Direct Diode Detection (3D),

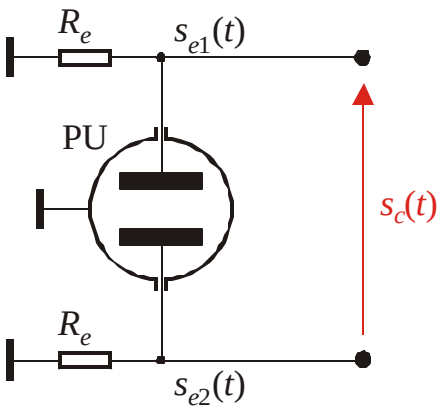
Base-Band Q (BBQ) Measurement,

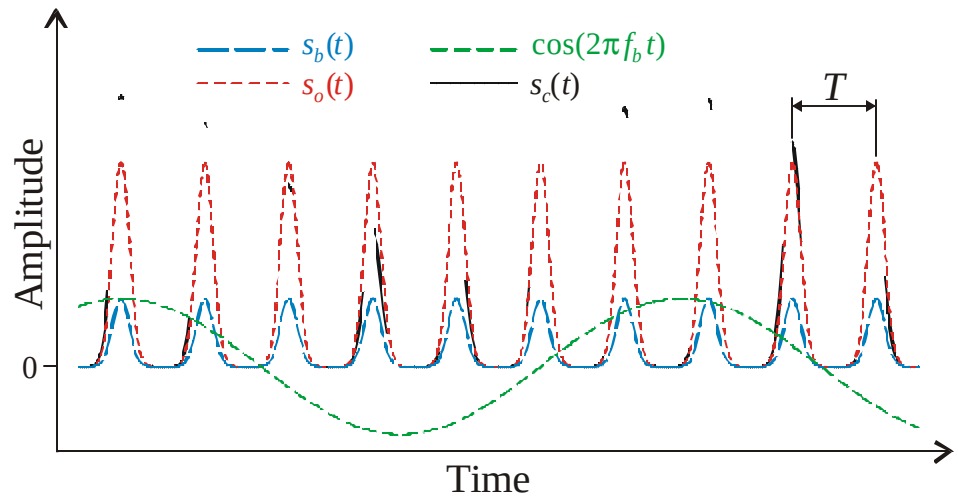
Some SPS and PS 2004 Results

Marek GASIOR, CERN-AB-BDI

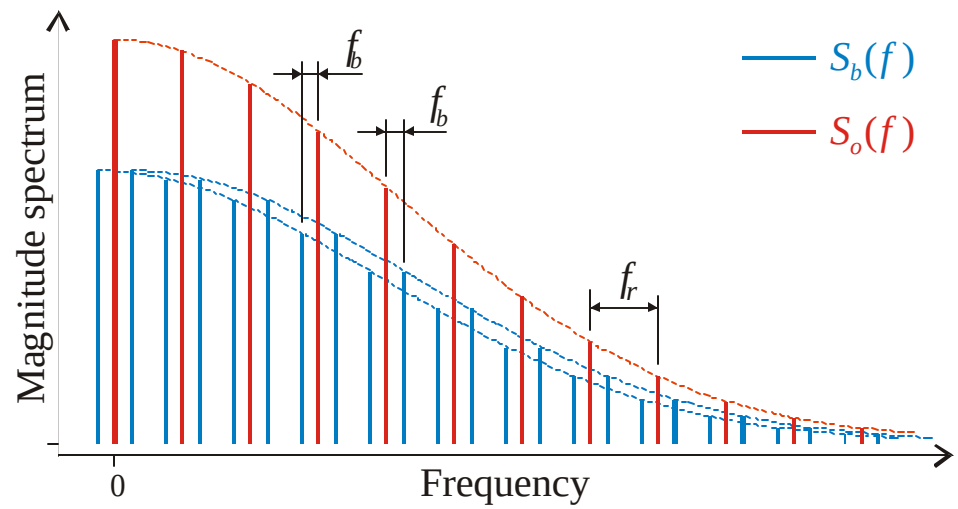
Tune Measurement – Classical Approach

$$s_c(t) = \cos(2\pi f_b t)\left(s_{b1}(t) * \sum_{n=-\infty}^{\infty} d(t-nT) \right) + s_{o1}(t) * \sum_{n=-\infty}^{\infty} d(t-nT)$$





$$S_c(f) = \left| \frac{1}{2} S_{b1}(f-f_b) \sum_{n=-\infty}^{\infty} d\left(f - f_b - \frac{n}{T} \right) + \frac{1}{2} S_{b1}(f+f_b) \sum_{n=-\infty}^{\infty} d\left(f + f_b - \frac{n}{T} \right) + S_{o1}(f) \sum_{n=-\infty}^{\infty} d\left(f - \frac{n}{T} \right) \right|$$



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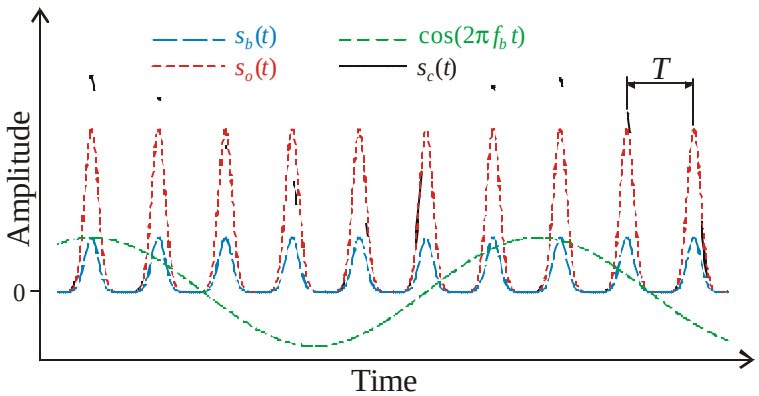
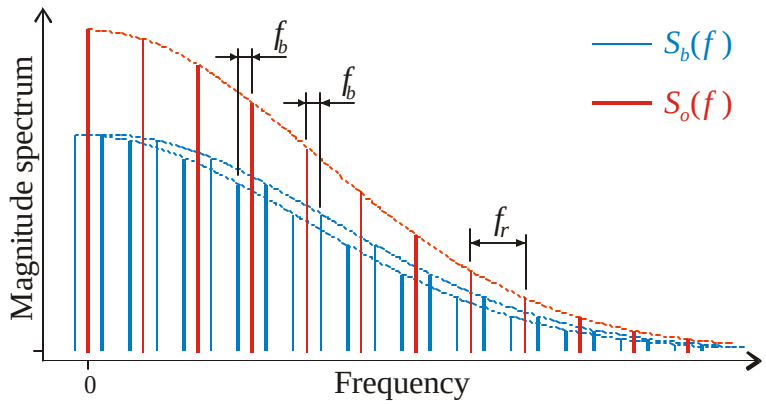




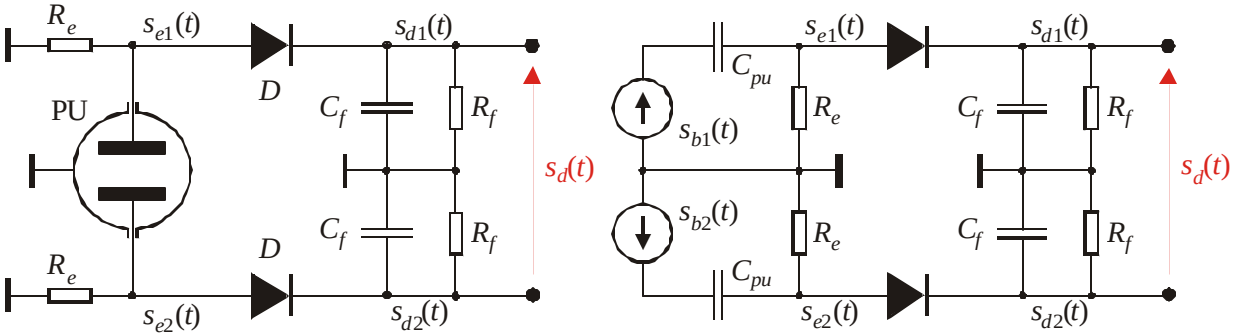
$$s_g(t) = \exp\left(-\frac{t^2}{2s^2}\right)$$

$$S_g(f) = \sqrt{2\pi}s\,\exp\left(-2\pi^2 s^2 f^2\right)$$

$$f_{cg} = \frac{\sqrt{\ln(2)}}{2\pi s} \cong \frac{0.133}{s}$$

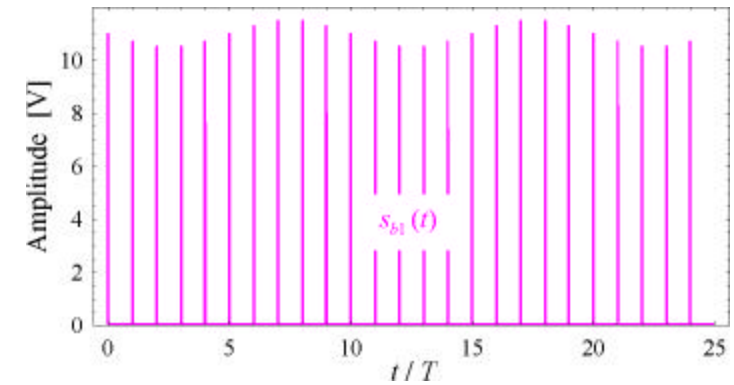
- The LHC bunch length ($4s$) is about 1 ns and the corresponding bunch spectrum cut-off is about 500 MHz.
- With just one bunch in the machine, the revolution spectral lines are spaced by 11 kHz, so there are some 50 000 of these, and some 100 000 betatron lines.
- When using the classical “one line filtering method”, ones looks on (approximately) 0.00001 of the spectral content.
- This results in very small signals, requiring low noise amplifiers and mixers, which have small dynamic ranges. They can be saturated by a huge revolution content.
- Resonant PU = larger signals. Does not work for single bunches (bunches pop-up in the PU not often enough to maintain the resonance)

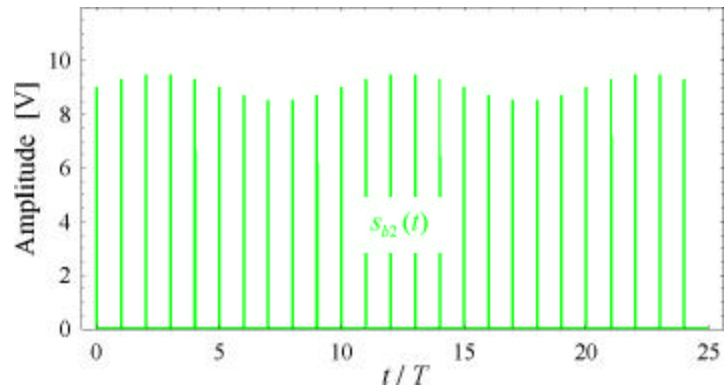
Direct Diode Detection – the Principle

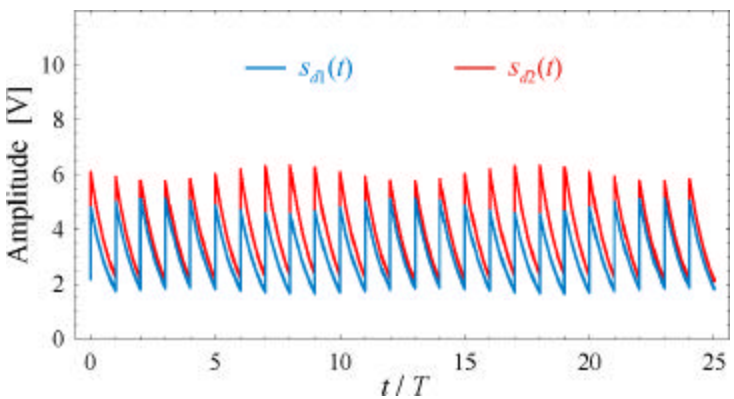


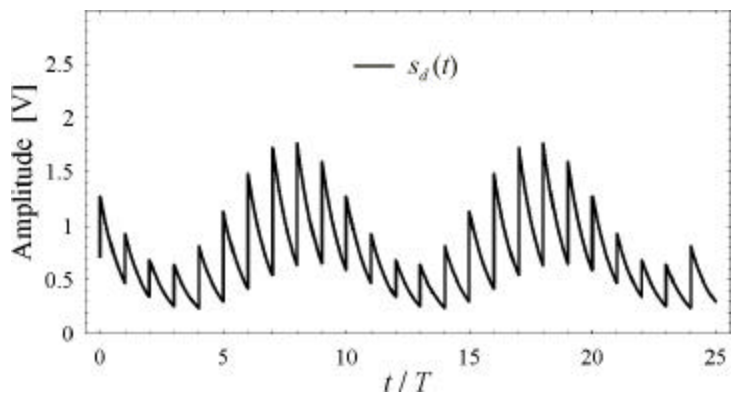
$$s_{b1}(t) = s_b(t)(1+a)(1+b\cos(2p\, f_b\, t))$$
$$s_{b2}(t) = s_b(t)(1-a)(1-b\cos(2p\, f_b\, t))$$

beam relive offset $a = 0.1$
betatron oscillation relative amp. $b = 0.05$
simulated tune value $q = 0.1$
filter time constant $t = T$
storage capacitor $C_f = C_{pu}$ (PU electrode C)

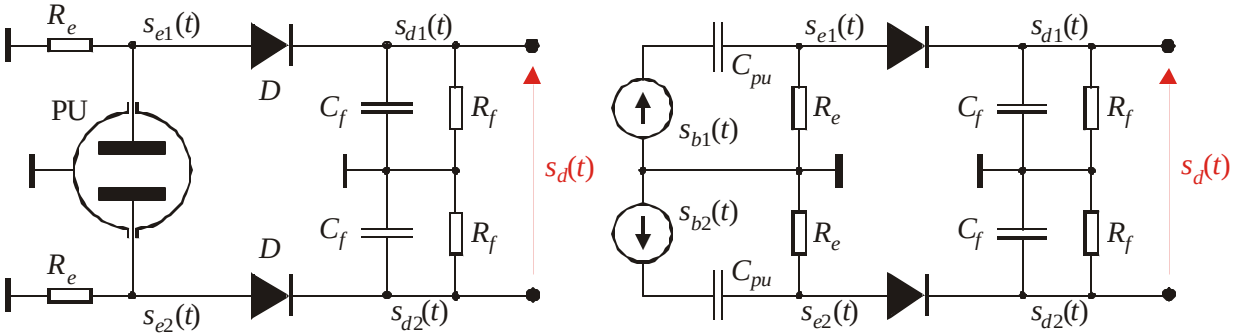








Direct Diode Detection – the Principle



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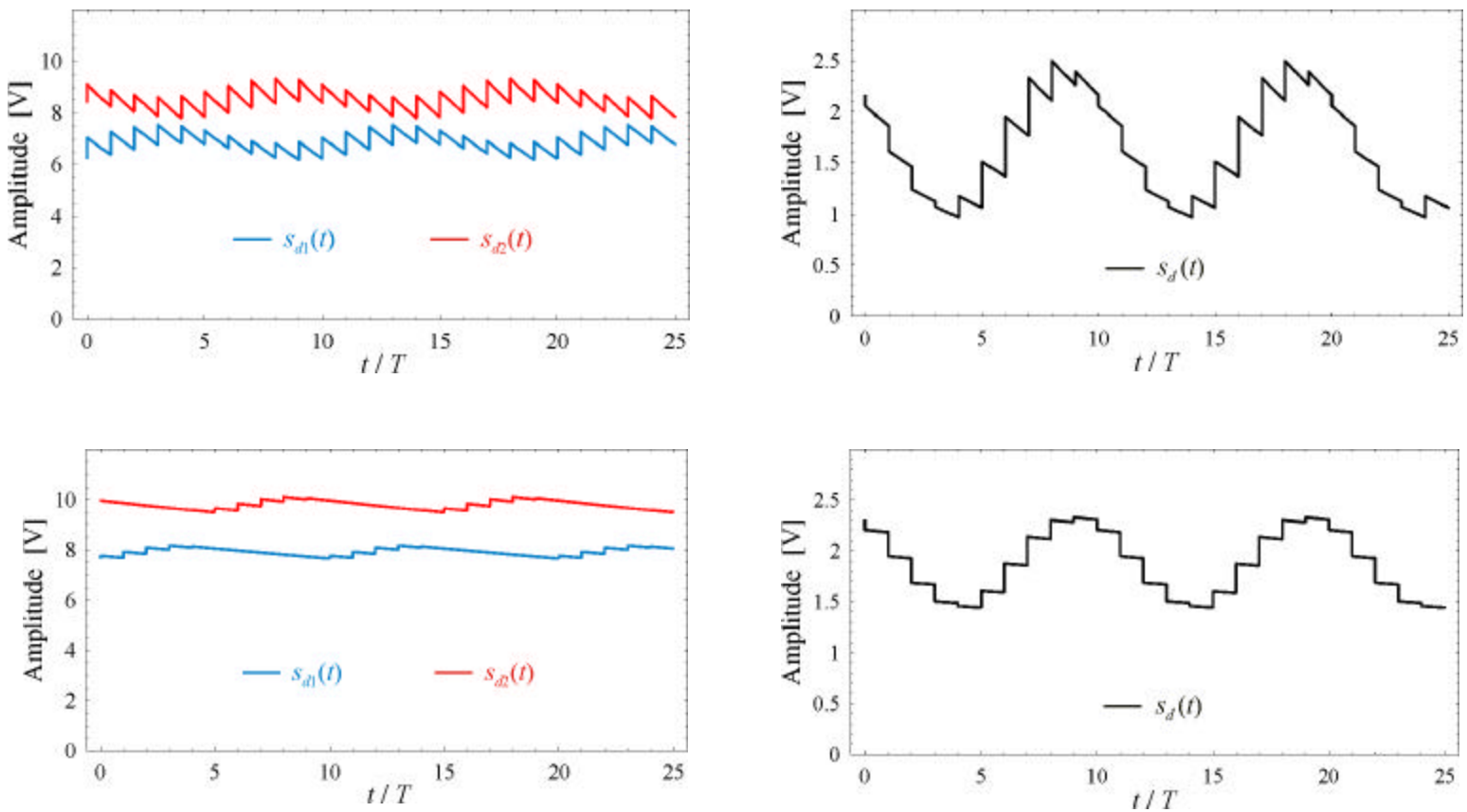
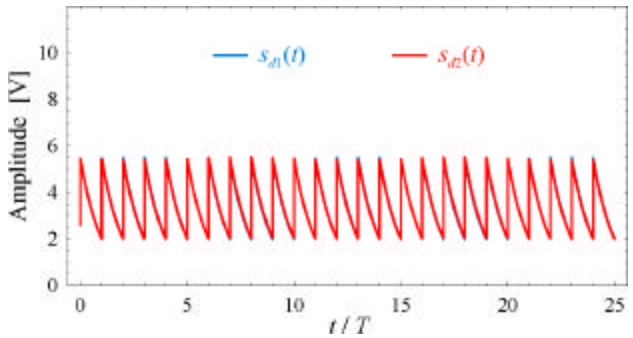
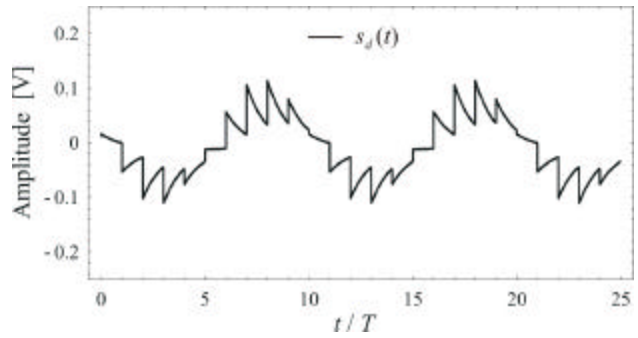


$t = 10\,T$

$t = 100\,T$

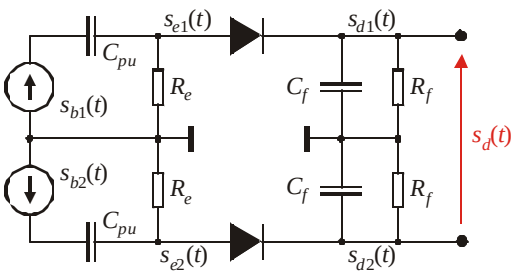
Direct Diode Detection – the Principle

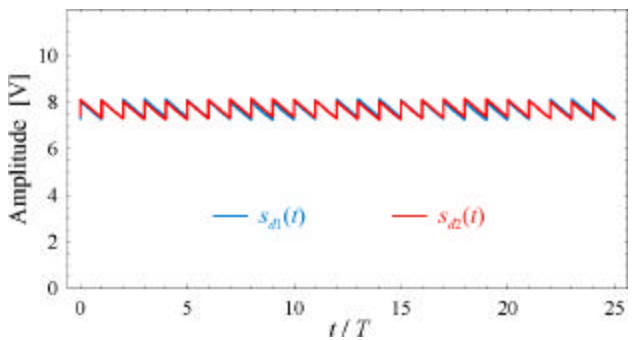


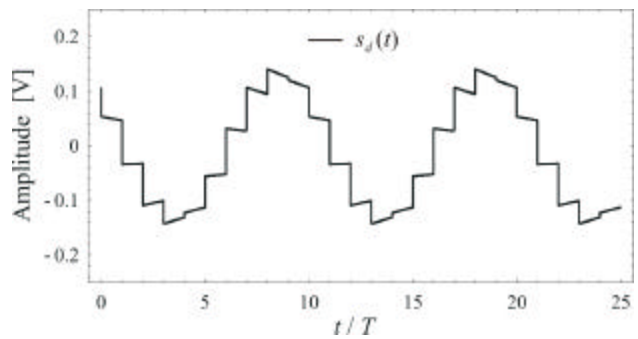


$a = 0,\ b = 0.01$
$q = 0.1,\ C_f = C_{pu}$

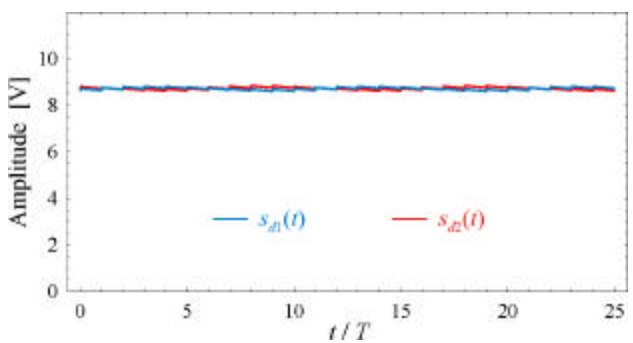
$t = T$

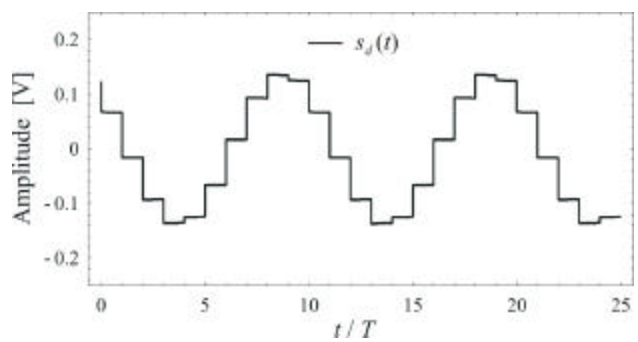






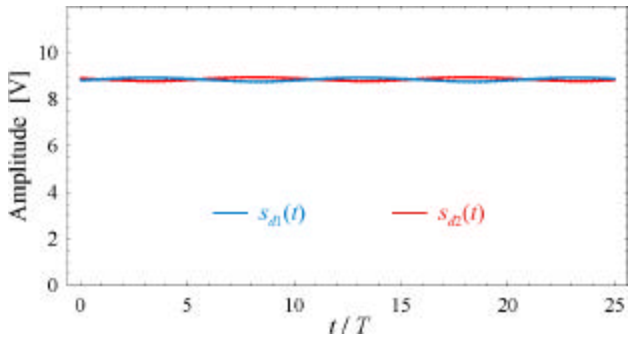
$t = 10\ T$

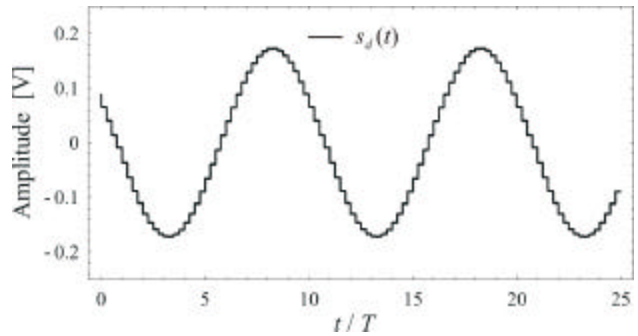




$t = 100\ T$

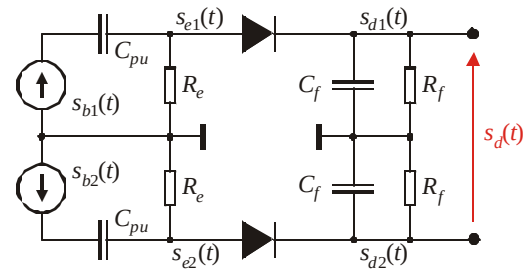
Direct Diode Detection – the Principle

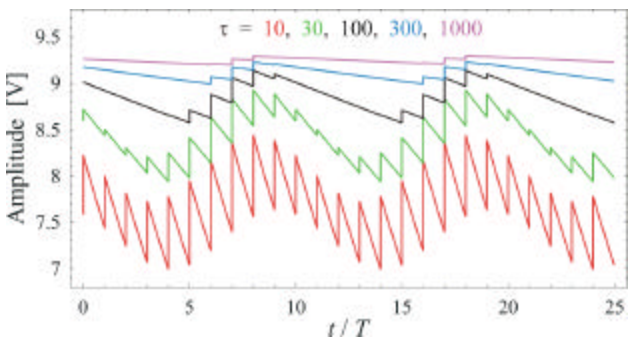


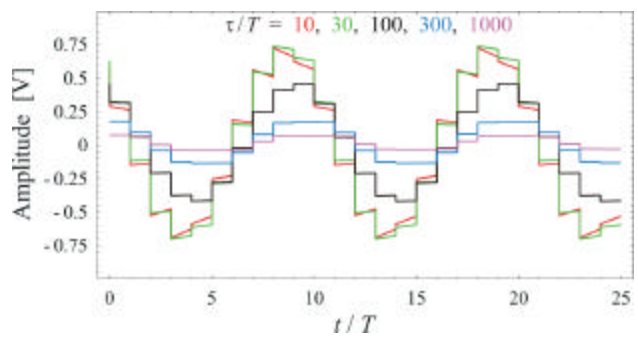


$a = 0,\ b = 0.01$
$q = 0.1,\ C_f = C_{pu}$
$t = 100\ T$

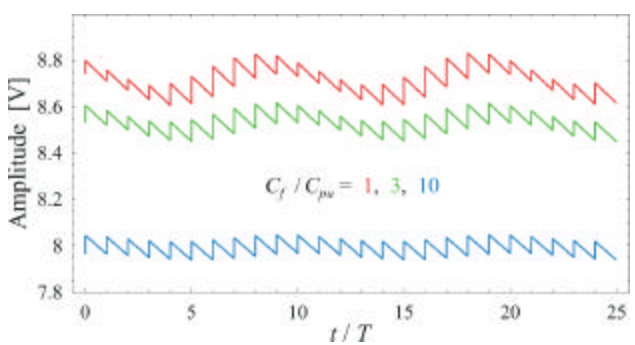
4 bunches

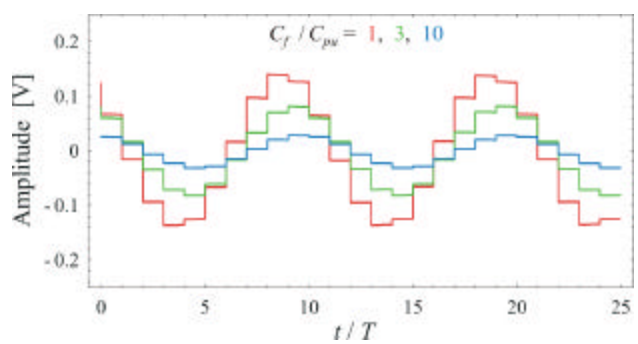






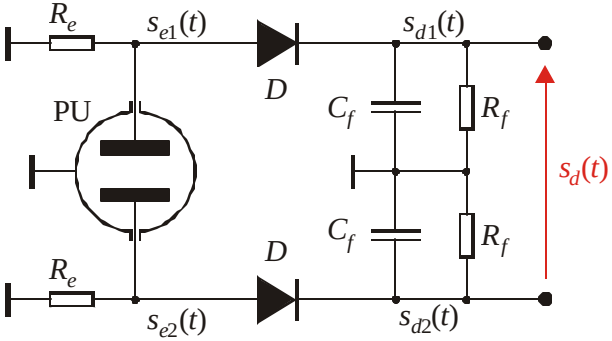
$a = 0,\ b = 0.05$
$q = 0.1,\ C_f = C_{pu}$





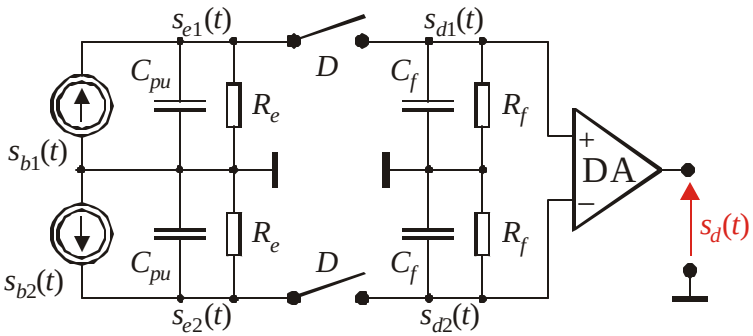
$a = 0,\ b = 0.01$
$q = 0.1,\ t = 100\ T$

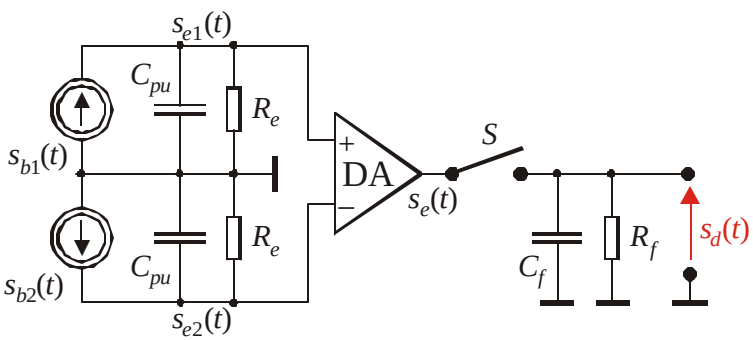
Direct Diode Detection

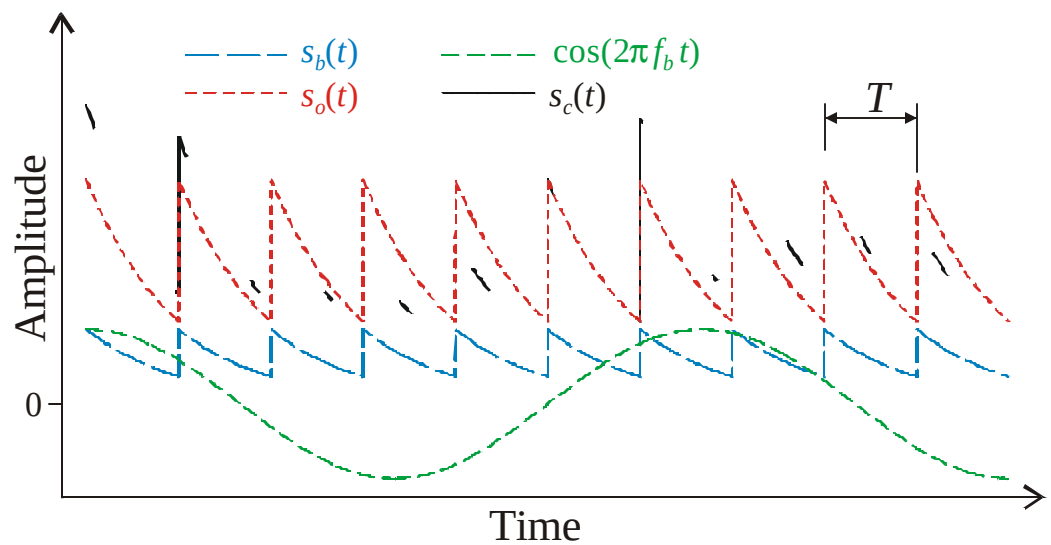


$$s_d(t) = A_b\, s_f(t) * \left(\cos(2\mathrm{p}\, f_b\, t) \cdot \sum_{n=-\infty}^{\infty} d(t - nT) \right) +$$

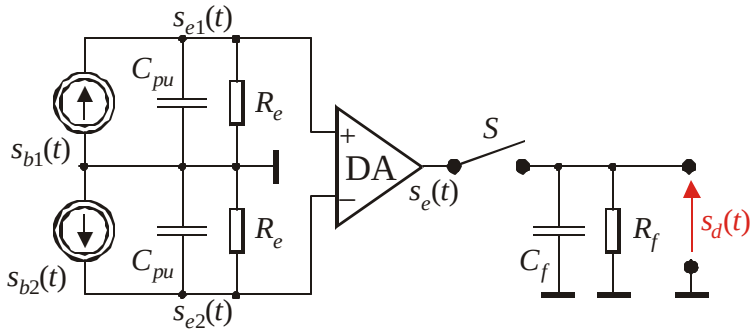
$$+\ A_o\, s_f(t) * \sum_{n=-\infty}^{\infty} d(t - nT)$$





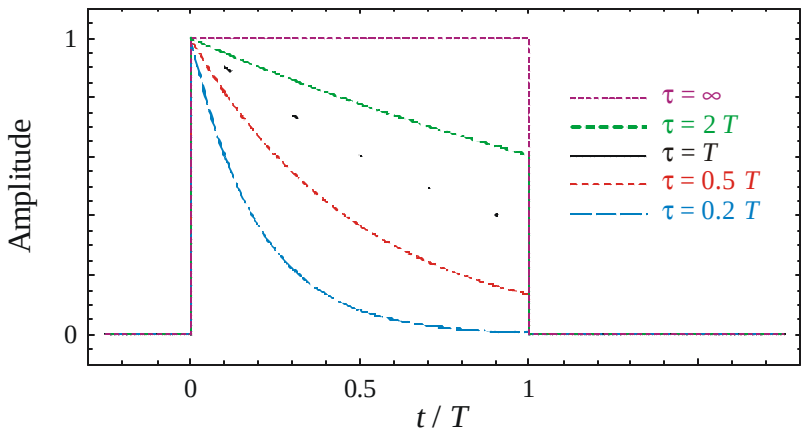


Direct Diode Detection



$$s_d(t) = A_b\, s_f(t) * \left(\cos(2\pi f_b t) \cdot \sum_{n=-\infty}^{\infty} d(t - nT) \right) +$$

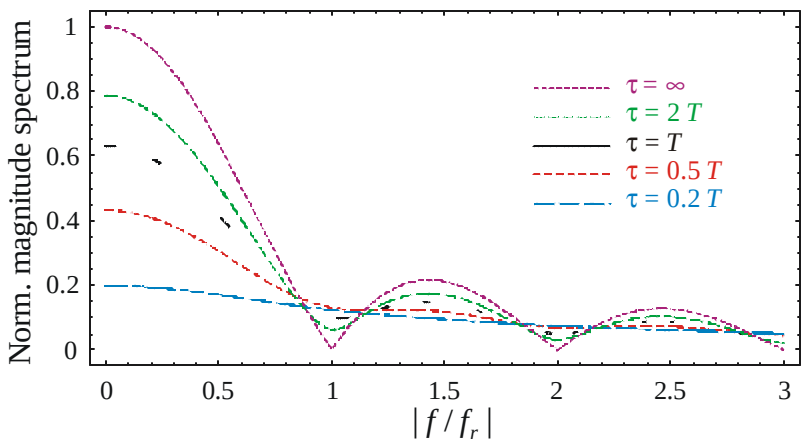
$$+ \; A_o\, s_f(t) * \sum_{n=-\infty}^{\infty} d(t - nT)$$



$$S_d(f) = \left| S_f(f) \cdot \frac{A_b}{2} \sum_{n=-\infty}^{\infty} d\left(f - f_b - \frac{n}{T} \right) + \right.$$

$$+ S_f(f) \cdot \frac{A_b}{2} \sum_{n=-\infty}^{\infty} d\left(f + f_b - \frac{n}{T} \right) +$$

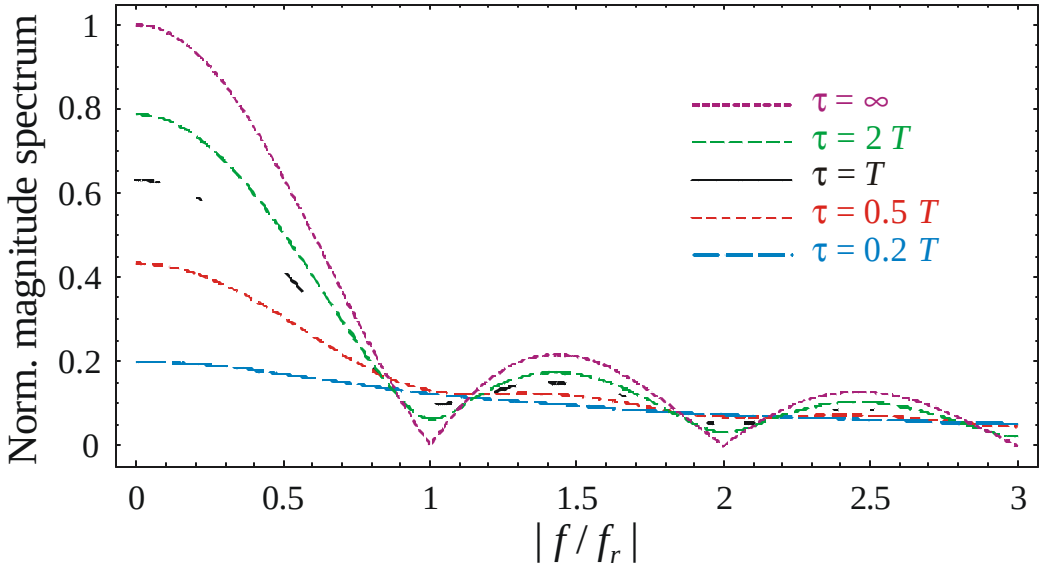
$$\left. + S_f(f) \cdot A_o \sum_{n=-\infty}^{\infty} d\left(f - \frac{n}{T} \right) \right|$$

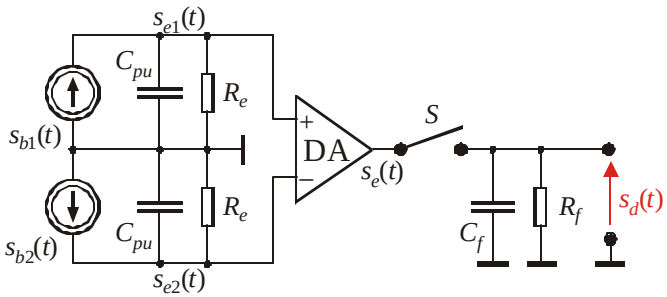


$$s_f(t) = \left(\$(t) - \$(t - T) \right) \exp\left(-\frac{t}{t} \right)$$

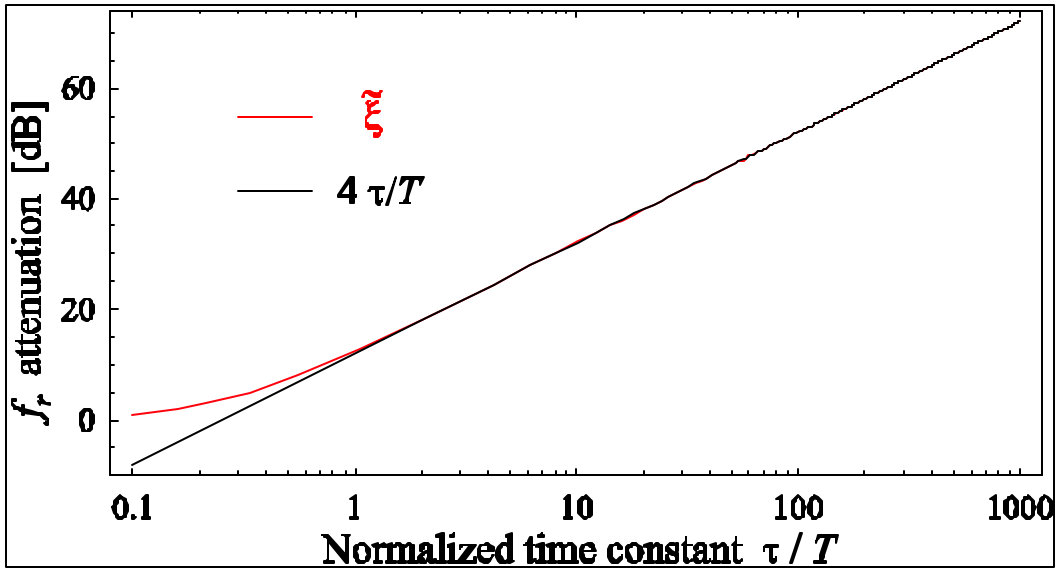
$$S_f(f) = t \left| \frac{1 - \exp\left(-j 2\pi f T - \frac{T}{t} \right)}{1 + j 2\pi f T} \right|$$

Direct Diode Detection





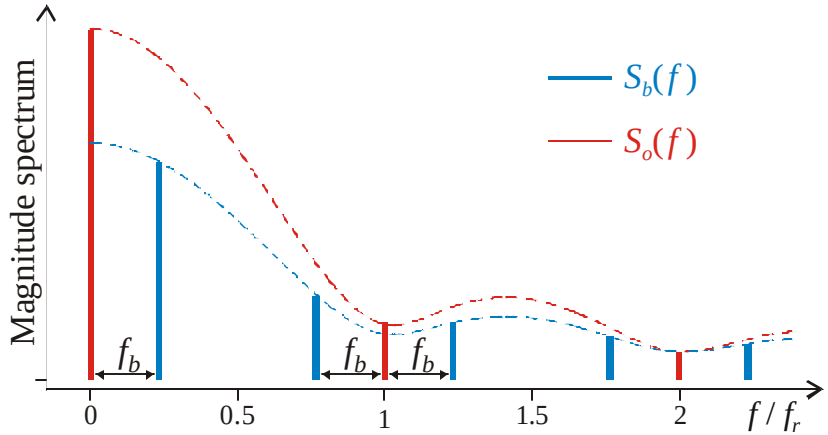
$$S_f(f) = t\left|\frac{1-\exp\left(-j2p\,f\,T-\frac{T}{t}\right)}{1+j2p\,f\,T}\right|$$

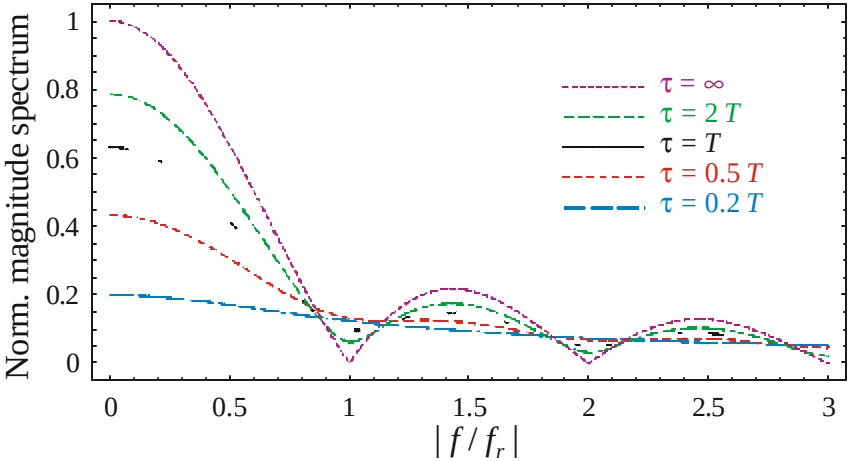


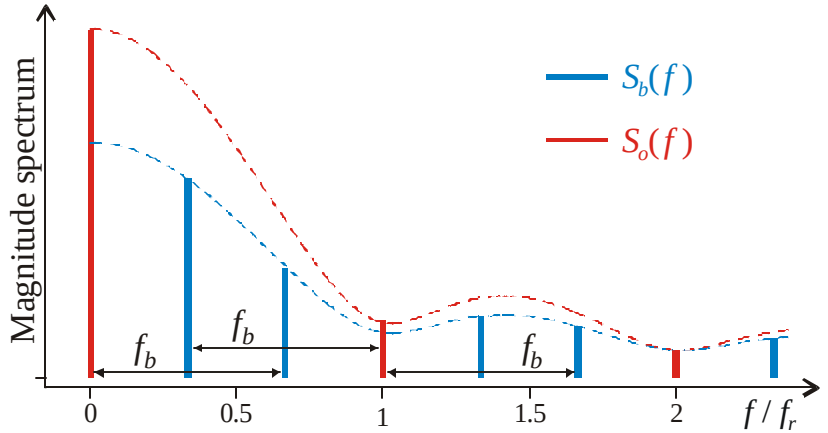
$$\tilde{x} = \frac{S_f\left(\frac{f_r}{2}\right)}{S_f(f_r)} = \sqrt{4-\frac{3T^2}{T^2+p^2t^2}}\,\coth\left(\frac{T}{2t}\right)$$

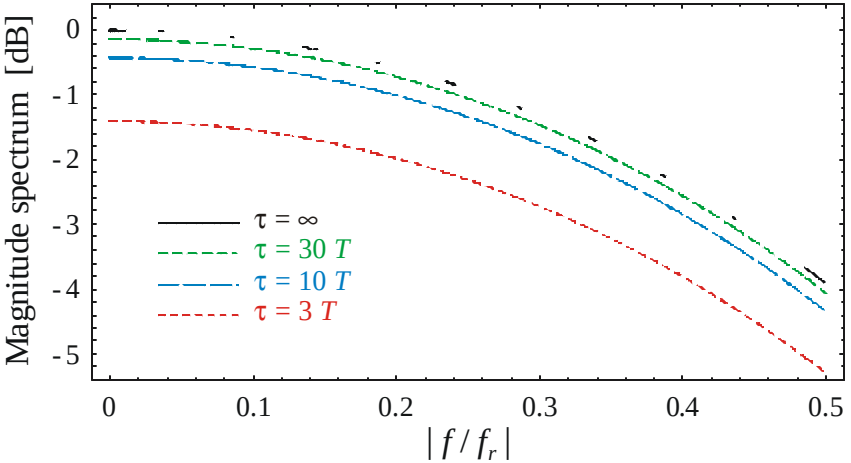
$$x = 4t$$

Direct Diode Detection





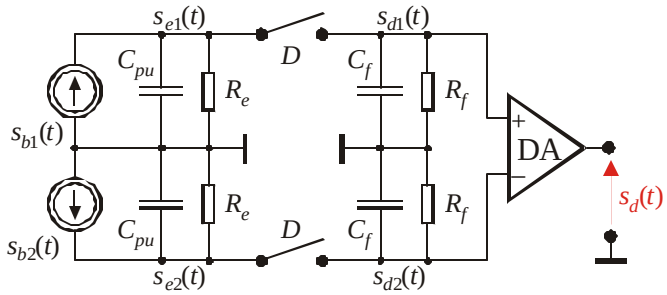




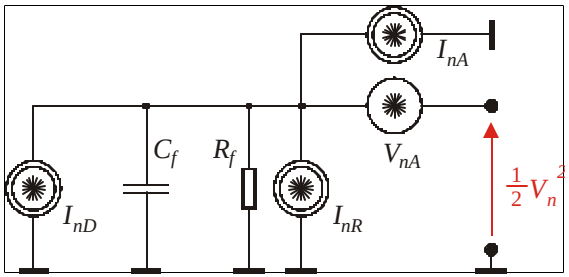
$$S_f(f) = t\left|\frac{1-\exp\left(-\mathrm{j}\,2\mathrm{p}\,f\,T-\frac{T}{t}\right)}{1+\mathrm{j}\,2\mathrm{p}\,f\,T}\right|$$

$$S_r(f) = T\left|\frac{\sin(\mathrm{p}\,f\,T)}{\mathrm{p}\,f\,T}\right|$$

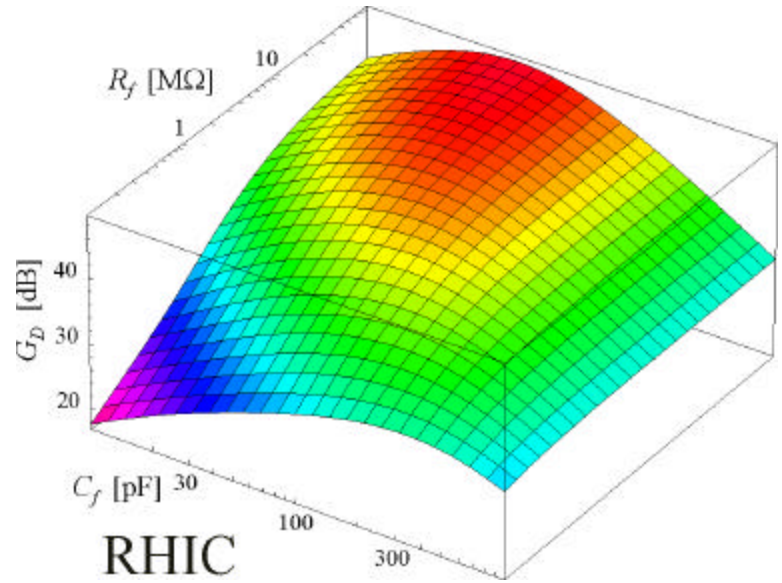
Direct Diode Detection – SNR



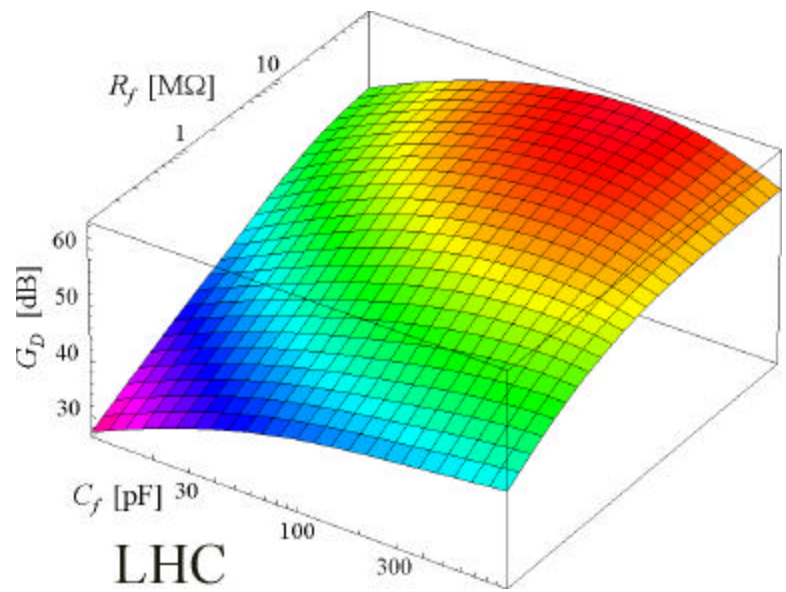
$$G_S = \frac{T}{\sqrt{2\pi s}} \cdot \frac{C_{pu}}{C_{pu}+C_f} \cdot \left| \frac{t\left(1-\exp\left(-j2\pi q - T/t\right)\right)}{1+j2\pi q} \right|$$



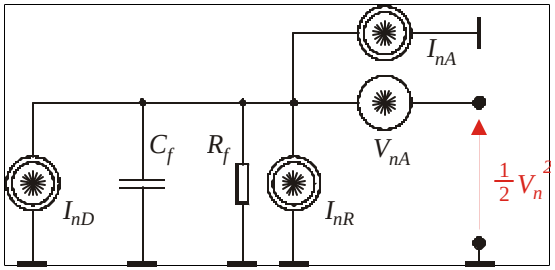
$$G_D = \frac{\dfrac{V_{nC}T}{\sqrt{\pi s}} \cdot \dfrac{R_f C_f C_{pu}}{C_{pu}+C_f} \left| \dfrac{1-\exp\left(-j2\pi q - T(R_f C_f)^{-2}\right)}{1+j2\pi q} \right|}{\sqrt{V_{nA}^2 + \dfrac{T^2 R_f^2 \left(2eI_{RD} + \dfrac{4k\Theta}{R_f} + I_{nA}^2\right)}{T^2 + (2\pi q R_f C_f)^2}}}$$



$t = 100\,T$

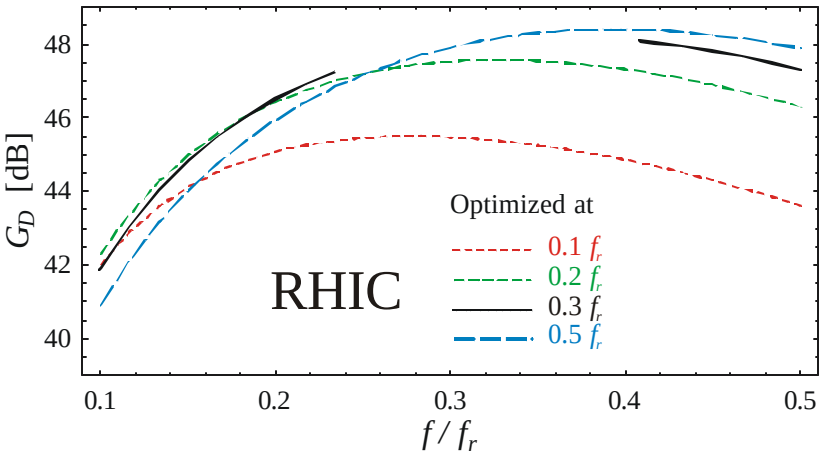


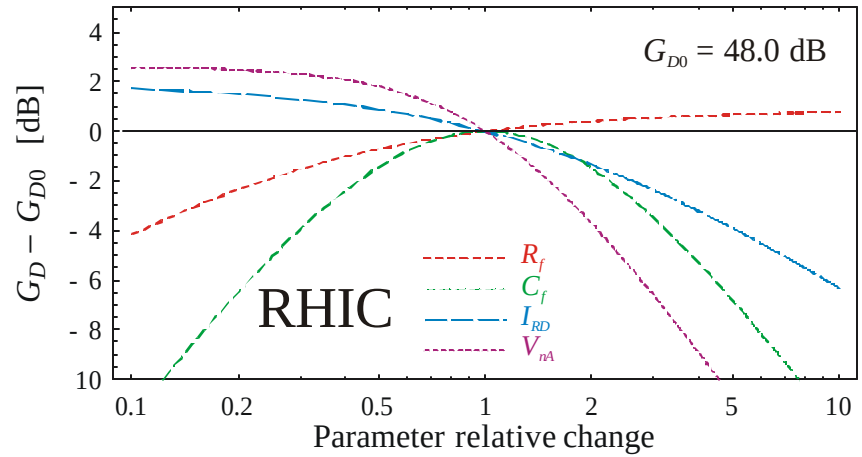
Direct Diode Detection – SNR

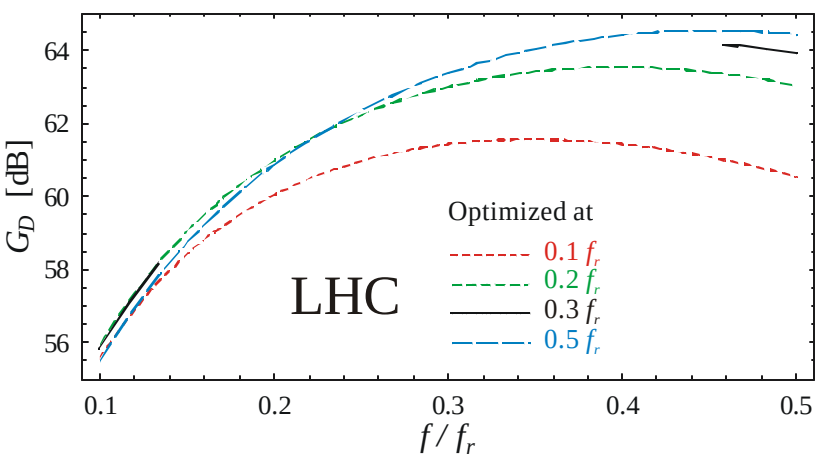


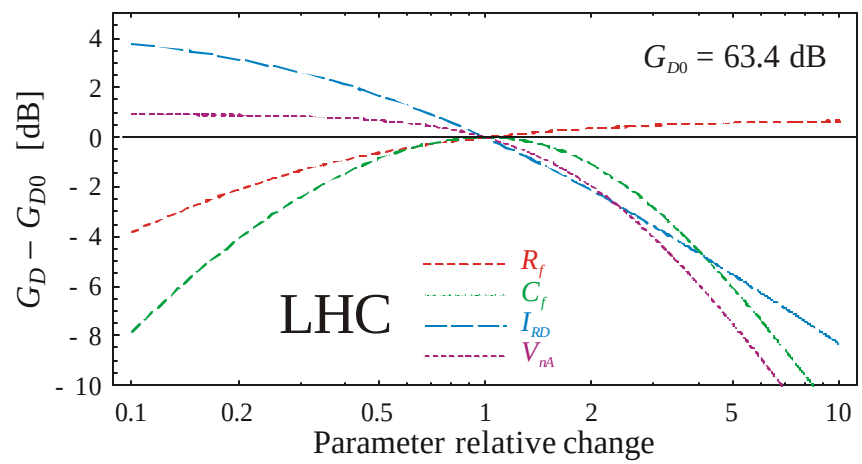
$$G_D = \frac{V_{nC}\dfrac{T}{2\sqrt{p}\,s}\cdot\dfrac{C_{pu}}{C_{pu}+C_f}\cdot\dfrac{\sin(\mathrm{p}\,q)}{\mathrm{p}\,q}}{\sqrt{V_{nA}^{\;2}+\dfrac{T^2}{(2\mathrm{p}\,q\,C_f)^2}\left(2\,e\,I_{RD}+\dfrac{4k\Theta}{R_f}+I_{nA}^{\;2}\right)}}$$

$t = 100\,T$

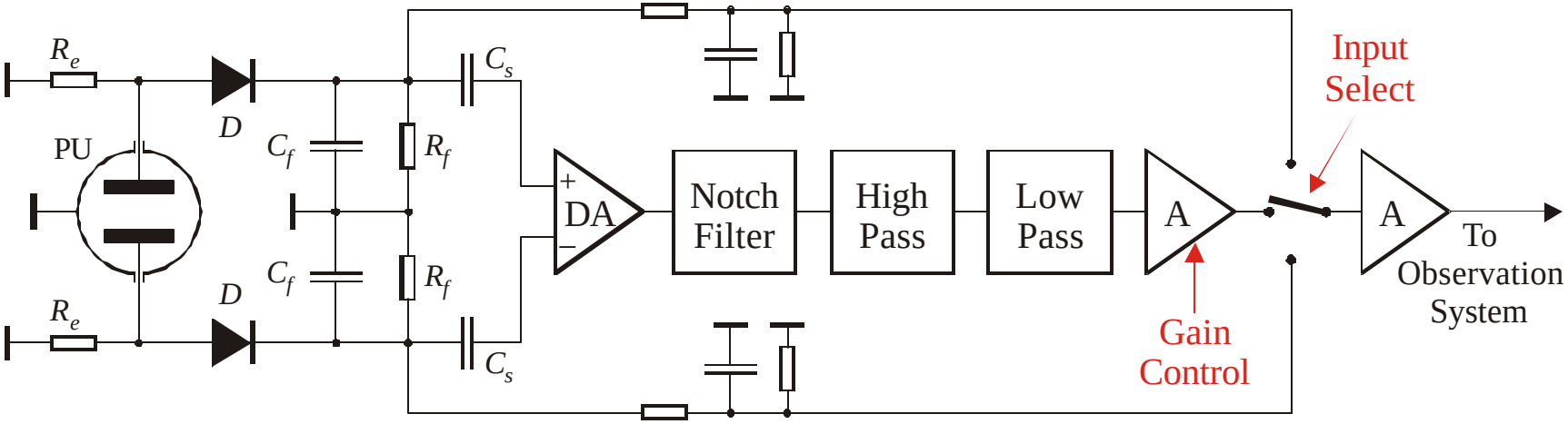




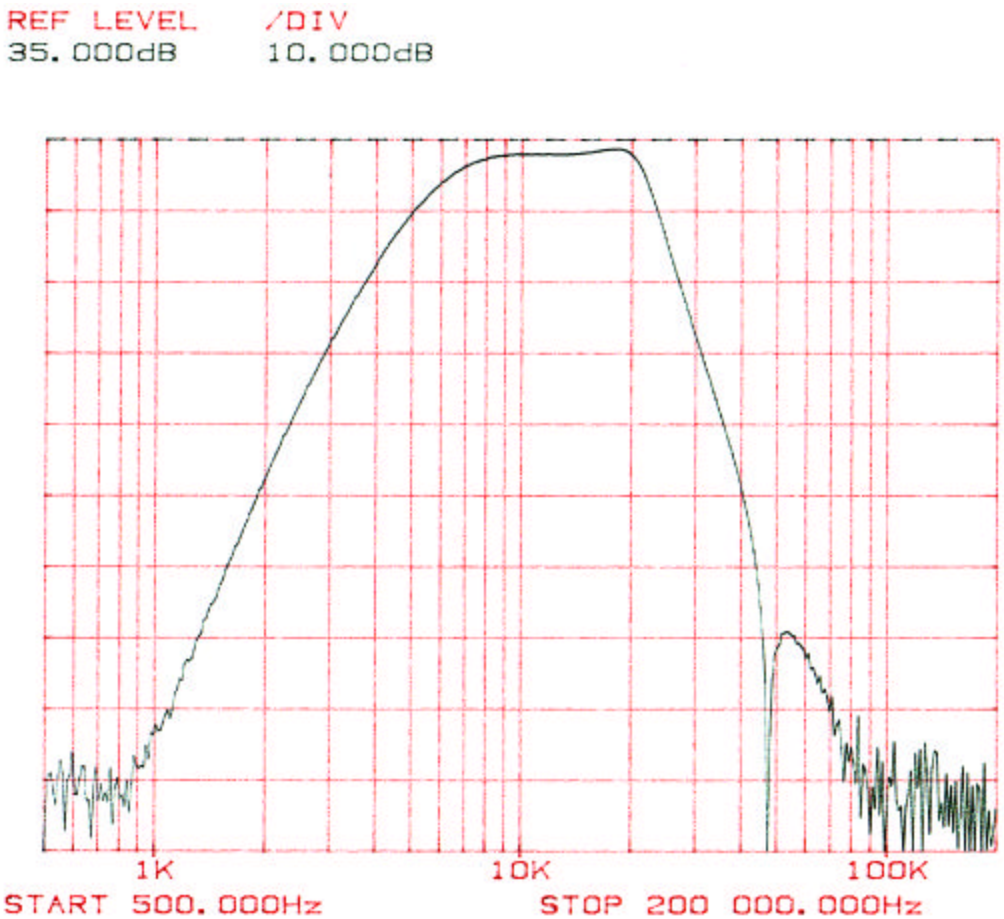


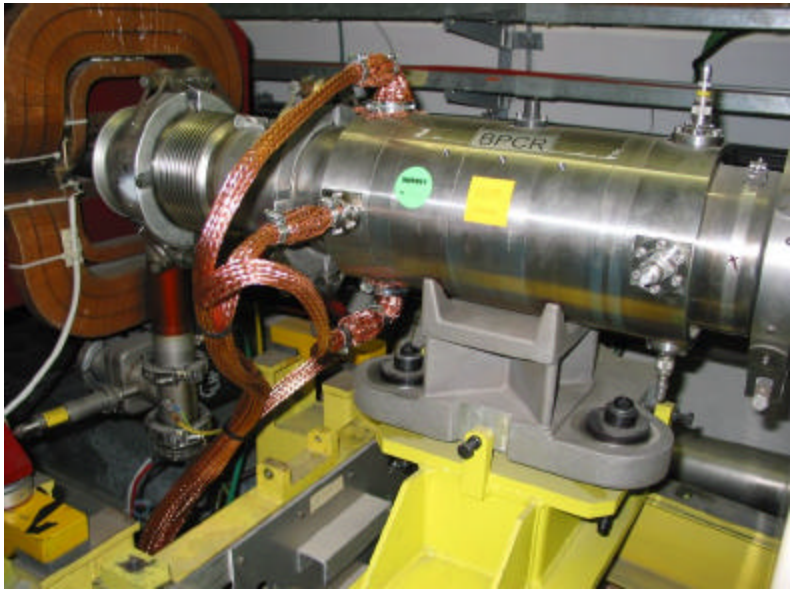


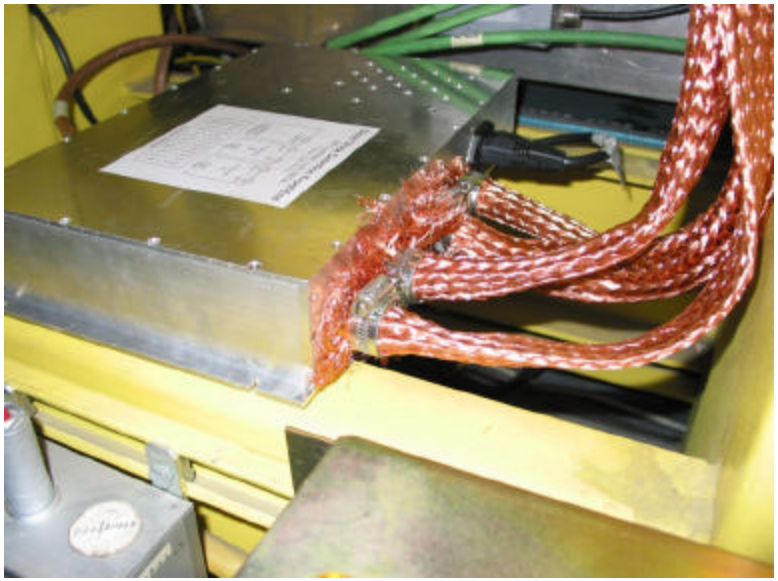
BBQ Architecture



BBQ Architecture







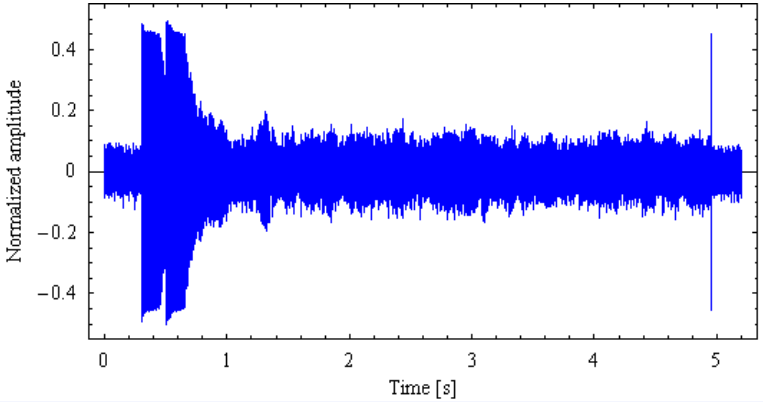
- Revolution frequency is attenuated by some 100 dB over an octave ($f_r/2$ is still within the bandwidth)
- The dynamic range of the first amplifier is some 15 V

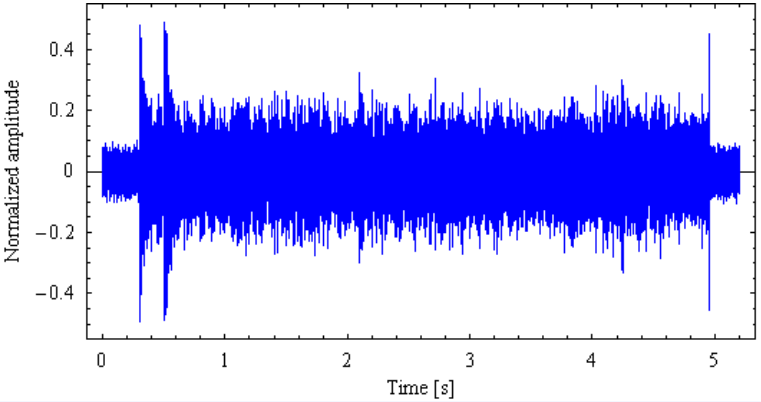
SPS BBQ Measurements – Transverse Damper Noise

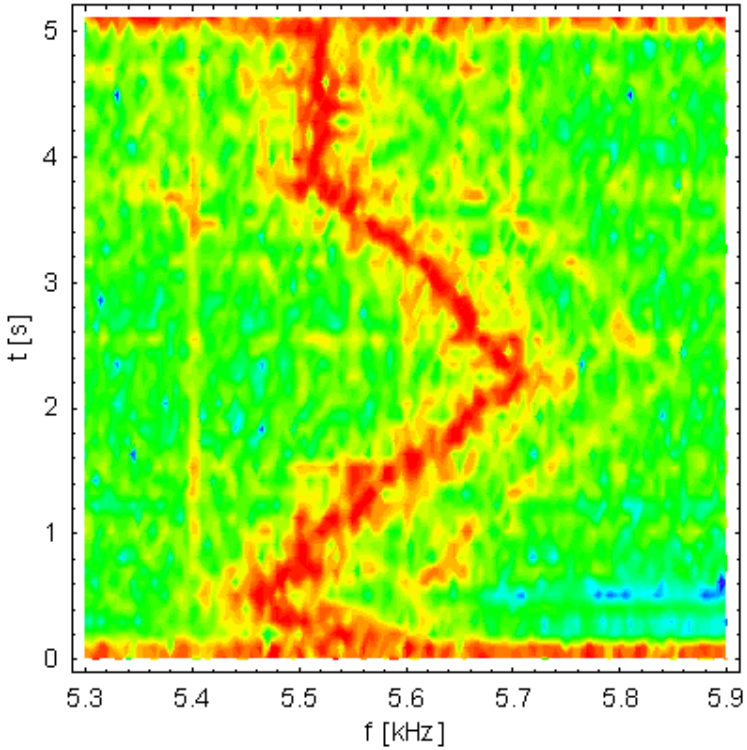
Damper system OFF

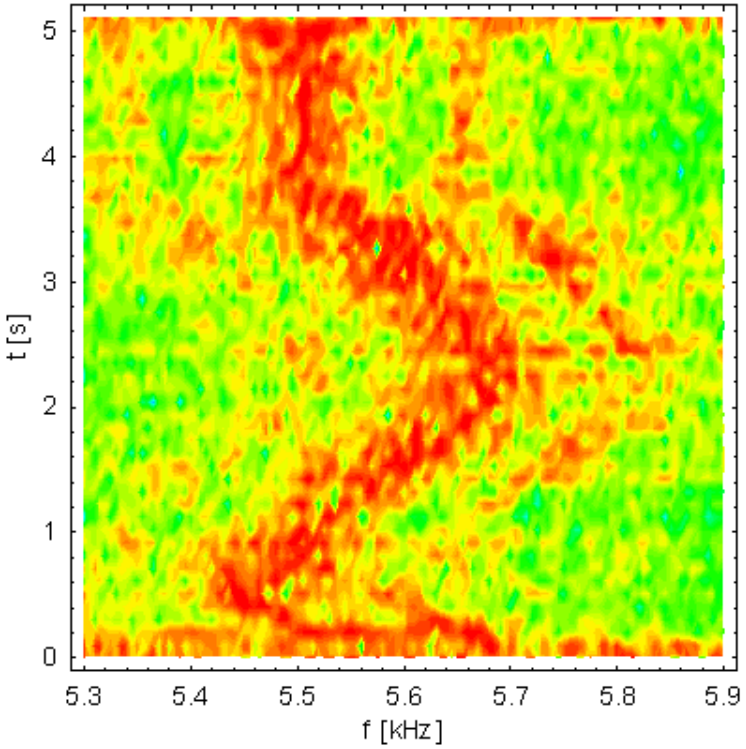
One LHC pilot bunch, intensity ca 5e9

Damper system ON

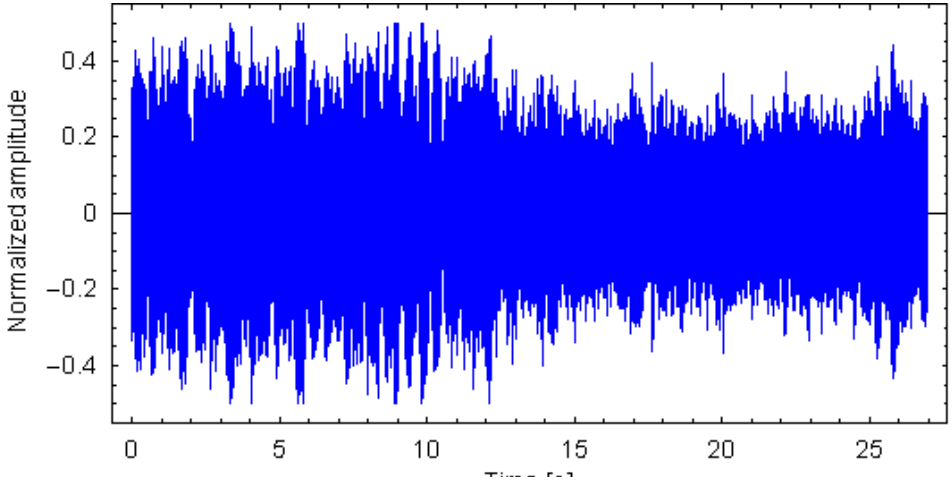




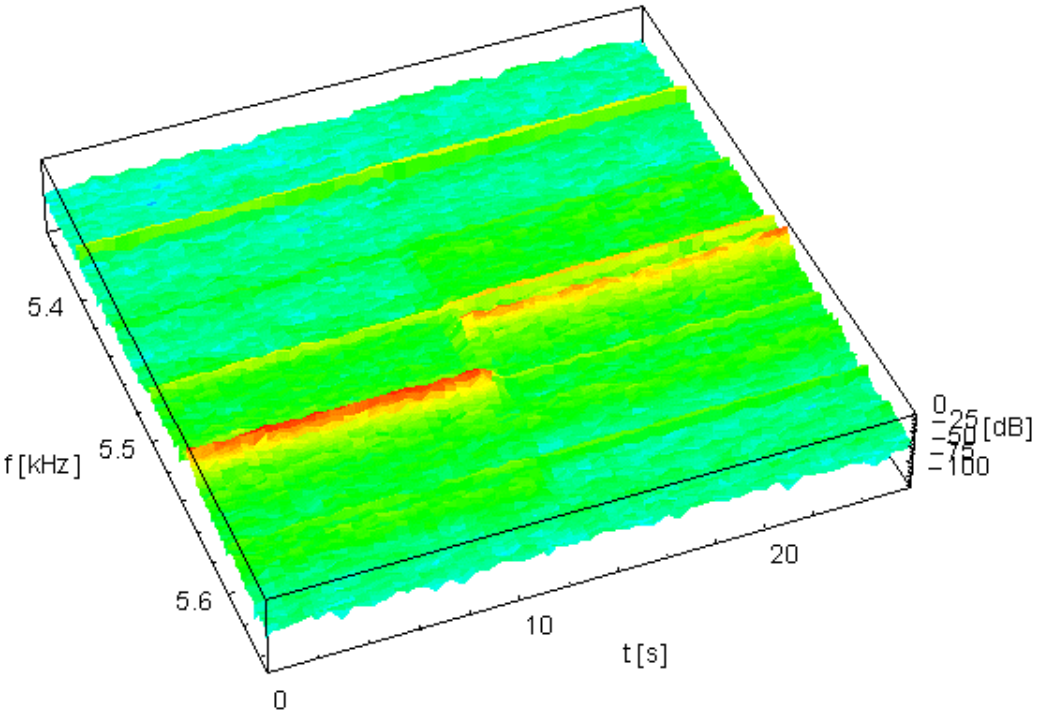


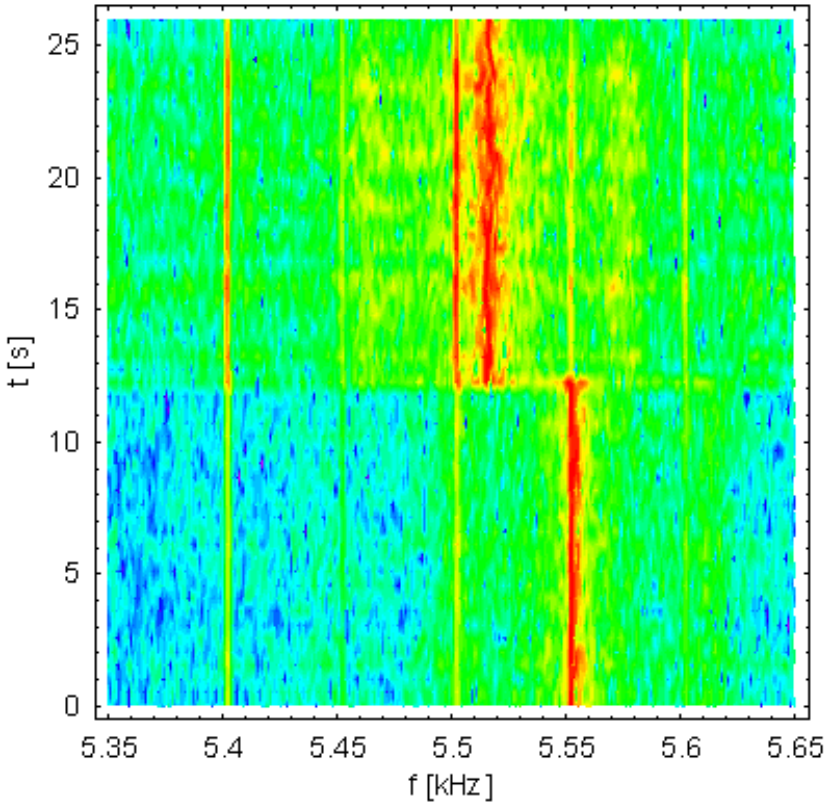


SPS BBQ Measurements – Mains Ripple in the Beam Spectrum

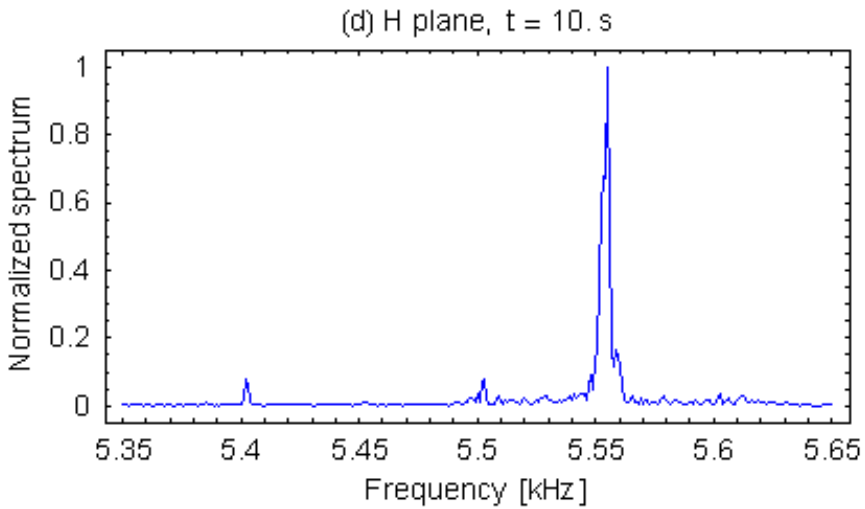


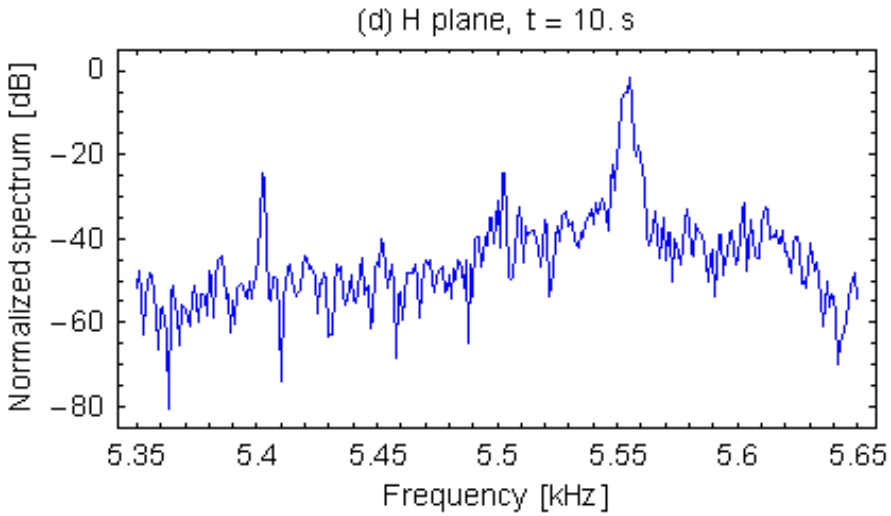
72 LHC bunches,
intensity ca 1e11,
coasting (RF on)

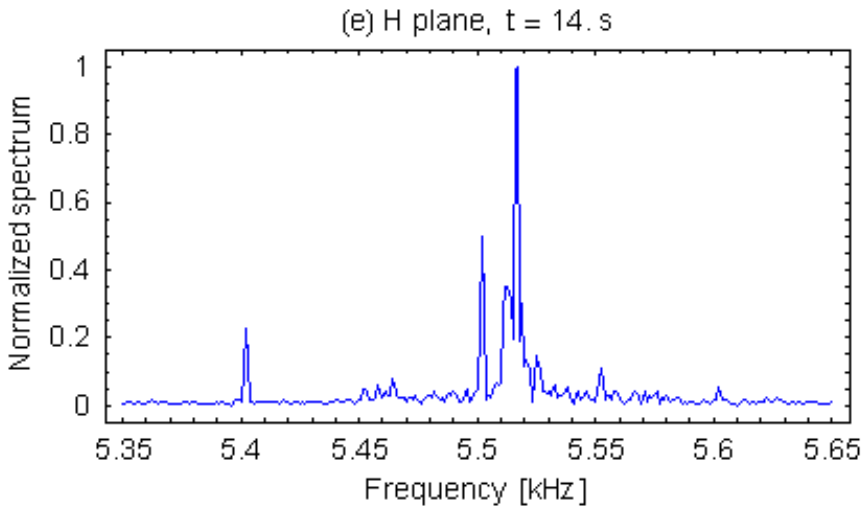


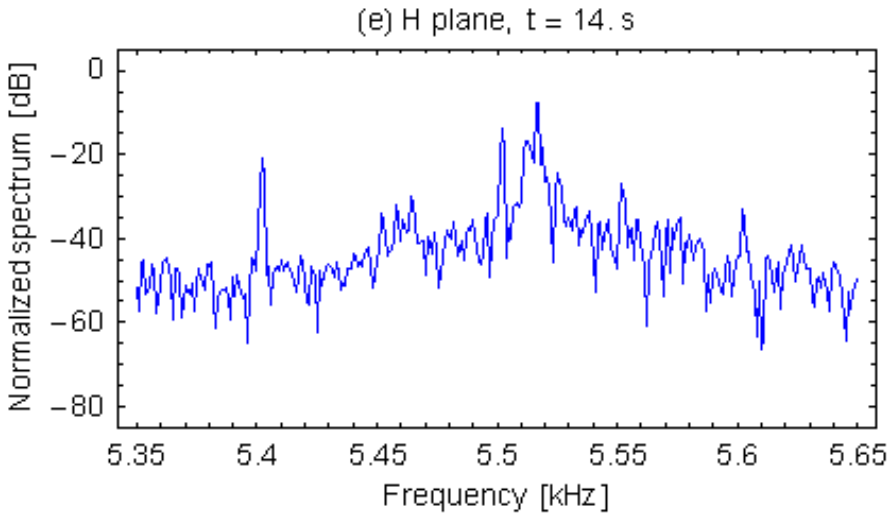


SPS BBQ Measurements – Mains Ripple in the Beam Spectrum

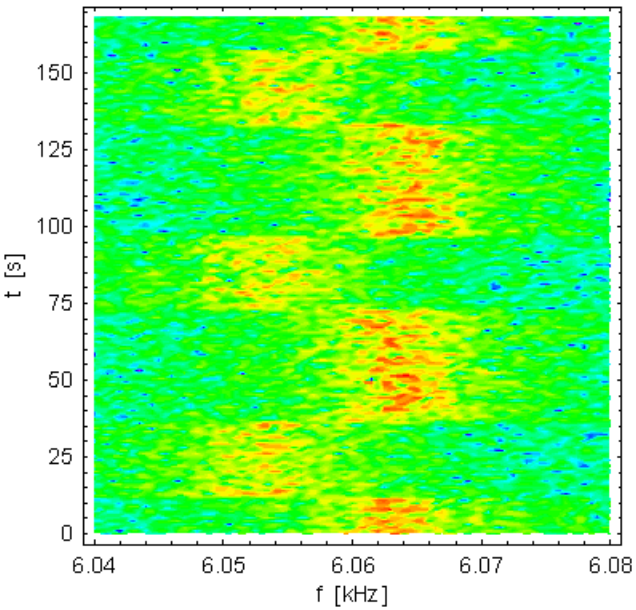


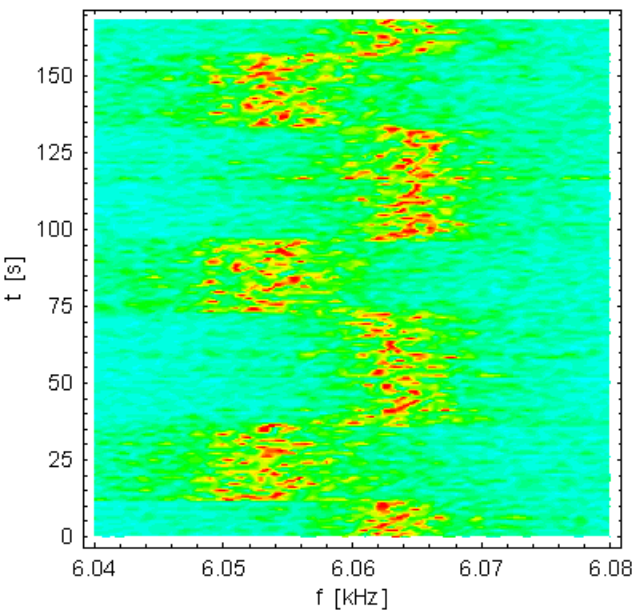






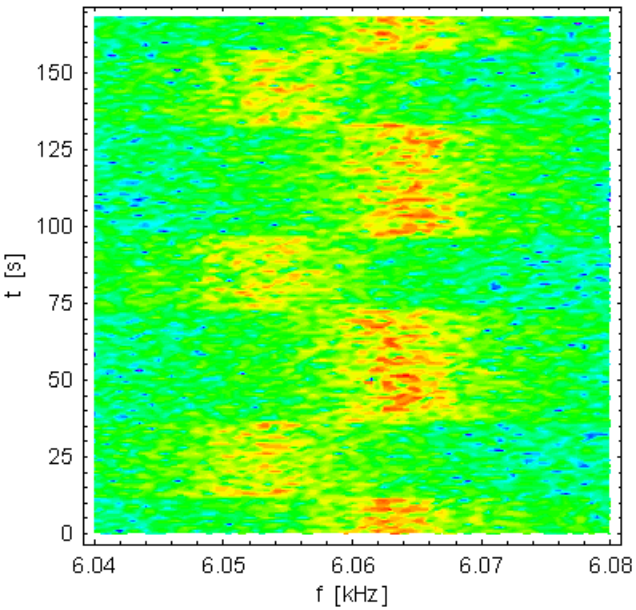
SPS BBQ Measurements – LHC Collimator Impedance

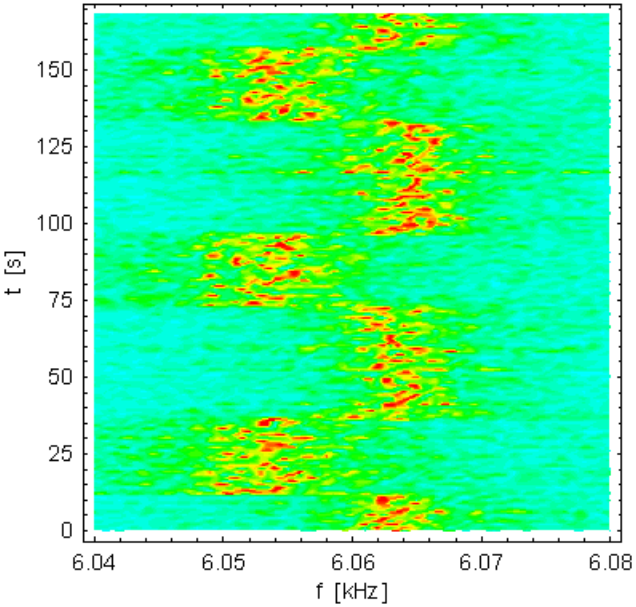


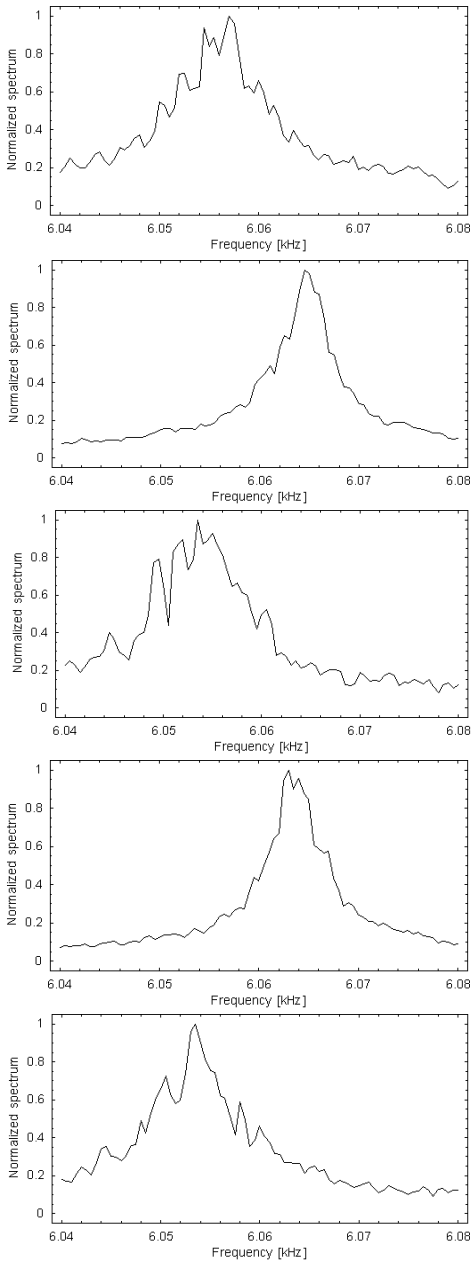


- The top picture shows spectra from the measurement at 4:40 (gap of 1.96 mm) with log color scaling. The bottom one – with linear color scaling.
- BBQ signal samples were acquired with a 24-bit USB sound card at 48 kS/s rate (16-bit samples stored).
- Each spectrum segment is calculated from 96000 Hanning windowed samples, so the FFT bin spacing is 0.5 Hz. Two adjacent data segments overlap by 50%, so there is one spectrum segment per second. These parameters are a compromise between the frequency and time resolution required by the measurements.
- "Collimator in" and "collimator out" spectra are grouped by calculating an RMS sum. For the discussed measurement this gives three "in" and two "out" spectra.
- For each RMS summed spectra is evaluated an RMS center of gravity of the main distribution, within a few Hz bandwidth to not take into account the distribution tails. In this way there are produced five frequency numbers.
- Out of these 5 numbers there are calculated 4 frequency differences.
- Out of these differences there are calculated a mean and a standard deviation.
- The mean is considered as the frequency change due the collimator movement and the standard deviation is considered as the measurement error estimate.
- The procedure is used to calculate 5 frequency changes for each of two measurement series. For more difficult cases it is taken longer time record at the expense of much longer PC processing time.
- Note that the achieved resolution is a consequence of a very long observation time. For a 150 s record one stores some 7 millions of samples, corresponding to some 6.5 millions of turns. This is only possible with continuous beam excitation, self-excitation in this case.

SPS BBQ Measurements – LHC Collimator Impedance





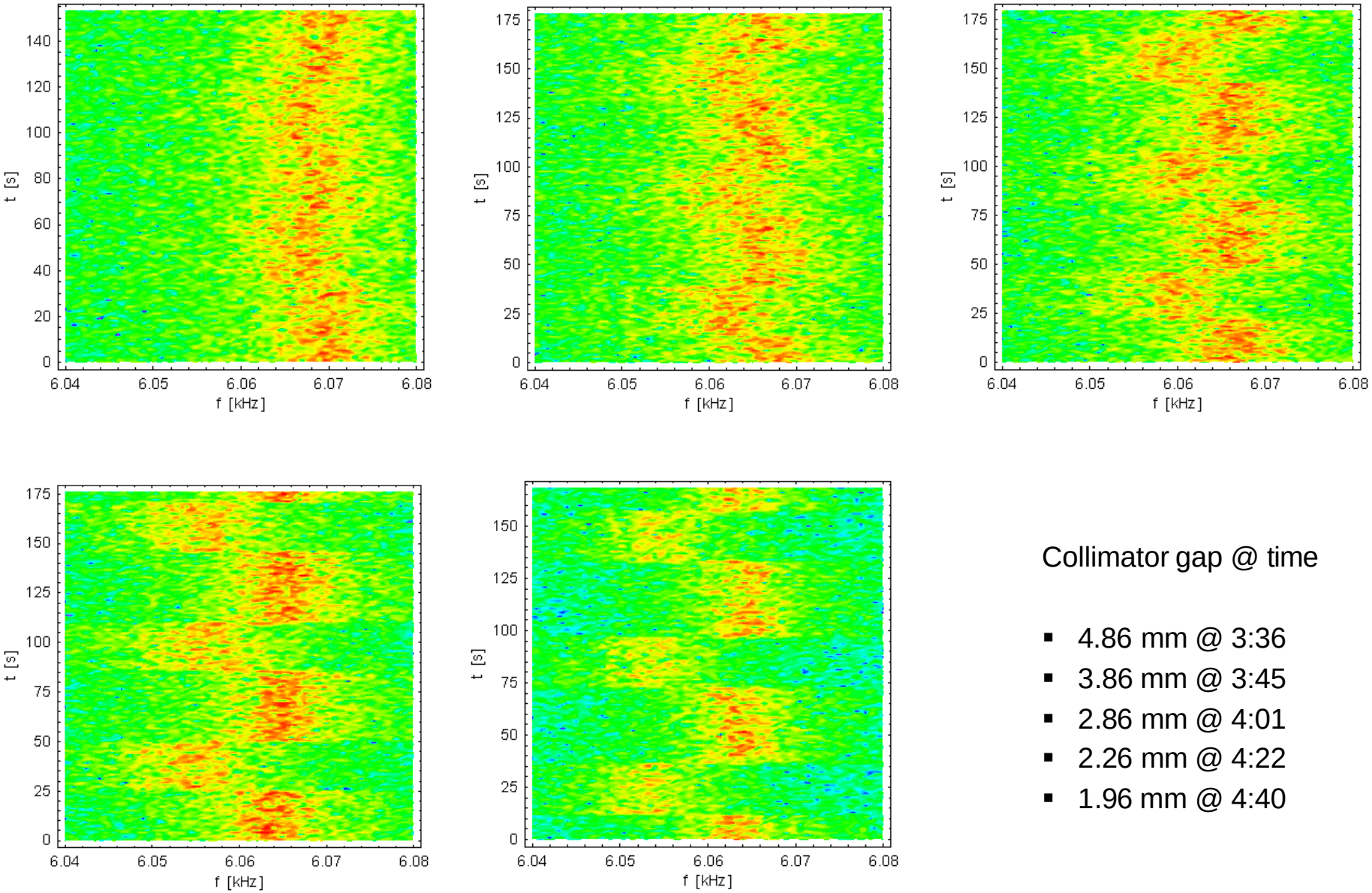


f [Hz]	Δf [Hz]
6053.43	
	10.16
6063.59	
	9.80
6053.80	
	10.88
6064.68	
	10.71
6053.97	

mean
10.4 Hz
$2.4\times10^{-4}\, f_r$

st. dev.
0.5 Hz
$1.2\times10^{-5}\, f_r$

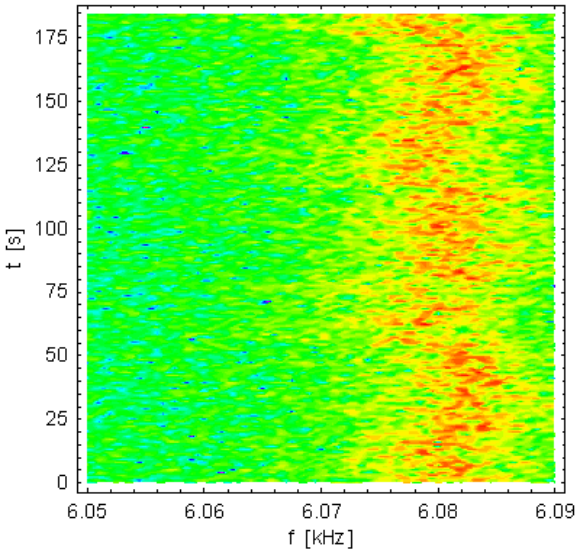
SPS BBQ Measurements – LHC Collimator Impedance

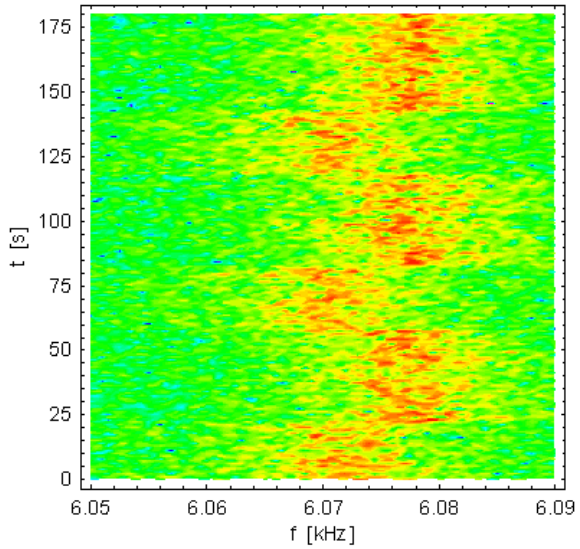


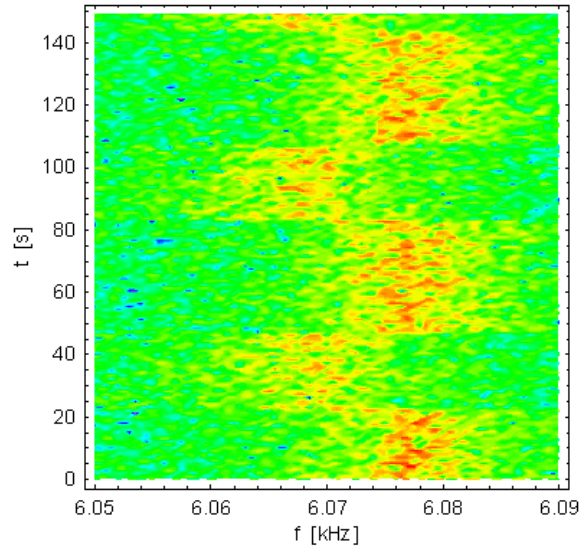
Collimator gap @ time

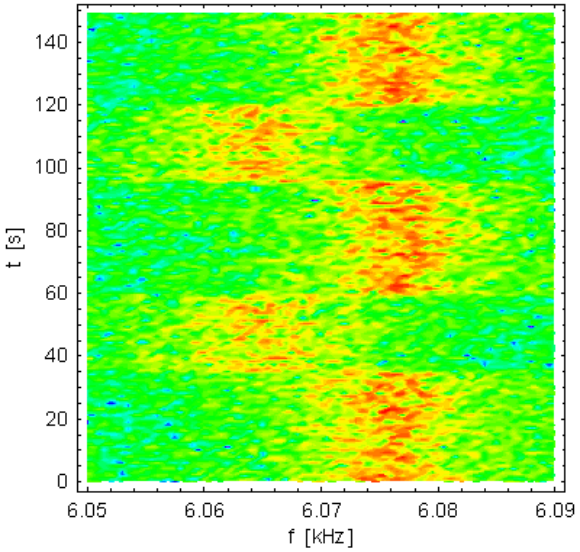
- 4.86 mm @ 3:36
- 3.86 mm @ 3:45
- 2.86 mm @ 4:01
- 2.26 mm @ 4:22
- 1.96 mm @ 4:40

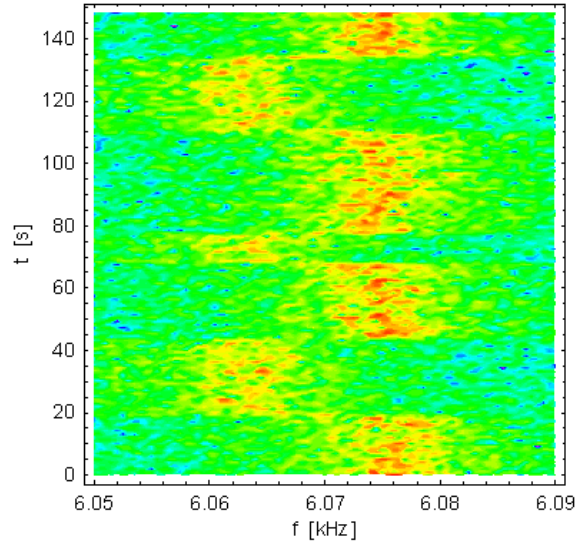
SPS BBQ Measurements – LHC Collimator Impedance







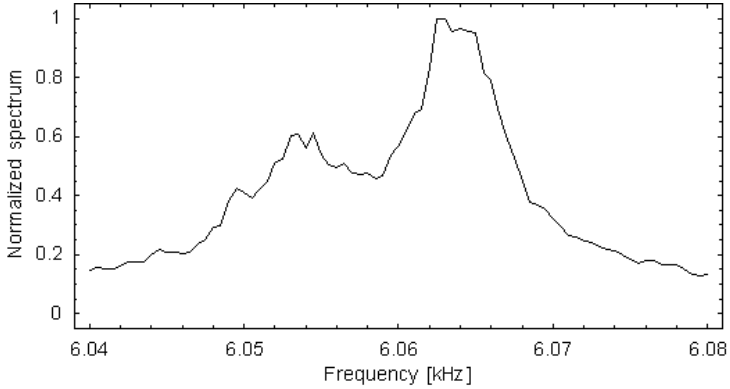


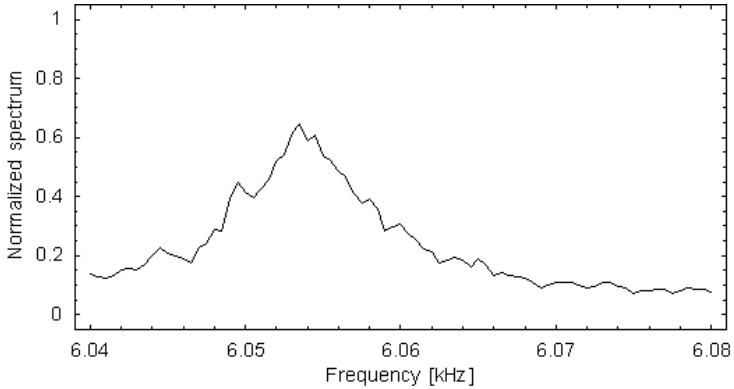


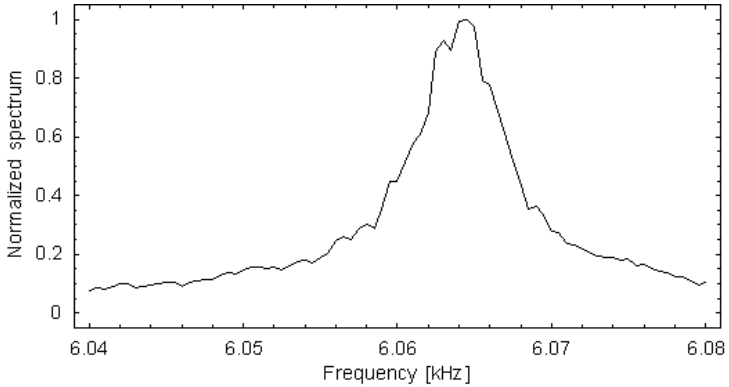
Collimator gap @ time

- 3.86 mm @ 5:30
- 2.86 mm @ 5:38
- 2.46 mm @ 5:46
- 2.06 mm @ 5:53
- 1.86 mm @ 6:05

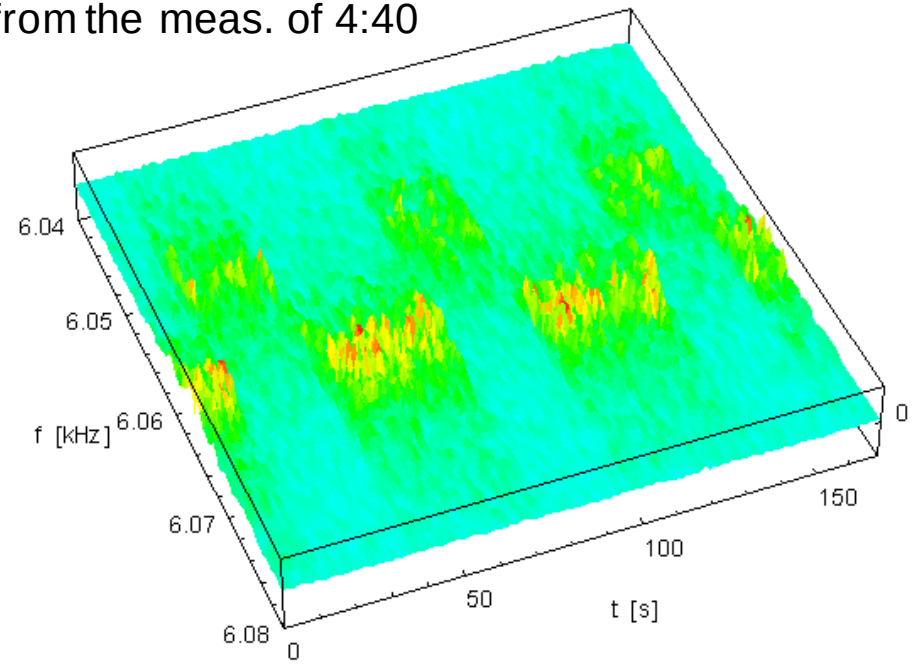
SPS BBQ Measurements – LHC Collimator Impedance

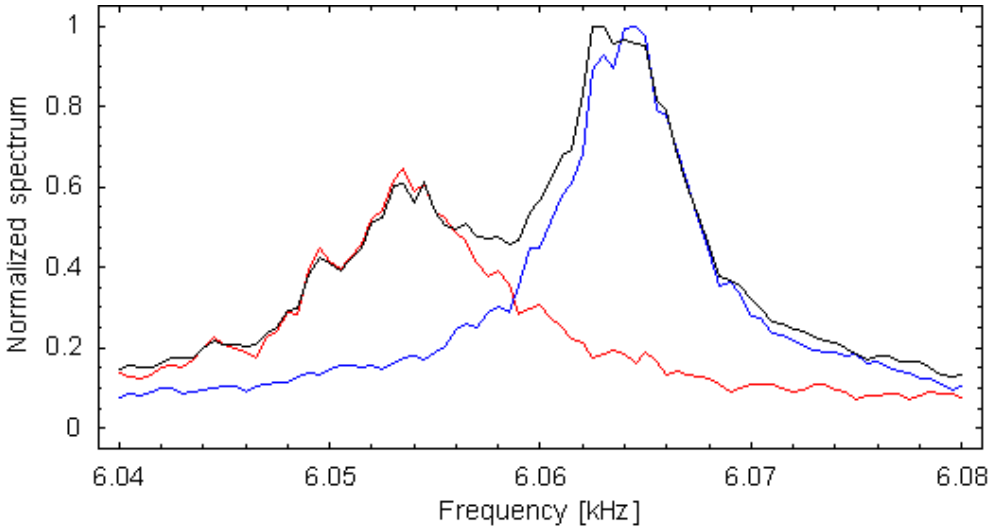




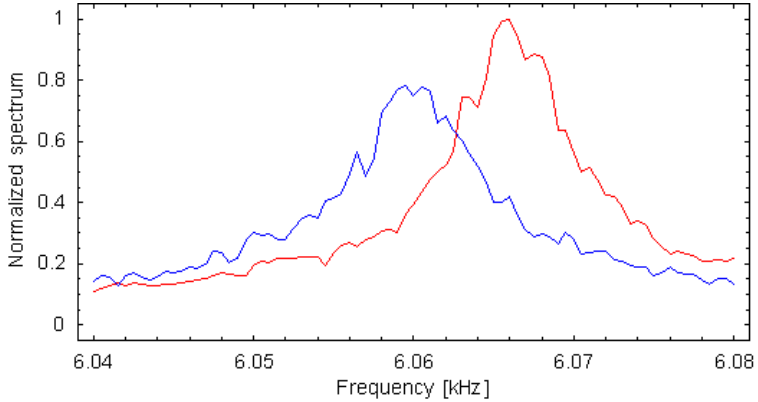


Spectra from the meas. of 4:40

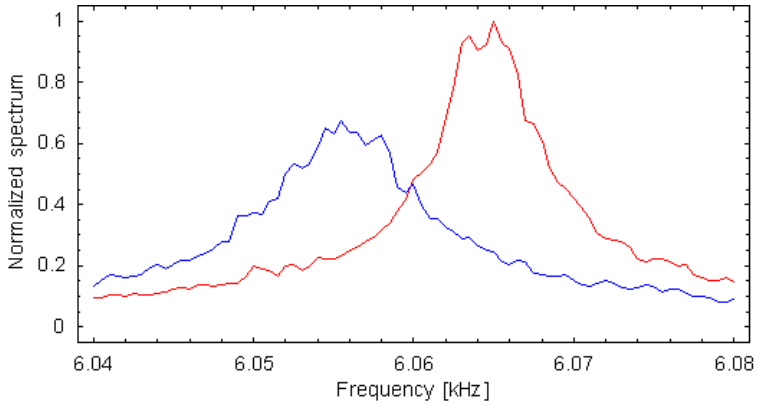




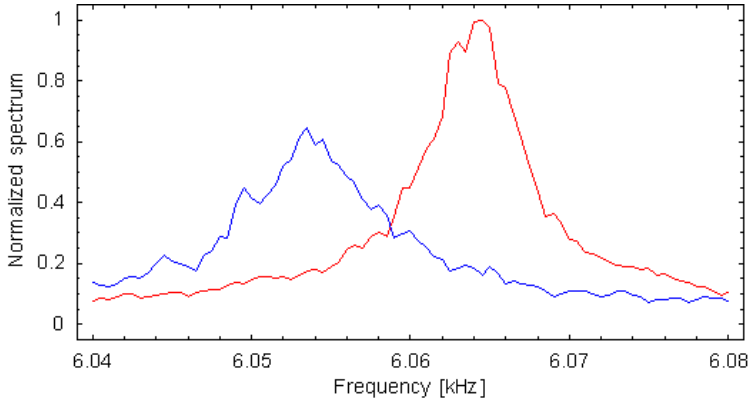
SPS BBQ Measurements – LHC Collimator Impedance



4:01

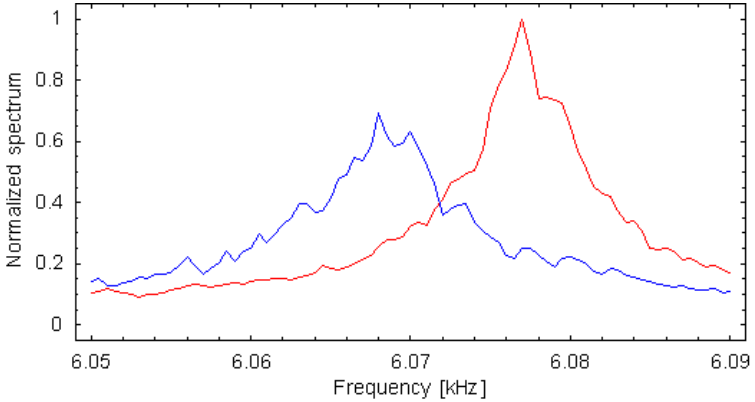


4:22

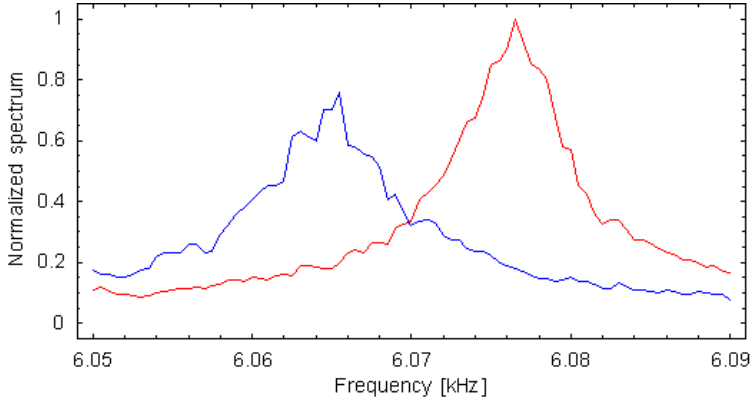


4:40

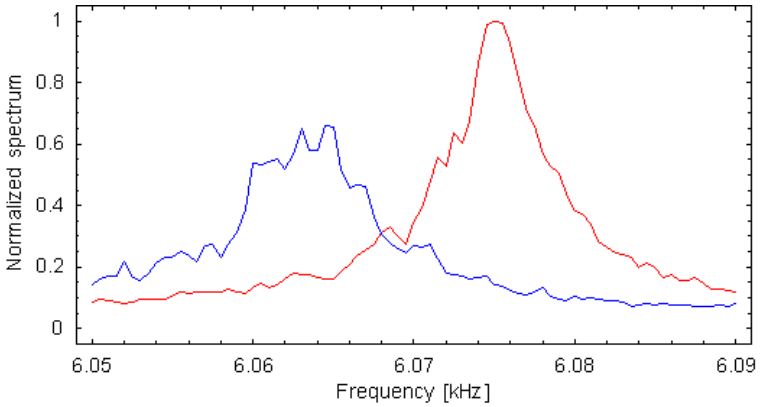
5:46



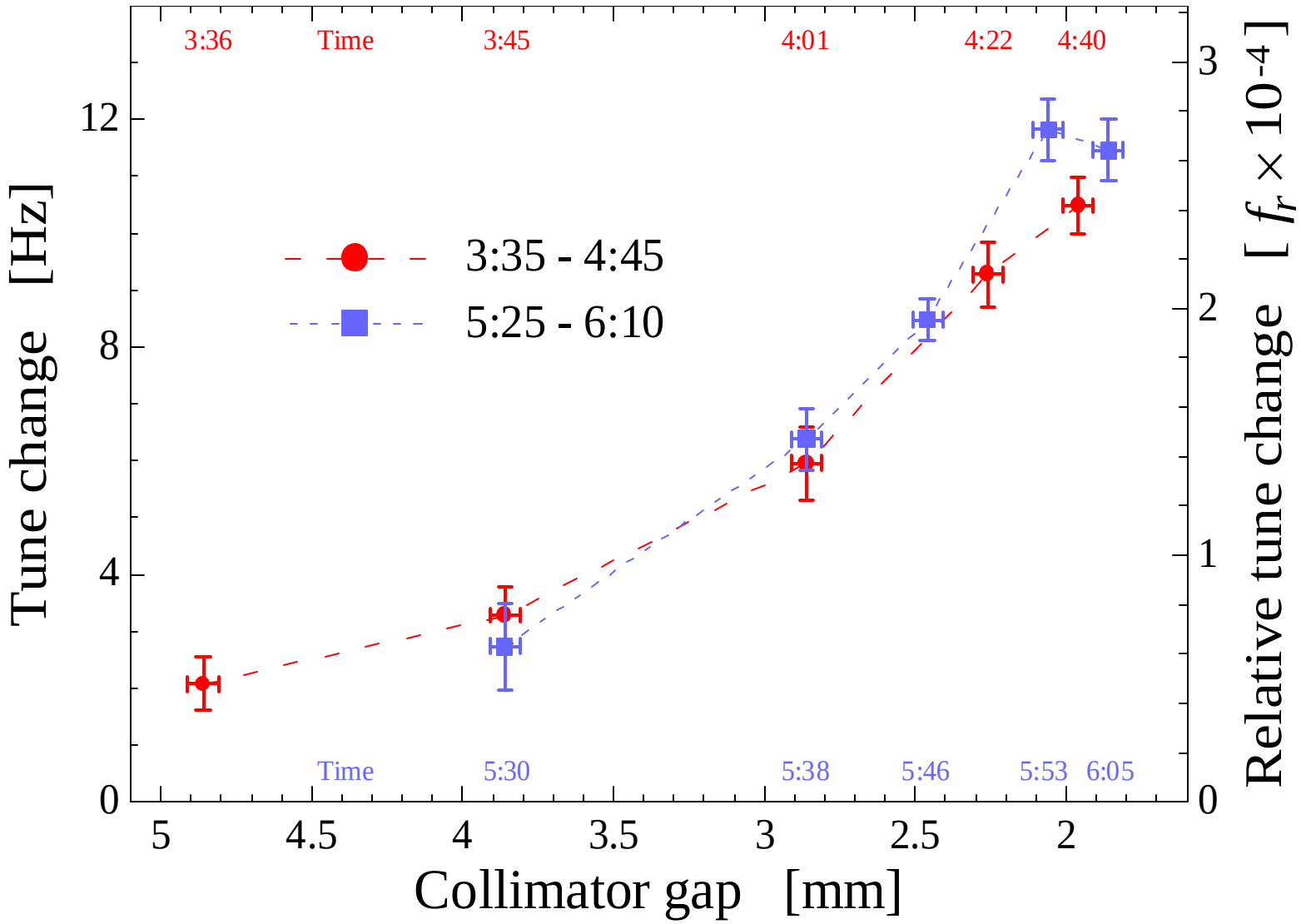
5:53



6:05



SPS BBQ Measurements – LHC Collimator Impedance



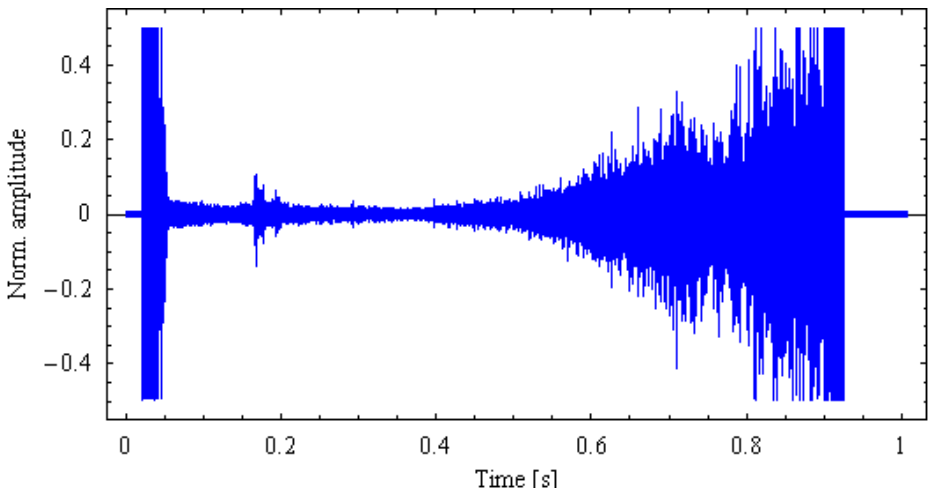
Smallest frequency error is 0.37 Hz (9 ppm of f_r)

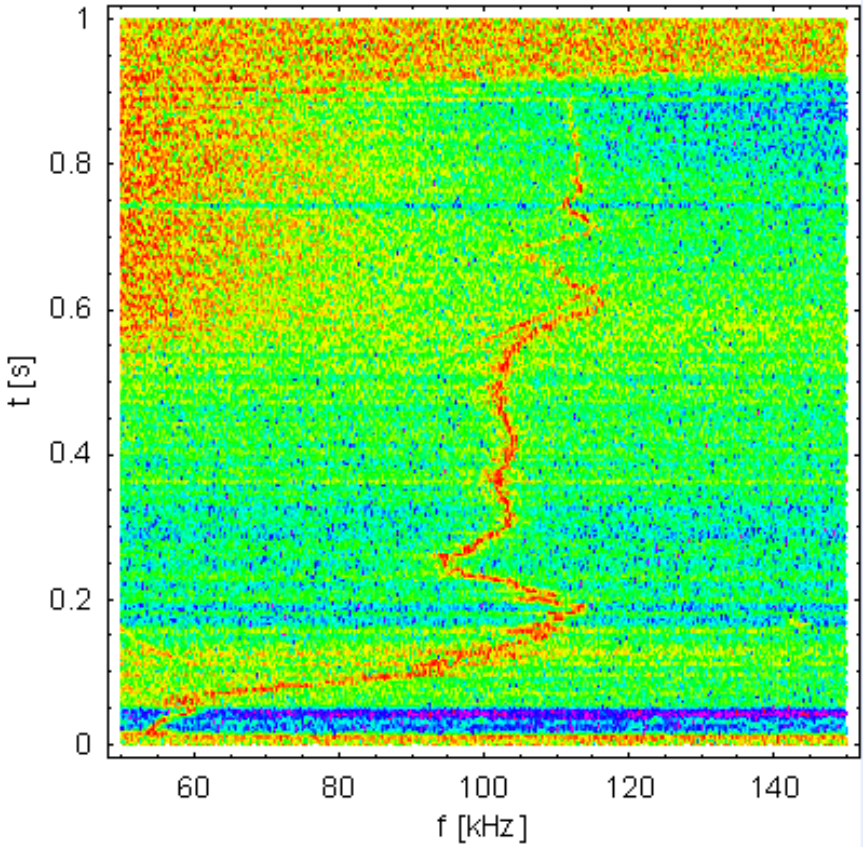
Largest frequency error is 0.77 Hz (18 ppm of f_r)

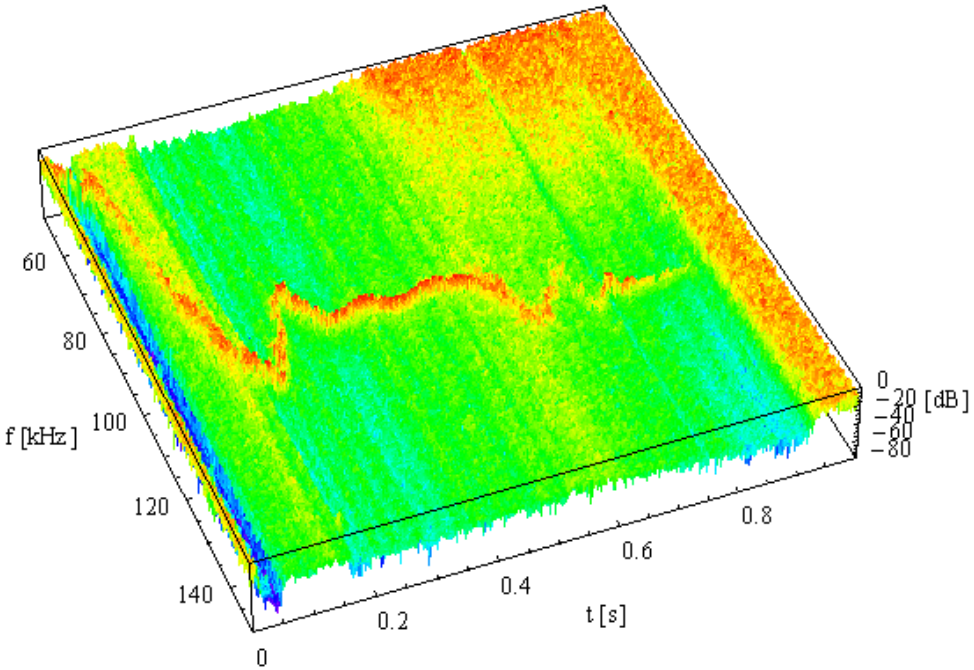
Error average is 0.54 Hz (13 ppm of f_r)

SPS f_r is 43376

PS BBQ Measurements – AD Cycle

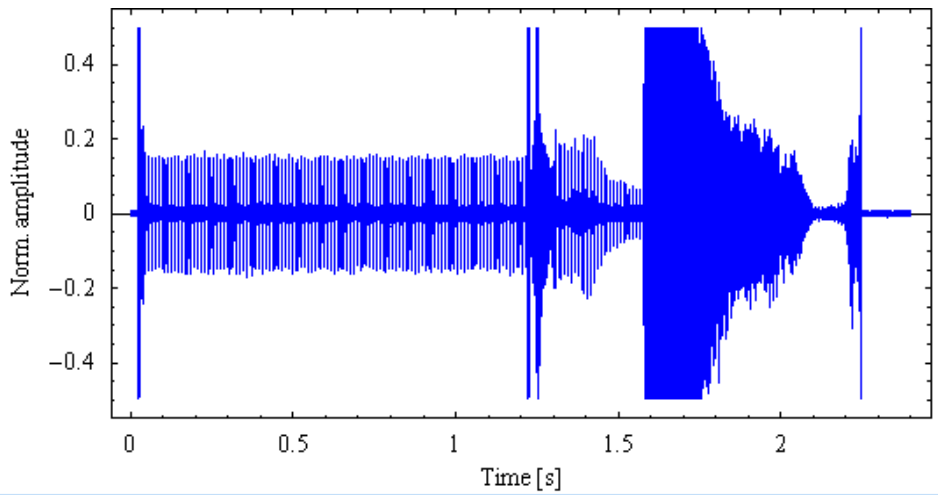


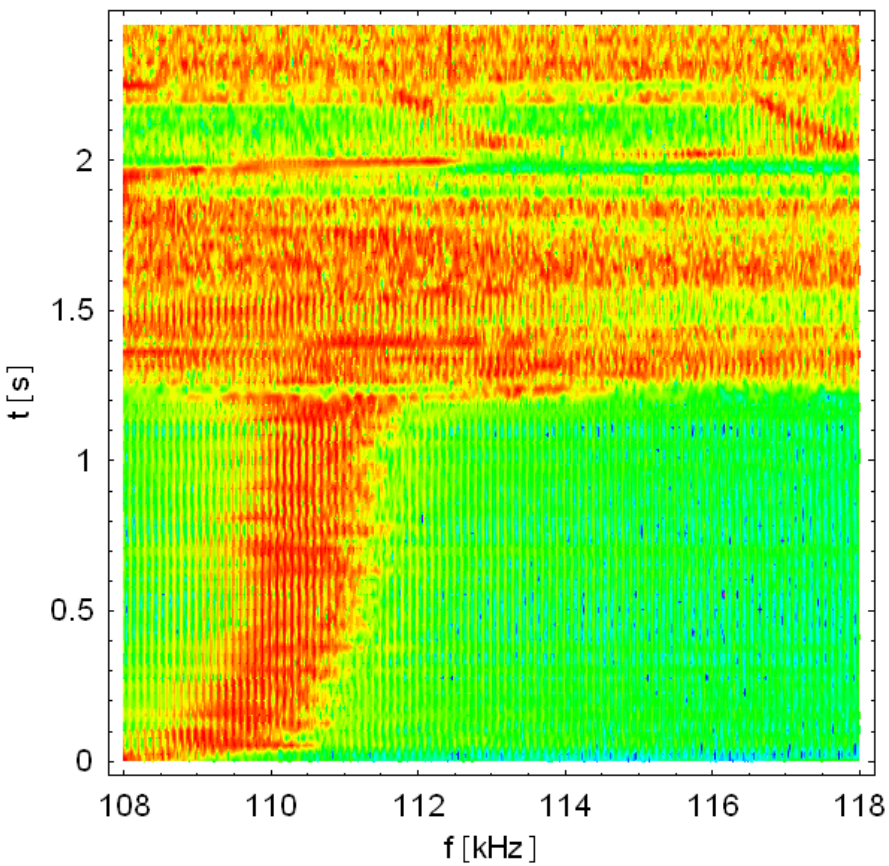


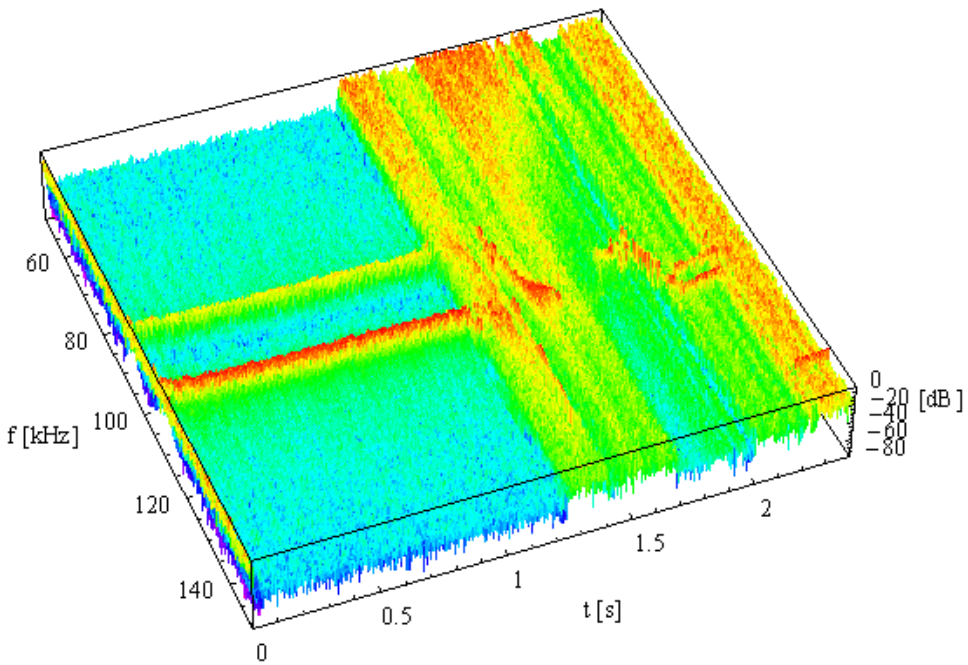


No explicit excitation

PS BBQ Measurements – LHC Cycle – Mains Ripple

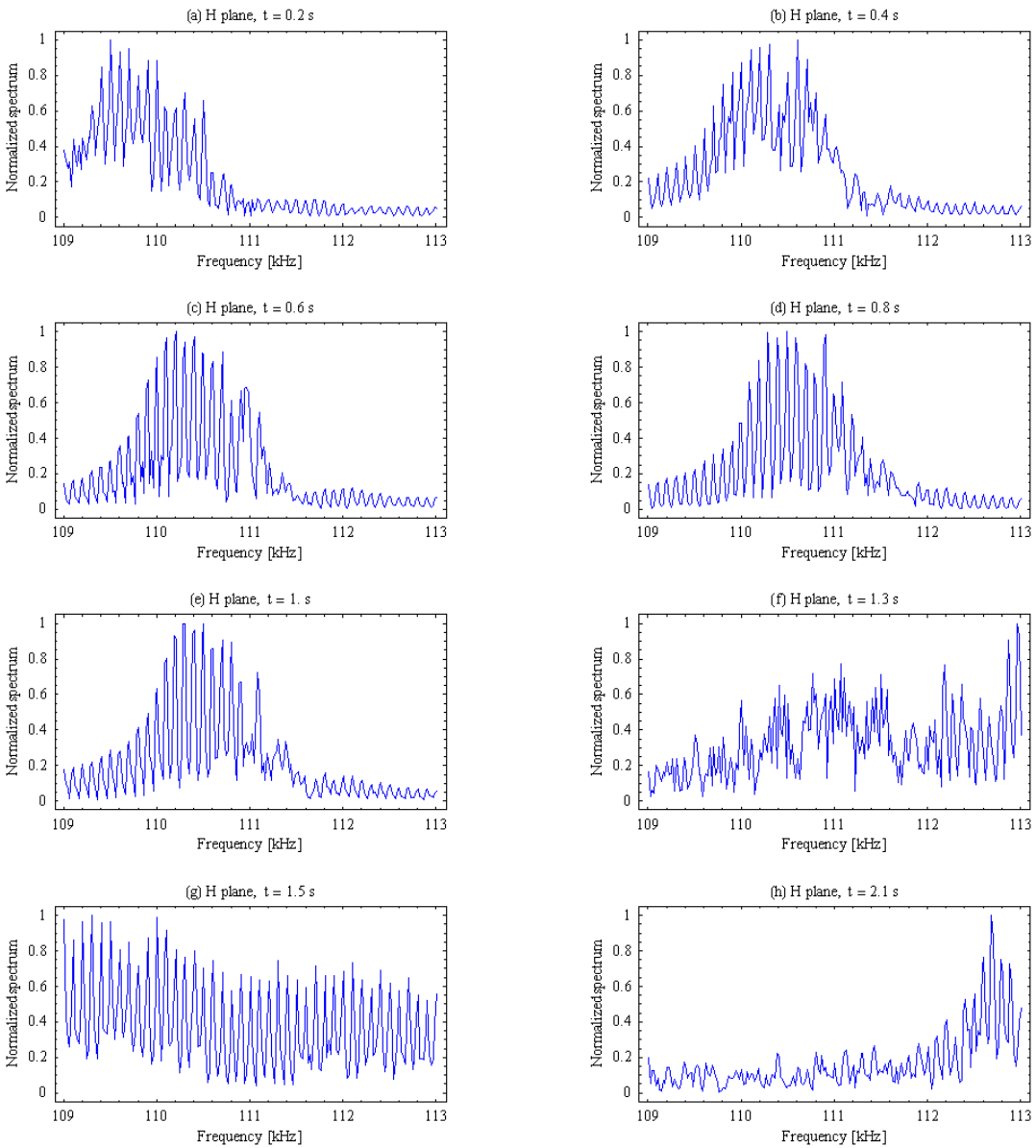


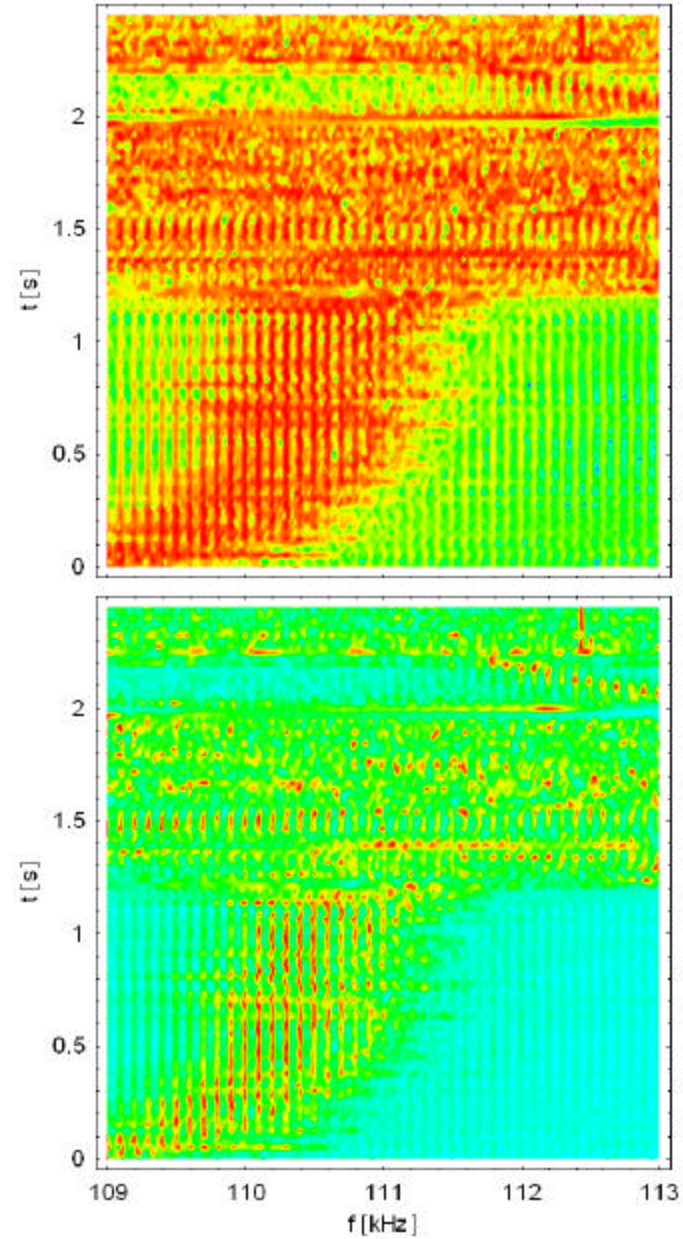




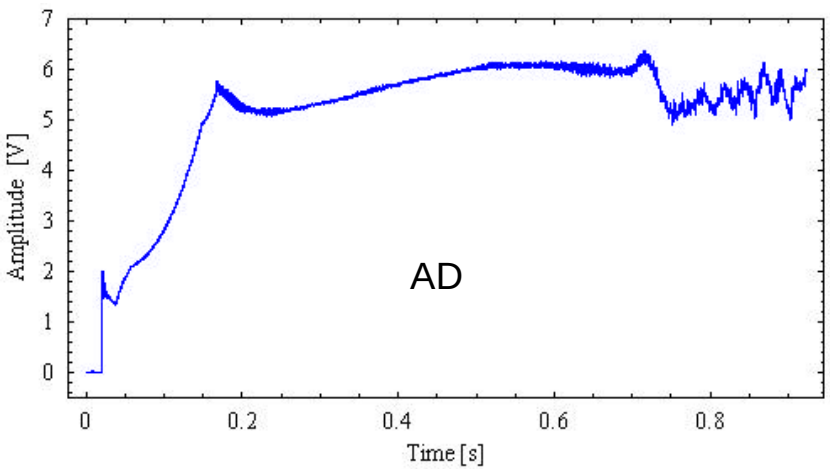
Q kicker fired every 10 ms with the minimal strength

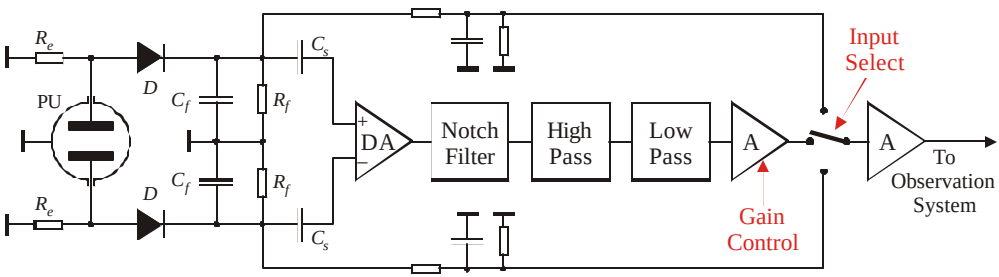
PS BBQ Measurements – LHC Cycle – Mains Ripple

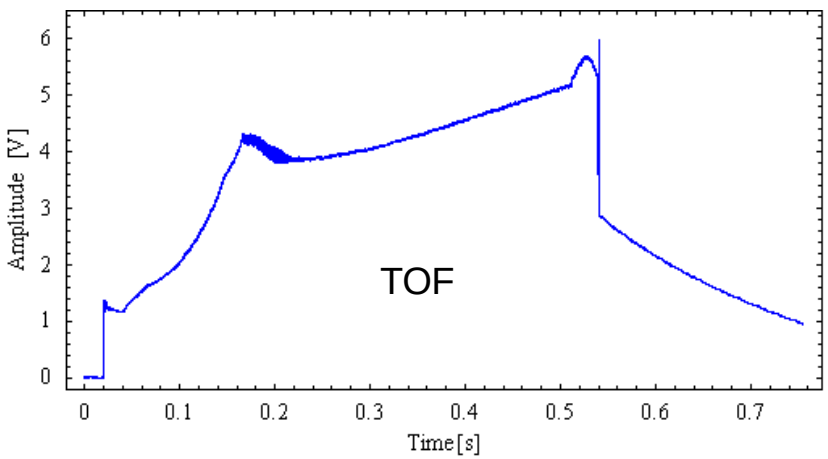


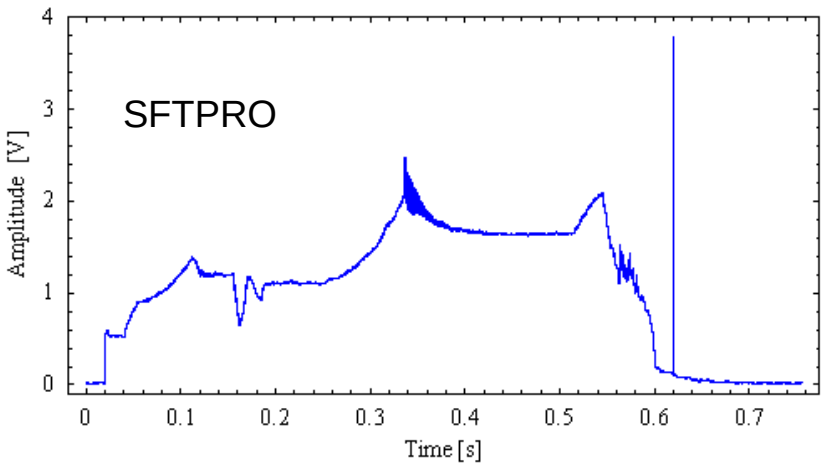


PS BBQ Measurements – Detector DC Voltages









BBQ Advantages / Disadvantages

Advantages

- Sensitivity
- Virtually impossible to saturate
- Simplicity
- No resonant PU, no movable PU, no hybrid, no mixers
- It can work with any PU
- Base-band operation guaranties the independence of the machine filling pattern
- Signal conditioning / processing in the base-band is easy (powerful components for low frequencies)
- Flattening out the beam dynamic range (small sensitivity to the bunch number)

Disadvantages

- Operation in the low frequency range
- It is sensitive to the "bunch majority"

More measurements and other plots from the presented measurements can be seen on the BBQ web site

www.cern.ch/gasior/pro/3D-BBQ/3D-BBQ.html