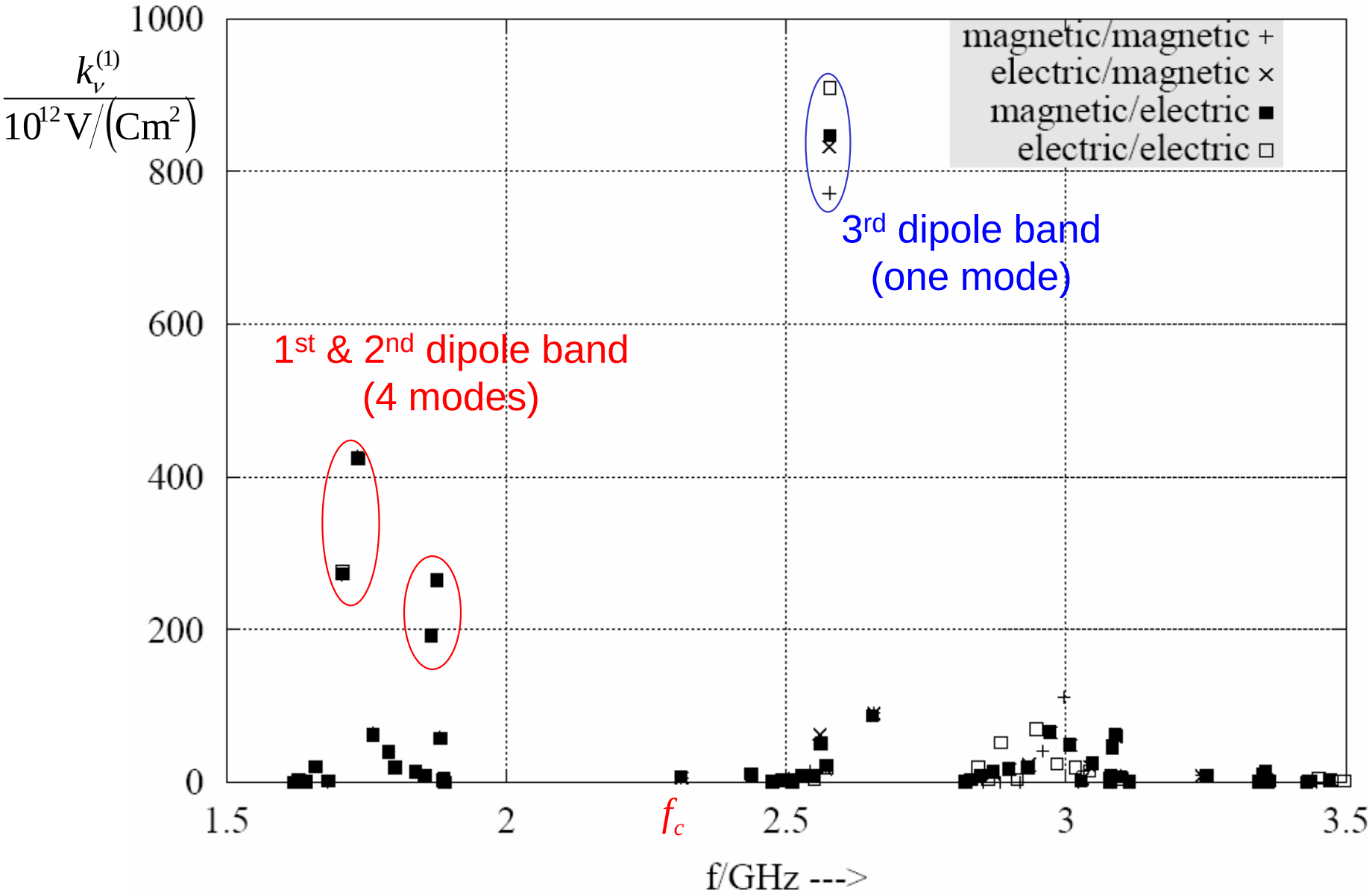
Accelerating Cavity Design for the International Linear Collider

A. Kabel, …

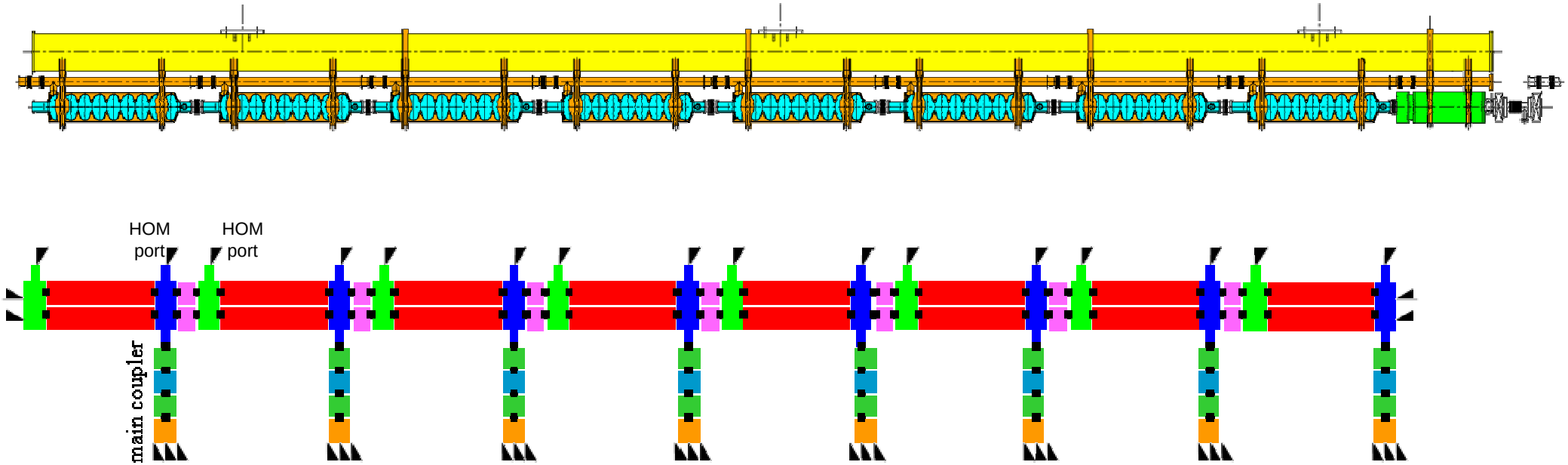
ICAP 2006, Chamonix Mont-Blanc, October 2-6, 2006

above f_c: 3rd dipole band

frequencies & loss parameters from rz eigenmode calculation



above f_c: 3rd dipole band
coupled scattering matrix calculation



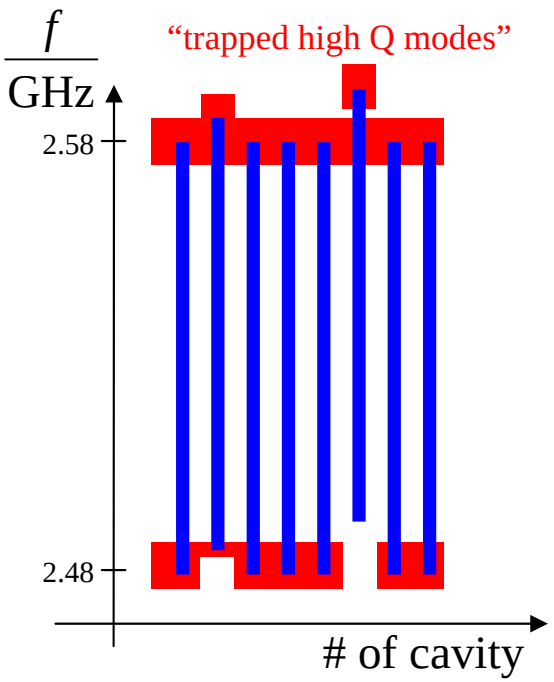
- cavity
- upstream coupler
- downstream coupler
- beampipe bellows
- coax bellows (4K or 70K)
- cold window
- doorknob, warm window

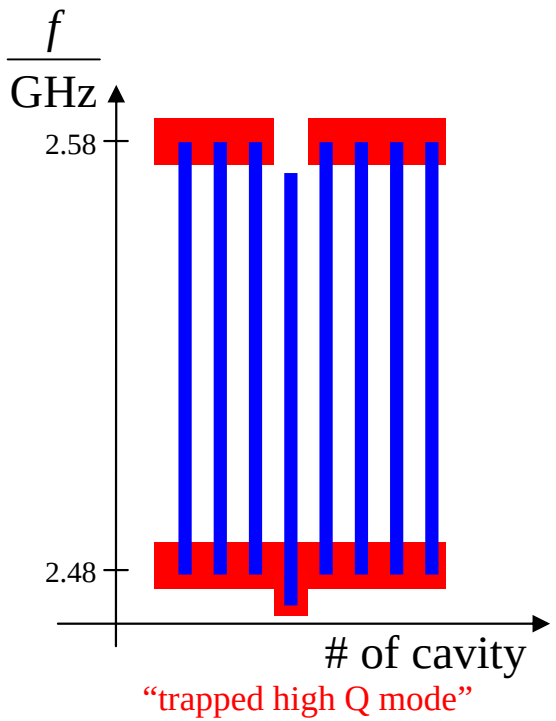
19 different components
78 sub components
136 ports

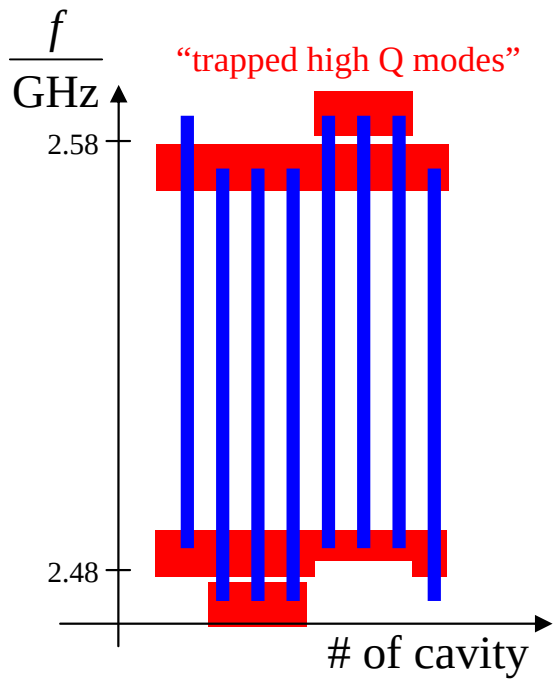
from TESLA meeting Saclay Apr. 2002

distributed modes (many cavities) and localized modes

eg. 2.5906 GHz mode
cavity 7 / module 3







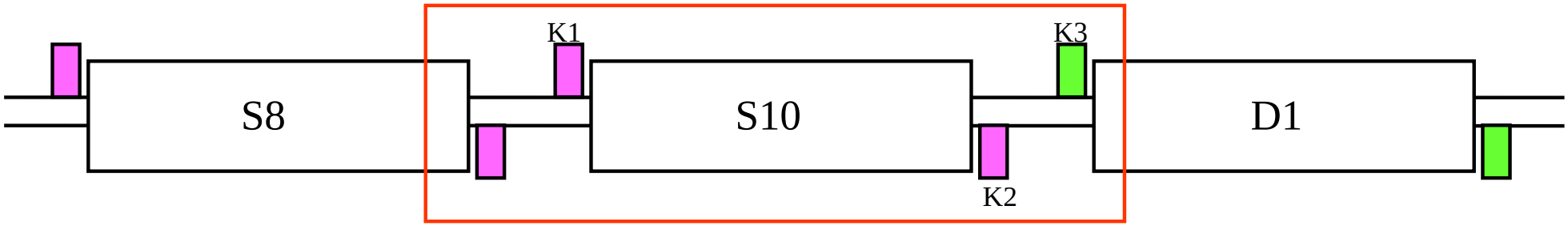
from TESLA meeting Saclay Apr. 2002

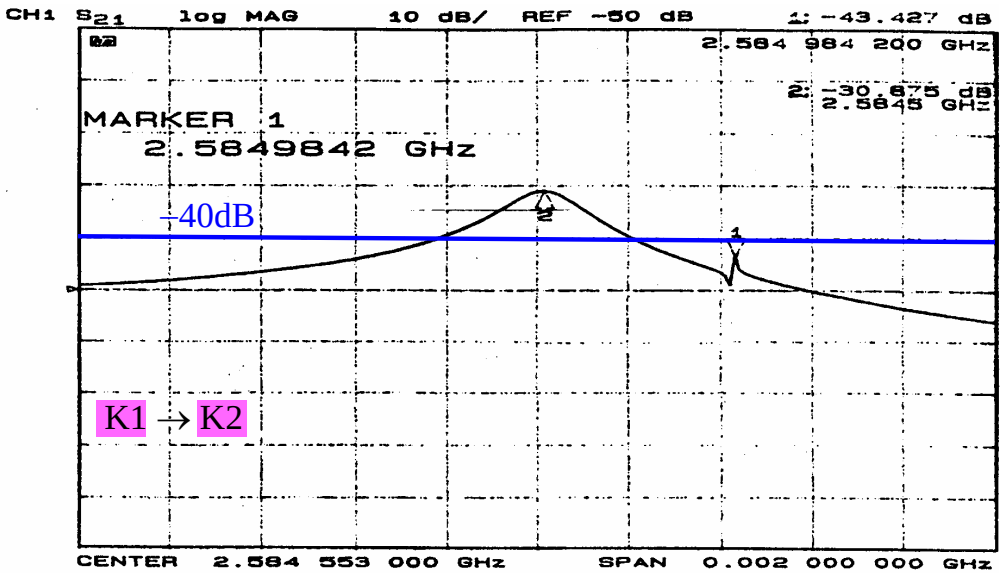
inhomogeneous modules
(e.g. module 1; cavity S8/S10/D1)

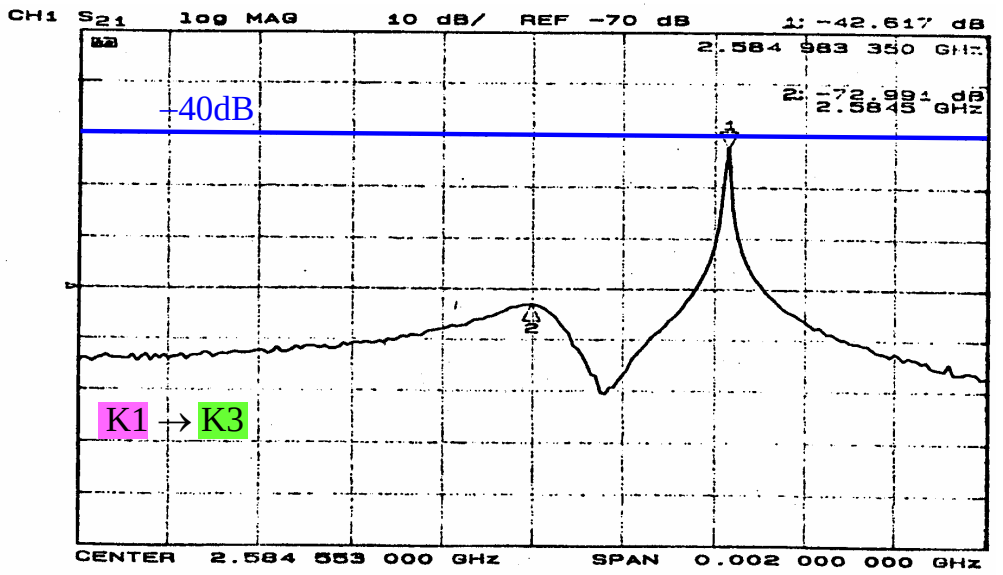
SACLAY coupler - vertical — wrong polarization of coupler fields

DESY coupler - horizontal — cancellation of coupling fields

S10: $\Delta f \approx 10$ MHz $\Rightarrow$ trapped mode



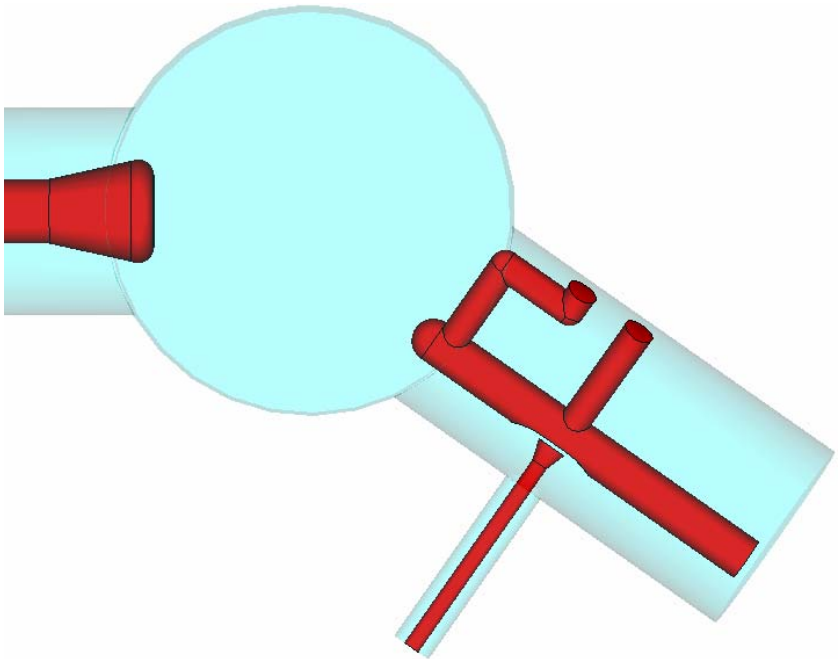




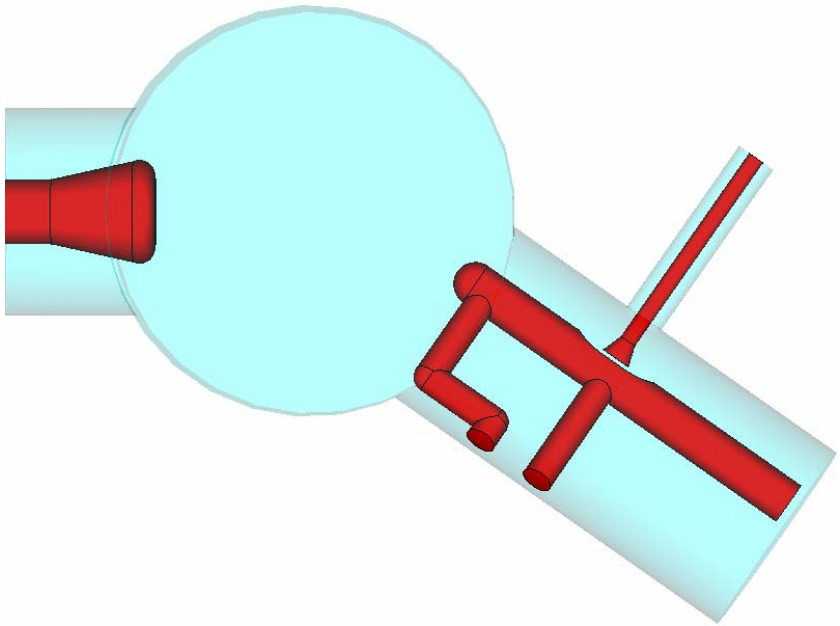
from TESLA meeting Saclay Apr. 2002

above f_c: 3rd dipole band
modified downstream coupler

old HOM coupler orientation



new HOM coupler orientation



questions / problems

what determines the polarization of dipole modes ?

random geometry errors ↔ asymmetries by design

what types of polarizations ?

linear / elliptical / circular

is there an orthogonality (of modes that are related to the same rz-mode)

spread of mode properties (same mode, different cavities)

e.g. dipole bands 1 & 2:

ΔQ ~ 1 order of magnitude

Δf ~ 5 MHz

modes above fc

what modes have to be considered?

how to treat them? (how many cavities or modules are involved?)

trapped modes