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)
diagnostic of plasma density by means of microwaves is well known technique since many decades; intensive applications e.g. in tokamaks, but there usually operating in the mm wave range due to the high plasma density

- for typical e- clouds in accelerators with $\rho \sim 10^{12} \text{ /m}^3$, plasma frequency is much lower and thus signal transmission becomes already possible at $\sim 30 \text{ MHz}$

- 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 ($\omega_{rf}$) above plasma cutoff ($\omega_p$=plasma frequency which contains the plasma density) without static magnetic field over the length $L$ ($c=3 \times 10^8$ m/s)

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

For TEM waveguide mode propagation with $\omega_c$=waveguide cutoff frequency:

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

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): $1/\left(1 - \left( eB / (\omega_{rf} m_e) \right)^2 \right)$
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 = \(10^{16} \text{ e}^-/\text{m}^2\))

TEC = total electron content

TECU = TEC unit

This phenomenon is often referred to in the context of SPACE WEATHER

This first setup had a conventional spectrum analyzer 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 amplifier 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 $f_{\text{rev}}$ 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

with 44 kHz revolution frequency (CERN-SPS) we expect sidebands at ± 44 kHz; a sensitivity of better -80 dBc is possible
Improved setup with narrowband filters (40 Mhz BW)
Display from a conventional spectrum analyzer.

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

The beam induced signal are the two bigger peaks next to the center line.
key question: is faint modulation line ONLY phase modulation?
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.
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.
Cyclotron resonance PEP-II LER Chicane

Measured!

\[ f_{\text{cor}} = 2.015 \text{ GHz} \]

\[ B \approx 700 \text{ G} \ (\sim 1.96 \text{ GHz}) \]
LBNL SIMULATIONS AND PEP II EXPERIMENT REVEAL RESONANCES BETWEEN CYCLOTRON MOTION AND BUNCH SPACING

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

- bunch spacing = \( n \times \) cyclotron period

question: can one measure microwave signals caused by the cyclotron motion?
MICROWAVE E-CLOUD DIAGNOSTIC
EXPERIMENTS AT CORNELL SINCE 2008 (1)

Transmitter/Receiver Positions (L0)

CLEO straight (~17.4 m)

Available RF cables. Each drives 4 BPM’s

Courtesy: Stefano de Santis
Phase detector (LO – central BPM)

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 $\Delta \varphi$ measured.

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

Courtesy: Stefano de Santis
Thus, we also see a nice, but smaller electron cloud with the electron beam!!!
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:

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

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

For an electron cloud
\[
\omega_p^2 = 4\pi \rho_e r_e c^2
\]
is proportional to e density

Courtesy: Manfred Wendt
**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).

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Courtesy: Manfred Wendt
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

Courtesy: Anke Müller

Observation of side bands during operation

- 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-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 E CLOUD

- in 2002 first, rough attempt to model the combined effect by adding an RF microwave to the E CLOUD 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 4\(\times\)10\(^5\) m/s, which corresponds to a kinetic energy of only 0.44 eV, and to an excursion of +/- 18 \(\mu\)m

- effect of \(TE_{11}\)-wave for LHC proton-beam parameters at injection was analyzed, assuming maximum sec. emission yield \(\delta_{\text{max}}\) =1.6, & including elastic electron reflection on chamber wall
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
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 threshold 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