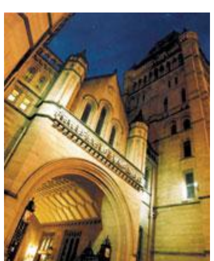
High Precision THIRD HARMONIC SC Cavity Alignment/Diagnostics/BPM with HOM Measurements

Roger M. Jones

Univ. of Manchester/ Cockcroft Inst.



- EuCARD WP10.5 Task leader on HOM Distribution (inc. 3 sub-tasks)
- EuCARD Board member

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WP 10.5 Aspects of HOMs in SC Accelerator Cavities –EuCARD FP7

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)**

EuCARD FP7 Tasks on ACC39

10.5.1 HOM based Beam Position Monitors (HOMBPM)

- Smaller irises, compared to TESLA cavities, means wakefield in 3.9 GHz cavities is larger. Emittance dilution must be managed by suitable alignment and damping
- Major goal is to develop electronics for beam and cavity alignment Multi-bunch issues need to be understood.

10.5.2 HOM based Cavity Diagnostics (HOMCD)

- Simulations conducted on complete spectrum (up to 6 bands) –dipole, monopole, quadrupole, sextupole. Single cavity + entire module + sensitivity to errors.
- HOM spectrum allows one to ascertain the cavity alignment and cell geometry:

- mechanical deviations of individual cells from the ideal geometry,
- cell-to-cell misalignment,
- deformation of fields by couplers.

10.5.3 HOM based Geometrical Dependencies (HOMGD)

- Combining finite element and S-matrix cascading techniques allows the eigenmodes in multiple accelerating cells and cavities to be efficiently modeled. CSC method used here.
- Mode sensitivity to errors in fabrication

- In HOMCD and HOMCD The University of Rostock and the University of Manchester have developed a suite of codes to rapidly calculate S matrices.
- Common goal of all sub-tasks is to develop electronics for suitable modal characterisation for HOM-BPM!

Task 10.5 HOM Diagnostics in SC Accelerator Cavities -Staff

- **Sub-task leaders**: 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)
- PhDs: Nawin Juntong (CI/Univ. Manchester), Chris Glasman, Pei Zhang (CI/Univ. Manchester/DESY)

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, PhD Student

U. Van Rienen, Univ. of Rostock

WP 10.5.1

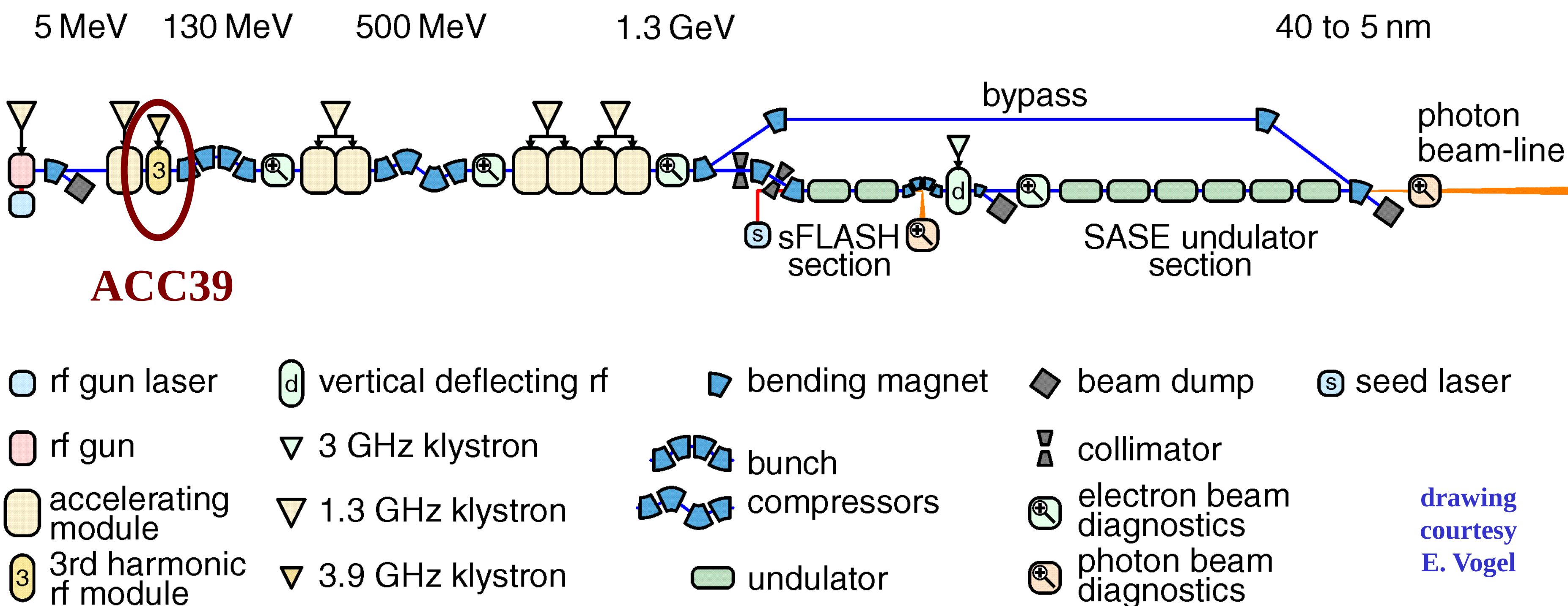
N. Baboi, DESY

P. Zhang, DESY/Univ. Of Manchester

FLASH Facility at DESY

Dual Purpose:

- User facility for VUV SASE-FEL radiation exps.
- Accelerator Test facility: for XFEL and the ILC.

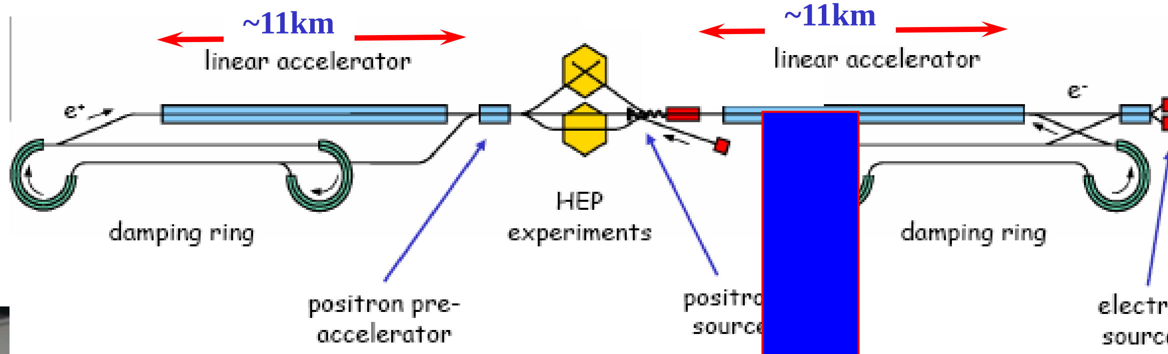


drawing courtesy E. Vogel

3. HOMs in SCRF Cavities

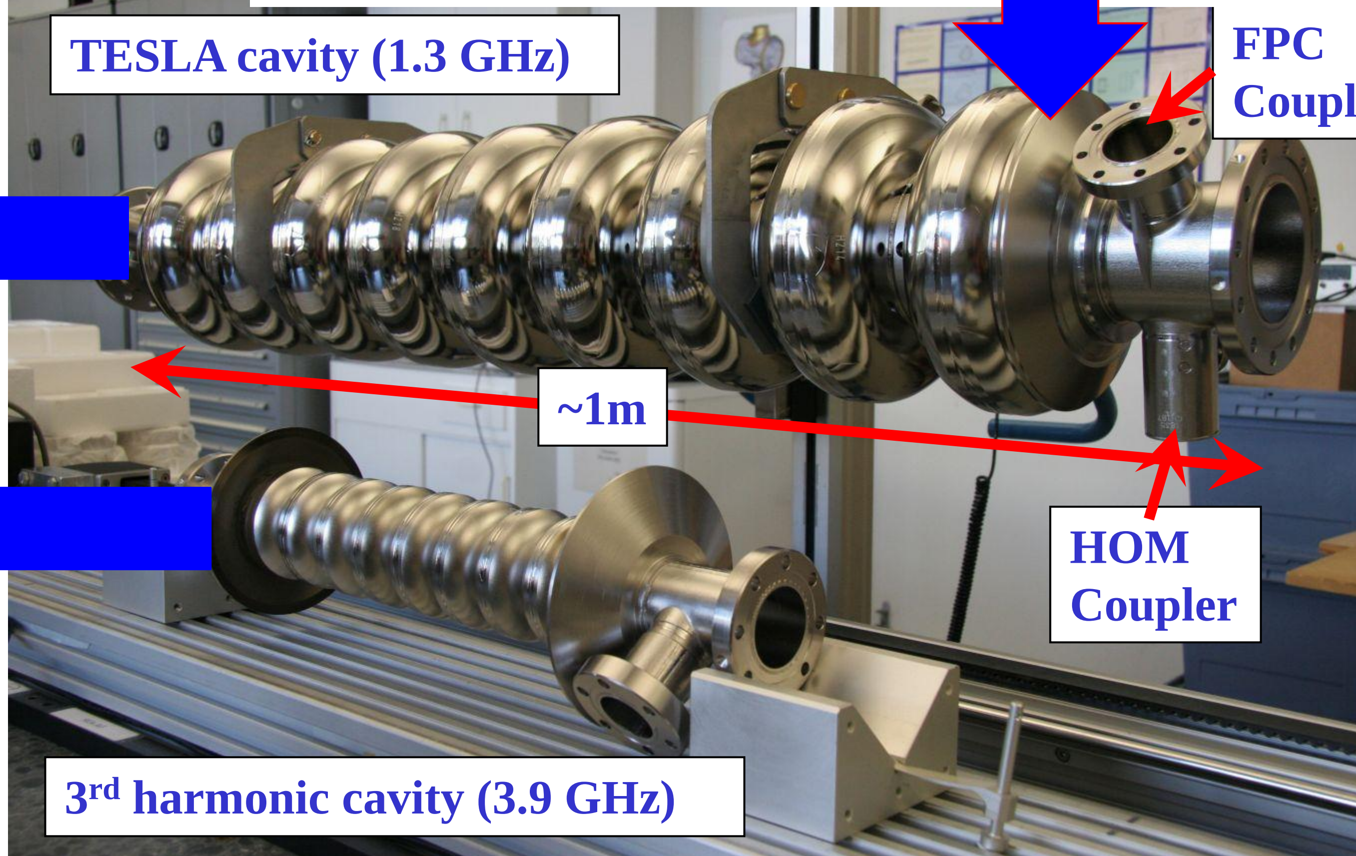
Schematic of International Linear Collider (ILC)

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.



3.9 GHz Module Installed at DESY

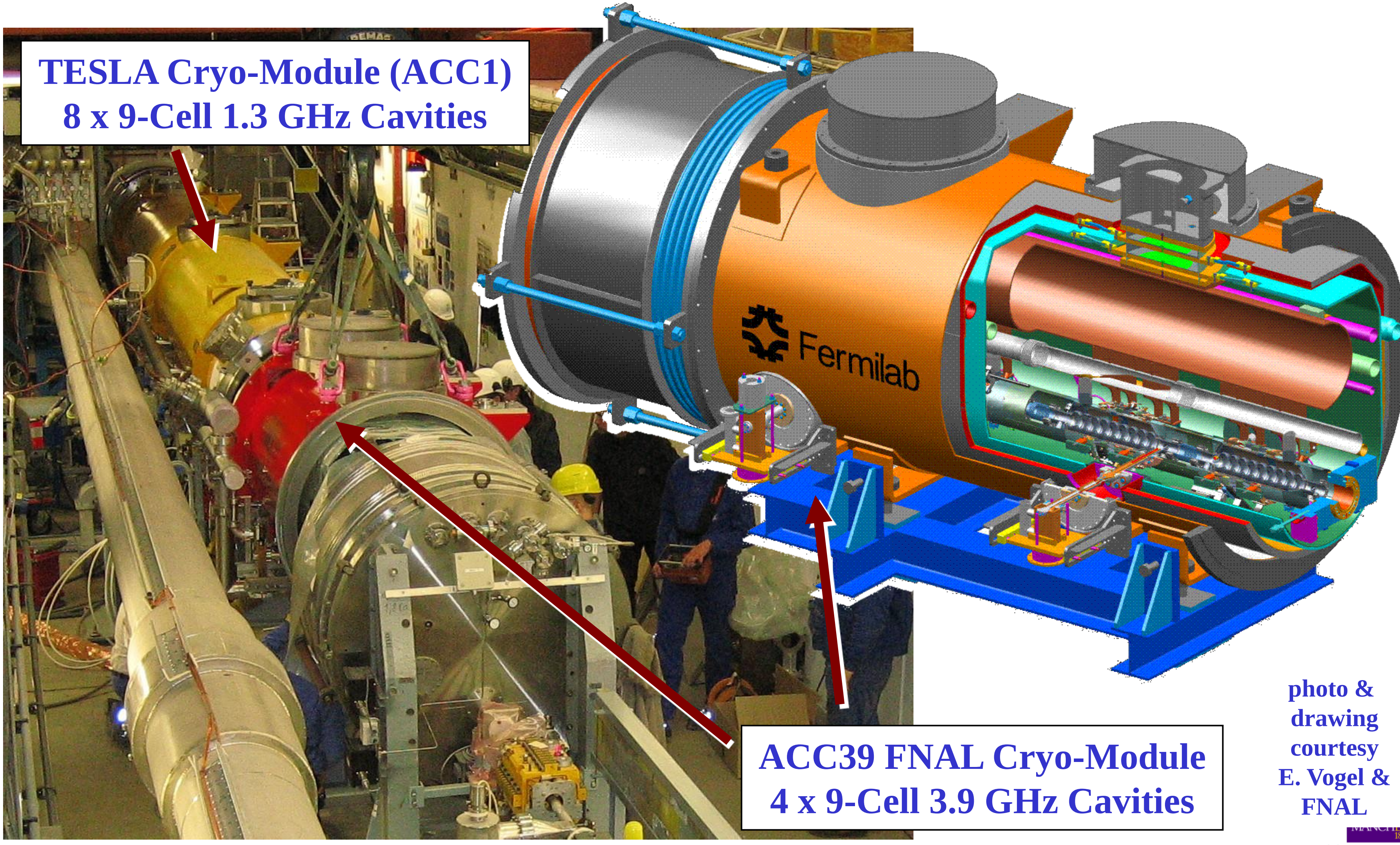
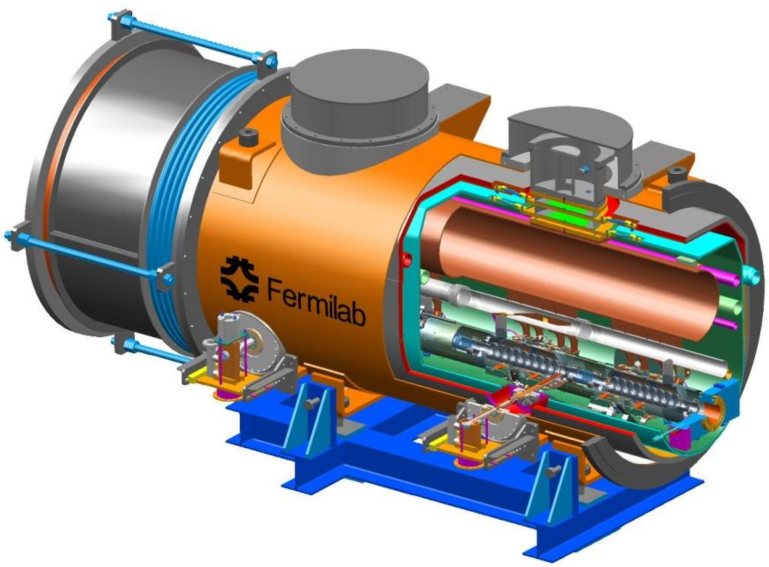


photo & drawing courtesy E. Vogel & FNAL

Overview of the Function of Third Harmonic Cavities

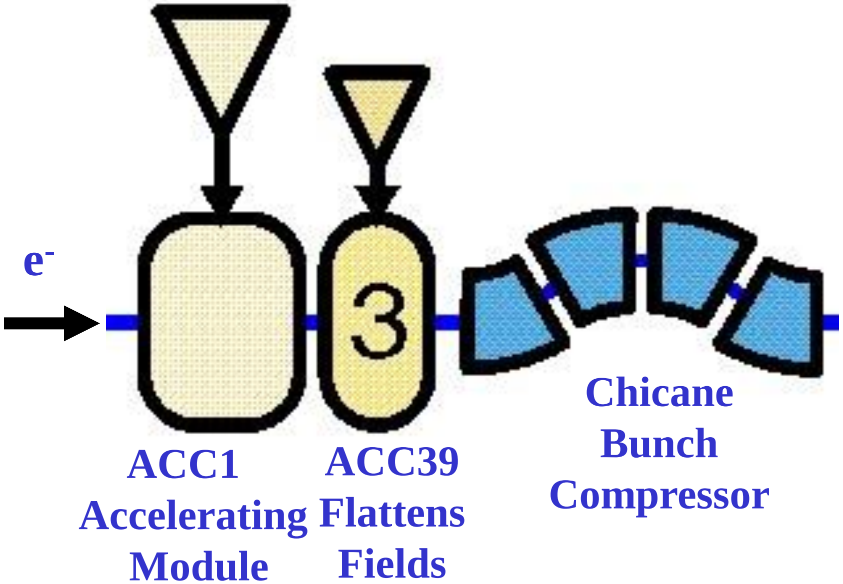
- Fermilab has constructed a third harmonic (3.9GHz) superconducting module and cryostat, ACC39, for a new generation high brightness photo-injector.
- This system will compensate the nonlinear distortion of the longitudinal phase space due to the RF curvature of the 1.3 GHz TESLA cavities prior to bunch 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 will provide the energy modulation, ~20 MV, needed for compensation.

Function of Third Harmonic Cavities

- **Bunch compression**
  - —Bunch accelerated off-crest in ACC1
  - —Head of bunch takes longer path through magnetic chicane (bunch compressor) than faster tail
    $\Rightarrow$ shorter bunch length



- **Problem**
  - —Non-linearity of RF fields in 1.3 GHz cavities gives rise to energy spread
- **Solution**
  - —Linearize RF fields with 3rd harmonics cavities

Minimising Emittance Dilution and HOMBPMs

- **Source of Emittance Dilution**

—W_t, transverse wakefields ($W_t \sim r^3$).

—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**

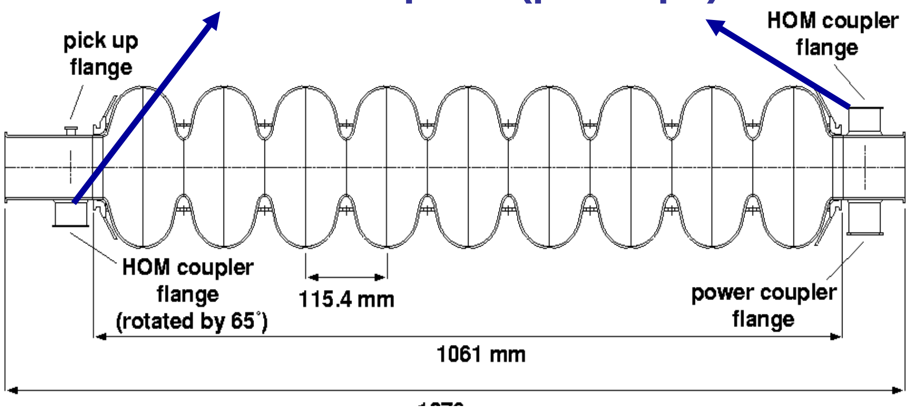
—Sample HOMs to ascertain beam position (HOMBPM).

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

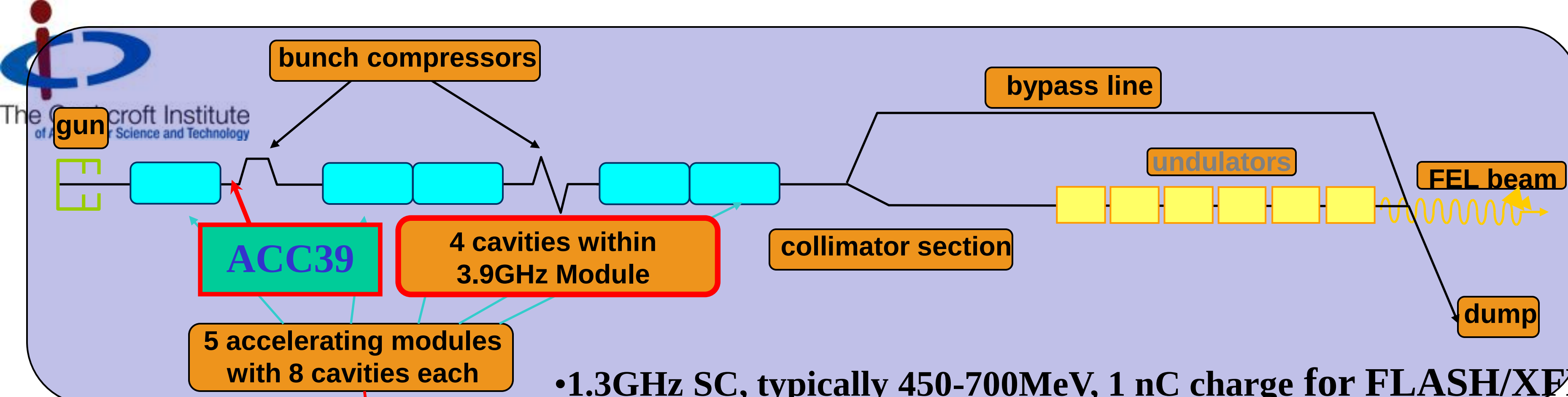
– Can also be used for measuring beam charge, phase etc.

HOMBPM Task

- 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



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



•1.3GHz SC, typically 450-700MeV, 1 nC charge for FLASH/XFEL

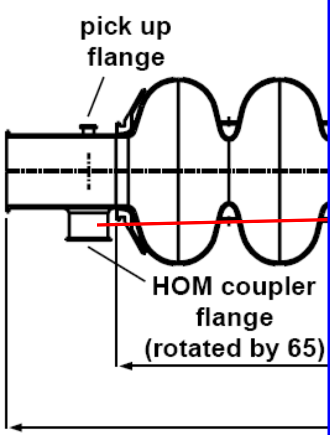
•HOMs generated in accelerating cavities must be damped.

•Monitored HOMs facilitate beam/cavity info

• Forty cavities exist at FLASH.

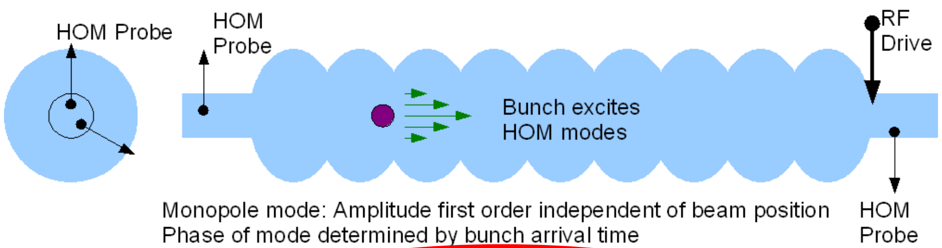
-Couplers/cables already exist.

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

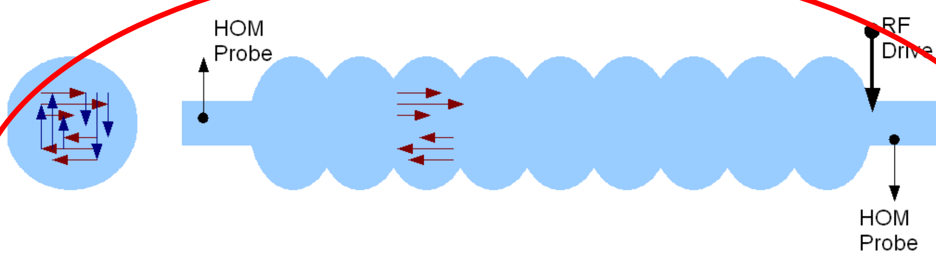


Based on 1.3 GHz (SLAC/FNAL/DESY) Diagnostics – will be redesigned for ACC39 as part of EuCARD

Response of HOMs to Beam



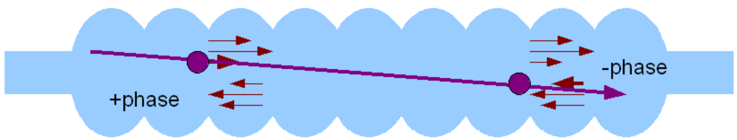
Monopole mode: Amplitude first order independent of beam position
Phase of mode determined by bunch arrival time



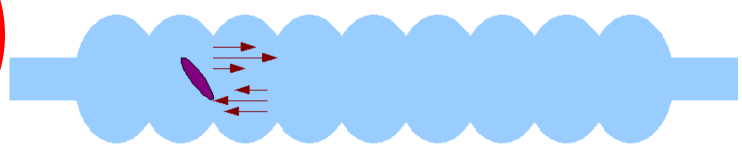
Dipole Modes: Each mode has 2 polarizations
Frequencies degenerate for ideal cavities
Frequency degeneracy broken by power coupler and fabrication errors

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



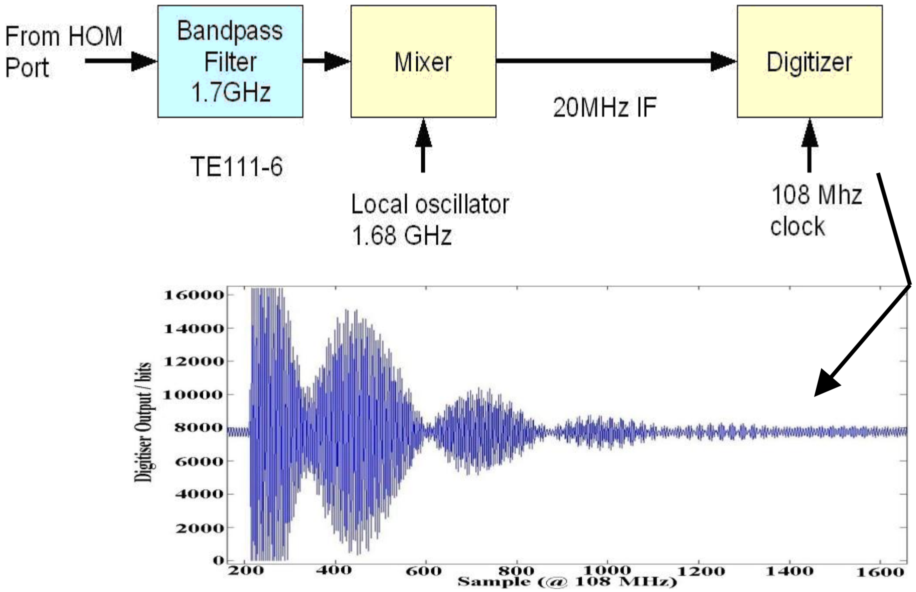
Beam at an angle will excite dipole mode with 90 degree phase shift relative to signal from position offset
Amplitude proportional to angle X effective mode length (~ 1 Meter)



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

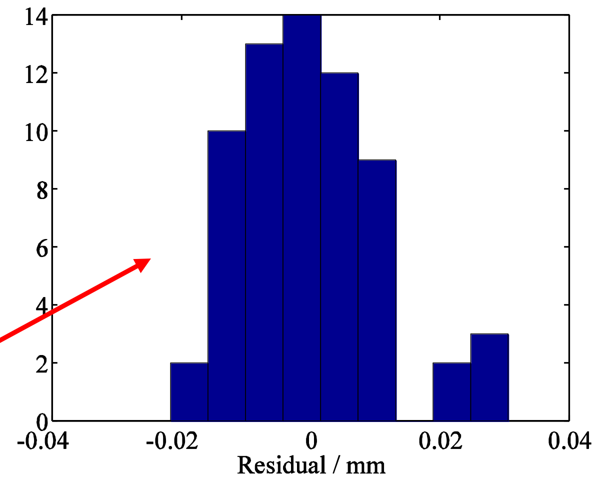
- **HOM-BPMs at 1.3GHz cavities**
  - Use dipole mode at 1.7 GHz
  - Installed in 5 accelerating modules (40 cavities)
  - Calibration: with SVD technique
    - problem: unstable in time
- **Beam Alignment in Modules**
  - Now routinely used in FLASH!

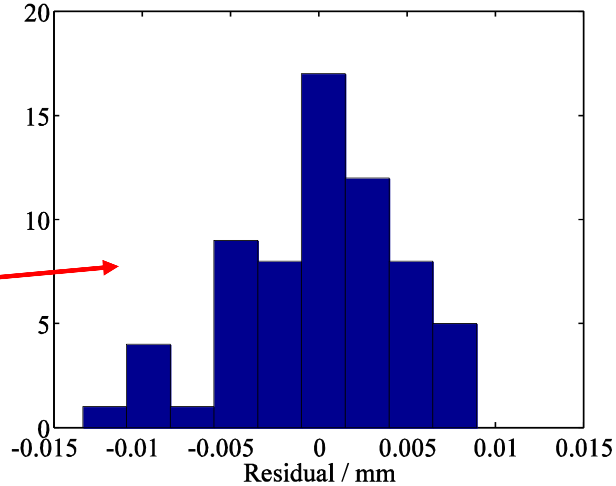


- **Other studies**
  - Cavity alignment in cryo-module
  - Beam phase measurement with monopole modes at ~2.4GHz
- **XFEL Plans:**
  - Install in some 1.3 GHz and in <u>all 3.9 GHz cavities</u>

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



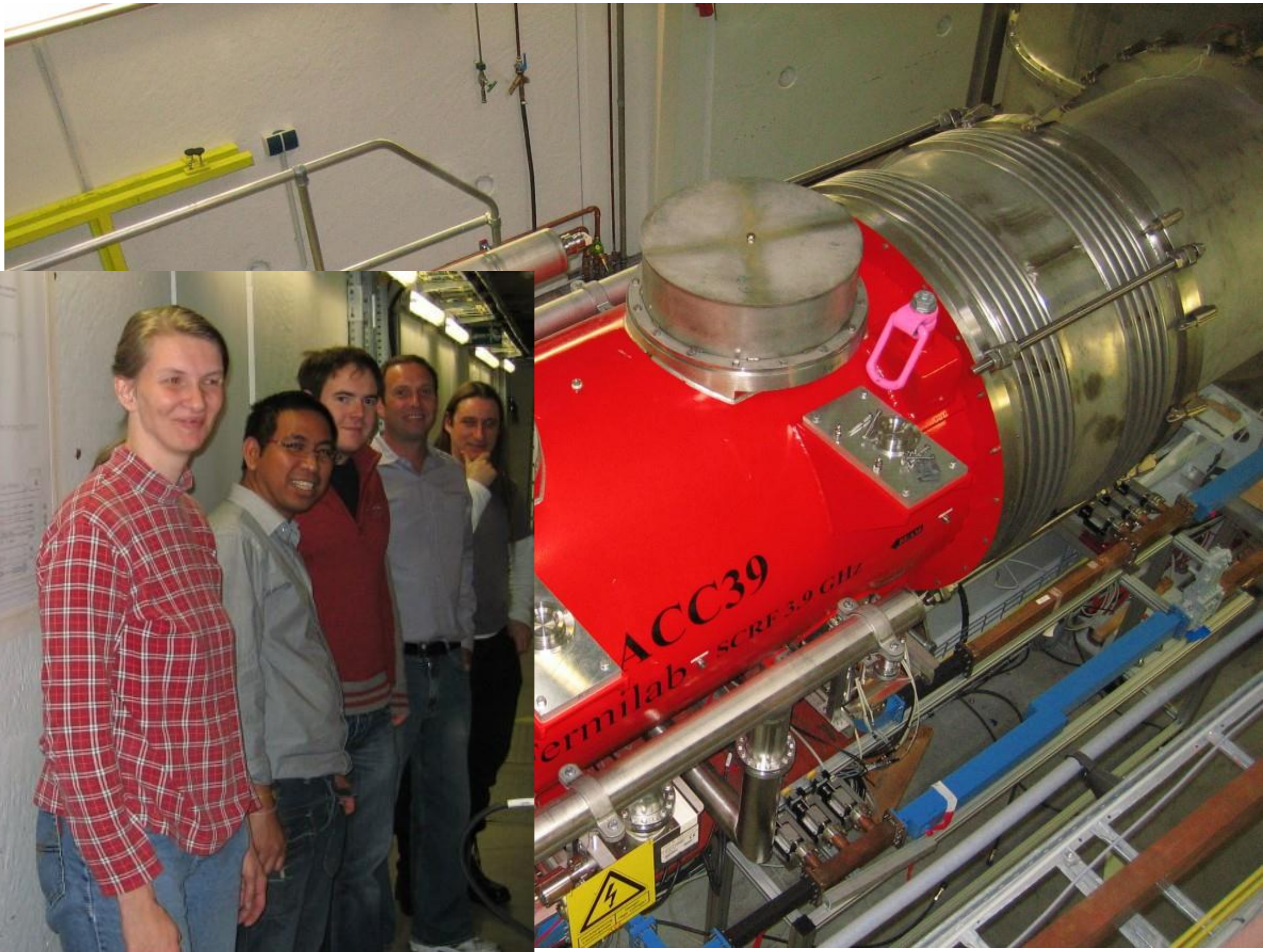


Extant Work at 3.9 GHz: HOM Spectra in ACC39

- **Prior to installation at FLASH, Spectra Measurements performed at CMTB (Cryo-Module Test Bench) facility within DESY**
  - **Sep. – Oct. 2009**
  - **Together with other EuCARD sub-tasks and with participation of Fermilab scientists (T.N. Khabiboulline e*t al*.)**
  - **First measurements in cold cryo-module**
  - **Earlier measurements made at Fermilab on isolated cold cavities**

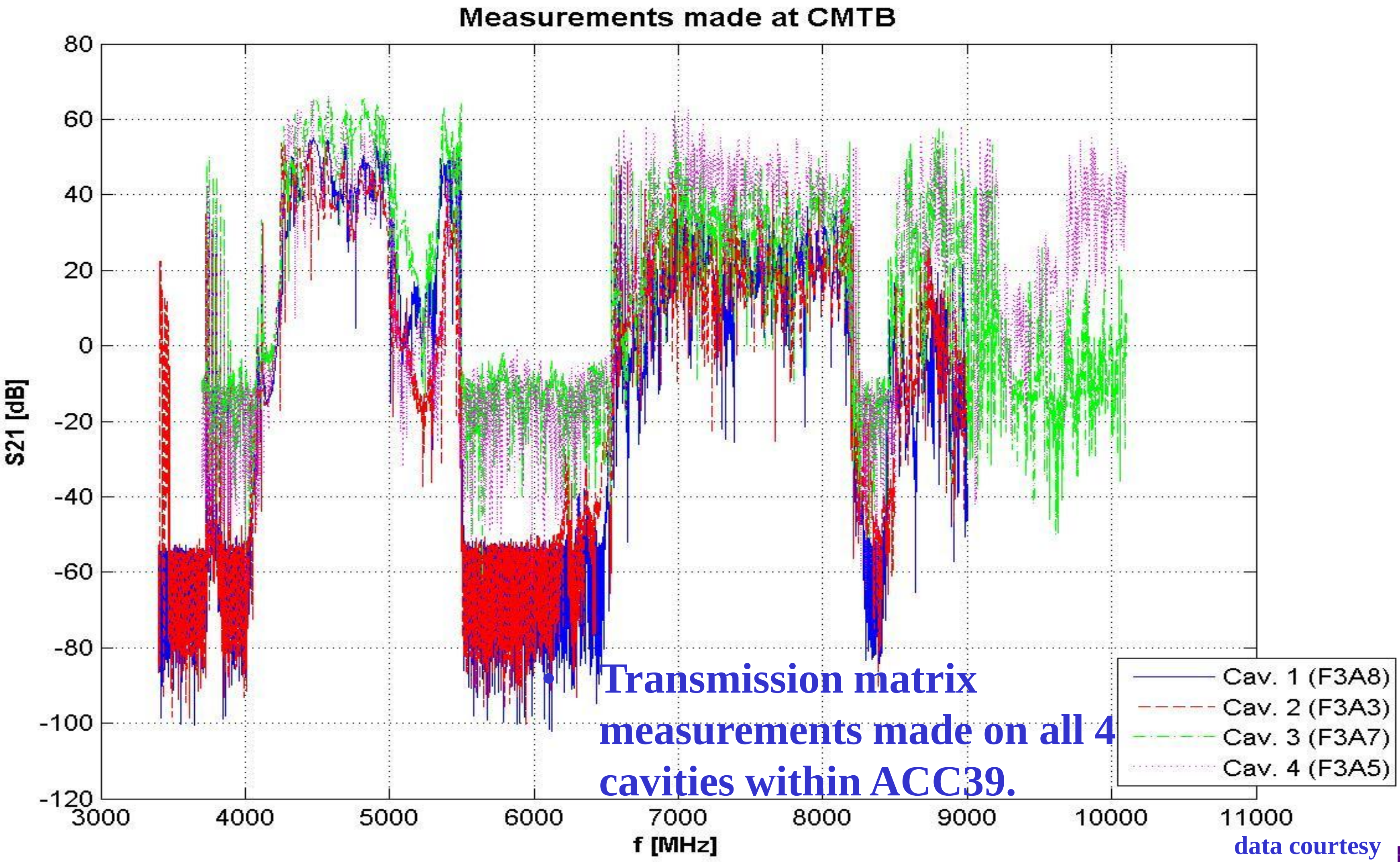
ACC39 in Cryo-Module Test Bench

Manchester University/ Cockcroft Institute
Rostock University
Fermilab
DESY



courtesy E. Vogel

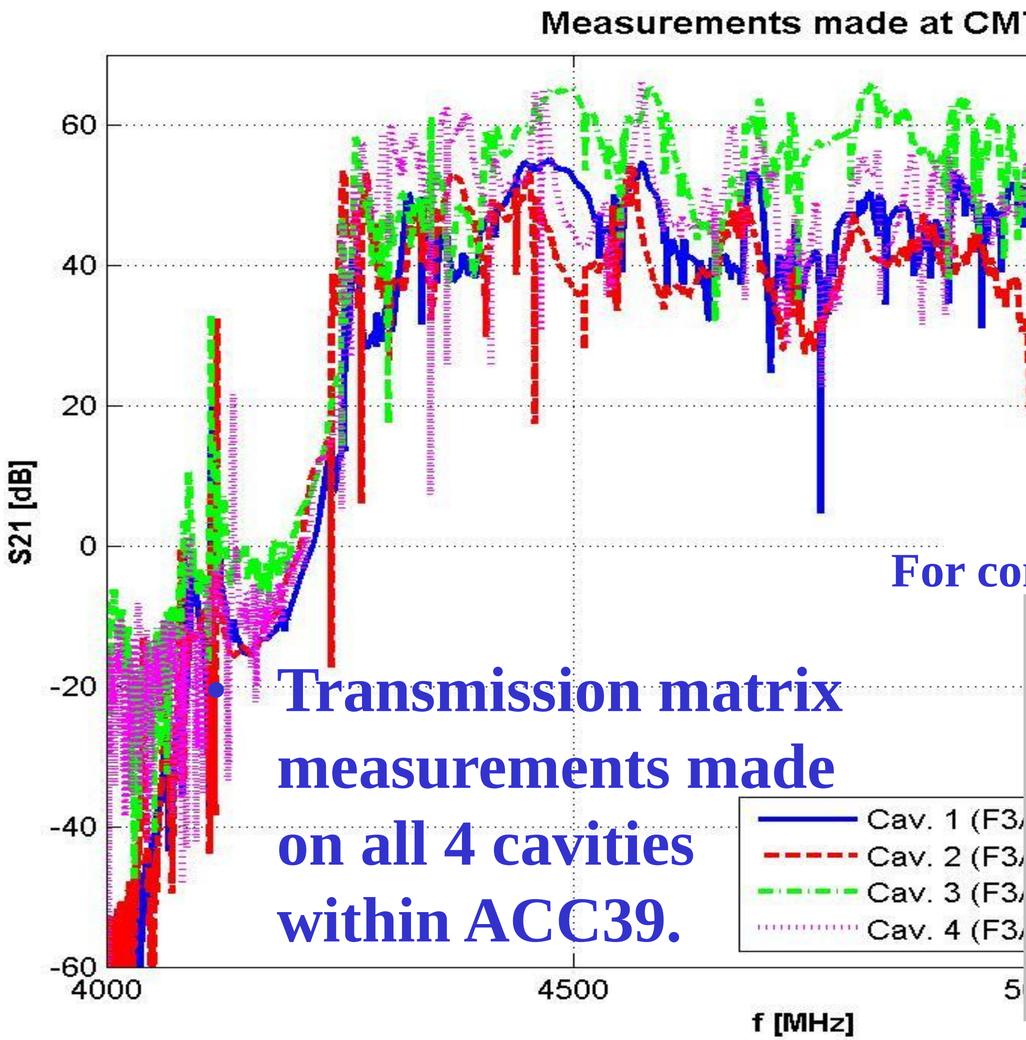
ACC39 Spectra Measured in CMTB



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

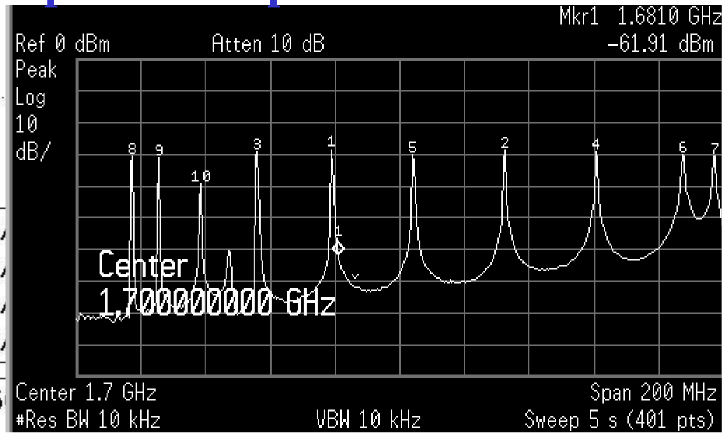
data courtesy
T. Khabibouline

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 cavi



Modes in 3.9 GHz vs 1.3 GHz Cavities

- **Higher fundamental frequency**
  - ⇒ **higher mode density than in TESLA cavities**

- **Larger beam pipe diameter coupling adjacent cavities**
  - – **low cut-off frequency (~4.39 GHz)**
    - ⇒ **most HOMs are coupled to all cavities**
  - – **TESLA cavity:**
    - **First 2 dipole bands are below beam pipe cut-off**
    - **(conveniently, modes from each cavity remain isolated)**

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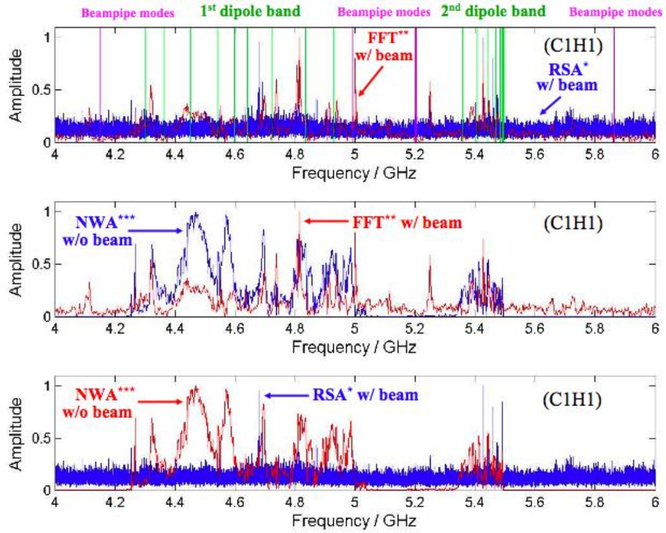
Beam-Excited Spectra of HOMs

of Accelerator Science and Technology

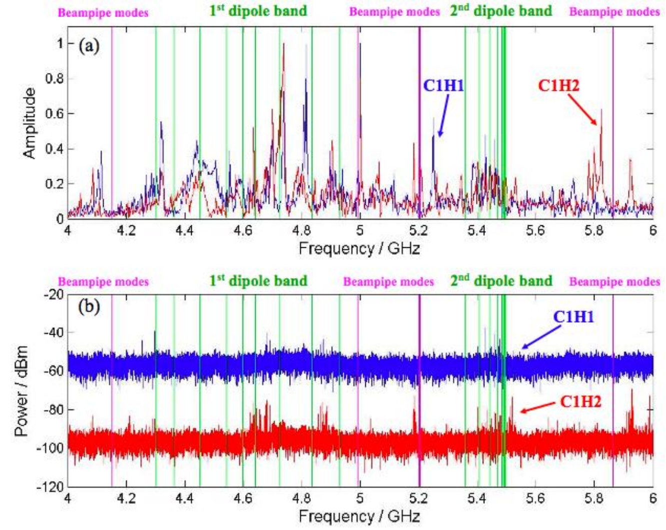
MATLAB®

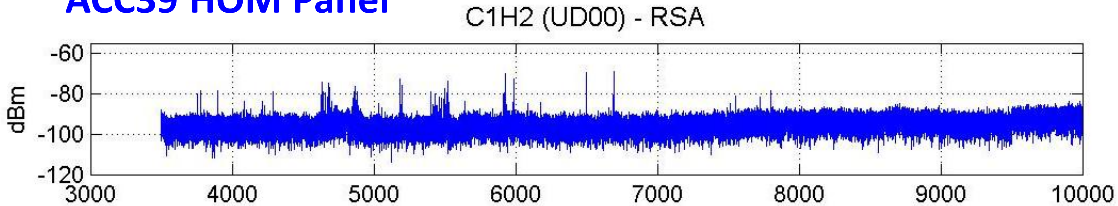
ACC39 HOM Panel

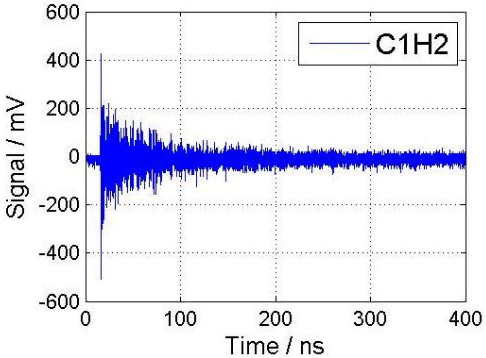
Dipole spectra comparison



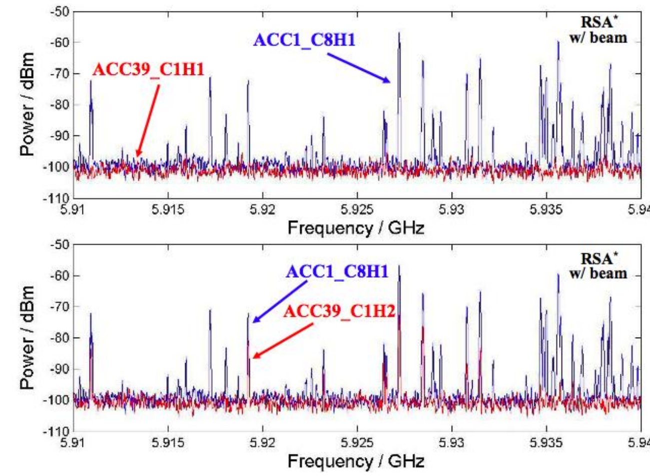
c.f. HOM Coupler Spectra







Transmission from ACC1



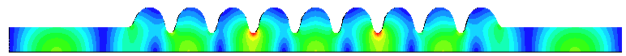
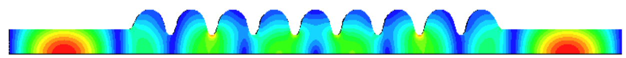
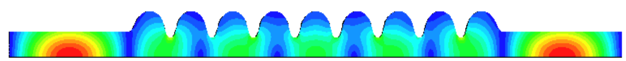
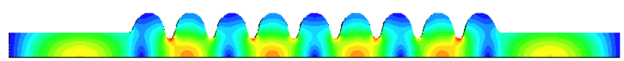
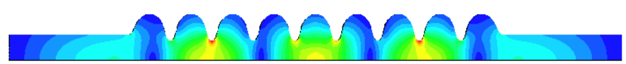
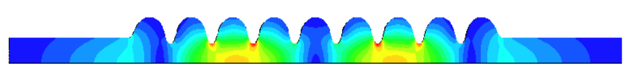
Outlook

- Detailed beam-excited mode study
- Find suitable mode(s) for diagnostic electronics design

HOMs in 3.9 GHz SC Cavities

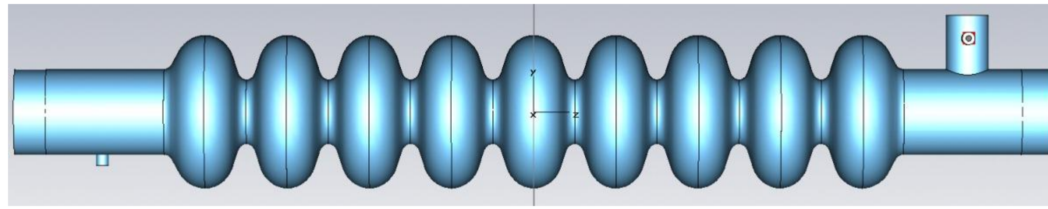
- Cavity modes up to 10GHz –allows identification of potential trapped modes and modal types, monopole, dipole, quadrupole and sextupole
- Contains all 6 cavity dipole bands below 10GHz
- Conspectus of modes from HFSS simulations (cf MAFIA simulations)

Band	HFSS		MAFIA	
	f: GHz	R/Q:Ω/cm^2	f: GHz	R/Q:Ω/cm^2
1	4.2953	0	4.3019	0
1	4.358	0.29	4.3641	0.29
1	4.446	0	4.4514	0
1	4.5388	1.08	4.5428	1.07
1	4.5972	0.79	4.5993	0.82
1	4.6399	0.16	4.6422	0.13
1	4.7227	10.37	4.726	10.39
1	4.8312	50.2	4.8341	50.7
1	4.926	30.38	4.9282	30.41

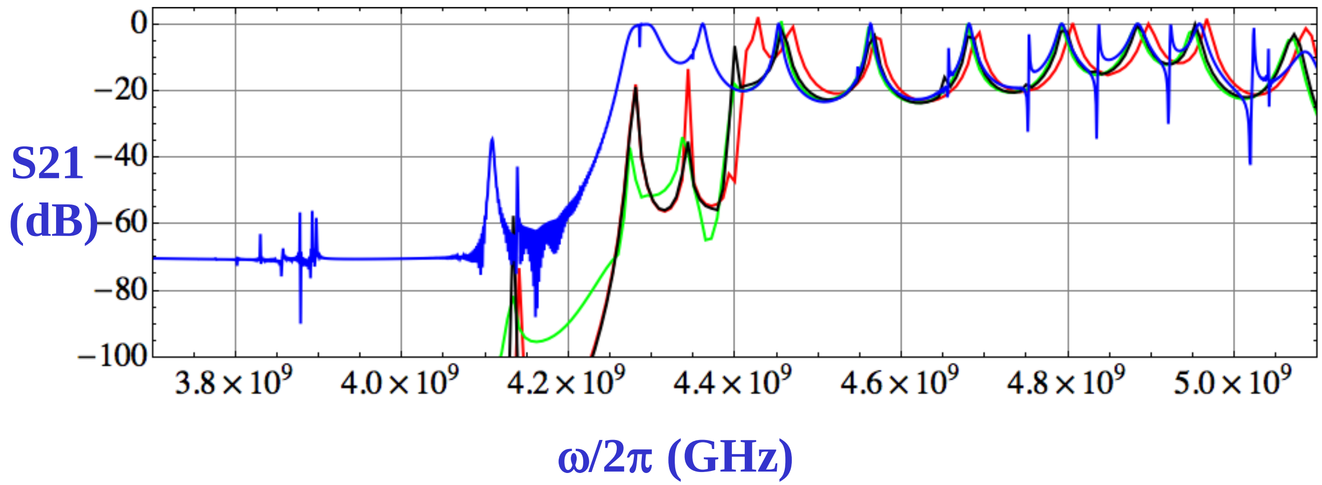
E-field distribution	ω/2π (GHz)	Band type	R/Q: Ω/cm^2
	4.2953	D Band 1 #1 EE	0.00
	4.3580	D Band 1 #2 EE	0.29
	4.4460	D Band 1 #3 EE	0.00
	4.5388	D Band 1 #4 EE	1.08
	4.5972	D Band 1 #5 EE	0.79
	4.6399	D Band 1 #6 EE	0.16

CSC Simulations of HOMs in 3.9 GHz Cavities

Simplified CAD model of single ACC39 cavity



Transmission Spectra



➢Mode spectra of a single cavity (including HOM couplers) of ACC39 obtained from CST and mode cascading simulations.

➢Here the reference result, CSC-computations using tetrahedral the f-domain solver, hexahedral t-domain and eigenmode-based solver, are shown in blue, red, green and black, respectively.

See talk by Hans-Walter Gloch, University of Rostoch

Rapid Calculations of ACC39 with GSM

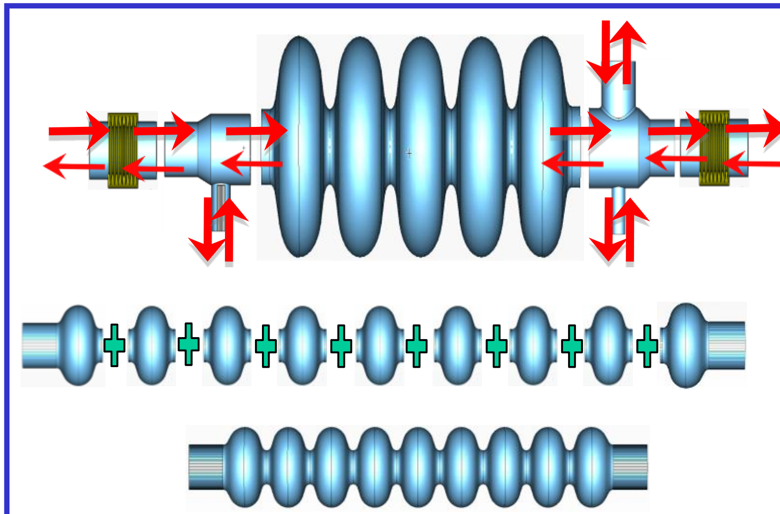
- The globalised Scattering Matrix (GSM) method is a well -established RF technique that enables the rapid calculations of large structures through the discretization of the entire structure into a series of smaller structures that can be simulated separately.
- The S-matrix of each individual section (A and B) is calculated accurately with HFSS or CST.
- The overall matrix is obtained by concatenation:

$$S_{11} = S_{11}^{A}\left(U - S_{11}^{B}S_{22}^{A}\right)^{-1} S_{11}^{B}S_{21}^{A}$$

$$S_{12} = S_{12}^{A}\left(U - S_{11}^{B}S_{22}^{A}\right)^{-1} S_{12}^{B}$$

$$S_{21} = S_{21}^{B}\left(U - S_{22}^{A}S_{11}^{B}\right)^{-1} S_{21}^{A}$$

$$S_{22} = S_{22}^{B} + S_{21}^{B}\left(U - S_{22}^{A}S_{11}^{B}\right)^{-1} S_{22}^{A}S_{12}^{B}$$

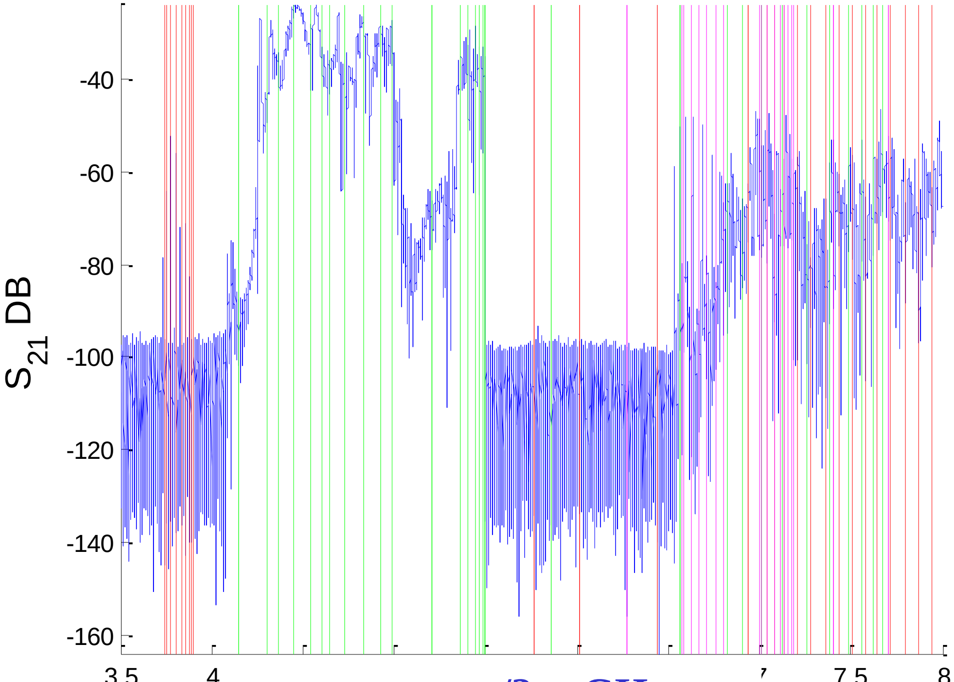


Decomposition of Single Cavity

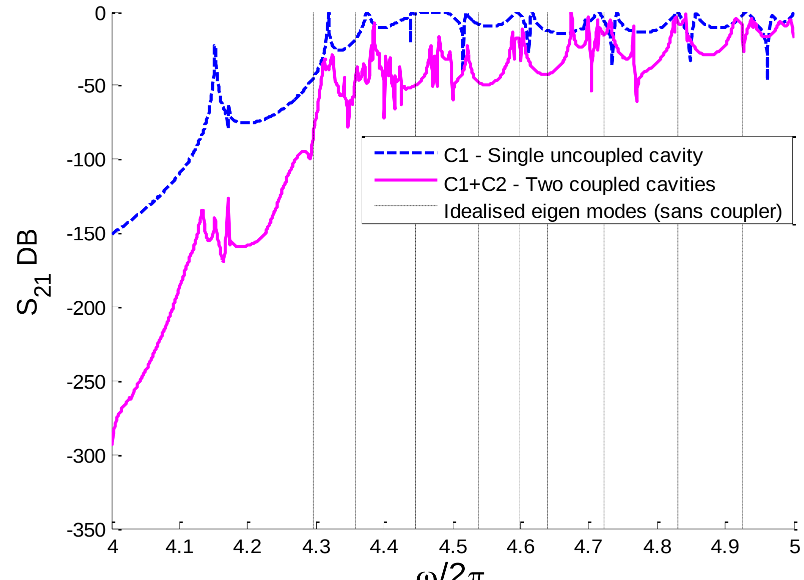
- A similar procedure is applied to an arbitrary number of sections

Interpretation of HOM Spectra

- **Detailed measurements on spectra indicate modes above the cut-off frequency of the beam tubes are radically shifted in frequency**
- **Simulations verify the strong inter-cavity coupling of modes**



ω/2π: GHz

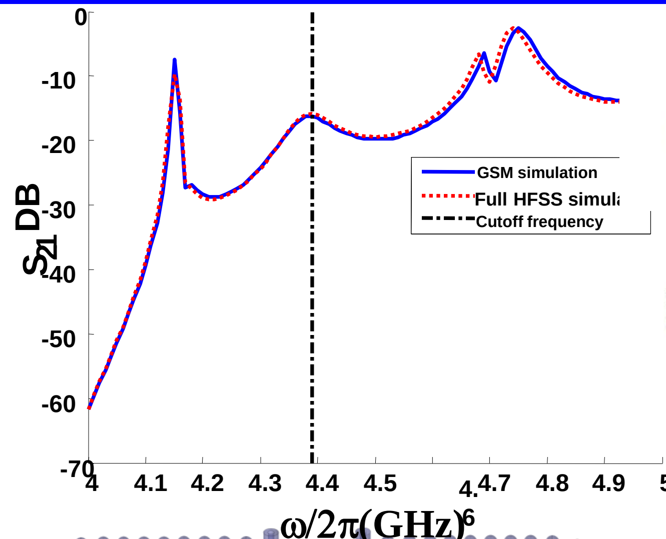


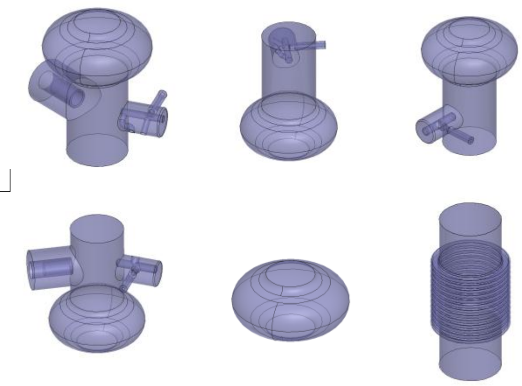
- **S21 transmission data up to 9GHz taken across C1 (from the downstream HOM of C1 to the upstream HOM of C1).**
- **Vertical lines indicate the HFSS simulations of cavity modes: red lines are monopole bands, green lines are dipole bands and magenta lines are quadrupole bands.**

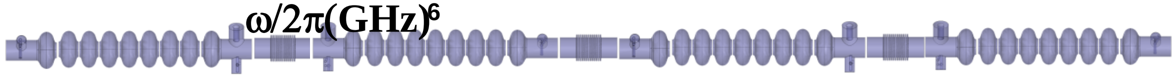
- **GSM simulations of a single cavity (C1) contrasted with two coupled cavities (C1+C2) is illustrated rightmost above**
- **HOM couplers have been included in the simulations**
- **HOM couplers split the modal degeneracy**
- **The beam-pipes ($\omega_c/2\pi$>4.39GHz) couple the dipole modes in adjacent cavities**
- **Interference effects are evident**

Applying GSM to ACC39

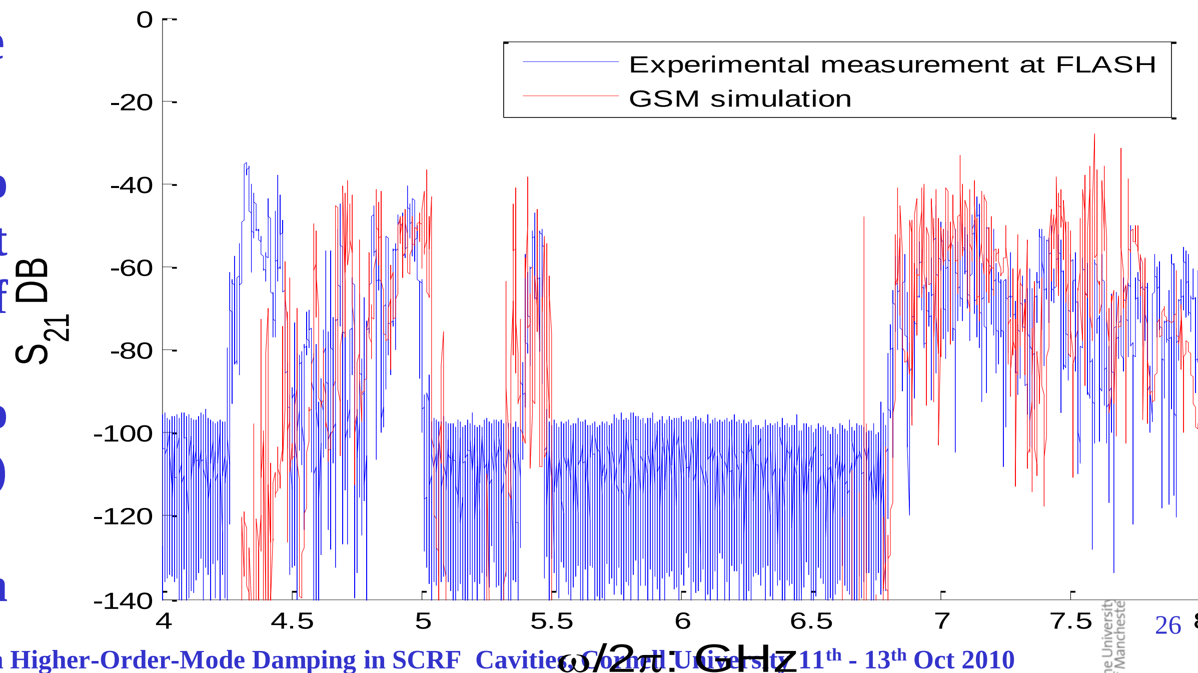
- ➢Globalised Scattering Matrix (GSM) enables rapid calculations of large structures through the discretization of structure into a series of smaller ones that can be accurately simulated separately.
- ➢Concatenated using matrix techniques to obtain the complete structure



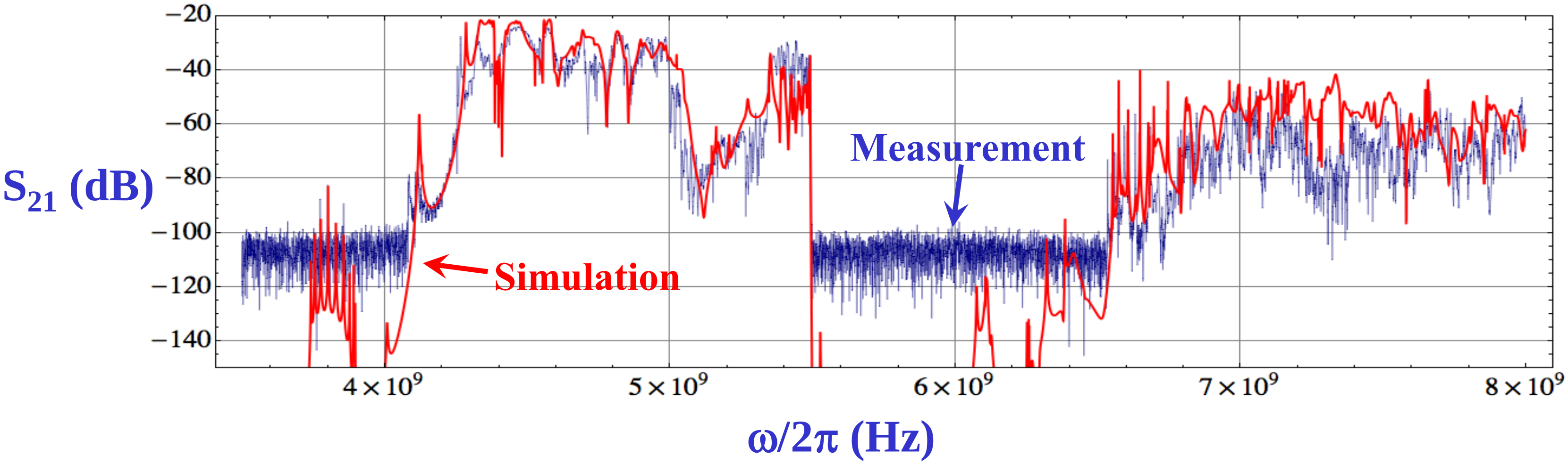




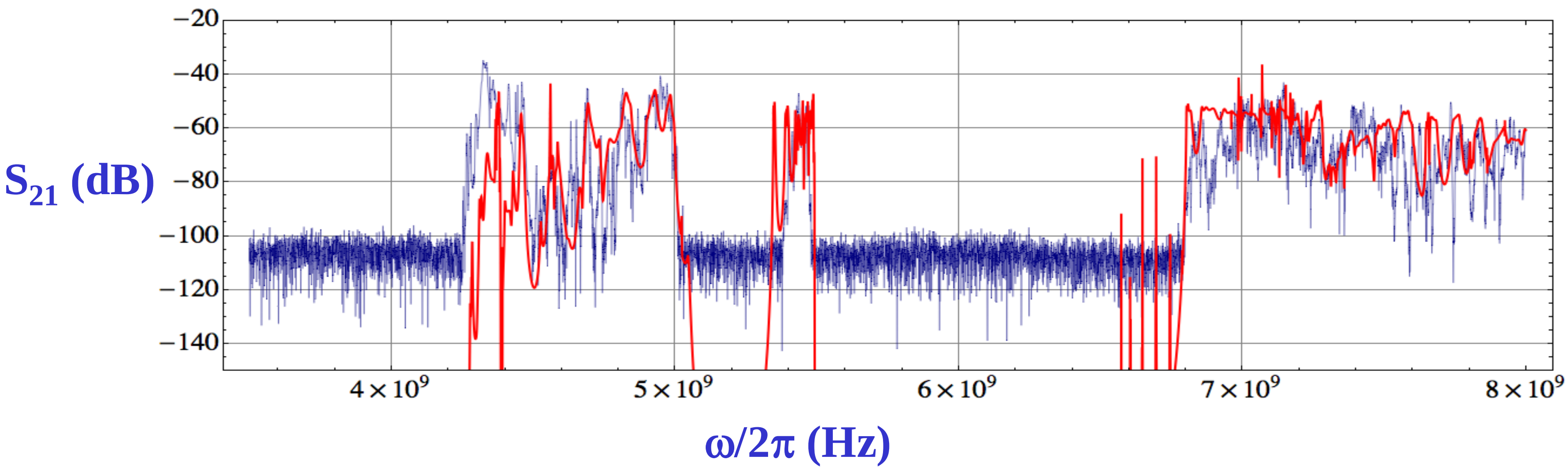
- ➢GSM method applied to ACC39 module (first HOM port of C1 to the last HOM port of C4)
- ➢Discrepancy may be due to modes below cut-off (4.39GHz) in the cascaded blocks.
- ➢Additional simulations in progress.



S21 Simulation in ACC39



Transmission through a single non-isolated cavity (C3) in chain of 4 cavities



Transmission, through complete chain (C1 to C4), HOM to HOM coupler

Concluding Remarks on HOM Third Harmonic Cavities

- ➢Third harmonic cavity module, 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 scheduled (parasitic and dedicated beam time) to assess suitable modes for HOM diagnostics.
- ➢HOM electronics will be designed and tested for 3.9 GHZ cavities in 2010/2011.
- ➢We welcome participation from other interested parties in this project –lots of problems to work on!

Acknowledgements

I wish to express thanks for the 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), 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.

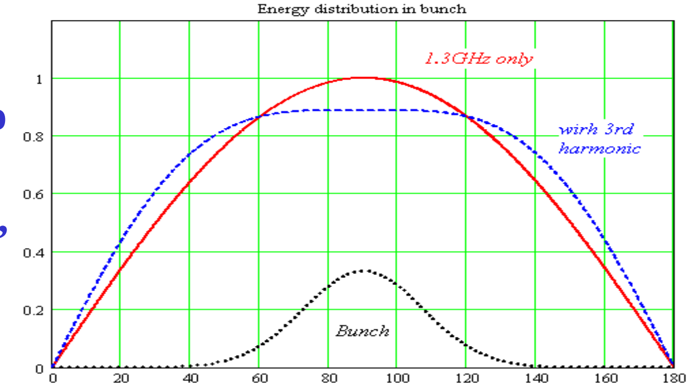
Additional Slides!

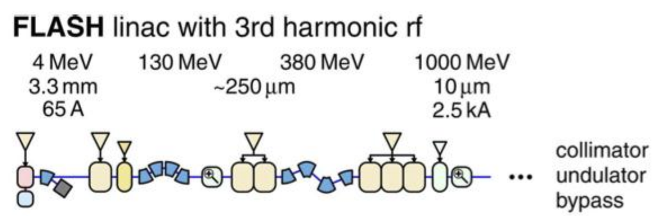
WP 10.5 ACC39 Module Parameters

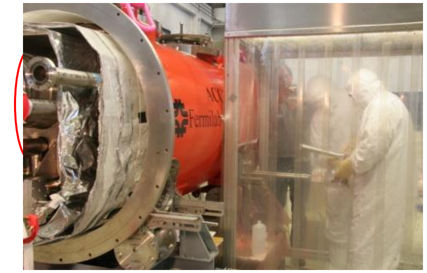
Number of Cavities	4
Active Length	0.346 meter
Gradient	14 MV/m
Phase	-179º
R/Q [$=U^2/(wW)$]	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc} = 14 MV/m)	68 mT
Q_{ext}	1.3 X 10^6
BBU Limit for HOM, Q	<1 X 10^5
Total Energy	20 MeV
Beam Current	9 mA
Forward Power, per cavity	9 kW
Coupler Power, per coupler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

- Adding 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 will linearise the energy distribution upstream of the bunch compressor thus facilitating a small normalized emittance ~1.10^{-6} m*rad.

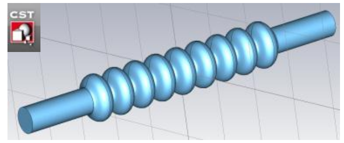
Illustrative energy (not to scale)





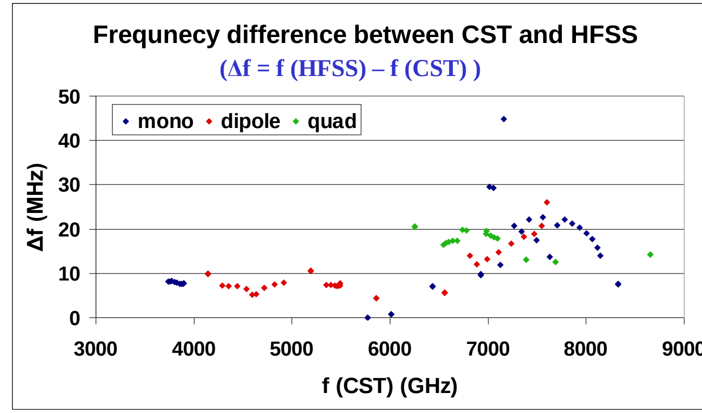


• CST Simulation

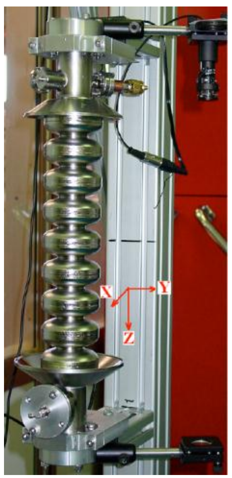


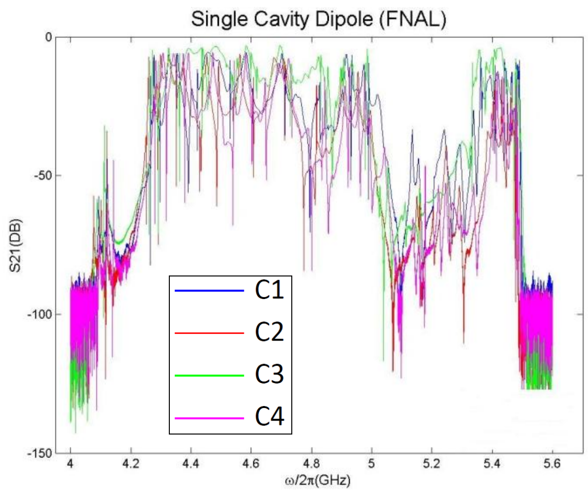
- ideal cavity using eigenmode solver

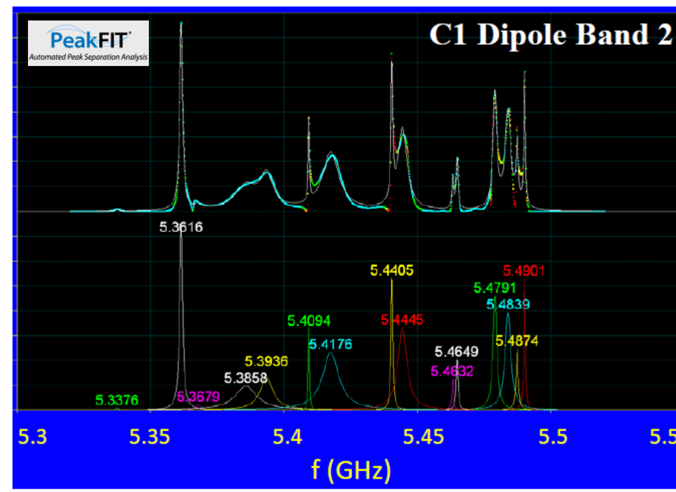
- consistent with other simulation tool

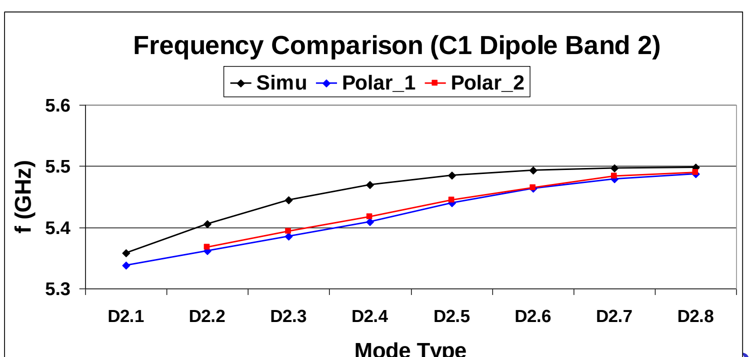


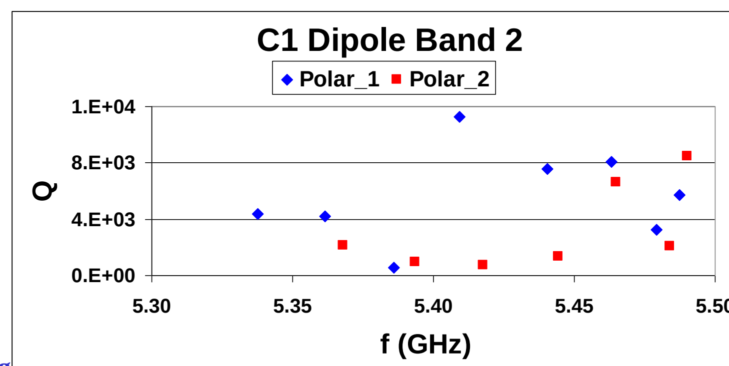
• Single Cavity Analysis (cold data from FNAL)











10.5 Aspects of HOMs in 3.9 GHz SC Accelerator Cavities

10.5.1 HOM based Beam Position Monitors (HOMBPM)

- Initial electronics have been developed for single bunch and installed at FLASH allowing the beam to be centered to ~ 5 μm.
- Method needs to be verified with additional modes
- Multi-bunch issues need to be understood.
- The 3.9 GHz bunch shaping cavities installed in FLASH can readily dilute the beam emittance –important to instrument with electronics modules to diagnose the beam position and improve the emittance.

I. Shinton, CI/Univ. Manchester PDRA at

FLASH (DESY) HOM shift

10.5.2 HOM based Cavity Diagnostics (HOMCD)

- Simulations conducted on complete spectrum (up to 6 bands)
- Participated in characterisation, S21 of HOMs at DESY CMTF
- HOM spectrum allows one to ascertain the cavity alignment and cell geometry.

- In process of investigating:
  - mechanical deviations of individual cells from the ideal geometry,
  - cell-to-cell misalignment,
  - deformation of fields by couplers.
- This requires beam-based measurements at FLASH/DESY

C. Glasman, CI/Univ. Manchester Ph.D. student at FLASH (DESY) HOM Shift

10.5.3 HOM based Geometrical Dependencies (HOMGD)

- **Combining finite element and S-matrix cascading techniques allows the eigenmodes in multiple accelerating cells and cavities to be efficiently modeled. The University of Rostock and the University of Manchester have developed a suite of codes.**
- **Means to determine**
- **Applying these powerful computing methods in order to specify allowable tolerances on fabrication and alignment of the TESLA cells and cavities (see Shinton *et al.*, SRF 2009)**

Manchester/Cockcroft 2008-2010 Exp/Beam Time Shifts at FLASH (DESY)

Jan/Feb 2010 installation in FLASH anticipated and beam-based measurements of modes

Oct 2009 -Shinton (PDRA)/Juntong (Ph.D. Student); CI/Univ. of Manchester

Participated in S21 mode measurements of 4-cavity modules at CMTF (Cryo-Module Test Facility), DESY. Coupled modes observed. Data analyzed.

September 2008 -Shinton (PDRA)/Glasman (Ph.D. Student), CI/Univ. of Manchester)

21/9/08 – 29/9/08: 1: Collaborative shift, 3 HOM phase/position assigned shifts

January 2008

15/1/08-23/1/08: 5 shifts in total: remote access control of the machine achieved, 5 collaborative shifts in which calibration data was taken, Multibunch data taken, Phase measurements taken across module 5 for various offsets (beam moved in a circle) – broadband data.

Shinton/Juntong, Oct'09 CMTF measurements