European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

LHC
Wide Band Time Normaliser
Design and operational experience

Eva Calvo (CERN , BI-QP)

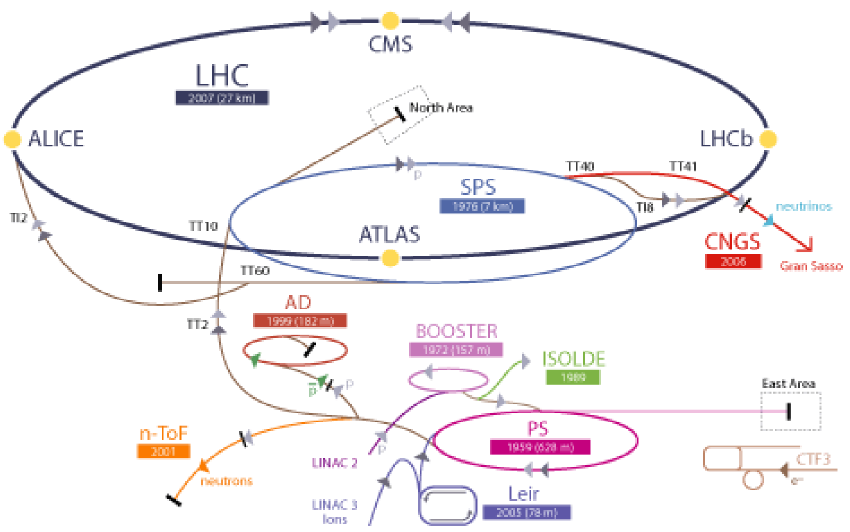
Outline

- LHC Beam parameters
- The Amplitude to Time Normalizer principle
- The WBTN card elements
- The Digital Acquisition card
- Performance results

Beam structures

- The system is used in the LHC ring, the SPS to LHC transfer lines and the LHC dump lines. 2406 channel (planes) in total.
- frev= 11.245kHz and the min. bunch spacing 25ns. (Last year run @50ns).
- The bunch charge can be from 5e9p (pilot) up to 1.7e11 p (ultimate).
- The machine can have from a single bunch up to 2808 bunches, (using many bunch patterns). So, beam current goes from 9uA → 0.86Amps.

CERN Accelerator Complex



If the system integrate all the bunches :
DR > 99dB
Integrating every SPS batch: DR > 80dB
Measuring bunch-by-bunch: DR > 30dB !

+ ~10dB more for position variation
+ safety margin

Choice of the processing method…

Requirements:

Bunch type		*Pilot Bunch*		*Bunches of Nominal Intensity*		
Mode of operation		**Trajectory** (single shot)	**Orbit** (224 turn average)	**Trajectory** (single shot, single bunch)	**Trajectory** (single shot, average of all bunches)	**Orbit** (average of all bunches over 224 turns)
Electr.	**Resolution (rms)**	200μm	20μm	50μm	5μm	5μm
Electr.	**Accuracy (rms)**	150μm				
Mech.	**Alignment Error (rms)**	200μm				
Mech.	**Residual after k-modulation (rms)**	<50μm				

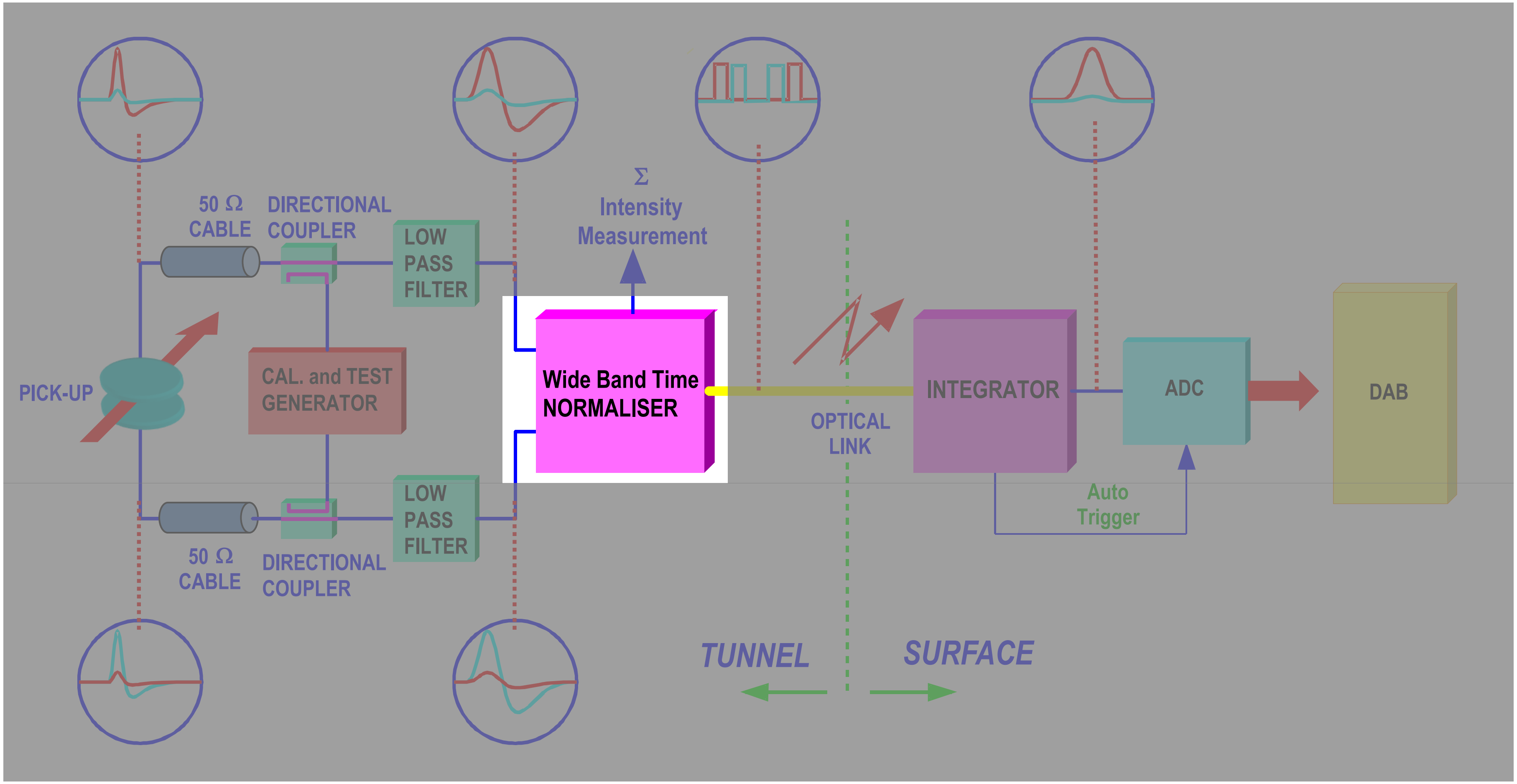
Accuracy and alignment error together: $\sigma = \pm 250\mu m$

- Auto-trigger system ("plug&play")
- Without variable attenuator, or many gains
- Able to do bunch-by-bunch

Requirements:

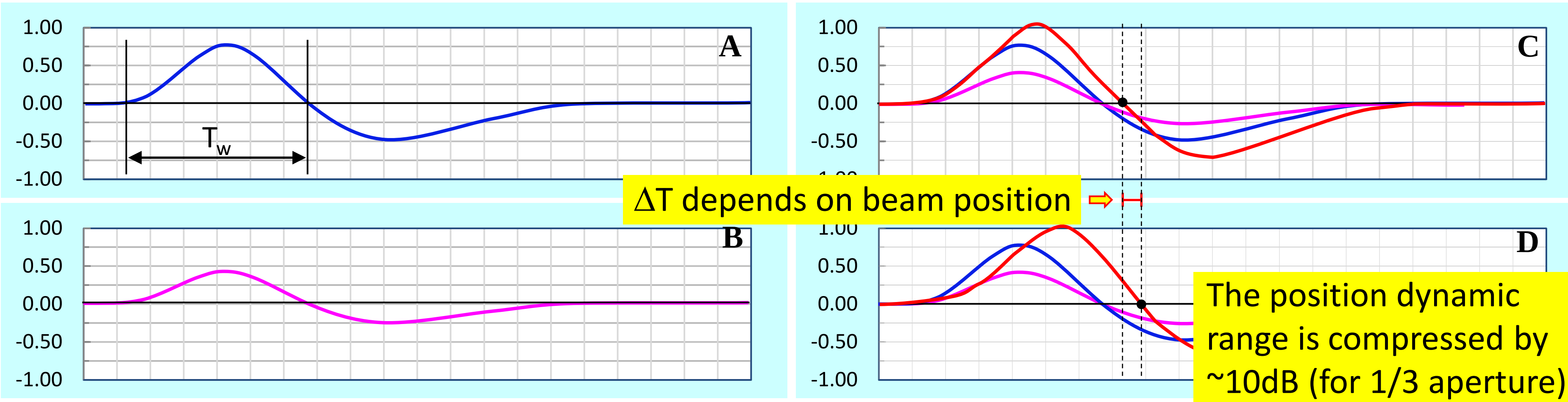
- Homodyne receivers : Limited DR.
- Individual signal digitalisation: Would require relay switches gain stages and use most of the ADC resolution for the common mode signal.
- LogAmps : Would not do bunch-by-bunch.
- Amplitude to phase normalization: Would not do bunch-by-bunch measurements.
- Amplitude to time normalization scheme seemed a very nice candidate to fulfil all the requirements.

Read out scheme



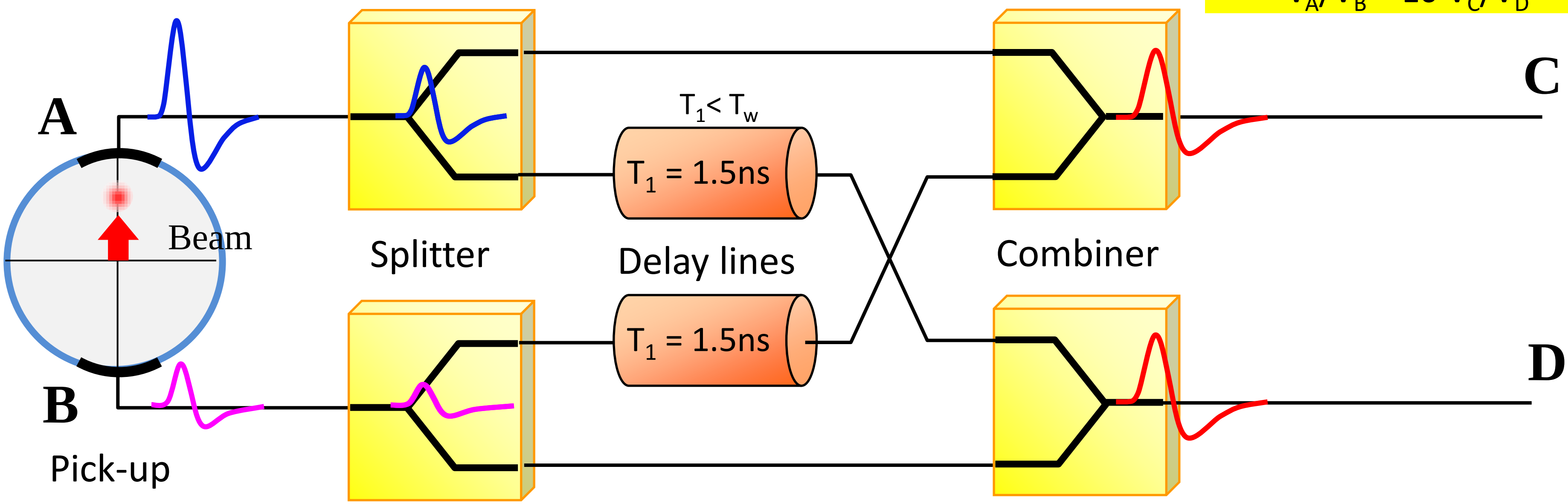
Designed by D.Cocq (CERN), ~1996

Amplitude to Time Normalisation

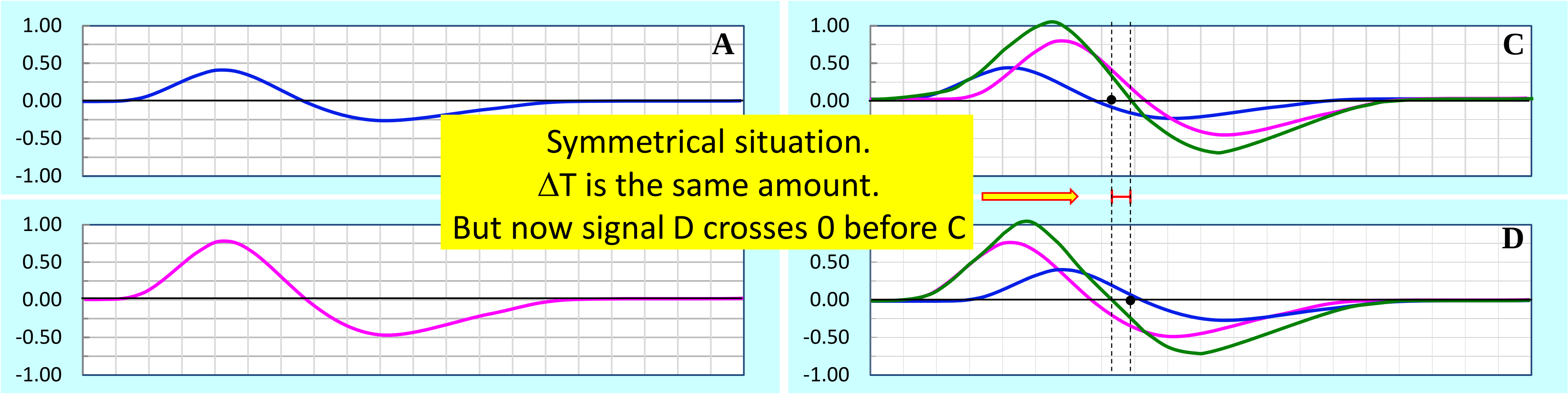


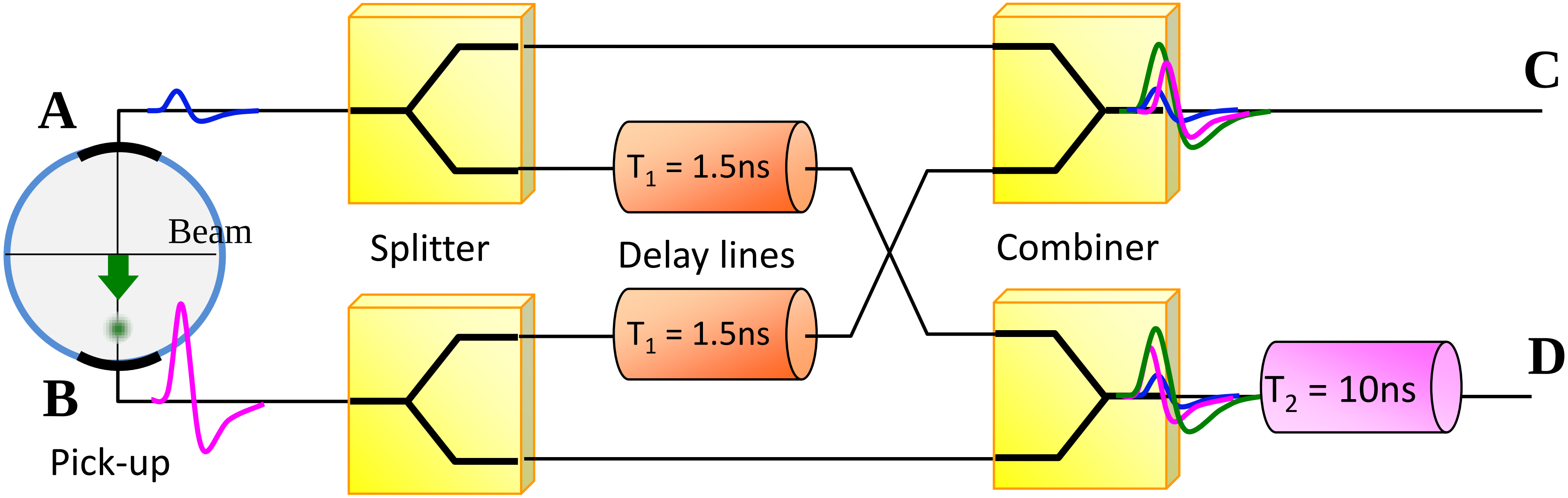
ΔT depends on beam position

The position dynamic range is compressed by ~10dB (for 1/3 aperture)
$V_A/V_B \sim 10\, V_C/V_D$

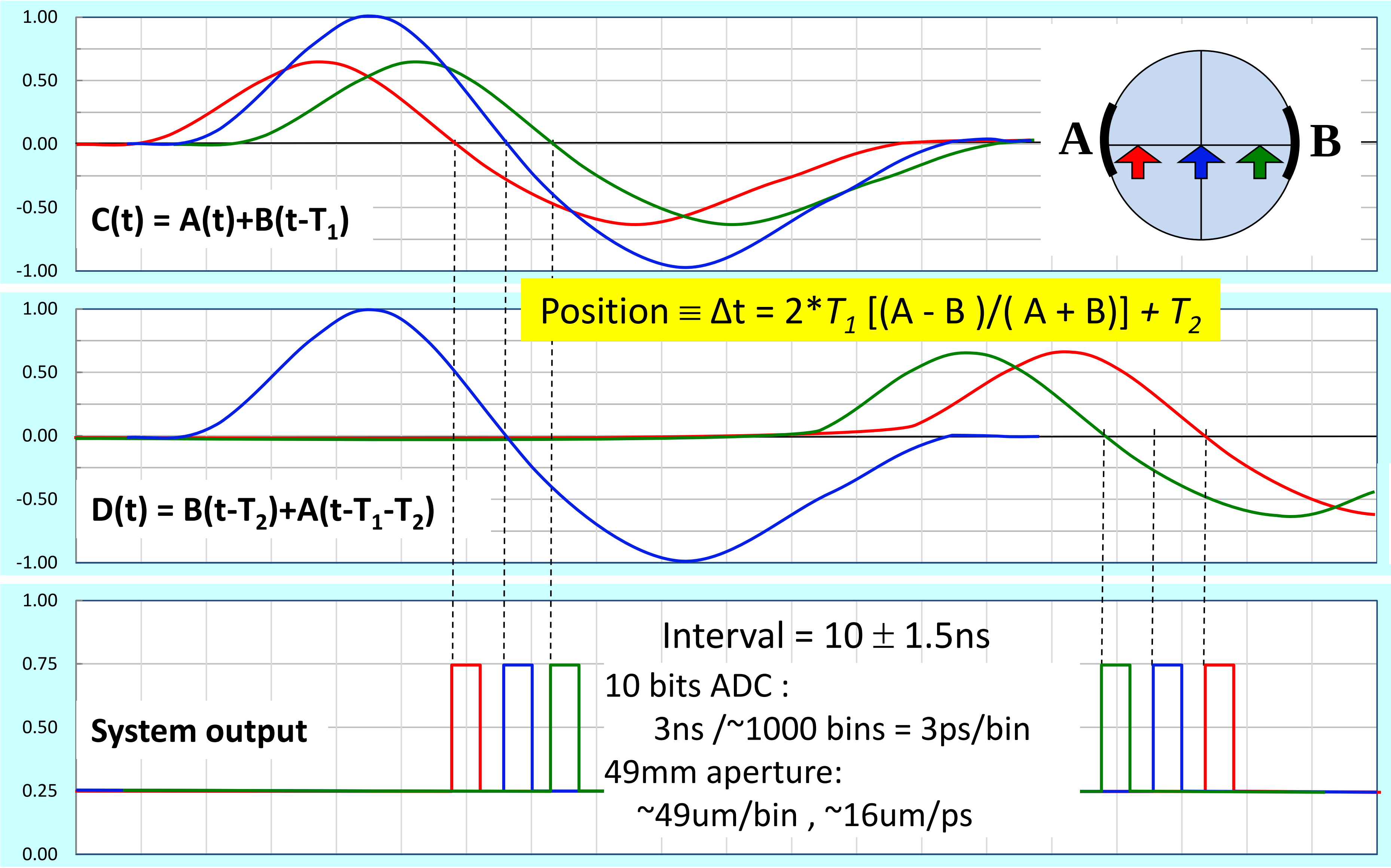


Amplitude to Time Normalisation



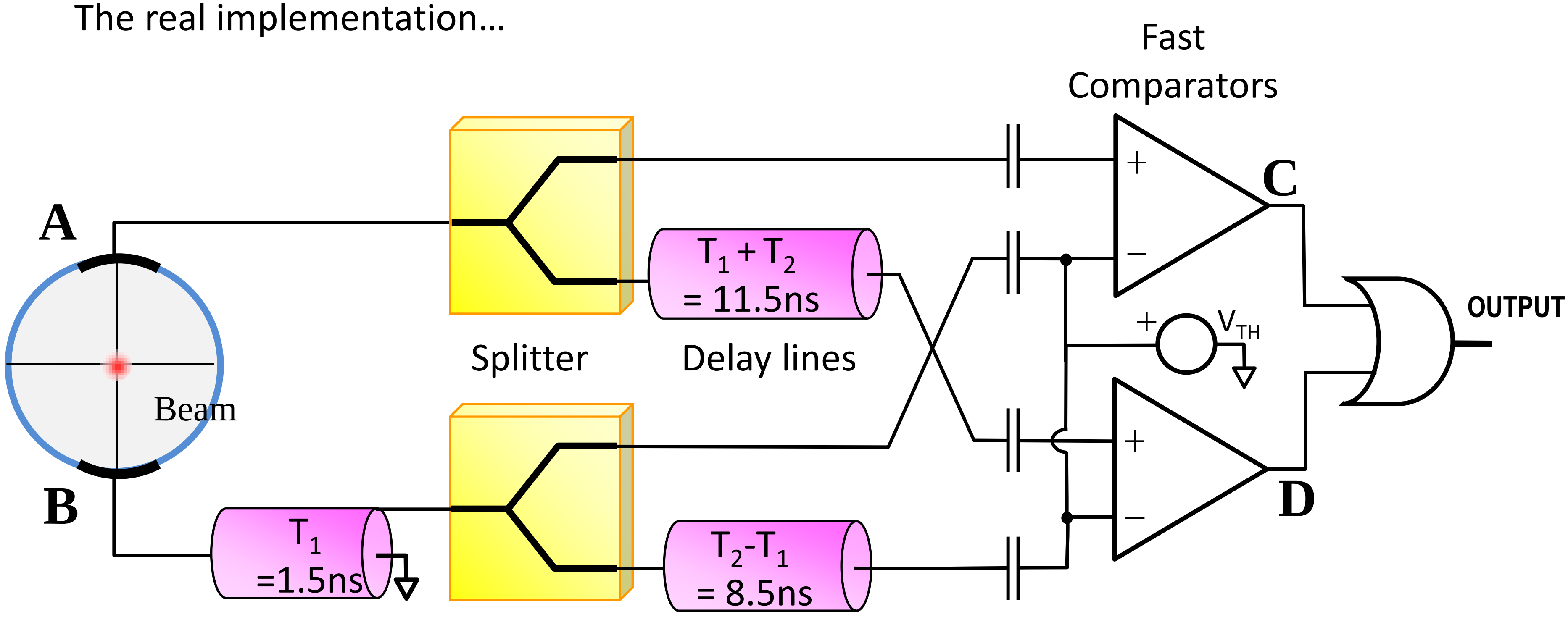


Amplitude to Time normalization



Amplitude to Time Normalisation

The real implementation…



For your fun…

Amplitude to Time Normalisation

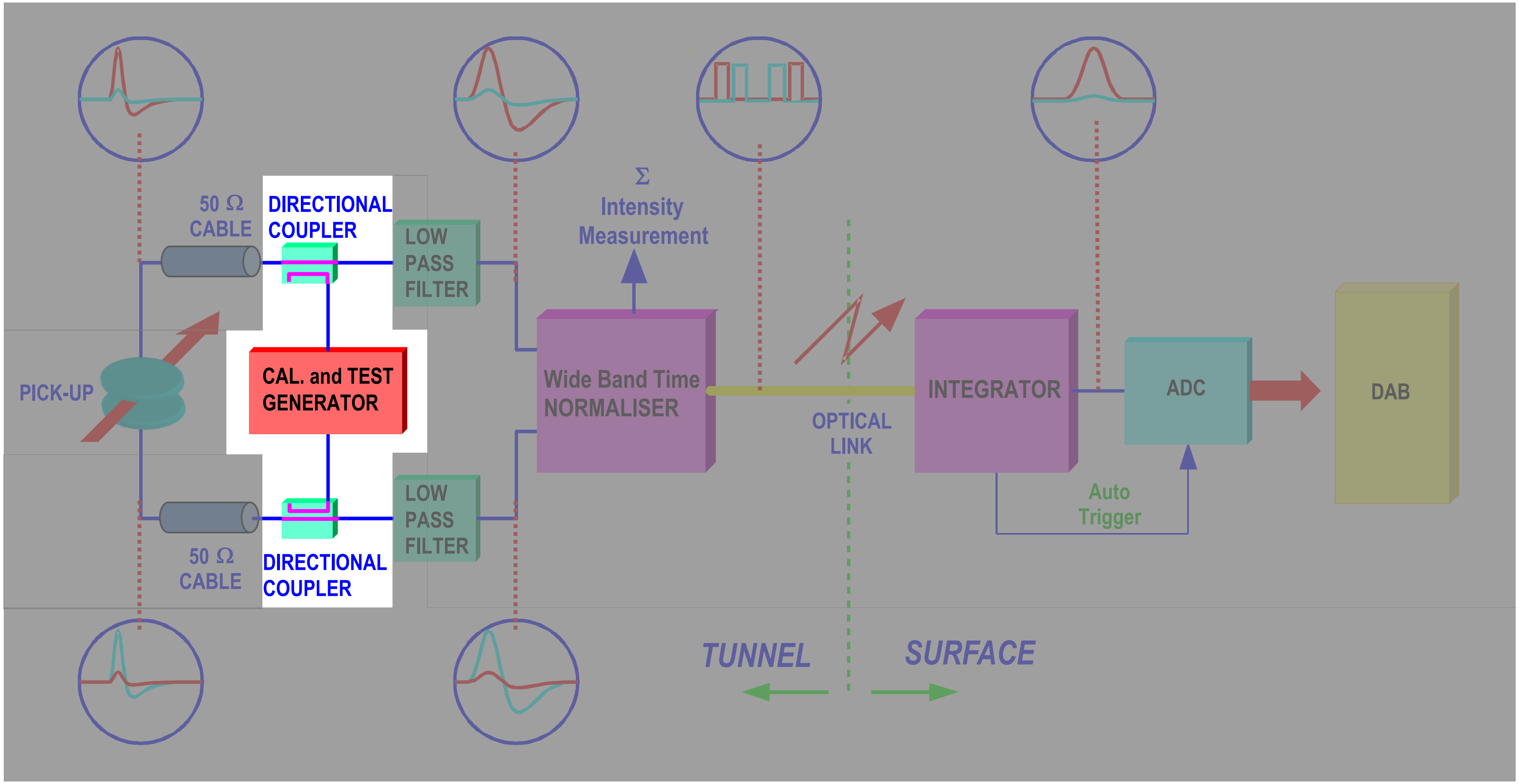
Advantages

- Fast normalisation (< 25ns) allowing bunch to bunch measurement
- Signal dynamic independent of the number of bunches and the machine filling pattern
  - Input dynamic range ~50 dB
  - No need for gain selection
- Reduced number of channels
  - normalisation at the front-end
- ~10 dB compression of the position dynamic due to the recombination of signals at 1/3 of the norm. ap.
- Independent of external timing
- Time encoding allows fibre optic transmission to be used

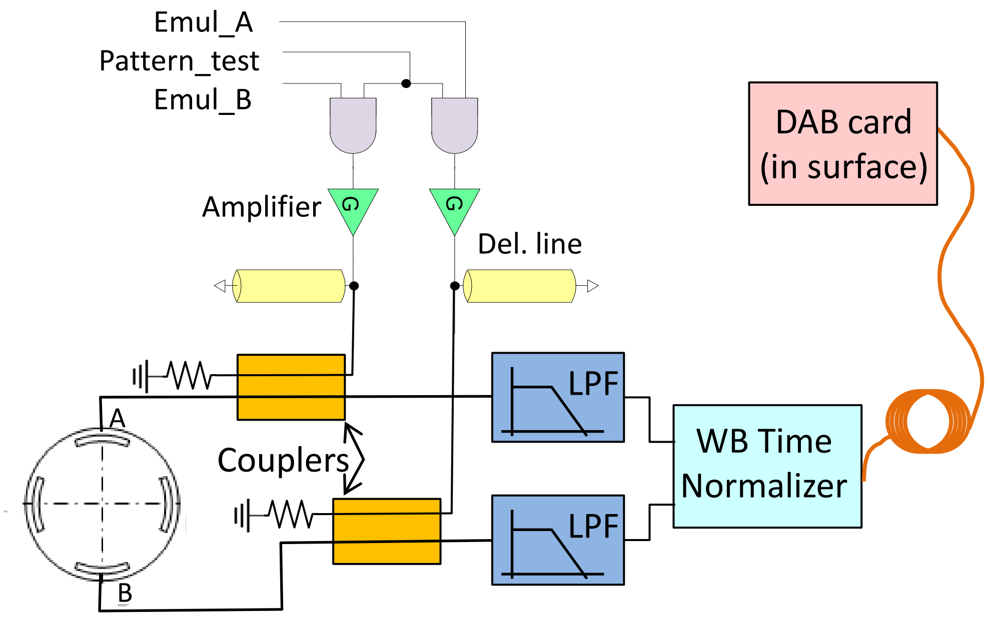
Limitations

- Currently reserved for bunched beams with long bunch spacing (> T1+T2).
- Very tight time adjustment required
- No Intensity information
- Propagation delay stability and switching time uncertainty are the limiting performance factors

Read out scheme

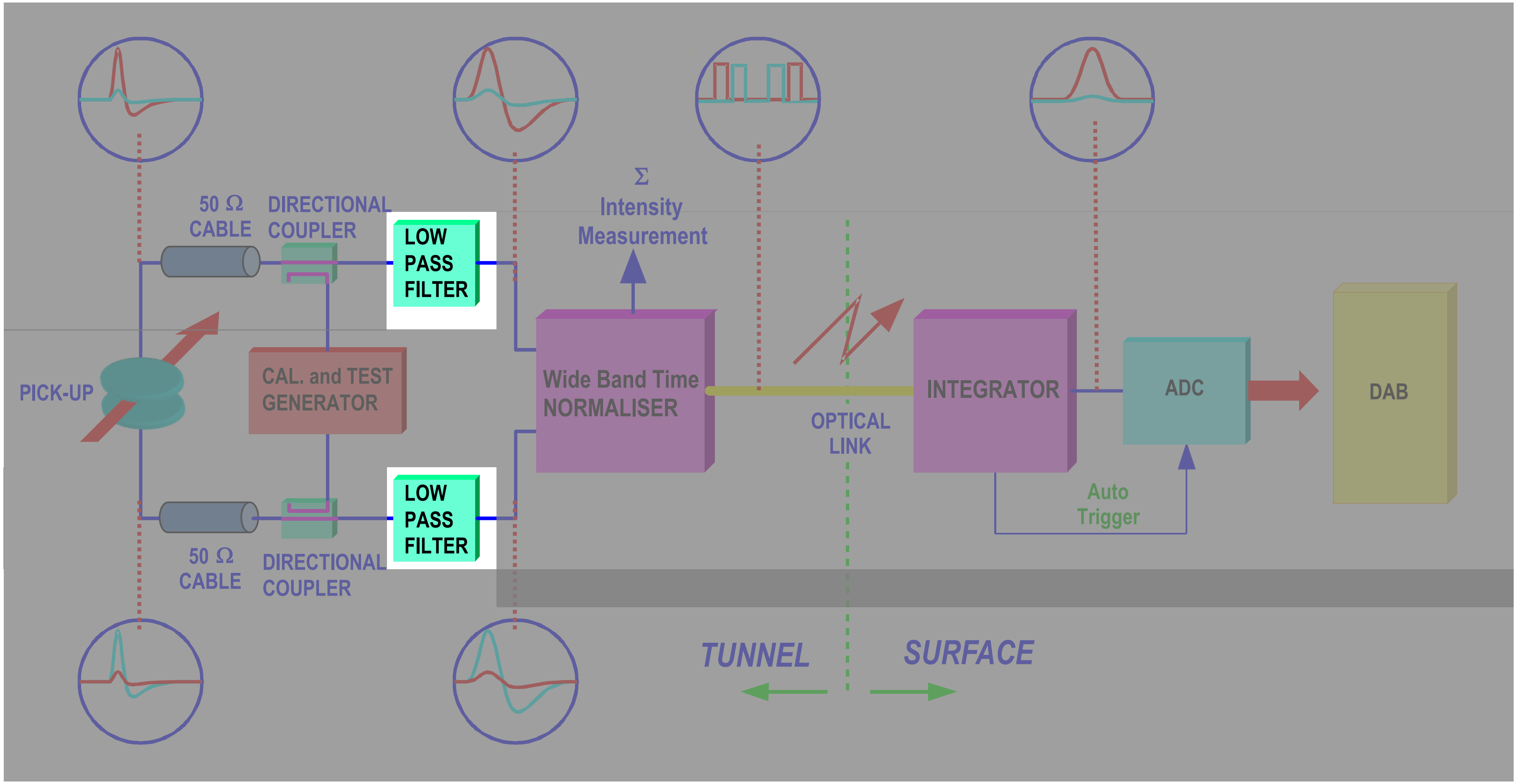


Calibration method

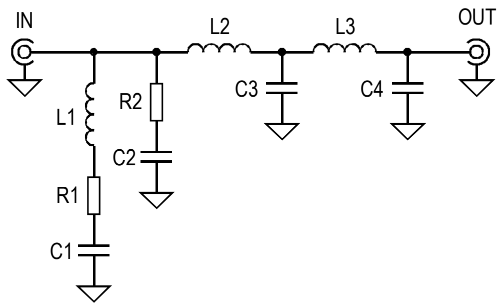


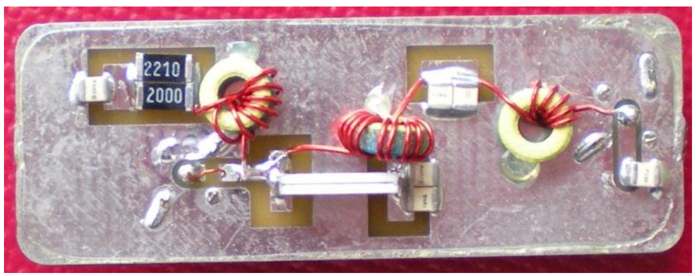
- Emul_A and Emul_B signals allow simulating 3 normalized beam positions : x_n={+1,0,-1}
- Pattern_test signal allows simulate different filling patterns (40MHz, 20MHz, single train, single bunch, etc).
- The test signals enter the front-end electronics at its first stage by means of a coupler
  - → All the electronic chain can be tested ! 🙂
  - → But not the cables and the BPM itself! 🙁

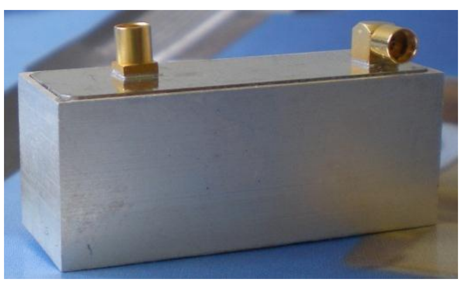
Read out scheme

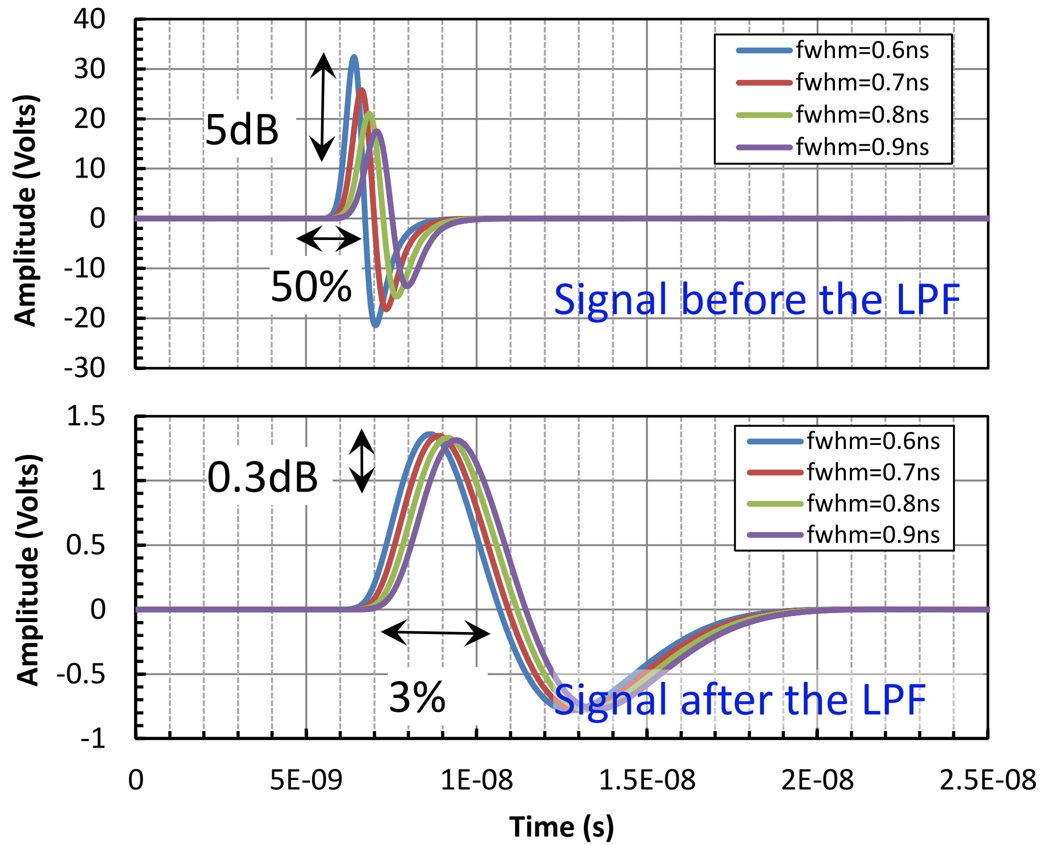


The low pass filter



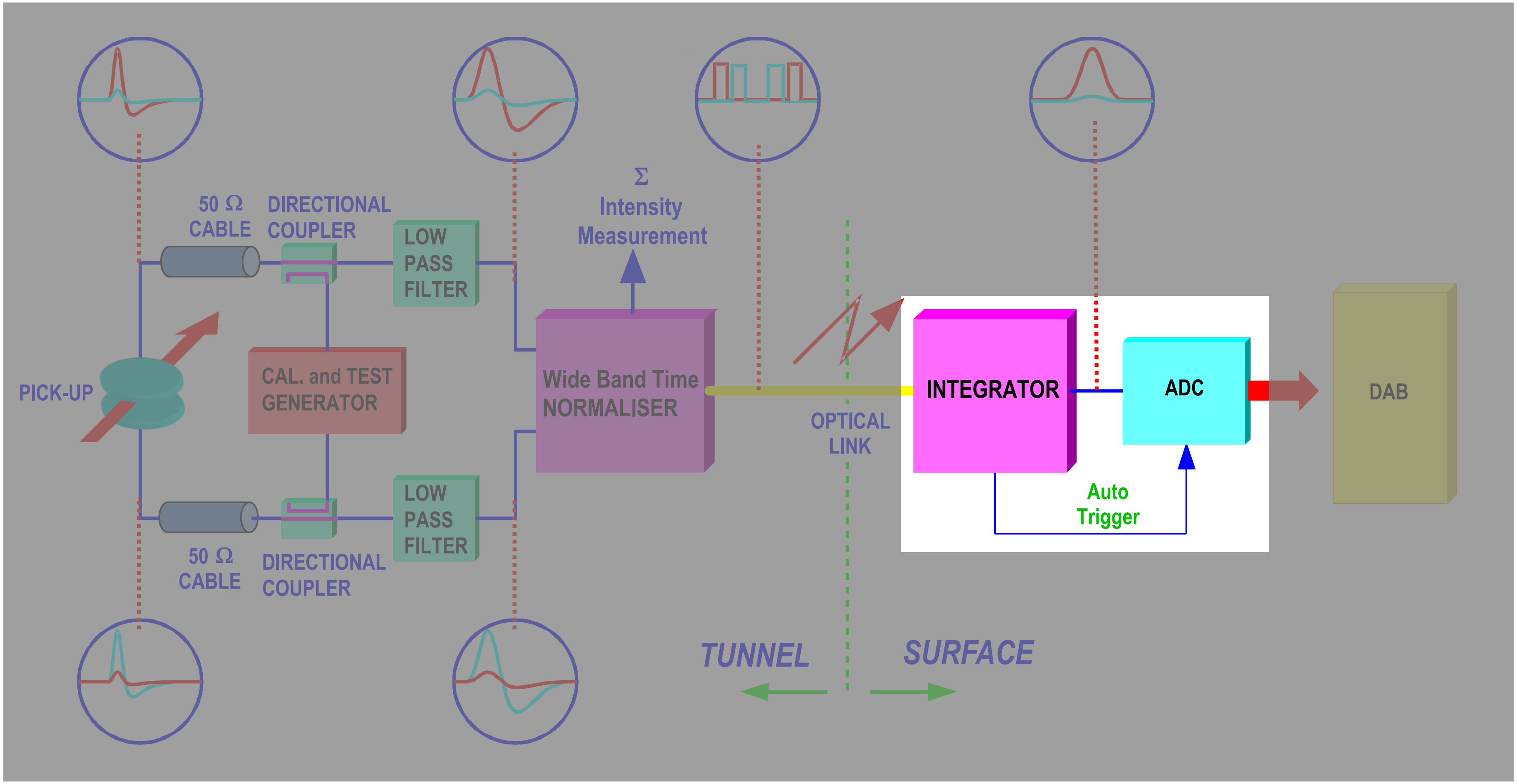




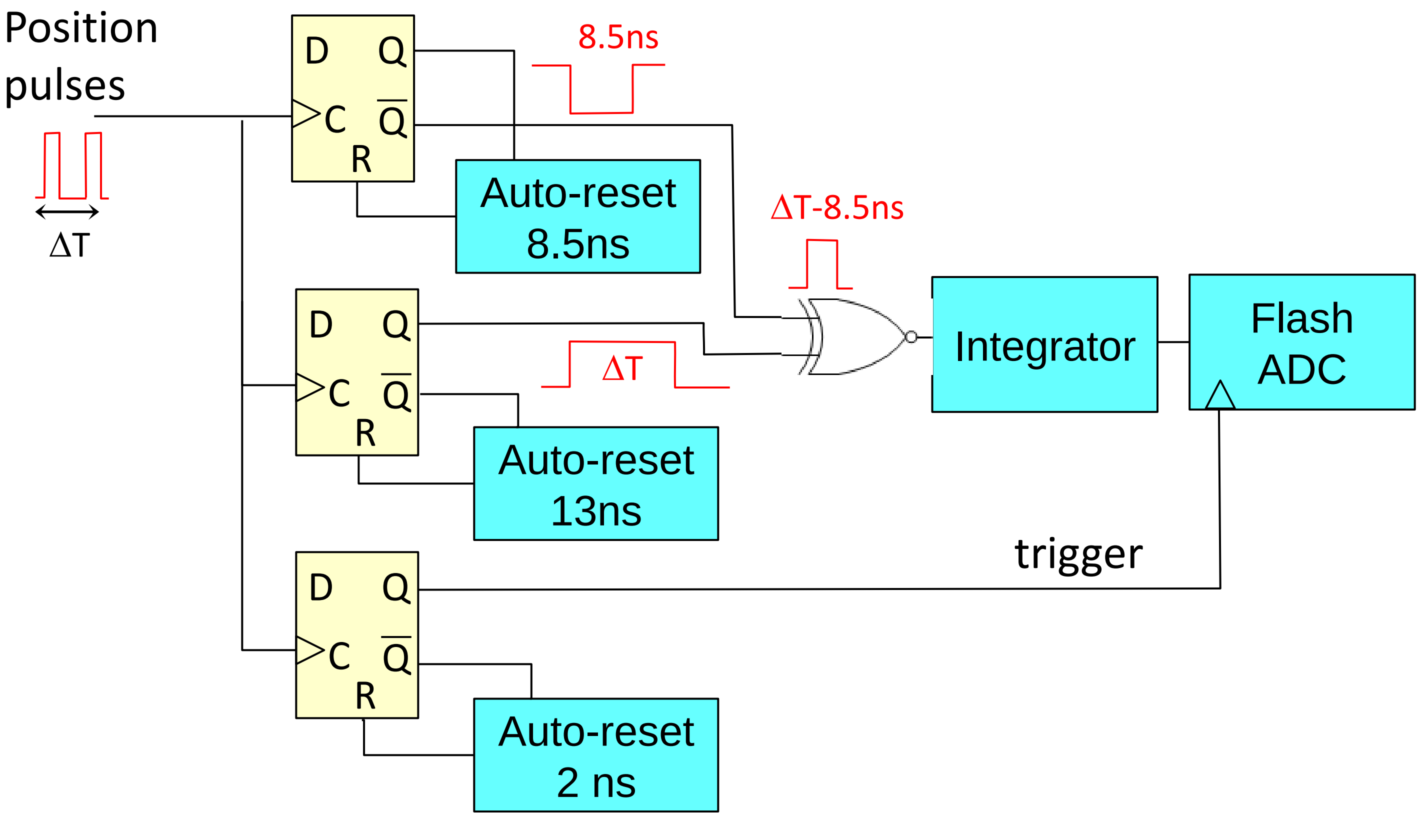


The LPF consists on a Gaussian filter of 4th order.
The cut off frequency should be such that the output pulse shape is independent of the bunch length variations. (70MHz for the LHC WBTN).
The LHC specifications ask for residual amplitude of <0.2% for a bunch spacing of 25 ns

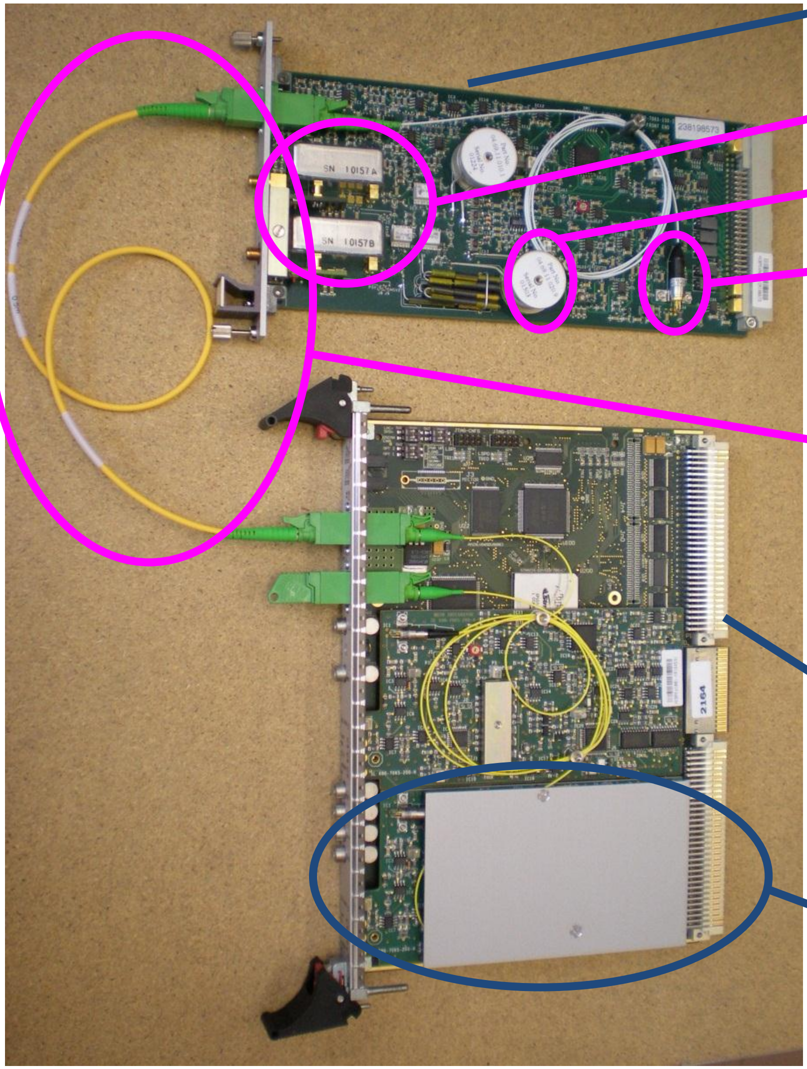
Read out scheme



Integrator


Position
pulses
ΔT
D
Q
C
Q
R
8.5ns
Auto-reset
8.5ns
ΔT-8.5ns
D
Q
C
Q
R
ΔT
Auto-reset
13ns
Integrator
Flash
ADC
trigger
D
Q
C
Q
R
Auto-reset
2 ns

The LHC BPM Acquisition System



Very Front-End WBTN Card

70MHz Low Pass Filters

Delay lines

1310nm Diode Laser Transmitter

Tunnel

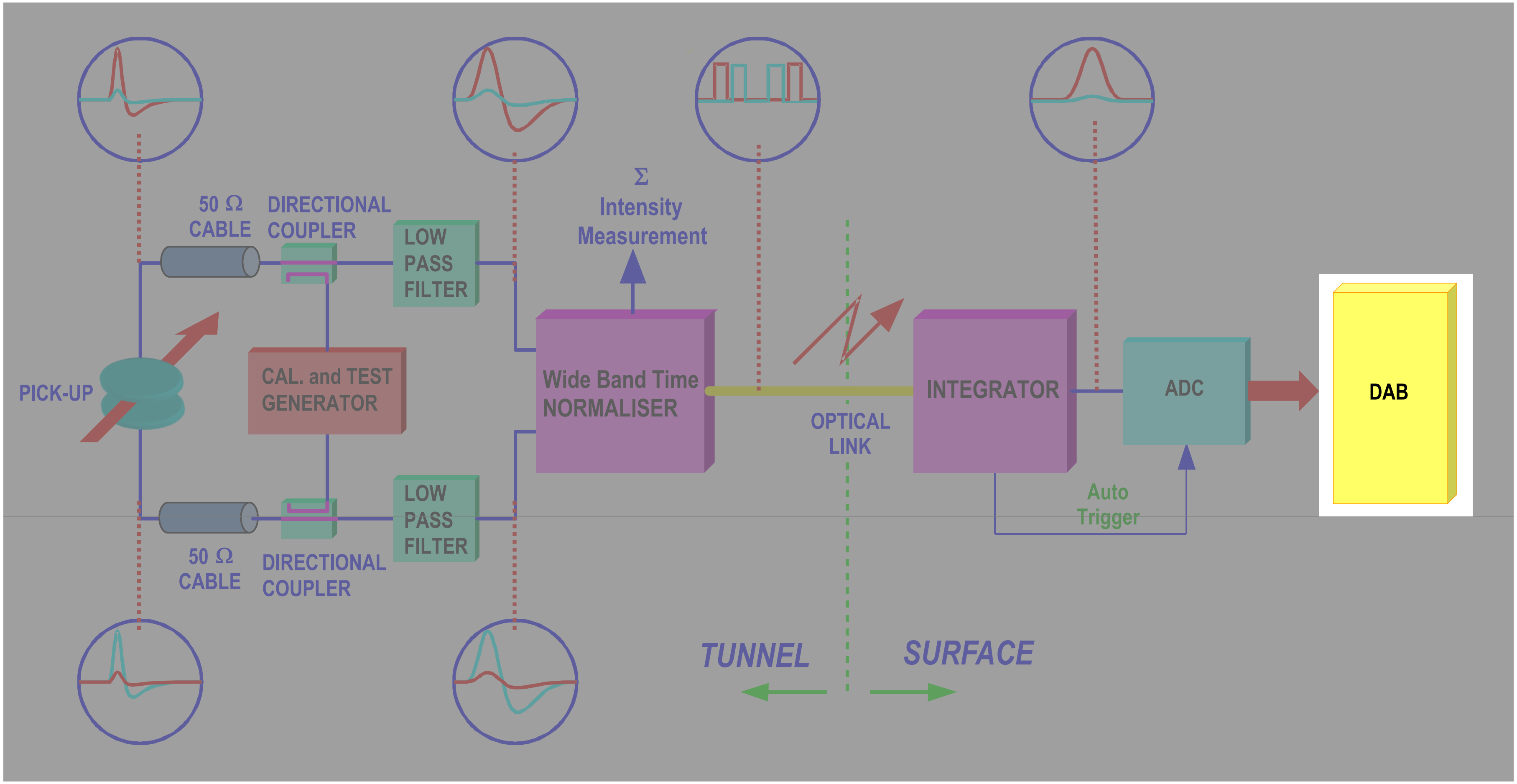
Single-Mode Fibre-Optic Link

Surface

VME based
Digital Acquisition Board (DAB)
TRIUMF (Canada)

WBTN Mezzanine Card
(10bit digitisation at 40MHz)

Read out scheme



TRIUMF Digital Acquisition Board

Orbit modes:

- <u>Asynchronous</u> (default): An IIR filter calculates de Exponential Moving Average of all the bunches. The time constant can be setup manually or automatically as function of the number of bunches in the machine.
- <u>Synchronous</u>: Where only selected bunches are averaged (225 turns).

Bunch orbit mode:

- Average of every bunch through T turns.

Capture mode (Triggered on demand):

- Synchronous process that allows to acquire every single selected bunch position (up to N bunches) over T turns either consecutive or spaced by a fixed step. (NxT < 128K)

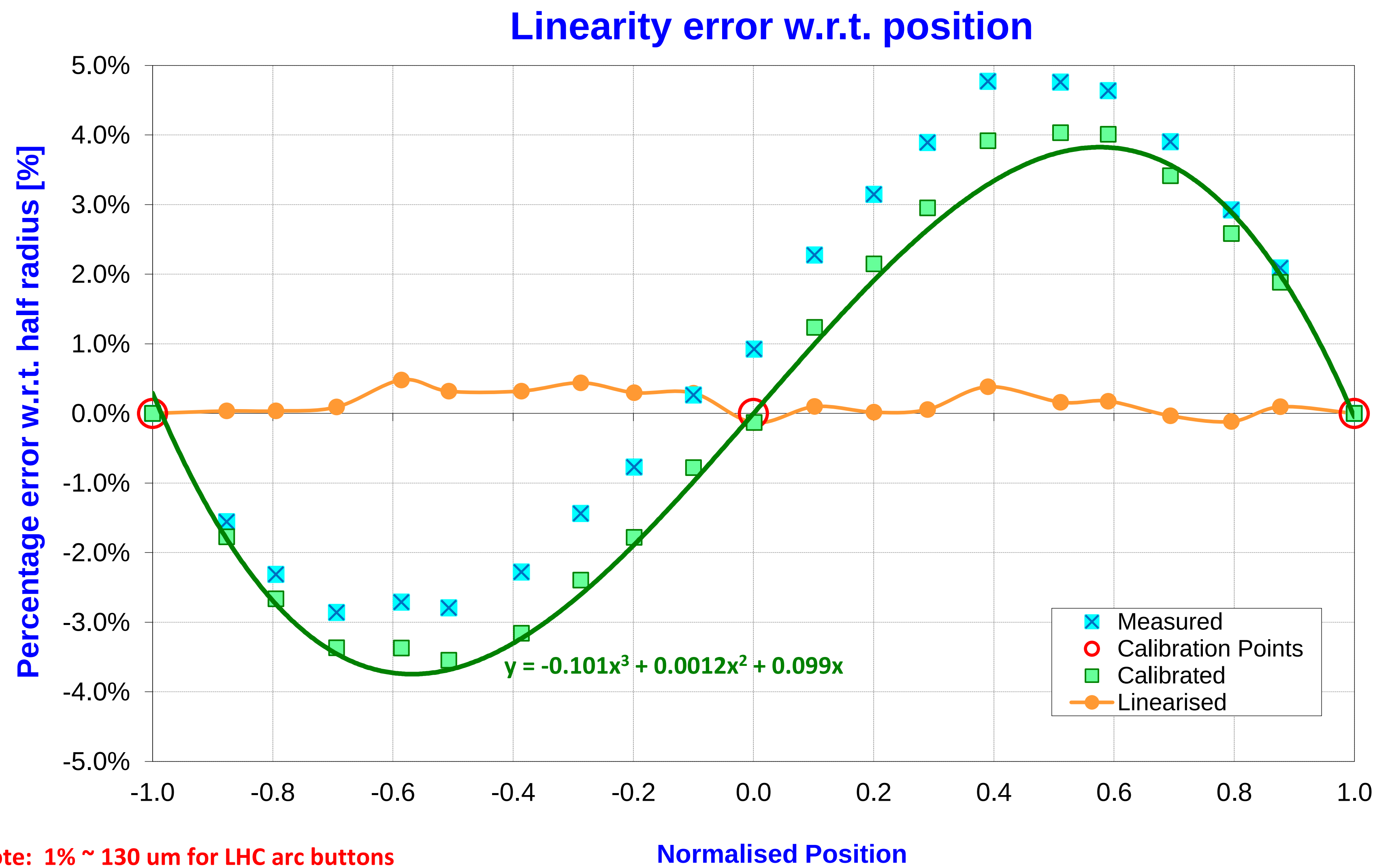
Post-Mortem (Continuously updated):

- Average of all bunches over 1 turn for last 1000 turns
- Last 1000 orbit acquisitions

Interlock mode:

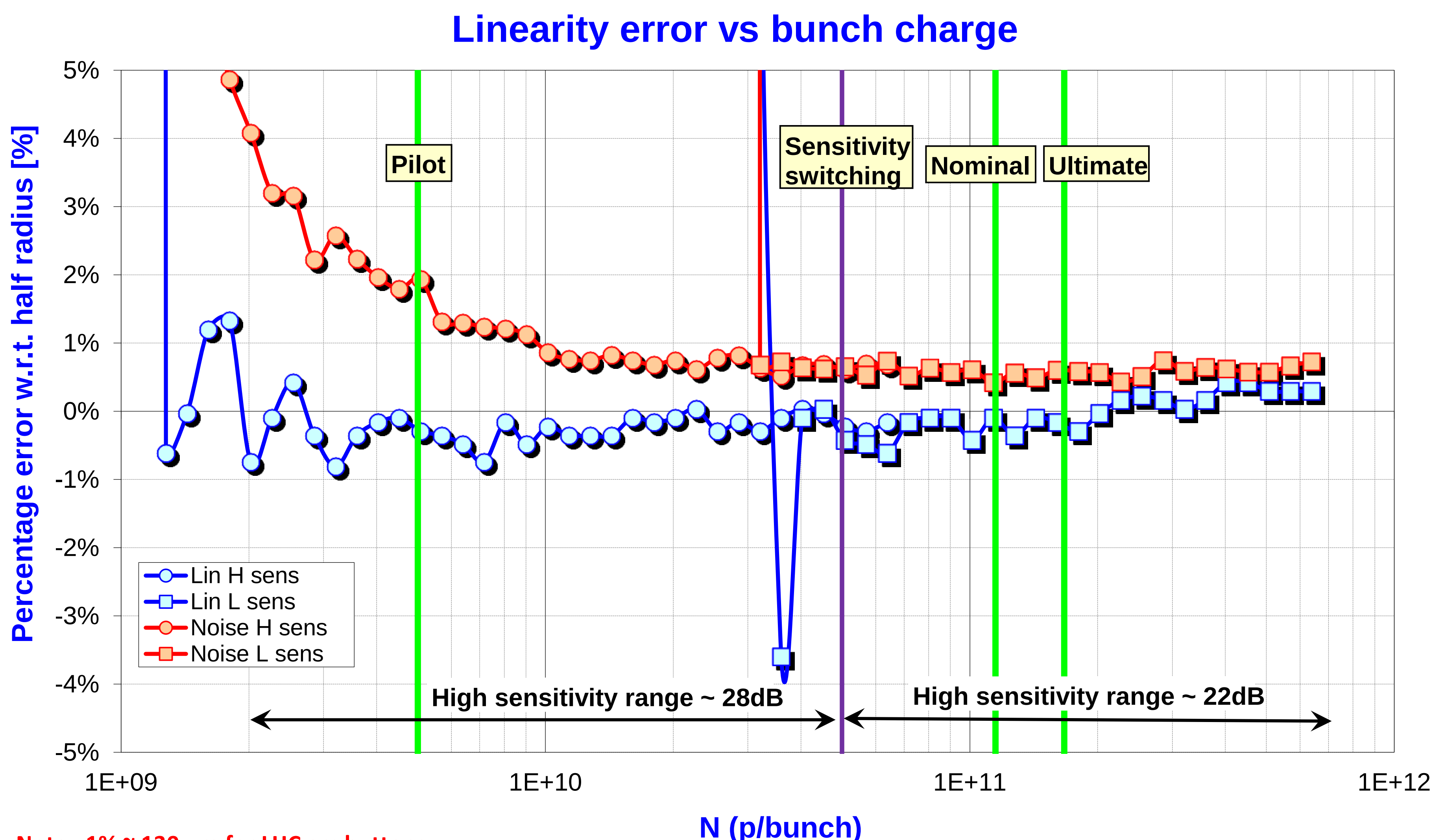
- Triggers an interlock signal that will dump the beam if N bunches for T turns are beyond certain configurable limits.

WBTN - Linearity vs Position



Note: 1% ~ 130 um for LHC arc buttons

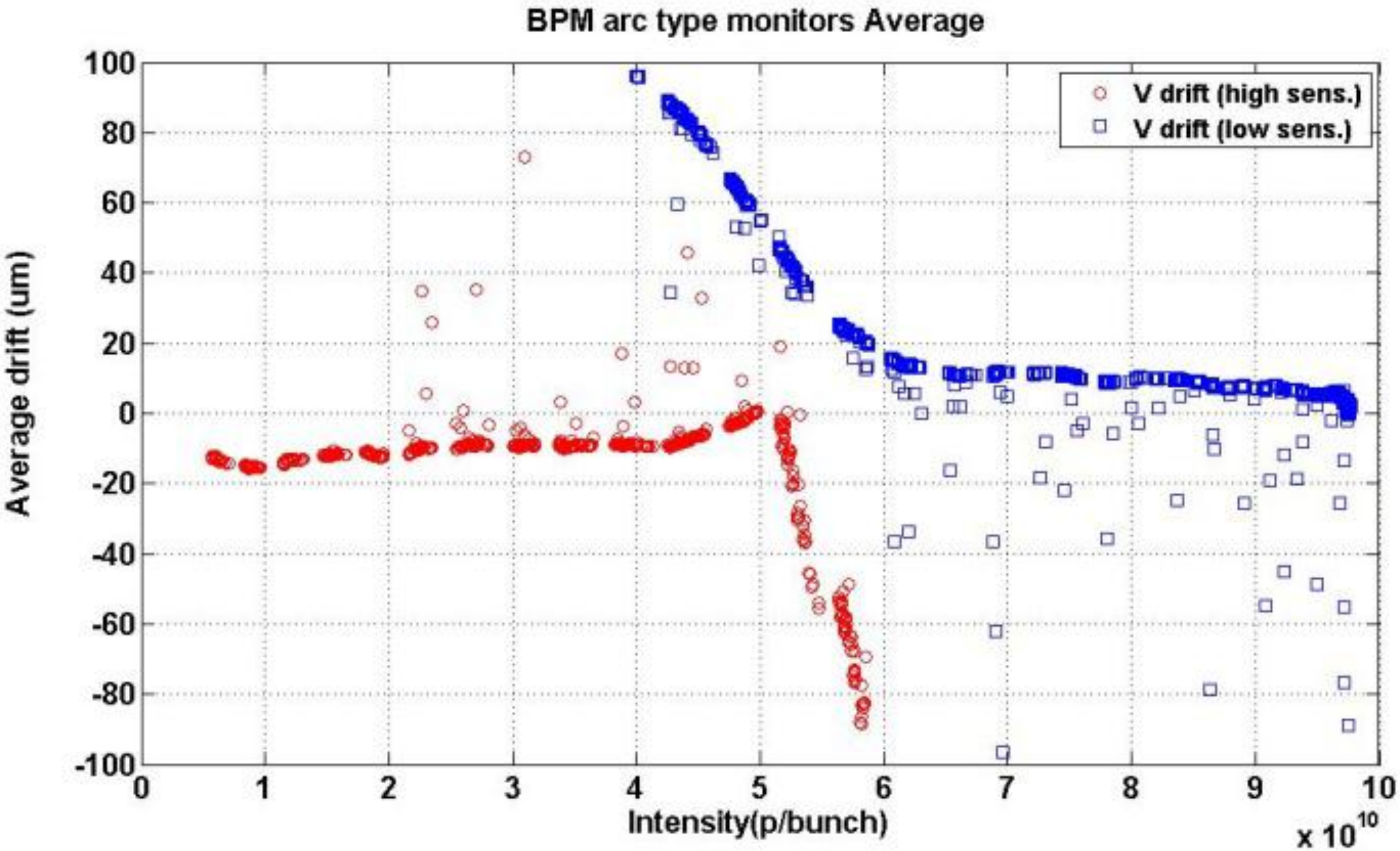
WBTN - Linearity vs Intensity



Note: 1% ~ 130 um for LHC arc buttons

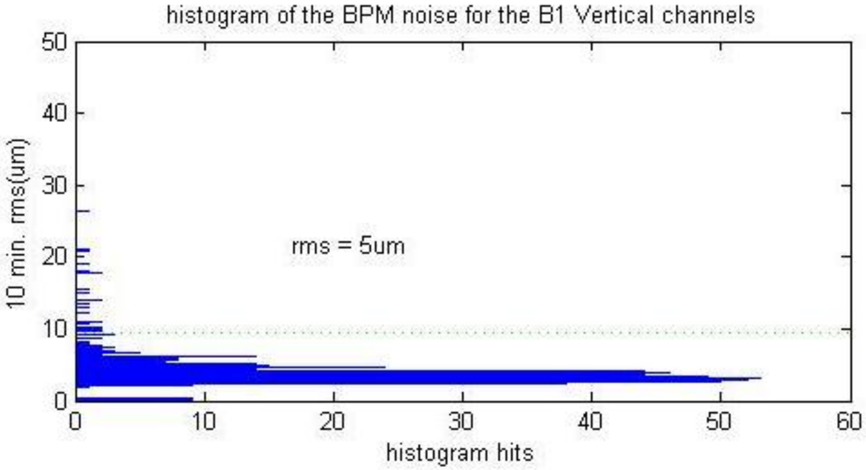
Intensity dependence

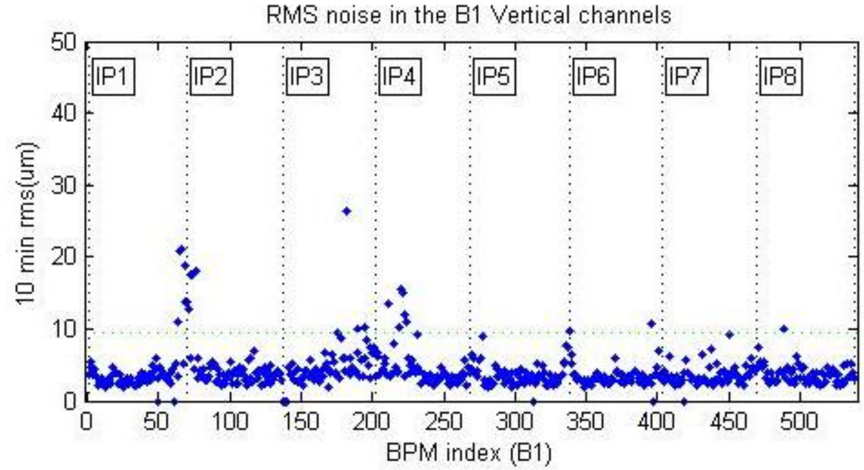
- Intensity dependence was measured by scrapping slowly the beam with the collimators. Bunch charge from ~1e11 → ~5e9 p/bunch (single bunch)
- The plot show the average measure of all the button BPMs.
- Drift on the orbit due to intensity over the whole range ~50um.

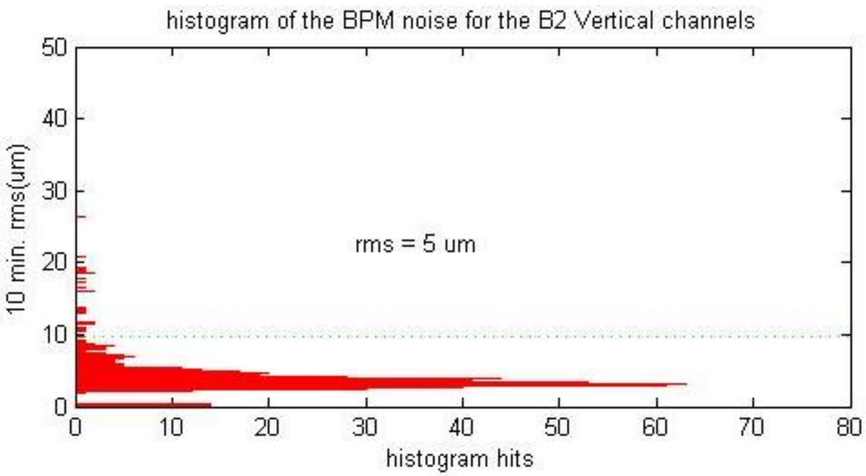


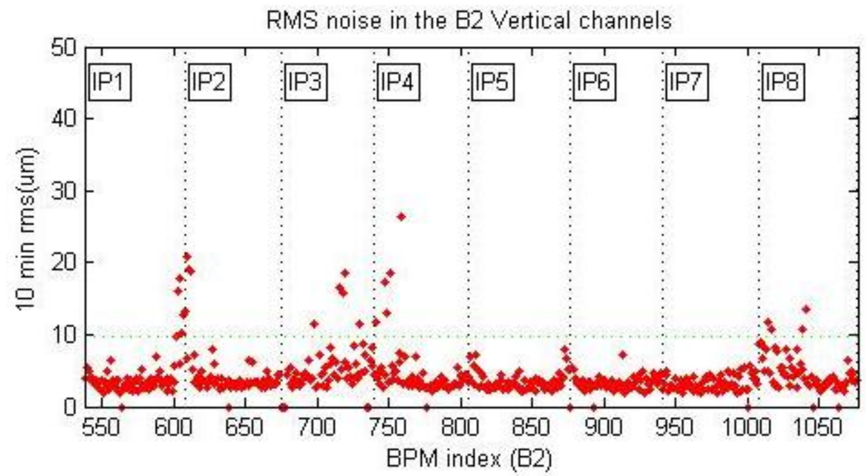
Orbit Resolution

- Resolution of LHC BPM system in closed-orbit mode is ~5um.





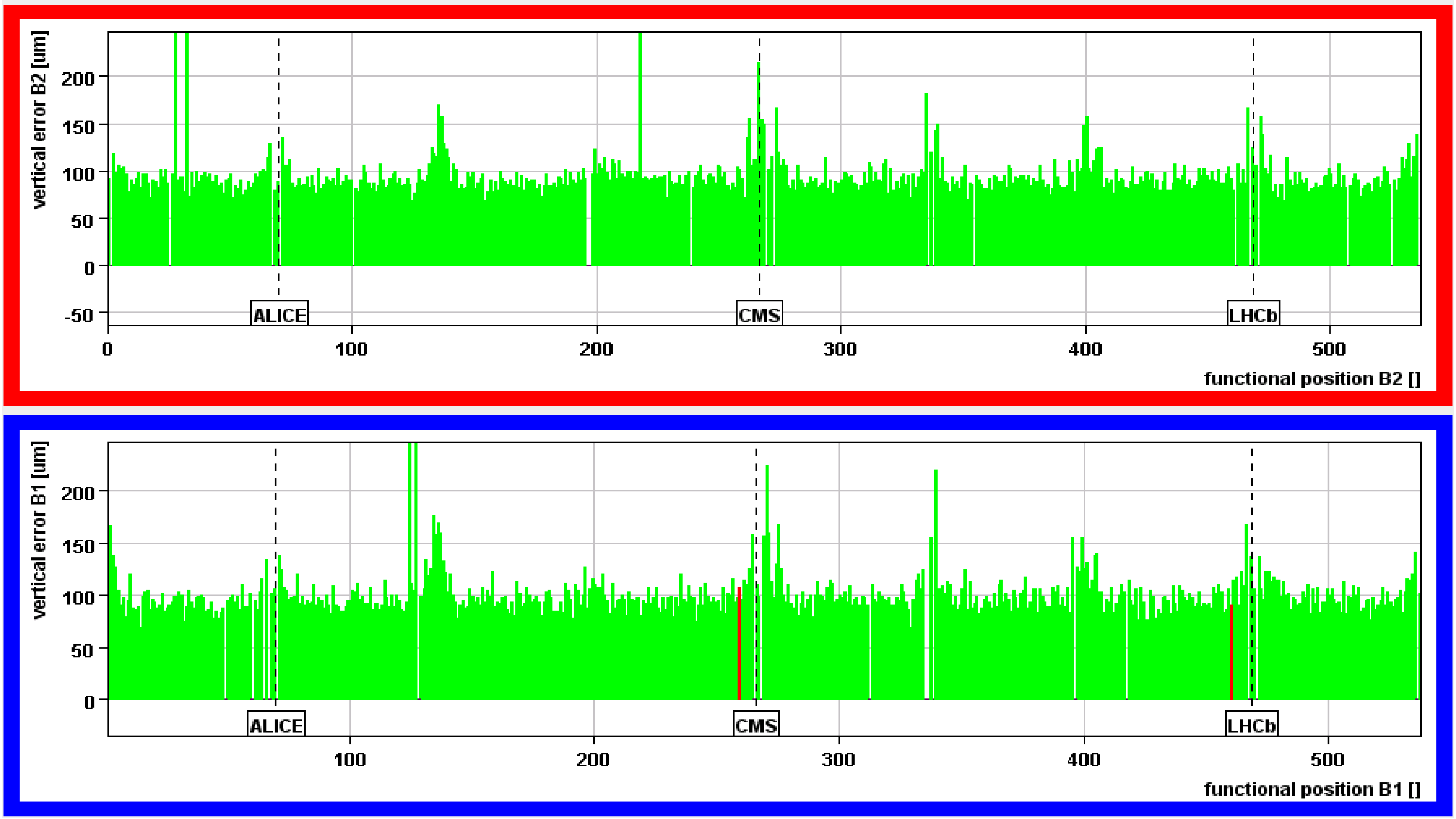




Bunch-by-bunch resolution

➢The resolution of the BPM system in bunch by bunch basis is <100 um

RMS from the Orbit Feedback GUI

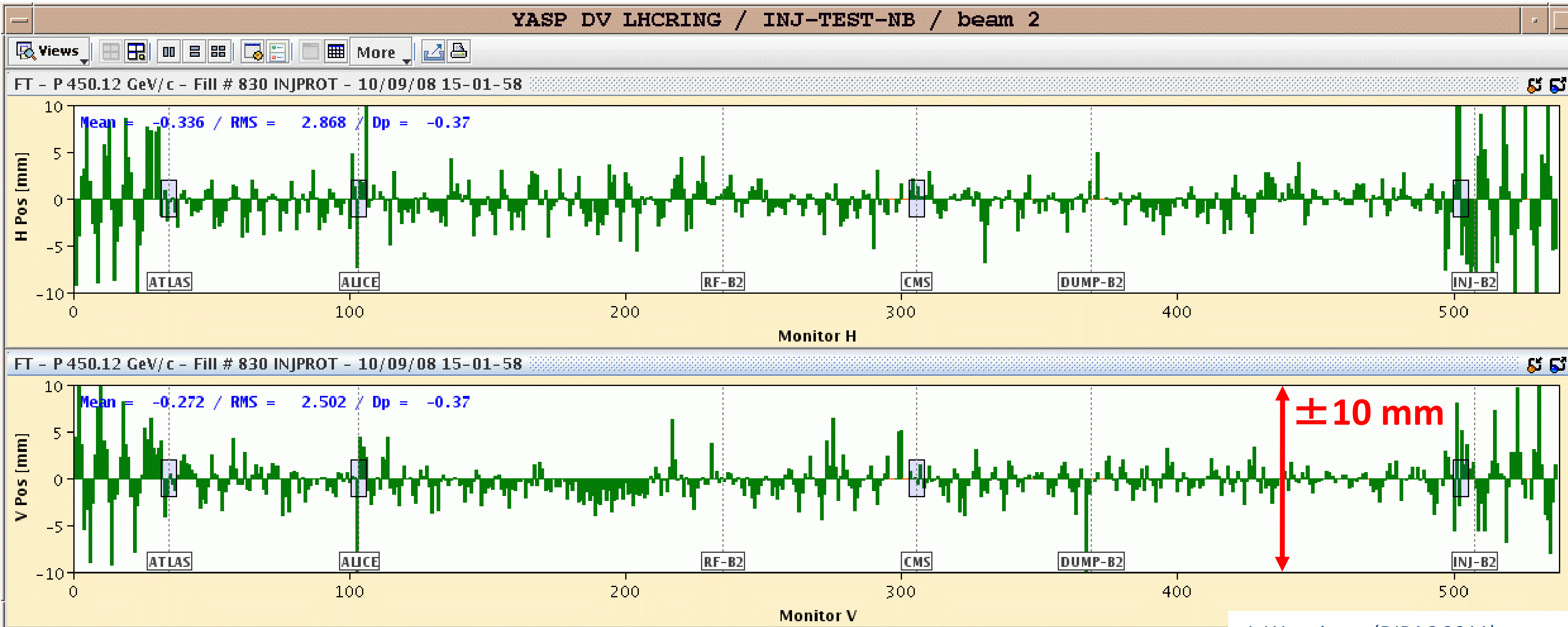


The LHC BPM system live show:

- All of CERN (and more) follows threading of the beams around the rings.
- Fantastic availability, negligible amounts of sign errors.

BPM availability ~ 99%

Beam 2 threading

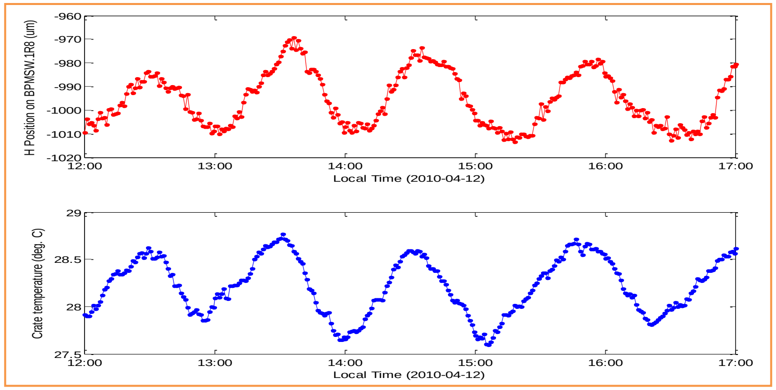


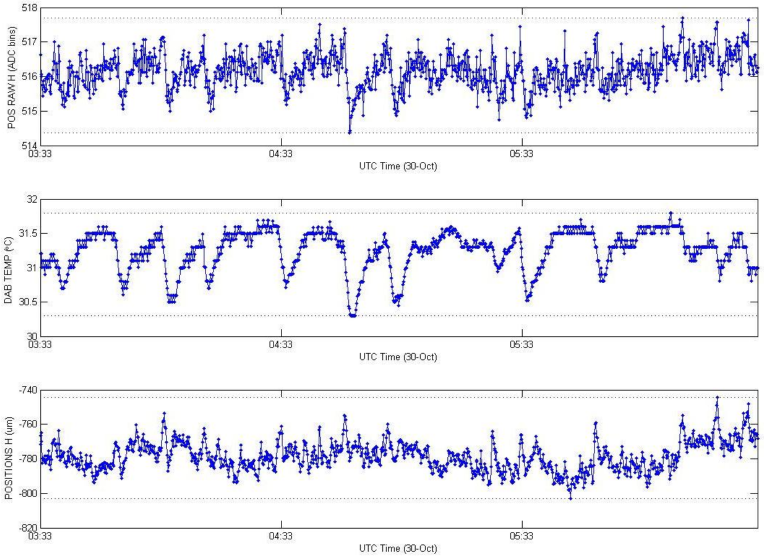
J. Wenninger (DIPAC 2011)

Limitations

Currently the most important limitations are :

- The temperature dependence of the integrator mezzanine card. ~2.2 ADC bins/˚C (Arc BPM ~100 um/˚C). This effect has been reduced to about 20um/˚C, by on-line temperature corrections.





- The limited directivity of the directional couplers (~24dB), creates a crosstalk between beam signals, making the orbit of the strip-line couplers very noisy. The synchronous orbit will mitigate this effect, but it would require to setup different parameters every time the filling scheme change.

Conclusions

The system was working from day one, very reliably.

It has prove to be very flexible from the point of view of having many different filling schemes (bunch spacing).

It has provided the resolution expected.

Still some issues should be improved, like temperature dependence, or beam-cross-talking.

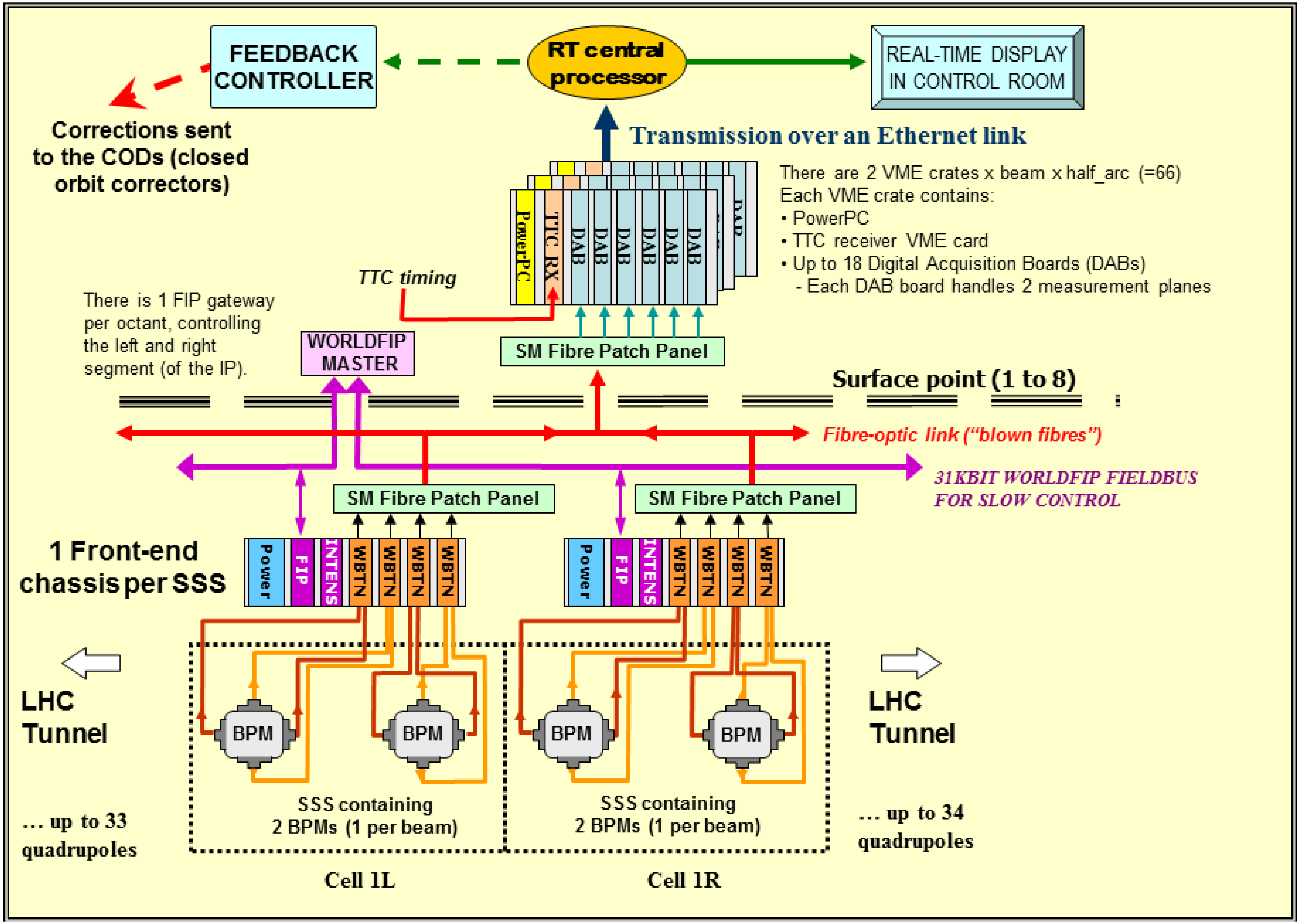
References

- **From Narrow to Wide Band Normalization for Orbit and Trajectory Measurements,** D. Cocq, G. Vismara, *CERN, Geneva, Switzerland.*
- **The wide band normaliser — a new circuit to measure transverse bunch position in accelerators and colliders**, Daniel Cocq*, Nuclear Instruments and Methods in Physics Research A 416 (1998), 1—8
- **A new wide band time normalizer circuit for bunch position measurements with high bandwidth and wide dynamic range**, D.Cocq et al., CERN Note "SL-98-064 BI",*HEACC'98, DUBNA, 7-12 September 1998.*
- **Caracteristiques du signal utile après filtrage pour les pick-up de TI2 & TI8 et du LHC,** D. Cocq, CERN Note "SL-Note-97-87".
- **Digital Acquisition firmware for the LHC beam position monitors,** J.Savioz, CERN internal note.
- **BPM read-out electronics based on the braodband AM/PM normalization scheme.,** M. Wendt, DIPAC 2001 proceedings.

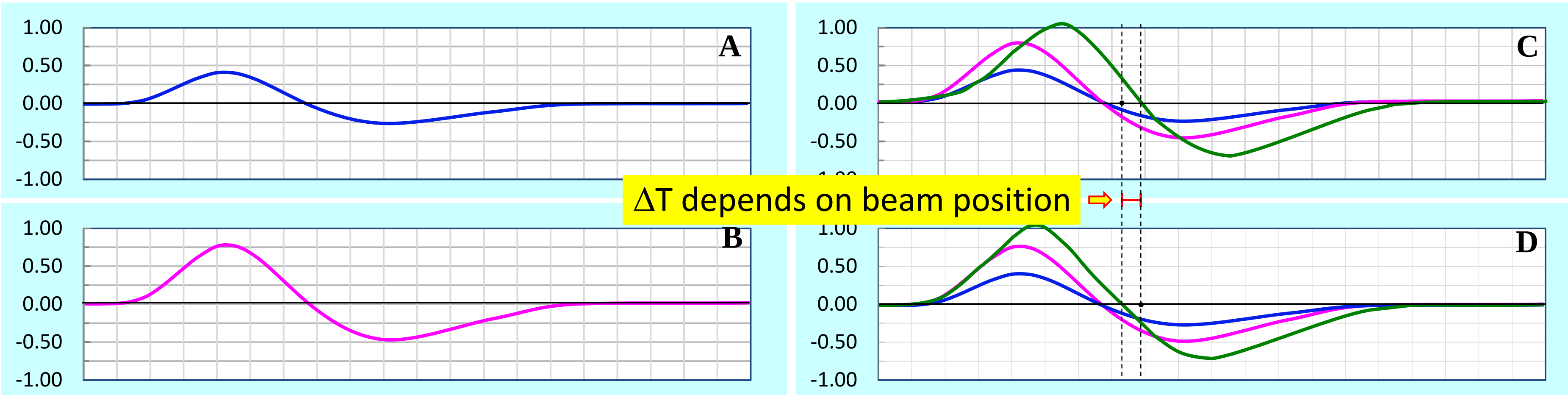
Thank you for your attention

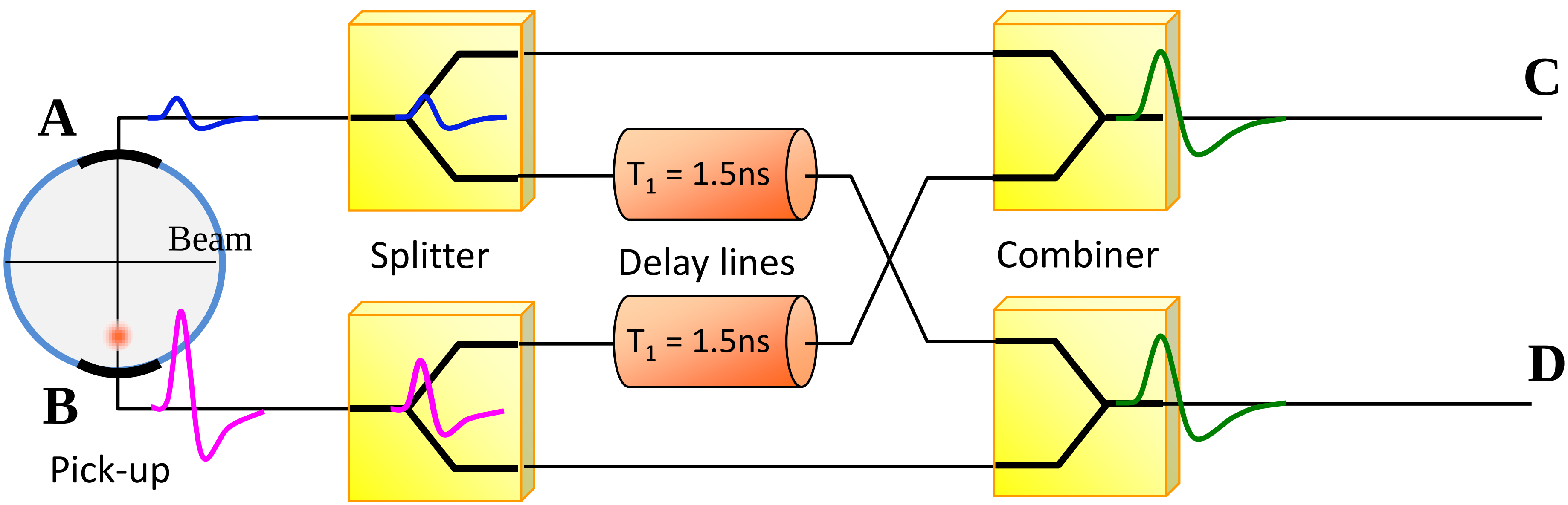
Spares

Complete system layout

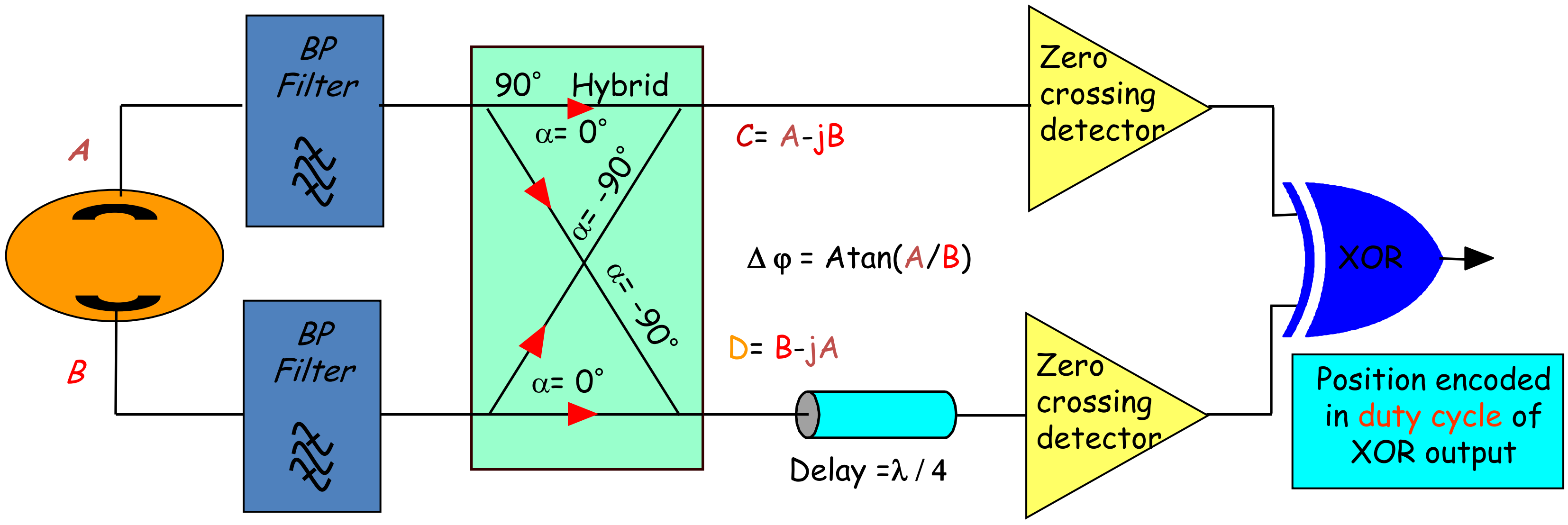


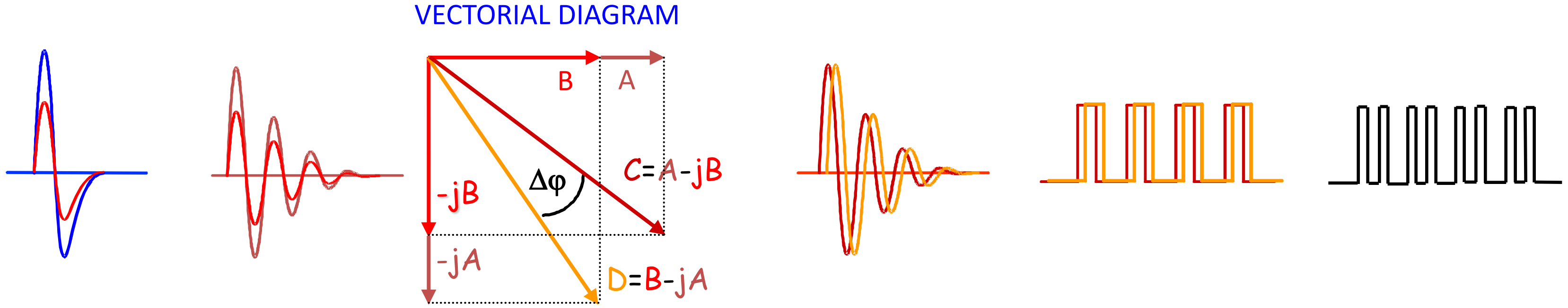
Amplitude to Time Normalisation



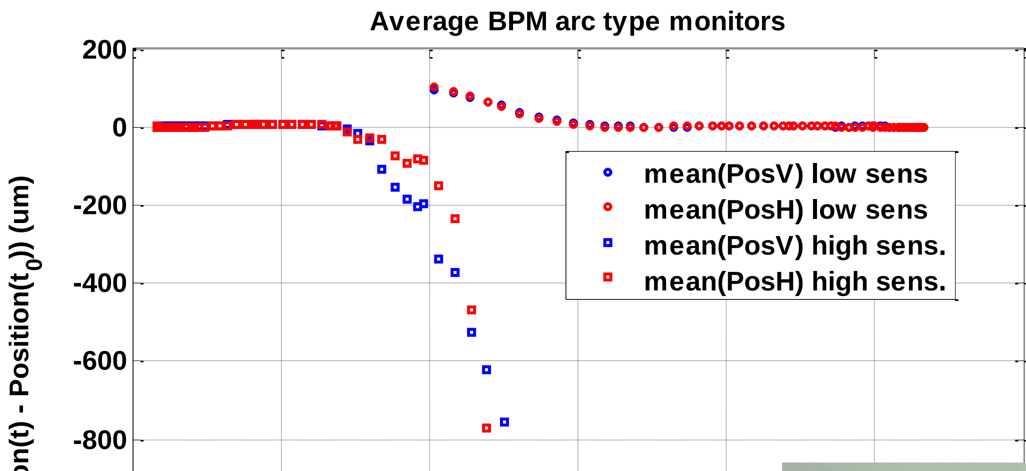


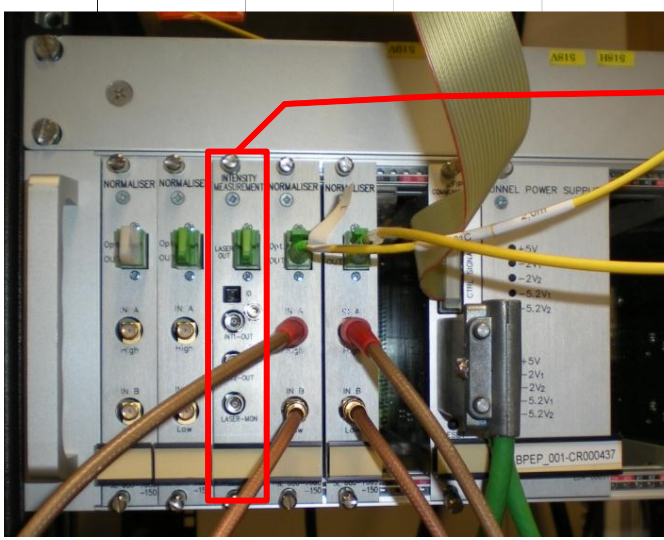
Amplitude to Phase Normalizer

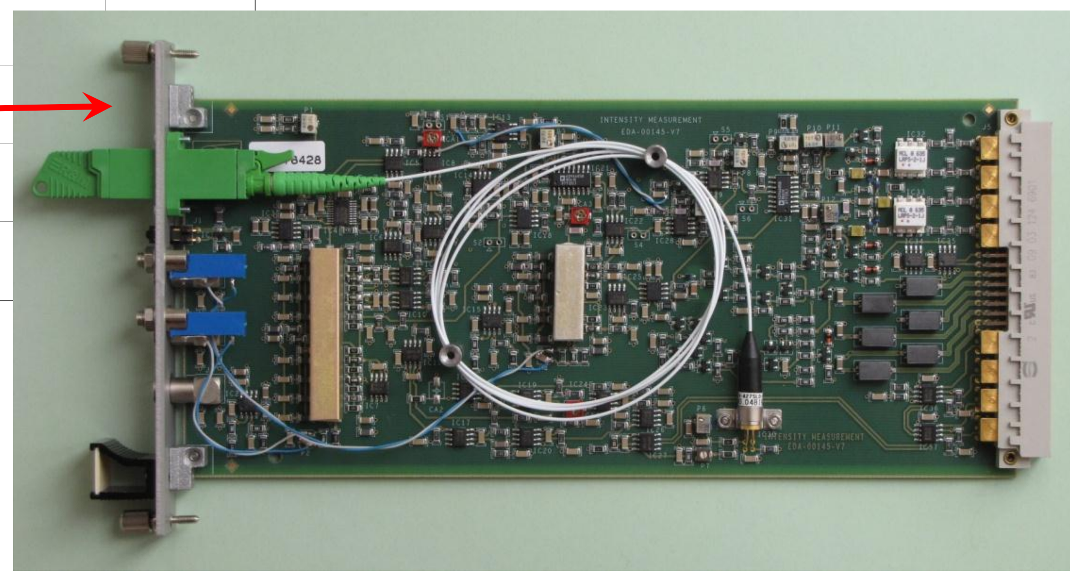




Intensity dependence #4





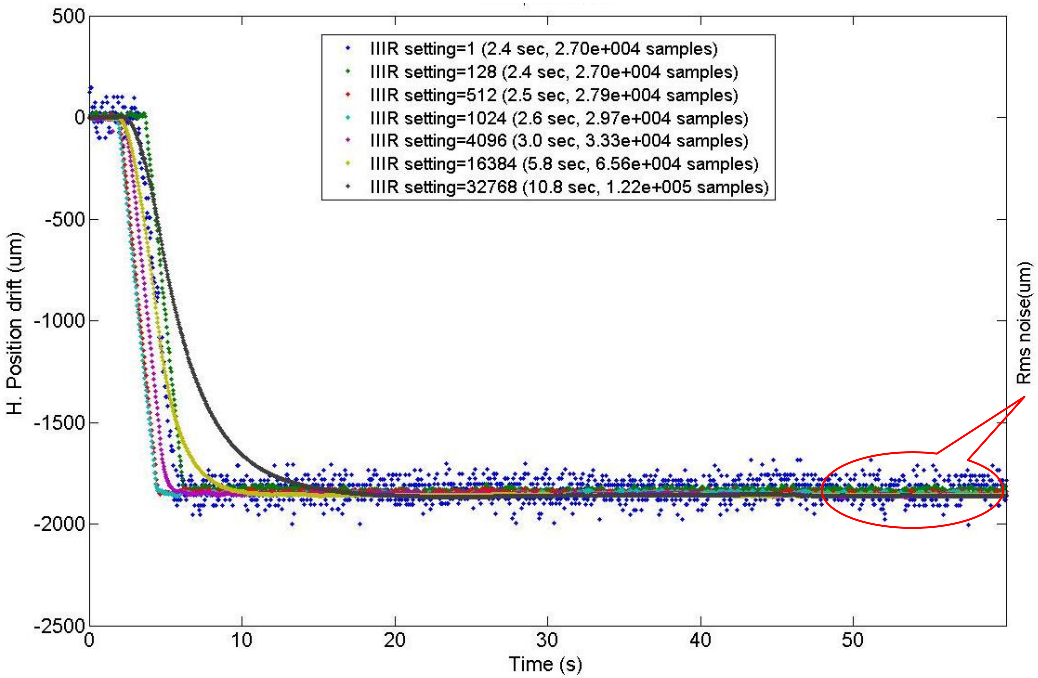


- **Beam 1** was found to have a stronger dependency.

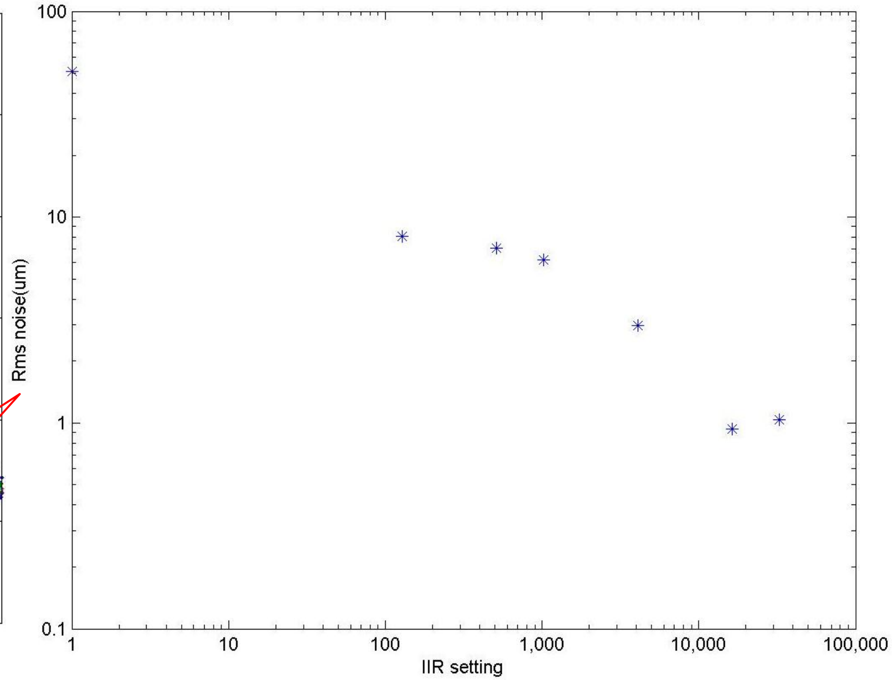
- This was trace back to a bad input impedance mismatching in a neighboring card used to measure the bunch intensity.

Time response and resolution for different IIR filter constant times:

Time response (with a single bunch) to a 100Hz RF trim for different settings.

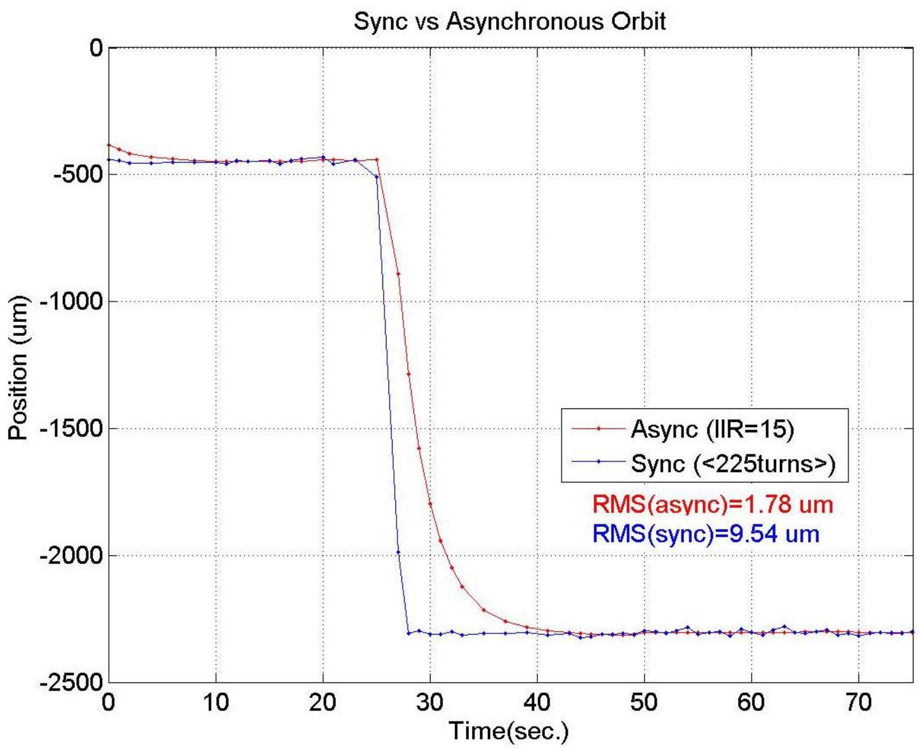


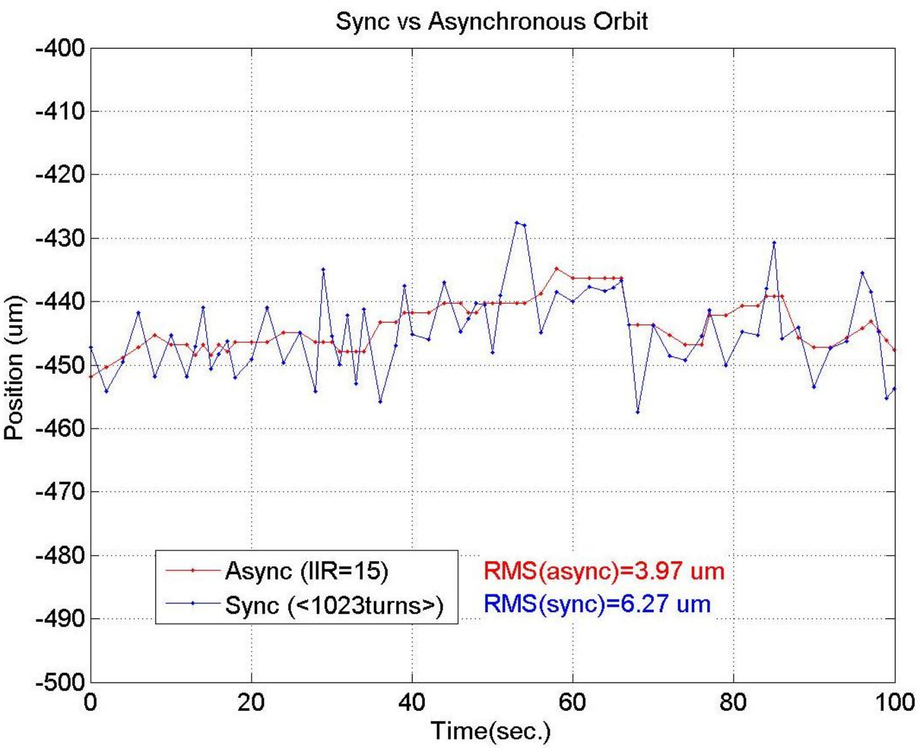
Filter output rms noise vs. IIR settings



With 1380 bunches the filter would have reached the final value in about 8 ms (~88 turns).
The IIR setting should be setup accordingly with the filling scheme of the machine (high order for many bunches, and small with few).

24th August MD – BPM results :
Aim: Comparison between the Synchronous and Asynchronous orbit modes.



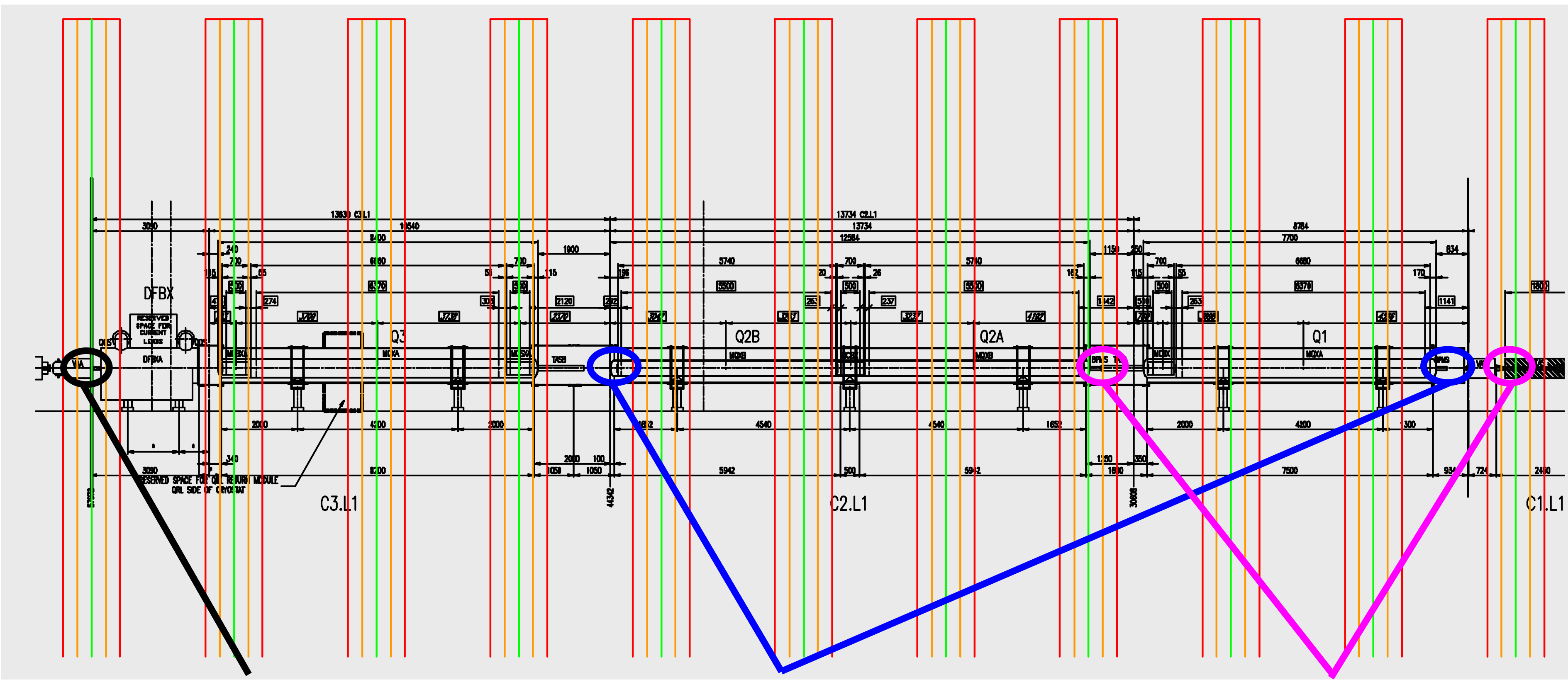


The synchoronous orbit allows to select all or a single bunch in the machine. As it can be observed in the plots, it provides very similar position and spread than the asynchronous orbit, and can be used in the strip line monitors for avoiding the directivity problems.

Improving the directivity

Use Time Structure of Beams to Enhance Directivity

IP 1 or 5

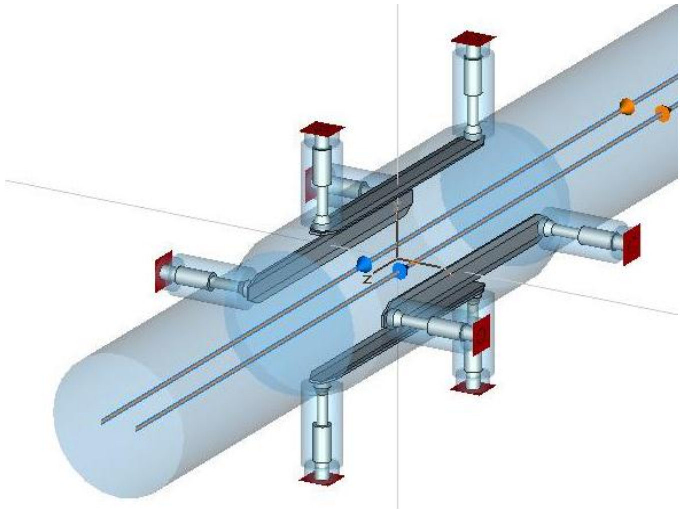


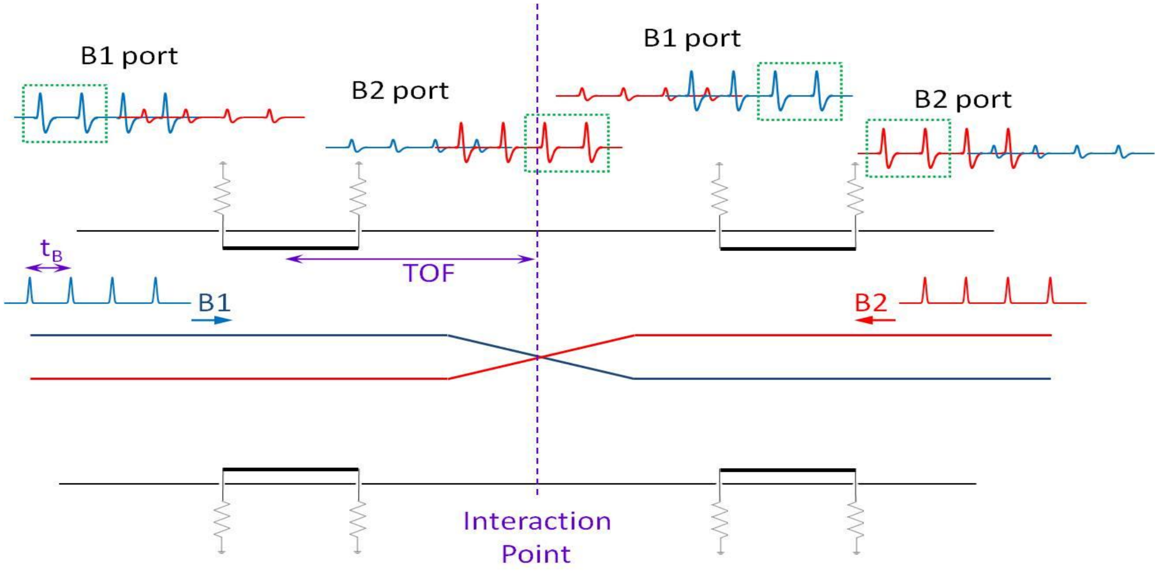
Additional Coupler

Original Coupler Locations

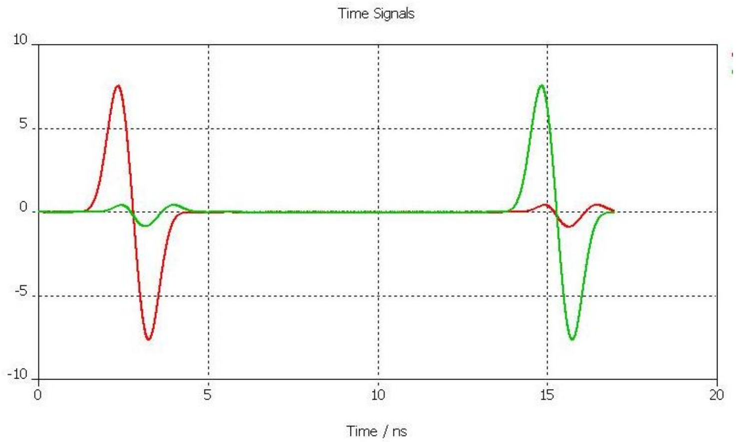
New Coupler Locations

- Ideal position - maximum bunch1 to bunch 2 separation (6.25ns)
- Zone 1 limit - 50μm resolution possible for nominal & weak-strong beams
- Zone 2 limit - 50μm resolution possible only for nominal beam



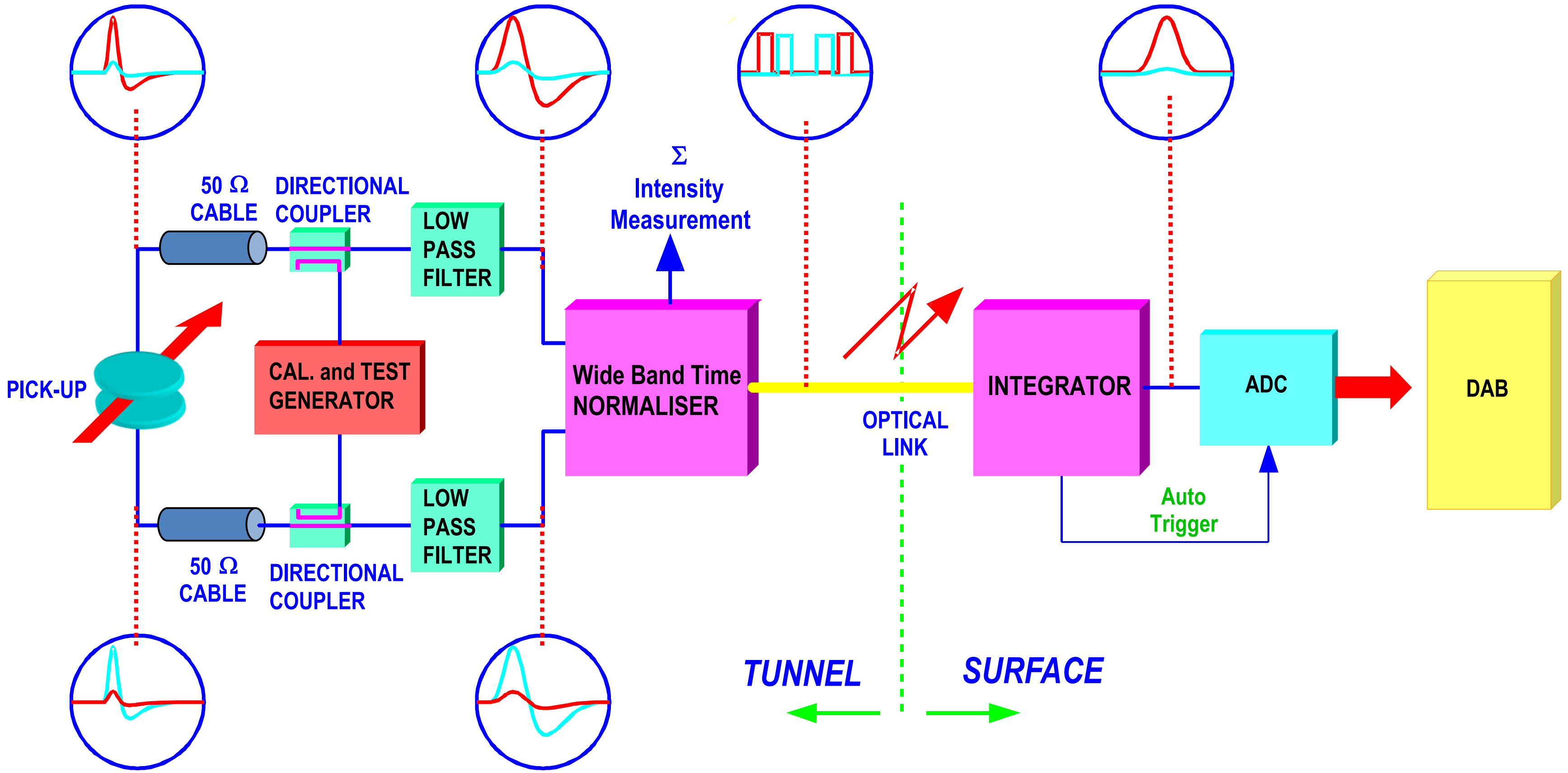


B1 port
B2 port
B1 port
B2 port
t_B
TOF
B1
B2
Interaction Point



Time Signals
10
5
0
-5
-10
0
5
10
15
20
Time / ns

Read out scheme



Temperature issues