Unexpected Results on Microwave Waveguide Mode Transmission Measurements in the SPS Beam Pipe

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Agenda

- Motivation
- Expected results
- Measurement set-up
- The observed spectrum
- Time domain measurements
  - Without beam and without CW microwave signal
  - Results with different beams in the SPS
- Summary & Discussion
- Outlook

(electron cloud laughing at us)

Motivation (1)

- Initial idea: Measure electron cloud induced modulation of first TE waveguide modes in the SPS beam pipe.
- The results should be directly related to the averaged electron cloud density.

- The maximum density for a classical electron cloud is assumed to be in the order of 10^6 per cm^3 (10^{12} per m^3).
- This density should lead to a small phase shift of roughly 20 degrees over 1km for frequencies between 2 and 3 GHz.

- A similar effect can be observed in the ionosphere, too. It's one of the major factors limiting the accuracy of GPS.

Motivation (2)

- Since the phase shift is modulated with the SPS revolution frequency of 43kHz, it should result in small but measurable FM side bands.

- In principle there should be no interaction between a highly relativistic beam and TE modes.
- This statement is strictly valid only for a homogeneous beam-pipe.
- At cross-section changes and other inhomogeneities some interactions might occur, but the impact should stay small due to a very small transit-time factor.
- Such effects generally show up only in very limited frequency bands.

Expected Phase Shift

The phase shift for an angular frequency ω is given by

$$\Delta\phi = -\frac{1}{2}\frac{\omega_p^2}{\omega c}L$$

with the plasma frequency $\omega_p = \sqrt{4\pi \rho_e r_e c^2}$

$\rho_e = 10^{12}/m^3$ designating the electron volume density,
r_e the classical electron radius and c the speed of light

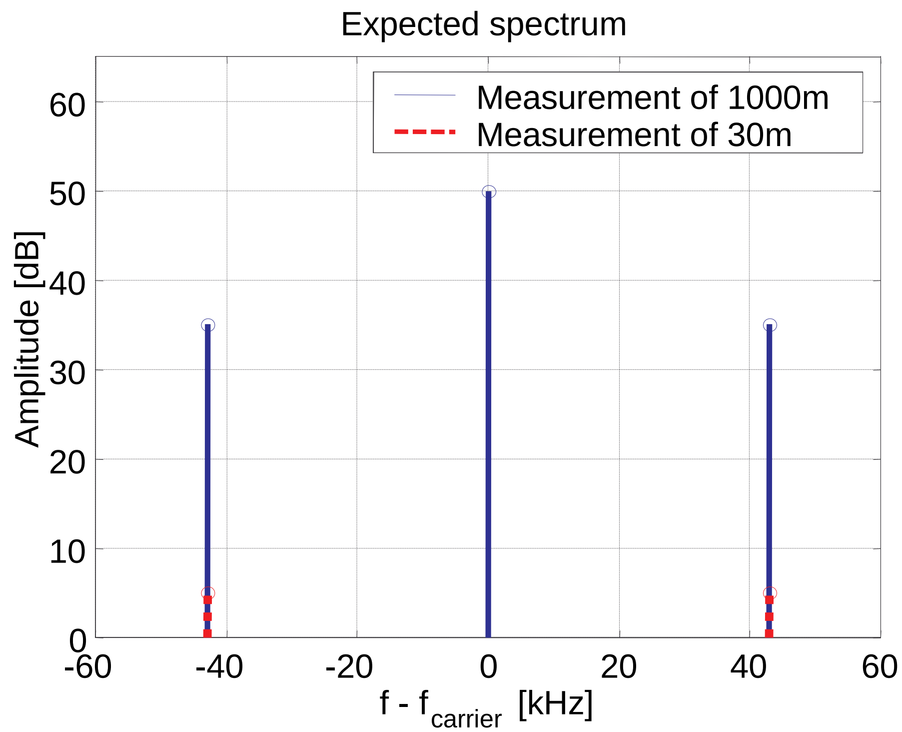
For the SPS @ f=2 to 3GHz over 1km this would give a phase shift of roughly –25 to -17^o.

Carrying out the Experiment

- The measurement series was performed parasitically, that is, without any dedicated beam time.
- It was a low-budget experiment without specially allocated funding.
- Standard LHC beams, fixed target beams and other beams during machine development sessions were used.

Expected Results

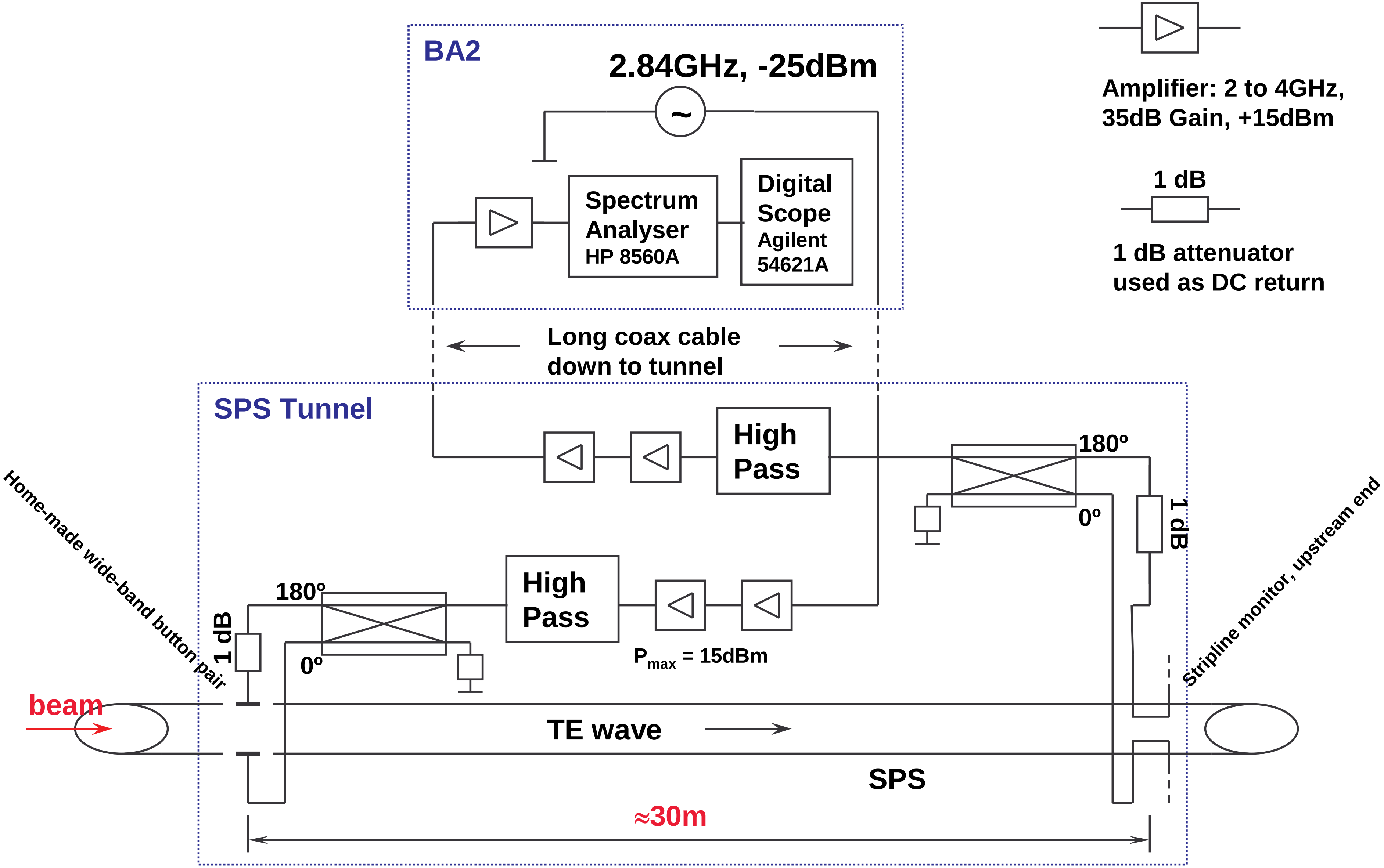
- Measurement between 2 and 3 GHz over 1 km.
- No amplitude modulation expected, only a
- Phase modulation of roughly 20 degrees.
- This should give sidebands 15 dB below the carrier when measuring over 1km.



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

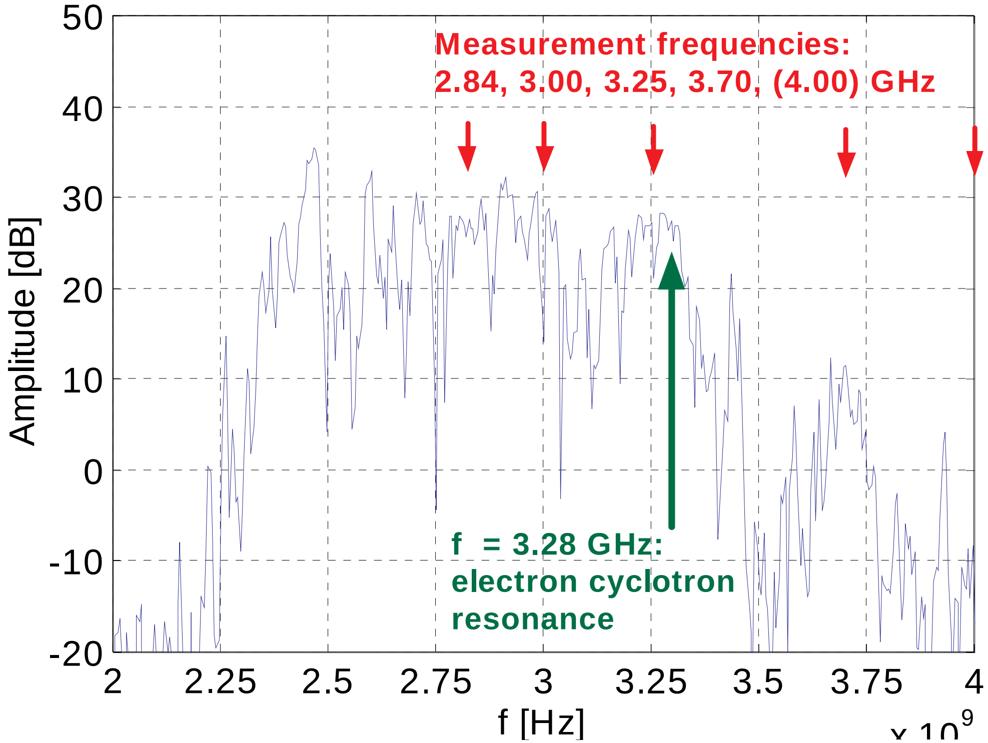
Modulation index $\beta = \Delta\varphi$ [rad]
Side-band amplitude = $\beta/2$

Measurement Set-up



Frequency Range

- Due to the maximum frequency of the SPA of 2.9 GHz, the signal was transposed to a lower frequency band by an external mixer and an additional local oscillator.
- Measurements up to 4.0 GHz were performed.
- Limitation by drop-off of hardware transfer function.



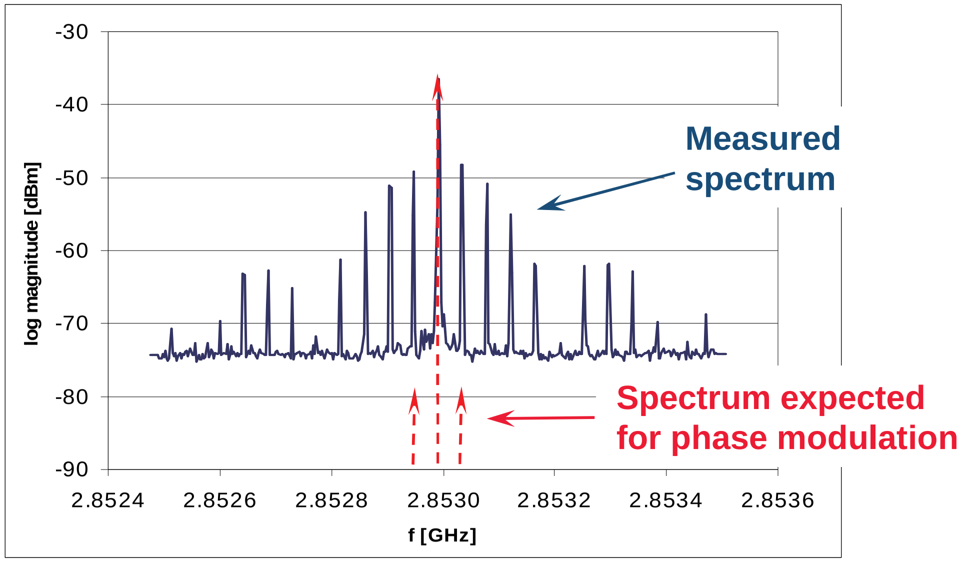
Hardware transfer function (transmission measurement without beam)

The Measured Spectrum

- Measurement over 1000 m found impossible due to
  - high additional attenuation by cross-section changes.
  - bad coupling efficiency of the bottons used (below –10 dB for the left button on the schematic).

=> Measurement just performed over 30 m (quick and dirty modification)

- Strong modulation in amplitude found.
- Basically the same modulation spectrum at all frequencies, except near cyclotron resonance.
- Completely different to what we expected.



LHC type accelerated,

72 bunch (1E11)
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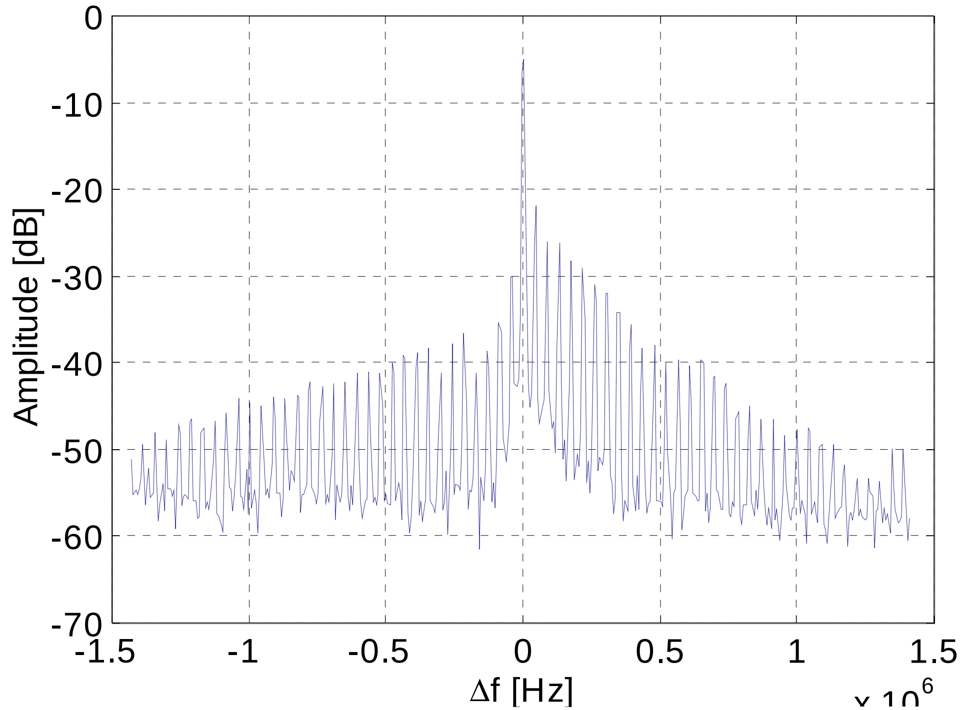
Electron Cyclotron Resonance

- Cyclotron resonance of electrons occurs at 28 GHz/T, thus at more than 3.25 GHz with B = 0.117 T in the magnets at injection.
- Close to this frequency a very asymmetric spectrum was found, pointing at an additional phase modulation (AM+PM).
- But: No asymmetric spectrum was observed during the ramping of the magnets at other frequencies.



Time Domain Measurements (1)

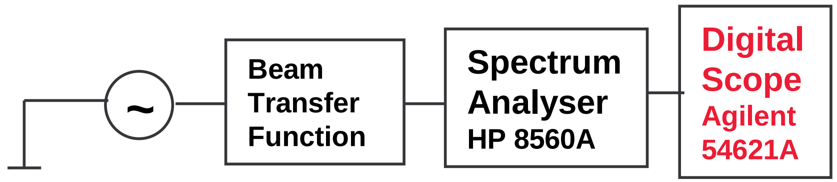
In short:

- We expected to observe the electron cloud density by measuring the phase modulation of a microwave running through the beam pipe.
- What we found instead was a very strongly amplitude and, for certain parameters, phase modulated signal.
- It is difficult to interprete such a signal in frequency domain, but one can do it more easily in time domain.

This is what was done next…

Time Domain Measurements (2)

- Just the carrier was displayed on a digital storage scope.
- To put it another way: We looked at the CW transmission over time.



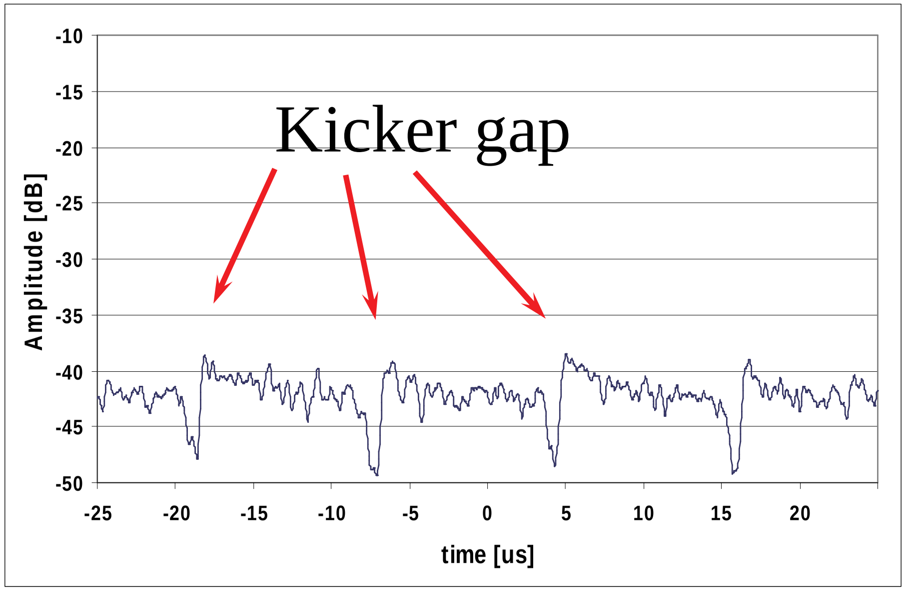
More technically,

- The video output in logarithmic format of the analog (!) spectrum analyser contains the screen information with 2 MHz maximum resolution bandwidth.
- This analog signal was transmitted to a digital storage scope to be able to display it in time domain.

- The initial concept of measuring a faint phase modulation by observing tiny side bands was suspended.

Measurement without Microwave Carrier

- The beam-induced signals can be seen as a noisy signal at roughly –40 dB.
- Please note that the absolute amplitude level is determined by the amplifier chain and the settings of the SPA. Vertical shifts from plot to plot are not physically relevant.
- Every ~11μs (corresponding to 2 SPS batches) the kicker gap can be observed as a little notch.



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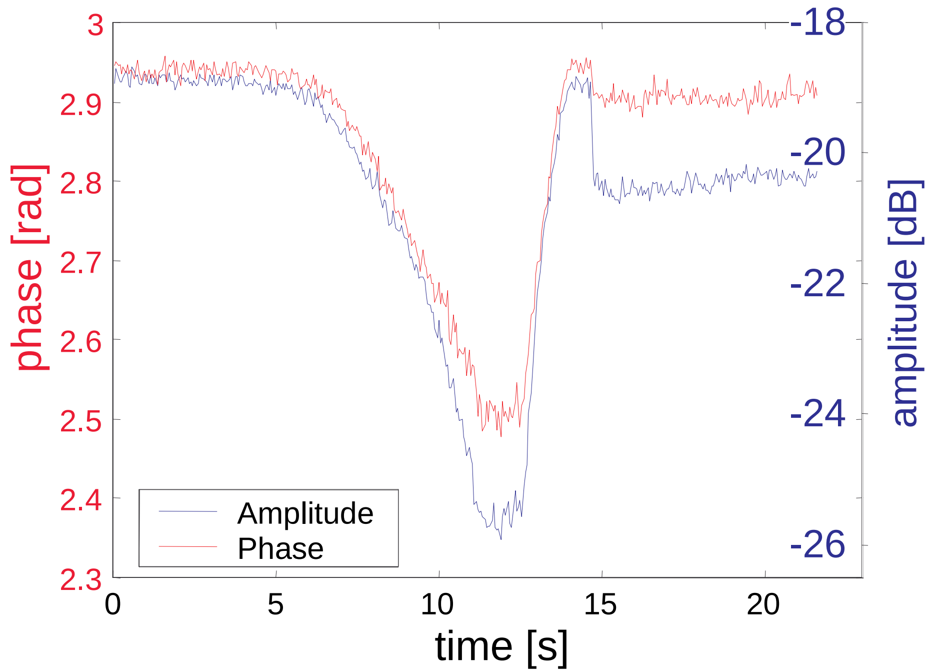
Measurement without Beam (1)



Surprise surprise!!!

SPS magnetic cycle shows up in amplitude and phase display versus time!

- Measurement performed on a vector network analyser in CW mode.
- To our surprise we noticed a bending field dependent amplitude and phase modulation.
- This magnetic field related modulation effect was very pronounced at certain frequencies and weak at others.

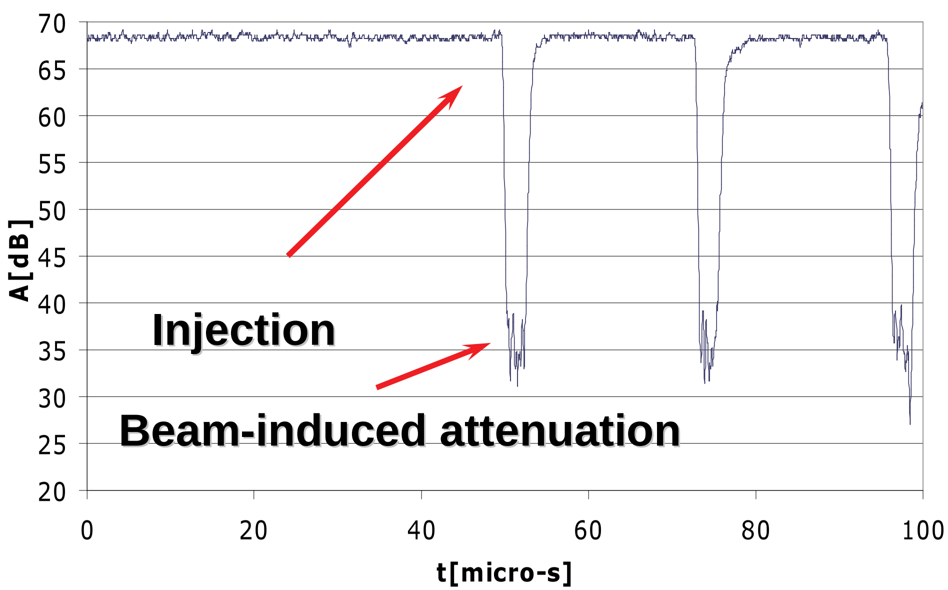
Measurement without Beam (2)

- Trying to find an explanation, we looked for elements in the beam-pipe with changing electromagnetic properties in the microwave range as a function of the bending field.
- Likely candidates are the NiCr layer coated ceramic tubes used for microwave absorption in the pumping ports in the fringe field of the bending magnets.
- However, the changes due to the ramping of the magnetic field are relatively small and happen over a much longer time scale than the beam-related observations.
- The effect of the changing magnet field was neglected in the following.

Measurements with Different Beams

Mesurements were performed for the following beam types:

- LHC type: 25 ns bunch spacing, 26 GeV/c at injection, acceleration up to 450 GeV/c
- FT type: 5 ns bunch spacing, injected at 14 GeV/c and accelerated mostly up to 400 GeV/c
- Single bunch beam



LHC type, 25ns bunch spacing, 1 batch

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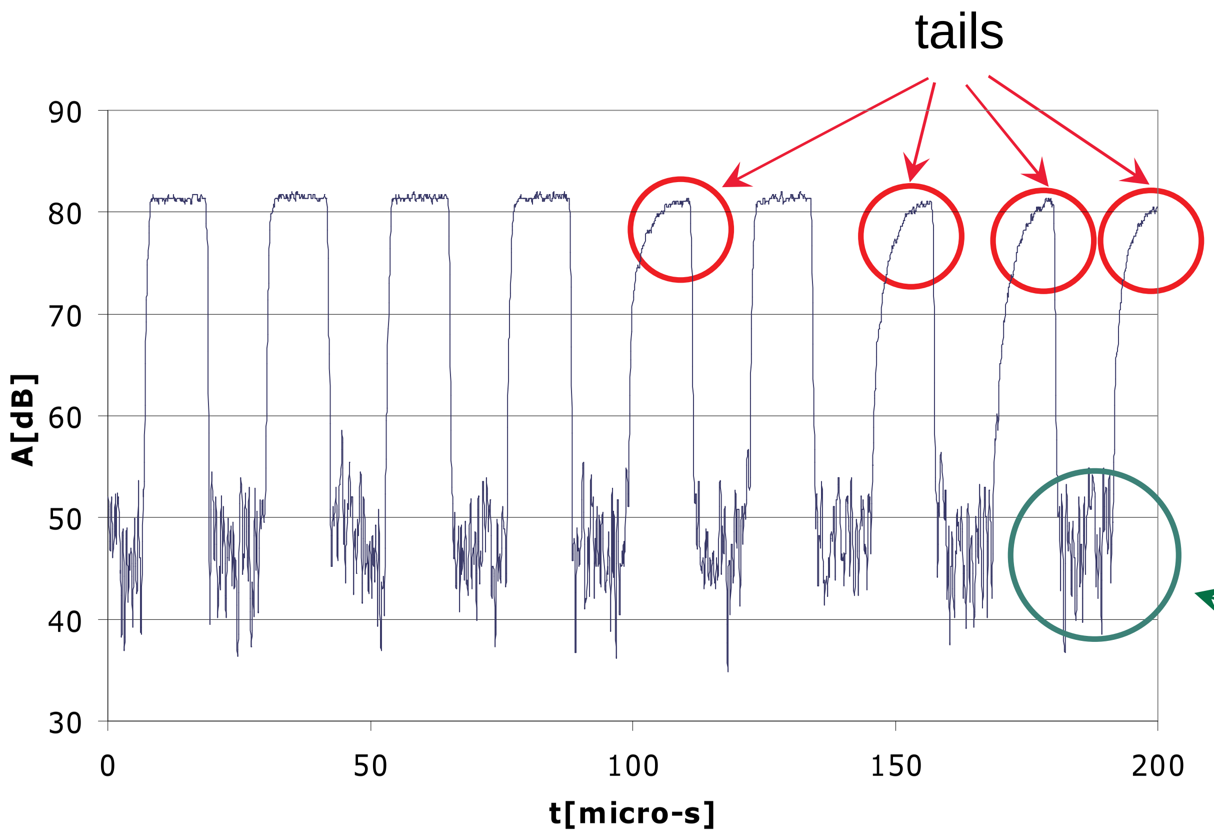
Tails

- Tails appearing in a random (?) manner.



FT type

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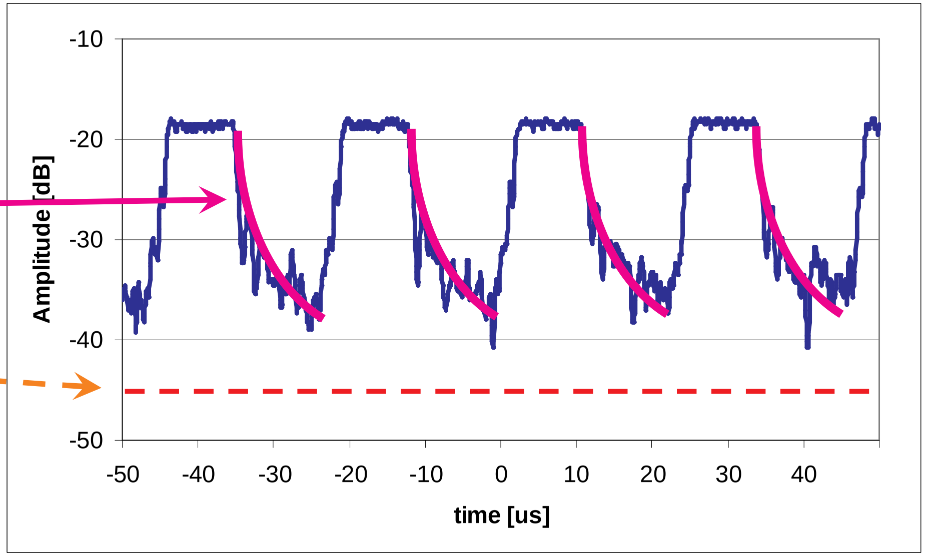
Noise floor (mainly determined by SPA noise figure)

Build-up Time

- When we have tails, we would also expect a build-up time.
- For fairly small beam we can distinguish a change in slope before reaching a kind of steady state (caution: vert. scale: dB).
- For higher intensities we were limited by the noise floor of our instrumentation.
- It is assumed that this build-up time is always present but often masked by the general system noise floor for strong beams.

Build-up time in the range of a few μs

Noise floor



FT type

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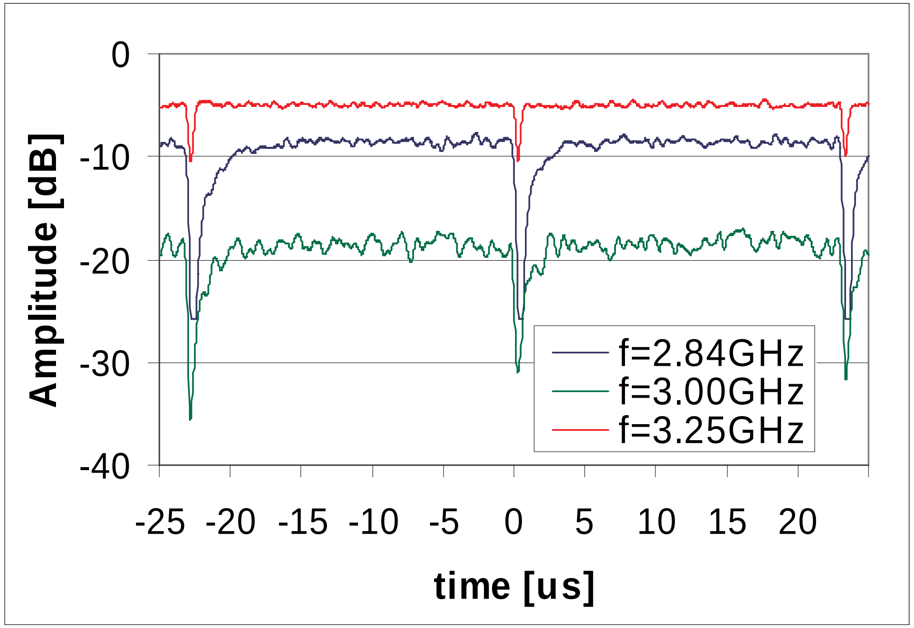
Single Bunch Beam

- Tails still appear…
- For frequencies above ~3 GHz they seem to be less pronounced.



Single bunch beam

Tuesday, July 22, 2003, 7:57:27 PM

PS logbook:

Mesures d'emittances MESPS (1 bunch, low intensity)

Int. (ej.): 1.03 E10

Bunch lenght (ej.): 4.13 ns

Dp/p (ej): 1.695E-3

eL: 0.291 eVs/u (at c 1100)

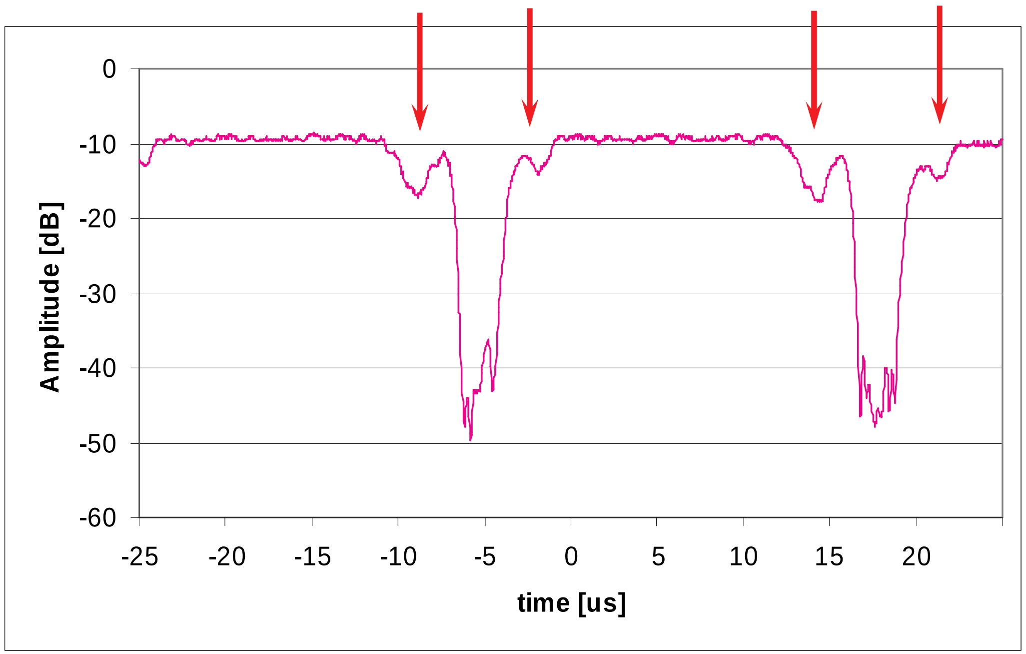
eH: 3.48 (1 sigma)

eV: 0.54 (1 sigma)

Longitudinal Bunch Shape

- Time structure of the batch shape can be observed very nicely.

Longitudinal spill after injection
(injection mismatch?)

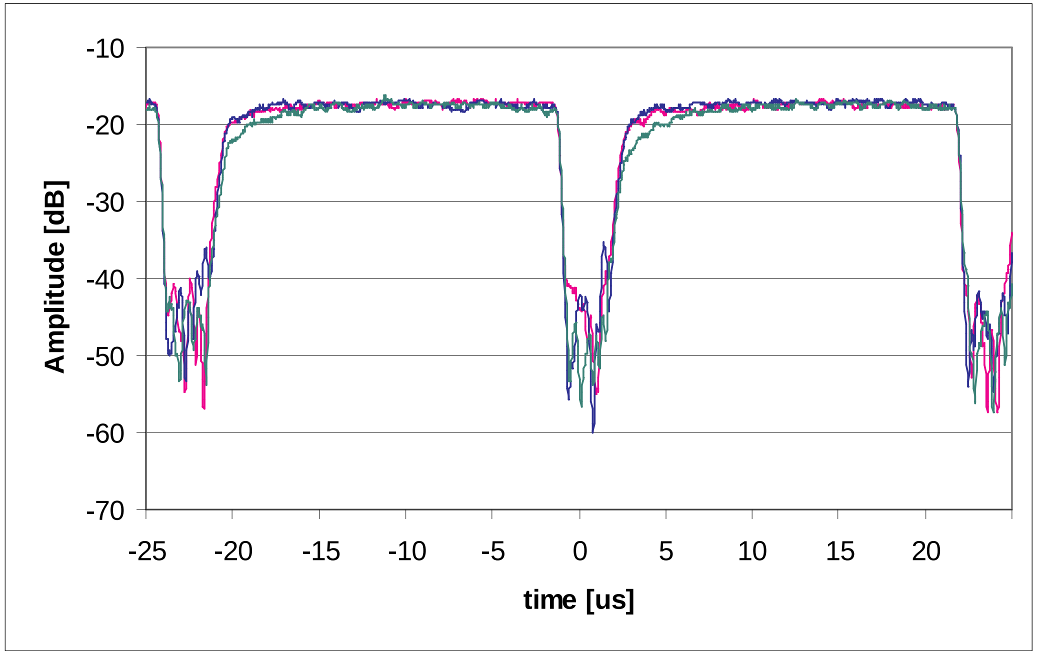


Machine Development Session,

Tuesday, June 03, 2003, 2:50:44 AM

Measurements over the Machine Cycle

- Measurements were performed at injection, during the ramping and on the flat top.
- No change in the tail's behaviour as a function of the "static" magnetic field could be found.



$f = 2.84$ GHz,

$B \approx 1.3$ T (Flat top)

Three traces selected at random

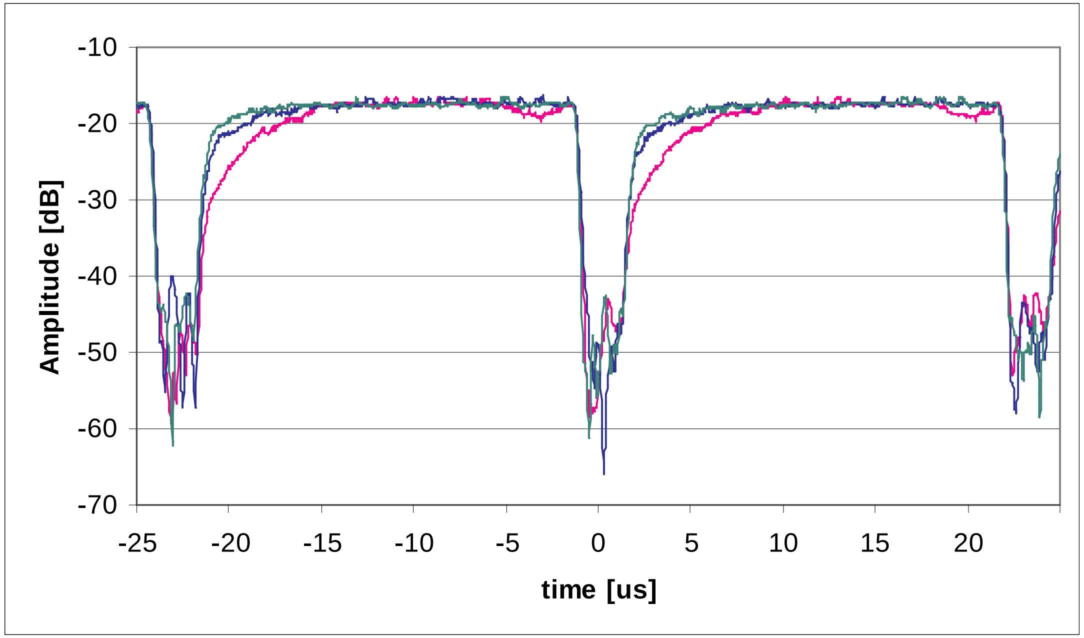
Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

Measurements at Various Microwave Carrier Frequencies

- Frequencies between 2.84 and 3.25 GHz used.
- Basically the same effect observed for all frequencies: erratic tails.
- Less pronounced for higher frequencies.



f = 2.84 GHz,

B = 0.117 T (injection)

Three traces selected at random

Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

Changing the Vacuum Pressure

- Concept: the vacuum pressure should have an impact on all kinds of ionization effects, thus giving some measurable effect.
- Measurements were performed with vacuum pressure increasing from $3*10^{-9}$ to $1.3*10^{-8}$ Torr.
- No significant change was observed at f = 2.84 GHz.

Summary of the Time Domain Observations

- We have observed
  - a very high microwave signal attenuation during the passage of the beam
  - a reproducible build-up time for small beams
  - erratic tails
- The tails were found
  - for many different microwave carrier frequencies
  - during the entire machine cyle
  - for different beam intensities
  - for single bunch beams
- The “life-time” and “build-up time” of these memory effect is in the range of a few μs.
- There seems to be no threshold unlike for (classical) electron-cloud formation.
- A variation of vacuum pressure (by a factor of 4) did not show any visible change.

Discussion (1)

- There is a lack of quantitative understanding about the observed high attenuation with beam and about the memory effects.

- Assuming that the beam-induced plasma is the relevant ingredient we conclude that at microwave frequencies we can see interactions with the electrons of this plasma only.

- The high attenuation with beam could indicate that the plasma frequency is above the microwave frequency used. However, the theoretical plasma density should be extremely high, that is beyond 10^{16} per m^3.
- Such a plasma may be very localized.

Discussion (2)

- There are two common theories that could be thought of trying to explain the <u>memory effects</u>:
  - Pinch effect. During the passage of a bunch electrons are attracted towards the center of the beam pipe. The high local density may be explained, but simulations [1] predict that the electrons are cast against the wall with life times in the order of ns.
  - Secondary electrons bouncing back from the walls. This could explain the observed life time in the order of a few μs, but the predicted electron densities are four orders of magnitude off.

[1] Electron-Cloud Simulations: An Update, F. Zimmermann, Chamonix XI, 2002

Discussion (3)

- Another possibility might be microparticles with diameters in the order of 1 μm in the beam line.
- Dust trapping should not occur since we are dealing with positive beams, but occasional passages of dust particles could still be possible.
- If a dust particle gets hit by the beam, a plasma with sufficiently high electron density might form locally, giving rise to the observed tails.

- The raising of dust by a positive potential was observed in other fields of science, for example scanning electron microscopy or dust accelerators used in planetary and space science.

Outlook

Following many suggestions, the measurement assembly has been modified:

- A high power end amplifier was added, providing up to 30 W output power compared to 30 mW before.
- An additional pick-up was installed only 7 m from the first pick-up in a section with only one bending magnet.
- A electromechanical relay was mounted on the beam pipe. When it vibrates, dust particles should come off the walls of the beam pipe, thus allowing to verify the dust hypothesis.

The following new measurements are in discussion:

- Inverse direction
- In other machines (volunteers welcome!!)

Acknowledgements

- We would like to thank Thomas Bohl and Frank Zimmermann for help and advice. Thanks to Flemming Pedersen for inspiring discussion, Trevor Linnecar for support and last but not least Noel Hilleret for the initial suggestions and helpful discussion.