HOM Beam Based Diagnostics at FAST

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Abstract of application to France and Chicago Collaborating in the Sciences (FACCTS) Program

Superconducting Radio-Frequency (SRF) technology has been established as a cost effective mean for accelerating particle beams. SRF cavities are high quality symmetric resonators which are able to support many different modes of oscillation. Higher Order Modes (HOM) excited by bunched beams in SRF cavities have already been in use for beam diagnostics. The complete exploitation of their full potential in beam diagnostics has not been realized. FAST at Fermilab offers SRF cavity HOM-based R&D opportunities. We would like to explore and identify physics and engineering challenges in implementing novel HOM-based diagnostics at the FAST electron linear accelerator at FERMILAB.

15 $k request over one year (notification 28 Feb. 2018, funds in April 2018)

PI's : Dan Broemmelsiek (FNAL) and myself (CEA)

Introduction

Innovative beam diagnostics are a key for the construction and the operation of future accelerators in view of achieving higher performances at lower cost and better safety. Superconducting RF cavities have the property to offer a realm of well separated RF signals, with high precision and unsurpassable dynamic range, which couple to the beam bunch in a variety of ways. Owing to their approximate axial symmetry, modes can be easily identified according to their monopole, dipole and quadrupole nature, hence coupling respectively to the charge, position and size of the beam in a non-invasive fashion. Rudimentary HOM-based diagnostics have already been in use 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 is achieving minimal transverse wake kicks and transverse beam size measurement.

Our project aims at implementing such novel HOM-based diagnostics on the FAST linac by using the RF signals from the capture cavities CC1 and CC1 and the accelerating cavities in CM2.

Work Plan

Project Description

The workplan of the project will include:

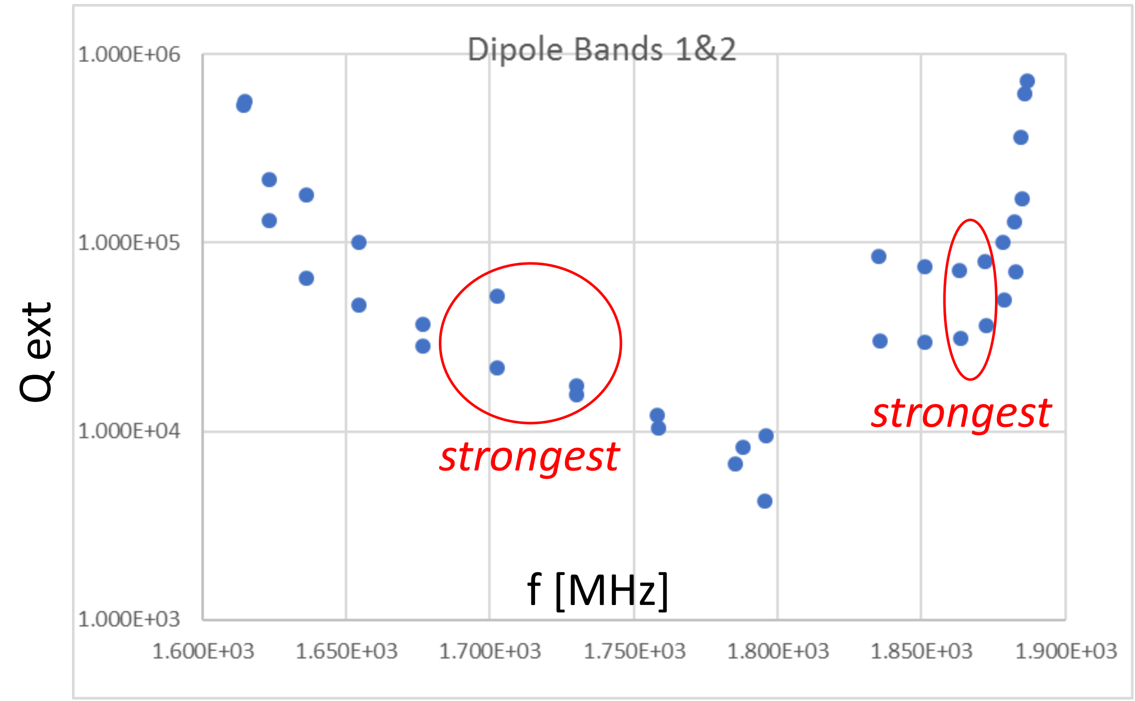
HOM CARTOGRAPHY
- Detailed characterization of the first transverse dipole (1^{st} to 3^{rd}) and quadrupole (1^{st} and 2^{nd}) passbands of each of the 10 SRF cavities (CC1, CC2, CM2).
- Verification of these characteristics (frequencies, damping time) from the beam excitation signal on a spectrum analyzer.
- Study of a dedicated broad-band electronics for HOM signal acquisition.
- Measurement of their electric center and polarization, by beam-based alignment techniques.
- 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.

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.

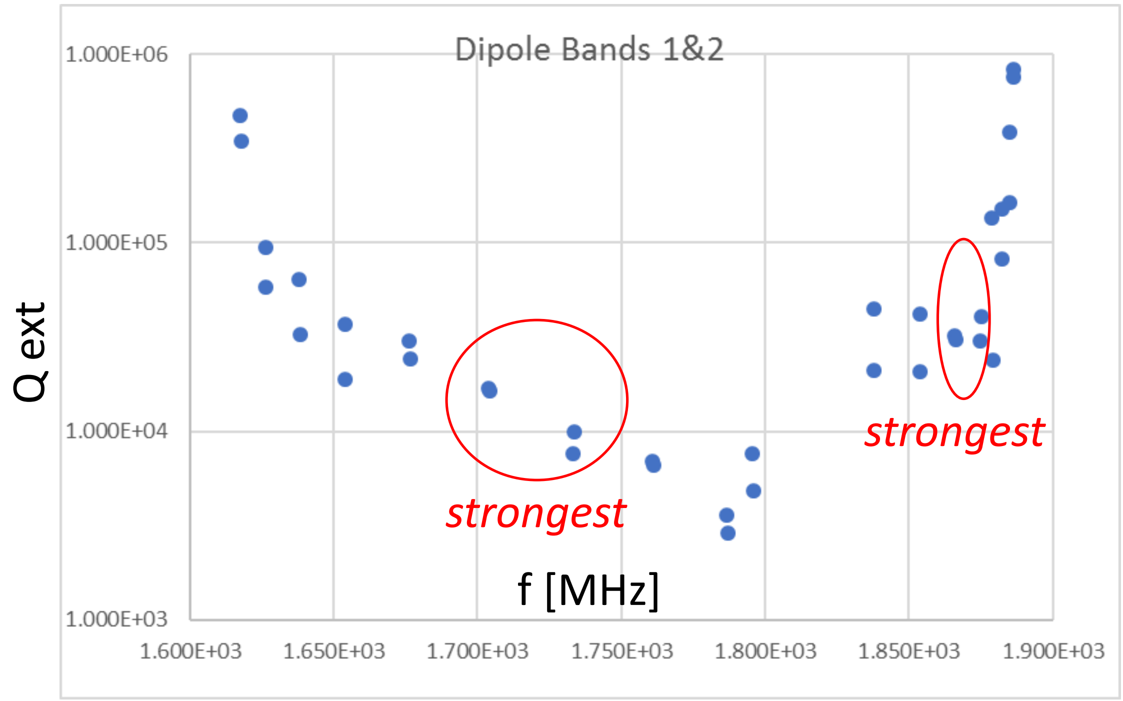
HOM spectra at 2K : CC1, CC2; CM2 ?

- HOM frequencies have been measured at 2K in the FAST gallery
- Note the arrangement in polarization doublets

CC1 Dipole: 1st and 2nd passbands



CC2 dipole: 1st and 2nd passbands



TM-like Dipole Mode (**m=1**) Impedances

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

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

On the polarisation plane:

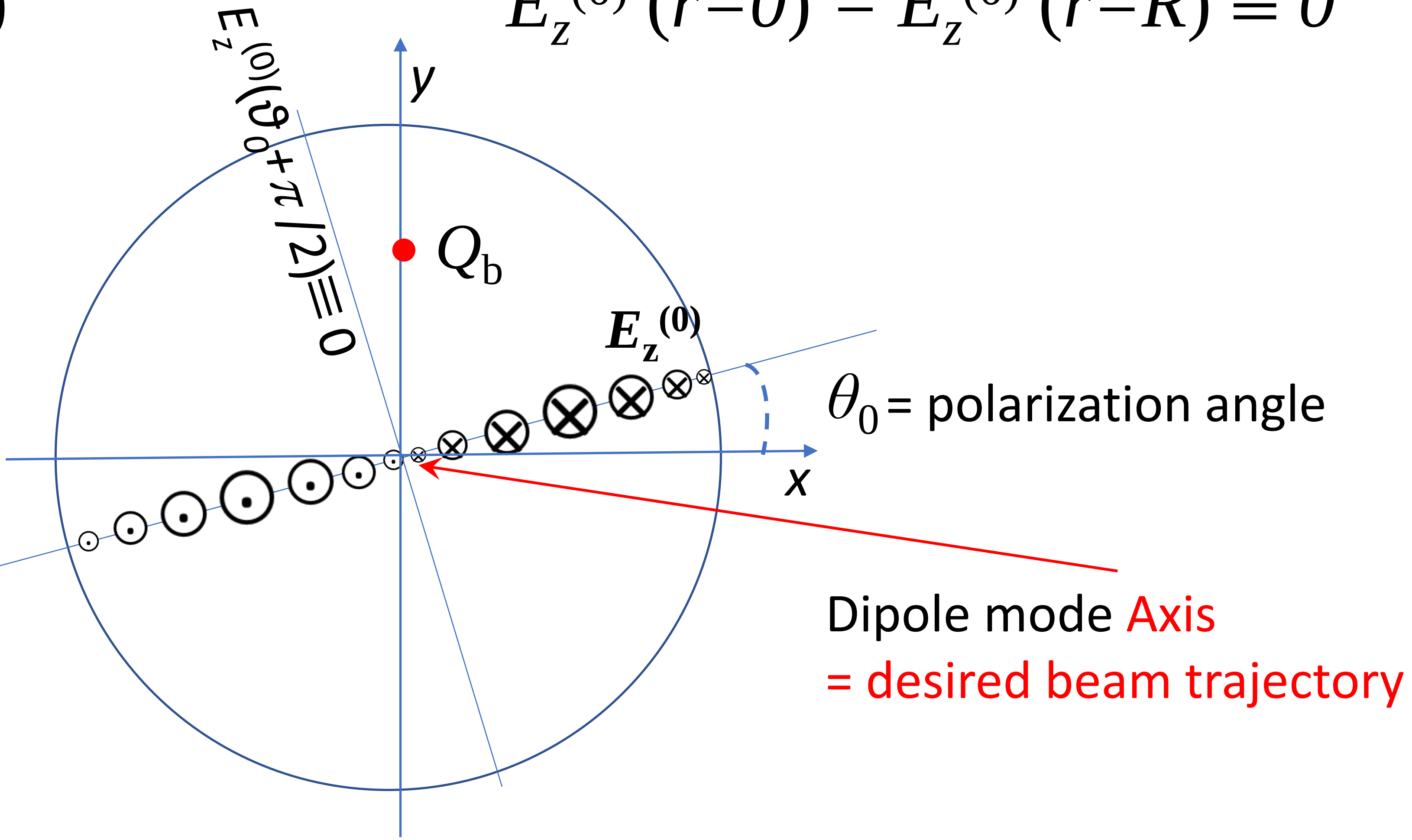
$U = \int dz\, E_z(z,t=z/c)$

$\propto rU'$

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

Off the polarisation plane:

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



Energy lost by the first bunch $\propto Q_b^2\, R/Q^{(m=1)}\cos^2(\theta-\theta_0)$

TM-like Dipole Mode (**m=1**) Transverse Fields

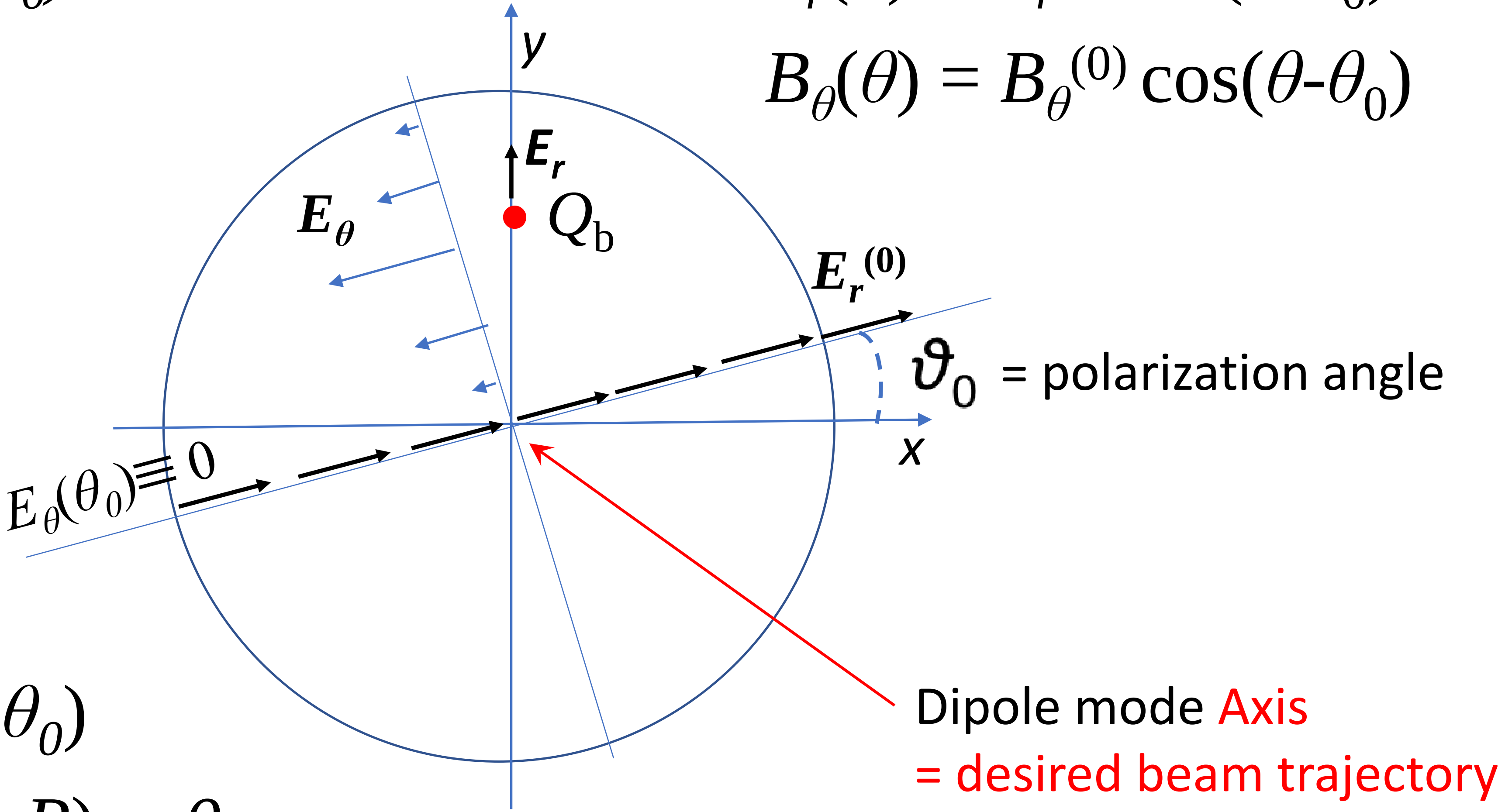
$E_r(\theta) = E_r^{(0)} \cos(\theta\text{-}\theta_0)$

$E_r^{(0)}(r=0) \neq 0$

$E_r^{(0)}(r=R) \neq 0$

$B_r(\theta) = B_r^{(0)} \sin(\theta\text{-}\theta_0)$

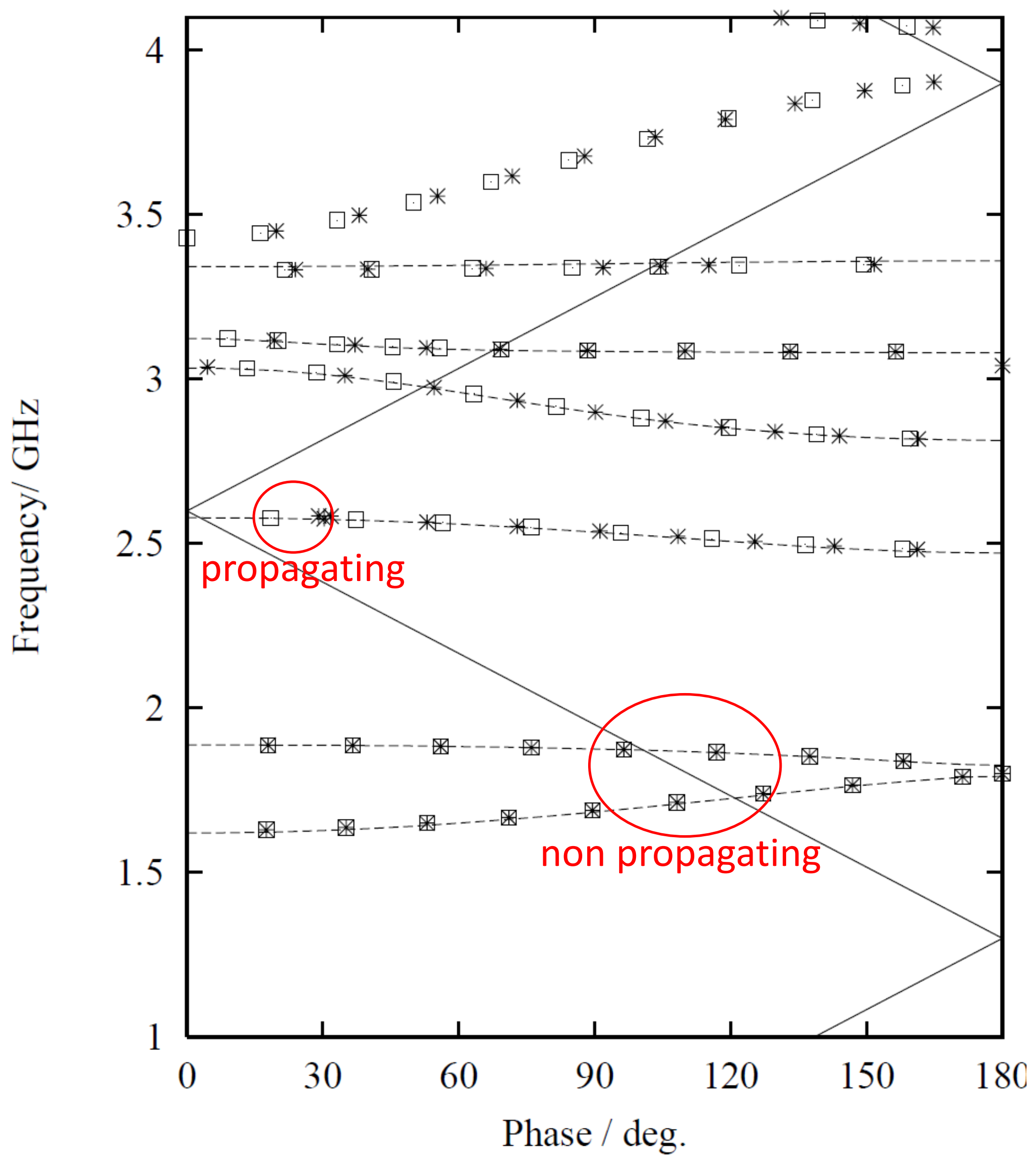
$B_\theta(\theta) = B_\theta^{(0)} \cos(\theta\text{-}\theta_0)$



$E_\theta(\theta) = E_\theta^{(0)} \sin(\theta\text{-}\theta_0)$

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

Dipole Mode Couplings



	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**
Band 1	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**
Band 2	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)

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

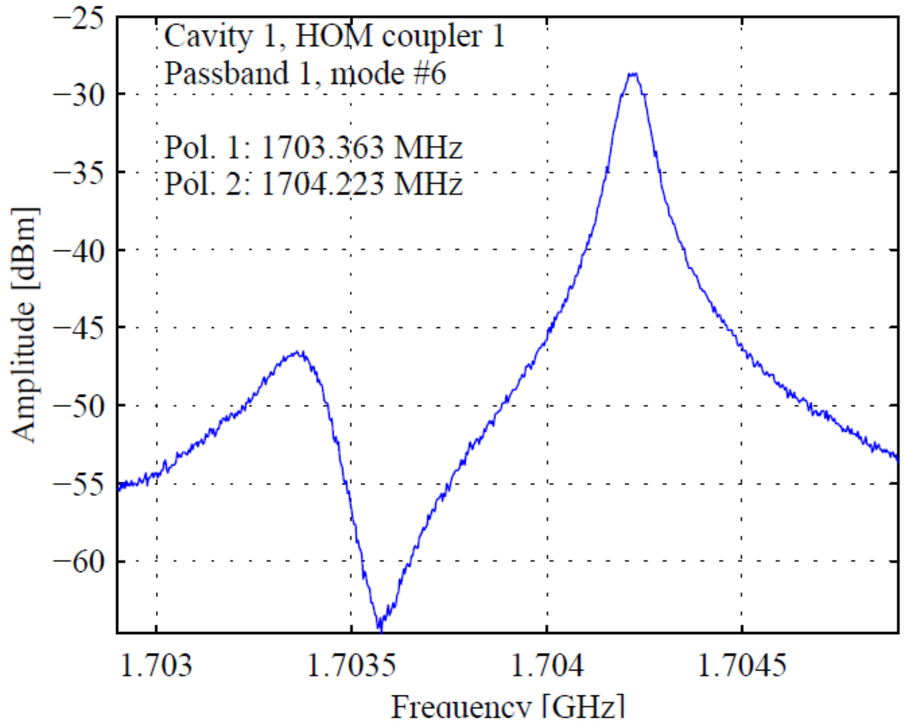


Figure 2: Mode #6 of the first dipole passband in cavity 1 of ACC1

Example of a FLASH cavity

Measurement electric center

- Steer the beam through the HOM center by minimizing signals

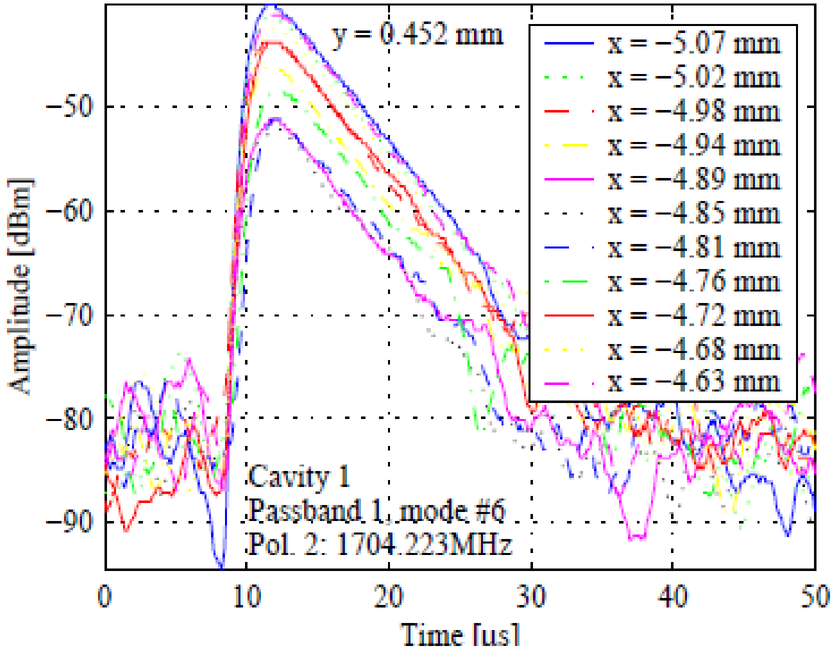


Figure 4: Time domain signals for the first polarization of the 6th mode of the 1st dipole band of the first cavity.

Example of a FLASH cavity: 50 µm steps

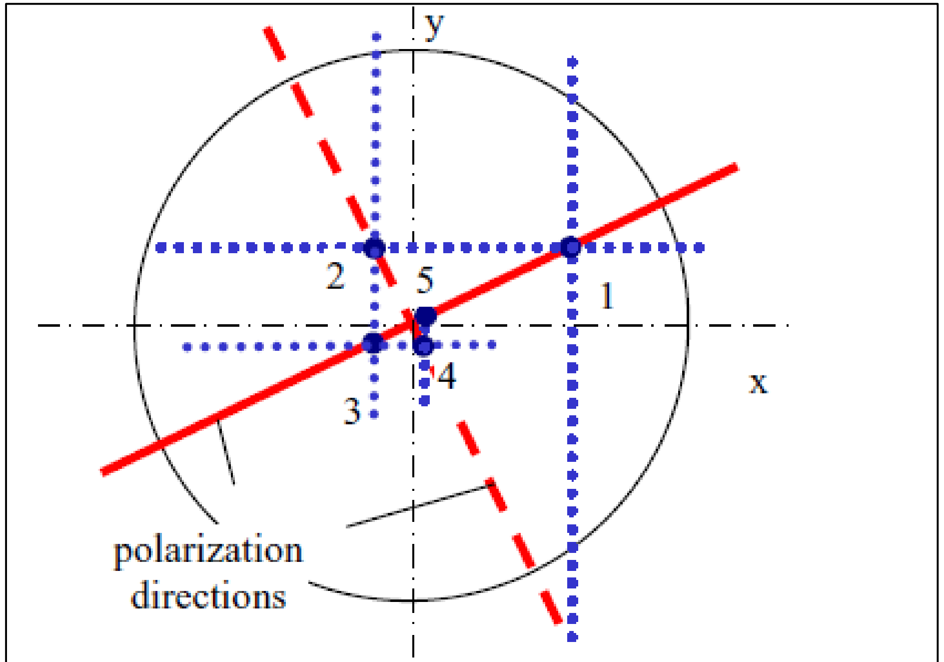


Figure 3: Alternate horizontal and vertical beam position scans for a mode with oblique polarization axes.

Perform systematic studies for most significant HOM

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

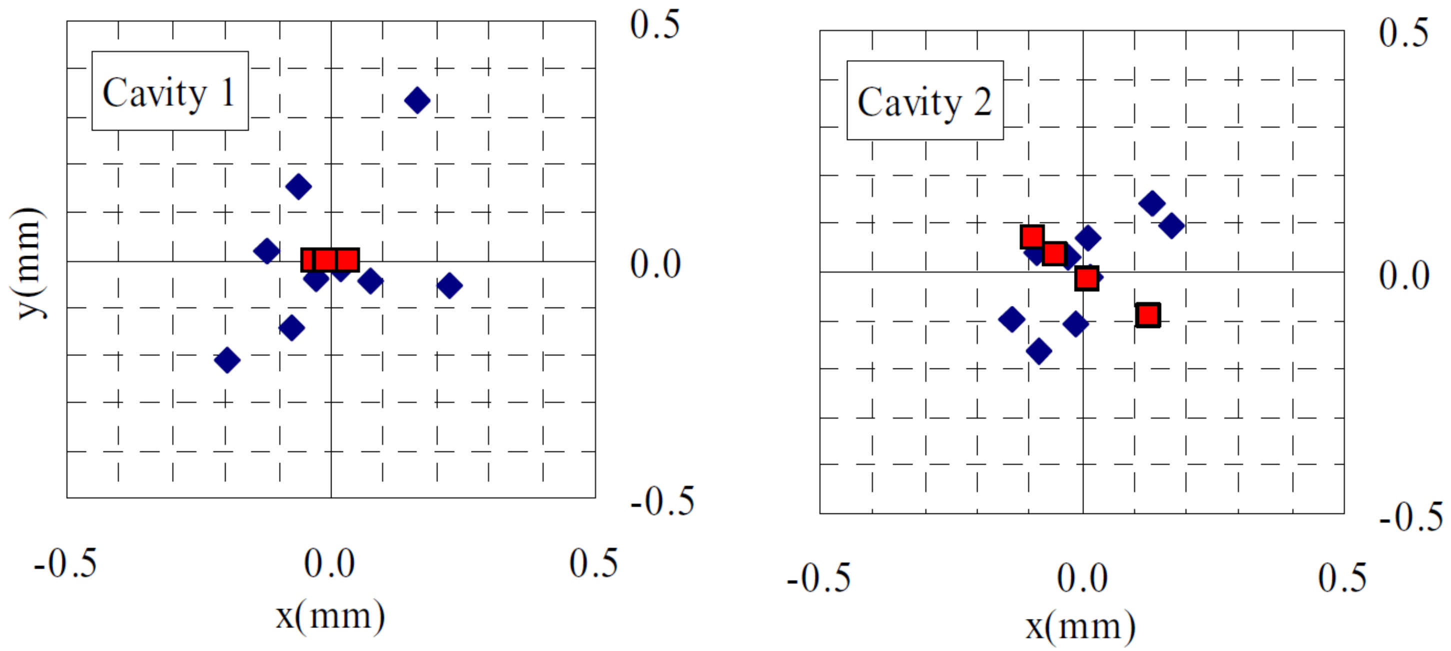


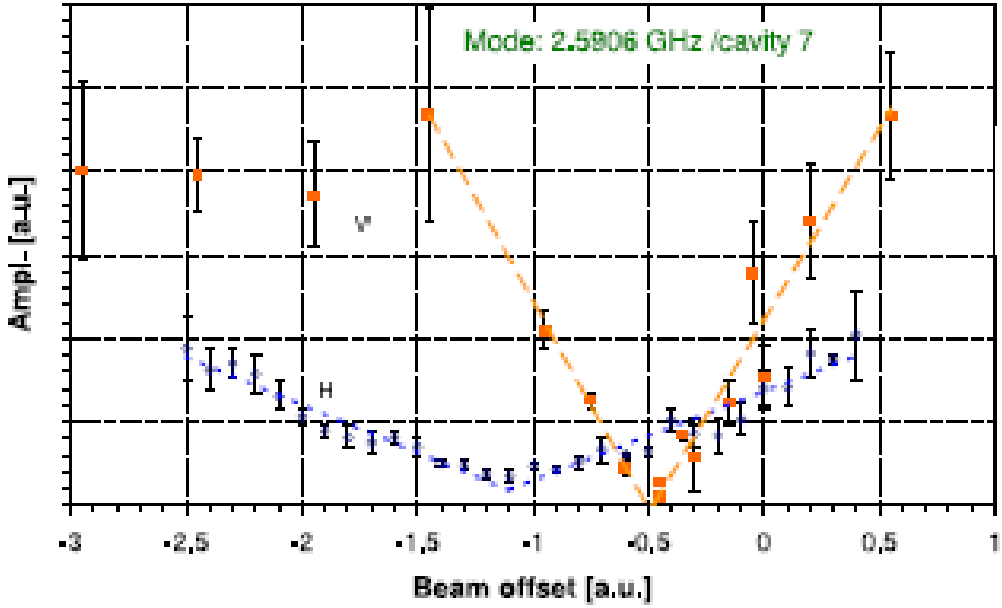
Figure 6: Relative positions of the 9 cell centers (blue diamonds) and of the 4 dipole mode centers (red squares).

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 dipole modes preferentially ‘H’ and ‘V’, or at random angles ?
- Is there a correlation between dipole low / high frequency vs polarisation angle ?
- …

Example of a FLASH cavity

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

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

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

On the polarisation plane:

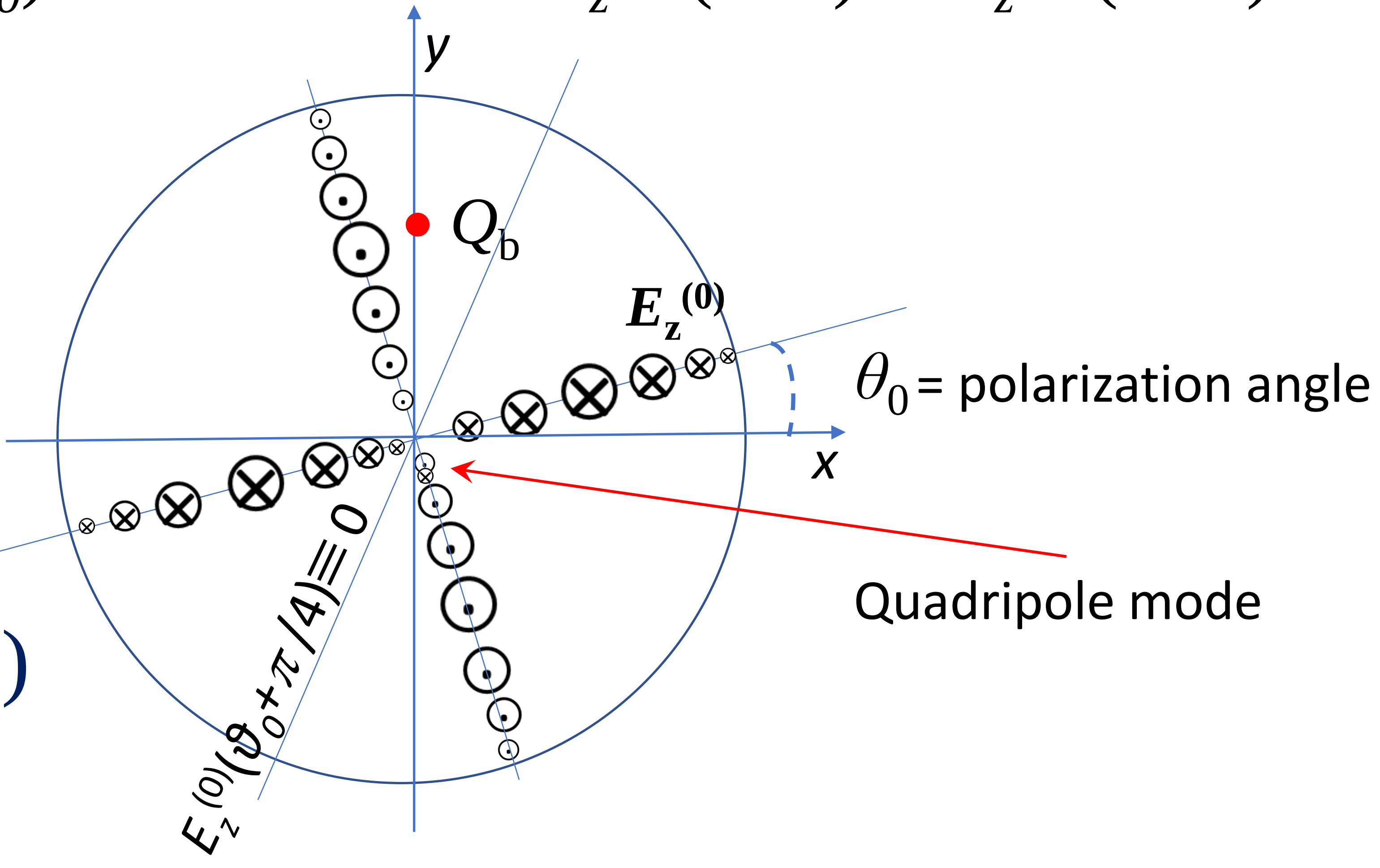
$U = \int dz\, E_z(z, t=z/c)$

$\propto r^2 U''$

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

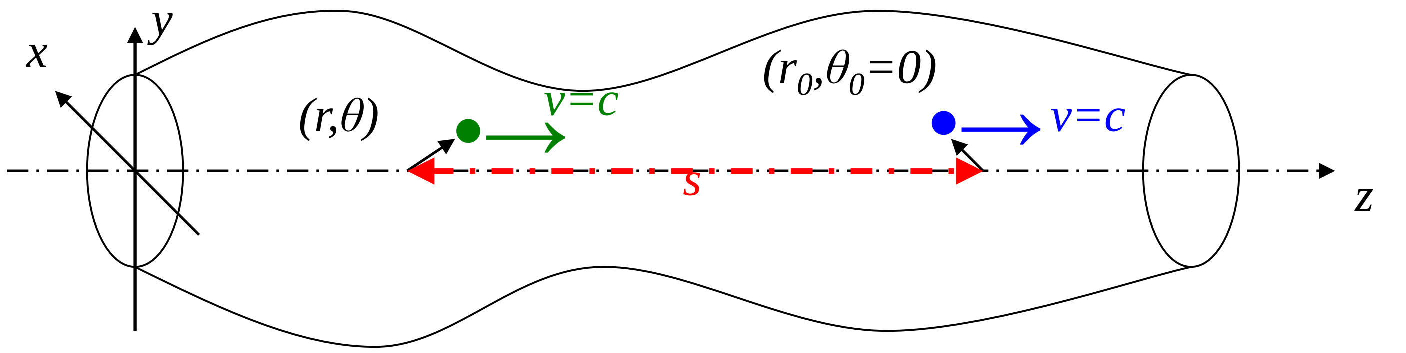
Off the polarisation plane:

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



Energy lost by the first bunch $\propto Q_b^2\, R/Q^{(m=2)} \cos^2(2(\theta-\theta_0))$

Wake potentials are integrating the HOM field over the beam trajectory in the RF structure

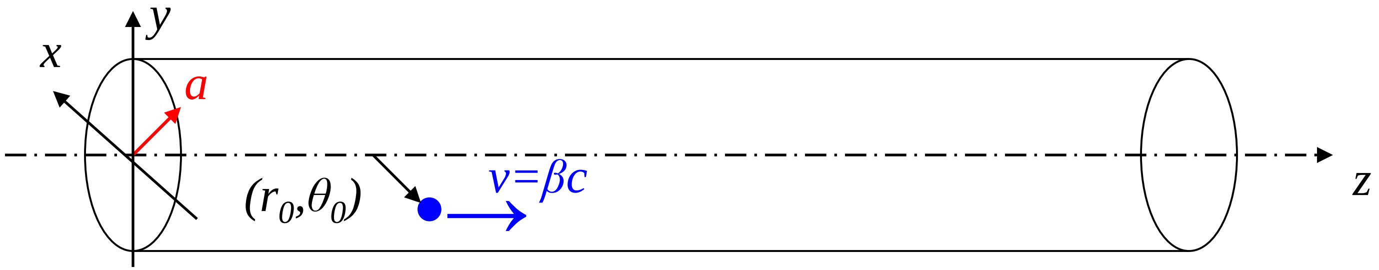


In axi-symmetric structures, wake potentials follow the multipolar expansion:

$$W_z(r,\theta,s;r_0)=\sum_{m=0}^{\infty} r_0^m r^m \cos(m\theta)\, w'_m(s)$$

$$\vec{W}_\perp(r,\theta,s;r_0)=\sum_{m=0}^{\infty} m r_0^m r^{m-1}(\cos(m\theta)\hat{r}-\sin(m\theta)\hat{\theta})\, w_m(s)$$

Champs e.m. dans un tube conducteur



- En utilisant la décomposition en modes polaires

$$\delta(\vec{r}-\vec{r}_0)=\frac{1}{2\pi}\sum_{m=-\infty}^{+\infty}e^{im(\theta-\theta_0)}\int_0^\infty k\,dk\,J_m(kr)J_m(kr_0)$$

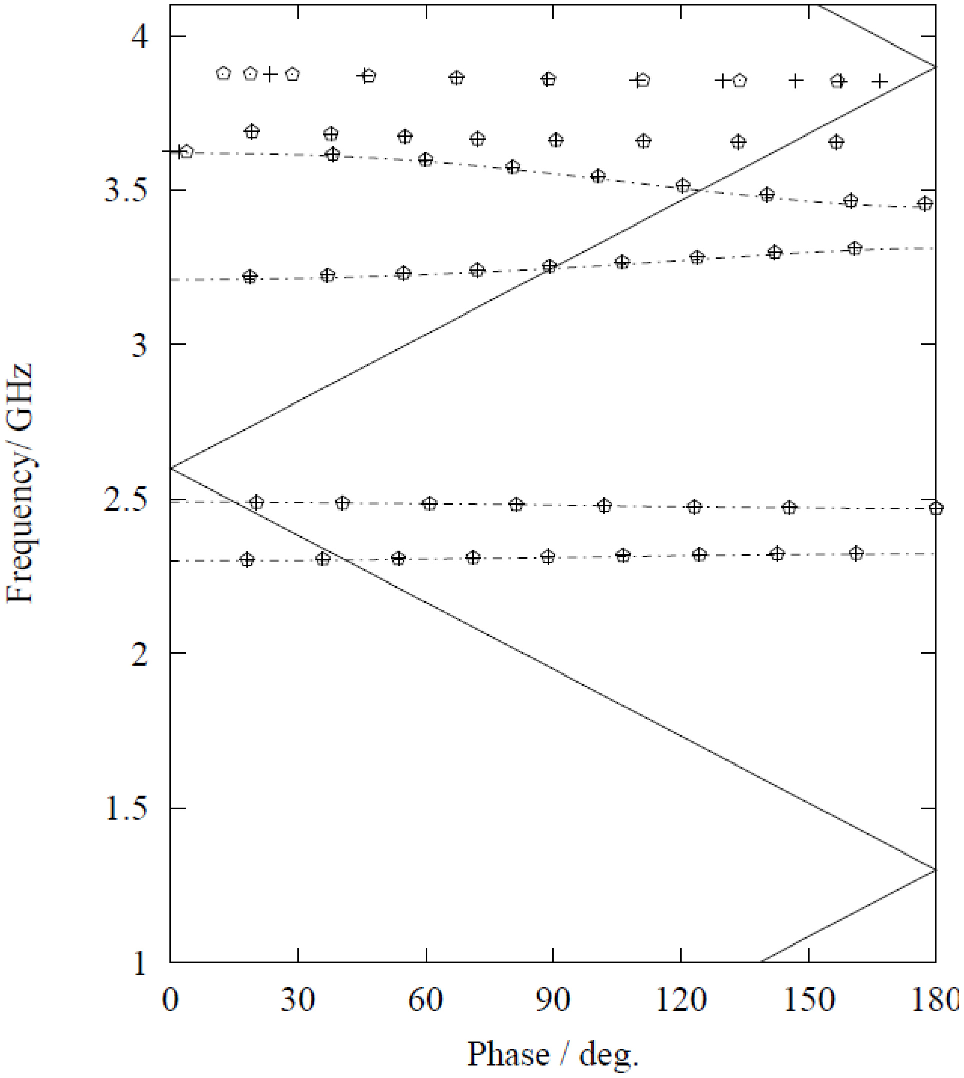
on résout pour $v < c$

$$\Phi(\vec{r},z,t)=\frac{q}{4\pi^2\varepsilon_0}\sum_{m=-\infty}^{+\infty}e^{im(\theta-\theta_0)}\int_0^\infty dk\,e^{ik(z-vt)}\left[I_m(kr_</\gamma)K_m(kr_>/\gamma)-I_m(ka/\gamma)K_m(kr_0/\gamma)I_m(kr/\gamma)/I_m(ka/\gamma)\right]$$

Dans la limite $v=c$

$$\Phi(\vec{r},z,t)=\frac{q}{2\pi\varepsilon_0}\delta(z-ct)\left[\ln\left(\frac{a}{r_>}\right)+\sum_{m=1}^{+\infty}\frac{\cos(m(\theta-\theta_0))}{m}\left(\left(\frac{r_<}{r_>}\right)^m-\left(\frac{rr_0}{a^2}\right)^m\right)\right]$$

Quadrupole modes in TESLA cavity



Quadrupole modes at FAST

In a perfect machine, i.e.:

- perfectly round and aligned cavity cells
- 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.

In a machine where these errors are larger than tansverse 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.