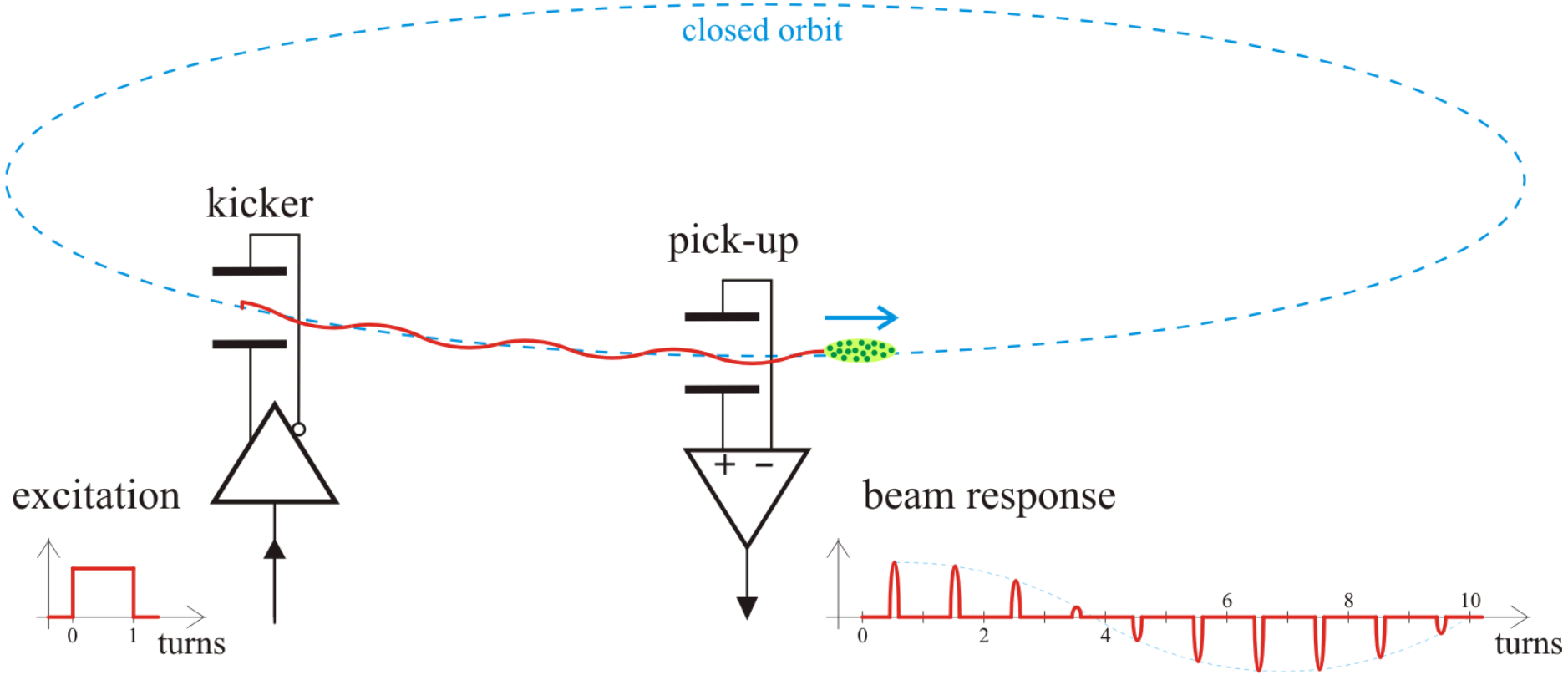
Base Band Tune (BBQ) measurement systems - observing beam oscillations with sub-micrometre amplitudes

Marek Gasior

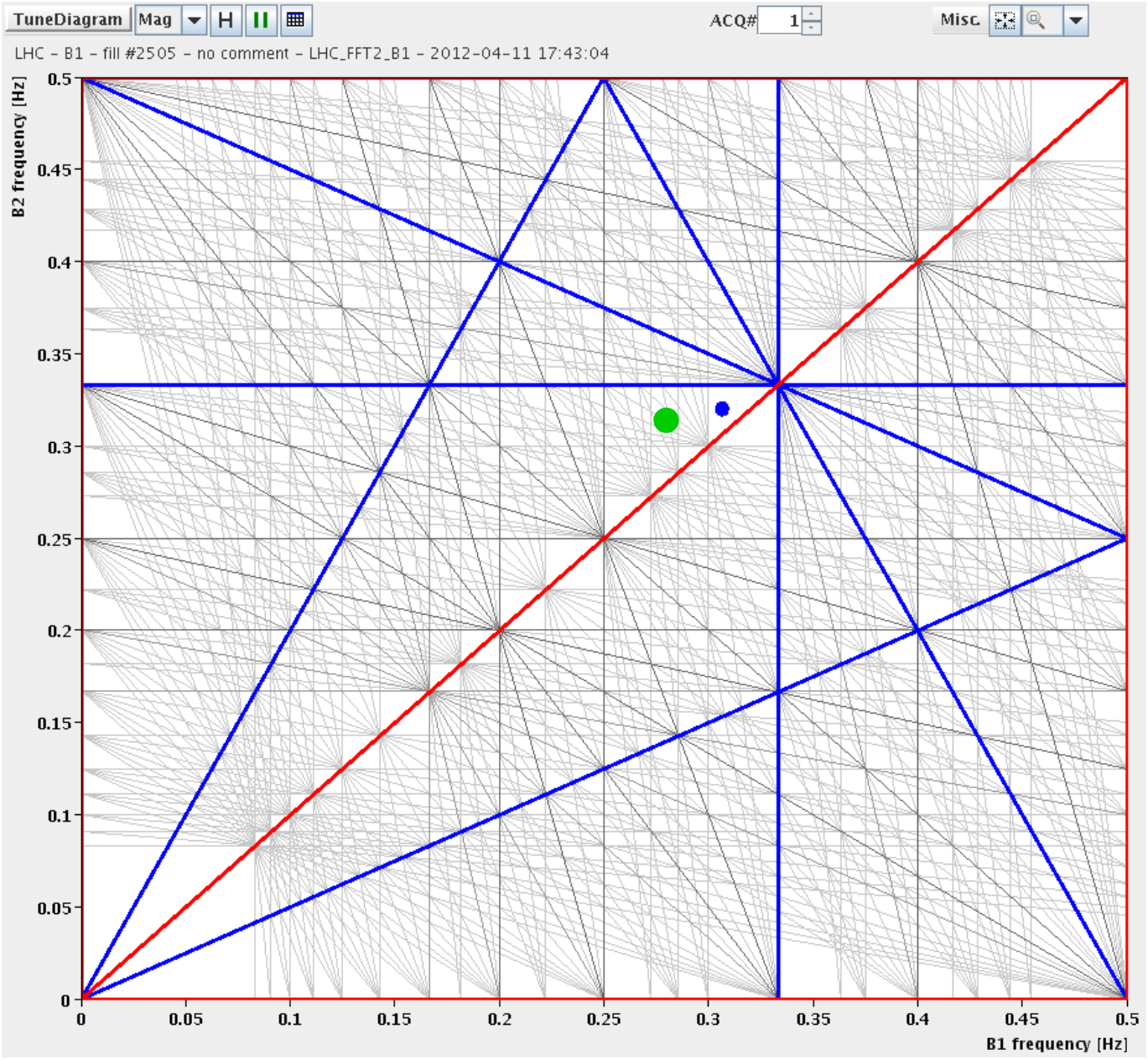
Beam Instrumentation Group
Beams Department

Tune measurement – the principle



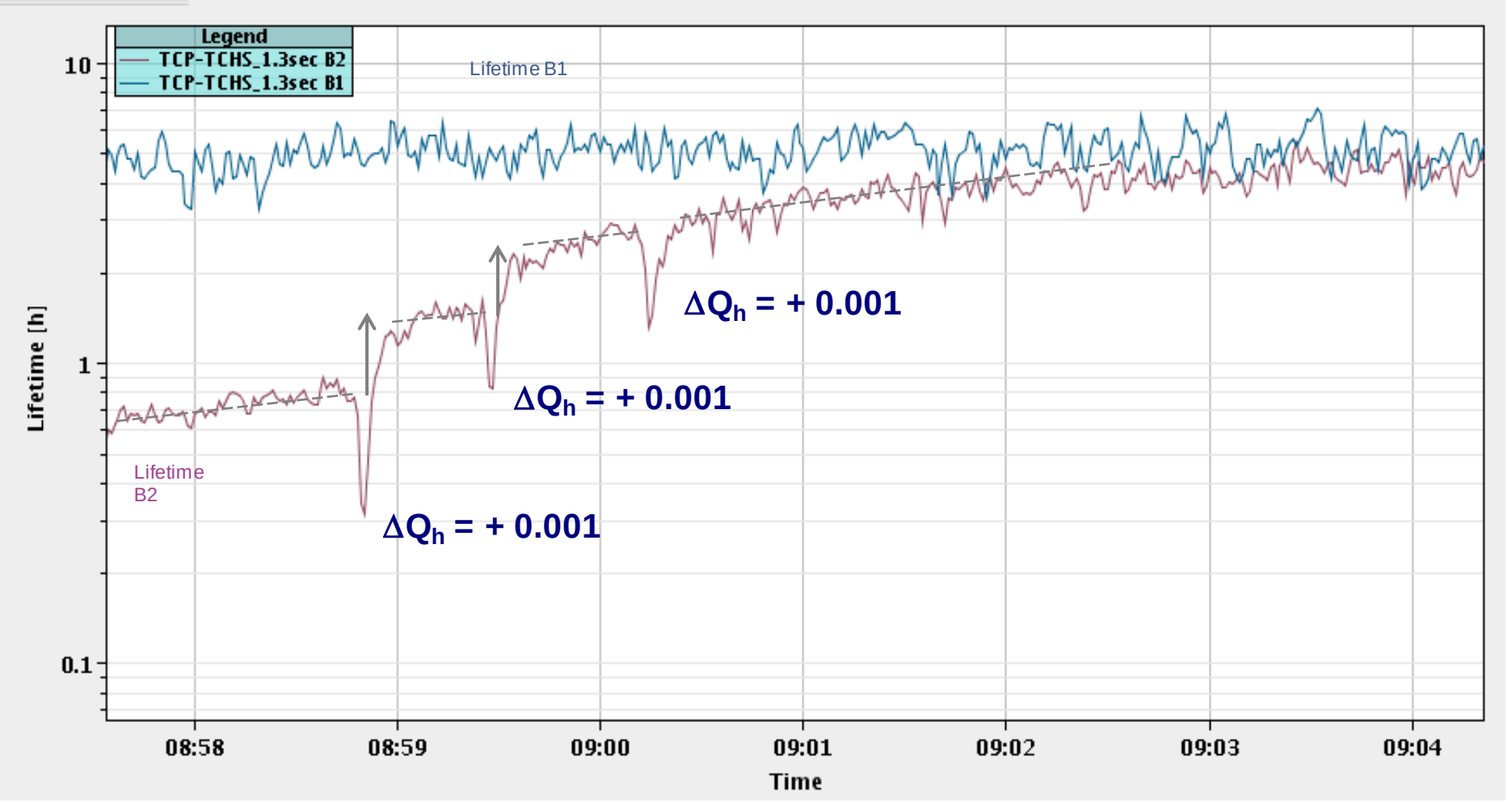
- Beam betatron oscillations are observed on a position pick-up
- Oscillations of individual particles are incoherent – an excitation needed for “synchronization”
- The machine tune is the frequency of betatron oscillations related to the revolution frequency.
- Betatron oscillations are usually observed in the frequency domain.
- With one pick-up only betatron phase advance form one turn to the next is known – only fractional tune can be measured.

LHC tune diagram



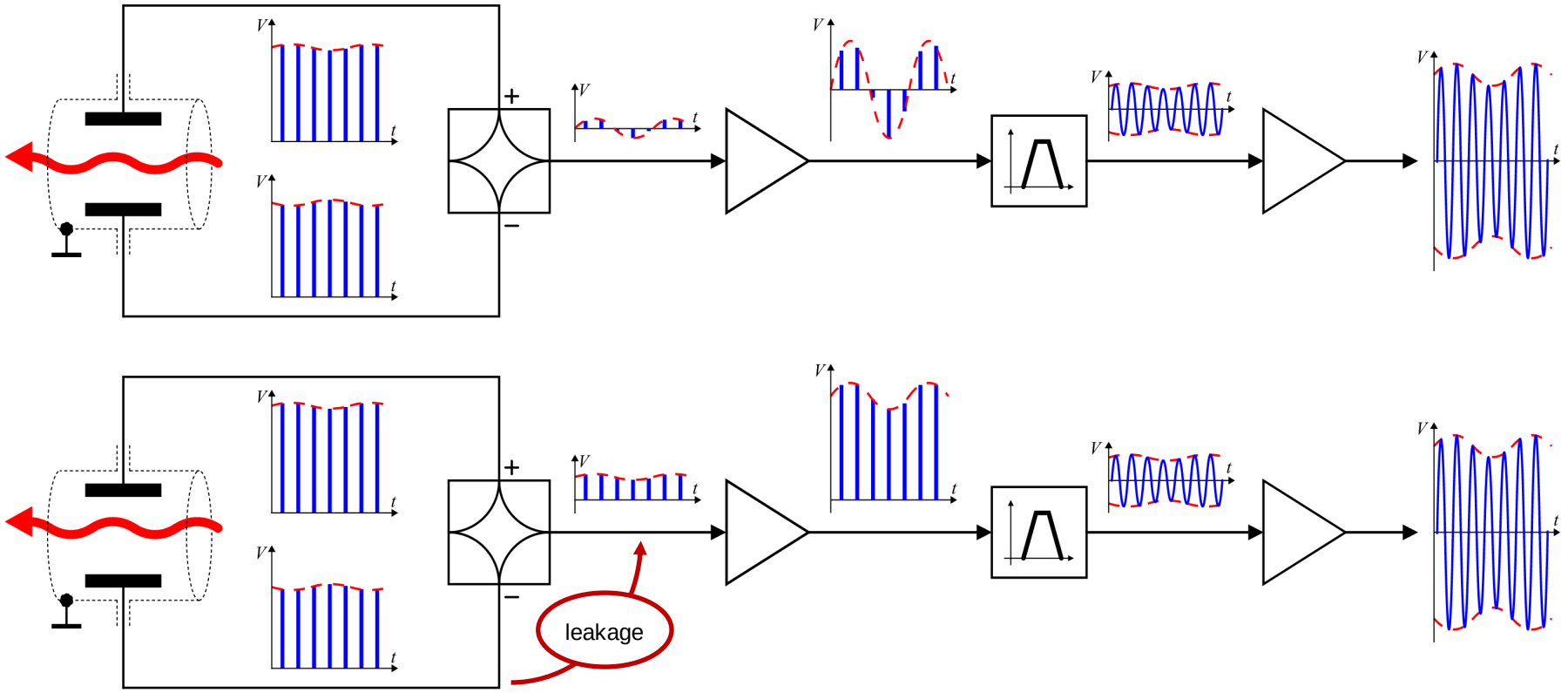
- LHC physics tunes:
  H: 0.31, V: 0.32
- The **blue** dot comes from a real measurement during collisions at 4 TeV.
- LHC injection tunes:
  H: 0.28, V: 0.31
- LHC integer tunes:
  H: 59, V: 64
- LHC tunes must be kept on the design values within ≈ 0.001.
- LHC has a tune feed-back system, i.e. during the ramp the LHC tunes are measured continuously and the readings are used to calculate the necessary corrections applied to the quadrupoles to keep the tunes on the design values.

Importance of tunes in real life – an LHC example



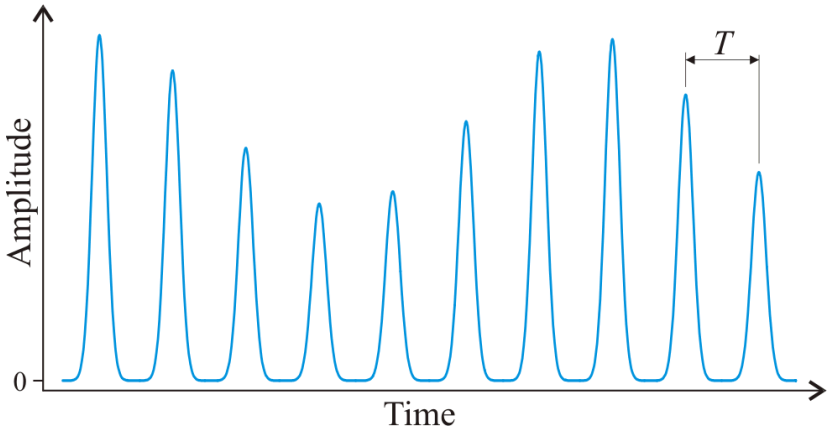
Plots from the morning LHC operation meeting of 29 May 2012.

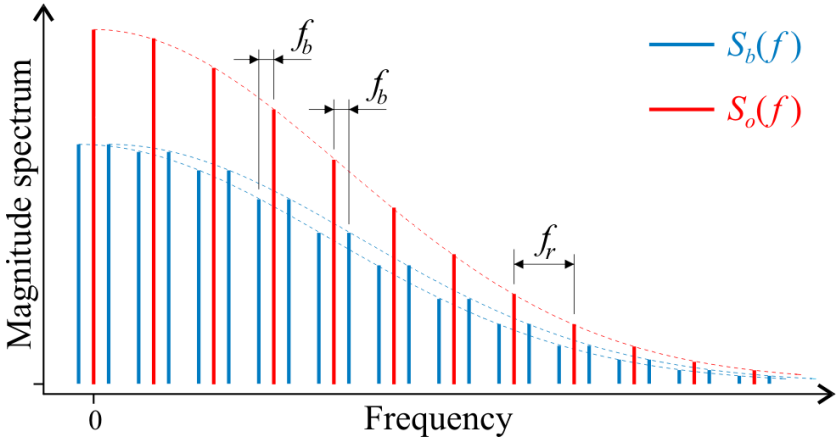
Tune measurement challenges – the time domain view



- Linear processing of position pick-up signals
- Dynamic range problems:
  - Signals related to betatron oscillations are small with respect to the beam offset signals.
  - Even if the beam is centred, the subtraction of the signals from the pick-up opposing electrodes is not perfect. The leakage is in the order of 1-10 % for ns beam pulses.
- Options to decrease beam offset signals:
  - centre the beam;
  - centre the pick-up;
  - equalise the signals by attenuating the larger one (electronic beam centring).

Tune measurement challenges – the freqnecy domain view



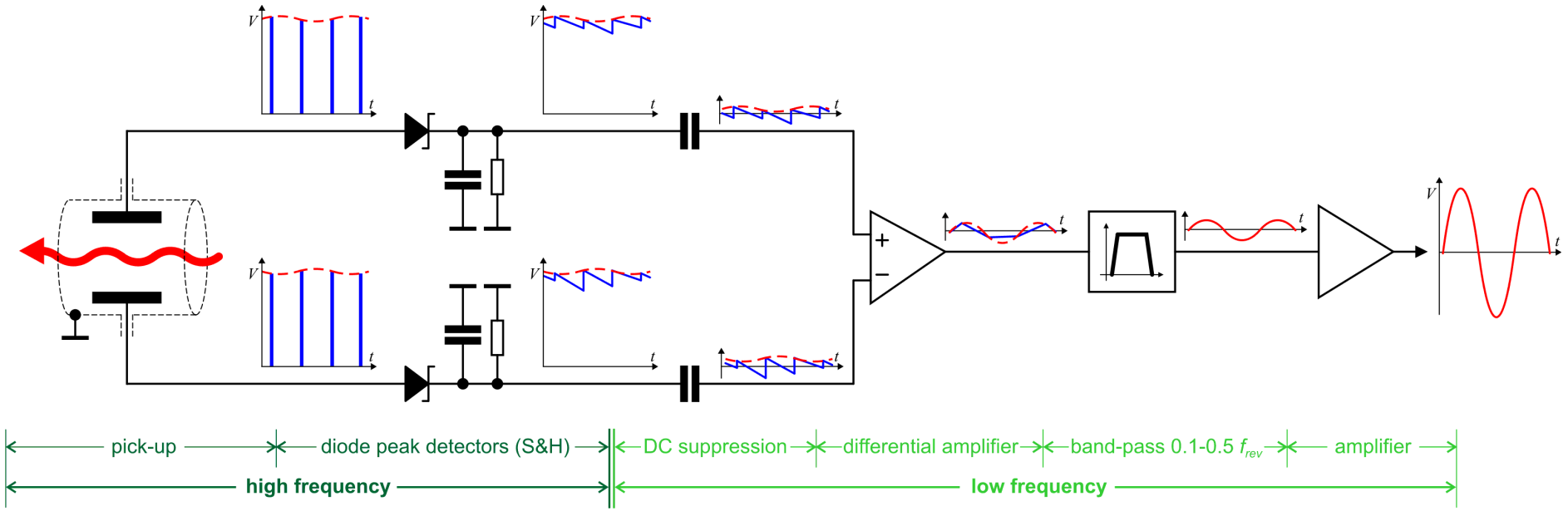


- Spectrum envelope is defined by the bunch shape. For a gaussian bunch the spectrum envelope is gaussian as well.
- The harmonic structure of the beam spectrum is defined by the time beam time structure.
- Short single bunches give large spectra, with many lines; most often this is the largest challenge for the tune meas. system.
- The LHC bunch length (4σ) is about 1 ns and the corresponding bunch power spectrum cut-off is about 500 MHz.
- With just one bunch in the machine the revolution spectral lines are spaced by 11 kHz, so by 500 MHz there are some 50 000 of them and some 100 000 betatron lines.
- In the classical tune measurement method only one betatron line is observed, so in the LHC case it is only some 10^{-5} (-100 dB) of the total spectral content.
- This results in very small signals, requiring low noise amplifiers and mixers, which have small dynamic ranges; they can be saturated even with relatively small beam offset signals.

- The “order of magnitude” estimates for pick-up signals, assuming electrode distance 100 mm and 100 V electrode signals:

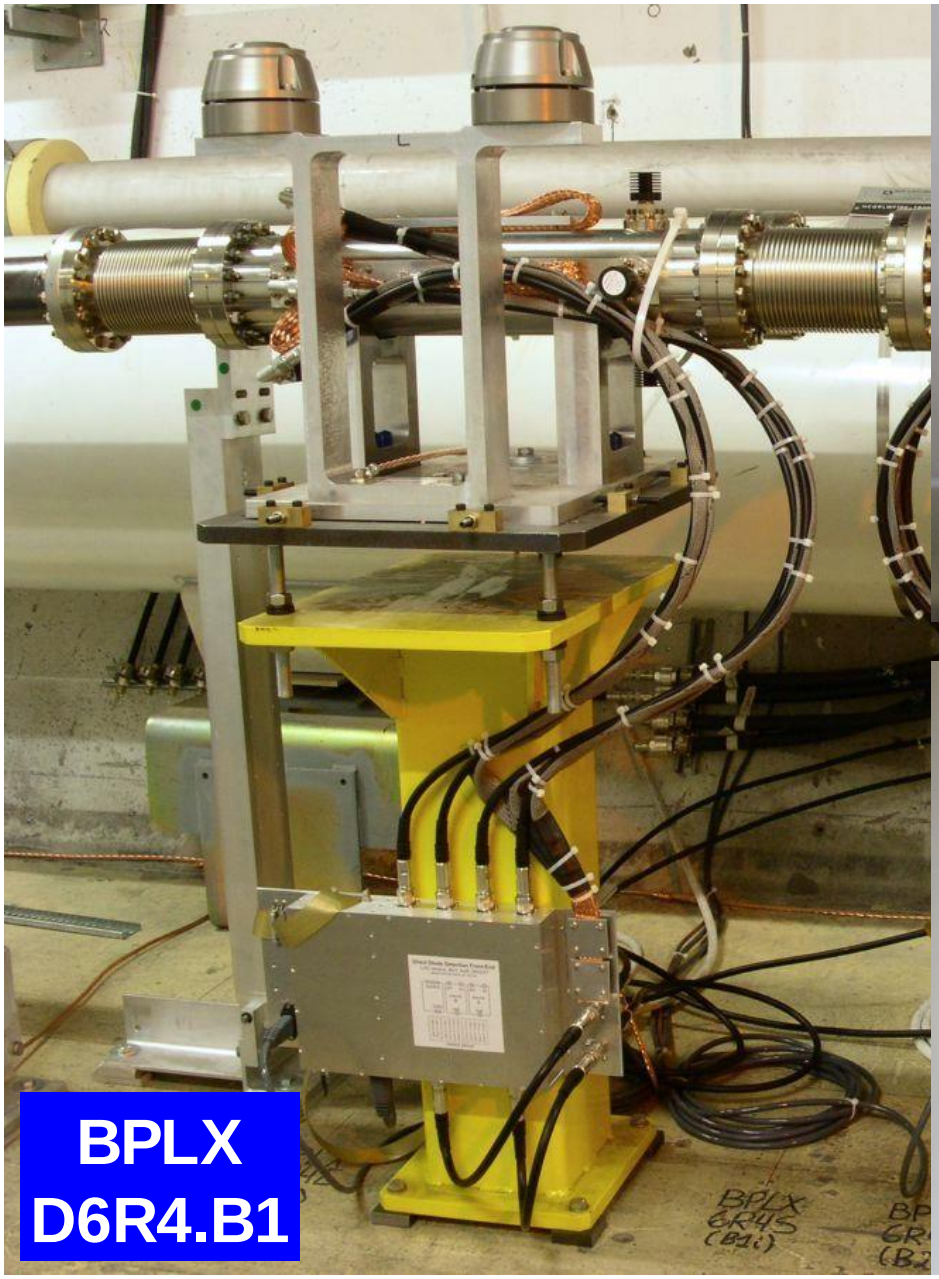
1 mm beam offset signal:	1 mm / 100 mm * 100 V ≈ 1 V
1 µm beam oscillation signal:	1 µm / 100 mm * 100 V ≈ 1 mV
1 µm beam oscillation signal observed at a single frequency:	1 mV * 10^{-5} ≈ 10 nV

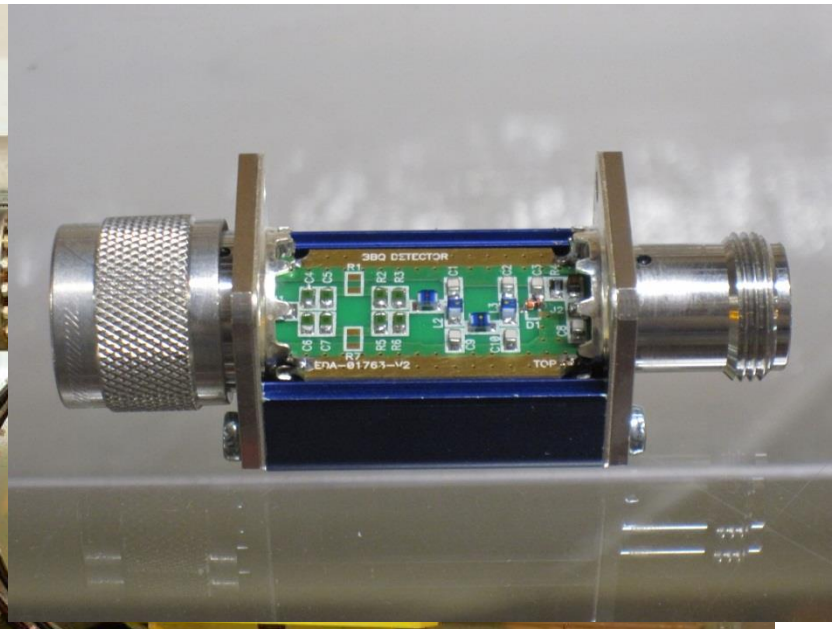
Direct Diode Detection (3D) – the idea



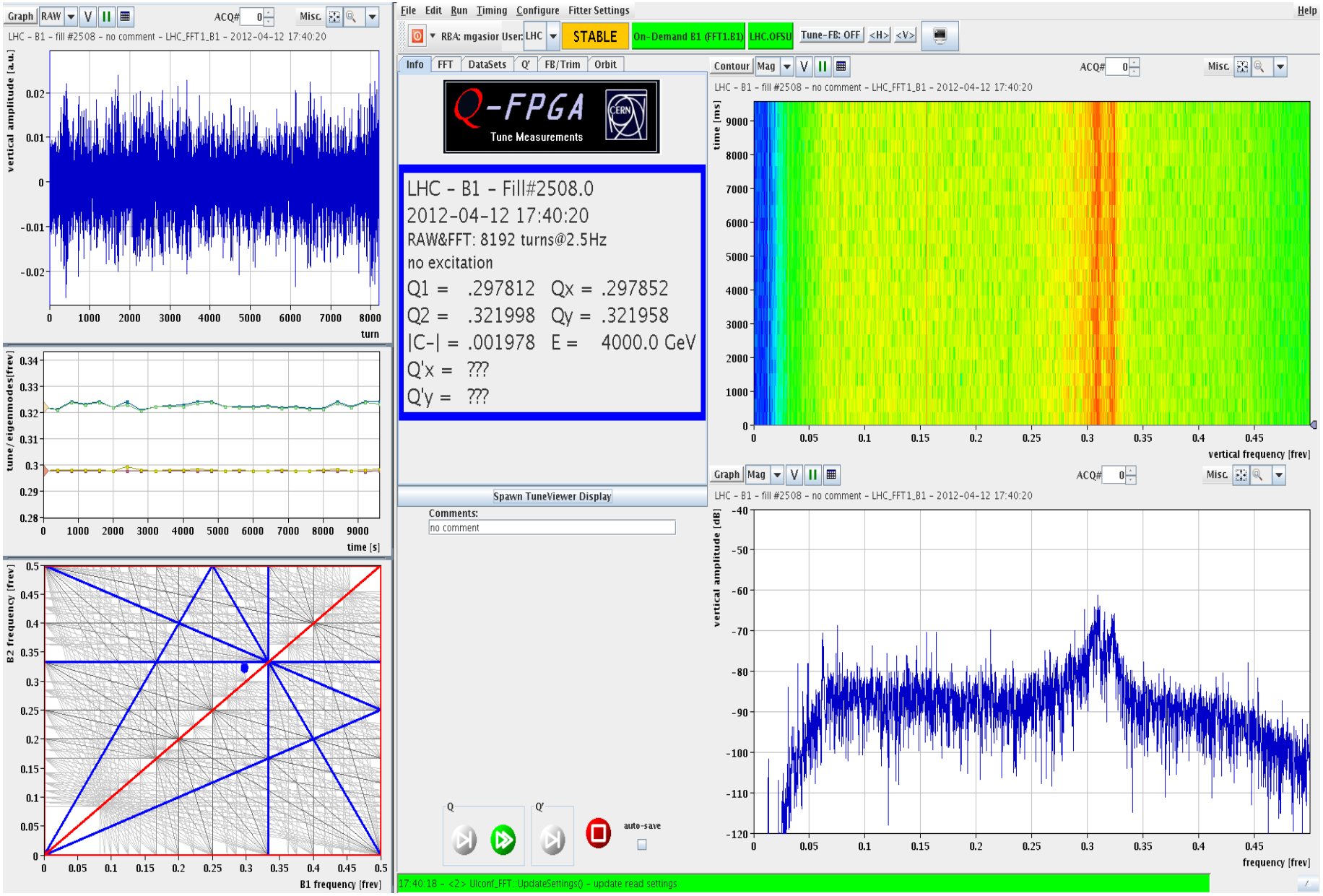
- Peak detection of signals from a position pick-up electrode, a simple sample-and-hold, with the sampling triggered by the beam pulses.
- An RF Schottky diode can handle up to 50 V of beam pulses; more is possible with a few diodes in series (LHC detectors have 6 diodes).
- Betatron modulation is downmixed to a low frequency range, as after the diodes the modulation is on much longer pulses.
- Revolution frequency background gets converted to the DC and removed by series capacitors, while the betatron modulation is passed for amplification and filtering ("collecting just the cream").
- Most of the betatron modulation amplitude is passed to the following circuitry, resulting in very high sensitivity of the method.
- The diode detectors can be put on any position pick-up.
- Low frequency operation after the diodes allows:
  - very efficient signal conditioning and processing with powerful components for low frequencies;
  - using 24-bit inexpensive audio ADCs (160 dB dynamic range possible).
- What is new with respect to the classical peak detectors used in the past for BI applications:
  - Slow discharge, in the order of 1 % per turn (for LHC 100 MΩ resistors required).
  - Usage of high impedance amplifiers, not easy to build in the past if low noise was required.
  - Brutal filtering to the band 0.1 – 0.5 of f_{rev}.
  - Notch filter for the first f_{rev} harmonic, resulting in the total f_{rev} attenuation beyond 100 dB.

LHC BBQ installation

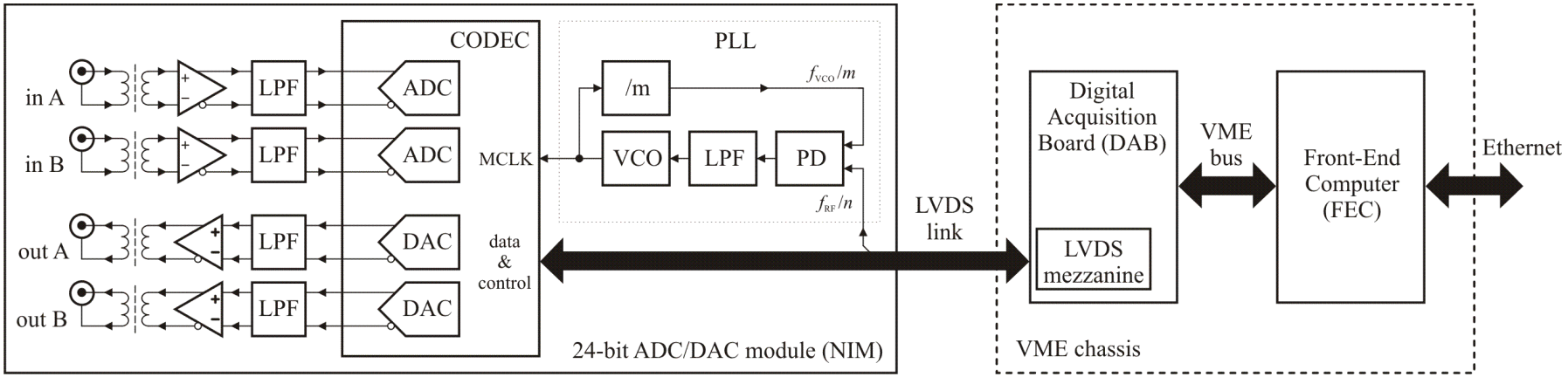


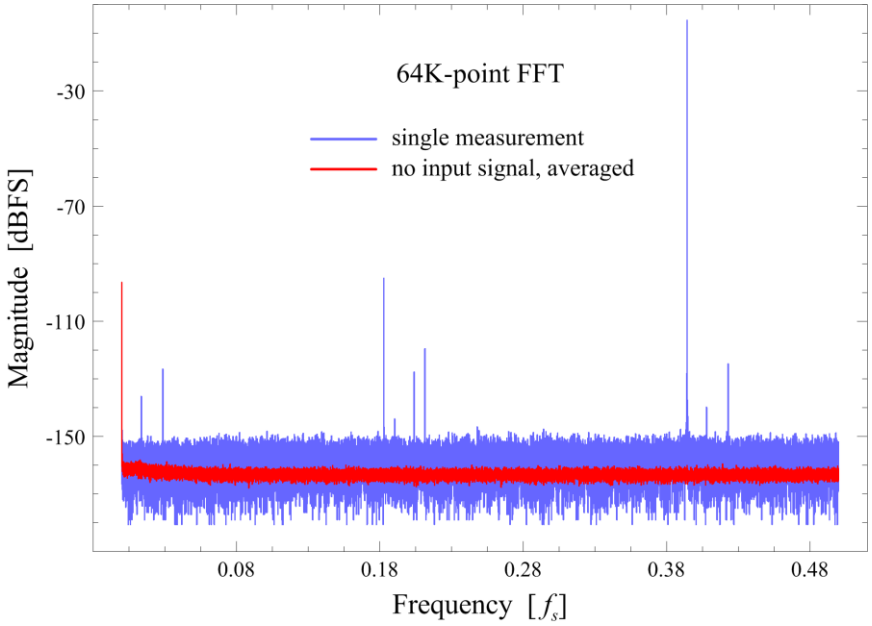


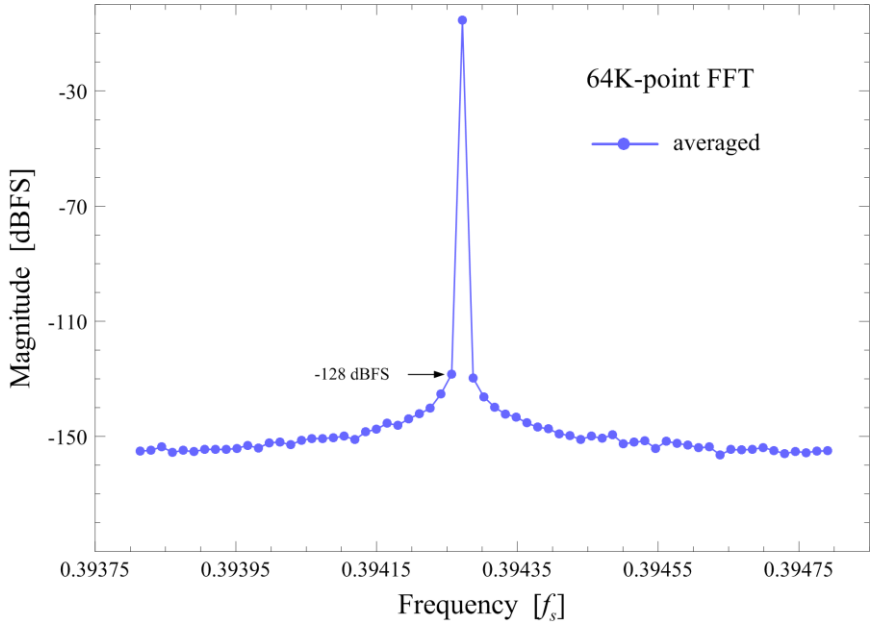
LHC tunes seen from the control room



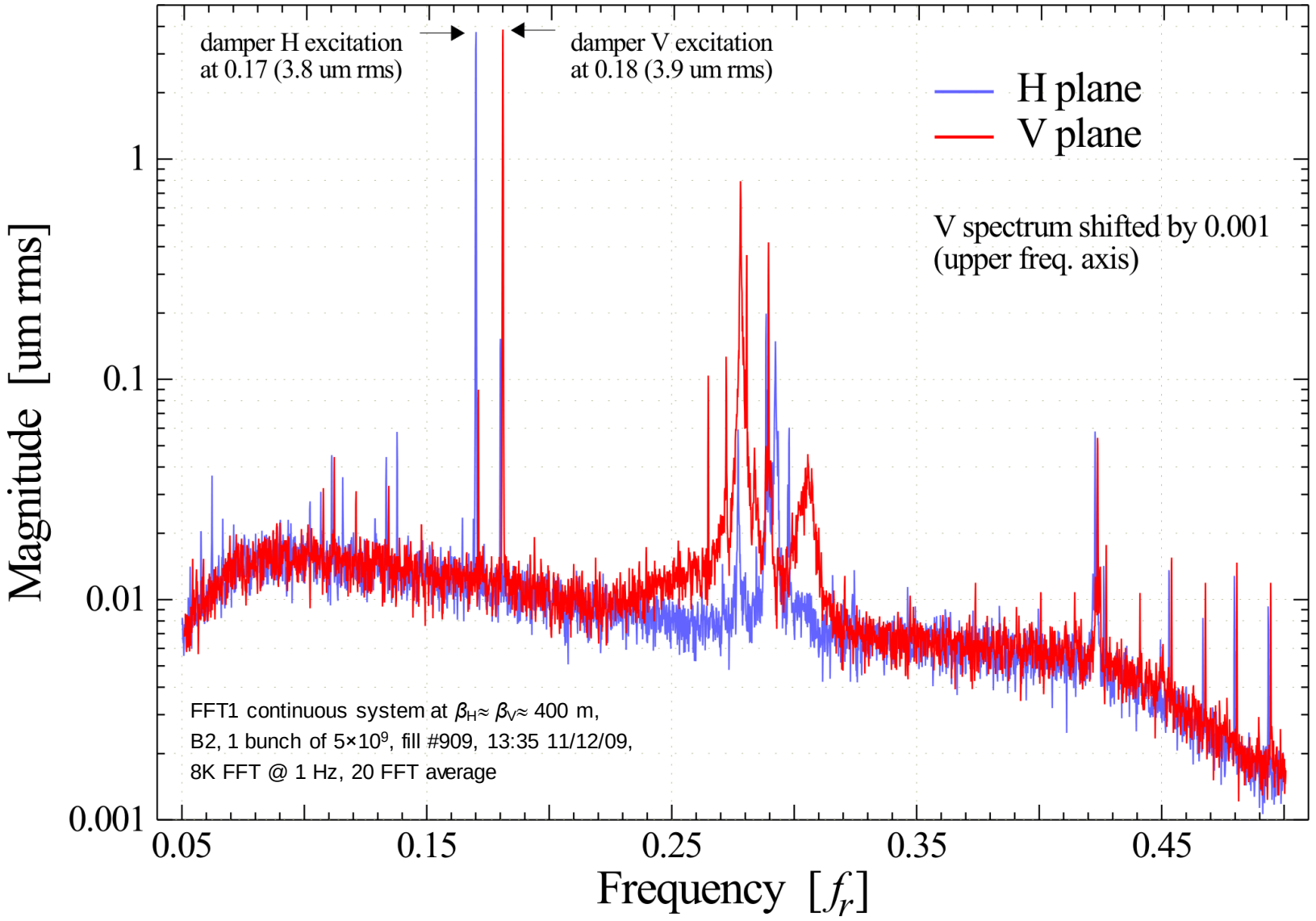
Acquisition in the kHz range: excellent 24-bit ADCs available





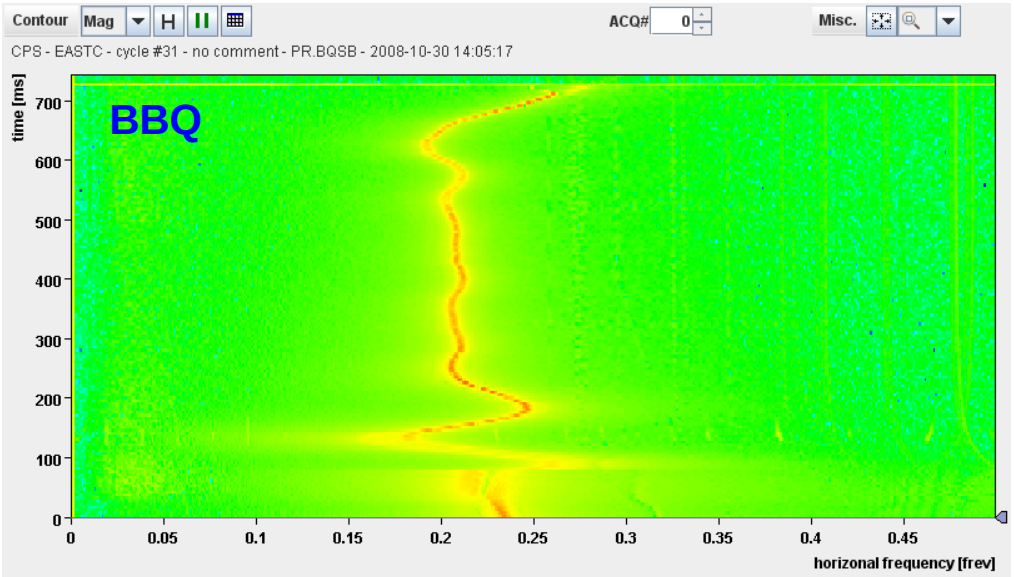


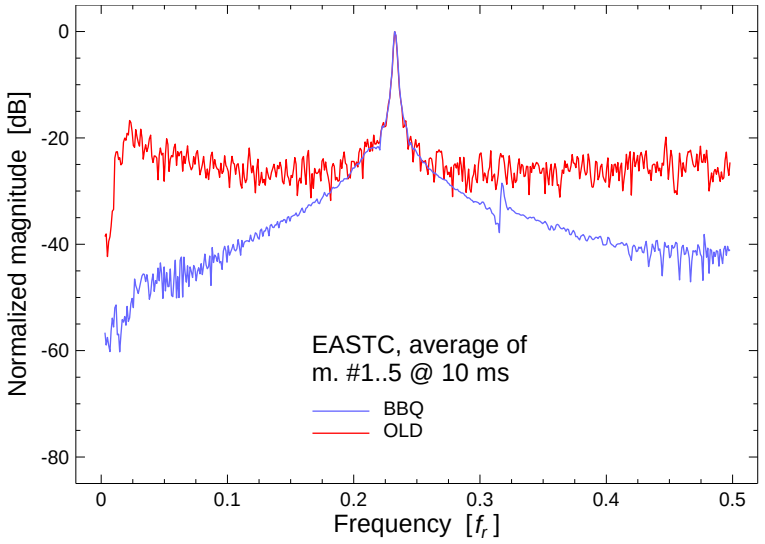
LHC beam spectrum, one pilot bunch

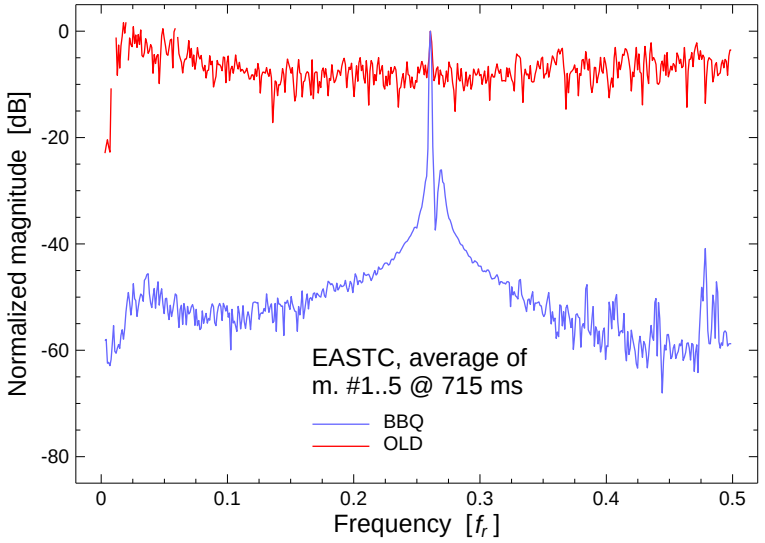


- Absolute amplitude calibration was done by exciting the beam to the amplitudes seen by regular LHC BPMs.

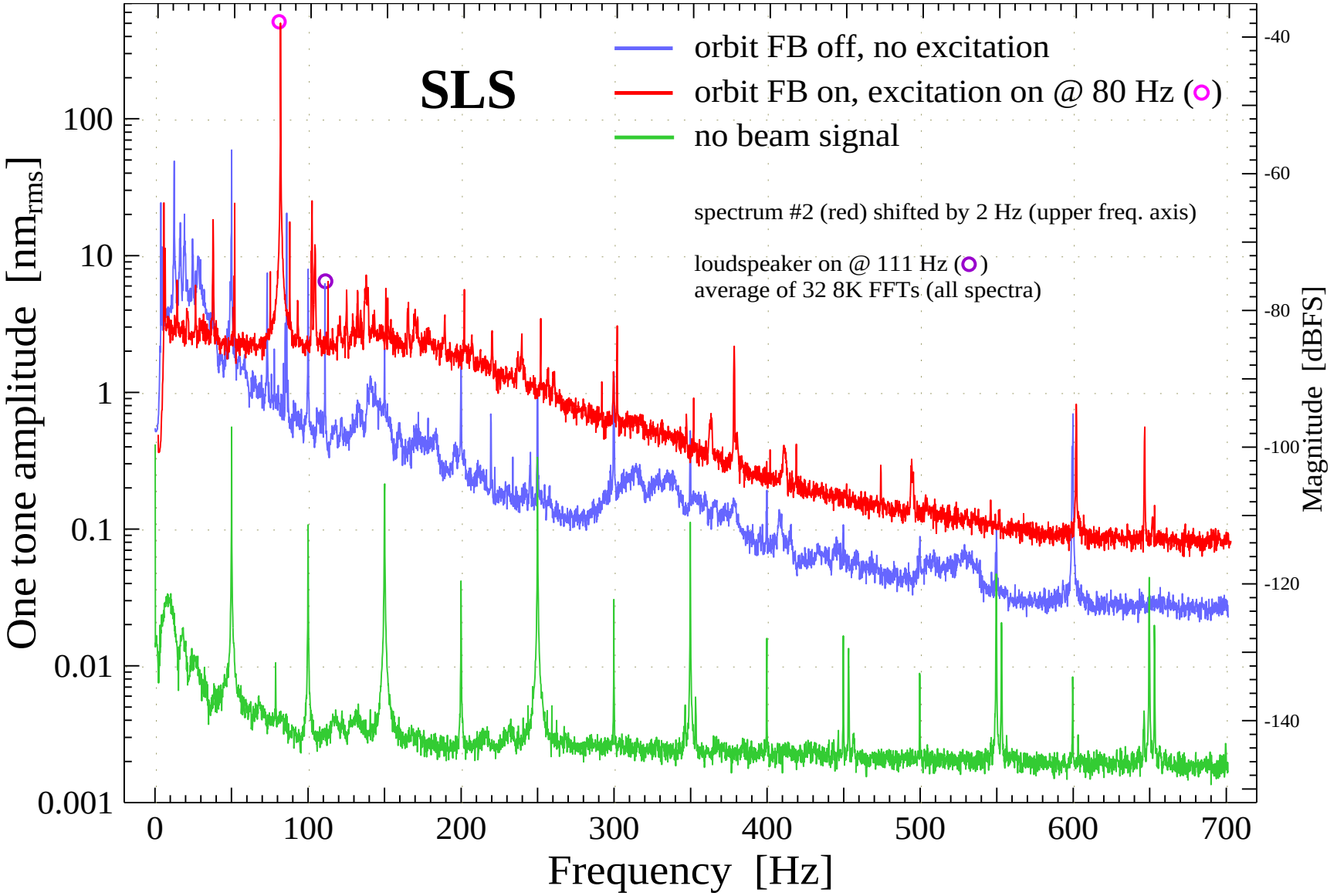
Comparison of the PS classical and BBQ tune systems





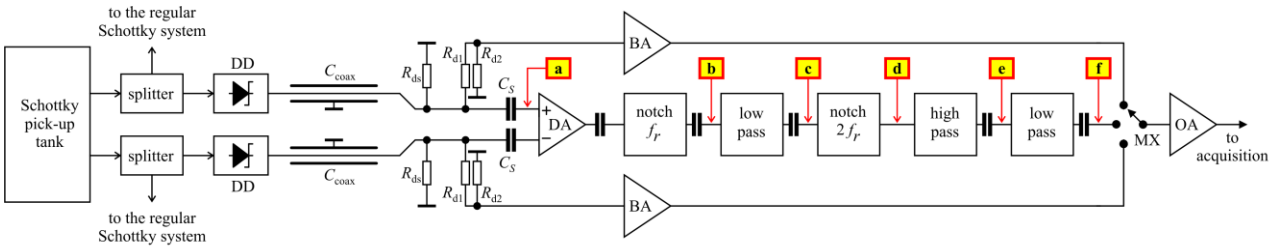


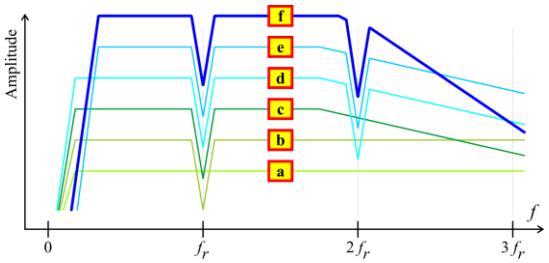
SLS beam spectrum measured with the diode detector system

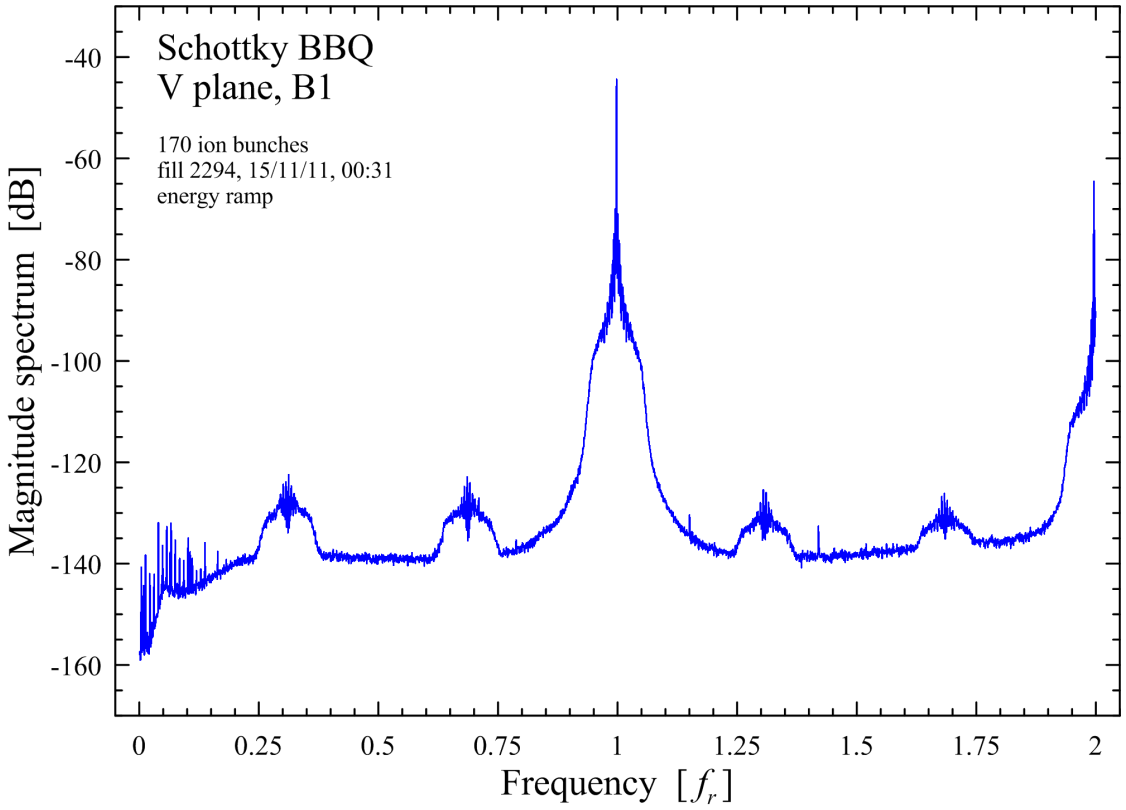


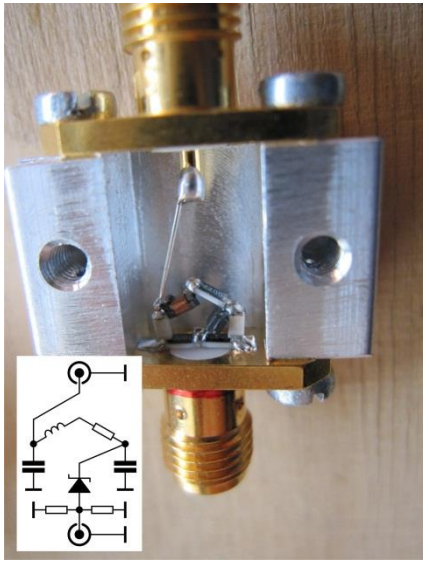
- Absolute amplitude calibration was done by exciting the beam to the amplitudes seen by regular SLS BPMs.

4.8 GHz LHC Schottky spectra





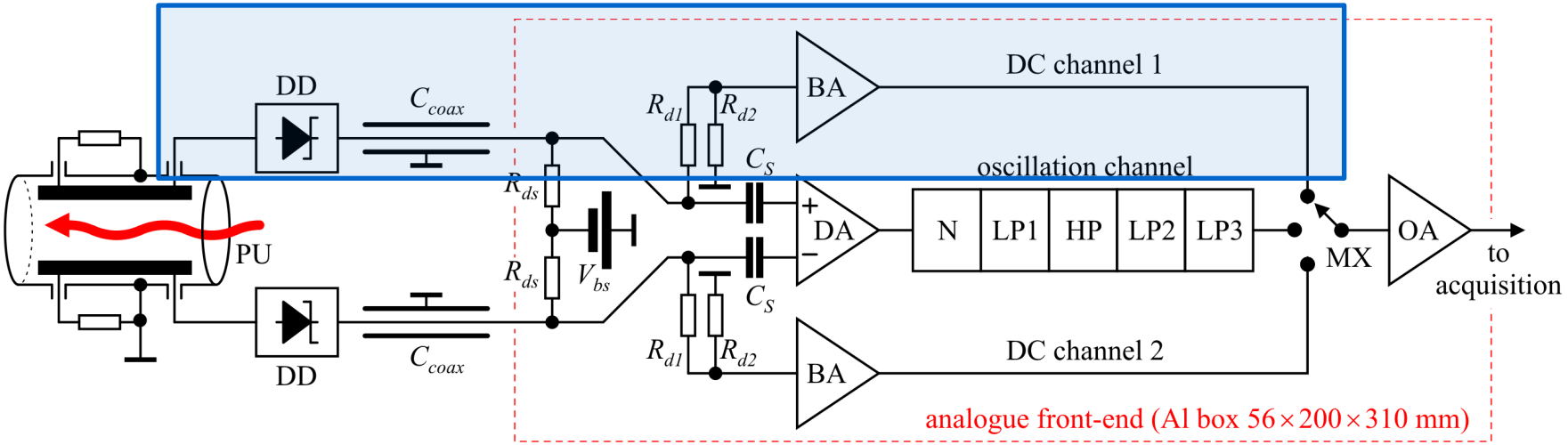


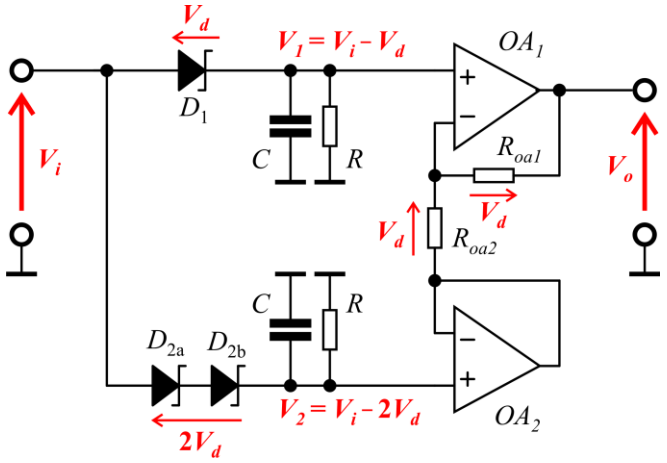


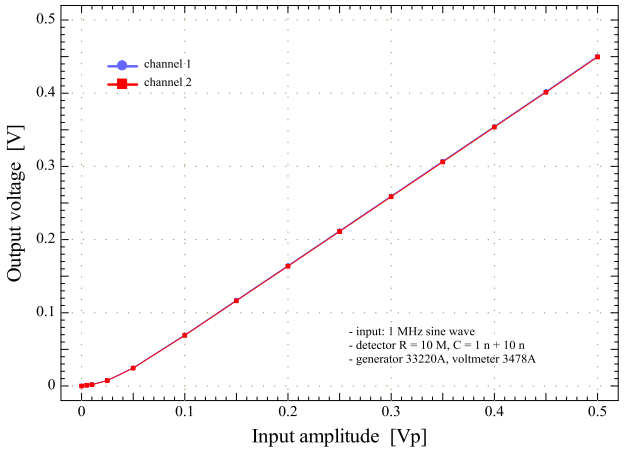
Detector diode	V_{max} [V]	4.8 GHz		1 GHz	
		Vo [V]	S11 [dB]	Vo [V]	S11 [dB]
BAS283	70	0.723	-6.8	0.740	-20.8
HSMS286	4	1.486	-9.3	0.871	-27.5
2x HSMS286	8	1.031	-17.4	0.771	-31.4
HSMS282	15	1.642	-2.9	0.865	-18.4
HSMS286+280	70	1.662	-10.8	0.781	-23.0
2x HSMS280	140	0.749	-6.6	0.750	-21.0

- BBQ system optimised for 4.8 GHz operation.
- A development system installed in 2011.

Orbit measurement with diode detectors

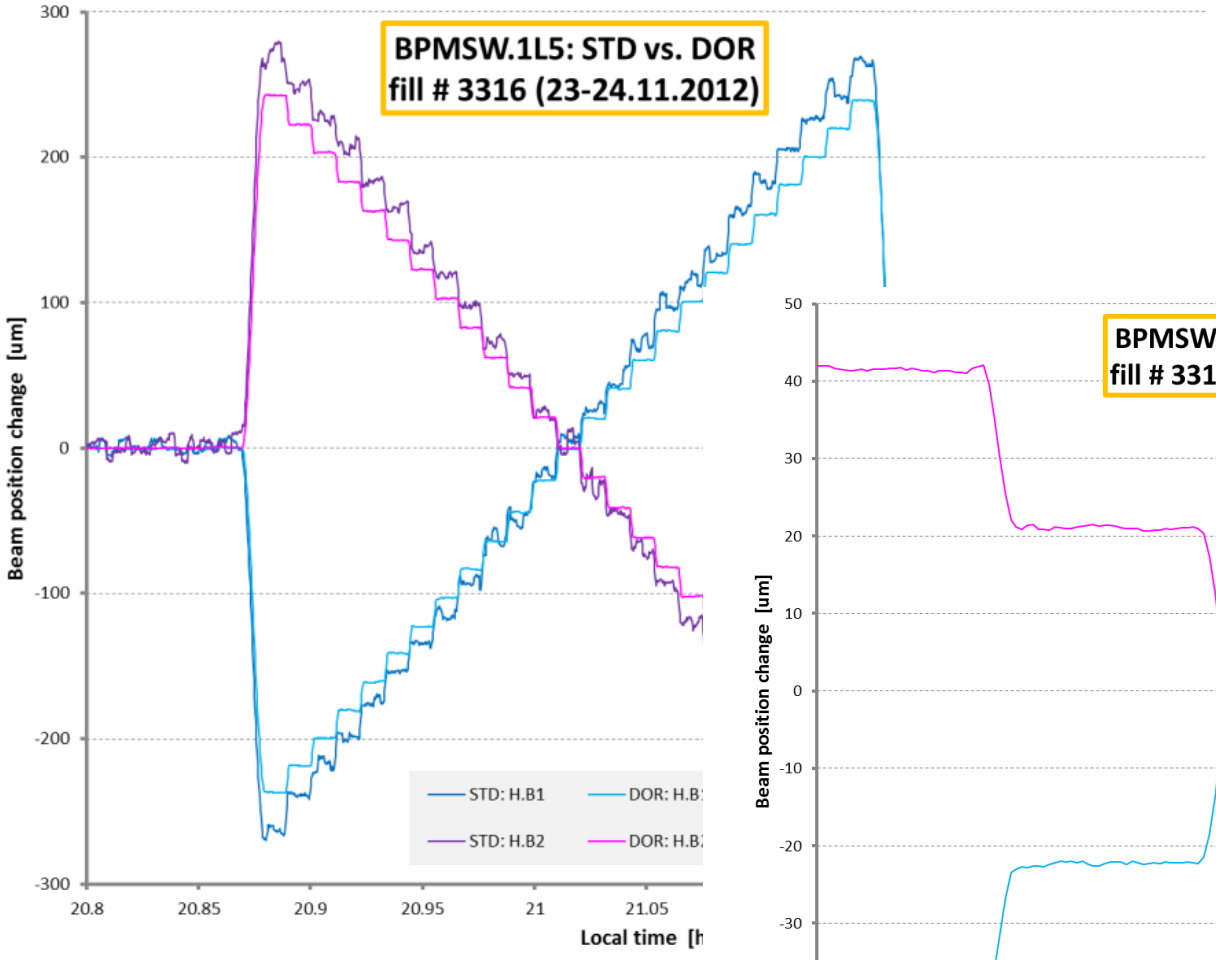


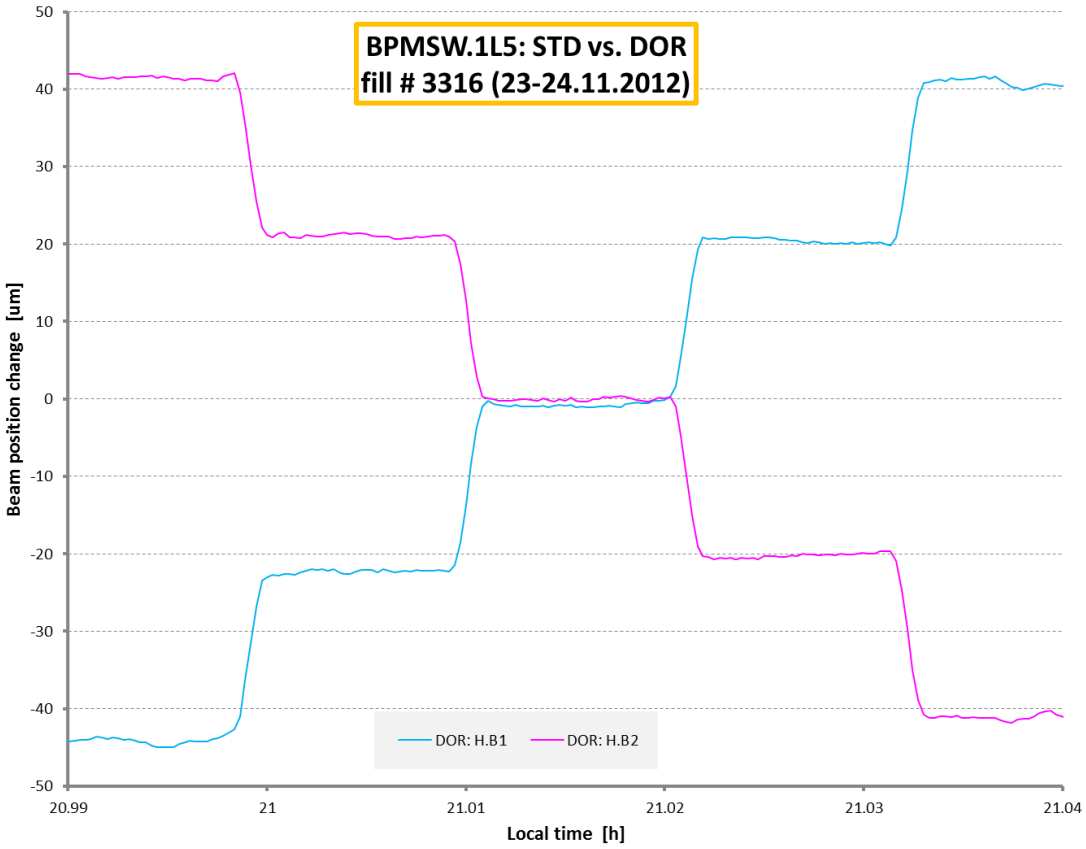




- Analogue front-end has dedicated channels to monitor detector DC voltages (testing purposes).
- DC signals can be measured with lab voltmeters (6 - 8 digit resolution possible).
- Simple diode detectors are nonlinear.
- A compensation scheme to achieve a linear characteristic.

Compensated diode detector for beam orbit measurement



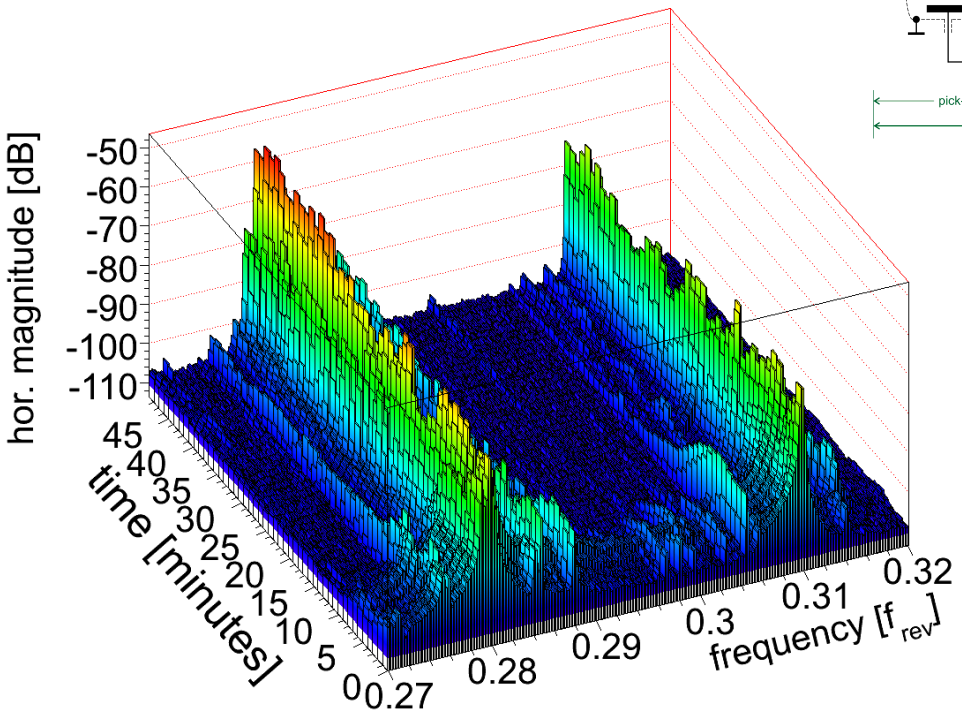


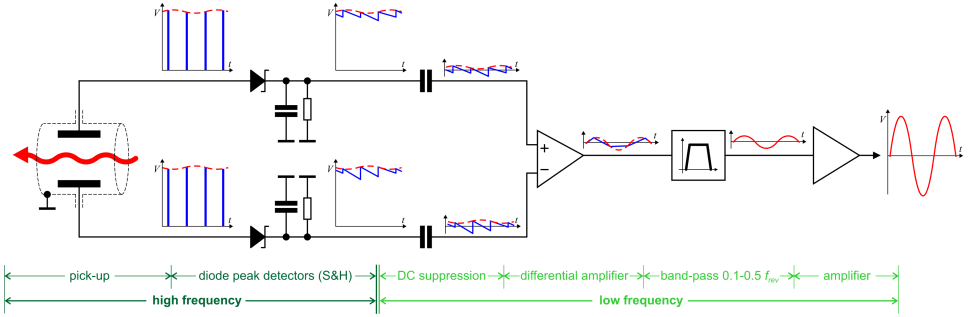
- Sub-micrometre resolution can be achieved with relatively simple hardware and signals from any position pick-up.
- To be used for the future LHC collimators with embedded BPMs.

Conclusions

- Even with the excellent ADCs that we have today good analogue processing may pay off.
- Diode-based tune measurement works well already on quite a few machines.
- Ideas based on diode detectors are being still studied in the Beam Instrumentation group.

- A few pieces of beam sound can be found at: www.cern.ch/gasior/pro/BBQ/index.html



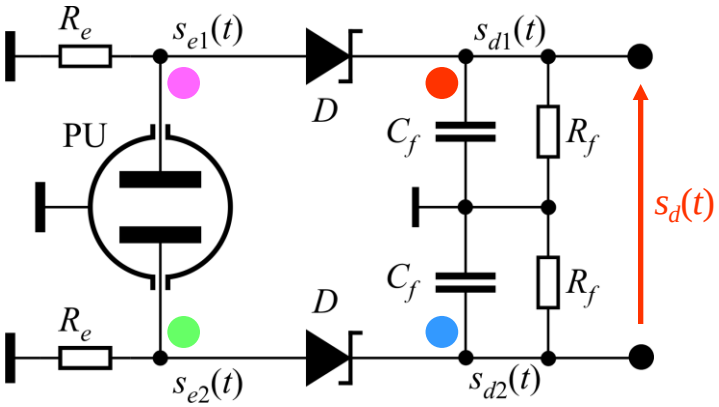


Diode tune systems

Machine	Lab	max f_{rev} [kHz]
LHC	CERN	11
SPS	CERN	43
PS	CERN	477
PSB	CERN	1800
LEIR	CERN	1440
RHIC	BNL	78
Tevatron	Fermilab	48
SIS18	GSI	1400
CNAO	CNAO	2800
CesrTA	Cornell	390

Spare slides

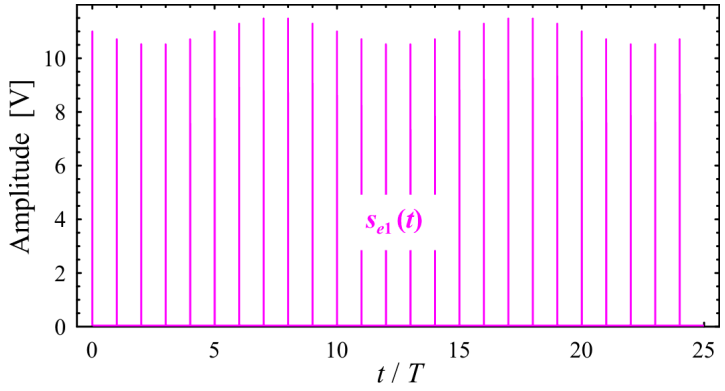
Direct Diode Detection – The principle

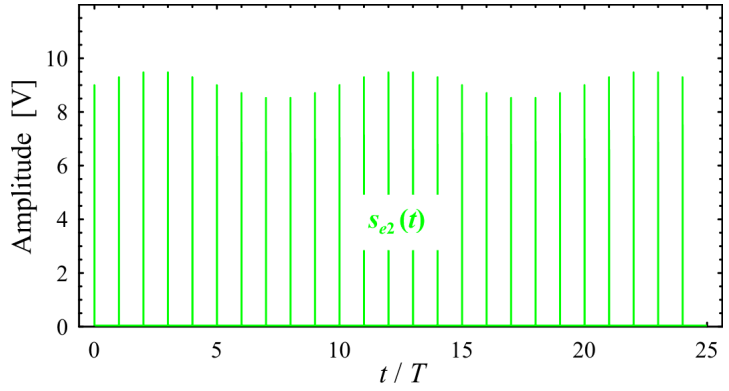


$$s_{e1}(t) = s_b(t)(1+\alpha)\left(1+\beta\cos(2\pi f_b t)\right)$$
$$s_{e2}(t) = s_b(t)(1-\alpha)\left(1-\beta\cos(2\pi f_b t)\right)$$

Simulation parameters:
beam relative offset $\alpha = 0.1$
betatron oscillation relative amplitude $\beta = 0.05$
simulated tune value $q = 0.1$
filter time constant $\tau = 10T$ (T – revolution period)
storage capacitor $C_f = C_{pu}$ (PU electrode capacitance)

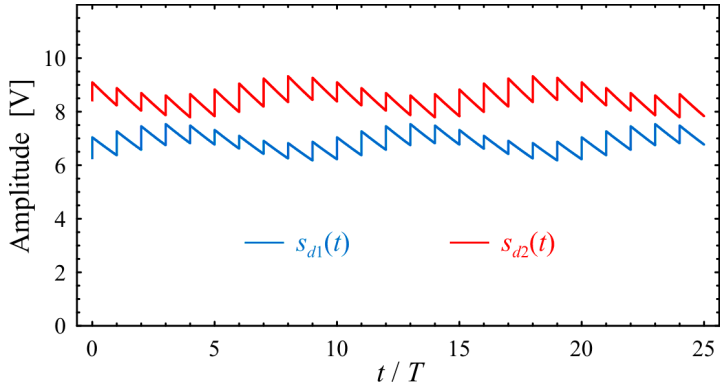
electrode 1 signal

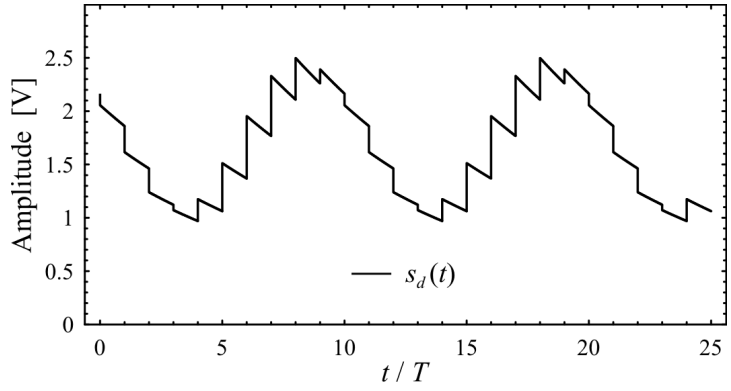




electrode 2 signal

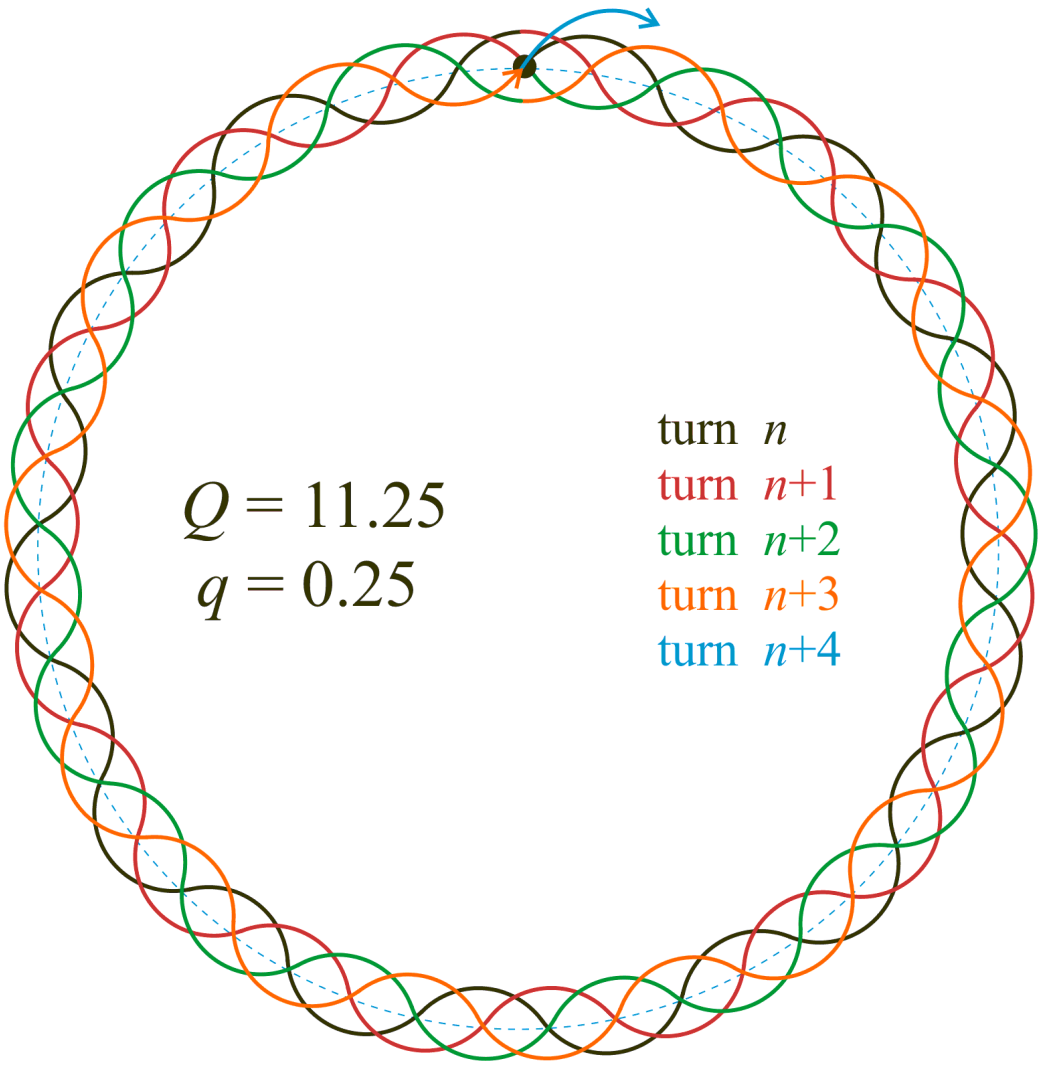
peak detector output signal





detector signal difference

Betatron motion, tune and resonances



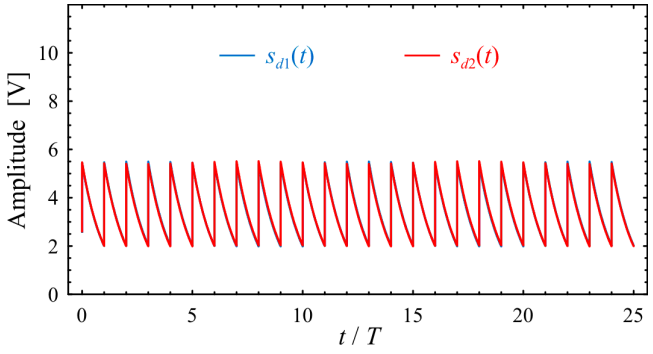
Q – betatron tune,
betatron wave number

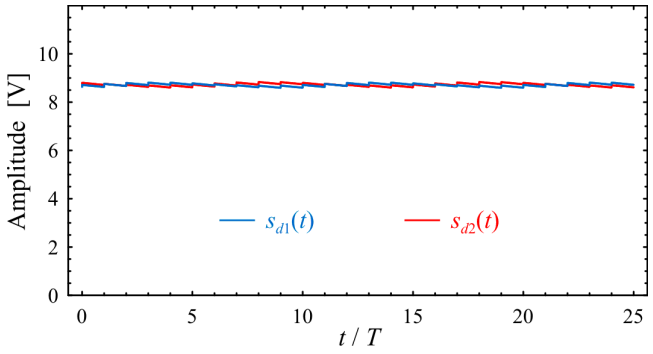
q – fractional tune,
operation point

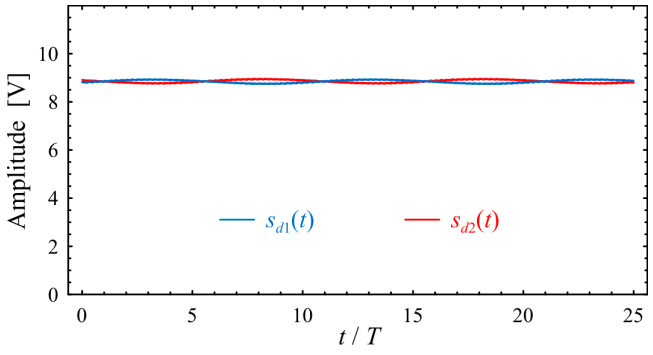
- All particles undergo betatron motion, forced by the machine quadrupoles.
- Betatron oscillations must not superimpose in-phase on themselves after few revolution periods.
- In-phase superposition of betatron oscillations leads to a resonant amplitude build-up.
- Eventually betatron oscillations may not fit into available aperture and beam can be lost.
- Real life is more complex than that:
  - two motion planes, horizontal and vertical;
  - coupling between the planes;
  - oscillation amplitude in each plane changes from one location to another according to a function (so called β-function);
  - betatron motion with larger amplitudes is nonlinear.

Direct Diode Detection – The principle

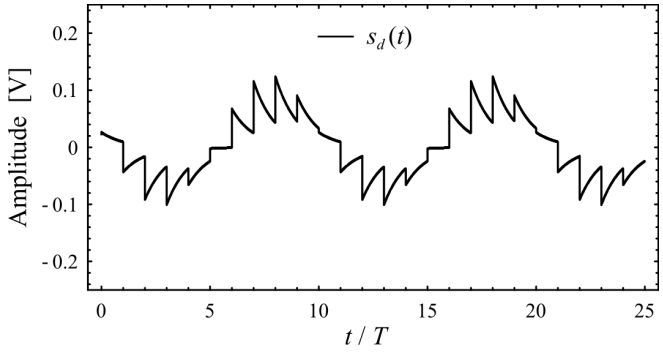
signals on the detector outputs

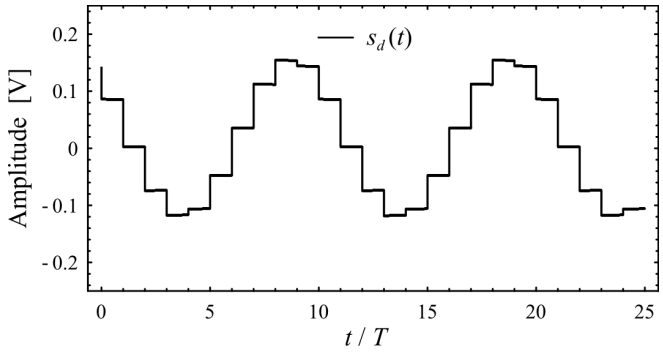


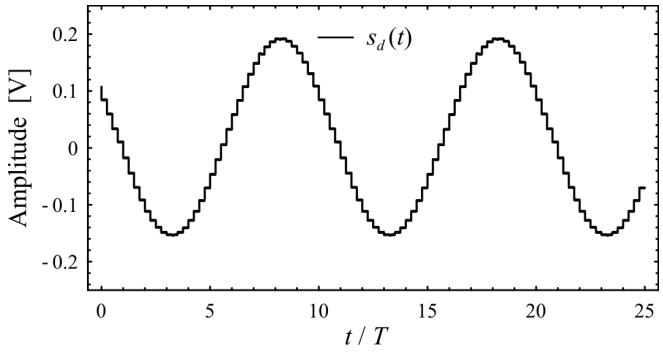




detector signal difference

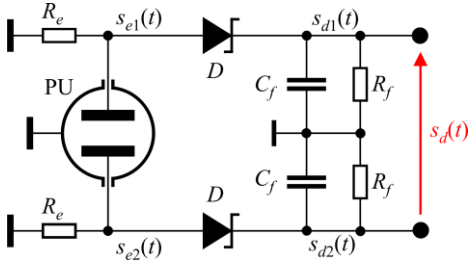






Simulation parameters:
$\alpha = 0$, $\beta = 0.01$
$q = 0.1$, $C_f = C_{pu}$

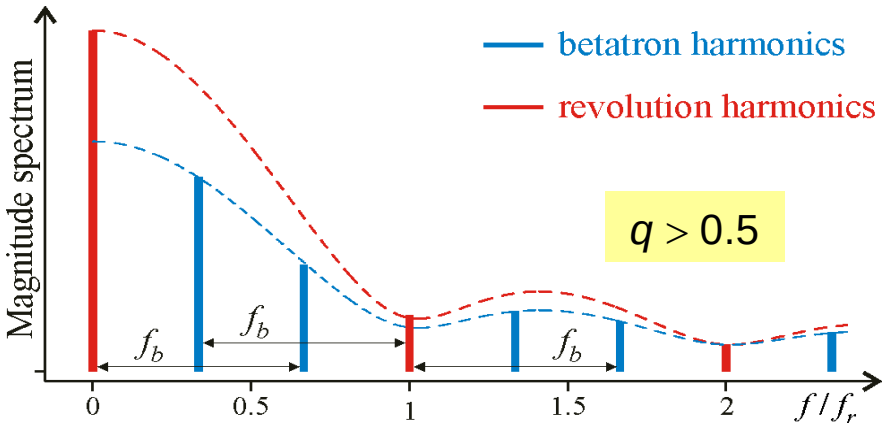
$\tau = T$

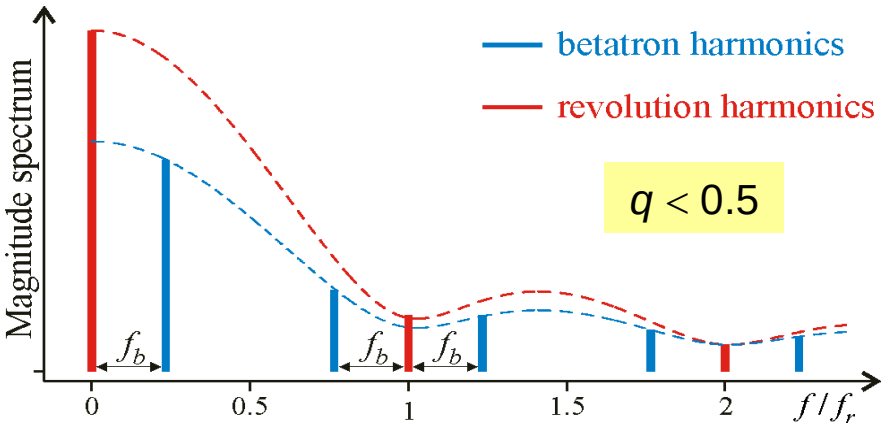


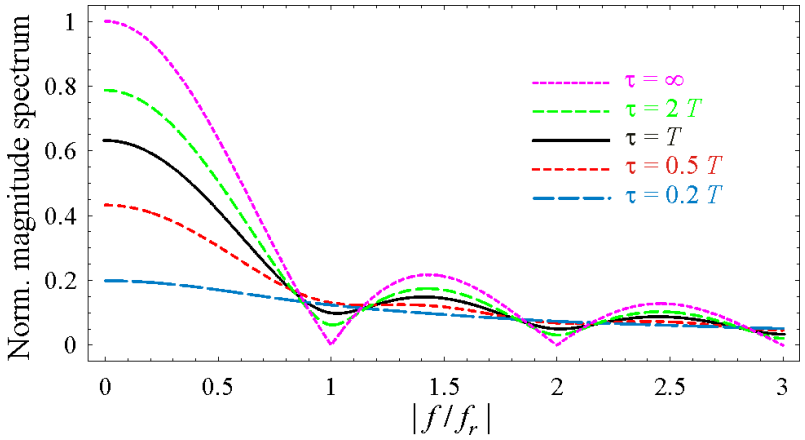
$\tau = 100\ T$

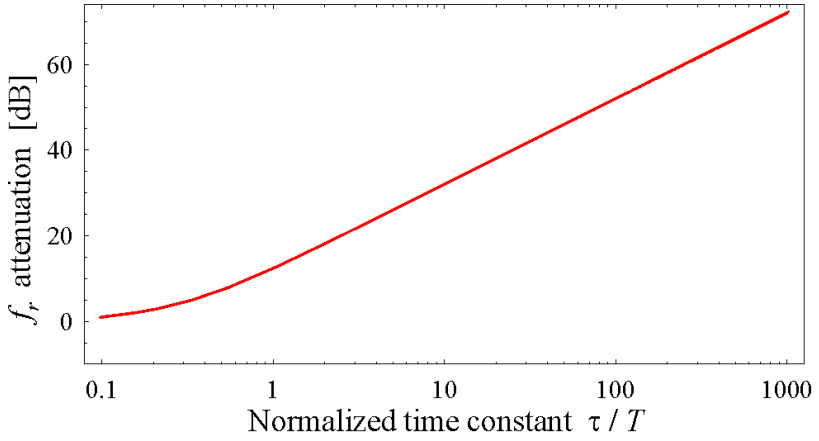
4 bunches
$\tau = 100\ T$

Direct Diode Detection – Base band spectrum







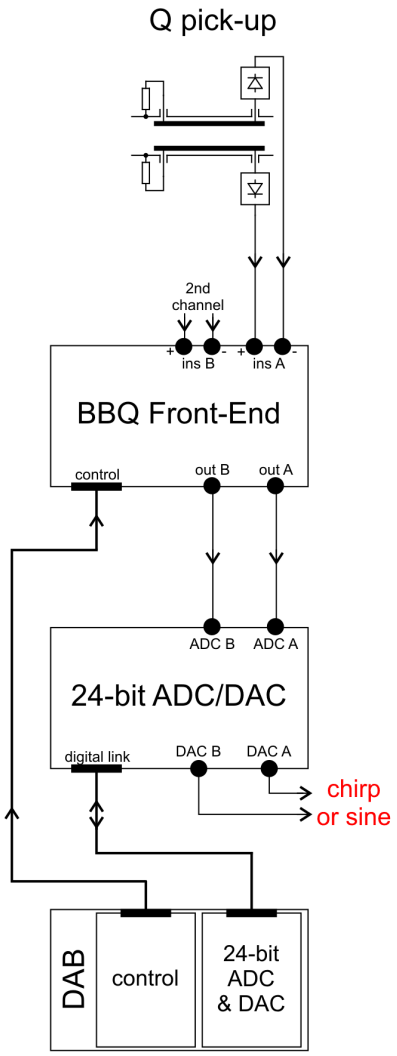


$$S_f(f) = \tau \left| \frac{1 - \exp\left(-\mathrm{j}2\pi f T - \frac{T}{\tau}\right)}{1 + \mathrm{j}2\pi f T} \right|$$

$$\tilde{\xi} = \frac{S_f\left(\frac{f_r}{2}\right)}{S_f(f_r)} = \sqrt{4 - \frac{3T^2}{T^2 + \pi^2 \tau^2}} \coth\left(\frac{T}{2\tau}\right)$$

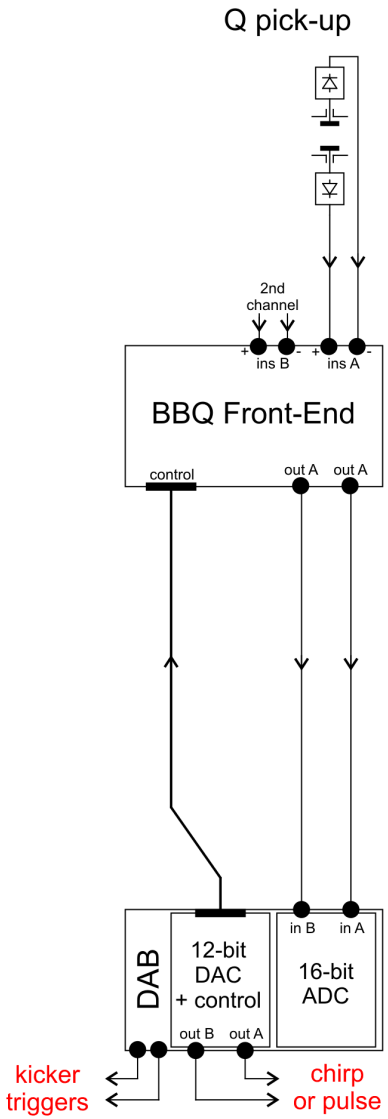
BBQ systems at CERN

LHC, SPS

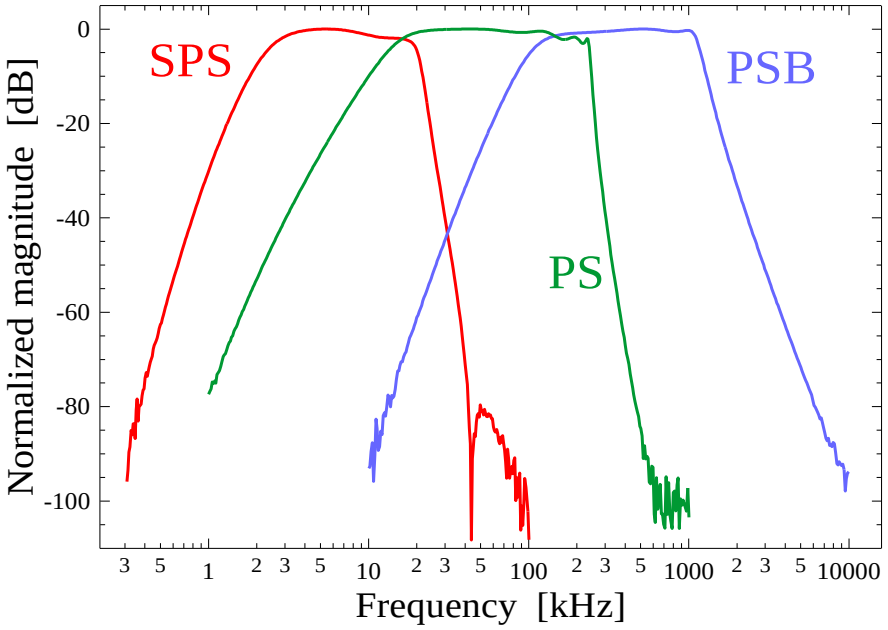


LEIR, PSB, PS,

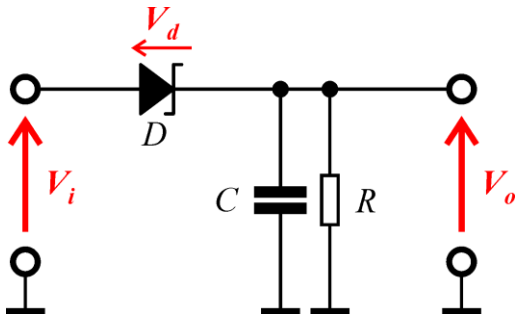
AD: ADCs + DACs only



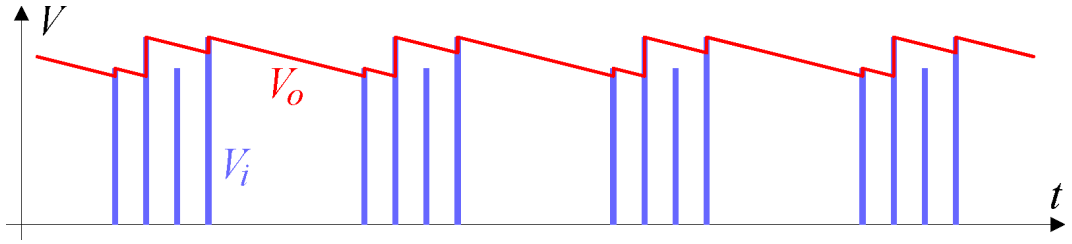
Machine	Front-End	Acquisition
LHC	"constant f_{rev} type"	24 bits (up to 100 kHz)
SPS	"constant f_{rev} type"	24 bits
PS	"constant f_{rev} type"	16 bits (up to 40 MHz)
LEIR	"varying f_{rev} type"	16 bits
PSB	"varying f_{rev} type"	16 bits



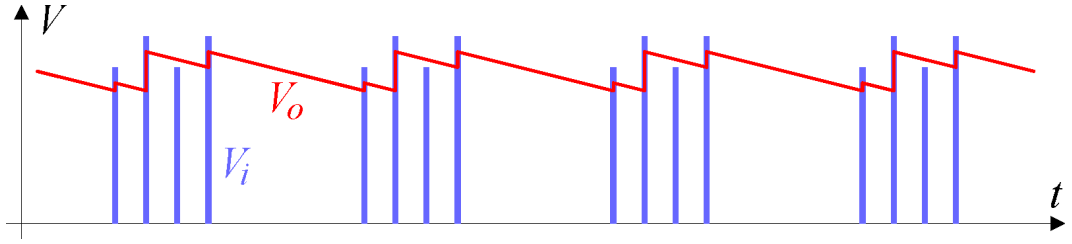
Different regimes of operating a diode detector



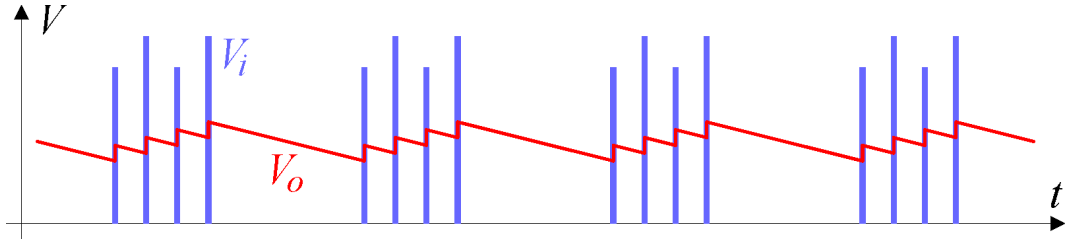
- The discharge resistor *R* can be used to change the regime in which the detector operates.
- Number of bunches have influence on the operation mode. An average detector with single bunch can be a peak detector with the full machine.



Input (V_i) and output (V_o) voltages of a peak detector with an ideal diode

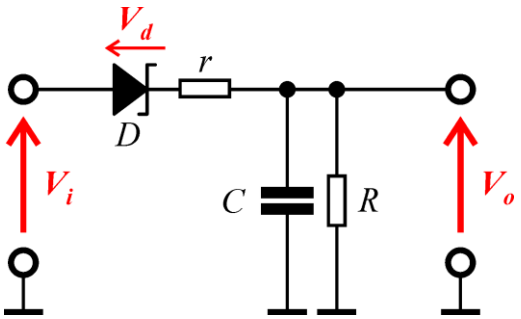


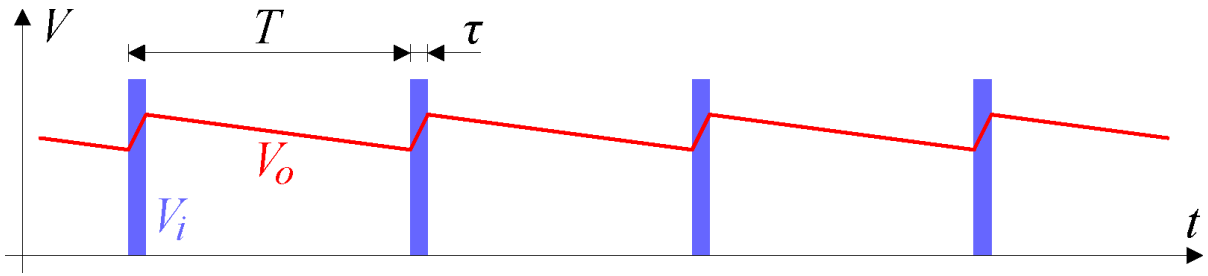
Input (V_i) and output (V_o) voltages of a peak detector with a real diode



Input (V_i) and output (V_o) voltages of an average-value detector

Charge balance in a diode detector





Charge balance equation for the following assumptions:

- a simple diode model with a **constant** forward voltage V_d and a **constant** series resistance *r*.
- constant charging and discharging current, i.e. output voltage changes are small w.r.t. the input voltage.

$$\frac{V_o}{R}T = \frac{V_i - V_o - V_d}{r}\tau$$

$$\frac{V_o}{V_i - V_d} = \frac{1}{1 + \frac{r}{R}\cdot\frac{T}{\tau}}$$

A numerical example: LHC, one bunch.

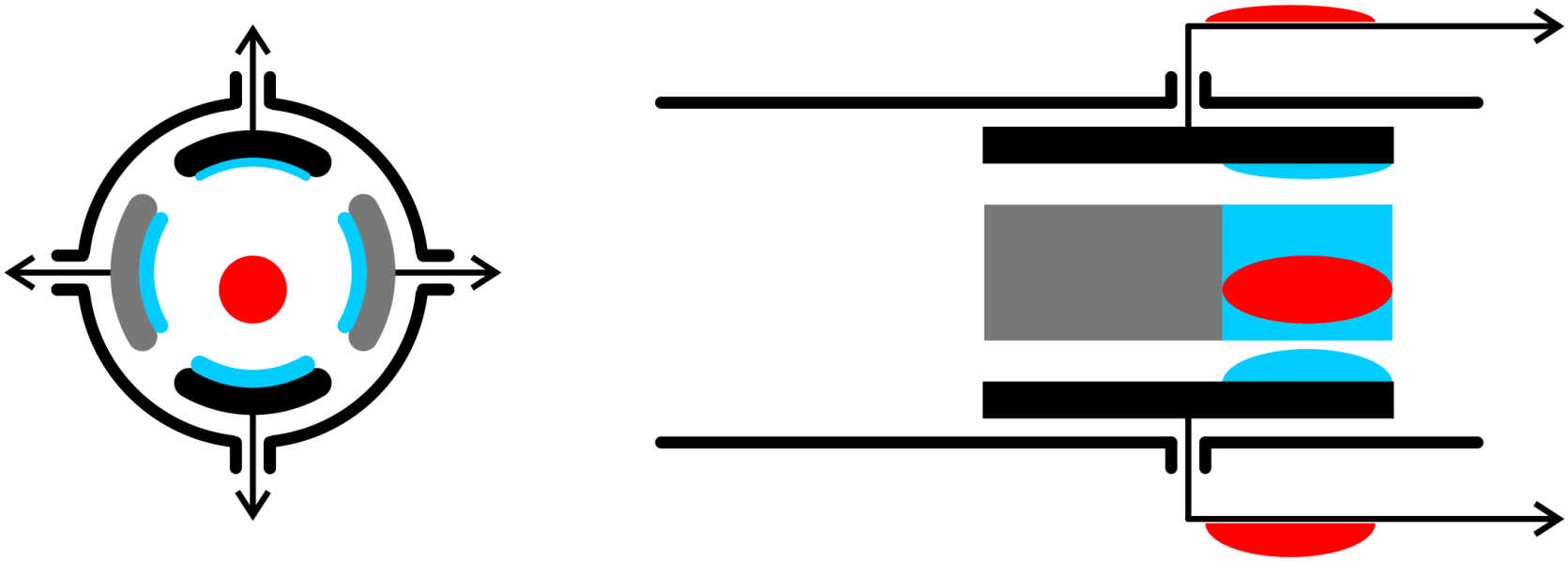
For LHC $\tau \approx 1$ ns and $T \approx 89$ µs, so for $V_o \approx V_i$ one requires $R/r > T/\tau$.
Therefore, for $r \approx 100\ \Omega$, $R > 8.9$ MΩ.

- $V_i >> V_d$
- *n* bunches

$$\frac{V_o}{V_i} = \frac{1}{1 + \frac{r}{R}\cdot\frac{T}{n\tau}}$$

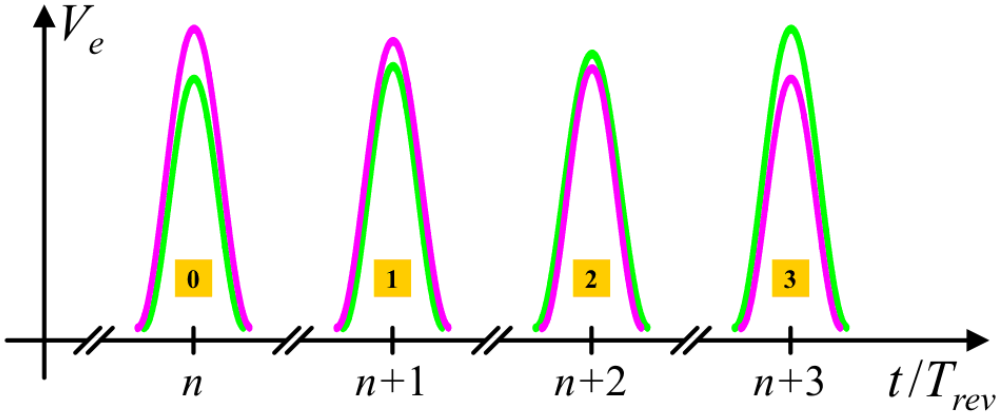
- For large T to τ rations peak detectors require large R values and a high input impedance amplifier, typically a JFET-input operational amplifier.
- The slowest capacitor discharge is limited by the reverse leakage current of the diode (in the order of 100 nA for RF Schottky diodes).

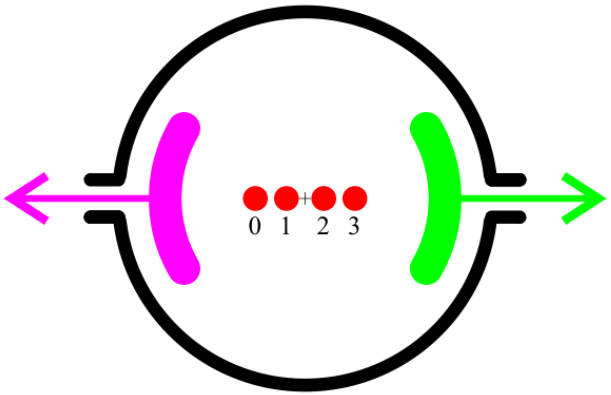
Beam position monitor (BPM) – the principle



- Beam image current – the principle of operation of many beam instrumentation devices.
- Electrode signals are proportional to BOTH, beam position AND beam intensity.
- For measuring beam position the intensity component must be removed (often measured and used for a normalisation).
- There are many BPM types, with different electrode geometries, one or two ports per electrode.
- A stripline pick-up with two ports per electrode can distinguish signals of beams passing in the opposite directions (very useful for the LHC parts close to the experiments with both beams circulating in one pipe).
- The simplest beam kicker is a BPM working the other way around: it RECEIVES an excitation signal.

Beam position monitor (BPM) – the principle (cont.)





- Electrode signal has the temporal shape corresponding to the temporal structure of the passing beam.
- For single short bunches and large machines (as the LHC) the electrode signal has very small duty cycle.
- For the LHC nominal beams that means nanosecond pulses with the amplitudes in the order of 100 V.
- Such signals are very difficult to simulate in the lab.
- Continuous sampling of LHC single bunch signals would contain some 99.999 % of silence and sampling would have to be done at least at a few GHz rate.