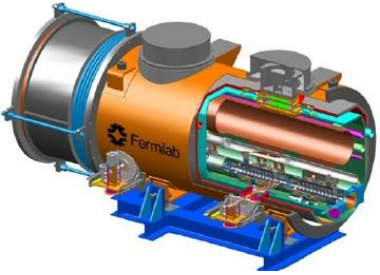
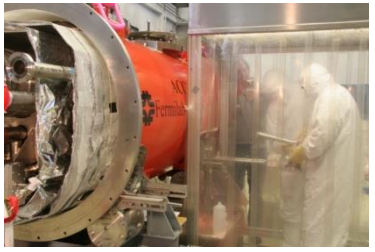
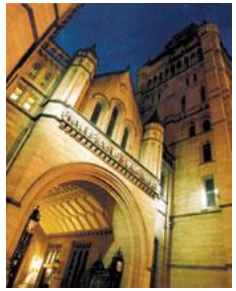
SRF HOM Diagnostics for the European XFEL





Nicoleta Baboi, Ursula van Rienen
Roger M. Jones
DESY, Univ. of Rostock, Univ. of Manchester/ Cockcroft Inst.



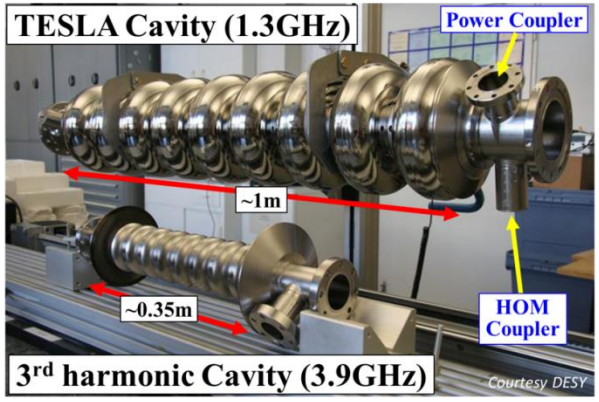
https://indico.cern.ch/event/353446/

WP 12.4 SRF HOM Diagnostics for for European XFEL

TASK 12.4	HOM Distribution	R.M. Jones
Sub-Task	**Name**	**Coordinating Institute/Univ.**
12.4.1	HOMBPM	DESY
12.4.2	HOMCD	Cockcroft/Univ. Manchester
12.4.3	HOMGD	Univ. Rostock

❑ Overall Aim

- ✓ Beam phase (w.r.t. R.F.) and position within both 3.9 GHz and 1.3 GHz cavities
- ✓ Potentially provides remote structure alignment
- ✓ Transverse wakes are an issue! ($\sim \omega^3$)



- ➢Four-year task due to staff resources commuted to Three years
- ➢P. Jain, PDRA (now at Roorkee, IIT)

Task 12.4 HOM Diagnostics in SC Accelerator Cavities -Staff

- Sub-task leaders: Nicoleta Baboi (DESY), Ursula van Rienen (Univ. Rostock), Roger M. Jones (CI/Univ. Manchester).

- P.D.R.A.: Puneet Jain, N. Joshi (CI/Univ. of Manchester)
- Ph.D.s: Liangliang Shi (DESY/Univ. of Manchester), Thomas Flisgen (Univ. of Rostock)

WP 12.4.1

N. Baboi, DESY

L. Shi , Univ. of Manchester/DESY

WP 12.4.2

P. Jain, CI/Univ. of Manchester

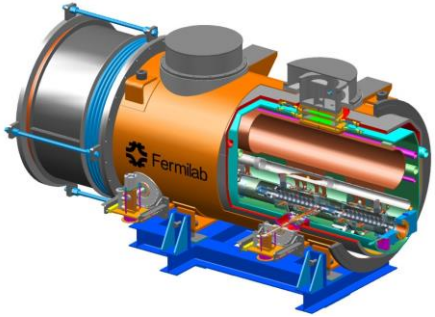
N. Joshi, CI/Univ. of Manchester

WP 12.4.3

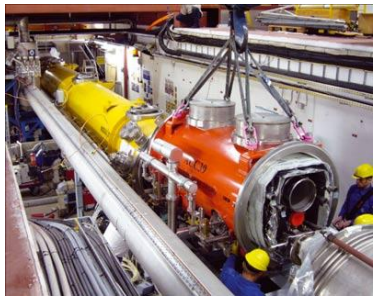
T. Flisgen, Univ. of Rostock

U. Van Rienen, Univ. of Rostock

12.4 FLASH Third Harmonic Cavities



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



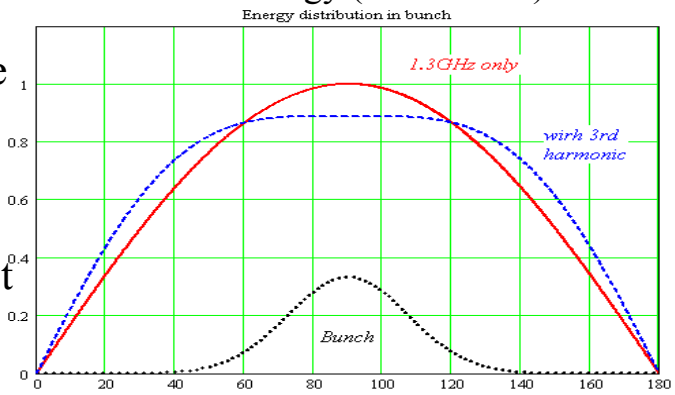
- The cryomodule, consisting of four 3.9GHz cavities, has been installed in the FLASH photoinjector downstream, of the first 1.3 GHz cryomodule (consisting of 8 cavities).
- Four 3.9 GHz cavities provide the energy modulation, ~20 MV, needed for compensation.
- Eight cavities are required per module for XFEL

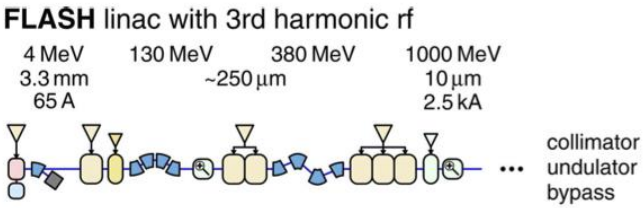
WP 12.4 FLASH 3.9 GHz Parameters

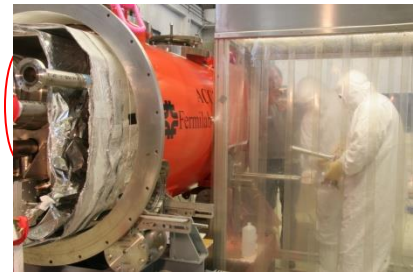
Number of Cavities	**4**
Active Length	**0.346 meter**
Gradient	**14 MV/m**
Phase	**-179°**
R/Q [=U^2/(wW)]	**750 Ω**
E_{peak}/E_{acc}	**2.26**
B_{peak} (E_{acc} = 14 MV/m)	**68 mT**
Q_{ext}	**1.3 X 10^6**
BBU Limit for HOM, Q	**<1 X 10^5**
Total Energy	**20 MeV**
Beam Current	**9 mA**
Forward Power, per cavity	**9 kW**
Coupler Power, per coupler	**45 kW**

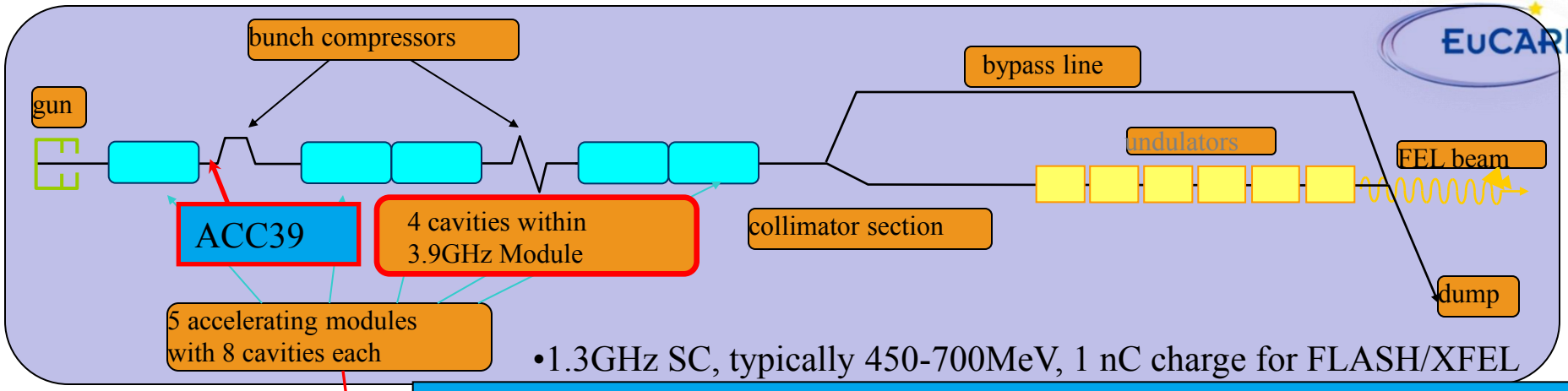
- Adding a harmonic ensures the 2nd derivative at the max is zero for total field (could use any of the harmonics in the expansion, but using the lowest freq. ensures the transverse wakefields ~ ω^3 are minimised).
- The third harmonic system (3.9GHz) compensates for the nonlinear distortion of the longitudinal 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)









•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

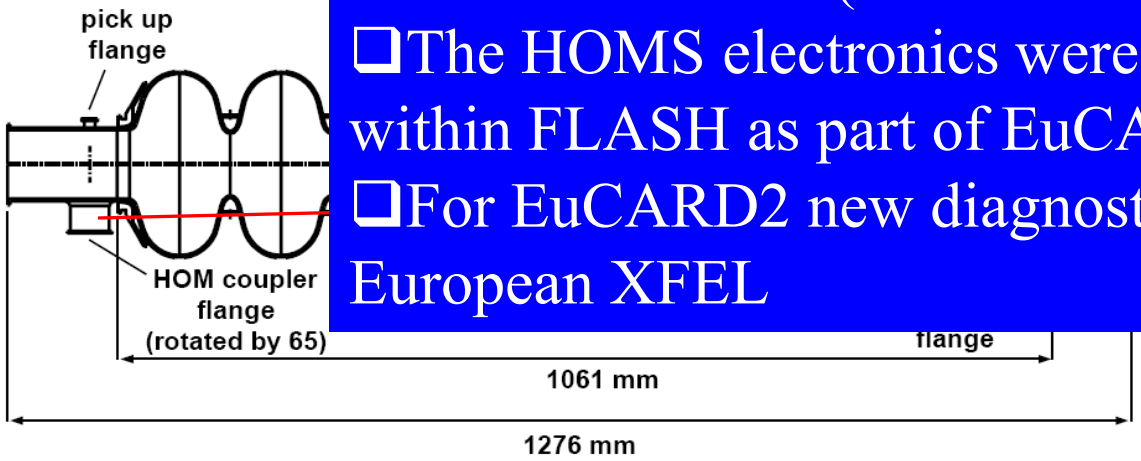
• Forty cavities exist at FLASH.

-Couplers/cables already exist.

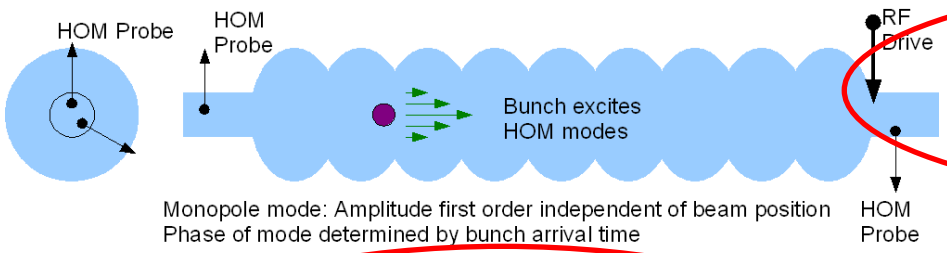
-Electronics enable monitoring of HOMs (wideband and narrowband response).

Based on 1.3 GHz (SLAC/FNAL/DESY) Diagnostics –

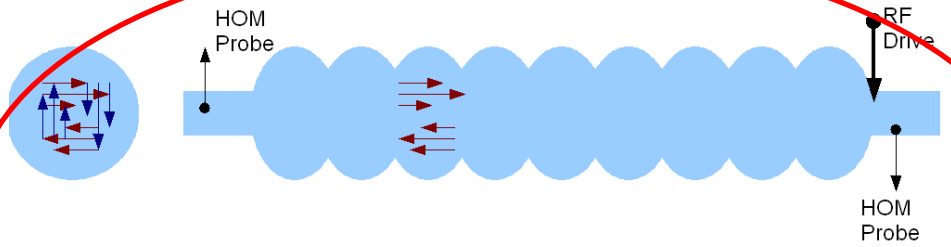
- The HOMS electronics were redesigned for ACC39 within FLASH as part of EuCARD
- For EuCARD2 new diagnostics will be required for the European XFEL



WP 12.4 Response of HOM modes to beam

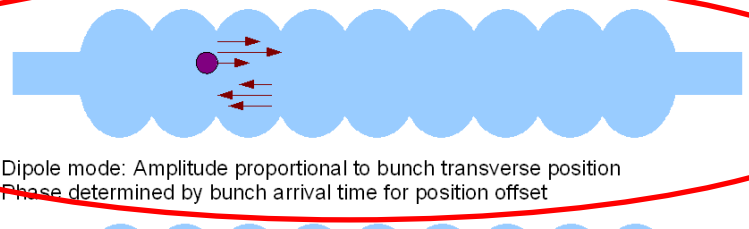


Monopole mode: Amplitude first order independent of beam position
Phase of mode determined by bunch arrival time

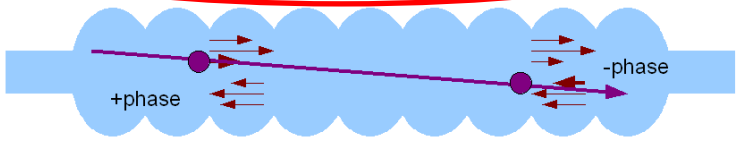


Dipole Modes: Each mode has 2 polarizations
Frequencies degenerate for ideal cavities
Frequency degeneracy broken by power coupler and fabrication errors

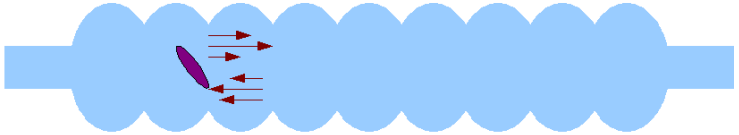
If frequency splitting is < line width, Need both couplers to separate polarizations



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

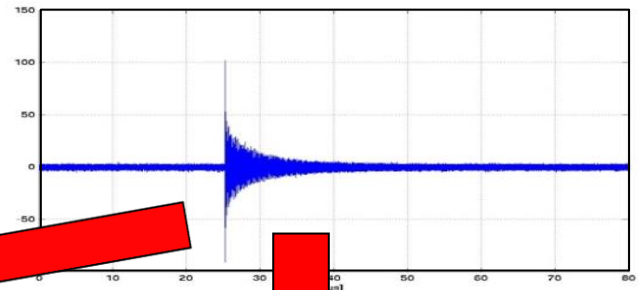


Beam at an angle will excite dipole mode with 90 degree phase shift relative to signal from position offset
Amplitude proportional to angle X effective mode length (~ 1 Meter)

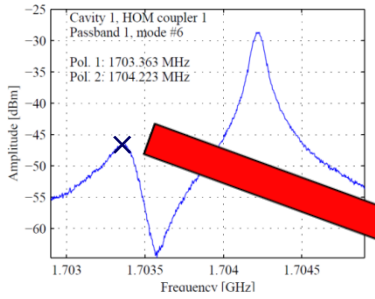


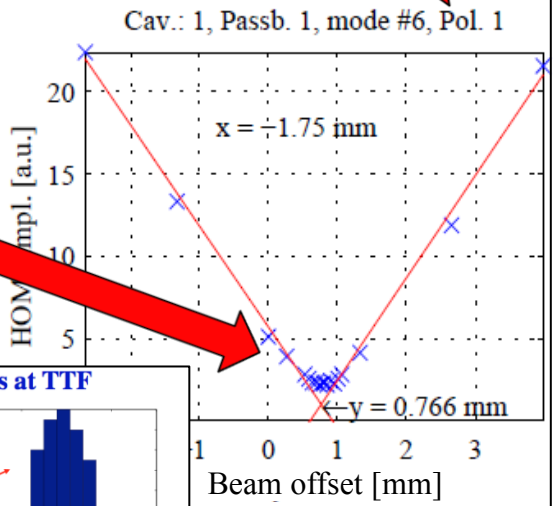
Tilted bunch will also excite signal at 90 degrees, amplitude proportional to bunch length and tilt: Not significant for short TTF bunches

WP 12.4 Analysis of Narrowband Signals – Beam Position and Beam Phase



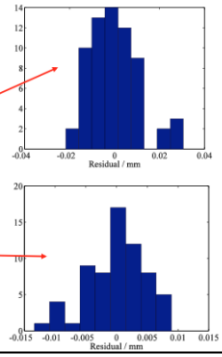
❑ Filter higher dipole mode for beam position





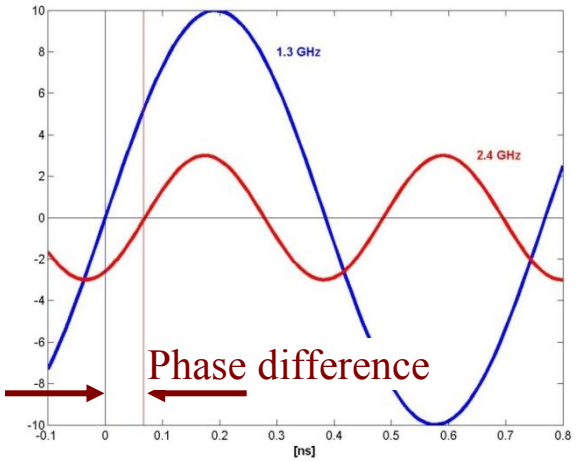
Earlier Results on 1.3 GHz Cavities at TTF

- 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 microns
- Y resolution
  - 4 microns



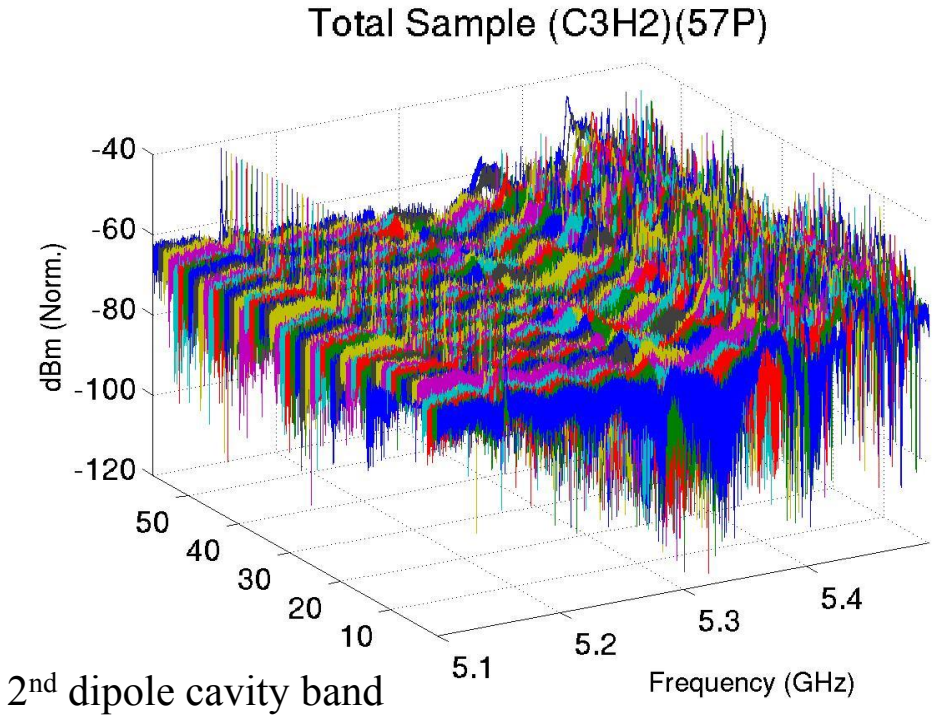
Beam Position Monitor (BPM)

❑ Filter higher monopole mode for beam phase

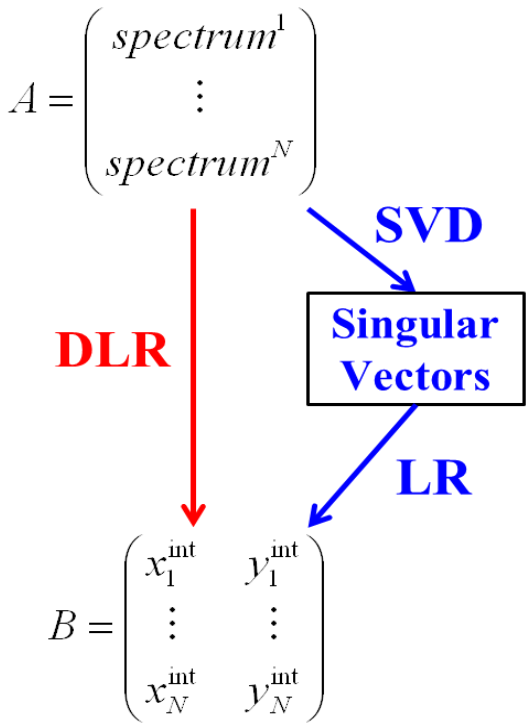


Beam Phase Monitor (BPhM)

WP 12.4 Principle of HOM BPMs: DLR & SVD



2nd dipole cavity band



- **Direct Linear Regression (DLR)**

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

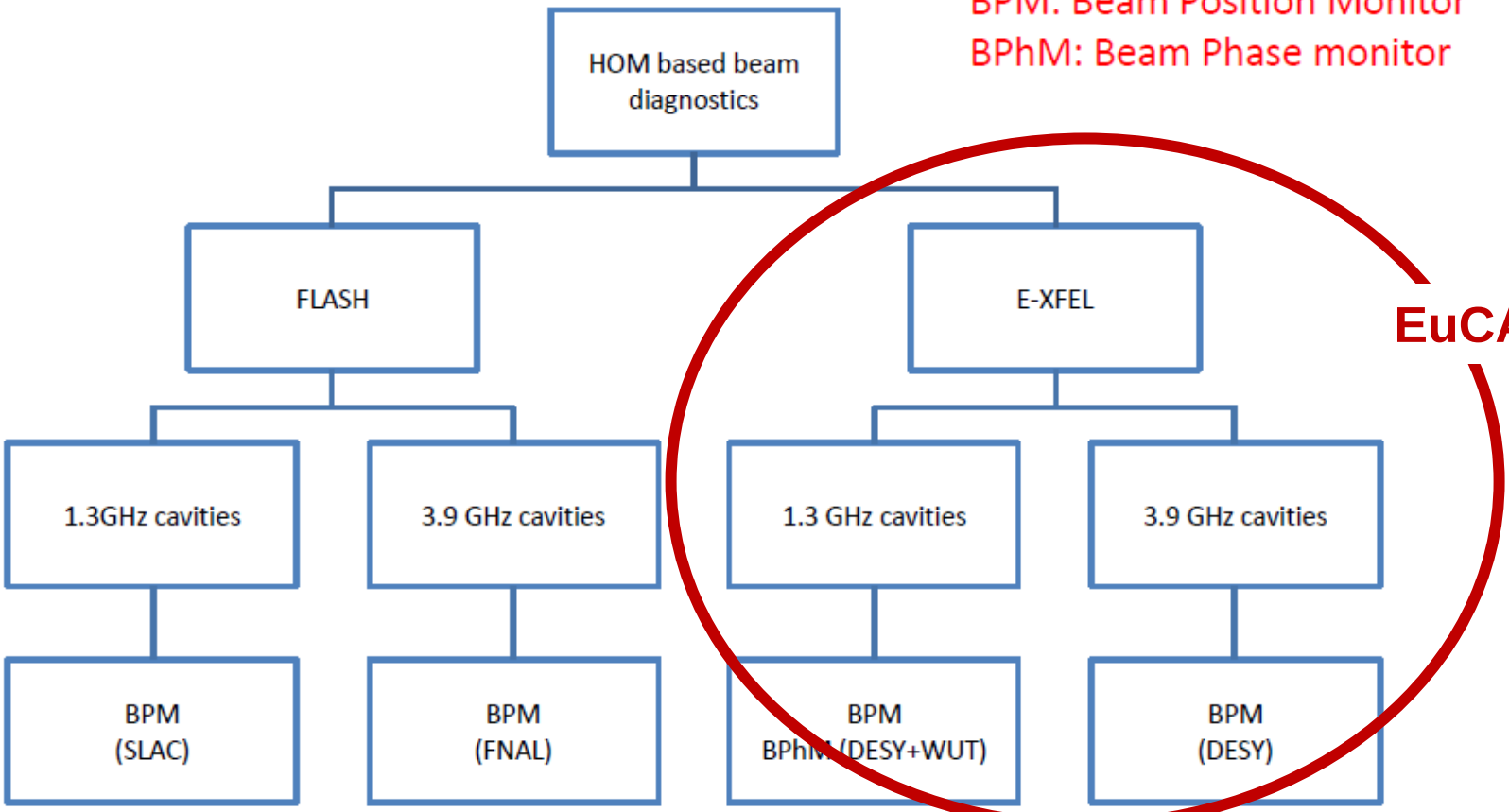
- **Singular Value Decomposition (SVD)**

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

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

WP 12.4 Response of HOM modes to beam EuCARD -> EuCARD2

BPM: Beam Position Monitor
BPhM: Beam Phase monitor



FLASH.
Free-Electron Laser FLASH

European XFEL

12.4 Summary of Plans and Status of HOM Position Diagnostics

	FLASH	European XFEL
1.3 GHz Cavities	- Electronics installed in 40 cavities (SLAC/CEA/DESY) - Raw signals used for beam centering - **EuCARD²**: Unstable calibration (phase or even frequency drifts?)	- Electronics under design, based on same frequency as for FLASH (WUT/DESY)
3.9 GHz Cavities	- Theoretical and experimental studies (**EuCARD**: UROS, UMAN, DESY together with FNAL) - Defined specs for HOMBPM electronics (also for XFEL) - Electronics under construction (FNAL), to be installed and tested/ commissioned this autumn - **EuCARD²**: Unstable calibration (same problem as for 1.3 GHz?)	- Electronics under design, based on same frequency ranges as for FLASH (DESY) - But much more challenging: 8 coupled cavities cf. 4 4.5 cf 1 MHz bunch frequency Different orientation of cavities - **EuCARD²:** Need significant theoretical and experimental studies

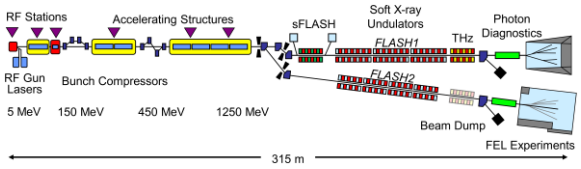
12.4 Summary of Plans and Status of HOM Phase Diagnostics

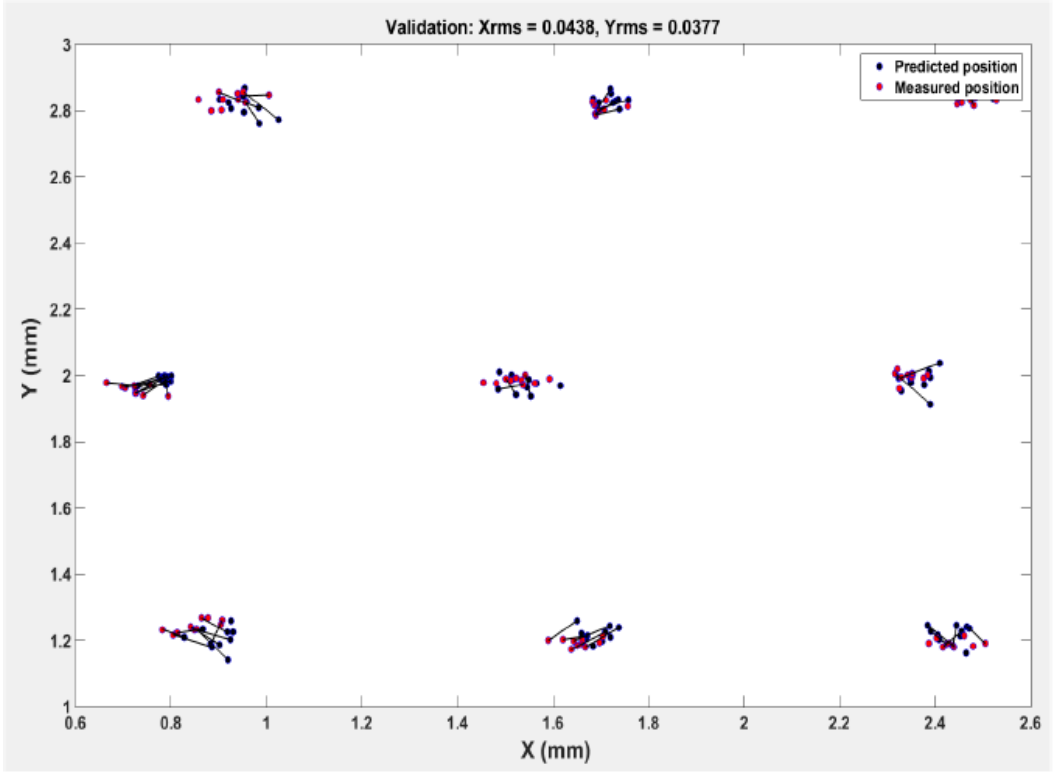
	FLASH	European XFEL
1.3 GHz Cavities	- Proof-Of-Principle made (SLAC/ CEA/DESY) - Electronics under design (same as for XFEL HOMBPM, WUT/DESY) - **EuCARD²**: experimental studies	- Same as for FLASH
3.9 GHz Cavities	- So far no isolated monopole mode identified, which could be used for phase monitoring - Theoretical (and experimental) studies (lower priority in EuCARD²)	- Same as for FLASH

➢See WP12.4.1 talk by L. Shi/N. Baboi

WP 12.4 Repeatability Measurements on HOMBPMs

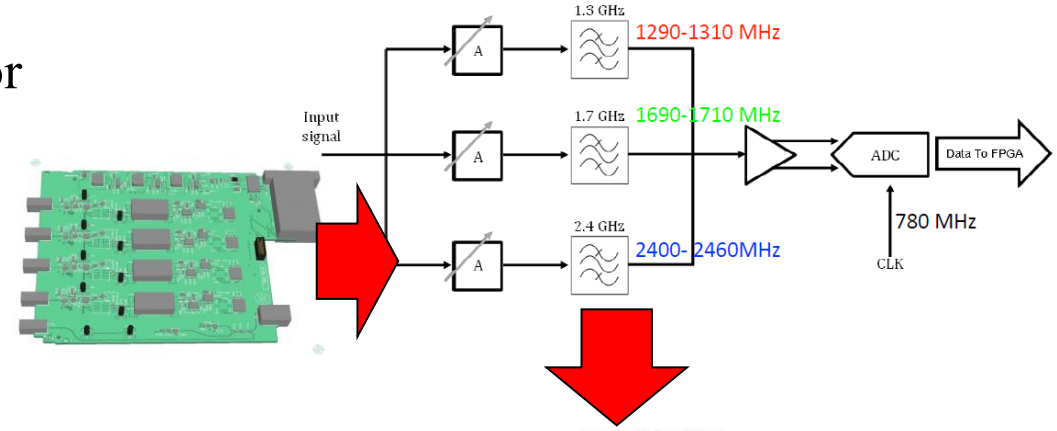
- Stable beam position recorded over a period of 5 days using HOMBPMs in 1.3 GHz cavities –first measurement
  - Repeated measurements over time
  - Dedicated beam time has been limited and consequently has impeded further progress (L. Shi & N. Baboi)

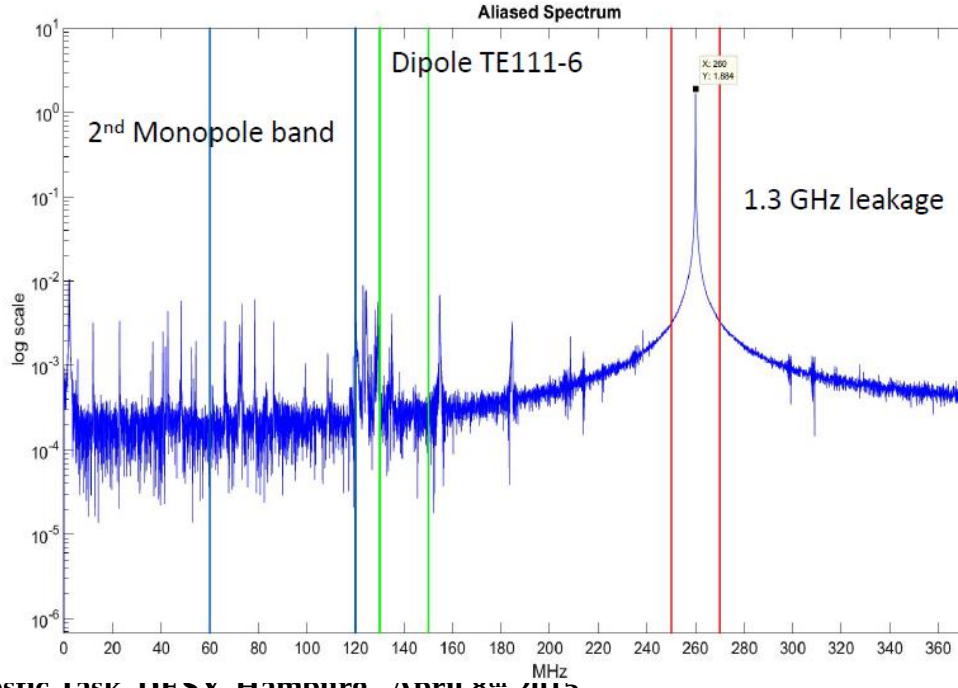




WP 12.4 Repeatability Measurements on 1.3 GHz HOMBPMs

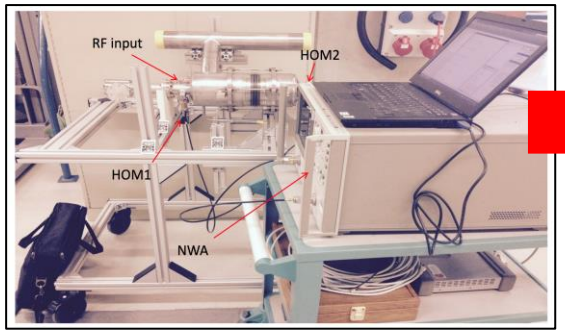
- Initial beam with test electronics for 1.3 GHz cavities
  - Identified monopole and dipole mode regions
  - Prototype electronics being fabricated (Samer Bou Habib – WUT & DESY)
- Redesign of non-functioning 5 GHz electronics for 3.9 GHz cavities complete (see M18 report)
  - Boards under construction (Thomas Wamsat -DESY)
- Expected to be complete in 2 months (~ June 2015)

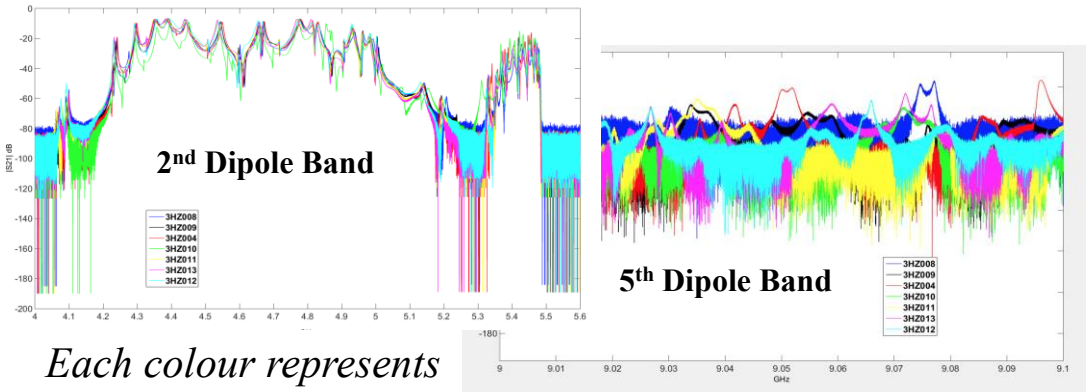




WP 12.4 Summary of Transmission Measurements on Third Harmonic Cavities

- Measured (L. Shi & N. Baboi) S21 for seven out of the eight 3.9 GHz cavities needed for XFEL modules
  - Room temperature measurements of S21 (sans final input coupler)
  - 3HZ010 has an input coupler and was also measured at 2K
  - These measurements may shed some light on subsequent measurements to be performed on the 8 cavities with a module (coupled cavity spectrum)





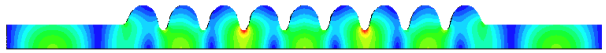
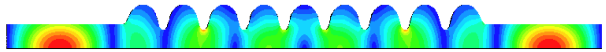
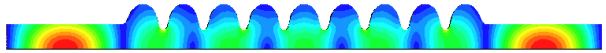
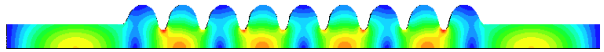
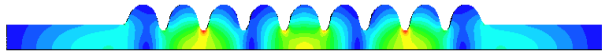
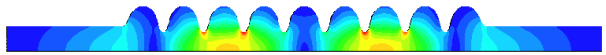
Each colour represents a different cavity

- Next steps:
  - Measure S21 for cavities in string (at room temperature and at 2K)
  - Measure S21 for reserve 3.9GHz cavities (and later for 2nd injector)
- See WP12.4.1 talk by L. Shi

12.4 HOMs in 3.9 GHz SC Cavities

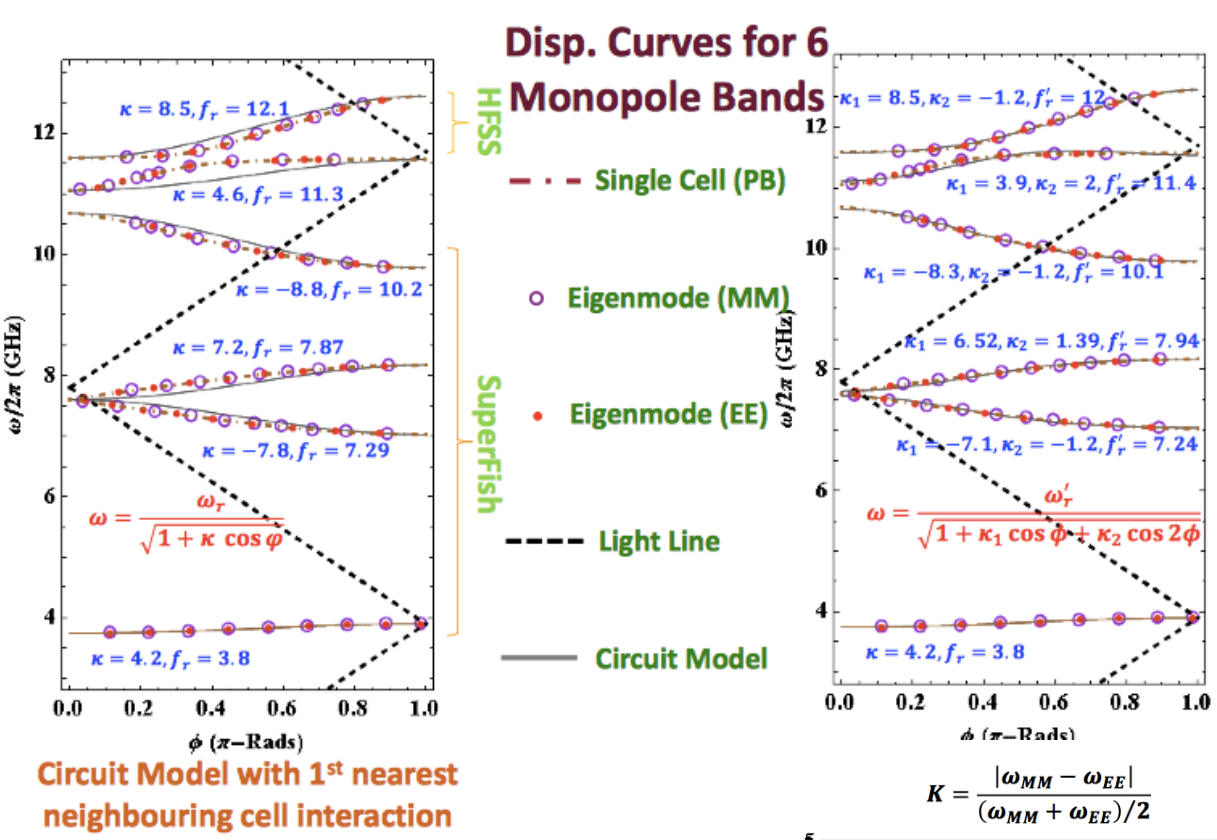
- Cavity modes up to 10GHz – allows identification of potential trapped modes and modal types, monopole, dipole, quadrupole and sextupole
- Contains all 6 cavity dipole bands below 10GHz
- HFSS results agree well with by MAFIA simulations

- Modes within the modules can be inter-cavity, beam pipe or trapped
- Majority within the first six passbands are inter-cavity – computationally expensive and sensitive to small geometrical perturbations!

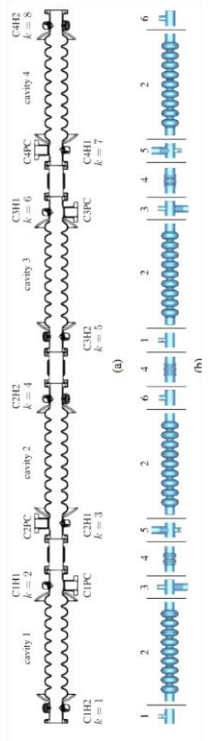
E-field distribution	ω/2π (GHz)	Band type	R/Q: Ω/cm²
	4.2953	D Band 1 #1 EE	0.00
	4.3580	D Band 1 #2 EE	0.29
	4.4460	D Band 1 #3 EE	0.00
	4.5388	D Band 1 #4 EE	1.08
	4.5972	D Band 1 #5 EE	0.79
	4.6399	D Band 1 #6 EE	0.16

- We require characterization of a limited number of modes for HOM diagnostics (large R/Q desirable)

WP 12.4 Mode Characterisation

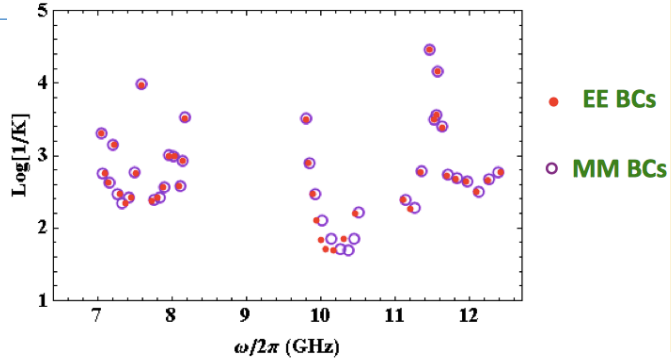


Circuit Model with 1st nearest neighbouring cell interaction



- Modes of passbands have been characterised to aid diagnostics
- P. Jain WP 12.4.2

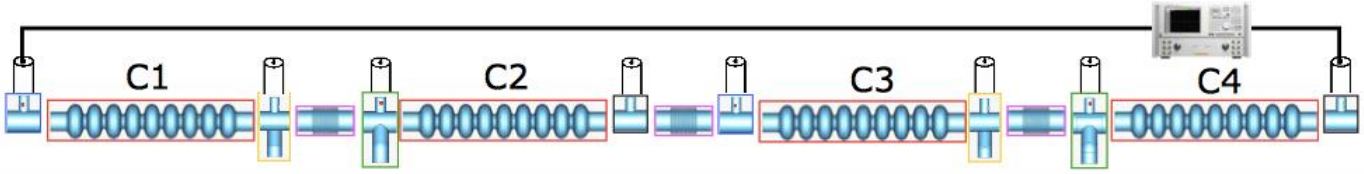
$$K = \frac{|\omega_{MM} - \omega_{EE}|}{(\omega_{MM} + \omega_{EE})/2}$$

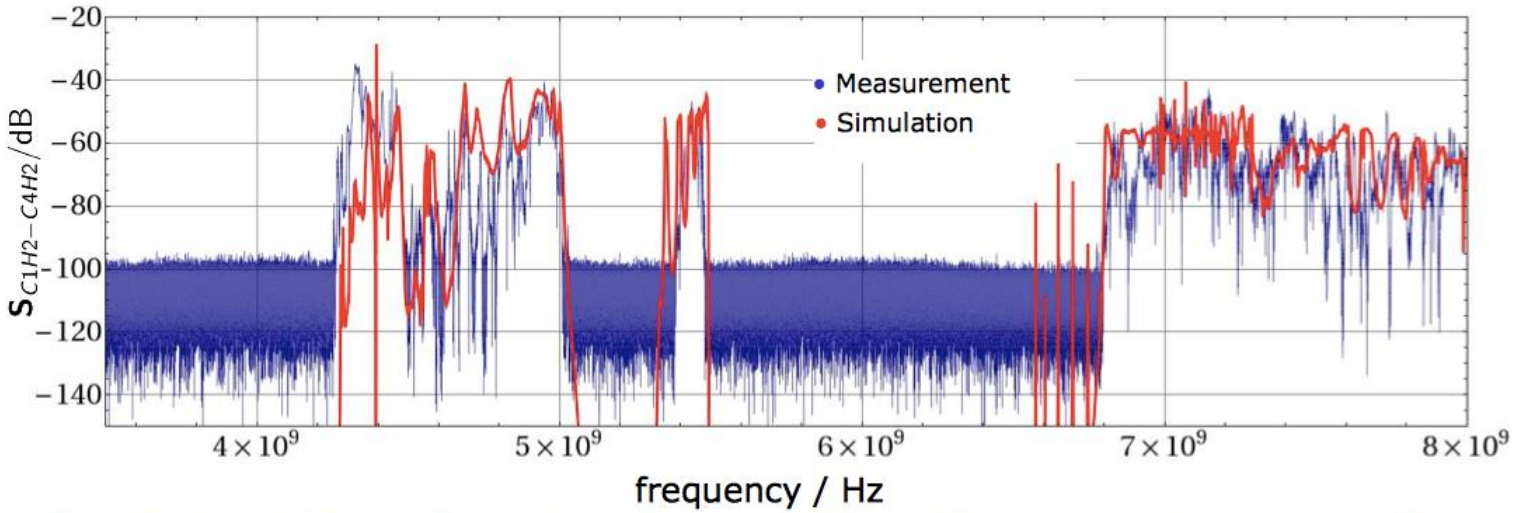


K provides an indication as to the degree at which the mode is contained within the cavity – i.e. it indicates the sensitivity to the boundary conditions and is a means of understanding whether or not the mode is a coupled cavity mode or a true trapped cavity mode

(Ref:) Schuhmann & Weiland TESLA-Report 2000-08, DESY

WP 12.4 S_{21} of HOMs in 3.9 GHz SC Accelerator Cavities

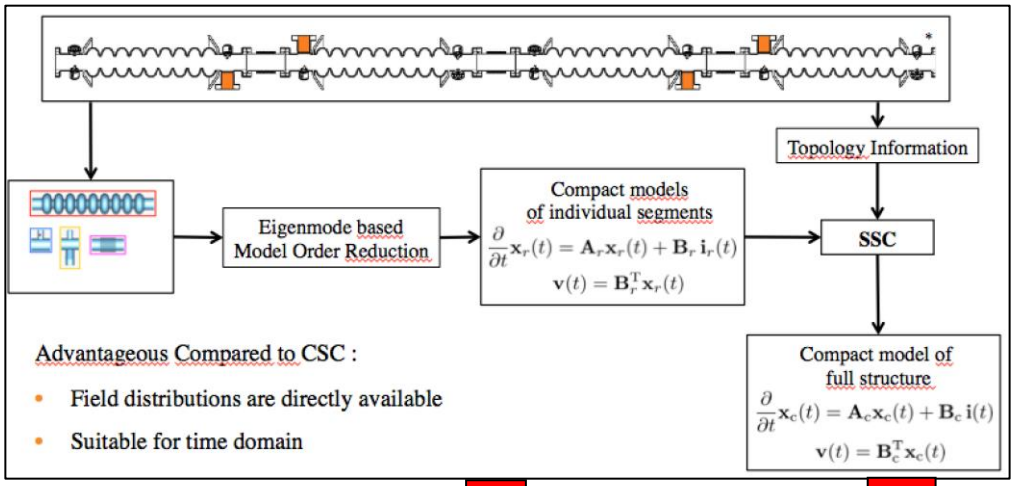




T. Flisgen, H.-W. Glock, P. Zhang, I. R. R. Shinton, N. Baboi, R. M. Jones, and U. van Rienen: "Scattering parameters of the 3.9 GHz accelerating module in a free-electron laser linac: A rigorous comparison between simulations and measurements", Phys. Rev. ST Accel. Beams, 17:022003, February 2014

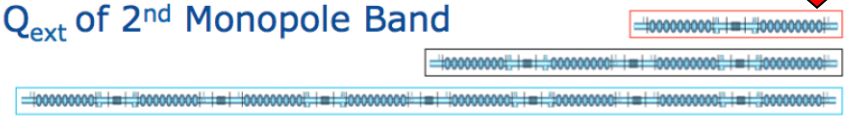
- **Using concatenation techniques transmission through the complete FLASH module ACC39 is possible- using Coupled Scattering Calculation (CSC)**
  - **Accurately compute each section**
  - **Concatenate for complete module**
- See WP12.4.3 talk by T. Flisgen

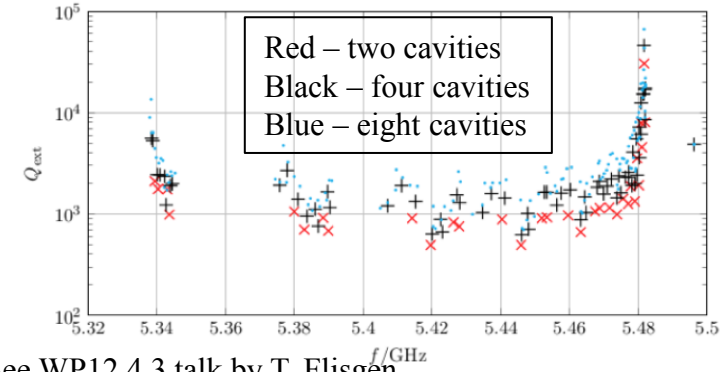
WP 12.4 Field Computation in 3.9 GHz SC Accelerator Cavities



- **Coupled Scattering Calculation (CSC) is inherently a frequency domain approach**
- **State Space Calculation (SSC) allows the e.m. fields to be directly computed**

Q_{ext} of 2nd Monopole Band





Visualization of Eigenmodes using ParaView

Modes from the second dipole band (from 5.3 GHz to 5.5 GHz) are able to propagate through the entire structure

- **Calculation of fields in 4-cavity chain (FLASH)**
- **First calculation of Q in 8-cavity chain (XFEL)**

- See WP12.4.3 talk by T. Flisgen

Deliverables & Milestones

All taken from:
Deliverables (http://eucard2.web.cern.ch/science/deliverables)
Milestones (http://eucard2.web.cern.ch/science/milestones)

Deliverables

- D12.3 Design of electronics for XFEL HOM diagnostics (M18 –complete)†
- D12.7 Completed characterisation of HOMS in the 8-cavity XFEL module (M36)†
- D12.4.1 Report on characterisation of HOMS in XFEL coupled 3HC cryomodule (M48 –April 2017)‡

Milestones

- MS82 Completed coupled cavity simulations of 8-cavity module (M36)

†Commuted from milestones
‡ Original deliverable

Concluding Remarks on Task 12.4

- Ongoing measurements (both parasitic and otherwise) on HOM diagnostics at FLASH provide vital information on methodology for XFEL
- Stand-alone S21 measurements on 3rd harmonic cavities indicate similar spectra
- Simulation of 4 coupled cavities was challenging -8 in the XFEL module is even more computationally demanding. Initial results e-field encouraging!
- A Compendium of modes will be generated for the 8-cavity chain within modules in XFEL
- On track for deliverables/milestones with caveats (see N. Baboi's Saclay talk). Had several skype meetings to review progress to date.
- HOMSC14 well attended from our WP12.4 in July 2014 at FNAL
- PRST-AB paper (T. Flisgen et al, *Scattering parameters of the 3.9 GHz accelerating module in a free-electron laser linac: A rigorous comparison between simulations & measurements*). Ph.D. to be submitted as EU Monograph.
- Faulty electronics board (M18 report), rebuilt and on-track for retesting in ~ 3months.
- New PDRA will take up appointment in Manchester, eta in May 2015

Task 12.4 Talks

- *Overview of SRF HOM Diagnostics for the European XFEL task*,
R.M. Jones (*University of Manchester/Cockcroft Inst.*)

- HOMBPM Beam Position Monitors:
HOMBPM Resolution Study,
L. Shi, N. Baboi (*DESY*)

- HOMGD Geometric Dependencies:
Results of RF Simulations for Chains of Superconducting Cavities,
T. Flisgen, U. Van Rienen (*University of Rostock*)