HOM Beam Coupling Measurements at the TESLA Test Facility

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Outline

I. HOMs of TTF modules

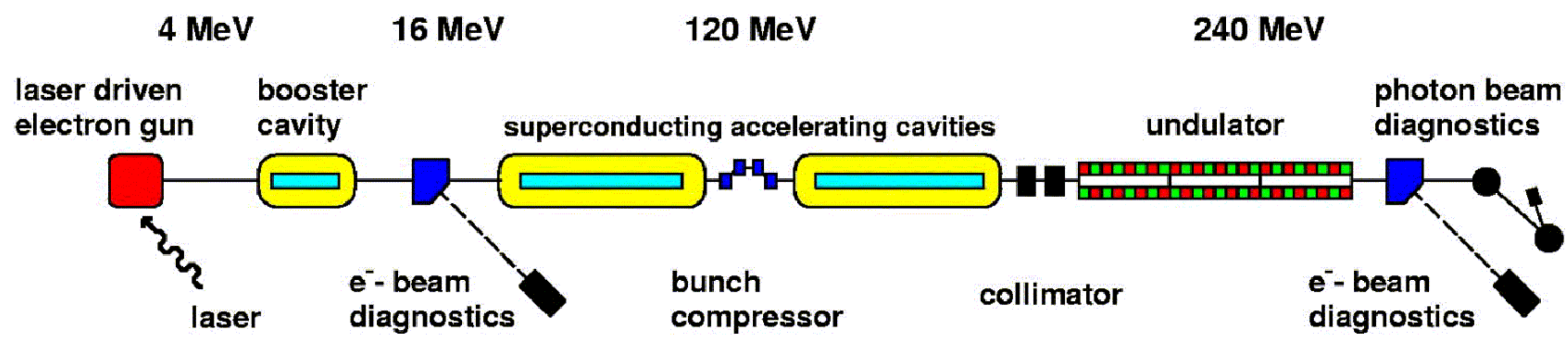
II. Dipole 3rd band

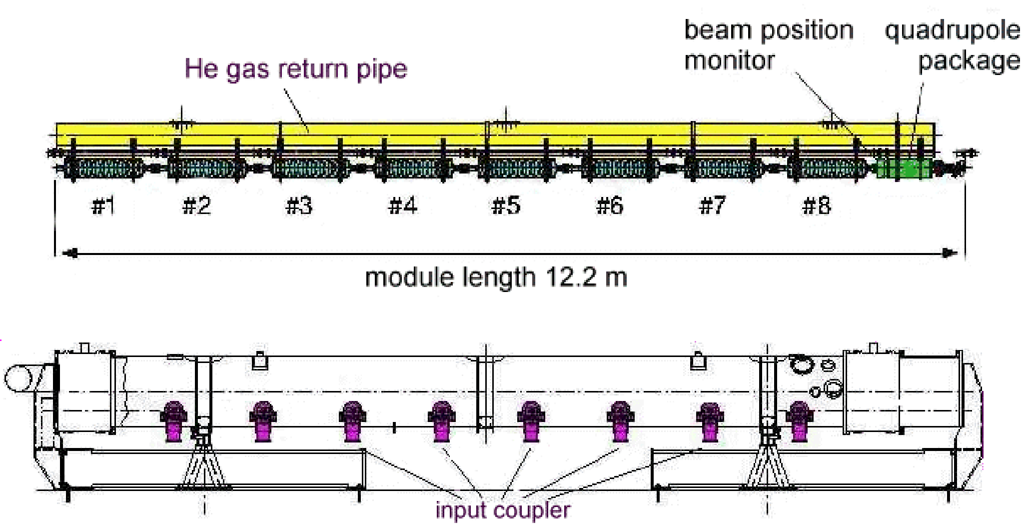
III. Higher HOM bands

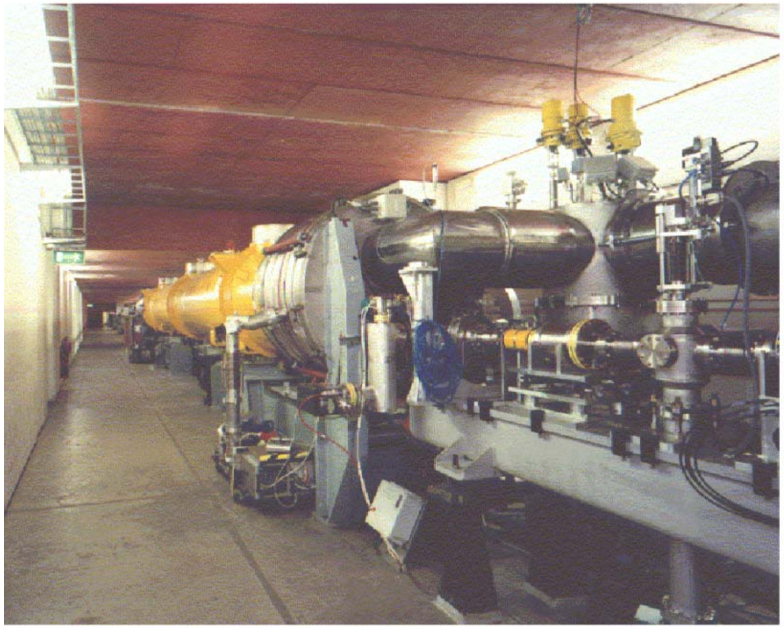
IV. Beam position measurement with HOMs

V. Conclusion

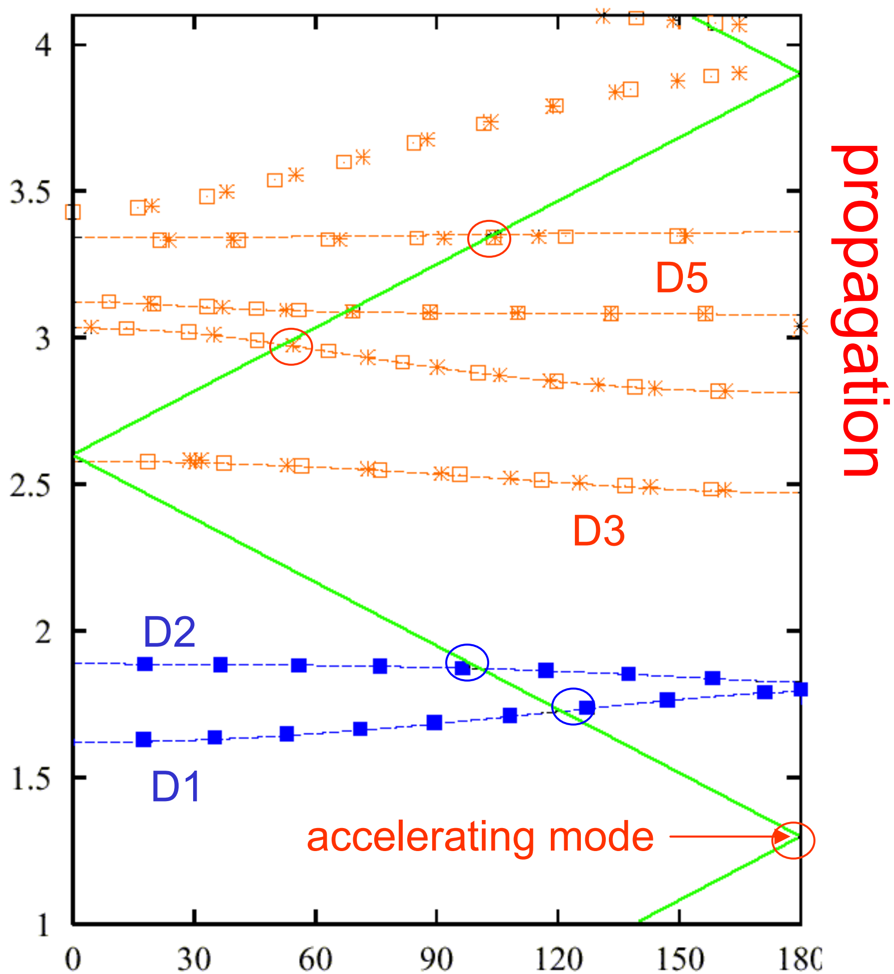
TTF Linac


4 MeV
16 MeV
120 MeV
240 MeV
laser driven electron gun
booster cavity
superconducting accelerating cavities
undulator
photon beam diagnostics
laser
e⁻- beam diagnostics
bunch compressor
collimator
e⁻- beam diagnostics


beam position monitor
quadrupole package
He gas return pipe
#1
#2
#3
#4
#5
#6
#7
#8
module length 12.2 m
input coupler



TTF 9-cell cavity HOMs



R. Wanzenberg

Beyond cutoff = no propagation
mode properties easy to compute for one cavity.

ex: M1,M2 bands
D1,D2 bands

Above cutoff = propagation

BUT trapped mode may exist (high Q)

difficult to predict field distribution for whole module since mode properties depend both
on individual cavity characteristics
on beam tube, couplers

ex: D3 band

Effects of HOM

beam looses energy into HOMs, mostly on monopole

- extra cryogenic power
- energy spread - much smaller than σ_E due to RF stabilisation

off-axis particles receive kicks from dipole HOMs

- Beam Break-Up - depends on frequency distribution among cavities
- emittance growth

Tilt of cavities

- monopole modes transverse component when projected on beam trajectory
- beam receives an extra kick

interaction with beam depends on (r/Q)

- ➢ HOMs close to light cone are likely to interact strongly with beam

interaction with beam depends on stored energy

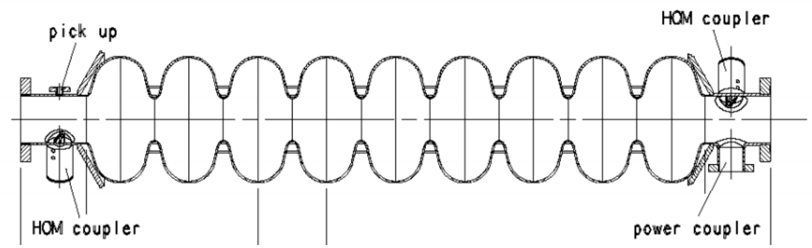
- ➢ high Q HOM are more dangerous

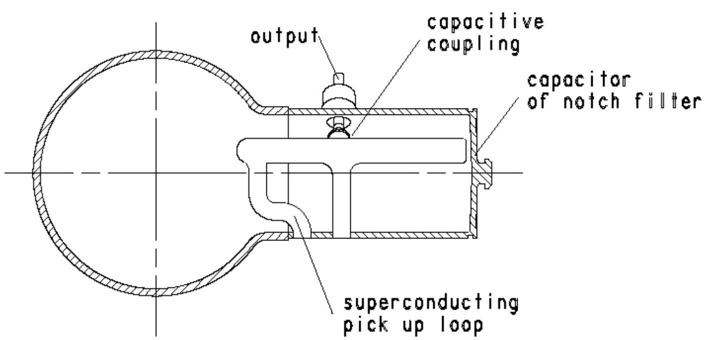
Damping of high (r/Q) HOM is mandatory

HOM damping

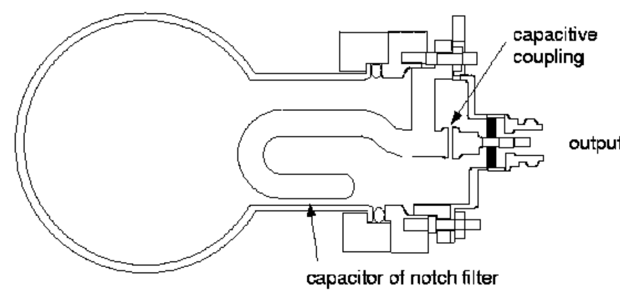
HOM Couplers

- extract HOM power out of cryomodule = reduce stored energy
- design HOM couplers in order to get Q_{ext} as low as possible
  for SC cavities, $Q_0 >> Q_{ext}$ so $Q_L = Q_{ext}$
- SC couplers to reduce RF losses
- 2 couplers per cavity





DESY

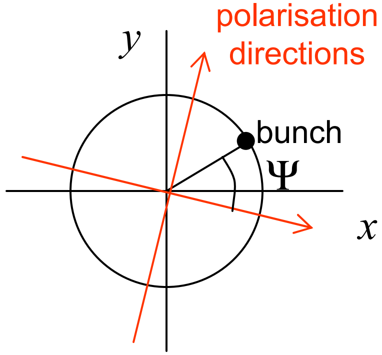


SACLAY

Beam-HOM interaction

single bunch, charge q ➔ HOM ($\omega_0, Q, r/Q$)

cavity voltage just after bunch passage $V_0 = 2\,k\,q$ k loss factor
then decays like $e^{-t/\tau}$ $\tau = Q/\omega_0$



monopole

$$k = \frac{\omega_0}{4}\left(\frac{r}{Q}\right)$$

dipole

$$k = \frac{\omega_0}{4}\left(\frac{r}{Q}\right)\mathrm{r}^2 \qquad \mathrm{r}^2 = x^2 + y^2$$

$$P_{out} = \frac{\omega_0 W}{Q} \qquad W = \frac{V_0^2}{\omega_0\left(\frac{r}{Q}\right)}$$

W : stored energy

$$P_{out} = \frac{\omega_0^2 q^2}{4Q}\left(\frac{r}{Q}\right)\mathrm{e}^{-t/2\tau} \qquad P_{out} = \frac{\omega_0^2 q^2}{4Q}\left(\frac{r}{Q}\right)\mathrm{r}^2\mathrm{e}^{-t/2\tau}$$

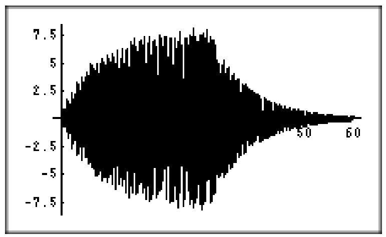
monopole dipole

Beam-HOM interaction

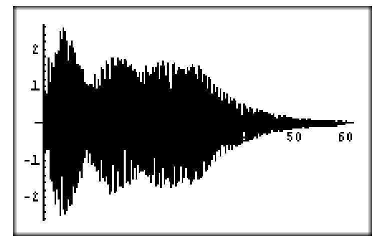
Bunch train , frequency f_b ➔ HOM (ω_0 , Q , r/Q)

Single bunch signals add up

coherently
if mode frequency is a multiple of f_b



Incoherently
if not



for most modes in TTF τ x $f_b >> 1$: small decay between bunches

time dependant part of generated voltage depends on ω_0 , Q and f_b

steady state :

$$P_{\text{train}} = P_{\text{single bunch}} \times F(\omega_0 , Q , f_b)$$

HOM measurements @ TTF

GOAL :

- check that damping requirements are met $Q_{ext} < 10^5$
- look for unexpected dangerous modes

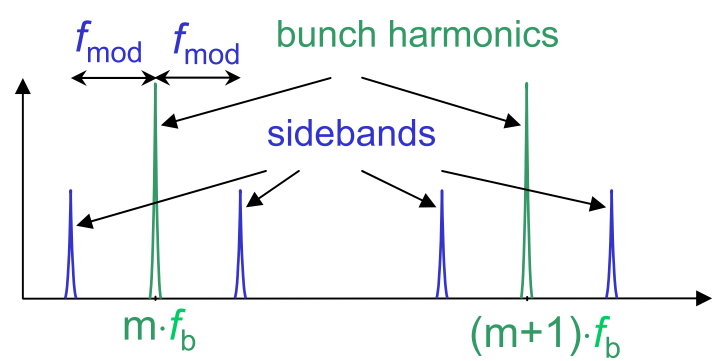
METHODS to excite HOM at resonance with beam :

- Use beam harmonics and detune the cavity by Δf

$$f_{HOM} = m\, f_{Beam} \pm \Delta f$$

- beam charge modulation f_{mod} $\rightarrow$ tunable sidebands (S. Fartoukh)

$$f_{HOM} = m\, f_{Beam} \pm f_{mod}$$

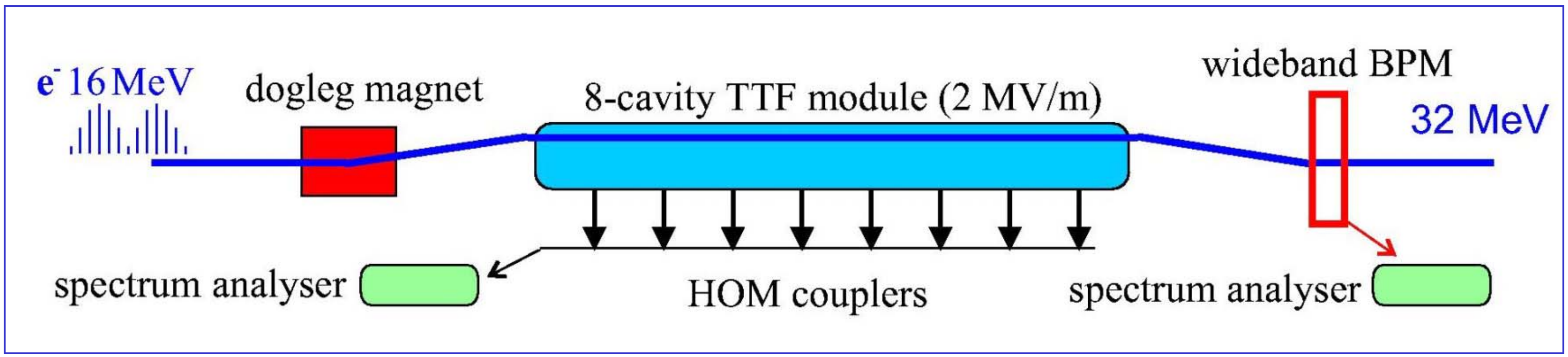


Dipole HOM excitation

Wake Potentials :

$W_{||} \propto (r/Q) \times r_0^{\,m} r_1^{\,m} \times \cos m(\theta_0 - \theta_{HOM})$ $\rightarrow$ HOM couplers

$W_{\perp} \propto (r/Q) \times r_0^{\,m} r_1^{\,m-1} \times m \cos m(\theta_0 - \theta_{HOM})$ $\rightarrow$ BPM



TTF dogleg magnet operates only in x-plane : $\delta x = \pm$ 2cm

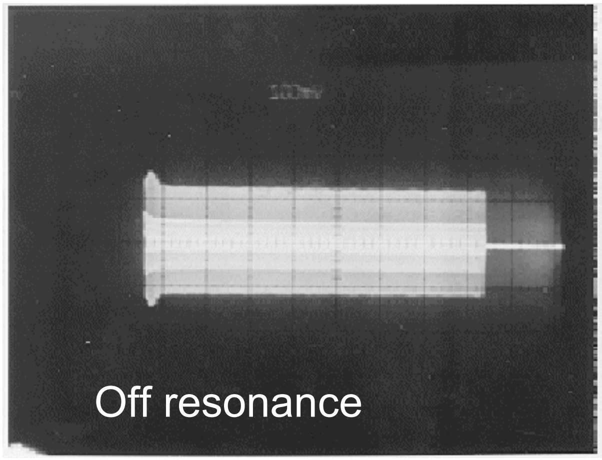
monopole	m = 0 : $P_{HOM} \propto \delta x^0$, $\delta x_{BPM} = 0$
dipole	m = 1 : $P_{HOM} \propto \delta x^2$, $\delta x_{BPM} \propto \delta x$
quadrupole	m = 2 : $P_{HOM} \propto \delta x^4$, $\delta x_{BPM} \propto \delta x^3$

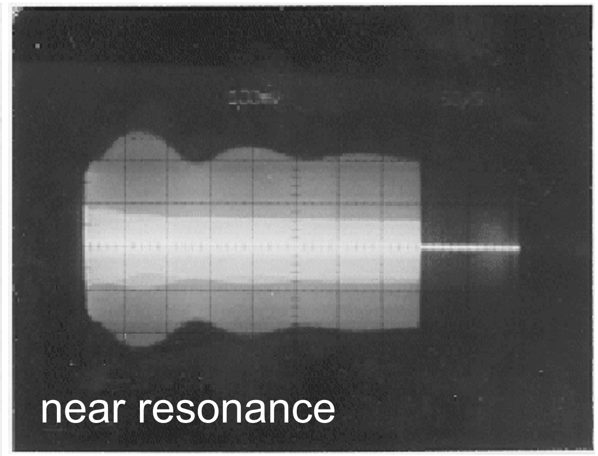
3rd dipole passband high Q HOMs

HOM : f = 2.585 GHz , $Q = 10^6$
measured with 216 MHz Injector #1 in Module 1, in 1998.

f_{mod} =15 MHz

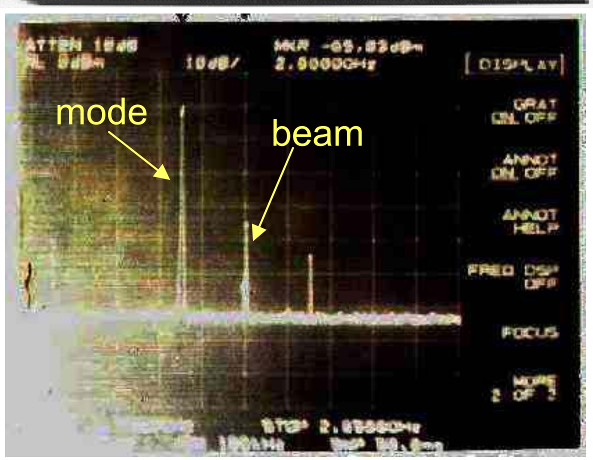
BPM signal



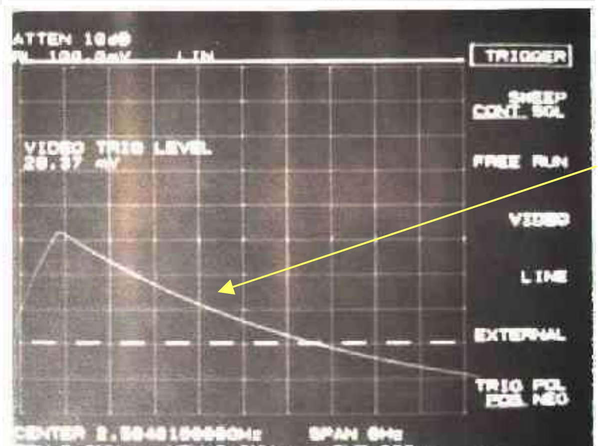


125 µs beating due to 8 kHz off resonance

HOM coupler signal



frequency domain

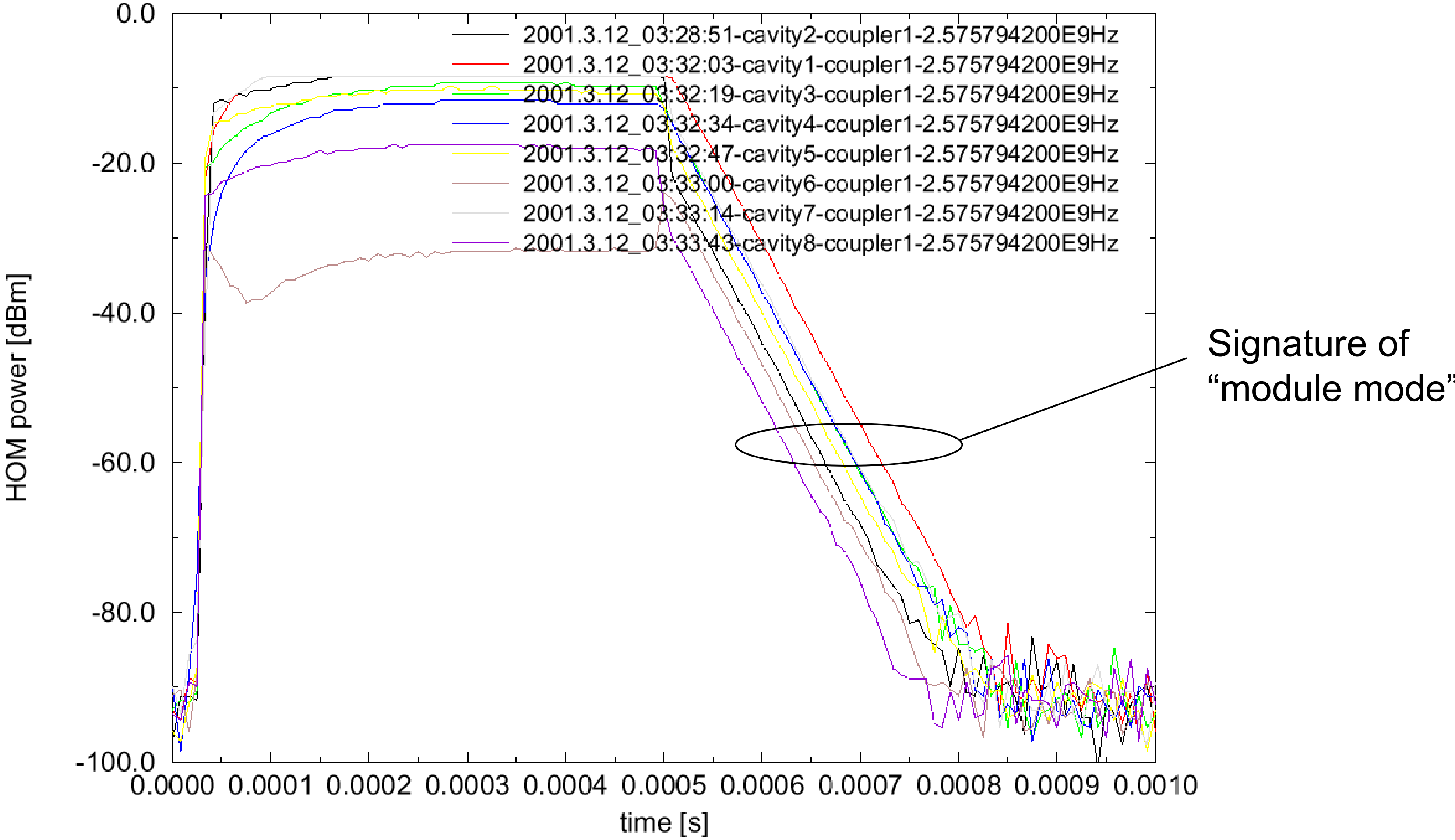


time domain

decay time
$\Rightarrow Q = 10^6$

D3 passband module III

HOM f =2.575794 GHz, Q=2 10^6
measured with modulated 54 MHz beam Injector #2



D3 passband module III

HOM freq. with beam [GHz]	Modulation freq. [MHz]	HOM freq. with N.A. [GHz]	Q with beam	max. HOM signal -dBm		cpl	Q with N.A.	R/Qcosϕ with beam [Ω.cm-2]	Co-excited bands	Co-excited cavities	HOM freq. Urmel mm [GHz] ee		R/Q Urmel [Ω.cm-2]	
2.568617	22.785	*2.568623	$8.4\ 10^4$	25	25	1	*$7.4\ 10^4$			all				
2.568620	22.788	*2.568623	$8.4\ 10^4$	28	28	2	*$7.4\ 10^4$		d4, q2	all				
2.575679	24.324		$2.9\ 10^5$	15	42	1								
2.575675	24.324		$2.9\ 10^5$	21	46	2			d5, q2, q1	all				
2.575794	24.205	*2.575795	$2.9\ 10^5$	8	8	1	$2.6\ 10^5$	7.4		all	2.5630	2.5745	1.4	7.3
2.576016	23.983		$3.0\ 10^5$	8	49	1		9.9		all	2.5630	2.5745	1.4	7.3
2.576224	23.775		$8.8\ 10^4$	17	46	2			d3, q1	all				
2.577211	22.788		$1.3\ 10^5$	8	8.8	2				all				
2.578136	21.863		$1.6\ 10^5$	8	50	1		21.1		1, 2, 3	2.5774	2.5836	23.5	18.6
2.578274	21.725	*2.578277	$1.5\ 10^5$	8	21	1	*$6.5\ 10^4$		many	all	2.5774	2.5836	23.5	18.6

* measured by Ch. Magne through all module (24/03/01)

Why high Q modes in D3 ?

Work by M. Dohlus et al. :
Poster TODAY : WEPRI081 - Higher Order Mode Absorption in TTF Modules in the Frequency Range of the Third Dipole Band

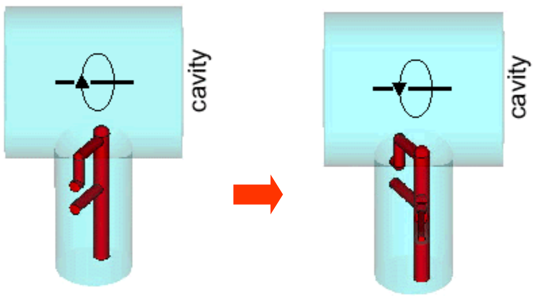
Full RF modelling of TTF module taking into account :
- detuned cavities within the module
- detailed modelling of HOM and power couplers

Reproduces measured D3 S parameters accurately

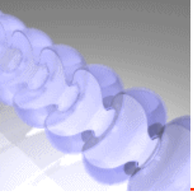
DESY and SACLAY HOM couplers damping of V & H polarisation differ
-> homogenous module (1 type of coupler) ->1 polarisation may not be damped

Remedies :
- A - 2 coupler types + better cavity shape control (no frequency spread)
- B - use mirrored geometry of upstream HOM DESY coupler

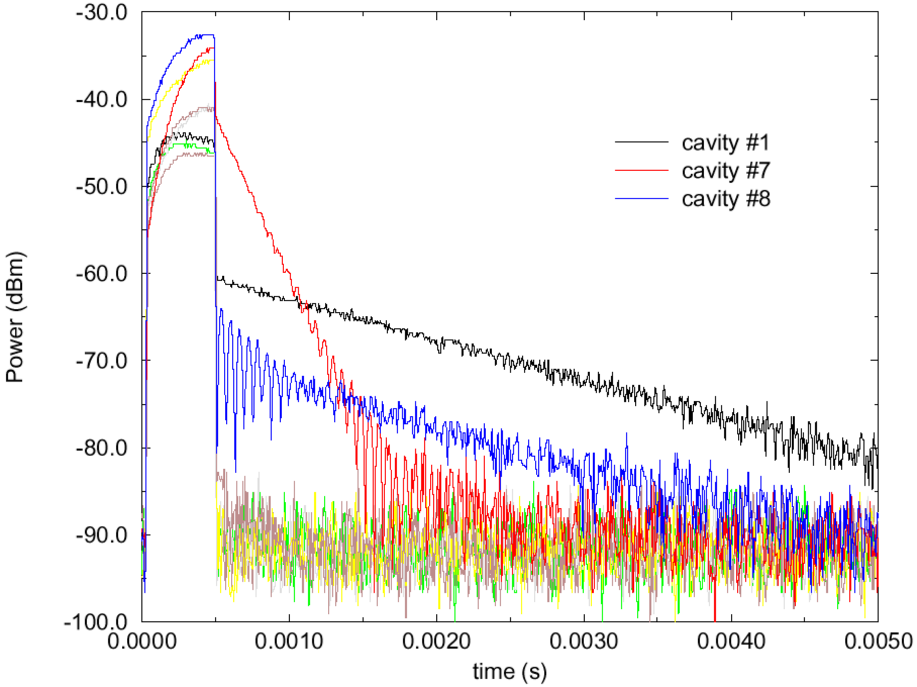
Solution B computed :
- All D3 modes with $Q < 10^5$
- Damping still OK for D1 & D2

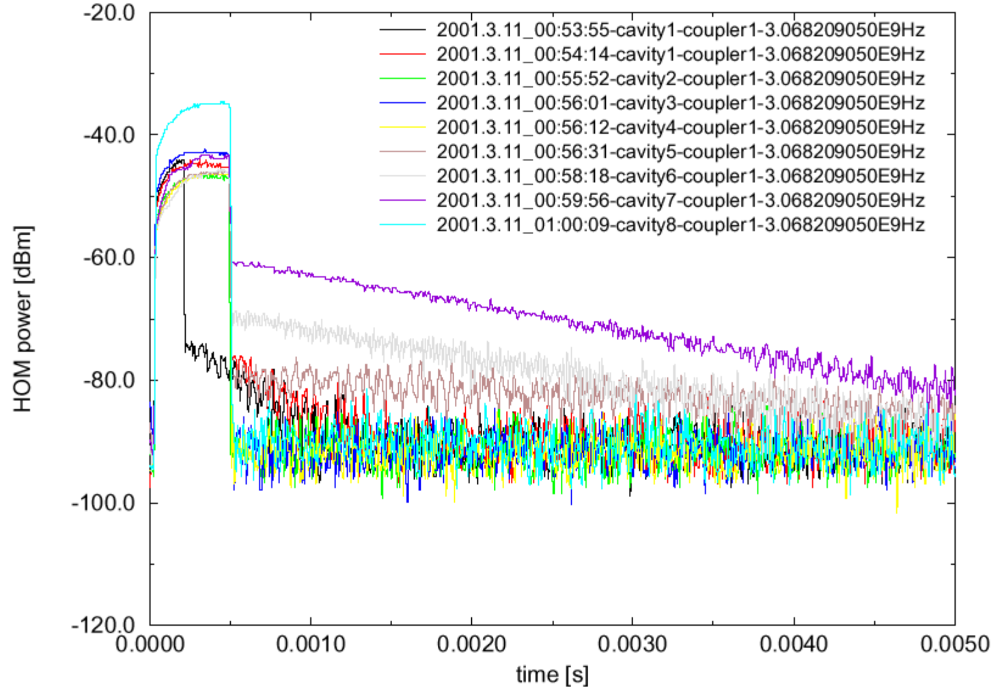


D5 passband



High Q modes





f = 3.063724 GHz

Q = 1.7 10^7

f = 3.068209 GHz

Q = 3.4 10^7

D5 passband (2)

Automated measurement procedure triggered by BPM signal:

For a given f_{mod} quadrupole modes are co-excited

$\Rightarrow$ BPM signal is dominated by quadrupole kick
$\Rightarrow$ No r/Q can be estimated from BPM

Alternate method to estimate r/Q: use HOM RF signal

If HOM with $r/Q > 1\ \Omega/cm^2$ exist, output levels of the order of 0 dBm are predicted   BUT no such levels were observed : -40 dBm on average

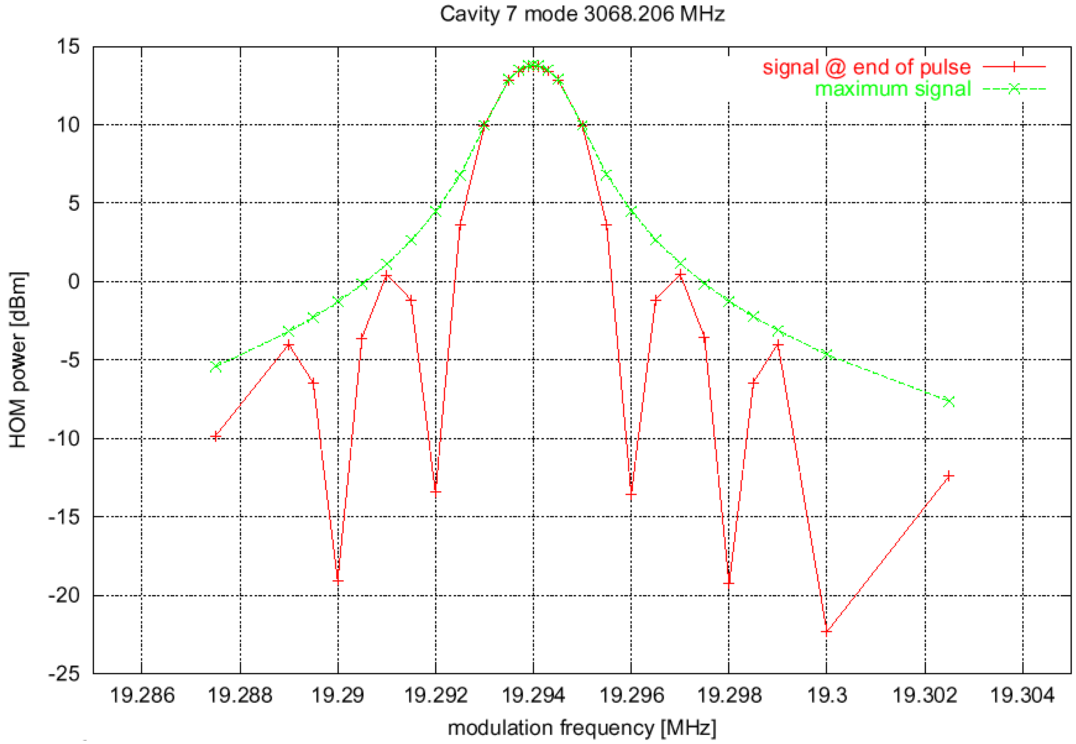
Possible scenarii

- only harmless modes
- dangerous HOM with vertical polarisation $\Rightarrow$ HOM not excited

D5 passband (3)

- HOM RF signal is filtered at $m\,f_{beam} + f_{mod}$ at max. BPM signal which may be different from f_{HOM} of dipole mode ⇒ **off resonance**

⇒ reduced output power



⇒ incoherent regime : last bunches may have taken mode energy

⇒ start of decay at lower power

HOM couplers as BPMs

Output power from a dipole mode (2 polarisations) in a cavity:

$$P_1 = C_1 \ x^2 \qquad \Rightarrow \qquad \mathbf{r^2 = P_1/C_1 + P_2/C_2}$$

$$P_2 = C_2 \ y^2$$

If HOM f, r/Q and Q are known, so are C_1 and C_2 :

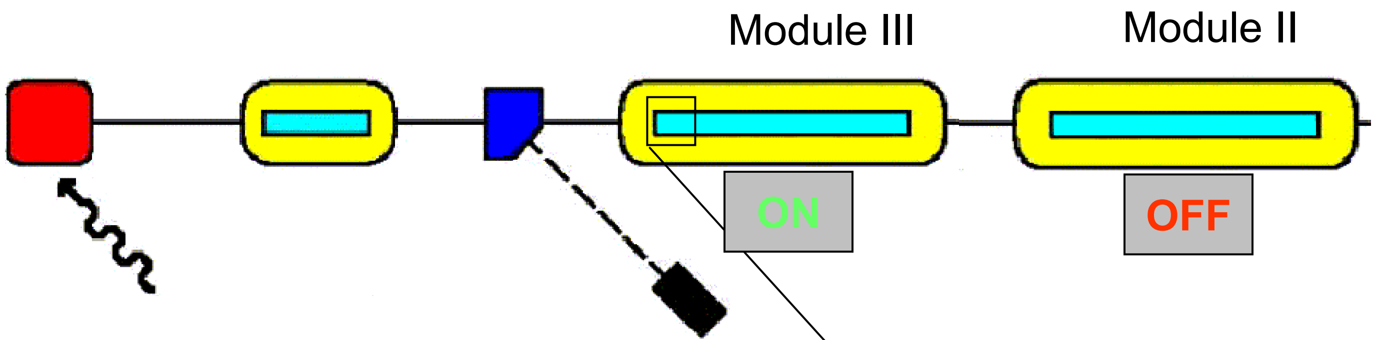
1 power measurement $\Rightarrow$ **r**

2 power measurement with known beam offset δx $\Rightarrow$ $\mathbf{x}$ **and** $\mathbf{y}$

repeat for each cavity $\Rightarrow$ ***orbit inside the module***

Minimising the dipole HOM output power = align beam on cavity axis

HOM couplers as BPMs

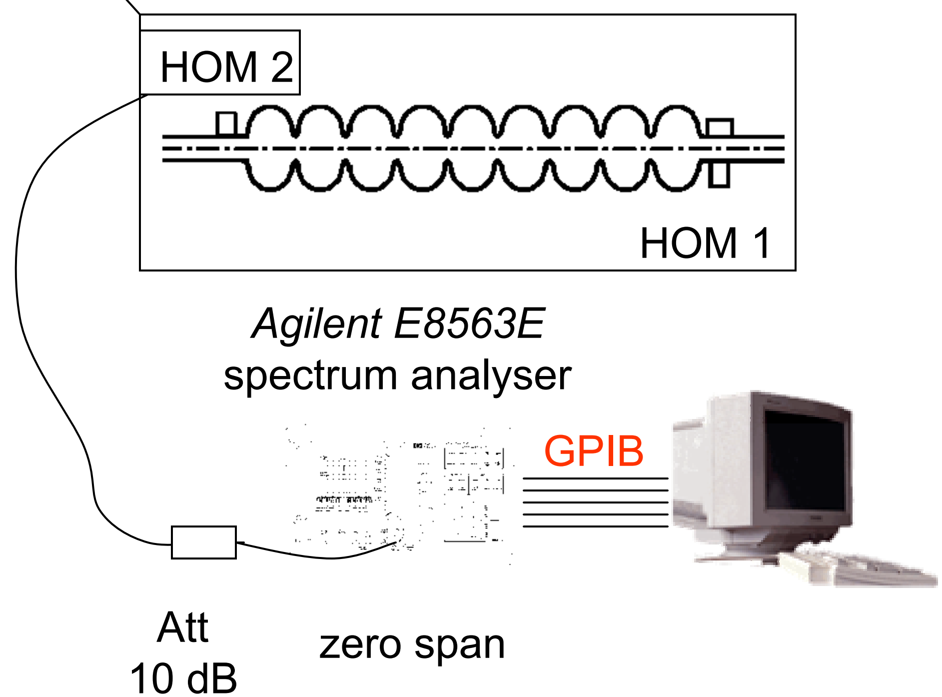


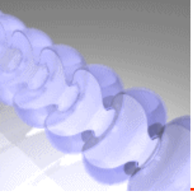
Beam

$q = 3.5$ nC
$f_b = 2.25$ MHz
$Tp = 780\ \mu s$

Spectrum analyser

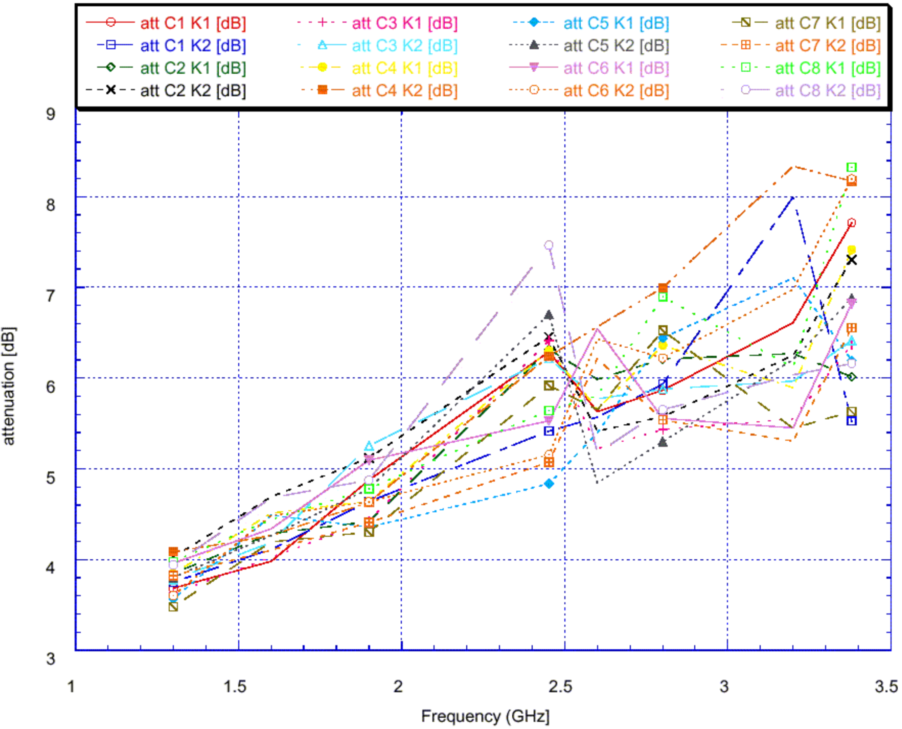
- used as a parametric bandpass filter:
  - central frequency
  - width (RBW)
- signals in time domain



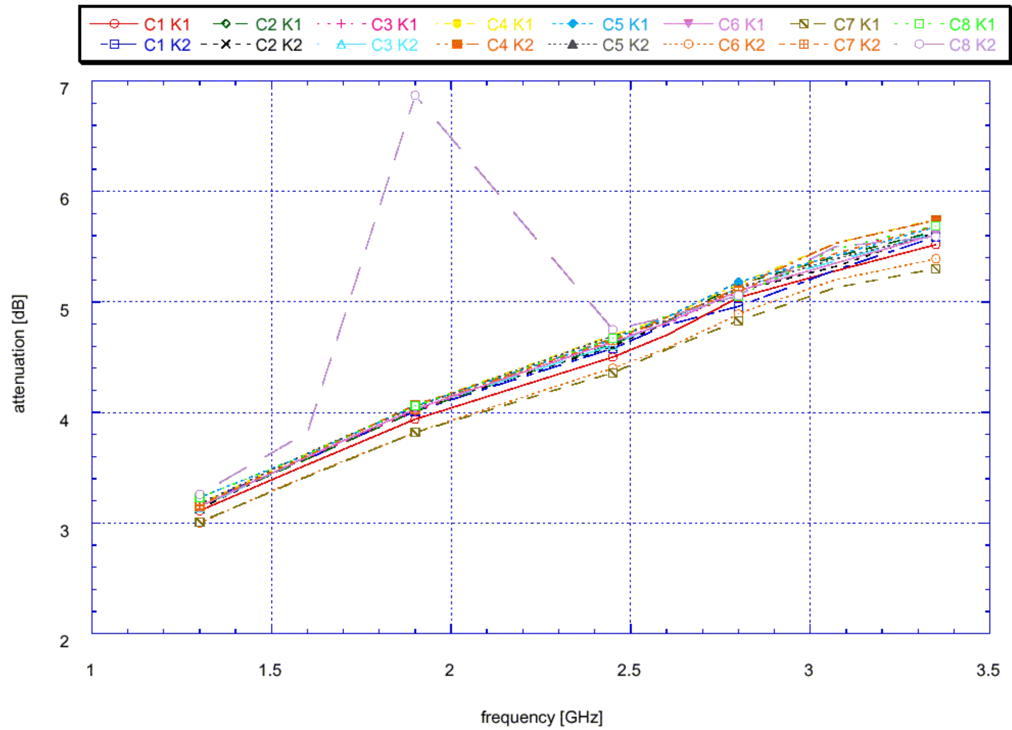


Cable calibration

Cables inside cryostat
reflection measurement with network analyser



Cables outside cryostat :
attenuation measurement with power-meter



Check on monopole HOMs

GOAL

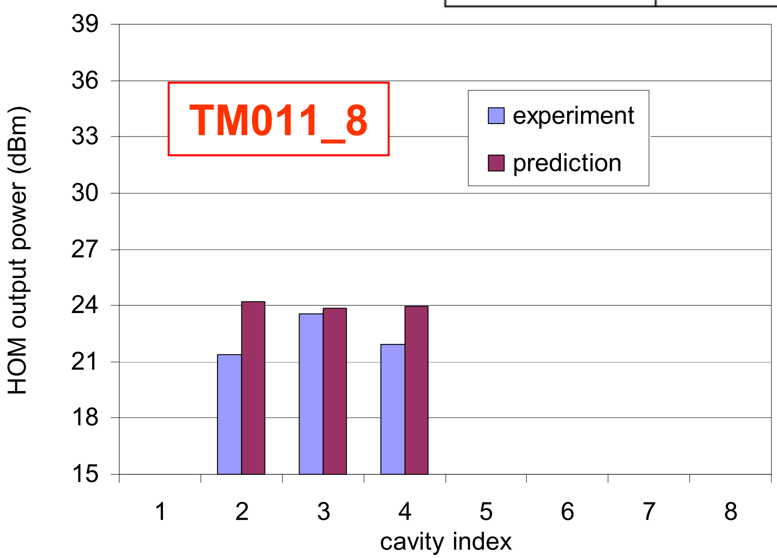
- check calculations
- check cable attenuation

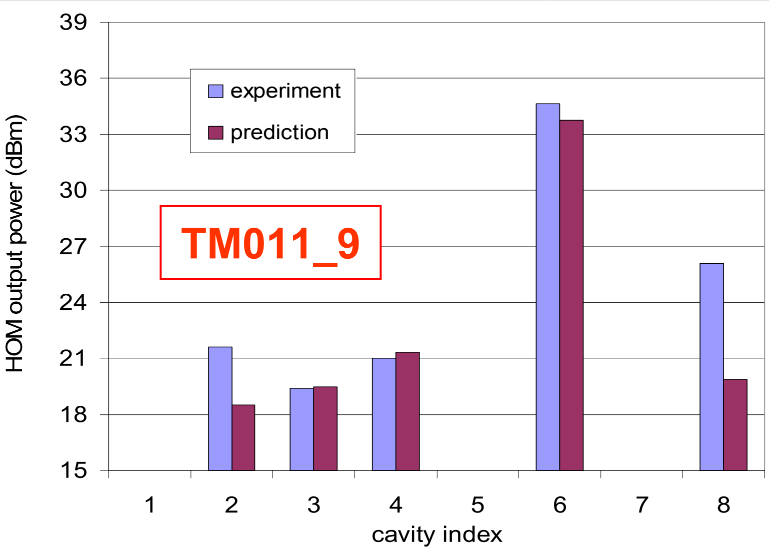
Choose HOM :

- well known HOM ⇒ non propagating bands
- high *r/Q* to get strong signal (for this experiment, all modes excited off resonance)

Best candidates in D2 passband

	frequency	computed r/Q	Q range (meas.)
TM011_8	~2.450 GHz	155.31 Ω	$5.7\ 10^4$ -$1.3\ 10^5$
TM011_9	~2.460 GHz	148.74 Ω	$9.5\ 10^4$ - $2.5\ 10^5$





Dipole mode measurements

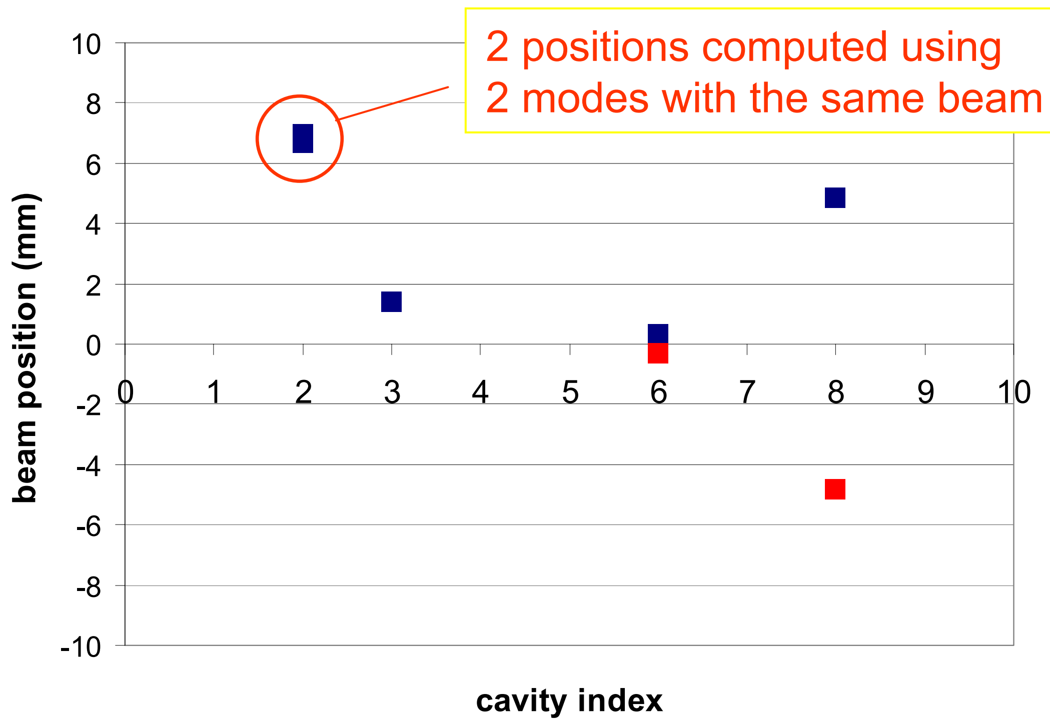
D1 & D2 band highest *r/Q* modes

	frequency	computed r/Q	Q range (meas.)
TE111_6	~1.705 GHz	11.067 Ω/cm^2	5.3 10^3 - 4.0 10^4
TE111_7	~1.730 GHz	15.570 Ω/cm^2	3.3 10^3 - 1.1 10^4
TM110_4	~1.865 GHz	6.365 Ω/cm^2	1.4 10^4 - 6.9 10^4
TM110_5	~1.875 GHz	8.977 Ω/cm^2	1.8 10^4 - 1.4 10^5

High gradient in cavities (~ 20 MV/m)

⇒ orbit is expected to cross axis if entering the module with an offset

Ideal case is to cross-check with 2 modes



Conclusion

Systematic scans led to the discovery of high Q modes and launched interesting studies for 3rd passband

No evidence for dangerous HOM in the other passbands although high-Q modes exists, especially in the 5th passband

HOM study in Superstructures planned this summer

Possibility to use cavities as BPMs : low resolution only, very dependent on mode distribution in cavities, guide to beam steering