HOM Beam Based Diagnostics at FAST

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with

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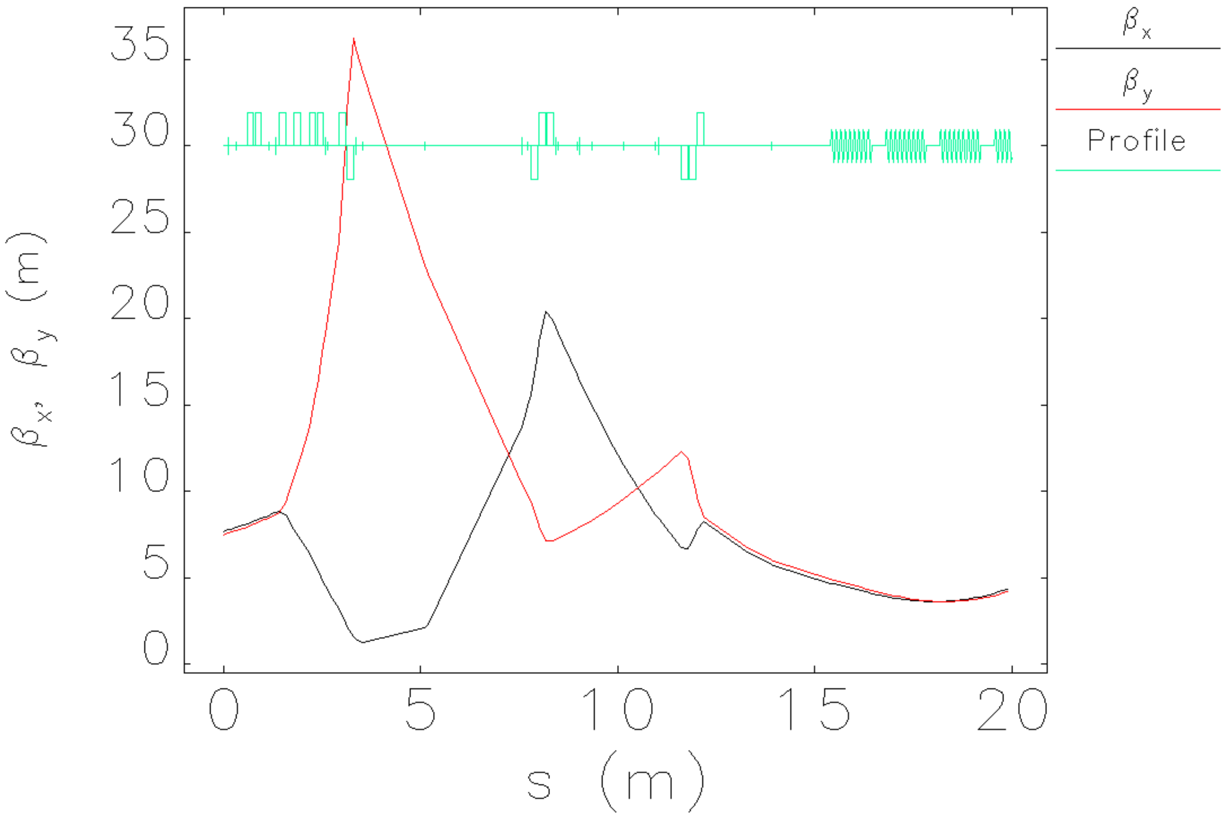
Introduction

Superconducting RF cavities are high quality symmetric resonators that support many different modes of oscillation, with high precision signals and unsurpassable dynamic range. Owing to their approximate axial symmetry, modes can be identified according to their ***monopole, dipole and quadrupole nature****. Higher Order Modes (HOM) excited by bunched beams in SRF cavities hence coupled respectively to the* ***charge, position and size*** *of the beam.*

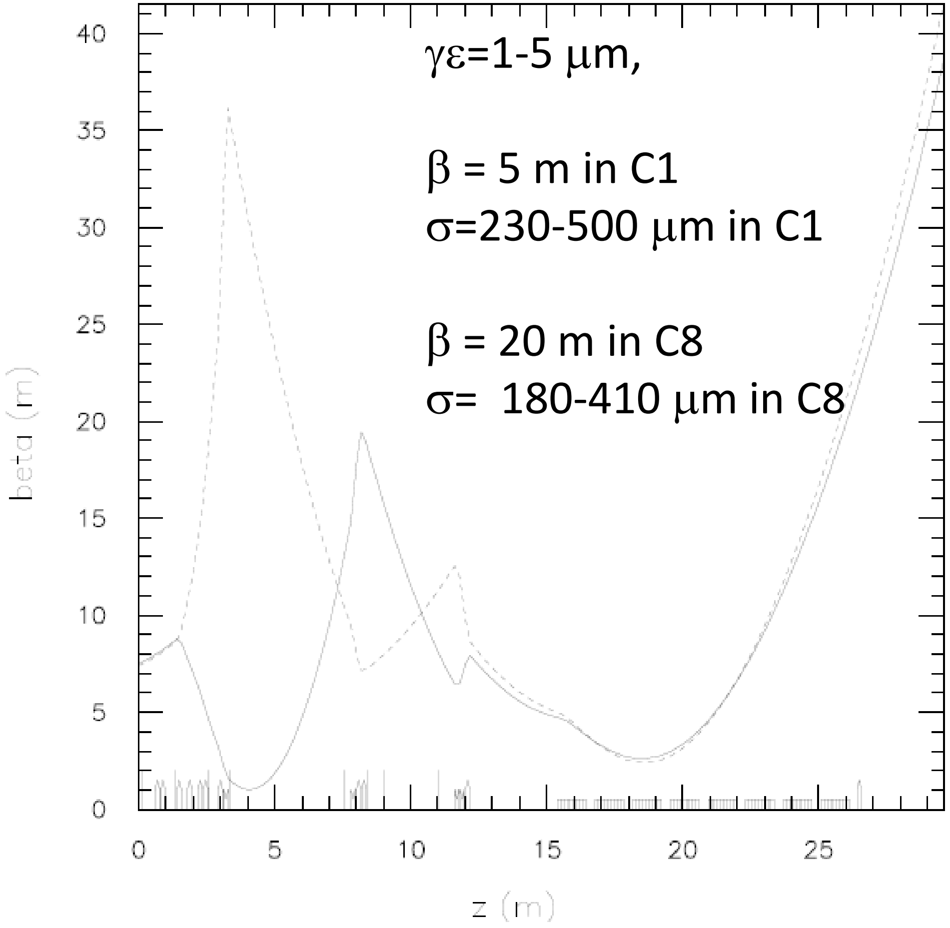
HOM-based diagnostics have already been used in various SRF accelerators like FLASH at DESY and FAST at Fermilab. However, the complete exploitation of their full potential in beam diagnostics and beam based tuning has not been realized, for instance in ***achieving minimal transverse wake kicks and transverse beam size measurement, in a non-invasive fashion****.*

We would like to explore and identify physics and engineering challenges in implementing HOM diagnostics using fully relativistic electron bunches through CM2 SRF cavities at FAST.

FAST Optics

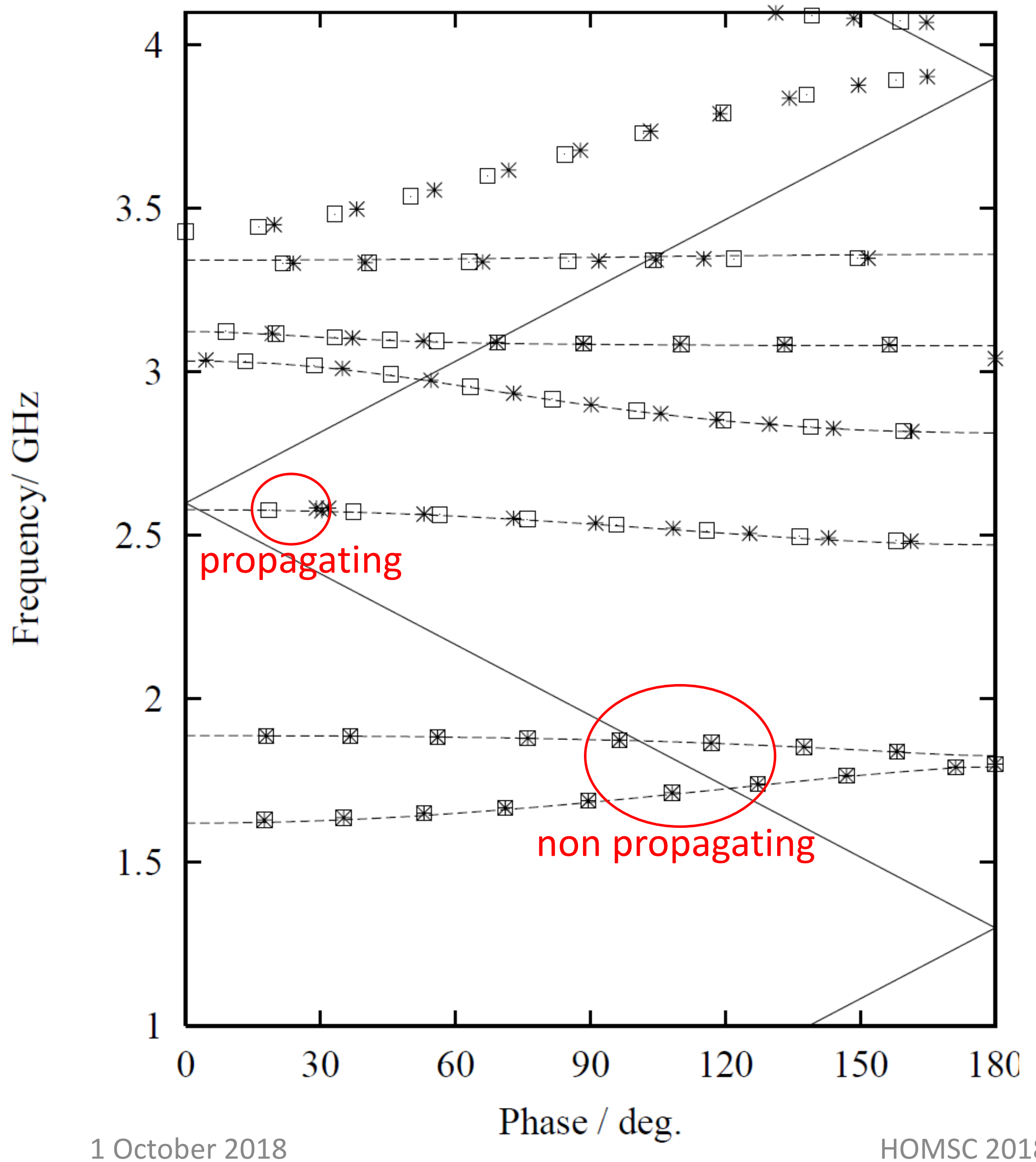


Elegant (courtesy Ph. Piot)



CEA Optics Code (used for TTF)

TESLA Cavity Dipole Mode Passbands (axial symmetry)



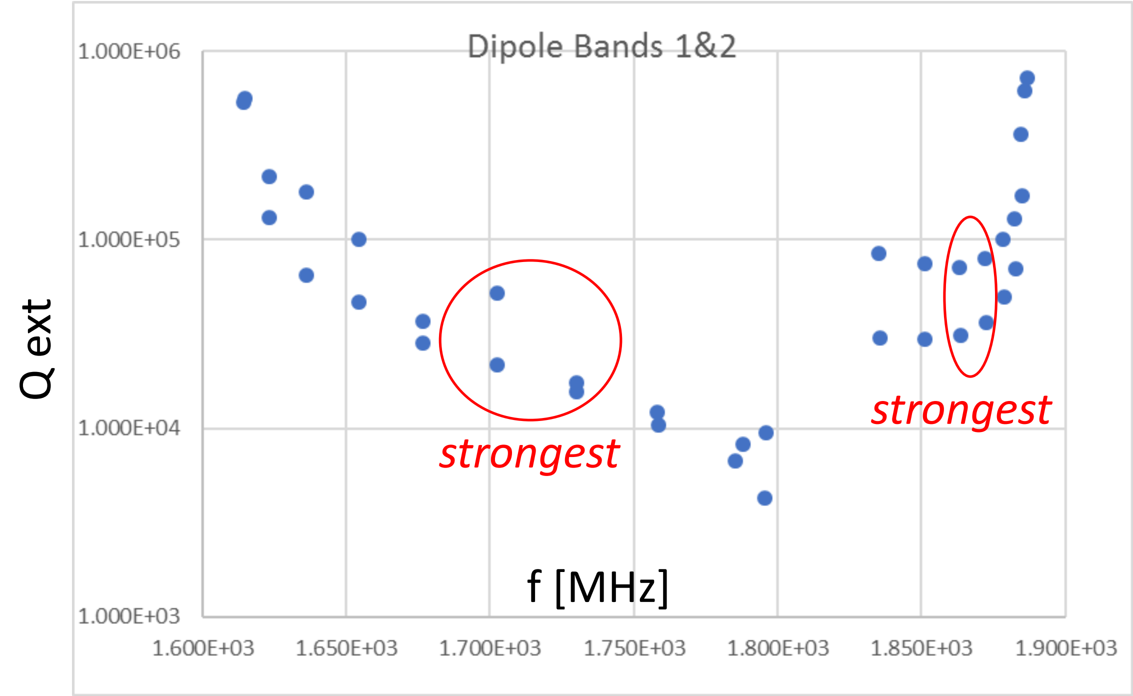
mode	f /GHz	$(R/Q)^{(1)}$ / Ω/cm^2
Band 1		
MM- 1	1.6291	2x 0.0014
MM- 2	1.6369	2x 0.0636
MM- 3	1.6497	2x 0.0015
MM- 4	1.6671	2x 0.3767
MM- 5	1.6885	2x 0.0684
Band 1 MM- 6	1.7129	2x **5.5335**
MM- 7	1.7391	2x **7.7852**
MM- 8	1.7656	2x 1.0492
MM- 9	1.7912	2x 0.8045
MM-10	1.8004	2x 0.3542
Band 2		
MM-11	1.8391	2x 0.2433
MM-12	1.8535	2x 0.1327
Band 2 MM-13	1.8650	2x **3.1825**
MM-14	1.8736	2x **4.4887**
MM-15	1.8795	2x 1.0501
MM-16	1.8834	2x 0.0210
MM-17	1.8858	2x 0.0808
MM-18	1.8871	2x 0.0015
Band 3 MM-30	2.5785	2x **13.1601**

Ref. R. Wanzenberg (DESY)

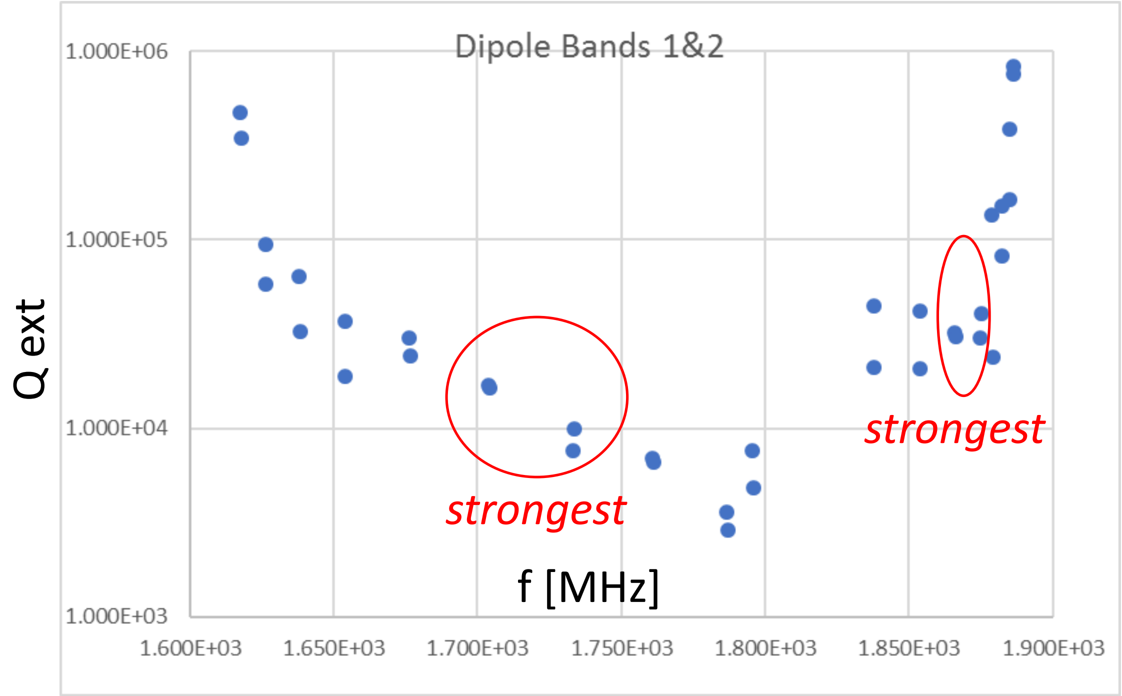
Dipole Mode 1st and 2nd Passbands

- The fabrication errors and coupler ports are ‘weakly’ breaking the axial symmetry, hence lifting the mode degeneracy.
- Note the arrangement in polarization doublets (CM2 data also available)

CC1 dipole: 1st and 2nd passbands



CC2 dipole: 1st and 2nd passbands



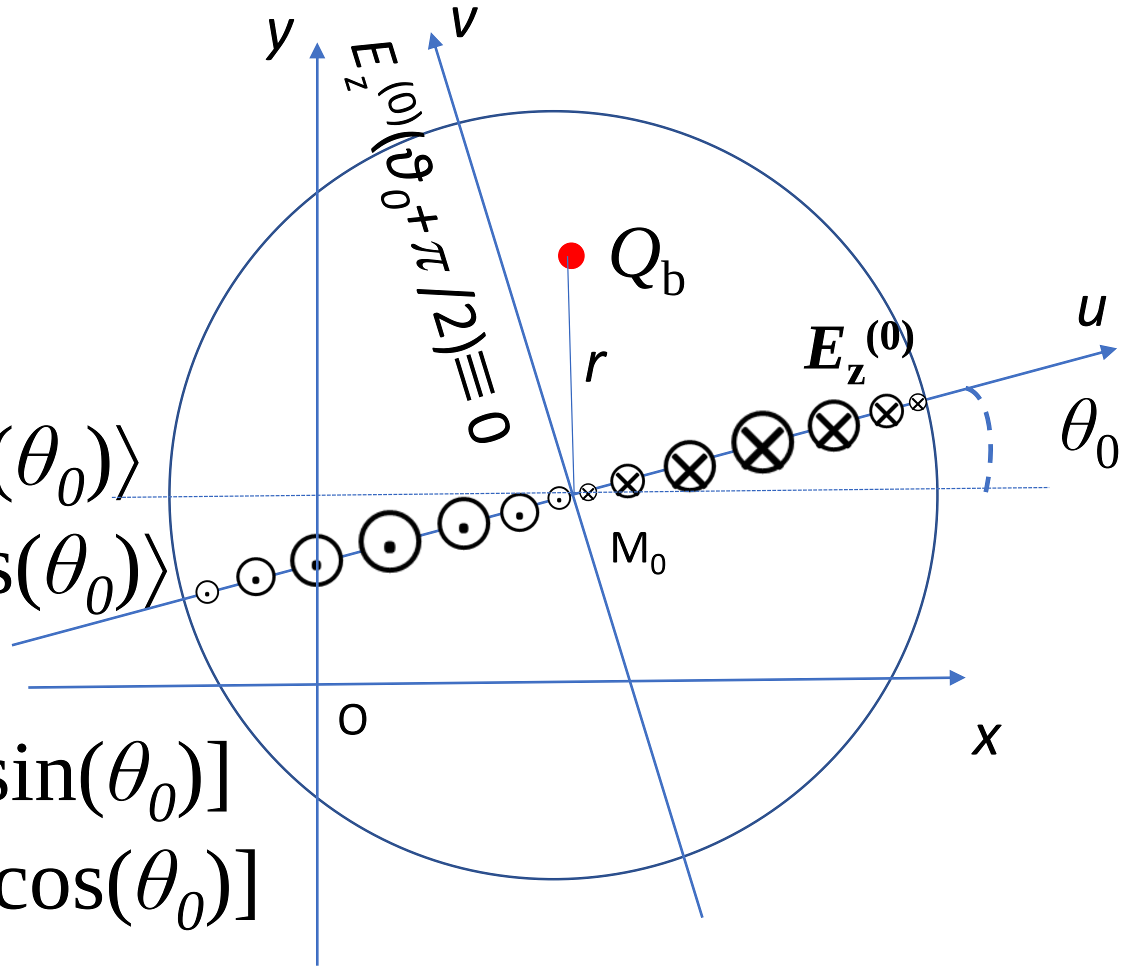
Dipole Mode (**m=1**) Excitation Amplitudes

Assuming that both polarisations have the same center and beam coupling factor, for $r \langle\langle R$:

$$A_1(Q_b) = C\,\langle r\cos(\theta\text{-}\theta_0)\rangle = C\,\langle u\rangle$$
$$A_2(Q_b) = C\,\langle r\sin(\theta\text{-}\theta_0)\rangle = C\,\langle v\rangle$$

$$A_1(Q_b) = C\,\langle (x\text{-}x_0)\cos(\theta_0) + (y\text{-}y_0)\sin(\theta_0)\rangle$$
$$A_2(Q_b) = C\,\langle \text{-}(x\text{-}x_0)\sin(\theta_0) + (y\text{-}y_0)\cos(\theta_0)\rangle$$

$$A_1(Q_b) = C[(\langle x\rangle\text{-}x_0)\cos(\theta_0) + (\langle y\rangle\text{-}y_0)\sin(\theta_0)]$$
$$A_2(Q_b) = C[\text{-}(\langle x\rangle\text{-}x_0)\sin(\theta_0) + (\langle y\rangle\text{-}y_0)\cos(\theta_0)]$$



Measurement plans

- Measure the two polarizations for each major dipole mode, usually separated by 1 MHz or less.

- Determine the horizontally / vertically

most coupled modes.

- Single bunch data 1 nC is enough

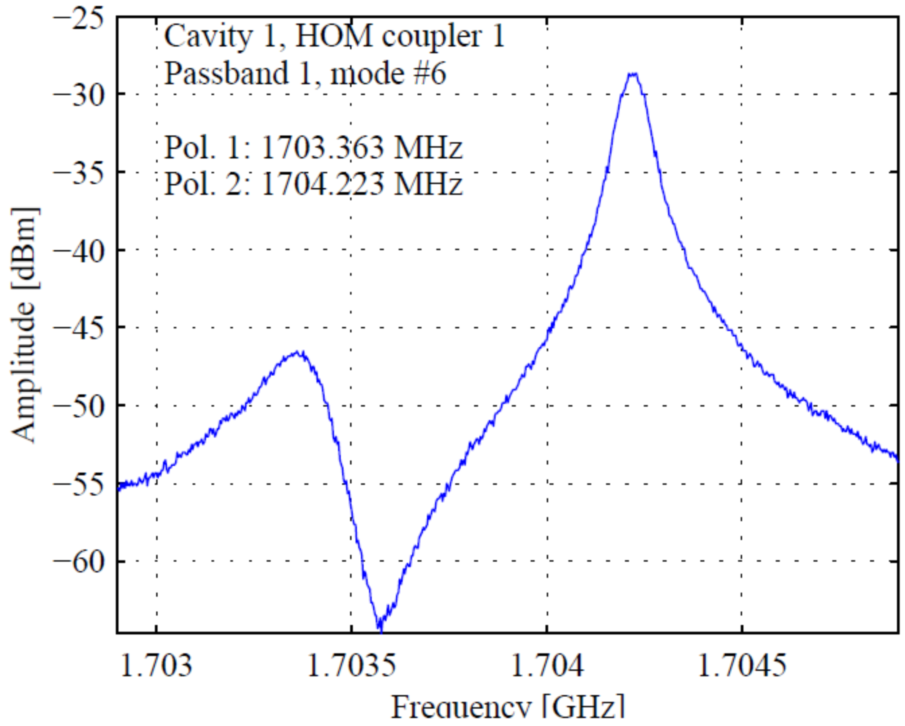


Figure 2: Mode #6 of the first dipole passband in cavity 1 of ACC1

Example of a FLASH cavity

Measurement electric center

- Steer the beam through the HOM center by minimizing signals

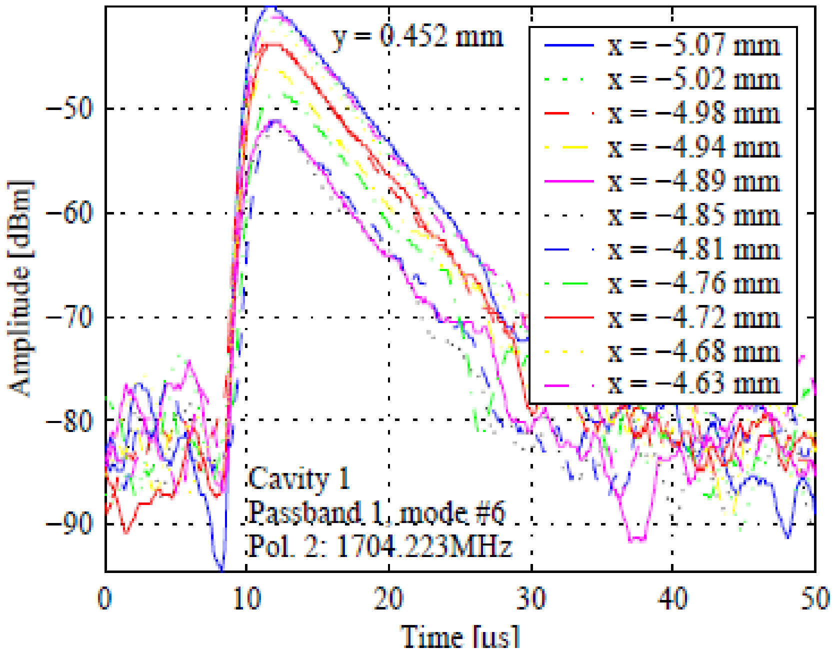


Figure 4: Time domain signals for the first polarization of the 6th mode of the 1st dipole band of the first cavity.

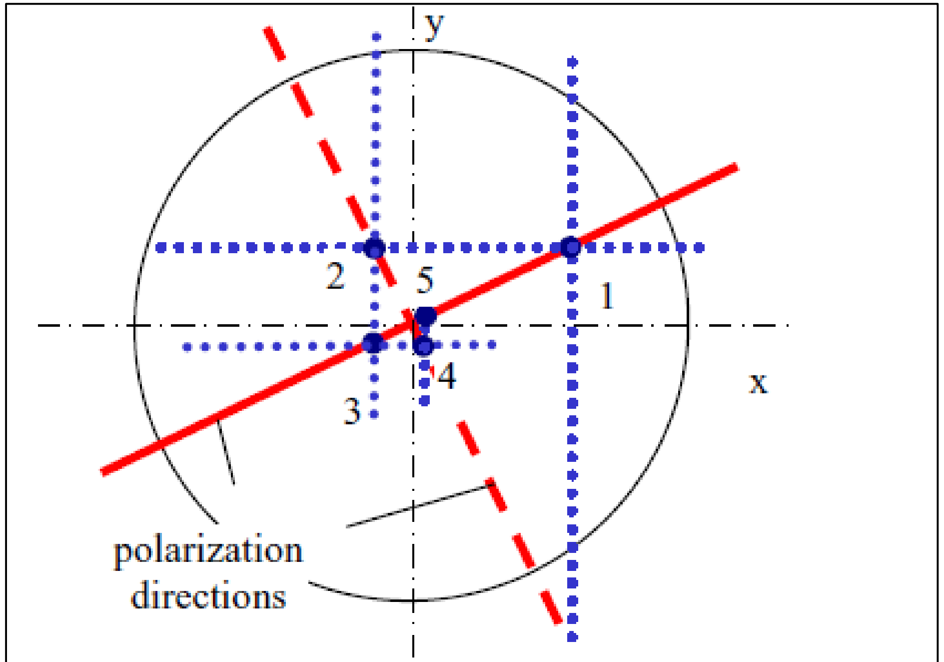


Figure 3: Alternate horizontal and vertical beam position scans for a mode with oblique polarization axes.

Example of a FLASH cavity: 50 µm steps

Perform systematic studies for most significant HOM

- Measure the polarization angle by comparing the x vs. y sensitivities

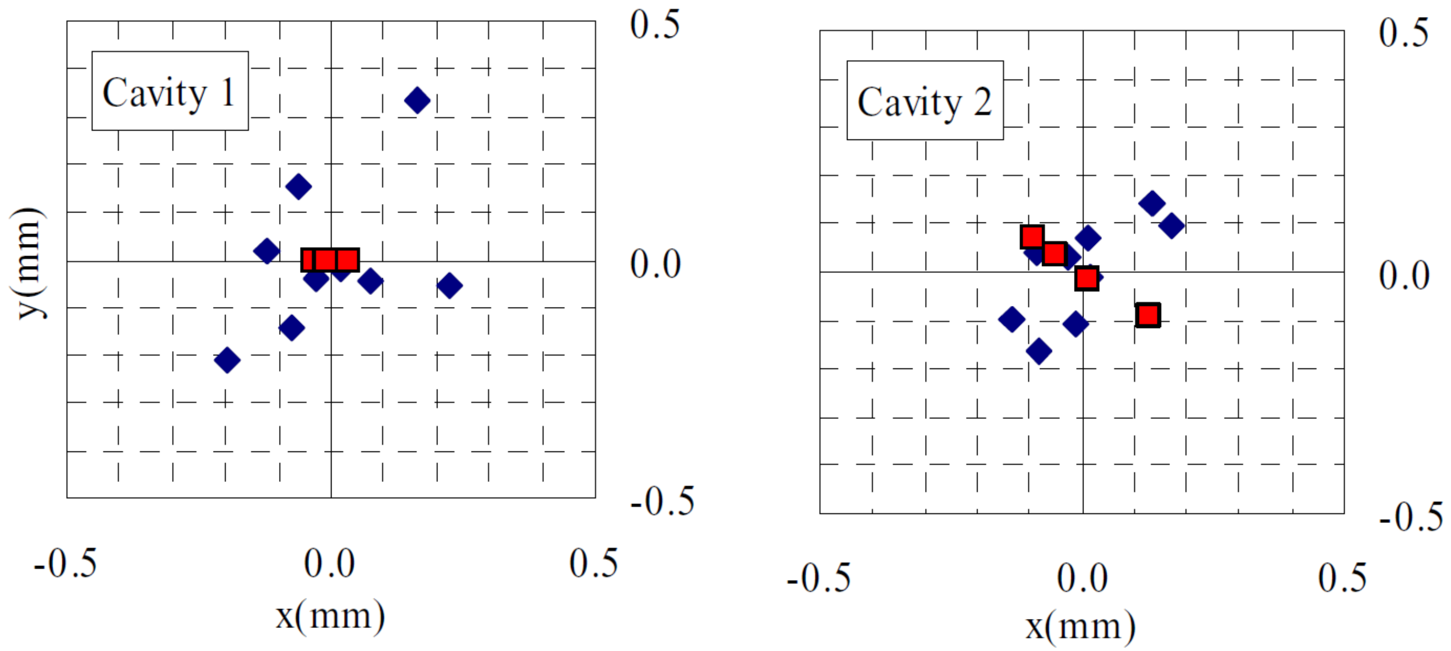


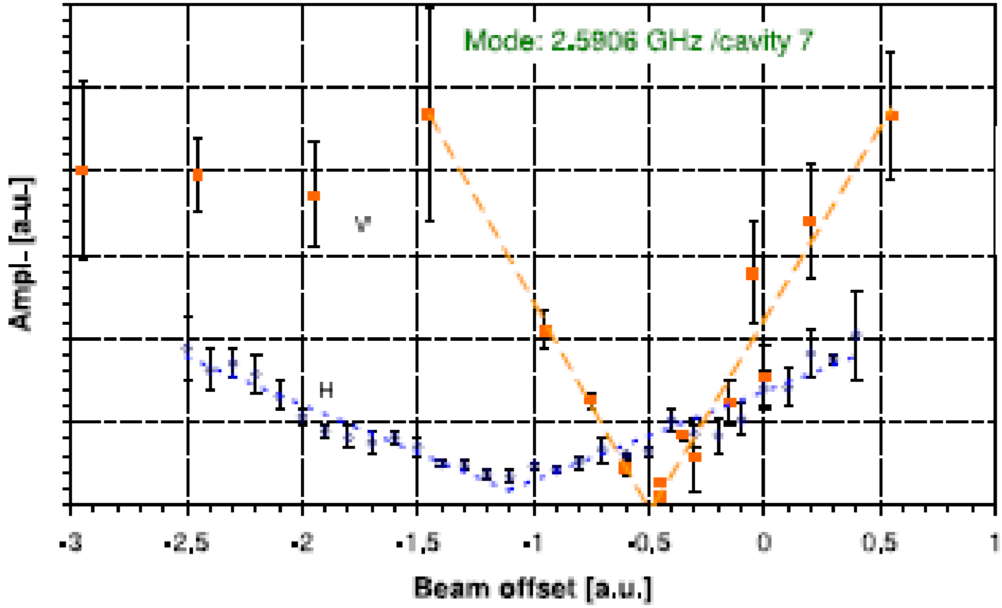
Figure 6: Relative positions of the 9 cell centers (blue diamonds) and of the 4 dipole mode centers (red squares).

Example of a FLASH cavity

Measurement polarization angle

- Measure the polarization angle by comparing the x vs. y sensitivities

$$\tan\varphi = \frac{A(\delta x = 0, \delta y)}{A(\delta x, \delta y = 0)}$$



$77^\circ \pm 8^\circ$

Figure 5.28: Amplitude of signal from HOM couplers as a function of the horizontal and vertical beam offset.

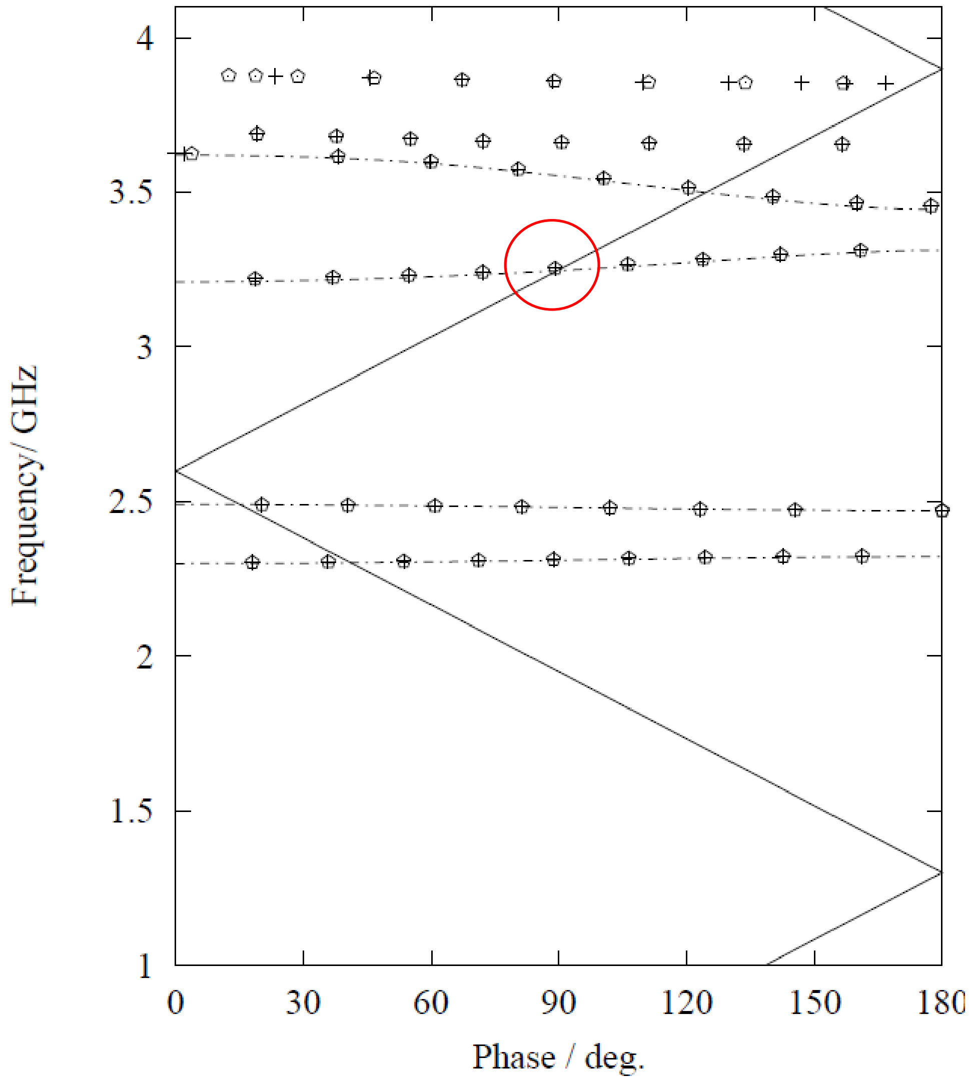
Example of a FLASH cavity

Questions to investigate:

- Are the CM2 cavities well aligned w.r.t. beam trajectory ?
- Is the beam trajectory through CM2 straight ?
- Are dipole modes preferentially ‘H’ and ‘V’, or at random angles ?
- Once the mode center and polarization are determined, can one develop an online electronics to read the amplitudes A_1 and A_2 , and infer the single bunch transverse position $\langle x \rangle$ and $\langle y \rangle$?
- PIP-II cavities are not equipped with HOM damping couplers. Can we measure the HOM amplitudes from the RF-pick-up and to which accuracy ?

Example of a FLASH cavity

Quadrupole modes in TESLA cavity



mode	f /GHz	$k^{(2)}(r)/r^4$/ V/(pC m^4)	G_1 /Ω	$(R/Q)^{(2)}$ / Ω/cm^4	Q_0/Q_{0FM}	φ /°
Band 1						
MM- 1	2.3039	4946.0	455.6	0.0068	0.568	18.0
MM- 2	2.3052	48631.7	457.5	**0.0672**	0.570	35.9
MM- 3	2.3074	42191.1	460.5	**0.0582**	0.572	53.6
MM- 4	2.3101	1438.9	464.4	0.0020	0.576	71.2
MM- 5	2.3133	2776.0	468.9	0.0038	0.580	88.7
MM- 6	2.3166	207.5	473.7	0.0003	0.584	106.4
MM- 7	2.3197	420.9	478.6	0.0006	0.588	124.4
MM- 8	2.3224	30.8	483.0	0.0000	0.592	142.7
MM- 9	2.3242	29.1	486.1	0.0000	0.595	161.3
Band 2						
MM-10	2.4702	2.6	447.2	0.0000	0.485	180.0
MM-11	2.4706	3819.9	448.5	0.0049	0.486	180.0
MM-12	2.4727	1.2	451.5	0.0000	0.488	145.5
MM-13	2.4757	2932.4	457.0	0.0038	0.493	123.2
MM-14	2.4791	99.8	463.5	0.0001	0.499	102.1
MM-15	2.4825	5532.6	470.0	0.0071	0.505	81.3
MM-16	2.4856	979.7	476.0	0.0013	0.510	60.9
MM-17	2.4881	23777.3	480.7	0.0304	0.514	40.5
MM-18	2.4896	60355.0	483.7	**0.0772**	0.516	20.3
Band 3						
MM-19	3.2195	845.5	395.1	0.0008	0.252	18.6
MM-20	3.2242	8108.9	397.4	0.0080	0.253	37.0
MM-21	3.2316	6016.5	401.2	0.0059	0.254	54.8
MM-22	3.2414	201688.8	406.9	**0.1981**	0.256	72.1
MM-23	3.2532	453226.2	414.8	**0.4435**	0.259	89.1
MM-24	3.2670	286421.0	425.1	**0.2791**	0.263	106.2
MM-25	3.2825	35929.7	437.3	0.0348	0.269	123.8
MM-26	3.2985	4175.8	450.4	0.0040	0.274	142.1
MM-27	3.3120	4955.2	461.9	0.0048	0.279	160.9
MM-28	3.4561	32706.0	547.5	0.0301	0.303	177.5

Table 21: List of quadrupole modes in a 9-cell TDR-like TESLA cavity, 1st, 2nd and 3rd passbands, (magnetic boundaries). The parameters of the modes EE-1 to EE-28 (electric boundaries) are identical with the modes MM-1 to MM-28 of this table.

TM-like Quadripole Mode (**m=2**) Impedances

$$E_z(\theta) = E_z^{(0)} \cos(2(\theta-\theta_0))$$

$$E_z^{(0)}(r=0) = E_z^{(0)}(r=R) \equiv 0$$

$$E_z^{(0)}(r) \propto r^2 \quad \text{for} \quad r \ll R$$

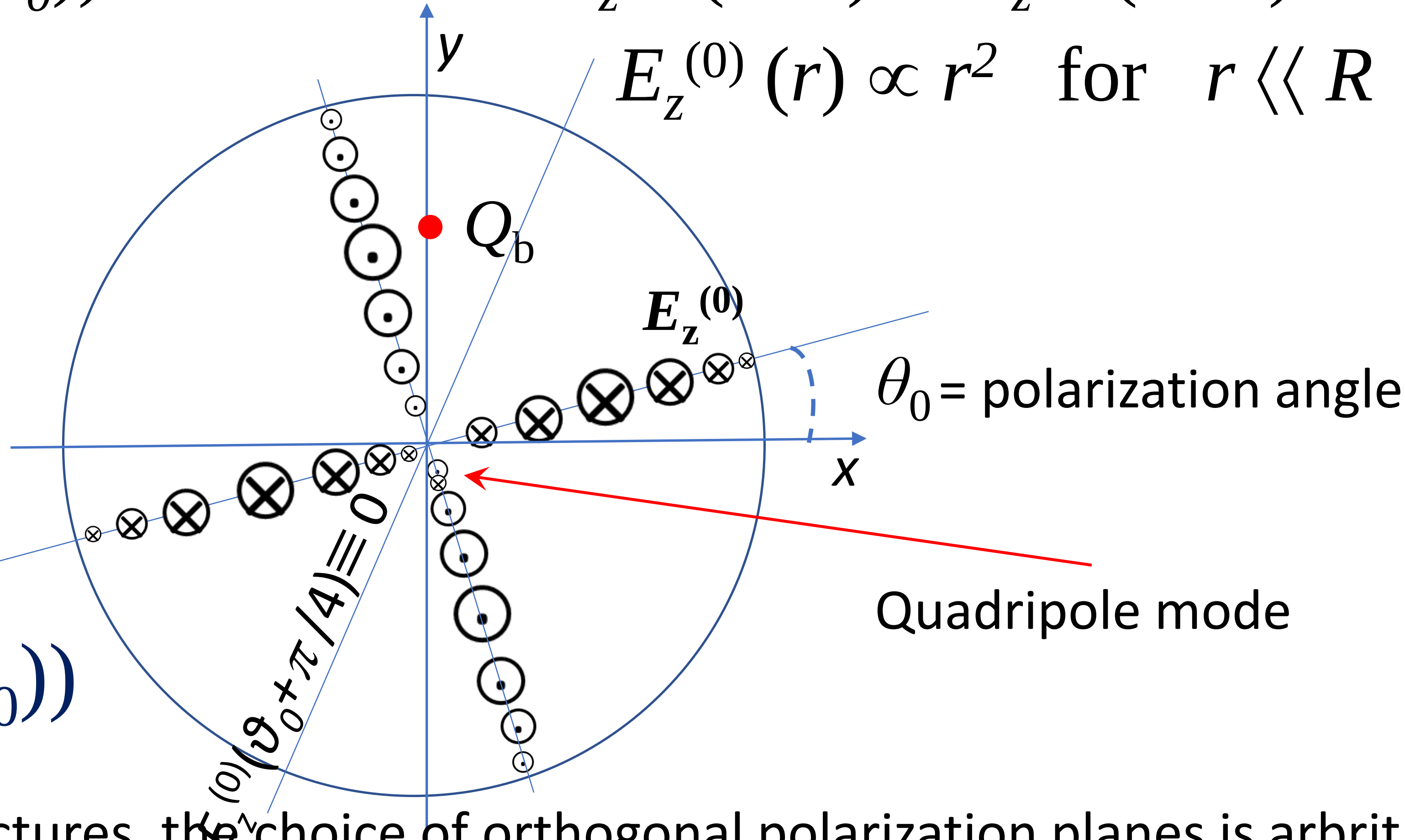
On the polarisation plane:

$$U = \int dz\, E_z(z, t=z/c)$$
$$\propto r^2\, U''$$

$$R/Q^{(m=1)} = U''^2/\omega_{RF} W$$

Off the polarisation plane:

$$U(\theta) = U \cos(2(\theta-\theta_0))$$



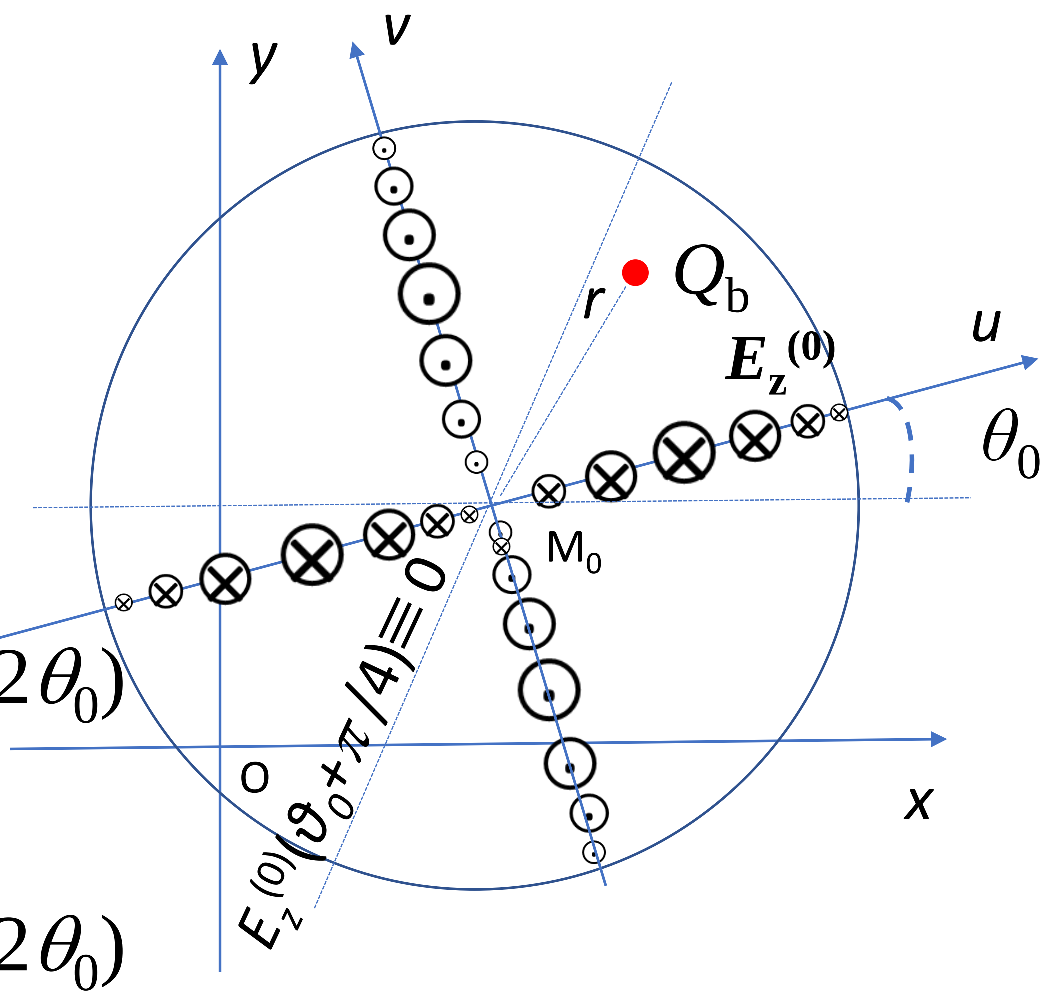
For axially symmetric RF structures, the choice of orthogonal polarization planes is arbitrary, and all modes electric axis coincide with the geometric axis.

Dipole Mode (**m=2**) Excitation Amplitudes

Assuming that both polarisations have the same center and beam coupling factor, for $r \langle\langle R$:

$$A_1(Q_b) = C\,\langle r^2 \cos(2(\theta\text{-}\theta_0))\rangle = C\,\langle u^2 - v^2\rangle$$

$$A_2(Q_b) = C\,\langle r^2 \sin(2(\theta\text{-}\theta_0))\rangle = C\,2\,\langle uv\rangle$$



$$A_1(Q_b) = C\,\mathrm{Tr}\begin{pmatrix} \sigma_{xx} - (\langle x\rangle - x_0)^2 & \cdot \\ \cdot & \cdot \end{pmatrix}\cdot\sigma_3\cdot\mathrm{R}(2\theta_0)$$

$$A_2(Q_b) = C\,\mathrm{Tr}\begin{pmatrix} \sigma_{xx} - (\langle x\rangle - x_0)^2 & \cdot \\ \cdot & \cdot \end{pmatrix}\cdot\sigma_1\cdot\mathrm{R}(2\theta_0)$$

Quadrupole-modes Beam Size Monitor

In a perfect machine, i.e.:

- perfectly aligned cavities
- perfectly centered beam trajectory

through Ez-coupling, quadripole mode signal is proportional to beam second moments, i.e. transverse beam matrix.

Therefore, one could consider 4D-emittance reconstruction if there is enough phase-advance that machine (not CM2 indeed, only a demonstration).

In a machine where these errors are larger than transverse beam sizes, the program might be irrealistic, because quadrupole signals will be dominated by beam offsets.

In a machine with no too large errors, the large redondance of HOM signals could be used to establish correlations between beam sizes and HOM signal magnitude.

Work Plan

Project Description

The workplan of the project will include:

HOM CARTOGRAPHY (with spectrum analyzer)

- Detailed characterization of the first dipole (1st to 3rd) and quadrupole (1st and 2nd) passbands of x-# SRF cavities (CM2).
- Verification of these characteristics (frequencies, damping time) from the beam excitation signal.
- Measurement of their electric center and polarization planes, by beam-based alignment techniques (single bunch).
- Determination the most precise higher order modes, namely with highest coupler impedance on the beam, and the lowest damping factor depending on beam resonance conditions.
- Study of a dedicated broad-band electronics for HOM signal acquisition

HOM-BASED BEAM DIAGNOSTICS

- Utilization of the most adequate dipole modes for beam position measurement and beam steering, on average and possibly on a bunch-to-bunch basis. Characterization of the measurement precision and resolution.
- First studies of beam size measurement using the RF signal of the adequate quadrupole modes, on average and possibly on a bunch-to-bunch basis. Characterization of the measurement precision and resolution.
- Elaborated statistical and minimization techniques, such as SVD, will also be used to provide an overview of the beam trajectories and beam sizes along the FAST linac using the many and redundant RF signals coming from the 10 superconducting cavities.