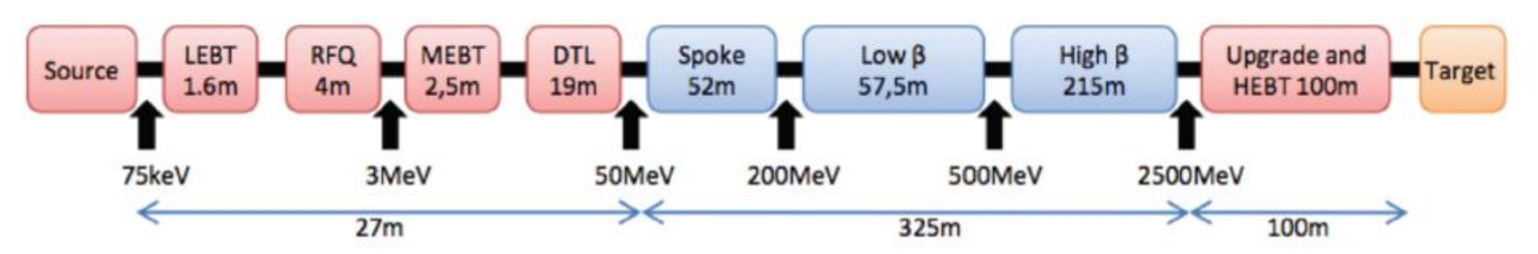
HOMs in ESS Cavities: Spoke and Elliptical Work Proposed

Roger M. Jones, Univ. Manchester/Cockcroft Inst.

1. **Wakefields and HOM beam dynamics for ILC and XFEL:**
   - **SC cavity high gradient optimisation**
   - **Main linac e.m. field and beam electrodynamics**
   - **HOM measurements/diagnostics at FLASH (FP7)**

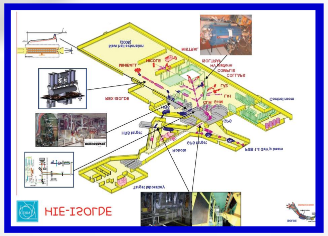
2. **HIE-ISOLDE –Collaboration with CERN colleagues on *LINAC* component of upgrade to REX-ISOLDE**
3. **Application to ESS cavities**

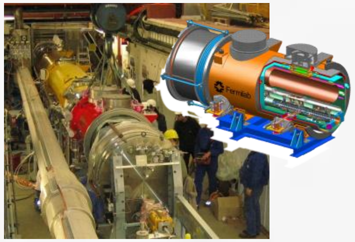


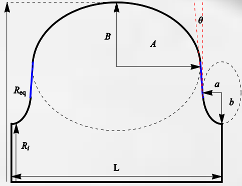
Source – LEBT 1.6m – RFQ 4m – MEBT 2,5m – DTL 19m – Spoke 52m – Low β 57,5m – High β 215m – Upgrade and HEBT 100m – Target

75keV, 3MeV, 50MeV, 200MeV, 500MeV, 2500MeV

27m, 325m, 100m







UK Membership

The United Kingdom will be the 17th country to join the European Spallation Source project. The UK was welcomed today at a meeting in Bilbao, Spain, by representatives from the current 16 Partner Countries.

- ***I am particularly happy that the UK now joins the project. The UK has a large and strong neutron research community, that will now be able to benefit from the opportunities that ESS can give, says Colin Carlile, the ESS Director-General. There is a vast knowledge of the necessary technology for building a spallation neutron source from the ion source to the instruments in the UK and there will be mutual benefits.*** **(source ESS news 15th April 2011)**

Overview

- **Focus of μ (Microwave Electrodynamics and Wakefields) group is on SC and NC cavities -with some other activities.**

- **SC cavities, frequency range ~ 1.3 GHz (XFEL/ILC) , 3.9 GHz (FLASH), 101 MHz (HIE-ISOLDE).**

- **ESS spoke and 704 MHz elliptical cavities**

- **We investigate wakefields/impedances, HOM damping, maximising gradient, computational methods.**

Personnel

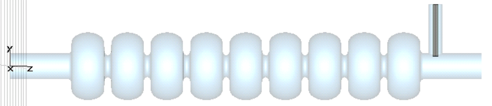
PDRAs: ***Ian Shinton (Univ. Manchester), Alessandro D'Elia (Univ. Manchester/CERN),*** Inna Nesmiyan, TBH

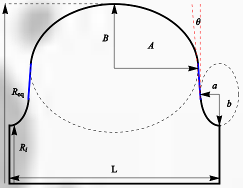
Ph.D. Students: ***Chris Glasman, Nawin Juntong, Lee Carver, Narong Chanlek, Matthew Fraser, Hugo Day , N. Shipman***

Graduated PhD students: Vasim Khan (now CERN Fellow)
Graduated MSc students: Narong Chanlek, Chris Glasman (Univ. Manchester)

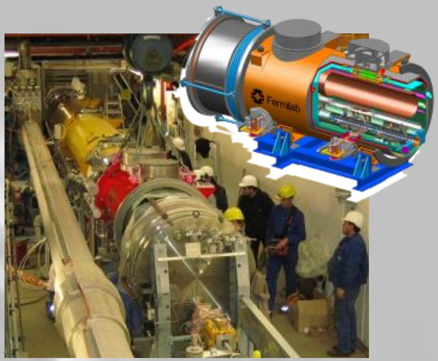
Collaborators: Walter Wuensch, Alexei Grudiev, Riccardo Zennaro, Germana Riddone (CERN), Nicoleta Baboi (DESY), Ulla van Rienen (Univ. Rostock), Mats Lindroos, Steve Peggs, Steve Molloy (ESS), Toshiyasu Higo, (KEK), Graham Burt, Amos Dexter, Richard Carter (Univ. Lancaster), Valery Dolgashev (SLAC)

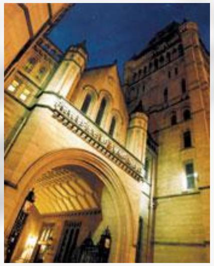
1. ILC High Gradient Cavities and FLASH/XFEL Third Harmonic Cavities





Roger M. Jones
Cockcroft Institute and
The University of Manchester





LC + XFEL SC Linac -Staff

- Roger M. Jones (Univ. of Manchester faculty)
- Ian Shinton (Univ. of Manchester PDRA based at Cockcroft –April 2009, 100%)
- Nawin Juntong (Ph.D. student, 100%)
- Chris Glasman (Ph.D. student, 100%)
- Part of EuCard (European Coordination Task Leader for Accelerator Research and Development) FP7 SCLinac Task 10.5. Three associated sub-tasks.

CI/Univ. of Manchester PDRA I. Shinton (left) and Ph.D. student N. Juntong (right; supported by the Royal Thai Government and Thai Synchrotron Light Source)

- EuCARD FP7 WP 10.5 Members:

R.M. Jones, N. Baboi (DESY), U. Van Rienen (Univ. Rostock)

Overview

Two Main Parts:

1.0 Introduction to Globalised Scattering Techniques

1.1 ILC High Gradient Cavities* * *: New Low Surface Field Design
-exploration of large parameter space

1.2 Third Harmonic Cavities at FLASH/XFEL –entails intensive simulations and construction of HOM diagnostics

***Detailed beam dynamics simulations by Glasman *et al.* on several alternative high gradient designs have also been conducted, but skipped here due to time constraints!**

Refs:
1. Juntong et al, PAC09, SRF2009
27Shinton et al, SRF 2009

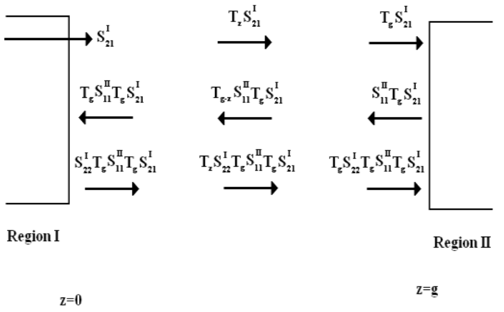
1.0 Introduction to Globalised Scattering Techniques

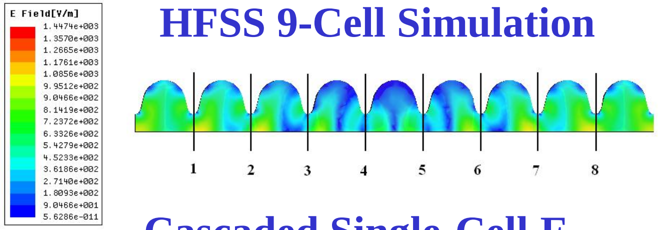
- **Simulation of Higher Order Modes (HOMs) in high gradient cavities**
- **Utilise 3D codes: GdfidL, HFSS, ACE3P suite**
- **Use 2D codes, ABCI, Echo2D for bulk of cavity structures.**
- **Develop interface that *cascades* given sections to make more efficient calculations of overall fields.**
- **Focus on:**

1. **Re-entrant -Cornell Univ. design**
2. **Low-loss (Ichiro variant) –KEK design.**
3. **Z. Li's redesign**

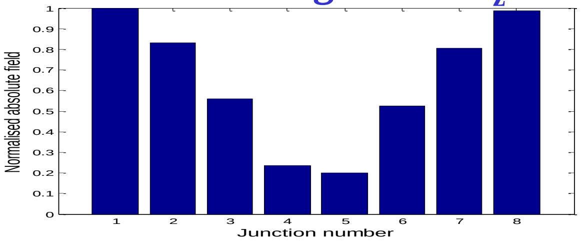
1.0 Cascaded Computation of EM Fields and Dispersion Relations

Field Calc. from S-Matrix




HFSS 9-Cell Simulation

Cascaded Single-Cell E_z



- ➢**Field distribution** at interface enables rapid determination of fields and potentially trapped modes

- ➢Fields obtained from HFSS single cells cascaded

$$\bar{a}_{nm} = \frac{2a^2 X_n J_0(X_n a/b)}{b^2 J_1(X_n)\left((X_n a/b)^2 - X_m{}^2\right)}$$

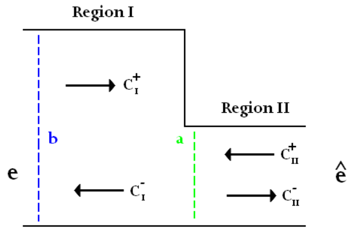
$$S_{21} = 2\left(U + \hat{Z}\bar{a}^t Y \bar{a}\right)^{-1} \hat{Z}\bar{a}^t Y$$

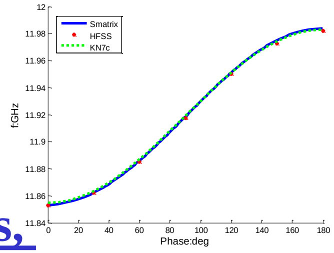
$$S_{11} = \bar{a} S_{21} - U$$

$$S_{22} = 2\left(U + \hat{Z}\bar{a}^t Y \bar{a}\right)^{-1} - U$$

$$S_{12} = \bar{a}(U + S_{22})$$

$$\cos\Phi = \frac{1 + S_{21}(1,1)^2 - S_{11}(1,1)^2}{2S_{21}(1,1)}$$





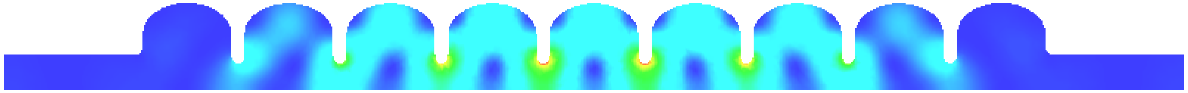
- ➢**Dispersion Calculations** via GSM enables efficient characterisation of cavities

- ➢**Bethe hole perturbation** coupling formulation investigated for X-band structures. Good agreement for a limited cells (thin iris approx)

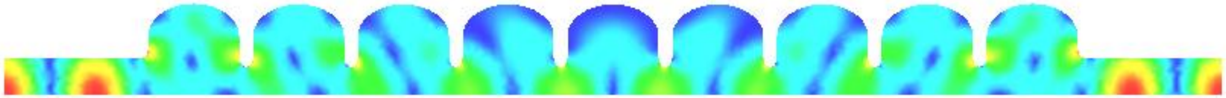
See Shinton and Jones, LINAC08.

1.0 HOMs studies for ILC ACD

Ichiro Cavity fabricated at KEK

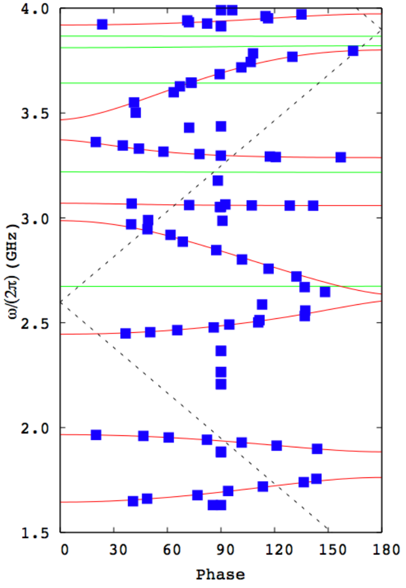


Trapped mode ~2.4498GHz



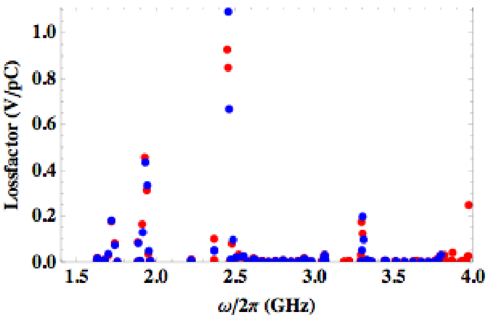
Multi-cavity mode ~2.6420GHz

Simulations of E-field of the 3rd band modes in Ichiro cavities



Dispersion curves of first 8 dipole and 5 sextupole bands

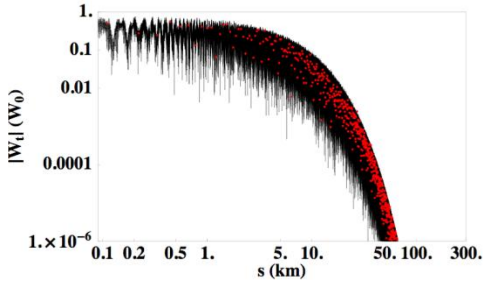
See Glasman, Jones et al. EPAC08 &LINAC08.



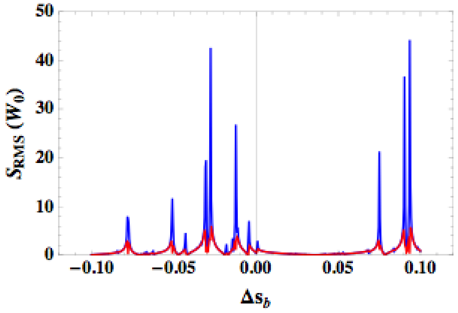
Comparison of Loss factors calculated with GdfidL (red) and MAFIA 2D (blue)

Detailed studies conducted on HOMS in Ichiro cavity. Sensitivity to systematic changes in frequency investigated.

Detailed comparison of codes – MAFIA,HFSS, GdfidL, Analyst.



Envelope of long-range wake-field

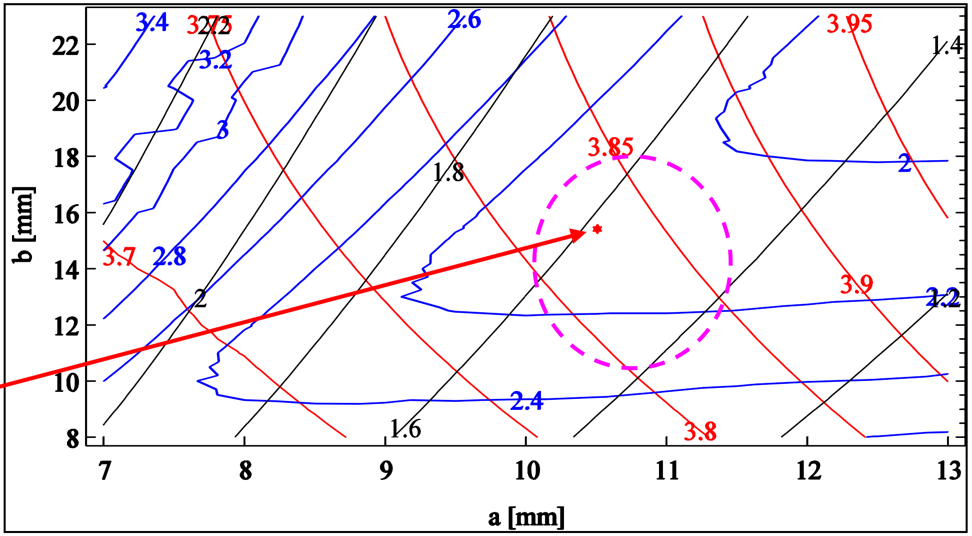


Sensitivity of RMS wake to small changes in bunch spacing

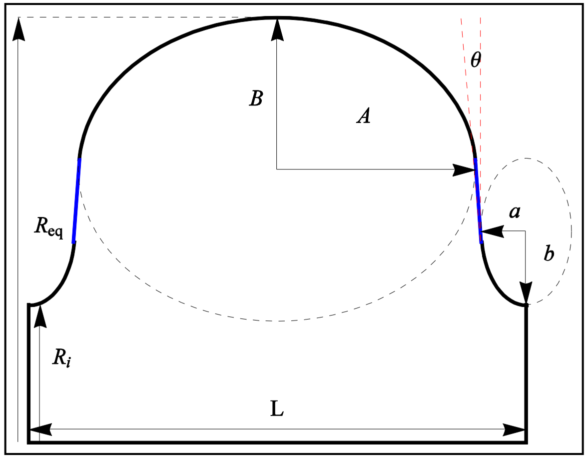
1.1 NLSF Design

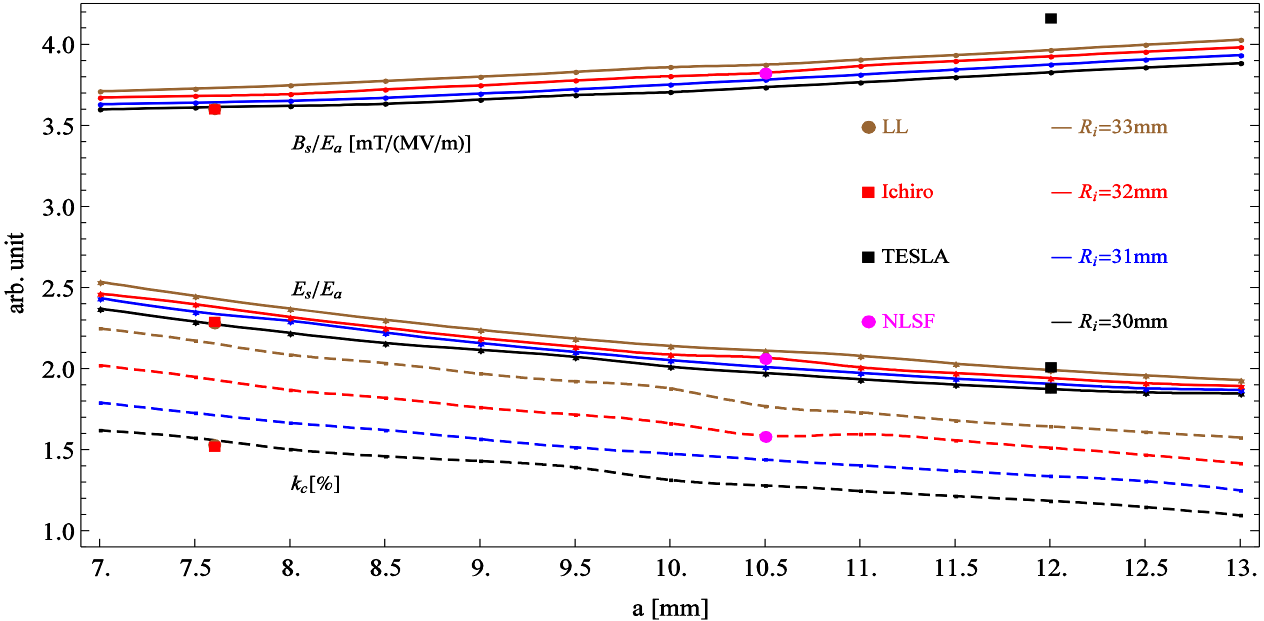
- ➢**Explore parameter regions for NLSF cavity with an iris range of 30 to 33 mm (whilst the iris thickness is varied).**
- ➢**The parameter regions for an iris of 32 mm is shown.**

Red- Bs/Ea, **Blue- Es/Ea**, **Black- k_c**

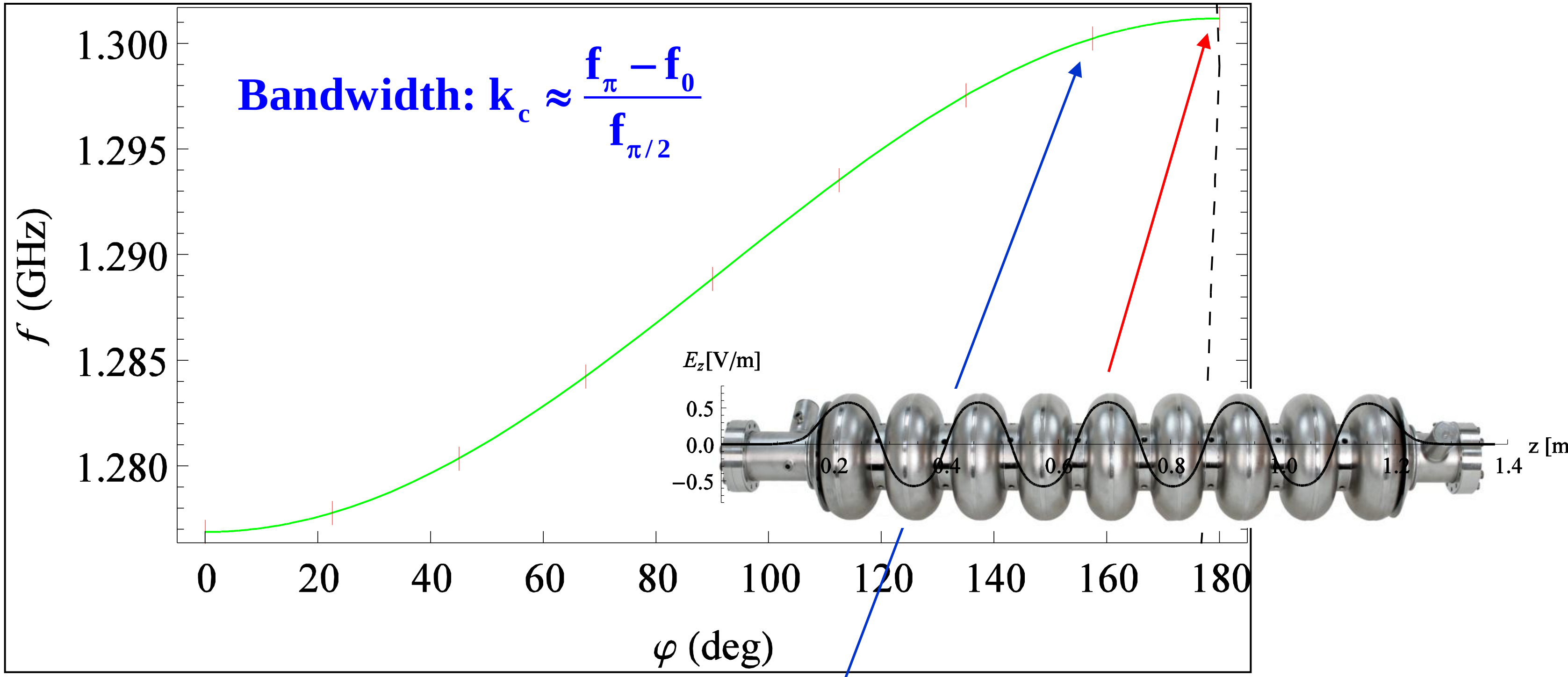


NLSF shape

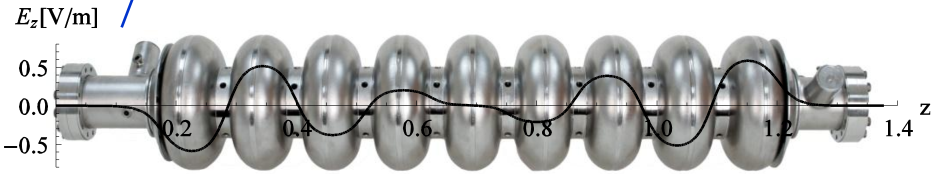




1.1 NLSF Design - Bandwidth



Bandwidth: $k_c \approx \dfrac{f_\pi - f_0}{f_{\pi/2}}$



1. Fundamental mode

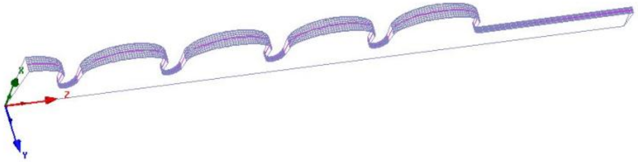
2. Nearest mode ($f_{8\pi/9}$) closely separated:

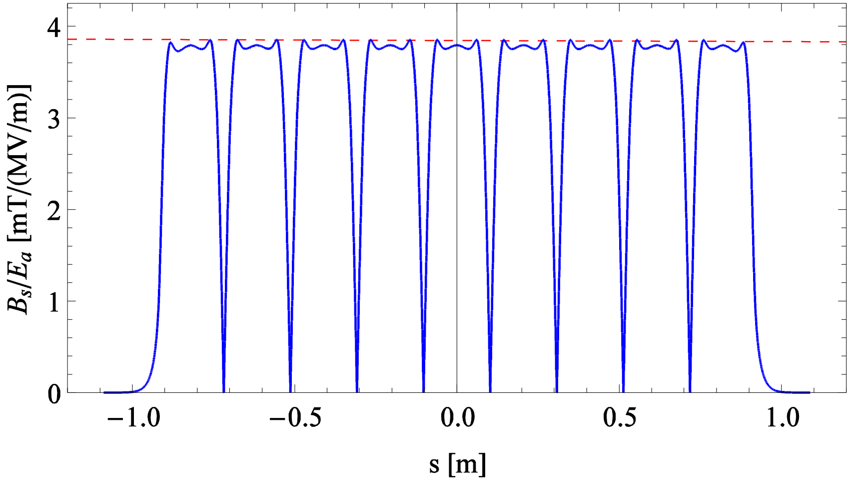
$$\Delta f_\pi = f_\pi - f_{8\pi/9} = \frac{k_c \pi^2}{4N^2} f_{\pi/2} \sim 0.69\ \text{MHz}$$

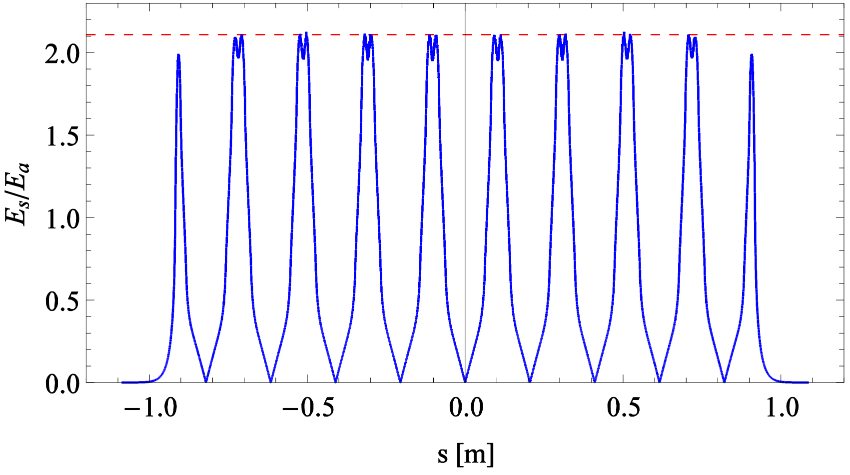
1.1 NLSF Design –Overall Surface Fields

- Earlier alternate designs were limited by field emission which occurred in the end cells.

- HFSS simulations indicate that NLSF cavity does not suffer from this problem.

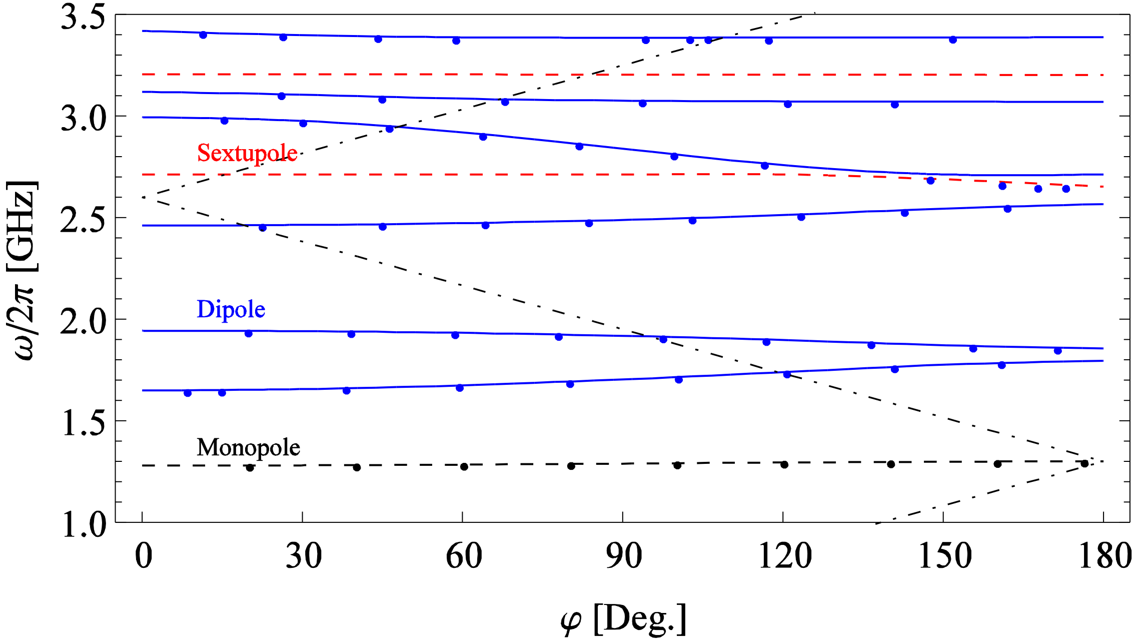


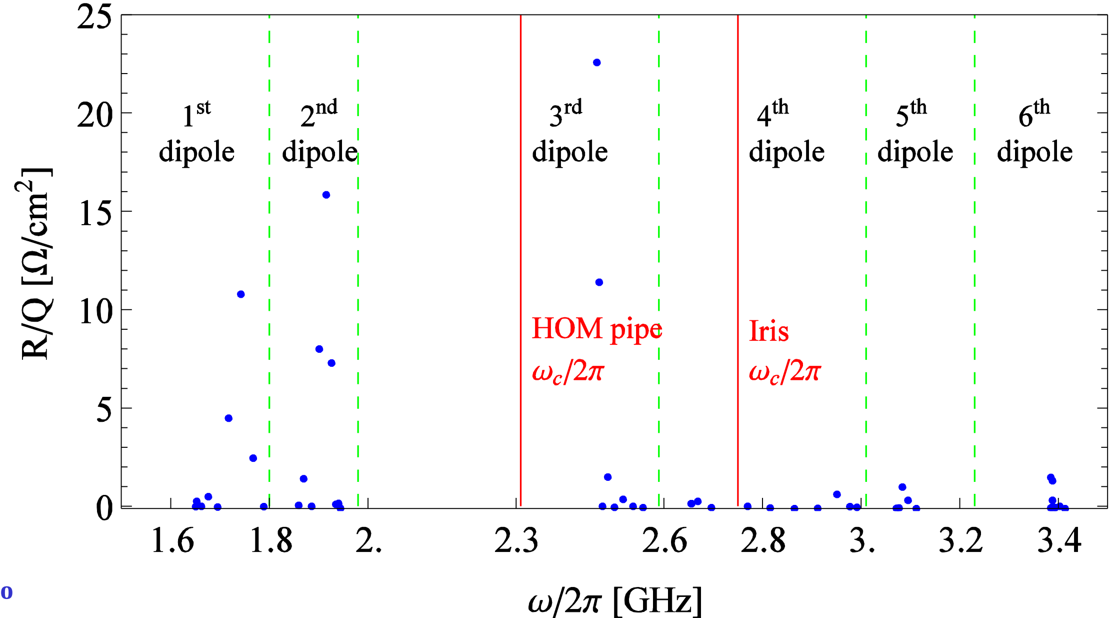

Surface Magnetic Field/Accel. Field


Surface Electric Field/Accel. Field

1.1 HOM Properties of NLSF Cavity

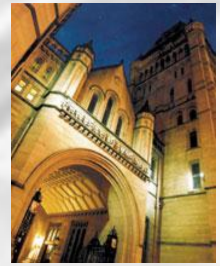
- **Higher order multipoles investigated for full 9-cell cavity**
- **Dipoles modes will dominate emittance dilution**
- **Corresponding transverse momentum kicks studied by calculating R/Qs.**
- **Similar, although redistributed R/Qs as TESLA shape**
- **Modify HOM couplers (no problems anticipated!)**

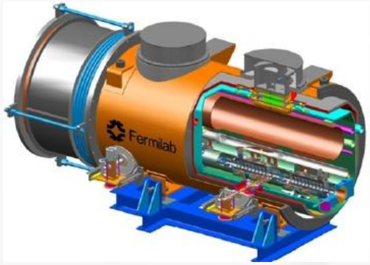




1.2 HOM DIAGNOSTICS IN THIRD HARMONIC CAVITIES AT FLASH

Roger M. Jones
University of Manchester/ Cockcroft Inst.





1.2 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.**

1.2 HOM Diagnostic in 3rd Harmonic Cavities at FLASH -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)**
- **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

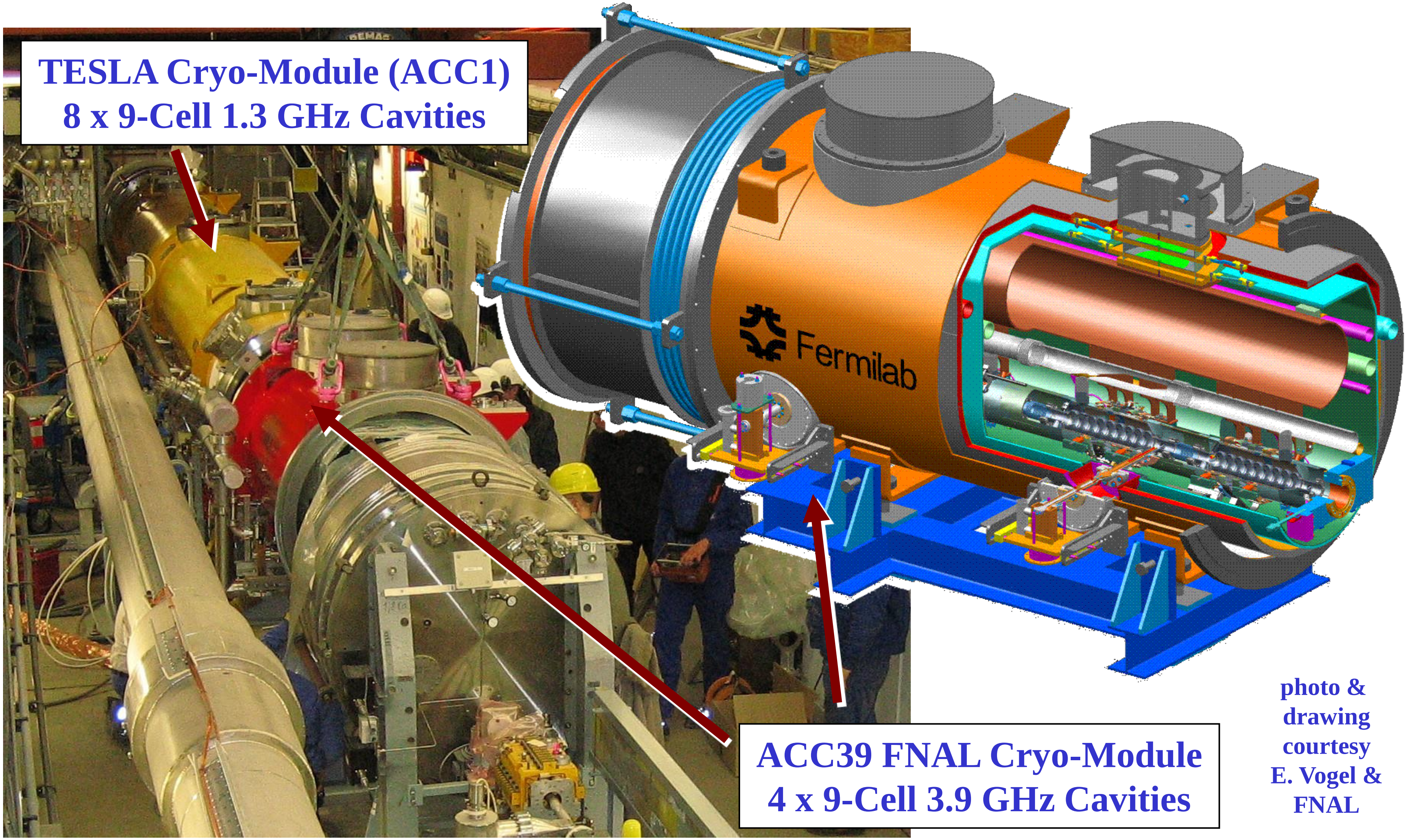
U. Van Rienen, Univ. of Rostock

WP 10.5.1

N. Baboi, DESY

P. Zhang, DESY/Univ. Of Manchester

1.2 3.9 GHz Module Installed at FLASH



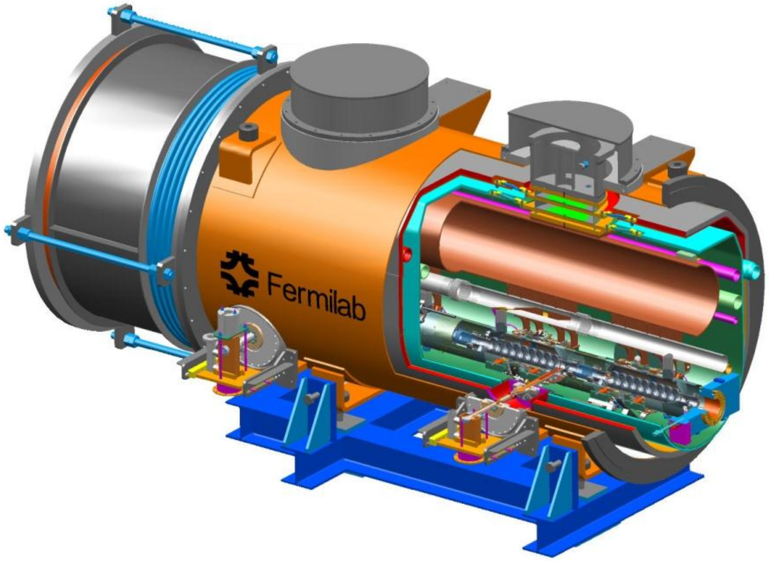
TESLA Cryo-Module (ACC1)
8 x 9-Cell 1.3 GHz Cavities

ACC39 FNAL Cryo-Module
4 x 9-Cell 3.9 GHz Cavities

photo &
drawing
courtesy
E. Vogel &
FNAL

1.2 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.



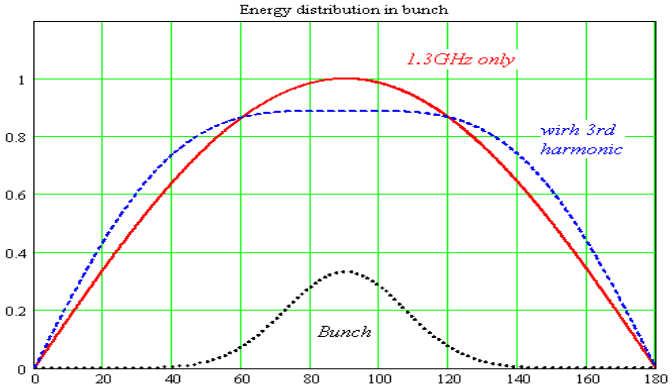
- The cryomodule, consisting of <u>four 3.9GHz cavities</u>, have been installed in the FLASH photoinjector downstream, of the first 1.3 GHz cryomodule (consisting of 8 cavities).
- Four 3.9 GHz cavities provide the energy modulation, ~20 MV, needed for compensation.

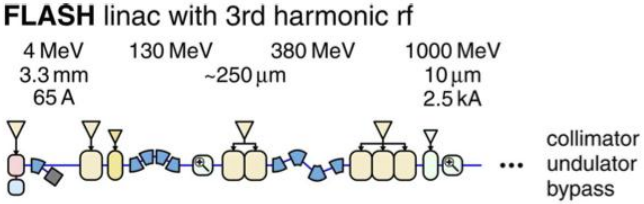
1.2 Third Harmonic Parameters

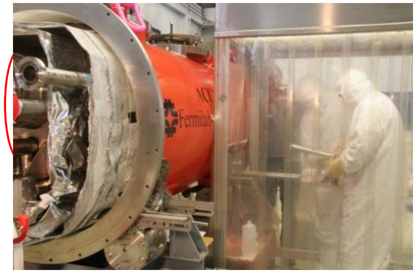
Number of Cavities	4
Active Length	0.346 meter
Gradient	14 MV/m
Phase	-179°
R/Q [=U²/(wW)]	750 Ω
E_{peak}/E_{acc}	2.26
B_{peak} (E_{acc} = 14 MV/m)	68 mT
Q_{ext}	1.3 X 10^6
BBU Limit for HOM, Q	<1 X 10^5
Total Energy	20 MeV
Beam Current	9 mA
Forward Power, per cavity	9 kW
Coupler Power, per coupler	45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





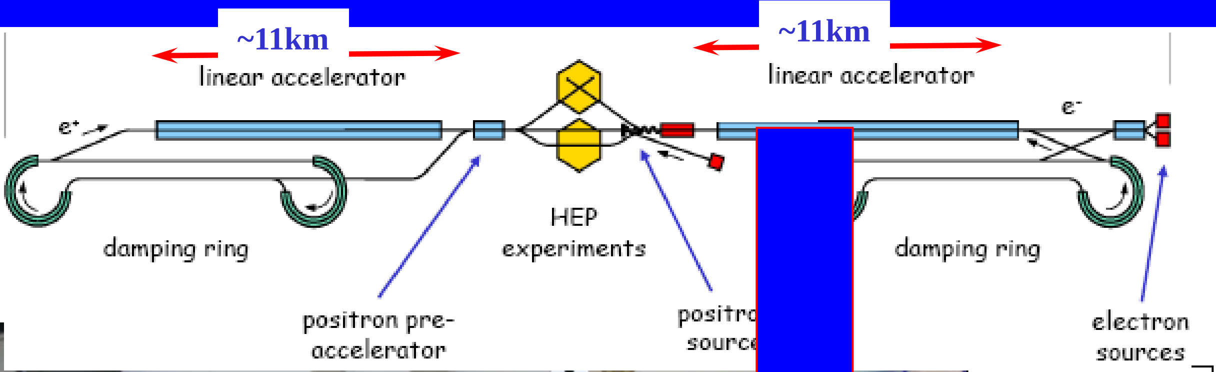


1.2 HOMs in SCRF Cavities

of Accelerator Science and Technology

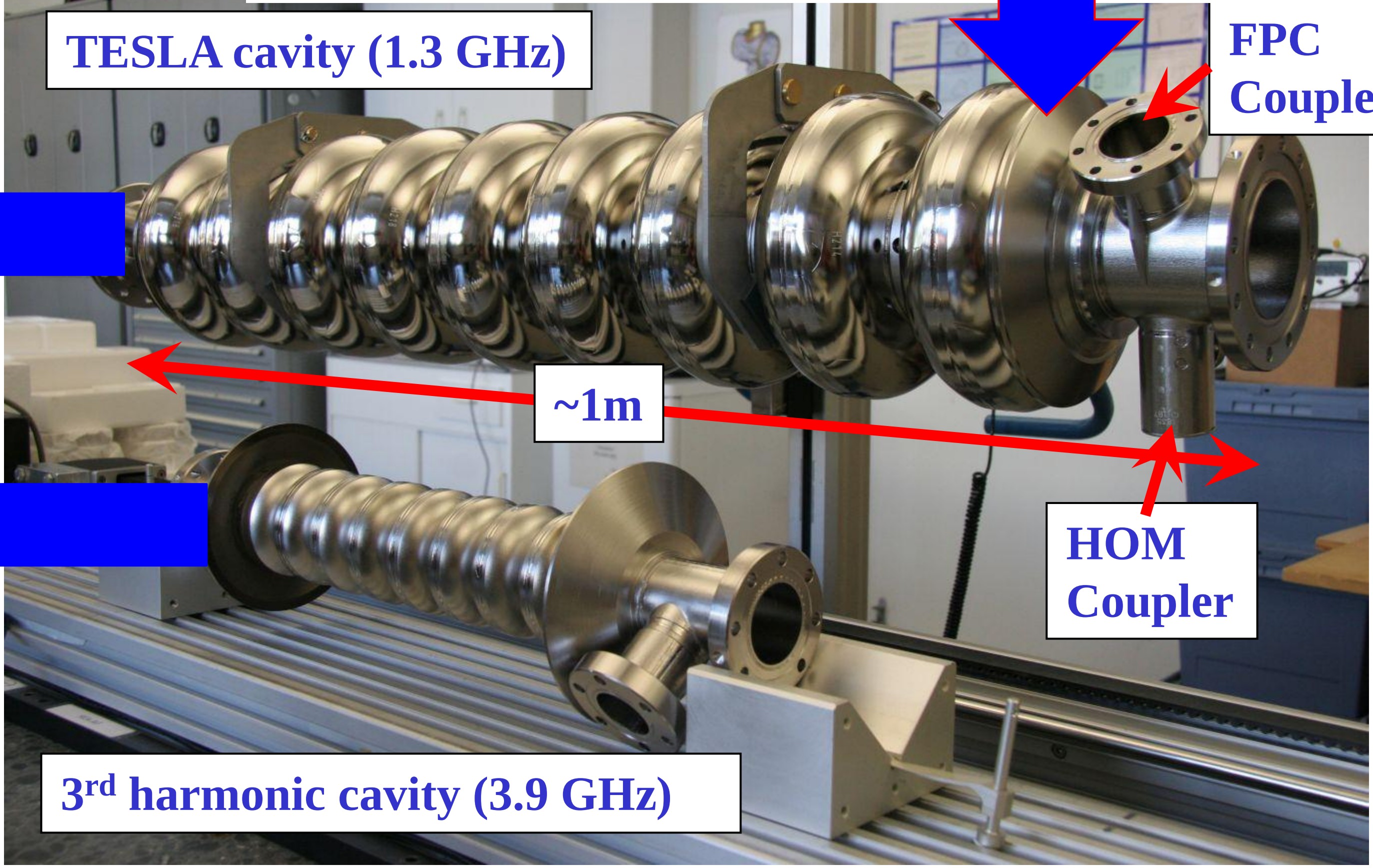
Schematic of International Linear Collider (ILC)

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.



1.2 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.**

1.2 HOMs in SCRF Cavities

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

  - influence the beam both longitudinally and transversely

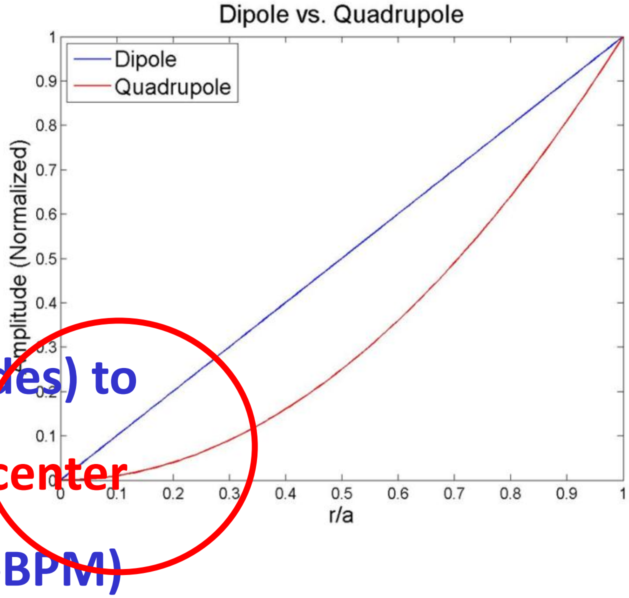
  - non-monopole modes excited by off-axis particles effect bunch itself (intra) and subsequent (inter) bunches

- 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)

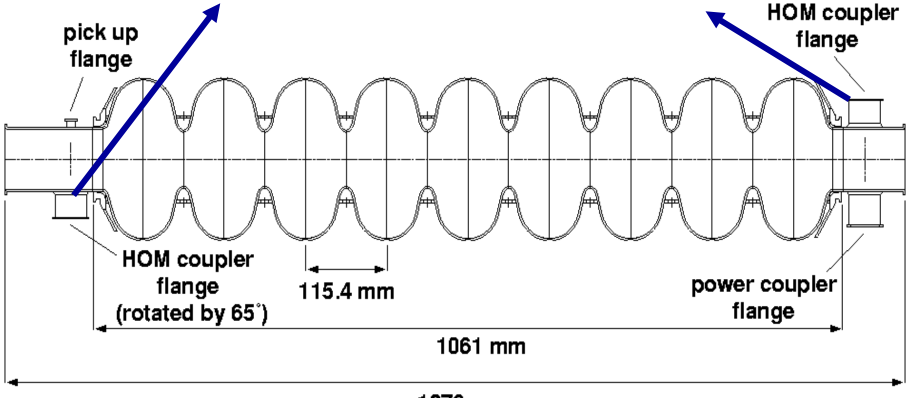
Region of interest

Earlier work on 1.3 GHz demonstrated the principle
[1] G. Devanz et al., EPAC2002, WEAGB003
[2] N. Baboi et al., LINAC2004, MOP3

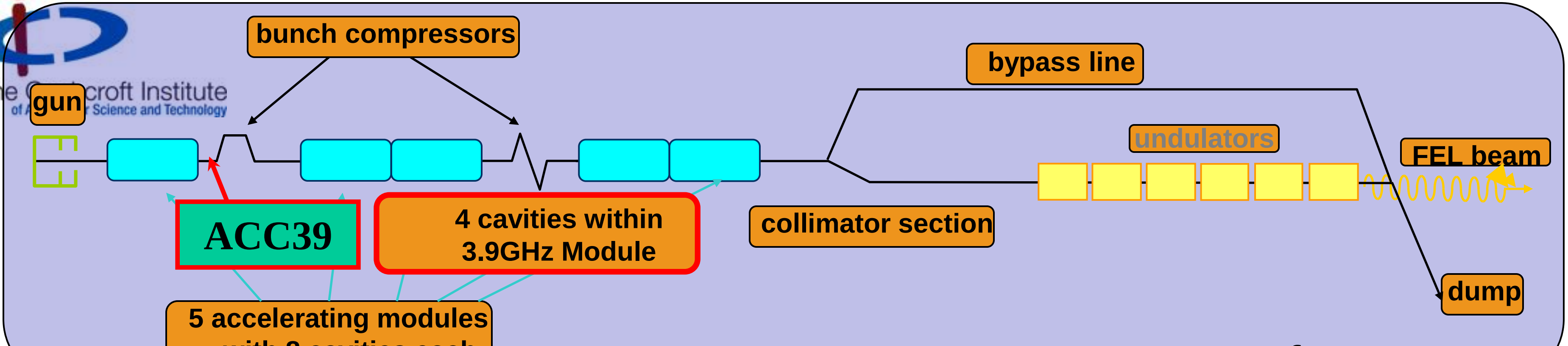
1.2 HOMs in SCRF Cavities

- **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**

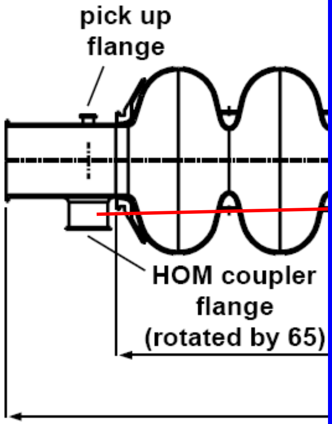
HOM-couplers (pick-ups)



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

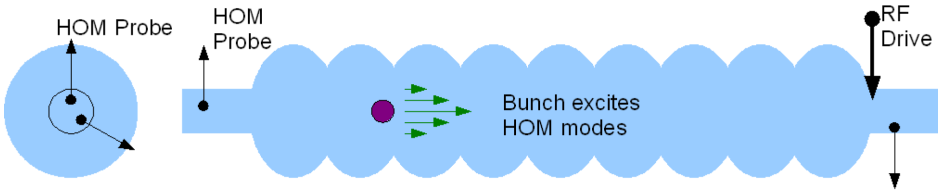


- 1.3GHz SC, typically 450-700MeV, 1 nC charge for FLASH/XFEL
- HOMs generated in accelerating cavities must be damped.
- Monitored HOMs facilitate beam/cavity info
- Forty cavities exist at FLASH.
  - -Couplers/cables already exist.
  - -Electronics enable monitoring of HOMs (wideband and narrowband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

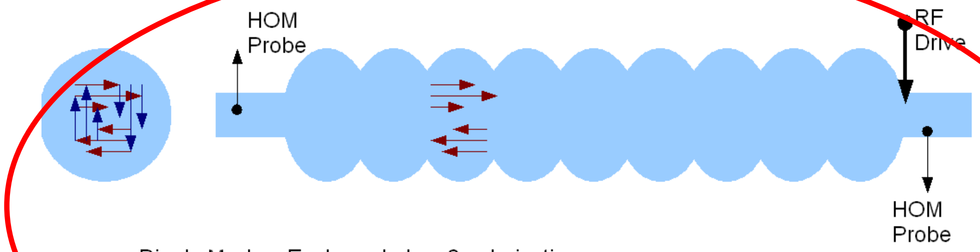


Based on 1.3 GHz (CEA/SLAC/FNAL/DESY) Diagnostics –redesigned for ACC39 as part of EuCARD

1.2 Response of HOM to Beam

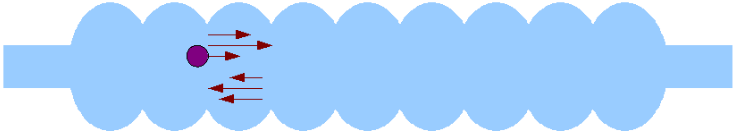


Monopole mode: Amplitude first order independent of beam position
Phase of mode determined by bunch arrival time

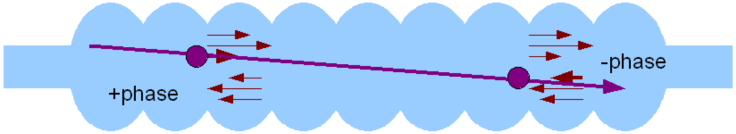


Dipole Modes: Each mode has 2 polarizations
Frequencies degenerate for ideal cavities
Frequency degeneracy broken by power coupler and fabrication errors

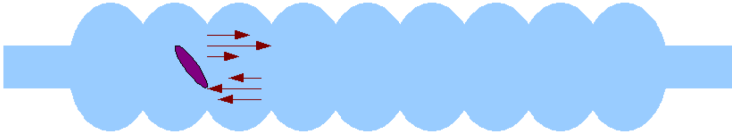
If frequency splitting is < line width, Need both couplers to separate polarizations



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



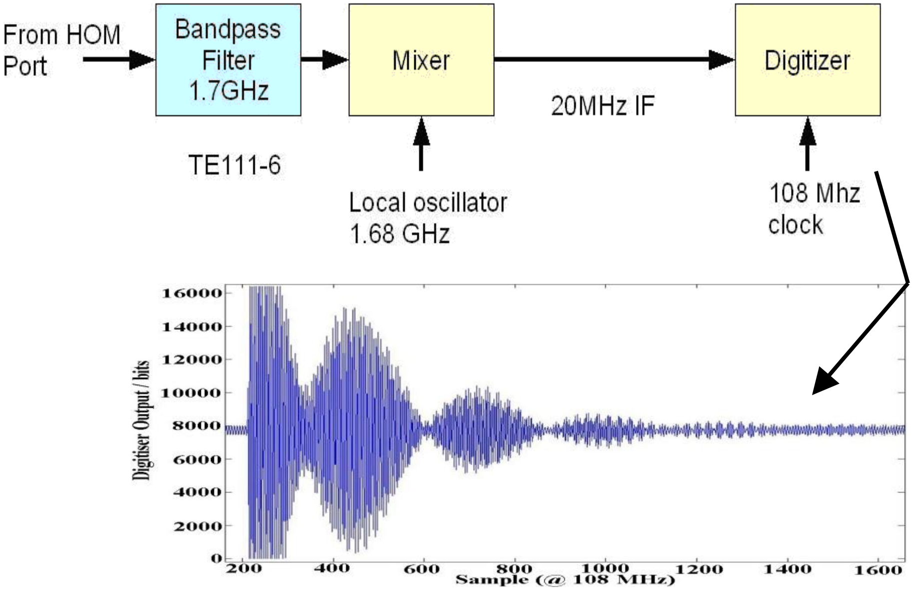
Beam at an angle will excite dipole mode with 90 degree phase shift relative to signal from position offset
Amplitude proportional to angle X effective mode length (~ 1 Meter)



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

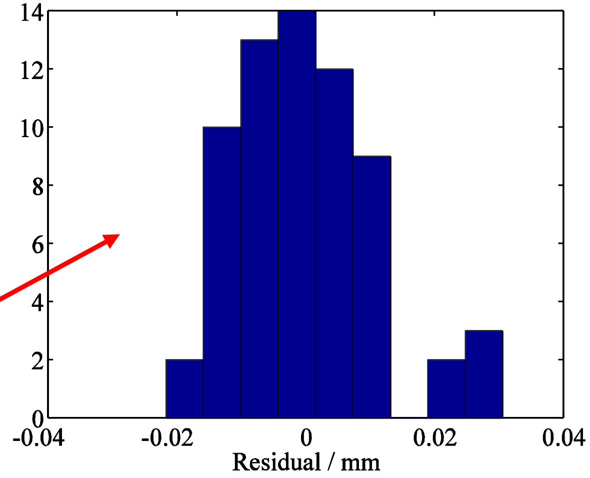
1.2 Extant Work at 1.3 GHz: HOM-BPMs in TESLA Cavities

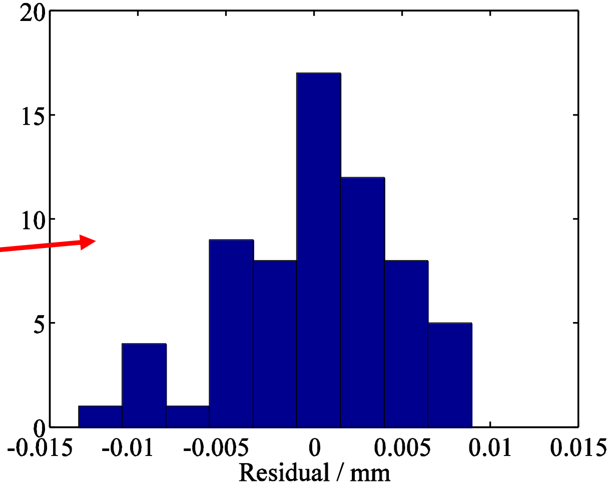
- HOM-BPMs at 1.3GHz cavities
  - Use dipole mode at 1.7 GHz
  - Installed in 5 accelerating modules (40 cavities)
  - Calibration: with SVD technique
    - problem: unstable in time
- Beam Alignment in Modules
  - Now routinely used in FLASH
- Other studies
  - Cavity alignment in cryo-module
  - Beam 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>



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

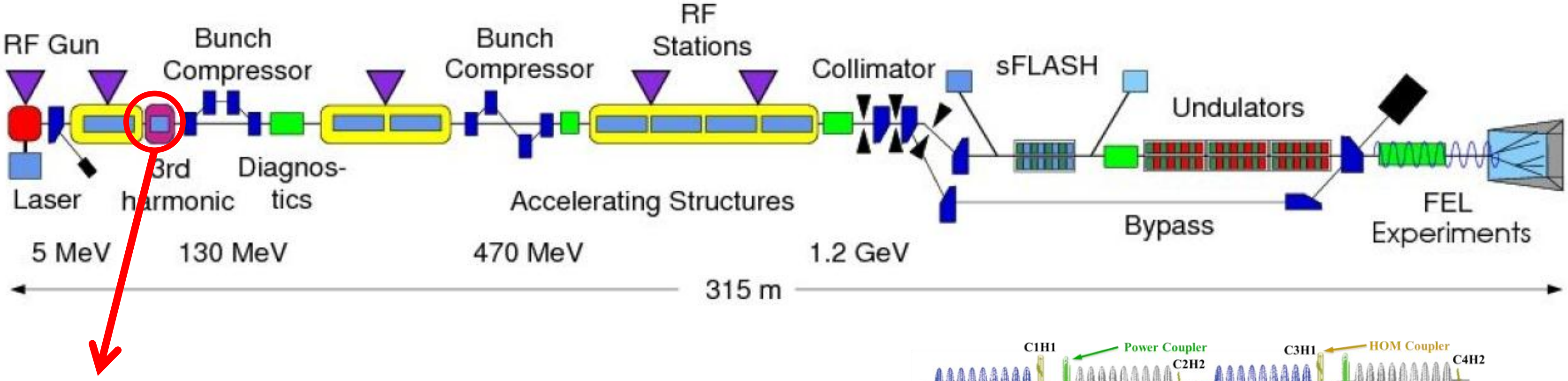
- Resolution of position measurement.
  - Predict the position at cavity 5 from the measurements at cavities 4 and 6.
  - Compare with the measured value.
- X resolution
  - ~9 µm
- Y resolution
  - ~4 µm

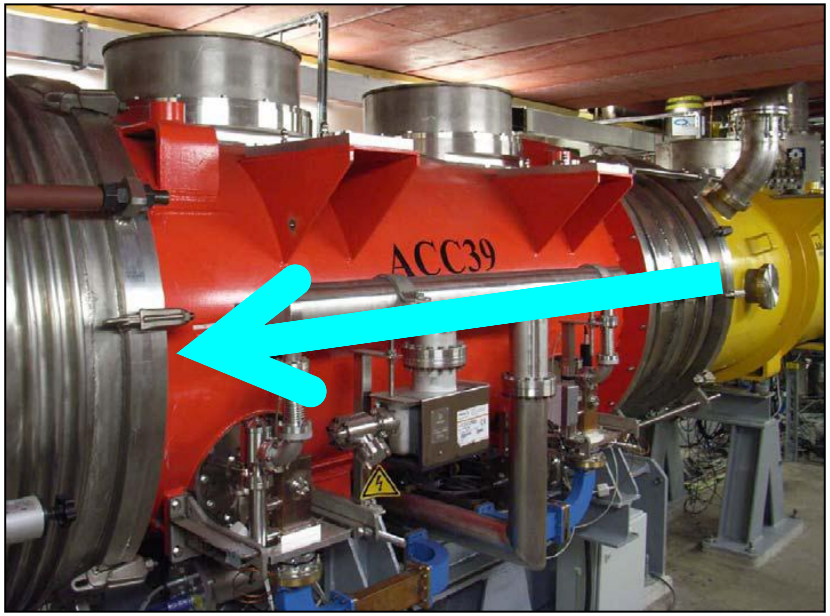


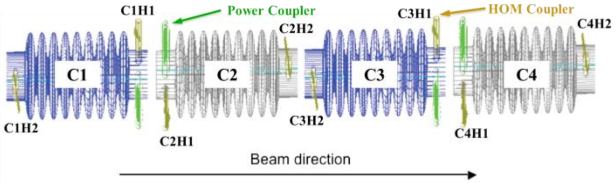


1.2 FLASH and ACC39

Free-electron LASer in Hamburg (FLASH)







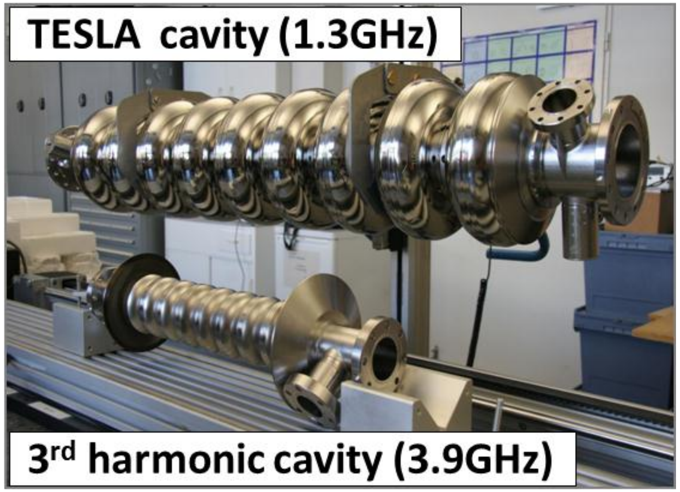


Photo courtesy E. Vogel & DESY

1.2 Selected Highlights

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

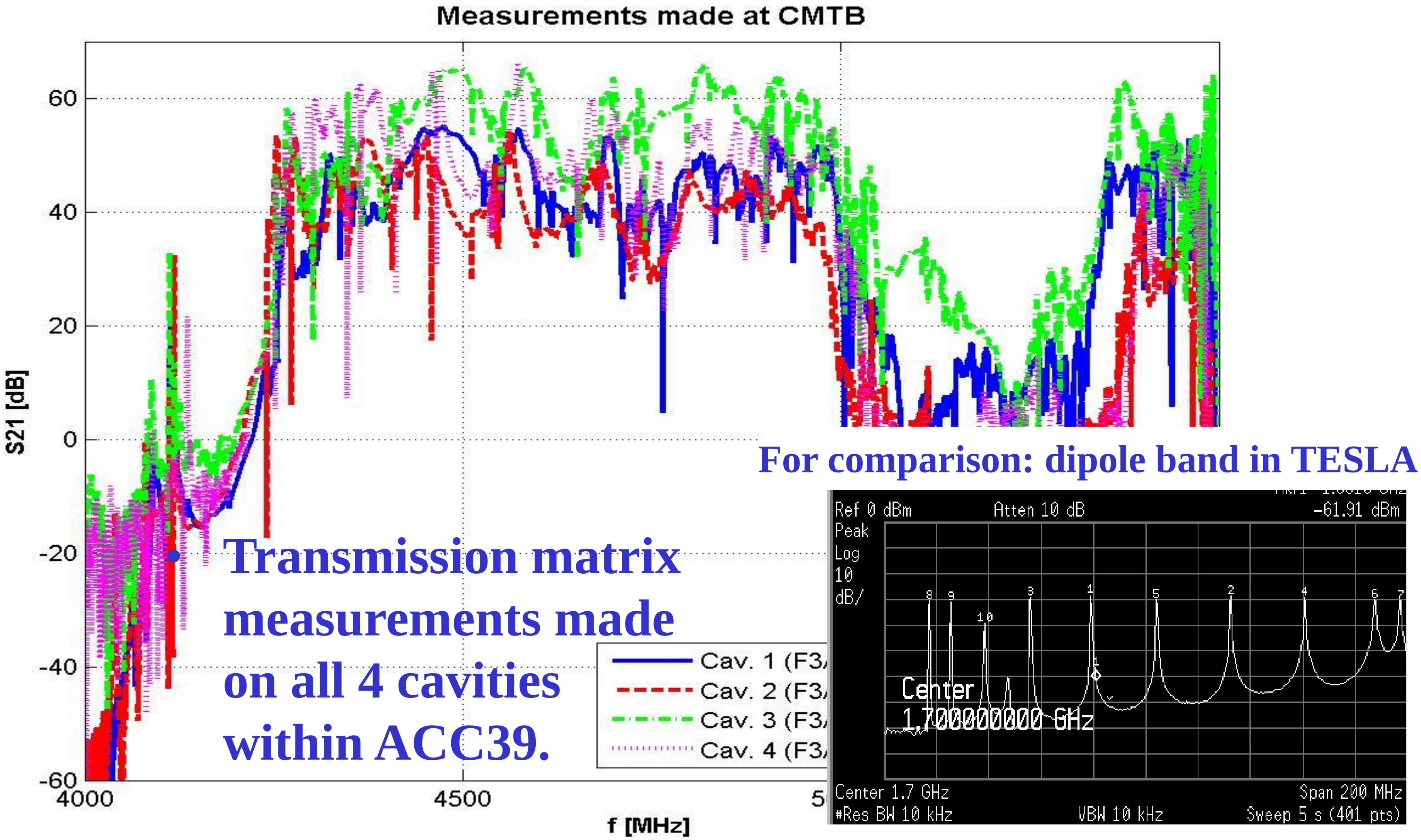
- **Beam-based mode characterisation.**
  - **HOM pickup vs beam offset for trapped/isolated modes**

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

1.2 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

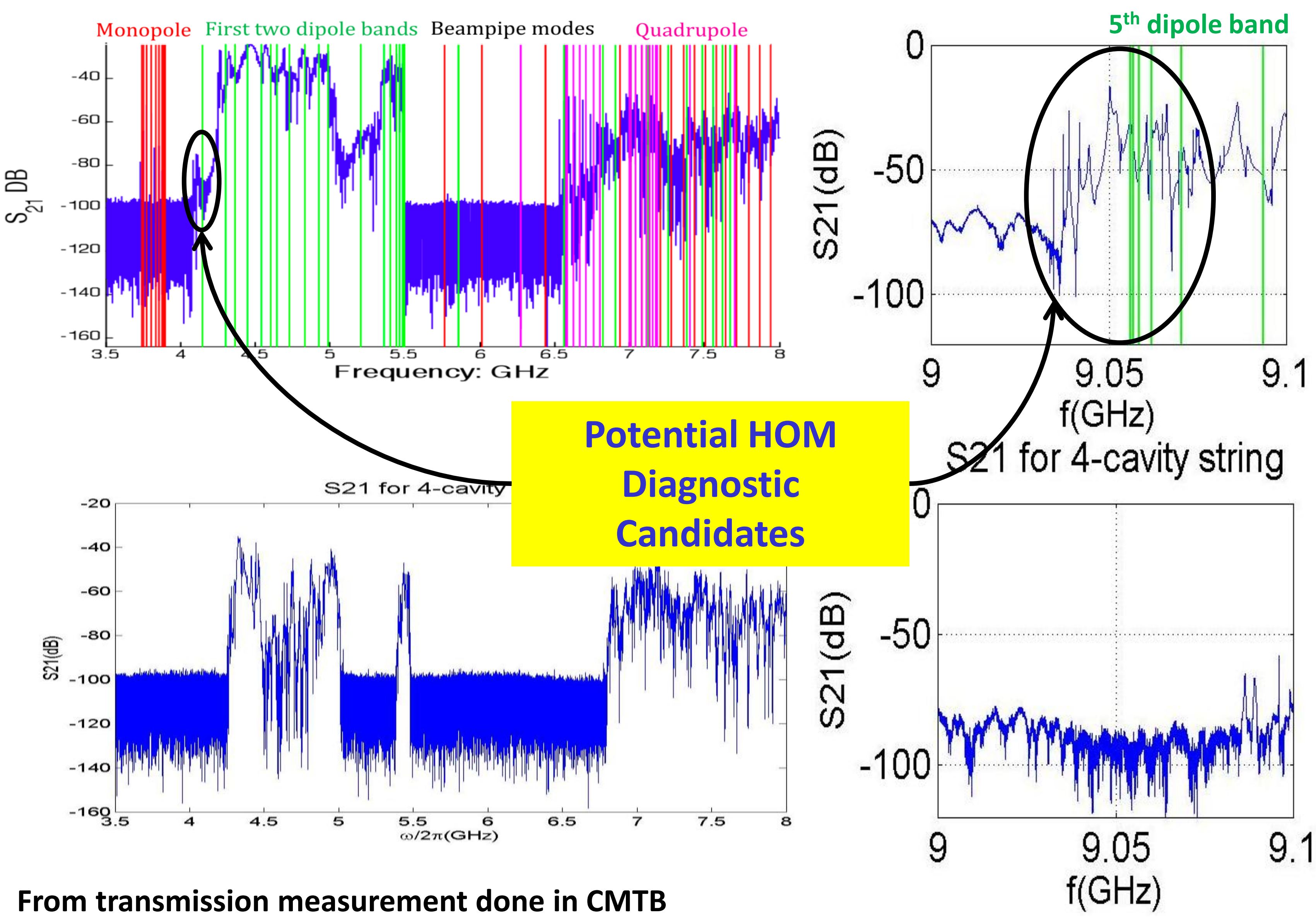
1.2 ACC39 Spectra Measured in CMTB: Focused on Dipole and Other Bands



For comparison: dipole band in TESLA ca

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

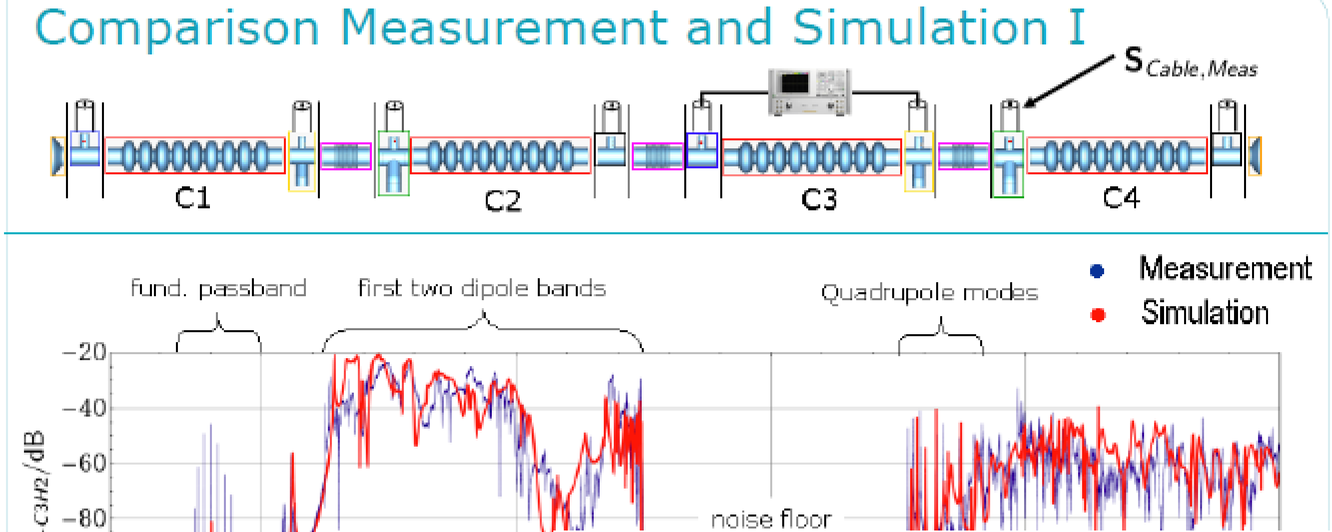
1.2 Band Structure



Potential HOM Diagnostic Candidates

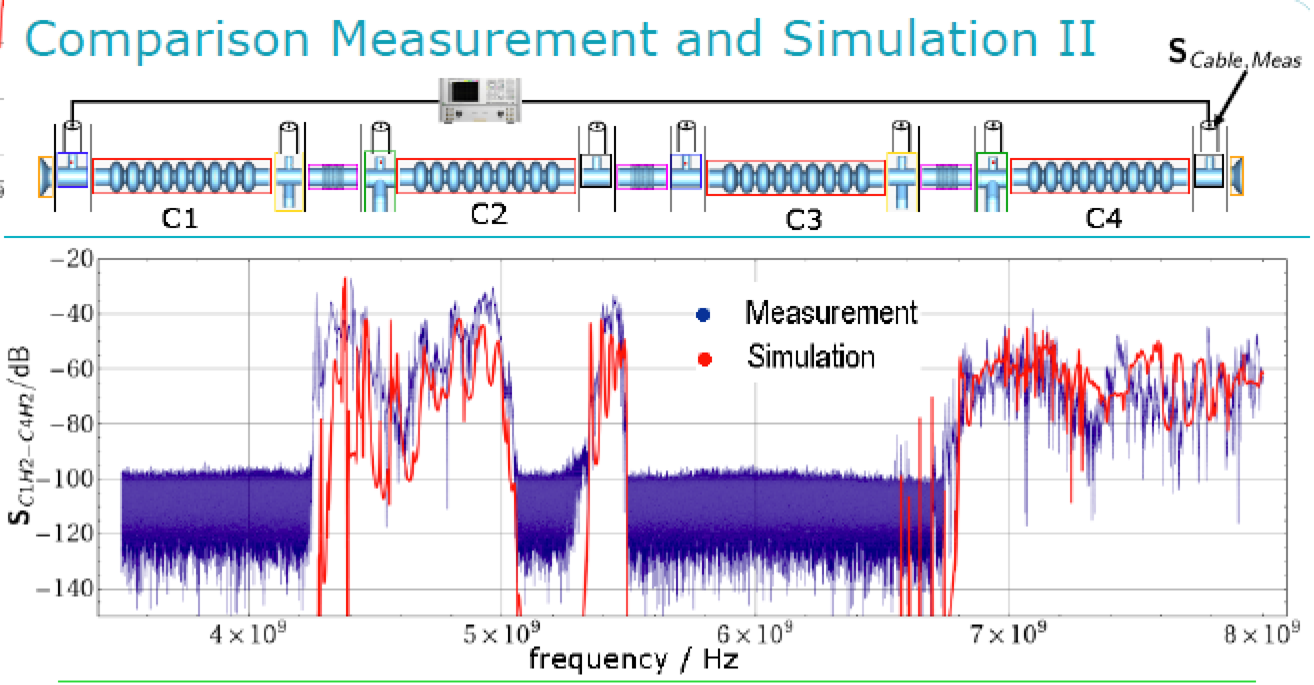
From transmission measurement done in CMTB

1.2 S_{21} Exp vs Simulations



Comparison Measurement and Simulation I

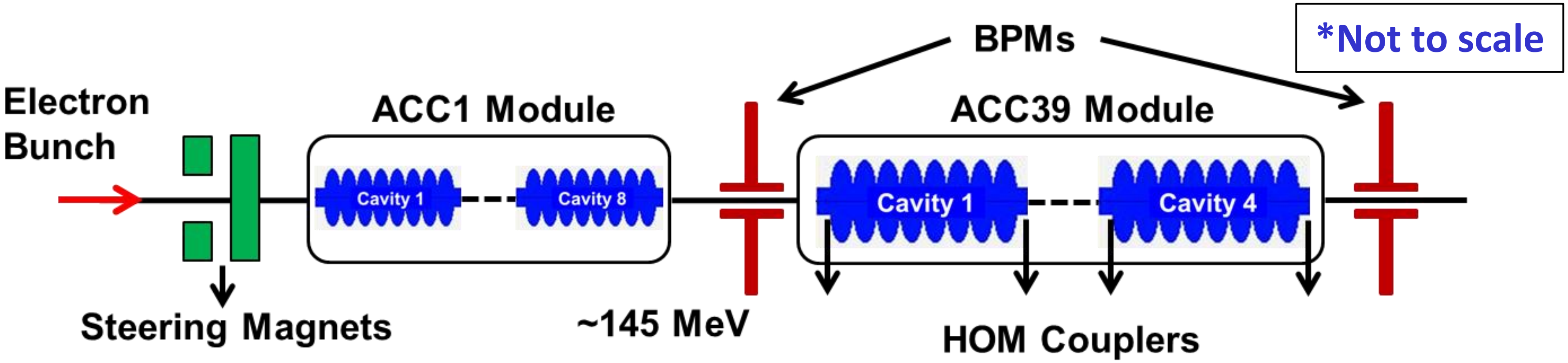
- ➢ **Transmission through single cavity in chain.**

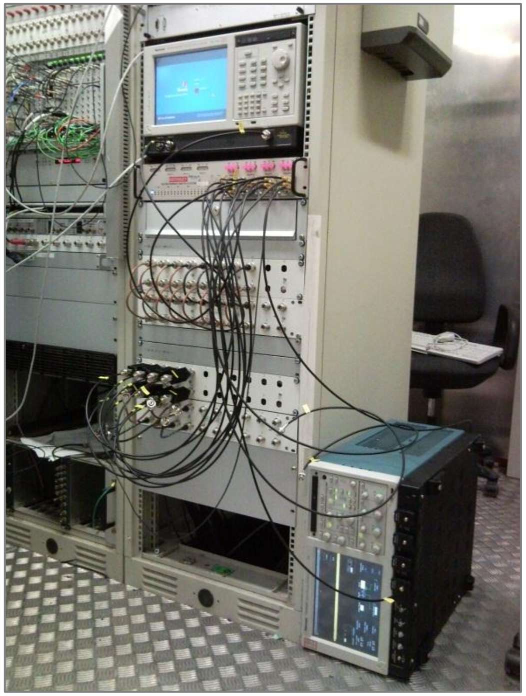


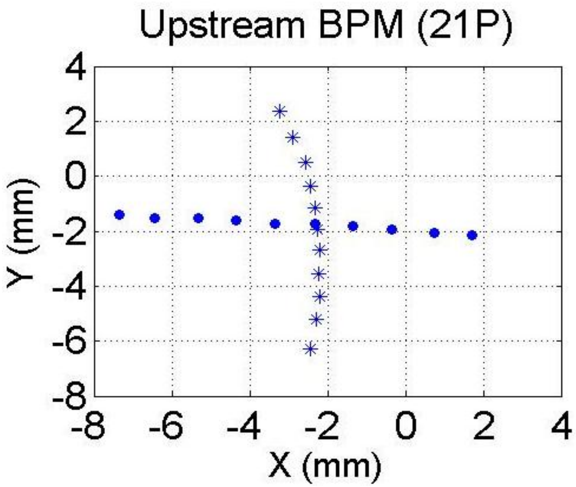
Comparison Measurement and Simulation II

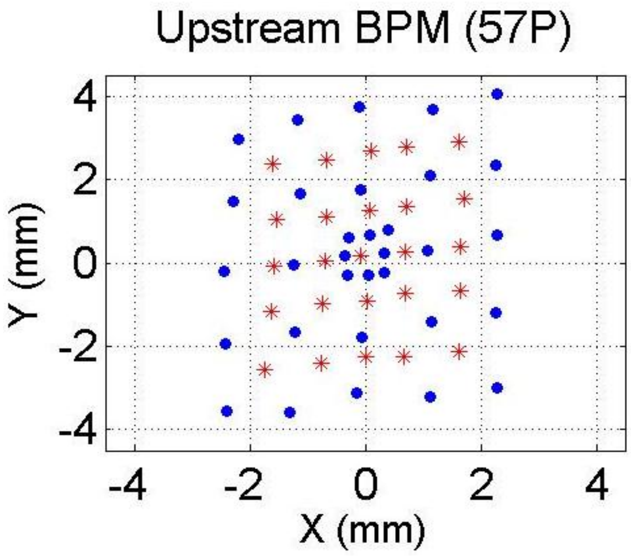
- ➢ **Transmission through complete chain.**

1.2 Beam-Based HOM Measurements



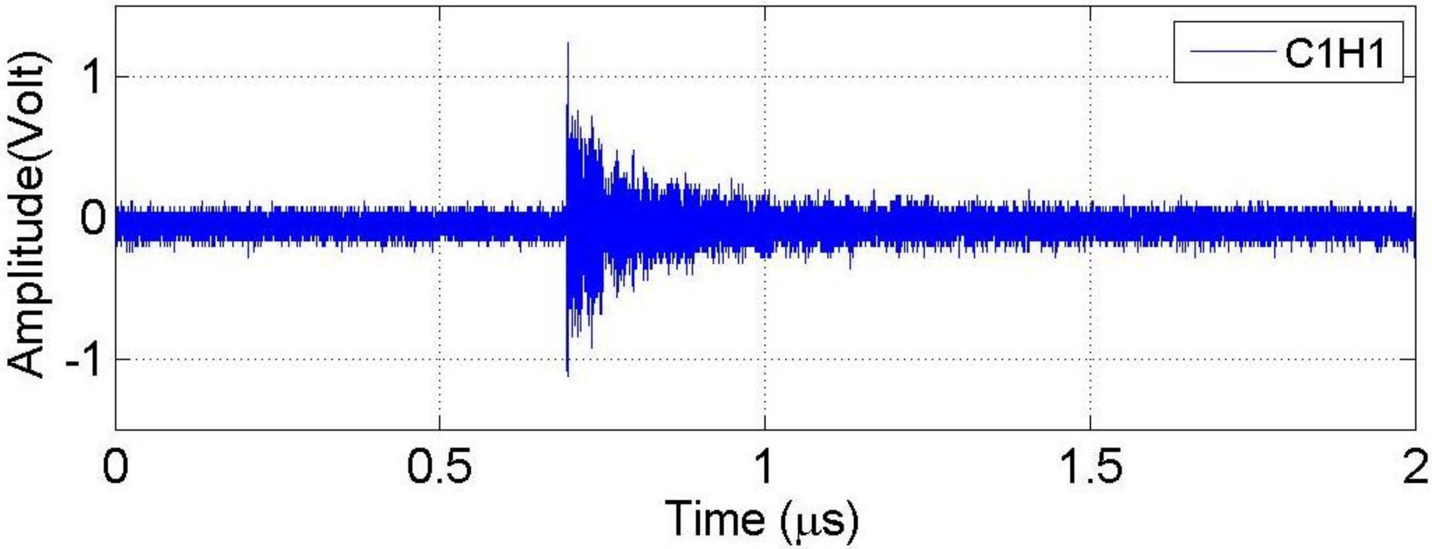




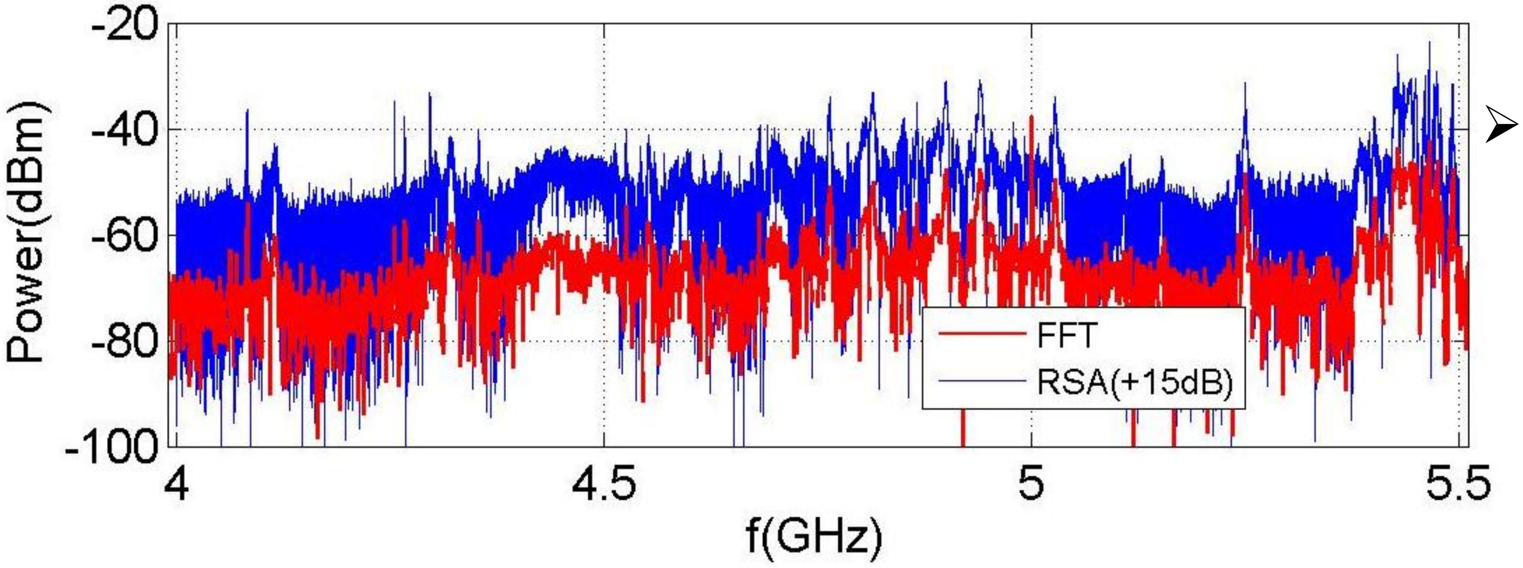


Steer the beam in various ways

1.2 HOM Signal (1st Two Dipole Bands)

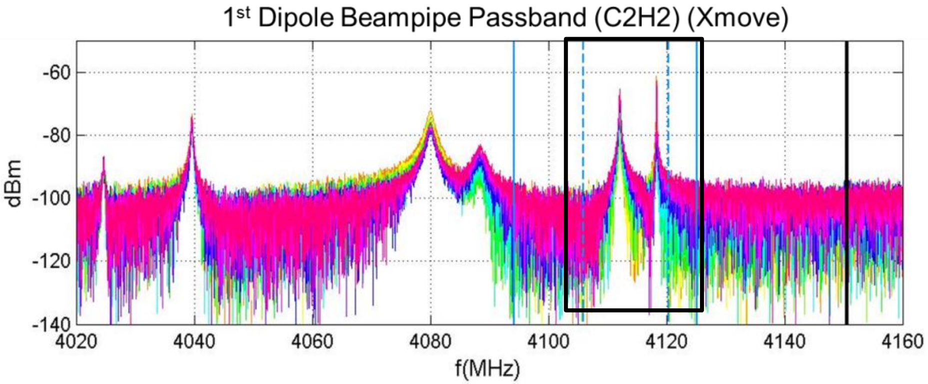


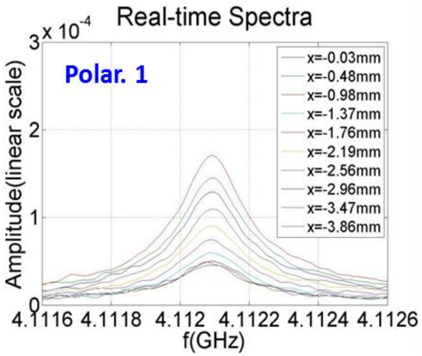
- Time Domain HOM pickup

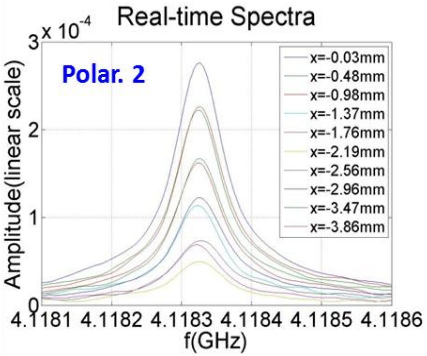


- Comparison of FFT of HOM pickup vs RSA

1.2 1st Dipole Beampipe Modes

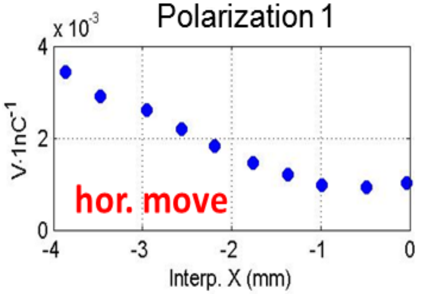


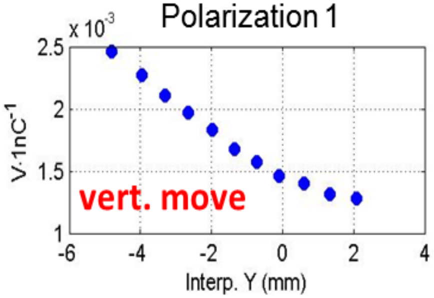


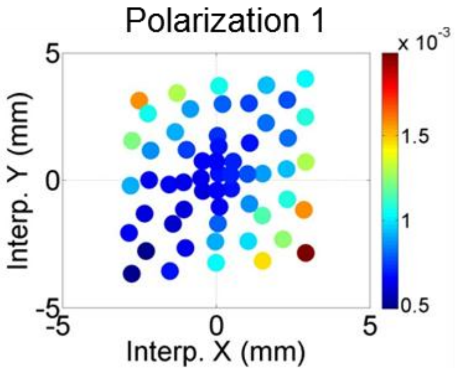


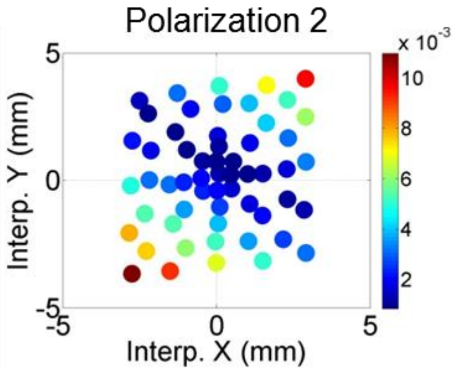
- **Lorentzian fit to get mode amplitude**

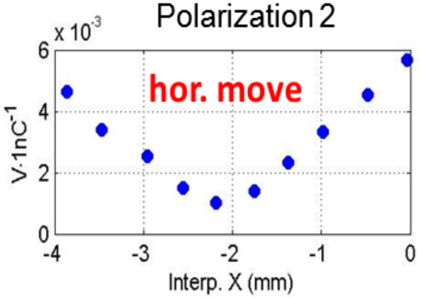
$$y = y_0 + A \cdot \frac{w^2}{(x - x_0)^2 + w^2}$$

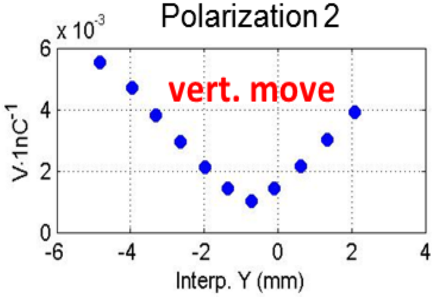


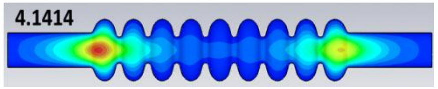


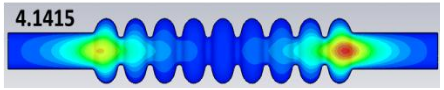




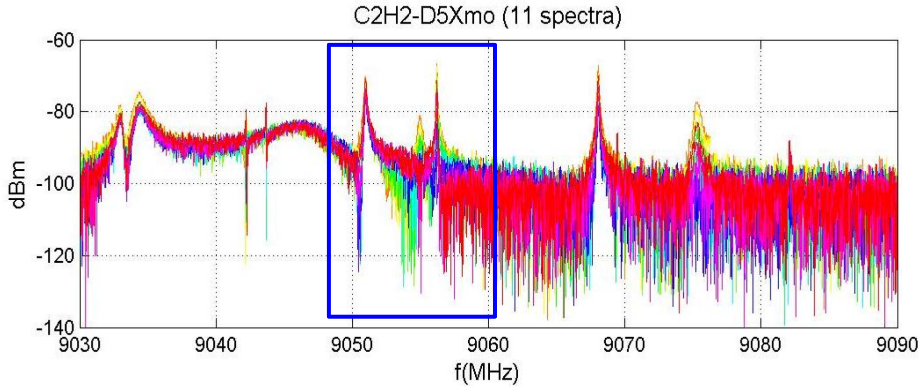


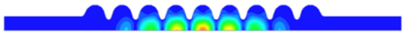
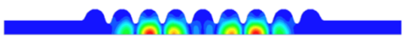
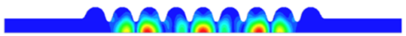
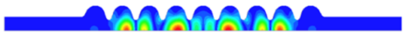
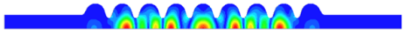
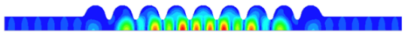


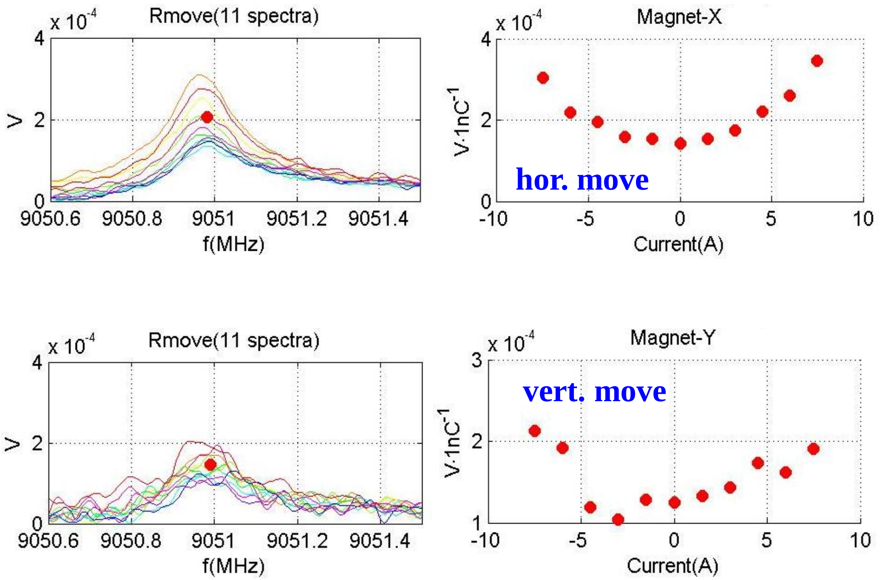




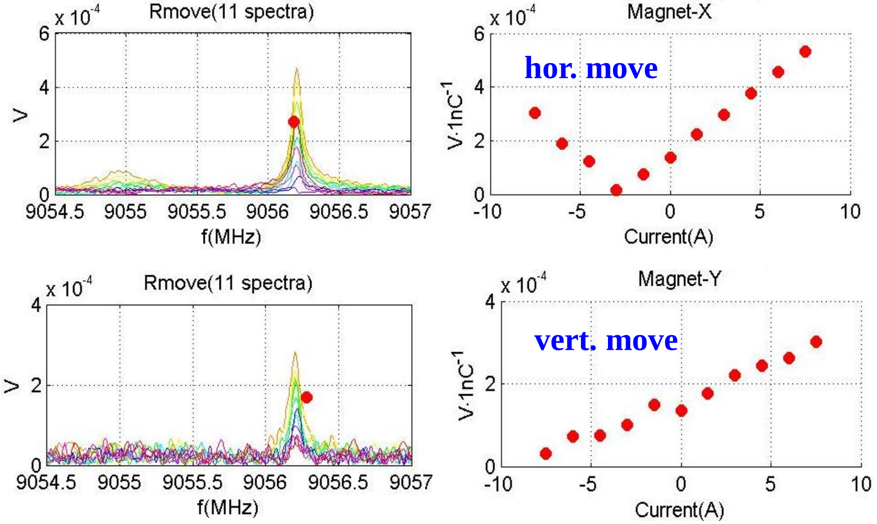
1.2 5th Dipole Cavity Band



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

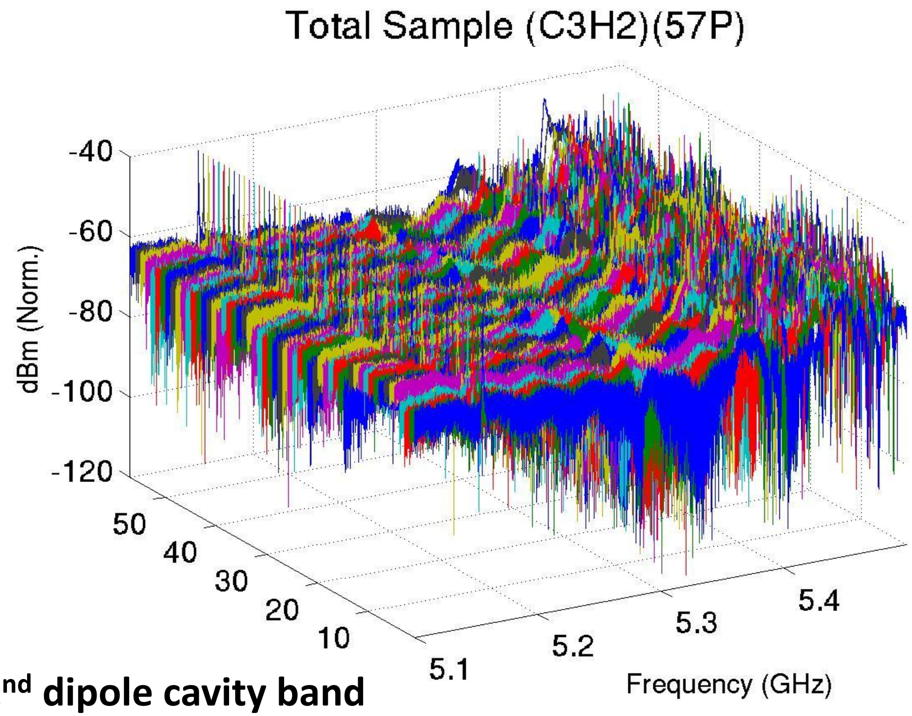


localized!

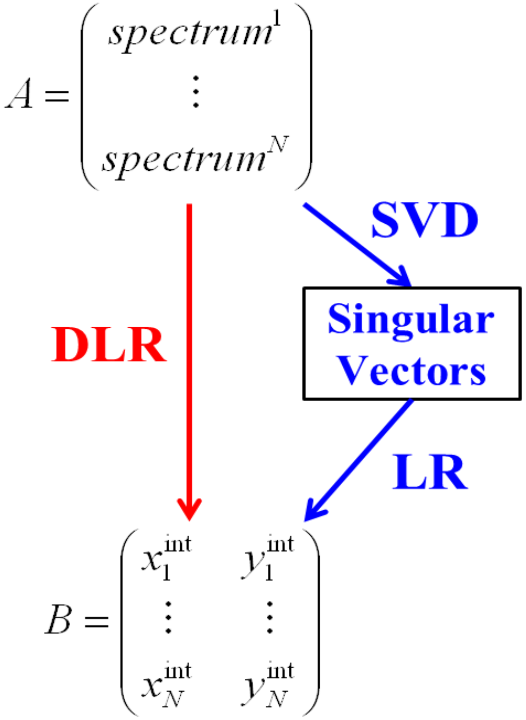


[†] I.R.R. Shinton, et al., “Mode Distribution …”, CI Internal Note

1.2 Comparison of DLR vs SVD



2nd dipole cavity band



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

DLR

SVD

Singular Vectors

LR

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

- Direct Linear Regression (DLR)

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

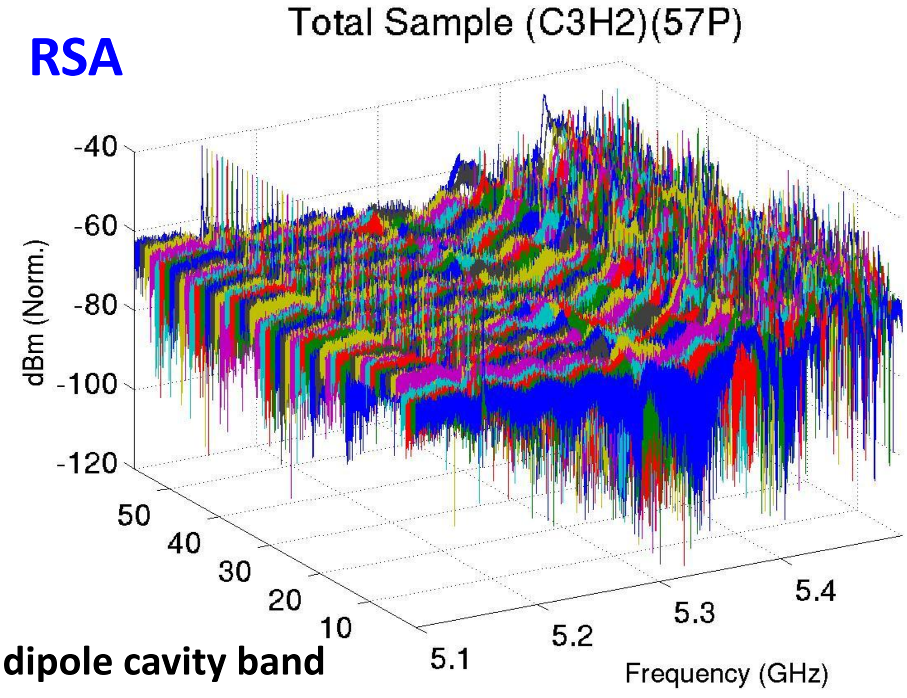
- Singular Value Decomposition (SVD)

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

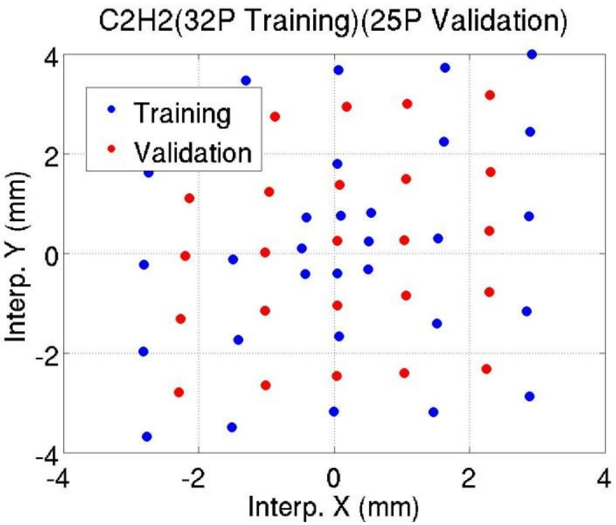
$$A_S \cdot M_S + B_{0S} = B$$

1.2 Direct Linear Regression

RSA



2nd dipole cavity band

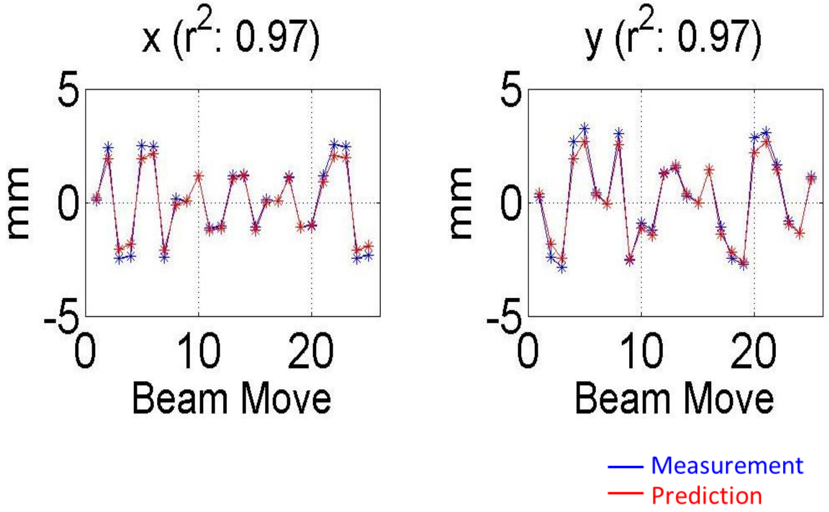


- **Direct Linear Regression (DLR)**

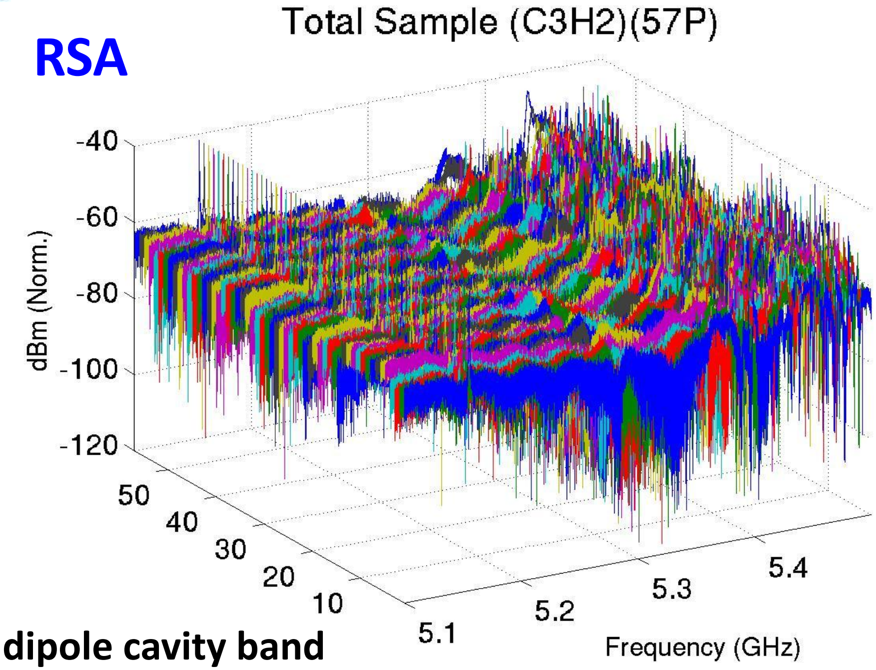
$$A \cdot M + B_0 = B$$

A: spectra matrix

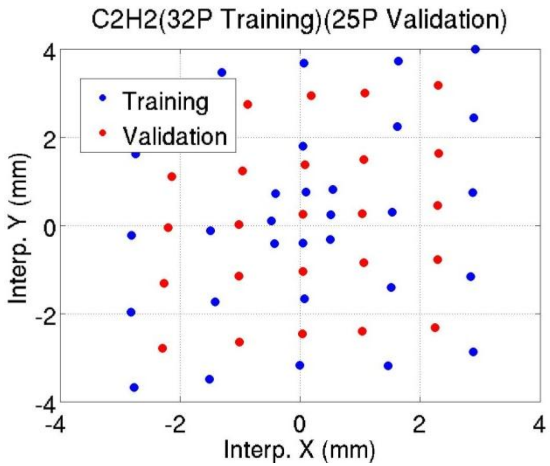
B: beam position matrix



1.2 Singular Value Decompostion



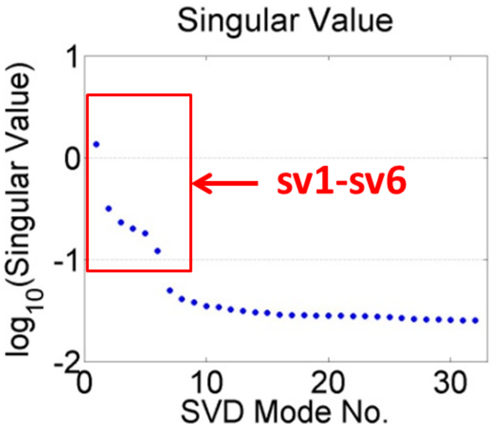
2nd dipole cavity band

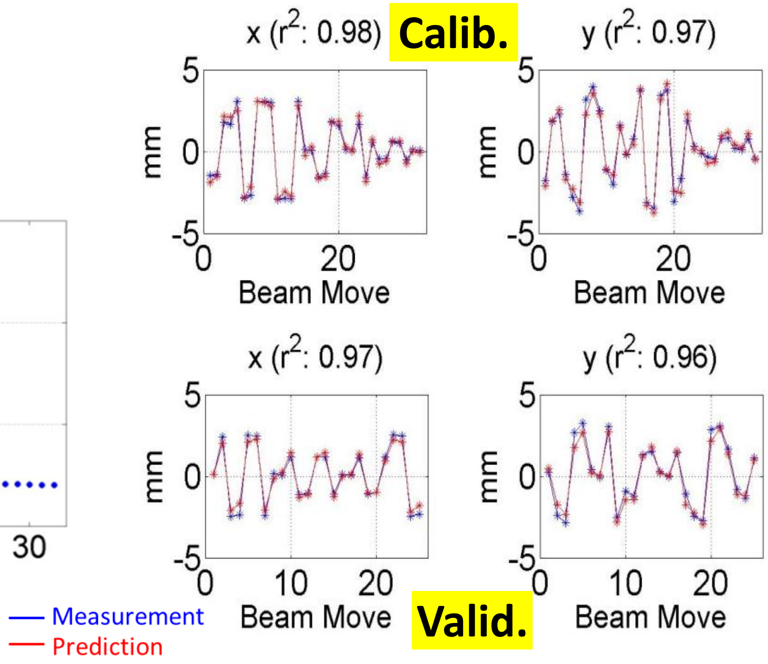


- **Two steps**

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

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





1.2 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!

Acknowledgements

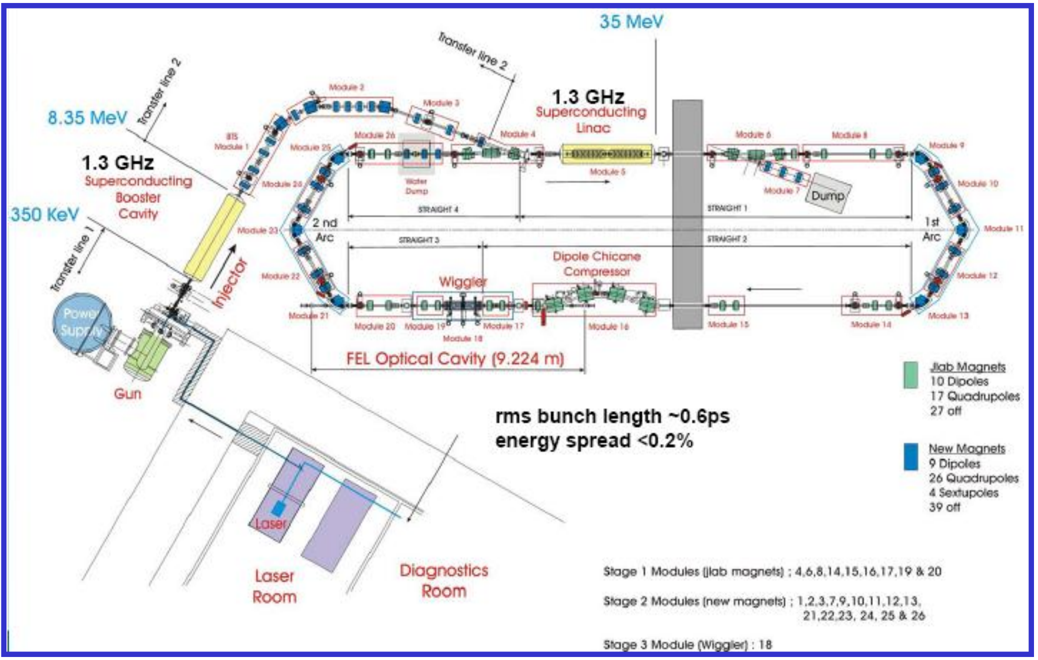
- **I wish to express thanks for the organising committee for giving me this opportunity to report on the work of this task.**
- **I acknowledge materials supplied, and/or many useful discussions with: N. Baboi, E. Vogel (DESY), P. Zhang (University of Manchester/Cockcroft Inst./DESY) , I.R.R. Shinton (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.**

1.2 HOMs in SC Accelerator Cavities

- Experience gained on FLASH measurements will be invaluable.
- HOMs in ALICE TESLA cavities will provide information on:
- 1. Beam position (effectively a built-in BPM)
- 2. Alignment of cells (and groups thereof).



rms bunch length ~0.6ps
energy spread <0.2%

Stage 1 Modules (jlab magnets) ; 4,6,8,14,15,16,17,19 & 20

Stage 2 Modules (new magnets) ; 1,2,3,7,9,10,11,12,13,
21,22,23, 24, 25 & 26

Stage 3 Module (Wiggler) : 18

Schematic illustrating ALICE*

CI/Univ. of Manchester PDRA I. Shinton (left) and Ph.D. student N. Juntong (right; supported by the Thai Government) participated in ALICE commissioning in Dec 2008

1.2 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).**

1.2 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.**

Concluding Remarks on SCRF

- New Low Surface Field (NLSF) Design has the potential to reach in excess of 50 MV/m –all three parameters optimised!

- Third harmonic cavities received by DESY, characterised at the CMTF, beam-based tests ongoing.

- Strong coupling of cavity modes within module ACC39 –suite of simulations in progress to assess mode for electronics diagnostics.

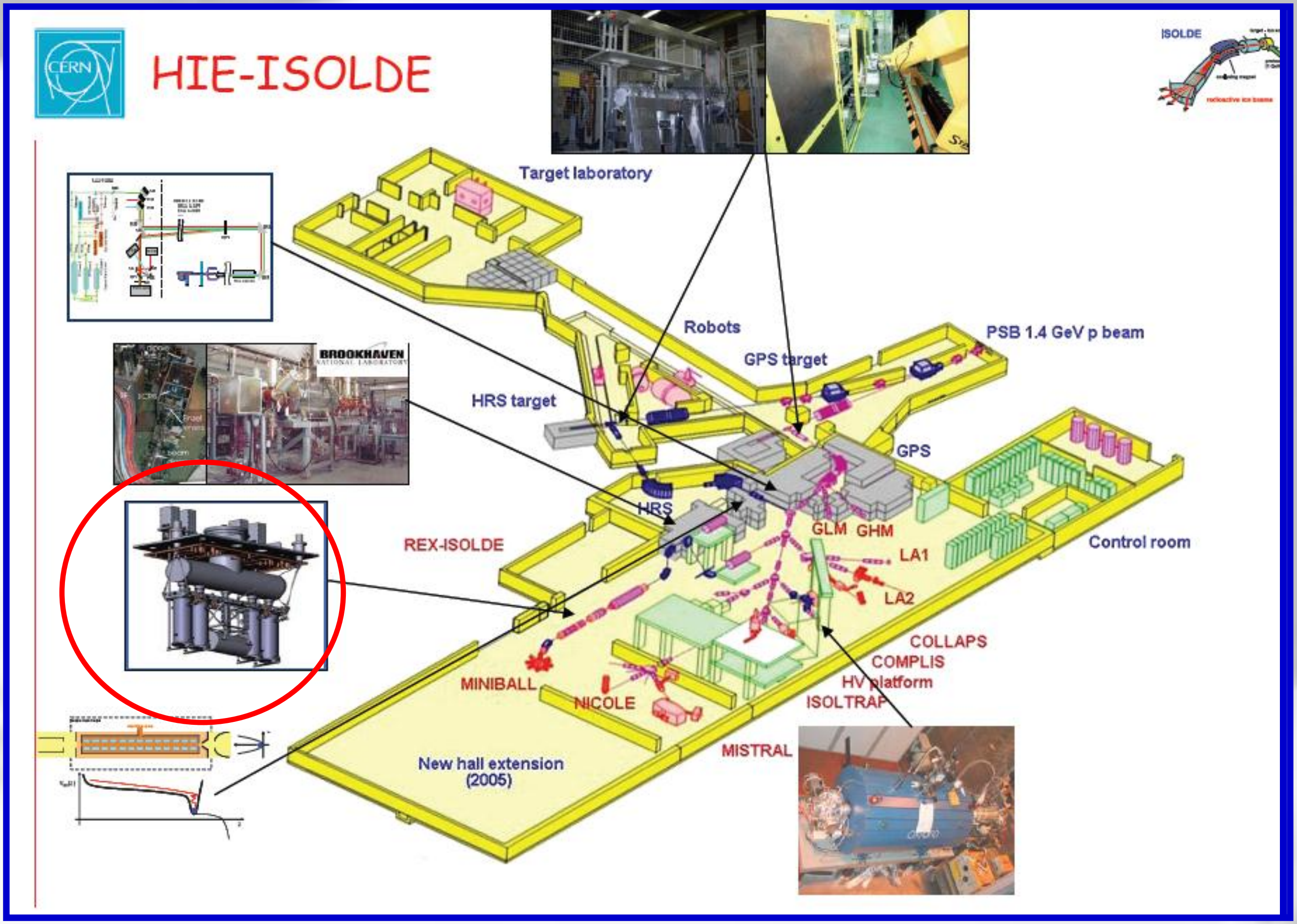
- HOM electronics will be built designed and tested for 3.9 GHZ cavities in 2012.

- HOM simulations on cavity alignment/beam based alignment in progress for third harmonic cavities.

Isotope Separation
On-Line (ISOL)

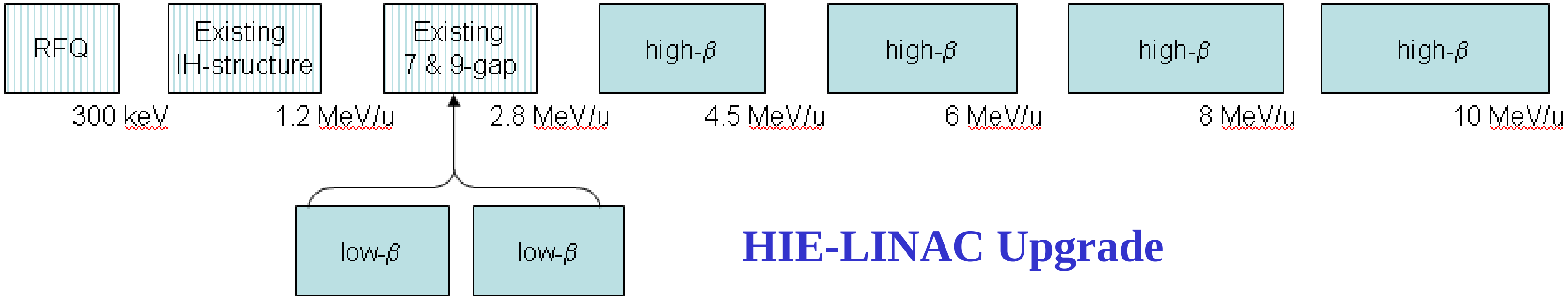
2. HIE-ISOLDE

High Intensity and Energy at ISOLDE



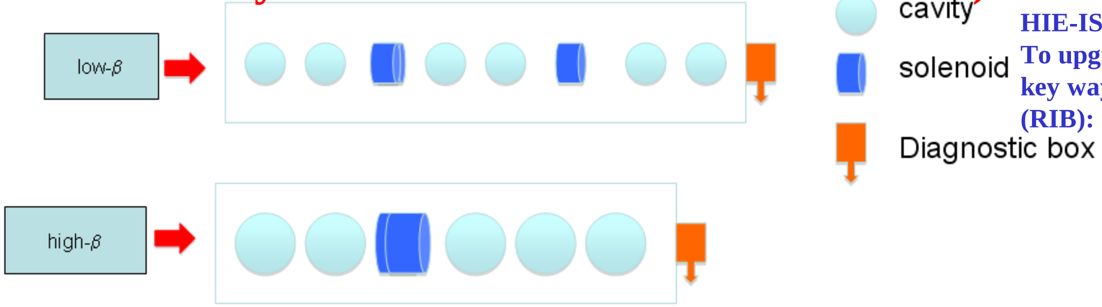
- M. Fraser, Univ. Manchester/Cockcroft Inst. PhD student, Leads Beam Dynamics Work
- Alessandro D’Elia, Univ. Manchester/Cockcroft Inst. , Leads RF Cavity Design

2. HIE-LINAC



HIE-LINAC Upgrade

Energy – provided by the HIE-LINAC (superconducting machine providing full energy variability from 1.2 Mev/u to over 10 MeV/u)



Cryo-Module Schematic

HIE-ISOLDE project aim:

To upgrade the current ISOLDE nuclear research facility in three key ways, with a focus on post-accelerated radioactive ion beams (RIB):

1. **Intensity (upgrade of proton driver to 10 kW through linac4) – R&D is required for the production target.**
2. **Quality (improved isotope selection using laser ionisation, improved charge breeding, cooling and accumulation stages prior to post-acceleration).**

Focussed on the cavity rf and beam dynamics design for the HIE-LINAC including:

1. **A first-order beam dynamics study of the whole linac.**
2. **A realistic field beam dynamics study of the high-energy section of the HIE-LINAC.**
3. **Single particle dynamics study in QWR to investigate the effects of beam steering and transverse field asymmetry intrinsic to the cavity.**
4. **Compensation of field asymmetry by geometric modifications to the cavity.**
5. **Error and misalignment study.**

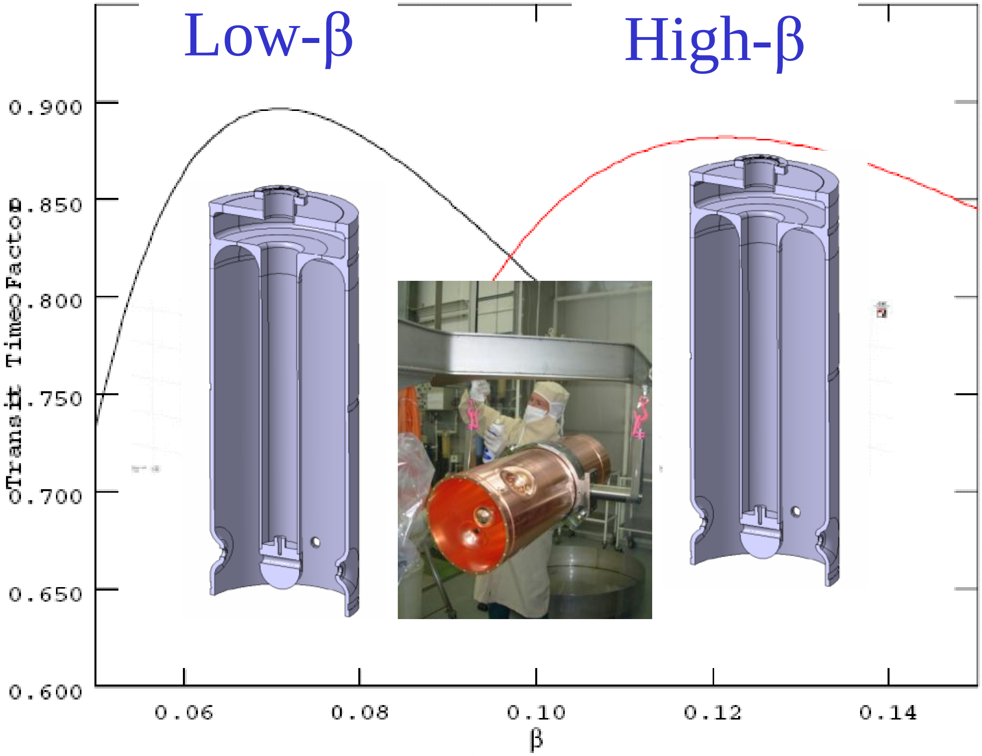
2. HIE-LINAC

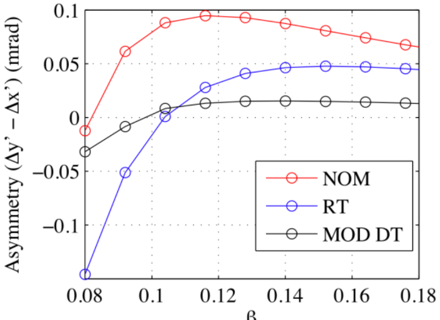
WP3: Cavity RF and Beam Dynamics

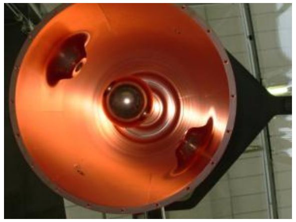
High-β cavity RF Design

f (MHz)	**101.28**
Inner Cond. Diam (mm)	**90**
Outer Cond Diam (mm)	**300**
Mechanical Length (mm)	**320**
Gap length (mm)	**85**
Beam Apert. Diam. (mm)	**20**
U/Ea^2 (mJ/(MV/m))^2	**207**
Ep/Ea	**5.6**
Hp/Ea (Oe/MV/m)	**100.7**
Rsh/Q (Ohm)	**548**
Q0 min for 6 MV/m at 7W	**5x10^8**
TTF max	**0.9**
β_0	**10.3%**
Design Gradient E$_{acc}$ (MV/m)	**6**
Number of cavities	**20**

Transit Factor







2. HIE-LINAC

Summary

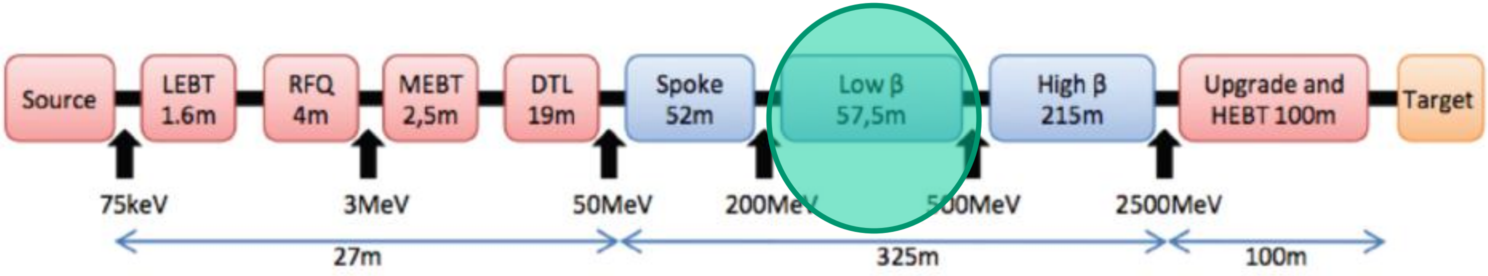
- SC cavities will facilitate the provision of variable-energy beams of exotic ions with concomitant improvement in beam quality.

- Nb sputtered onto Cu quarter-wave cavities have the potential to radically reduce costs and serve as a technological base for future accelerators. Prototype high-β cavity built and sputtered, tested at TRIUMF. Re-sputtered and in tests at CERN

- RF cavity and beam dynamics studies to both design the overall system and to perform "cradle to grave" simulations – improvements beam port designs completed

- Influence of transverse kicks to the beam has been investigated utilising state-of-the art beam dynamics RF computer codes (LANA and others).

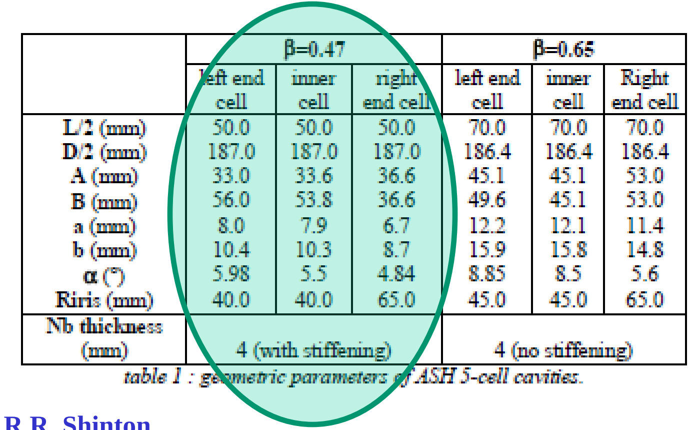
3. HOM Studies on ESS Cavities



Schematic of ESS

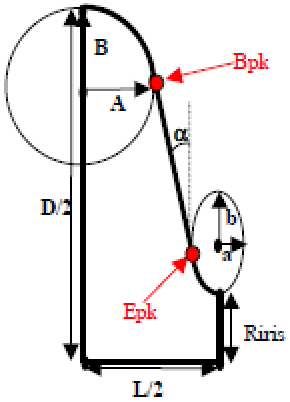
- ➢Initially focus on the low β end of ESS, which has ~15 modules with 4 cavities per module. After HOM studies on this section have been made investigation of the high β end of ESS will be made, followed by a concatenation of the results.

- ➢ESS cavity geometry unavailable – conduct some preliminary studies with dimensions taken from different cavity (2001 ASH cells). Objective: HOM's in a high intensity proton machine



	β=0.47			β=0.65		
	left end cell	inner cell	right end cell	left end cell	inner cell	Right end cell
L/2 (mm)	50.0	50.0	50.0	70.0	70.0	70.0
D/2 (mm)	187.0	187.0	187.0	186.4	186.4	186.4
A (mm)	33.0	33.6	36.6	45.1	45.1	53.0
B (mm)	56.0	53.8	36.6	49.6	45.1	53.0
a (mm)	8.0	7.9	6.7	12.2	12.1	11.4
b (mm)	10.4	10.3	8.7	15.9	15.8	14.8
α (°)	5.98	5.5	4.84	8.85	8.5	5.6
Riris (mm)	40.0	40.0	65.0	45.0	45.0	65.0
Nb thickness (mm)	4 (with stiffening)			4 (no stiffening)		

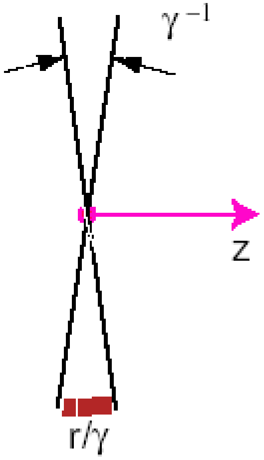
table 1 : geometric parameters of ASH 5-cell cavities.



- ➢Focused on looking at low beta ASH (Superconducting Accelerator for Hybrid) cell geometry [J–L Biarrotte et al.," 704 MHz superconducting cavities for a high intensity proton accelerator", Proc. of SRF99, Santa-Fe, NM, 1999.], as a precursor investigating ESS cavities.

3. HOM Studies on ESS Cavities

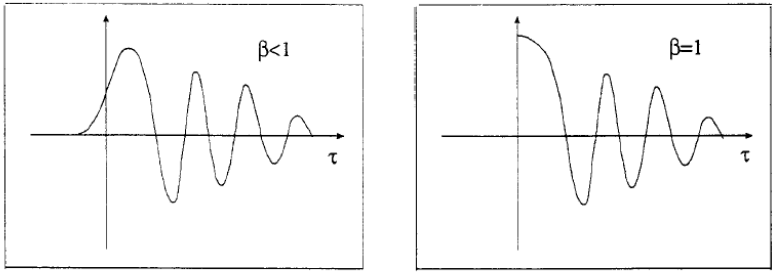
- Major difference between electron and low to medium β cavity is of course the charged particles are not ultra-relativistic (v<c)
- The major consequence of this is the usual modal formula –summation over discrete modes –needs modification to take into account the velocity variation and to make use of the characteristic pancake shape of the transverse field. The wakefield peers ahead, as well as behind, the bunches
- Needs to be incorporated into beam dynamics studies



$$\mathbf{E}=\frac{q\mathbf{R}}{4\pi\varepsilon_0\gamma R_*^3},\quad H=Y_0\frac{\mathbf{v}}{c}\times\mathbf{E}$$

$$R_*^2=z^2+r^2/\gamma^2$$

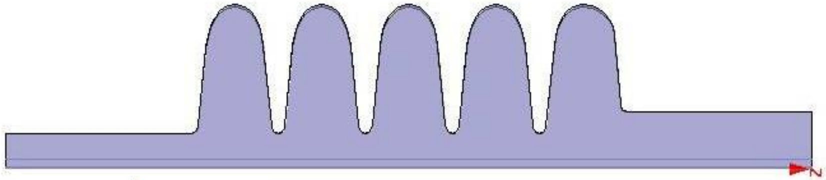
$$E_r(z,r)=\frac{q\gamma r}{4\pi\varepsilon_0\left(z^2\gamma^2+r^2\right)^{3/2}}$$

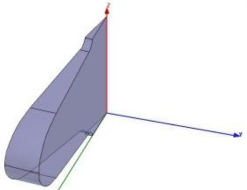


Envelope of Transverse Wakefield

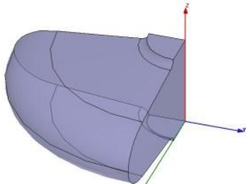
3. HOM Characterisation of 704 MHz Cavities

- ➢Initial results will involve simulations with HFSS of an idealised cavity, this results will give an overview for any potentially harmful HOMs

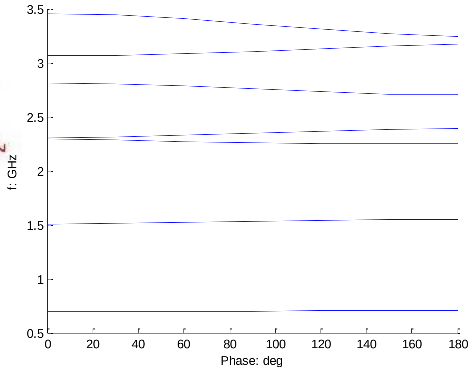




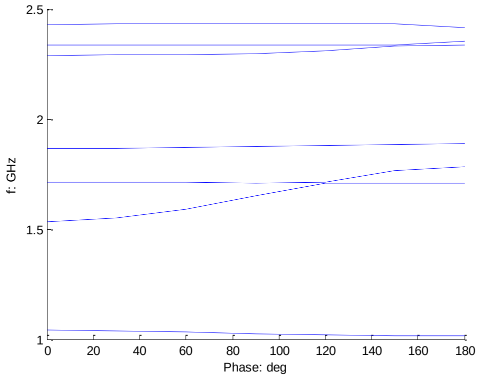
Slice used to simulate monopole modes



Quarter cell used to simulate dipole modes

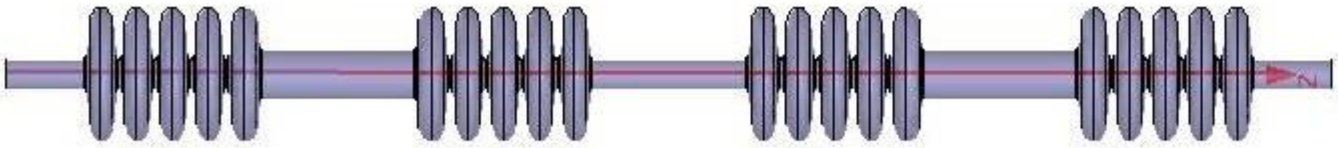


Monopole

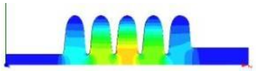
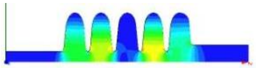
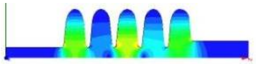
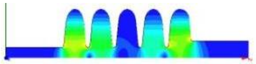
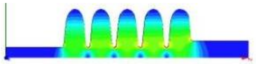


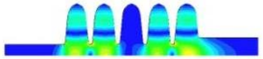
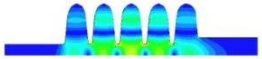
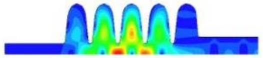
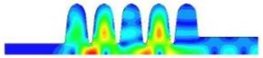
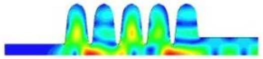
Dipole and Sextupole

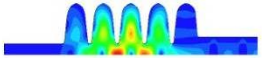
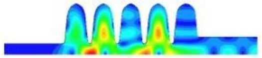
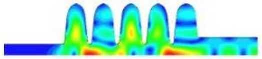
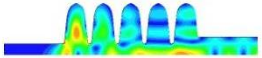
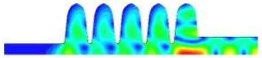
- ➢Simulations capitalise scalable properties of Omega3P (part of ACE3P suite) to simulate a series of cavity strings will be used to investigate the effects of HOM's including trapped modes and multi-cavity modes (above the beam-pipe cut-off) that propagate throughout the entire structure (work in progress!)



3. HOM Characterisation of 704 MHz Cavities

	F:MHz	Band
	696.4	1
	698.9	1
	701.7	1
	703.9	1
	704.8	1

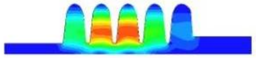
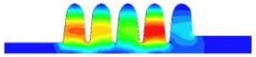
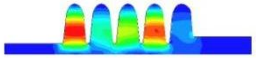
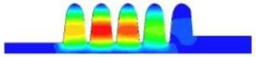
	F:GHz	Band
	1.540	2
	1.548	2
	2.250	2
	2.258	2
	2.270	2

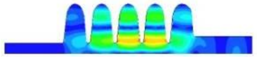
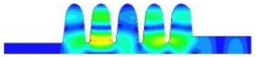
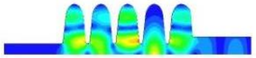
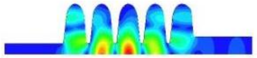
	F:GHz	Band
	2.250	3
	2.260	3
	2.270	3
	2.282	3
	2.294	3

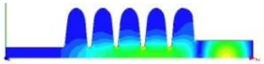
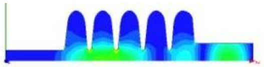
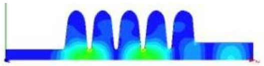
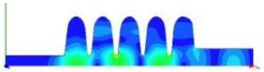
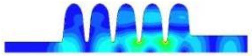
- **All monopole bands below 2nd are below cut-off of the power coupler beam-pipe**
- **Simulations performed with eigenmode module of HFSS**

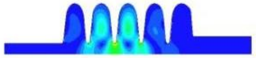
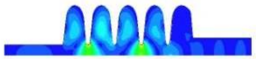
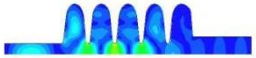
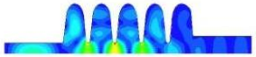
Monopole bands

3. HOM Characterisation of 704 MHz Cavities

The first dipole band is localised within the cavity	F:GHz	Band
	1.025	1
	1.032	1
	1.040	1
	1.047	1

	F:GHz	Band
	1.868	4
	1.871	4
	1.875	4
	1.883	4

All dipole bands above 2nd are above cut-off of the power coupler beam-pipe	F:GHz	Band
	1.546	2
	1.570	2
	1.628	2
	1.702	2
	1.765	2

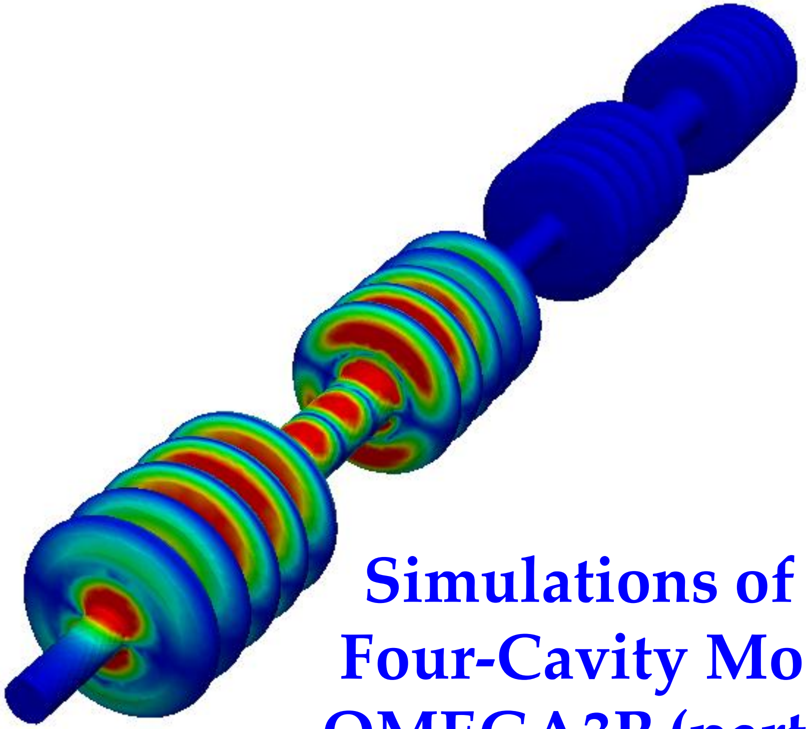
	F:GHz	Band
	2.292	5
	2.302	5
	2.324	5
	2.334	5

Selected Dipole Bands

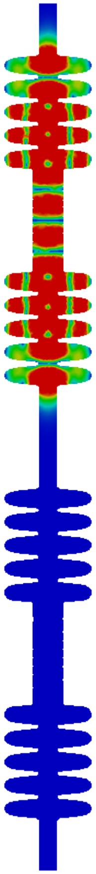
3. HOM Characterisation of 704 MHz Cavities

- Preliminary study of multi-cavity modes using the Omega3P frequency domain solver of the ACE3P suite
- Additional full module simulations and strings of modules in progress (in NERSC job queue!)

I.R.R. Shinton



Simulations of Coupled Four-Cavity Module with OMEGA3P (part of ACE3P Suite)



- Example of a diple mode at ~1.76378GHz in the second dipole band
- Frequency shift from idealised single cavity values due to propagation through power coupler beam-pipe

Summary

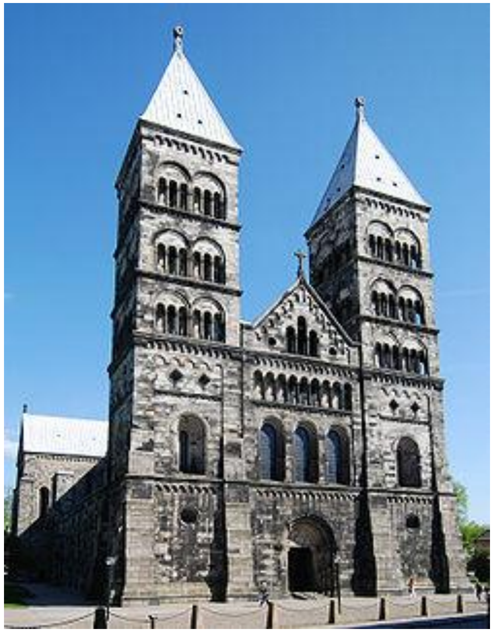
- **1. HOM characterisation of cavity wake-fields and beam dynamics for ILC/XFEL. Globalised scattering technique provides a unique method to enable trapped modes in modules to be probed.**
- **1. HOMs as BPM diagnostic for ILC/XFEL: FP7 as part of DESY/Cockcroft/Univs Manchester & Rostock collaboration. Participating in exp program at FLASH/DESY.** ***EuCARD FP7, R.M. Jones, Task Leader***
- **2. HIE-ISOLDE energy upgrade ongoing. Protoype quarter wave cavity built (inc. tuners). Well-reviewed by recent intl. committee. Ph.D. student – beam dynamics simulations, PDRA –cavity/coupler/tuner design. Sputtered cavity tested at TRIUMF,VA. Re-sputtered being tested at CERN.**

- **3. HOMs in spoke and elliptical cavities will be analysed and means to provide sufficient Q damping suggested.**

- ☐ ***Both isolated and multi-cavity modes will be simulated and analysed.***
- ☐ ***HOM as diagnostic BPMs could be advantageous in these cavities also.***
- ☐ ***Anticipate exchange of information, on both sets of cavity structures, from our European and international collaborators!***

ESS HOMs -Summary Cont.

- **Wakefield is distributed among the HOMs generated. Main issue is how much transverse momentum is distributed to the beam –or how large are the kick factors?**
- **Beam dynamics simulations will indicate how much (if any?!) suppression of modes is necessary.**
- **Experience with SNS indicated that the couplers may not be necessary (and indeed introduced a major headache due to multipacting)**
- **Project X is investigating whether or not HOM damping/couplers are necessary -influence of (inevitable during fabrication) random errors reduces the overall average kick to the beam!**
- **Overall conclusion :**
  - ***Full analysis of coupled multi-cavity modes needed and the largest ones isolated . If there are trapped modes –do they matter (inconsequential R/Q)?***
  - ***Beam dynamics study incorporating these modes (including realistic sources of errors).***



Thank you for your attention!

The Cockcroft Institute
of Accelerator Science and Technology

Additional Slides

2009/2010 Publications of μ Group

Journal Pubs.

1. **R. M. Jones**, Wake field Suppression in *High gradient linacs for lepton linear colliders*, Phys. Rev. ST Accel. Beams 12, 104801, 2009, 14pp.

2. **R. M. Jones**, V. A. Dolgashev, and J. W. Wang, *Dispersion and energy compensation in high-gradient linacs for lepton colliders*, Phys. Rev. ST Accel. Beams 12, 051001 2009, 11pp.

3. **R.M. Jones**, C.E. Adolphsen, R.H. Miller, J.W. Wang , T. Higo, *Influence of fabrication errors on wake function suppression in NC X-band accelerating structures for linear colliders*, New J. Phys.11:033013,2009, 13pp.

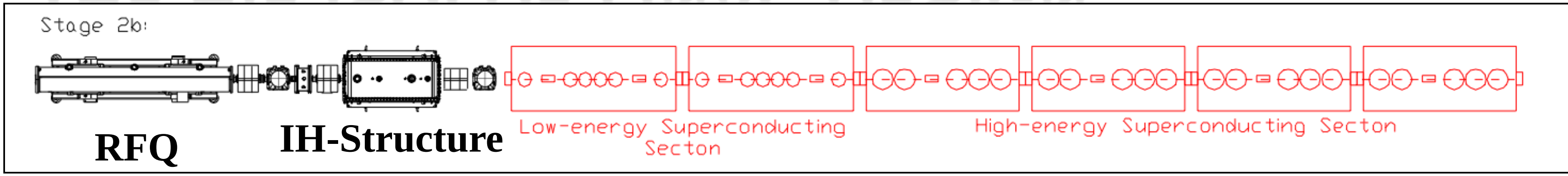
4. W. Salah, **R.M. Jones**, J.L. Coacolo, *Analysis of space charge fields using lienard-wiechert potentials and the method of images in the RF-free electron laser photoinjectors*, doi:10.1016/j.nima.2009.05.188 .

5. W. Salah, **R.M. Jones**, J.L. Coacolo, *Analysis of the transverse kick to beams in low-frequency photoinjectors due to wakefield effects*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 601, Issue 3, 1 April 2009, Pages 264-269

Conf. Pubs.

In 2009 (2010) we published ~10 (12) conference proceedings pubs

THE HIE-ISOLDE LINAC DESIGN



- ✓ Acceleration: 2-gap superconducting QWRs.
  1. Low-energy section: $\beta_g = 6.3\ \%$
  2. High-energy section: $\beta_g = 10.3\ \%$

- ✓ Each cavity independently powered allowing for a flexible velocity profile: $2.5 < A/q < 4.5$.

- ✓ Focusing: superconducting solenoids.

- ✓ Dedicated lattices for low and high-energy:
  1. Strong RF defocusing at low-energy so 2 solenoids per cryomodule are used.
  2. First low-β cavity separated to operate as a buncher.