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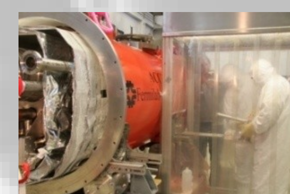
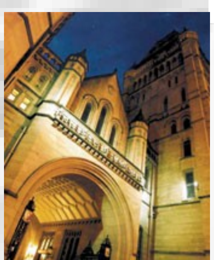
DESY

HOM DIAGNOSTICS IN THIRD HARMONIC CAVITIES AT FLASH

Roger M. Jones

University of Manchester/ Cockcroft Inst.





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Task 10.5 HOM Diagnostic in 3rd Harmonic Cavities at FLASH

TASK 10.5	HOM Distribution	R.M. Jones
Sub-Task	Name	Coordinating Institute/Univ.
10.5.1	HOMBPM	DESY
10.5.2	HOMCD	Cockcroft/Univ. Manchester
10.5.3	HOMGD	Univ. Rostock

- 10.5.1 HOM based Beam Position Monitors (HOMBPM)
- 10.5.2 HOM based Cavity Diagnostics (HOMCD)
- 10.5.3 HOM based Geometrical Dependancy (HOMGD)

- **All pool together to ensure success of instrumentation of diagnostics for FLASH cavities.**

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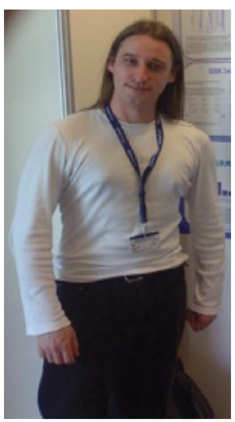
HOM Diagnostic in 3rd Harmonic Cavities at FLASH -Staff

- **<u>Sub-task leaders</u>: Nicoleta Baboi (DESY), Ursula van Rienen (Univ. Rostock), Roger M. Jones (CI/Univ. Manchester).**
- **PDRAs: Hans-Walter Glock (Univ. Rostock), Ian Shinton (CI/Univ. of Manchester)**
- **Ph.Ds: Nawin Juntong (CI/Univ. Manchester), Pei Zhang (DESY/Univ. Manchester/CI), Thomas Flisgen (Univ. Rostock)**

WP 10.5.2



I. Shinton, CI/Univ. of Manchester PDRA

N. Juntong, CI/Univ. of Manchester PhD student (PT on FP7)

C. Glasman, CI/Univ. of Manchester PhD student (PT on FP7)

WP 10.5.3

H-W Glock, Univ. of Rostock, PDRA

T. Flisgen ,Univ. of Rostock

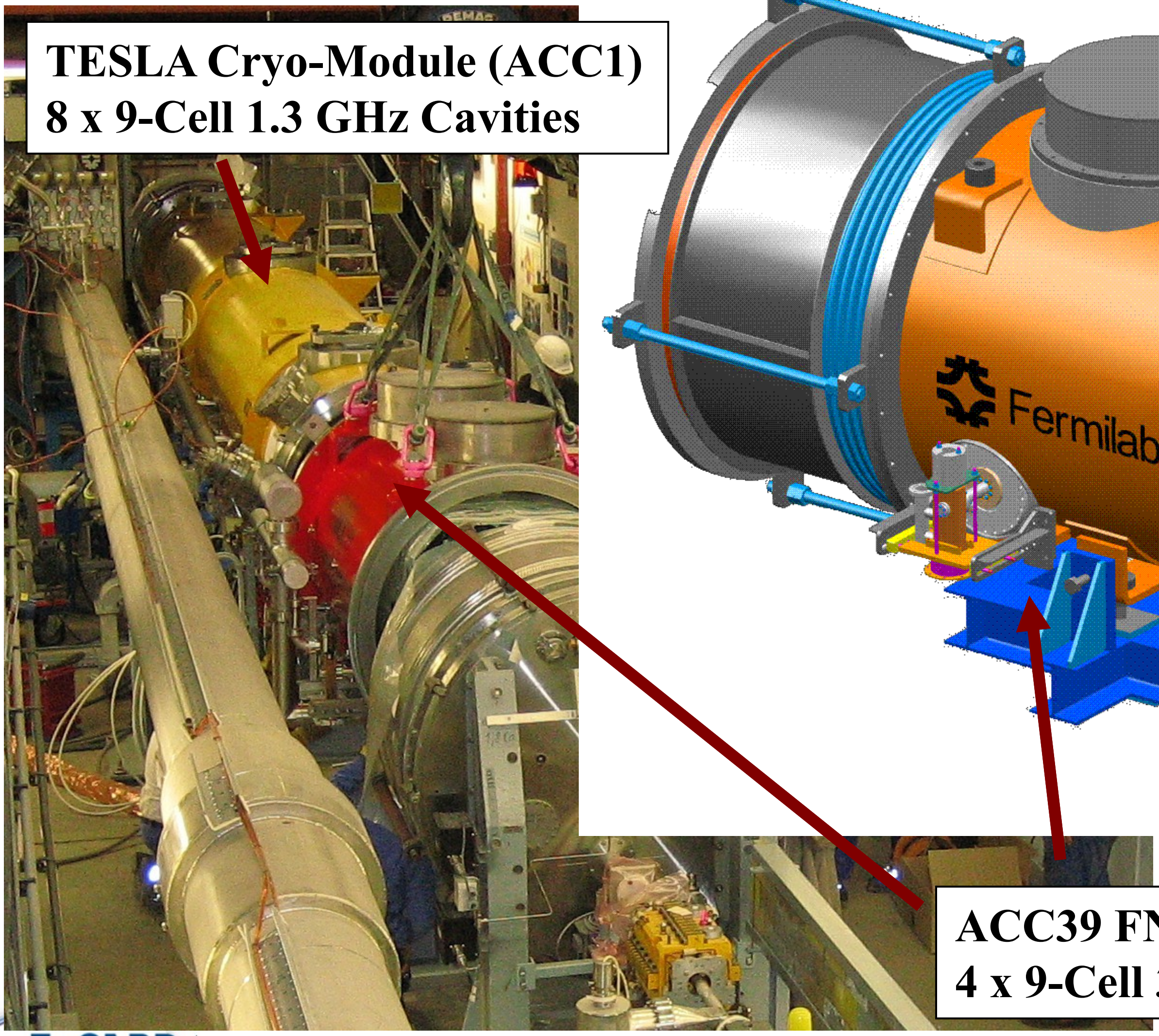
U. Van Rienen, Univ. of Rostock

WP 10.5.1

N. Baboi, DESY

P. Zhang, DESY/Univ. Of Manchester

3.9 GHz Module Installed at FLASH



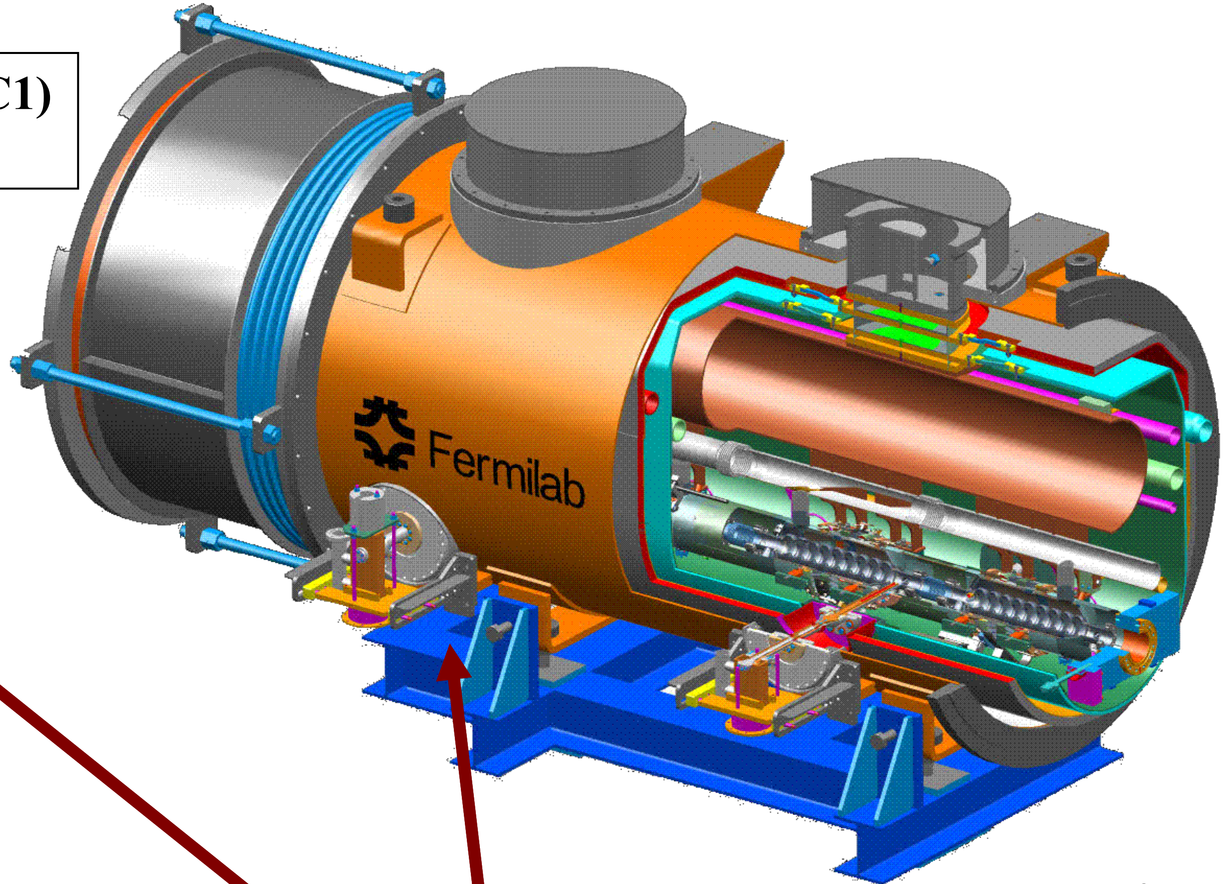
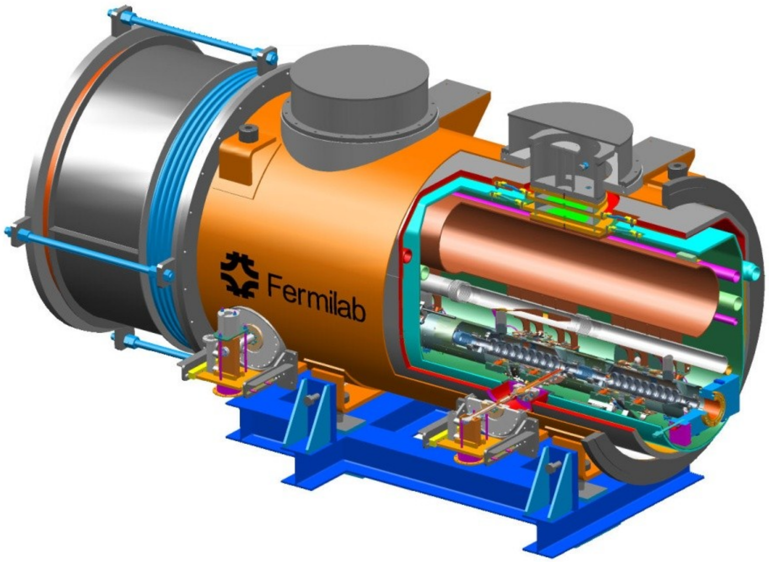


photo & drawing courtesy E. Vogel & FNAL

HOM Diagnostic in 3rd Harmonic Cavities at FLASH

- **Fermilab has constructed a third harmonic accelerating (3.9GHz) superconducting module and cryostat for a new generation high brightness photo-injector.**
- **This system compensates the nonlinear distortion of the longitudinal phase space due to the RF curvature of the 1.3 GHz TESLA cavities prior to bunch compression.**



- **The cryomodule, consisting of <u>four 3.9GHz cavities</u>, have been installed in the FLASH photoinjector downstream, of the first 1.3 GHz cryomodule (consisting of 8 cavities).**
- **Four 3.9 GHz cavities provide the energy modulation, ~20 MV, needed for compensation.**

Third Harmonic (3.9 GHz) Parameters

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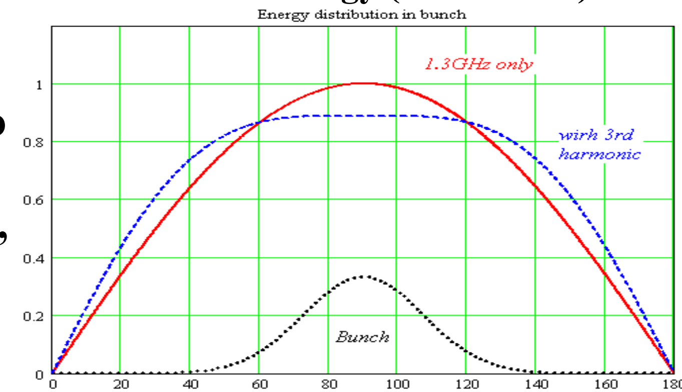
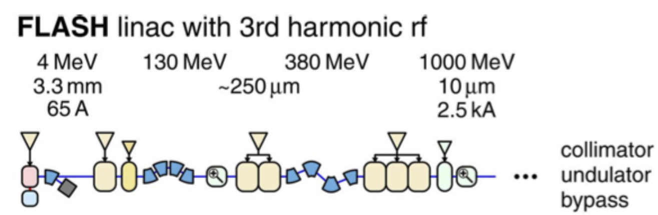
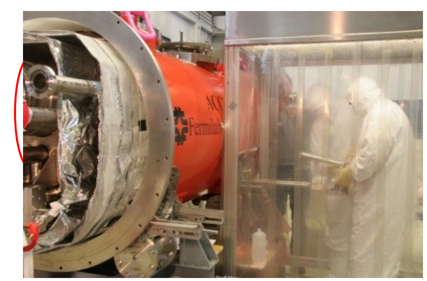
Number of Cavities	4
Active Length	0.346 meter
Gradient	14 MV/m
Phase	-179°
R/Q [=U²/(wW)]	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc} = 14 MV/m)	68 mT
Q_{ext}	1.3 X 10^6
BBU Limit for HOM, Q	<1 X 10^5
Total Energy	20 MeV
Beam Current	9 mA
Forward Power, per cavity	9 kW
Coupler Power, per coupler	45 kW

- Adding harmonic ensures the 2nd derivative at the max is zero for total field (could use any of the harmonics in the expansion, but using the lowest freq. ensures the transverse wakefields ~ ω^3 are minimised).
- The third harmonic system (3.9GHz) will compensate the nonlinear distortion of the longitudinal phase space due to cosine-like voltage curvature of 1.3 GHz cavities.
- It linearises the energy distribution upstream of the bunch compressor thus facilitating a small normalized emittance ~1.10⁻⁶ m*rad.

Illustrative energy (not to scale)



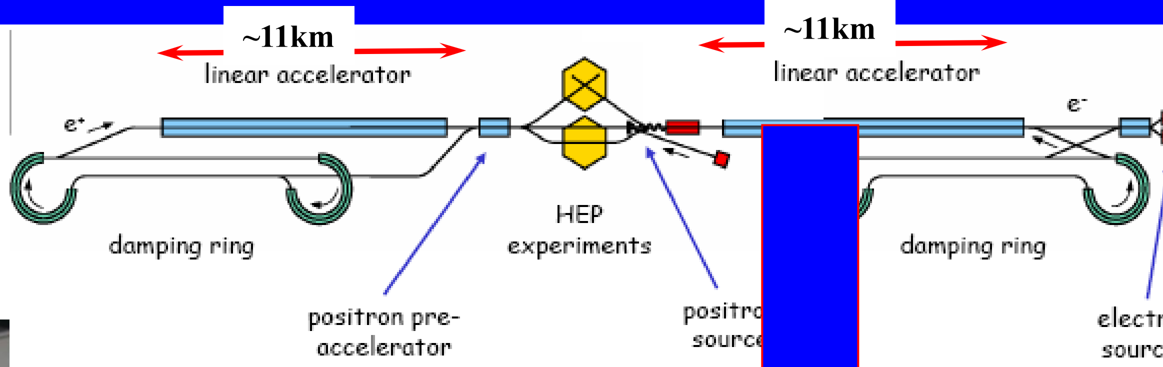


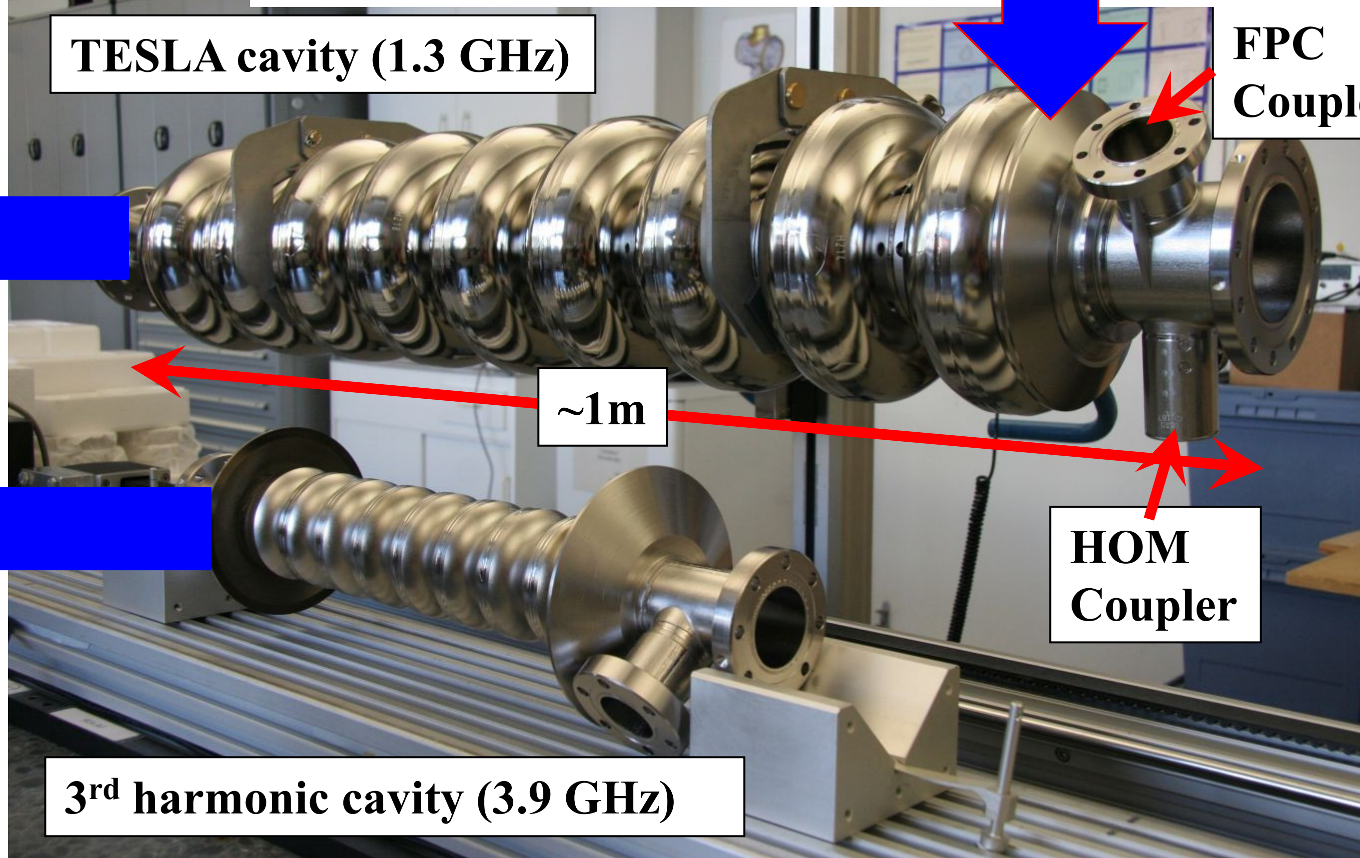


HOMs in SCRF Cavities

Schematic of International Linear Collider (ILC)

http://www.linearcollider.org





Used at XFEL and FLASH. Baseline design for main accelerators in ILC.

Used at XFEL and FLASH in order to flatten the field profile and reduce energy spread.

Minimising Emittance Dilution and HOMBPMs

- **Source of Emittance Dilution**

—**W_t, transverse wakefields ($W_t \sim a^3$ –*a* iris aperture)**

—**Much stronger in 3.9 GHz than in 1.3 GHz cavities (each iris is r ~ 15 mm compared to 35 mm for TESLA).**

- **Utilise Wakefields as Diagnostic**

—**Sample HOMs to ascertain beam position (HOMBPM).**

—**Move beam to minimise impact on itself and to align to electrical axis.**

  – **Can also be used for measuring beam charge, phase etc.**

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HOMs in SCRF Cavities

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- **Higher order modes (HOMs) are excited by charge particles in cavity**

  - influence the beam both longitudinally and transversely

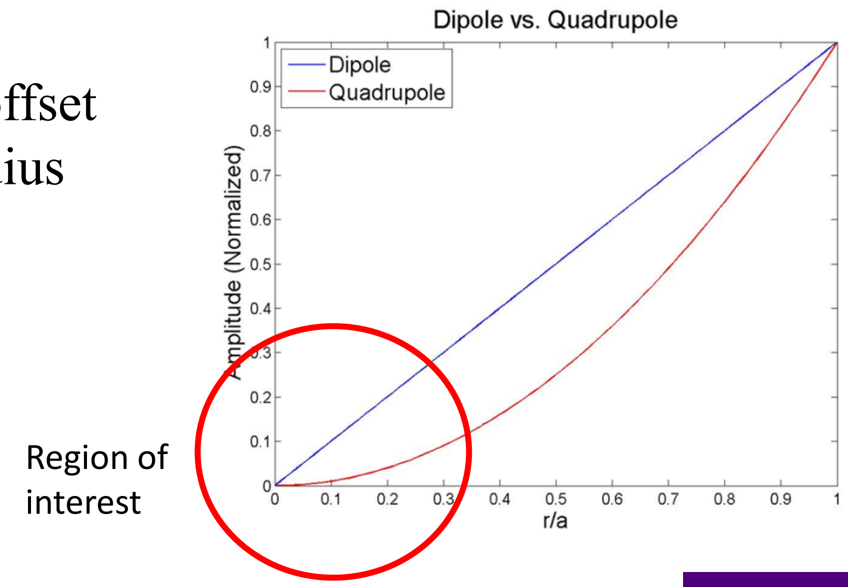
  - non-monopole modes excited by off-axis particles effect bunch itself (intra) and subsequent (inter) bunches

- **Dipole modes dominate transverse wake potentials**

$$(Amplitude)_m \sim W_{\perp}^{m} \sim \left(\frac{r}{a}\right)^m$$

r: beam offset
a: iris radius

m=1, dipole; *m*=2, quadrupole



- **Use HOMs (non-monopole modes) to**

  - align the beam to the electric center

  - monitor beam position (HOM-BPM)

Earlier work on 1.3 GHz demonstrated the principle

[1] G. Devanz et al., EPAC2002, WEAGB003
[2] N. Baboi et al., LINAC2004, MOP3

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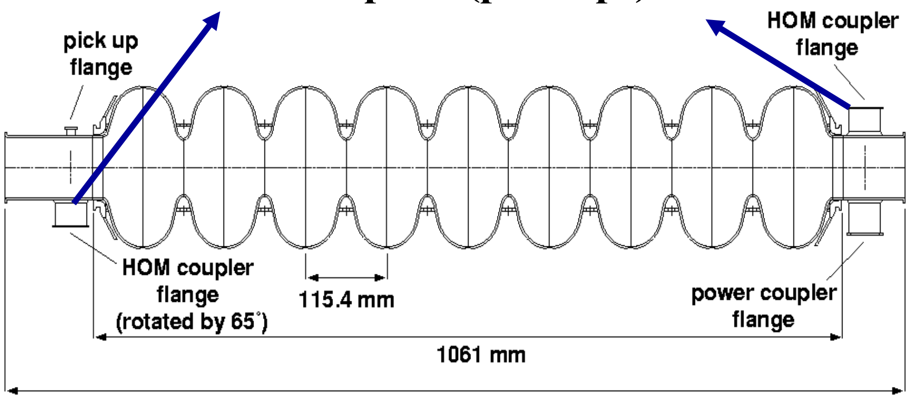
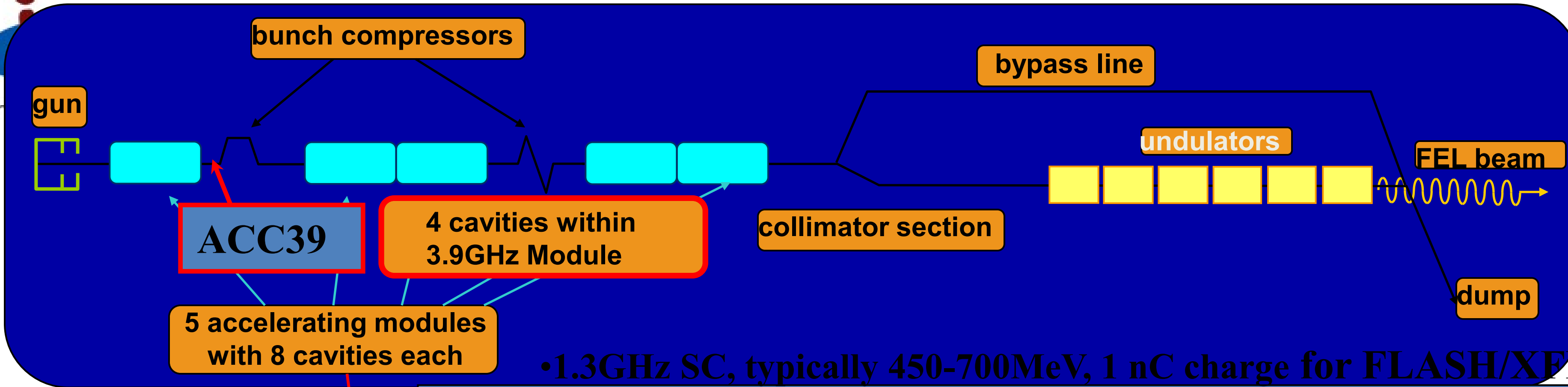
HOMs in SCRF Cavities

- **Task:**
  - Develop, build, test electronics for 3.9 GHz cavities
  - Interpret signals and integrate in control system
  - Measure cavity alignment
- **HOM-couplers**
  - At end of each cavity
  - Enable monitoring the HOMs excited by beam

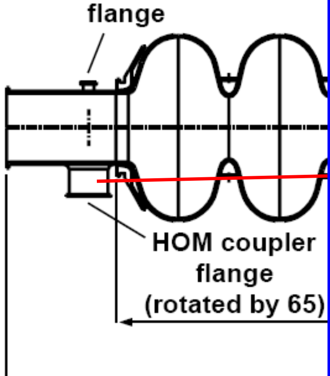
HOM-couplers (pick-ups)



TESLA cavity Illustrated
(similar features present in 3.9 GHz cavity)

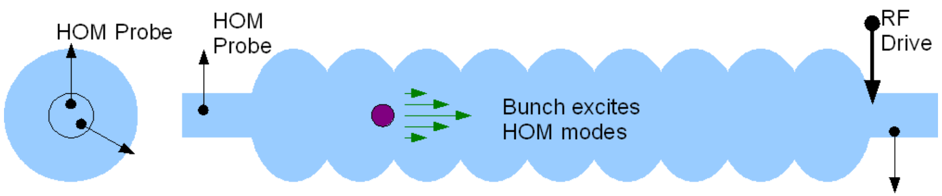


- 1.3GHz SC, typically 450-700MeV, 1 nC charge for FLASH/XFEL
- HOMs generated in accelerating cavities must be damped.
- Monitored HOMs facilitate beam/cavity info
- Forty cavities exist at FLASH.
  - -Couplers/cables already exist.
  - -Electronics enable monitoring of HOMs (wideband and narrowband response).

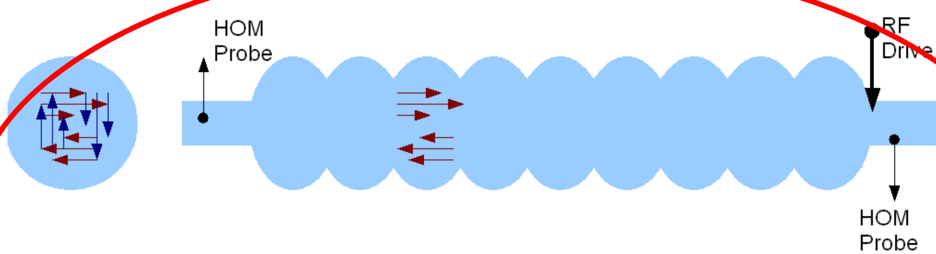


Based on 1.3 GHz (CEA/SLAC/FNAL/DESY) Diagnostics –redesigned for ACC39 as part of EuCARD

Response of HOM Modes to Beam

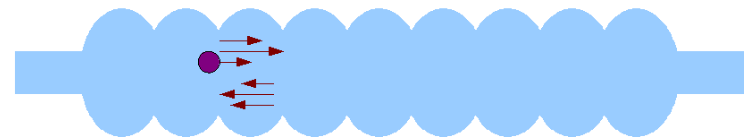


Monopole mode: Amplitude first order independent of beam position
Phase of mode determined by bunch arrival time

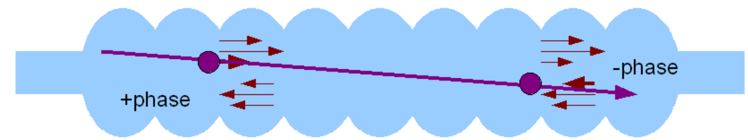


Dipole Modes: Each mode has 2 polarizations
Frequencies degenerate for ideal cavities
Frequency degeneracy broken by power coupler and fabrication errors

If frequency splitting is < line width, Need both couplers to separate polarizations



Dipole mode: Amplitude proportional to bunch transverse position
Phase determined by bunch arrival time for position offset

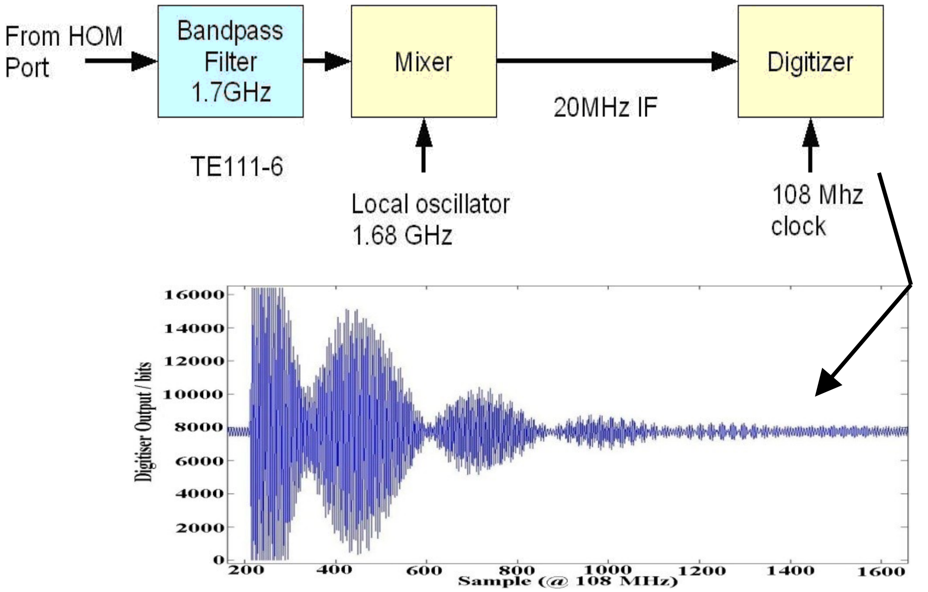


Beam at an angle will excite dipole mode with 90 degree phase shift relative to signal from position offset
Amplitude proportional to angle X effective mode length (~ 1 Meter)

Tilted bunch will also excite signal at 90 degrees, amplitude proportional to bunch length and tilt: Not significant for short TTF bunches

Extant Work at 1.3 GHz: HOM-BPMs in TESLA Cavities

- HOM-BPMs at 1.3GHz cavities
  - Use dipole mode at 1.7 GHz
  - Installed in 5 accelerating modules (40 cavities)
  - Calibration: with SVD technique
    - problem: unstable in time
- Beam Alignment in Modules
  - Now routinely used in FLASH
- Other studies
  - Cavity alignment in cryo-module
  - Beam phase measurement with monopole modes at ~2.4GHz
- XFEL Plans:
  - Install in some 1.3 GHz and in <u>all 3.9 GHz cavities</u>



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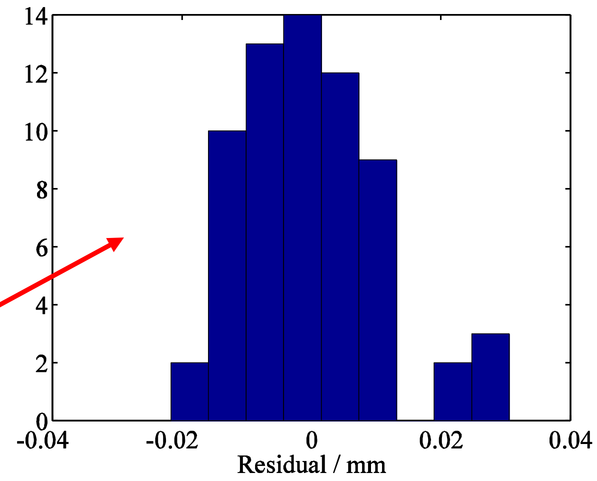
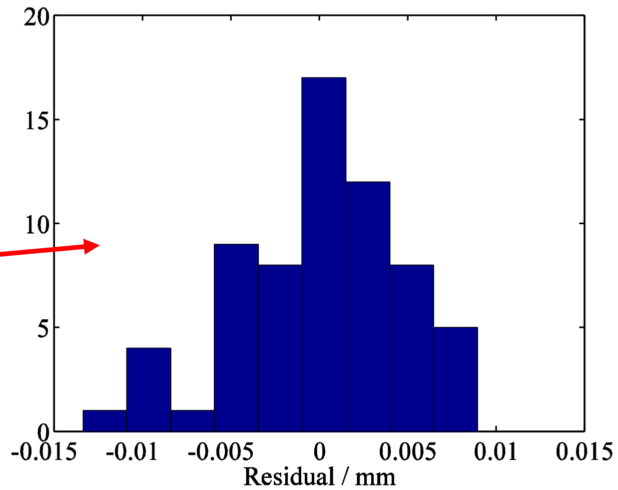
Analysis of Narrowband Signals – Beam Position (Previous 1.3 GHz Study)

- Resolution of position measurement.
  - Predict the position at cavity 5 from the measurements at cavities 4 and 6.
  - Compare with the measured value.
- X resolution
  - ~9 µm
- Y resolution
  - ~4 µm





FLASH and ACC39

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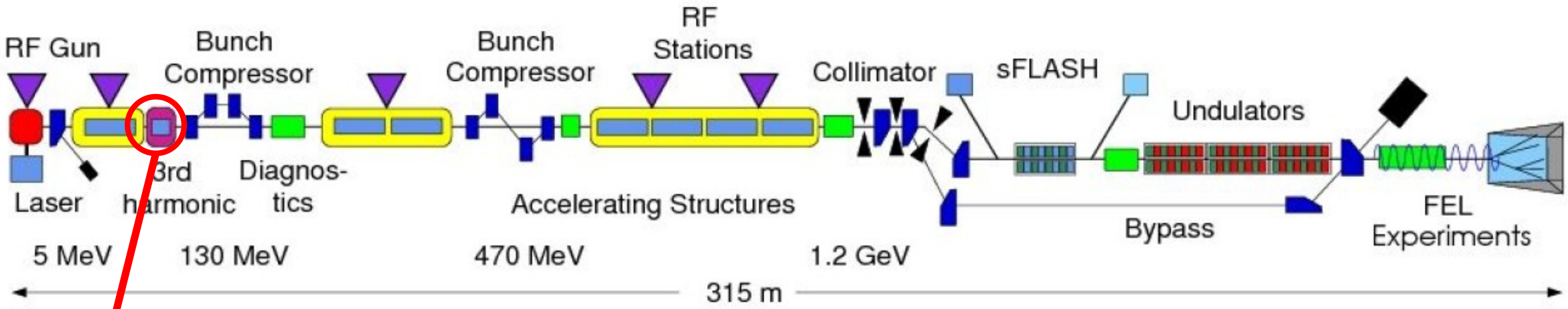
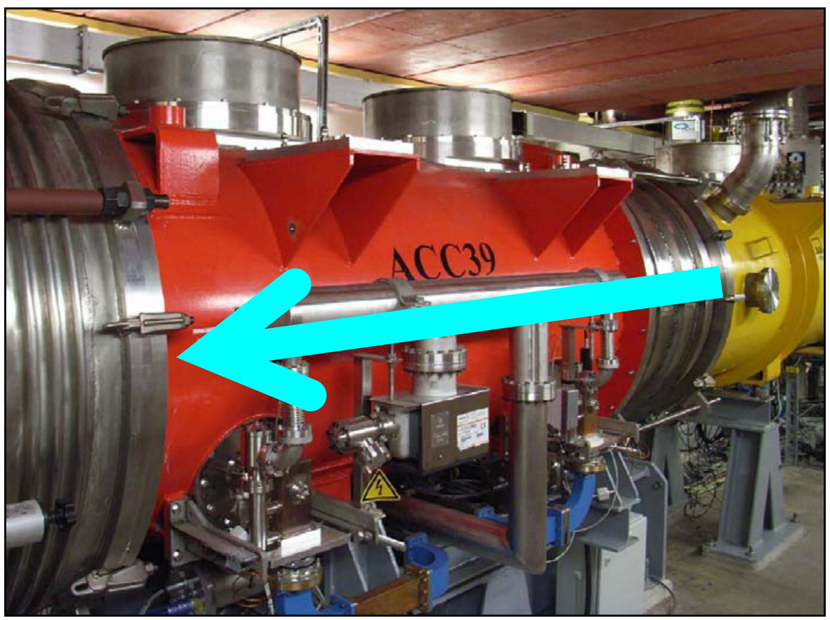
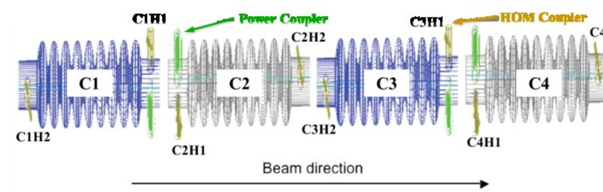
Free-electron LASer in Hamburg (FLASH)







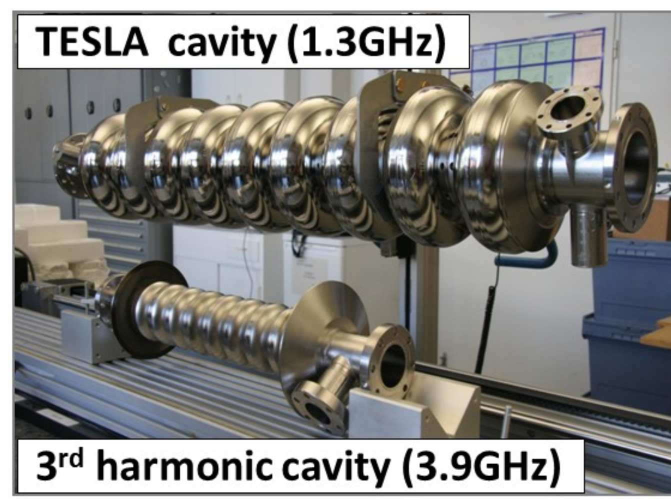


Photo courtesy E. Vogel & DESY

Selected Highlights

- ➢S-matrix measurements and comparison with simulations.
  - Transmission measurements.
  - Multi-cavity modes.

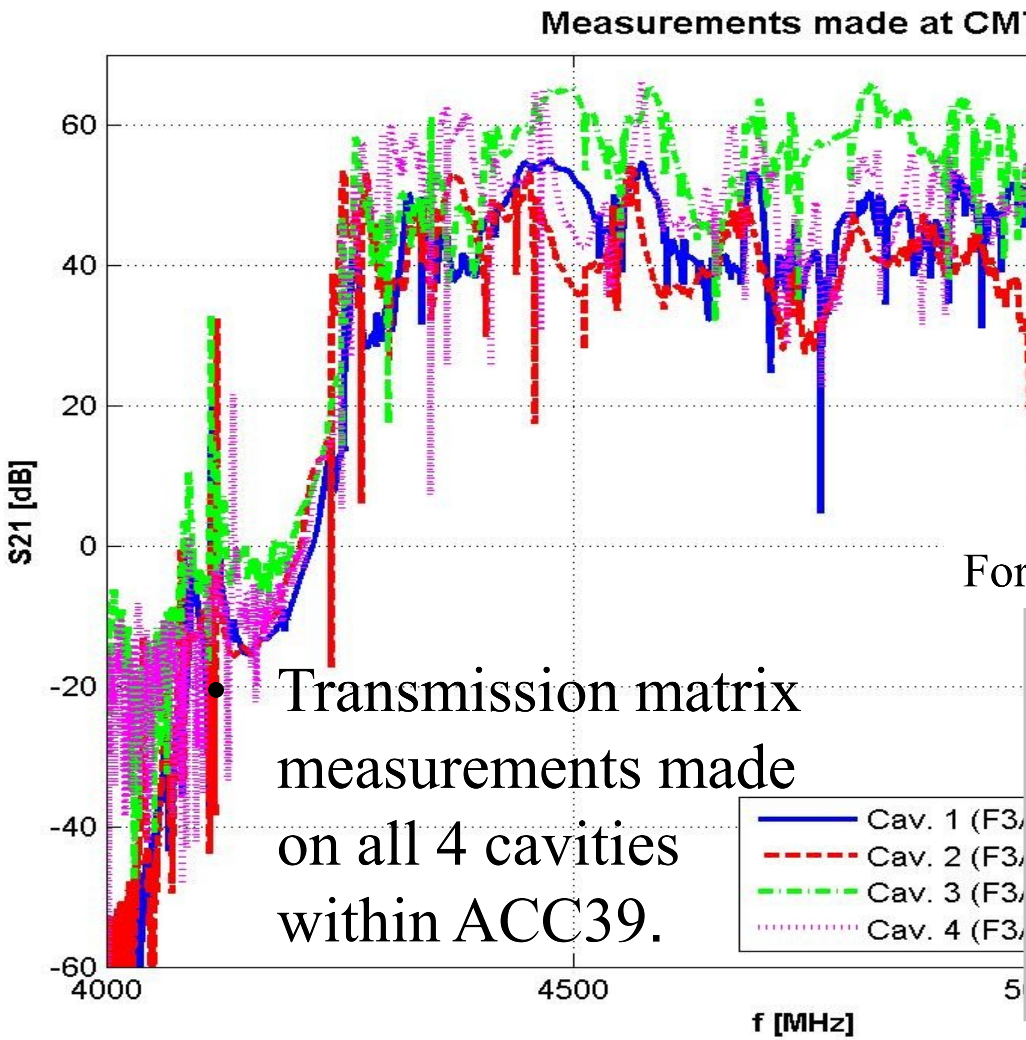
- ➢Beam-based mode characterisation.
  - HOM pickup vs beam offset for trapped/isolated modes

- ➢ Comparison of analysis of data
  - Direct Linear Regression (DLR) vs Singular Value Decomposition (SVD)

Measurement Programme (since last SRF WP10 review meeting)

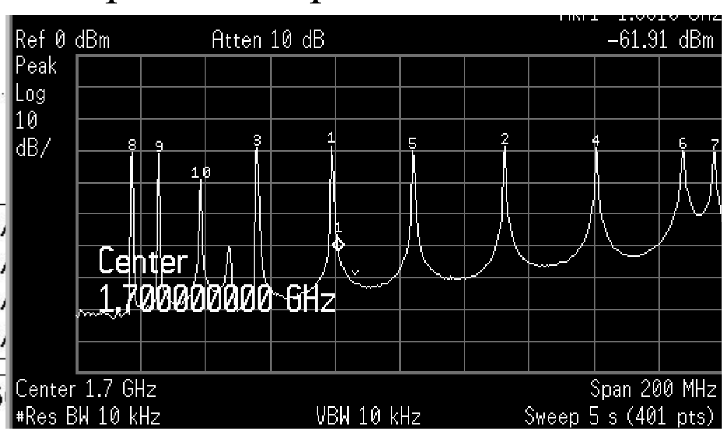
Data	Measurement info	Beam info
Apr. 2010	Transmission measurement	w/o beam
Jul. 2010	1st parasitic measurement	w/ beam
Nov. 2010	2nd parasitic measurement	w/ beam
Jan. 2011	1st dedicated measurement	w/ beam
Feb. 2011	Multi-bunch measurement	w/ beam
Mar. 2011	2nd dedicated measurement	w/ beam
Apr. 2011	Transmission measurement	w/o beam
May 2011	Mini measurement	w/ beam

ACC39 Spectra Measured in CMTB: Focused on Dipole and Other Bands

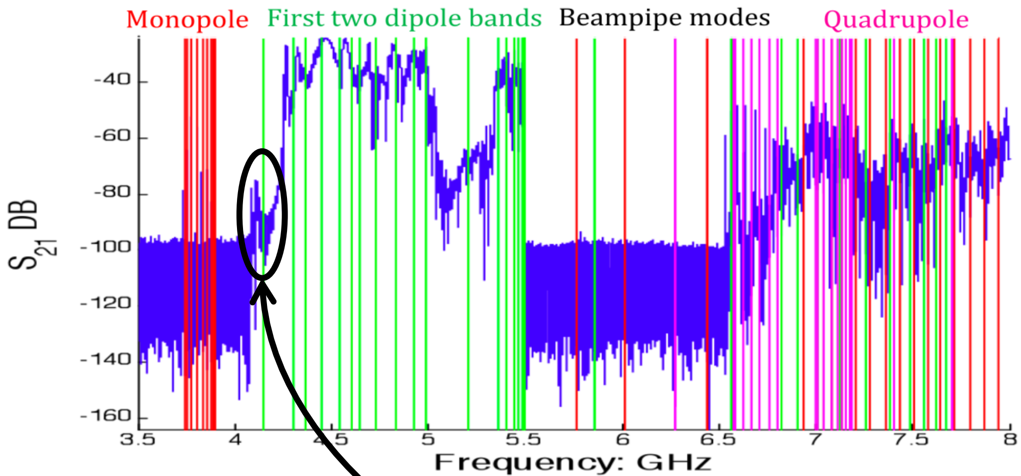


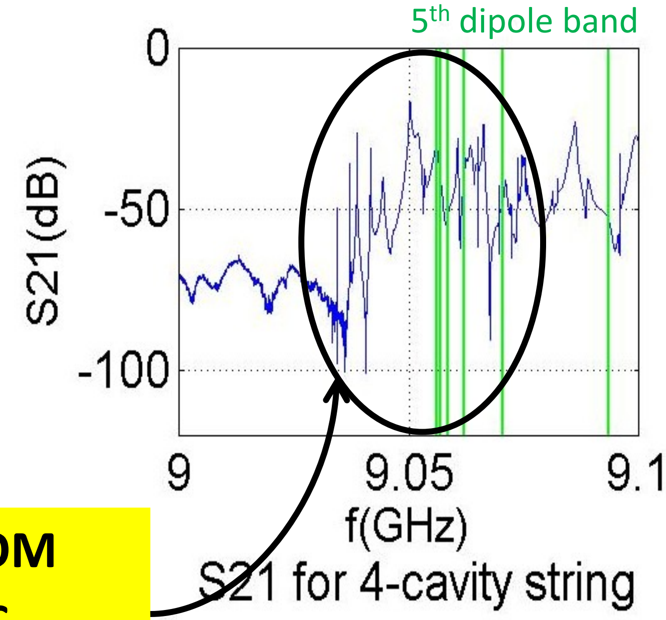
- Transmission matrix measurements made on all 4 cavities within ACC39.

For comparison: dipole band in TESLA cav

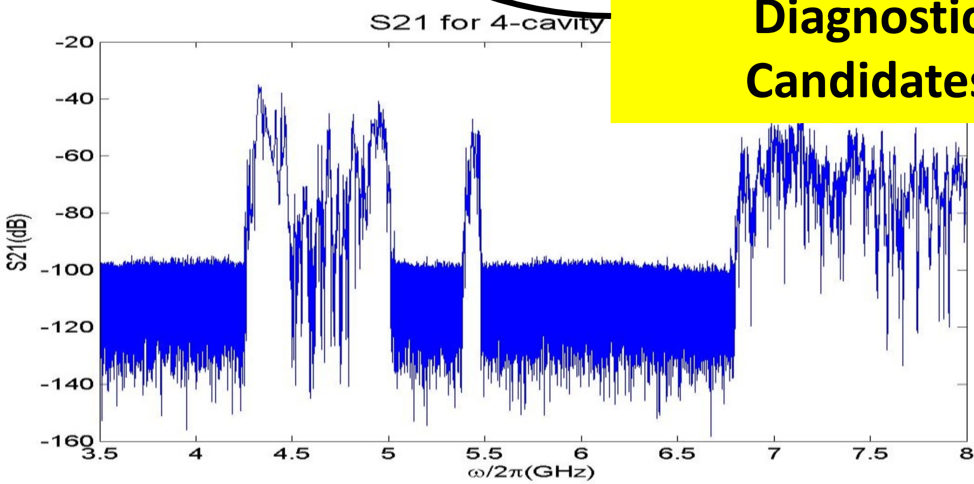


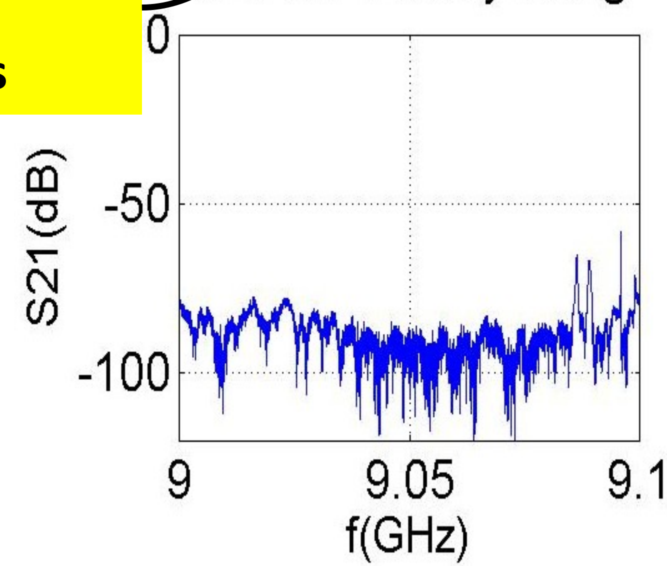
Band Structure





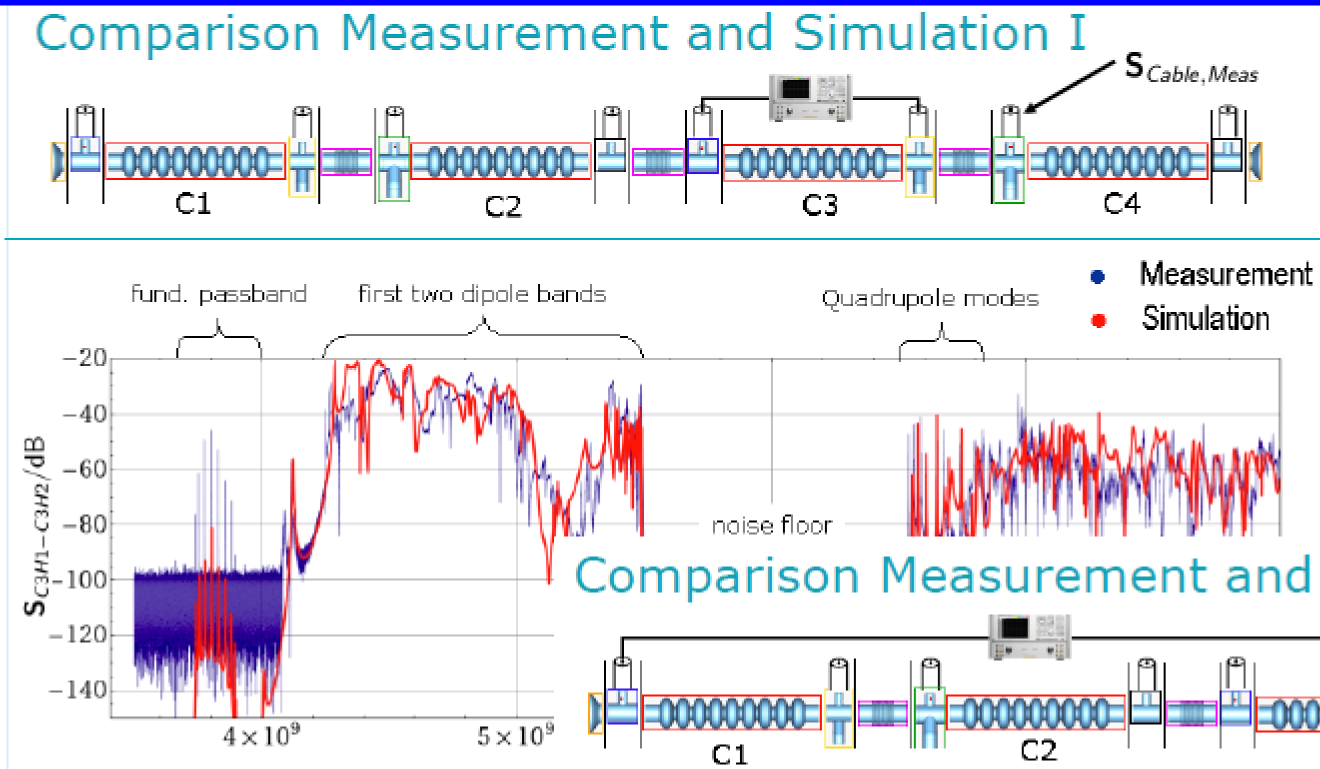
Potential HOM Diagnostic Candidates



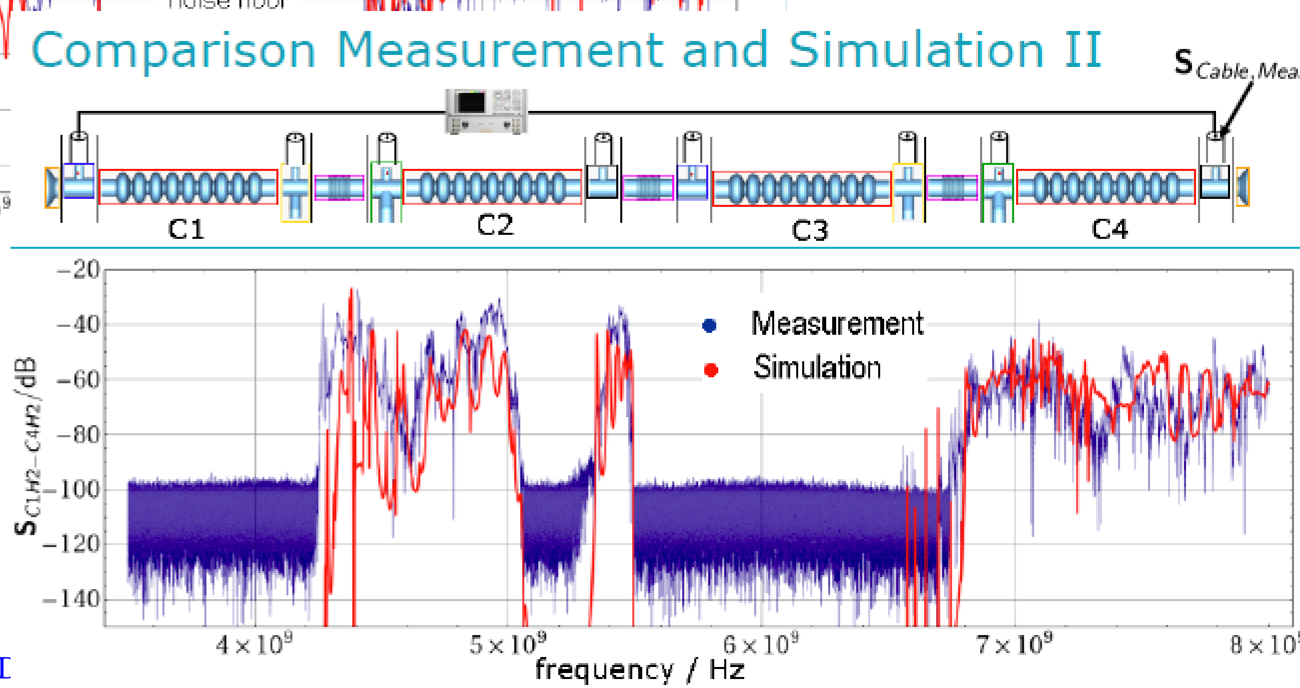


From transmission measurement done in CMTB

S_{21} Exp vs Simulations

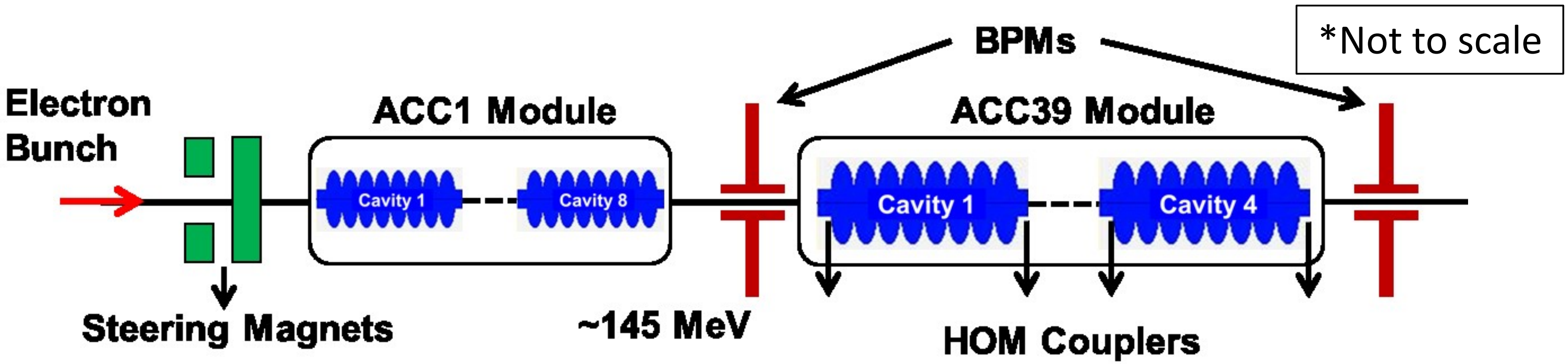


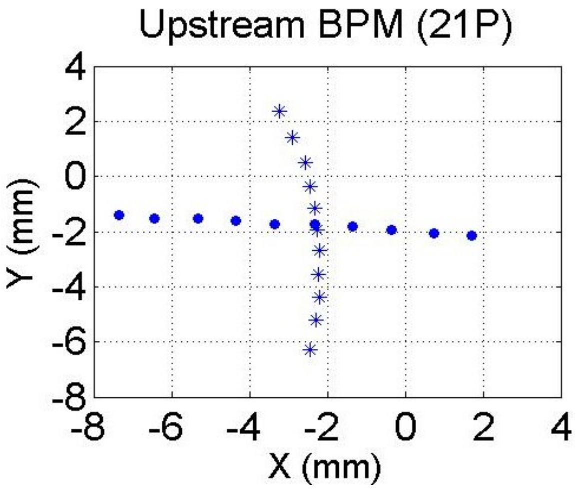
- Transmission through single cavity in chain.

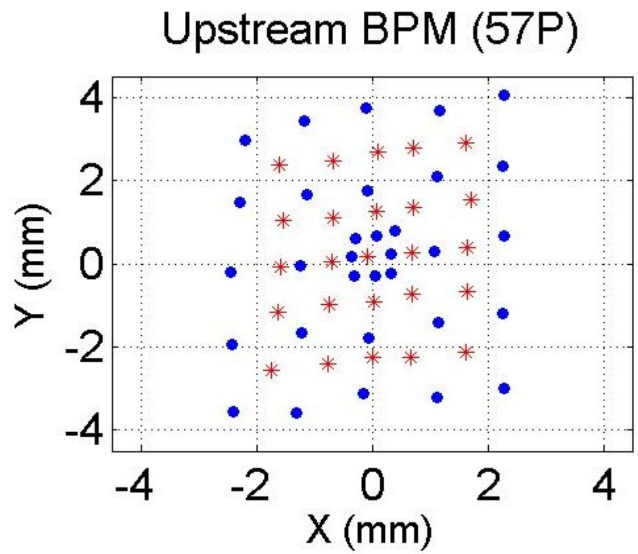


- Transmission through complete chain.

Beam-Based HOM Measurements







Steer the beam in various ways

HOM Signal (1st Two Dipole Bands)

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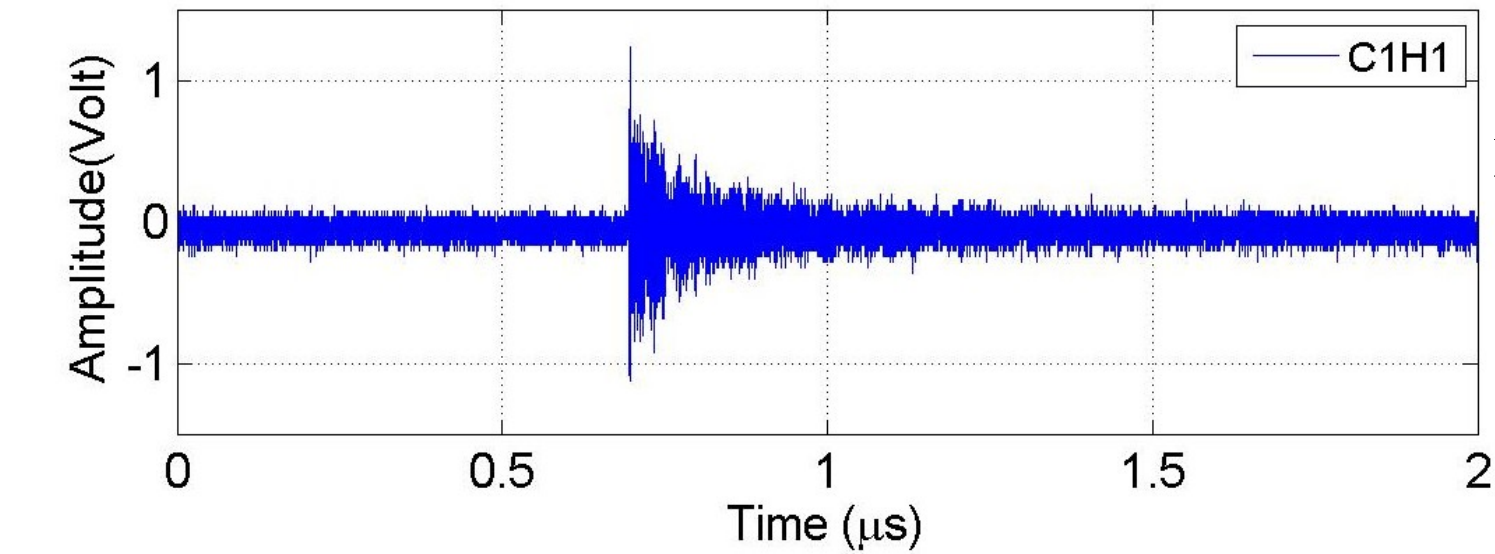
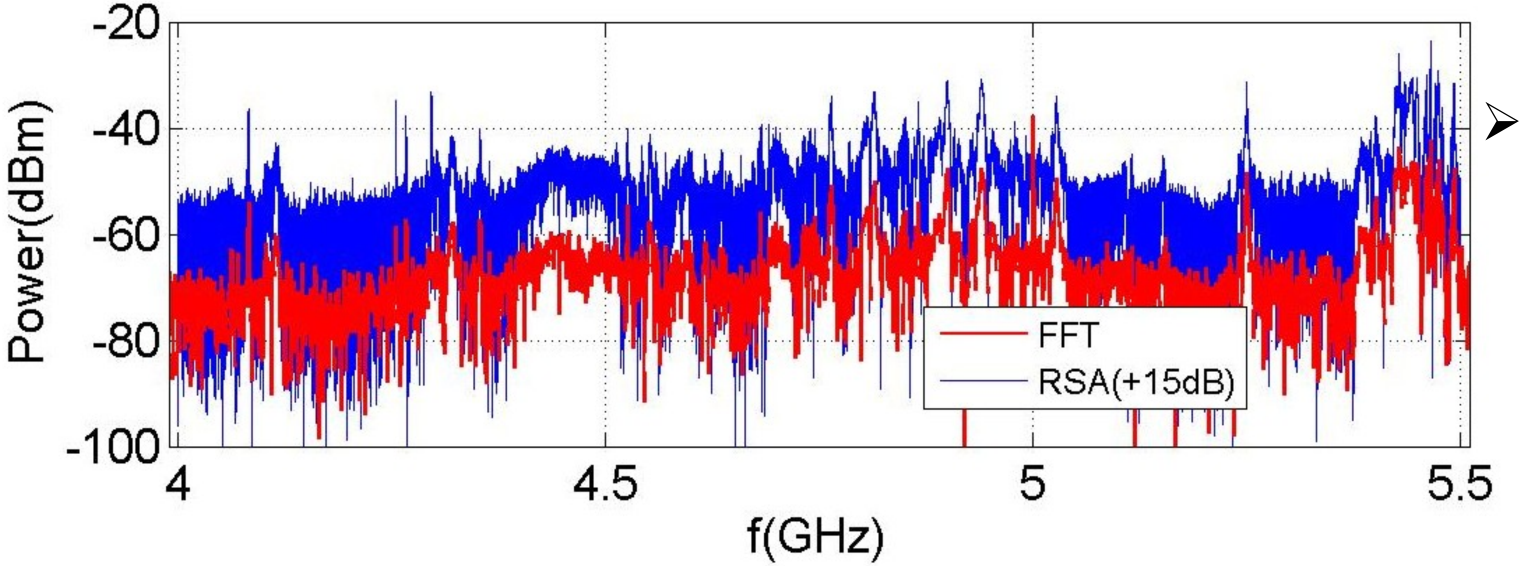


- Time Domain HOM pickup



- Comparison of FFT of HOM pickup vs RSA

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1st Dipole Beampipe Modes

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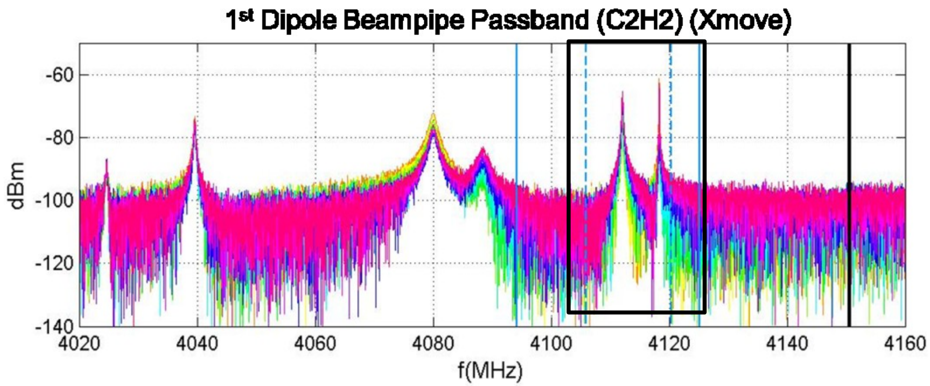
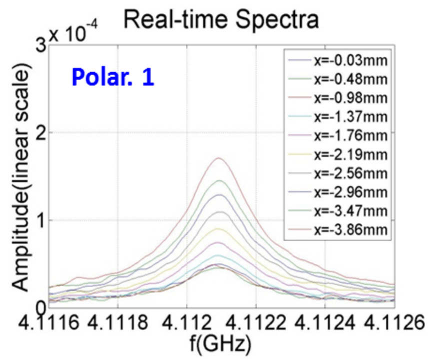
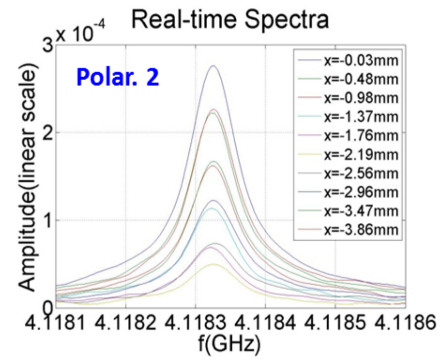
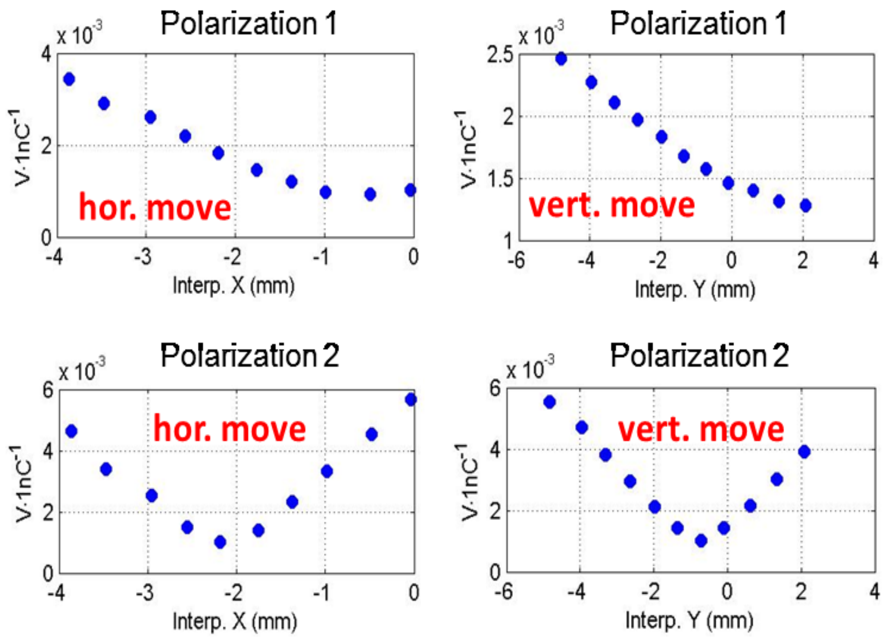


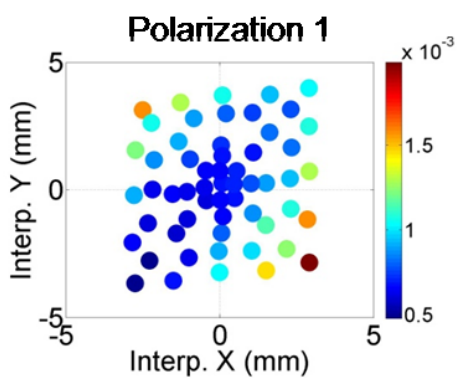


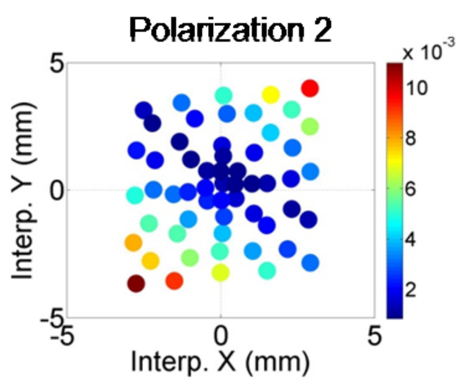


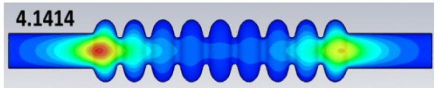
- Lorentzian fit to get mode amplitude

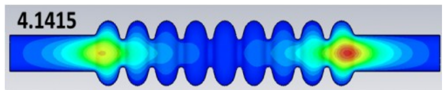
$$y = y_0 + A \cdot \frac{w^2}{(x - x_0)^2 + w^2}$$











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5th Dipole Cavity Band

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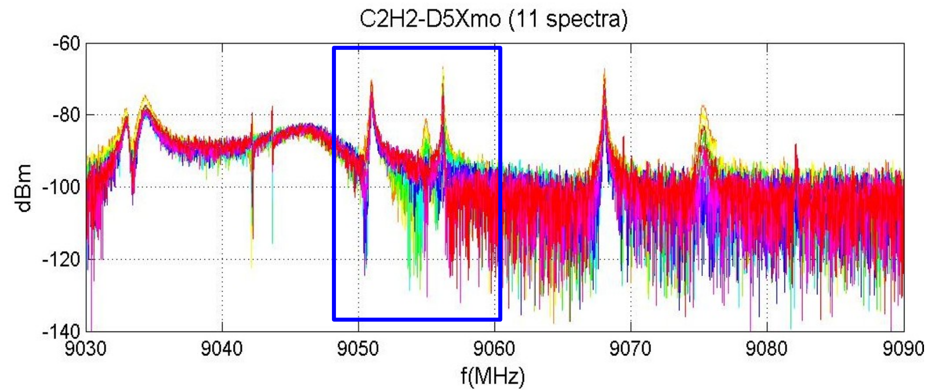
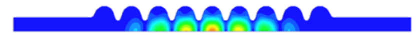
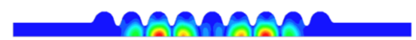
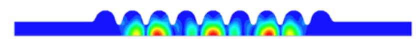
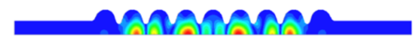
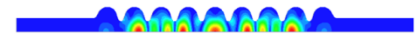
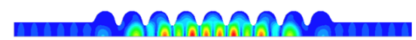
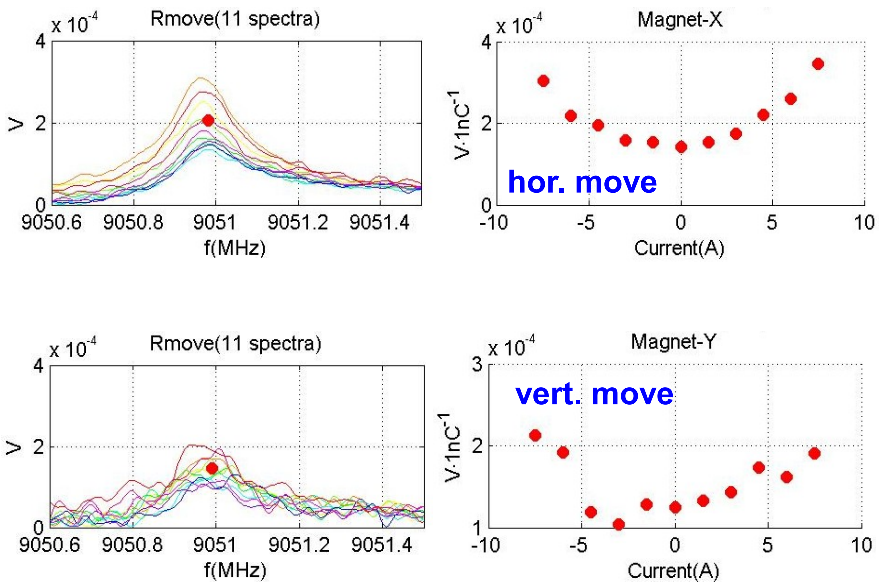
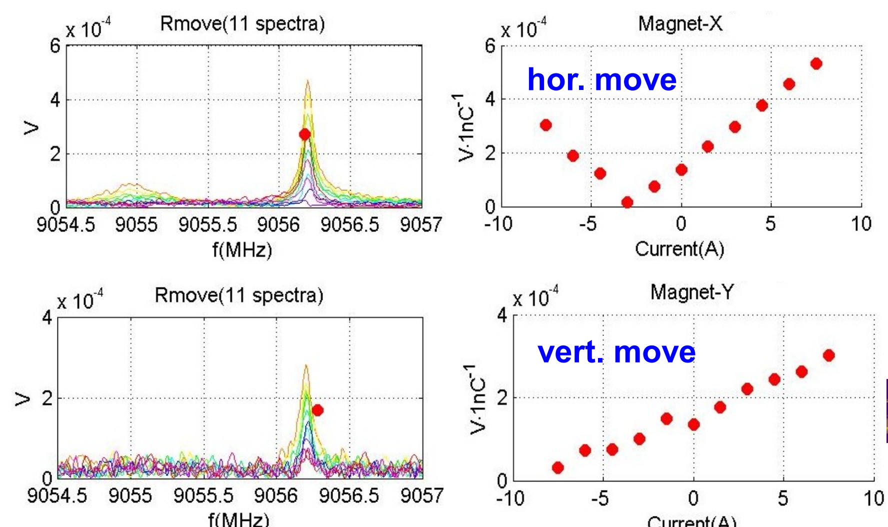


5th Dipole Band†	*f* (GHz)	R/Q
	9.0560	0.00
	9.0568	0.05
	9.0585	0.07
	9.0620	2.17
	9.0703	4.04
	9.0933	0.55

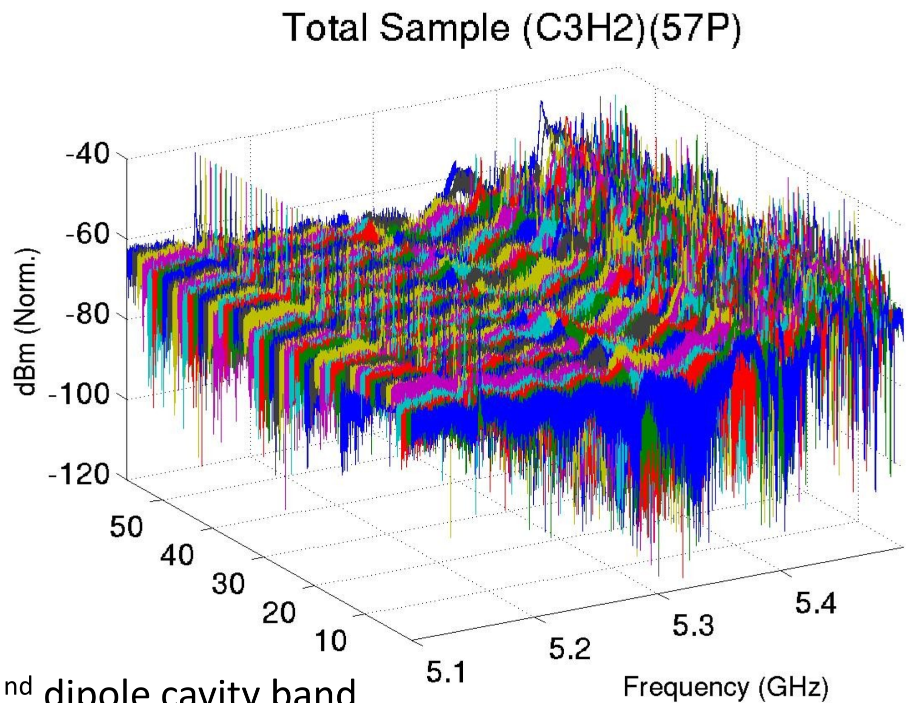
localized!



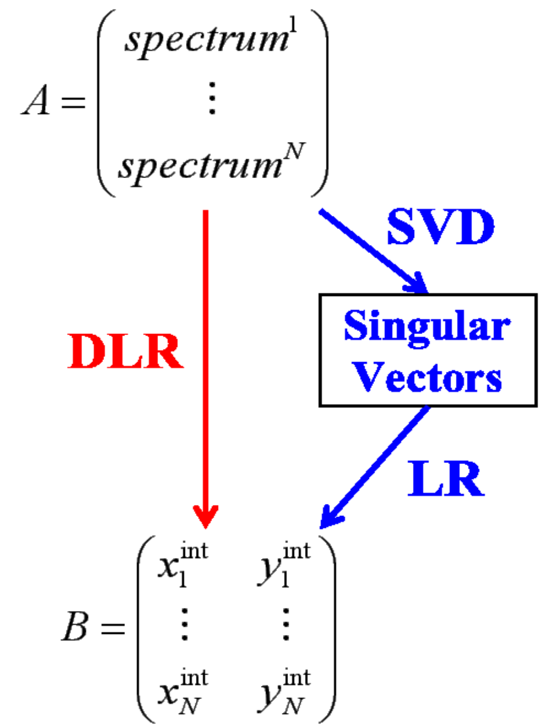


† I.R.R. Shinton, et al., "Mode Distribution …", CI Internal Note

Comparison of DLR vs SVD



2nd dipole cavity band



- **Direct Linear Regression (DLR)**

$$A \cdot M + B_0 = B$$

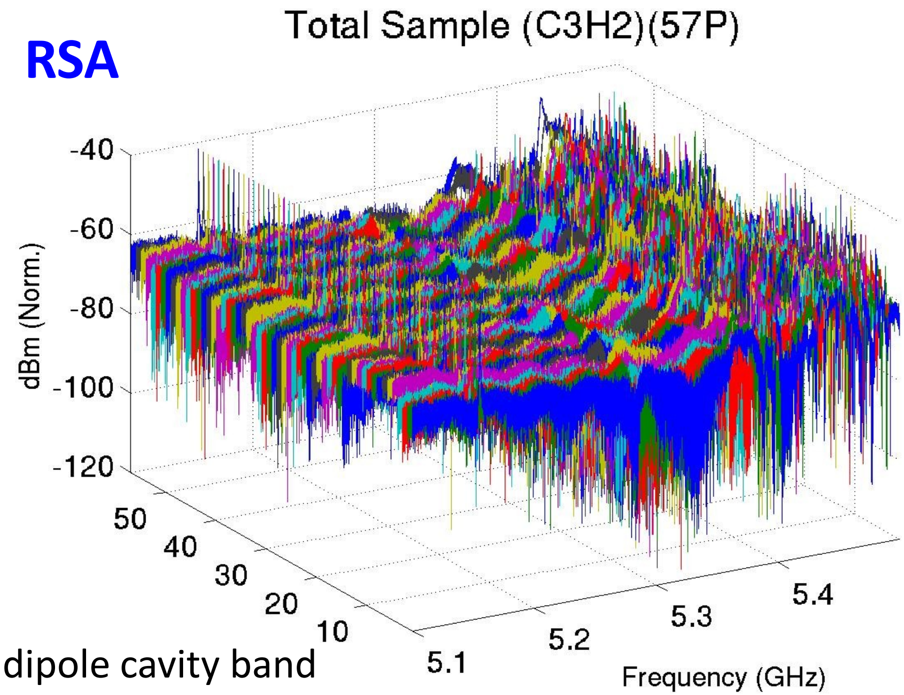
- **Singular Value Decomposition (SVD)**

$$A = U \cdot S \cdot V^T \longrightarrow A_S$$

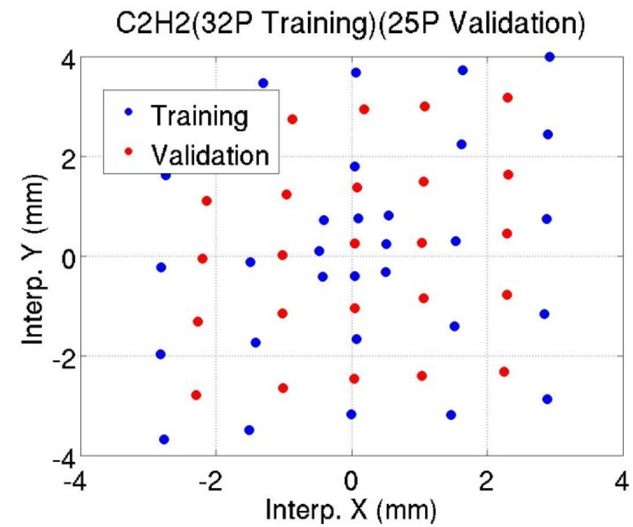
$$A_S \cdot M_S + B_{0S} = B$$

Direct Linear Regression

RSA



2nd dipole cavity band

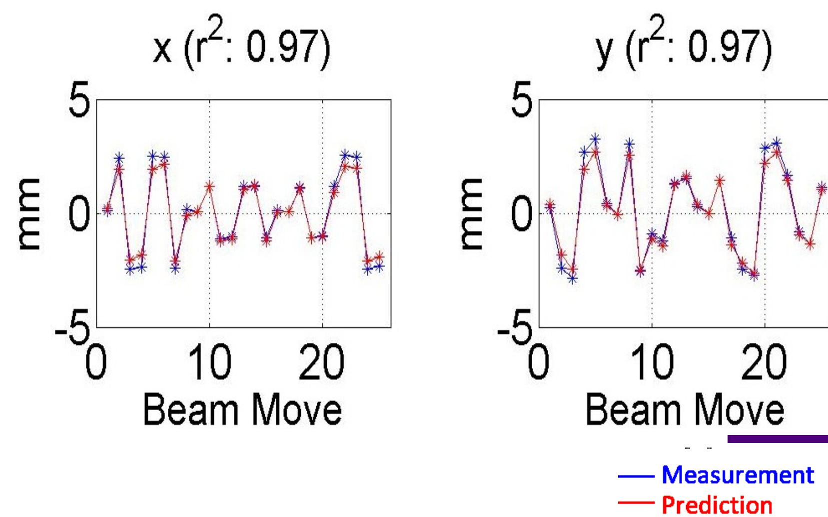


- **Direct Linear Regression (DLR)**

$$A \cdot M + B_0 = B$$

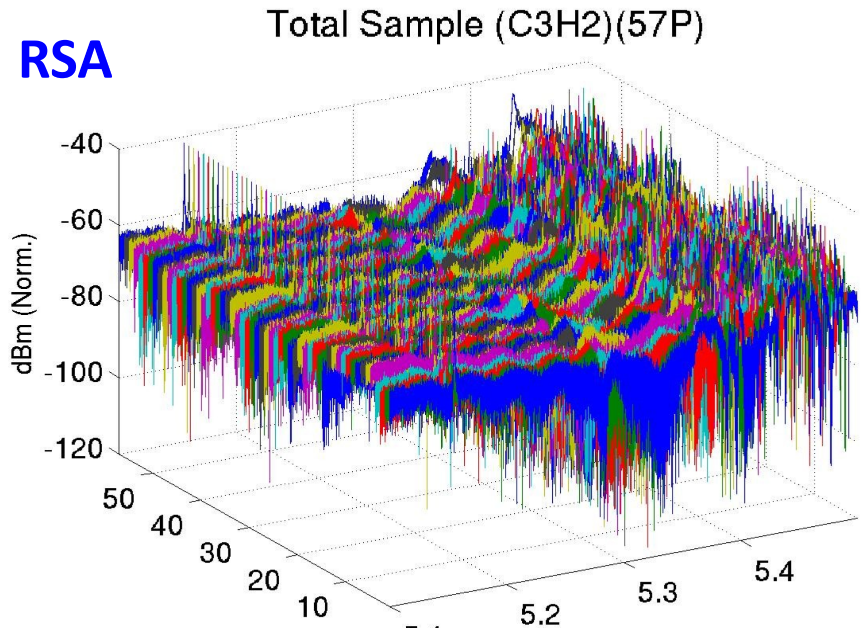
A: spectra matrix

B: beam position matrix

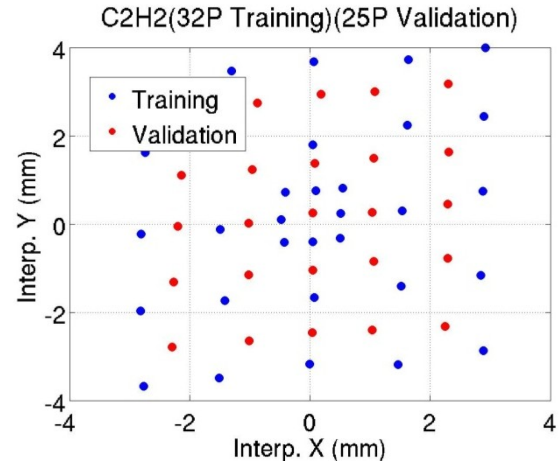


Singular Value Decompostion

RSA



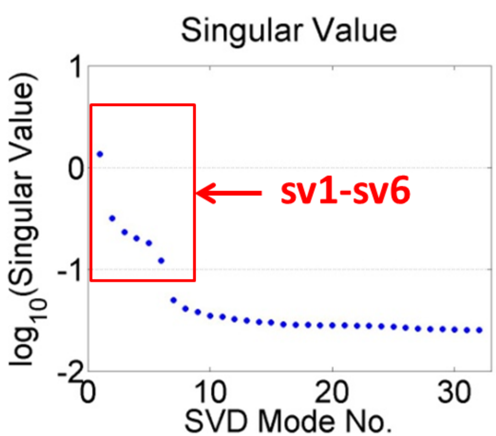
2^{nd} dipole cavity band

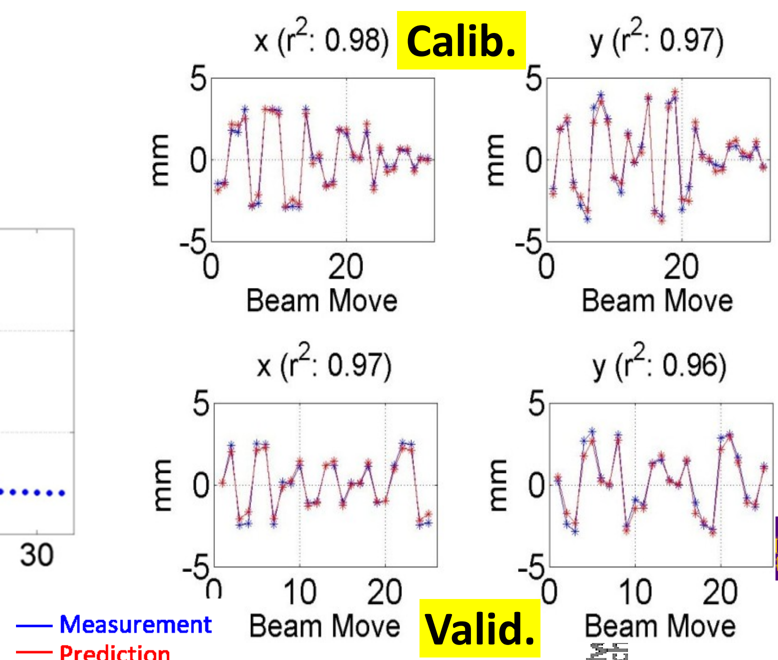


- **Two steps**

$$A = U \cdot S \cdot V^{T} \longrightarrow A_S$$

$$A_S \cdot M_S + B_{0S} = B$$





Concluding Remarks on HOM Third Harmonic Cavities

- **ACC39, has been received by DESY, characterised at the CMTF, and subsequently installed at FLASH.**

- **Beam tubes connecting cavities are above cut-off and allows for strong coupling between all 4 cavities –suite of simulations being used to characterise the coupling and sensitivity to geometrical perturbations.**

- **Experiments indicate trapped modes in 5th band (~ 9GHz) and expected linear dependence. Mode candidate for diagnostics? First systematic comparison of DLR vs SVD indicates consistent behaviour. (other candidates are based on modes which exist in the beampipe and stretch over the complete module)**

- **HOM electronics will be tested for 3.9 GHZ cavities in 2012.**

- **Good overall progress**

- **We welcome participation from other interested parties in this project –lots of problems to work on!**

Acknowledgements

➢I wish to express thanks for the organising committee for giving me this opportunity to report on the work of this task.

➢I acknowledge materials supplied, and/or many useful discussions with: N. Baboi, E. Vogel (DESY), P. Zhang (University of Manchester/Cockcroft Inst./DESY) , I.R.R. Shinton (University of Manchester/Cockcroft Inst.), U. Van Rienen, H.-W. Glock, T. Flisgen (University of Rostock), S. Molloy (RHUL/ESS), N. Eddy, T.N. Khabiboulline (FNAL).

Publications

1. *Higher Order Modes In Third Harmonic Cavities at FLASH*, I.R.R. Shinton, N. Baboi, T. Flisgen, H.W. Glock, R.M. Jones, U van Rienen, P. Zhang, Proc. Of Linac 2010
2. *First Beam Spectra of SC Third Harmonic Cavity at FLASH,* P. Zhang, N. Baboi, T. Flisgen, H.W. Glock, R.M. Jones, B. Lorbeer, U van Rienen, I.R.R. Shinton, Proc. Of Linac 2010.
3. *SCRF Third Harmonic Cavity HOM Diagnostics and the Quest for High Gradient Cavities for XFEL and ILC,* By MEW Collaboration (R.M. Jones for the collaboration). 2010. 4pp. Published in ICFA Beam Dyn.Newslett.51:182-185,2010
4. *Higher Order Modes in Third Harmonic Cavities for XFEL/FLASH,* I.R.R. Shinton, N. Baboi, N. Eddy, T. Flisgen, H.W. Glock, R.M. Jones, N. Juntong, T.N. Khabiboulline, U van Rienen, P. Zhang, FERMILAB-CONF-10-302-TD.
5. *Third Harmonic Cavity Modal Analysis*, B. Szczesny, I.R.R. Shinton, R.M. Jones, Proc. Of SRF 2009.

Thank you for your attention!