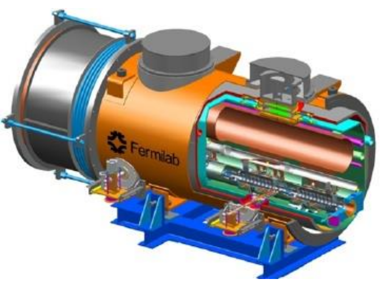
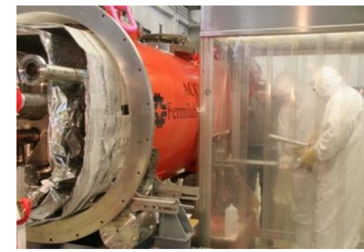
SRF HOM Diagnostics for the European XFEL



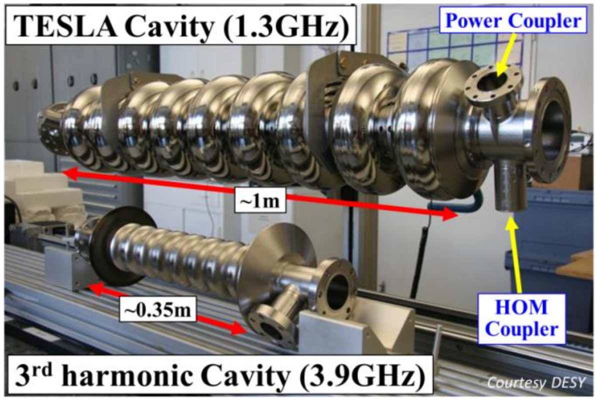


Nicoleta Baboi, Ursula van Rienen
Roger M. Jones
DESY, Univ. of Rostock, Univ. of Manchester/ Cockcroft Inst.

https://indico.cern.ch/event/494553/overview

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
- ➢N. Joshi, PDRA (grad. RHUL)

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

WP 12.4.1

N. Baboi, DESY

L. Shi , Univ. of Manchester/DESY

WP 12.4.2

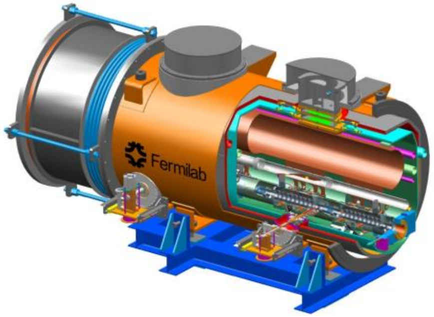
N. Joshi, CI/Univ. of Manchester

WP 12.4.3

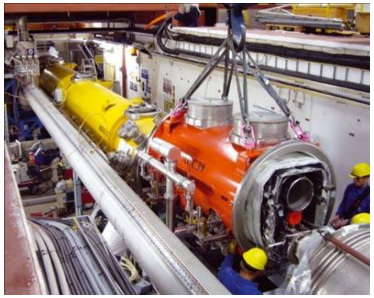
T. Flisgen, Univ. of Rostock

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.



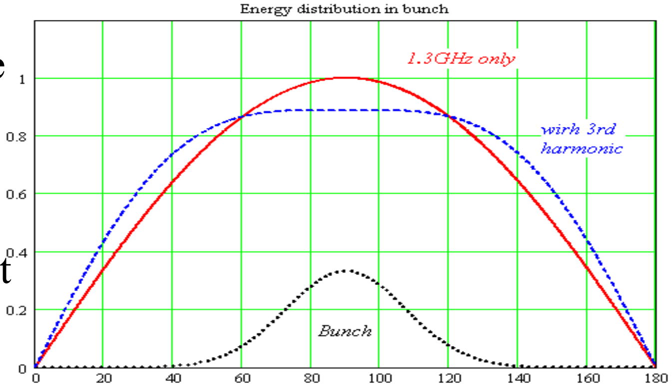
- The cryomodule, consisting of <u>four 3.9GHz cavities</u>, has been installed in the FLASH photoinjector downstream, of the first 1.3 GHz cryomodule (consisting of 8 cavities).
- Four 3.9 GHz cavities provide the energy modulation, ~20 MV, needed for compensation.
- Eight cavities are required per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

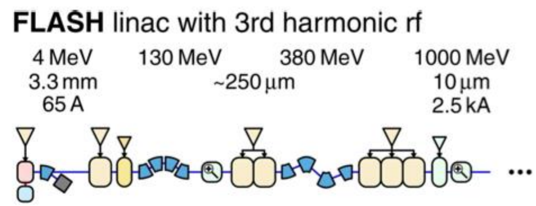
WP 12.4 FLASH 3.9 GHz Parameters

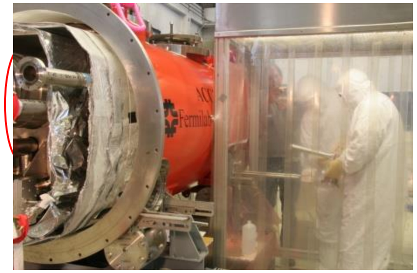
Number of Cavities	**4**
Active Length	**0.346 meter**
Gradient	**14 MV/m**
Phase	**-179º**
R/Q [=U²/(wW)]	**750 Ω**
E_{peak}/E_{acc}	**2.26**
B_{peak} (E_{acc} = 14 MV/m)	**68 mT**
Q_{ext}	**1.3 X 10^6**
BBU Limit for HOM, Q	**<1 X 10^5**
Total Energy	**20 MeV**
Beam Current	**9 mA**
Forward Power,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

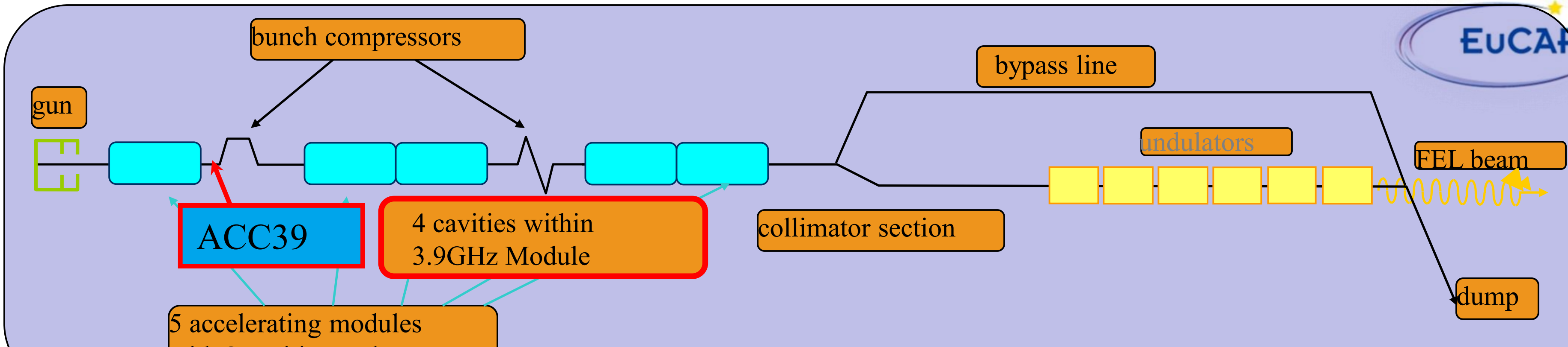
- Adding a harmonic ensures the 2^{nd} derivative at the max is zero for total field (could use any of the harmonics in the expansion, but using the lowest freq. ensures the transverse wakefields ~ ω^3 are minimised).
- The third harmonic system (3.9GHz) compensates for the nonlinear distortion of the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

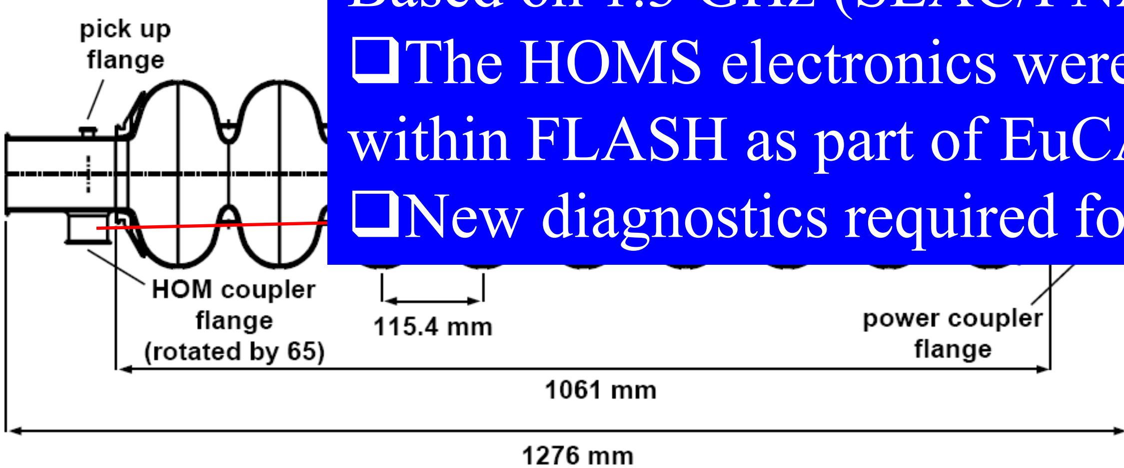
-Couplers/cables already exist.

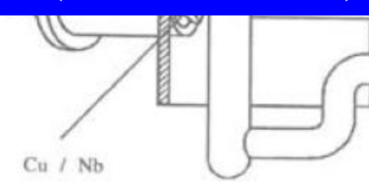
-Electronics enable monitoring of HOMs (wideband and narrowband response).

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

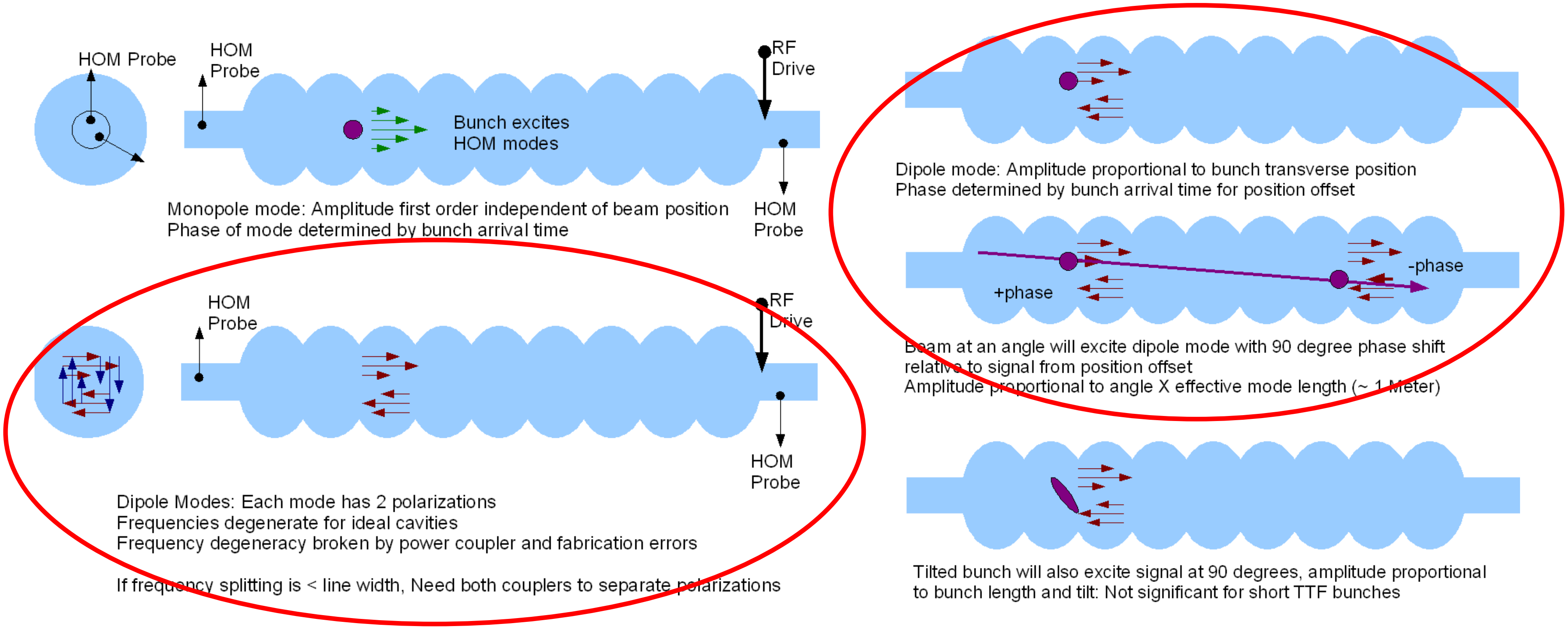
❑The HOMS electronics were redesigned for ACC39 within FLASH as part of EuCARD

❑New diagnostics required for E-XFEL (EuCARD2)

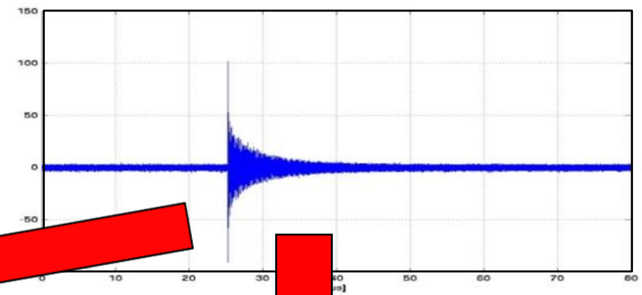




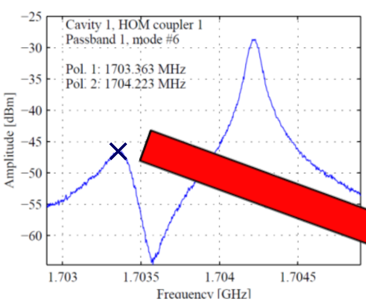
WP 12.4 Response of HOM modes to beam

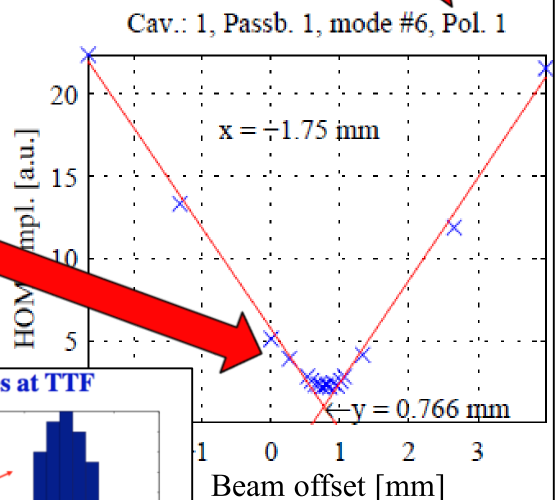


WP 12.4 Analysis of Narrowband Signals – Beam Position and Beam Phase



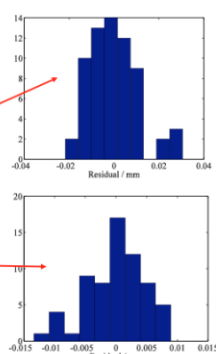
- Filter higher dipole mode for <u>beam position</u>





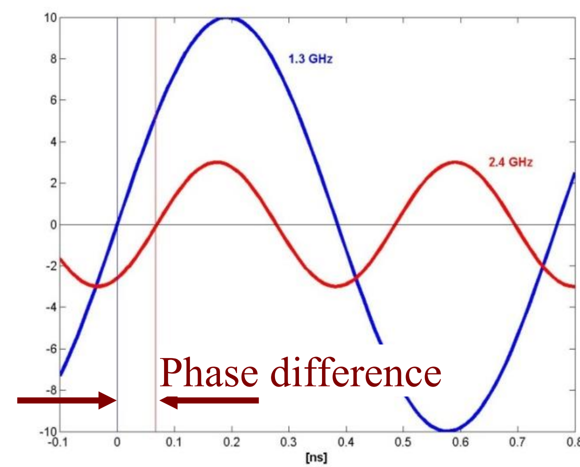
Earlier Results on 1.3 GHz Cavities at TTF

- 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 <u>beam phase</u>



Beam Phase Monitor (BPhM)

12.4 Band Structure of HOMs in 3.9 GHz Cavities

Coupled Cavity Modes

Trapped Cavity Modes

C.F. 1.3 GHz Cavity Modes

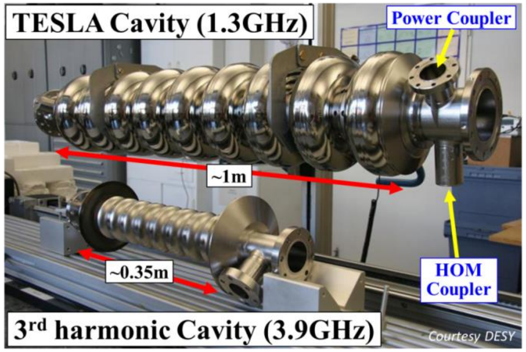
Dipole band	Frequency (GHz)	R/Q (Ω/cm²)
1	4.7245	10.572
1	4.8327	50.307
1	4.9270	30.174
2	5.4050	5.057
2	5.4427	20.877
2	5.4678	15.776
5	9.0581	2.171
5	9.0664	4.116
1	1.7	5.5

RESOLUTION

x ~ 12 μm , y ~40 μm (FLASH Module mode at 5 GHz)[1]

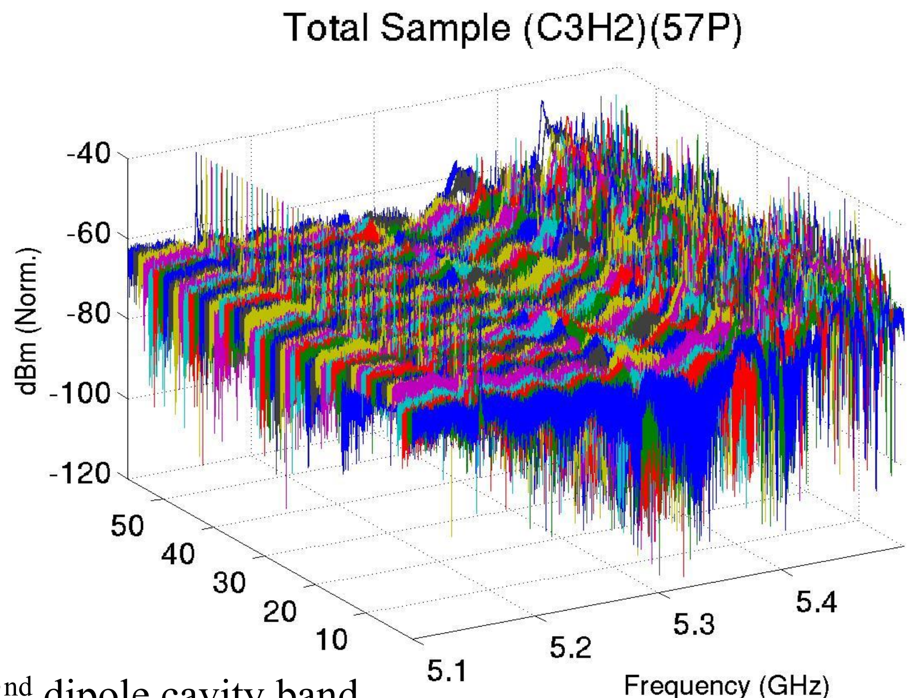
x ~ 50 μm , y~ 100 μm (FLASH Cavity mode at 9GHz)[1]

x ~ 9 μm , y~ 4 μm (FLASH 1.3 GHz cavities)[2]

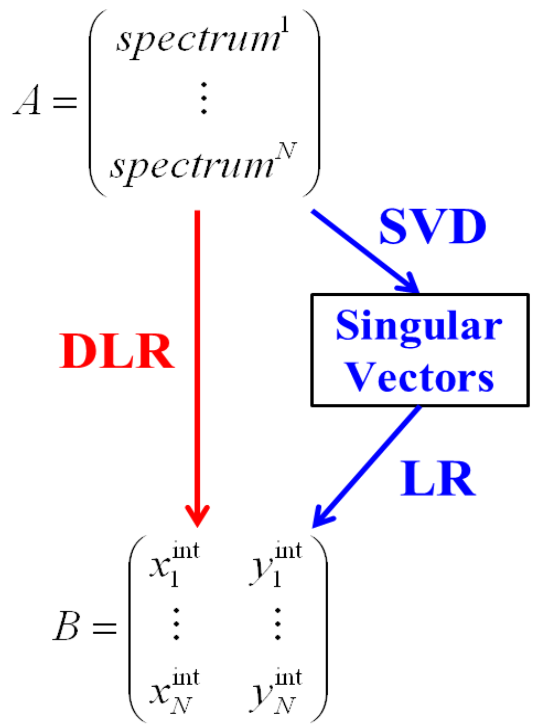


1. Baboi et al, IBIC 2014
2. Molloy et a., PRST-AB 2006

WP 12.4 Principle of HOM BPMs: DLR & SVD



2nd dipole cavity band



$$A = \begin{pmatrix} spectrum^1 \\ \vdots \\ spectrum^N \end{pmatrix}$$

$$B = \begin{pmatrix} x_1^{\text{int}} & y_1^{\text{int}} \\ \vdots & \vdots \\ x_N^{\text{int}} & y_N^{\text{int}} \end{pmatrix}$$

- ❑ **Direct Linear Regression (DLR)**

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

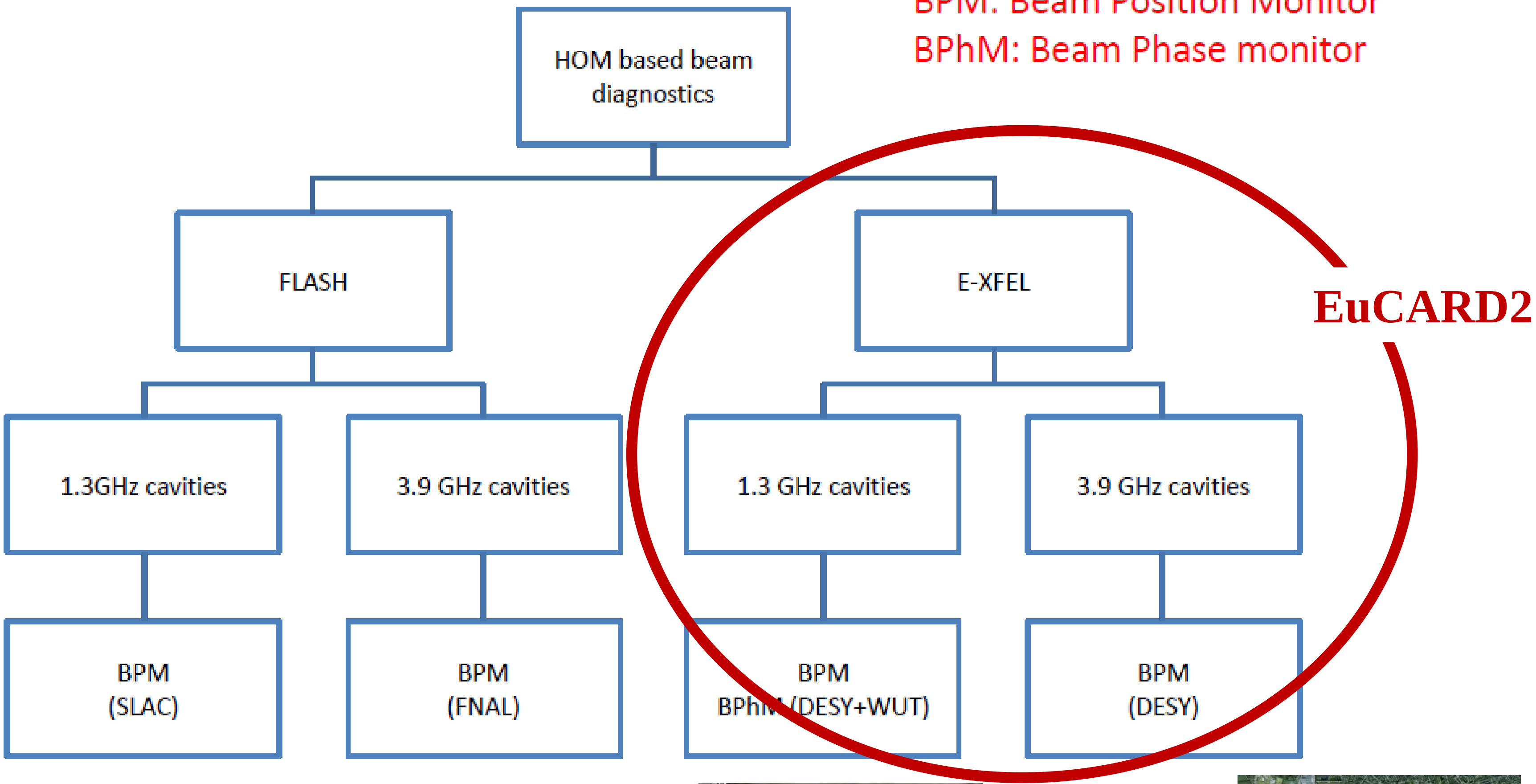
- ❑ **Singular Value Decomposition (SVD)**

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

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

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

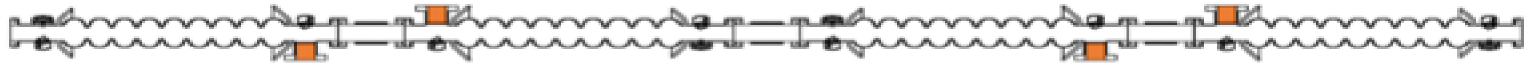
	FLASH	European XFEL
1.3 GHz Cavities	- Electronics installed in 40 cavities (SLAC/CEA/DESY) - Raw signals used for beam centering - **EuCARD²**: Unstable calibration (phase or even frequency drifts?)	- Electronics under design, based on same frequency as for FLASH (WUT/DESY)
3.9 GHz Cavities	- Theoretical 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

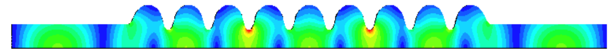
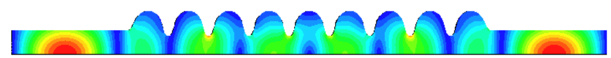
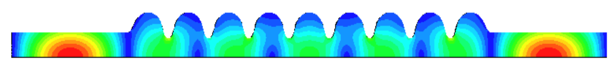
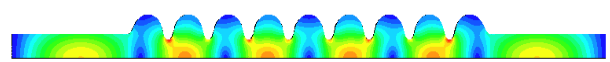
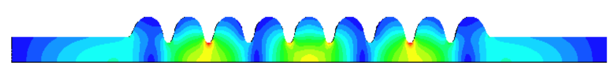
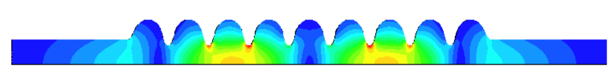
	FLASH	European XFEL
1.3 GHz Cavities	- Proof-Of-Principle made (SLAC/ CEA/DESY) - Electronics under design (same as for XFEL HOMBPM, WUT/DESY) - **EuCARD²**: experimental studies	- Same as for FLASH
3.9 GHz Cavities	- So far no isolated monopole mode identified, which could be used for phase monitoring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

➢See WP12.4.1 talk by L. Shi/N. Baboi

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

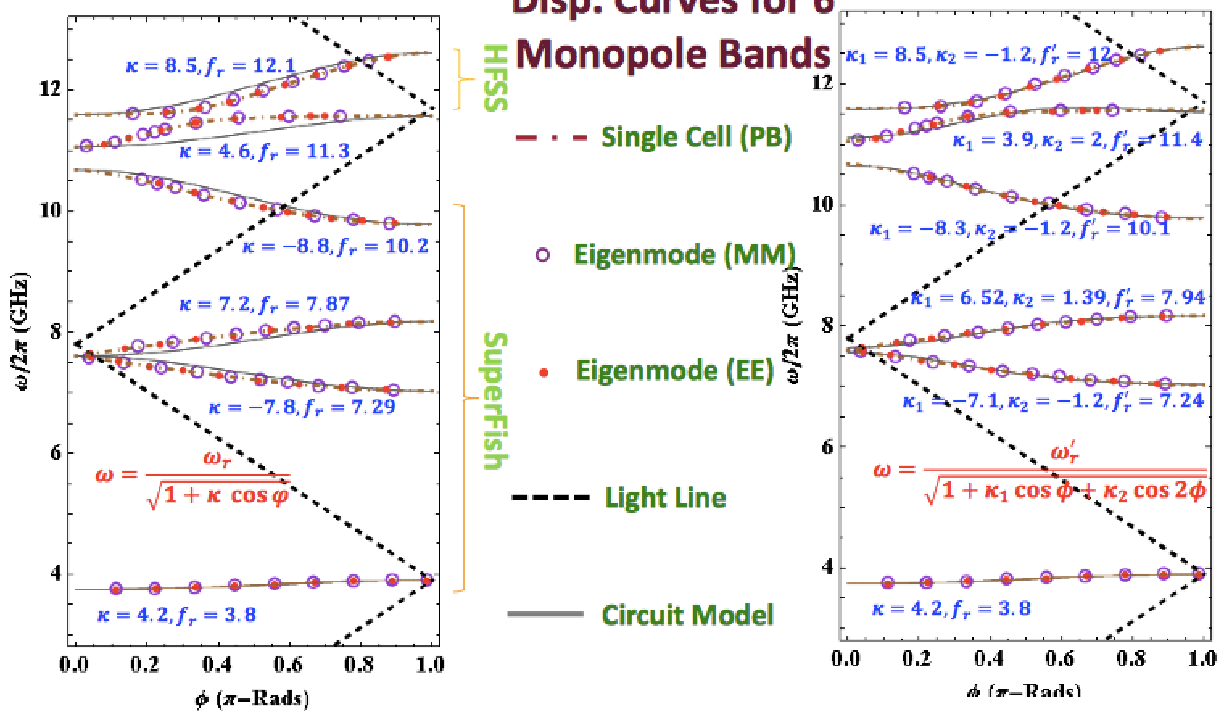
E-field distribution	ω/2π (GHz)	Band type	R/Q: Ω/cm²
	4.2953	D Band 1 #1 EE	0.00
	4.3580	D Band 1 #2 EE	0.29
	4.4460	D Band 1 #3 EE	0.00
	4.5388	D Band 1 #4 EE	1.08
	4.5972	D Band 1 #5 EE	0.79
	4.6399	D Band 1 #6 EE	0.16

- ❑ 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!

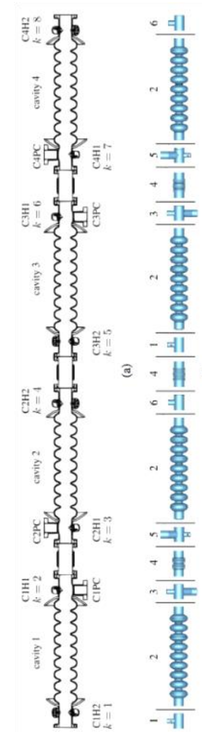
- ❑ We require characterization of a limited number of modes for HOM diagnostics (large R/Q desirable)

WP 12.4 Mode Characterisation

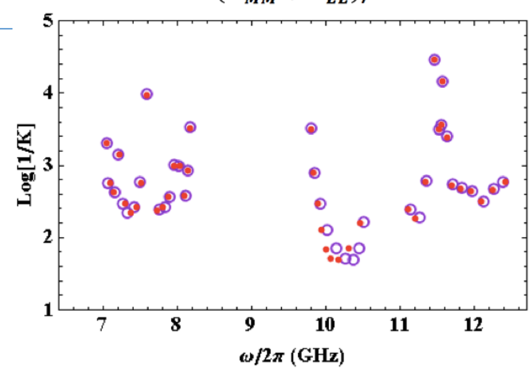
Disp. Curves for 6 Monopole Bands



Circuit Model with 1st nearest neighbouring cell interaction



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



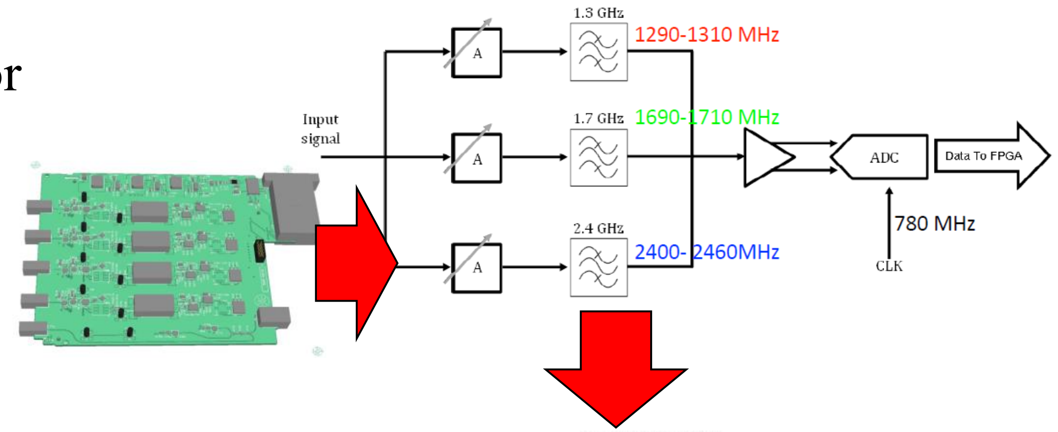
K provides an indication as to the degree at which the mode is contained within the cavity – i.e. it indicates the sensitivity to the boundary conditions and is a means of understanding whether or not the mode is a coupled cavity mode or a true trapped cavity mode

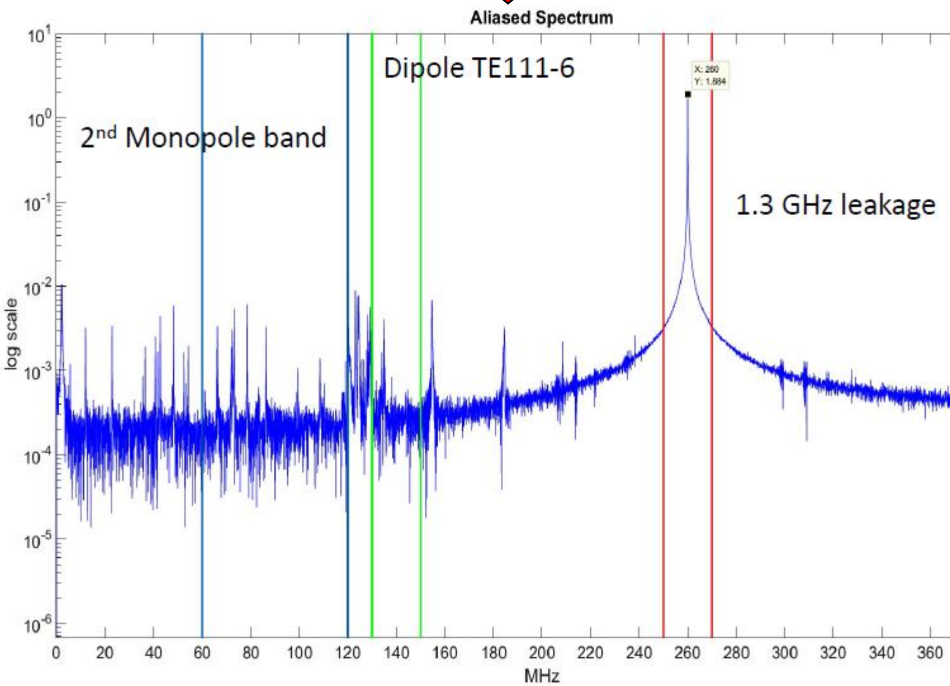
(Ref:) Schuhmann & Weiland TESLA-Report 2000-08, DESY

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

WP 12.4 Repeatability Measurements on 1.3 GHz HOMBPMs

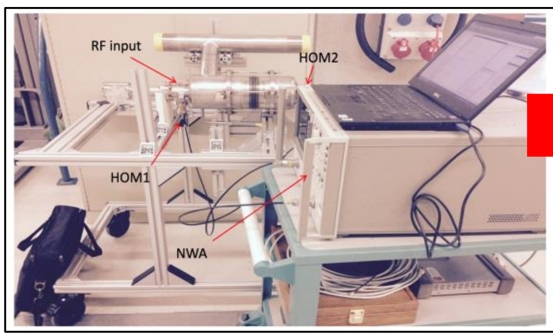
- Initial beam with test electronics for 1.3 GHz cavities
  - Identified monopole and dipole mode regions
  - Prototype electronics being fabricated (Samer Bou Habib – WUT & DESY)
- Redesign of non-functioning 5 GHz electronics for 3.9 GHz cavities complete (see M18 report)
  - Boards under construction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

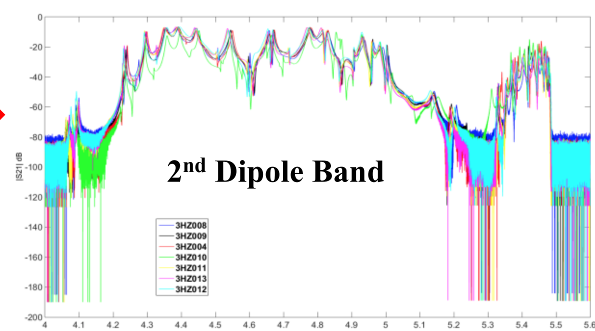


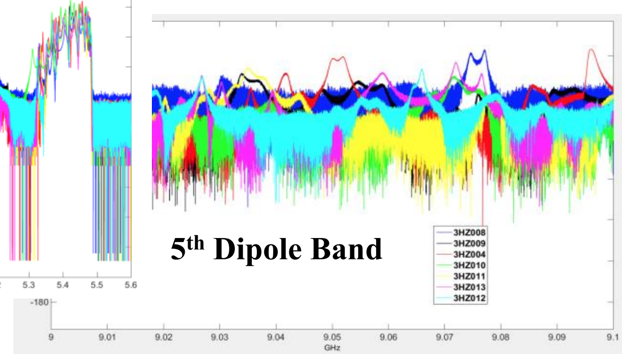


WP 12.4 Summary of Transmission Measurements on Third Harmonic Cavities

- 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)



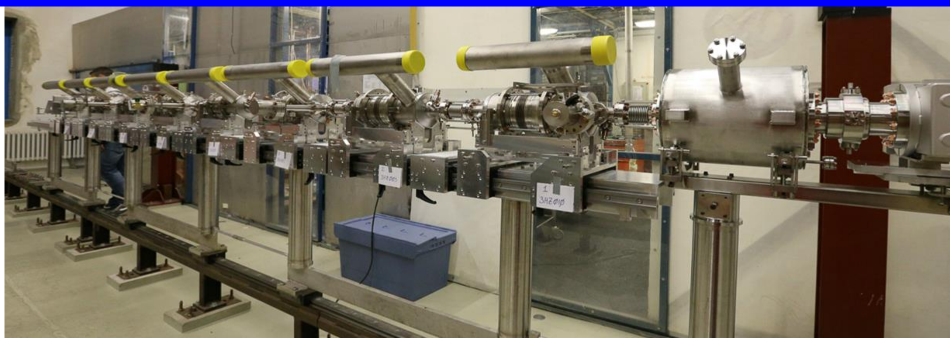




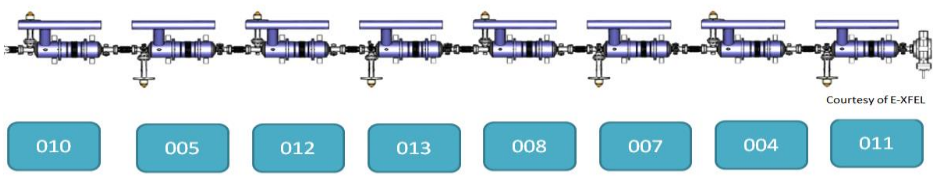
Each colour represents a different cavity

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

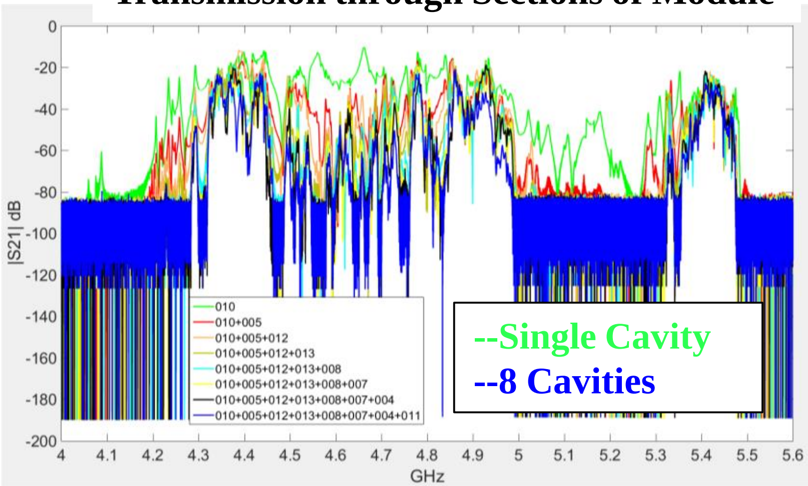
WP 12.4 Measurements on S-Matrices through 3.9 GHz 8-Cavity Module



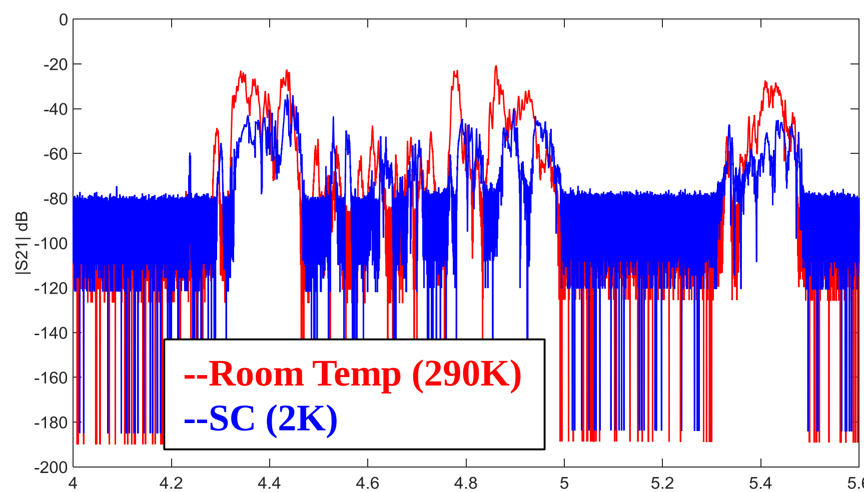
- ❑ Transmission measurements at 293 K and 2 K. (see L. Shi's talk) -ports terminated with 50 Ω loads
- ❑ Dense spectrum of coupled modes



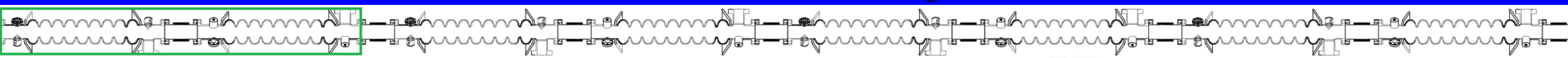
Transmission through Sections of Module

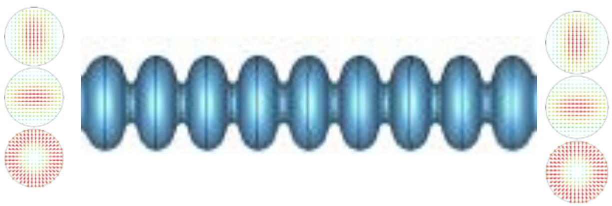


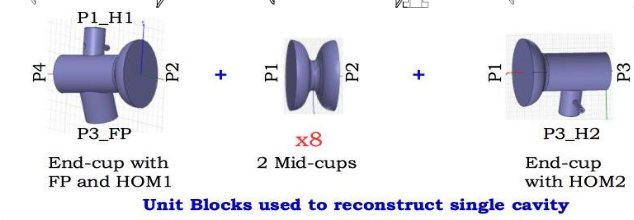
Transmission through Complete Module

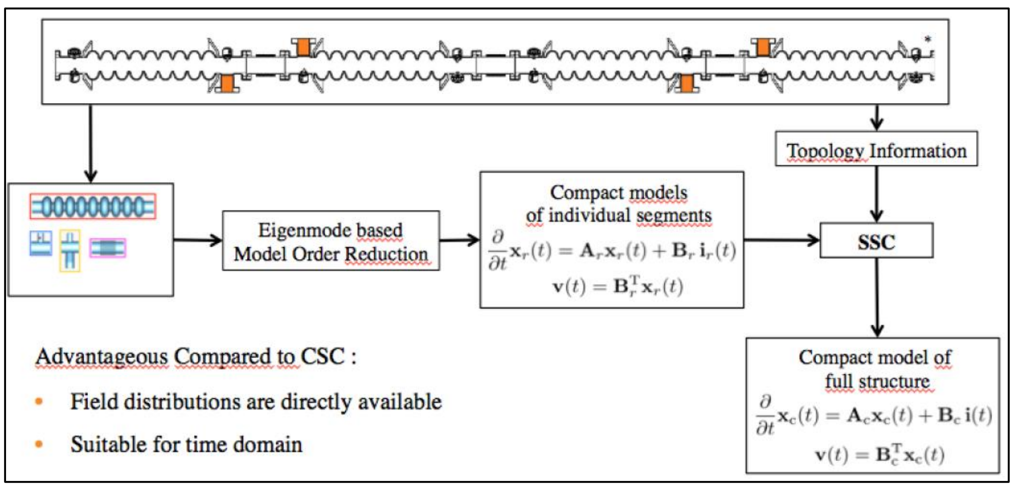


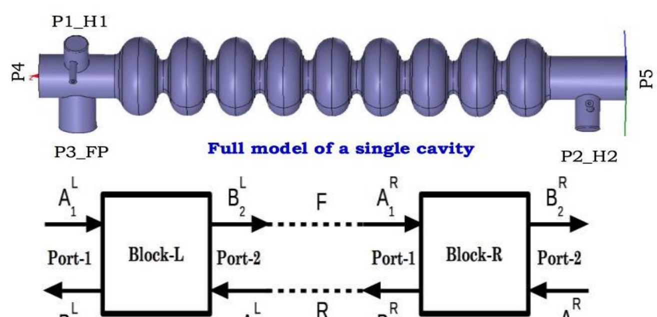
WP 12.4 Simulations of S-Matrices and Eigenmodes through XFEL 3.9 GHz 8-Cavity Module











$$S_{11}^{LR} = S_{11}^{L} + S_{12}^{L}\left[I - S_{11}^{R}S_{22}^{L}\right]^{-1} S_{11}^{R}S_{21}^{L}$$

$$S_{12}^{LR} = S_{12}^{L}\left[I - S_{11}^{R}S_{22}^{L}\right]^{-1} S_{12}^{R}$$

$$S_{21}^{LR} = S_{21}^{R}\left[I - S_{22}^{L}S_{11}^{R}\right]^{-1} S_{21}^{L}$$

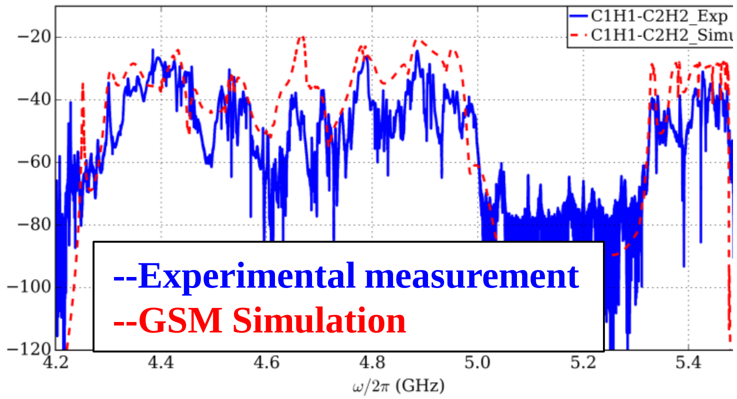
$$S_{22}^{LR} = S_{22}^{R} + S_{21}^{R}\left[I - S_{22}^{L}S_{11}^{R}\right]^{-1} S_{22}^{L}S_{12}^{R}$$

CSC –to State Space Concatenation (SSC)
–see T. Flisgen's talk

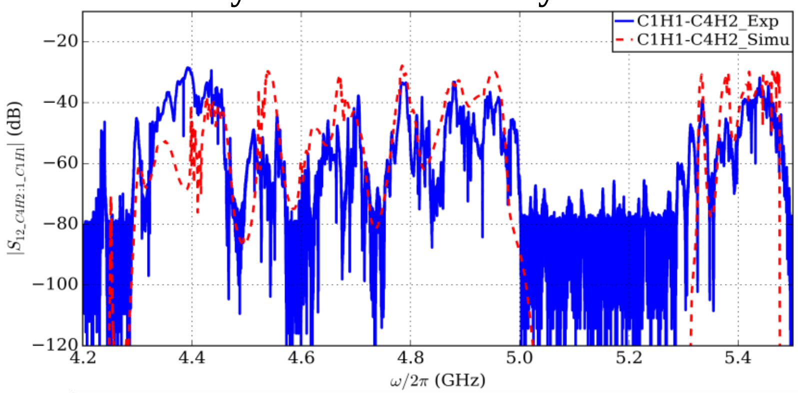
Globalised Scattering Matrix (GMS)
–see N. Joshi's talk

WP 12.4: Experimental Measurement of S_{21} vs GSM Simulations in 8-Cavity XFEL Chain

Cavity-1 HOM1 to Cavity-2 HOM2



Cavity-1 HOM1 to Cavity-4 HOM2

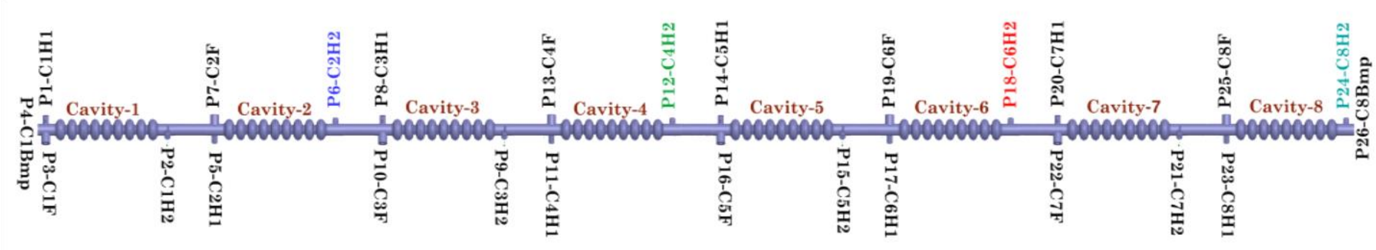


- ❑ First comparison of HOM spectrum from 8 cavity module AH1 at 2K (<u>see N. Joshi's talk</u>) In this initial simulation some parameters were modified to aid comparison:

-bellows excluded to enable rapid calculation

-attenuation in cables, transitions etc accounted for by rescaling ordinate

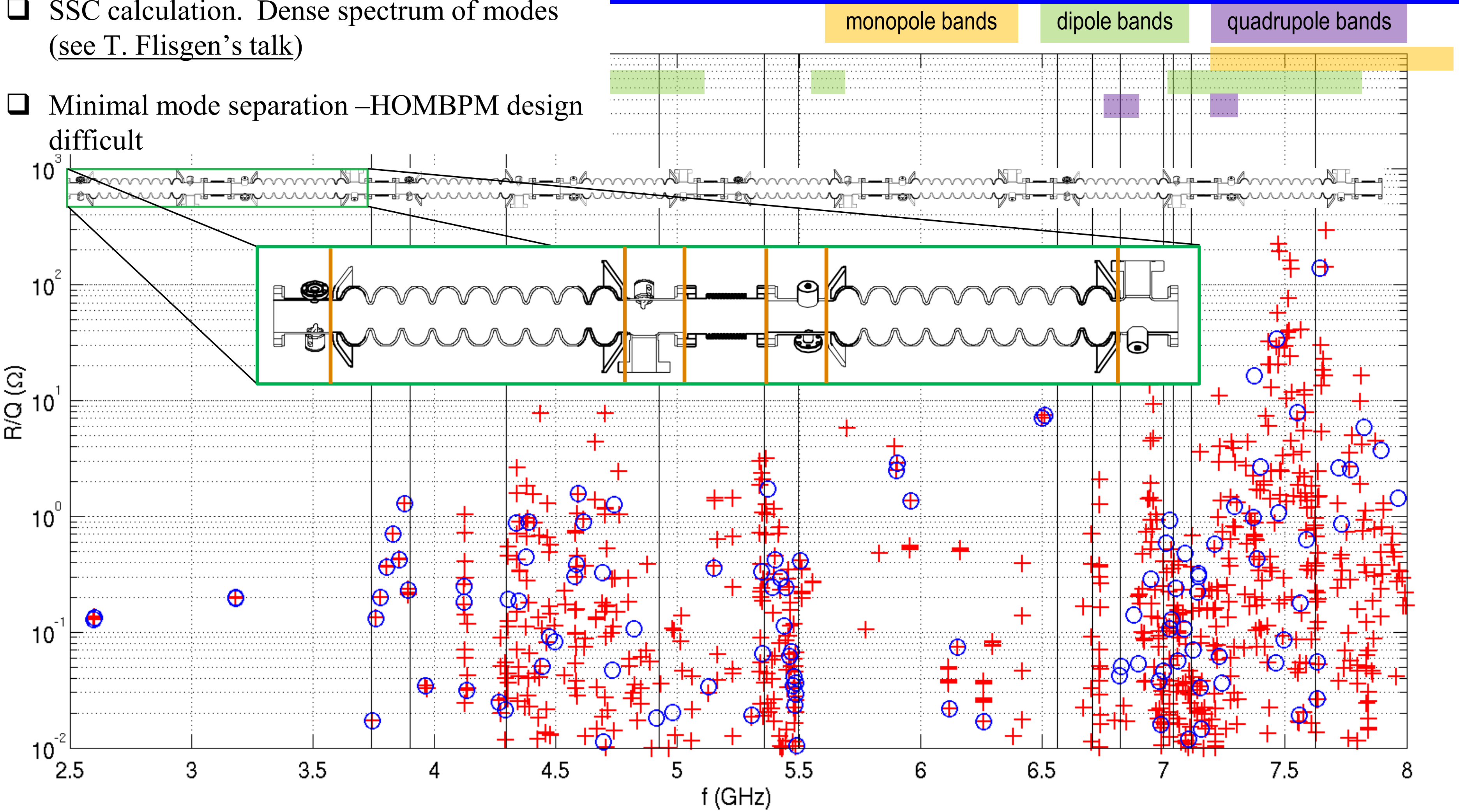
- beam pipe reflections accounted for by 45 MHz & 25 MHz rescaling of 1st and 2nd bands



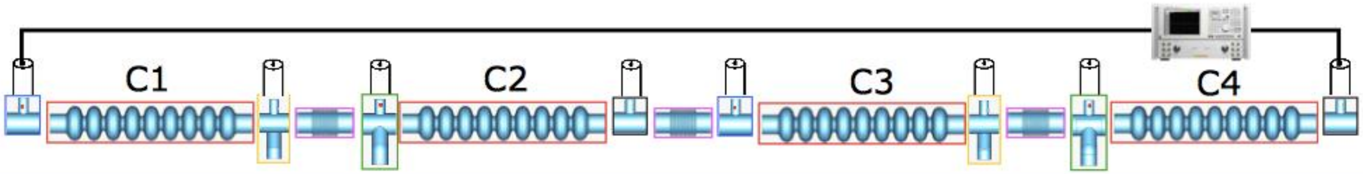
2016

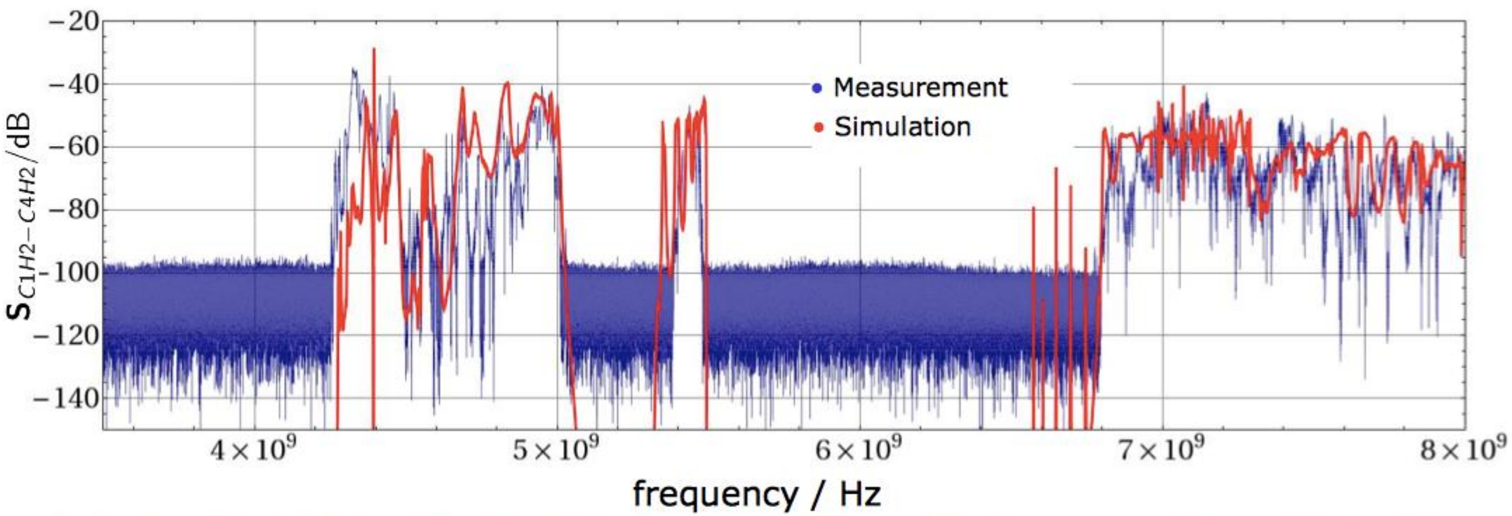
WP 12.4 R/Q Calculations for Complete 3.9 GHz 8-Cavity XFEL Module

- SSC calculation. Dense spectrum of modes (see T. Flisgen's talk)
- Minimal mode separation –HOMBPM design difficult



WP 12.4 S_{21} of HOMs in 3.9 GHz Cavities at FLASH





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**

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 Characterisation of HOMS in the 8-cavity XFEL module (M36)†✓
- ❑ D12.4.1 Additional 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
✓ On track

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 3^{rd} harmonic cavities indicate similar spectra

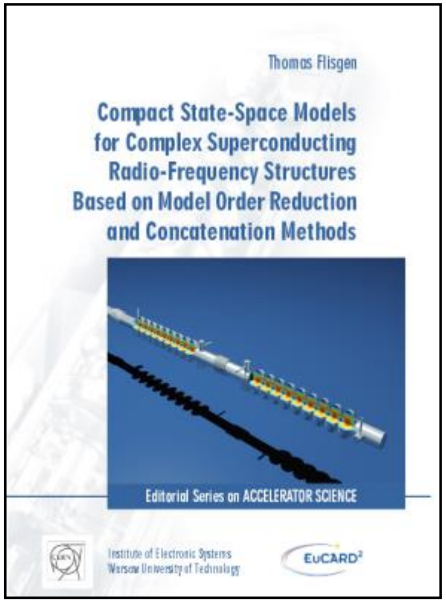
- Simulation of 4 coupled cavities was challenging -8 in the XFEL module is even more computationally demanding. Initial results e-field encouraging!

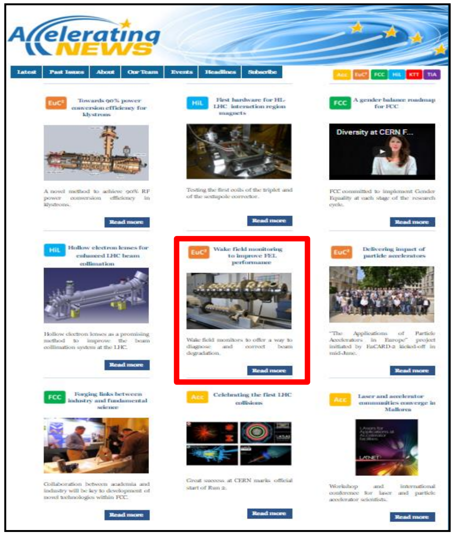
- A compendium of modes will be generated for the 8-cavity chain within modules in XFEL

- On track for deliverables/milestone. Had several skype meetings to review progress to date.

- Publication highlights: PRST-AB paper 2014 (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. Published as a EU Monograph -Vol. 33, Oct 2015 + Accel. News article June 2015 (N. Baboi + M. Dehler) on wakefield HOM monitors. Several IPAC06 + Linac06 papers

- HOMSC16 August 2016 will be held at the Univ. of Rostock (http://indico.cern.ch/event/465683/)

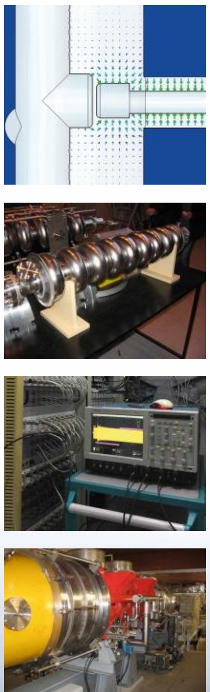




International ICFA Mini-Workshop on

High Order Modes in SC Cavities

Rostock-Warnemünde (Germany) at the Baltic Sea coast | August 22 - 24, 2016



General Information and Objectives

The workshop High Order Modes in Superconducting Cavities 2016 (HOMSC16) will be held on August 22 - 24, 2016 in Rostock-Warnemünde at the Baltic Sea. The conference venue will be "Technologiezentrum Warnemünde". The object of the workshop is to bring together researchers studying high order mode supression in superconducting cavities. The workshop will discuss the current status of both experimental and theoretical work. HOMSC16 follows HOMSC12 at the Cockcroft Institute and ASTeC, Daresbury, UK, and HOMSC14 at Fermilab, Batavia, USA.

Scientific Programme Committee (SPC)

Carsten Welsch / Cockcroft Institute
Erk Jensen / CERN
Georg Hoffstaetter / Cornell University
Jacek Sekutowicz / SLAC
Jean Delayen / Old Dominion University
Jens Knobloch / Helmholtz Zentrum Berlin
John Corlett / Lawrence Berkeley National Laboratory
Matthias Liepe / Cornell University
Nicoleta Baboi / DESY
Nikolay Solyak / Fermilab
Olivier Napoly / CEA Saclay
Roger Jones / University of Manchester
Ursula van Rienen (Chair) / Universität of Rostock
Vyacheslav Yakovlev / Fermilab

Local Organising Committee (LOC)

Ursula van Rienen (Chair) / Universität of Rostock
Thomas Flisgen / Universität of Rostock
Dirk Hecht / Universität of Rostock

Further Information and Registration

Early Bird Deadline: 25/06/2016

http://indico.cern.ch/event/465683

For further information contact:
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Workshop on HOMs in SC Cavities

- ❑ HOMSC16 at Univ. of Rostock
- ❑ Dates: Aug 22-24, 2016
- ❑ Early Reg June 25^{th}, 2016
- ❑ Papers published as NIMA special issue?
- ❑ Contact Thomas Flisgen for further details!

Task 12.4 Talks

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

- HOMBPM: Measurements of FLASH and XFEL Cavities, L. Shi (*DESY/University of Manchester*), N. Baboi (*DESY*)

- HOMCD: Characterisation of HOMs in FLASH and XFEL Coupled Cavities using GSM, N. Joshi, R.M Jones (*University of Manchester*)

- HOMGD: Progress On SCC Simulations in FLASH and XFEL Cavities, T. Flisgen, U. Van Rienen (*University of Rostock*)