

A Wall Current Transformer for bunch-by-bunch intensity measurements in the LHC

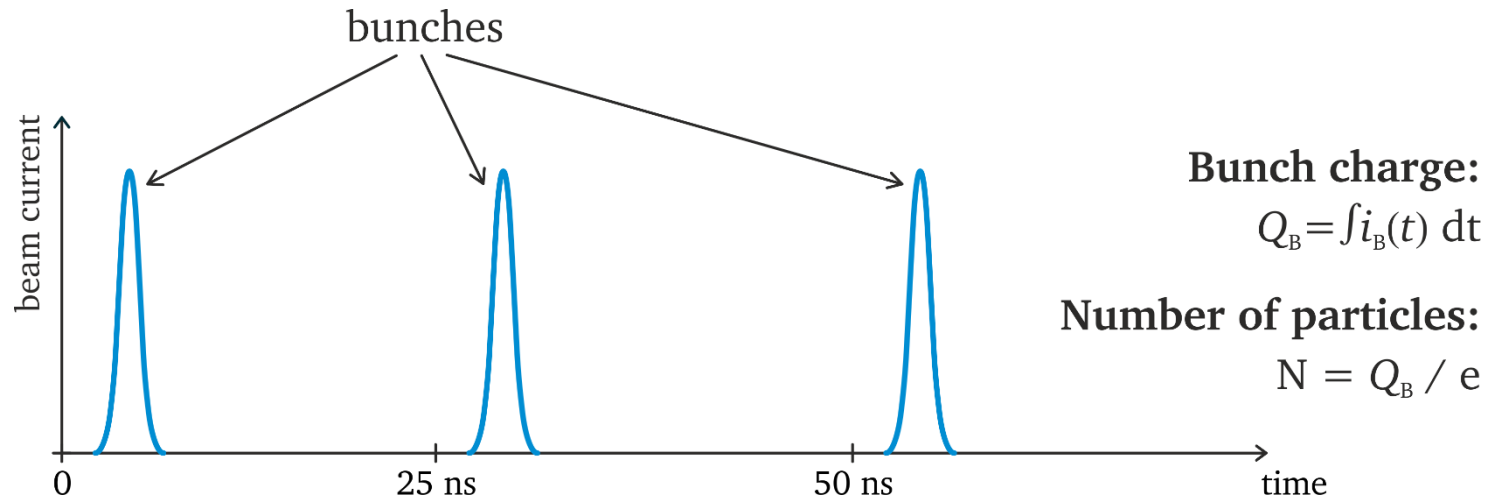
Michal Krupa
10/03/2016



Outline

- Bunch-by-bunch intensity measurements in the LHC
- Wall Current Transformer design and installation
- Laboratory and beam measurements
- Summary

Bunches in the LHC



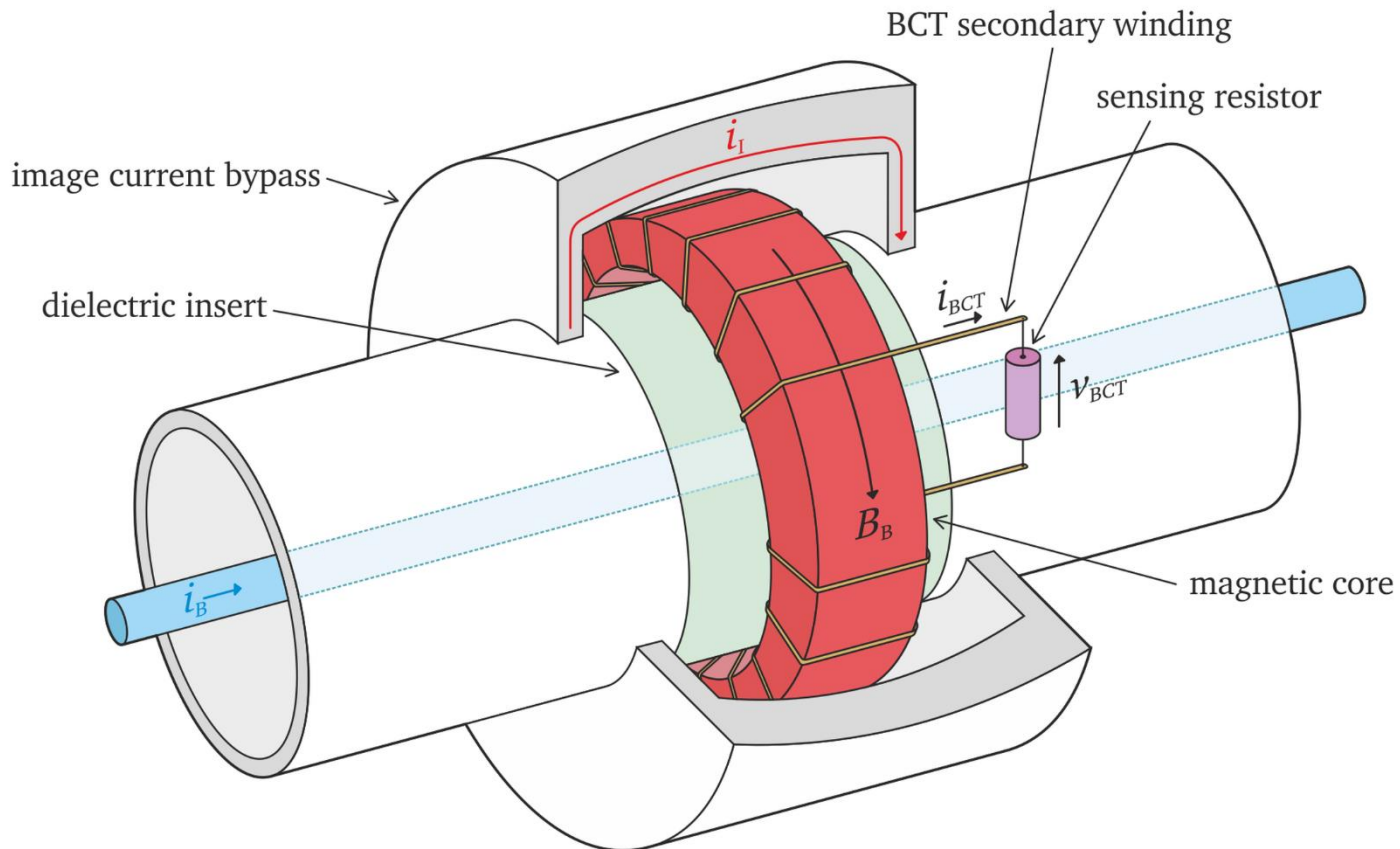
Typical LHC values:

- Bunch intensity: $5 \cdot 10^9 - 1.5 \cdot 10^{11}$ particles
- Bunch length: 1 - 2 ns
- Bunch spacing: 25 ns

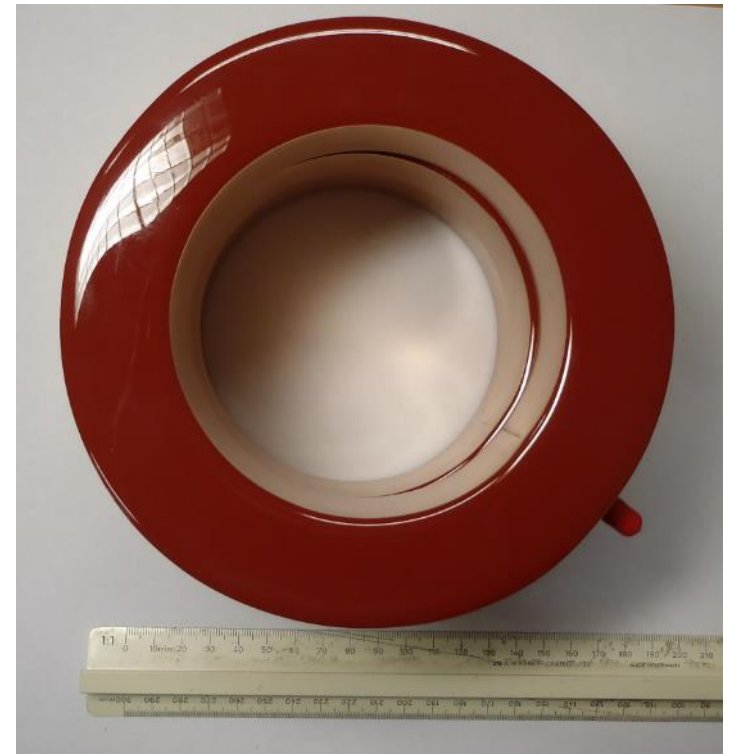
From FBCT to ICT / WCT

- **Run 1:** Fast Beam Current Transformers (**FBCT**) used for bunch-by-bunch intensity measurements in the LHC. Sensitivity to the transverse beam position and bunch length.
- **LS1:** Design of new monitors for absolute bunch-by-bunch intensity measurements. Two developments in parallel:
 - Integrating Current Transformer (**ICT**) by Bergoz
 - Wall Current Transformer (**WCT**) by CERN
- **2015:** Commissioning of ICT and WCT
- **2016:** Installation of two WCTs as the operational system

FBCT principle of operation

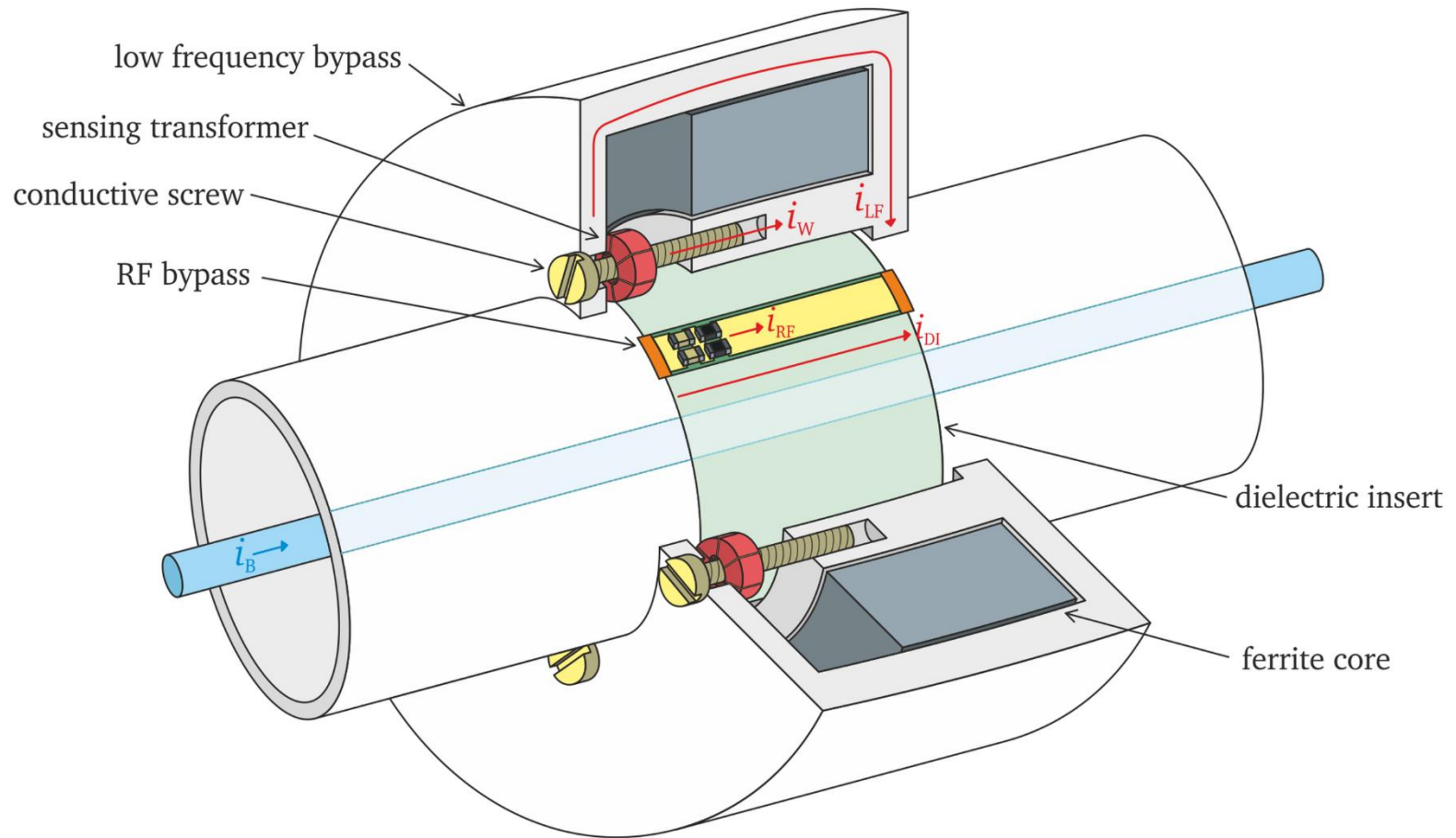


Bergoz ICT



Commercially available toroid compatible with the existing LHC FBCT mechanics and cooling system

WCT principle of operation

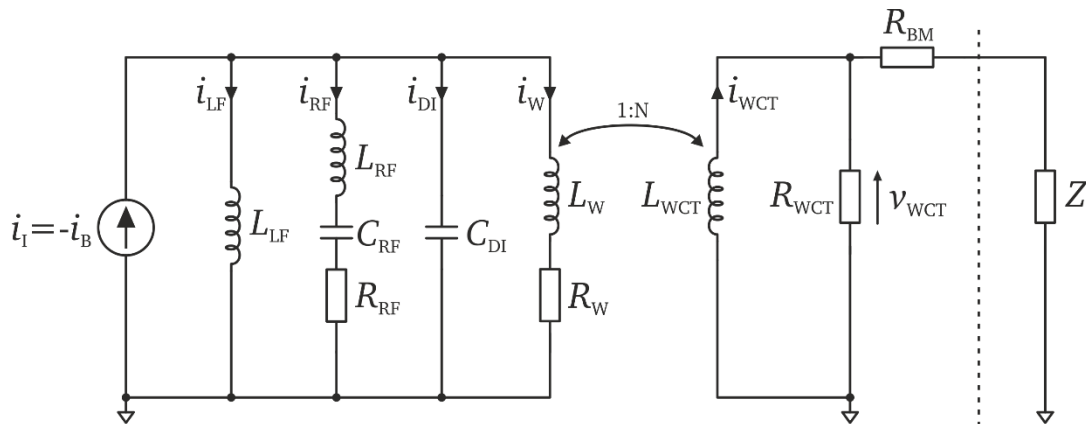
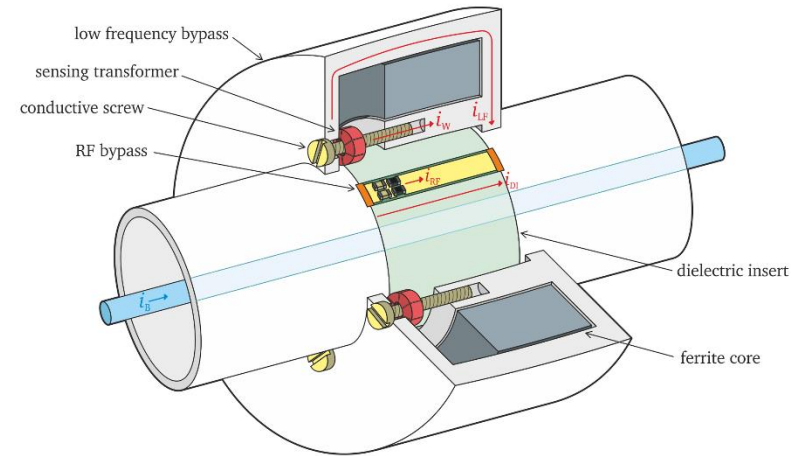
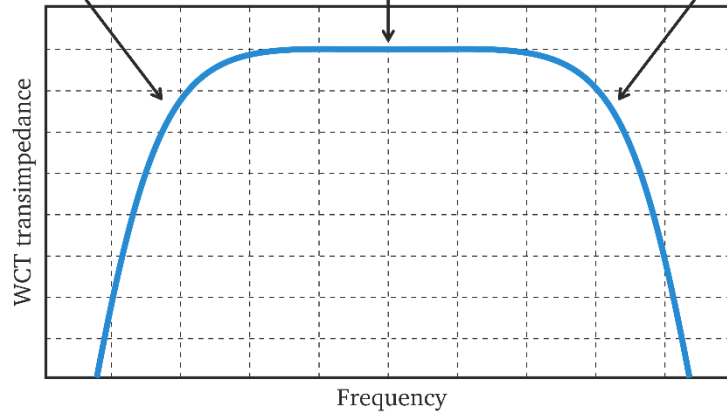


WCT principle of operation

Low cut-off: ~ 500 Hz
 $f(L_{LF}, R_W, N, R_{WCT}, L_{WCT})$

Sensitivity: ~ 50 mV/A
 $f(N, R_{WCT})$

High cut-off: ~ 500 MHz
 $f(L_{RF}, R_{RF}, L_W, N)$



$$L_{LF} \sim 10 \mu\text{H}$$

$$L_{RF} \sim 0.1 \text{ nH}$$

$$C_{RF} \sim 50 \text{ nF}$$

$$R_{RF} \sim 1 \Omega$$

$$C_{DI} \sim 1 \text{ pF}$$

$$L_W \sim 1 \text{ nH}$$

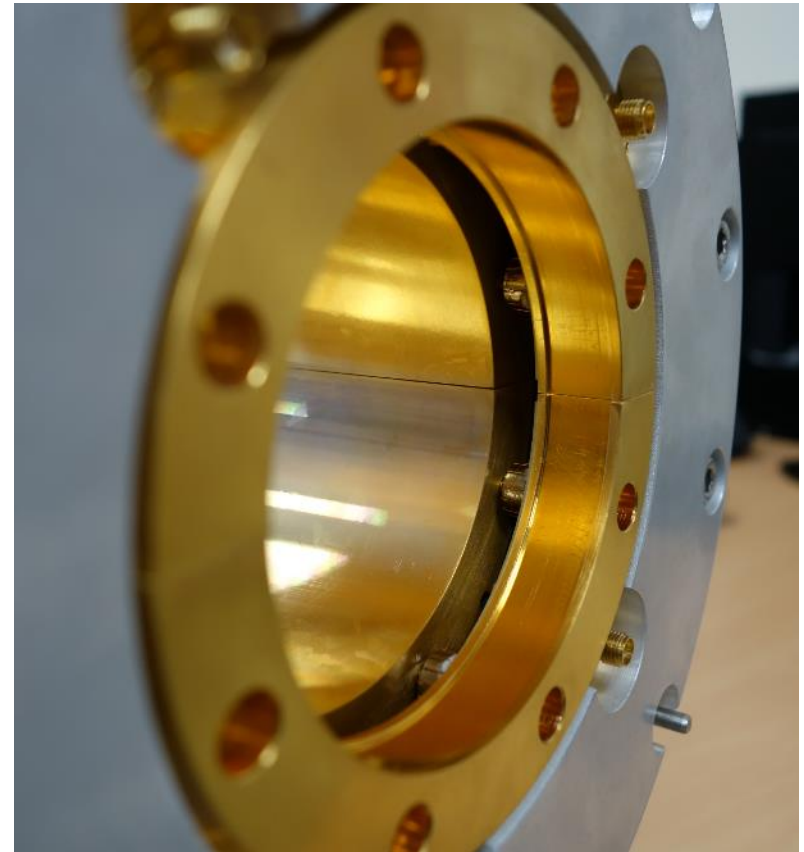
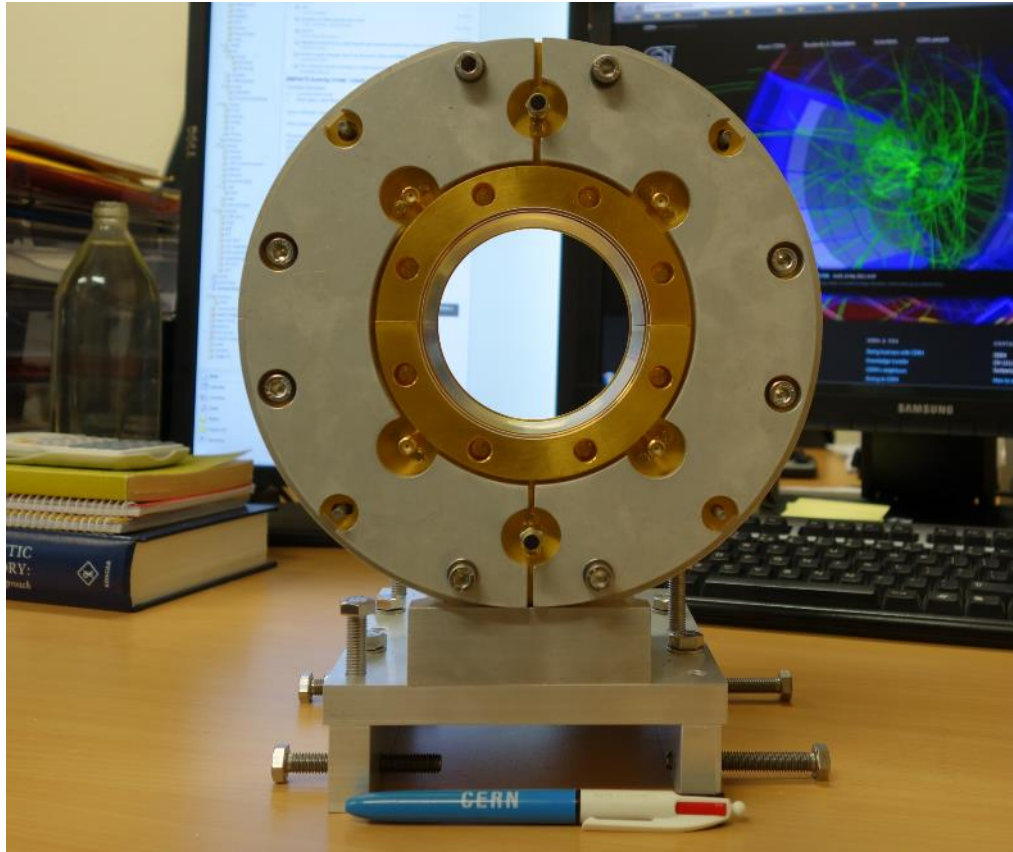
$$R_W \sim 50 \text{ m}\Omega$$

$$L_{WCT} \sim 1 \text{ mH}$$

$$R_{WCT} \sim 5 \Omega$$

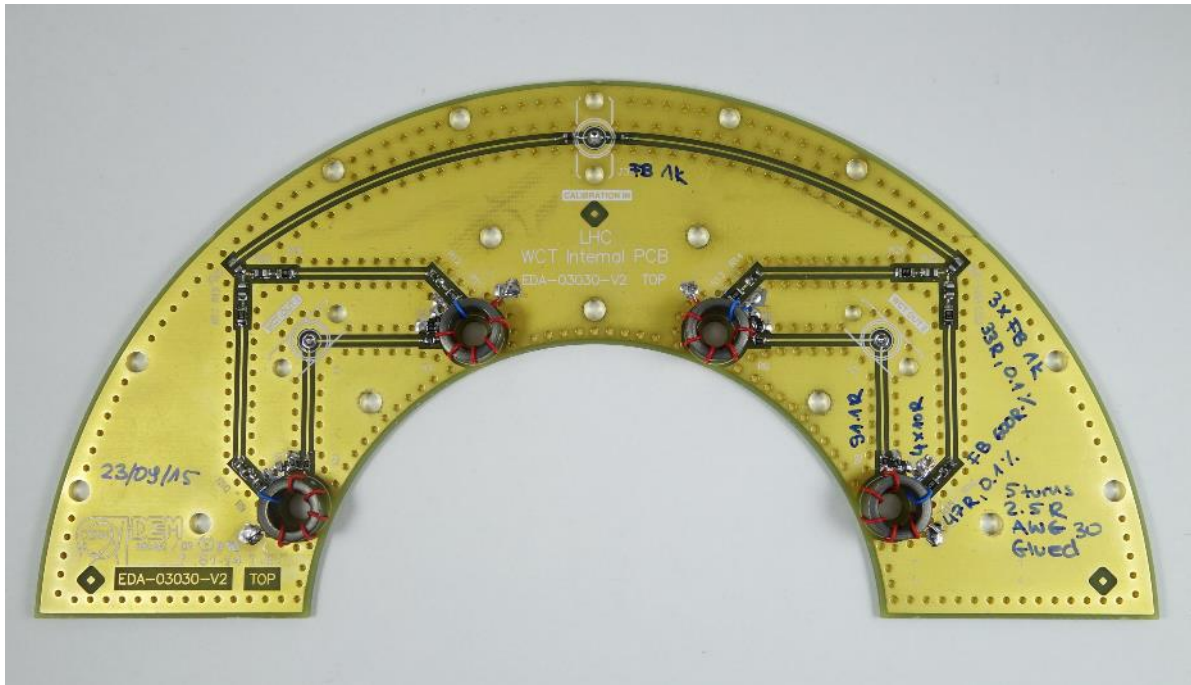
$$N \sim 10$$

WCT design



All parts cut in half – installation and removal does not require breaking the accelerator vacuum

WCT design

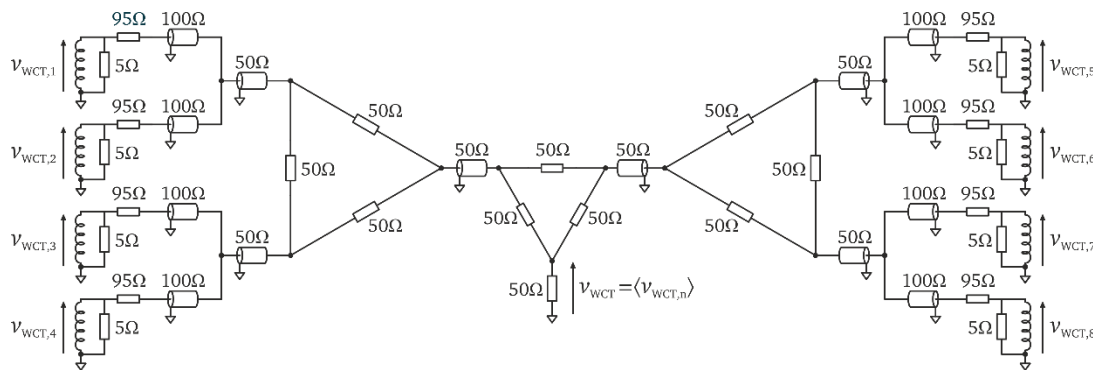


Calibration winding:

- single turn
- calibration with current
- low resistance at low frequencies (minimising power dissipation)
- high impedance at high frequencies (decoupling from beam)

Signal winding:

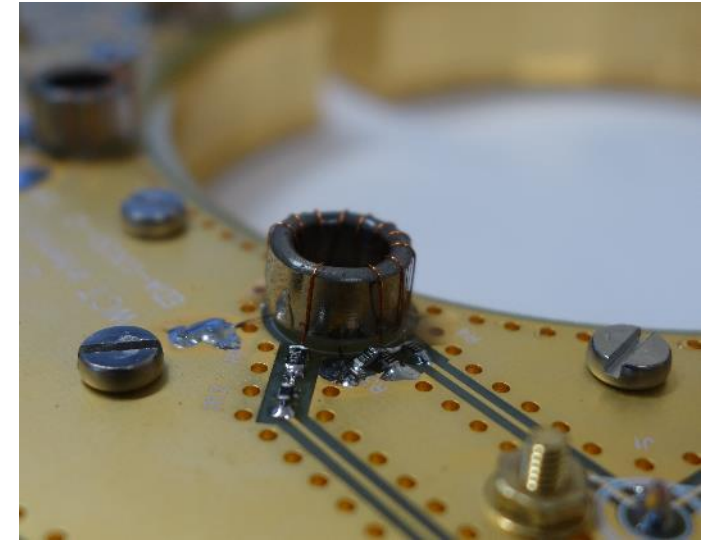
- few turns
- low impedance
- averaging two nearest transformers on the PCB



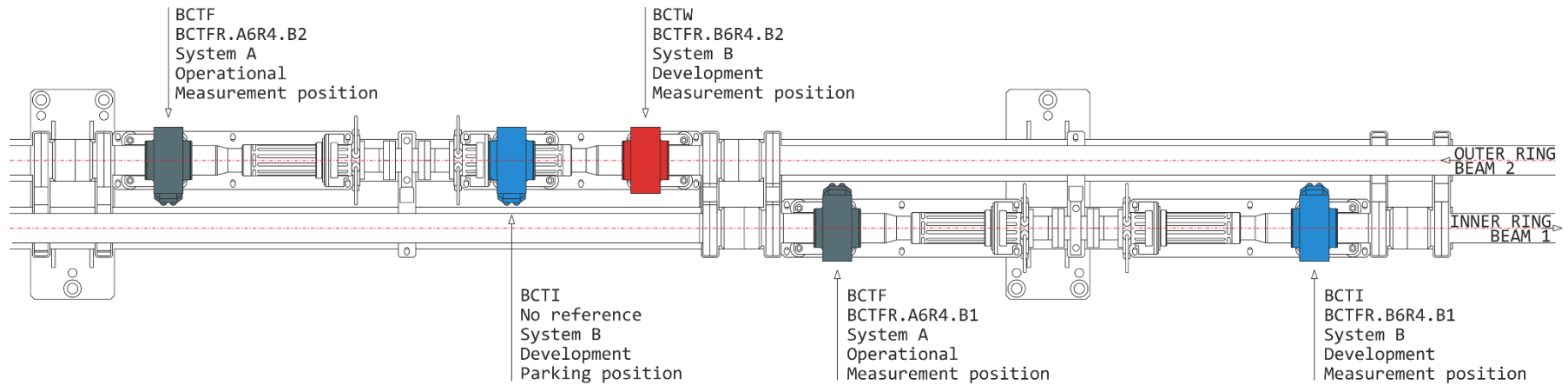
Signal addition:

the four outputs are passively summed (averaged) outside, but close to, the monitor

Magnetic cores



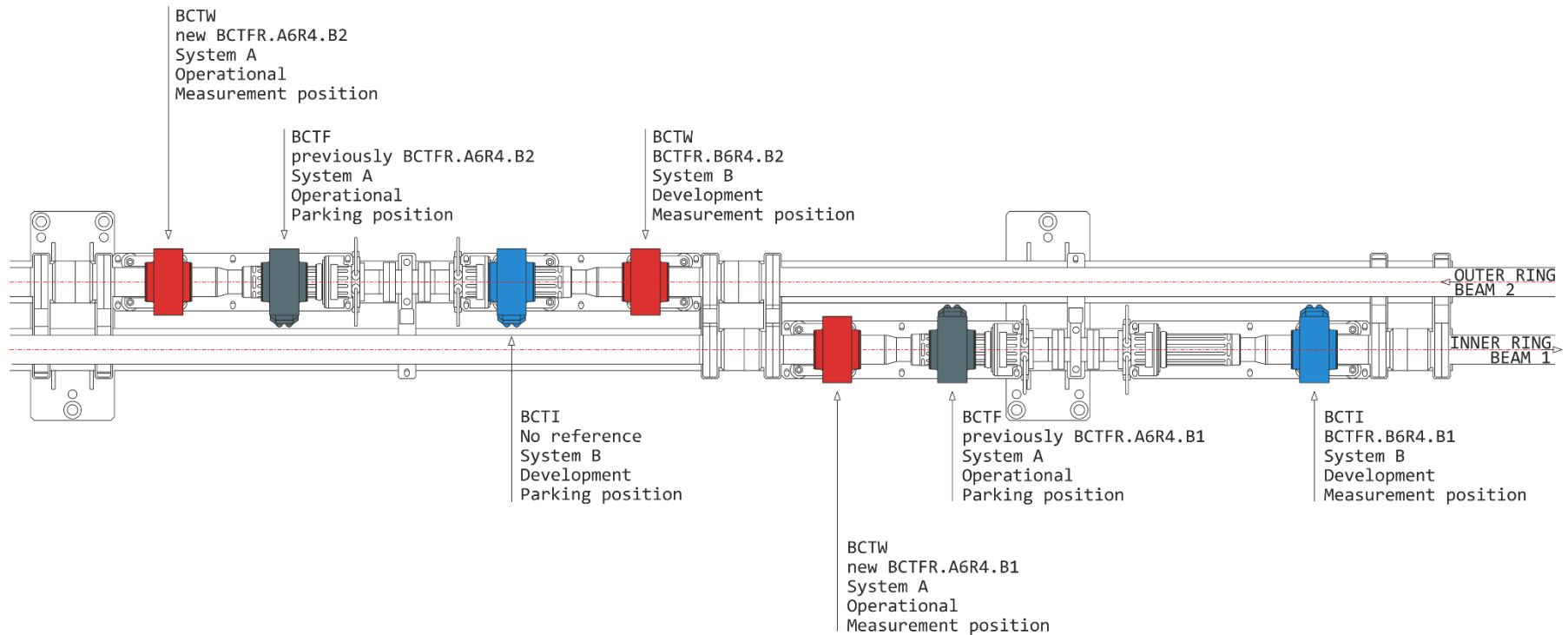
LHC Point 4 installation in 2015



System A (operational): no change during LS1

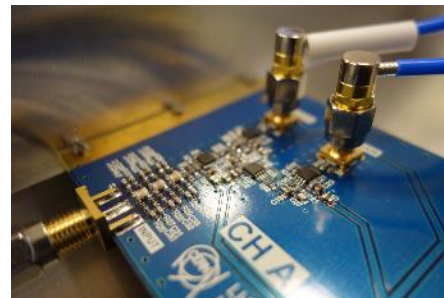
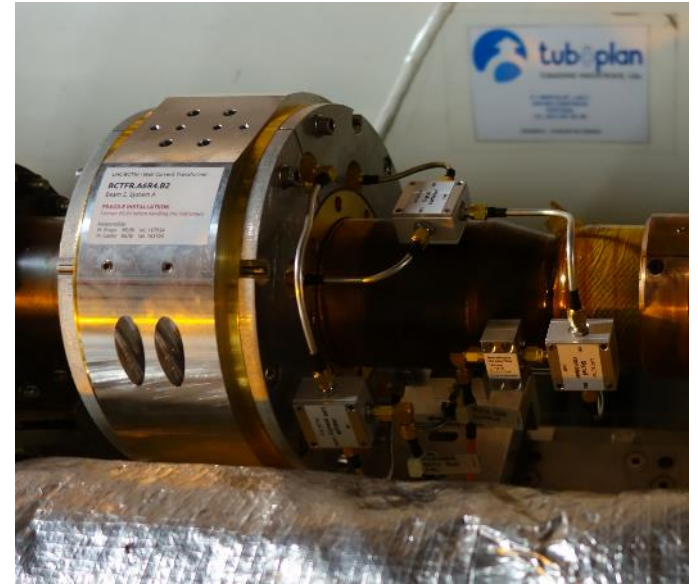
System B (development): two new monitors (WCT + ICT), digital acquisition in parallel to DABs

LHC Point 4 installation in 2016



System A (operational): two new WCTs installed during YETS 2015/2016 to be commissioned in 2016

LHC WCT installation



Design launched: 01/10/2013

First installation in the LHC: 02/03/2015



10/03/2016

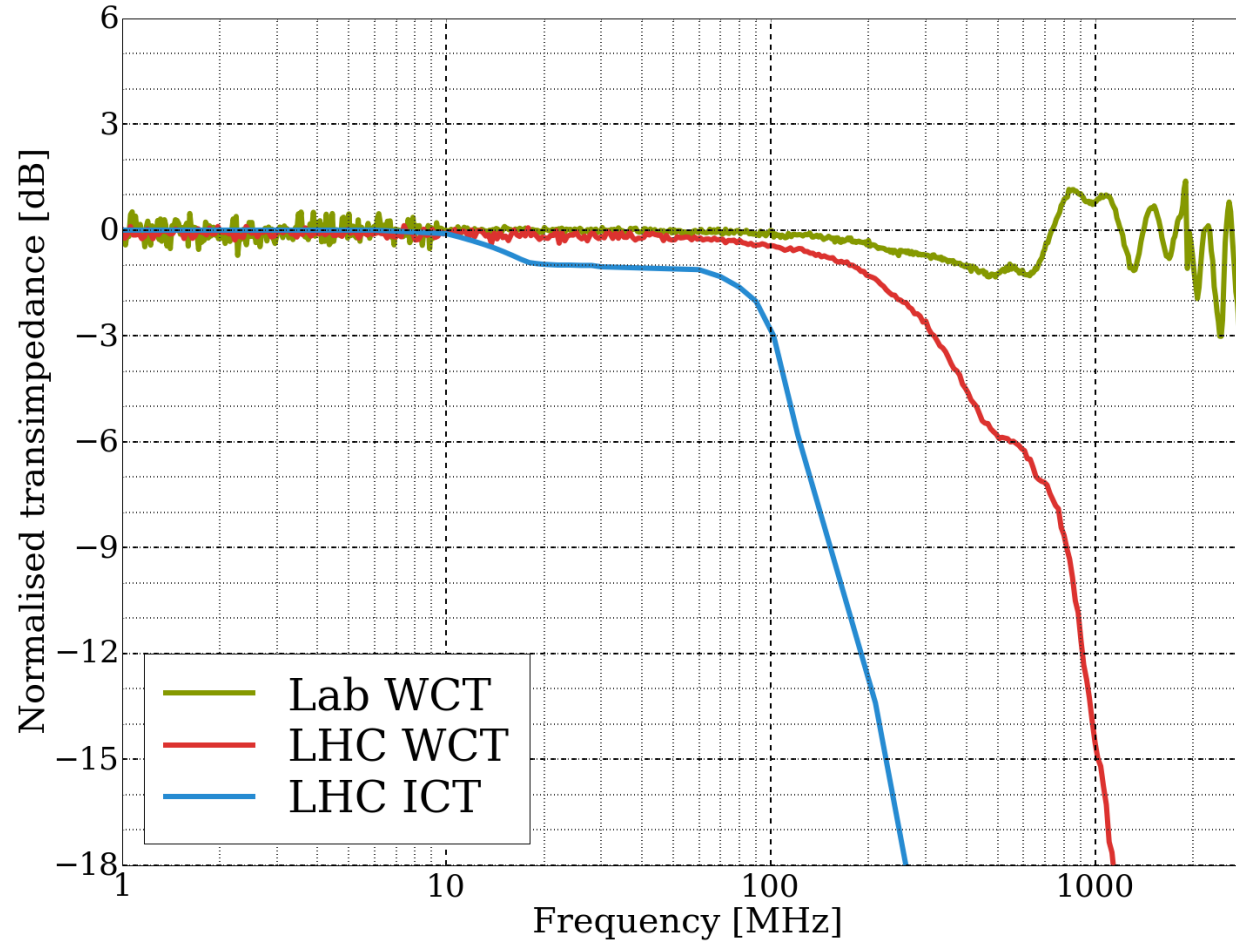
M. Krupa

BI Day 2016

14

Bandwidth

Test bench bandwidth measurements



Lab WCT:

- work in progress
- RF bypass
- 1.1 GHz filter
- low cut-off: 500 Hz

LHC WCT:

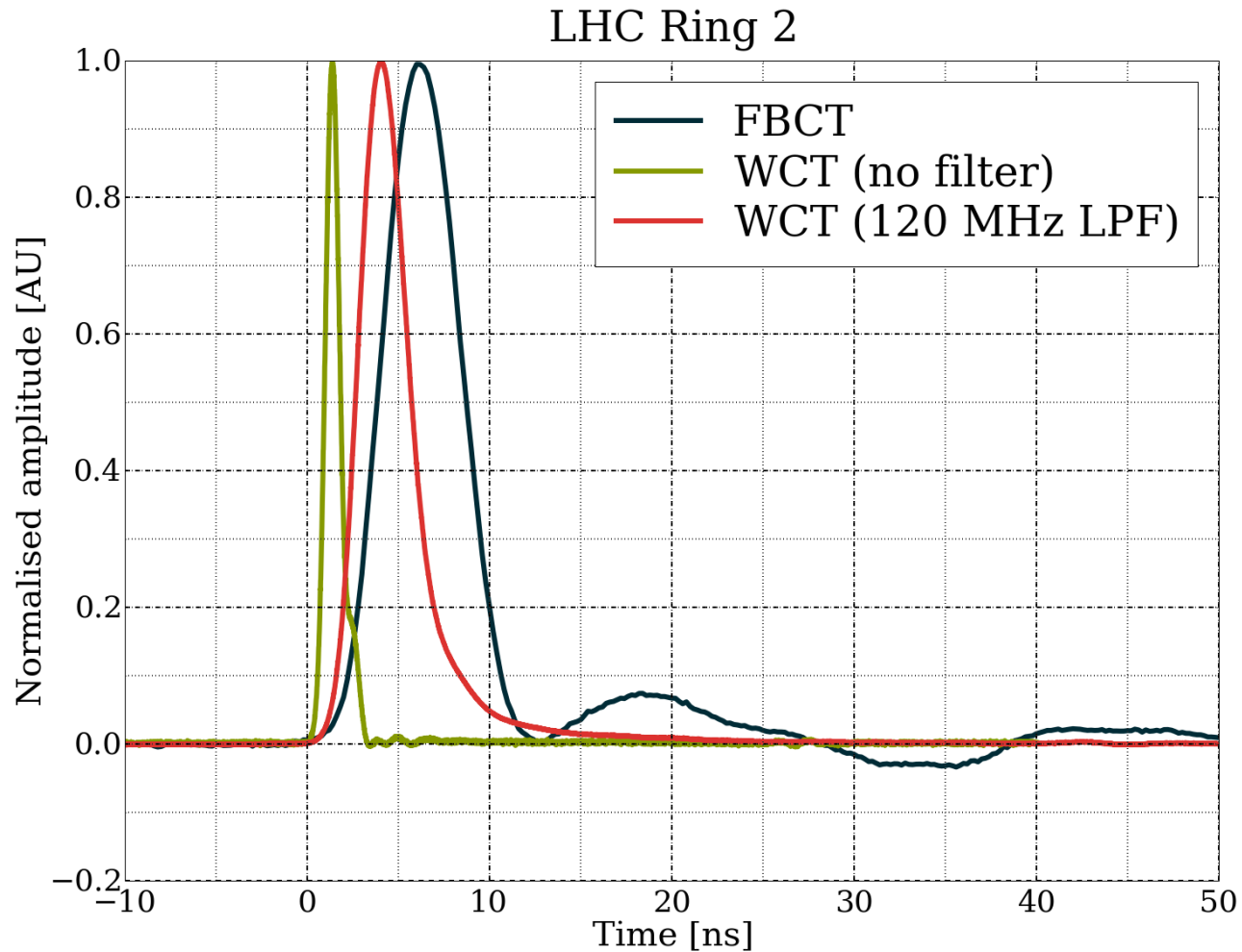
- RF bypass
- 400 MHz filter
- low cut-off: 500 Hz

LHC ICT:

- no filter
- low cut-off: 600 Hz

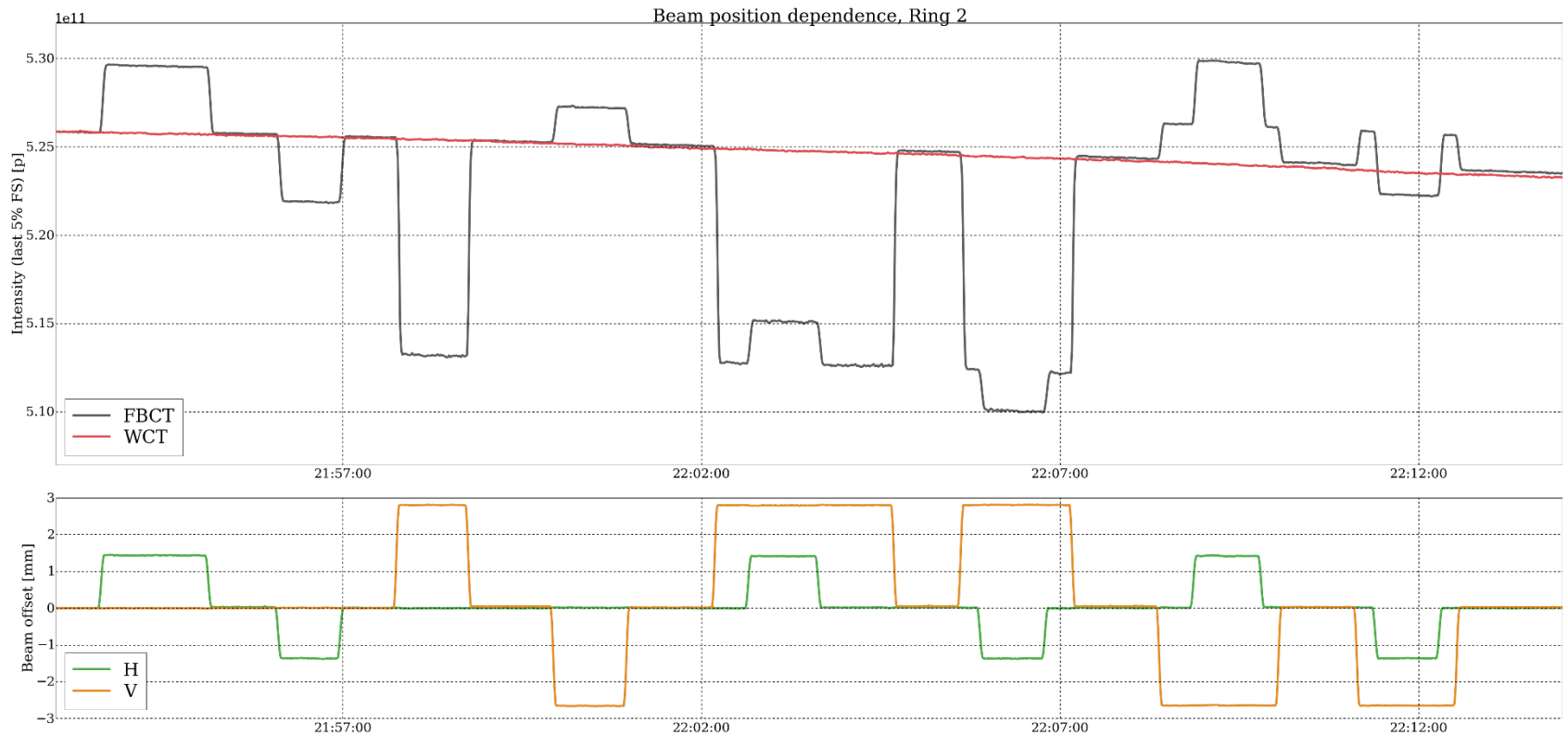
Test bench not very reliable
above 1 GHz

FBCT / WCT nominal bunch



Bunch position sensitivity MD

Dedicated MD on 20/07/2015



FBCT

$\Delta I/I \approx (0.3 - 0.7)\% / \text{mm}$

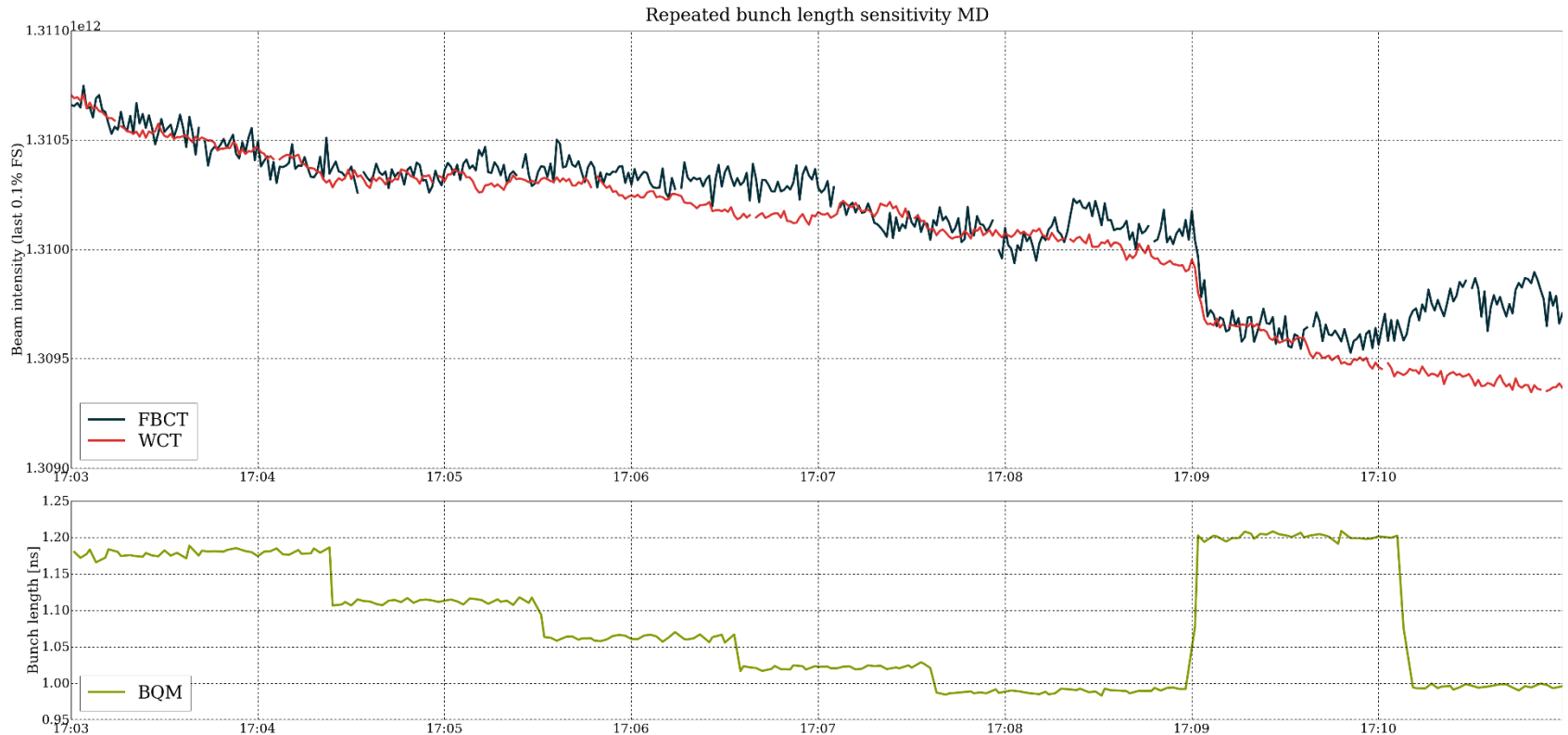
WCT

$\Delta I/I < 0.001\% / \text{mm}$

Not measurable

Bunch length sensitivity MD

Ad-hoc MD on 22/09/2015



FBCT

$\Delta I/I < 0.2\% / \text{ns}$

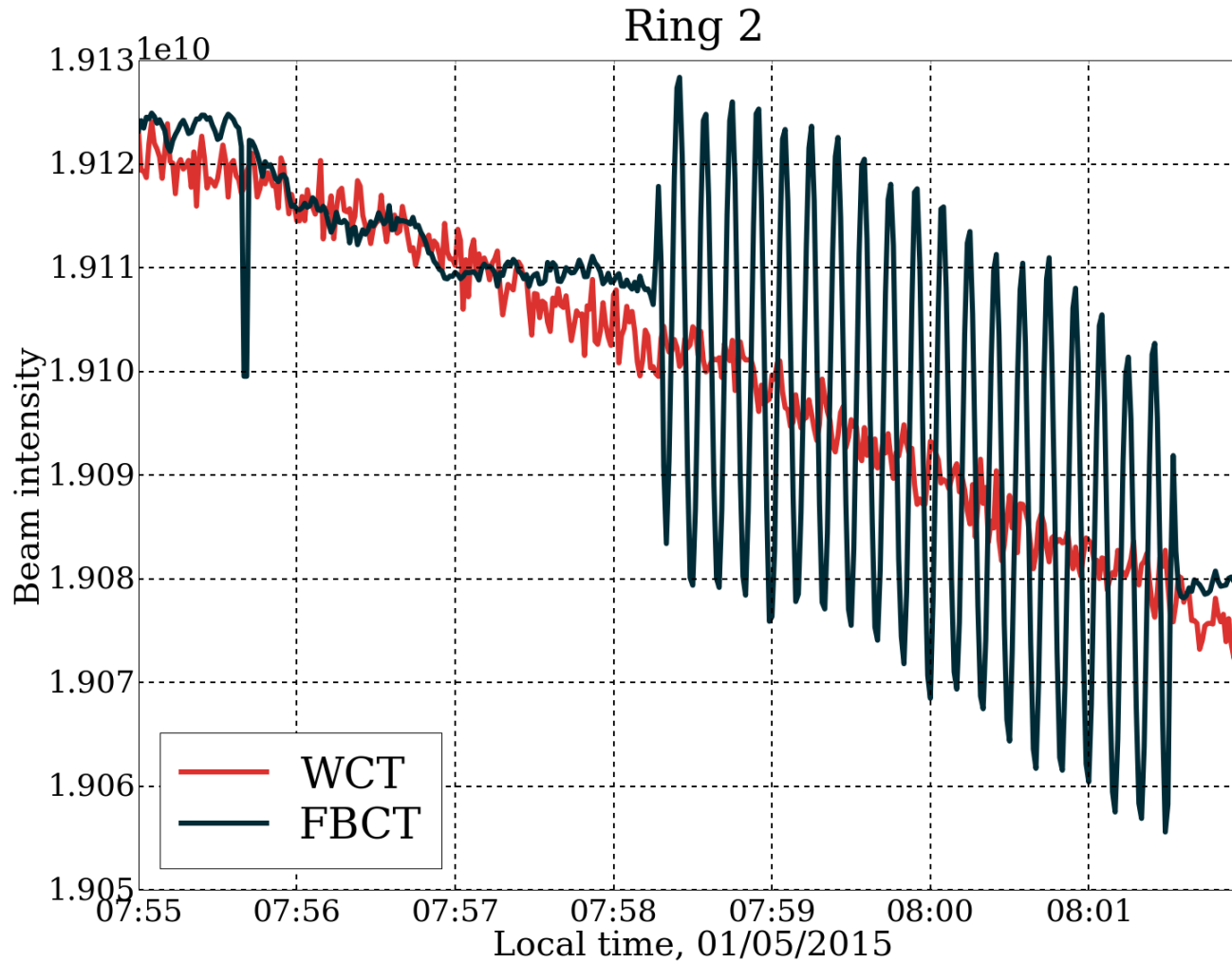
WCT

$\Delta I/I < 0.2\% / \text{ns}$



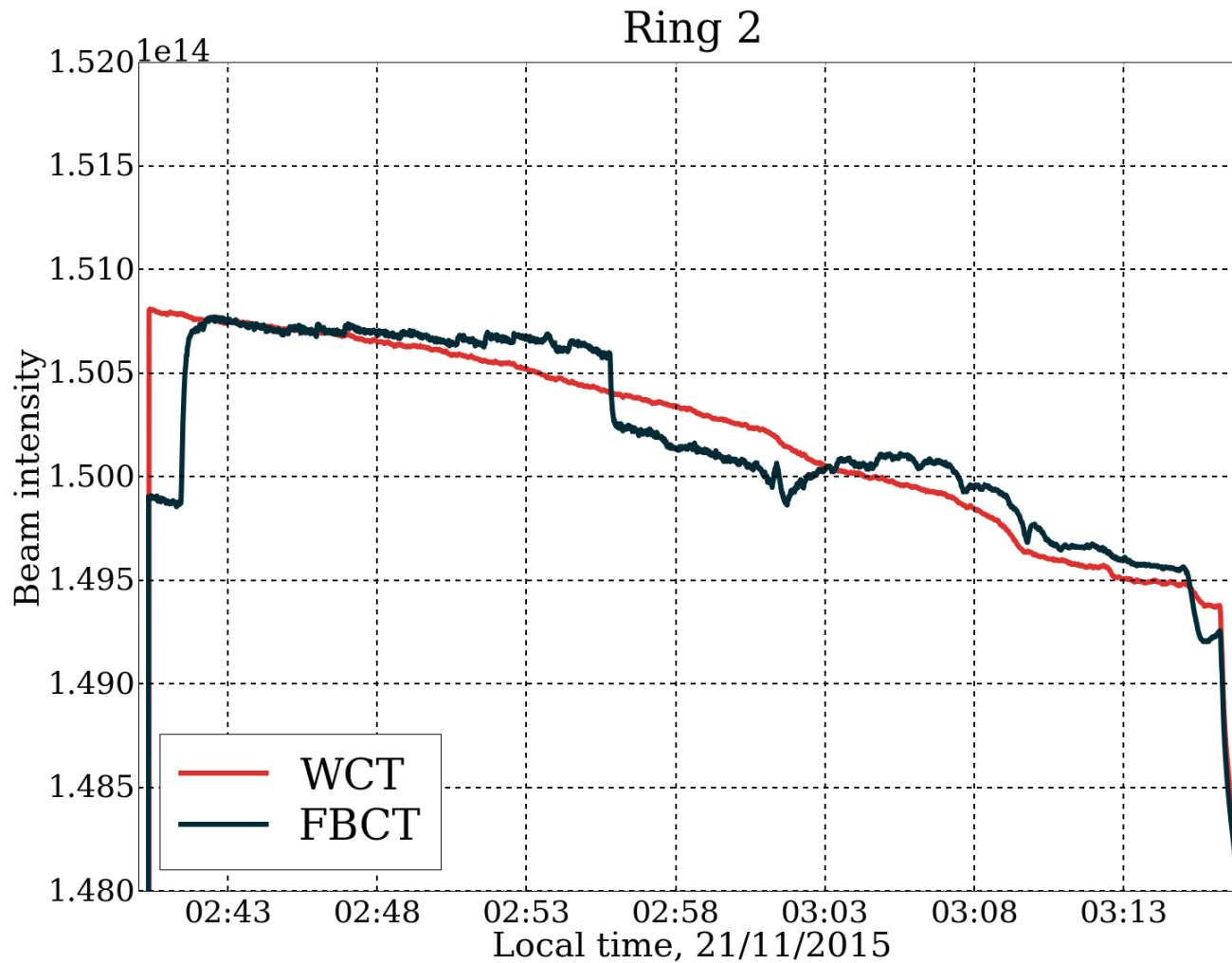
Radial modulation

Chromaticity measurement by modulation of the RF frequency.



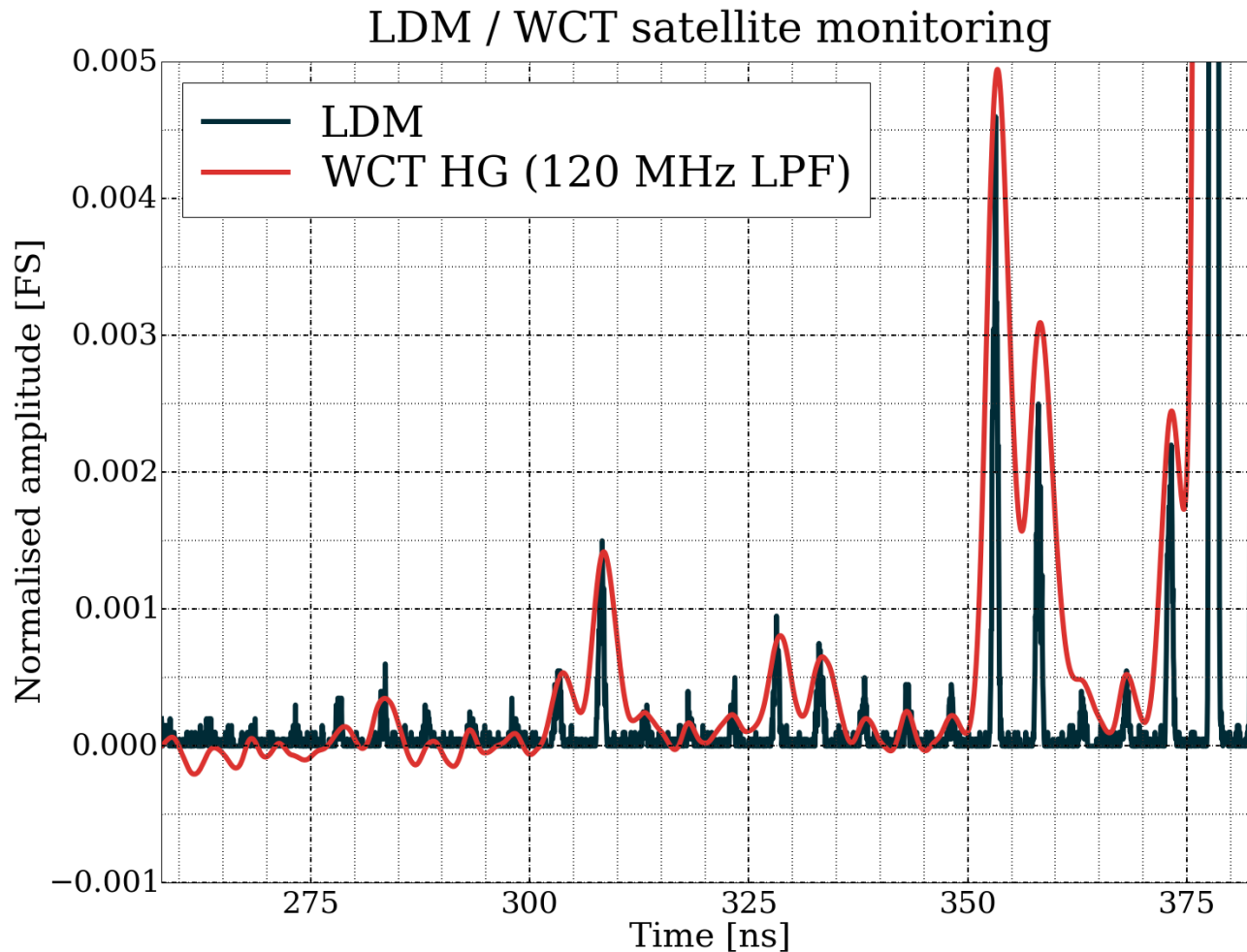
LHC fill: 3670
01/05/2015
Post LS1 commissioning
WCT was rescaled to overlap
with the FBCT

Orbit correction



LHC fill: 4640
21/05/2015
Proton physics
WCT was rescaled to overlap
with the FBCT

Satellite and ghost bunches



LDM:
single photon counting
over 3 million turns
(5 min)

WCT:
averaging on a 12-bit
oscilloscope over 500
turns (50 ms)

LHC fill: 4569
03/11/2015
Stable beams

Summary

- During 2015 performance of the first prototype WCT was evaluated with the LHC beams
- The WCT was shown to be insensitive to beam position and bunch length variations
- The WCT output pulse is shorter than the output pulse of the FBCT – measurements are easier
- During YETS 2015/2016 the two operational FBCTs were replaced with the WCTs
- The new WCTs are waiting for commissioning with beam

Thanks for the attention

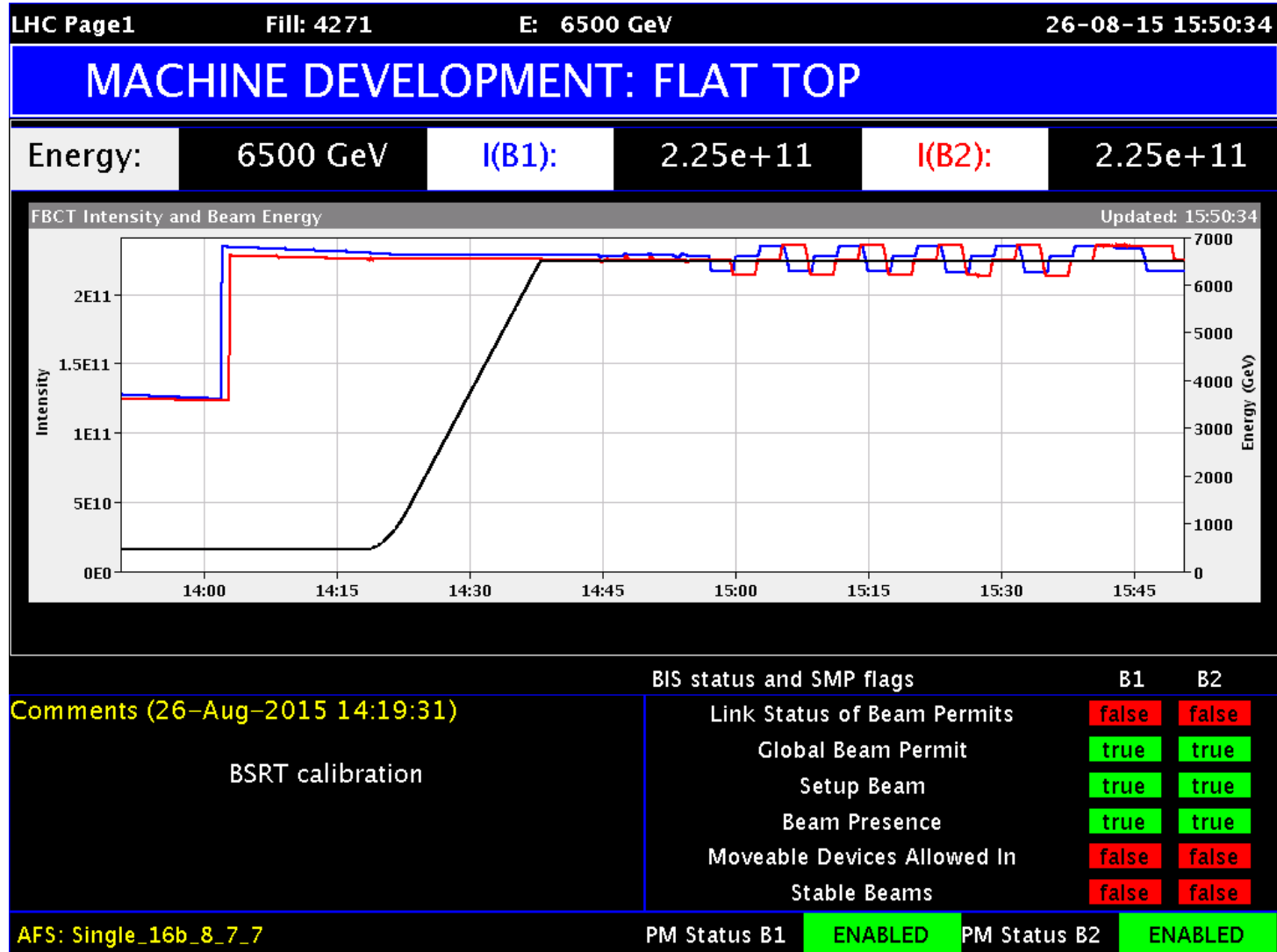
Questions?

Special thanks to:

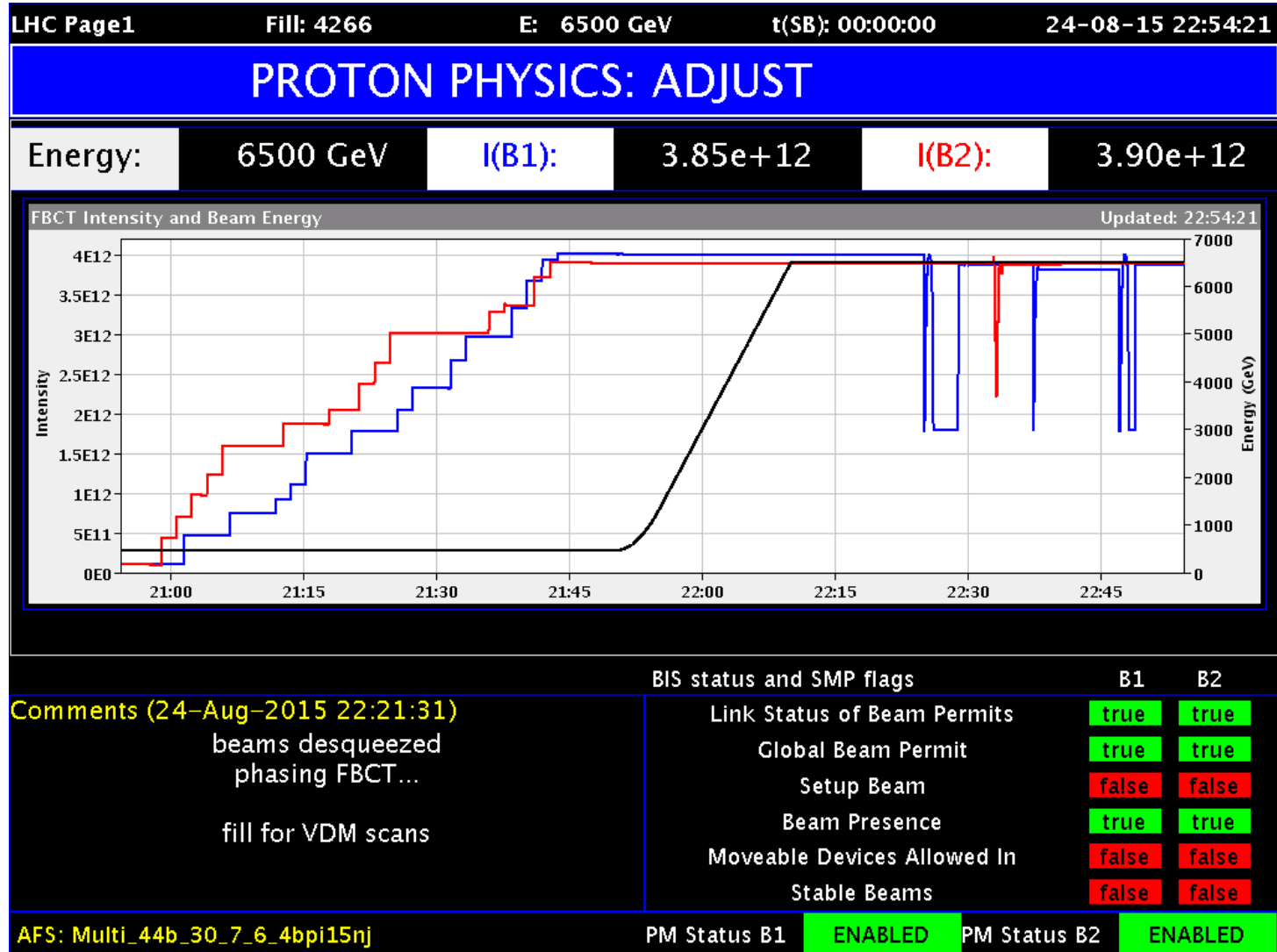
M. Gasior and S. Bart Pedersen, D. Belohrad, N. Chritin, F. Guillot-Vignot, J. Kral, T. Lefevre, P. Odier, L. Soby, BI Day organisation



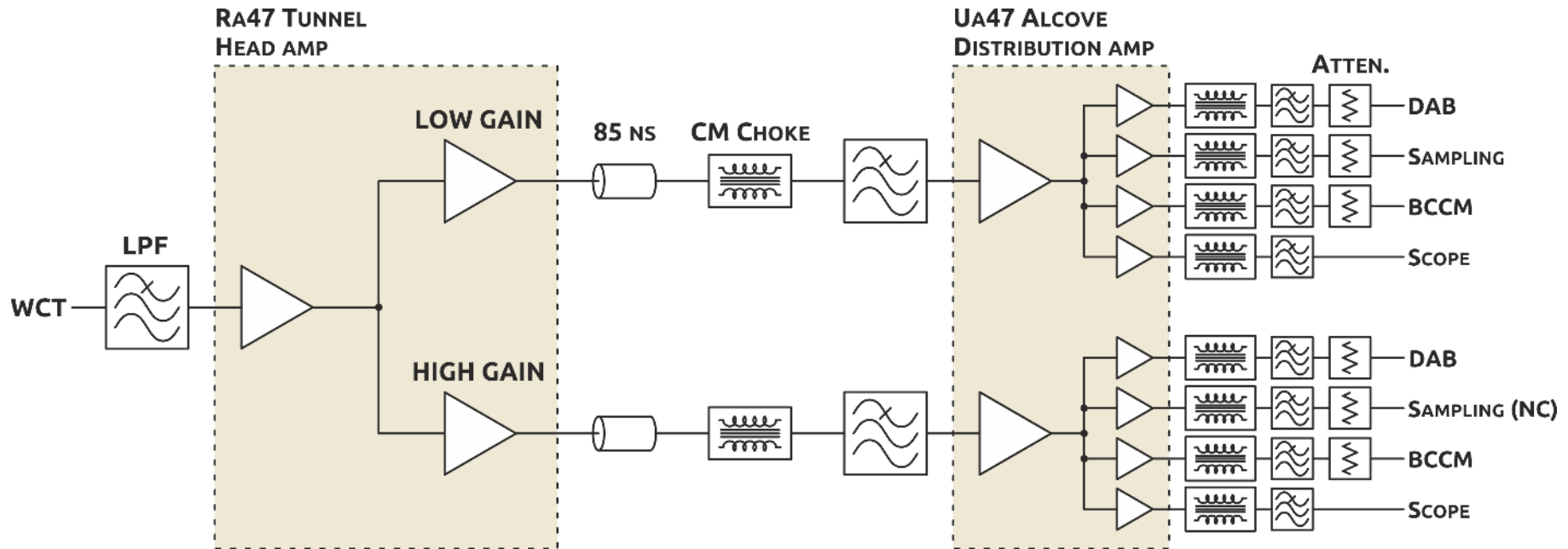
BSRT calibration



FBCT phasing

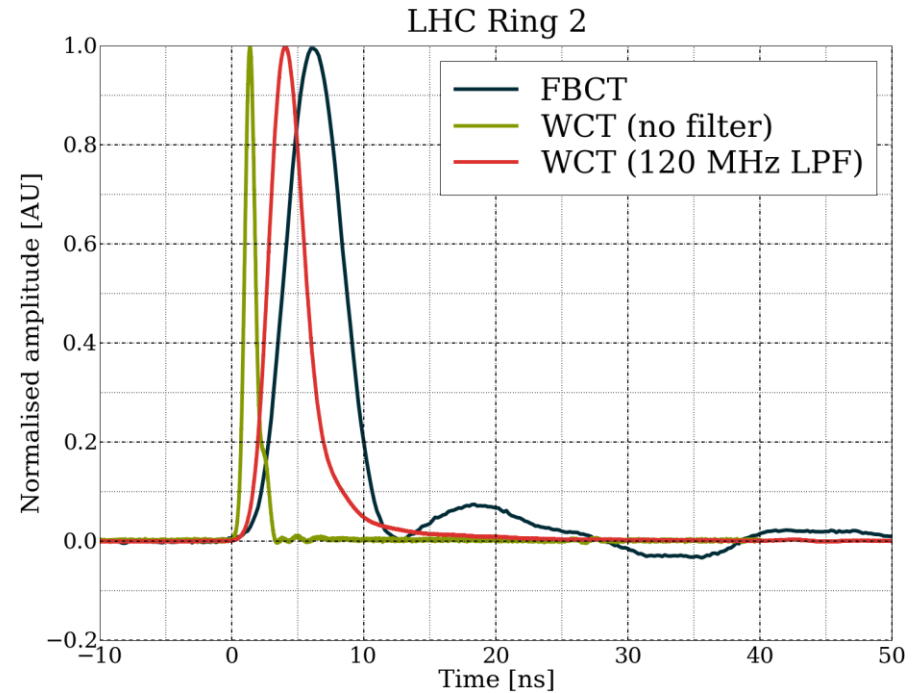
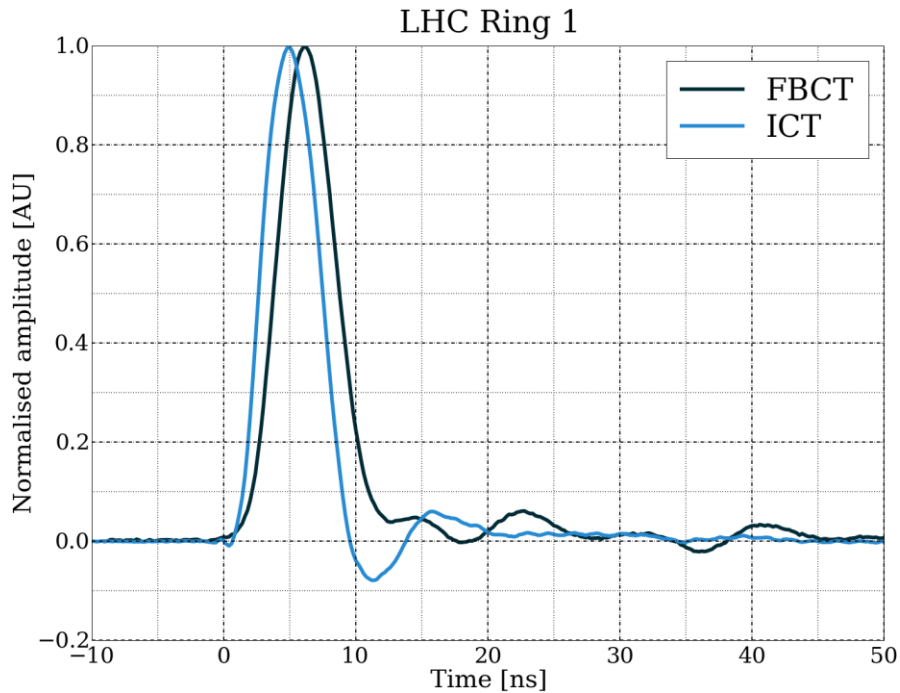


LHC WCT installation

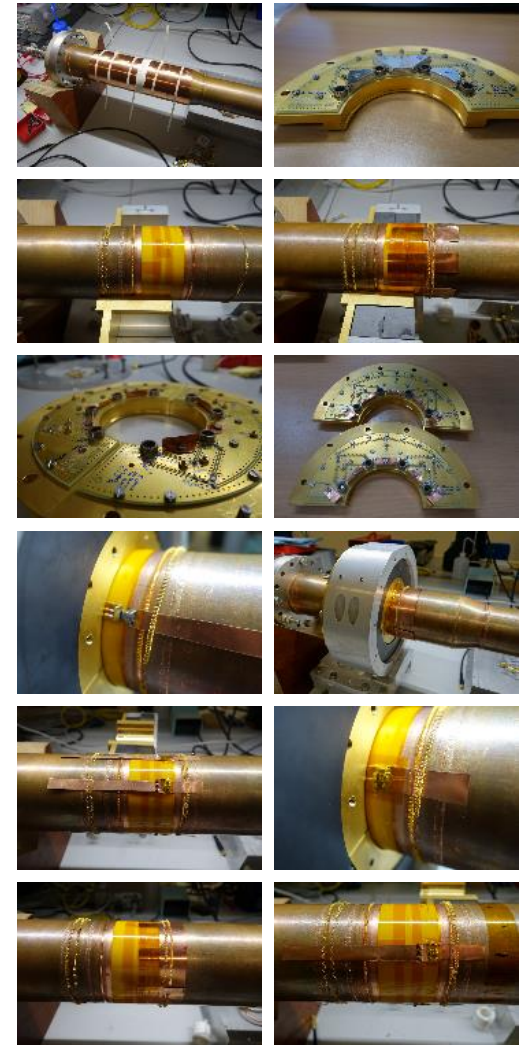
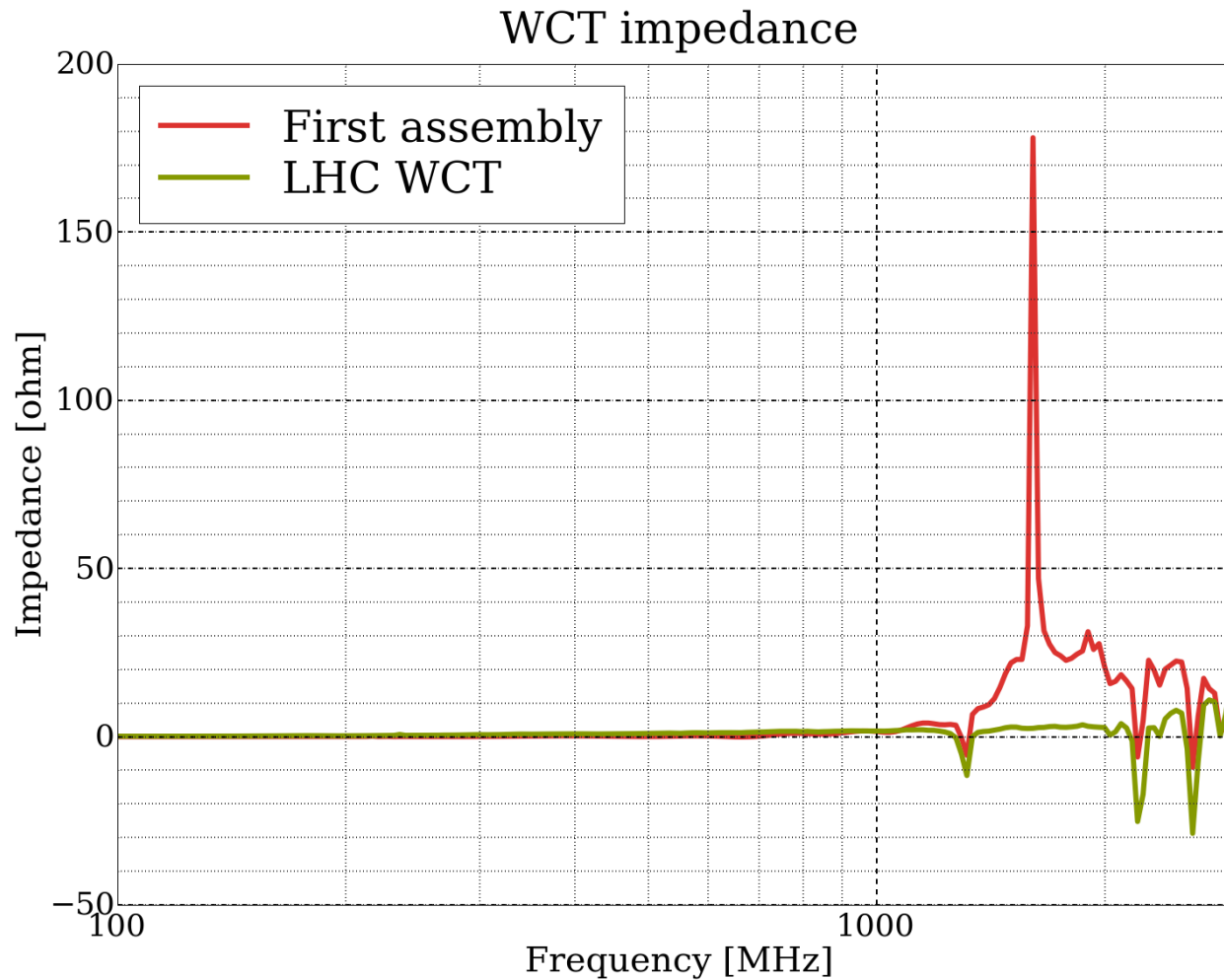


Active splitting – no cross-channel reflections
Different gain and bandwidth for each channel

FBCT / ICT / WCT nominal bunch

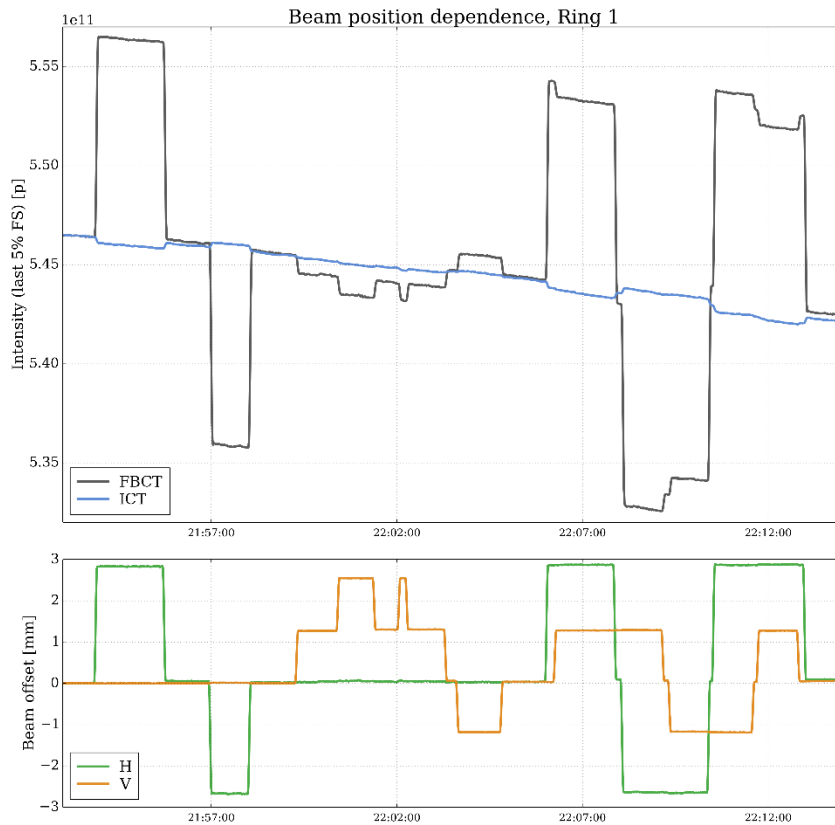


Impedance



Beam position sensitivity MD

Dedicated MD on 20/07/2015



FBCT

$$\Delta I/I \approx (0.3 - 0.7)\% \cdot \text{mm}^{-1}$$

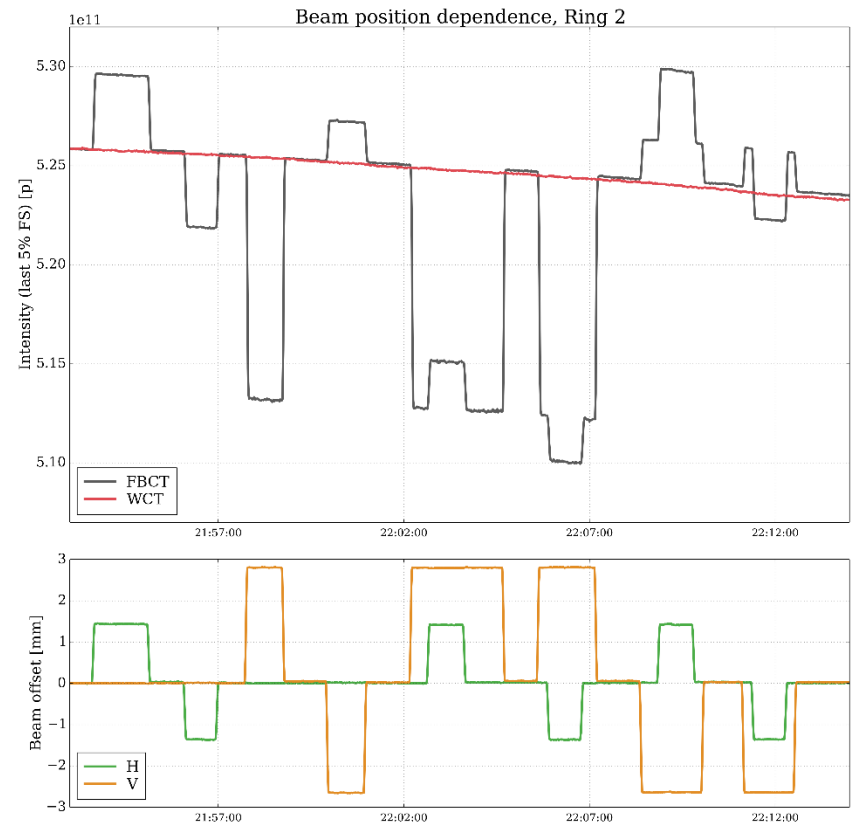
ICT

$$\Delta I/I \approx (0.01-0.02)\% \cdot \text{mm}^{-1}$$

WCT

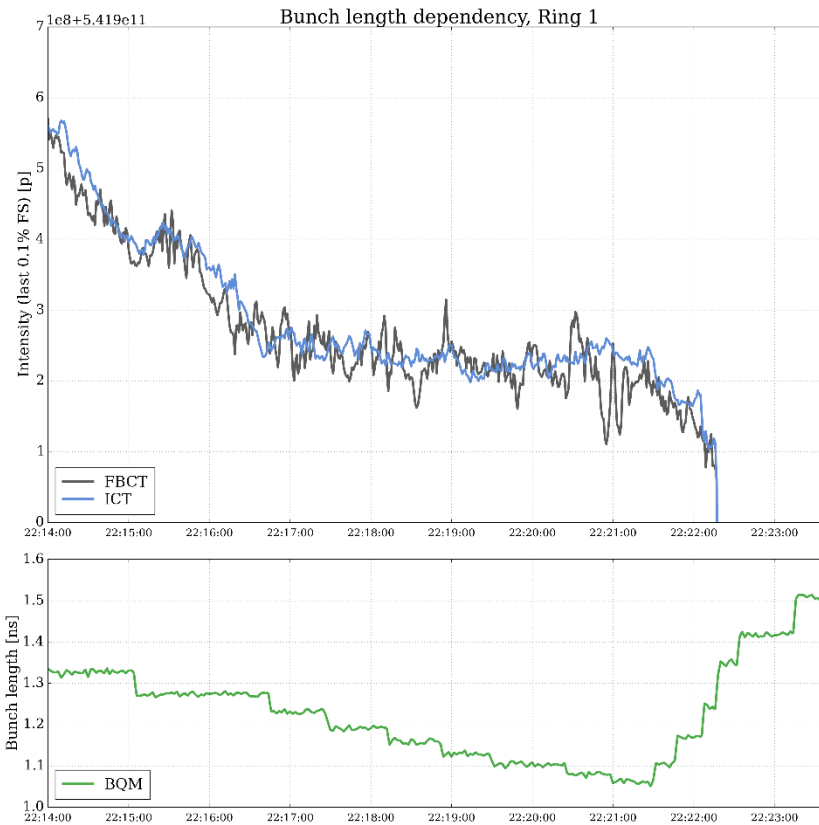
$$\Delta I/I < 0.001\% \cdot \text{mm}^{-1}$$

Not measurable



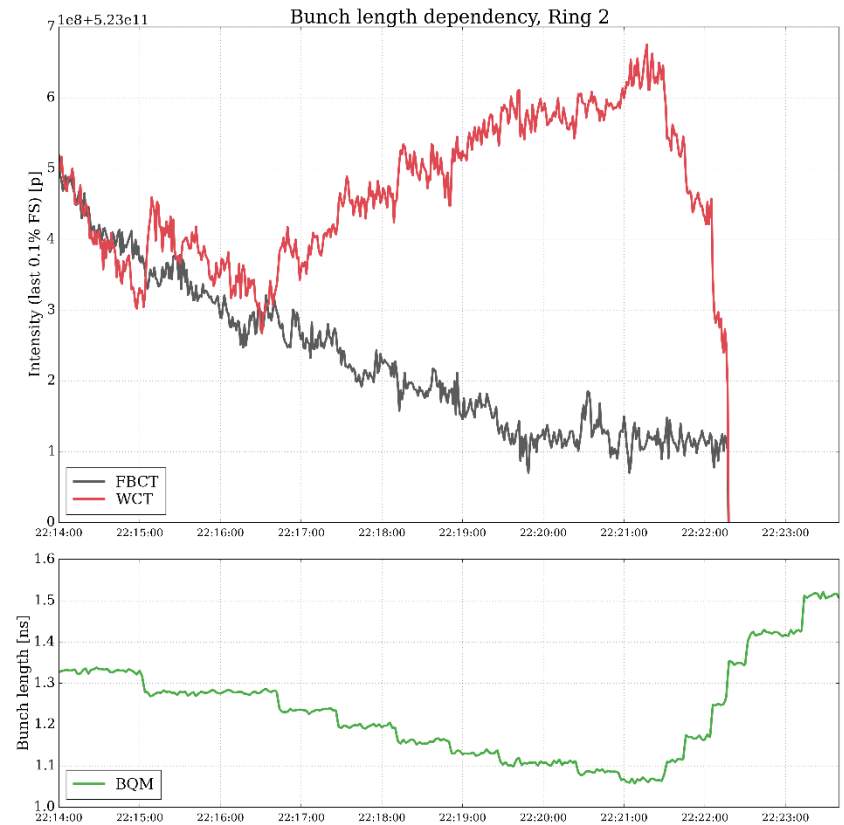
Bunch length sensitivity MD

Dedicated MD on 20/07/2015



FBCT
 $\Delta I/I < 0.2\% \cdot \text{ns}^{-1}$

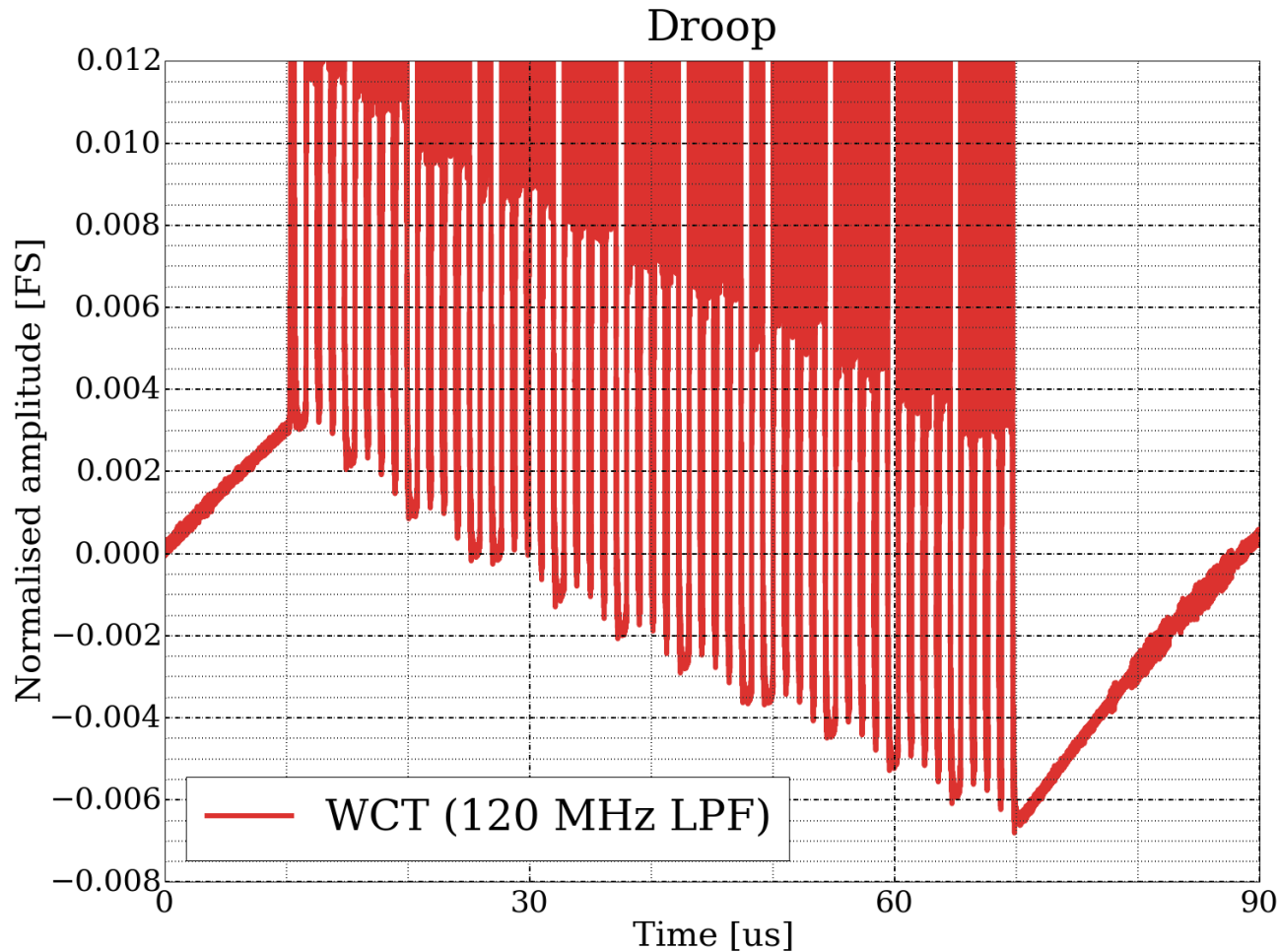
ICT
 $\Delta I/I < 0.2\% \cdot \text{ns}^{-1}$



WCT
 $\Delta I/I \approx 0.5\% \cdot \text{ns}^{-1}$
Not understood at the
time of the MD



Baseline droop and restoration

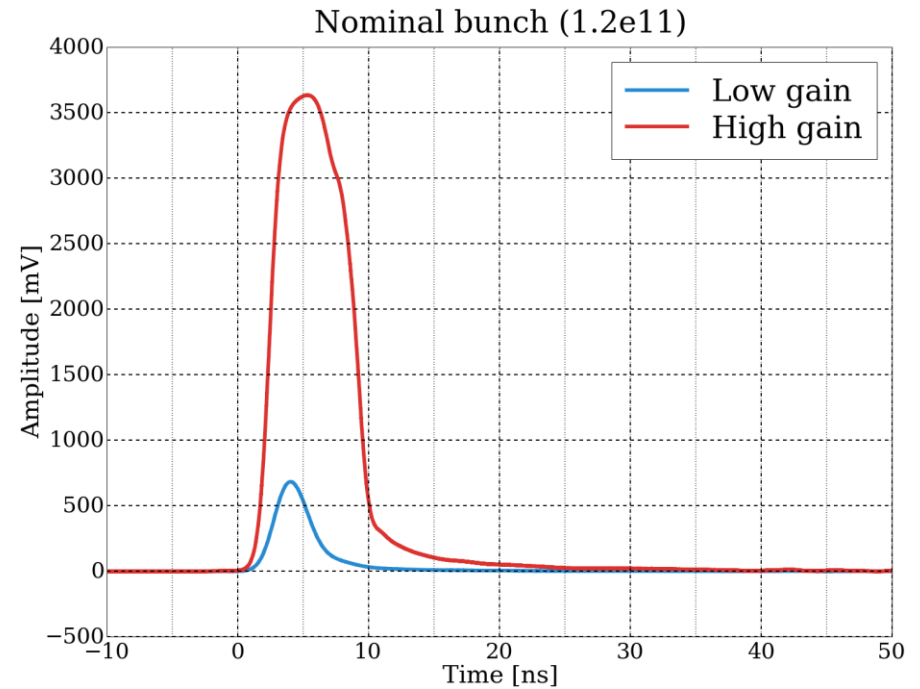
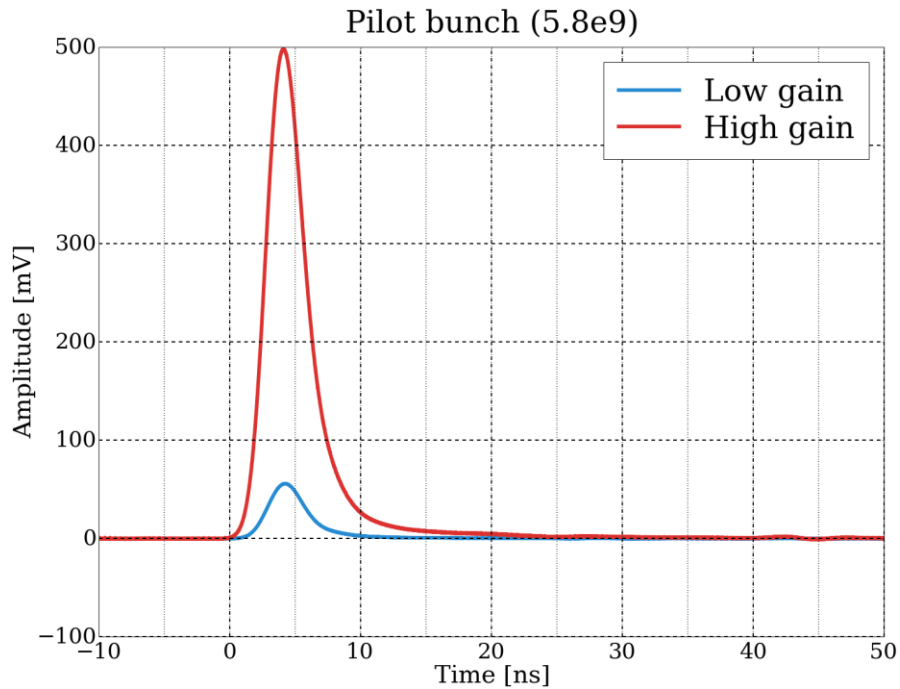


WCT:
low cut-off: 500 Hz

Beam:
1632 bunches
2.1e14 total intensity

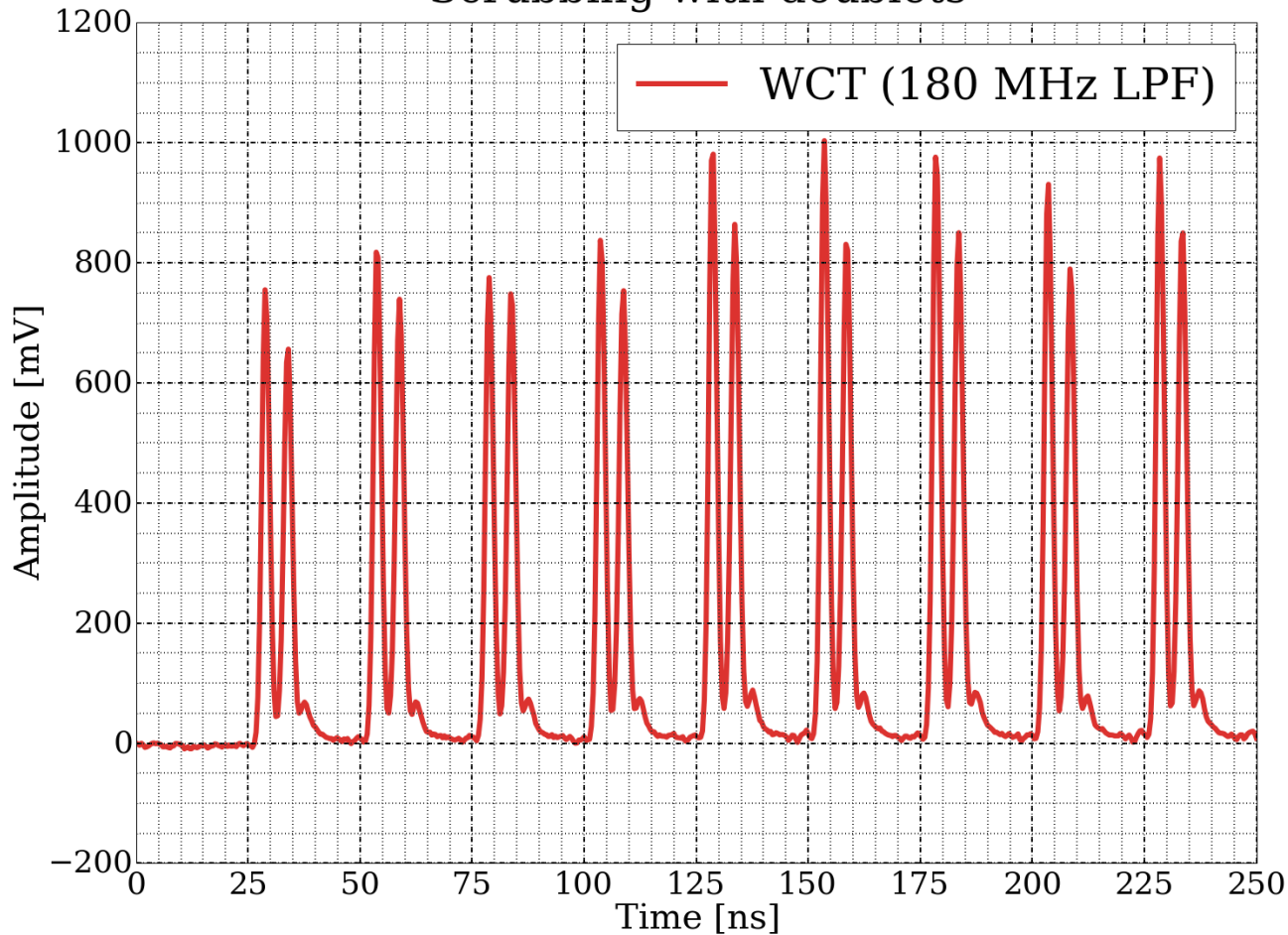
LHC fill: 4567
02/11/2015
Injection energy

WCT bunch response



Doublet bunches

Scrubbing with doublets

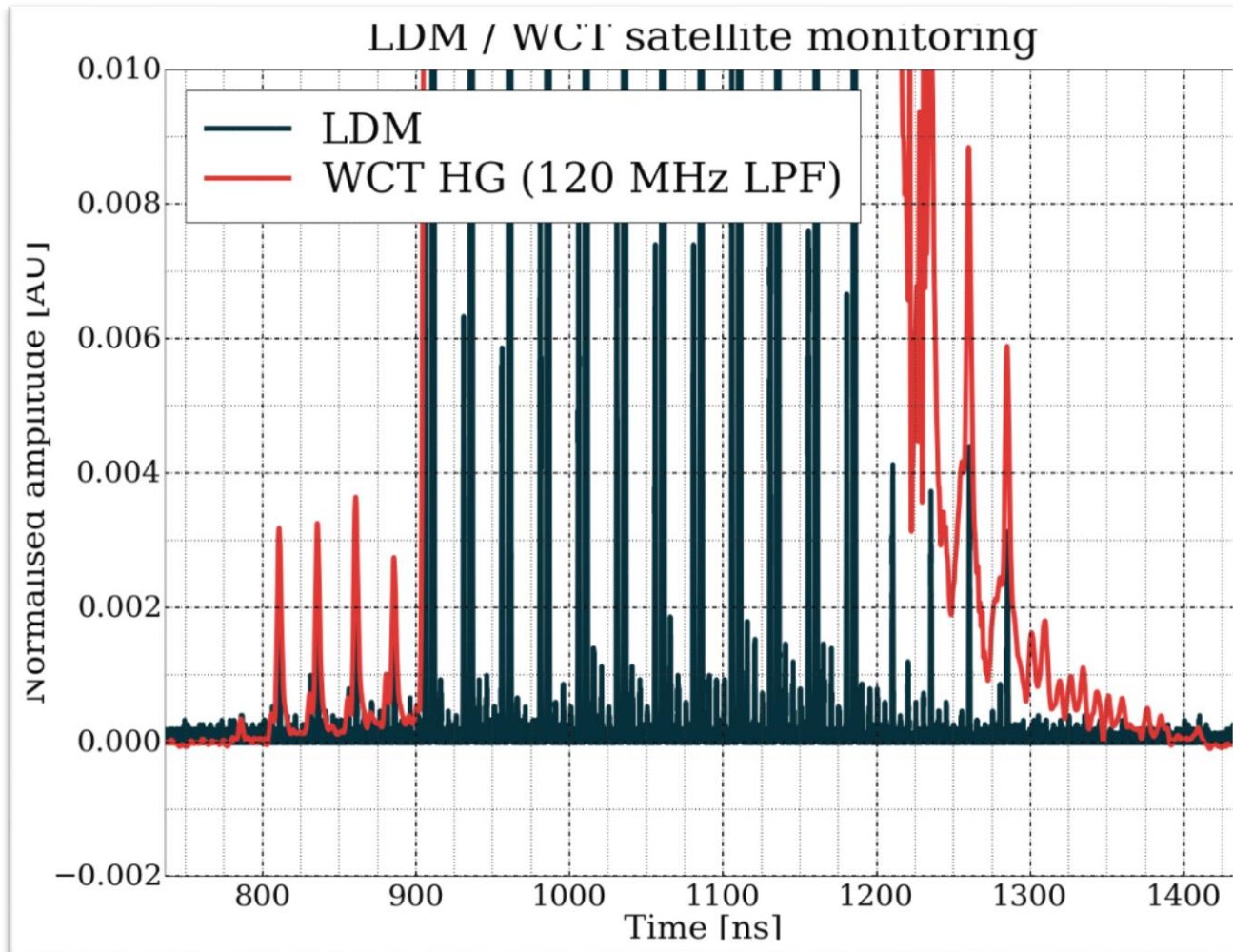


WCT:
averaging on a 12-bit
oscilloscope over 50
turns (5 ms)

Old amplifiers

LHC fill: 4064
26/07/2015
Scrubbing run

Satellite and ghost bunches



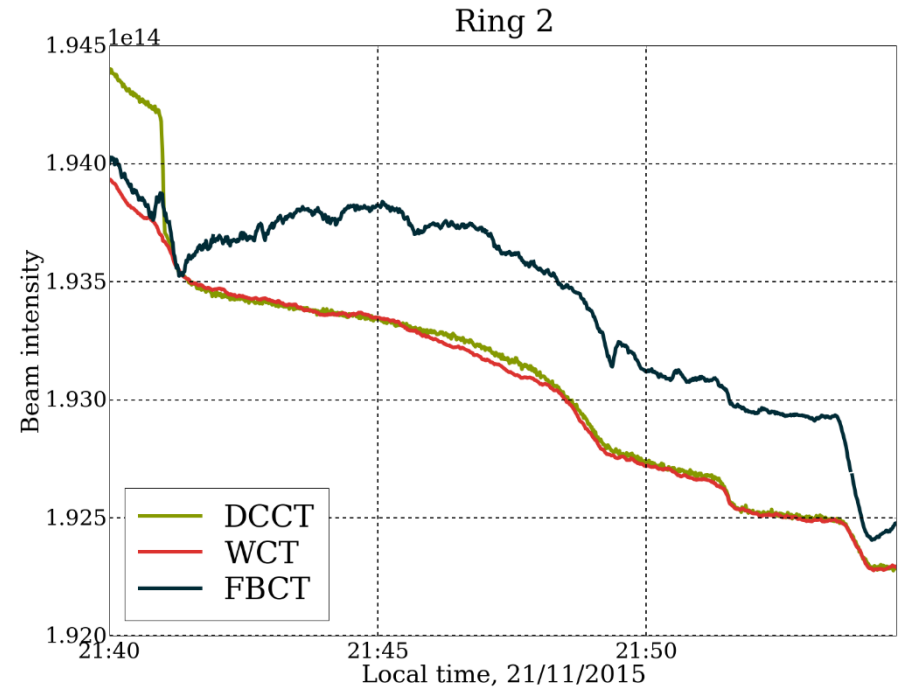
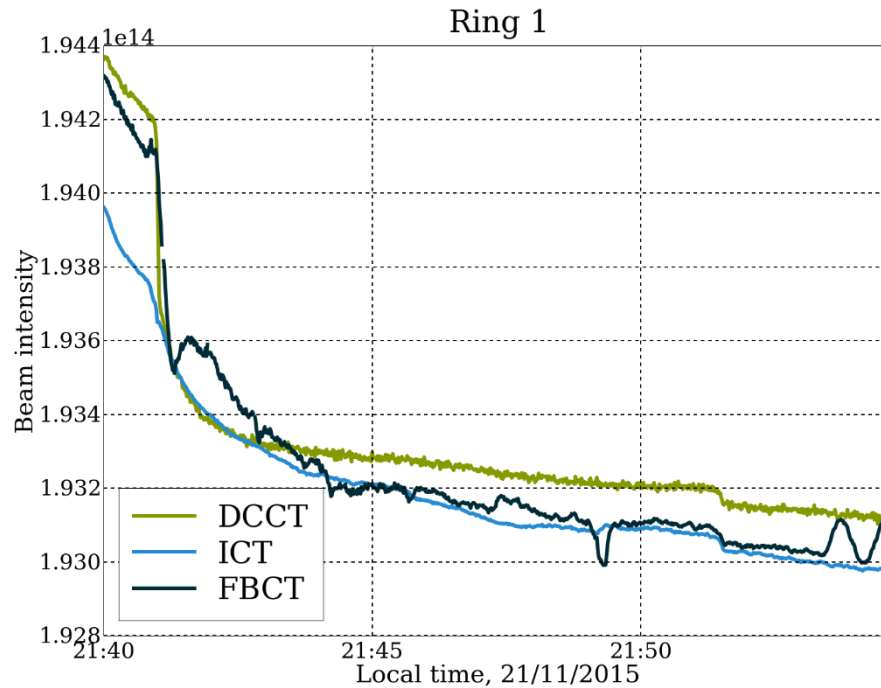
LDM:
single photon counting
over 3 million turns
(5 min)

WCT:
averaging on a 12-bit
oscilloscope over 500
turns (50 ms)

LHC fill: 4640
21/11/2015
Stable beams

Energy ramp

Bunch length reduction, RF change, orbit change, unbunched beam loss

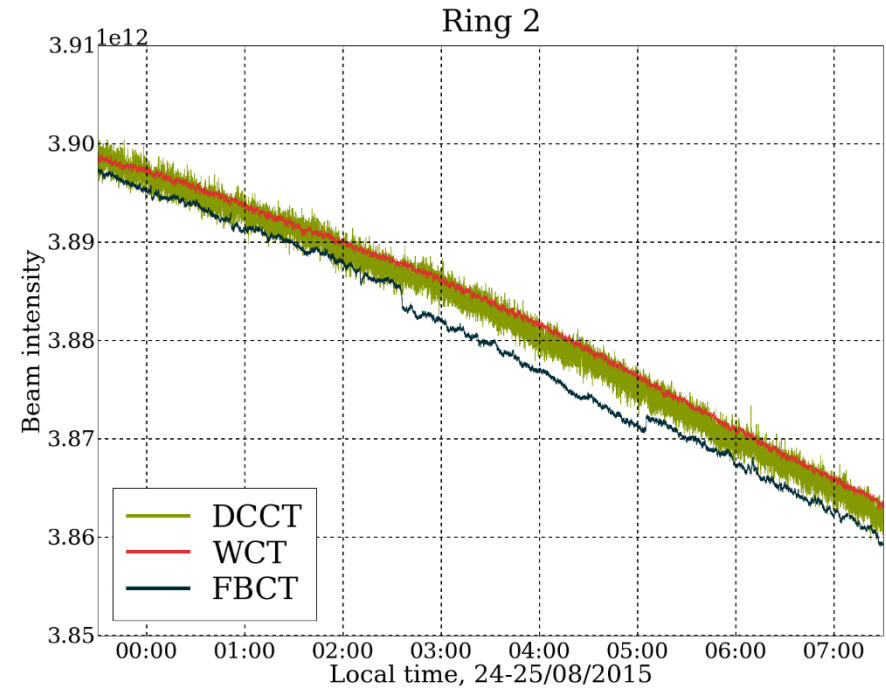
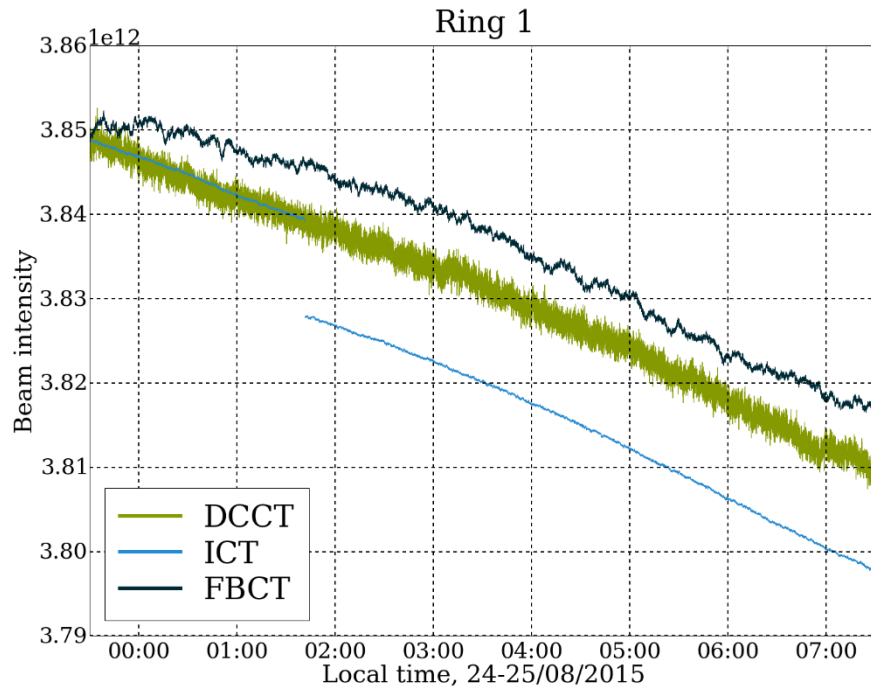


LHC fill: 4643 21/11/2015 Ramp
FBCT, ICT and WCT were rescaled to overlap with the DCCT



Van der Meer scans

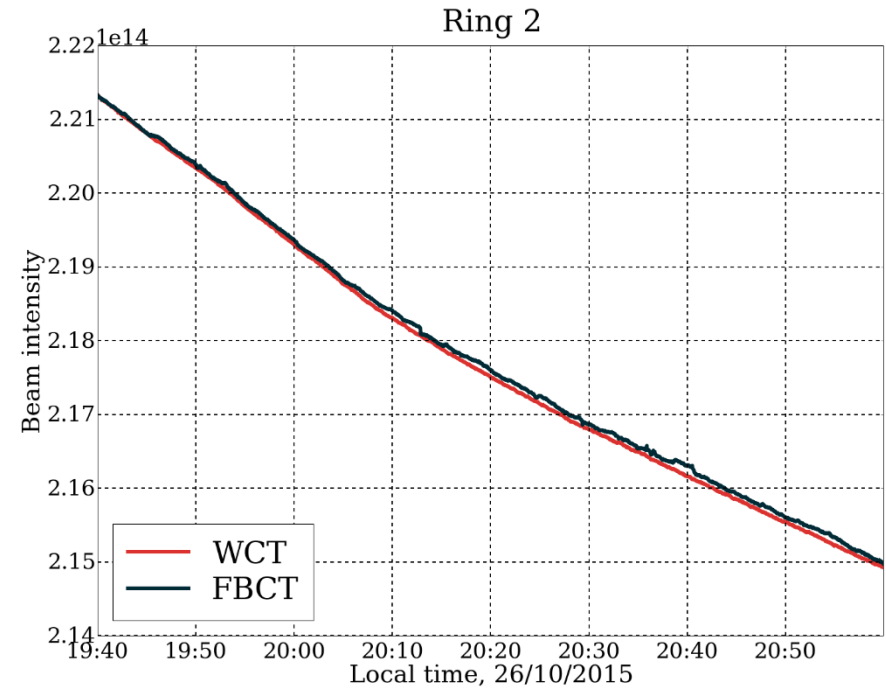
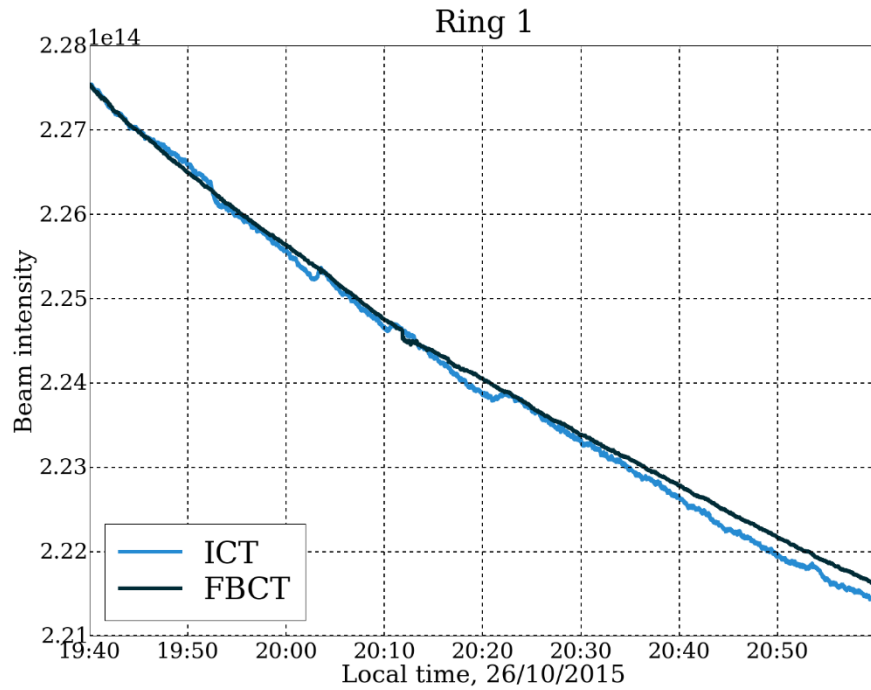
Absolute bunch-by-bunch measurements



LHC fill: 4538 24-25/08/2015 VDM scans
No rescaling, all plots as logged



(un)Stable beams



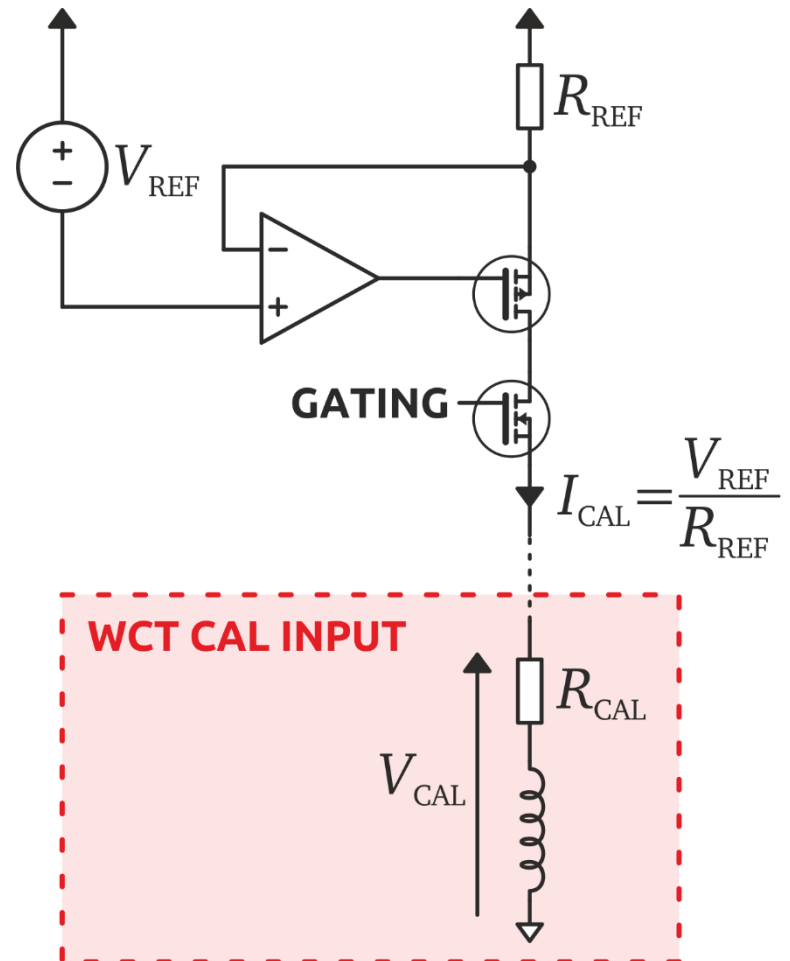
LHC fill: 4538 26/10/2015 Stable beams
ICT and WCT were rescaled to overlap with the FBCT



WCT calibration circuit

Current source:

- ~10 ppm shot-to-shot stability
- ~100 ppm accuracy
- ~5 μs switch-on time
- I_{CAL} limited by V_{CAL}
(~1.5 A for $R_{\text{CAL}} \sim 10\ \Omega$)
- $R_{\text{REF}}: 5\ \Omega \pm 0.01\%$
< 0.2 ppm/ $^{\circ}\text{C}$



WCT calibration circuit

Current measurement:

- Half-bridge principle
- Variable reference voltage source controlled by potentiometer and DAC (coarse / fine)
- R_{REF} : $10\ \Omega \pm 0.01\%$
 $< 0.2\ \text{ppm}/^\circ\text{C}$
- R_{HB} : $100\ \text{k}\Omega \pm 0.01\%$
 $< 1\ \text{ppm}/^\circ\text{C}$

