TE Wave Measurement and Modeling

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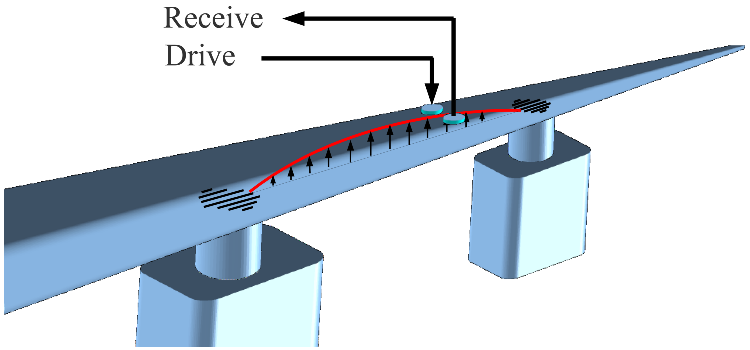

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Acknowledgements

Many thanks to **Seth Veitzer** of Tech-X Corp. for his help with VORPAL simulations [1].

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Outline

- Transmission vs. Resonance Model
- Examples of Resonant Beam-pipe
- EC Density Calculation for Resonances
- Examples of TE Wave Resonance Data
- Importance of the Field Distribution
- Bead Pull Measurements
- Simulations
- Simulations and Data with Magnetic Fields
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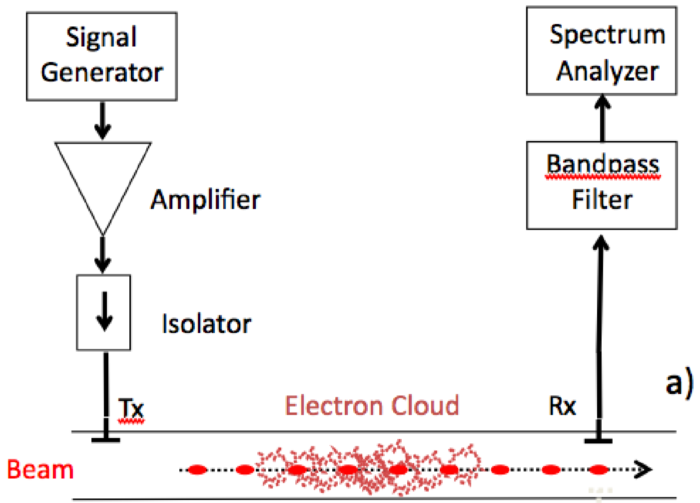
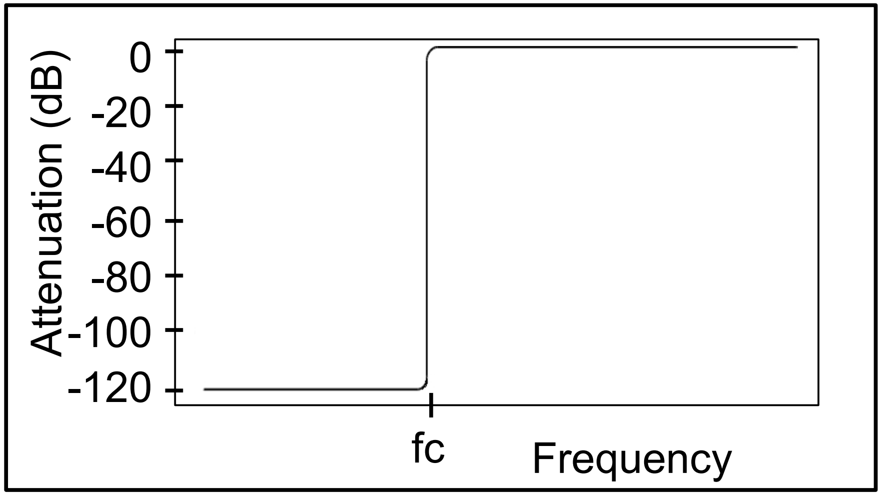
Transmission Model



The original idea was to propagate microwaves through the beam-pipe as if it were a waveguide.

The electron cloud produces a phase shift in the transmitted microwaves [2,3].



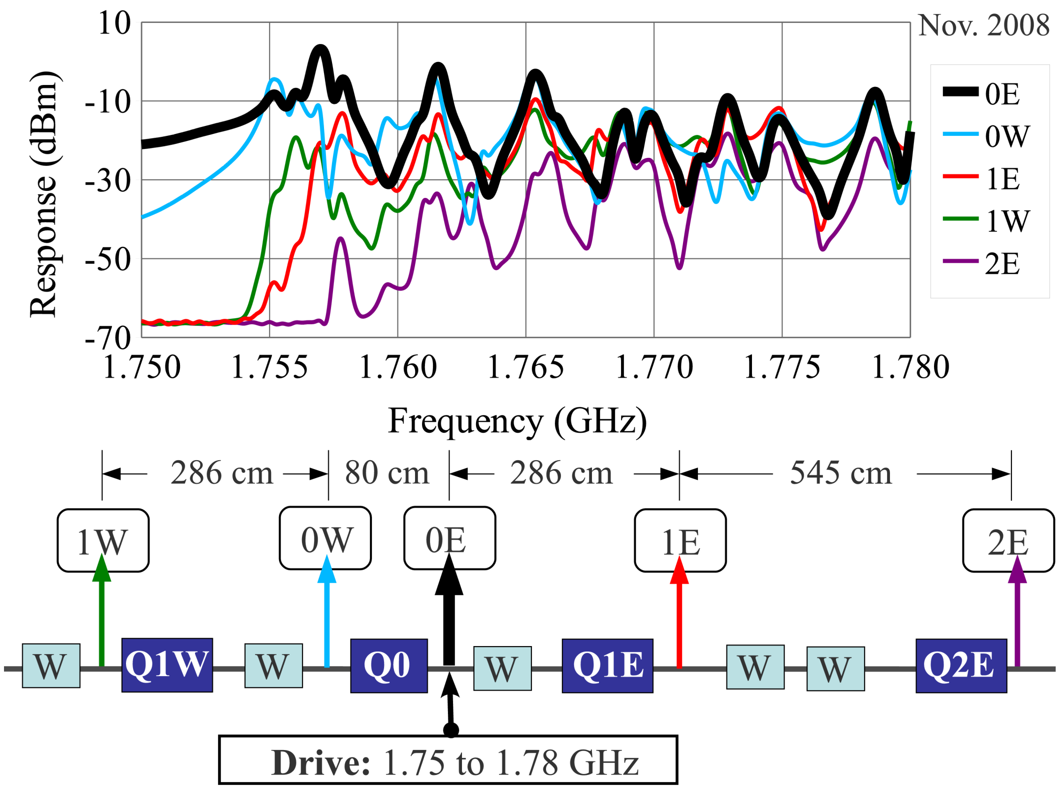
In an ideal waveguide, microwaves do not propagate at frequencies below the cutoff frequency.

Above the cutoff frequency, they propagate with little attenuation.

Transmission vs. Resonance

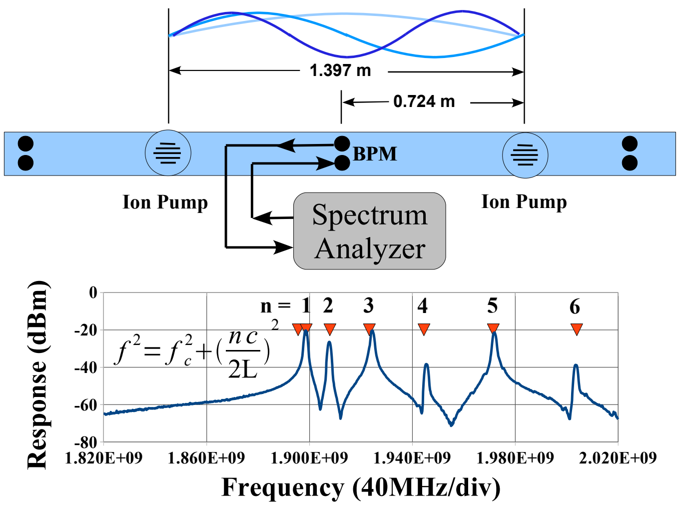
The response of beam-pipe is often not like a waveguide.

With input at 0E, the response was observed at other detectors including 0E itself. Many of the resonances are common to all of the detectors.

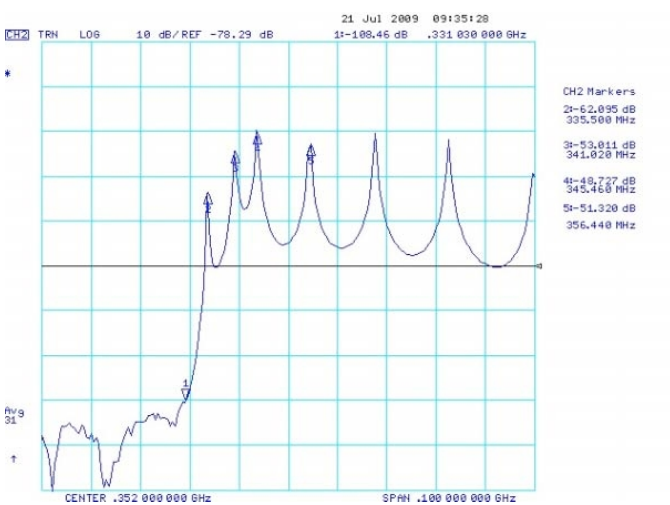


Examples of Resonant Beam-pipe

Beam-pipe often has the characteristics of a cavity.

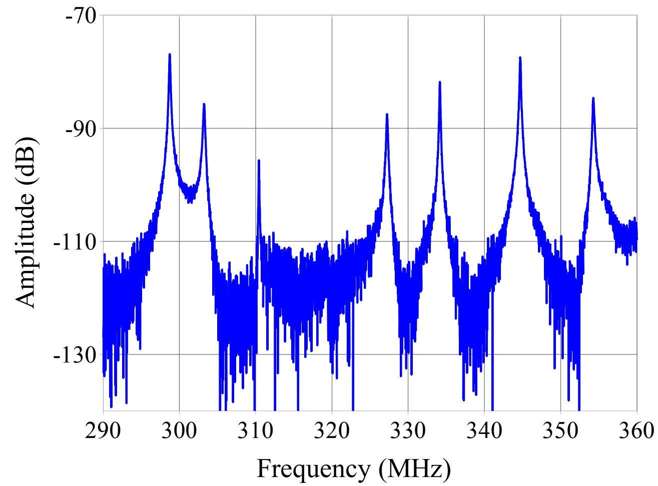


At 43E in CESRTA, a BPM is located between two ion pumps with longitudinal slots. The response closely matches that of a rectangular cavity. Triangles show the frequencies that correspond to n half wavelengths in the length L.

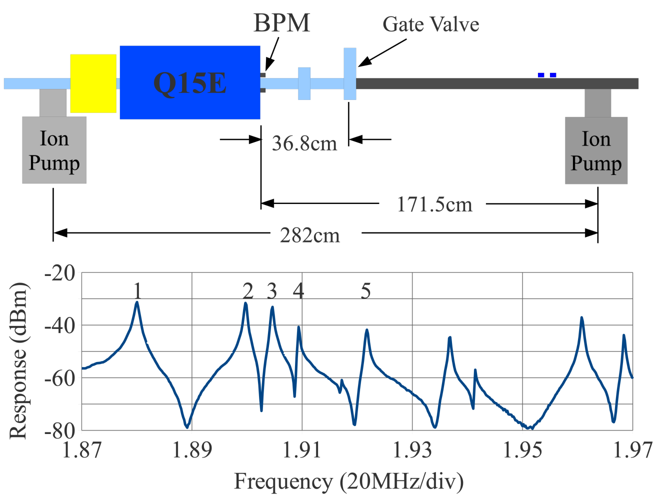


At the APS (Argonne National Laboratory), resonances are produced between bellow end flanges of the vacuum chambers (plot courtesy of Robert Lill). This response also matches that of a rectangular cavity.

Some more complicated resonances.



The positron ring at DAΦNE shows strong resonances, but the spacing of the peaks needs careful analysis.

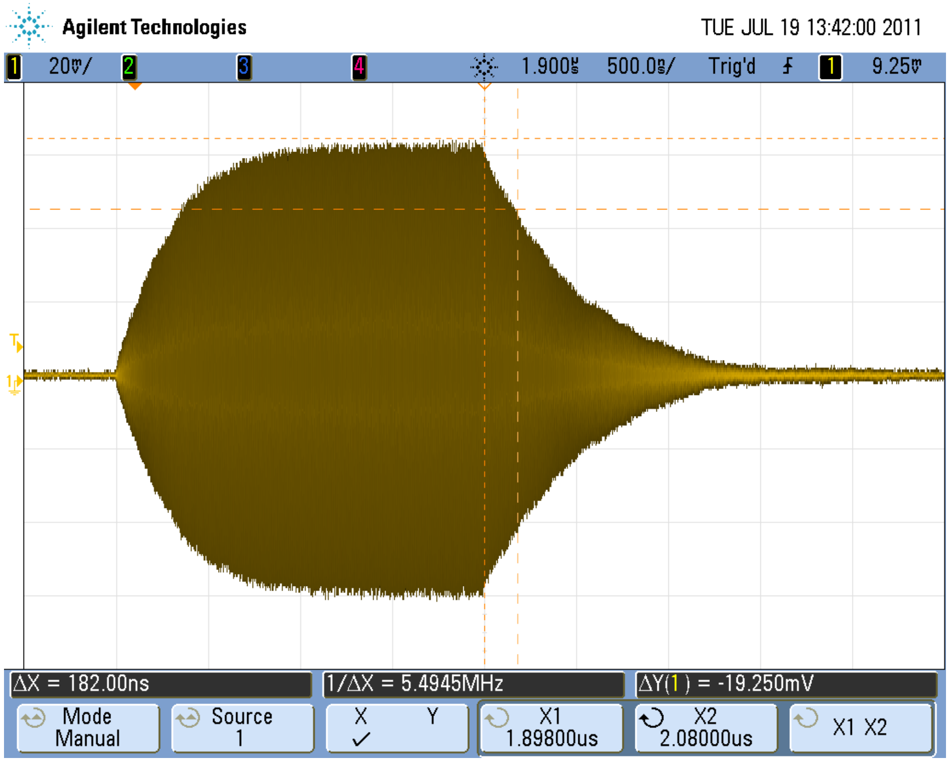


At 15E in CESRTA, the lowest resonance is much lower than might be expected of a rectangular cavity.

Examples of Resonant Beam-pipe

The time response of the beam-pipe was measured, using a 2 μs pulse of microwaves at one of the resonant frequencies.

Exciting and receiving at 0W, the damping time is about 500 ns, corresponding to a Q of about 3000.



The effect of EC density on the resonant beam-pipe:

Plasma physicists have been using cavities to measure plasma densities for many years. The resonant frequency of the cavity will be shifted according to

Local Electron Cloud Density

$$\frac{\Delta\omega_n}{\omega} = \frac{e^2}{2\varepsilon_0 m_e \omega^2} \frac{\int_V n_e E_0^2 dV}{\int_V E_0^2 dV} \qquad (1)$$

Where the product of the EC density n_e and the cavity electric field E^2 are integrated over the cavity volume V [4].

EC Density Calculation for Resonances

Some simplifying assumptions:

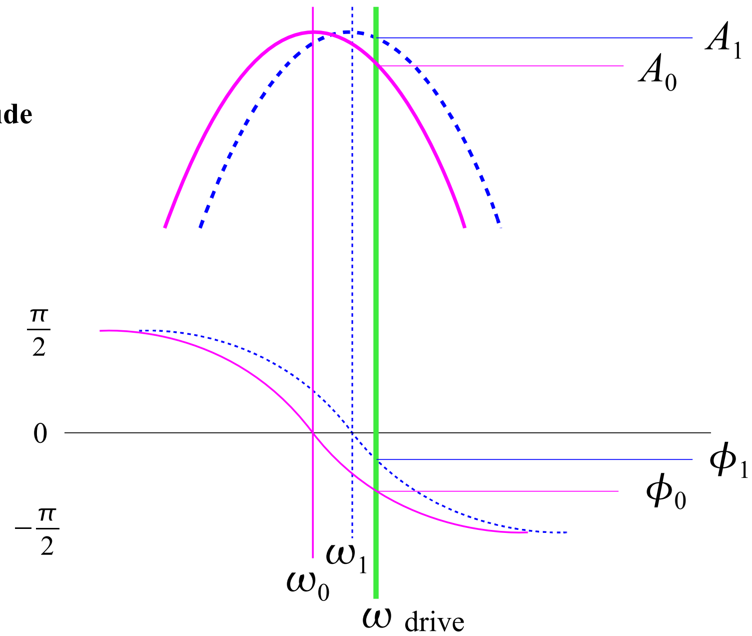
- That n_e is spatially uniform over the cavity volume.
- That n_e is a constant during the bunch train, zero otherwise.

Then the EC density can be calculated easily, since the integrals of Eq. 1 give just n_e itself.

A Fourier transform is used to correct the calculated EC density for its non-sinusoidal shape – a fixed amplitude pulse.

EC Density Calculation for Resonances

If the duration of the EC density is long compared to the cavity damping time, then the effect on a fixed frequency drive is a change in phase and amplitude across the cavity [5].



For small frequency shifts near resonance

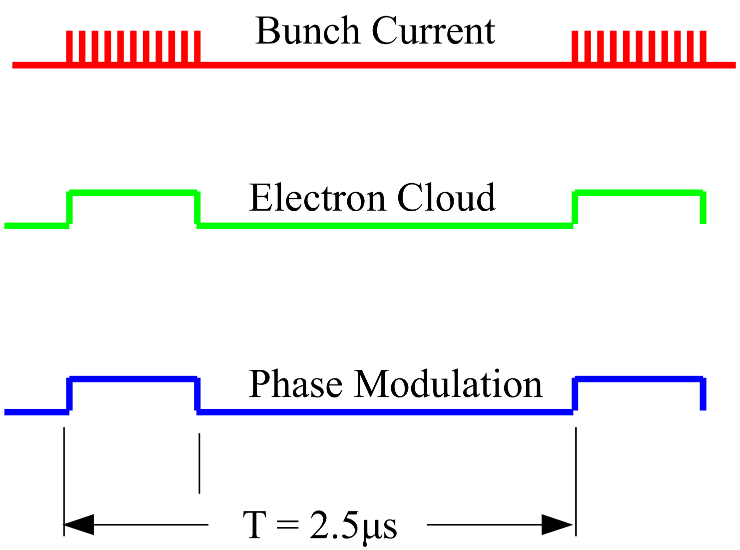
$$\Delta\phi_n \approx 2Q\frac{\Delta\omega_n}{\omega} \qquad \text{Phase Modulation}$$

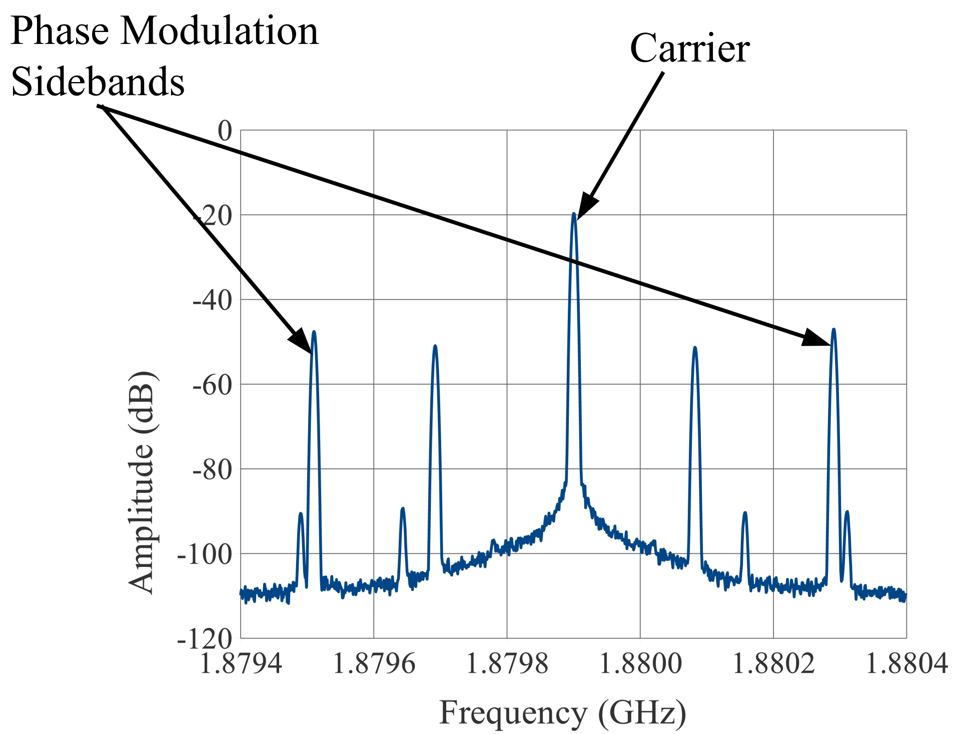
Combine this with the previous expression and use the fact that the ratio of the first sideband amplitude to the carrier is approximately $\frac{1}{2}\Delta\phi_n$

$$n_e \approx S_{ratio} \cdot \frac{\omega_n^2}{Q \cdot 1.59 \times 10^3}$$

EC Density Calculation for Resonances

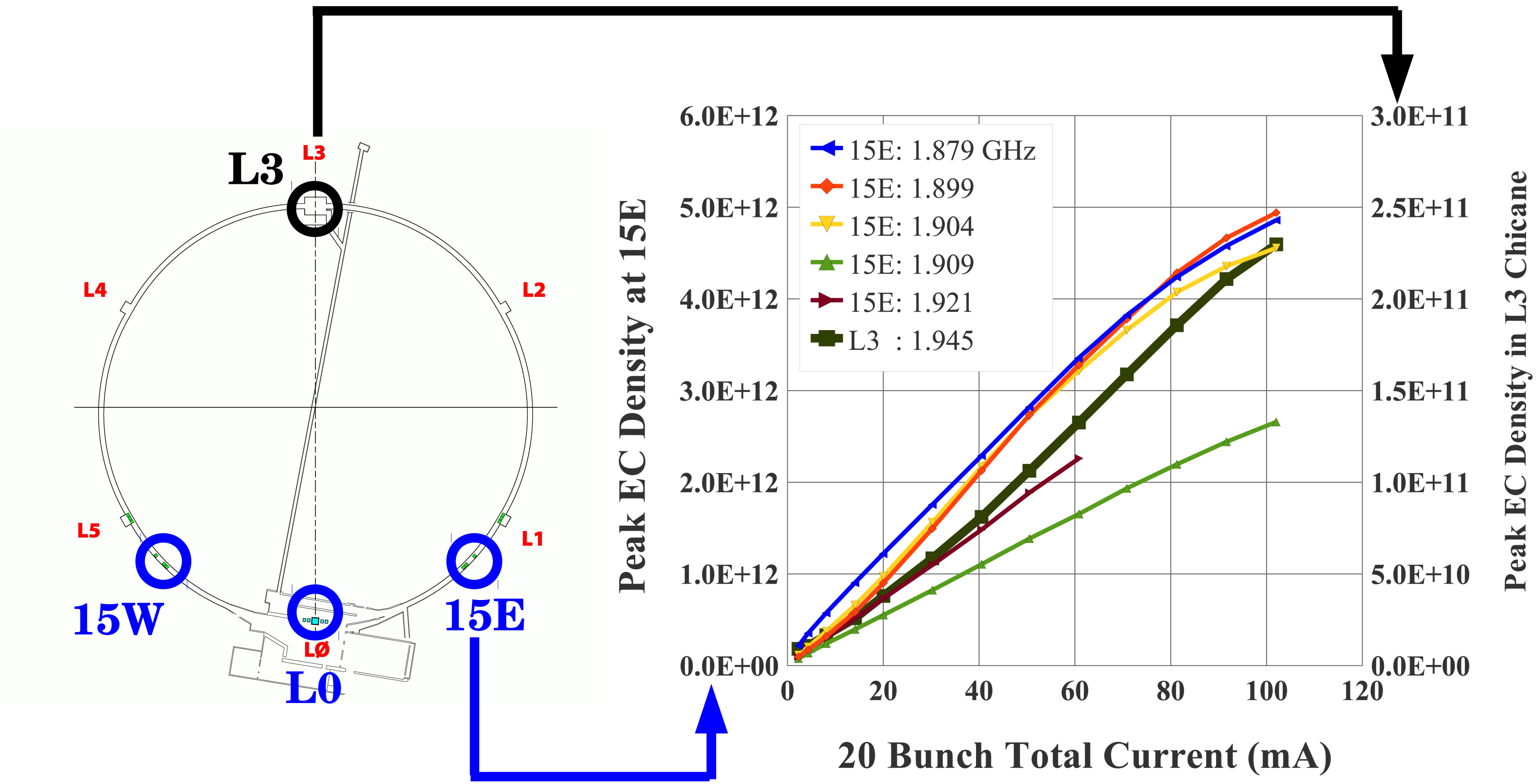
A modulation of the EC density will produce phase modulation sidebands. Close to resonance, the contribution of AM sidebands will be small. Detailed analysis is ongoing.





EC Density Calculation for Resonances

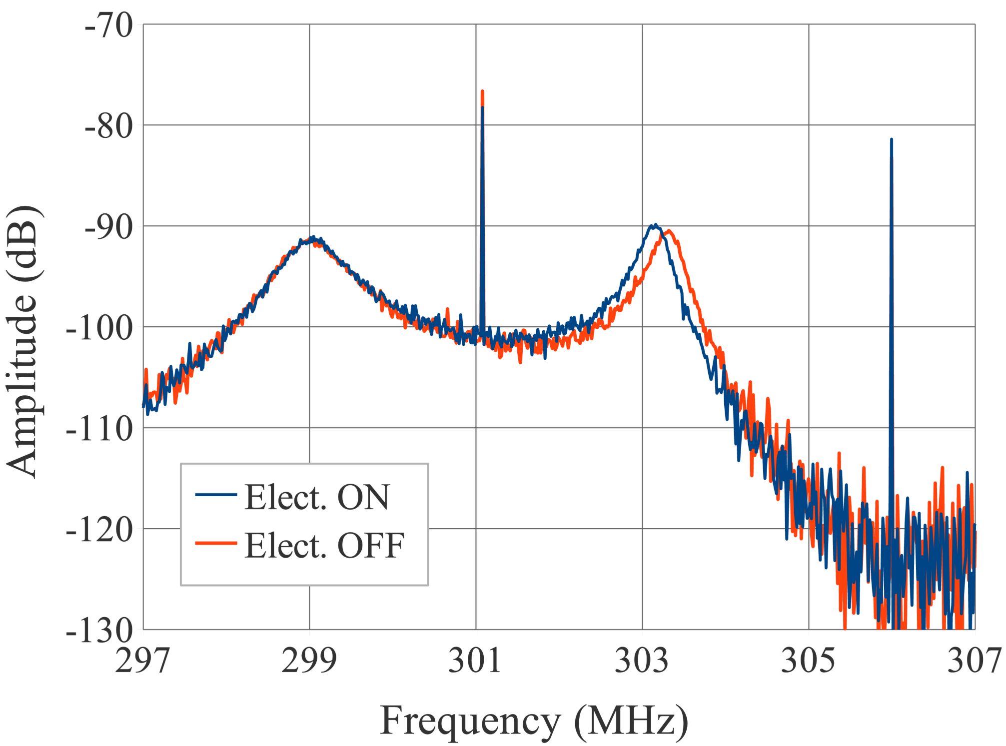
At two locations in CESRTA, sidebands were used to measure the EC density vs positron current with a 20 bunch train at 5 GeV.



Examples of TE Wave Resonance Data

Data from DAΦNE with 800mA of positrons.

There were 100 bunches with a gap of 20 bunches. Clearing electrodes were turned OFF/ON and the response recorded. The large duty factor allows the frequency shift to be observed directly. In this case about 200 kHz corresponding to a EC density of about 1.5 x 10^{12} m^{-3} [6].



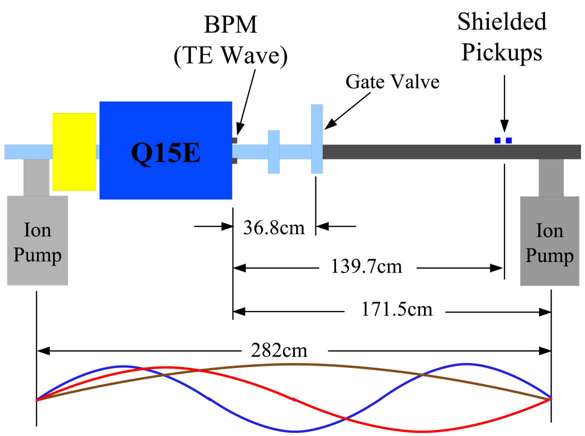
The amount of frequency shift varied from peak to peak. Here the lowest frequency resonance is unshifted, while the next peak is shifted by 200kHz as the clearing electrodes are turned OFF/ON.

The sensitivity of the method depends on the product of the local EC density and E^2.

This points to the need to understand the field patterns that are set up by the TE wave resonance.

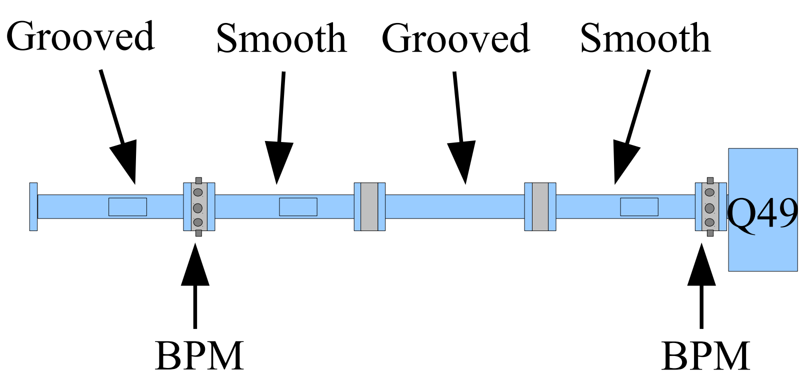
Importance of the Field Distribution

The electric field of the resonance determines *where* the the measurement is made.



At 15E, roughly half of the chamber is bare aluminum, the other half is coated with diamond-like carbon. Also, the synchrotron radiation varies by a factor of 3 in this region.

So n_e is not uniform.



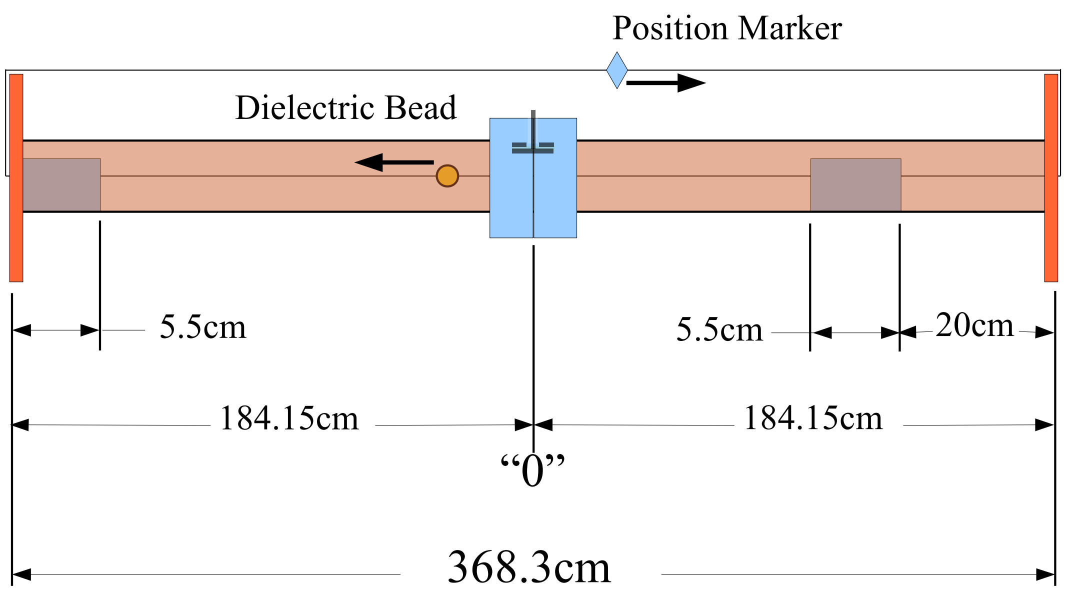
In the L3 chicane region, there are sections of both smooth and grooved round beam-pipe

What is the field distribution?

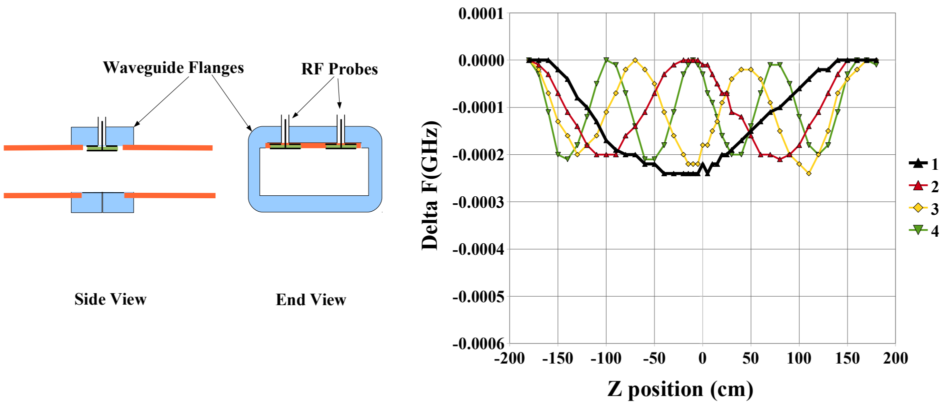
Bead Pull Measurements

Bead pull measurements are commonly used to measure the fields of cavities.

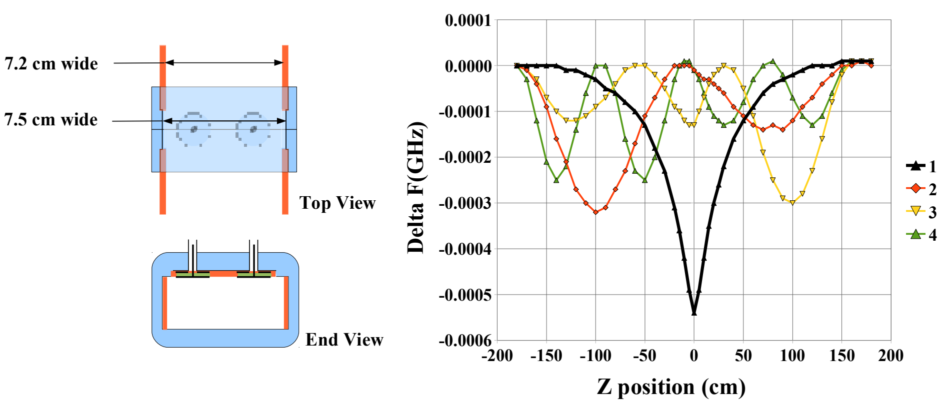
A dielectric bead is supported by a thin mono-filament line and pulled through the cavity. The change in resonant frequency is proportional to E^2 at the bead.



Bead pull measurement on waveguide



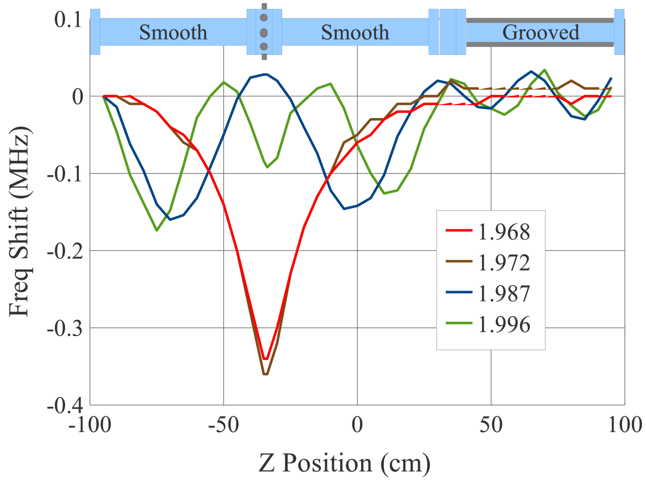
With a drive flange that matches The inner dimensions of the waveguide, the frequency shift vs. position shows the expected sequence of half wavelengths.



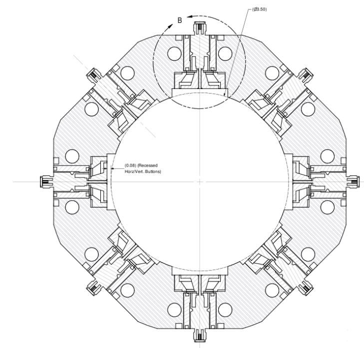
But if the drive flange is modified, the lowest resonance has a very different characteristic. The field decreases exponentially with distance from the drive point (cutoff mode).

Bead Pull Measurements

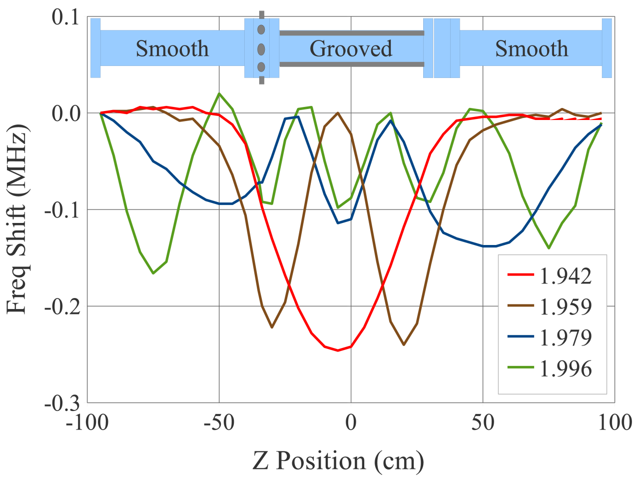
Measurements on round beam-pipe as is used in the L3 Chicane



In a measurement with two smooth sections of beam-pipe at the drive point, a cutoff mode response is observed. This is due to the design of the BPM.

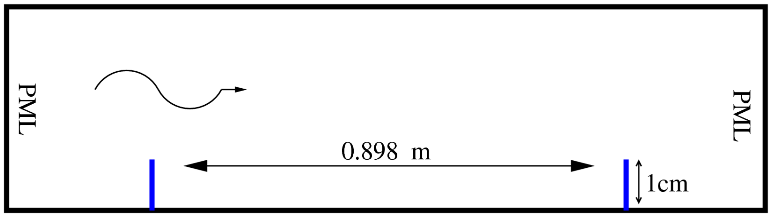


The BPM flange has recesses That protect the buttons from synchrotron radiation. This lowers the cutoff frequency at the drive point.

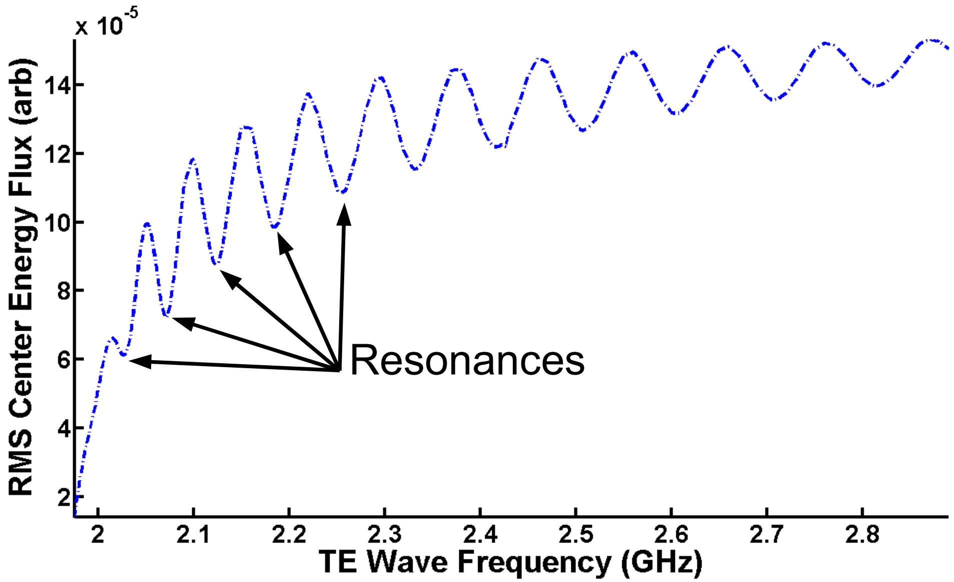


With smooth and grooved beam-pipe at the drive point, the first two resonances are mostly within the grooved section. the cutoff frequency of the grooved pipe is lower than that of the smooth pipe which explains the effect.

VORPAL simulation of reflections:

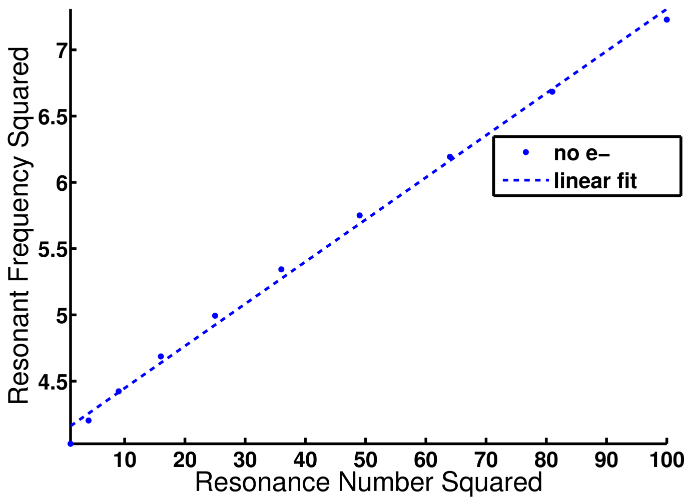


Two obstacles are placed in the waveguide to generate reflections.



At resonances, the Poynting vector **E** x **H** will have minima.

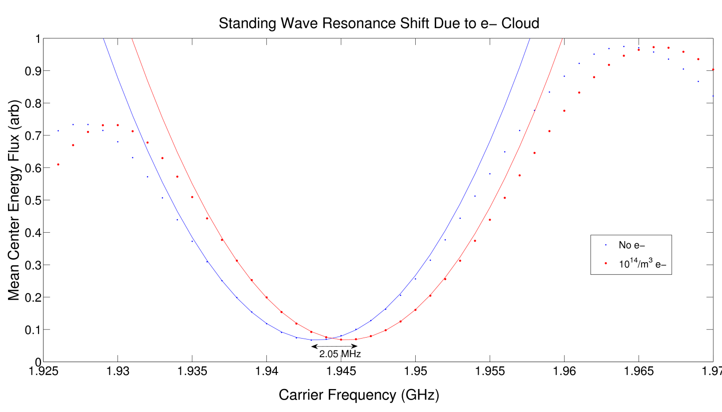
Plotting the minima in the Poynting vector:



In a rectangular cavity, resonances
Will occur at the following frequencies:

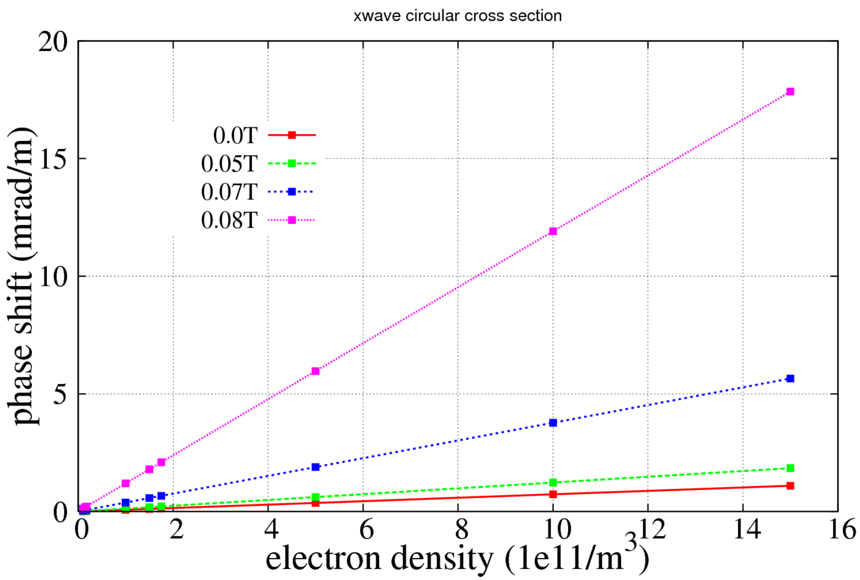
$$f^2 = f_c^2 + \left(\frac{n c}{2L}\right)^2$$

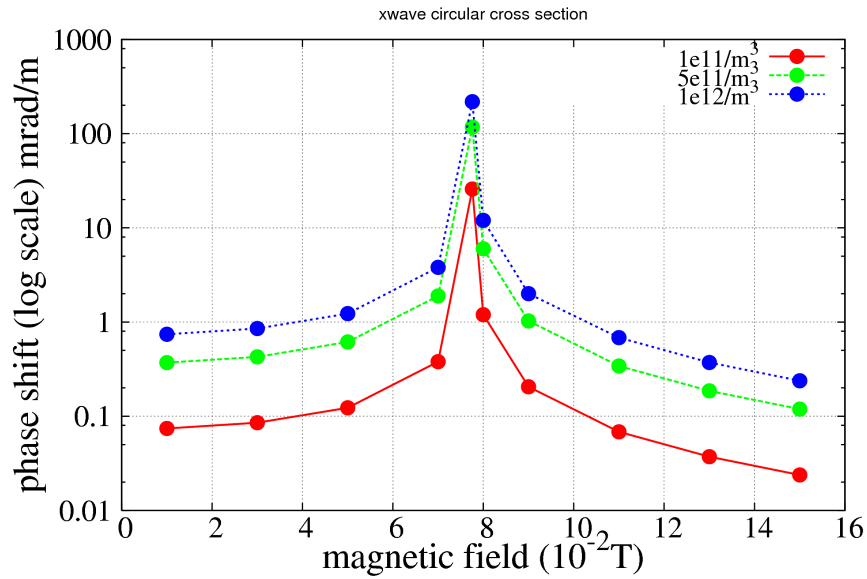
The location of the minima in the simulation is in fair agreement with the analytical expression.



The shift in resonant frequency for
A density of 10^{14} m^{-3}, is about 2 MHz.
This also agrees with Equation 1.

Simulations of Phase Shifts with Low Magnetic Field

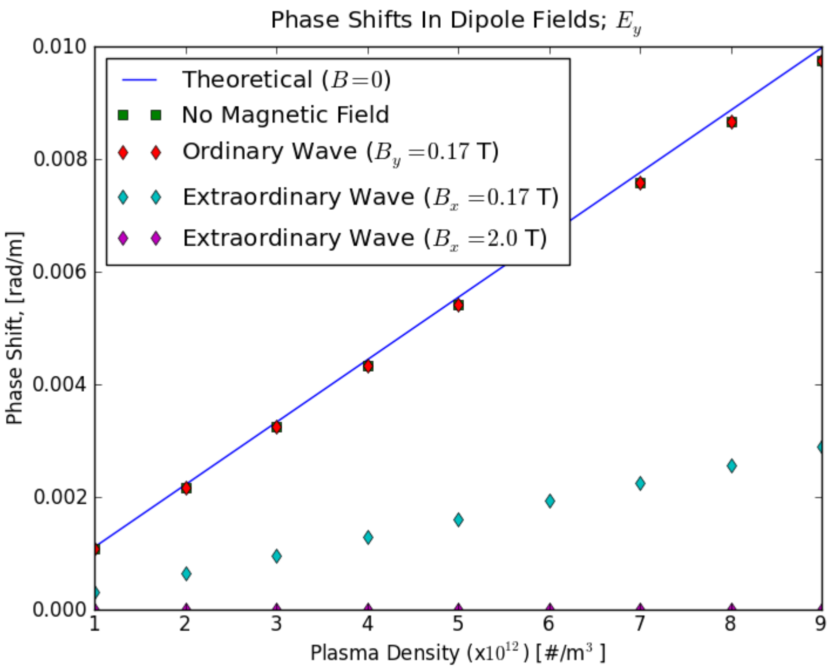




When E of the TE wave is perpendicular to the dipole field (x-wave) there is a magnification of the phase shift. This is due to the proximity of the cyclotron resonance. The TE wave frequency was 2.17 GHz

Changing the magnetic field at fixed EC densities, the cyclotron (upper hybrid) resonance occurs at 0.07757 T.

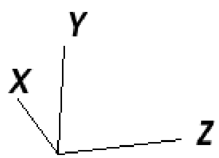
Simulations of Phase Shifts with High Magnetic Field



With larger dipole fields, such that the cyclotron frequency is much higher than the TE wave excitation, there is a reduction in the phase shift of the x-wave.

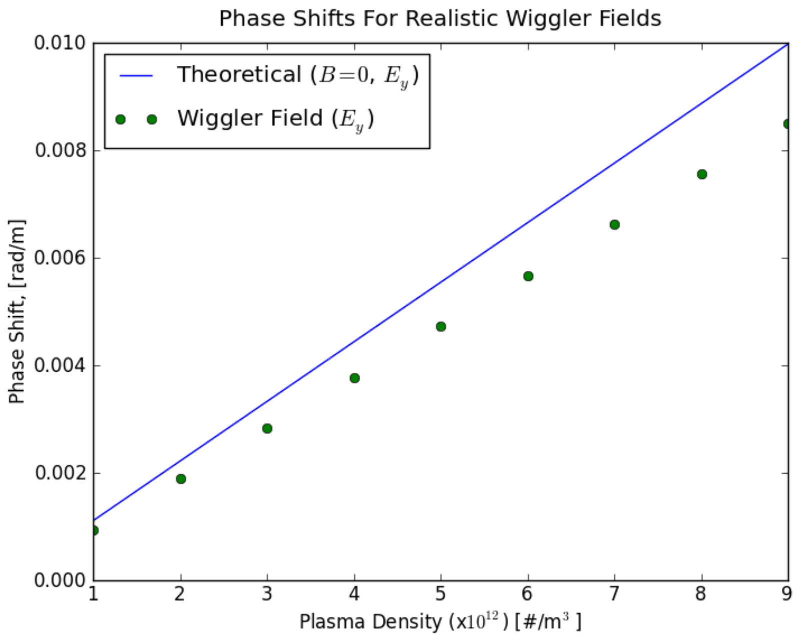
When E of the TE wave is parallel to the dipole field (o-wave) the phase shift is unaffected by a 0.17 T field [7].

F_{co} = 1.66 GHz
$B_{resonance}$ = 0.06 T

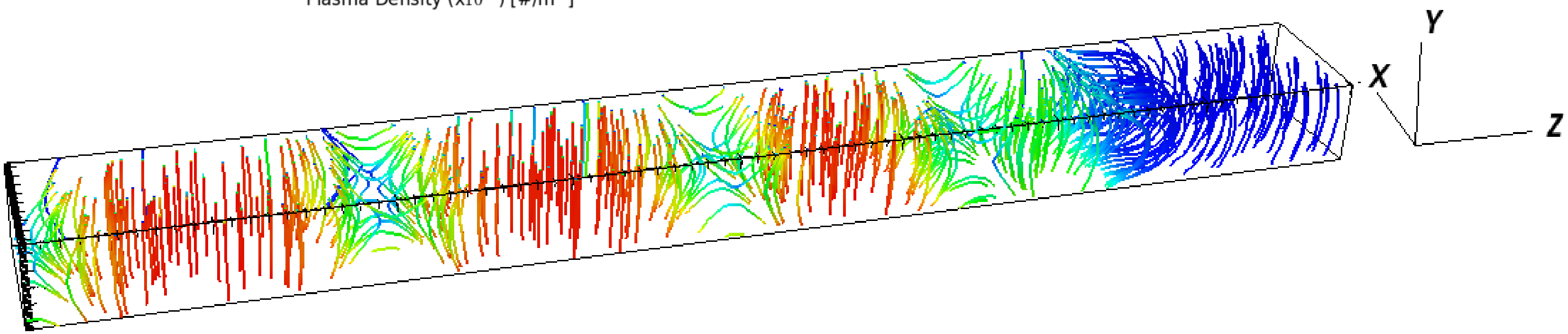


Simulation by Seth Veitzer of Tech-X.

Simulations of Phase Shifts in a Wiggler Field



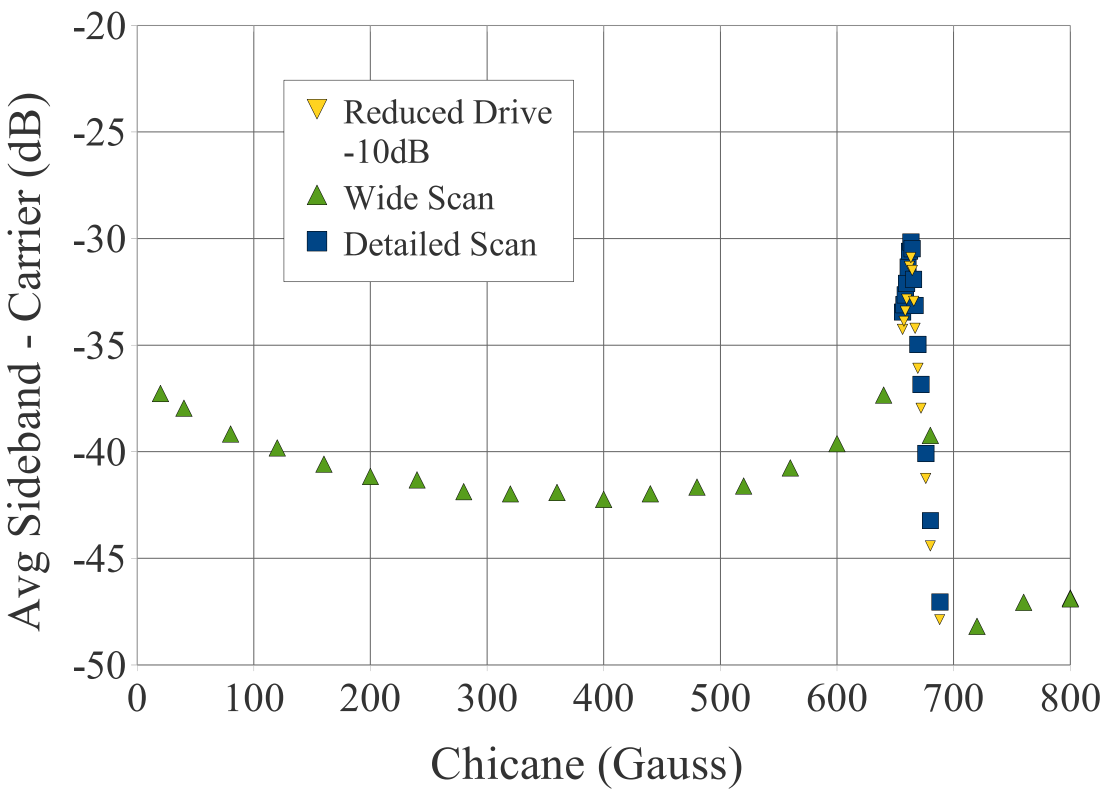
The simulated phase shift through a wiggler gives a somewhat reduced phase shift even Though E is parallel to the main wiggler field.



Simulation by Seth Veitzer of Tech-X.

CESRTA Chicane: Cyclotron (Upper Hybrid) Resonance

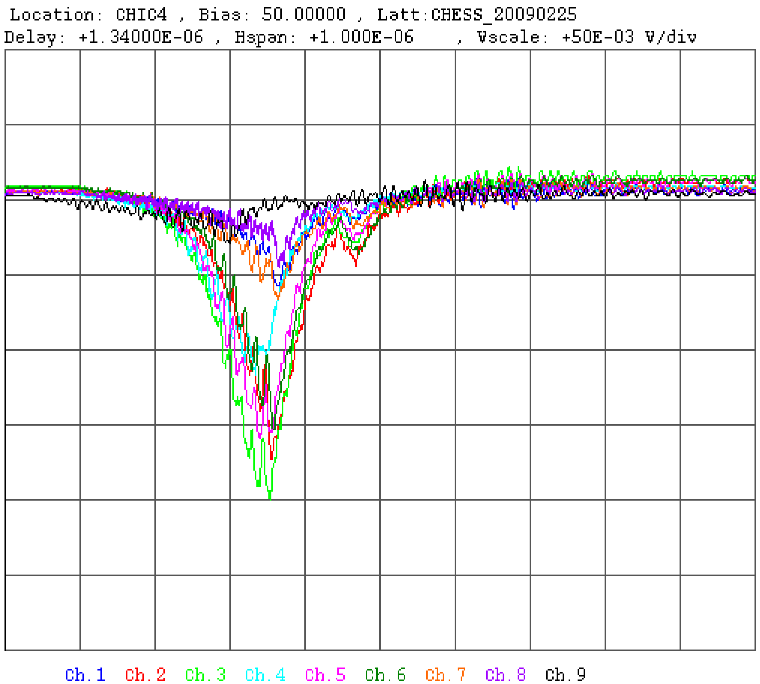
With 10 Bunches of positrons (+ witness) at 5.3 GeV, 145 mA total current and resonant excitation of the aluminum chamber at 1.9714 GHz. The chicane dipole magnet field was scanned from 0 to 800 Gauss.



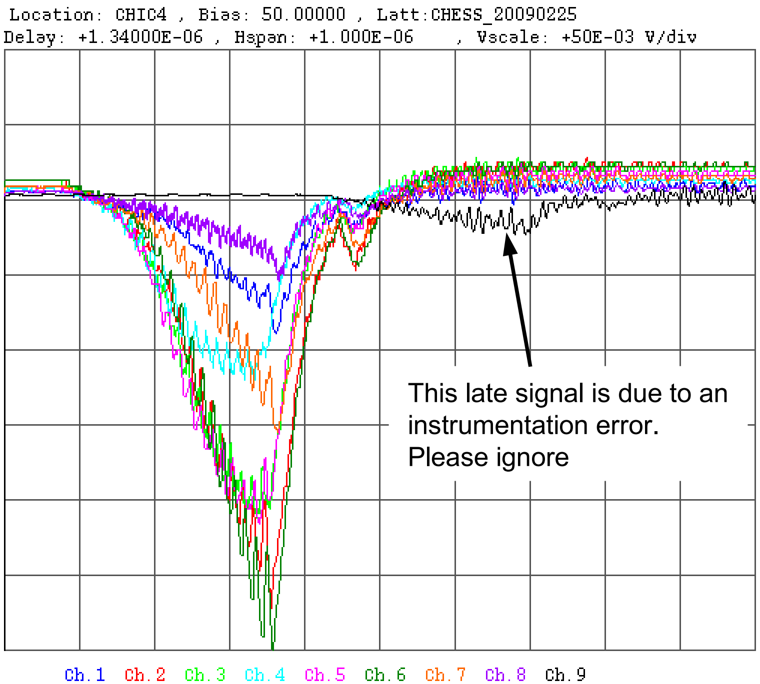
CESRTA Chicane: Response of the Time Resolved RFA

Then with the chicane dipole set on the resonance, the TE wave drive was turned off and on. The signal below is from the Time Resolved RFA in the same aluminum chamber. Are we affecting the cloud or the RFA response?

Drive OFF



Drive ON



Conclusions and Future Work

Conclusions:

- EC density measurements have been made using resonances.
- The field distribution is important if the EC density is non-uniform.
- Bead pull measurements can be an aid in knowing the fields.
- Simulations have made progress, both in resonance measurements and in transmission measurements including magnetic fields.

Future Work

- Resonant field distribution estimates and simulations are needed.
- Detailed analysis of the cavity transient response is ongoing.
- Simulation and measurement in magnetic fields should continue.
- The effect observed in the Time Resolved RFA needs further study.
- A detector for localized measurement (cutoff mode) is possible.

Thank you for your attention.

[1] C. Nieter and J. R. Cary, "VORPAL: a versatile plasma simulation code", J. Comp. Phys. 196, 448-472 (2004).

[2] E. Mahner, T. Kroyer and F. Caspers, Phys. Rev. ST Accel. Beams 11, 094401 (Sep. 2008).

[3] S. De Santis, J. M. Byrd, F. Caspers, et al, Phys. Rev. Lett. 100, 094801 (Mar. 2008).

[4] J. P. Sikora et al., " Resonant TE Wave Measurements of Electron Cloud Densities at CESRTA", in Proc. of IPAC'11, San Sebastián, August 2011, TUPC170, p.1434, (2011).

[5] S. De Santis, et al. "Analysis of Resonant TE Wave Modulation Signals for Electron Cloud Measurements", in Proc. of IPAC'12, New Orleans, May 2012, MOPPR073..

[6] D. Alesini, et al. "Experimental Measurements of e-Cloud Mitigation using Clearing Electrodes in the DAFNE Collider", in Proc. of IPAC'12, New Orleans, May 2012, TUOBC03.

[7] S. A. Veitzer, "3-Dimensional Modeling of Electron Clouds in Non-uniform Magnetic Fields", in Proc. of IPAC'12, New Orleans, May 2012, TUOAA01.

Transmission vs. Resonance

The transmitted signal will be phase shifted by the presence of the electron cloud (EC). So a periodic EC density would result in phase modulation sidebands.

$$\Delta \phi = \frac{L \omega_p^2}{2c\left(\omega^2 - \omega_c^2\right)^{1/2}}$$

We have measured sidebands. . .