HOMs in the TESLA 9-cell cavity

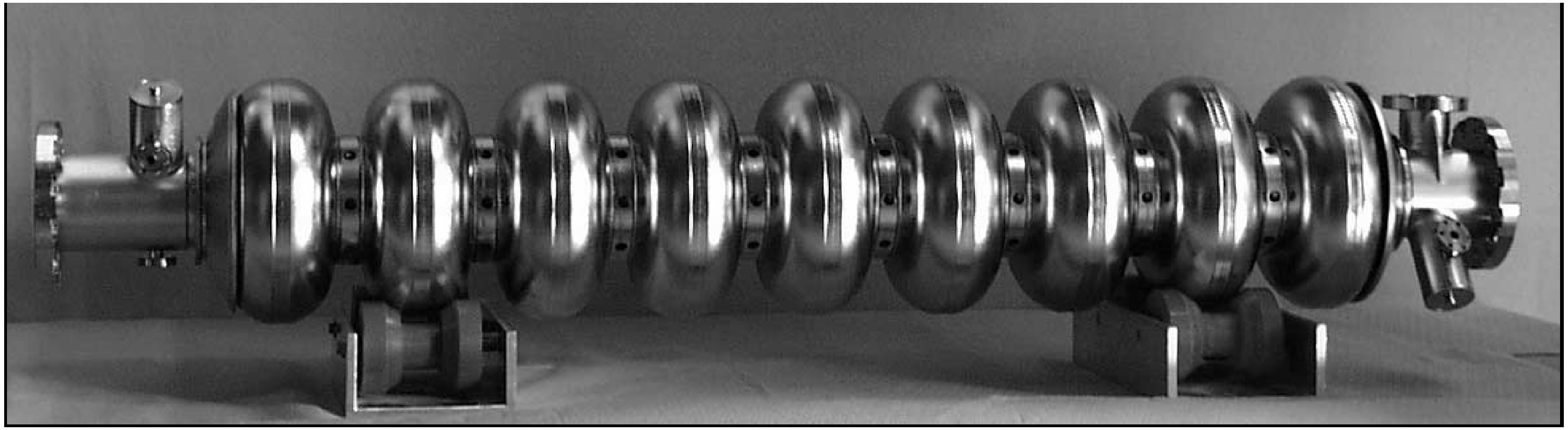
HOMs in the XFEL and ILC

Rainer Wanzenberg
SPL HOM workshop
CERN, June 25 – 26, 2009

Outline

> TESLA 9-cell cavity
> XFEL, FLASH, ILC
> Cavity shape
> Monopole and Dipole modes
> Long Range Wakefields, Multi-bunch Beam Dynamics
> RF Measurements
> Measurements with beam
> HOM coupler configuration
> 3^{rd} harmonic cavity
> Summary

Superconducting TESLA 9-cell cavity

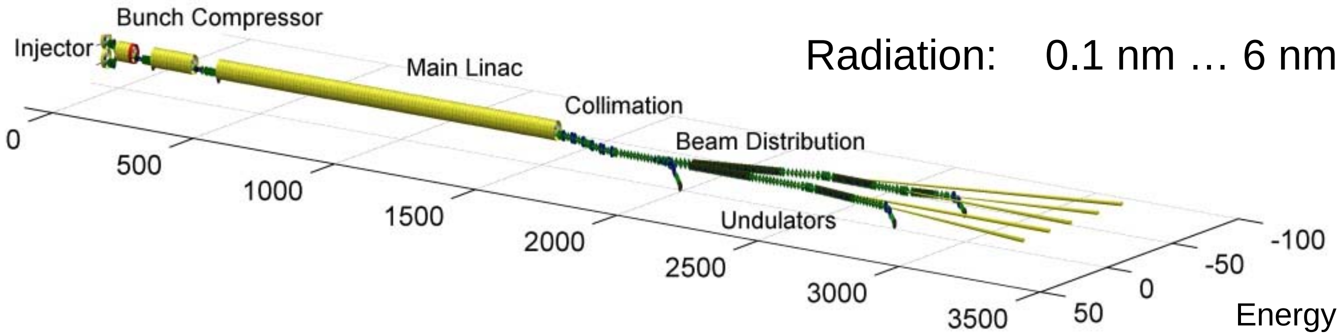


9-cell standing wave structure made from solid niobium

- length about 1 m
- operation mode 1300 MHz (π mode)
- one input coupler
- two HOM couplers

Ref.: B. Aune et al. , Phys. Ref. ST Acc. Beams Vol 3 (2000) 092001

XFEL



Radiation: 0.1 nm … 6 nm

DESY construction side

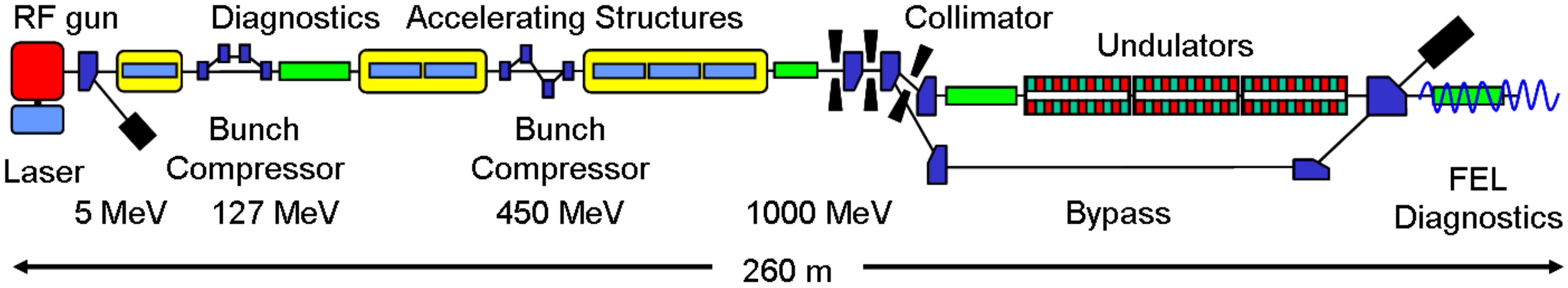
1 Module:
8 cavities

25 Klystrons
(3.8 MW)

Energy	17.5	GeV
Number of bunches	4000	
Bunch population	0.65	10^{10}
Emittance (normalized)	1.4	mm mrad
Bunch charge	1	nC
bunch spacing	200	ns
(free rf buckets)	260	
average current	5	mA
Puls length	0.8	ms
Number of cavities	**800**	
Gradient	23.6	MV / m
f_rep	10	Hz

web page: http://xfel.desy.de/

Flash

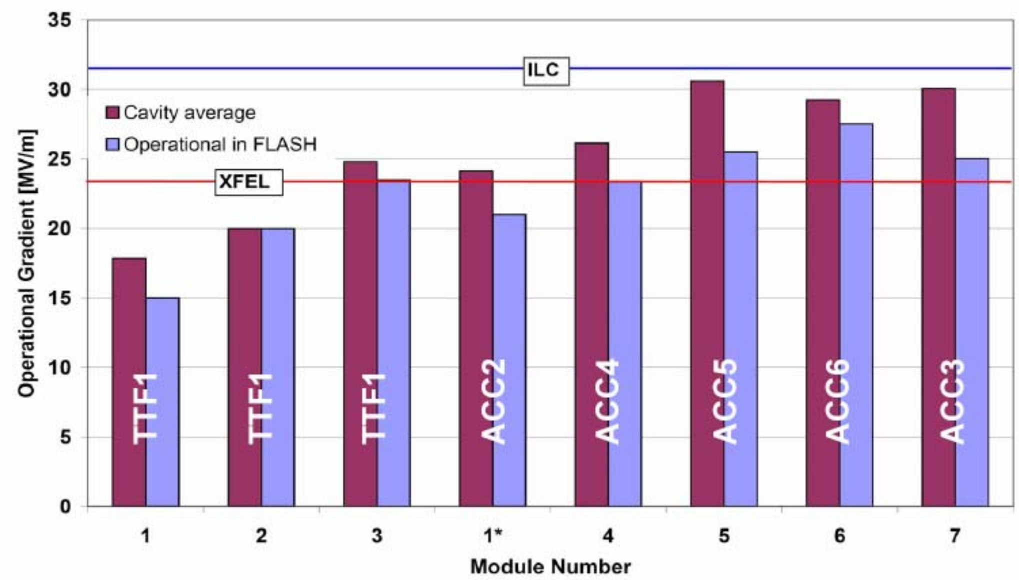


1 module = 8 cavities

Lasing at 6.5 nm (Sep. 2007)

Module 6 during installation

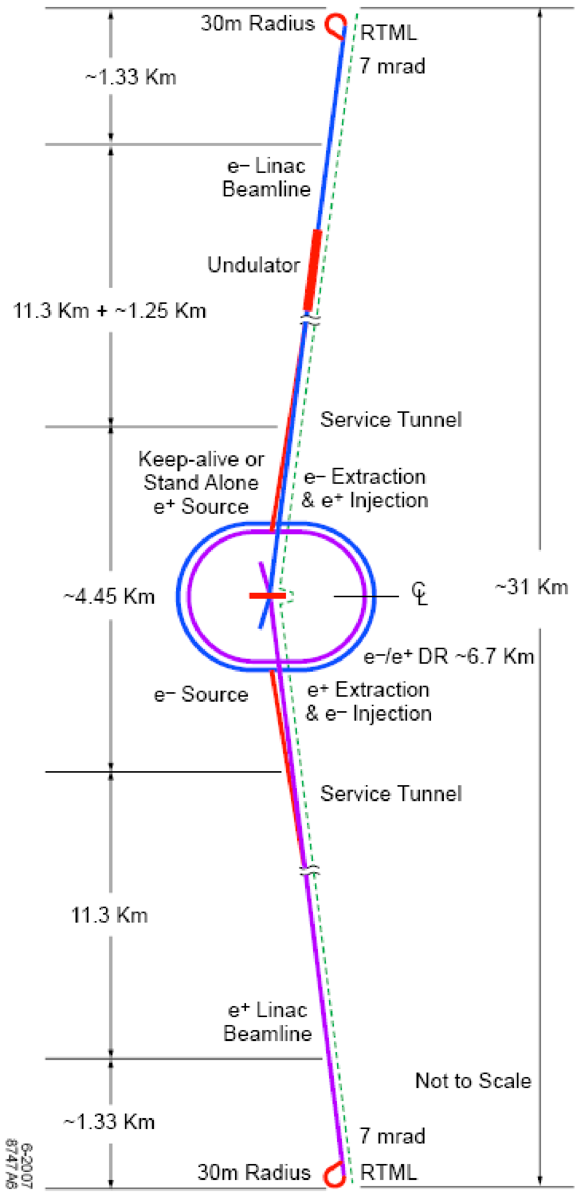
Module performance



webpage: http://flash.desy.de/

Ref: S. Schreiber, B. Faatz, K. Honkavaara, Proceedings, EPAC 08, Genoa, Italy

ILC - Reference Design



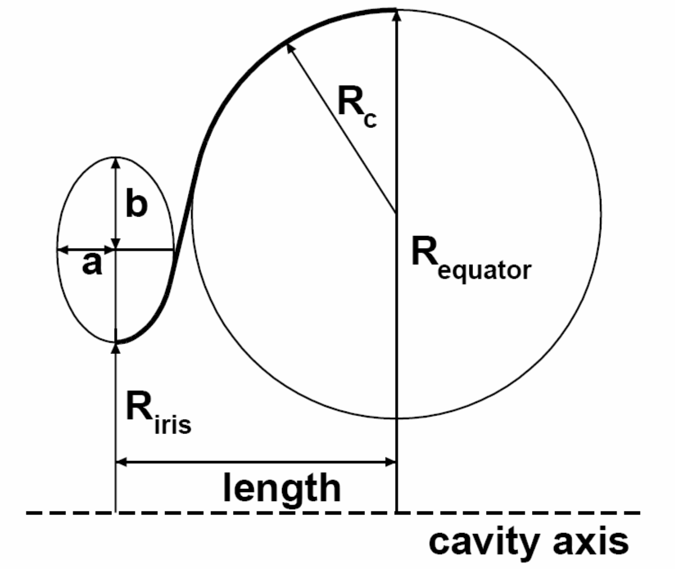
Parameter	Symbol/Units	Nominal
Repetition rate	f_{rep} (Hz)	5
Number of particles per bunch	N (10^{10})	2
Number of bunches per pulse	n_b	2625
Bunch interval in the Main Linac	t_b (ns)	369.2
in units of RF buckets		480
Average beam current in pulse	I_{ave} (mA)	9.0
Normalized emittance at IP	$\gamma\epsilon^*_x$ (mm·mrad)	10
Normalized emittance at IP	$\gamma\epsilon^*_y$ (mm·mrad)	0.04
Beta function at IP	β^*_x (mm)	20
Beta function at IP	β^*_y (mm)	0.4
R.m.s. beam size at IP	σ^*_x (nm)	639
R.m.s. beam size at IP	σ^*_y (nm)	5.7
R.m.s. bunch length	σ_z (μm)	300
Disruption parameter	D_x	0.17
Disruption parameter	D_y	19.4
Beamstrahlung parameter	Υ_{ave}	0.048
Energy loss by beamstrahlung	δ_{BS}	0.024
Number of beamstrahlung photons	n_γ	1.32
Luminosity enhancement factor	H_D	1.71
Geometric luminosity	$\mathcal{L}_{geo}$ $10^{34}/\mathrm{cm}^2/\mathrm{s}$	1.20
Luminosity	$\mathcal{L}$ $10^{34}/\mathrm{cm}^2/\mathrm{s}$	2

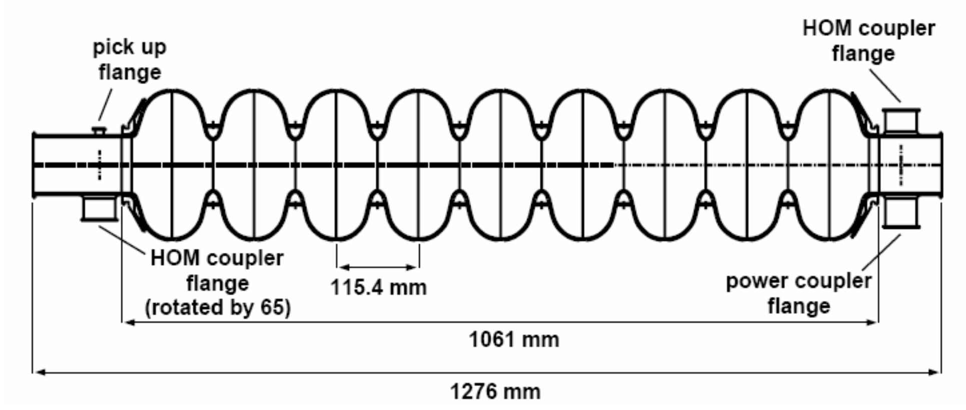
	XFEL	ILC	
Energy	**17.5**	**2 x 250**	**GeV**
Number of bunches	**4000**	**2625**	
Bunch populat-ion	**0.65**	**2**	**10^{10}**
Emittance (normaliz-ed)	**1.4**	**10 / 0.04**	**mm mrad**
bunch spacing	**200**	**369**	**ns**
average current	**5**	**9**	**mA**
Number of cavities	**800**	**2 x 8000**	
Gradient	**23.6**	**31.5**	**MV / m**

Acc. gradient 31.5 MV/m
Number of 9-cell cavities 2 x 8000
(two linacs)

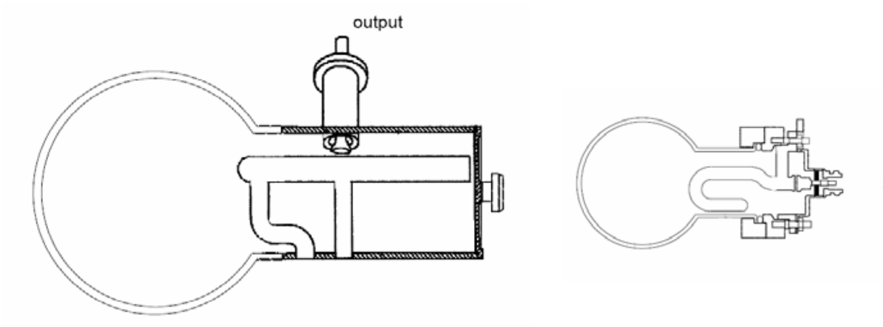
Ref: Reference Design Report, ILC-REPORT-2007-001, Aug. 2007

Cavity shape





HOM coupler



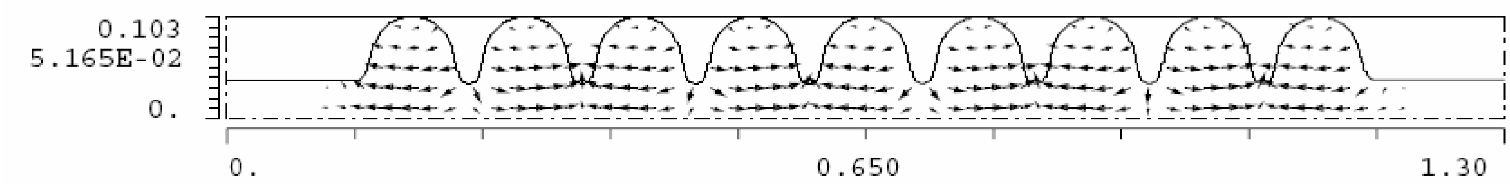
Cavity shape parameter	Midcup	Endcup 1	Endcup 2
Equator radius R_{equat}	103.3	103.3	103.3
Iris radius R_{iris}	35	39	39
Radius R_{arc} of circular arc	42.0	40.3	42
Horizontal half axis a	12	10	9
Vertical half axis b	19	13.5	12.8
Length l	57.7	56.0	57.0

Cutoff frequencies: Midcup: monopole 3.27 GHz; dipole 2.51 GHz (TE) (r = 35 mm)
Endcup: monopole 2.94 GHz; dipole 2.25 GHz (TE) (r = 39 mm)

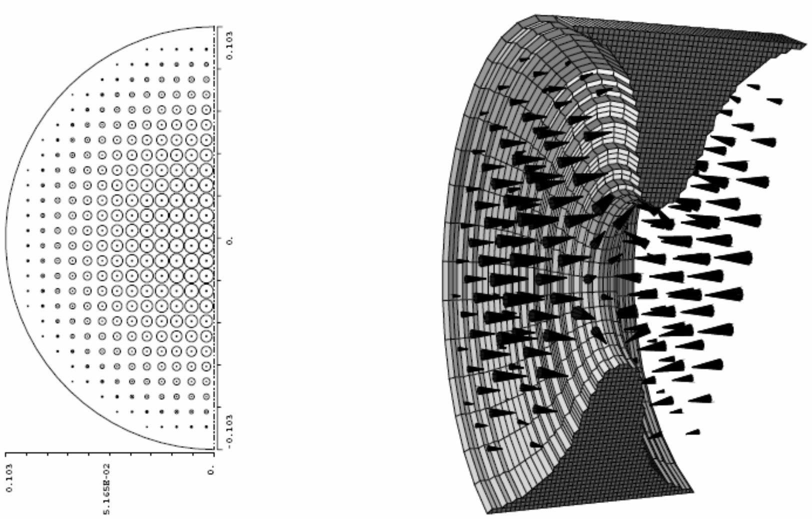
Monopole and Dipole Modes

MAFIA model of the TESLA cavity

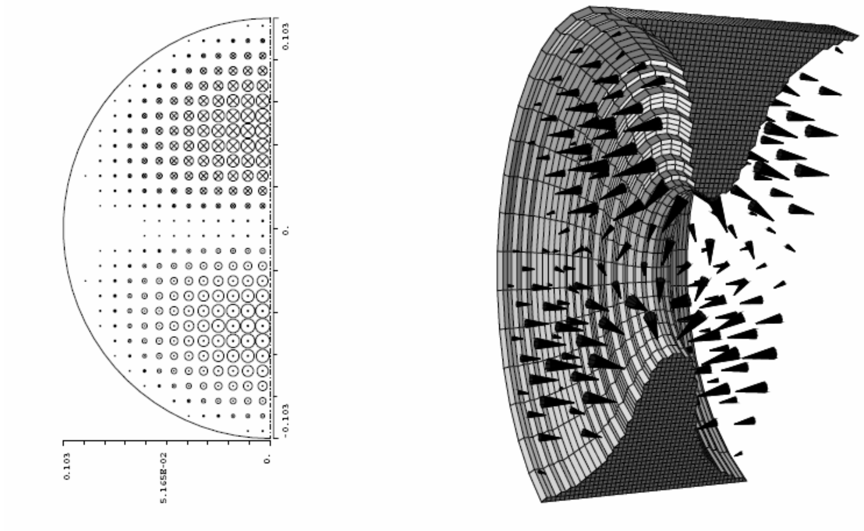
Mainly, a 2D (rz) model is used to calculate the HOMs



Some 3D (rϕz) calculations:



Monopole mode (1.3 GHz)

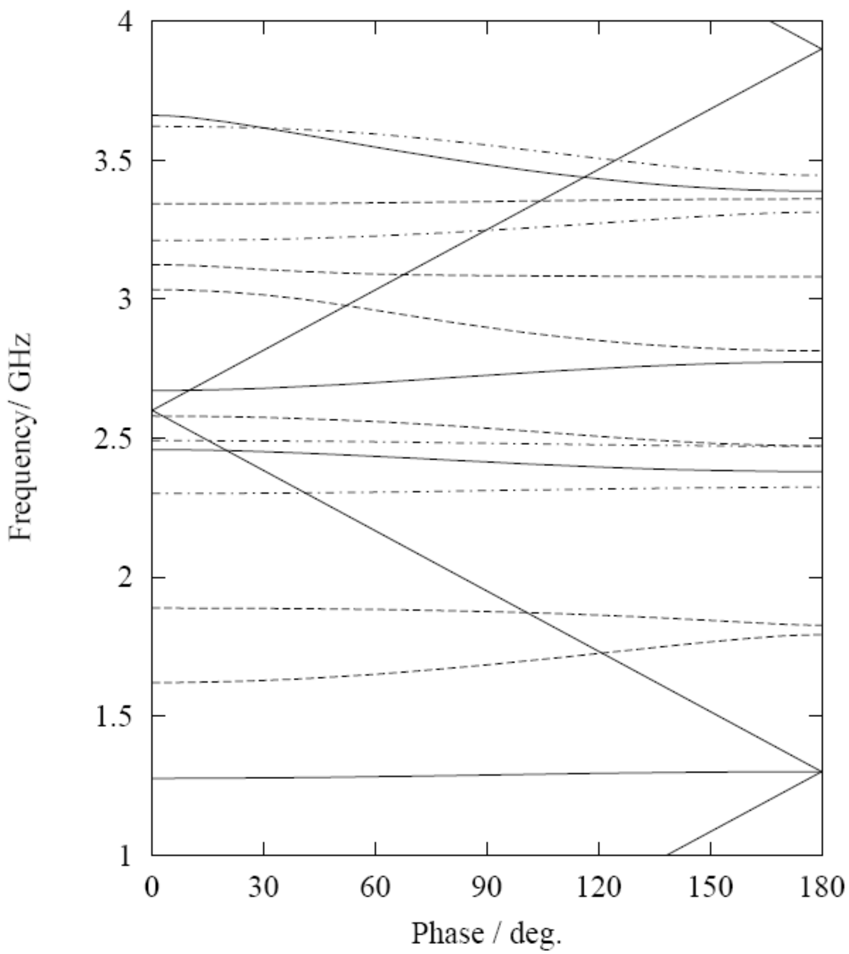


Dipole mode (1.79 GHz)

Ref.: R.W., TESLA 2001-33, Sep. 2001

Passbands

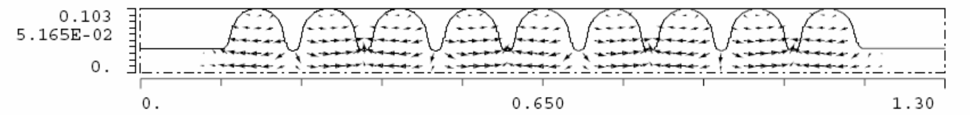
Passbands of the cavity midcell using periodic boundary conditions



type	band #	f_0 / GHz	f_π / GHz
M	1	1.2755	1.2996
D	1	1.6197	1.7920
D	2	1.8877	1.8261
Q	1	2.2996	2.3223
M	2	2.4576	2.3789
Q	2	2.4903	2.4699
D	3	2.5782	2.4713
M	3	2.6704	2.7730
D	4	3.0333	2.8134
D	5	3.1231	3.0802
Q	3	3.2096	3.3119
D	6	3.3419	3.3595
Q	4	3.6204	3.4443
M	4	3.6603	3.3871

solid: monopole
dashed: dipole
dash-dotted: quadrupole

Loss and kick parameter, R/Q, G_1



Solve Maxwell equation on a grid (MAFIA):

- Eigenmode (E,B field)
- frequency $f = \omega/(2\pi)$

Basic post processing

- voltage $V(r) = \int_0^L dz \; E_z(r,z) \; \exp(-i \; \omega \, z/c)$
- stored energy $U = \frac{\varepsilon_0}{2} \int d^3 r |\vec{E}|^2$
- dissipated power, Q-value $P_{sur} = \frac{1}{2} R_{sur} \int dA \, |H_\phi|^2$ $\qquad Q_0 = \frac{\omega \, U}{P_{sur}}$

Further parameters

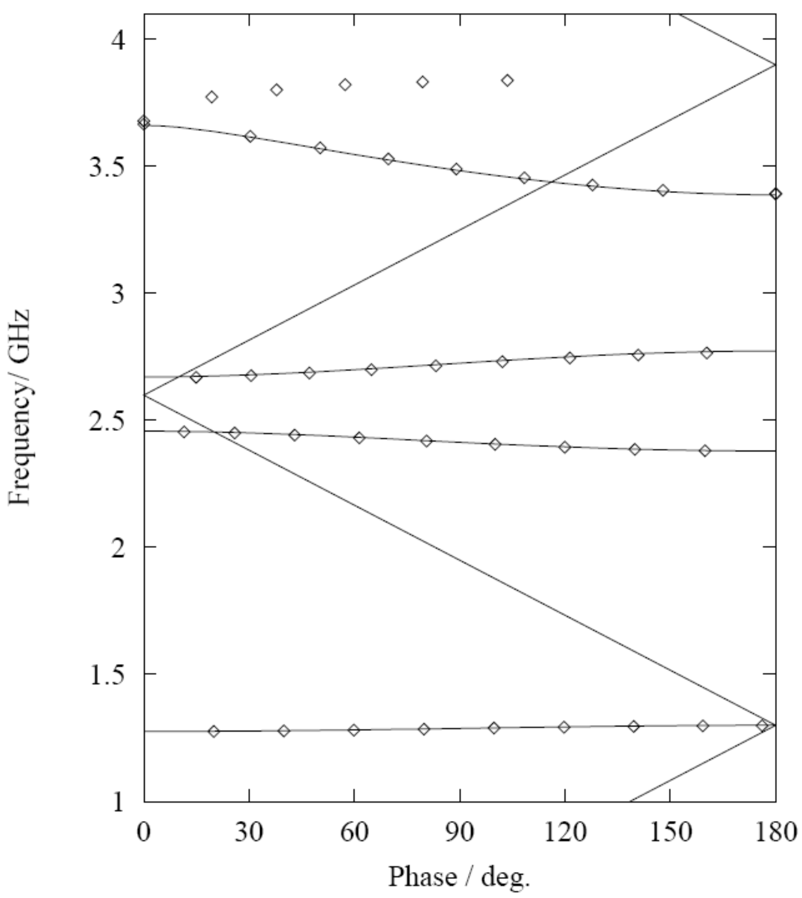
- loss parameter $k_\parallel(r) = \frac{|V(r)|^2}{4 \; U}$ V/C $\qquad \Delta E = q^2 \; k_\parallel(r)$
- kick parameter (dipole modes) $k_\perp = \frac{1}{\omega/c} \frac{1}{r^2} \frac{|V(r)|^2}{4 \, U}$ V/ (C m)
- R/Q (R = V² /2 P)

$$\left(\frac{R(r)}{Q}\right) = \frac{2 \; k_\parallel(r)}{\omega} \text{ Ohm} \qquad \left(\frac{R^{(1)}}{Q}\right) = \frac{1}{r^2} \frac{2 \; k_\parallel(r)}{\omega} \text{ Ohm / m}^2 \qquad Z_\perp = \left(\frac{R^{(1)}}{Q}\right) \frac{1}{\omega/c} Q$$

- G_1

$$G_1 = R_{sur} \; Q_0 = R_{sur} \frac{\omega \, U}{P_{sur}}$$

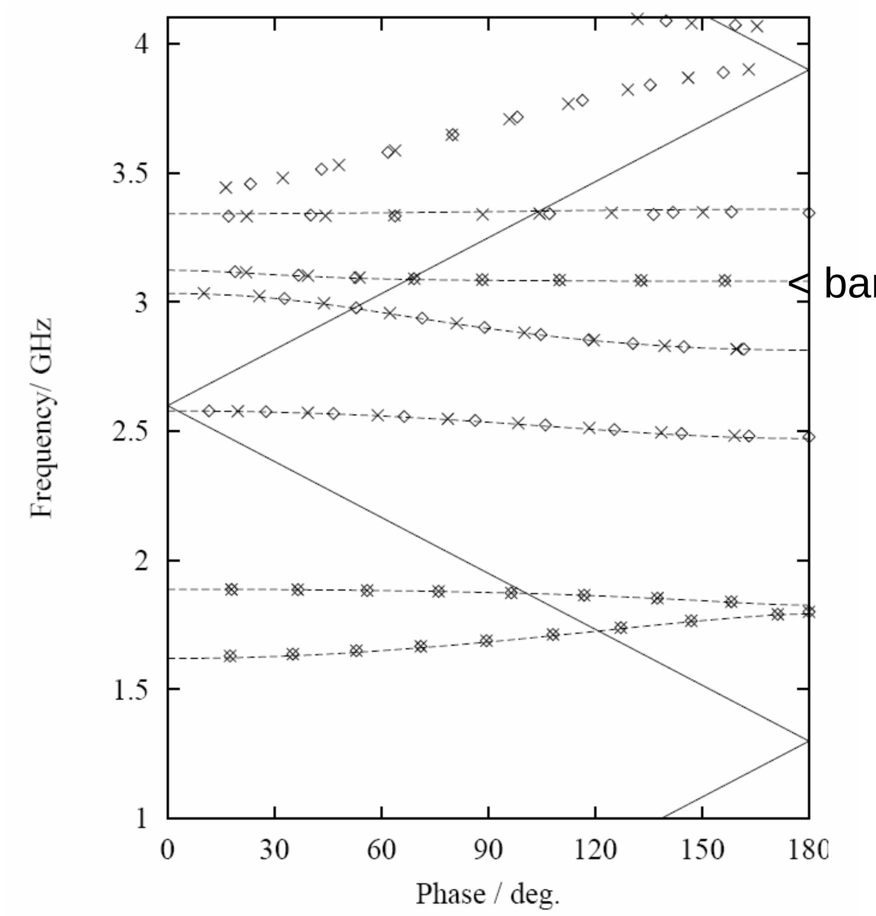
Monopole Modes



mode	f /GHz	$k^{(0)}$/ V/(pC)	G_1 /Ω	$(R/Q)^{(0)}$ / Ω	Q_0/Q_{0FM}	φ /°
Band 1						
MM- 1	1.2756	$0.848\ 10^{-06}$	252.7	0.0002	1.027	20.0
MM- 2	1.2776	$0.239\ 10^{-06}$	252.9	0.0001	1.025	39.9
MM- 3	1.2807	$0.523\ 10^{-05}$	253.2	0.0013	1.021	59.9
MM- 4	1.2845	$0.187\ 10^{-05}$	253.5	0.0005	1.017	79.8
MM- 5	1.2885	$0.217\ 10^{-05}$	253.9	0.0005	1.012	99.8
MM- 6	1.2924	$0.776\ 10^{-05}$	254.2	0.0019	1.007	119.7
MM- 7	1.2955	$0.138\ 10^{-03}$	254.5	0.0339	1.003	139.6
MM- 8	1.2976	$0.662\ 10^{-04}$	254.7	0.0163	1.001	159.2
MM- 9	1.2983	2.08	254.8	511.0652	1.000	176.1
Band 2						
MM-10	2.3800	$0.746\ 10^{-05}$	370.6	0.0010	0.433	159.9
MM-11	2.3856	$0.147\ 10^{-03}$	370.7	0.0196	0.431	139.9
MM-12	2.3943	$0.248\ 10^{-03}$	370.9	0.0329	0.428	119.9
MM-13	2.4055	$0.414\ 10^{-03}$	371.2	0.0547	0.424	100.1
MM-14	2.4181	$0.376\ 10^{-02}$	371.3	0.4943	0.420	80.6
MM-15	2.4308	$0.573\ 10^{-04}$	371.2	0.0075	0.416	61.4
MM-16	2.4419	0.08	370.6	10.2352	0.411	43.0
MM-17	2.4499	0.60	369.0	77.6533	0.407	25.9
MM-18	2.4539	0.57	365.9	73.8717	0.402	11.5
Band 3						
MM-19	2.6695	$0.363\ 10^{-03}$	546.8	0.0433	0.508	14.9
MM-20	2.6756	$0.291\ 10^{-02}$	548.7	0.3465	0.507	30.6
MM-21	2.6858	$0.118\ 10^{-02}$	550.9	0.1395	0.505	47.2
MM-22	2.6993	$0.141\ 10^{-02}$	554.2	0.1659	0.503	64.8
MM-23	2.7148	$0.166\ 10^{-02}$	559.7	0.1948	0.502	83.2
MM-24	2.7307	$0.198\ 10^{-03}$	567.6	0.0231	0.504	102.1
MM-25	2.7453	$0.825\ 10^{-03}$	577.1	0.0957	0.507	121.4
MM-26	2.7571	$0.236\ 10^{-05}$	586.4	0.0003	0.510	140.8
MM-27	2.7648	$0.965\ 10^{-04}$	593.3	0.0111	0.513	160.4

Cutoff frequencies: Midcup: monopole 3.27 GHz (r = 35 mm)
Endcup: monopole 2.94 GHz (r = 39 mm)

Dipole Modes



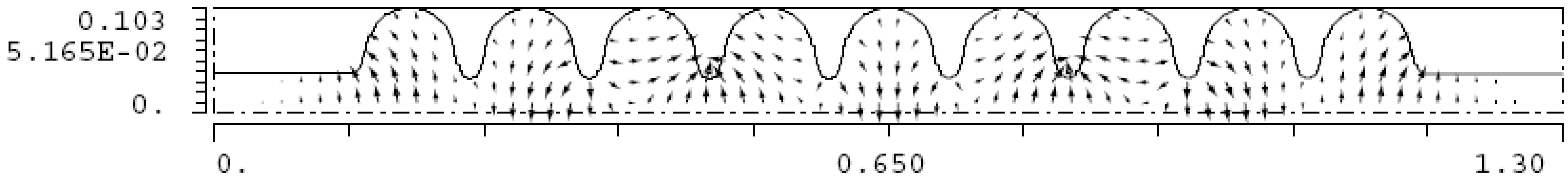
mode	f /GHz	$k^{(1)}(r)/r^2$/ V/(pC m^2)	G_1 /Ω	$(R/Q)^{(1)}$ / Ω/cm^2	$Q_0/Q_{0\,FM}$	φ /°
Band 1						
MM- 1	1.6291	0.1	286.7	0.0014	0.715	17.5
MM- 2	1.6369	3.3	290.5	0.0636	0.717	35.1
MM- 3	1.6497	0.1	296.6	0.0015	0.721	53.0
MM- 4	1.6671	19.7	304.4	0.3767	0.725	71.1
MM- 5	1.6885	3.6	313.2	0.0684	0.727	89.4
MM- 6	1.7129	297.8	322.1	**5.5335**	0.726	108.1
MM- 7	1.7391	425.4	329.5	**7.7852**	0.721	127.2
MM- 8	1.7656	58.2	332.7	1.0492	0.706	146.9
MM- 9	1.7912	45.3	332.4	0.8045	0.685	171.2
MM-10	1.8004	20.0	299.0	0.3542	0.610	180.0
Band 2						
MM-11	1.8391	14.1	433.0	0.2433	0.847	158.2
MM-12	1.8535	7.7	409.5	0.1327	0.789	137.5
MM-13	1.8650	186.5	401.4	**3.1825**	0.763	116.9
MM-14	1.8736	264.2	397.3	**4.4887**	0.749	96.4
MM-15	1.8795	62.0	394.7	1.0501	0.739	76.0
MM-16	1.8834	1.2	392.9	0.0210	0.733	56.0
MM-17	1.8858	4.8	391.8	0.0808	0.729	36.5
MM-18	1.8871	0.1	391.2	0.0015	0.727	18.0
MM-19	2.2884	4.8	265.1	0.0664	0.335	—
MM-20	2.2884	0.7	265.1	0.0104	0.335	—
Band 3						
MM-21	2.4778	1.5	484.0	0.0190	0.522	180.0
MM-22	2.4810	5.2	452.4	0.0664	0.486	163.2
MM-23	2.4911	2.8	453.3	0.0353	0.483	144.2
MM-24	2.5062	2.2	446.6	0.0278	0.470	125.3
MM-25	2.5239	1.7	433.7	0.0220	0.450	106.0
MM-26	2.5415	1.2	417.3	0.0156	0.427	86.4
MM-27	2.5568	0.1	401.3	0.0017	0.406	66.4
MM-28	2.5682	10.2	388.6	0.1263	0.390	46.5
MM-29	2.5753	8.5	380.4	0.1045	0.379	27.6
MM-30	2.5785	1066.0	376.5	**13.1601**	0.375	11.6

Boundary conditions: EE x MM ◇

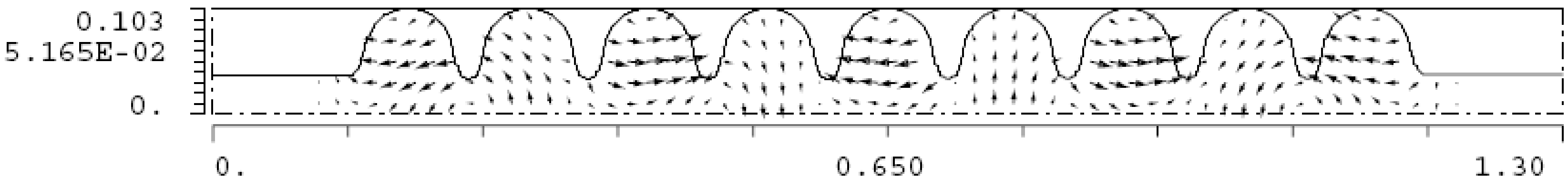
Cutoff frequencies:
Midcup: dipole 2.51 GHz (TE) (r = 35 mm)
Endcup: dipole 2.25 GHz (TE) (r = 39 mm)

Dipole Modes – Field Plots

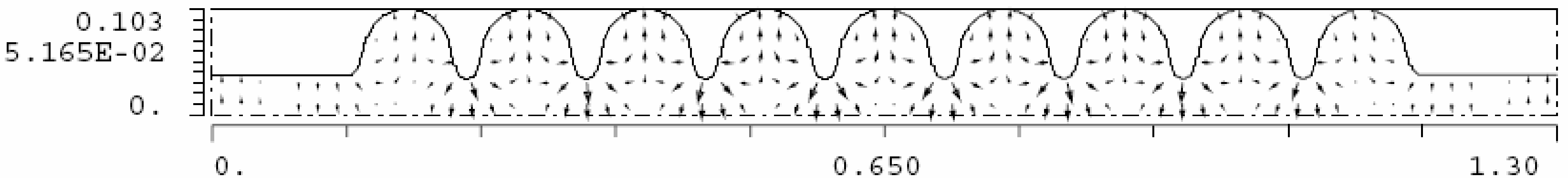
1st passband (largest R/Q), MM-7, 1.71 GHz



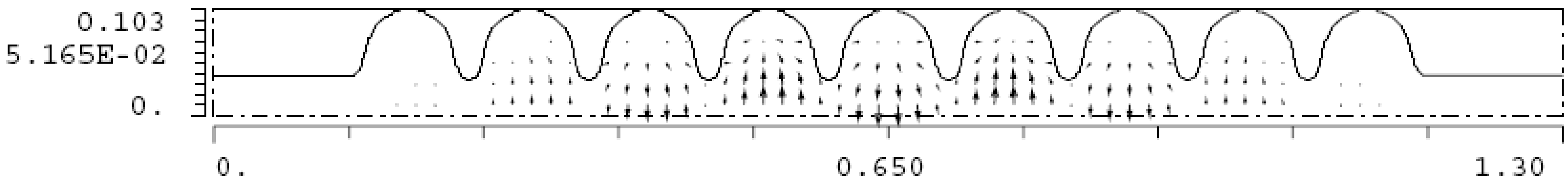
2nd passband (largest R/Q), MM-14, 1.87 GHz



3rd passband (largest R/Q), MM-30, 2.57 GHz



5th passband, (trapped) MM-42, 3.08 GHz

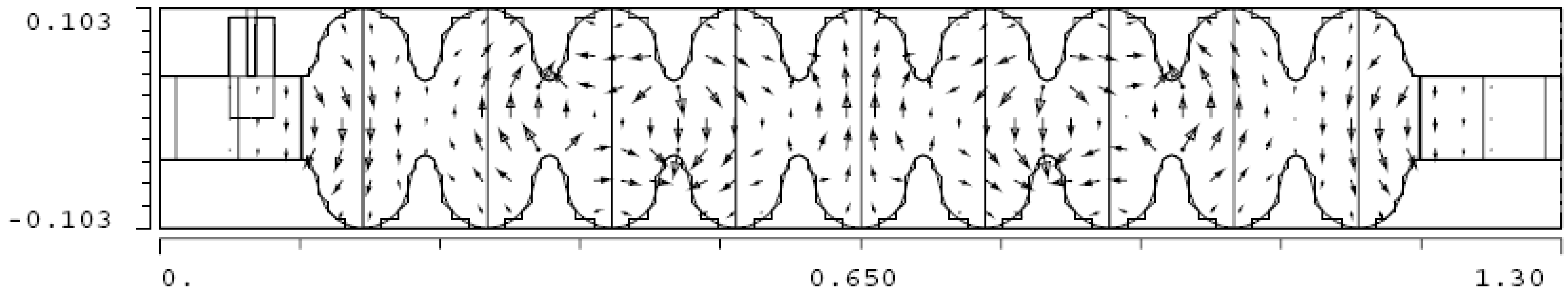


Estimation of external Q-values

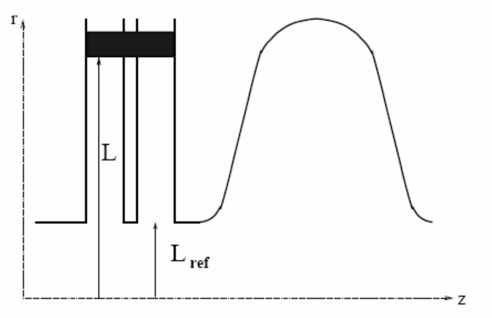
Kroll, Yu Method (Part. Acc., 1990, Vol 34, pp 231-250)

3D (xyz) MAFIA Model of the cavity

Electric field of 1.73 GHz mode from the first passband:



Coaxial port with plunger:



From different plunger position the external Q-value is fitted according to the theory by Kroll and Yu.

$$\psi(\omega) = -2 \arctan\left(\frac{2\,Q_r}{\omega_r}(\omega - \omega_r)\right) + \phi_r$$

$Q_{ext} \sim 4 \times 10^5$

for the mode from the first passband

Long Range Wakefields

Longitudinal

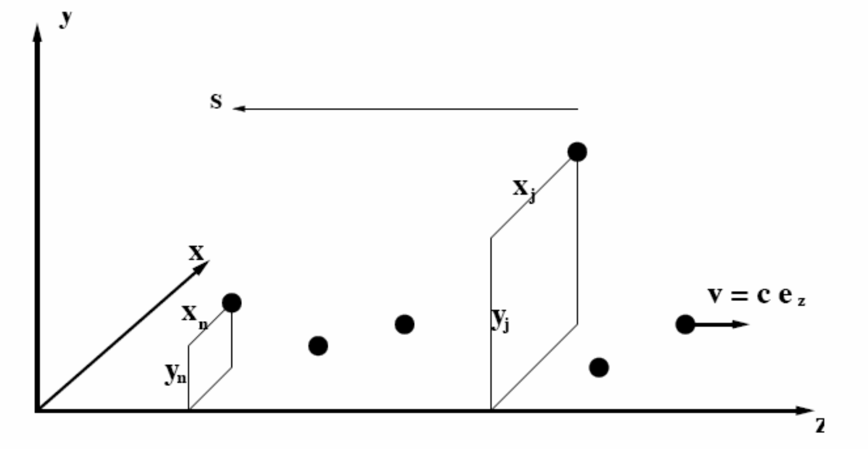
$$W_{\|}(s) = -\sum_{\text{Modes}} \omega \left(\frac{R}{Q}\right) \cos(\omega\, s/c)\ \exp(-\frac{1}{\tau} s/c) \qquad \frac{1}{\tau} = \frac{\omega}{2\ Q_{ext}}$$

Transversal
(Dipole)

$$W_{\perp}(s) = c \sum_{\text{Modes}} \left(\frac{R}{Q}\right)^{(1)} \sin(\omega\, s/c)\ \exp(-\frac{1}{\tau} s/c)$$

Kick on bunch n due to one dipole mode:

$$\vec{\theta}_n = \hat{\theta}_n \sum_{j<n} \left(\frac{x_j}{r_0} \vec{u}_x + \frac{y_j}{r_0} \vec{u}_y \right) \sin(\omega\, (s_n - s_j)/c)\ \exp(-\frac{1}{\tau}(s_n - s_j)/c)$$



$$\hat{\theta}_n = \frac{e q_{bunch}}{E_{beam}} c \left(\frac{R}{Q}\right)^{(1)} r_0$$

Kick on bunch n

One dipole mode and a bunch train **with constant offset**:

$$\theta_n = \hat{\theta} \sum_{j<n} \sin(\, \delta \ (n-j)) \ \exp(\,-d \ (n-j)\,) = \hat{\theta} \ \mathrm{Im}[S_n]$$

Phase

$$\delta = 2\pi \frac{f}{1.3 \ GHz} n_{fb}$$

Damping constant

$$d = 2\pi \frac{f}{1.3 \ GHz} n_{fb} \frac{1}{2 \, Q_{ext}}$$

Analytic formula:

$$S_n = \sum_{k=1}^{n} \exp((i\,\delta - d\,)\,k) \to \frac{1}{\exp(-i\,\delta + d\,) - 1} \,, \quad n \to \infty$$

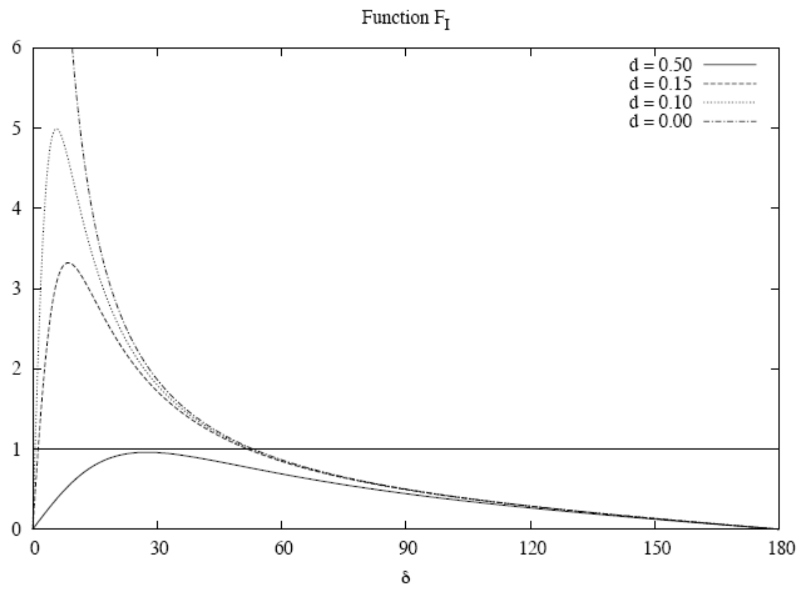
Asymptotic amplification of the kick:

$$\lim_{n\to\infty} \mathrm{Im}[S_n] = F_I(\delta, d) = \frac{\exp(-d)\,\sin(\delta)}{1 - 2\exp(-d)\,\cos(\delta) + \exp(-2d)}$$

Ref: P.B. Wilson, AIP Conf. Proceedings 87, New York (1982), p. 450-563
L. Bellantoni, H. Edwards, R.W., Internal report, DESY M 08-01, March 2008

Asymptotic amplification of the kick

$$\lim_{n\to\infty} \mathrm{Im}[S_n] = F_I(\delta,d) = \frac{\exp(-d)\sin(\delta)}{1-2\exp(-d)\cos(\delta)+\exp(-2d)}$$



f	R^1/Q	Kick	d
GHz	Ohm/m²	n rad	(Q = 10^5)
1.739	7.7	9.6	0.011
1.873	4.4	5.5	0.012
2.578	13.1	16.3	0.016

(kick of one cavity, E = 2.5 GeV, q = 1 nC, beam offset 1 mm)

$$\underset{\delta}{Max}(F_I(\delta,d)) = \frac{1}{2\sinh(d)}$$

$$\delta_{\max} = \arccos\left(\frac{1}{\cosh(d)}\right)$$

"Random phase"

Q = 10^5, d = 0.01, Max ~ 50, RMS ~ 5

$$\frac{d}{df}\delta = 2\pi\frac{1}{1.3\ GHz}n_{fb} = 72^\circ\frac{1}{MHz}$$

$$\underset{\delta}{RMS}(F_I(\delta,d)) = \frac{1}{2}\sqrt{\coth(d)-1} \approx \frac{1}{2\sqrt{d}}$$

(200 ns bunch spacing)

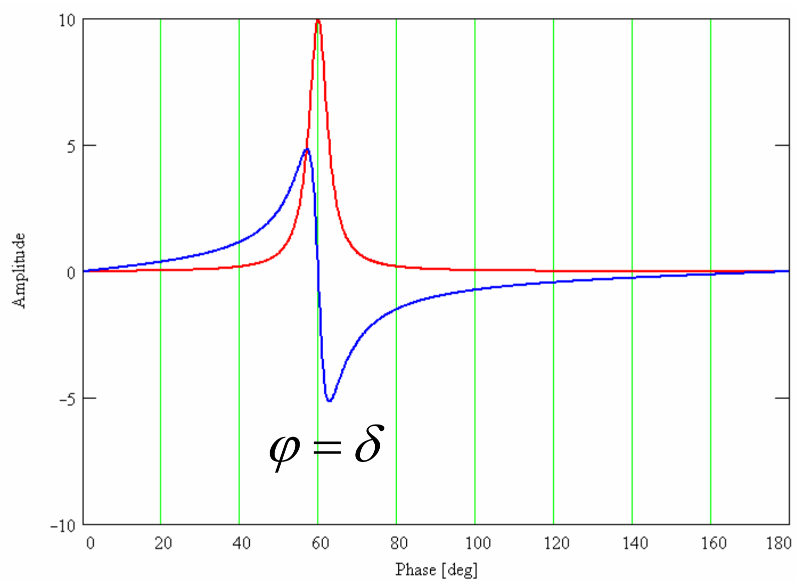
Resonant excitation – modulated bunch train

One dipole mode and a bunch train **with a modulated offset**:

$$x_j = x_0 \sin(\Omega \; \Delta t \; j)$$

$$\theta_n = \hat{\theta} \sum_{j<n} \sin(\varphi \; j) \; \sin(\delta \; (n-j)) \; \exp(-d \; (n-j))$$

$$\theta_n = \hat{\theta}\left(A_{+,n}(\varphi,\delta,d) \sin(n\varphi) - A_{-,n}(\varphi,\delta,d) \; \cos(n\varphi)\right)$$



$$\varphi = \Omega \; T_b = 2\pi \frac{1}{1.3\;\mathrm{GHz}} n_{fb}$$

$$A_{-,n}(\varphi,\delta,d) \xrightarrow[n\to\infty]{} A_{-}(\varphi,\delta,d) = \frac{\sin(\varphi)\sinh(d) \;\; \sin(\delta)}{2(\cosh(d)-\cos(\delta-\varphi))(\cosh(d)-\cos(\delta+\varphi))}$$

$$A_{+,n}(\varphi,\delta,d) \xrightarrow[n\to\infty]{} A_{+}(\varphi,\delta,d) = \frac{(\cos(\delta)-\cos(\varphi)\cosh(d)) \;\; \sin(\delta)}{2(\cosh(d)-\cos(\delta-\varphi))(\cosh(d)-\cos(\delta+\varphi))}$$

Resonant excitation:

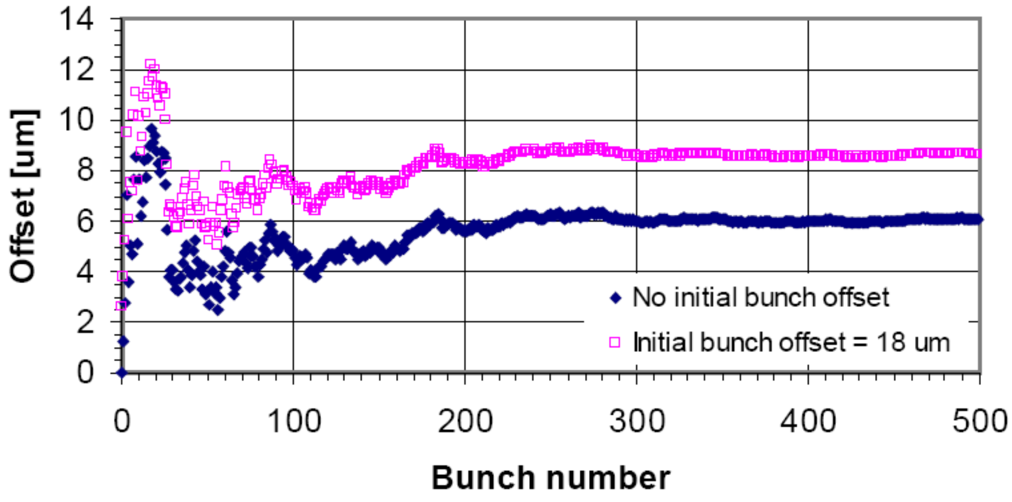
$$f_{HOM} = \mathrm{Integer} \times \frac{1}{T_b} + \frac{\Omega}{2\pi}$$

A_{+-} are plotted for d = 0.05, Q ~ 2 x 10^4

Ref.: S. Fartough, DAPNIA/SEA-98-04, TESLA 98-07, Feb 1998

Simulations

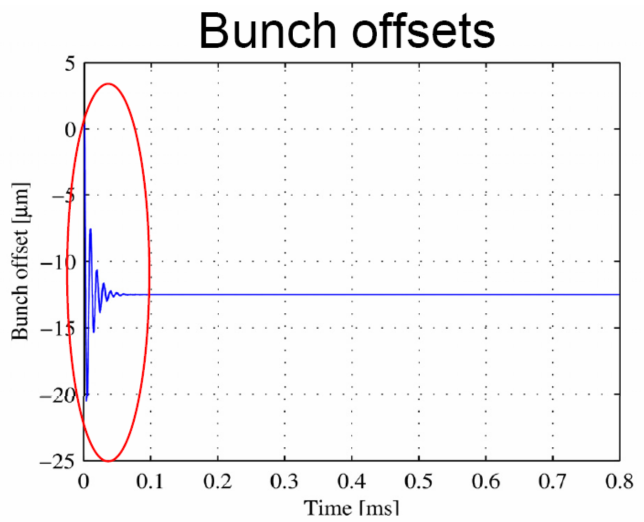
TESLA LC,
Technical Design Report, Part II, part 3.2.3
TESLA Report 2001-23, March 2001



Multi bunch beam simulations
(A. Mosnier)
0.5 mm rms cavity misalignment
Q-values: 2×10^4 ... 1×10^5
mode detuning

XFEL
beam dynamics working group

http://www.desy.de/xfel-beam/

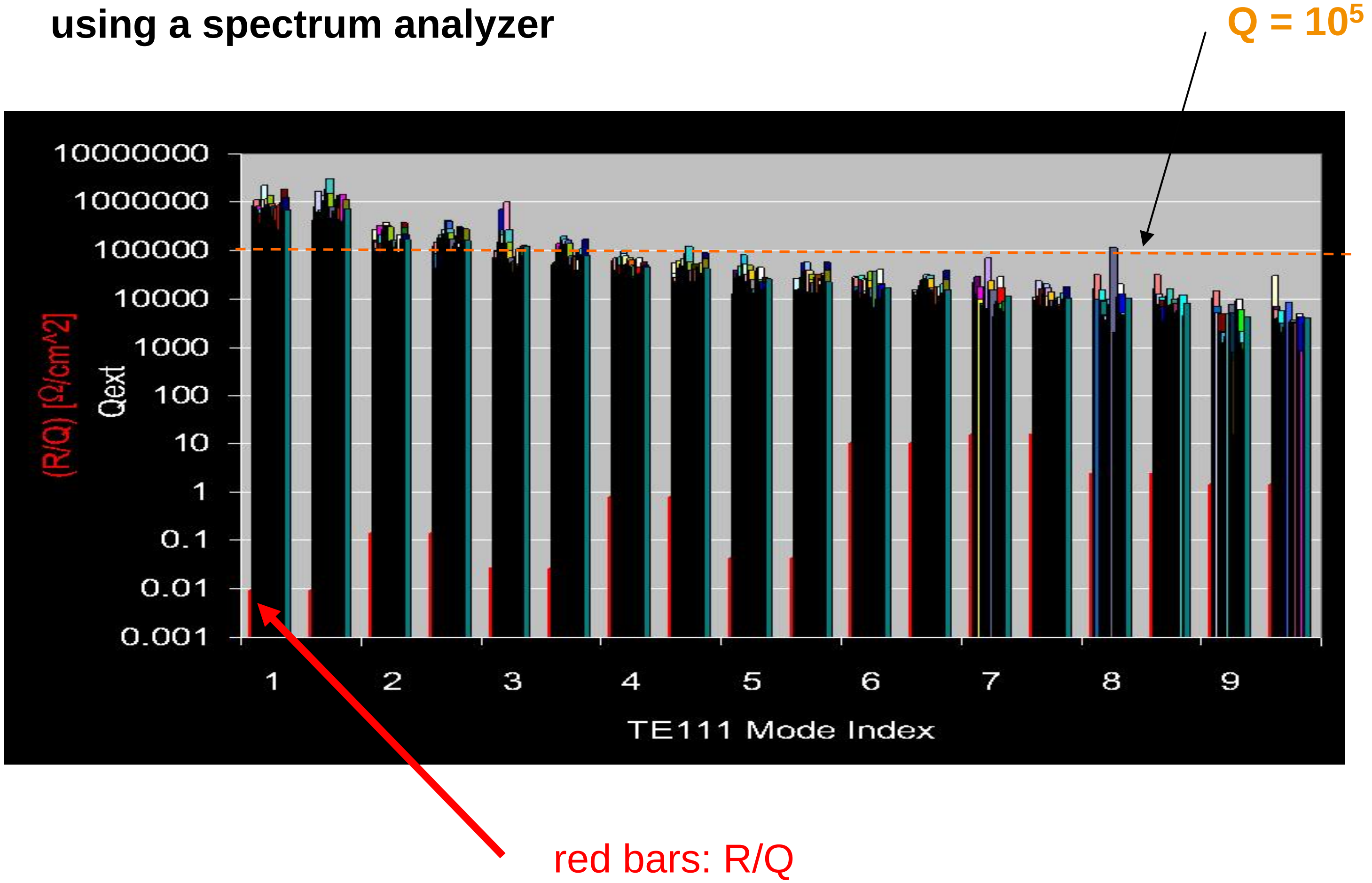


N. Baboi, Y. Kot
Multi Bunch Beam Dynamics
Linac Review Meeting - 2007-03-26

0.1 % rms mode detuning

RF measurements

Measurement of external Q-values using a spectrum analyzer

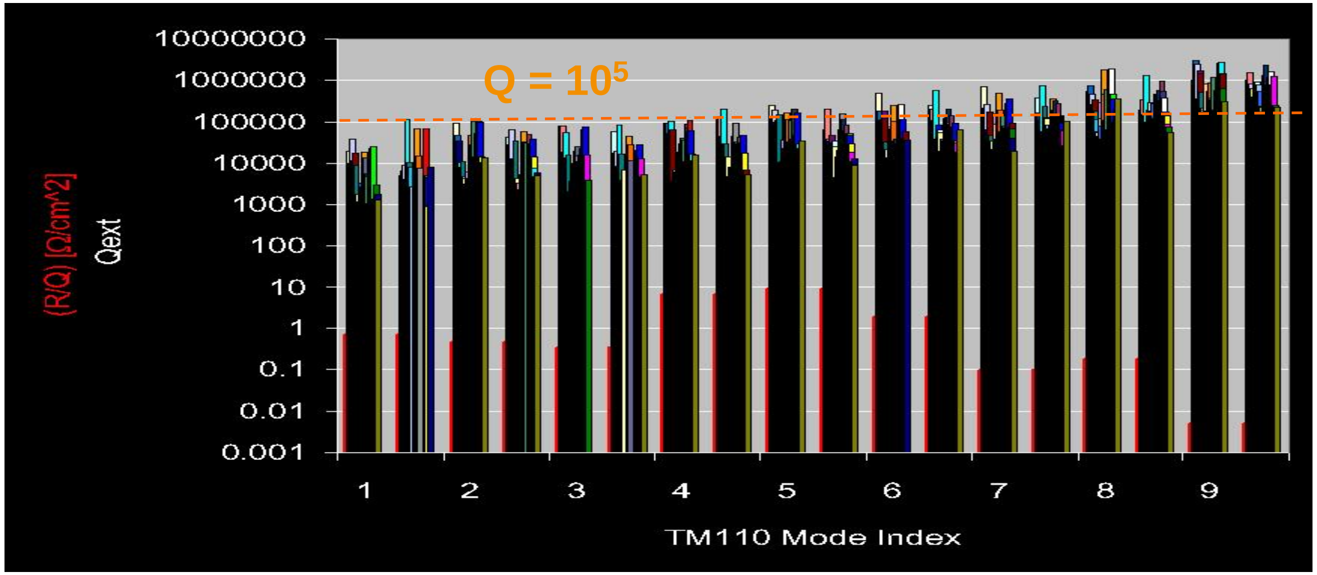


Qext of 1st dipole passband TE111

(50 cavities)

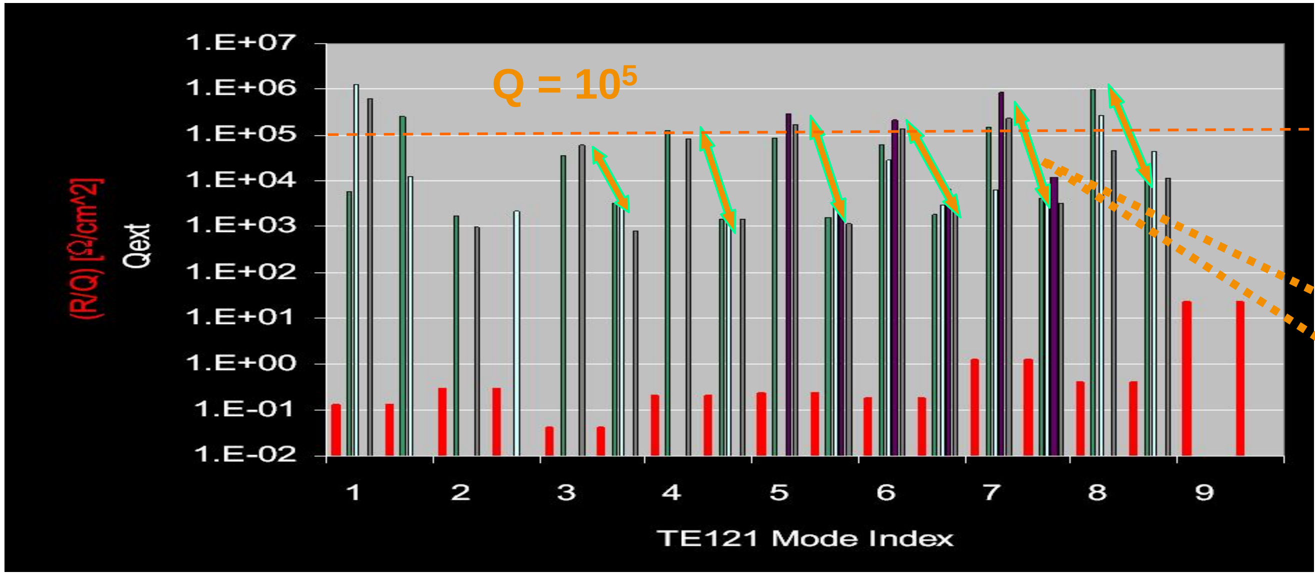
Ref.: J. Sekutowicz, ILC workshop, KEK, Nov. 2004

RF measurements (cont.)



Qext of 2nd dipole passband TM110

(50 cavities)



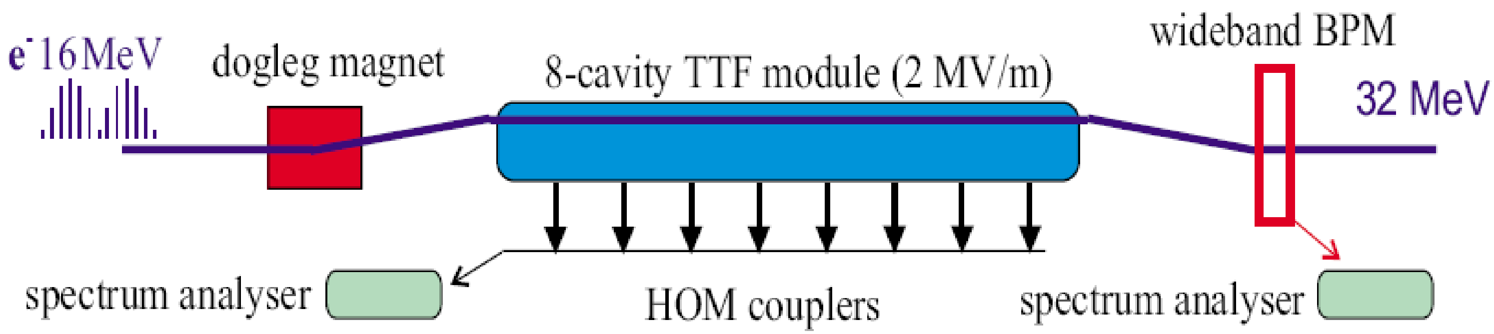
Qext of 3rd dipole passband TE121

(7 cavities measured in the horizontal cryostat CHECHIA)

Large difference in Qext of both polarization

Measurements with Beam

Measurements with beam at the TTF (now converted into the user facility FLASH)



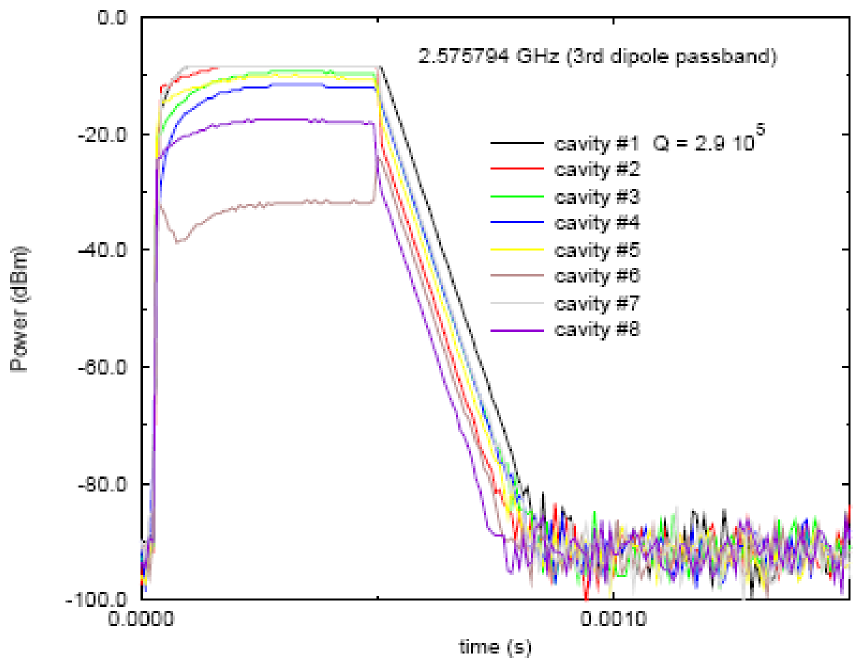
Modulation of the bunch charge

$$q_n = q_0 \left(1 + \lambda \sin(n \; 2\pi \; f_m \; T_b + \phi)\right)$$

Excited HOM

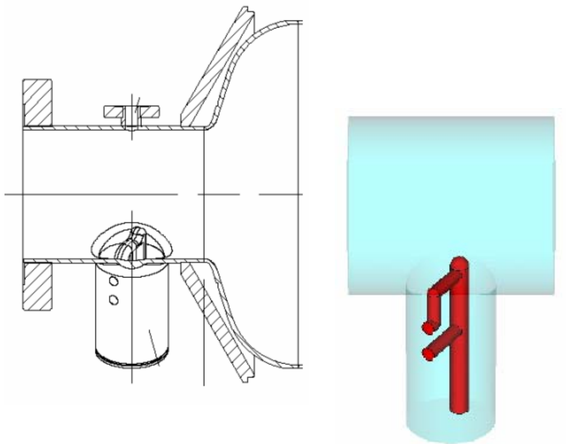
$$f_{HOM} = k \frac{1}{T_b} + f_m$$

HOM signal
2.57 GHz
Q ~ 2.9 10^5



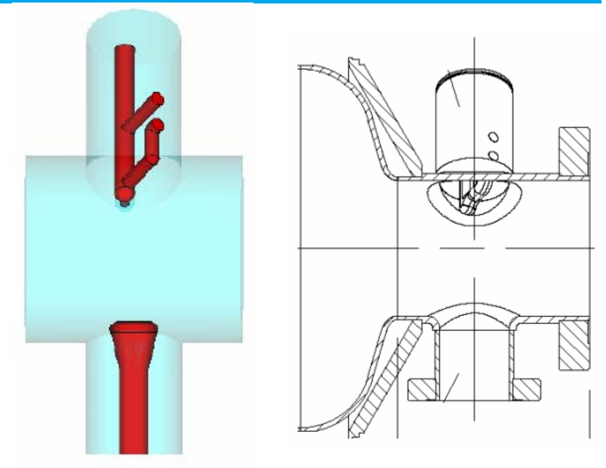
Ref.
S. Fartough, et al., Proceedings, PAC 1999, New York,
C. Magne, et al. , Proceedings, PAC 2001, Chicago,
S. Fartough, CEA/DAPNIA/SEA-98-18

Symmetries of the HOM couplers

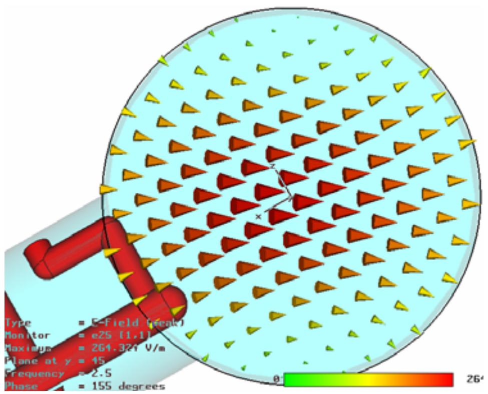


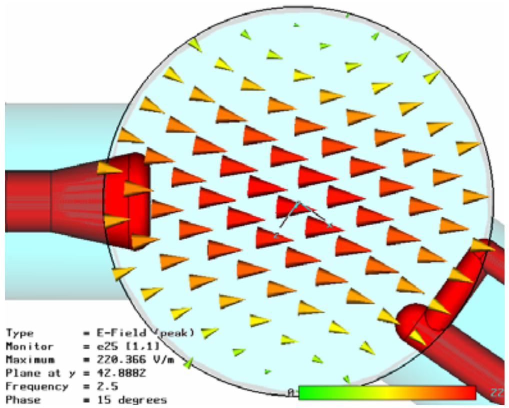
Original Configuration

The HOM couplers couple only weakly to vertical polarized modes of the 3rd passband



Field stimulated by HOM port, 2.5GHz

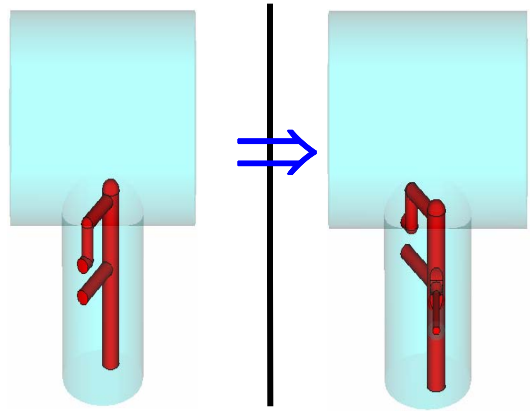


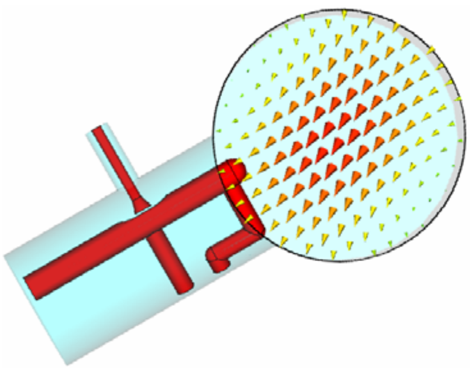


Ref.:
M. Dohlus, V. Kaljuzhny, S.G.Wipf , TESLA 2002-05

Improved configuration of the HOM couplers

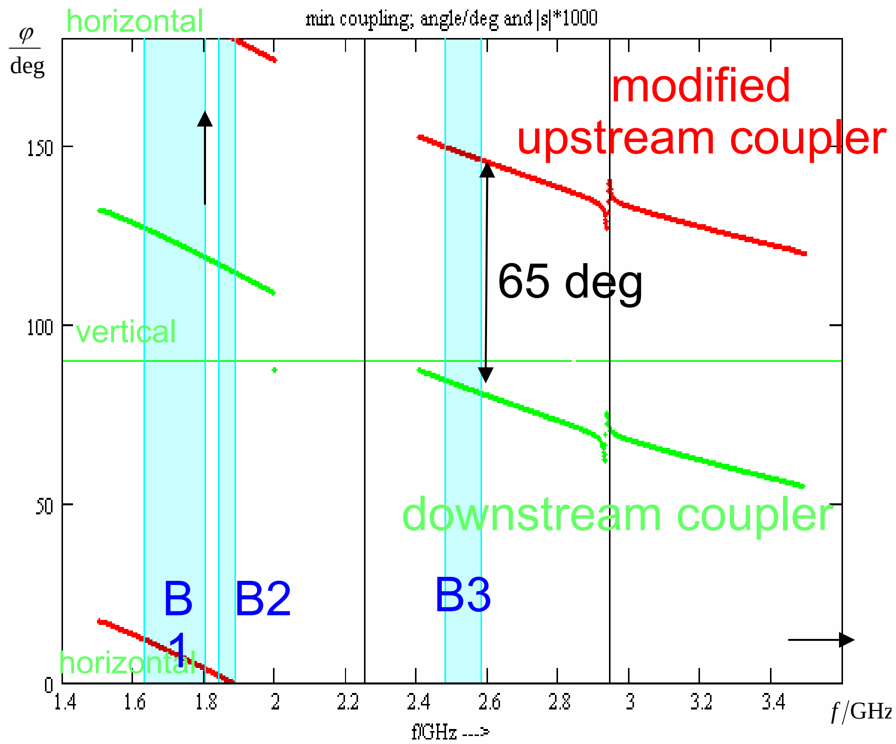
Modified upstream HOM coupler



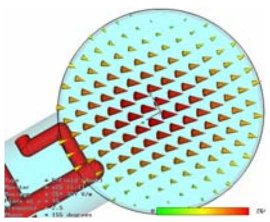


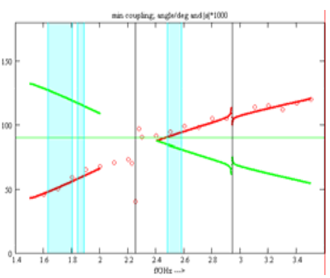
Modified Configuration

The HOM couplers couple to vertical and horizontal polarized modes



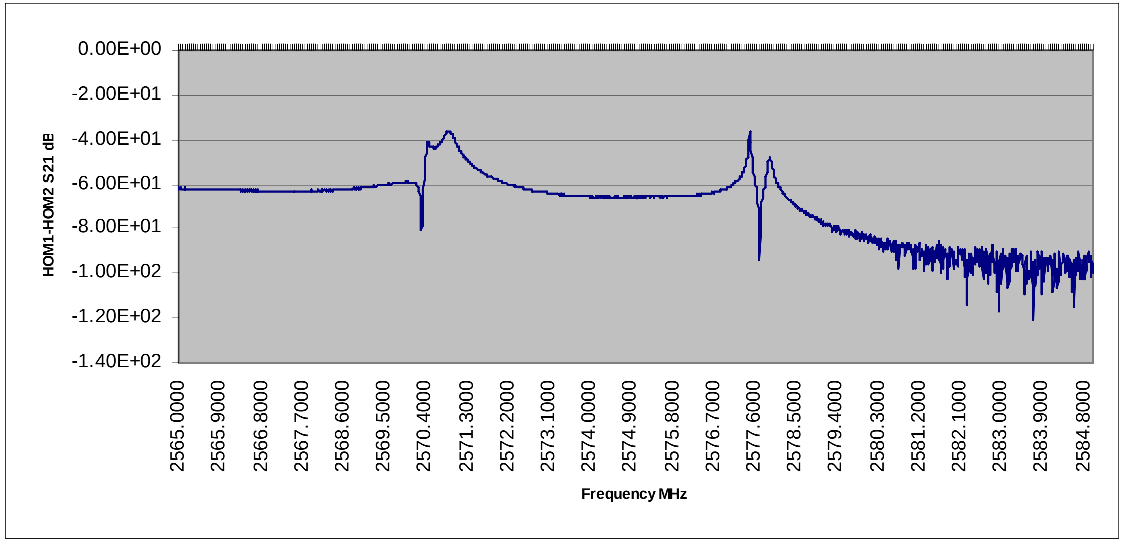
Original
Configuration





Cavity with modified upstream HOM coupler

- Calculations have been verified with Cu models
  (M. Dohlus, V. Kaljuzhny, S.G.Wipf , TESLA 2002-12)
- No Measurements with beam
- RF – Measurements: Q_{ext} of 3rd dipole passband
  vert. and horz. polarized modes are damped (G. Kreps)

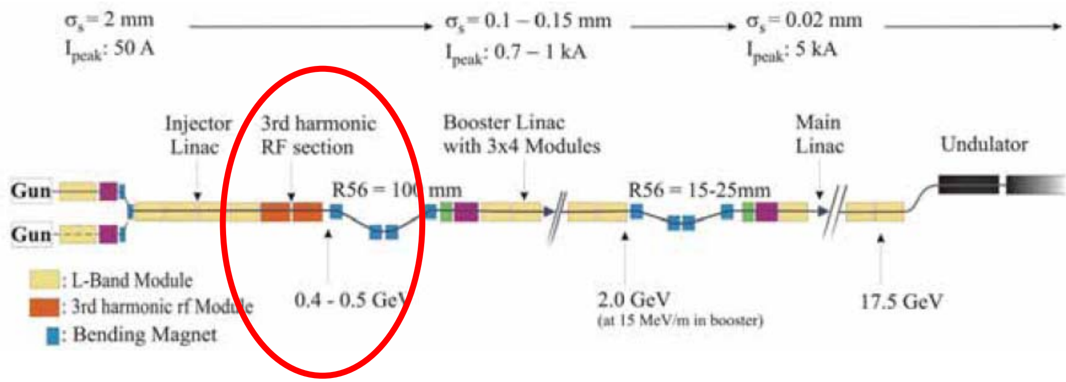


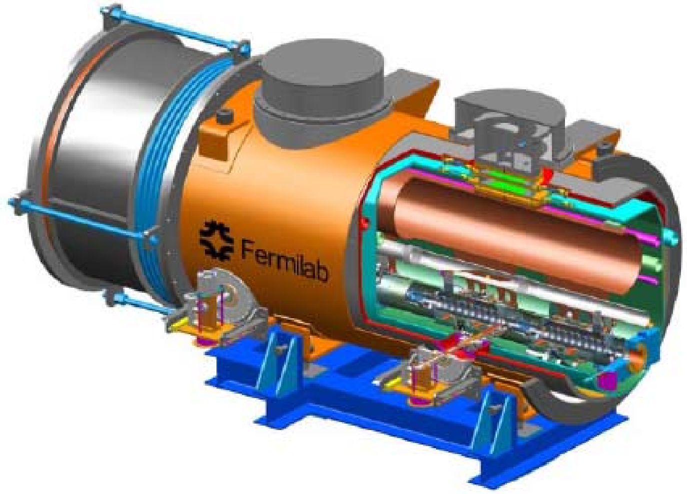
Cavity Z89

Q_{ext} < 5.0E+4

3rd harmonic cavity

Goal: improve the longitudinal phase space properties of the XFEL / FLASH beam





3.9 GHz 9-cell cavity, build at FERMILAB

Ref:
K. Flöttmann et al. TESLA-FEL 2001-06
J. Sekutowicz et. al. TESLA-FEL 2002-05, July 2002
N. Solyak, et al., Proceedings, EPAC 06, Edinburgh, UK

Summary

- FLASH is using s.c. TESLA 9-cell cavities (6 modules, 48 cavities)
- Good module performance, gradient above XFEL specifications
- The XFEL design is based also on TESLA 9-cell cavities (800 cavities)
- HOM's of the TESLA 9-cell cavities have been calculated (MAFIA)
  - two dipole pass-bands are below cutoff frequency
  - 3rd dipole pass-band is close to the cutoff frequency, 5th band some trapped modes
- Beam Dynamics studies, $Q_{ext} < 10^5$
- RF-Measurements, high Q_{ext} is found 3rd dipole pass-band
- Measurement with beam
- Improved HOM coupler design, vert. and horz. polarized modes of the 3rd dipole pass-band are damped

Acknowledgments

Thanks go to:

Martin Dohlus, Jacek Sekutowicz and Guennadi Kreps

for helpful discussion.

Thank you for your attention