Progress of the TESLA-type Cavity Transfer Matrix measurement at FAST

Alex Halavanau

Northern Illinois University/Fermilab

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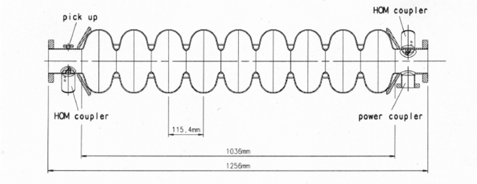
Outline

- Motivation
- Analytical model
- Simulation software model
- Beam alignment in the cavity
- Experimental setups
- Preliminary results
- Future planned experiments
- Conclusions

* FAST - Fermilab Accelerator Science and Technology facility

π-mode SW superconducting cavity

Motivation: Several proposed or operating accelerator facilities include standing-wave (SW) TESLA-type cavities, such as FAST, ILC, LCLS-II, PIP2 and etc. to accelerate electron, proton or muon beams.



The transverse-focusing properties of such a cavity and non-ideal transverse-map effects introduced by field asymmetries in the vicinity of the input and high-order-mode radiofrequency (RF) couplers play a crucial role in transverse beam dynamics

1. Compare the experimental transverse transfer matrix with analytical model
2. Attempt to characterize the effects discussed above

Analytical model

The transfer matrix of a π-mode RF resonator was first derived by Chambers (1962) and generalized by Serafini and Rosenzweig (1994)

A particle in a standing wave field $E_z(z,t) = E_0 \sum_n a_n \cos(nkz) \sin(\omega t + \Delta\phi)$ experiences a ponderomotive-focusing force $F_r = -e(E_r - vB_\phi) \approx er\frac{\partial E_z}{\partial z}$. This force, averaged over one RF-period in the first order of perturbation theory, yields the focusing strength $K_r = -\frac{(E_0 e)^2}{8(\gamma m)^2}$. The equation of motion then takes form:

$$x'' + \left(\frac{\gamma'}{\gamma}\right) x' + K_r \left(\frac{\gamma'}{\gamma}\right)^2 x = 0, \tag{1}$$

The solution of the Eq. 1 can be found in the form of $\mathbf{x}_f = R\mathbf{x}_i$, where the elements of 2×2 matrix R are (assuming ultra-relativistic beam and axially symmetric E-field):

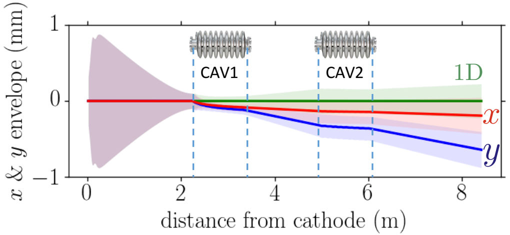
$$\begin{aligned}
R_{11} &= \cos\alpha - \sqrt{2}\cos(\Delta\phi)\sin\alpha, \\
R_{12} &= \sqrt{8}\frac{\gamma_i}{\gamma'}\cos(\Delta\phi)\sin\alpha, \\
R_{21} &= -\frac{\gamma'}{\gamma_f}\left[\frac{\cos(\Delta\phi)}{\sqrt{2}} + \frac{1}{\sqrt{8}\cos(\Delta\phi)}\right]\sin\alpha, \\
R_{22} &= \frac{\gamma_i}{\gamma_f}[\cos\alpha + \sqrt{2}\cos(\Delta\phi)\sin\alpha],
\end{aligned} \tag{2}$$

where $\alpha \equiv \frac{1}{\sqrt{8}\cos(\Delta\phi)} \ln\frac{\gamma_f}{\gamma_i}$, and $\gamma_f \equiv \gamma_i + \gamma' z$ is the final Lorentz factor.

Simulation software model

1. **FAST injector contains two Tesla-type cavities**
2. IMPACT-T start-to-end model of FAST beamline was established
3. ASTRA model with HFSS 3D-field maps of the cavities was established

The difference between 1D and 3D simulations



Beam steering by the cavities has been experimentally observed

Beam alignment in the cavities

Electron beam alignment in the cavities is very important for the performance of the beamline

The alignment is done in three steps

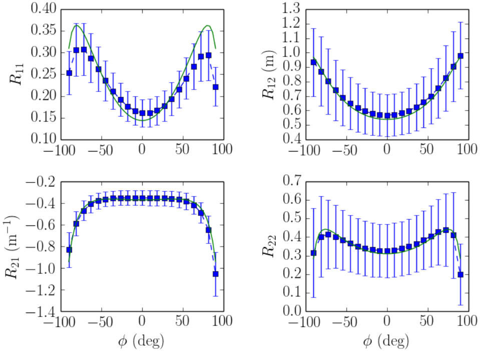
1. Manually send the beam through the cavity (0-th iteration)
2. Apply model dependent beam based alignment procedure to generate first set of trim values (work in progress by Sasha R.)
3. Apply conjugate gradient method that minimizes phase response of the cavity using BPM readouts (tested on quadrupoles and provided the alignment corrections that are being used at the moment; work in progress)
4. Verify the result by HOM signal from the cavities* (installation in progress)

*Assuming cavity was well aligned during the installation

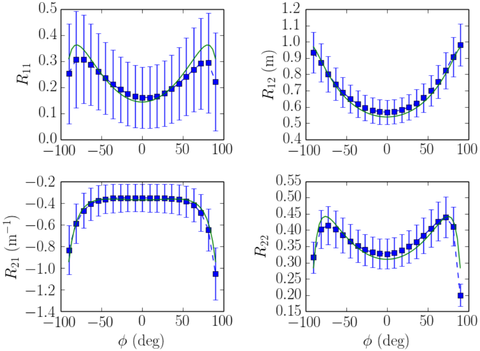
3D field map simulation results

ASTRA simulations

$\sigma = 1mm$



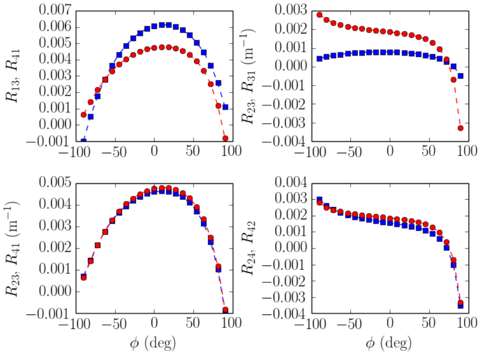
$\sigma = 0.1mm$



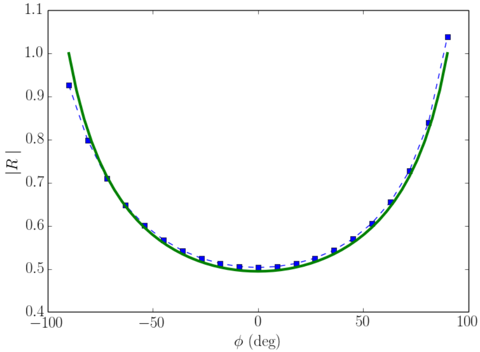
3D field map simulation results

ASTRA simulations

Small coupling terms

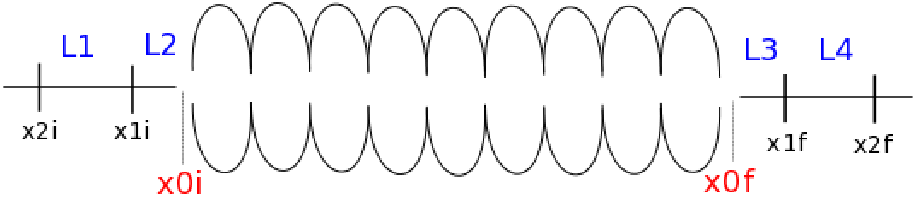


Matrix determinant



Experimental setup (2015)

Schematics of the experiment



Advantages

1. Only one cavity with two BPMs upstream/downstream

Issues

1. Beam matching in CAV2 was not optimal; significant bunch lengthening in drift (where CAV1 now installed).
2. Geometric emittance was large (5 μm for a 200 pC beam)
3. Laser-phase instabilities hampered some of the measurements

First measurement campaign at FAST

800 orbits were recorded for 7 phase datapoints

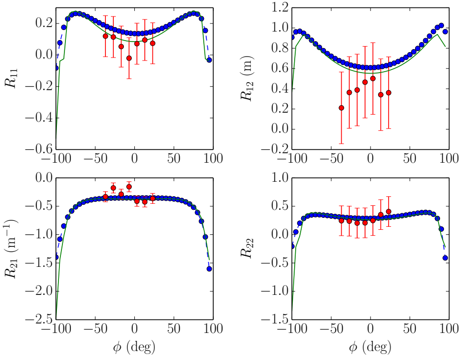
Transverse coordinates were reconstructed as:

$$x_{0i/f} = x_{1i/f} \pm L_{2,3}/L_{1,4}(x_{1i/f} - x_{2i/f}), \qquad x'_{0i/f} = \pm(x_{1i/f} - x_{2i/f})/L_{1,4} \qquad (3)$$

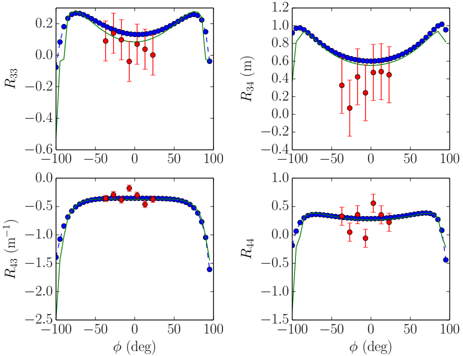
1. BPM nonlinear corrections were introduced in ACNET (by N. Eddy)
2. Developed measurement methods based on BPMs
3. Developed automated emittance measurement
4. Least-squares fitting code was implemented for data processing

Preliminary experimental results

XX' matrix elements



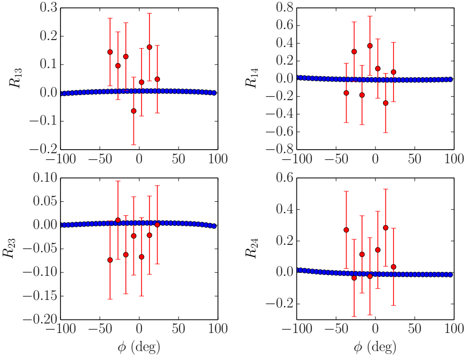
YY' matrix elements



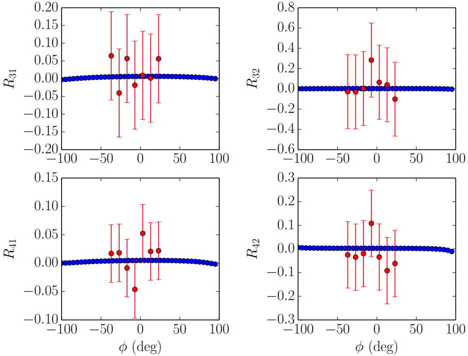
Matrix elements generally show agreement with theoretical prediction

Preliminary experimental results

XY' matrix elements



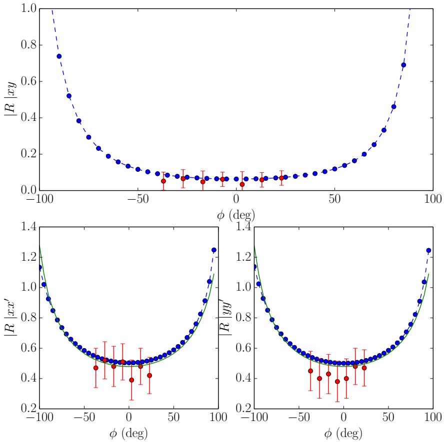
YX' matrix elements



Some coupling terms are large, possibly due to large beam size upstream of the CAV2

Preliminary experimental results

Matrix determinants



1. Matrix determinant agrees with simulations
2. Preliminary results were presented at IPAC16 (TUPMY038; Halavanau, A., et. al.)
3. Results, however, can't be finalized

Planned in 2016

1. Careful alignment in both CAV1/CAV2
2. Tranport matrix measurements
3. Determinant damping study by reducing the gradient in CAV1
4. HOM steering effect study

Conclusions

1. Time dependent HOM coupler kick affects transverse beam dynamics at low energy (verified by both simulations and first experiments)
2. Understanding transverse beam dynamics in CAV1/CAV2 is important for successful FAST injector operation
3. FAST beamline has skew quadrupole magnets and could possibly correct for the HOM/Input coupler correlations (proposed for LCLS-II by D. Dowell)
4. New data was taken last Friday (work in progress)
5. Many developed complimentary tools and scripts are routinely reused in other experiments

Thank you!