Microwave Transmission: Theory, Simulations, Experiments and Plans

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Overview

- Definition and derivation of phase shift
- Phase modulation and side bands
- Experimental and simulation results
- Some details behind the physics of “cyclotron resonance”
- Experimental and simulation results on “cyclotron resonance”
- Plans at ANKA : Support SC undulator research.
- Conclusions

What we mean by "Phase Shift" in Microwave Transmission due to eclouds

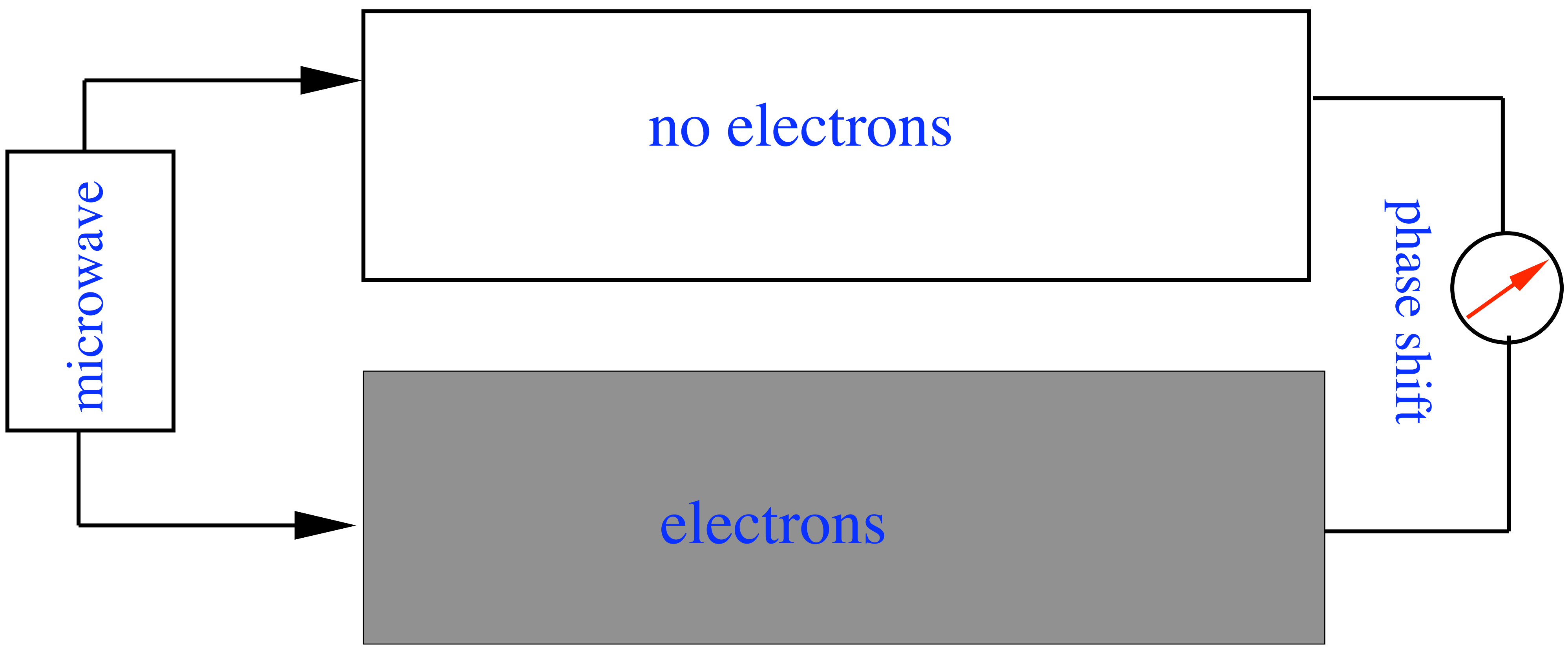


illustration of phase shift due to electrons

$$\sin(\omega t + \phi_1) - \sin(\omega t + \phi_2) =$$
$$2\sin[\omega_1 - \omega_2)/2]\cos[\omega t + (\phi_1 + \phi_2)/2]$$
$$\sim= (\phi_1 - \phi_2)\cos[\omega t + (\phi_1 - \phi_2)/2]$$

This Phase Shift for is simple to derive for unmagnetized plasmas

The dispersion relationship of a wave traveling through a plasma filled waveguide is given by

$$k^2 = \frac{\omega^2}{c^2} - \frac{\omega_p^2}{c^2} - \frac{\omega_c^2}{c^2}$$

where $\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e}$ plasma frequency, $\omega_c =$ waveguide cutoff

The "phase shift" is given by

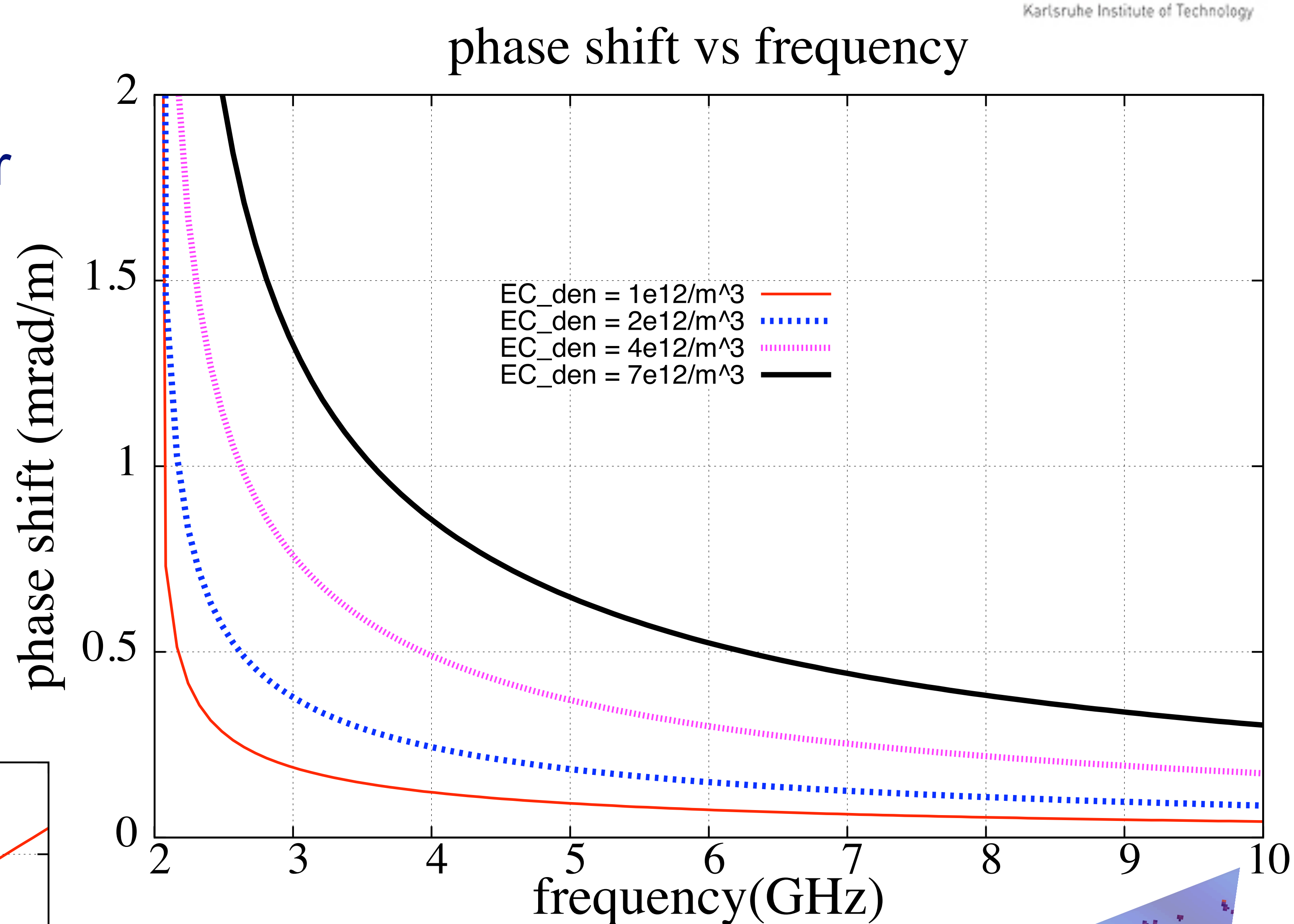
$$\Delta\Phi = [k(\omega_p) - k(\omega_p = 0)]L$$

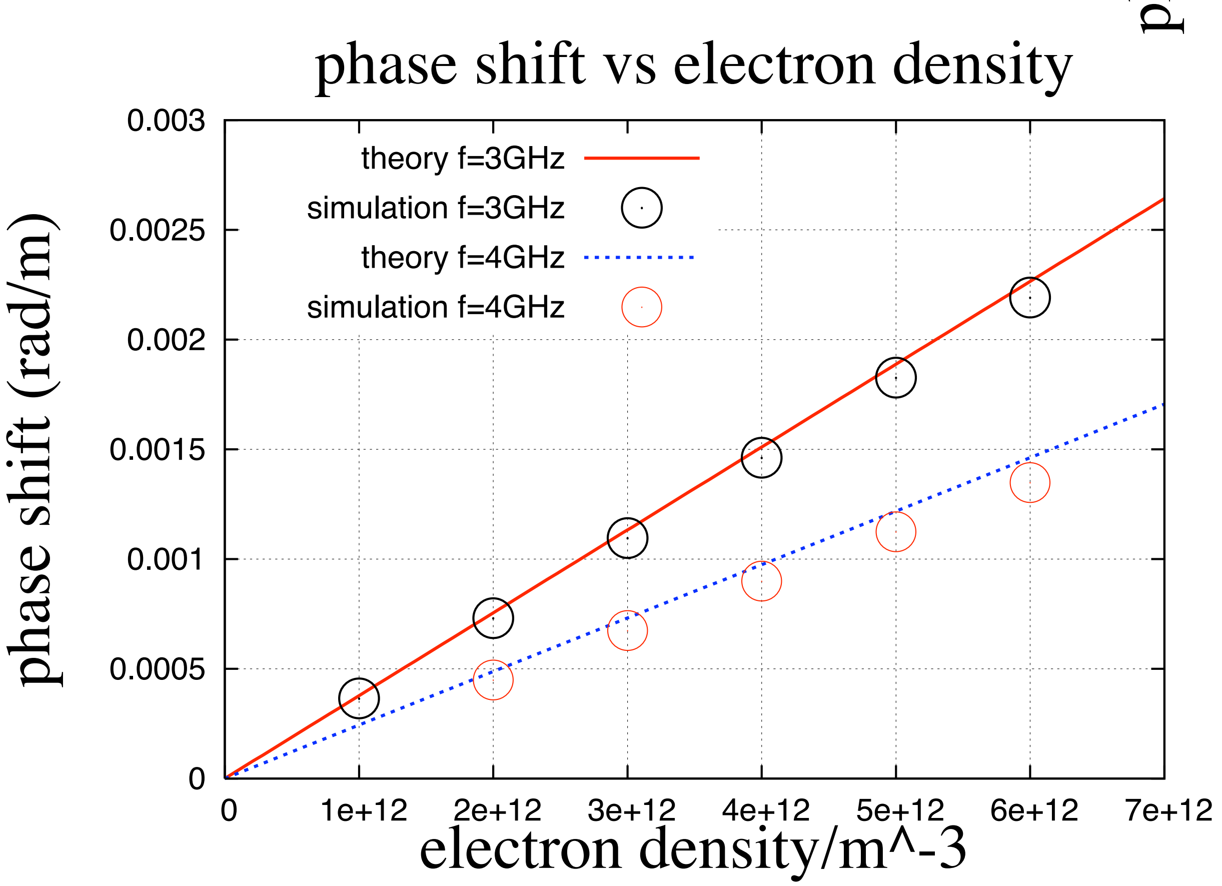
Linearize this about small plasma frequency, then for a unit length

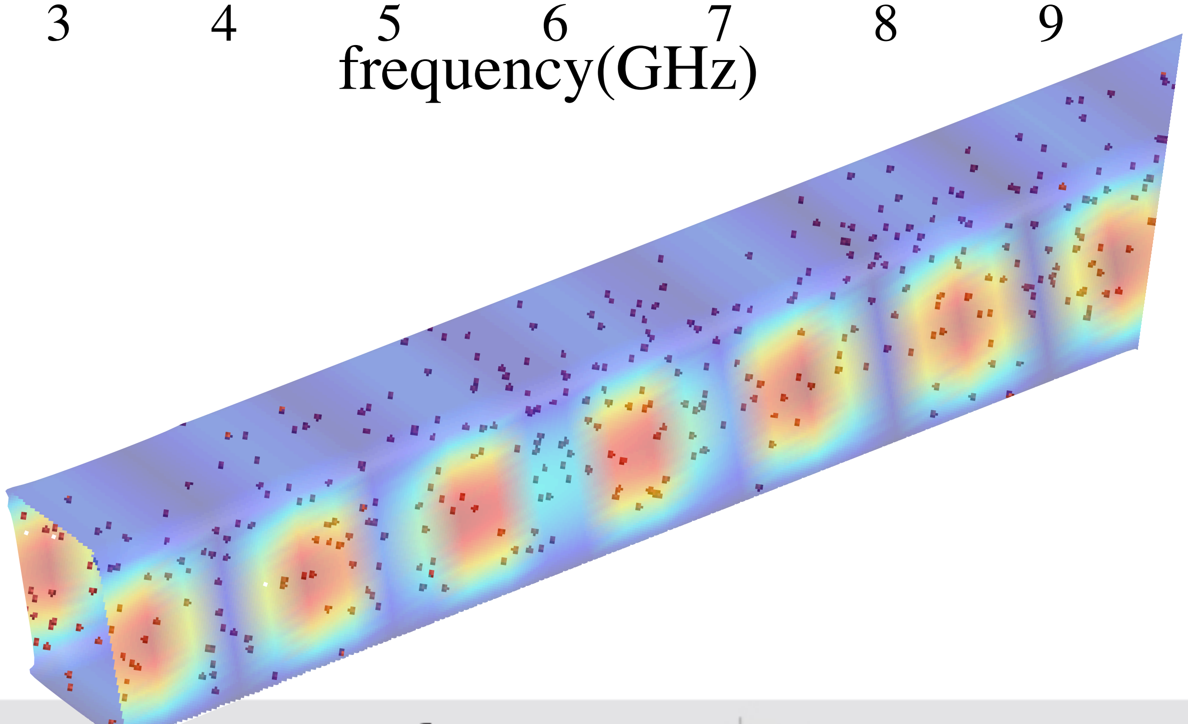
$$\Delta\Phi = \frac{\omega_p^2}{2c(\omega^2 - \omega_c^2)^{1/2}}$$

Analytic results agree with simulations

- Simulations were performed for a rectangular cross section
- They agreed well with analytic estimates of phase shift
- We used the electromagnetic PIC code VORPAL for this.







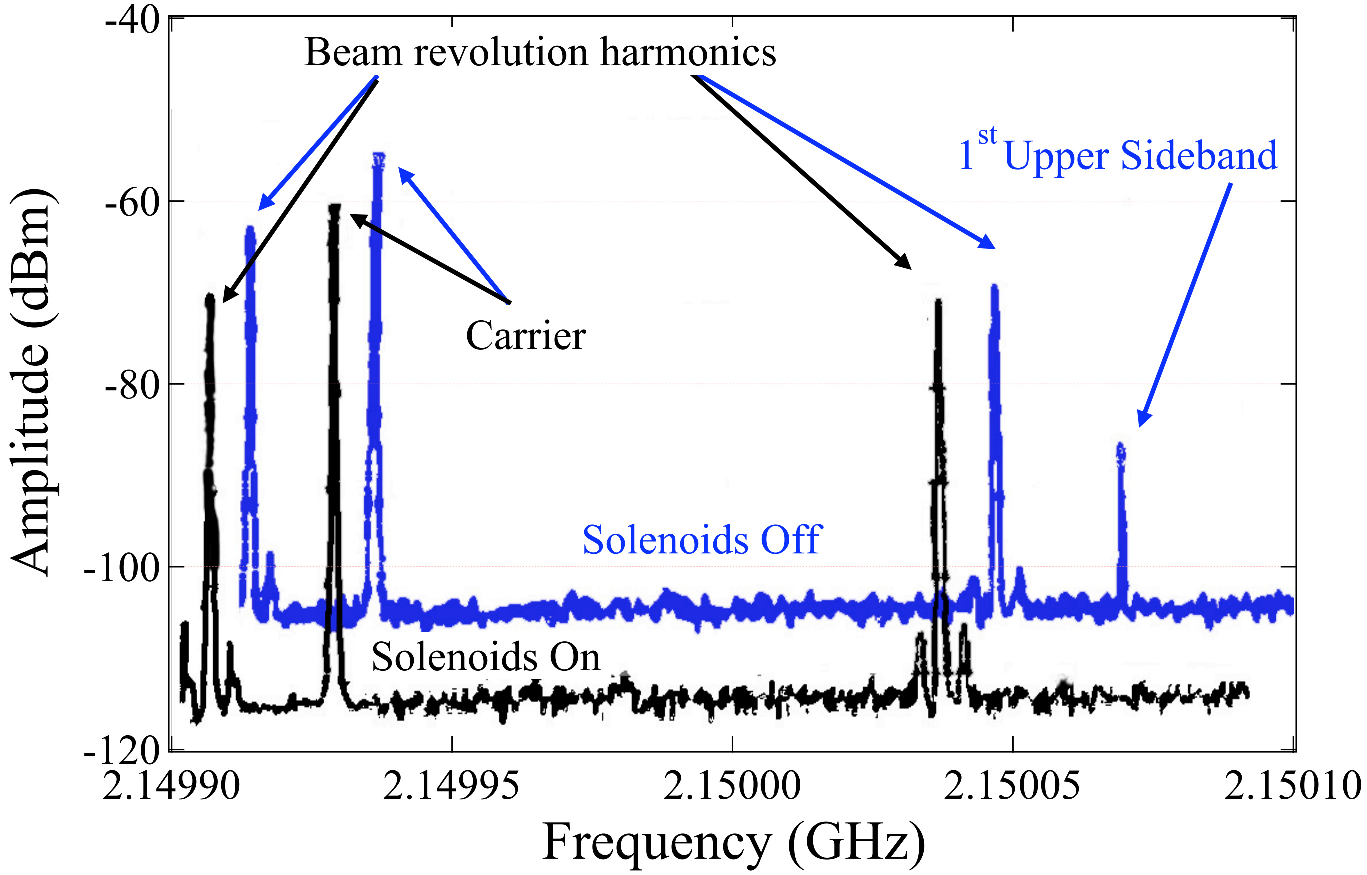
Phase Shift can be observed through "Side Bands" seen on a Spectrum Analyzer

- The gap in the bunch train creates a periodic clearing of the electrons at the revolution frequency.
- This leads to a phase modulation in the microwave signal.
- The phase modulation produces sidebands to the input signal frequency at harmonics of revolution frequency.
- Assuming sinusoidal modulation, we get ....

$$
\begin{aligned}
W(t) &= \cos[\omega t + \Delta\phi \cos(\omega_m t)] = J_0(\Delta\phi) cos(\omega t) \\
&+ J_1(\Delta\phi) \cos[\omega - \omega_m)t + \pi/2) + J_1(\Delta\phi) \cos[\omega + \omega_m)t + \pi/2) \\
&+ J_2(\Delta\phi) \cos[(\omega - 2\omega_m)t + \pi) + J_2(\Delta\phi) \cos[(\omega + 2\omega_m)t + \pi) \\
&+ \ldots \text{ (higher order terms)}
\end{aligned}
$$

- Expect 1st order peaks at higher revolution harmonics as well for non-sinusoidal modulation.

Phase Modulation was observed when electron clouds were present

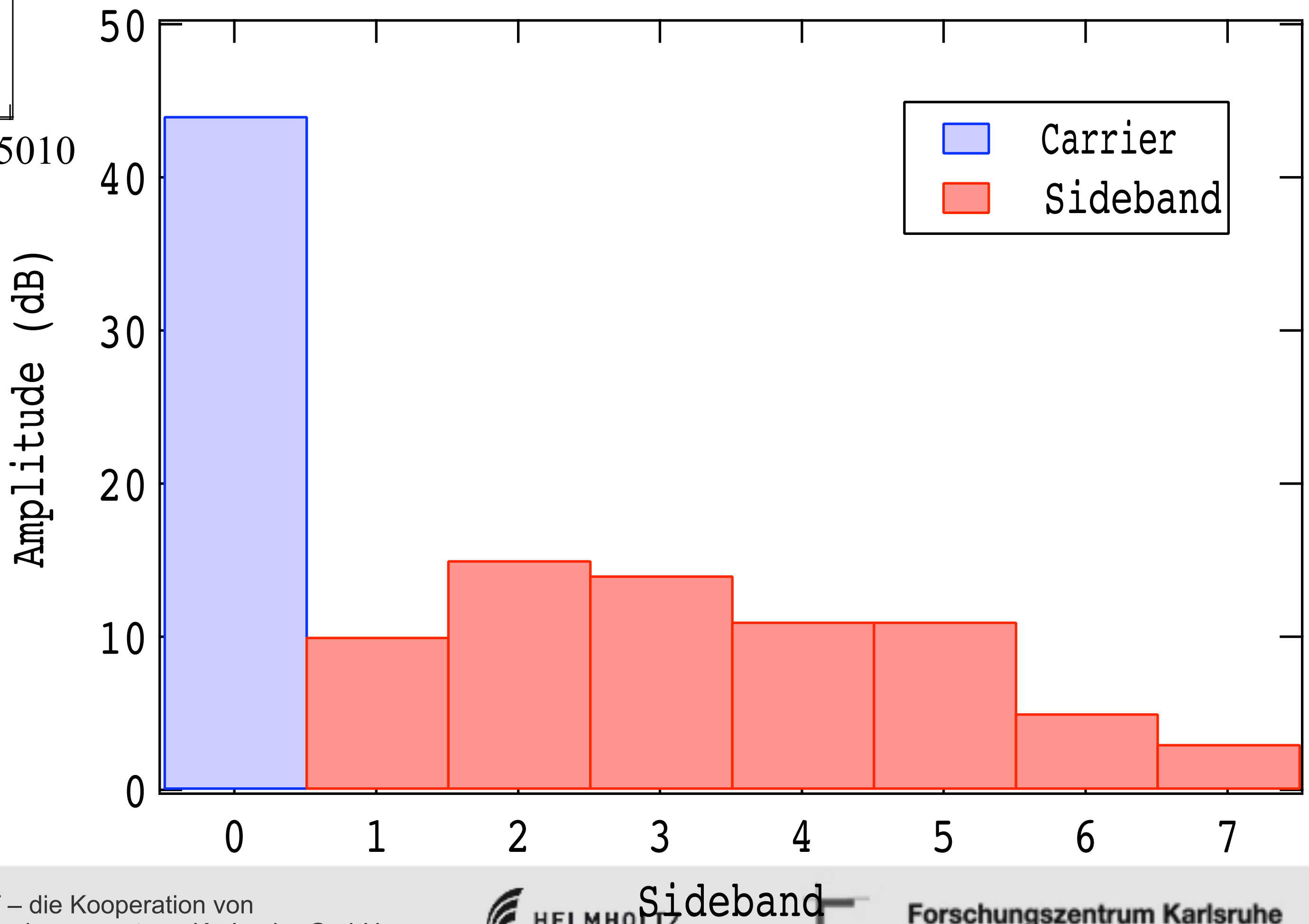


Experiment performed at the PEP II LER at SLAC in a straight section where solenoids were used to suppress electron clouds

Observation of multiple sidebands due to non sinusoidal modulation

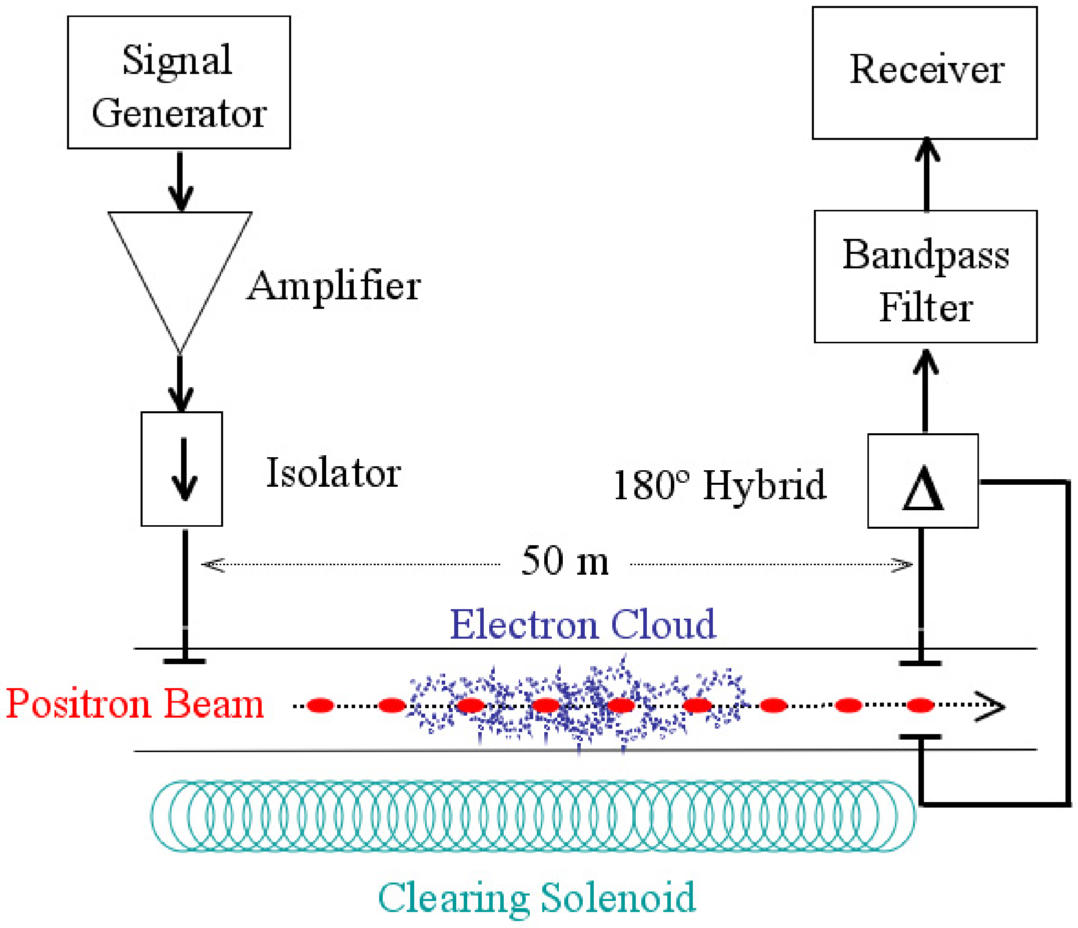
Carrier frequency =~ 2.15GHz
Cutoff frequency =~ 2GHz
Rev frequency 136 kHz (2.2 km)

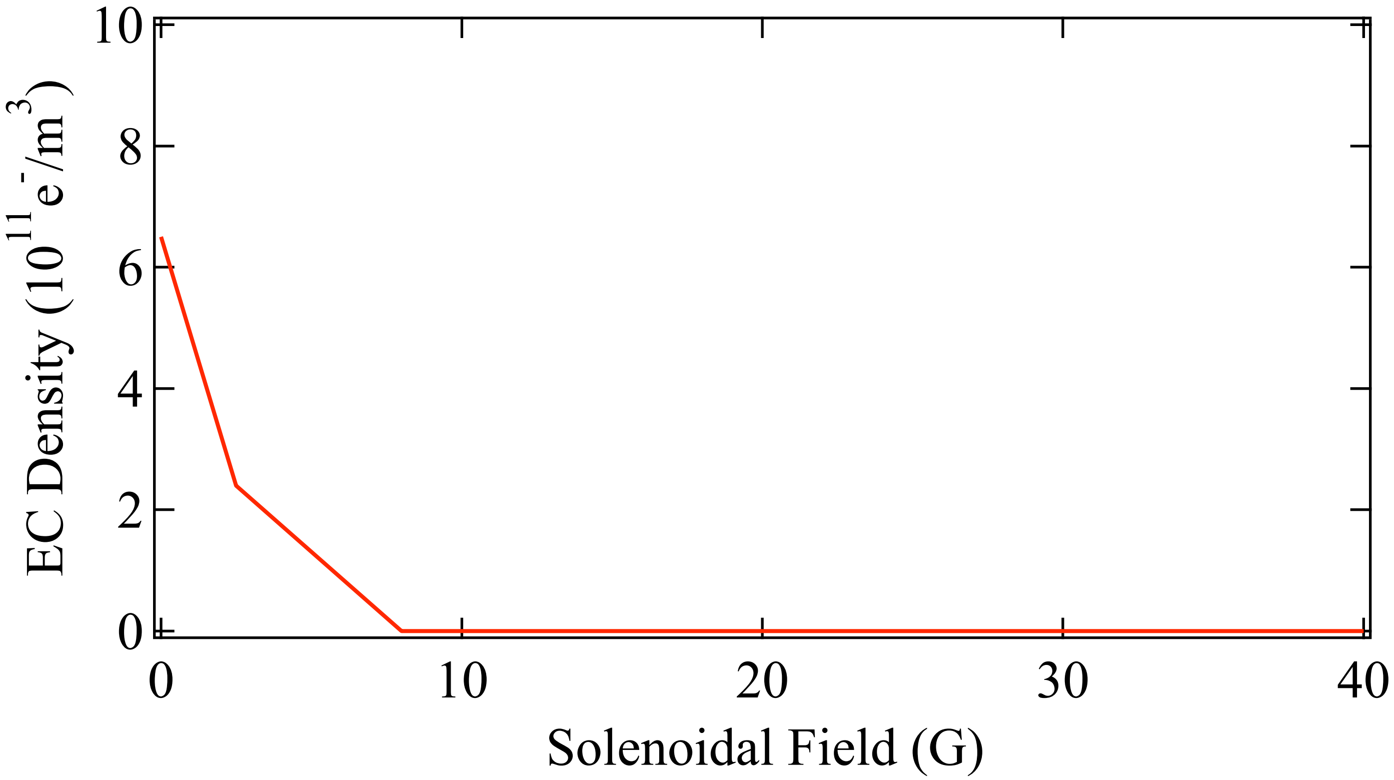
Phys. Rev. Lett. 100, 094801 (2008)



The solenoidal field was used to vary the electron cloud density

bunches ~= 1700 4.2ns apart
gap length ~= 100ns
bunch length = 30-40 ps (rms)
length of transmission = 50m





Estimation of electron cloud using the formula for phase shift (shown earlier) for different solenoidal fields.

Analysis of phase shift for electrons in a dipole magnetic field is more complex

- The wave propagates through an anisotropic medium.
- This can be divided into two components -
  (1) ordinary or O-wave corresponds to the case when the wave electric field is parallel to the external B field and
  (2) extraordinary or X-wave - when the wave electric field is perpendicular to the external B field
- For the O-wave, the external B field plays no role in the wave dynamics. So the dipole field is never noticed
- The X-wave has some "extraordinary" properties - mainly it leads to a the so called "upper-hybrid" resonance.

“Extraordinary waves”, what we understand

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For open boundaries, the wave dispersion relation is well known

$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2(\omega^2 - \omega_p^2)}{\omega^2(\omega^2 - \omega_h^2)}$$

where $\omega_h^2 = \omega_p^2 + \omega_c^2$ is the upper hybrid frequency,
$\omega_c = eB/m_e$ is the cyclotron frequency,
when $\omega = \omega_h, k \rightarrow \infty$ we reach upper hybrid resonance.

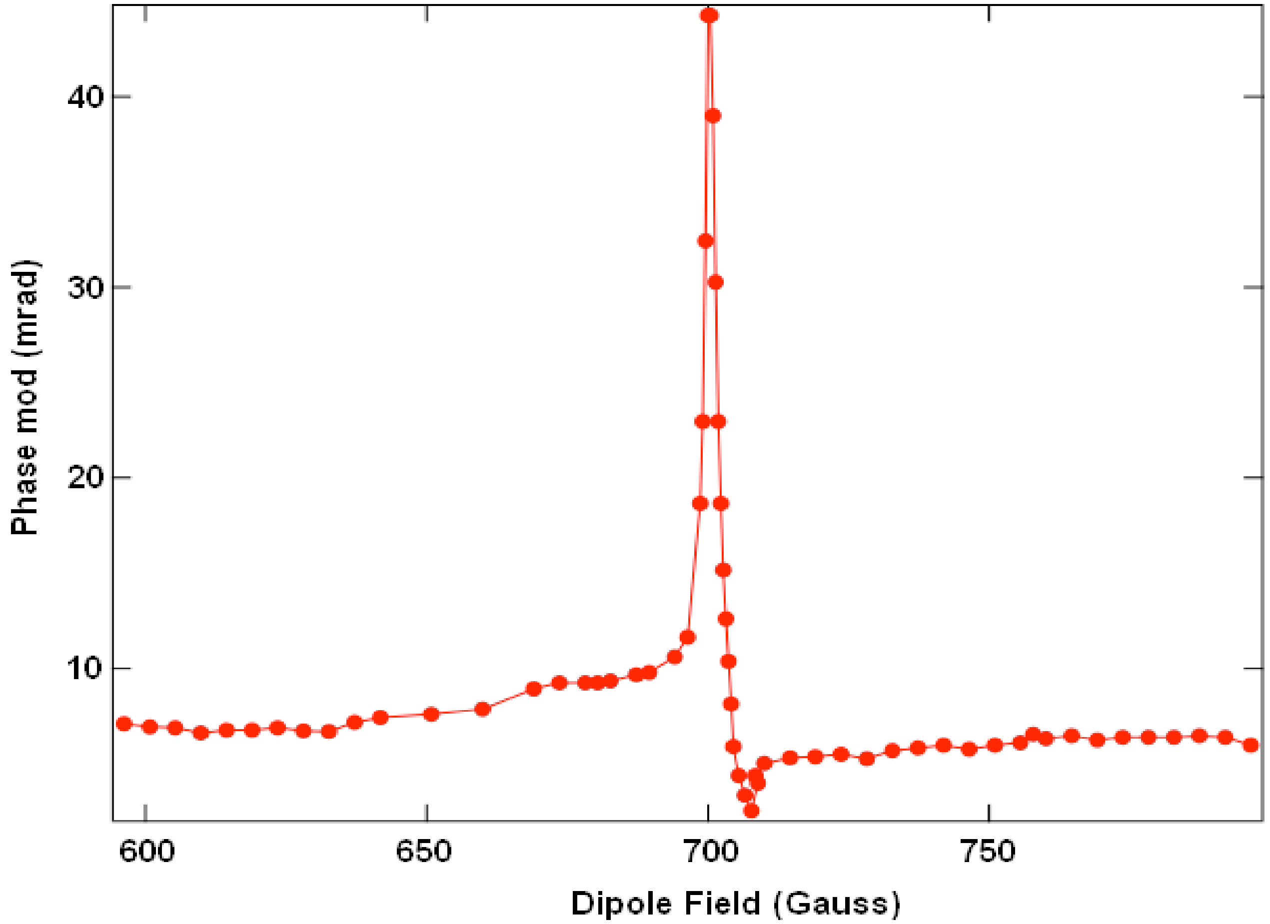
The resonance condition leads, theoretically,
to an infinite phase shift

“Extraordinary waves” , What we don’t understand yet

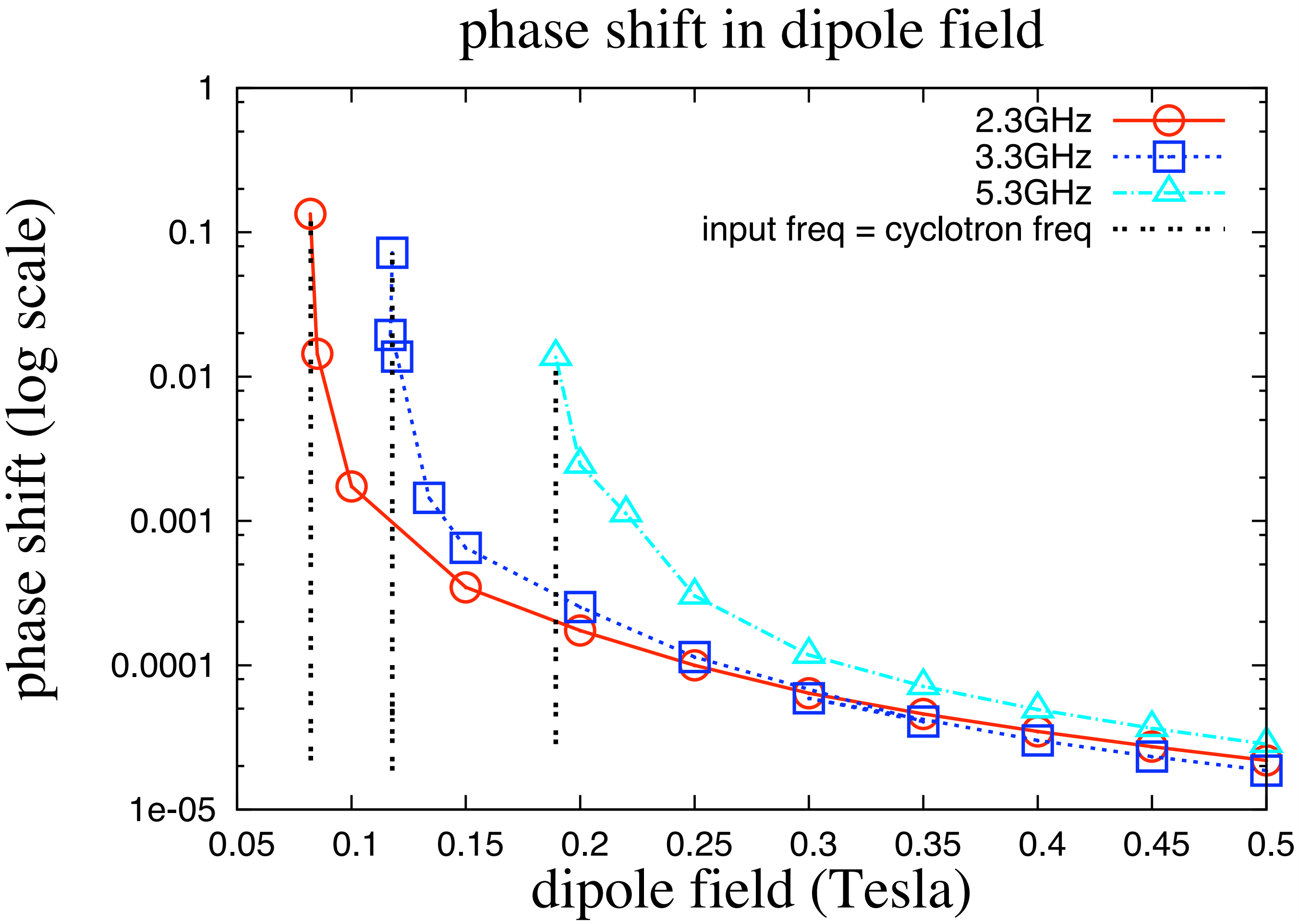
- We don’t have a dispersion relationship for plasma filled waveguides, for the dipole field case as yet.
- It is well known that at upper hybrid resonance, for open boundaries, the wave E field is parallel k.
- However, for a waveguide, simulations and experiments show the presence of resonance for pure TE modes.
- The theory is based on a linearized, cold fluid model. To what extent are these approximations valid?
- Even if we do have a dispersion relation, the X-wave component will need to be isolated from the O-wave in measurements before making a fit to the theoretical relationship.

Simulations and experiments showed the presence of resonance in a dipole field

Large phase shift observed when cyclotron freq = carrier freq



Measured at SLAC PEP II April 3rd '08

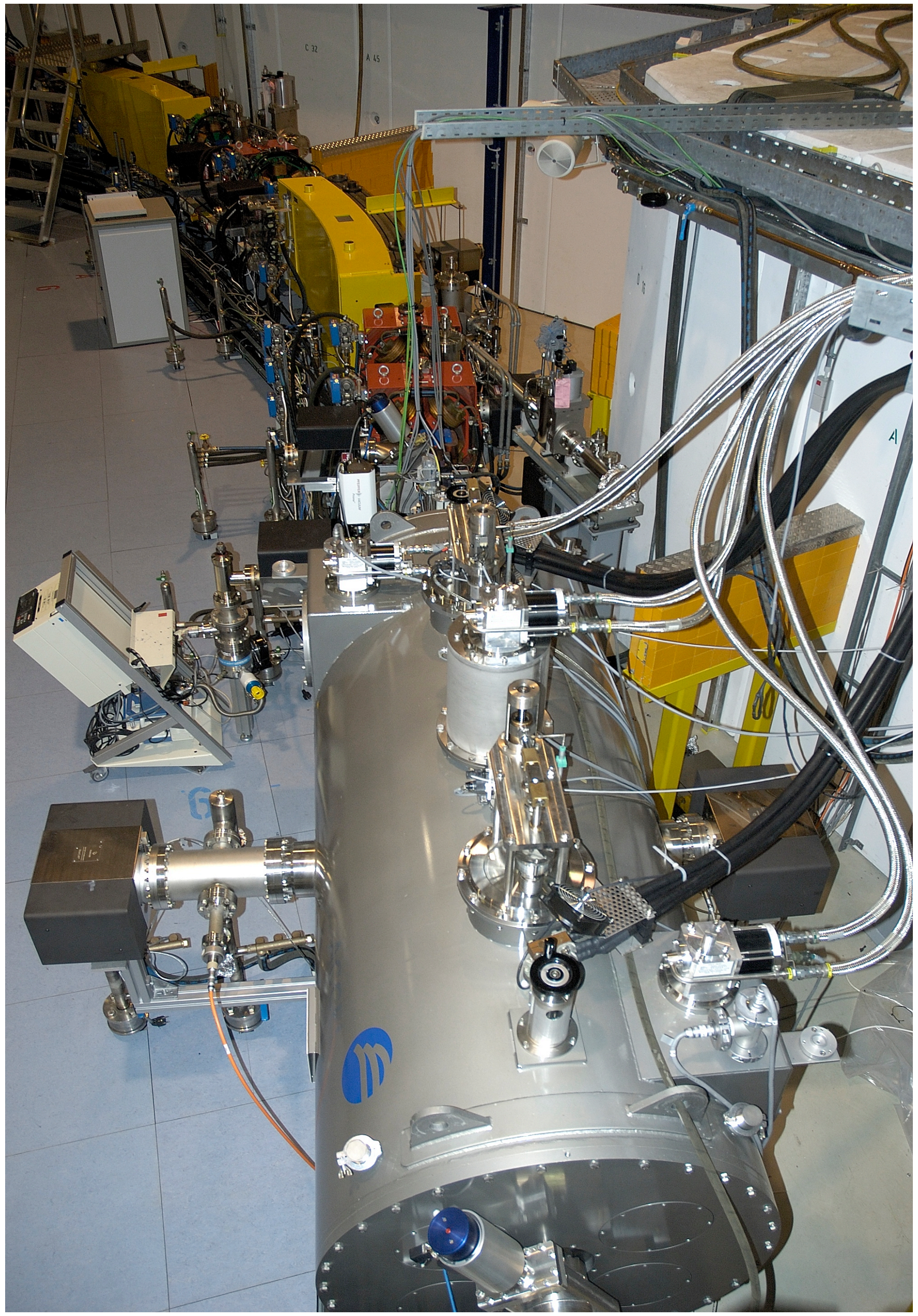


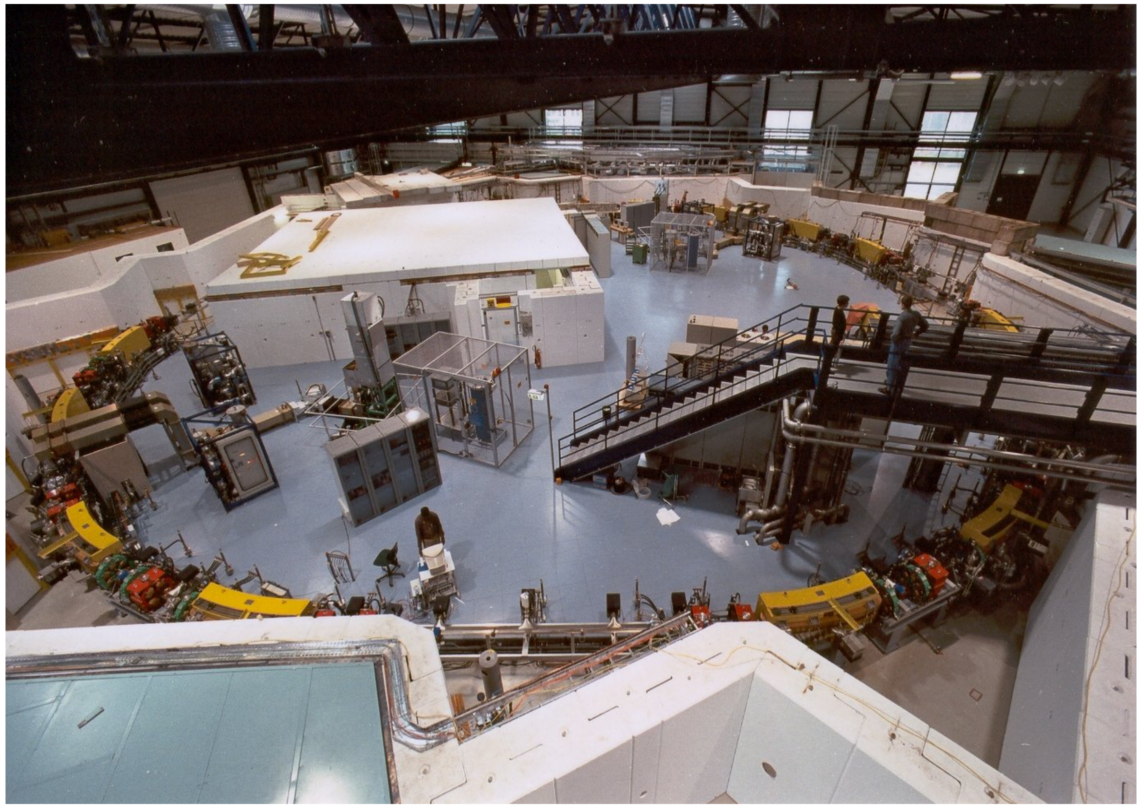
Simulation results using VORPAL

Resonance was seen for TE waves which means wave E field ⊥ k contradicts theory for open boundaries!

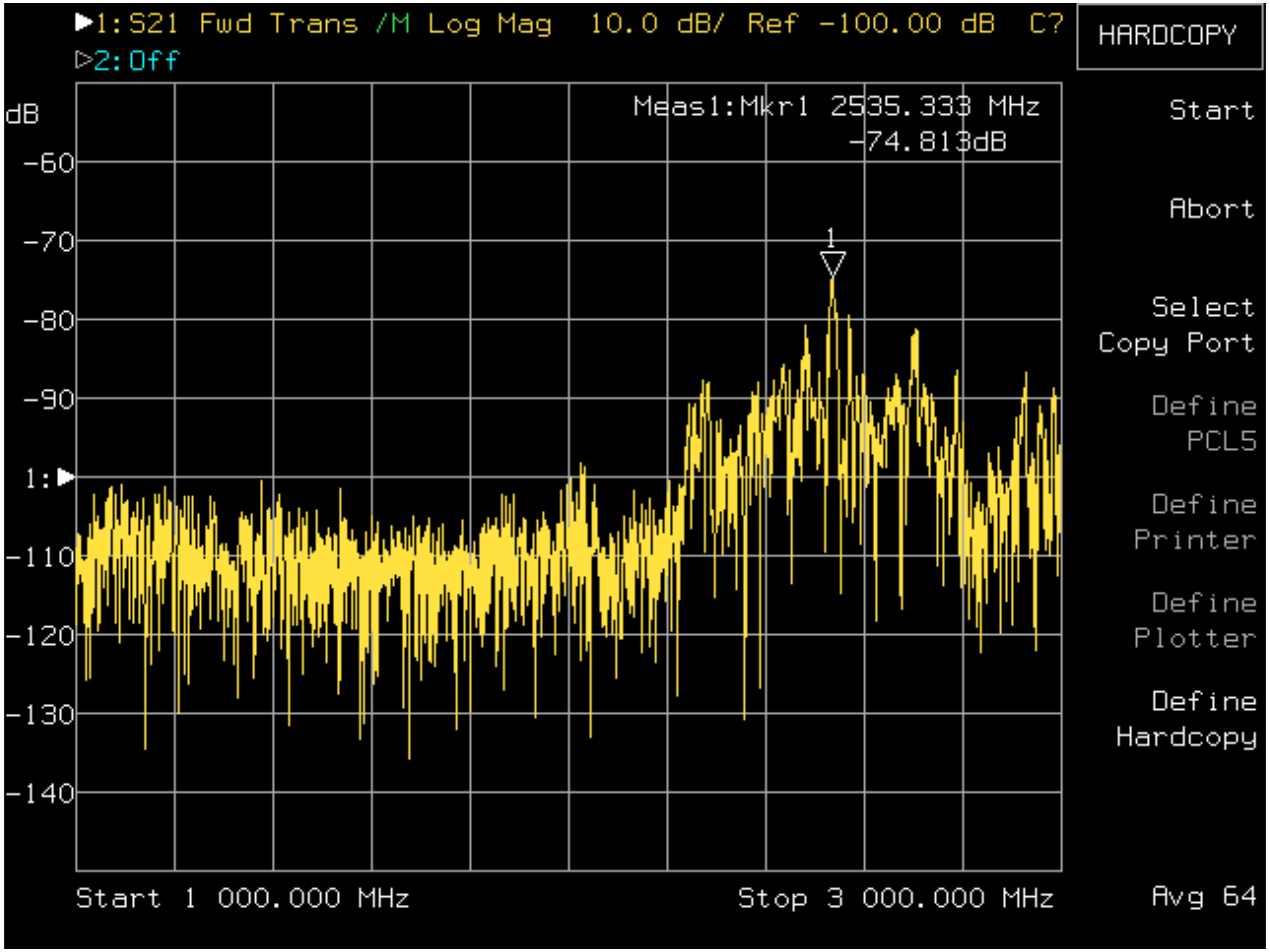
Electron cloud formation is important for super conducting structures.

➡ The effort would support superconducting undulator research (talk by Sara Casalbouni).
➡ EClouds will contribute to heat load.
➡ Our present goal is to make a qualitative diagnosis using the microwave technique.
➡ Estimations on ECloud buildup for this system have been made (talk by Ubaldo Iriso).

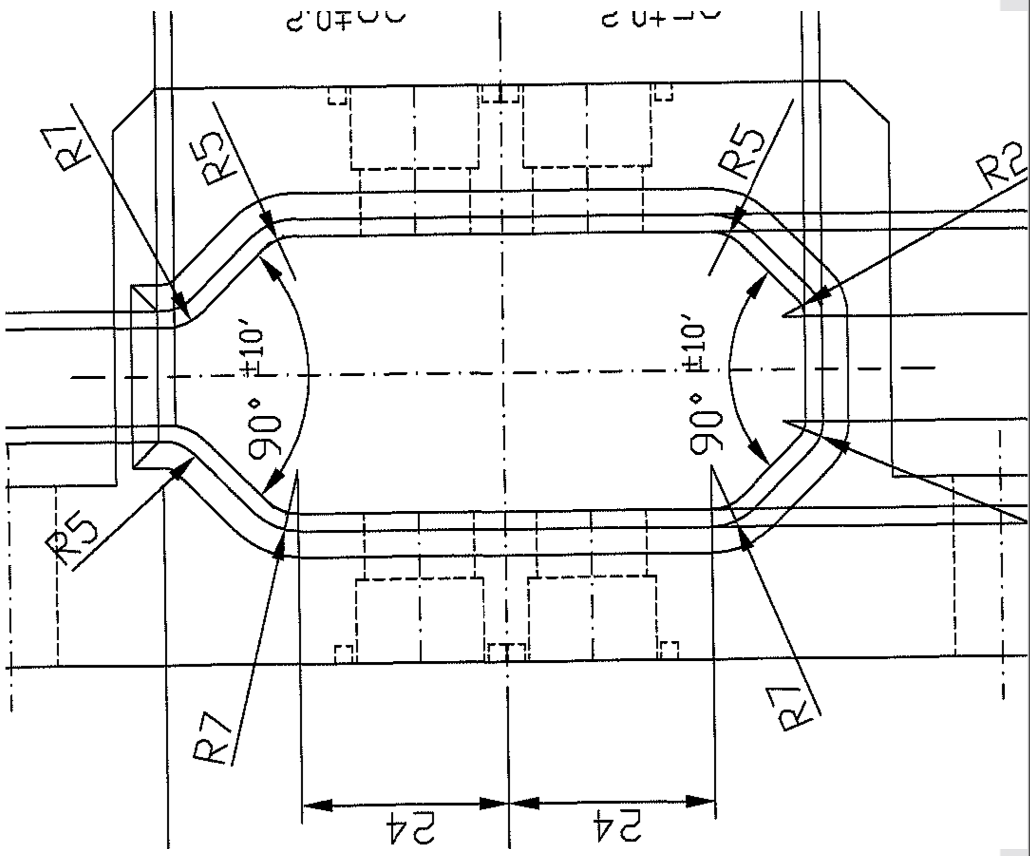




Transmission of signal currently under study



66.2 cm X 8-16mm

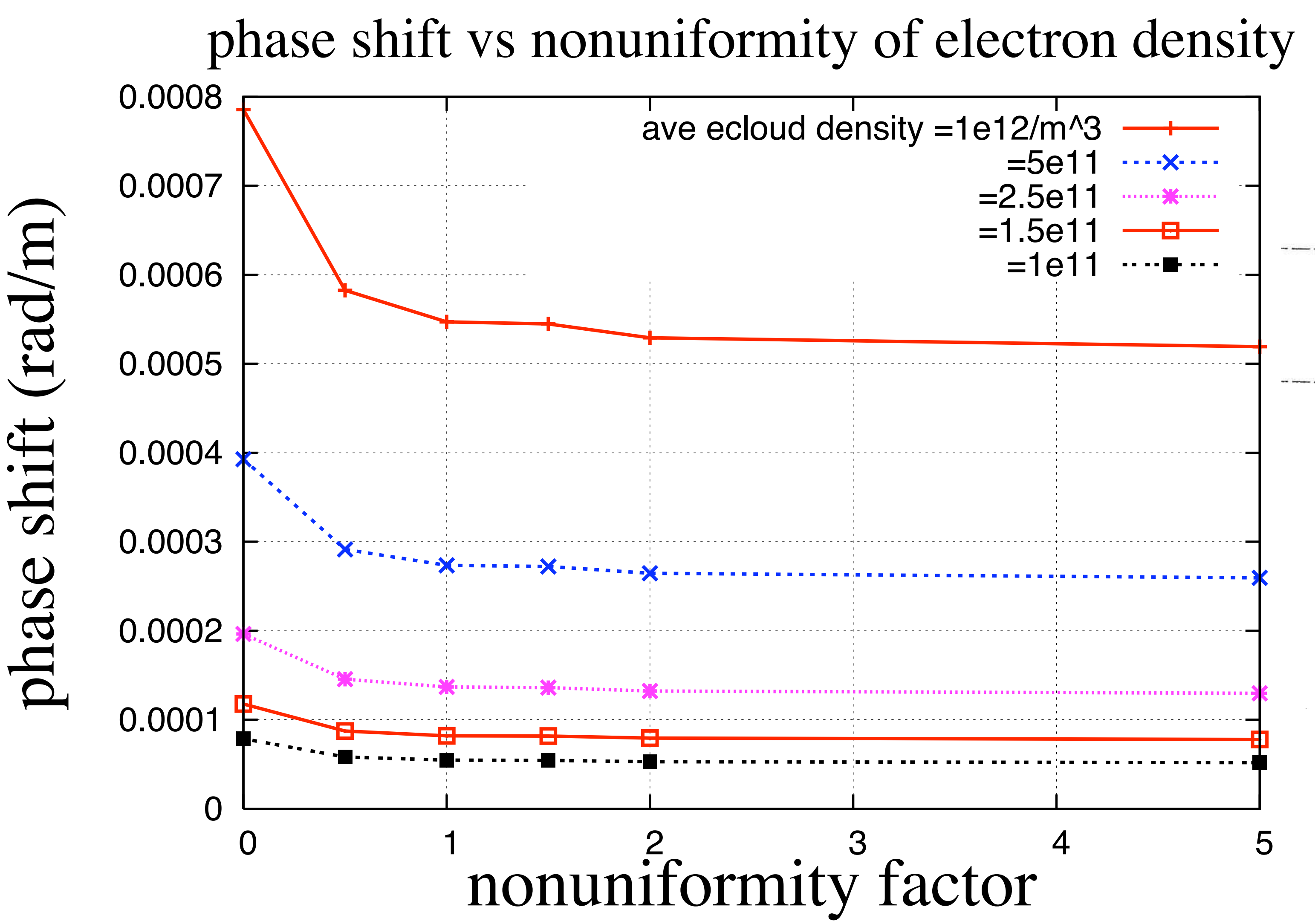


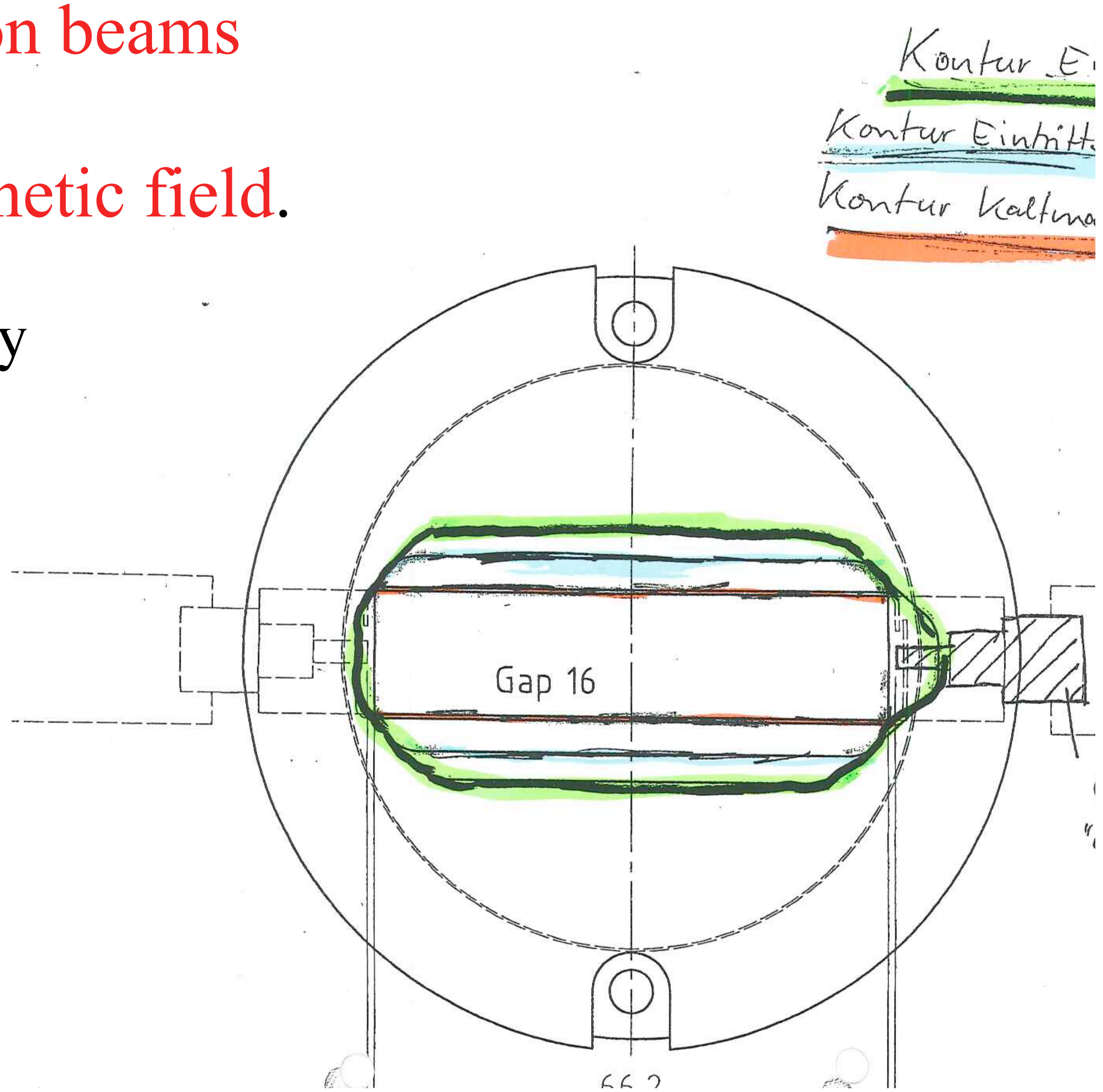
An attempt was made to match the transmission from BPMS into the chamber: D. Saez de Jauregui, R. Weigel etc.

4 BPMs. The one ones on the same side of the chamber were connected and the 2 pairs were used as electrodes. The wave was received on the other end using a similar arrangement

Phase shift does not vanish when electrons are pushed toward the walls

- This is important for EClouds formed in electron beams where you may expect this to be the case.
- Simulations were done in the absence of a magnetic field.





$$\rho(x, y) \sim [1 - \exp(-(x^2 + y^2)/K^2L^2] \text{ where K = "non uniformity factor"}$$

Summary

- Analytic expression for phase shift.
- Simulation and analytic results for phase shift.
- Obsevation of phase shift at SLAC PEP II LER
- Physics associated dipole field : with simulation and experimental results.
- Motivation of this study at ANKA.
- Study of transmission across the undulator chamber.
- Simulated phase shift for different transverse distributons of electrons.