ESS SCRF: Coupling, tuning, HOMs, …

ESS RF Systems, Uppsala,
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EUROPEAN SPALLATION SOURCE

Overview

- ESS-specific RF system concepts
  - Lumped element models
  - Forward/reflected power
  - Matching to cavity & beam parameters
    - Commissioning & upgrade scenarios
- Higher order modes in SC cavities
  - Excitation
  - Damping
    - Problems
- Field emission / multipactor

RF SYSTEM CONCEPTS

(MUCH OF THIS IS BORROWED FROM THE PHD THESIS OF THOMAS SCHILCHER, HAMBURG, 1998)

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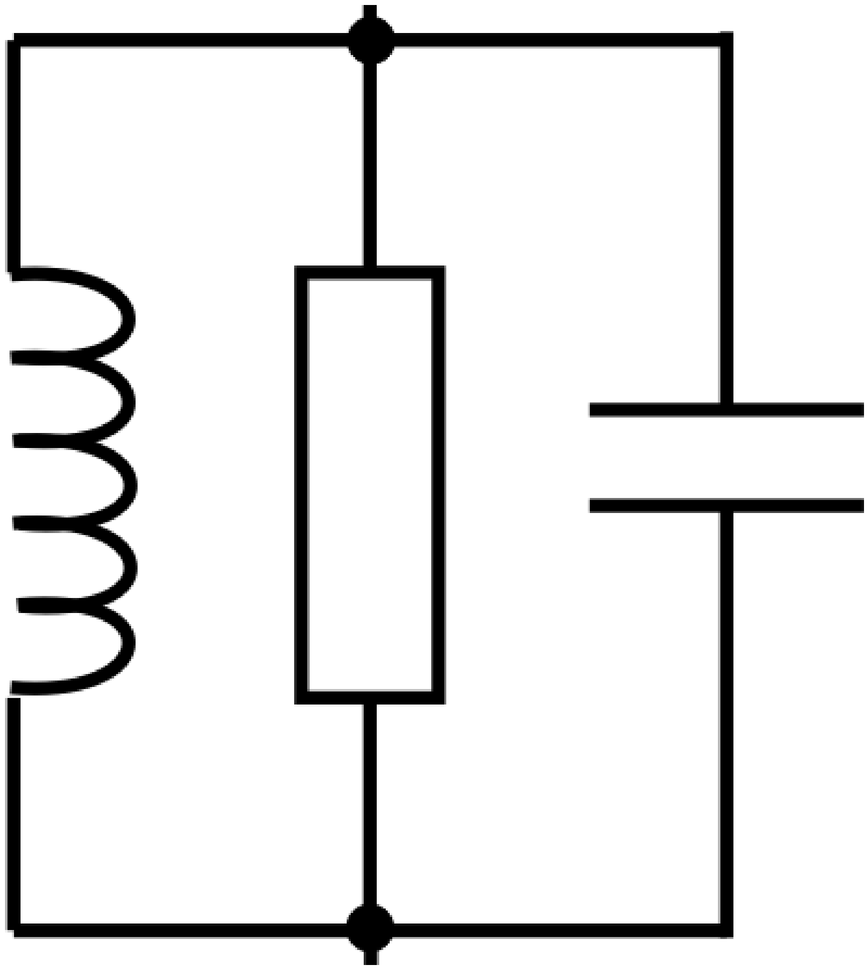
Lumped elements: RF cavity

Parallel LCR circuit. L, C, & R, depend on geometry. Resonant with a certain quality factor, Q_0.



$$Q_0 = \frac{wW}{P_{diss}}$$

$$P_{diss} = \frac{1}{2}\frac{V_{cav}^2}{R}$$

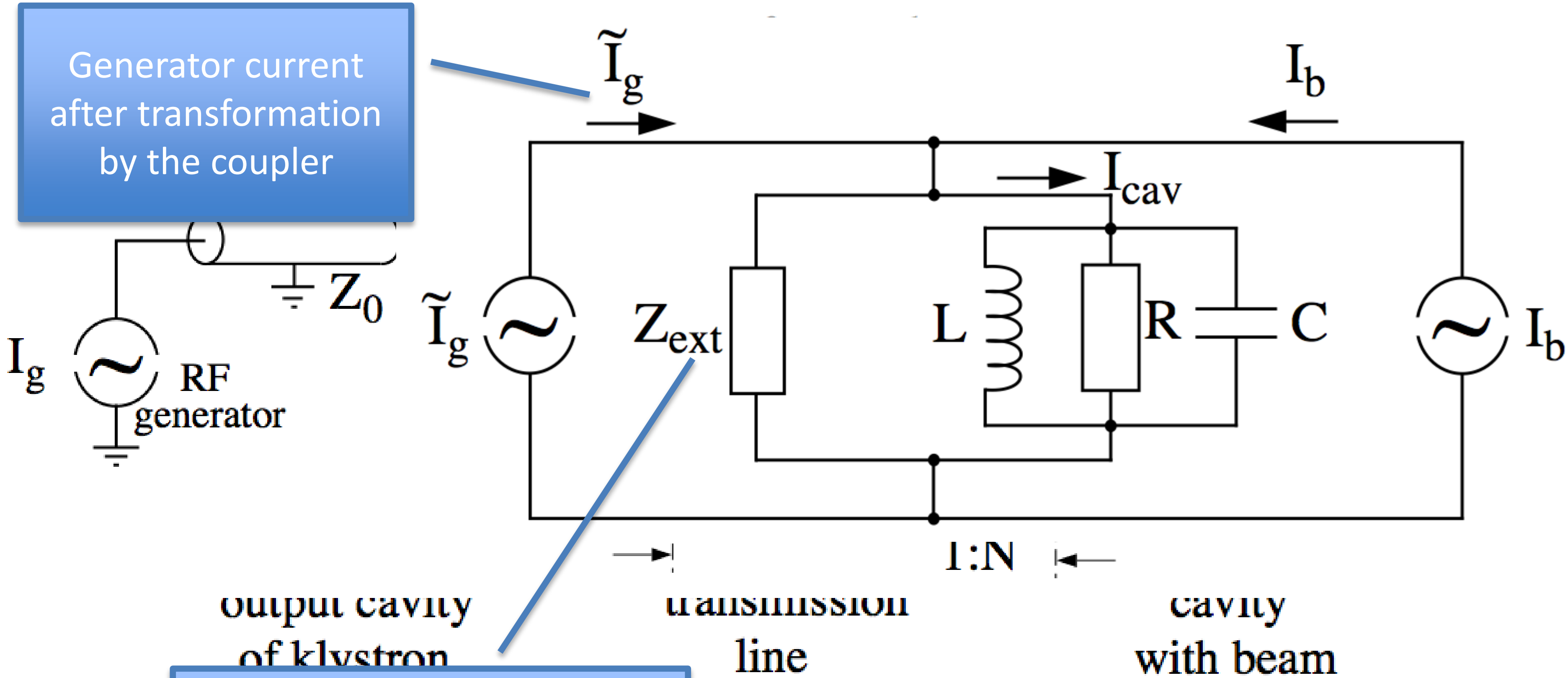
$$W = \frac{1}{2}CV_{cav}^2$$

$$Q_0 = wRC = \frac{R}{wL}$$

Note that Q∝R, so we design cavities with a high resistance.

Lumped elements: RF system

Generator current after transformation by the coupler

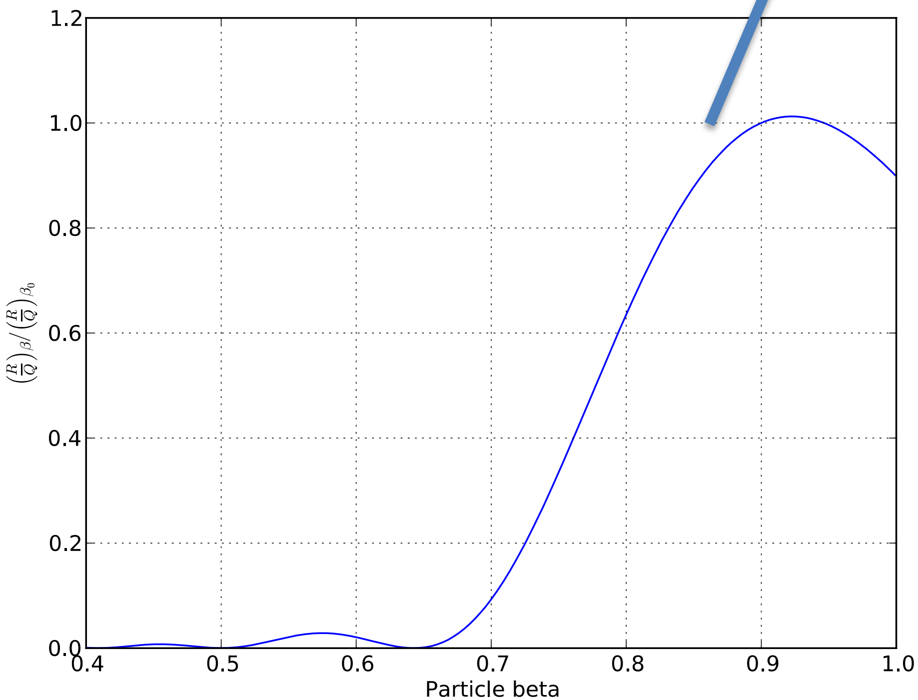


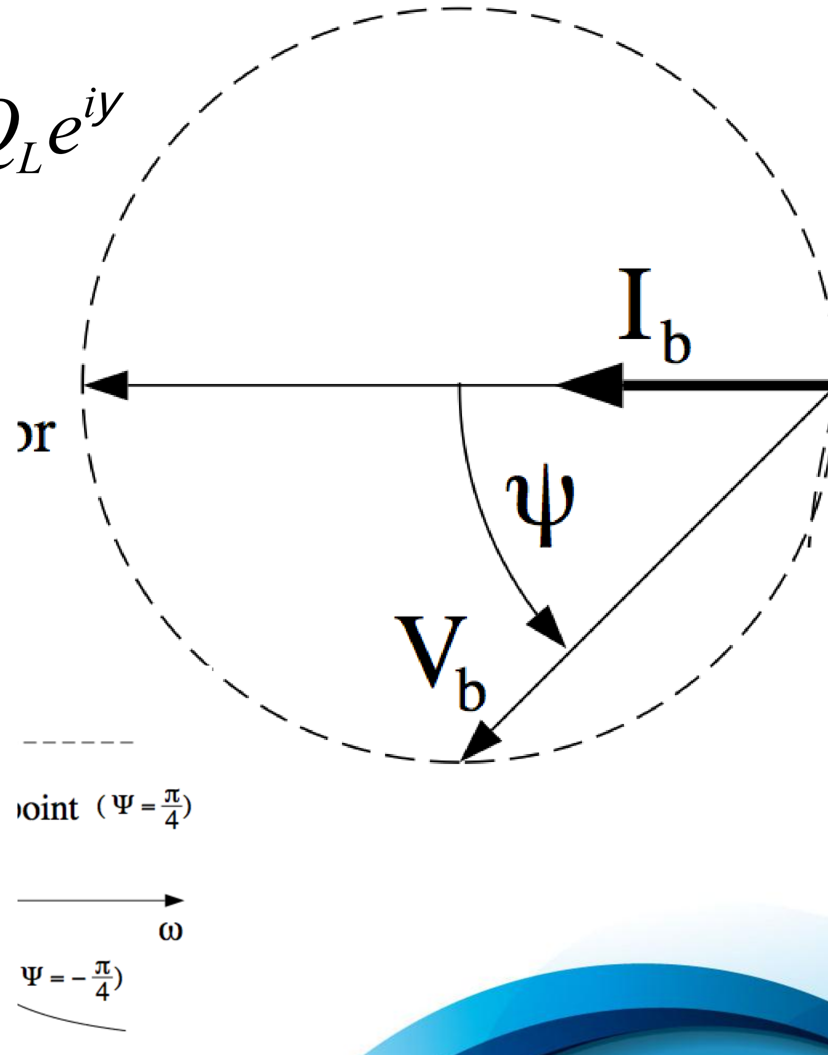
Transmission line impedance seen from "the other side" of the transformer.
Note it is in parallel with the cavity resistance, R.

$$\frac{1}{R_L} = \frac{1}{R} + \frac{1}{Z_{ext}} \qquad \frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}$$

Ohm's Law for resonant cavities

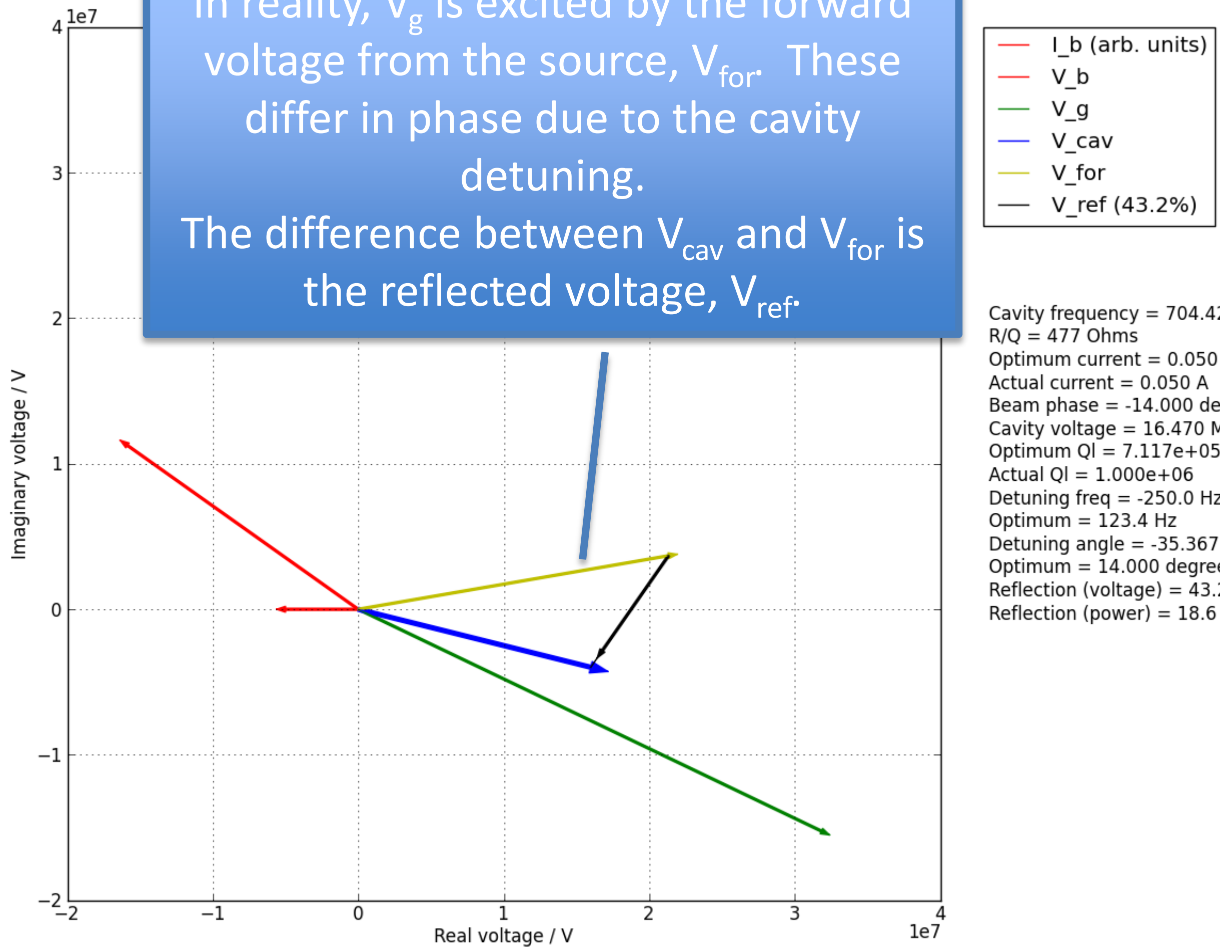
$$\vec{V}_b = \left(\frac{1}{\sqrt{1 + \left(2 Q_L \Delta\omega / \omega \right)^2}} \right) \vec{I}_b \left(\frac{R}{Q} \right) Q_L e^{i\psi}$$





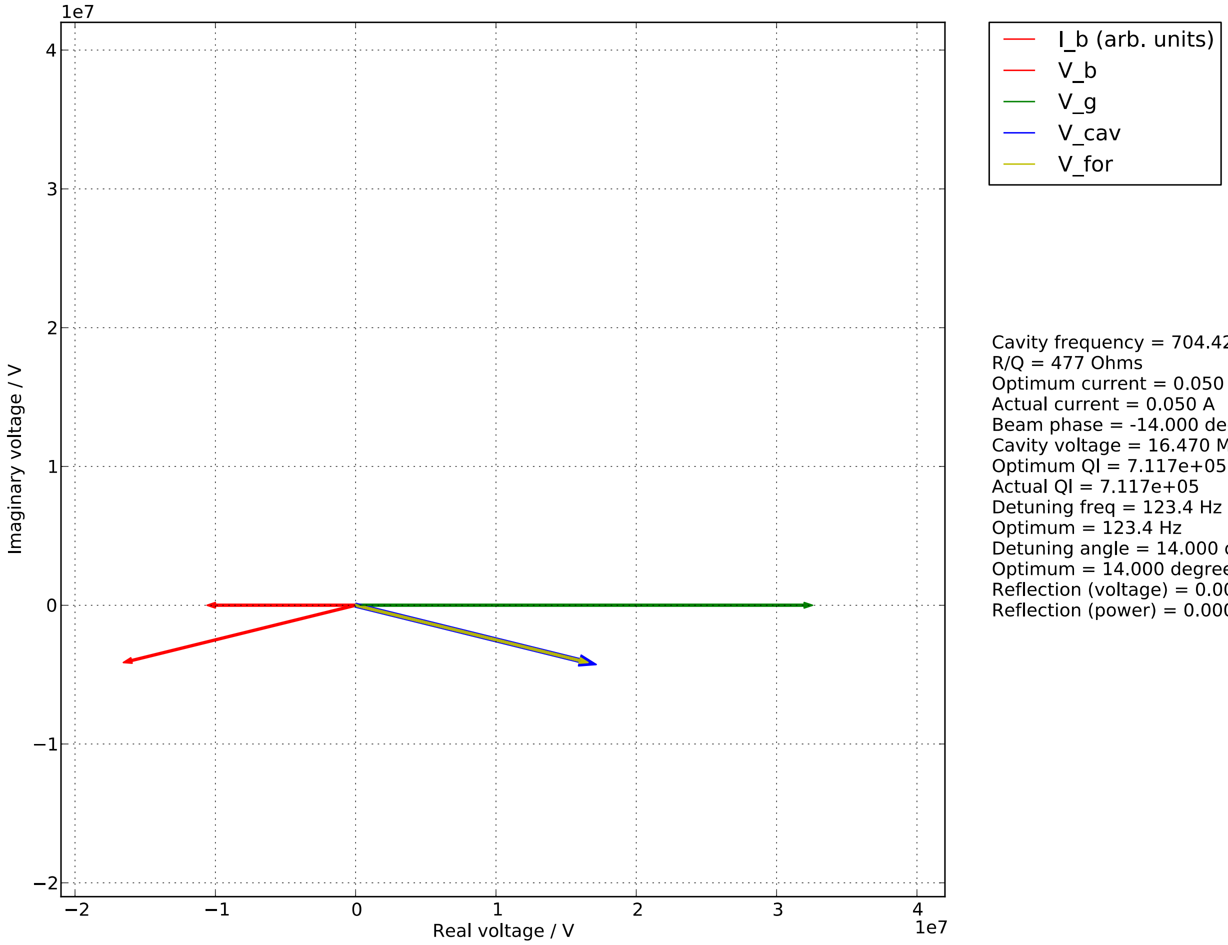
Vectors

In reality, V_g is excited by the forward voltage from the source, V_{for}. These differ in phase due to the cavity detuning.
The difference between V_{cav} and V_{for} is the reflected voltage, V_{ref}.



Cavity frequency = 704.420 MHz
R/Q = 477 Ohms
Optimum current = 0.050 A
Actual current = 0.050 A
Beam phase = -14.000 degrees
Cavity voltage = 16.470 MV
Optimum Ql = 7.117e+05
Actual Ql = 1.000e+06
Detuning freq = -250.0 Hz
Optimum = 123.4 Hz
Detuning angle = -35.367 degrees
Optimum = 14.000 degrees
Reflection (voltage) = 43.2 %
Reflection (power) = 18.6 %

A well designed cavity…



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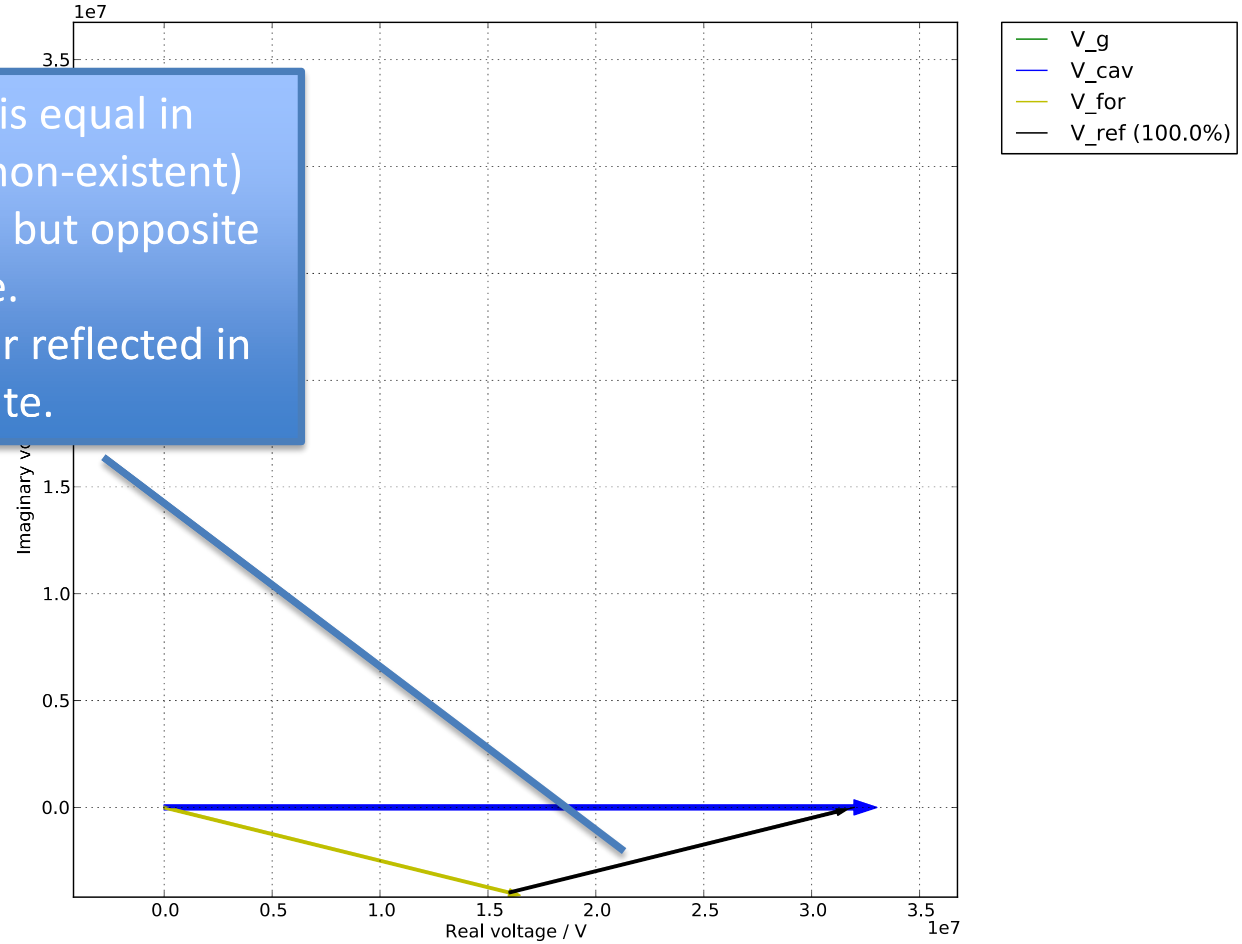
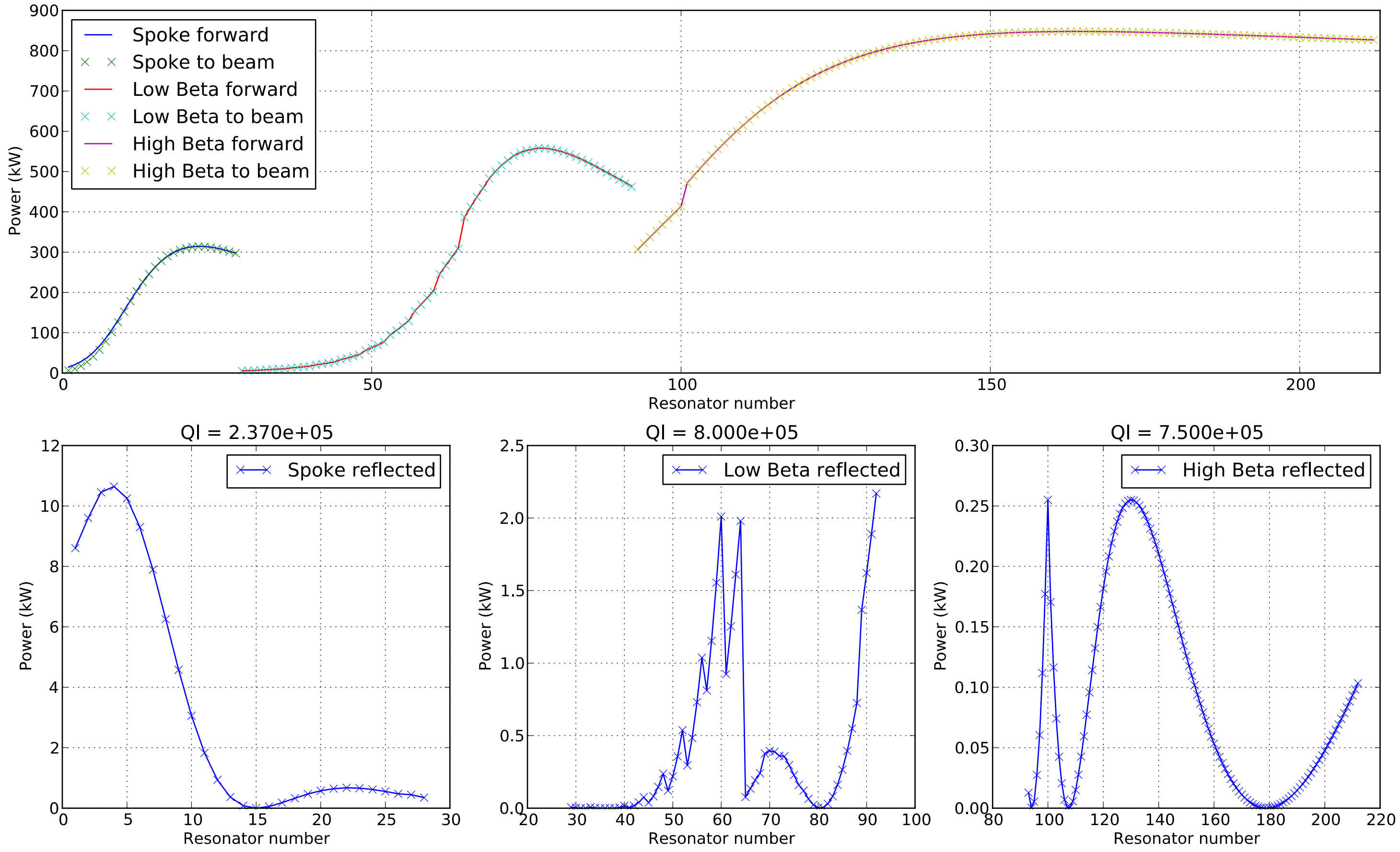
Detuning angle = 14.000 degrees
Optimum = 14.000 degrees
Reflection (voltage) = 0.000 %
Reflection (power) = 0.000 %

…with no beam

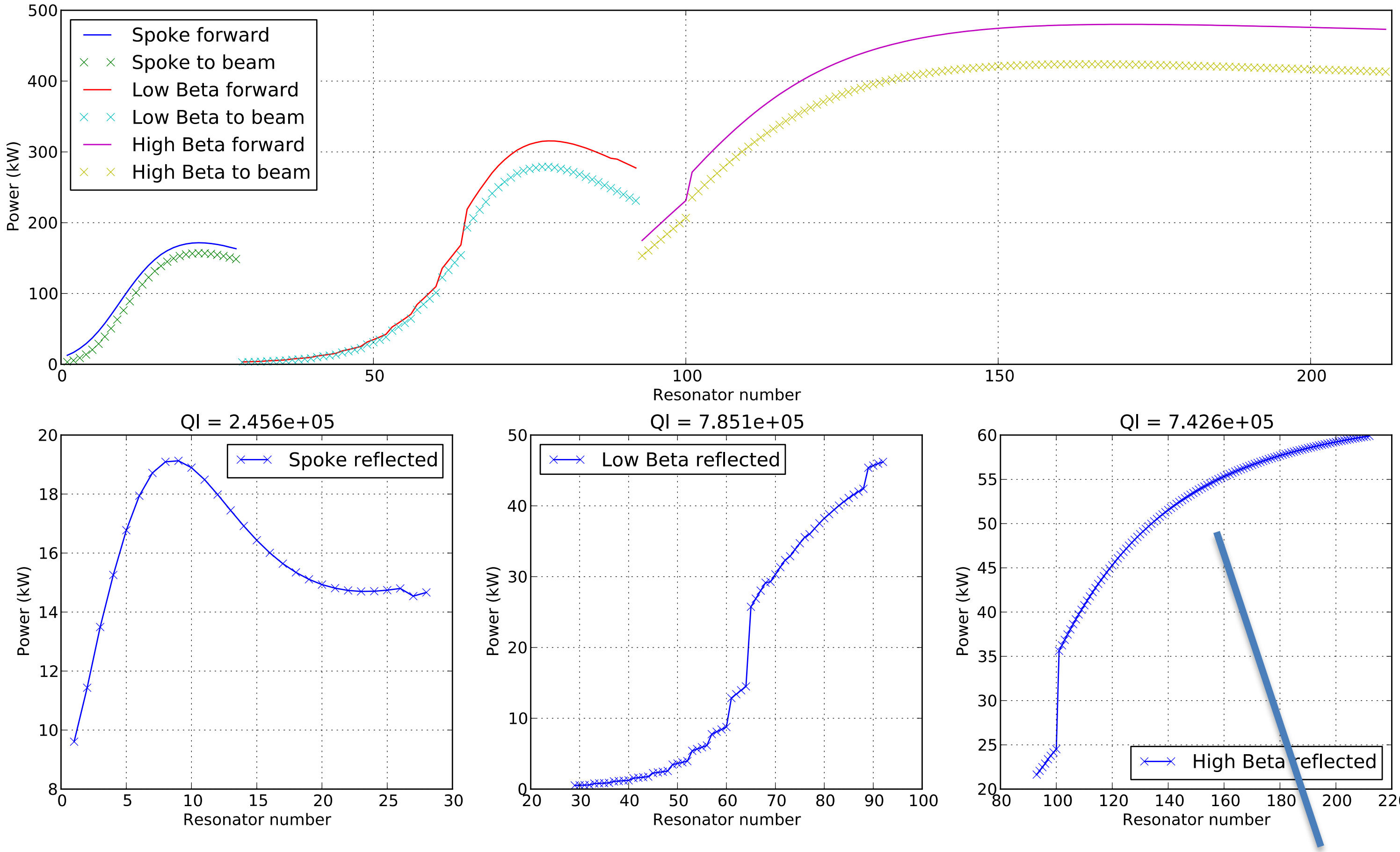
Reflected power is equal in magnitude to the (non-existent) beam-excited signal, but opposite in phase.
100% of input power reflected in steady state.



Forward & reflected SCRF: Nominal

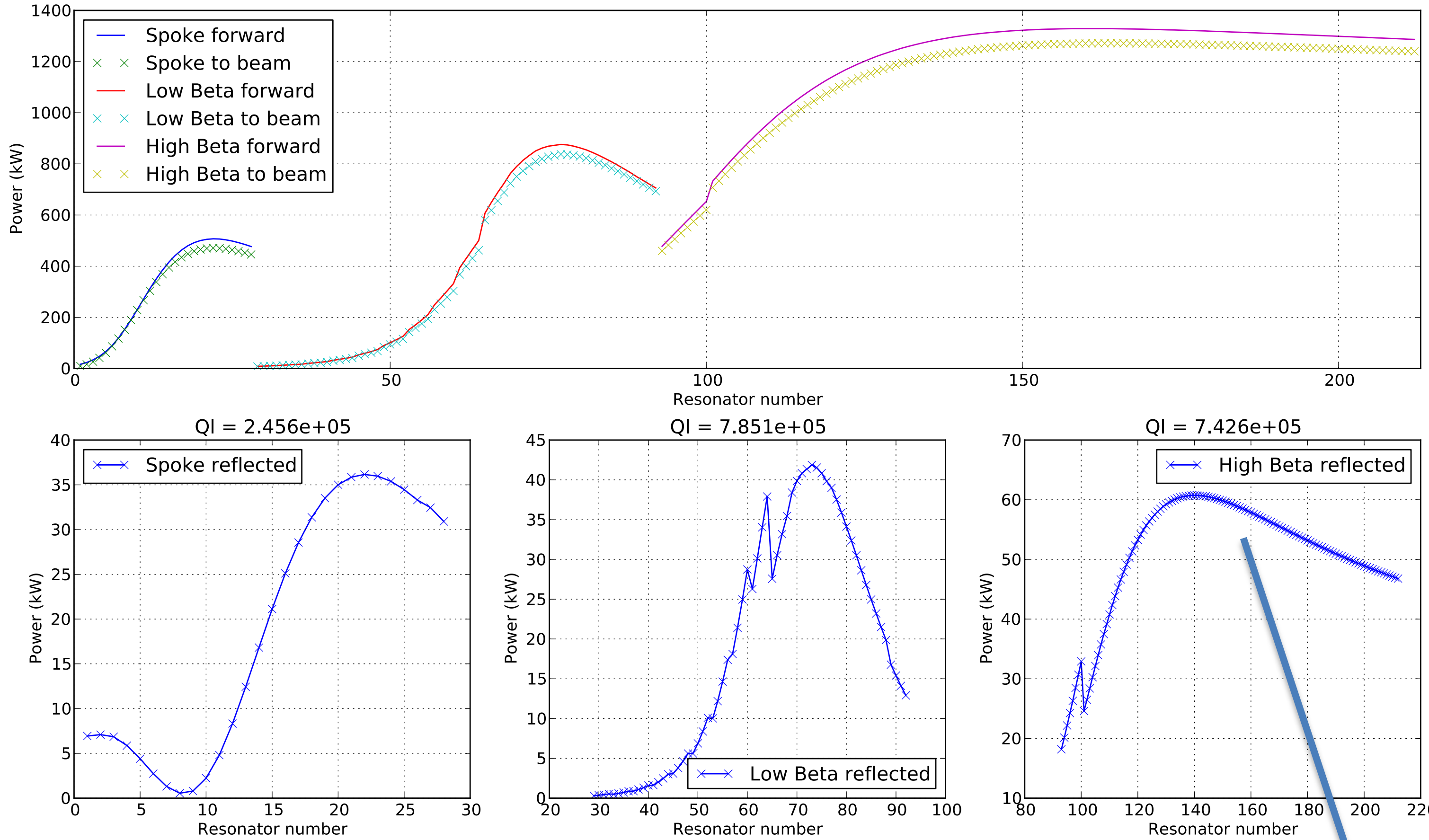


Forward & reflected SCRF: 50% beam current



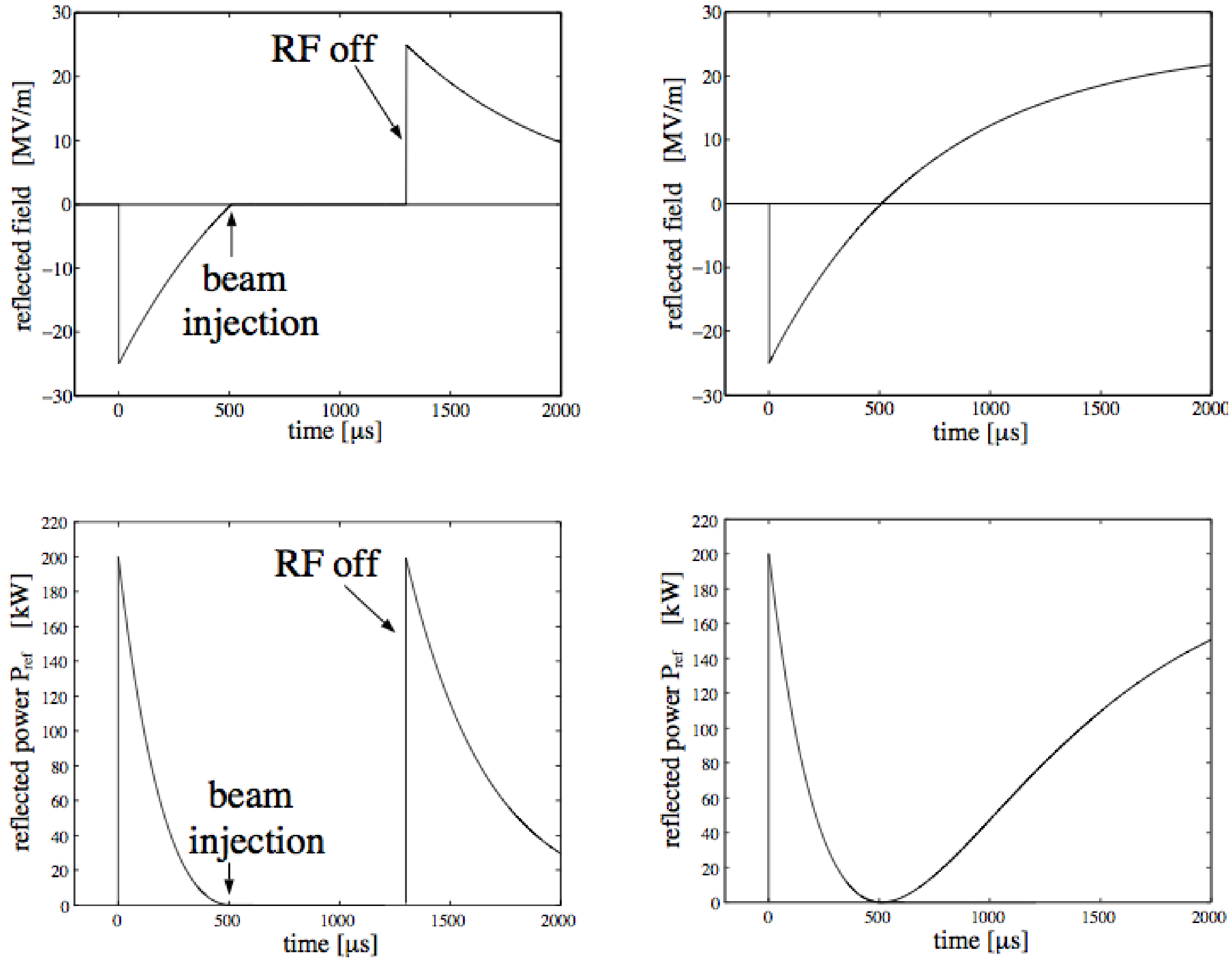
>10% of input power is reflected

Forward & reflected SCRF: 150% beam current



~5% of input power is reflected

Transient behaviour



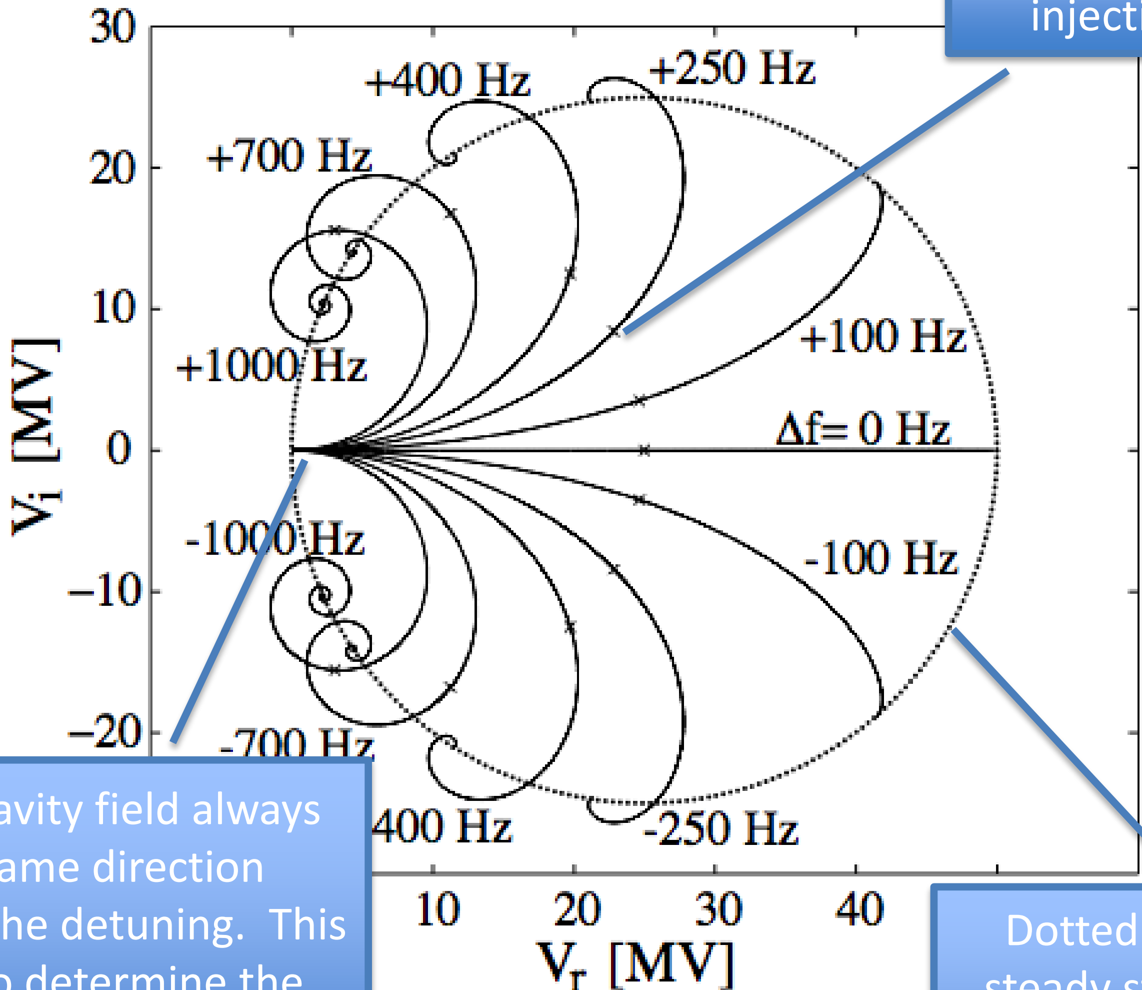
$$V_{cav}(t) = V_g + V_b = 2R_L I_g \left(1 - e^{-\frac{t}{\tau}}\right) - 2R_L I_{b0}\left(1 - e^{-\frac{1}{\tau}(t-t_{inj})}\right)$$

$$V_{ref}(t) = V_{cav}(t) - V_{for}$$

Calculations done for TESLA cavity, so ignore the scales.

Paths in complex space

Crosses represent injection time



Note that the cavity field always rises in the same direction independent of the detuning. This may be used to determine the phase in the presence of unknown cable lengths.

Dotted circle indicates steady state voltage as a function of detuning angle in the absence of beam.

TRANSIT TIME FACTOR CALCULATIONS

Beam→ cavity coupling

- Coupling composed of 2 signals
  - Cavity field vector (depends on position)
  - Cavity phase (depends on time)

$$V = E_1 \int_{-L/2}^{L/2} \cos\left(\frac{\omega}{\beta_0 c} z\right) \cos(\omega t)\, dz$$

$$V = E_1 \int_{-L/2}^{L/2} \cos\left(\frac{\omega}{\beta_0 c} z\right) \cos\left(\frac{\omega}{\beta c} z\right) dz$$

Magic!

$$V = 2\beta_0 \frac{E_1}{k} \frac{\beta^2}{\beta_0^2 - \beta^2} \cos\left(\frac{\beta_0}{\beta} \frac{5\pi}{2}\right)$$

Magic
- Integration by parts (twice)
- Cosine is an even function
- Sine is an odd function
- π phase advance per cell
- Five-cell cavity

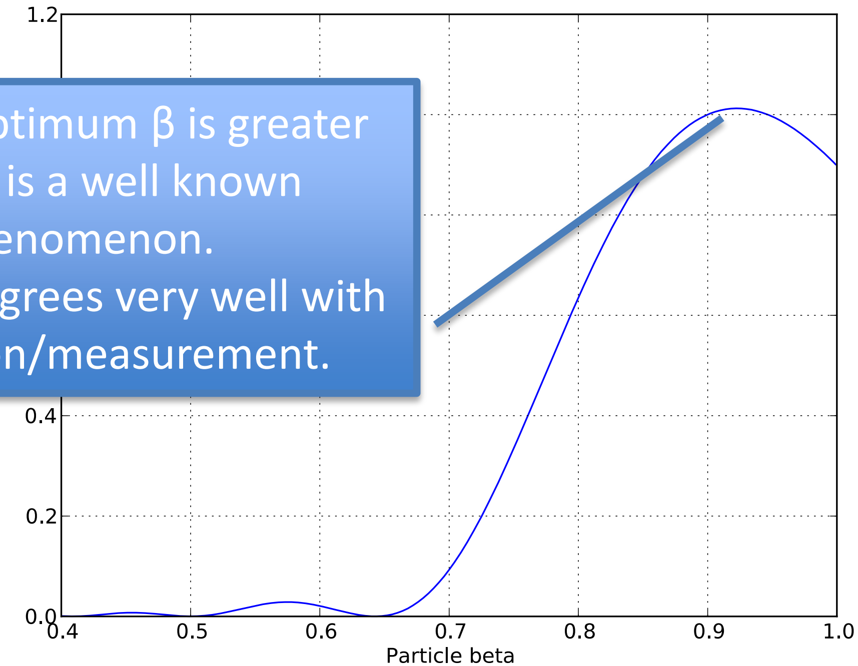
See ESS Tech Note: ESS/AD/0025

Discussion

Velocity bandwidth may be approximated by the closest zeros of the cosine:

$$\frac{5}{7} < \frac{\beta}{\beta_0} < \frac{5}{3}$$

That the optimum β is greater than β_0 is a well known phenomenon.
This curve agrees very well with simulation/measurement.



R/Q depends on square of *V*.

$$\left(\frac{R}{Q}\right)_{\beta} = \left(\frac{R}{Q}\right)_{\beta_0} \left[\frac{4}{5\pi}\frac{\beta^2}{\beta_0^2 - \beta^2}\cos\left(\frac{\beta_0}{\beta}\frac{5\pi}{2}\right)\right]^2$$

$$V = 2\beta_0 \frac{E_1}{k}\frac{\beta^2}{\beta_0^2 - \beta^2}\cos($$

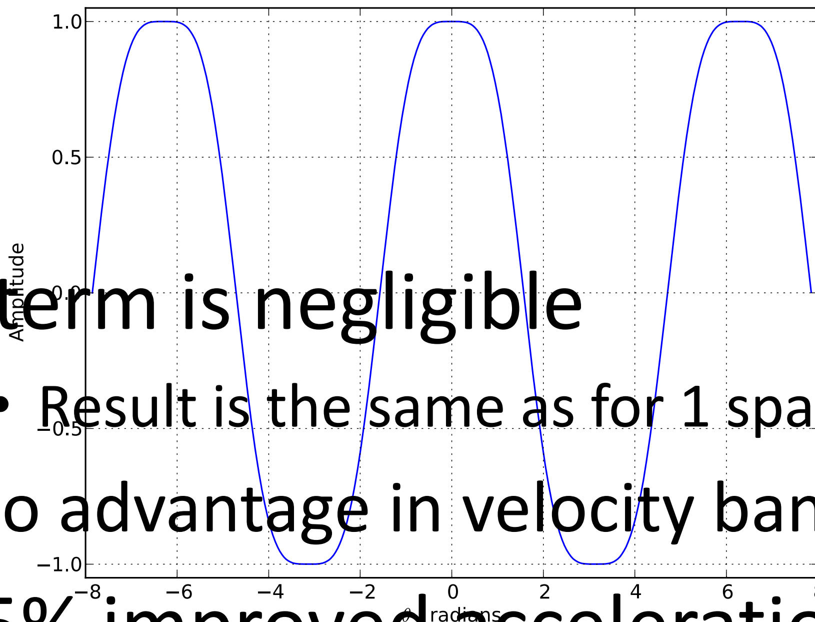
$\beta=\beta_0$ may seem problematic as the cosine will go to zero, however the denominator also goes to zero. In this limit:

$$V(\beta=\beta_0) = \frac{5\pi}{2}\beta_0\frac{E_1}{k}$$

Additional spatial harmonics?

$$V = \sum_{n=1}^{\infty} E_n \int_{-L/2}^{L/2} \cos\left(\frac{n\omega}{\beta_0 c} z\right)\cos\left(\frac{\omega}{\beta c} z\right) dz$$

$$V = \sum_{n=1}^{\infty} 2\frac{E_n}{k}\frac{\beta_0^2}{\beta_0^2 - n^2\beta^2}\left(\beta\cos\left(\frac{n\pi}{2}\right)\sin\left(\frac{\pi}{2}\frac{\beta_0}{\beta}\right) - \frac{n\beta^2}{\beta_0^2}\cos\left(\frac{\pi}{2}\frac{\beta_0}{\beta}\right)\sin\left(\frac{n\pi}{2}\right)\right)$$



$$E_1 = 1.125E$$

$$E_3 = \frac{1.125}{9}E$$

- 2nd term is negligible
  - Result is the same as for 1 spatial harmonic
  - – No advantage in velocity bandwidth
- 12.5% improved acceleration
  - With no increase in peak voltage!

$$V = 2.25\beta_0\beta^2\frac{E}{k}\cos\left(\frac{\pi}{2}\frac{\beta_0}{\beta}\right)\left[\frac{1}{\beta_0^2 - \beta^2} - \frac{1}{3\left(\beta_0^2 - 9\beta^2\right)}\right]$$

Transit-time factor conclusions

- Note assumptions:
  - Fixed cell length
  - No significant velocity change
  - π-mode cavity
- Observed voltage dependent on lots of things
  - Cavity β, particle β, peak voltage, frequency, etc.
- Velocity bandwidth depends….
  - Only on the number of cells!
- Increase effective voltage:
  - Increase number of cells
  - Increase 1st order spatial component
    - Add additional components to maintain reasonable peak field

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Any questions before we move on?

HIGHER ORDER MODES IN CAVITIES

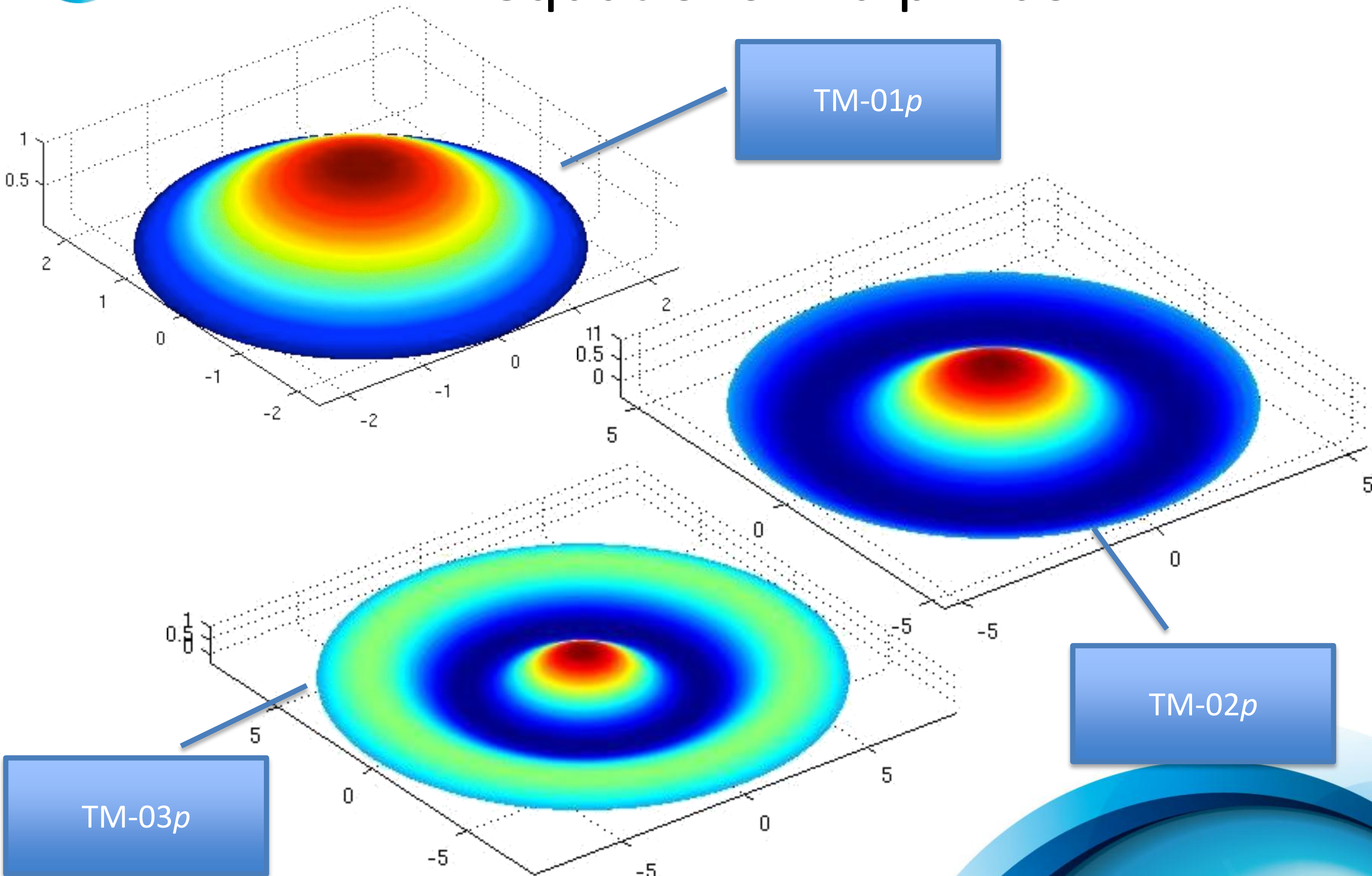
Introduction

- Why do we use accelerating cavities?
  - Maxwell leads to a good solution for acceleration
    - » TM_{010}
  - So, excite the cavity at the right freq., and inject beam
- But, Maxwell also provides a whole spectrum of higher solutions
  - TM_{mnp}, TE_{mnp}
  - Not excited by the klystron, but may couple to the beam
    - Thus extracting/adding momentum in an uncontrolled way

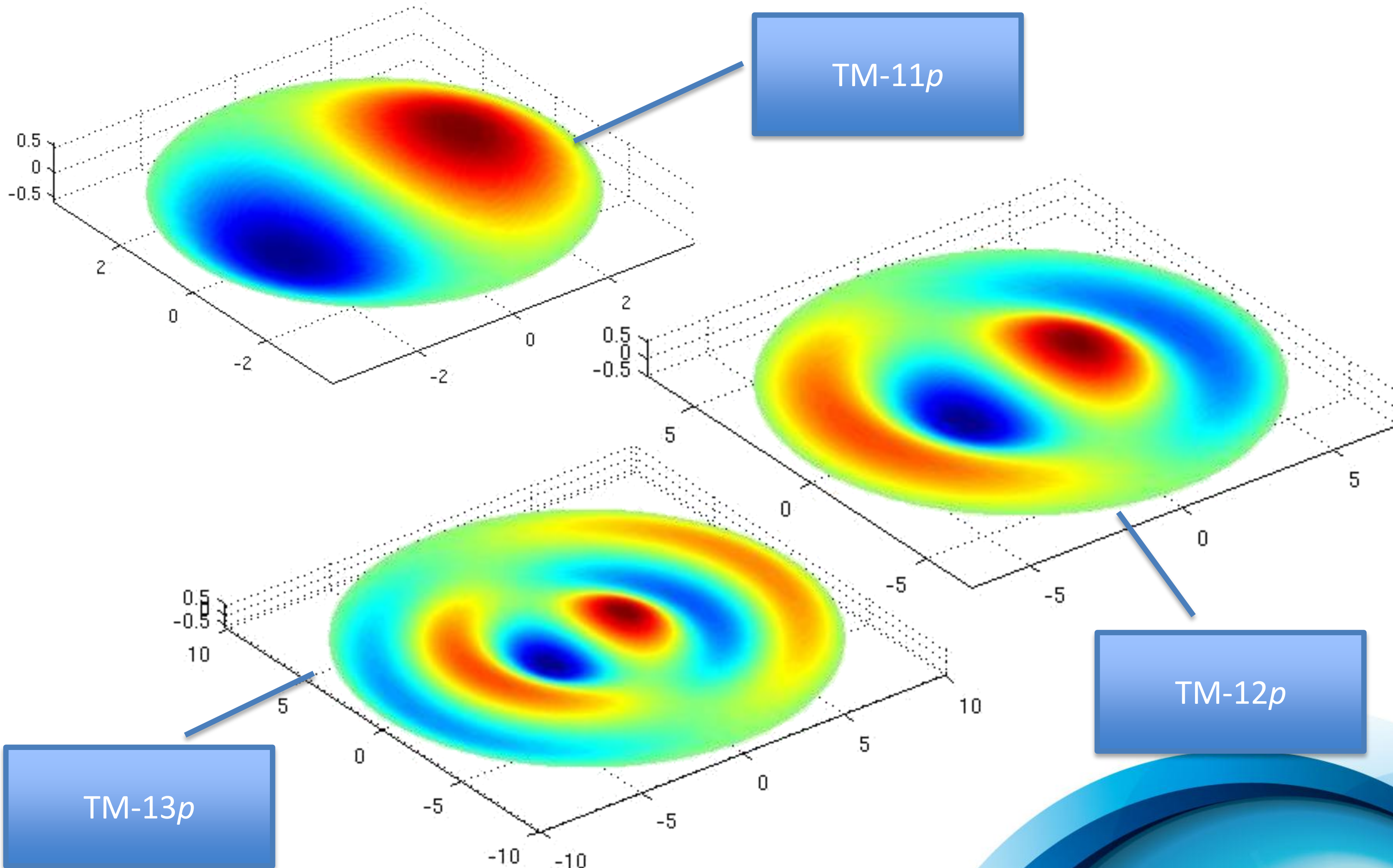
Derivation

- Maxwell's equations
  - Assume oscillatory solutions in time
    - $E(r,\theta,z,t)=E(r,\theta,z)e^{i\omega t+\phi_E}$ $\quad B(r,\theta,z,t)=B(r,\theta,z)e^{i\omega t+\phi_B}$
  - Apply boundary conditions
    - » E.g., right-cylindrical pill-box, conducting walls
- Solutions
  - TM_{mnp}, TE_{mnp}
  - – "Transverse magnetic" or "transverse electric"
  - – "m" gives azimuthal dependence $(\propto \cos(m\theta))$
  - – "n" counts radial zeros
    - n^{th} zero of the m^{th} order Bessel function
  - – "p" counts longitudinal zero-crossings

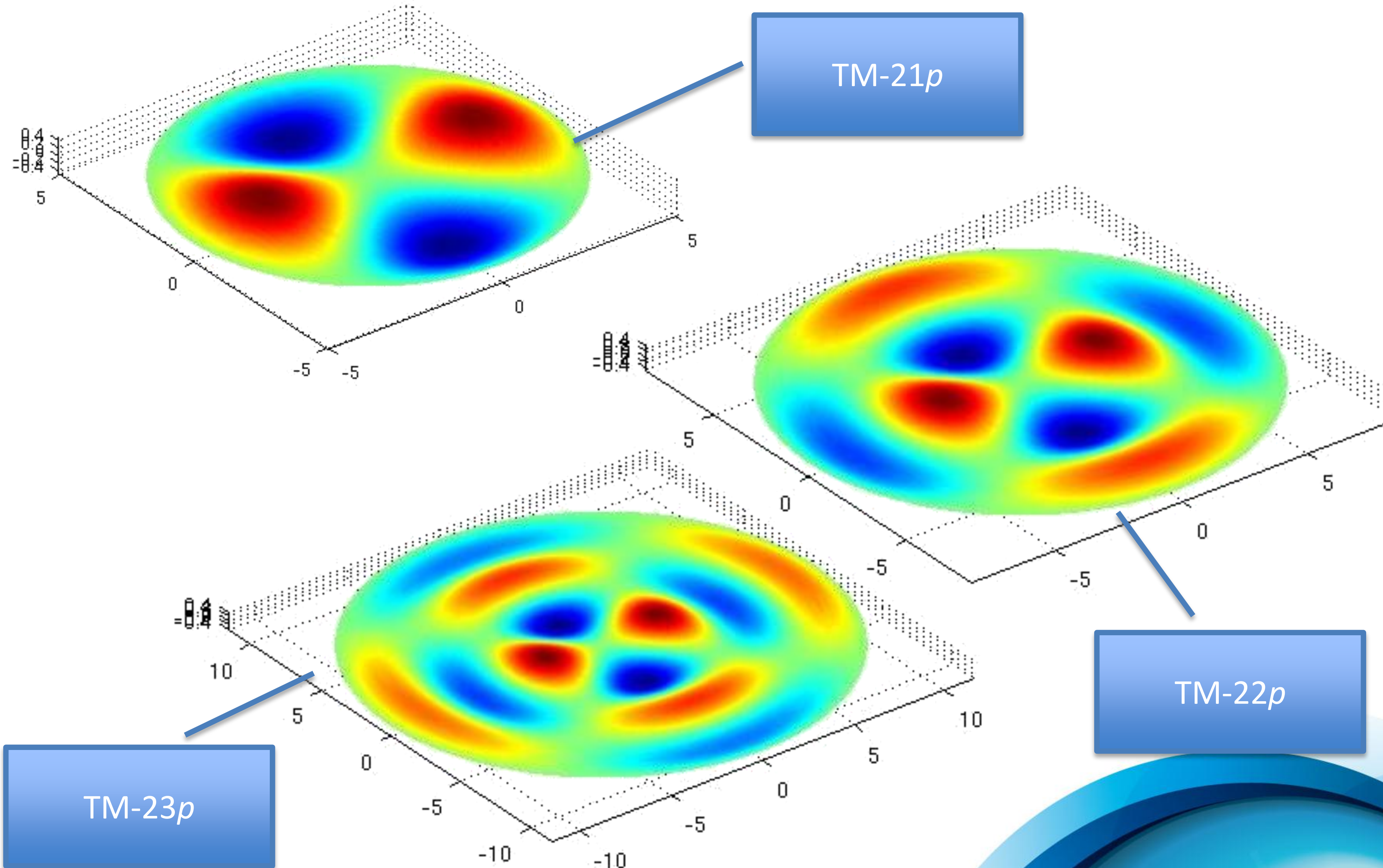
Monopole solutions to Maxwell's equations in a pill-box



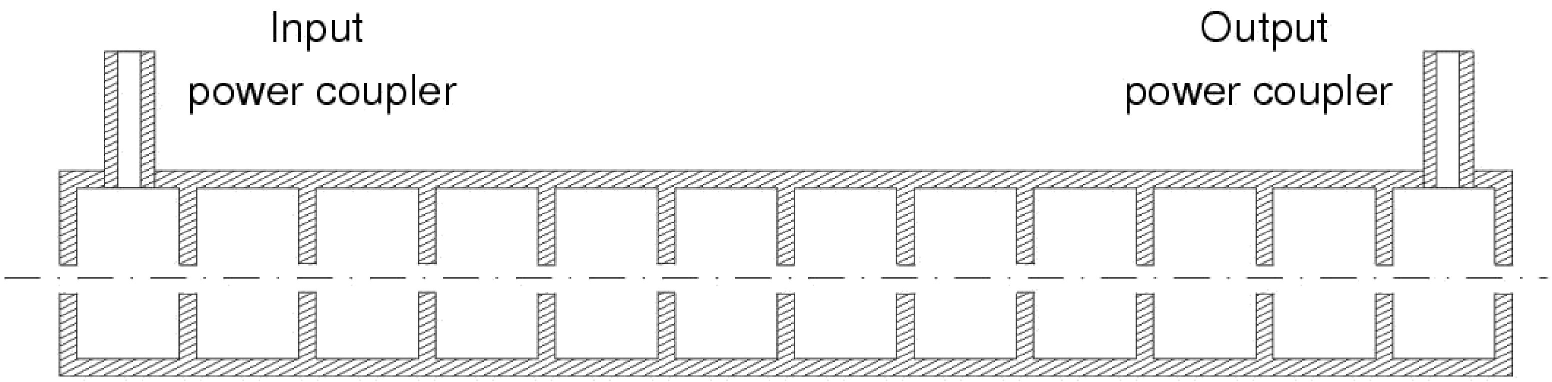
Dipole solutions



Quadrupole solutions

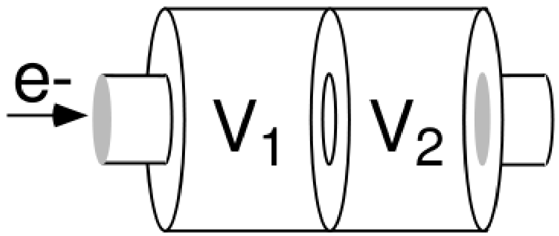


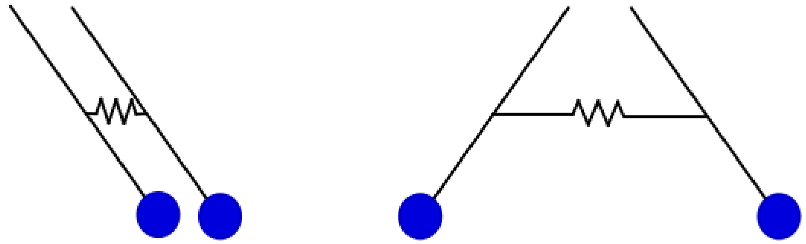
Real cavities aren't pillboxes!



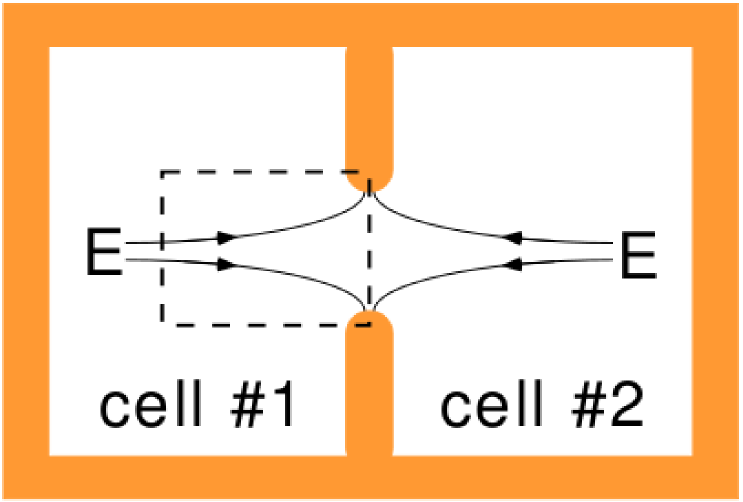
- Multiple, coupled, cells
- Beam aperture
- Each cell resonates
  - Coupled to its neighbour
  - Multiple ways for each oscillation to occur

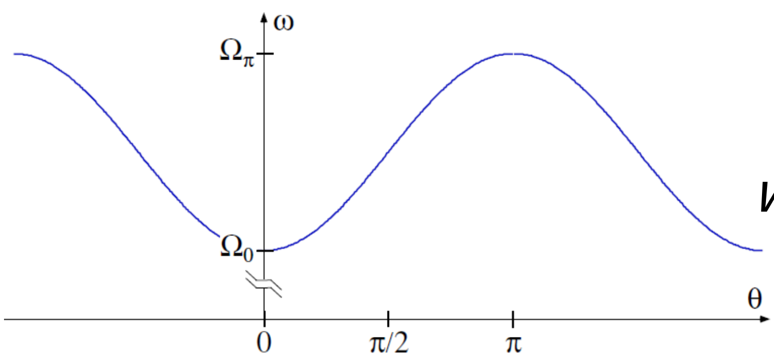
Coupled oscillators





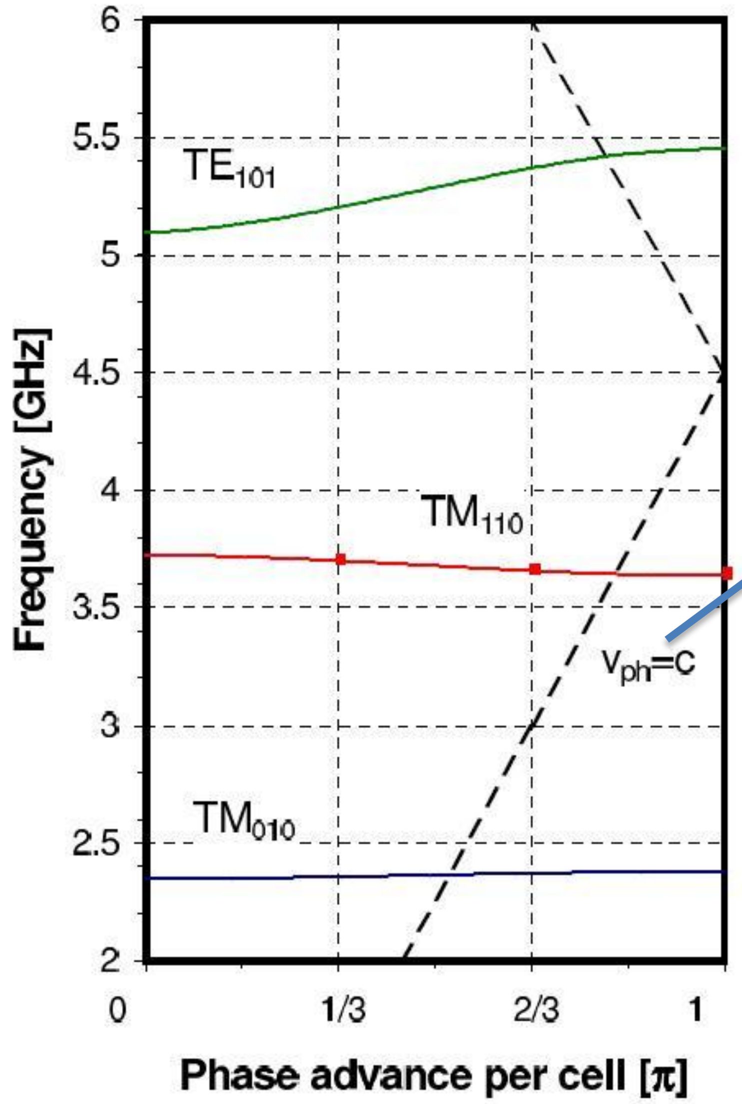
- Eigenmodes split according to the phase difference
  - “0-mode”, “π-mode”, etc.
- For *N*+1 coupled oscillators
  - *i*π/*N* radians phase advance (i=0,1,…*N*)
  - Frequency also splits
    - Dependent on the coupling strength
    - Each mode plotted on a Brillouin curve





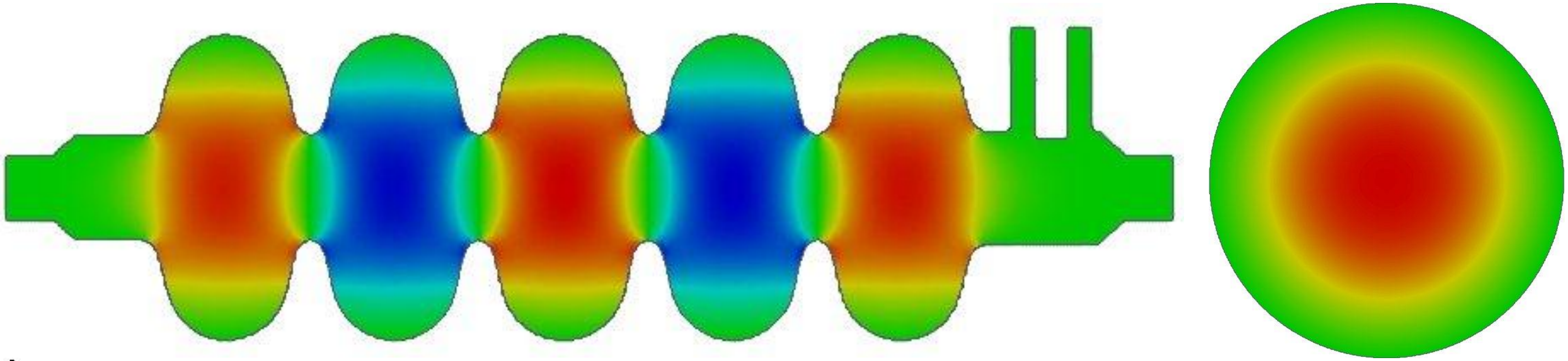
$$\omega_0^2 = \omega_{\pi/2}^2\left(1 - k\cos(\theta)\right)$$

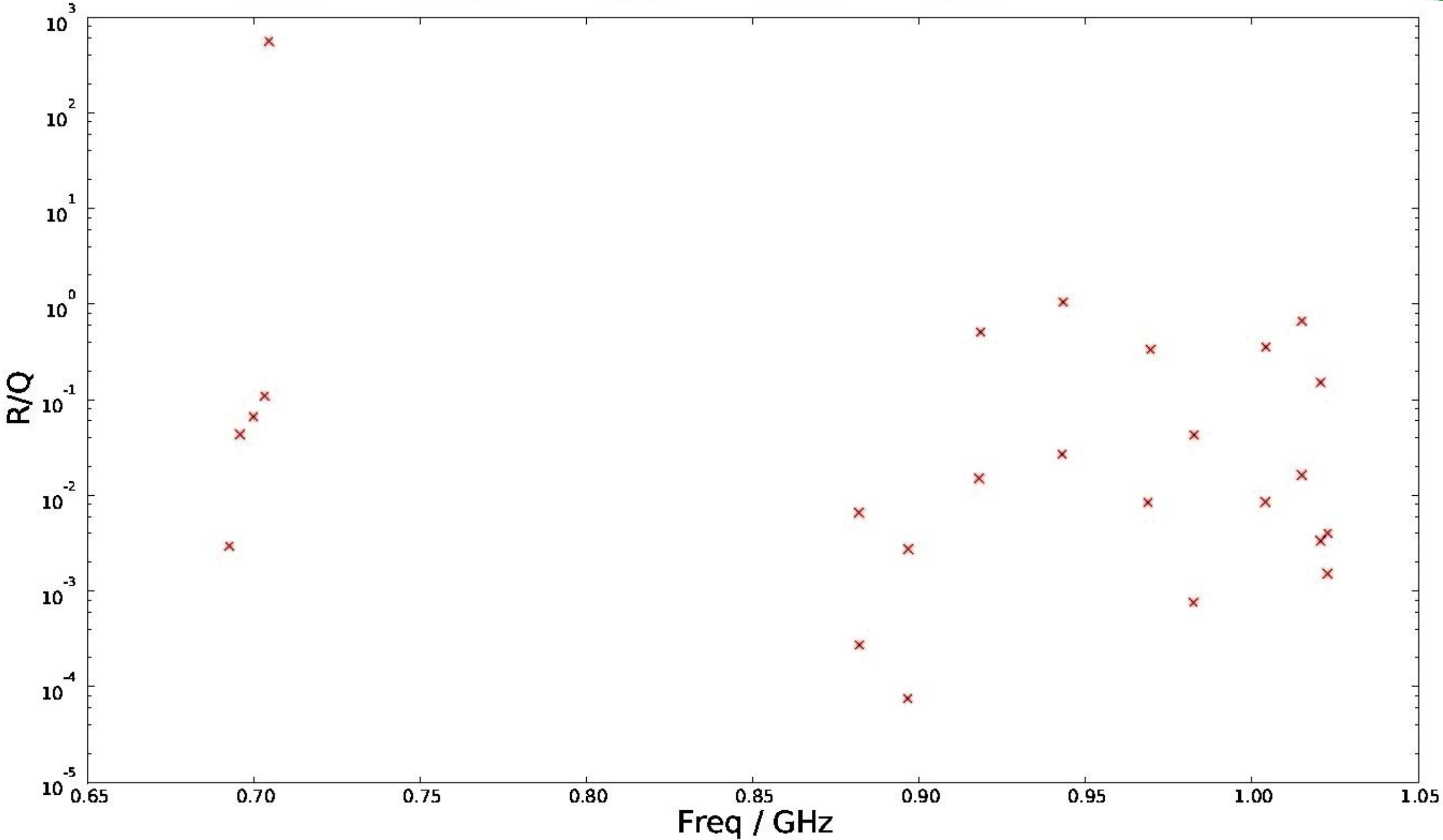
Beam coupling



Remember that $v_{ph}=\beta c$ is more appropriate for ESS!

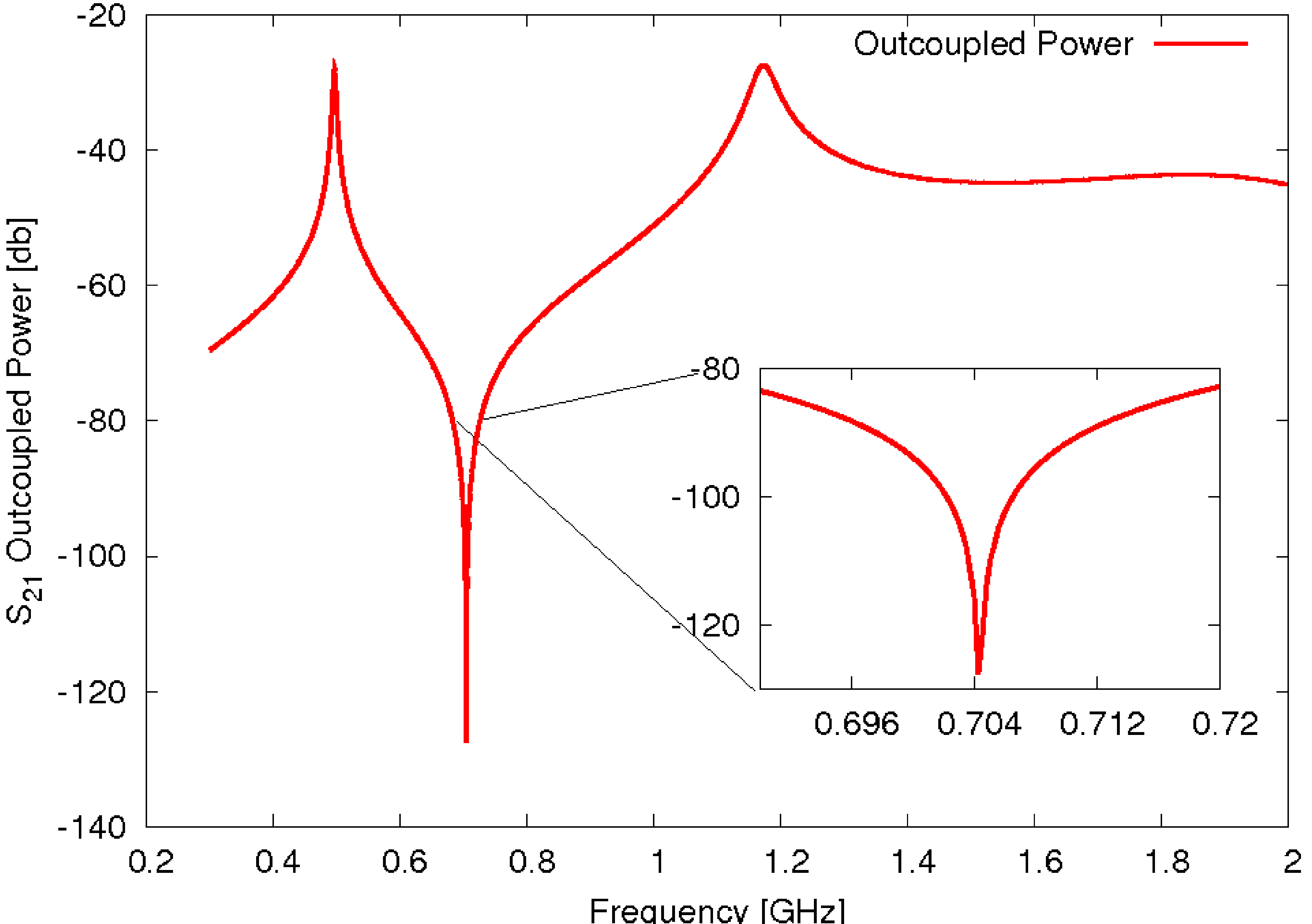
Example mode spectrum





How to damp modes?

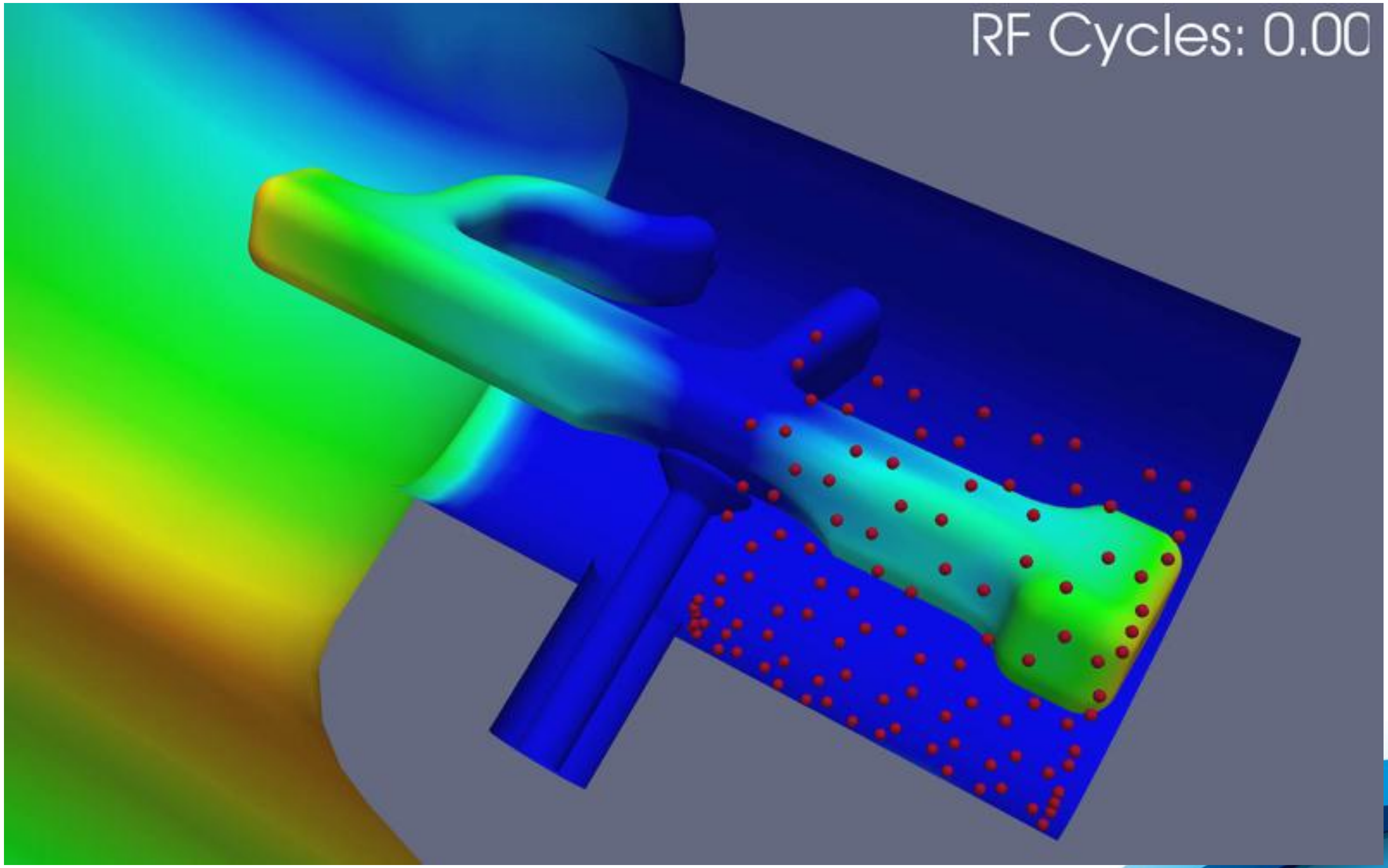
- Absorbing materials near the cavity
  - Field leaking from cavity is absorbed
    - Mode Q is reduced
  - Can affect the fundamental & the beam
- Dedicated couplers
  - Design band-stop coupler to extract HOM power
    - Strongly filter fundamental
  - Field emission, multipactor?
- Do nothing!
  - Modes are also absorbed by power coupler, bellows, etc.



Outcoupled Power
S_{21} Outcoupled Power [db]
Frequency [GHz]
-20
-40
-60
-80
-100
-120
-140
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
-80
-100
-120
0.696
0.704
0.712
0.72

Multipactor in the re-scaled TESLA design

Build cavity+coupler volume, and mesh → Find eigenmodes (using Omega3P) → Track electrons emitted from coupler surface (using Track3P → Find resonant impacts & scale by SEY



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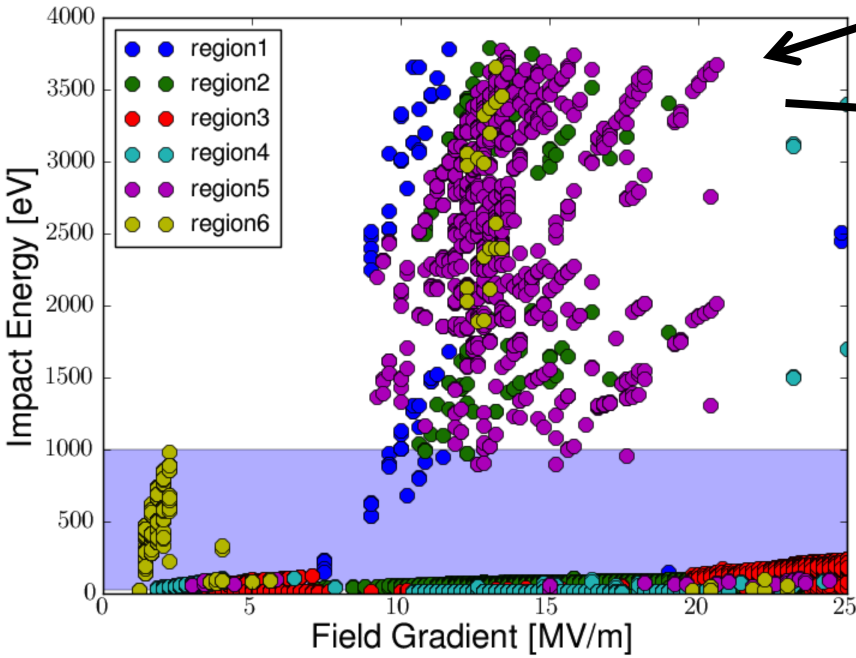
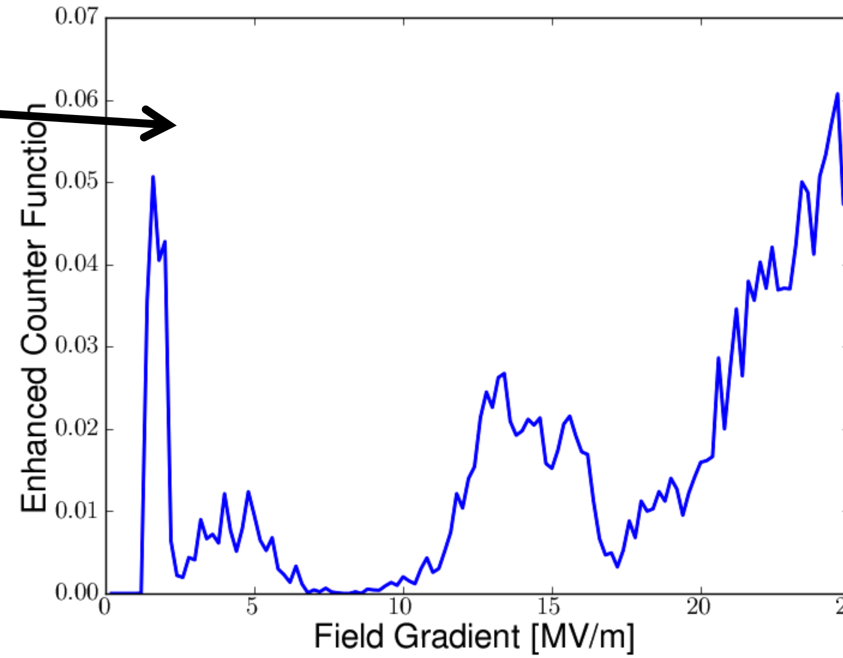
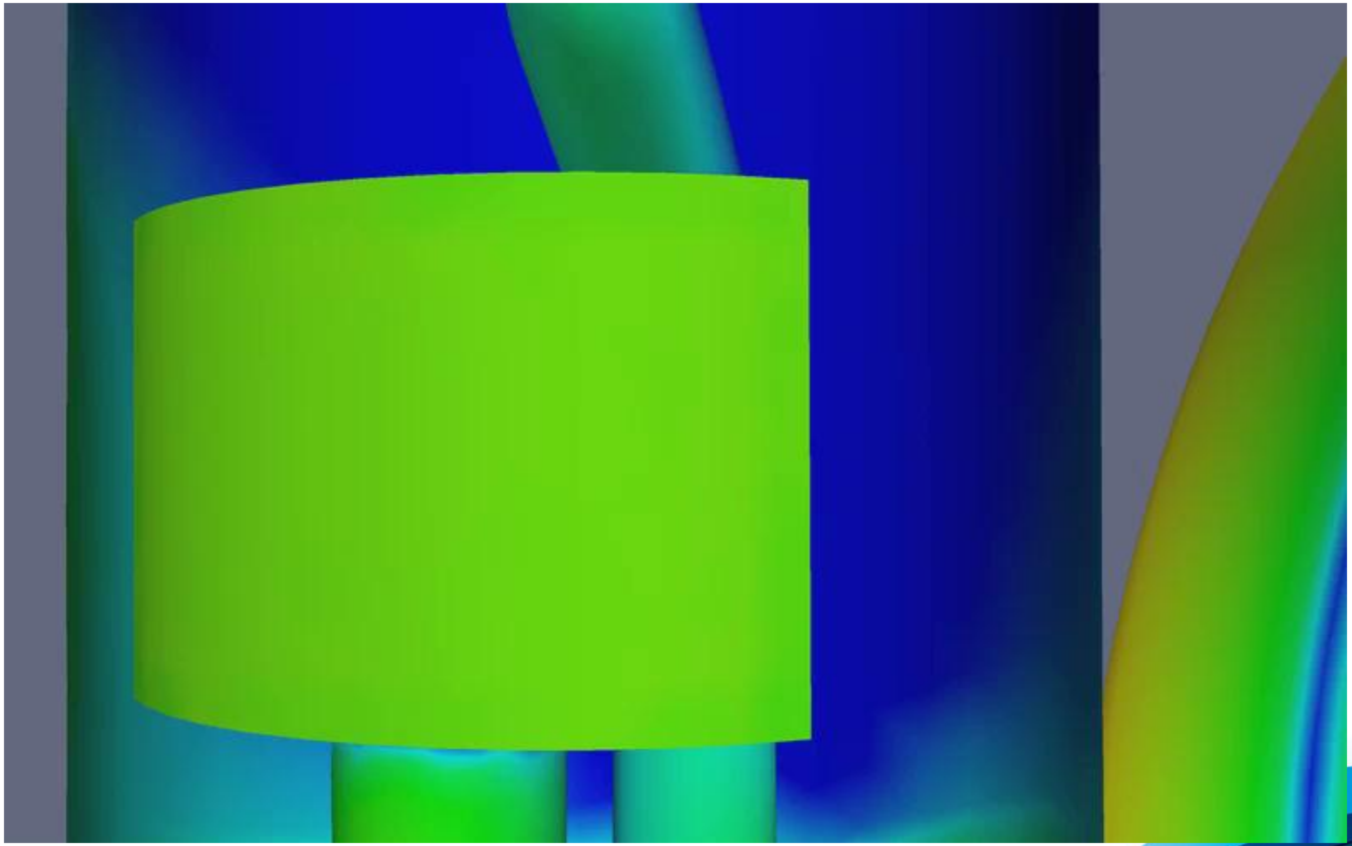




Multipactor in the Rostock design

Build cavity+coupler volume, and mesh → Find eigenmodes (using Omega3P) → Track electrons emitted from coupler surface (using Track3P → Find resonant impacts & scale by SEY



Multipactor in the Rostock design

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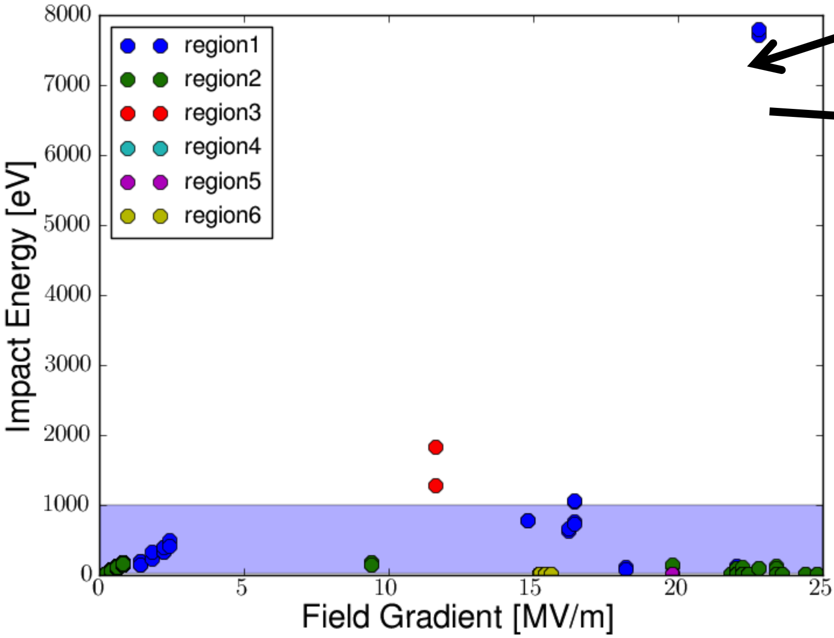
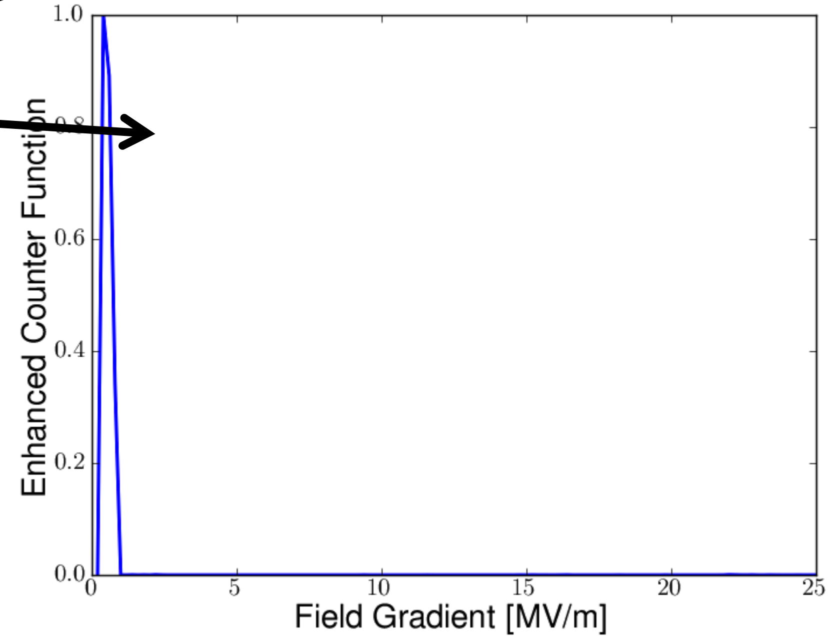
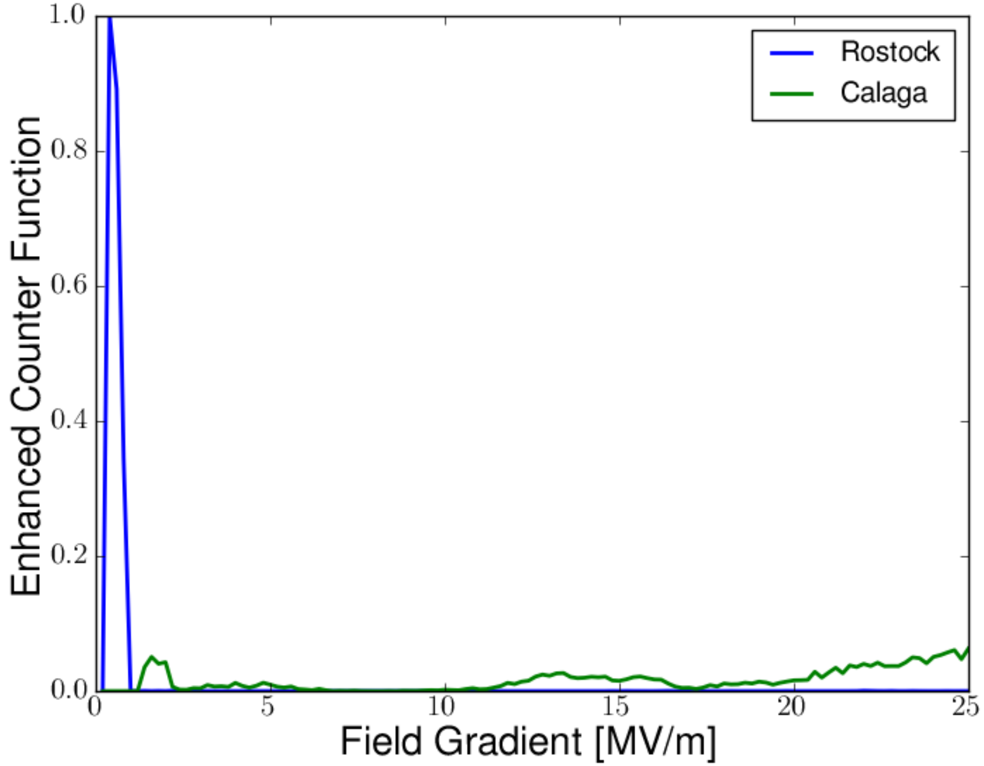




TESLA vs Rostock



Preliminary conclusions:

Large MP band in Rostock design appears risky.

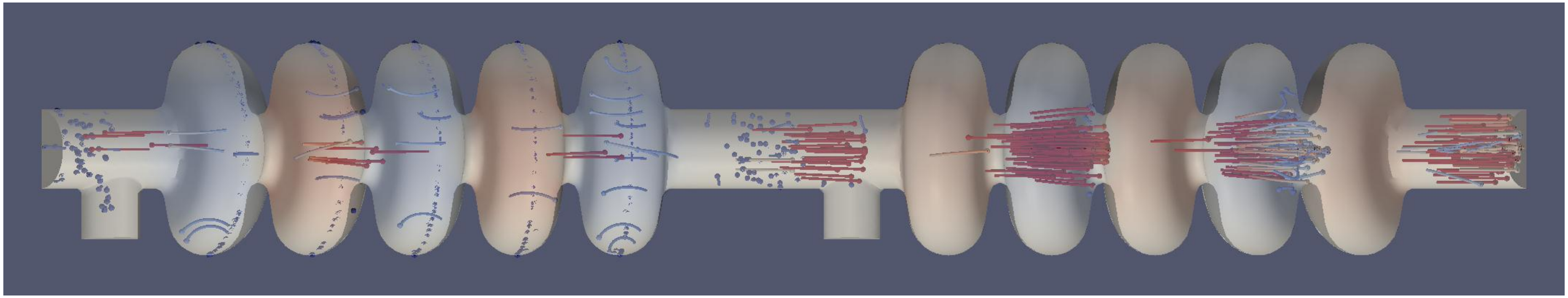
”Broadband” activity in TESLA design is undesirable

Questions:

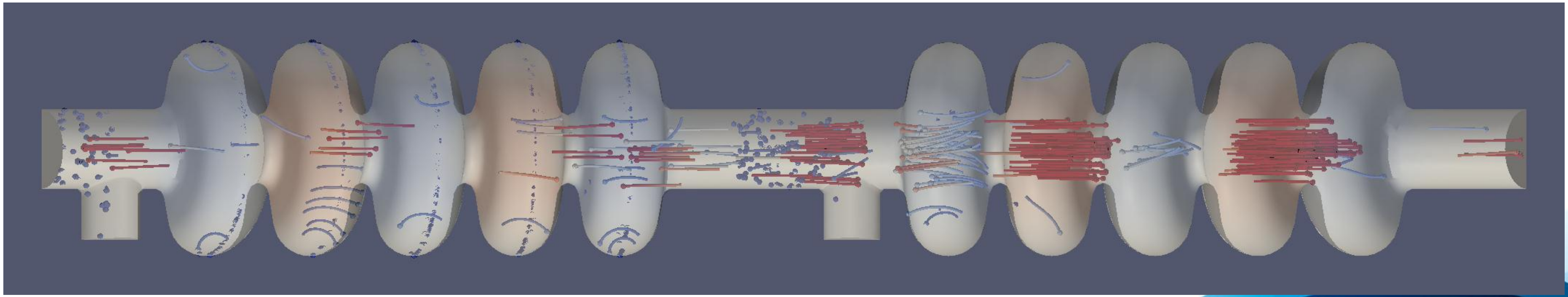
1. Ability to ”process away” MP bands?
2. How much could geometrical tweaks help?
3. Trustworthiness of code? (Questionable assumptions.)

Multi-cavity Field Emission

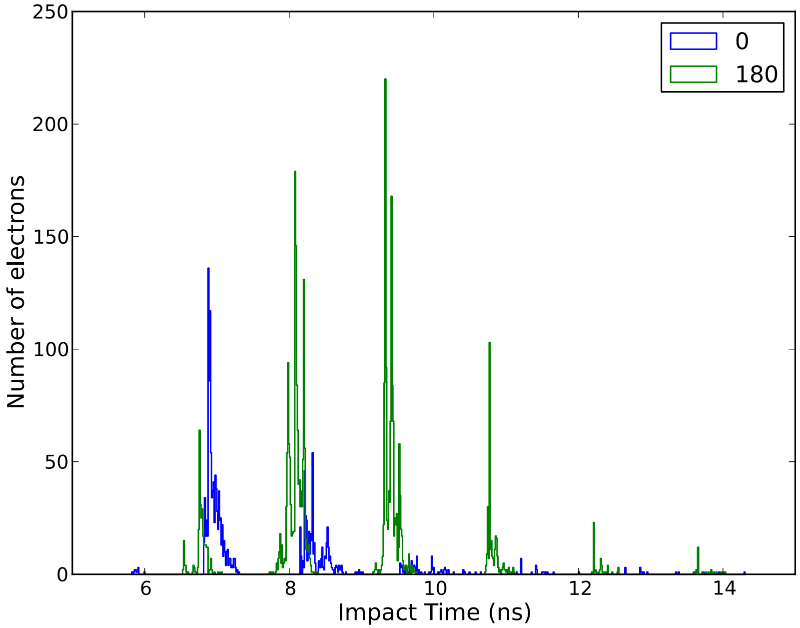
Instantaneous phase difference = 0

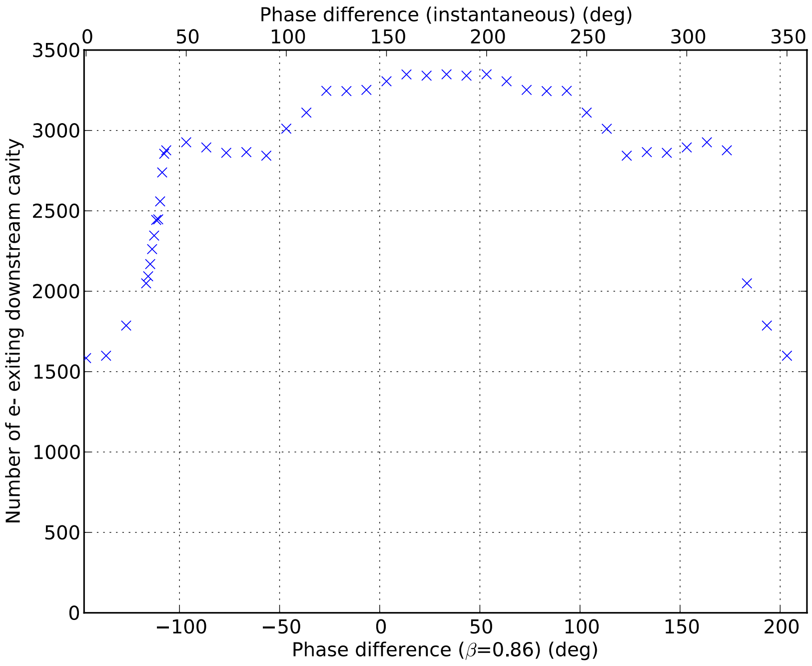


Instantaneous phase difference = 180°



FE current is dependent on cavity phase relationship





THANK YOU