Unexpected Beam Induced TE Waveguide Mode Modulation Effects in the SPS around 3 GHz

INFN Frascati, 28.11.2003

Fritz Caspers, Tom Kroyer, CERN AB-RF-FB

Agenda

- Motivation
- Expected results (theoretical predictions)
- 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 (no conclusion)

(electron cloud laughing at us)

Motivation (1)

- Initial idea: Measure electron cloud induced modulation of first waveguide mode, which are of TE type in magnet sections
- A measurement between BA2 and BA3 was envisaged in order to get a sizably height of the beam-induced modulation side bands
- The attenuation of a homogeneous ~1km long stainless steel beam-pipe was expected to be around 70dB @ 2GHz

- 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 3GHz.
- A similar effect can be observed in the ionosphere, too. It's one of the major factors limitating the accuracy of GPS

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

Expected phase shift (1)

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 -17º.

Expected phase shift (2)

For static magnetic field perpendicular to the beam the phase shift is proportional to

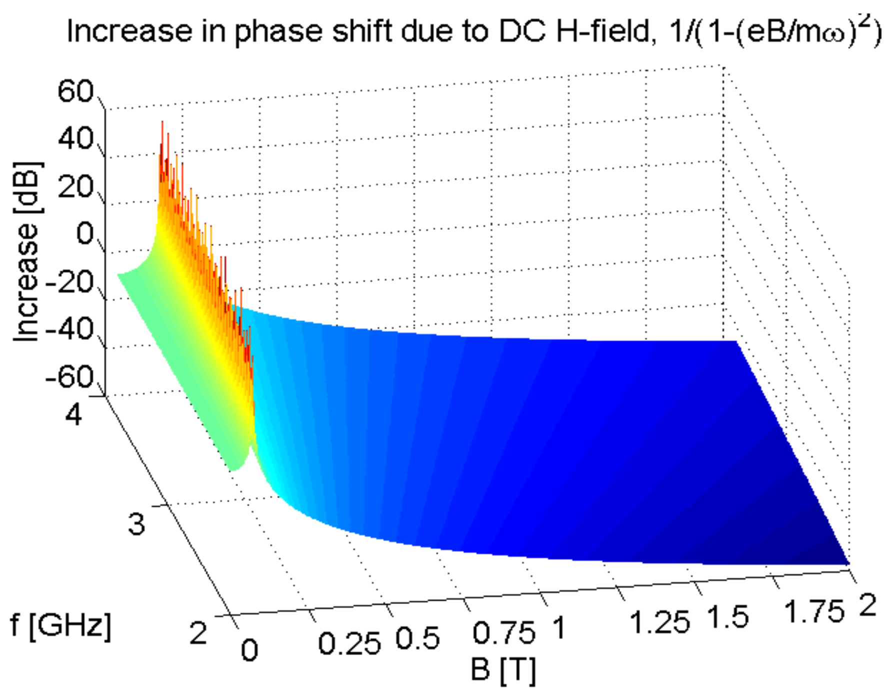
$$\frac{1}{1-\left(\frac{eB}{m\omega}\right)^2}$$

For the cyclotron resonance frequency (3.275 GHz @ B=0.117 T at injection) we have a singularity. For increasing magnetic fields this singularity moves linearily (~B) up in frequency.

References:
Private communication J. Tueckmantel, 29/09/2003

Expected phase shift (3)

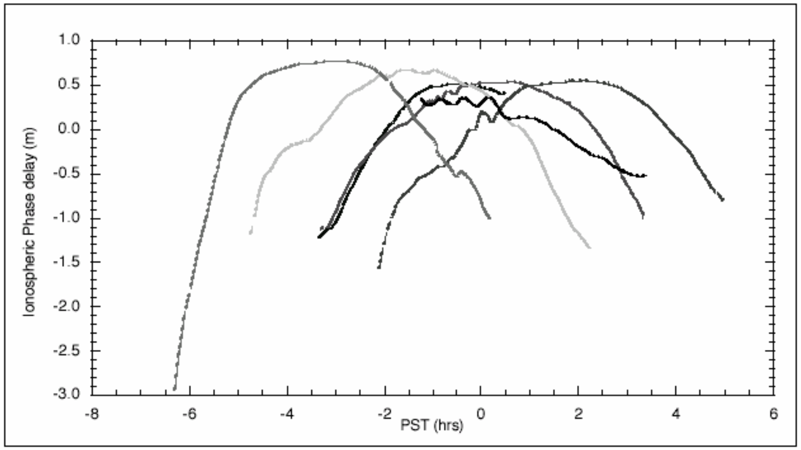
The plot shows the increase in phase shift due to the perpendicular B-field. For higher magnetic fields the phase shift should be considerably decreased. Vertical scale indicates sideband amplitude



Ionospheric delays in GPS

- In the ionosphere the maximum ion density is roughly 10^{12} per m^3, comparable to the (usual) electron cloud density
- Over say 500km of ionospheric propagation the measured phase delay is roughly 1m, corresponding to a phase shift of 4 degrees per km. This is in reasonably good agreement with the calculation done above.

Example of JPL in California



References:

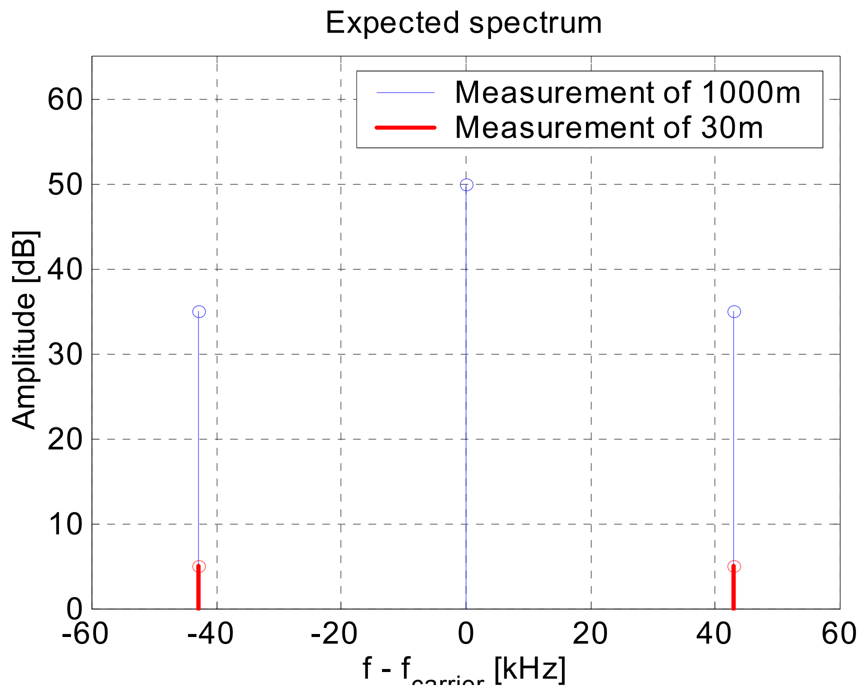
Modern Navigation,
Thomas Herring (tah@mit.edu),
http://bowie.mit.edu/~tah/12.215

Motivation (2)

- 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 results

- 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

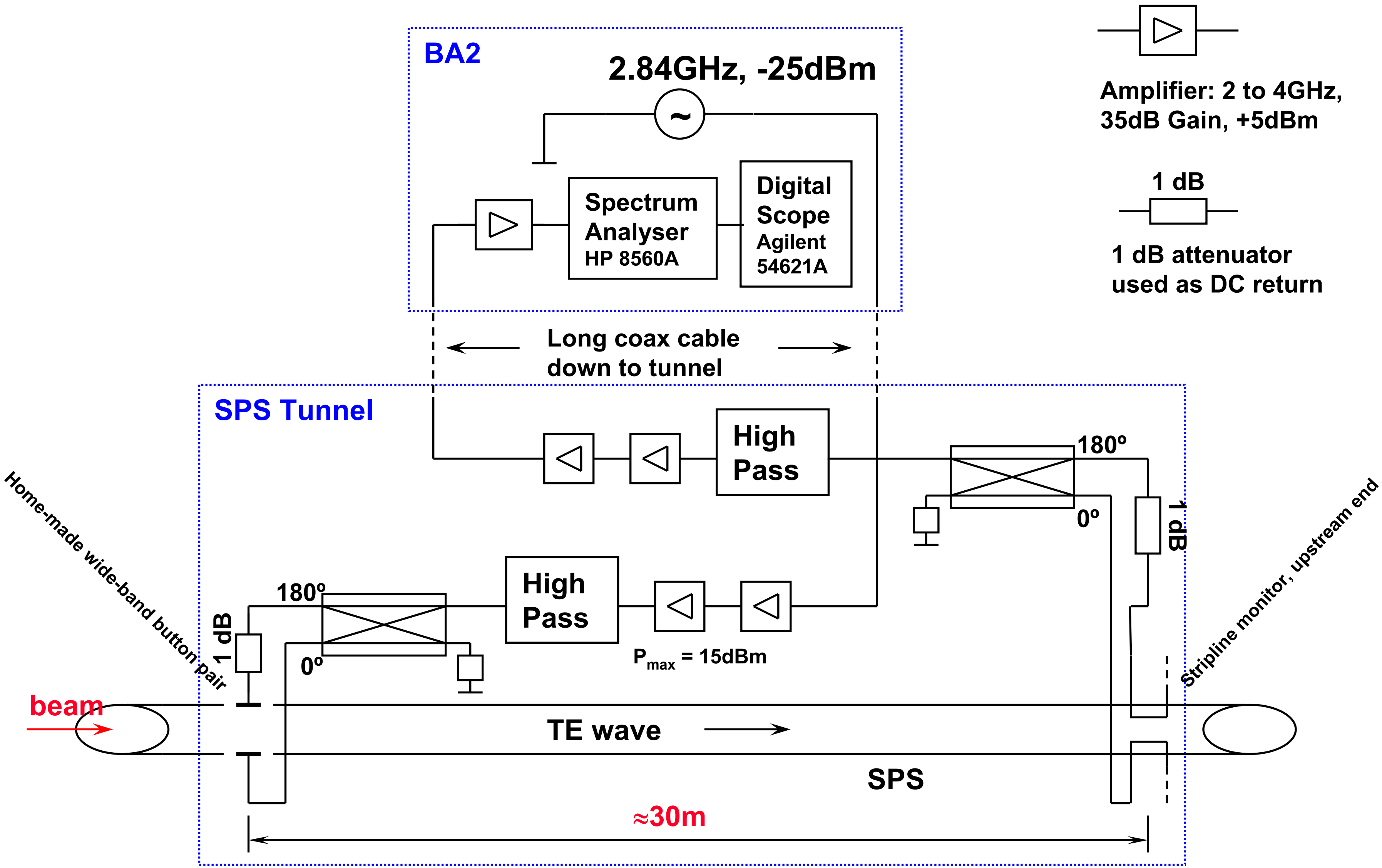


Length of line L [m]	Phase change $\Delta\varphi$ [°]	Modu-lation index β [1]	Side-band amplitude A_{sb} [dB]
1000	20	0.35	-15
30	0.6	0.01	-45

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

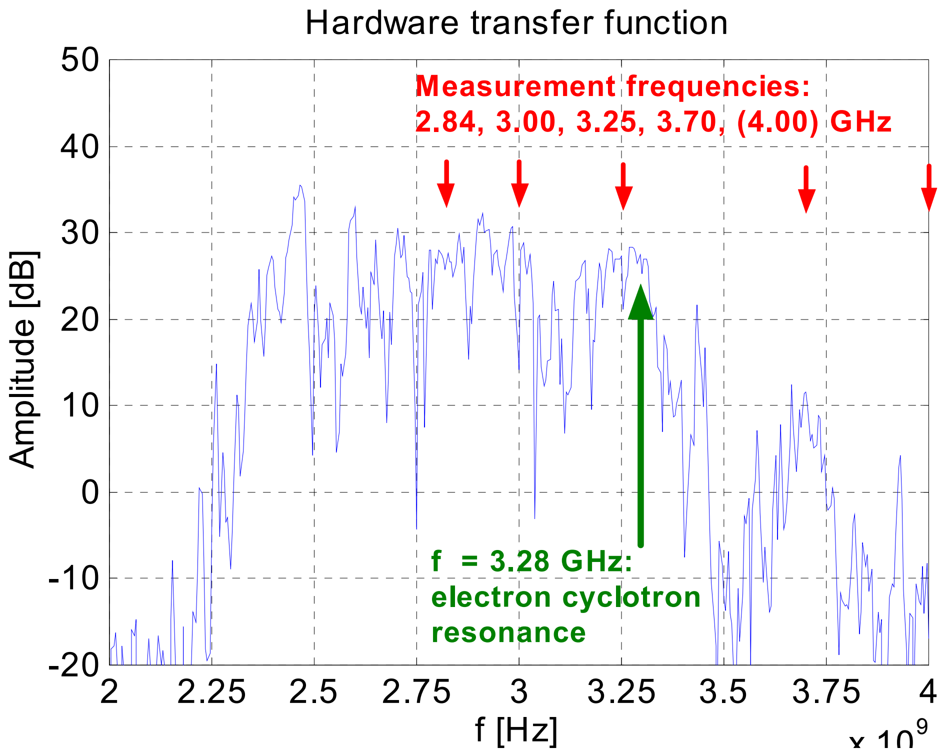
Side-band amplitude = $\beta/2$

Measurement set-up



Frequency range

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



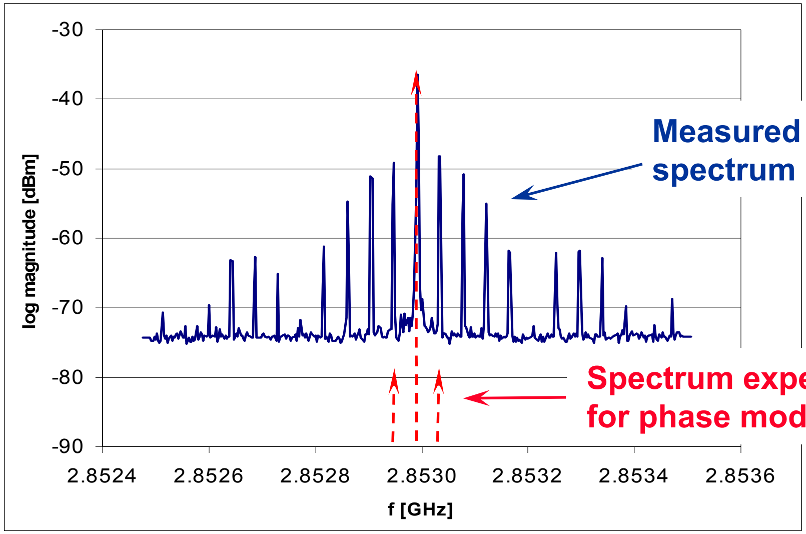
Transmission measurement without beam

The measured spectrum

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

=> Measurement just performed over 30m (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

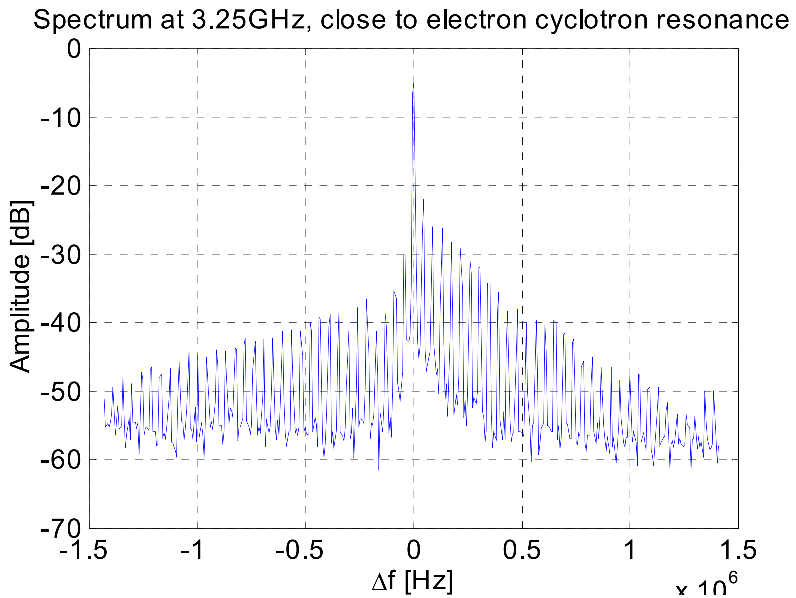


LHC type accelerated,

72 bunch (1E11)
Wednesday, July 02, 2003, 5:11:56 PM

Electron cyclotron resonance

- Cyclotron resonance of electrons occurs at 28GHz/T, thus at more than 3.25GHz with B=0.117 T in the magnet 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)

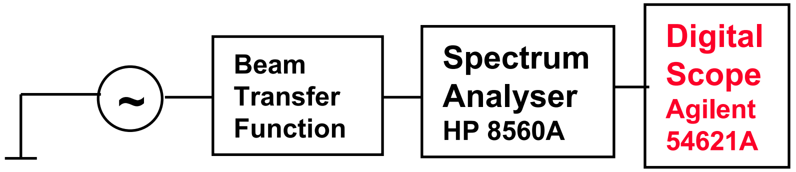
In short:

- 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



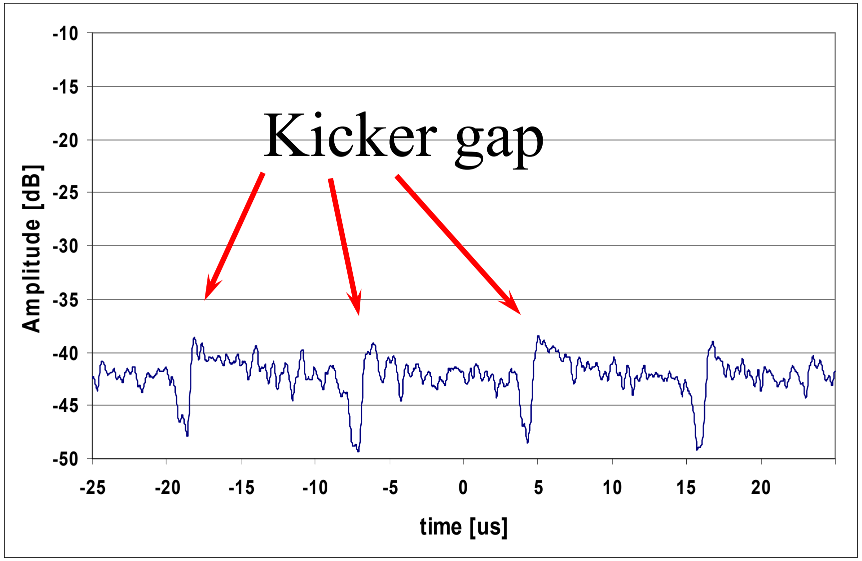
More technically,

- The video output in logarithmic format of the analog (!) spectrum analyser contains the screen information with 2Mhz maximum resolution bandwidth (from the rear of the spectrum analyser)
- 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

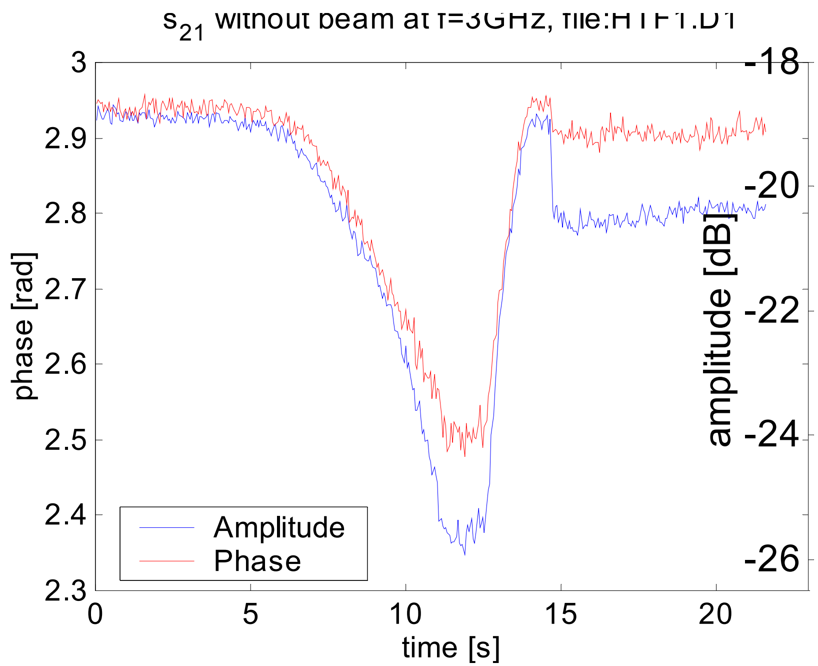
Measurement without carrier

- The beam-induced signals can be seen as a noisy signal at roughly –40dB. In fact, the absolute level is determined by the amplifier chain and the settings of the SPA.
- Every ~11μs (corresponding to 2 SPS batches) the kicker gap can be observed as a little notch



Thursday, August 07, 2003, 11:50:56 AM

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
- 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

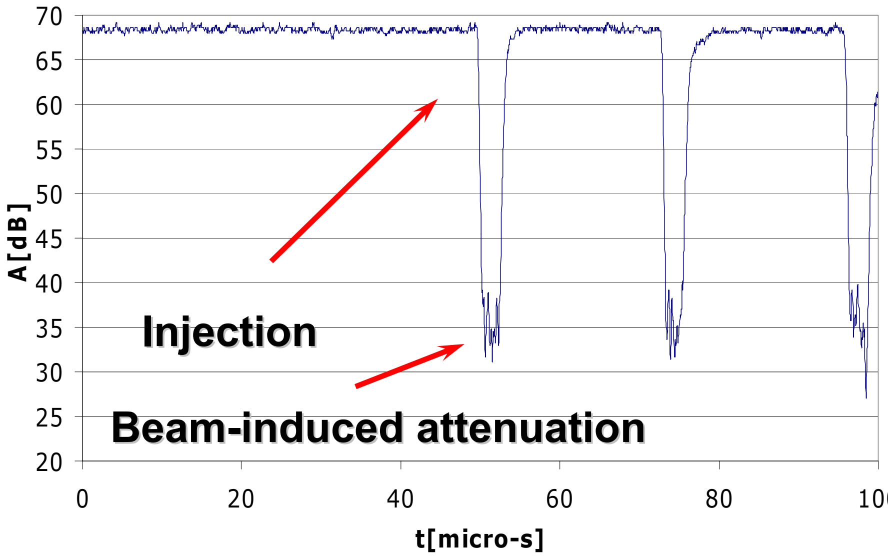
Measurement without beam (2)

- 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
- All active electronics (microwave amplifiers) were at least 1m away from the beam-pipe. Any B field-related impact on the solid state amplifiers should be not be frequency-selective
- A very promising candidate are the NiCr layer coated ceramic tubes used for microwave absorption in the pumping ports
- This resistive layer is much thinner ($R_S \sim 100\Omega$) than the skin depth @2GHz and exposed to the fringe field of the bending magnets
- At these frequencies NiCr has a μ_r of about 15 without a DC bias field, but μ_r depends on the DC magnetic field (saturation)

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 to 450 GeV/c
- Single bunch beam

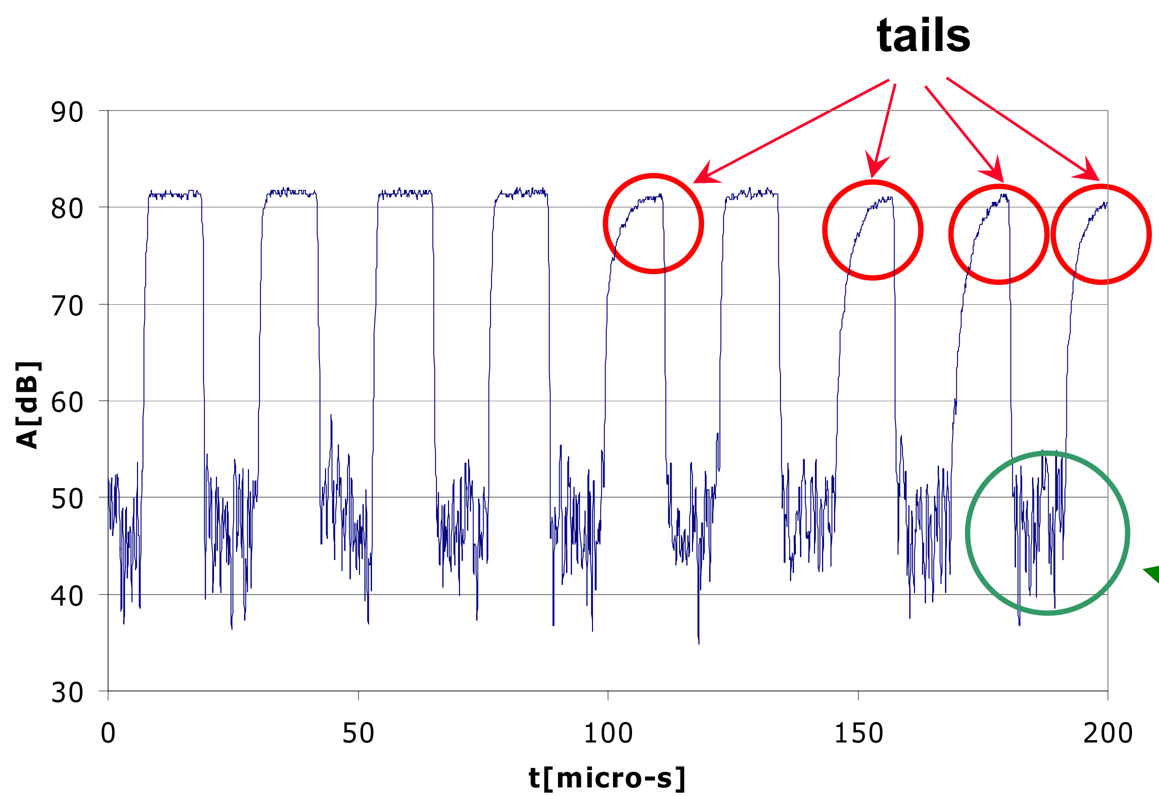


LHC type, 25ns bunch spacing, 1 batch

PRINT_203: Tuesday, June 10, 2003, 9:11:50 AM

Tails

- Tails appearing in a random (?) manner



FT type

PRINT_208: Wednesday, June 11, 2003, 10:09:30 AM

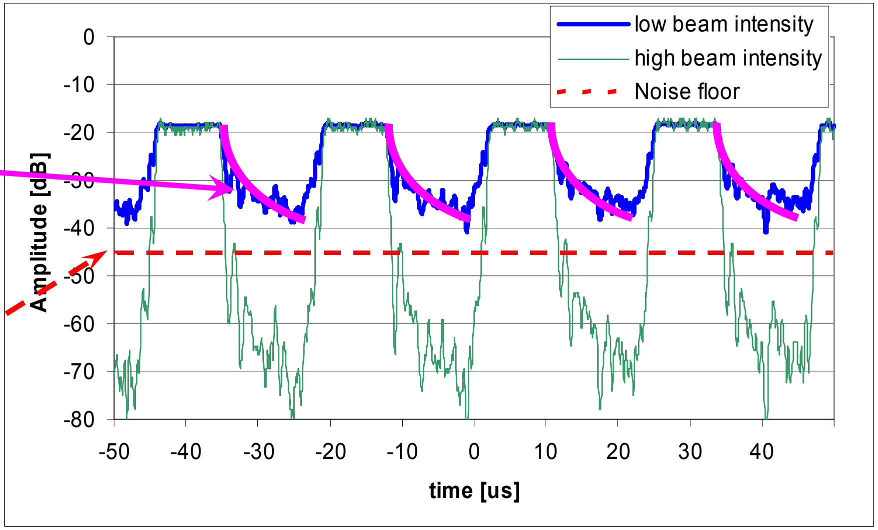
Noise floor (mainly determined by SPA noise figure)

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 attenuation we were limited by the noise floor of our instrumentation
- Is 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

Limitation by system noise level

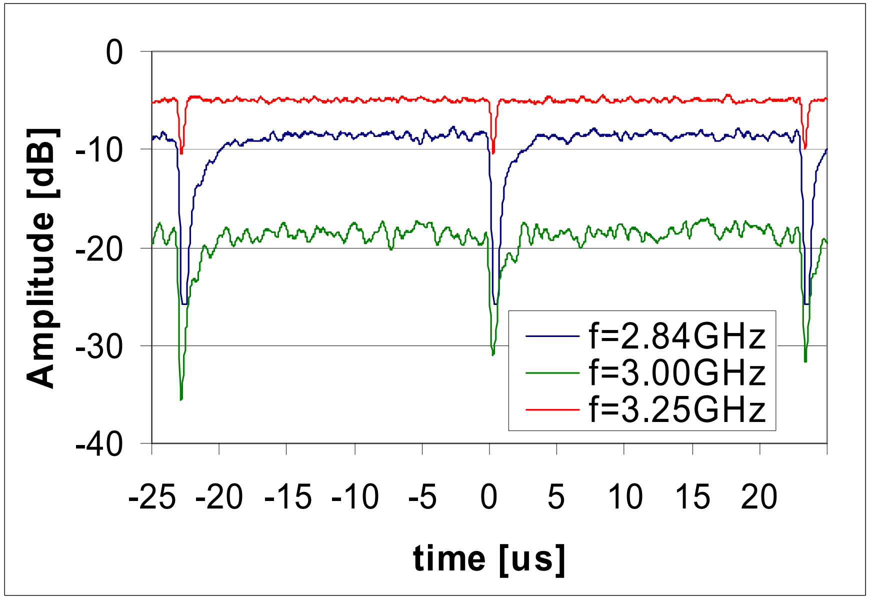


FT type

PRINT_210: Wednesday, June 11, 2003, 10:12:02 AM

Single bunch beam

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



Single bunch

Blue trace: PRINT_01

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)

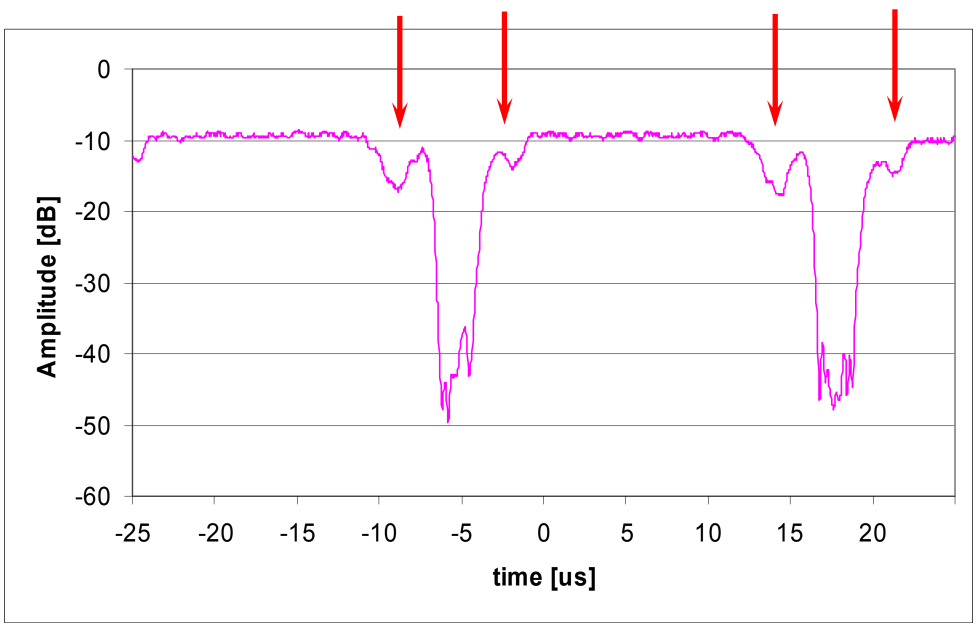
eH: 3.48 (1 sigma)

eV: 0.54 (1 sigma)

Longitudinal bunch shape

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

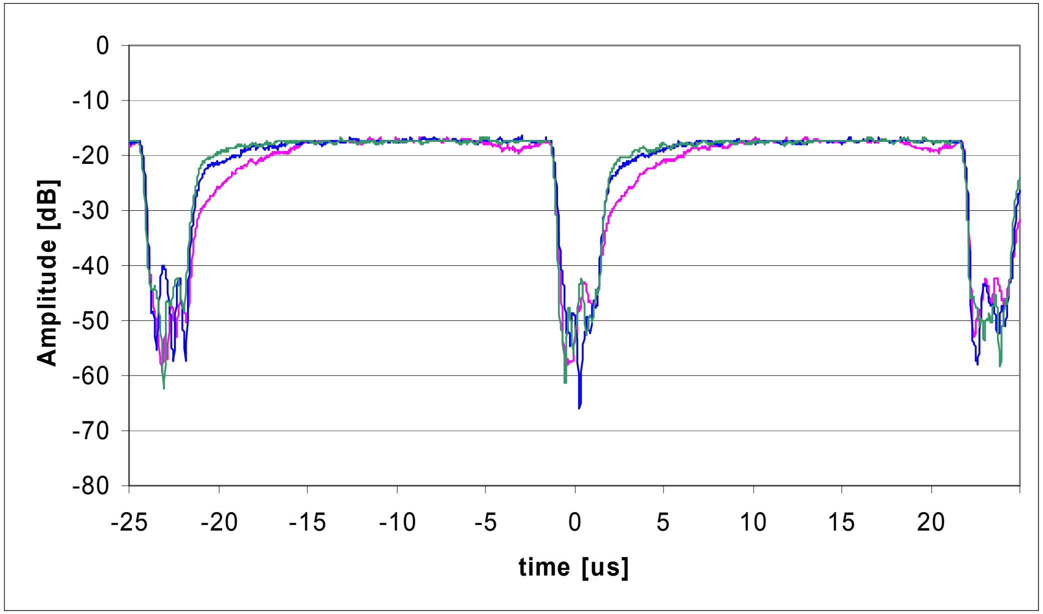
Longitudinal spill after injection
(injection mismatch?)



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

During the machine cycle (1)
Injection @ B=0.117 T

- Measurements for different magnetic fields at f=2.84GHz
- Three randomly selected traces, taken with the same operating conditions
- Usually we see fairly large variations between those traces



For the following traces:

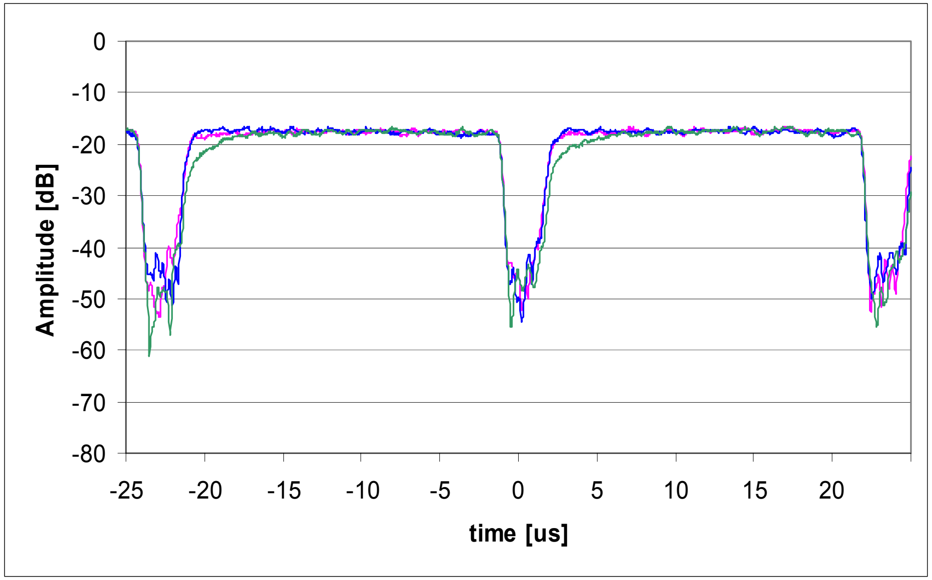
Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

During the machine cycle (2) Ramping

- Cyclotron resonance might appear in the fringe field, which is lower than ordinary bending field and thus be visible at 2.84GHz (corresponding to 0.1043T)
- During the ramping no distinct resonance absorption (additional attenuation) was observed



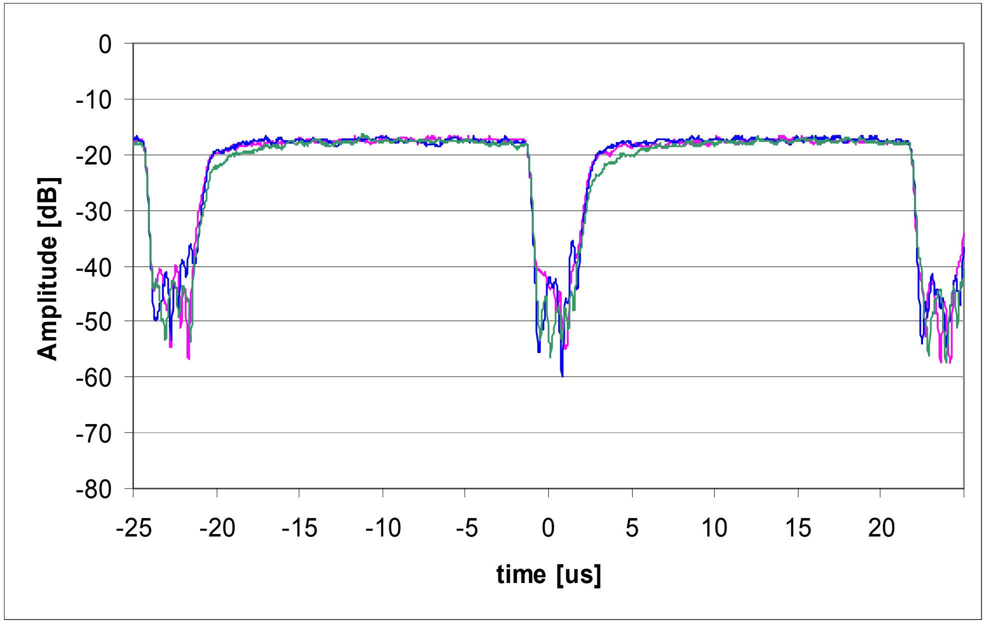
Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

During the machine cycle (3) Flat Top

- The traces look essentially the same during the entire machine cycle (i.e. between 26 and 450 GeV/c)



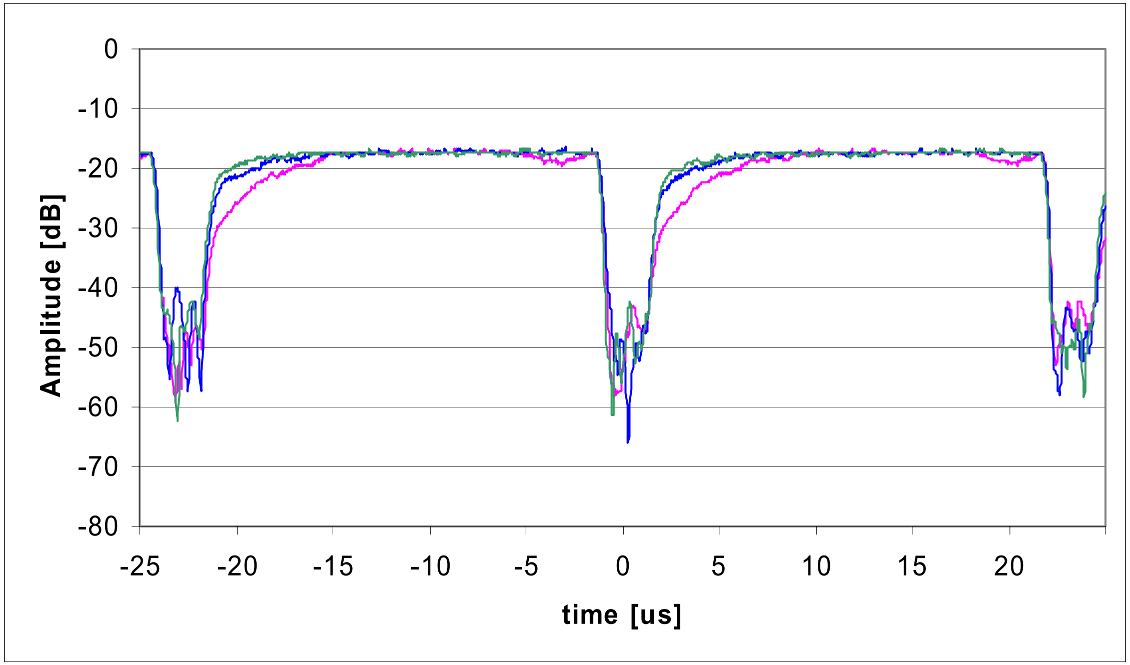
Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

At different frequencies (1)
f = 2.84 GHz

- Traces taken after injection at B=0.117 T are shown
- Again three traces per plot, taken under same conditions



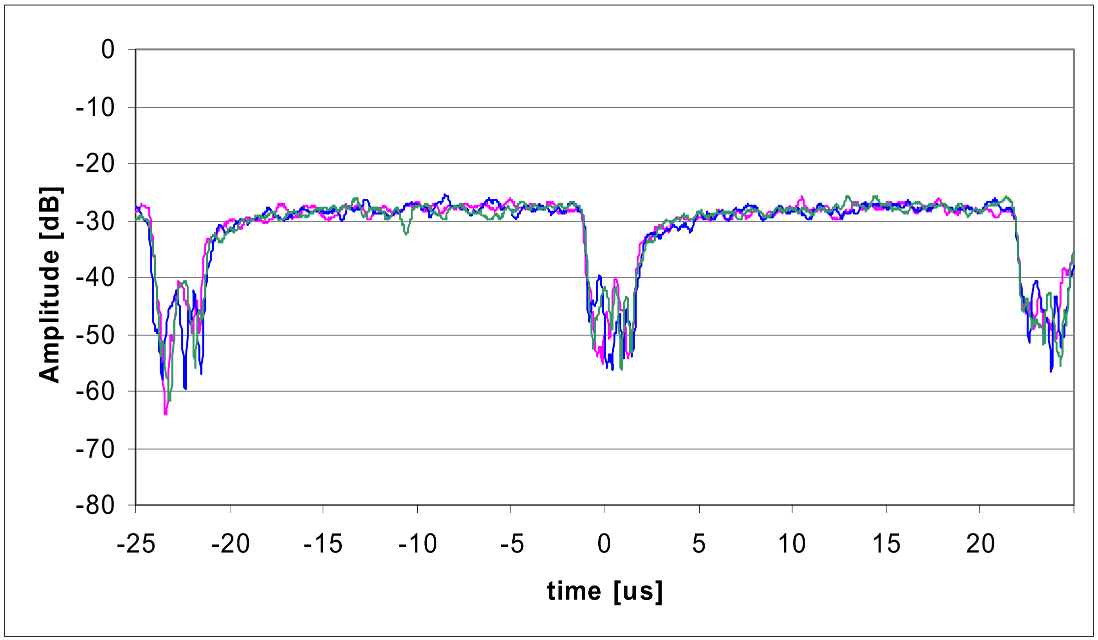
Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

At different frequencies (2)
f = 3.00 GHz

- Lower signal level due to strongly frequency-dependent Hardware Transfer function
- Tails less pronounced than at 2.84GHz



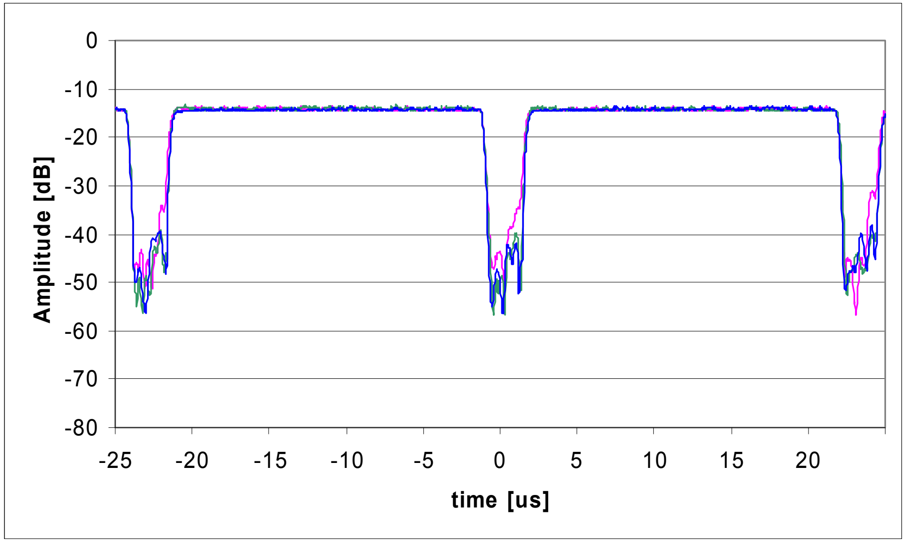
Thursday, 31/07/2003, before 13:00

72 bunches, 25 ns spaced.

Intensity: $3.2*10^{12}$

At different frequencies (3)
f = 3.25 GHz

- Tails still less pronounced than at 3.00GHz
- The observed effect appears to be frequency-dependent, decreasing with increasing frequency in our frequency range
- This observation could point towards a plasma frequency close to 3 GHz… ?!



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

72 bunches, 25 ns spaced.

Intensity: 3.2*10^{12}

Changing the vacuum pressure

- Concept: vacuum pressure should have an impact on all kinds of ionizion 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=2.84GHz

Potential sources of errors

- Saturation of amplifiers by beam charge hitting the buttons:
  - This effect can be ruled out due to precautions taken for the mesurement set-up
  - The amplifiers are separated from the buttons by a high-pass filter realized by a short waveguide section.
  - All signals from DC up to 2GHz are cut away
  - Direct beam-induced signals (pick-up effect) above 2 GHz have been measured and are small compared to the amplitude modulation observed here (c. f. slide Measurement without carrier)
  - Usually during the passage of a batch the output power of the amplifier is increased; here, the situation is exactly opposite (beam-induced attenuation)
- Others… ?

Summary of the time domain observations

- We have seen a reproducible build-up time for small beams and memory effects such as tails with a strong scatter
- They were observed at
  - many different frequencies
  - during all the machine cyle
  - for different beam intensities
  - even for single bunch beams
- The “life-time” and “build-up time” of this plasma appears to be in the range of a few μs
- There seems to be no threshold for this effect 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 memory effects, since direct beam-interaction can be ruled out
- No distinct threshold like for electron cloud formation has been observed

- Assuming that the beam-induced plasma is the relevant ingredient we can conclude that at microwave frequencies we see interactions only with the electrons of this plasma
- The theoretical plasma density should be extremely high, that is beyond 10^{16} per m^3. However, this plasma may be very localized (pinch effect as observed in other machines)

- At the Los Alamor Proton Storage Ring, electron survival after bunch passages has been observed which can linger for $\approx 1 \mu s$.

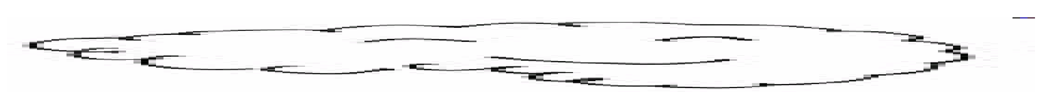
References: Electron cloud diagnostics in use at the Los Alamos PSR,
R.J. Macek at al., 2003

Discussion (2)

- A possible explanation could be given by a high density pencil-shaped electron plasma. However the electrons would be cast against the beam-pipe walls after the passage of each bunch (time constant: ns)
- According to common theories two effects could account for the observed behaviour:
  - Pinch effect. Very short range in the order of a few ns, but may explain high local density
  - Secondary electrons bouncing back from the walls. Could explain observed lifetime in the order of a few μs but not high local densities

Discussion (3)

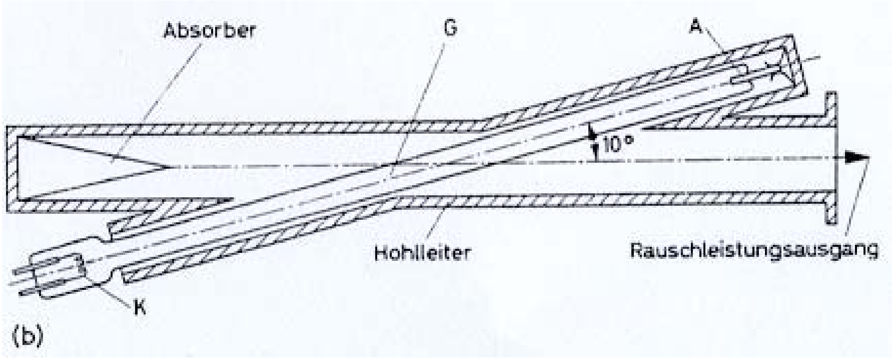
- Maybe there is some other effect that keeps the electrons in the center of the beam-pipe… the time constant of the ionization is in the range of μs, which corresponds to the observed time constants
- Another possibility might be some plasma-wakefield interaction in the fringe field of the magnets and/or at inhomogenities in the beam-pipe



(pencil shaped electron cloud laughing at us)

Analogy to old noise generators

- Argon or Neon Gas discharge tubes in waveguide instead of today's solid state noise generators
- In dependance of the state of the gas tube (hot/cold) the S-parameters of the device vary. This has to be taken into account for precise noise figure measurements
- A similar effect, of course on another scale, can be expected for the beam-pipe



Outlook

- Measure with higher microwave power (up to 10W compared to 10mW now)
- Check by measuring in reflection mode
- Measure in inverse direction (exchange pick-up and kicker)
- Measurement with indium ions in the SPS (coming soon)
- Injection of small quantities of other gases (Ar, N) in the measurement section with beam present (N. Hilleret dixit)
- Measurements in other machines (volunteers welcome!!)

- Whatever you can image…

Acknowledgements

- We would like to thank Jean-Francois Malo, Wolfgang Hoefle, Thomas Bohl, Joachim Tueckmantel and Frank Zimmermann for their help and advice. Thanks to Flemming Pedersen for inspiring discussion, Jose Miguel Jimenez for providing acces to the buttons, Trevor Linnecar for support and last but not least Noel Hilleret for the initial suggestions and helpful discussion.