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LC02, SLAC, Feb. 5, 2002

# Higher Order Modes Measurements with Beam at the TTF Linac

# TTF Measurements

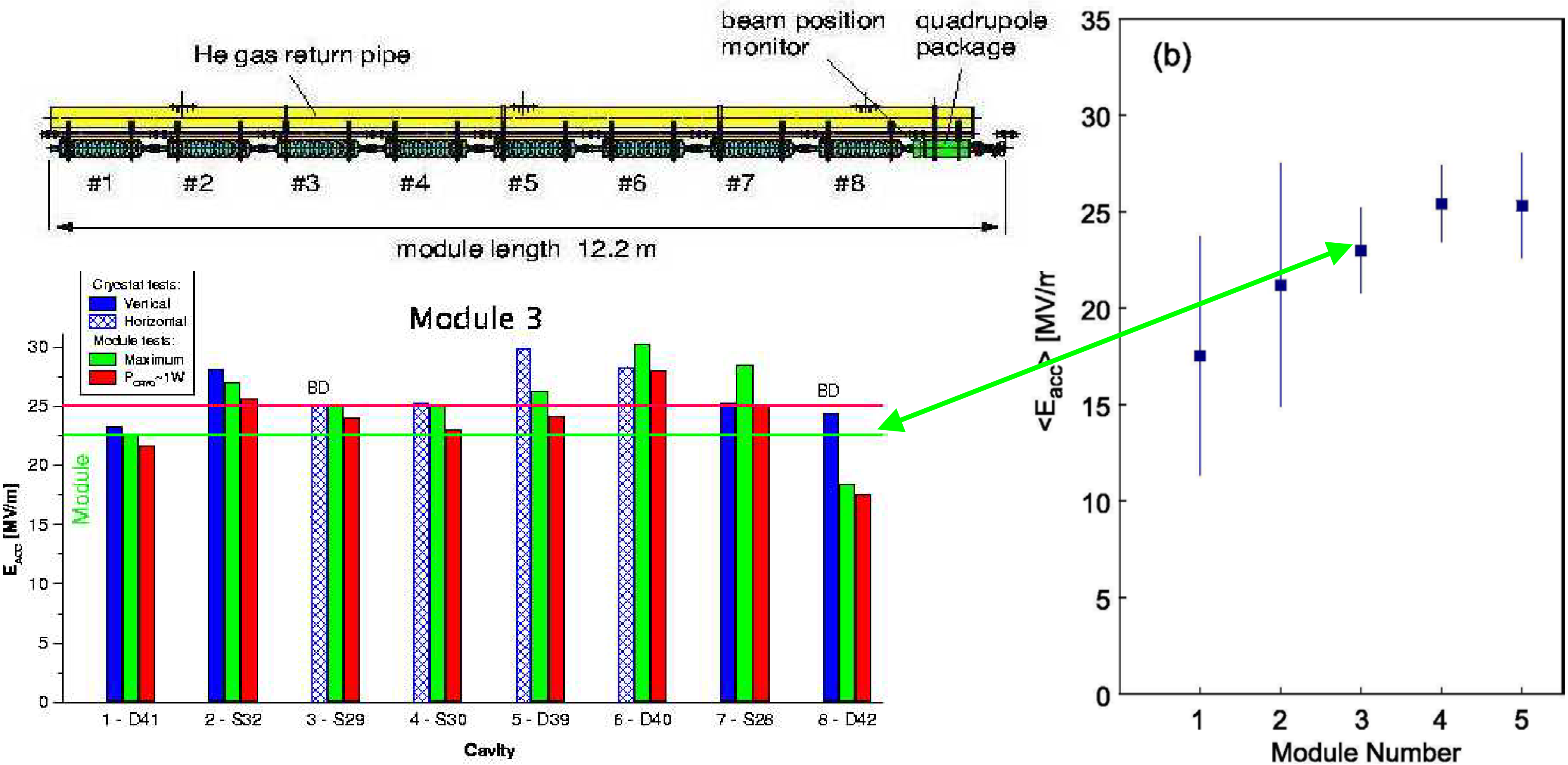
A collective effort including most of Saclay, Orsay and DESY TTF physicists :

S. Fartoukh, G. Devanz, C. Magne, M. Jablonka,
H.W. Glock, N. Baboi, M. Huening, G. Kreps, M. Liepe,
S. Schreiber, H. Weise, M. Wendt ..............

1) TTF Modules : HOMs below cut-off
2) Resonant Excitation : Experimental Methods
3) Results and Analysis for Dipole Passbands
4) Interpretation for the 3rd Dipole Passband

# TTF : Superconducting Modules

Five 8-cavity modules assembled , three modules tested in TTF linac



# TTF : The 3 Measured Modules

| Module 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cavity | D3 | S8 | *S10 | D1 | D2 | *S11 | D4 | S7 |
| Power coupler | FNAL | DESY | DESY | FNAL | FNAL | DESY | FNAL | FNAL |
| HOM couplers | DESY | Saclay | Saclay | DESY | DESY | Saclay | DESY | Saclay |

| Module 2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cavity | C22 | C21 | C25 | C23 | *A15 | C26 | C27 | C24 |
| Power coupler | FNAL | FNAL | FNAL | FNAL | FNAL | FNAL | FNAL | FNAL |
| HOM couplers | Saclay | Saclay | Saclay | Saclay | DESY | Saclay | Saclay | Saclay |

| Module 3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cavity | D41 | S32 | S29 | S30 | D39 | D40 | *S28 | D42 |
| Power coupler | DESY | DESY | DESY | DESY | AC | AC | DESY | AC |
| HOM couplers | DESY | DESY | DESY | DESY | DESY | DESY | DESY | DESY |

* Cavities with high-*Q*, 2.585 MHz mode

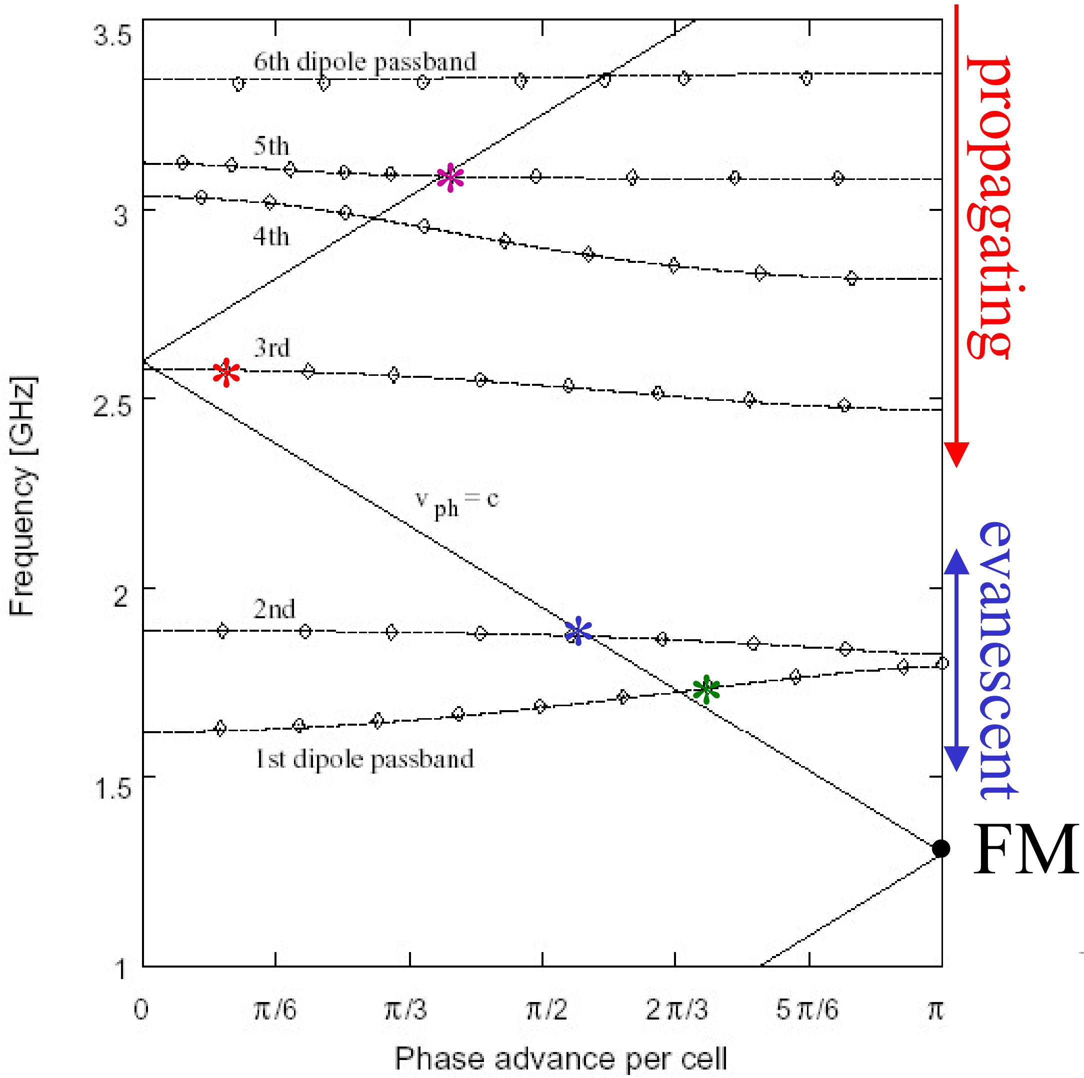
# Monopole HOMs

- Monopole HOMs ($m$=0 , TM0xx ) have a major impact on power dissipation in the HOM coupler (~ 30 W/ module)

- They have a negligible influence on longitudinal dynamics :
  $\rightarrow$ HOM induced multi-bunch energy spread $\approx 2\times10^{-6}$, smaller than the spread induced by RF-stabilisation

- Transverse effect through tilted cavities not yet taken into account.

# The Dipole Passbands




## The TDR Model

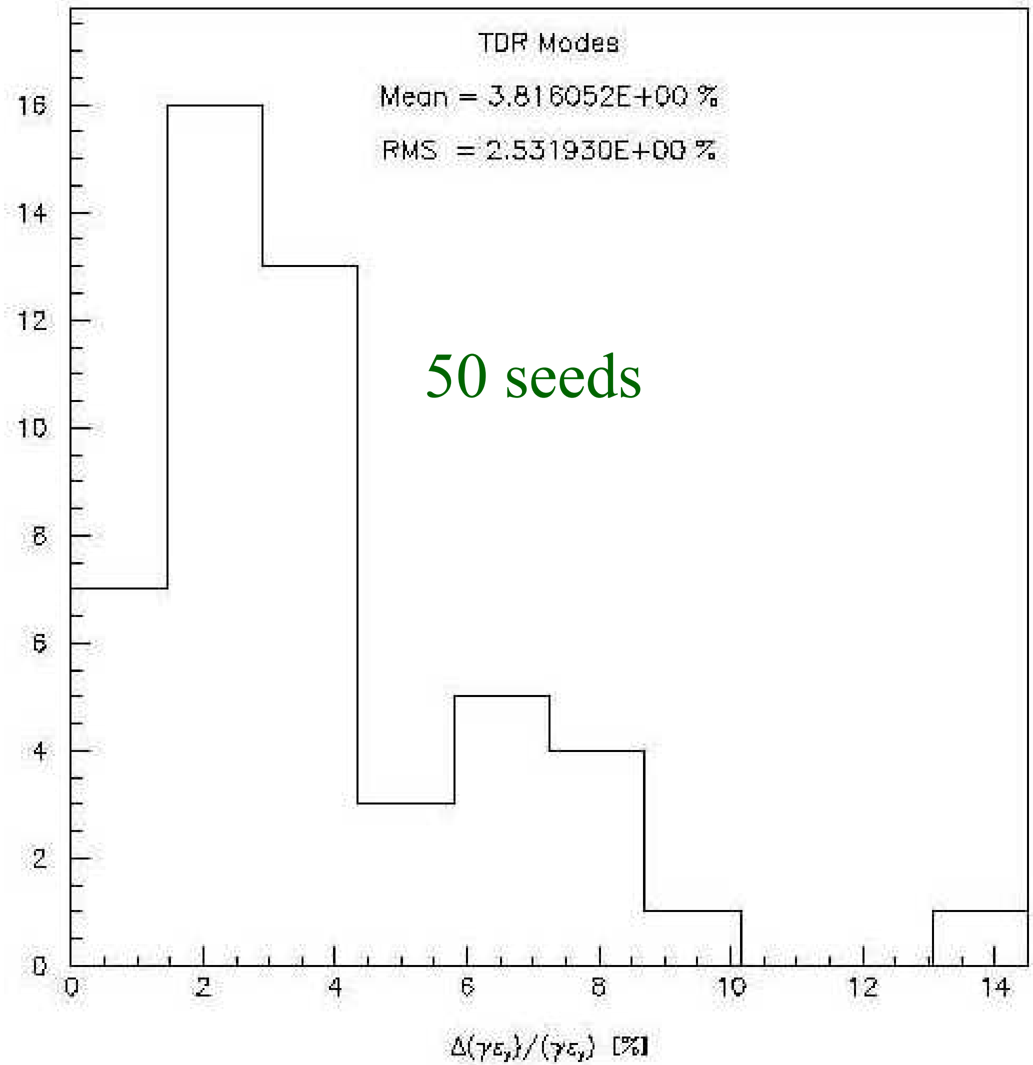
| $\omega_l / 2\pi$ [GHz] (measurement) | $(R/Q)_l$ [$\Omega$/cm$^2$] (simulation) | $Q_l$ (measurement) |
|---|---|---|
| **1st dipole passband** | | |
| 1.6506 | 0.76 | $7.0 \cdot 10^4$ |
| 1.6991 | 11.21 | $5.0 \cdot 10^4$ |
| 1.7252 | 15.51 | $2.0 \cdot 10^4$ |
| 1.7545 | 2.16 | $2.0 \cdot 10^4$ |
| 1.7831 | 1.75 | $7.5 \cdot 10^3$ |
| **2nd dipole passband** | | |
| 1.7949 | 0.77 | $1.0 \cdot 10^4$ |
| 1.8342 | 0.46 | $5.0 \cdot 10^4$ |
| 1.8509 | 0.39 | $2.5 \cdot 10^4$ |
| 1.8643 | 6.54 | $5.0 \cdot 10^4$ |
| 1.8731 | 8.69 | $7.0 \cdot 10^4$ |
| 1.8795 | 1.72 | $1.0 \cdot 10^5$ |
| **3rd dipole passband** *(measured since 1998 HOM experiments)* | | |
| 2.5630 | 1.05 | $1.0 \cdot 10^5$ |
| 2.5704 | 0.50 | $1.0 \cdot 10^5$ |
| 2.5751 | 23.80 | $5.0 \cdot 10^4$ |

# Emittance Growths : the TDR Situation

With the list of HOMs
from the TDR,
both the single bunch
and the multi bunch
emittance growths are small:

$$\delta\varepsilon_y/\varepsilon_y < 4\%$$

Assumptions :
- 1 MHz frequency spread
- 0.5 mm RMS cavity misalignments
- 1st bunch steered through all quadrupole centres




Emittance growth [%]

# Emittance Growths : 2.590 MHz mode

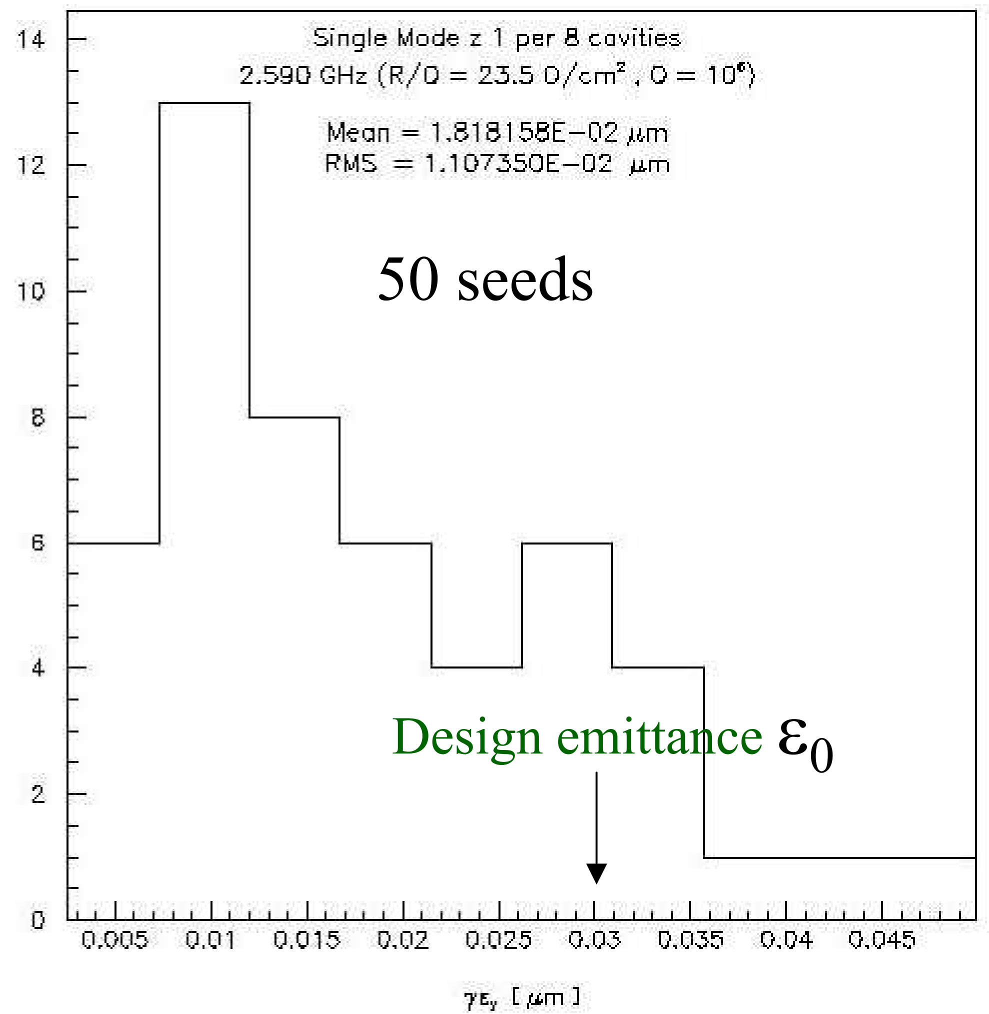
3rd passband 2.590 GHz HOM
( R/Q = 23.5 Ω /cm$^2$ , Q = $10^6$ ,
One mode / 8 cavities )

⇒ Multi-bunch emittance

$\varepsilon_{MB}$ = 0.018 mm·mrd
(on 50 seed average)

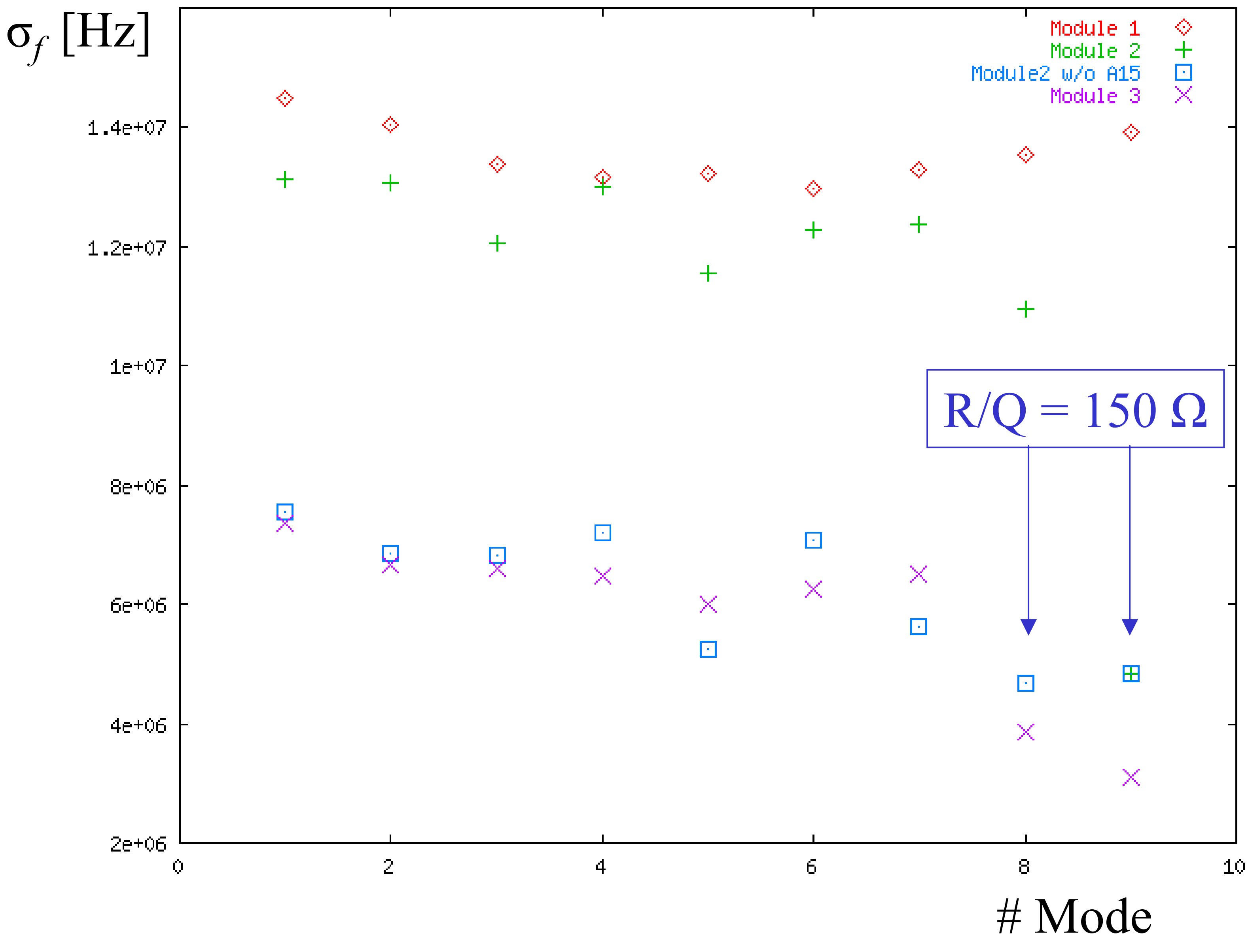
⇒ Single-bunch emittance

$\delta\varepsilon_{SB}/\varepsilon_0$ = 7 %
(only one seed)

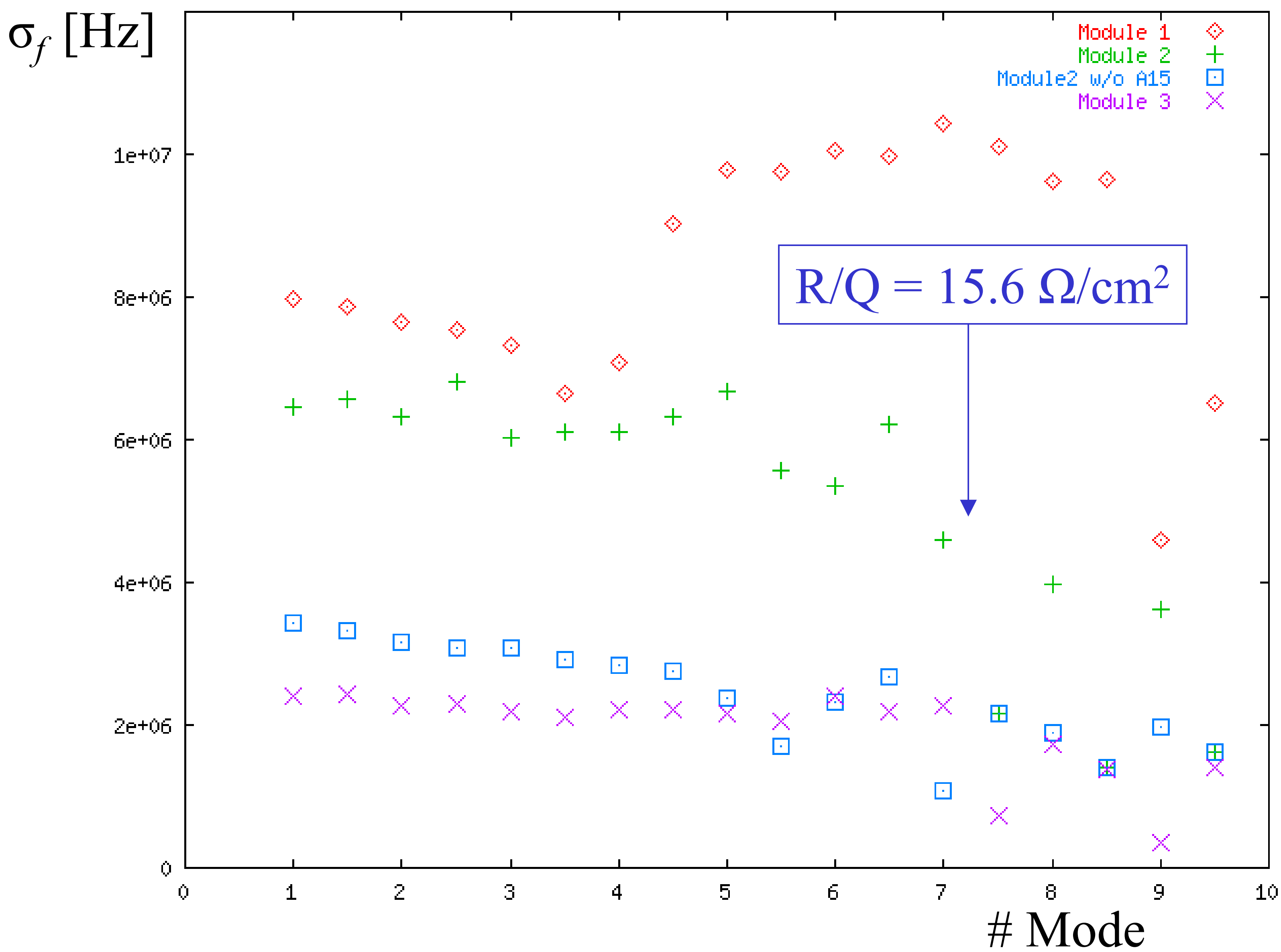



Multi bunch emittance [µm]

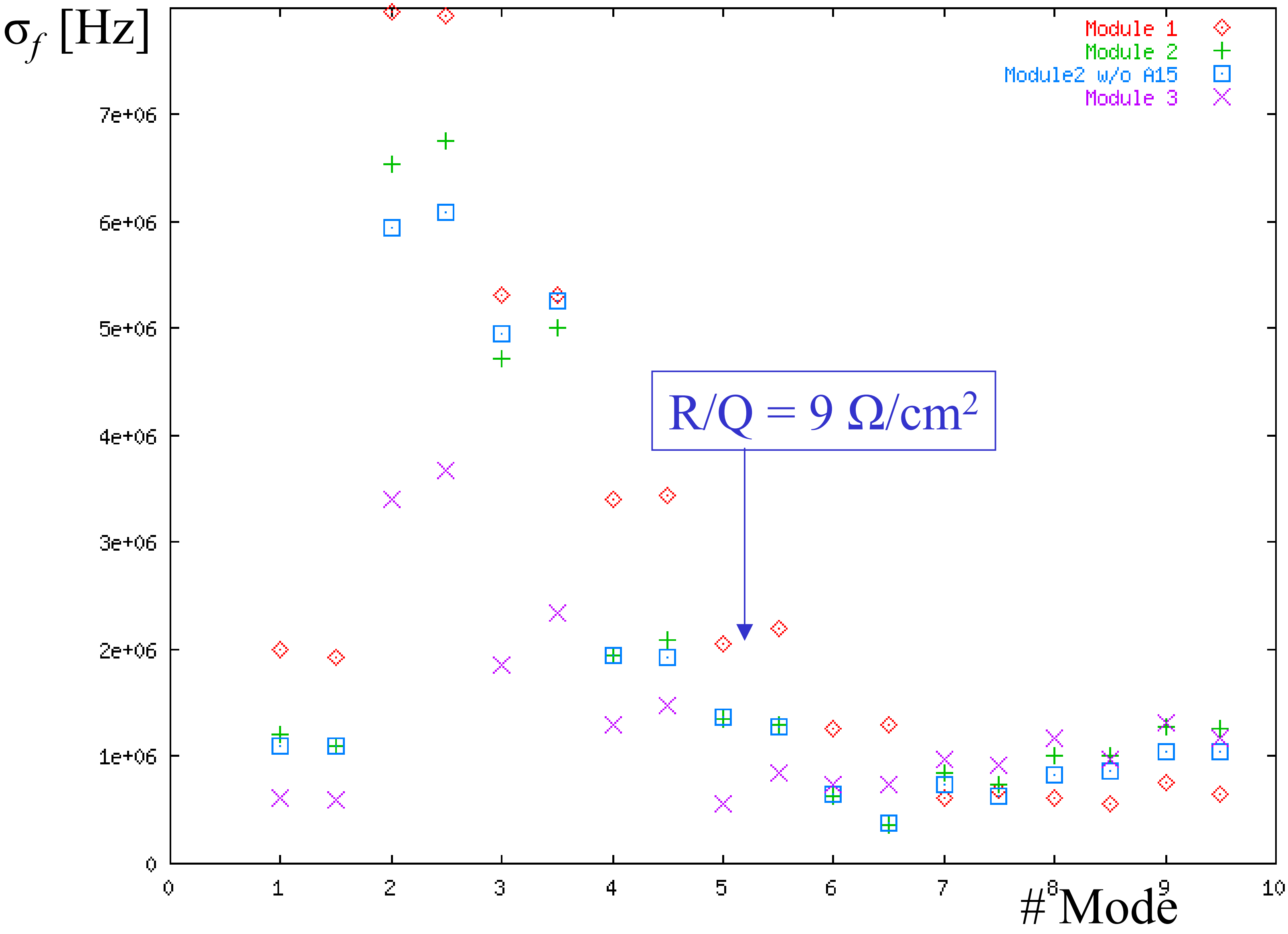
# TM011 : HOM Frequency Spread



# TE111 : HOM Frequency Spread



# TM110 : HOM Frequency Spread



# Resonant Excitation : Experimental Methods

- **Resonance HOM / Beam** by :

1. Cavity detuning : $f_{\mathrm{HOM}}$ shifted to $mf_{\mathrm{Beam}}$ harmonics

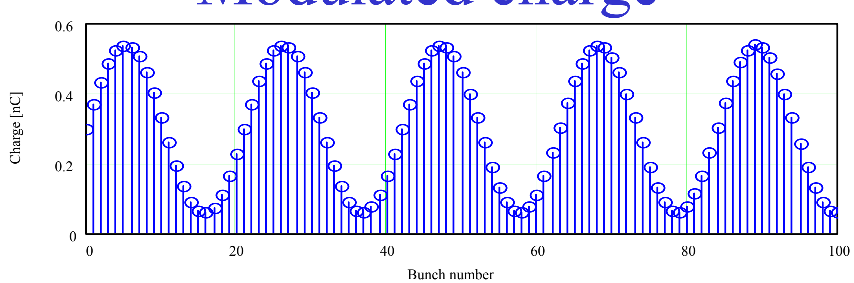
   $\Rightarrow\ f_{\mathrm{Beam}} <$ tuning range $\approx$ 1 MHz

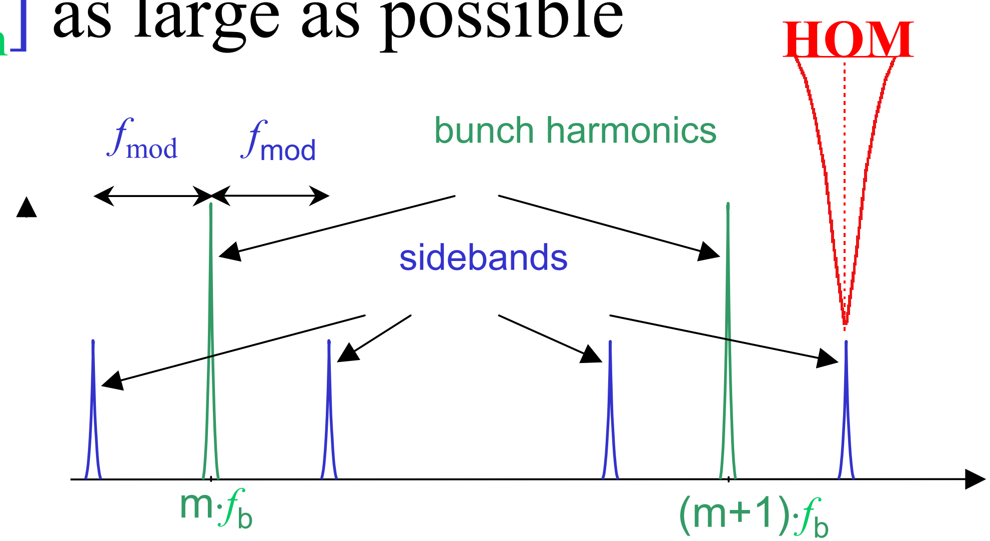
2. Beam charge modulation $f_{\mathrm{mod}} \rightarrow$ tuneable side-bands

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

   $\Rightarrow$ Brilloin zone $[0\ , f_{\mathrm{Beam}}]$ as large as possible

Modulated charge



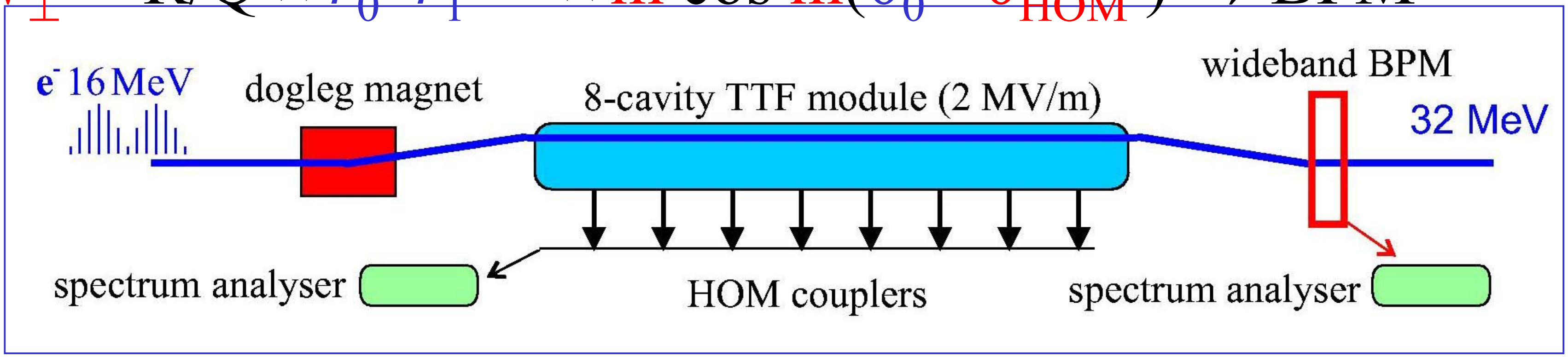



## ➢ **Dipole HOM excitation**:

Wake Potentials :

$W_{\square} \propto R/Q \times r_0^{\,m} r_1^{\,m} \times \cos m(\theta_0 - \theta_{HOM}) \quad \rightarrow$ HOM Pick Up

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




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

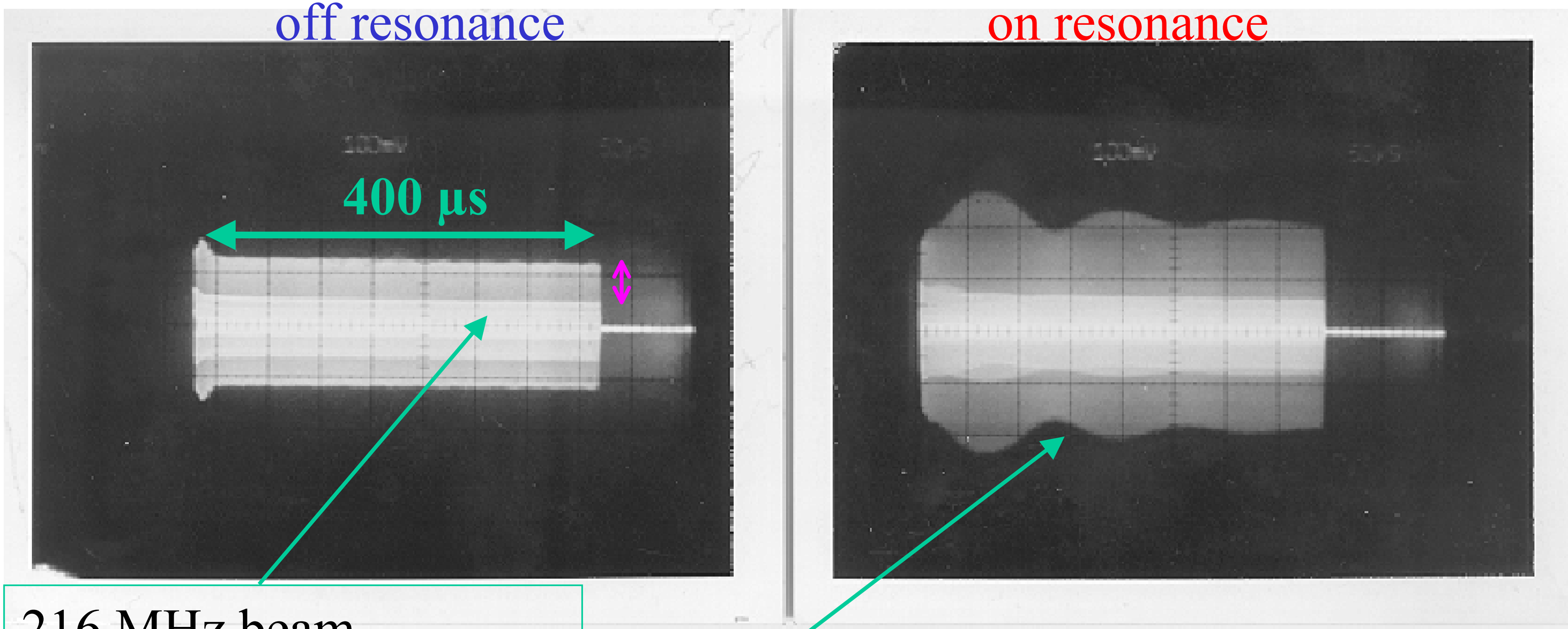
| | |
|---|---|
| monopole | $m = 0 : P_{HOM} \propto \delta x^0 , \delta x_{BPM} = 0$ |
| dipole | $m = 1 : P_{HOM} \propto \delta x^2 , \delta x_{BPM} \propto \delta x$ |
| quadrupole | $m = 2 : P_{HOM} \propto \delta x^4 , \delta x_{BPM} \propto \delta x^3$ |

# High-*Q* HOM in the 3rd Passband

**HOM** : $f$ = 2.585 GHz , $Q = 10^6$

measured with 216 MHz Injector #1 in Module 1, in 1998.

**BPM Signal**




216 MHz beam
with 15 MHz modulation

125 µs beating due to 8 kHz off resonance

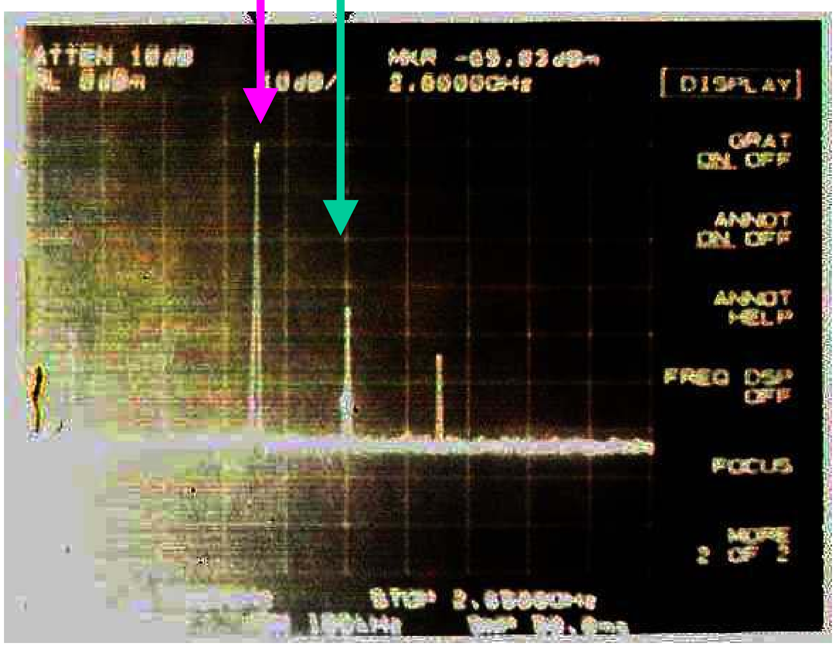
# High-*Q* HOM in the 3rd Passband

Frequency $f_{HOM}$, damping $Q$ and "m=1" are easily measured.
Coupling R/Q is not: requires beam parameters and polarisation

**HOM Pickup Signal**

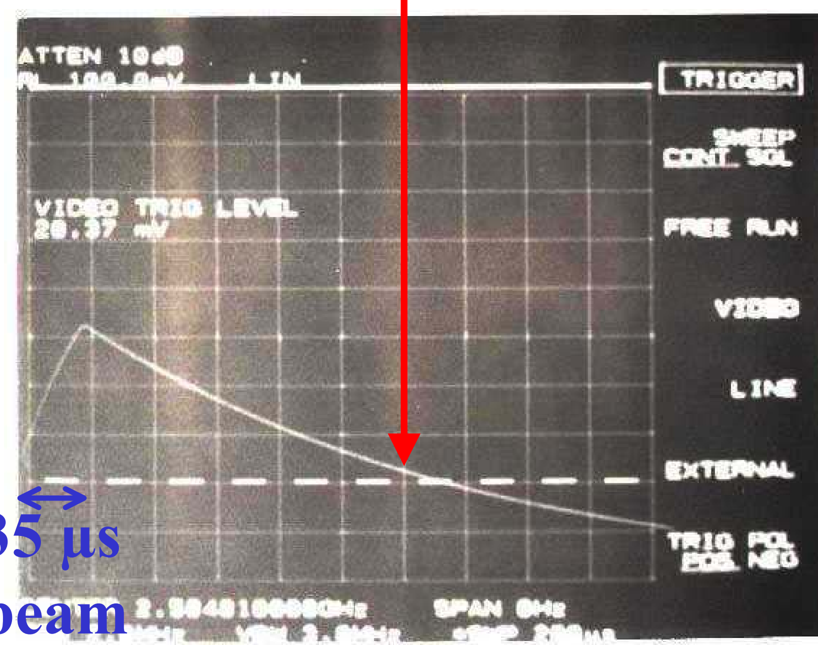
HOM at 2.585 GHz

Beam at 2.6 GHz




frequency domain

Decay time ⇒ $Q = 10^6$



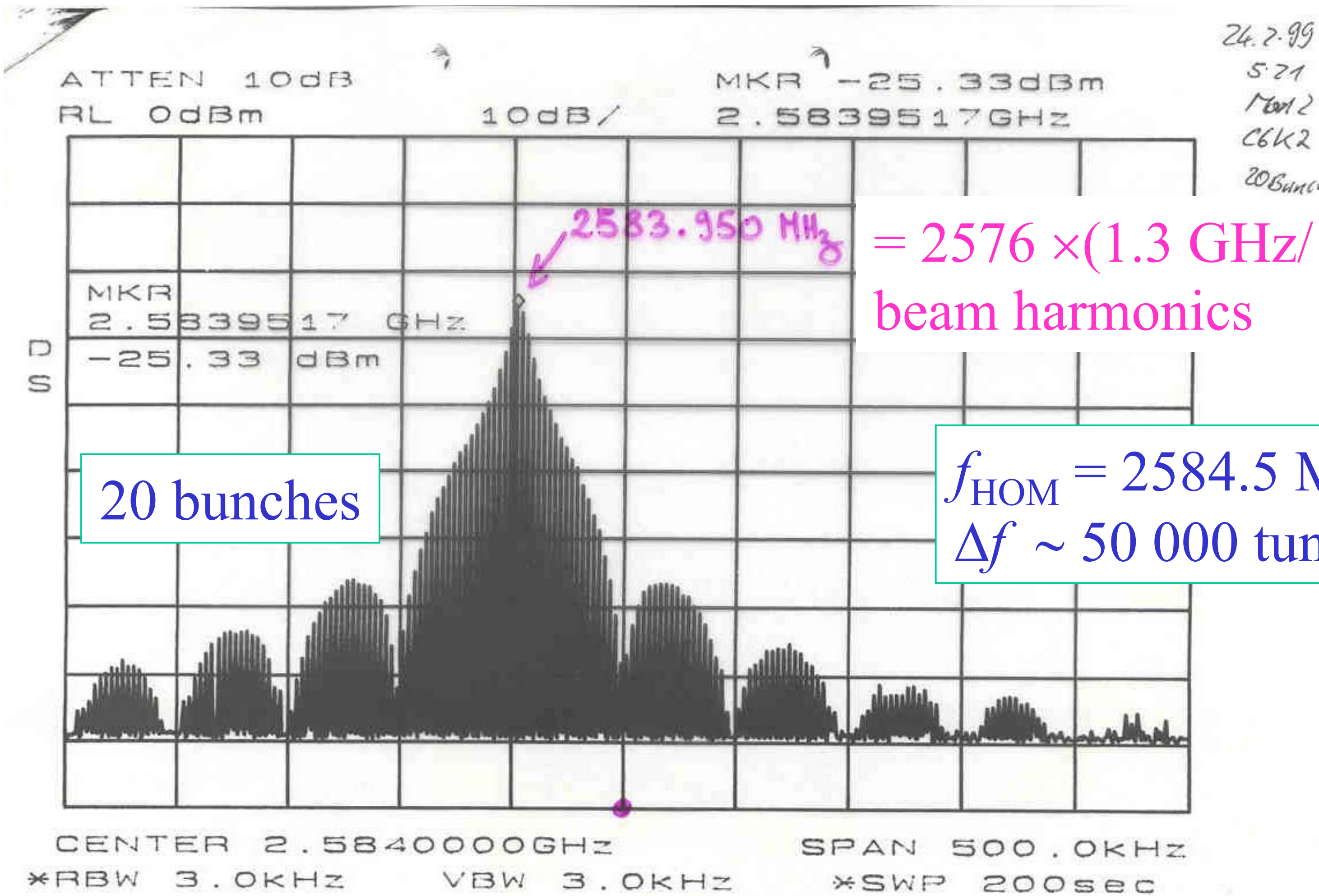

35 µs beam

time domain

# High-$Q$ HOM in the 3rd Passband

**HOM** : $f = 2.585$ GHz , $Q = 4 \times 10^5$

measured with 1 MHz Injector #2 in Module 2, in 1999.




= 2576 ×(1.3 GHz/1296) beam harmonics

20 bunches

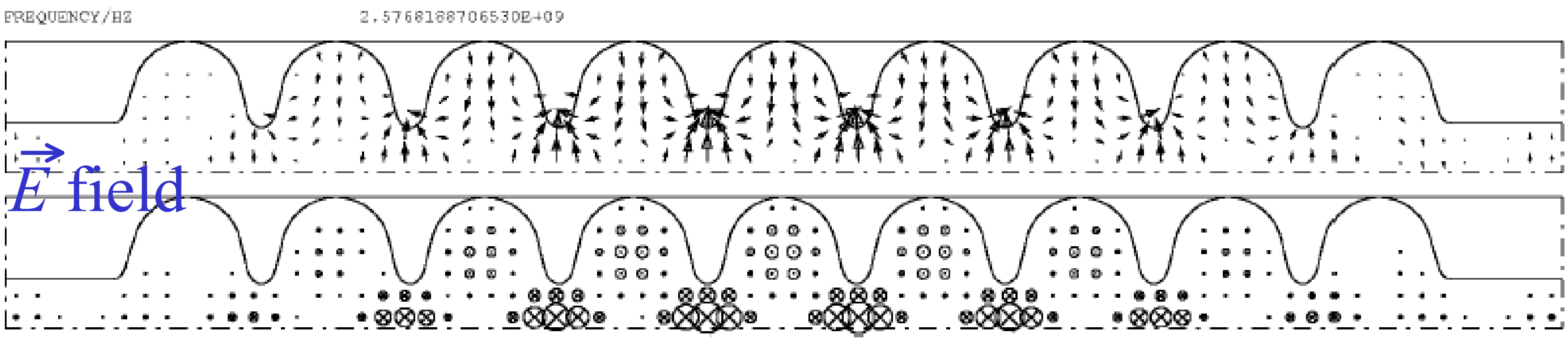
$f_{HOM}$ = 2584.5 MHz

$\Delta f$ ~ 50 000 tuner steps

# Results and Analysis for the Dipole Passbands

➢ **The 3rd Dipole Passband** :

The 2585 MHz identified as the highest frequency HOM within the 3rd dipole passband : NOT A SURPRISE !



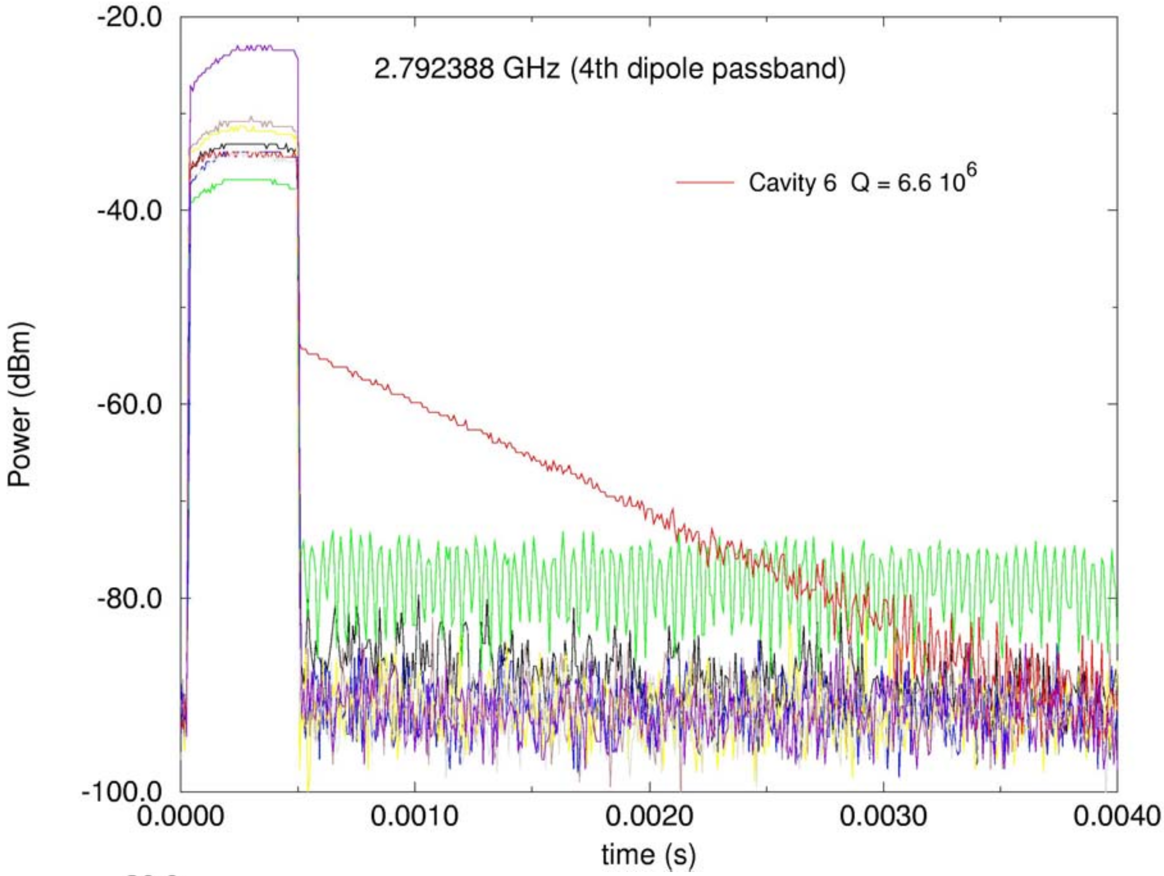

2π mode at ~ 2×1.3 GHz, synchronous with $e^-$ beam

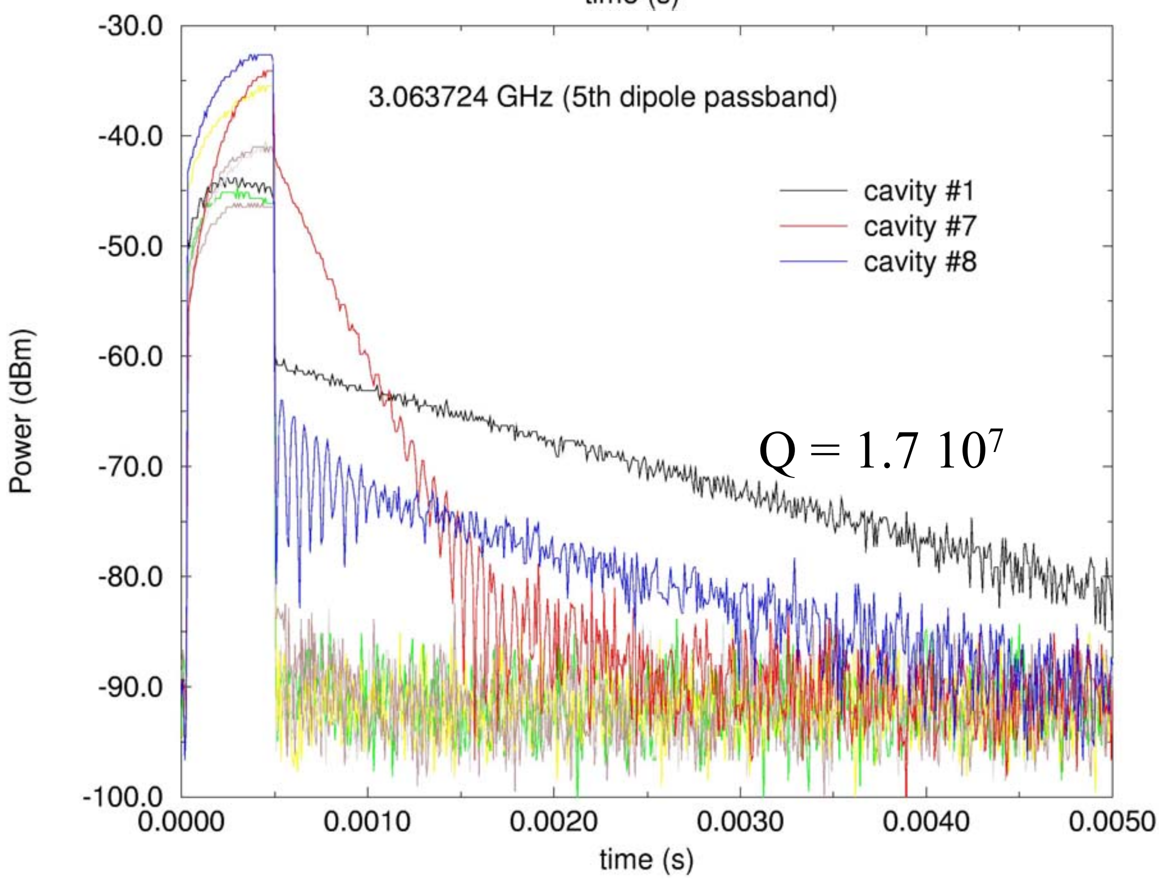
$\Rightarrow$ R/Q = 24 Ω/cm$^2$, the highest dipole coupling.

**QUESTIONS** : why the bad damping , $Q > 10^5$ ?

why only in 2 out of 8 cavities ?

# ➢ Higher Order Dipole Passband :



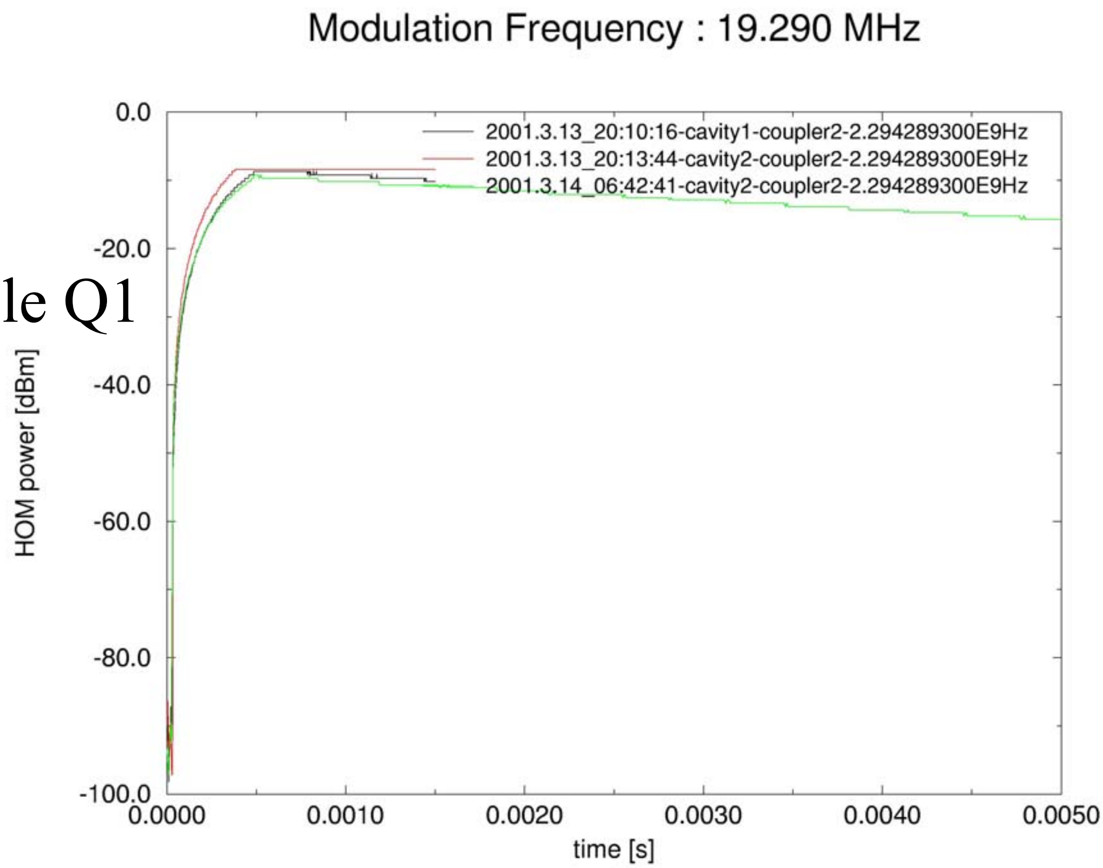
Goal : Prove or dis-prove the existence of long-lived HOMs, particularly in the $5^{th}$ dipole passband.

Three Methods : ( $f$ and $Q$ measured with beam)

1. Measure R/Q from beam excitation in the BPM : no way, most BPM signals are triggered by quadrupole modes !
2. Identify the position of measured modes in the passband : very difficult, because the measured passband is a forest !
3. Measure R/Q from beam excitation in the HOM couplers : main unknowns are the polarisations Ki / HOM / $x$-plane

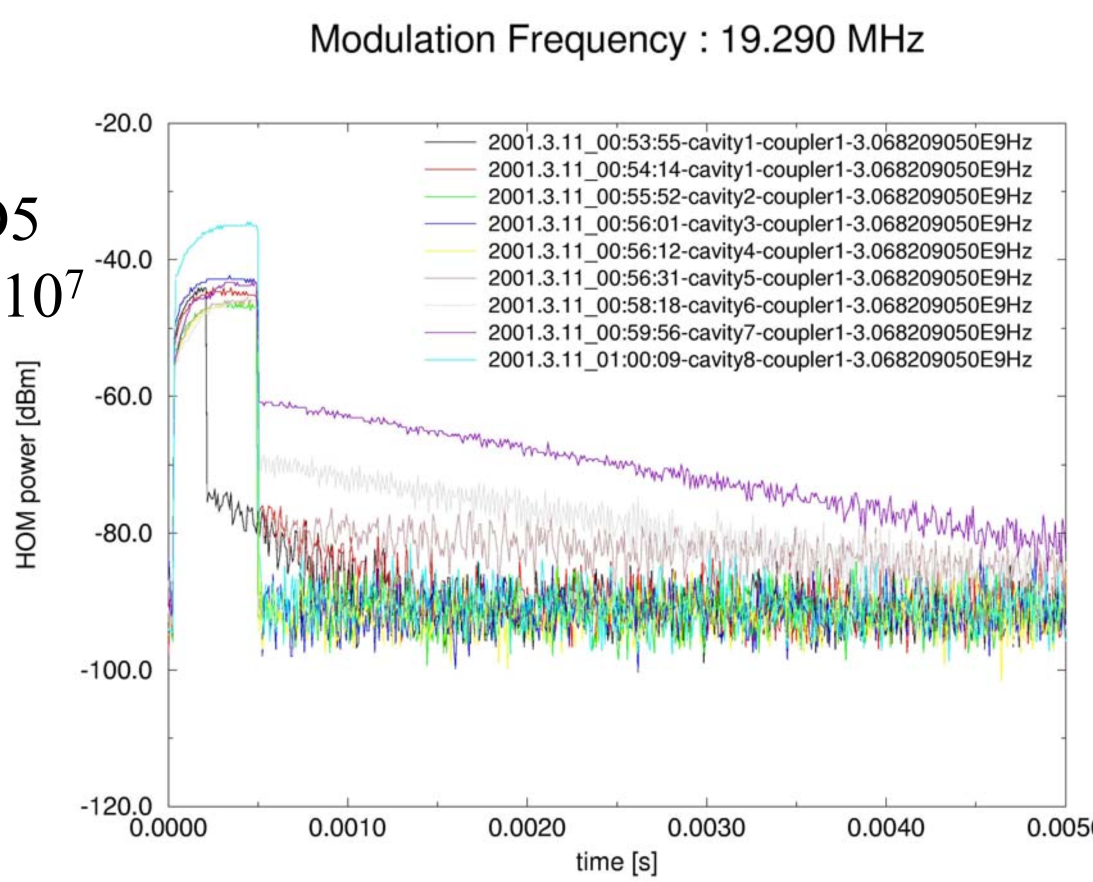
➢Powerful Quadrupole HOMs are co-excited

Quadrupole Q1

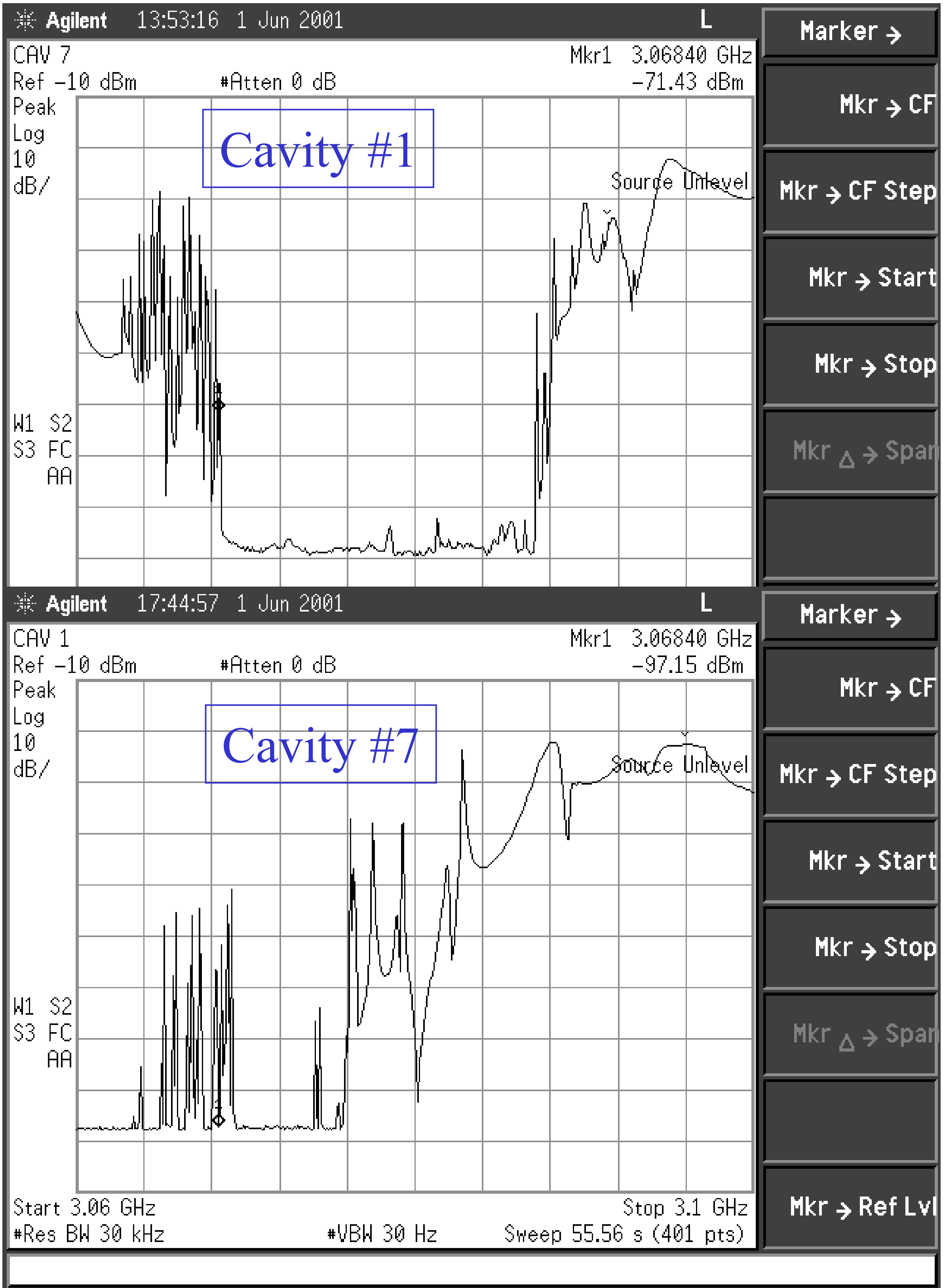



Dipole D5

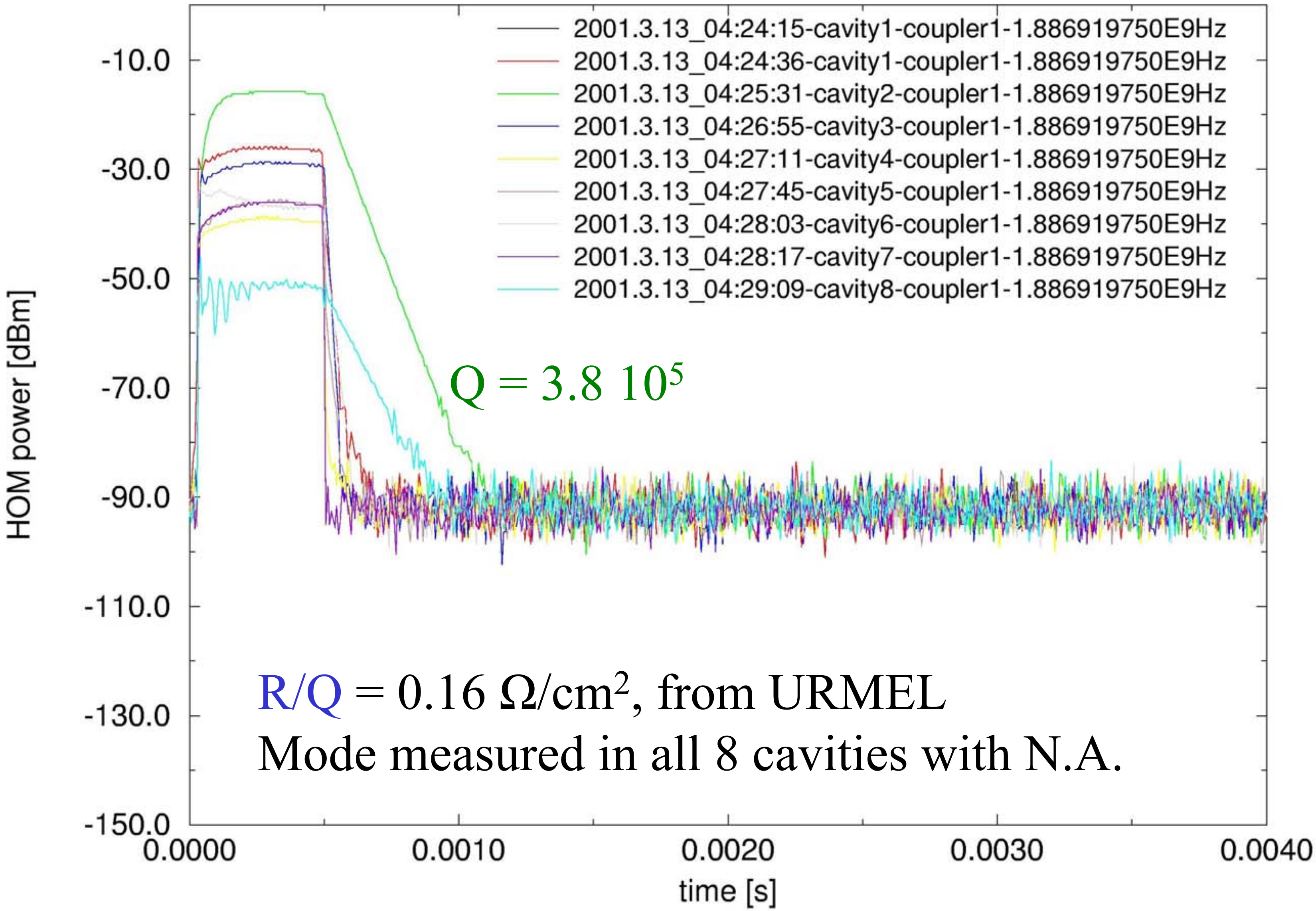
$Q = 3.4\ 10^7$

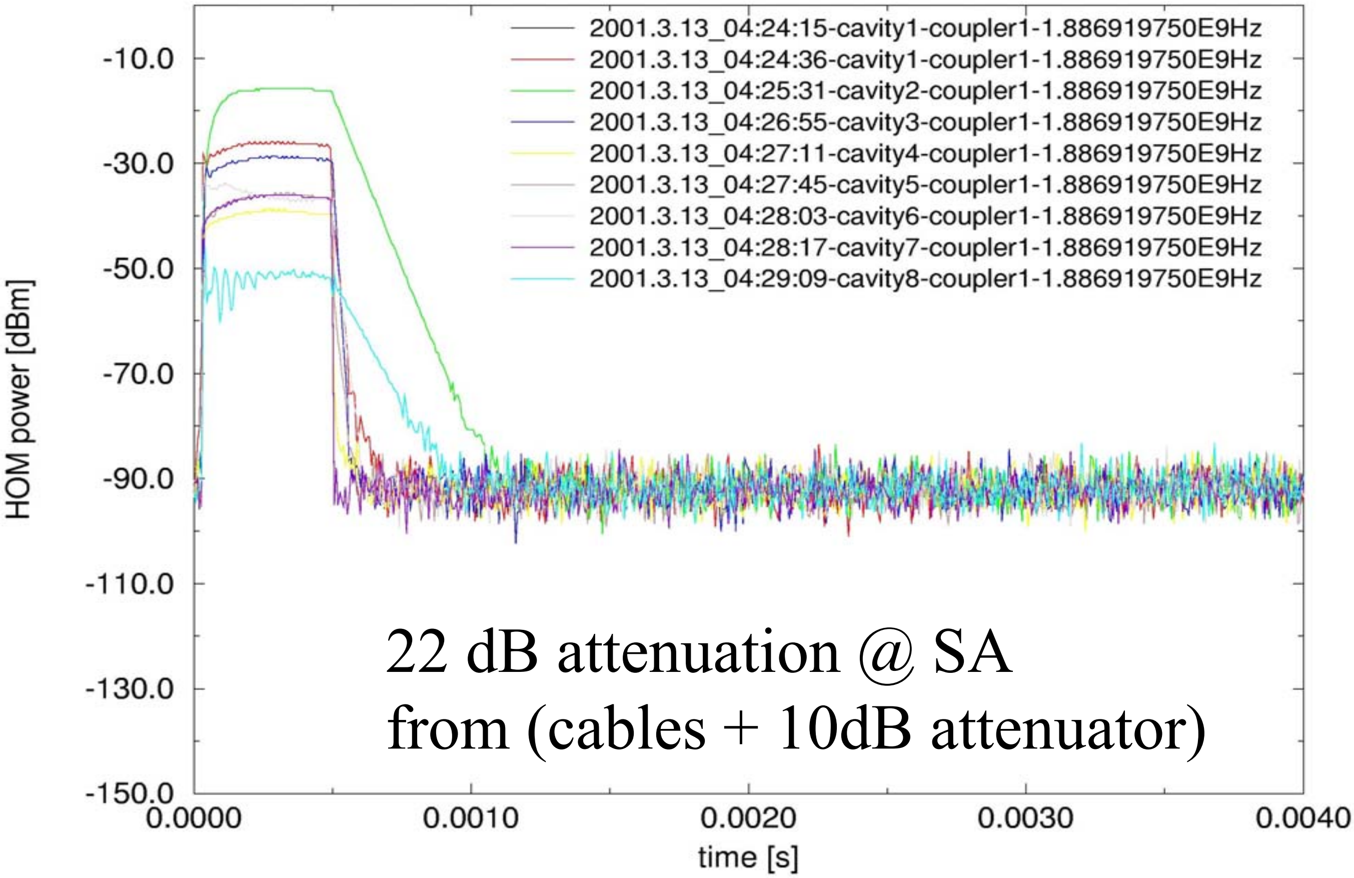


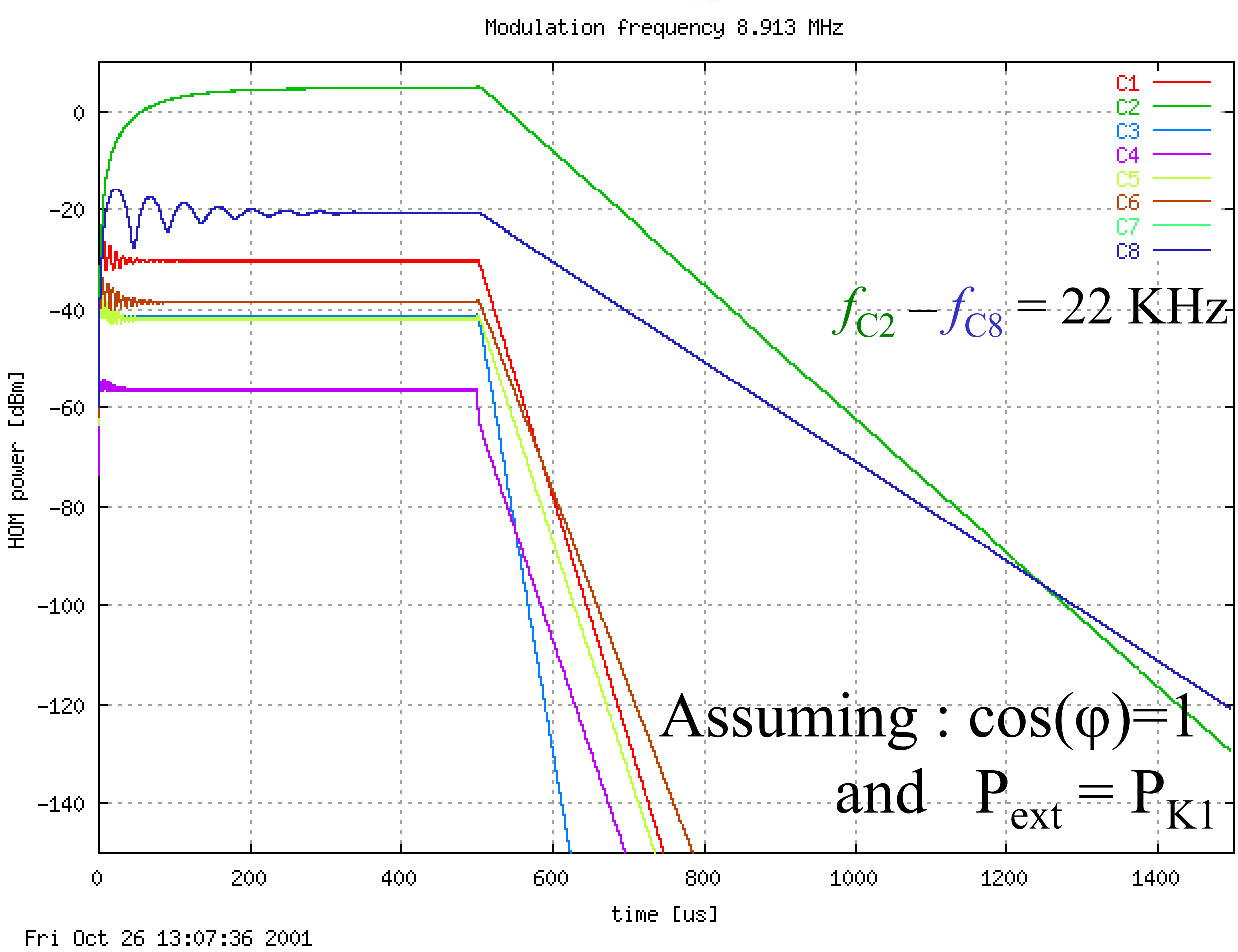
- The 5th dipole passband : module measurements are difficult to interpret .



# Benchmarking with TM110-8 @ 1887 MHz

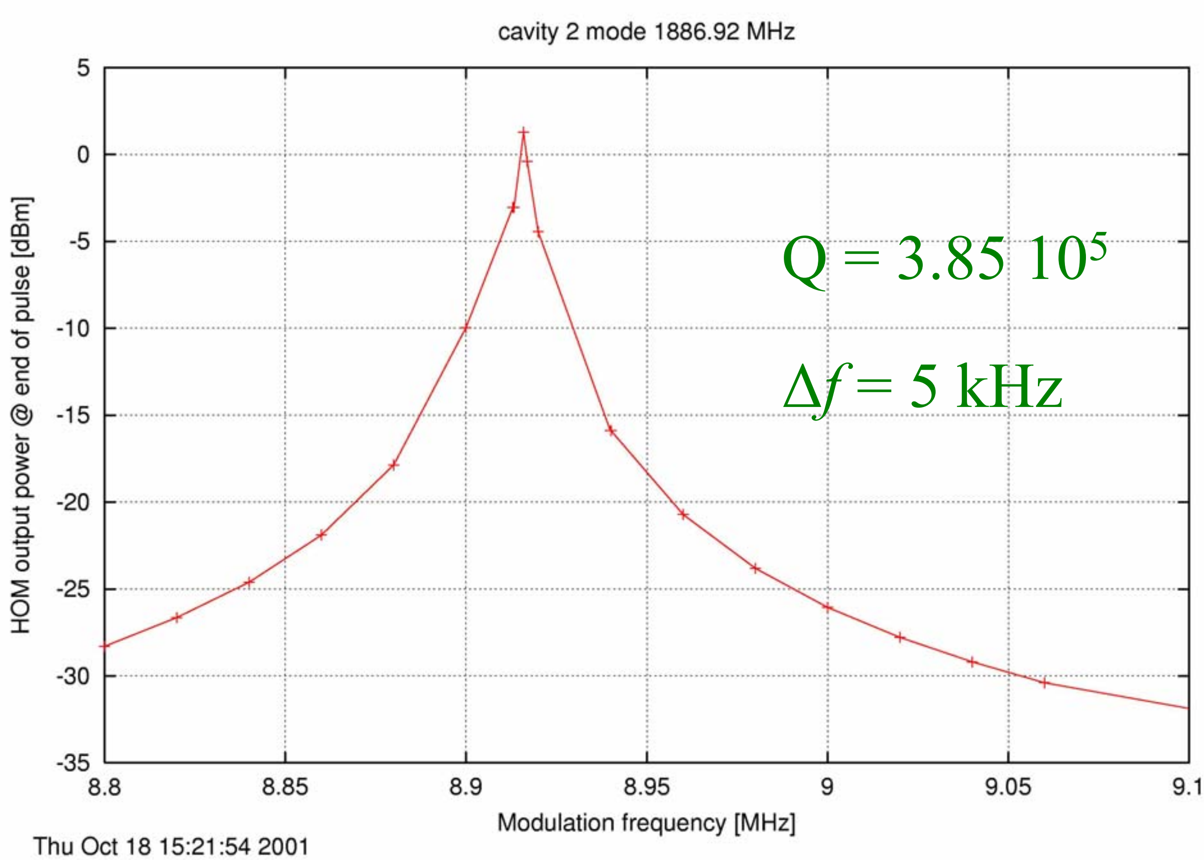



2001.3.13_04:24:15-cavity1-coupler1-1.886919750E9Hz
2001.3.13_04:24:36-cavity1-coupler1-1.886919750E9Hz
2001.3.13_04:25:31-cavity2-coupler1-1.886919750E9Hz
2001.3.13_04:26:55-cavity3-coupler1-1.886919750E9Hz
2001.3.13_04:27:11-cavity4-coupler1-1.886919750E9Hz
2001.3.13_04:27:45-cavity5-coupler1-1.886919750E9Hz
2001.3.13_04:28:03-cavity6-coupler1-1.886919750E9Hz
2001.3.13_04:28:17-cavity7-coupler1-1.886919750E9Hz
2001.3.13_04:29:09-cavity8-coupler1-1.886919750E9Hz
HOM power [dBm]
time [s]
22 dB attenuation @ SA
from (cables + 10dB attenuator)


Modulation frequency 8.913 MHz
C1
C2
C3
C4
C5
C6
C7
C8
$f_{C2} - f_{C8} = 22$ KHz
Assuming : cos(φ)=1
and $P_{ext} = P_{K1}$
HOM power [dBm]
time [us]
Fri Oct 26 13:07:36 2001

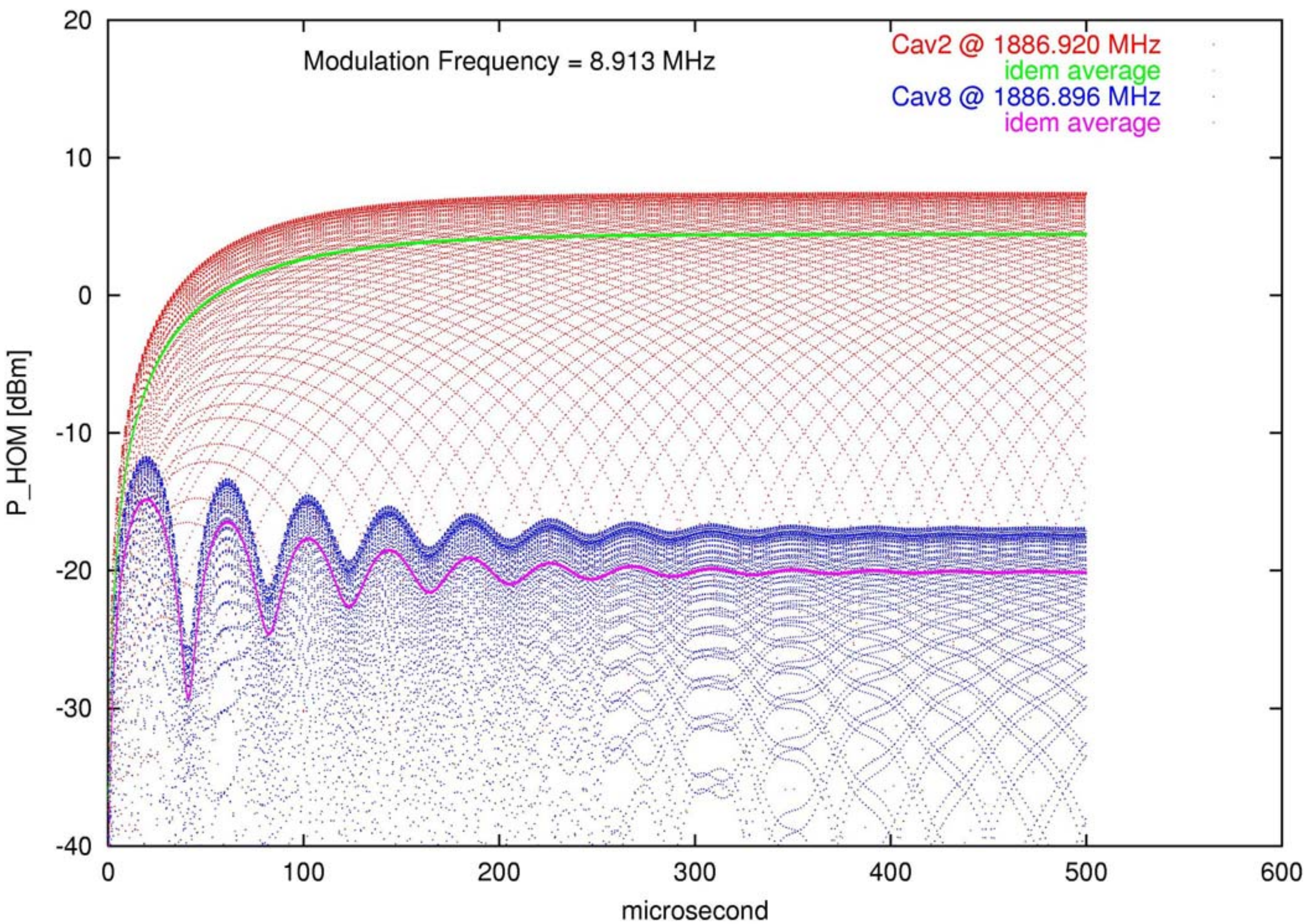
The modes TM110-8 in (C1-C6,C8) are spread by about 300 kHz ,
with mode in C7 about 3 MHz below !

## Off resonance cavity response



# The loaded cavity signal @ 54 MHz

$$P_n = U_n^2/(R/Q \times Q)$$




The exponential decay of the empty cavity

$$P = P_N \exp(-2t/\tau)$$

depends on number of bunches $N$

$\Rightarrow$ *The start of the decay can be a bit higher or much lower than the video signal*

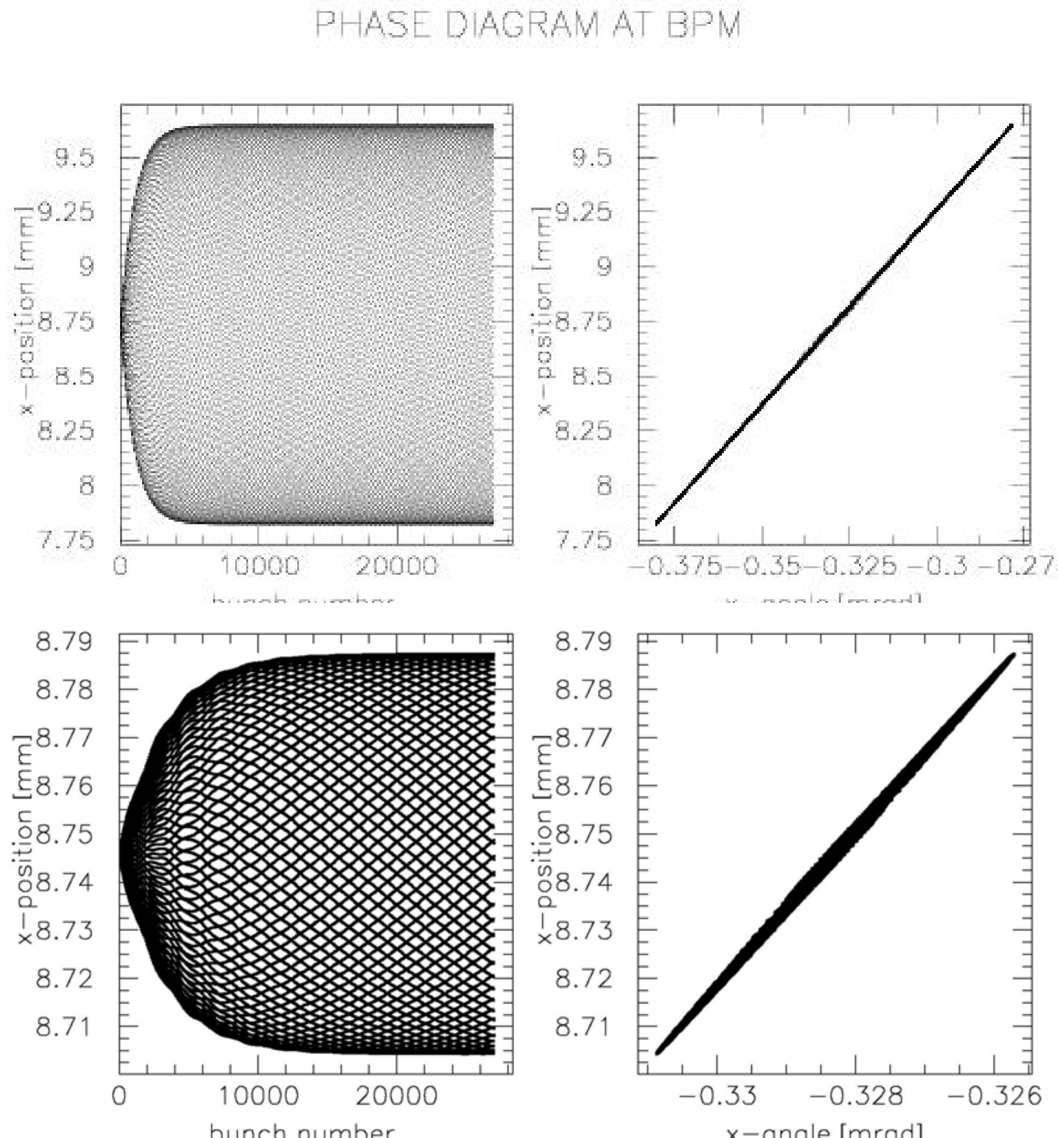
# TM110-5 vs. TM110-8

TM110-5 @ 1874 MHz

$R/Q = 8.7\ \Omega/\mathrm{cm}^2$ ,

$Q = 1.14\times10^5$

$\Rightarrow\quad \Delta x_{\mathrm{BPM}} = 1.75$ mm




TM110-8 @ 1887 MHz

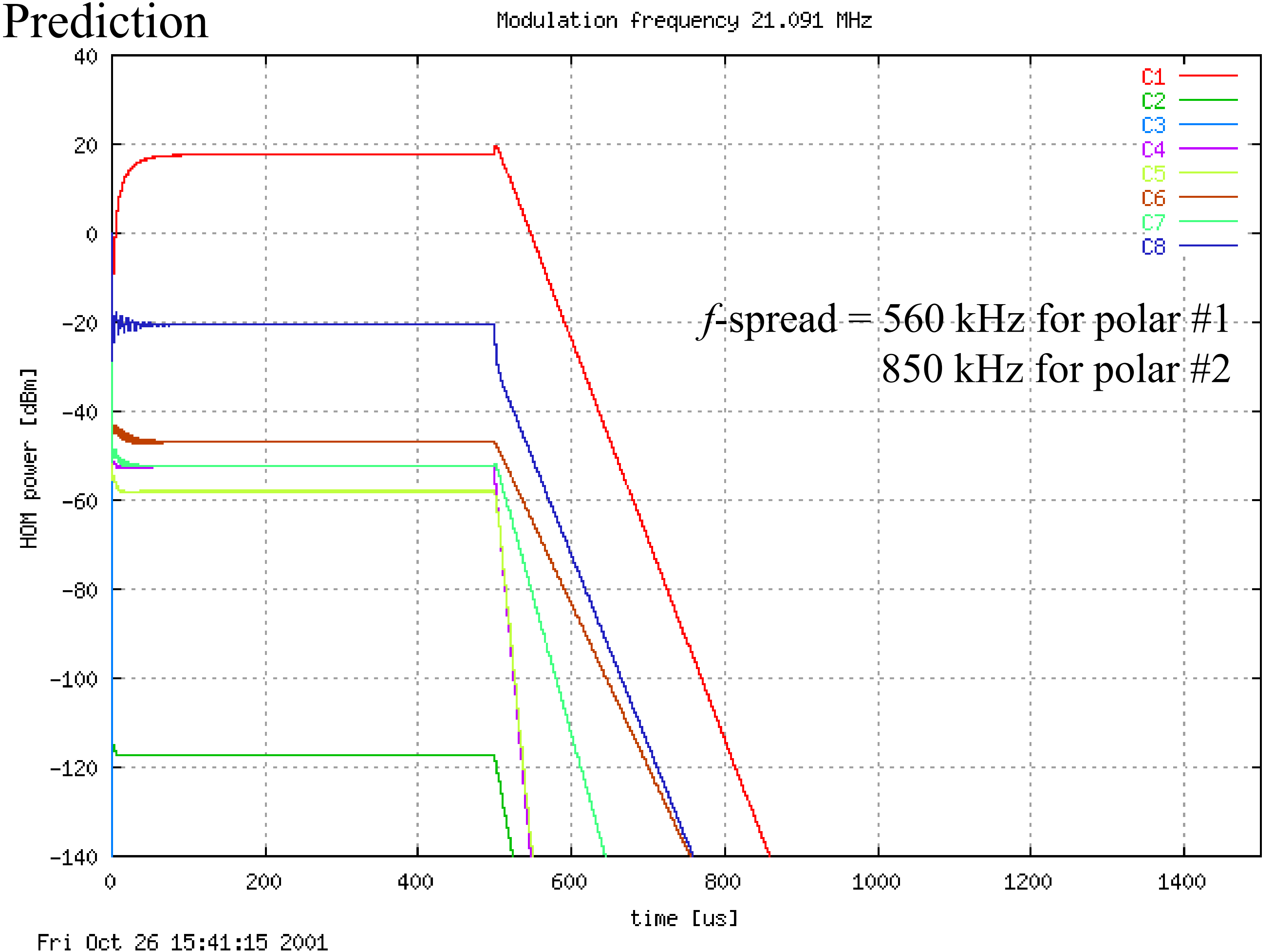
$R/Q = 0.16\ \Omega/\mathrm{cm}^2$ ,

$Q = 3.85\times10^5$

$\Rightarrow\quad \Delta x_{\mathrm{BPM}} = 0.085$ mm

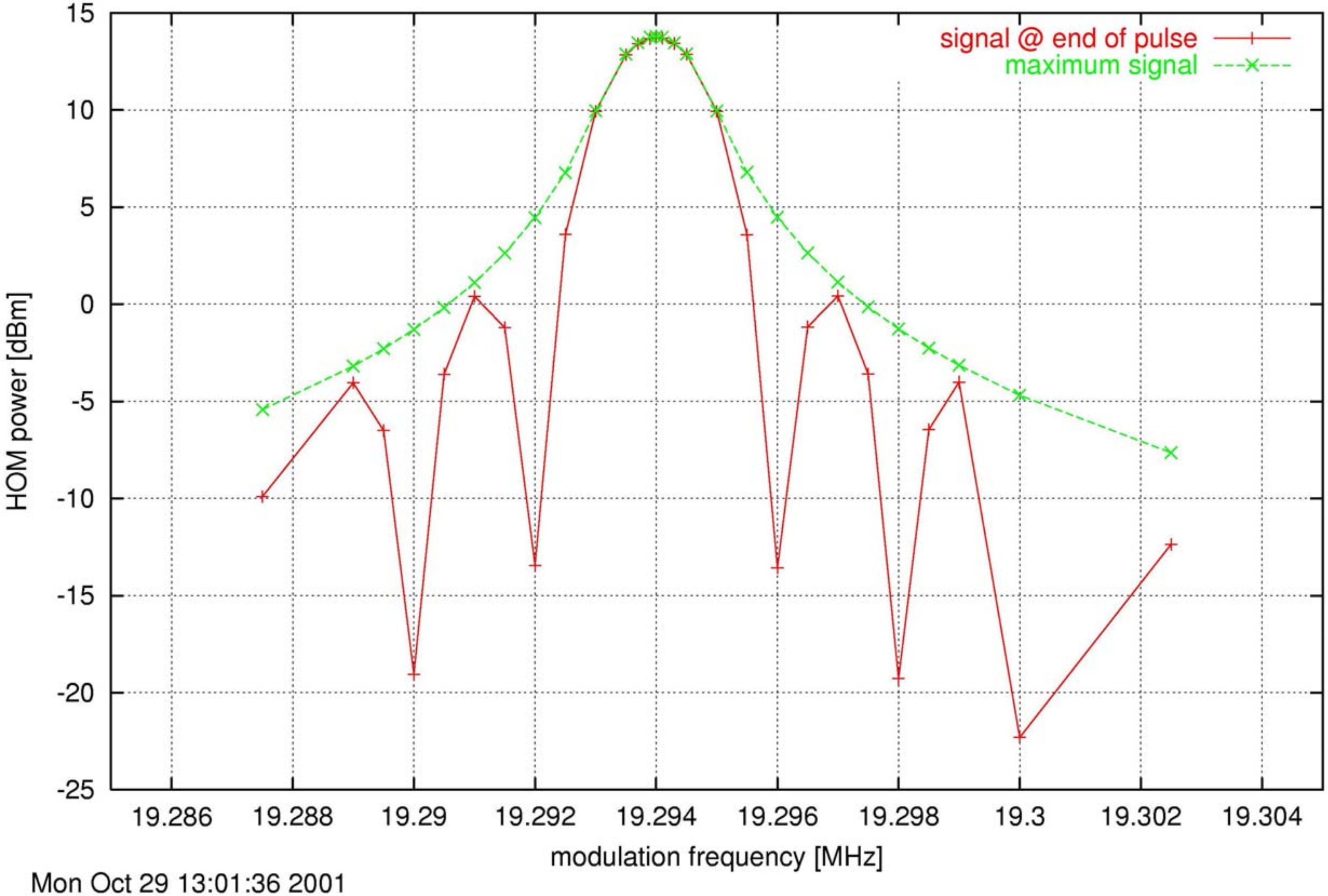
# TM110-5 @ 1887 MHz

Prediction



# $5^{th}$ Dipole Passband Trapped Mode

**Prediction** for : $f$ =3068 MHz , R/Q = 1.1 Ω/cm$^2$ , $Q$ = 3.4 $10^7$ in cavity C7, as a function of the modulation frequency



# Conclusions for Higher Passbands

- **No signal** (~ 0 dBm = 1 mW) of strong HOM
  with low damping ($R/Q \geq 1\ \Omega/\mathrm{cm}^2$, $Q \geq 10^6$)
- But, **no decisive proof** that such modes do not exist.
  Possible explanations for low power signal :
  ( ~ 40 dBm instead of ~ 0 dBm):
  - $R/Q$ ϒ $1\ \Omega/\mathrm{cm}^2$ $\Rightarrow$ HOM is harmless
  - Vertical polarisation
  - Signal is off resonance : $|f_{Q1} - f_{D5}| > 100$ kHz
  - Last bunch generates low field across gap

# Necessary Improvements

- Improve BPM resolution (complement with strip-line)
- Offset beam horizontally and vertically
- Check linearity for dipole modes
- Measure direct pick-up signal of HOM couplers
  - dependence on offset
  - dependence on coupler
  - dependence on modulation frequency
- Measure HOM power for well understood monopole modes, and compare to prediction
- Vary number of bunches by one unit.

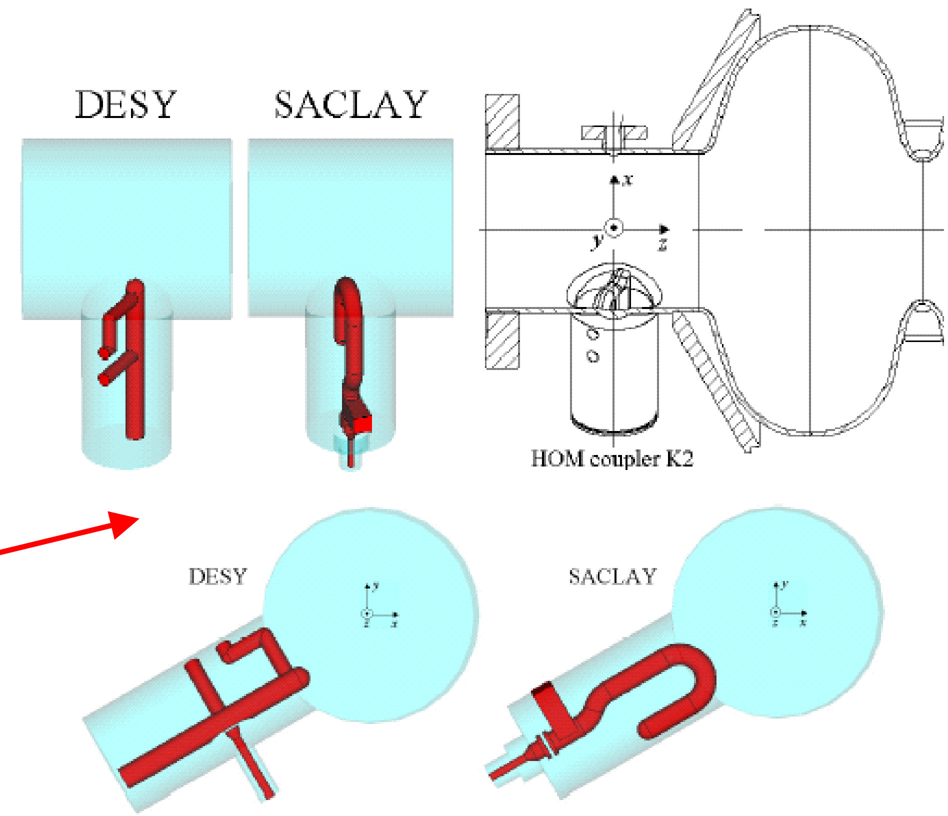
$\Rightarrow$ A complete frequency scan will be very long

# Interpretation of the 3rd Dipole Passband Puzzle

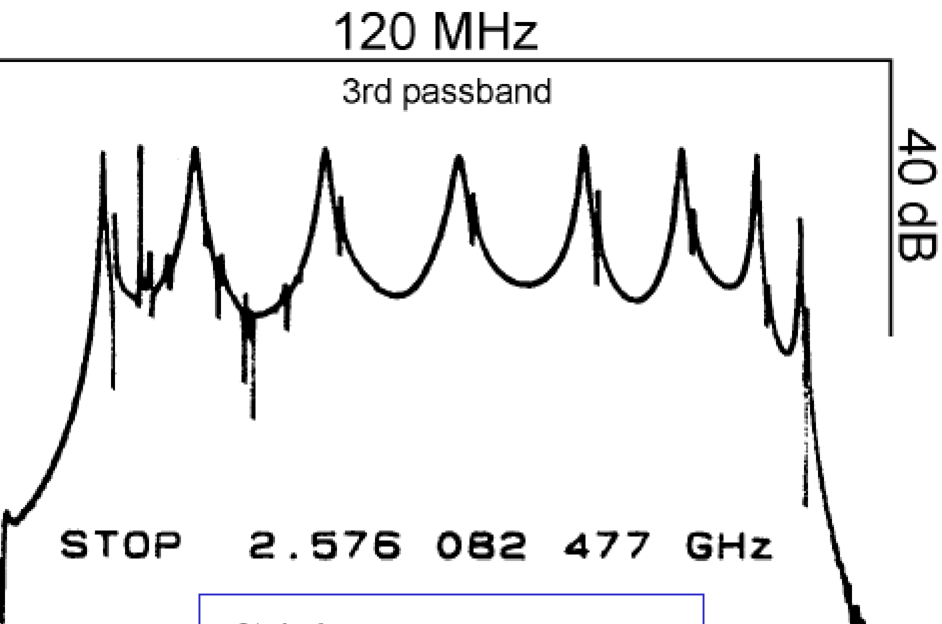
A recent *(preliminary)* calculation by M. Dohlus (DESY) might elucidate the problem of the 3rd dipole passband.

It combines S-parameter and MAFIA type of calculations, a method also developed at the Uty of Rostock.

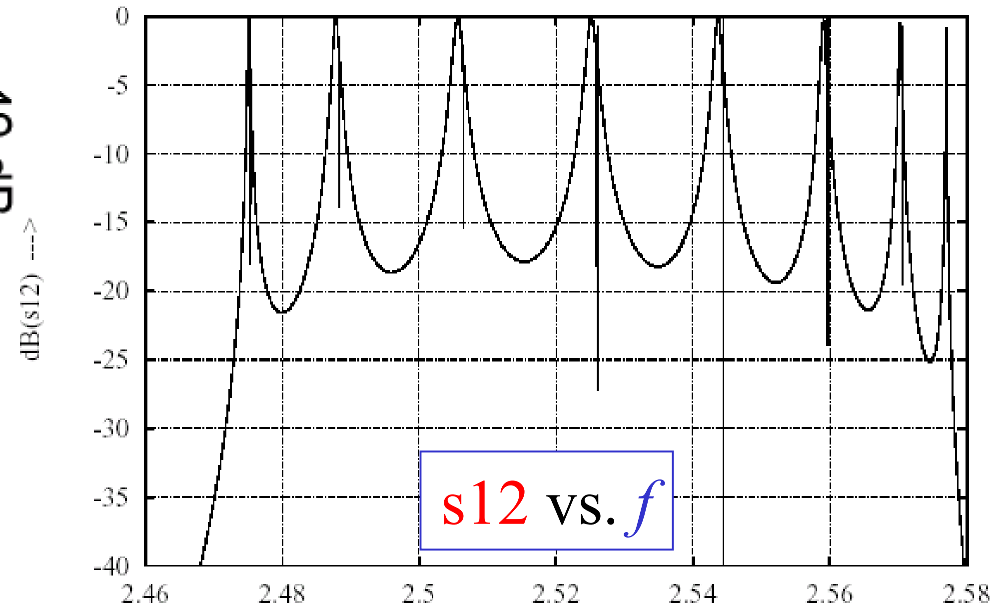
It is based on the real geometry of Input and HOM couplers.

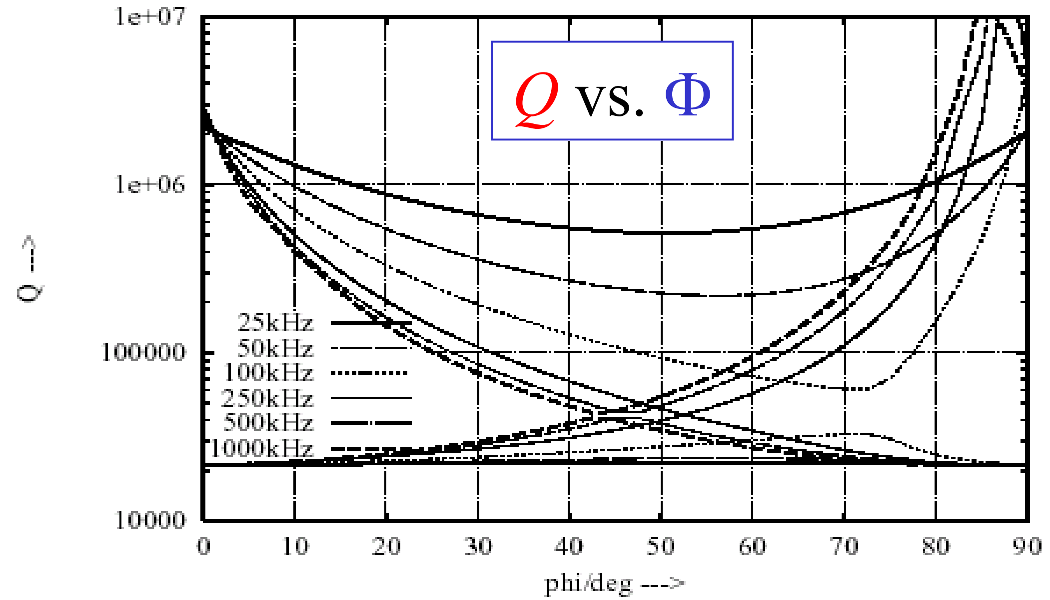


➢ It predicts the correct passband pattern and HOM damping



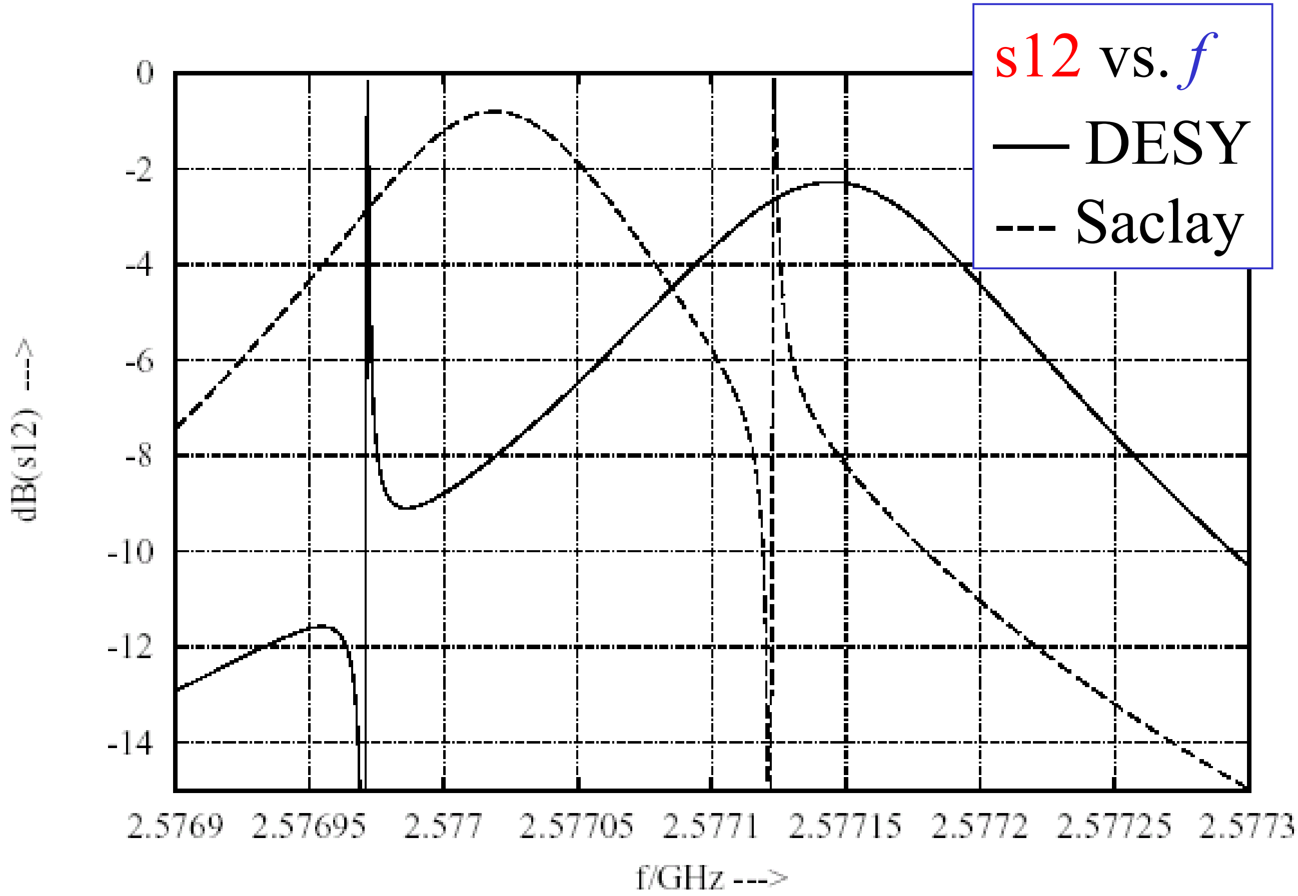

C46 measurement



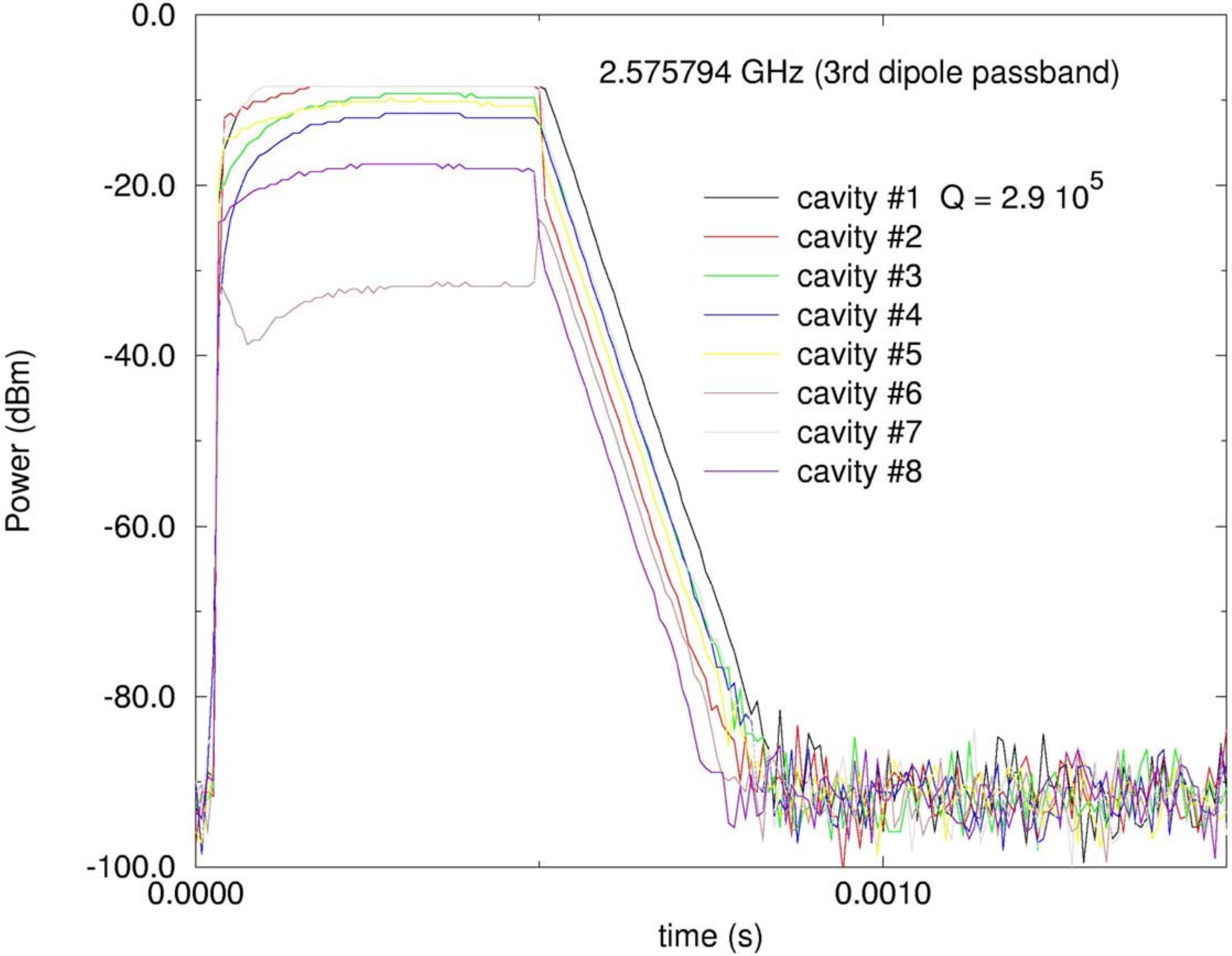




Example of cavity
with Saclay HOM couplers

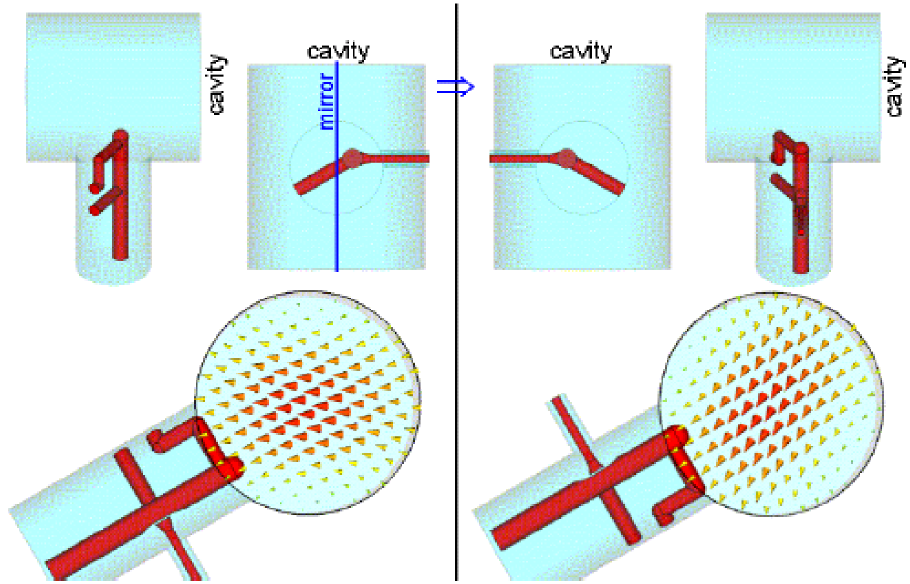
➢ It predicts:
- the correct pairing of polarisations, with high and low HOM damping
- the correct shape of s12 through HOM couplers K1-K2



- It predicts "module modes" extending over the entire module, in the case of homogeneous HOM coupler type.

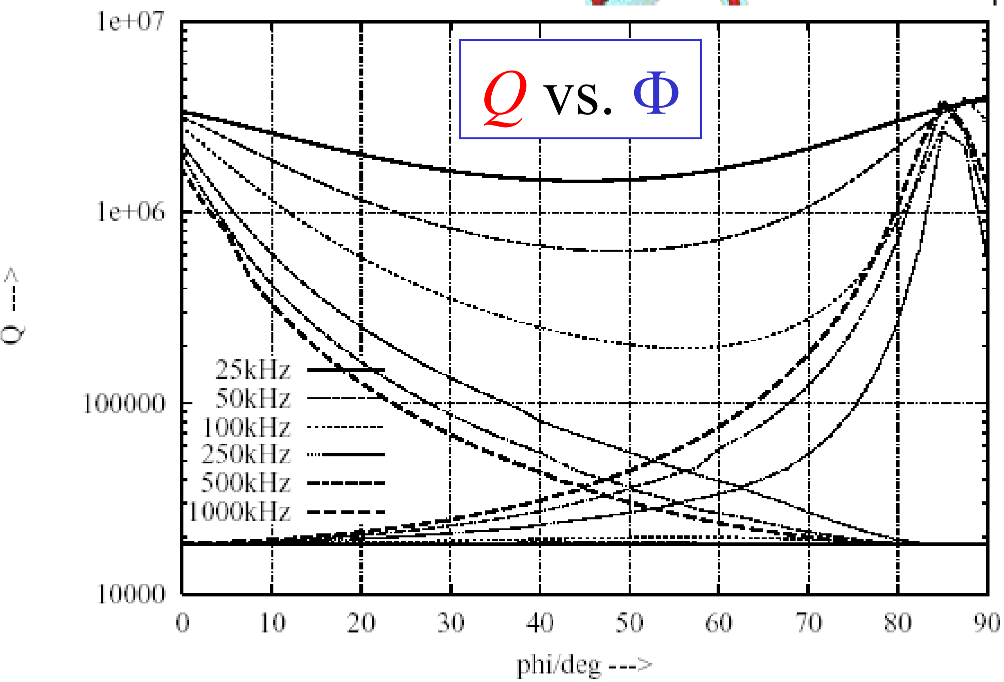


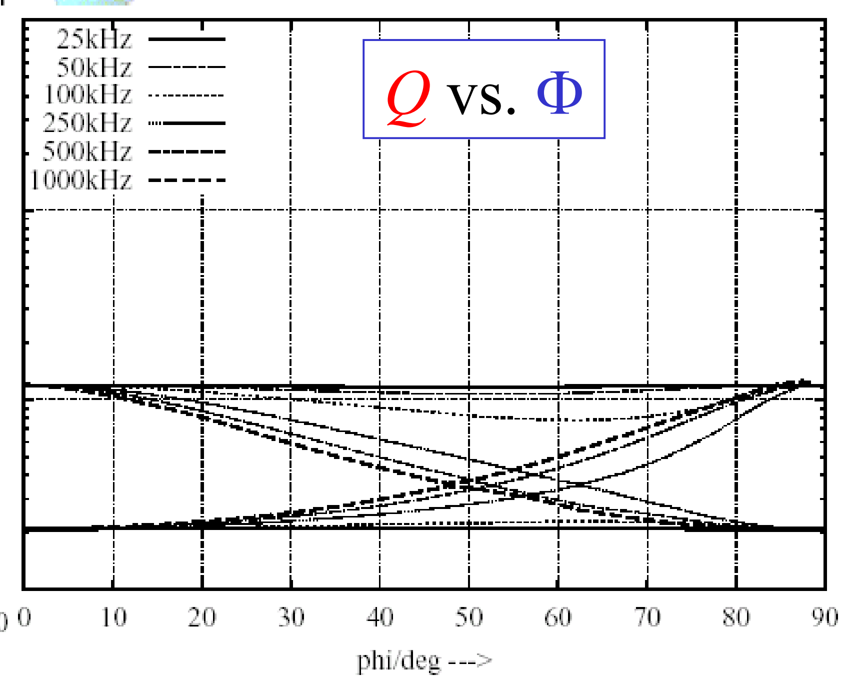
➢ It predicts a practical solution for reducing $Q < 10^5$



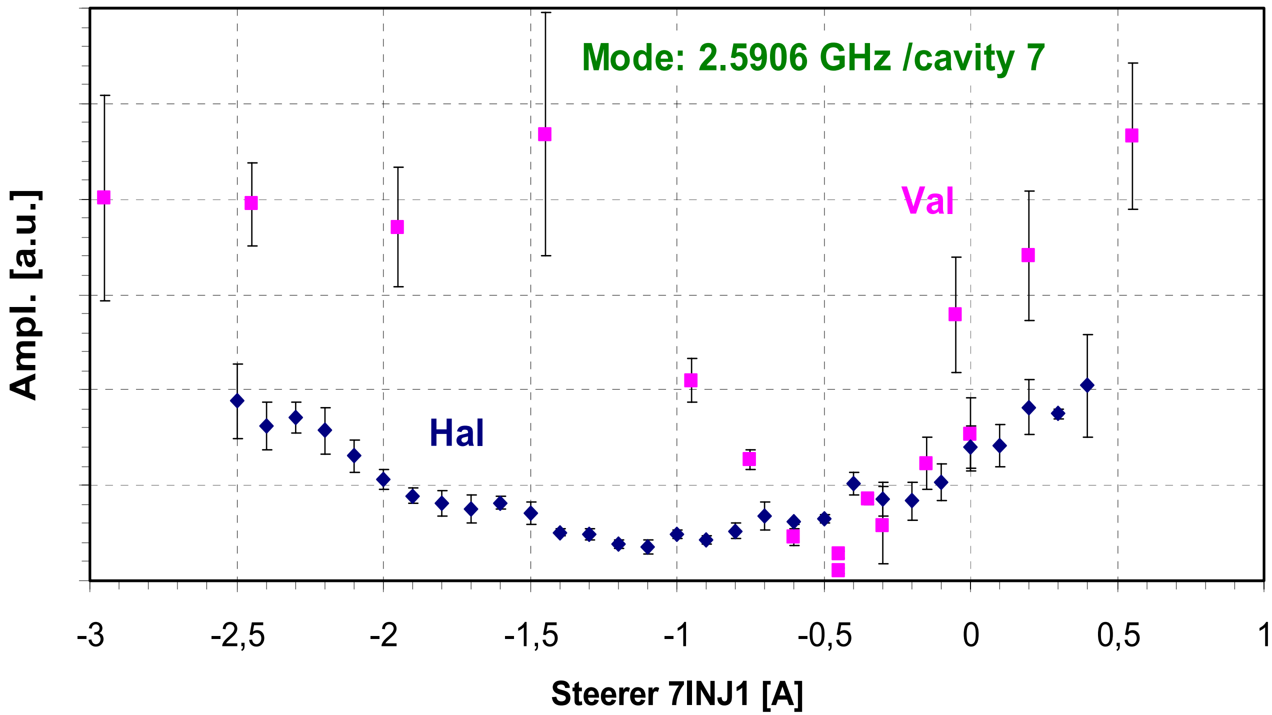

DESY type
HOM coupler

One coupler is
"mirrored"



## ➢ Polarisation pattern may not be completely understood




Example of S28 cavity (module 3) with DESY HOM couplers showing a vertically polarized HOM at 2590.6 MHz with $Q = 6.5\ 10^5$ :

- vertical polarisation → DESY coupler
- $f$ (low $Q$) < $f$ (high $Q$) → Saclay coupler

# Conclusions

## LESSONS

- HOM above cut-off may not be contained in a single cavity :

→ single cavity R/Q is not relevant, because field pattern is changed

→ module R/Q not useful for (m=1) modes because orbit not constant.

- Although used for *f* and *Q*, beam measurements MUST be used for measuring beam coupling R/Q and polarisation Φ.

→ requires qualitative improvement in experimental set-up.

## CONCLUSIONS

- The puzzle of 3rd dipole passband might be explained and cured.

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