Results of the 2004 SPS Microwave Transmission Measurements

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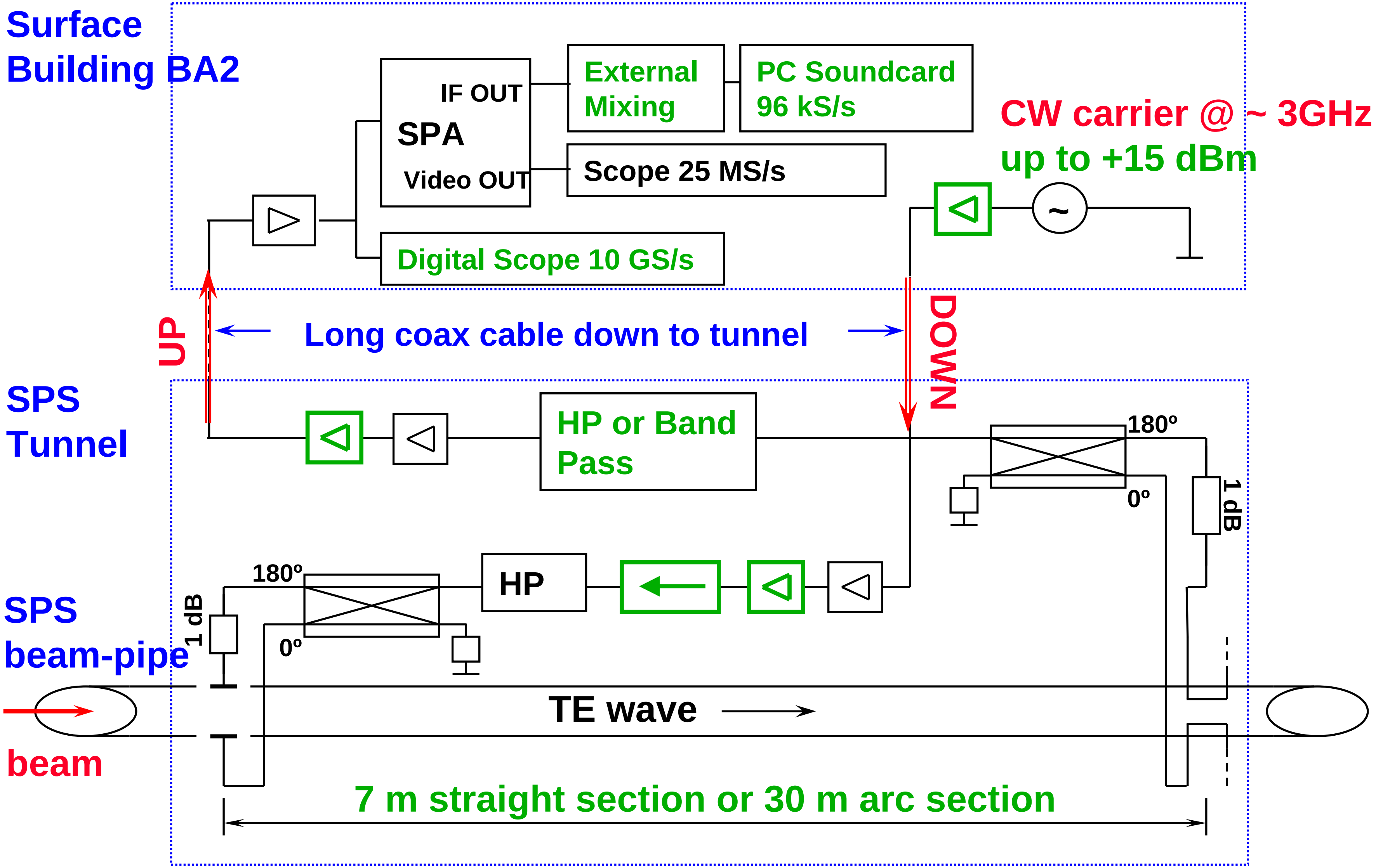
Agenda

- Motivation
- Measurement Set-up
  - Improvements since 2003
  - Check for potential error sources
- Results
- Bench Measurements
- Discussion
- Preliminary Conclusion

Motivation

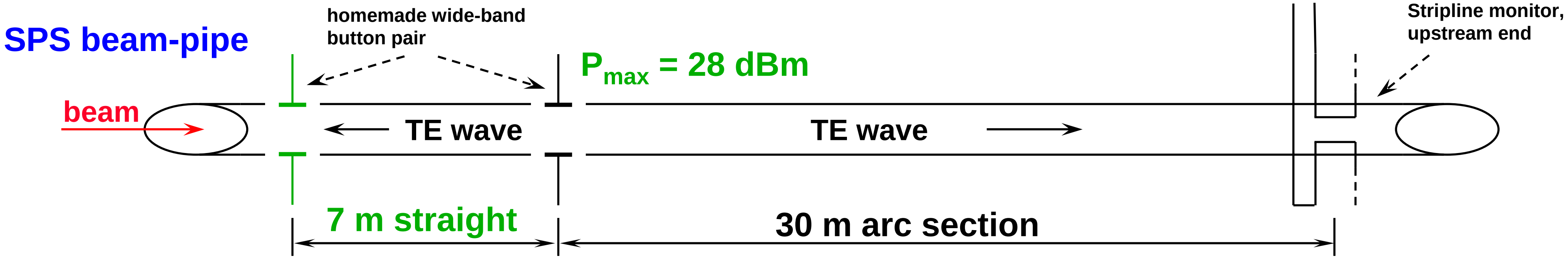
- When electromagnetic waves are transmitted through a not too dense plasma, the experience a phase shift and possibly a small attenuation
- Any such change is modulated at the SPS revolution frequency of about 43 kHz, which translates phase and amplitude changes into PM and AM
- Thus, highly sensitive sideband measurements possible.
- A measurement method based on such an effect could potentially determine the electron cloud density integrated over the measurement track.
- This would be interesting, since it allows an in-situ measurement in existing accelerators at relatively little cost
- This method could also be tried in LHC, where measurements over an entire arc are possible using the coupling structures of the LHC reflectometer

Measurement Set-up 2004



Changes to the Measurement Set-up (1)

- In addition to the 30 m arc section a 7 m straight section was used for the measurements. In this section there is only one corrector dipole and one skew quadrupole
- Wave propagation in the same direction as the beam on the 7 m track and in the opposite direction one the 30 m track



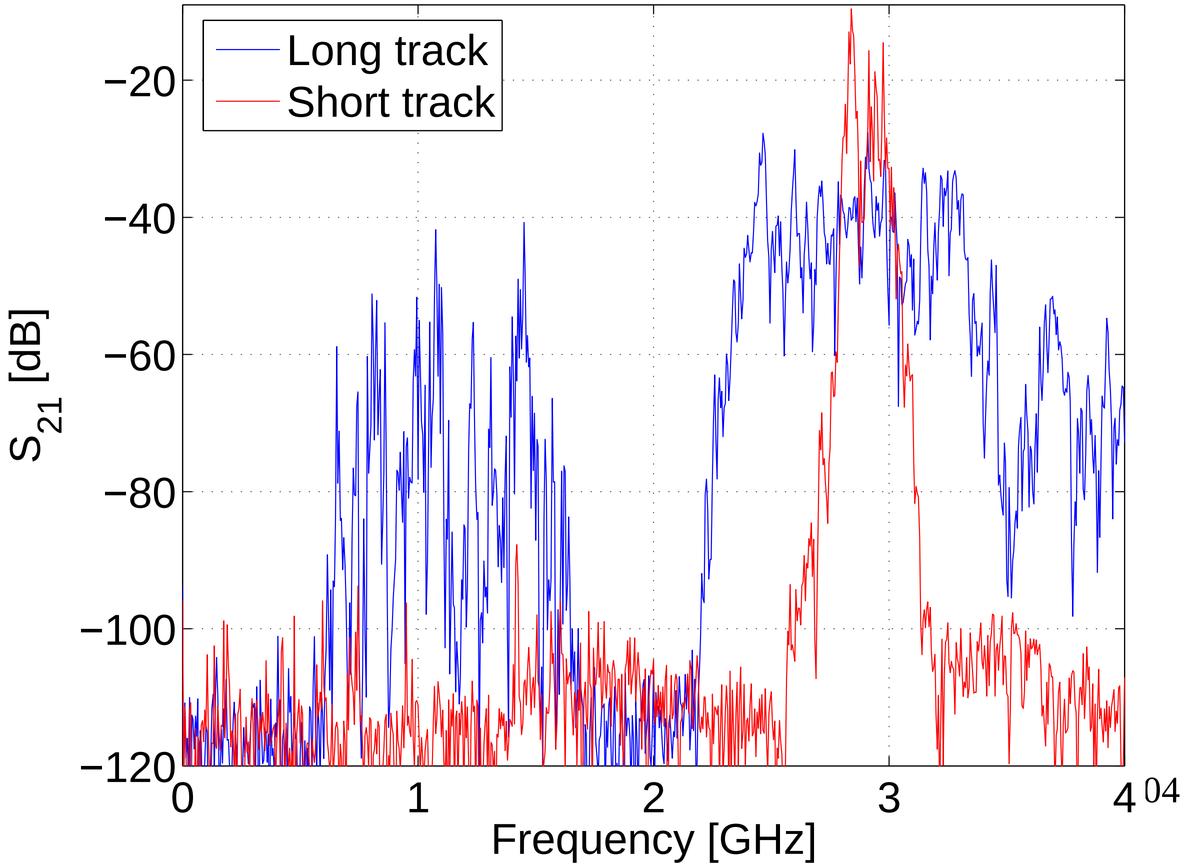
Changes to the Measurement Set-up (2)

- Three power amplifiers (P_{max} 28 dBm) were used in the tunnel to increase the dynamic range of the entire transmission chain
- An isolator was inserted after the power amplifier to protect it from in-band beam-induced signals
- 1 dB compression point for both tracks at ~12 dBm source power in BA2
- SNR without beam ~75 dB on short track and ~70 dB on long track

- A little bell was installed on the beam-pipe on the short track. It was meant for “shaking” the beam-pipe to stir up dust in the interior of the beam-pipe

Changes to the Measurement Set-up (3)

- In order to decrease the beam-induced signals, a 2.8 to 3.2 GHz band pass filter was installed in the short track (7 m)
- The waveguide filter in the long track (30 m) was elongated to increase the out of band rejection



Check for Potential Error s

- In the present measurement, the signals of interest are small compared to beam-induced signals => electromagnetic interference, saturation and intermodulation effects have to be checked carefully
- Cross-talk between cables was found to be negligible
- Static charge-up of the button type pick-ups was prevented by DC returns
- Beam-induced signals were reduced by use of filters (both paths) and an isolator (down-going path)
- However, in the up-going path in-band beam-induced signals were picked up by the amplifiers => needs to be studied in detail

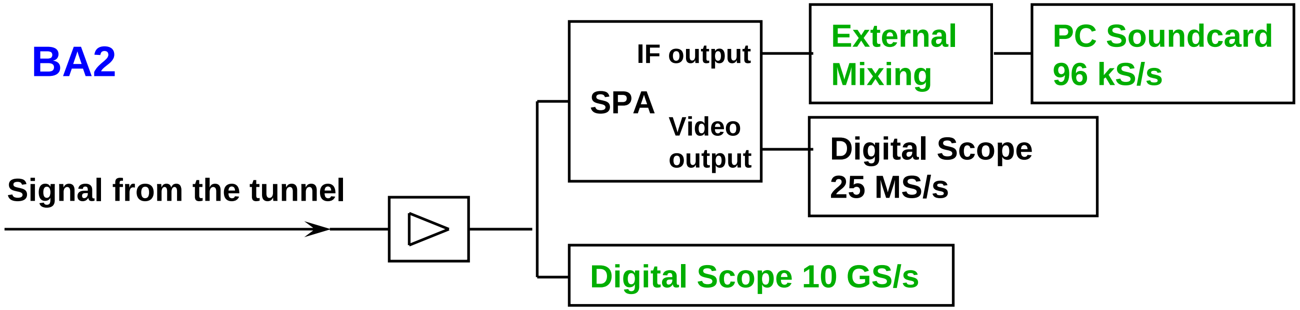
Amplifier Saturation & Intermodulation

- In the down-going path, the beam signal rejection by the installed filter and isolator is in the order of 40 dB
- Beam signals reaching the last stage of the power amplifier could have some impact on its gain
- Lab tests showed a very limited change in gain (0.2 dB) a strong signal (10 dBm) incident on the power amplifier’s output

- In the up-going path, beam signals could create intermodulation with the CW carrier
- Lab test: For the CW carrier and the parasitic signal in the range of the maximum specified input level, a 0.3 dB gain compression was found. Higher intermodulation can expected for still higher beam-induced signals
- For short severe overloads (signal from one bunch), the amplifiers show recovery times of the order of 1 ns

Data Acquisition (1)

- The data acquisition system was considerably improved
- The signal was observed in four different ways
  - Directly with 10 GS/s on a fast scope
  - On a spectrum analyser in frequency domain
  - Downconversion with the SPA and observation of the video output on a scope
  - Downconversion with the SPA and external mixing of the SPA’s IF output, data acquisition in base band with a PC soundcard



BA2

Signal from the tunnel

SPA

IF output

Video output

External Mixing

PC Soundcard 96 kS/s

Digital Scope 25 MS/s

Digital Scope 10 GS/s

Data Acquisition (2)

System	Advantage	Drawback
Direct observation on scope	No intermediate signal processing necessary All information preserved (within sampling theorem limitations)	very limited record length (~400 μs) large amounts of data to process (~50 MB per trace)
Direct observation on SPA	Easy No intermediate signal processing necessary	Not possible in real time => difficult to observe changes of the spectrum with time
SPA video output -> scope	Changes in time can be seen Relatively long record lengths (100 ms)	Rise time limited by SPA resolution bandwidth ~3 MHz SPA automatic amplitude adjustment may affect results
Downconversion with SPA -> IF out -> external mixing -> PC soundcard	Very long records possible (seconds to minutes) Evolution of beam-induced modulation over time can be observed Subsequent data processing easy	Only small part of spectrum can be seen due to soundcard sampling frequency of 96 kHz Tricky to measure exact sideband amplitude. Lots of calibrations necessary

Beams

- Data was taken with many of the beams available in the SPS, including

- SFT Pro beam
- LHC beam
- Single bunches
- Pilot bunch
- LHC coast

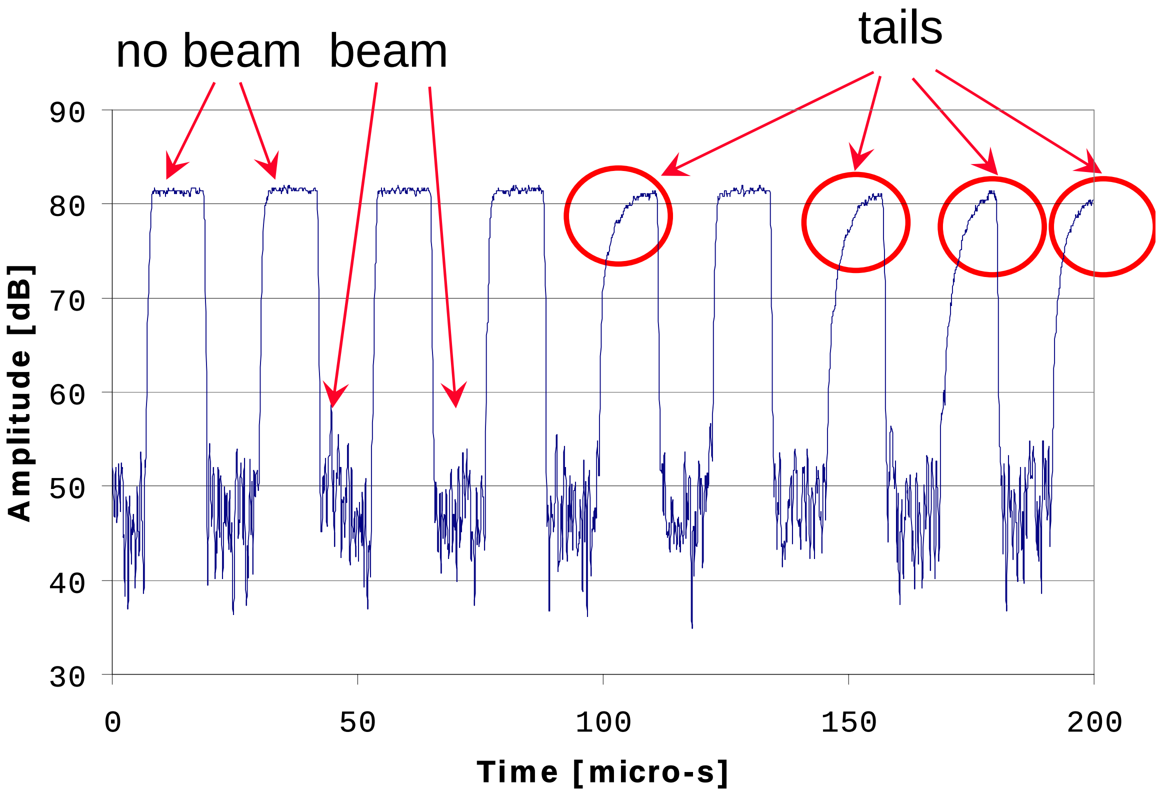
Results

Basically, the found can be grouped in five categories

- Microwave signal attenuation during the passage of the beam
- Tails. For certain beams, absorption still occurred after the passage of the beam with decay times of the order of 1 μs
- Asymmetric spectrum at cyclotron resonance
- Strong absorption peaks and periodicities after each injection
- For stored beams, the modulation (attenuation) decays gradually but not monotonically

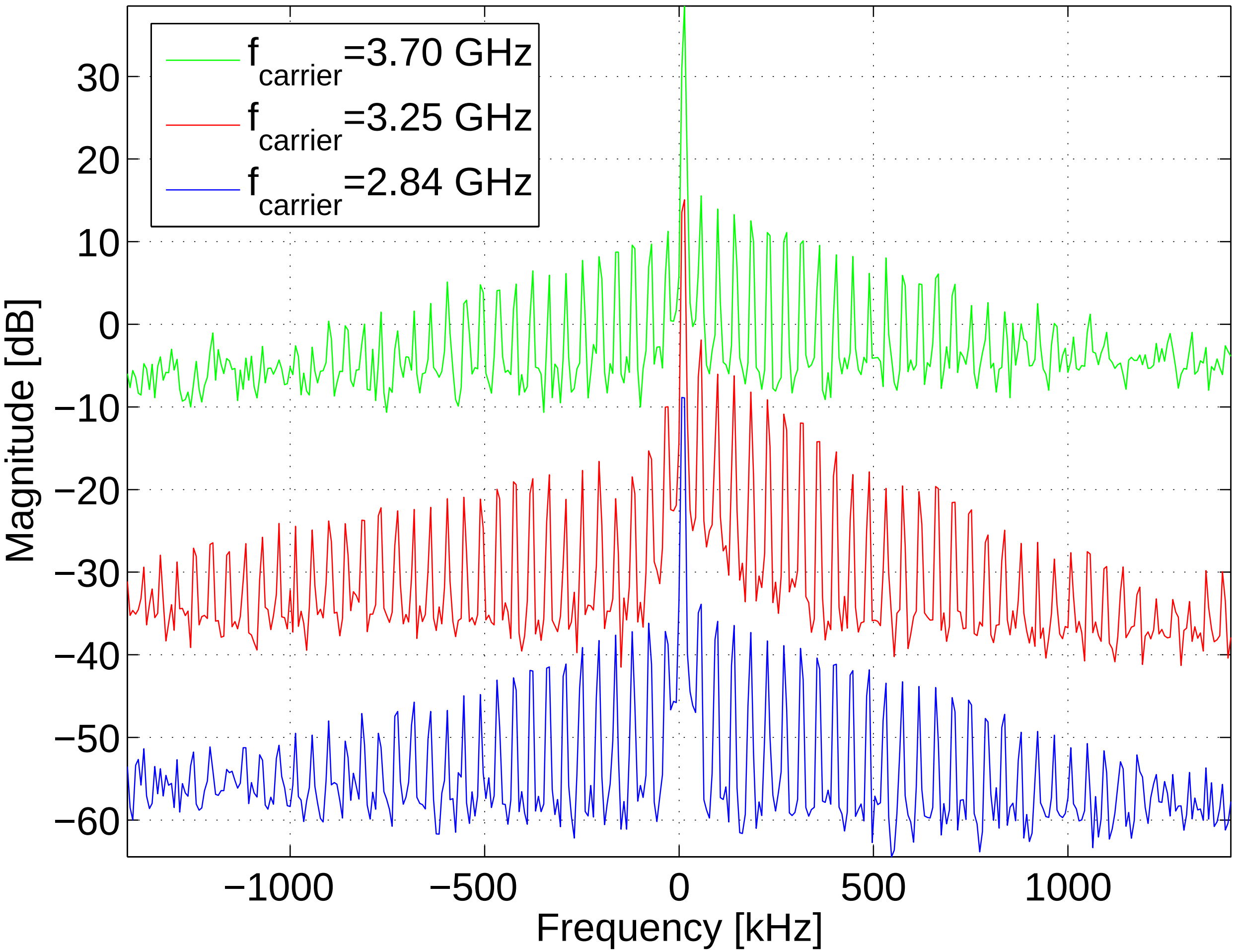
Signal Attenuation with Beam and Tails

- Data acquisition via SPA in CW mode with 3 MHz IF bandwidth -> Video output to scope
- Found especially for “strong” LHC beams
- Results from 2003 repeated qualitatively



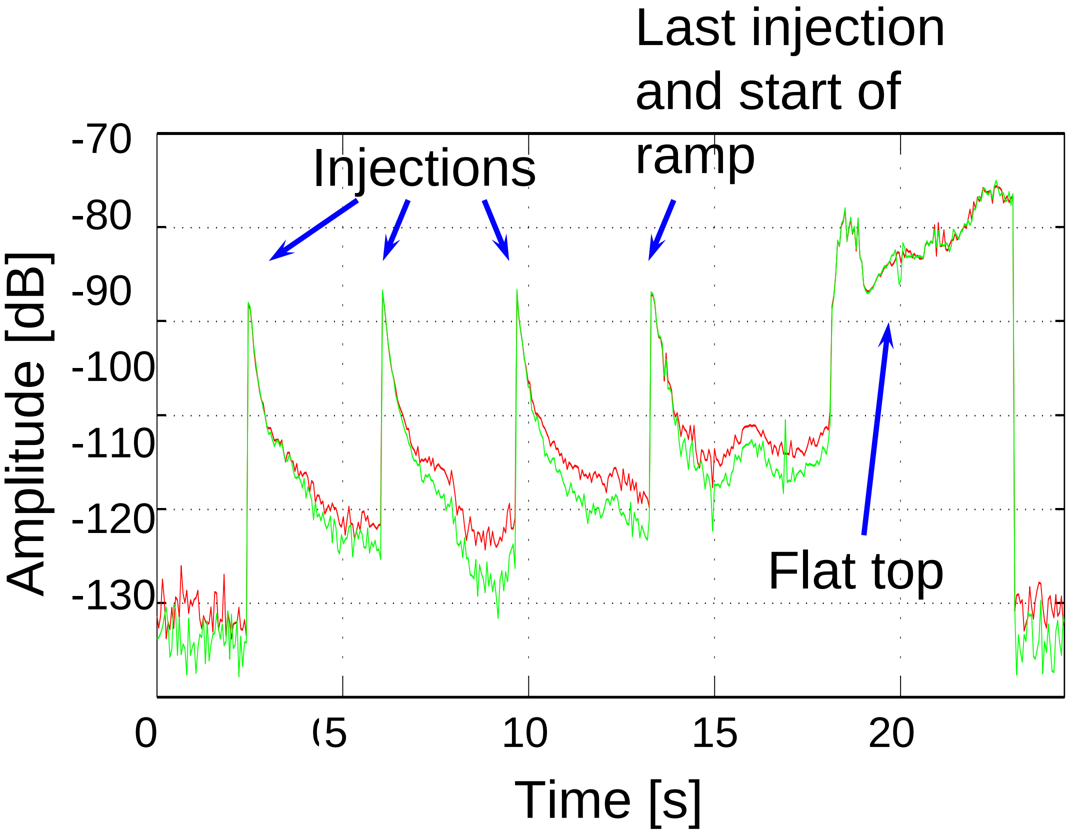
Asymmetric spectrum at cyclotron resonance

- Electron cyclotron resonance in the SPS main bending magnets at the injection flat bottom
- Visibly asymmetric modulation spectrum
- Superposition of AM and PM
- Amplifier saturation surely can’t play a big role here



Strong absorption peaks and periodicities after each injection (1/2)

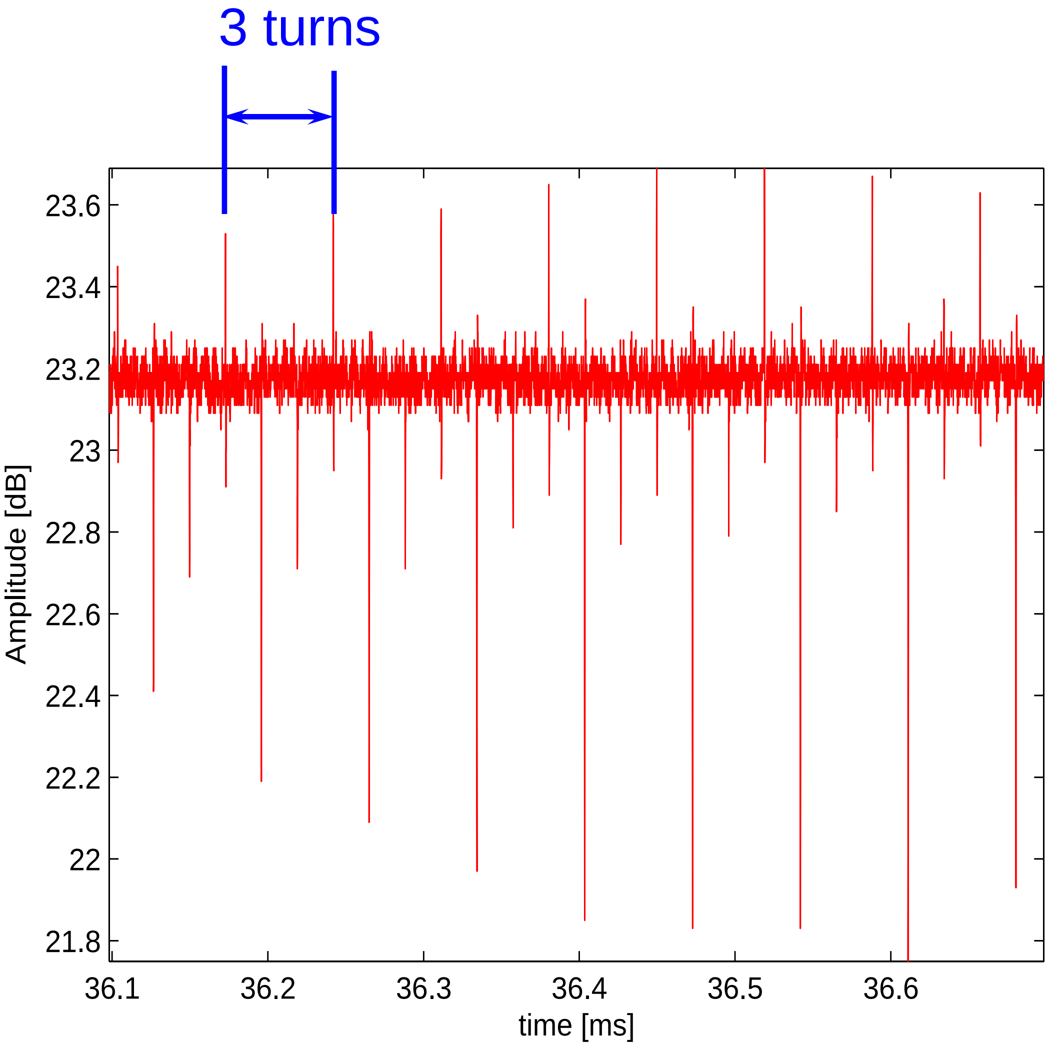
- Data acquisition by downmixing to baseband and commercial PC soundcard
- First modulation sideband tracked over entire cycle
- Strong absorption peaks after each injection
- Correlated to beam losses; strongly correlated to beam spectrum => may be related to saturation due to beam-induced signals



Full LHC beam cycle

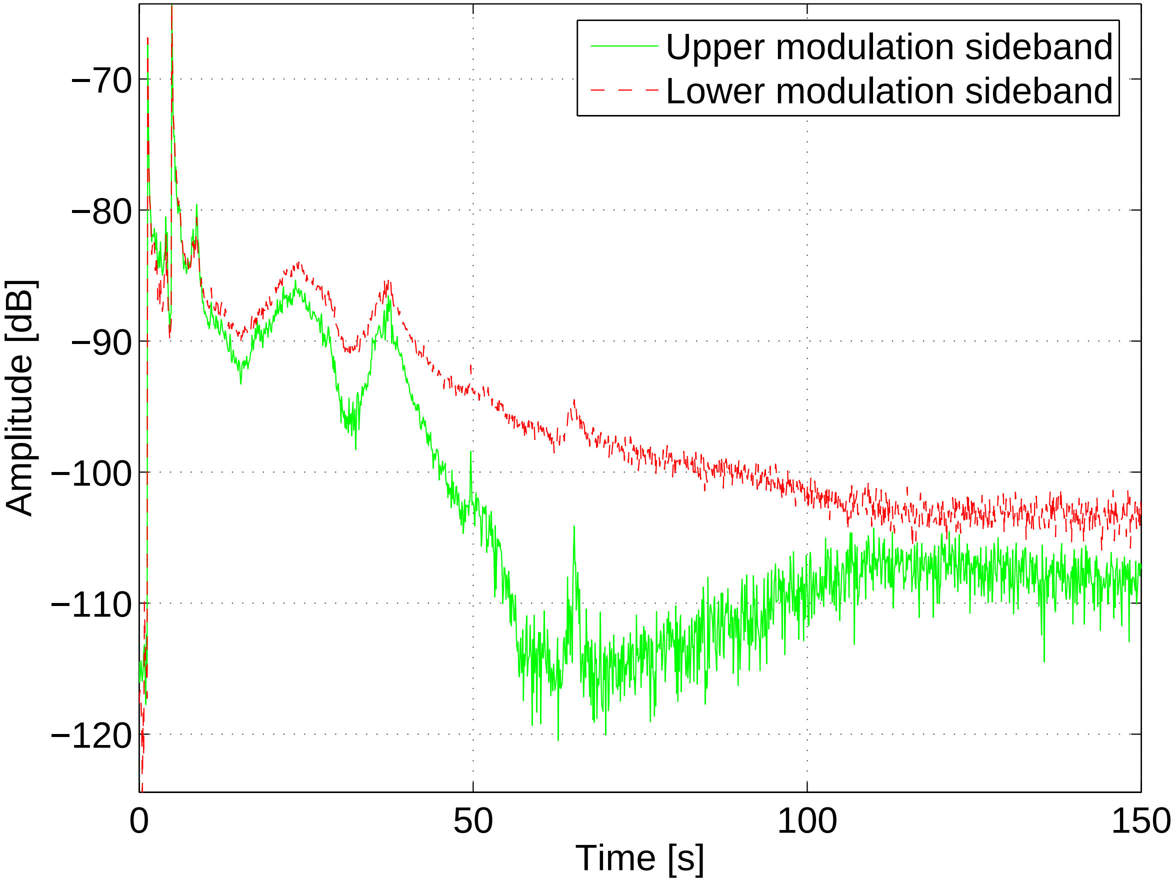
Strong absorption peaks and periodicities after each injection (2/2)

- For the absorption peaks just after injection, a 3-turn periodicity and an overlaid 1000 Hz structure could be resolved
- Apparently related to the vertical fractional tune of ~0.16 => twice the observed period
- 1000 Hz structure due to beating of the tune and the revolution frequency



Decreasing absorption in stored beams

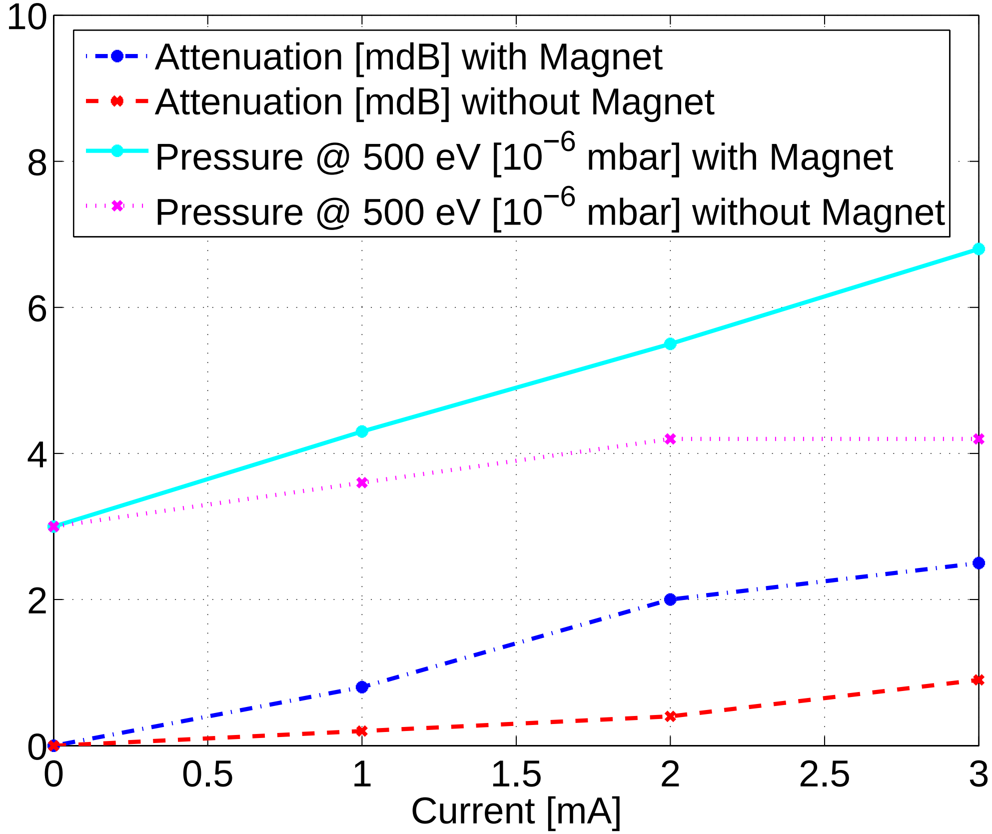
- After the ramping, the modulation sidebands decrease gradually => less absorption
- This decrease is not monotonic
- Spectra get asymmetric; superposition of AM and PM
- Possible correlation with beam spectrum
- Data from MD session 11/11/2004 (COAST5)



Bench Measurements (1/2)

- In order to get a better grip on the interaction between microwave waveguide modes and an electron cloud, bench measurements were carried out
- Electrons injected in pipe carrying waveguide mode
- In presence of electrons, small drop in microwave transmission and increase in reflection
- Larger attenuation when small magetic field applied (far below cyclotron resonance
- Vacuum pressure rise goes hand-in-hand with microwave attenuation

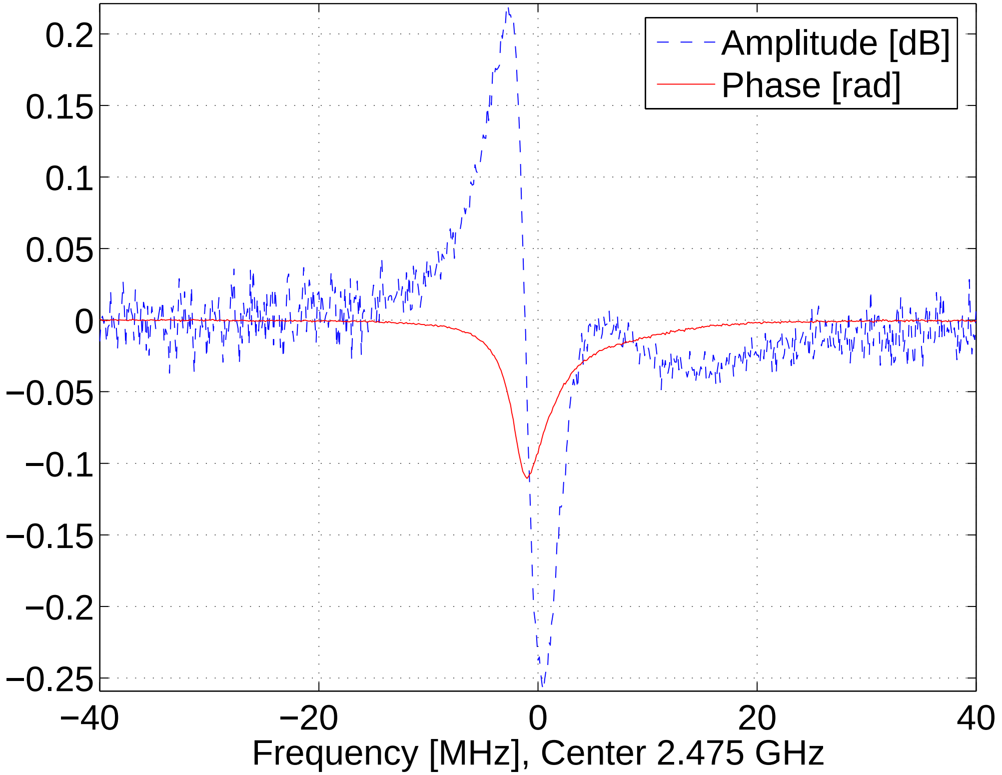
Additional attenuation and pressure rise when electron current on



Bench Measurements (2/2)

- In principle configuration of magnetron-type varactor that was tested at Triumf 1995 for cavity tuning
- Magnetron of disused microwave oven used on S-band waveguide
- Driven below oscillation
- Variation of reflection coefficient (impedance) measured as a function of anode voltage
- Effect of electron cyclotron motion clearly seen
- Space charge effects?!?
- Detuning...

Change in reflection coefficient when anode voltage goes from 0 to 200 V; corresponds to detuning



Discussion (1/3)

In the SPS we have a very complex case

- Inhomogeneous magnetic field
- Beam pipe with cross-section changes
- Strongly time variant and inhomogeneous electron plasma

- To our knowledge, there is presently no numerical simulation tool available that could easily handle such a system
- The drop in carrier signal when the beam is passing may be partially due to saturation of the amplifiers
- However, the strongly asymmetric spectrum at cyclotron resonance cannot be explained this way, since the beam-induced signals do not depend on the carrier frequency used

Discussion (2/3)

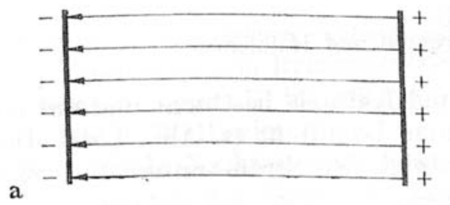
- In an unmagnetized neutral plasma in free space, there should only be a weak interaction between microwaves above the plasma frequency (~10 MHz for electron cloud) and the plasma
- Even below cyclotron resonance a transversely magnetized neutral plasma (quadrupoles) can interact strongly with waveguide modes, leading to reflection, absorption and mode conversion
- For operation at frequencies below cyclotron resonance in the main bending magnets, the cyclotron resonance condition is always fulfilled somewhere in fringe fields, quadrupoles etc.
- However, the electron cloud is not a neutral plasma => space-charge effects possible

Discussion (3/3)

- Space charge “capacity” in small electron tubes of the order of 1 pF
- Effect of space charge is that is changes electric field distribution; acts like a capacity
- 1 pF at 3 GHz is considerable; would lead to reflection of power rather than absorption

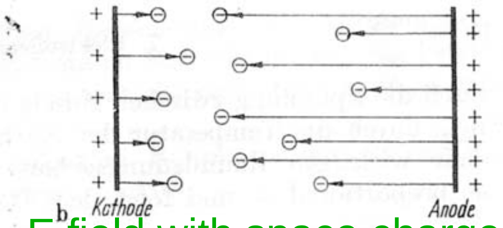
Effect of space charge in tube with planar electrodes

Cathode Anode

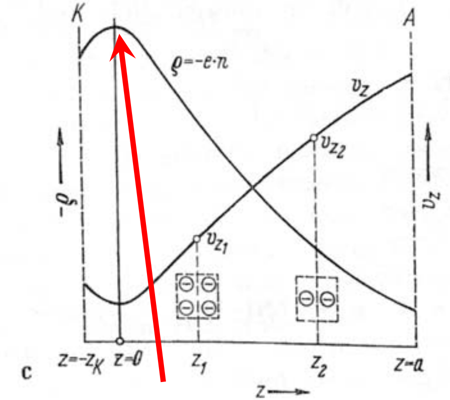


unperturbed E field

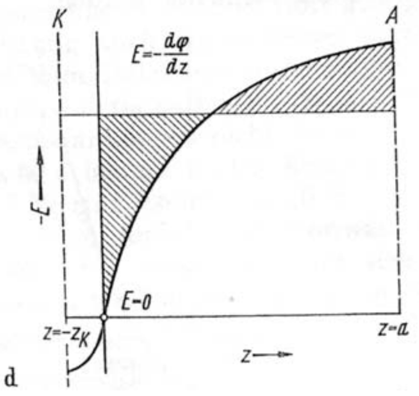
Cathode Anode



E field with space charge



Space charge density maximum close to cathode



Reference: Zinke, O., Brunswig, H., Lehrbuch der Hochfrequenztechnik, zweiter Band, Springer, Berlin, 1974

Lessons learned

Lots of experience was gained during the 2004 run. The following points have to be retained for future experiments

- Suppress the beam-induced signals as much as possible in both the down and the up-going signal path, e.g. using a waveguide cavity filter with a few MHz bandwidth.
- Choose straight sections of beam pipe without magnets or an arc section with dipoles only. Except for fringe fields the wave E field is then parallel to the static B field, making an interpretation of the results easier.
- Work with a carrier frequency a factor three or so above the highest electron cyclotron frequency. This should considerably reduce cyclotron absorption [5], making it easier to measure the expected phase shifts. In the LHC at injection energy, the cyclotron resonance is below 1 GHz, so this condition can be met using the fundamental TE or TM waveguide mode.

Conclusion

- Strong indications for interaction between guided waves in the SPS beam pipe and the electron cloud plasma were found
- Bench measurements completed this image by showing small but repeatable effects
- Cyclotron resonance and space charge effect appear to be mainly responsible for the observed signal attenuation
- A quantitative evaluation appears difficult due to the complexity of the situation
- The results obtained may be affected by effects related to amplifier saturation. A repetition of the principal measurements with special care taken on avoiding this parasitic effect is desirable

- It looks like we could have a very sensitive tool for detecting electron clouds in the beam pipe

Acknowledgements

- We would like to thank Thomas Bohl, Frank Zimmermann and Stefano Alberti for help and advice. Thanks to Flemming Pedersen for inspiring discussion, Trevor Linnecar for support, Edgar Mahner for setting up the bench measurements, Miguel Jimenez and Jean-Francois Malo for help with the experiment in the SPS.