INTERACTIONS OF MICROWAVES AND ELECTRON CLOUDS

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introduction & some history

microwave e-cloud diagnostics at

CERN, PEP II, Cornell, FNAL, ANKA

e-clouds mitigation with microwaves?

simulations

magnetron effect

the „electron cloud varactor“

emission from electron clouds

conclusions

INTRODUCTION

- electron multiplication on surfaces exposed to oscillating electromagnetic field → **multipacting**
- this can affect **radio-frequency accelerating cavities** and also **storage rings**, particularly ones operating with closely spaced positron or proton bunches
- **secondary electron emission, photo-emission** and/or gas ionization → **quasi-stationary 'electron cloud'** inside beam pipe, which interacts with the beam
- well known **effects** of electron clouds:

  pressure rise, coherent **beam instabilities**, interference with **beam diagnostic** monitors, **incoherent particle loss**, **heat load**, **nonlinear mixing** products in satellites (microwave payload)

SOME HISTORY

- **diagnostic of plasma density by means of microwaves** is well known technique since many decades; intensive applications **e.g. in tokamacs**, but there usually operating in the mm wave range due to the high plasma density
- for typical e^- clouds **in accelerators** with $\rho \sim 10^{12}/m^3$, plasma frequency is much lower and thus signal **transmission becomes already possible at ~30 MHz**
- **interesting analogy**: phase and delay modulation of **GPS** (global positioning system) signals passing through the earth's ionosphere where plasma density and frequency range is comparable to accelerators scenarios

THEORETICAL BASICS

Phase shift $\Delta\Phi$ for TEM wave (ω_{rf}) above plasma cutoff (ω_p=plasma frequency which contains the plasma density) without static magnetic field over the length L (c=3 10^8 m/s)

$$\Delta\phi = -1/2\,\omega_p^2 / \left(\omega_{rf}\, c\right) L$$

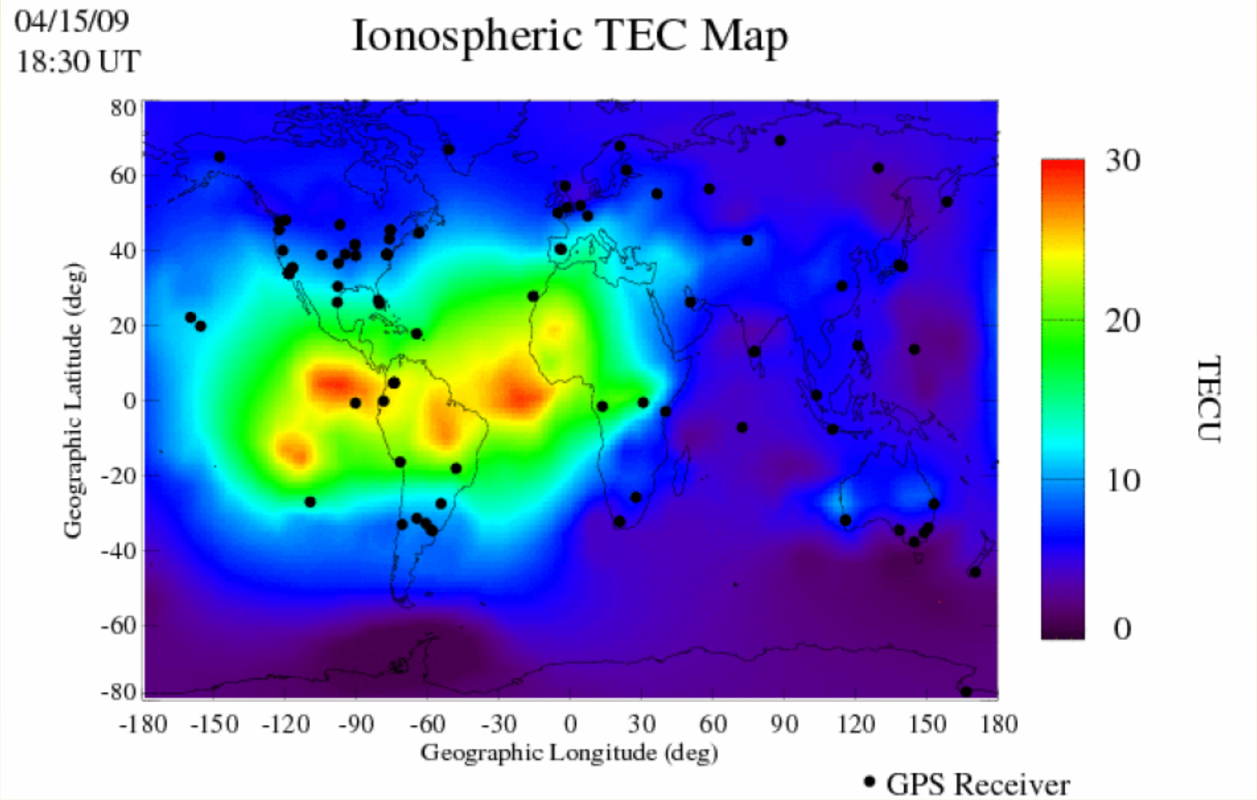
For TEM waveguide mode propagation with ω_c=waveguide cutoff frequency:

$$\Delta\phi = -1/2\,\omega_p^2 / \left(\sqrt{\omega_{rf}^2 - \omega_c^2}\, c\right) L$$

With static magnetic field B perpendicular to beampipe axis and aorthogonal to the transverse electric field component of the waveguide mode, a strong signal enhancement related to the cyclotron frequency (28 GHz/Tesla) appears which is proprtional to (m_e= electron mass): $1/\left(1-\left(eB/\left(\omega_{rf}\, m_e\right)\right)^2\right)$

IONOPHERIC DELAYS FOR GPS

over roughly 500 km of ionospheric propagation the measured delay variation is about 1 meter corresponding to a phase shift of 4 degree/km



TEC is defined as the number of free electrons along the ray path above one square meter on the ionosphere and its unit is represented as TECU (1 TECU = 10^{16} e^{-}/m2)

TEC=total electron content

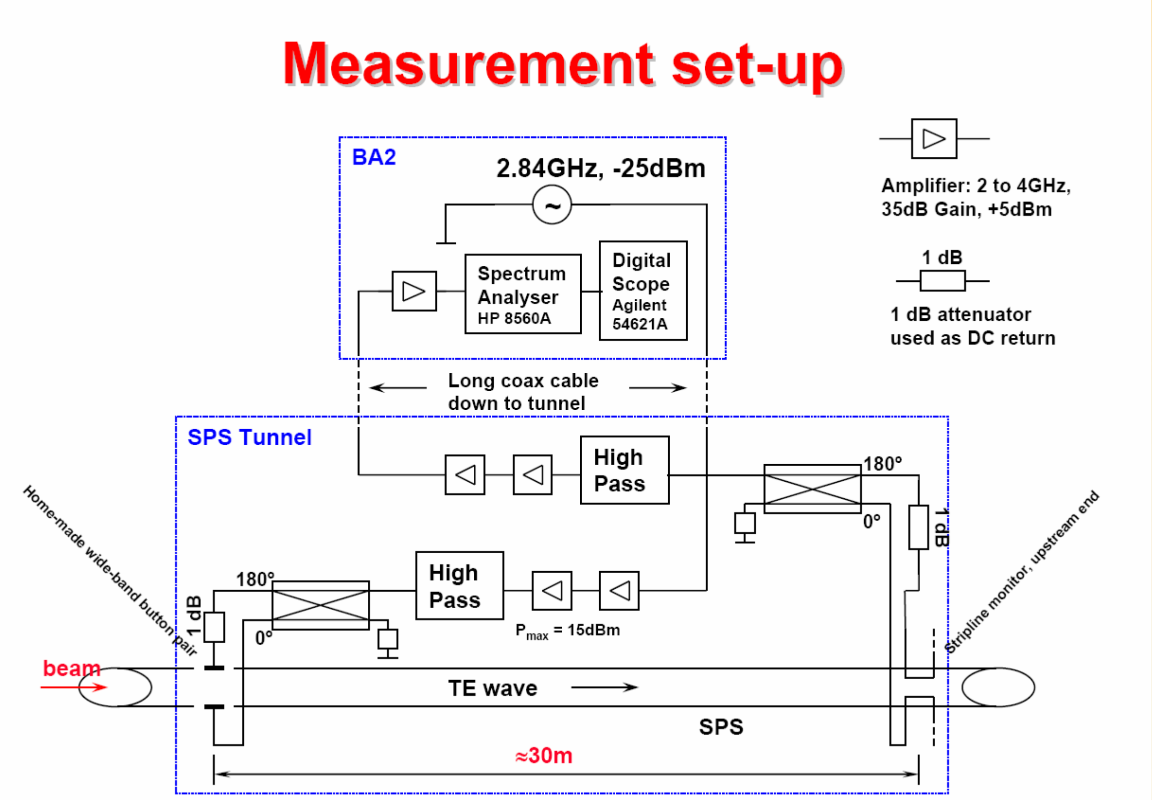
TECU= TEC unit

This phenomenon is often referred to in the context of

SPACE WEATHER

http://iono.jpl.nasa.gov/latest_rti_global.html

MICROWAVE E-CLOUD DIAGNOSTIC EARLY EXPERIMENTS AT CERN (2003)



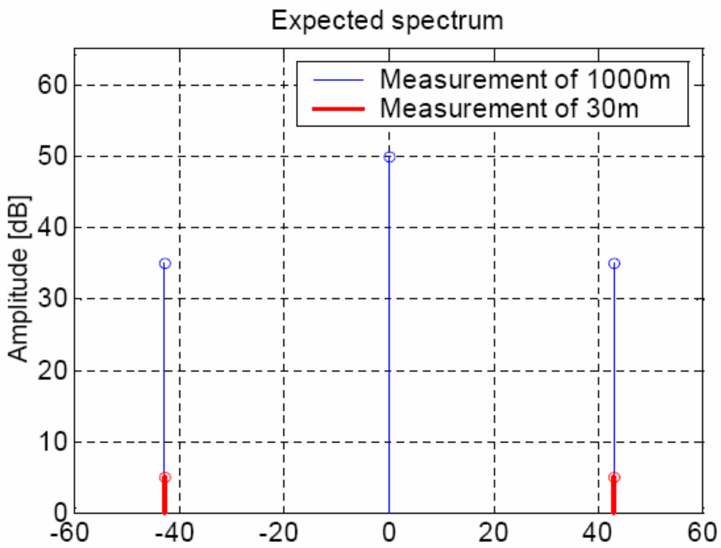
This first setup had a conventional spectrum analzyer with a digital scope connected to the (rear) IF output for time resolved signal acquisition

At that time it was believed that simple high pass filters around 2 GHz would be good enough to get rid of all the remaining coherent signals. However **signal compression by front end amplifer saturation turned out to be a VERY important issue**

due to the fact that e^- cloud builds up over a batch and thus leads to FM modulation sidebands at f_{rev} above and below CW carrier (2.84 GHz here) **we can easily measure phase modulation in the order of milli-degrees**

MICROWAVE E-CLOUD DIAGNOSTIC EARLY EXPERIMENTS AT CERN (2003) ESTIMATION OF SIGNAL STRENGTH

- Measurement between 2 and 3GHz over 1km
- No amplitude modulation expected, just a
- Phase modulation of roughly 20 degrees
- This should give sidebands 15dB below the carrier when measuring over 1km



CW signal in the center

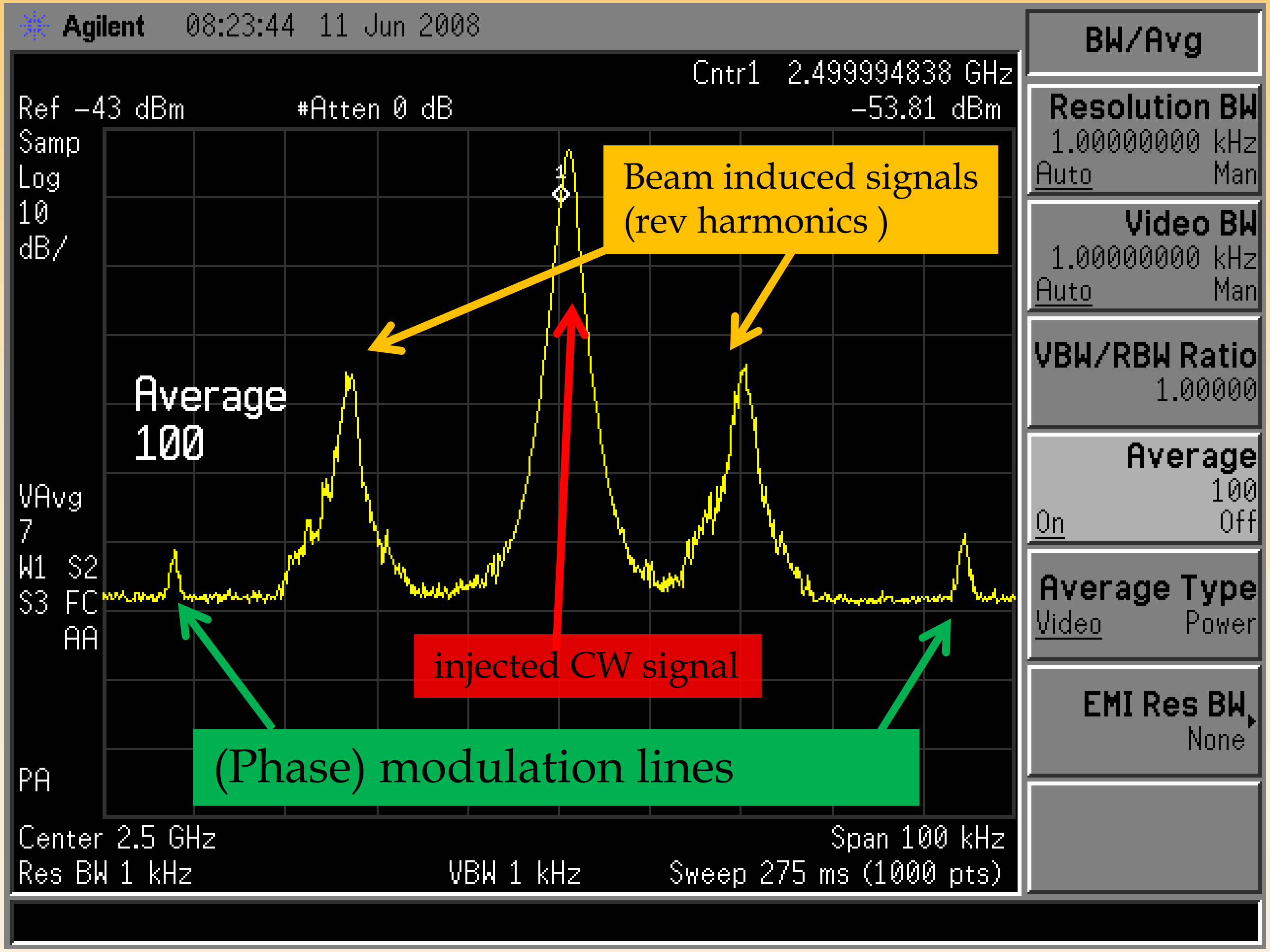
Length of line L [m]	Phase change $\Delta\varphi$ [°]	Modu-lation index β [1]	Side-band amplitude A_{sb} [dB]
1000	20	0.35	-15
30	0.6	0.01	-45

Modulation index $\beta = \Delta\varphi$ [rad]

Side-band amplitude = $\beta/2$

with 44 kHz revolution frequency (CERN-SPS) we expect sidebands at ± 44 kHz; a sensitivity of better -80 dBc is possible

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT CERN (2008) SPS –BA5

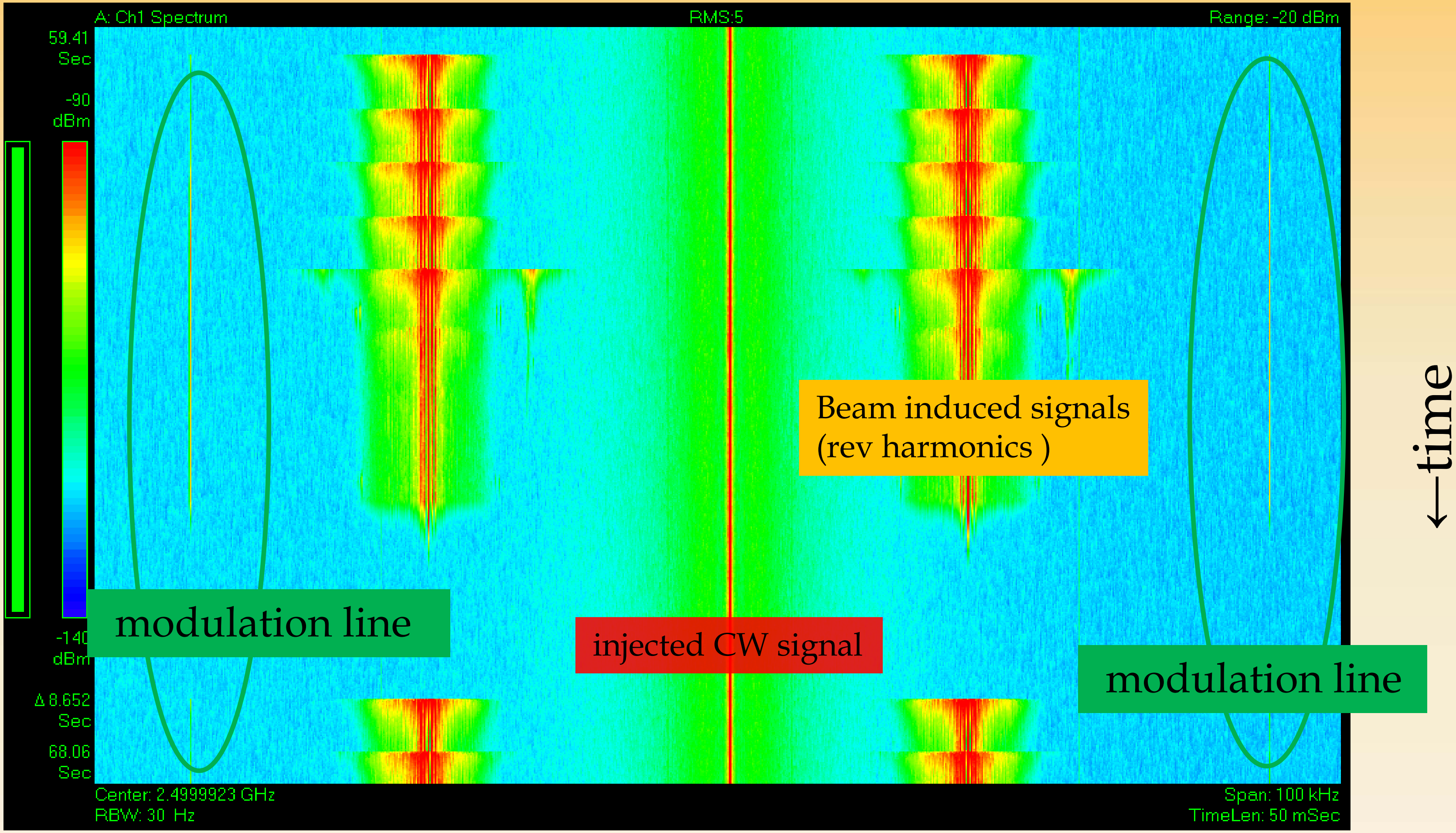


Improved setup with narrowband filters (40 Mhz BW) Display from a conventional spectrum analzyer.

The phase modulation is in the small peaks, which are +/- 44 kHz (=f_{ref}) away from the center.

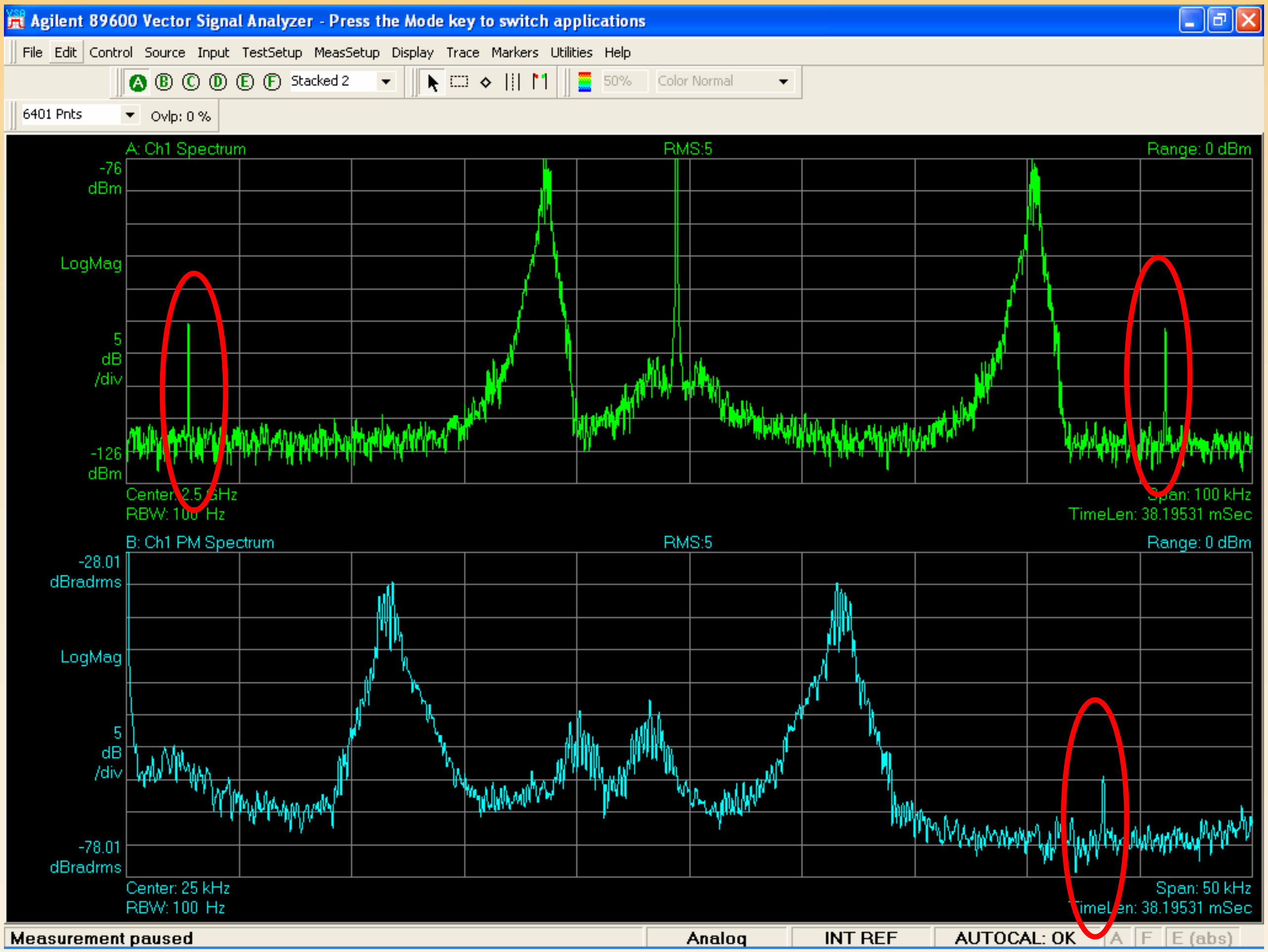
The beam induced signal are the two bigger peaks next to the center line.

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT CERN (2008) SPS –BA5 SPECTROGRAM DISPLAY



key question: is faint modulation line ONLY phase modulation?

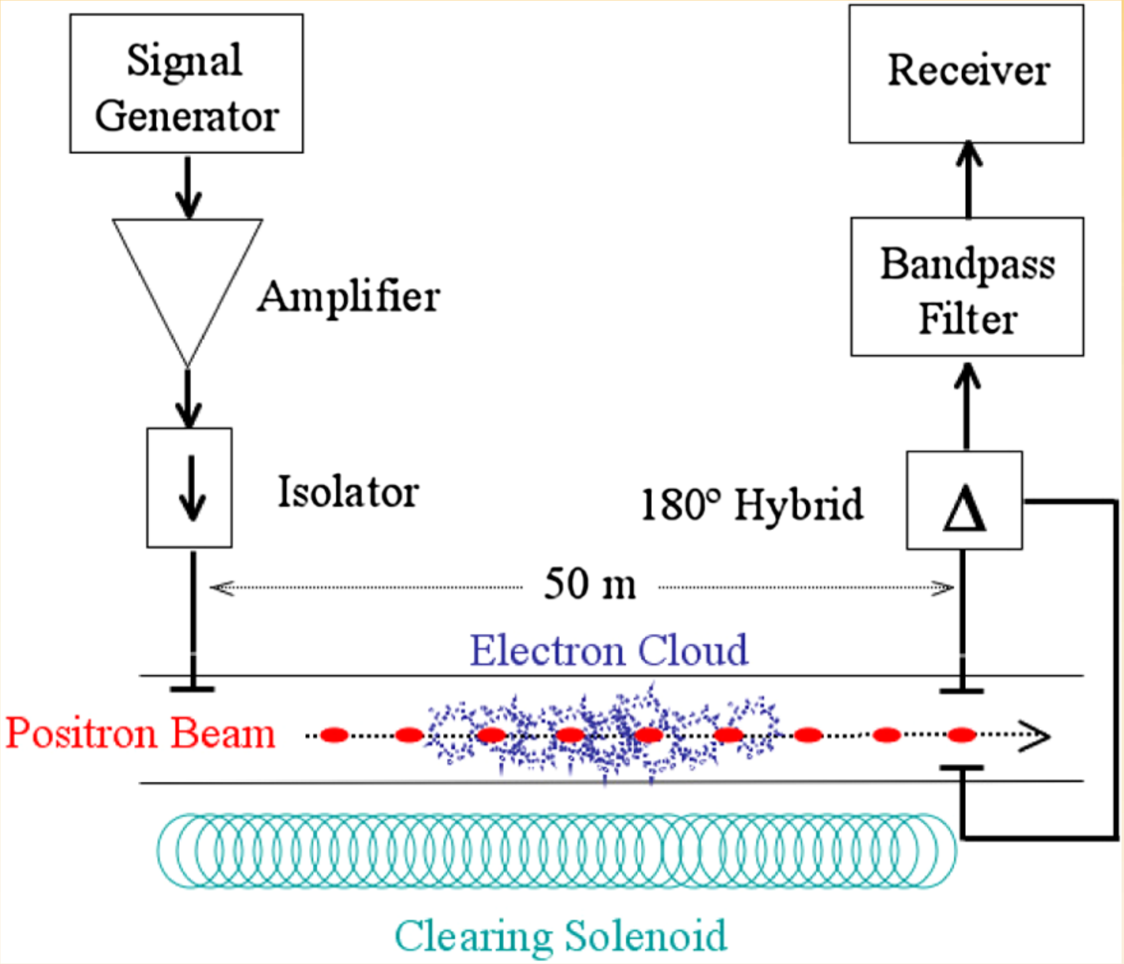
MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT CERN (2008) SPS –BA5 SPECTROGRAM DISPLAY: DEMODULATION MODE



Applying the demodulation function we can clearly see the **AM contamination**

Only the small peak on the lower (blue)trace is really phase modulation; **most of the signal in the upper trace is AM and thus originates most likely from signal compression in the front end electronics**

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT PEP II SINCE 2006 (1)

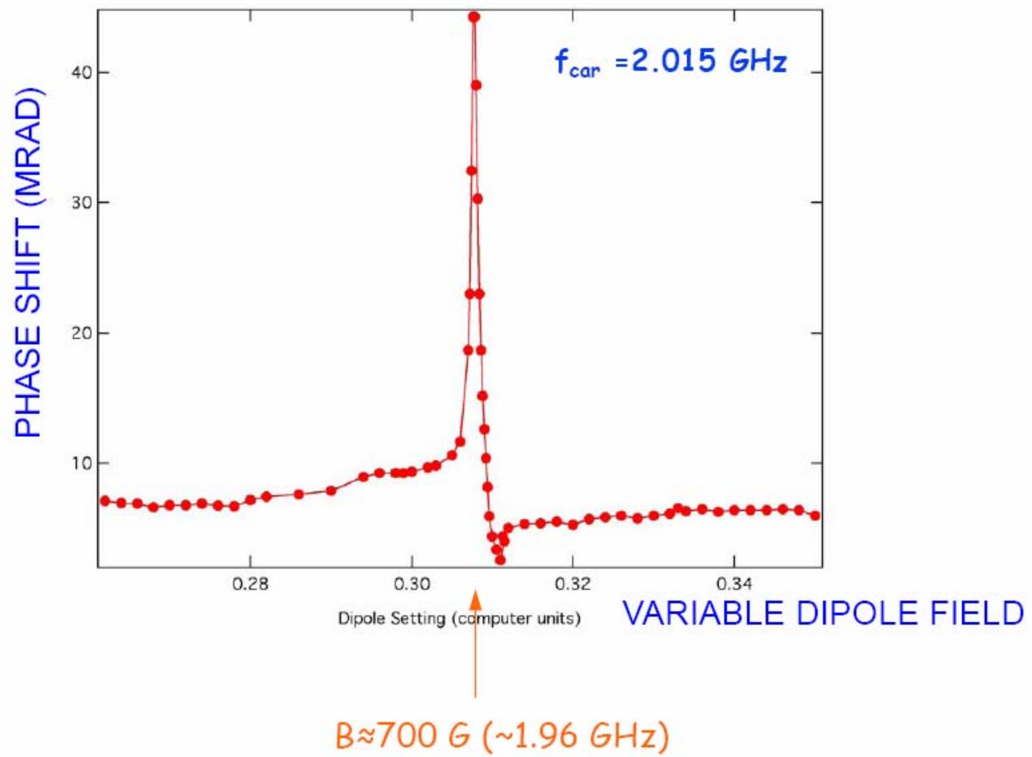


PEP II has the big advantage of **a 50 meter long drift space where the electron cloud can be turned ON and OFF** by just powering a long solenoid to create a field of about 20 Gauss

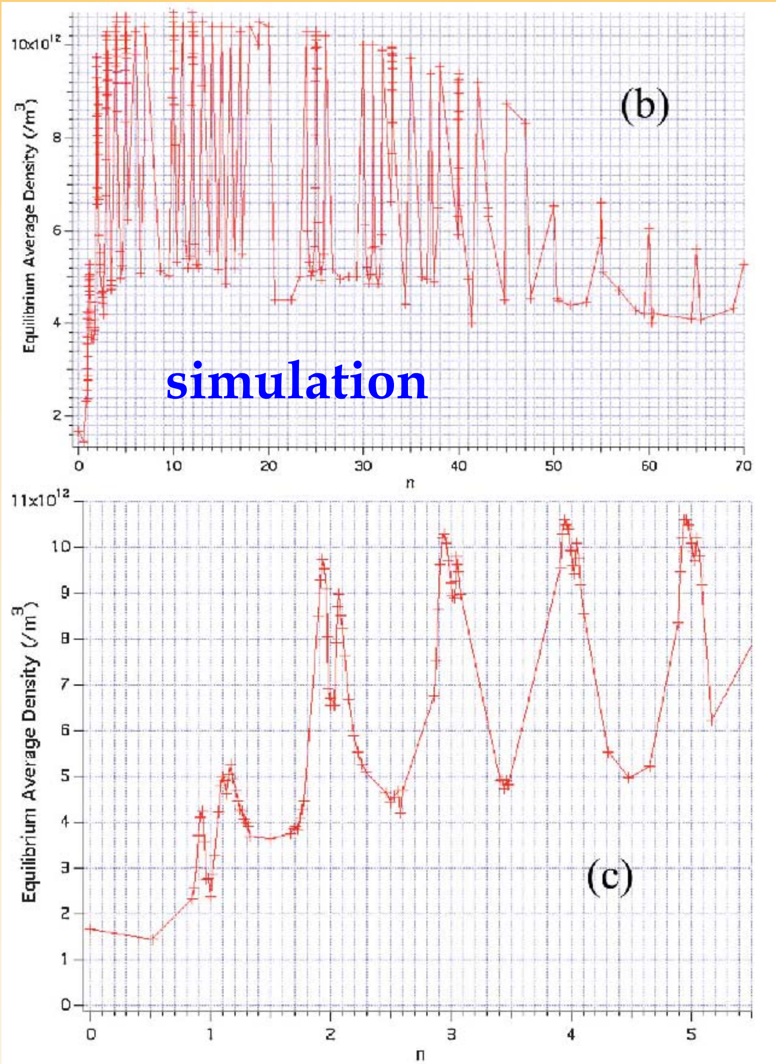
MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT PEP II SINCE 2006 (3) IMPACT OF THE CYCLOTRON RESONANCE

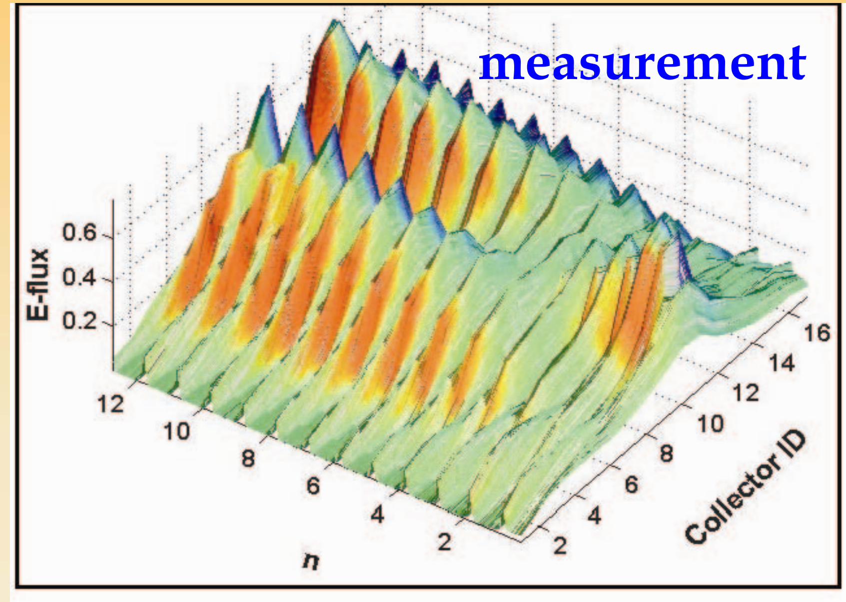
Cyclotron resonance PEP-II LER Chicane

Measured !



LBNL SIMULATIONS AND PEP II EXPERIMENT REVEAL RESONANCES BETWEEN CYCLOTRON MOTION AND BUNCH SPACING





Courtesy: Mauro Pivi

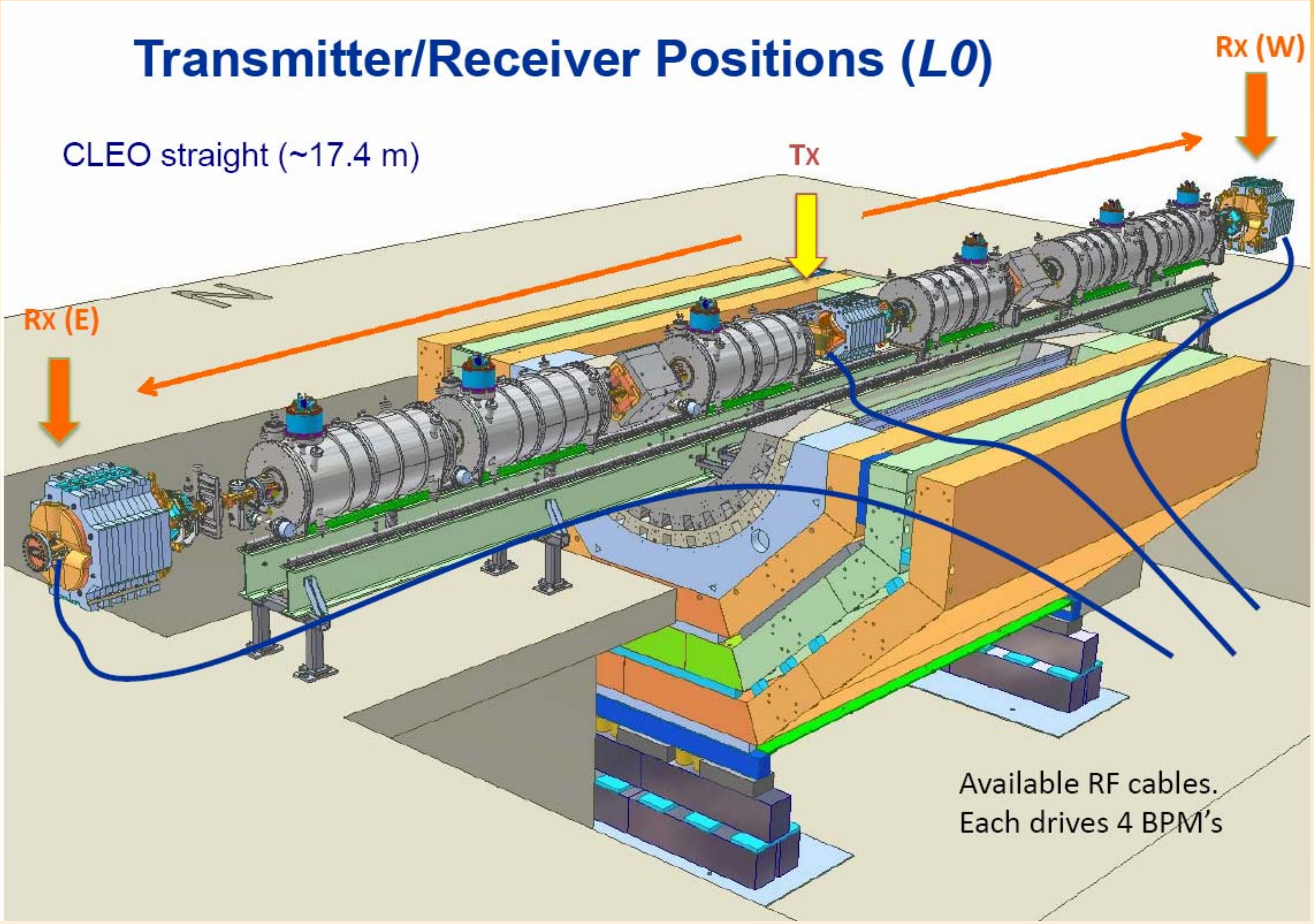
Courtesy: Christine Celata

with short e+ bunches passing through magnetic dipole field, **resonances in cloud build up** when:

bunch spacing =n x cyclotron period

question: can one measure microwave signals caused by the cyclotron motion?

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT CORNELL SINCE 2008 (1)

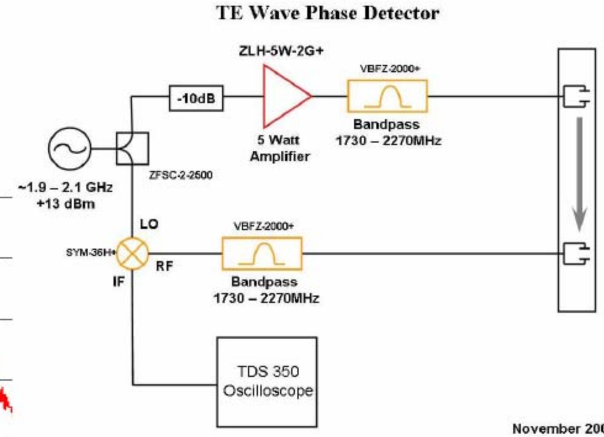


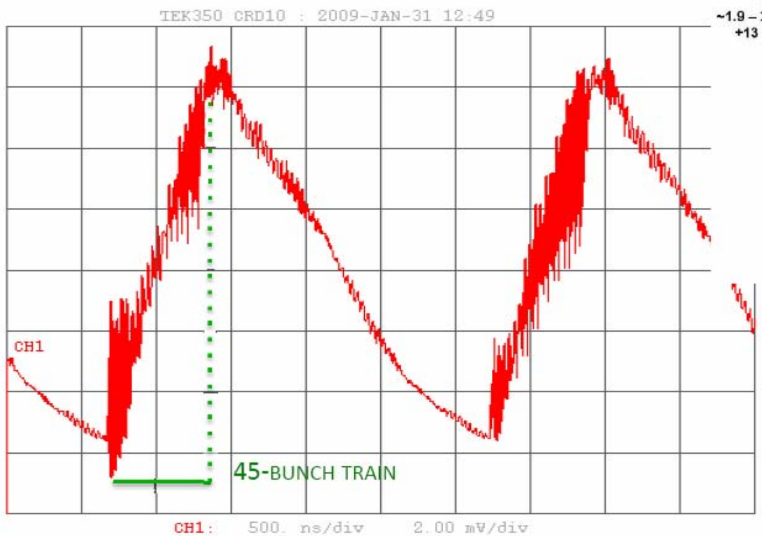
Courtesy: Stefano de Santis

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT CORNELL SINCE 2008 (2)

PHASE MEASUREMENTS WITH HIGH TIME RESOLUTION

Phase detector (L0 – central BPM)





hor. axis = 500ns/div
ver. axis = relative units
in terms of phase shift

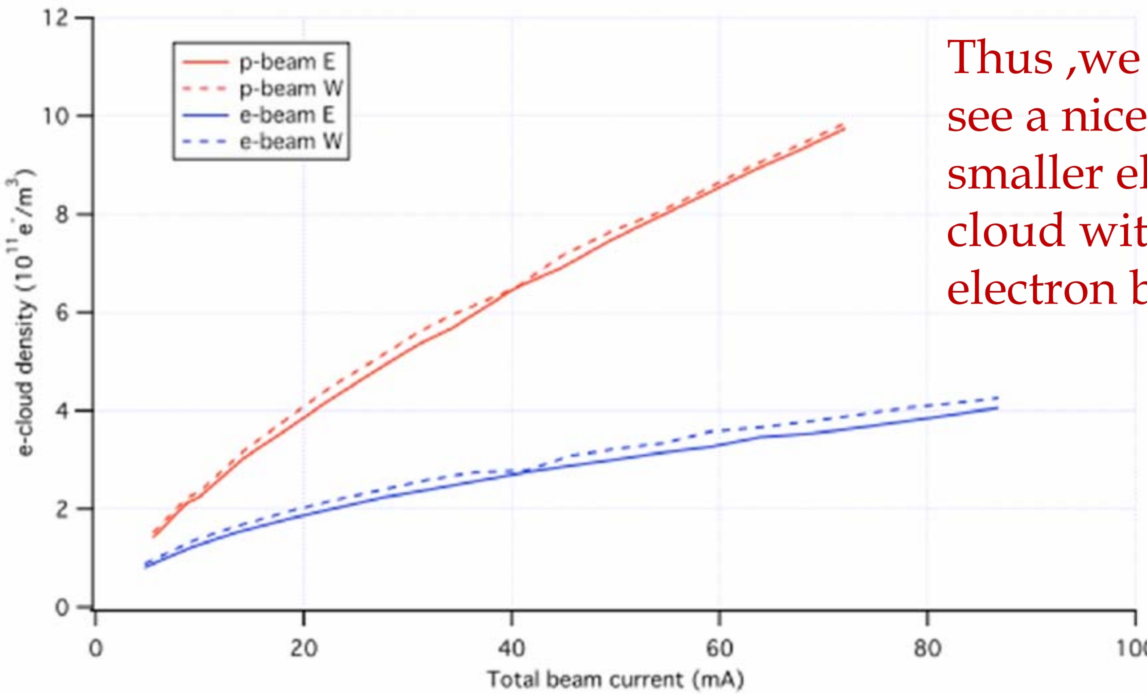
Phase shift dependence on beam current suggest electrons might reach higher densities near the beam pipe walls. That would be in good agreement with lower Δφ measured.

Courtesy: Stefano de Santis

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT CORNELL SINCE 2008 (3)

COMPARISON BETWEEN ELECTRON AND POSITRON BEAM

CLEO Straight Measurements



Thus ,we also see a nice, but smaller electron cloud with the electron beam !!!

Signal is propagated from the central BPM to the East and West ends of the straight. Vacuum chambers in the two sections are slightly different.

Courtesy: Stefano de Santis

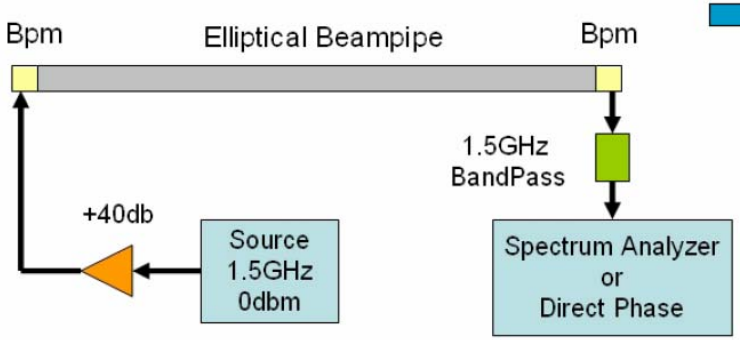
MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT FNAL 2009 CONFIGURATION IN THE MAIN INJECTOR (MI)

Project X e-Cloud Measurements

- Microwave transmission (phase velocity) measurement:
  - From plasma physics, microwaves travelling along a waveguide (vacuum chamber)
  - Phase shift due to a homogeneous plasma
  - Microwave dispersion relation:

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

$$\Rightarrow \frac{\Delta\phi}{l} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}}$$



For an electron cloud

$$\omega_p^2 = 4\pi\rho_e r_e c^2$$

is proportional to e density

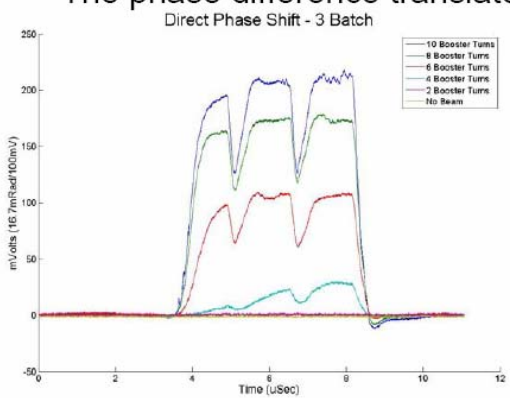
AAC, February 3, 2009 – Project X Instrumentation, Manfred Wendt *Page 11*

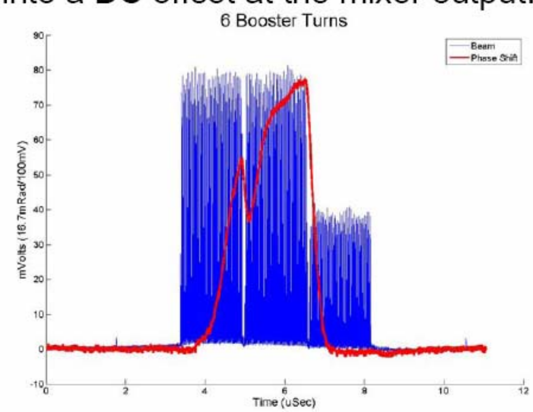
Courtesy: Manfred Wendt

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT FNAL 2009 FIRST MEASURED RESULTS (MI)

Project X Time Resolved Measurements

- Direct Phase e-Cloud Measurements
  - Mix the transmitted signal with the source and measure the baseband component.
  - The phase difference translates into a DC offset at the mixer output.





  - We can observe the development of the e-Cloud as the beam passes!
  - Data shown represents one machine turn (TbT time resolution).

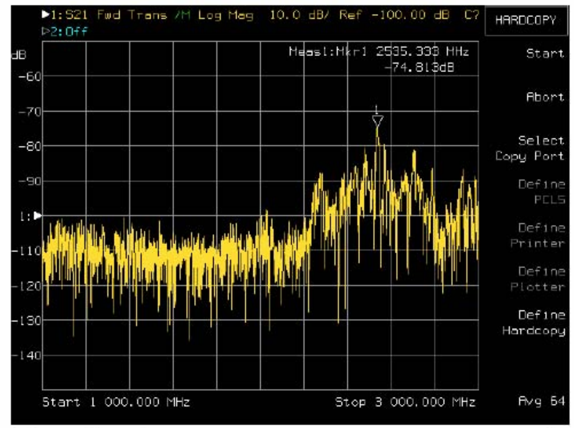
AAC, February 3, 2009 – Project X Instrumentation, Manfred Wendt *Page 12*

Courtesy: Manfred Wendt

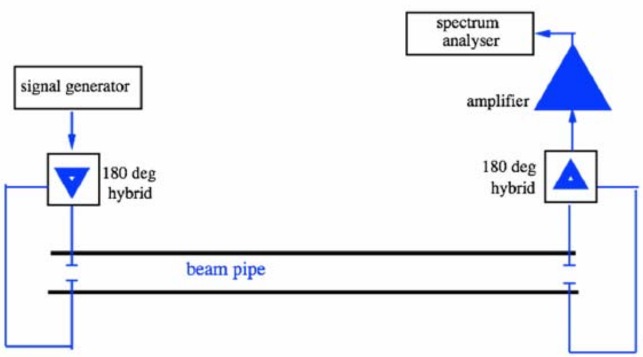
MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT ANKA 2008-2009 EXPERIMENTAL SET-UP (ONDULATOR)

Evidence of Trapped mode

- Length of transmission 1.5m
- The SC undulator has 100 periods
- Both sides have 4 BPMs each
- Signal enhancement was seen at about 2.54 GHz
- Corresponds to a "Trapped Mode"



Signal enhancement seen on a network analyzer



Setup for the real measurements across the undulator section

| 21.11.2008 | page 2 | ANKA

KIT – die Kooperation von Forschungszentrum Karlsruhe GmbH und Universität Karlsruhe (TH)

HELMHOLTZ GEMEINSCHAFT

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

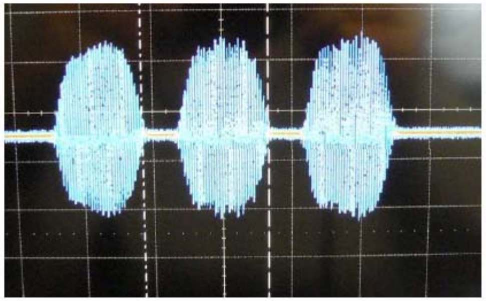
Courtesy: Anke Müller

MICROWAVE E-CLOUD DIAGNOSTIC EXPERIMENTS AT ANKA 2008-2009 PRELIMINARY RESULTS (APRIL 2009)

Observation of side bands during operation

KIT Karlsruhe Institute of Technology

- Rev. frequency ~ 2.73 MHz
- Side bands up to 5th order visible
- Need to eliminate the effect of intermodulation
- Setup needs to be refined to minimize intermodulation
- Poster TH5RFP044 (Thursday morning)



bunch fill pattern (span = 300ns)

Courtesy: Anke Müller

MITIGATION OF E-CLOUDS WITH POWERFUL MICROWAVES?

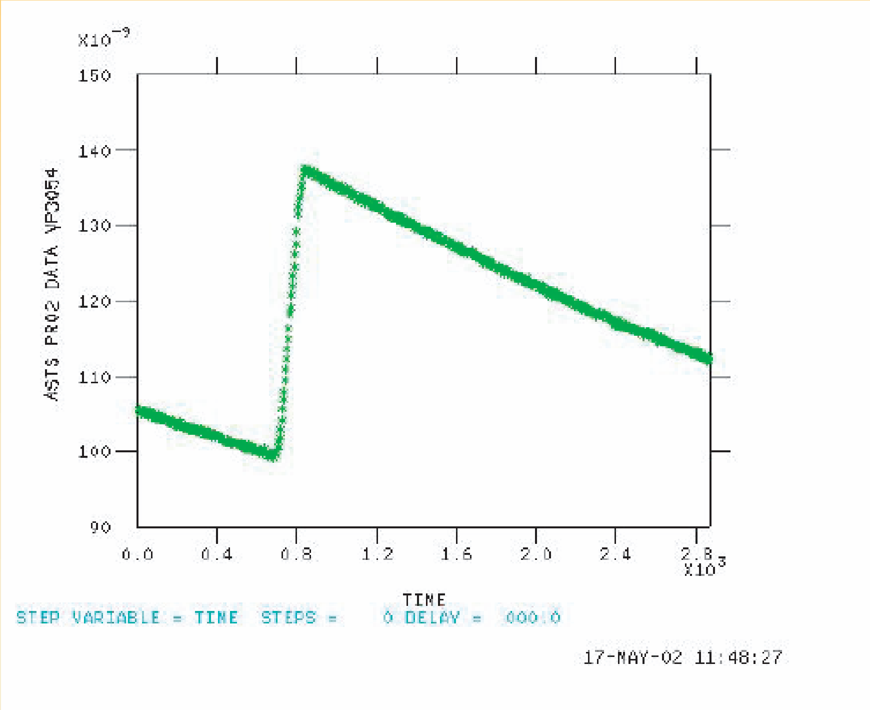
- mitigation of e-cloud using **clearing electrodes with static fields** at the CERN ISR in the **1970's** (O. Gröbner *et al*)

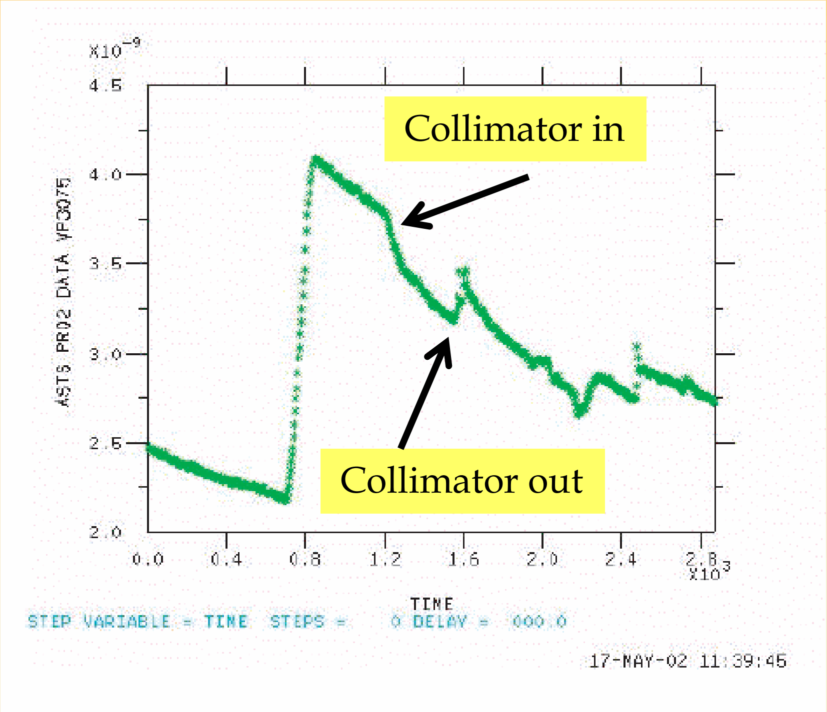
- at the time W. Schnell proposed **application of RF clearing fields in the MHz range** for the ISR; RF „clearing fields" with well defined frequencies in the MHz range were in fact later used for „beam shaking" to push trapped dust particles towards pumps in the AA

- in **1997** A. Chao suggested **use of microwaves for e-cloud mitigation**

- **experiment** was carried out in 2002 at the SLAC PEP II factory using „internally"created microwaves (wakefields) from collimators gave faint & indirect indications (vacuum reading) for a benefical effect

MITIGATION OF E-CLOUDS WITH POWERFUL MICROWAVES?
PEP II EXPERIMENT IN 2002





Evolution of vacuum pressure vs time with static collimators

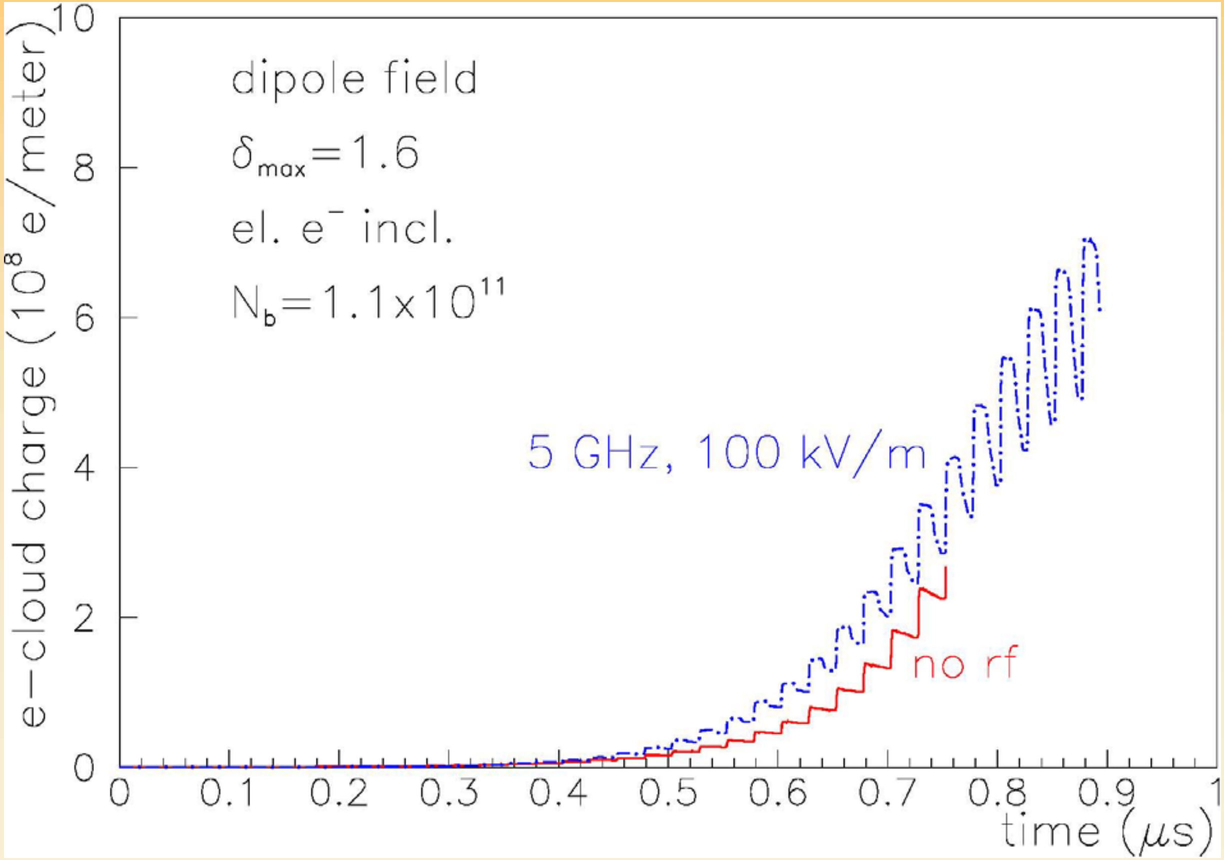
Evolution of vacuum pressure vs time with dynamic collimators

Courtesy: Franz-Josef Decker

SIMULATION OF ELECTRON MICROWAVE INTERACTION (1)

- various existing **simulation programs** model **either** the **electron multipacting under influence of microwaves**, such as FEST3D, **or** the **beam-induced multipacting in accelerators**, such as PEI, POSINST, and ECLOUD
- in **2002** first, **rough attempt to model the combined effect by adding an RF microwave to the ECLOUD code**; prior crude estimate suggested that e^- motion could only slightly be perturbed by microwaves, e.g. for a field amplitude of 100 kV/m at 5 GHz, the electrons are accelerated to $4x10^5$ m/s, which corresponds to a kinetic energy of only 0.44 eV, and to an excursion of +/- 18 μm
- **effect of TE_{11}-wave for LHC proton-beam parameters** at injection was analyzed, assuming maximum sec. emission yield δ_{max}=1.6, & including elastic electron reflection on chamber wall

SIMULATION OF ELECTRON MICROWAVE INTERACTION (2)



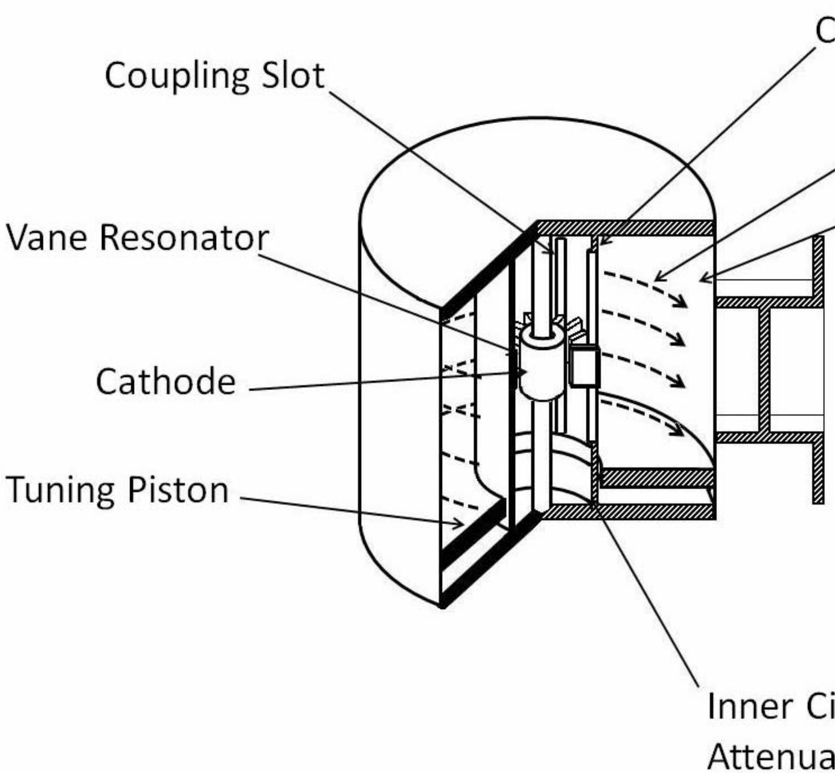
Simulation of electron-cloud build up in LHC dipole chamber with 2-cm radius with and without additional 5-GHz *TE*-mode microwave of amplitude 100 kV/m. We notice a degradation with additional RF power

THE MAGNETRON EFFECT (1)

ingredients for building a magnetron and getting it oscillating

- source of electrons (cathode) — LHC beam screen
- accelerating potential (anode) — beam potential
- static magnetic cross field orthogonal to the electron movement (28 GHz/Tesla) — bending field
- resonator with good transit time factor tuned in frequency according to magnetic field (28 GHz/Tesla) — trapped mode
- enough accelerating potential (anode voltage) to sustain oscillation (gain> loss) — beam intensity

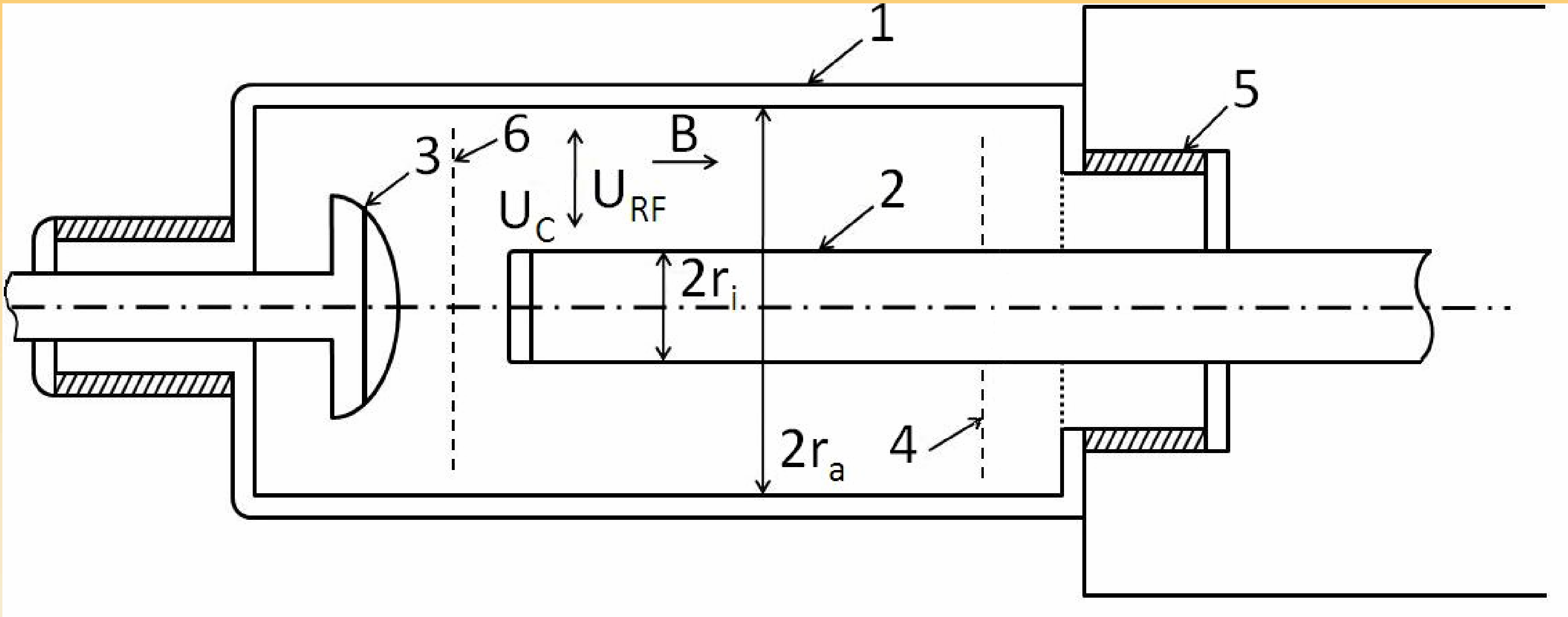
MAGNETRON EFFECT
THE COAXIAL MAGNETRON



Simplified drawing of a coaxial magnetron

analogy between coupling slots in this structure and slots in LHC beam-screen ; for the LHC case the anode and cathode would be inverted since electrons come via photoeffect or secondary emission from inner surface of the beam-screen

THE ELECTRON CLOUD VARACTOR DESIGNED AS A FAST CAVITY TUNER



schematic sketch of the varactor

1 - outer conductor
2 - inner conductor (anode)
3 – cathode
4 – reflector
5 - insulator,
6 -control grid

operates similar to a magnetron below oscillation threashold but has no dedicated resonator;
the size, density and position of the electron cloud are adjusted via control grid and reflector potential

CONCLUSIONS

- **interaction of microwaves with electron clouds in particle accelerators** gained considerable attention over last few years
- **microwave transmission method** has proven a useful diagnostics application for electron-cloud density measurement; it is **already applied in several accelerators** and is under construction in others
- **strong RF or microwave fields in the beampipe may affect the electron-cloud dynamics**, but experimental evidence is still scarce, and for the moment related practical applications are not in sight
- an important aspect concerns **accidentally coherent microwave electron cloud interaction**, where the electron cloud would enter a state of **coherent emission as in a normal magnetron**