BCCM: commissioning experience and status

230^{th} Machine Protection Panel Meeting, 21/10/22

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SY-BI-IQ

BCCM (dI/dt) system

shared BPMs:

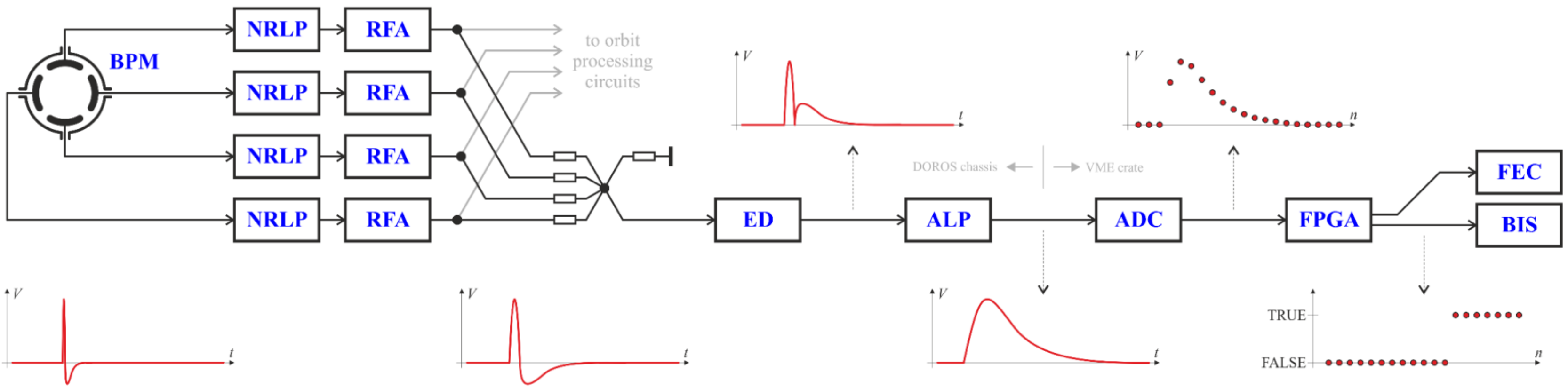
system A: BPMYA.5R4.B1+B2
system B: BPMYA.6R4.B1+B2

NRLP – Non-Reflective Low-Pass (≈ 80 MHz)

RFA – RF Amplifier

ED – Envelope Detector

ALP – Active Low-Pass (≈ 2 MHz)



- The system is based on BPM signals shared with the LHC beam position measurement system (passive RF splitters)
- The beam position dependence is removed by summing the four electrode signals
- Analog operations on the signals: low-pass filtering, amplification, envelope detection + rectification + level shifting, low pass filtering
- Digitization: 16-bit, 40 MHz sampling synchronous to the circulating beam (one revolution period is exactly 3564 ADC clocks).
  The 40 MHz ADC B1 and B2 clocks are derived from the 400 MHz RF frequencies received by optical fibers from the RF system.
- One turn “raw intensity” is a sum of ADC samples above a “beam presence threshold” minus “no beam offset”, selected from one turn 3564 samples
- One turn “raw dI/dt signal” is a difference of the one turn raw integrals from two consecutive turns
- “Raw dI/dt signals” in the five other integration windows are calculated as running sums of the one-turn “raw dI/dt signals”
- Every turn each of the “raw dI/dt signals” are compared to its corresponding raw dump threshold level and potential beam dump triggers are generated.
  All real-time calculations are done in the FPGA in an integer arithmetic.
- The BCCM absolute intensities in elementary charges are calculated by scaling the “raw intensities” using a “BCCM/BCT scaling factor”.
  The factor is a constant for each system and is obtained by matching the beam intensity evaluated by the BCCM to the corresponding BCT readings.
- The absolute dump thresholds in elementary charges are translated into “raw dump thresholds” using the same “BCCM/BCT scaling factor”.

BCCM (dI/dt) system

https://ibic2022.vrws.de/papers/wep06.pdf

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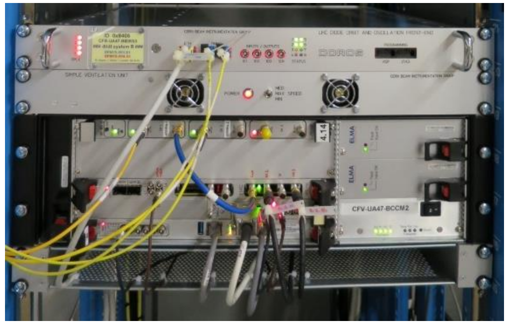

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AN LHC PROTECTION SYSTEM BASED ON FAST BEAM INTENSITY DROPS

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Abstract

The Large Hadron Collider (LHC) is protected against potentially dangerous beam losses by a distributed system based on some four thousand beam loss monitors. To provide an additional level of safety, the LHC has been equipped with a system to detect fast beam intensity drops and trigger a beam dump for potentially dangerous rates. This paper describes the architecture of the system and its signal processing, optimized to cope with dump thresholds in the order of 0.01% of the circulating beam intensity. The performance of the installed system is presented based upon beam measurements.

INTRODUCTION

The LHC Beam Charge Change Monitor (BCCM), also called the dI/dt system, is specified to trigger beam dumps for beam losses exceeding thresholds in six integration windows in two beam energy ranges, as summarised in Table 1. The integration window lengths, expressed in units of the LHC revolution period T_r (≈ 89 μs), have been chosen to correspond to integration periods of the Beam Loss Monitoring (BLM) system. The BCCM is required to operate for beam intensities from 5×10^9 elementary charges (q_0) for a single pilot bunch, up to $6\times10^{14}\,q_0$ for ≈ 2800 physics beam bunches of $2.1\times10^{11}\,q_0$, resulting in the intensity dynamic range of ≈ 10^5 and the beam signal dynamic range of ≈ 40. Thus, the smallest beam dump threshold of $0.5\times10^{11}\,q_0$ for the longest integration window in the high energy range corresponds to an intensity change of ≈ 0.008%. Such challenging beam dump threshold levels and the required operational reliability have proved to be very difficult to satisfy at the same time. The BCCM system design described in this paper was preceded by a few prototypes and the experience gained at each stage contributed to the improving performance.

The initial prototype of the system was based on signals from Fast Beam Current Transformers (FBCTs), with

Table 1: BCCM Beam Dump Threshold Levels in $10^{11}\,q_0$

Beam energy	Integration window lengths in T_r units					
	1	4	16	64	225	1125
< 0.5 TeV	6	6	6	6	6	6
≥ 0.5 TeV	3	3	3	3	2	0.5

The most fundamental change in the new BCCM is the source of the beam signal, where the WCT has been replaced by the sum signal of a beam position monitor (BPM). This way the development of the BCCM became independent of the beam intensity measurement system, which is critical for the LHC operation and therefore any changes to its parameters were very difficult. This was previously posing serious limitations during the development of the BCCM. The BPM also provides larger signals than the WCM, which contributes to the improved noise performance of the present system.

The signal processing now used in the BCCM provides a few improvements and simplifications:

- the fast beam signals are rectified, allowing the system bandwidth to be strongly limited by low-pass filters already before the ADC;
- in consequence, the beam synchronous ADC sampling could be lowered to 40 MHz, allowing to use high signal-to-noise ratio ADCs and facilitating the digital signal processing;
- the idea of one revolution digital delay line was introduced: the beam signal changes are calculated as plain differences of one revolution period integrals, allowing simple, reliable and efficient signal processing;
- the ADC sampling phase does not need to be adjusted to the beam signal, increasing the simplicity and robustness of the system operation.

The new LHC BCCM system based on the mentioned features is described in the following sections and its performance illustrated with beam measurements.

Dump threshold tables

OLD

Window [turn]	1	4	16	64	225	1125
< 0.5	6	6	6	6	6	6
≥ 0.5	3	3	3	3	2	0.5
Energy [TeV]	**Losses [1e11]**					

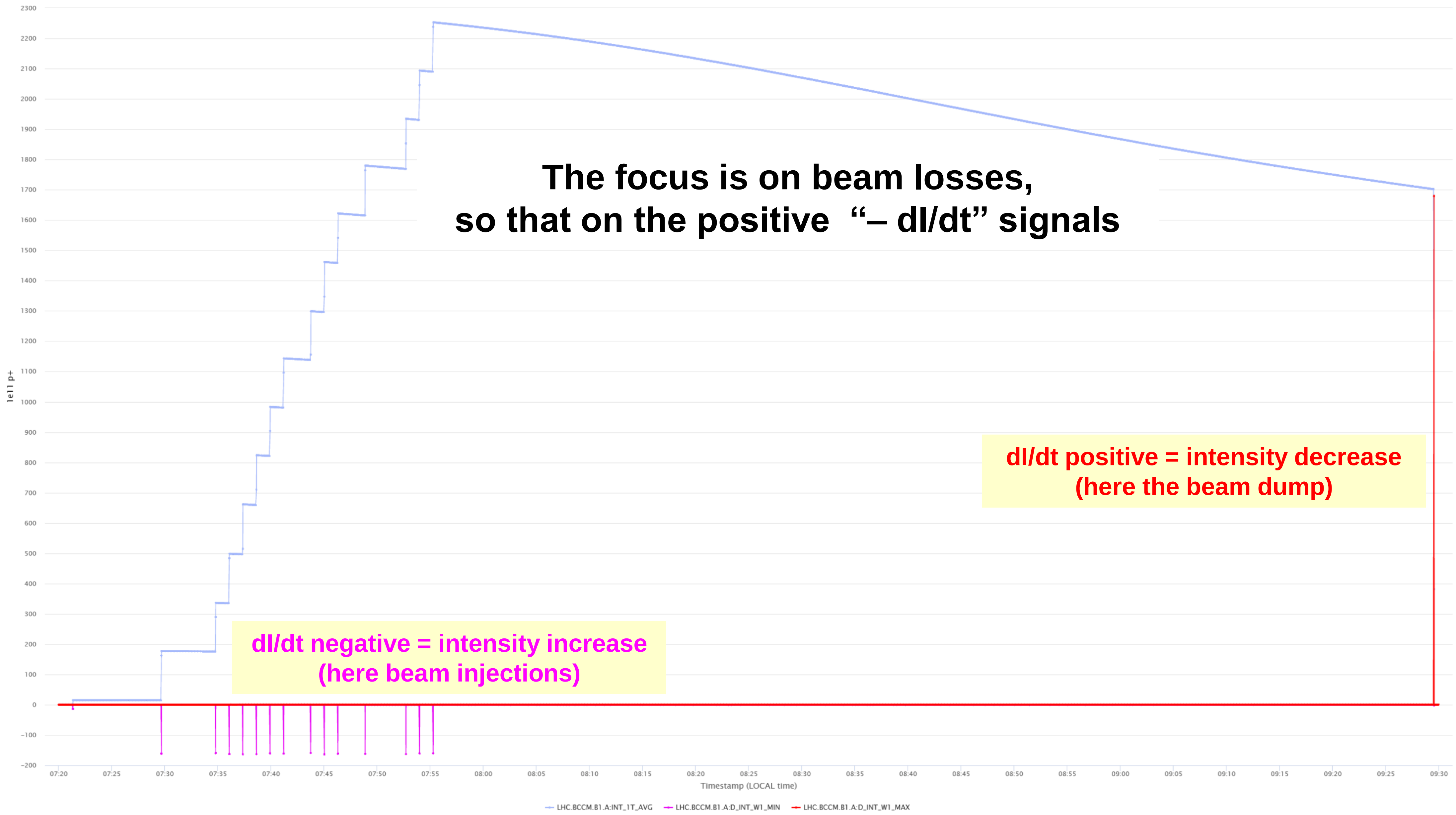
Window [turn]	1	4	16	64	225	1125
< 0.5	1	1	1	1	1	1
≥ 0.5	0.5	0.5	0.5	0.5	0.3	0.08
Energy [TeV]	**Relative losses [‰] (FS = 6e14)**					

NEW

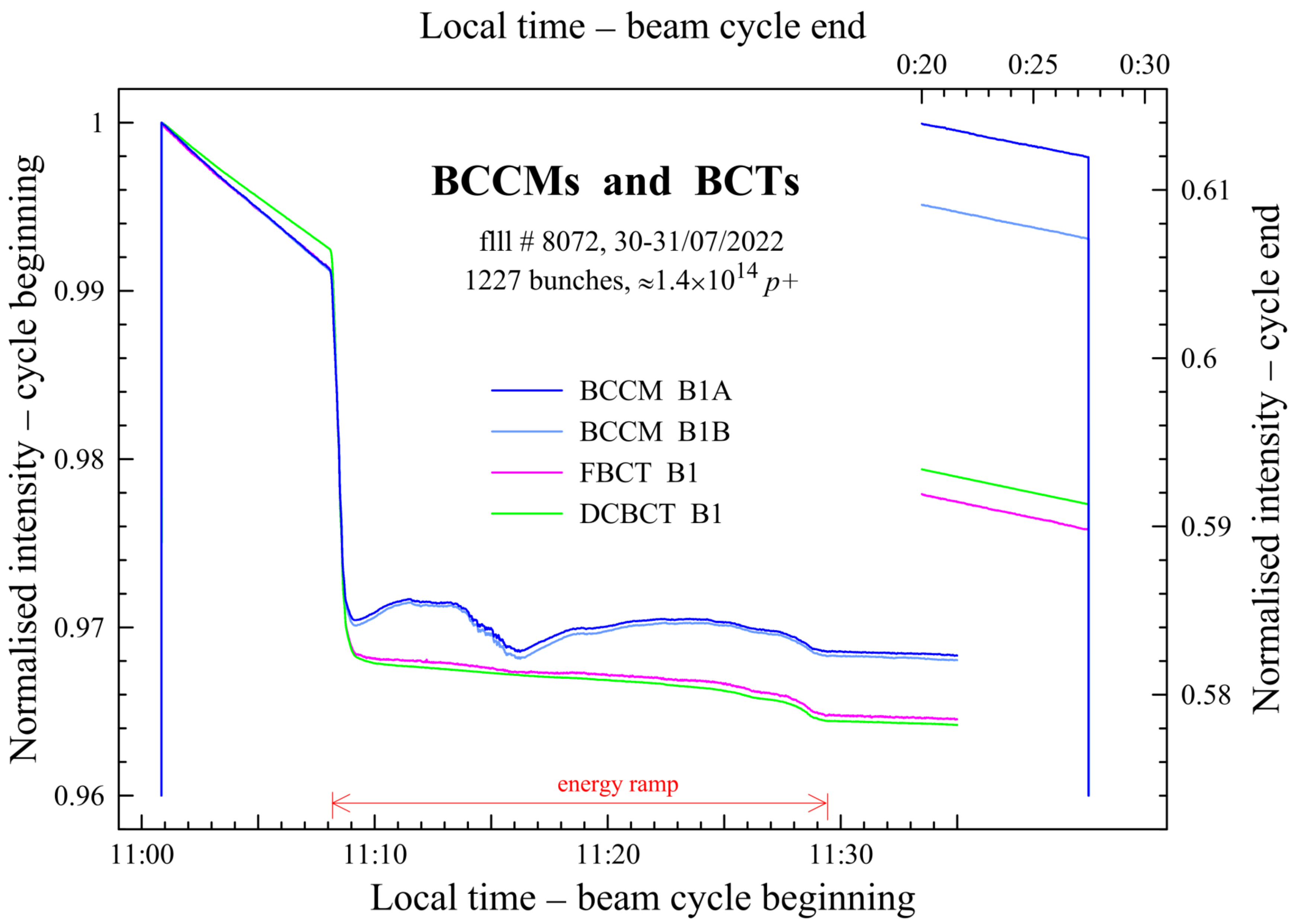
Window [turn]	1	4	16	64	225	1125
< 0.5	6	6	6	6	6	**10**
≥ 0.5	3	3	3	3	**5**	**10**
Energy [TeV]	**Losses [1e11]**					

Window [turn]	1	4	16	64	225	1125
< 0.5	1	1	1	1	1	**1.7**
≥ 0.5	0.5	0.5	0.5	0.5	**0.8**	**1.7**
Energy [TeV]	**Relative losses [‰] (FS = 6e14)**					

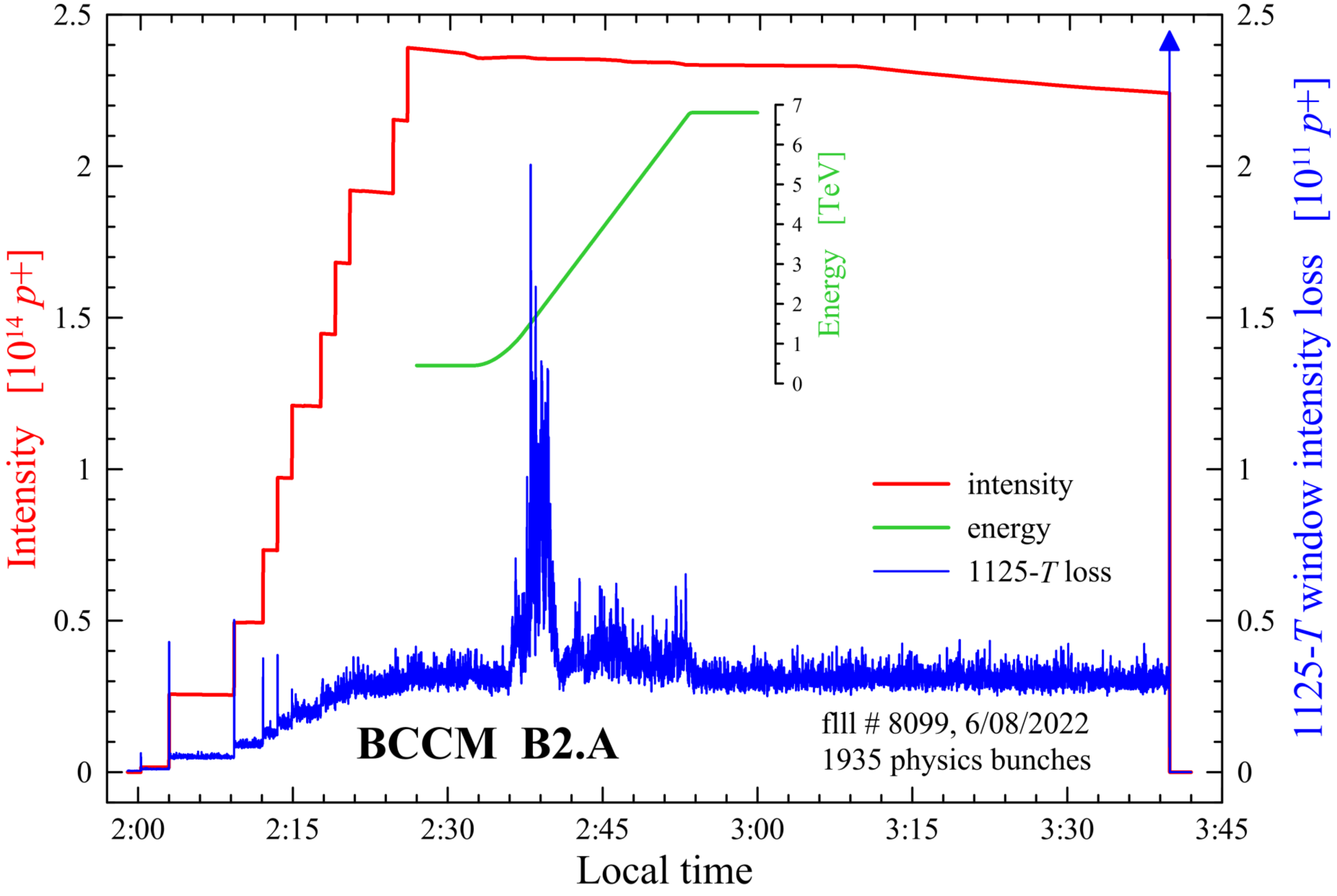
BCCM (– dI/dt) polarity convention



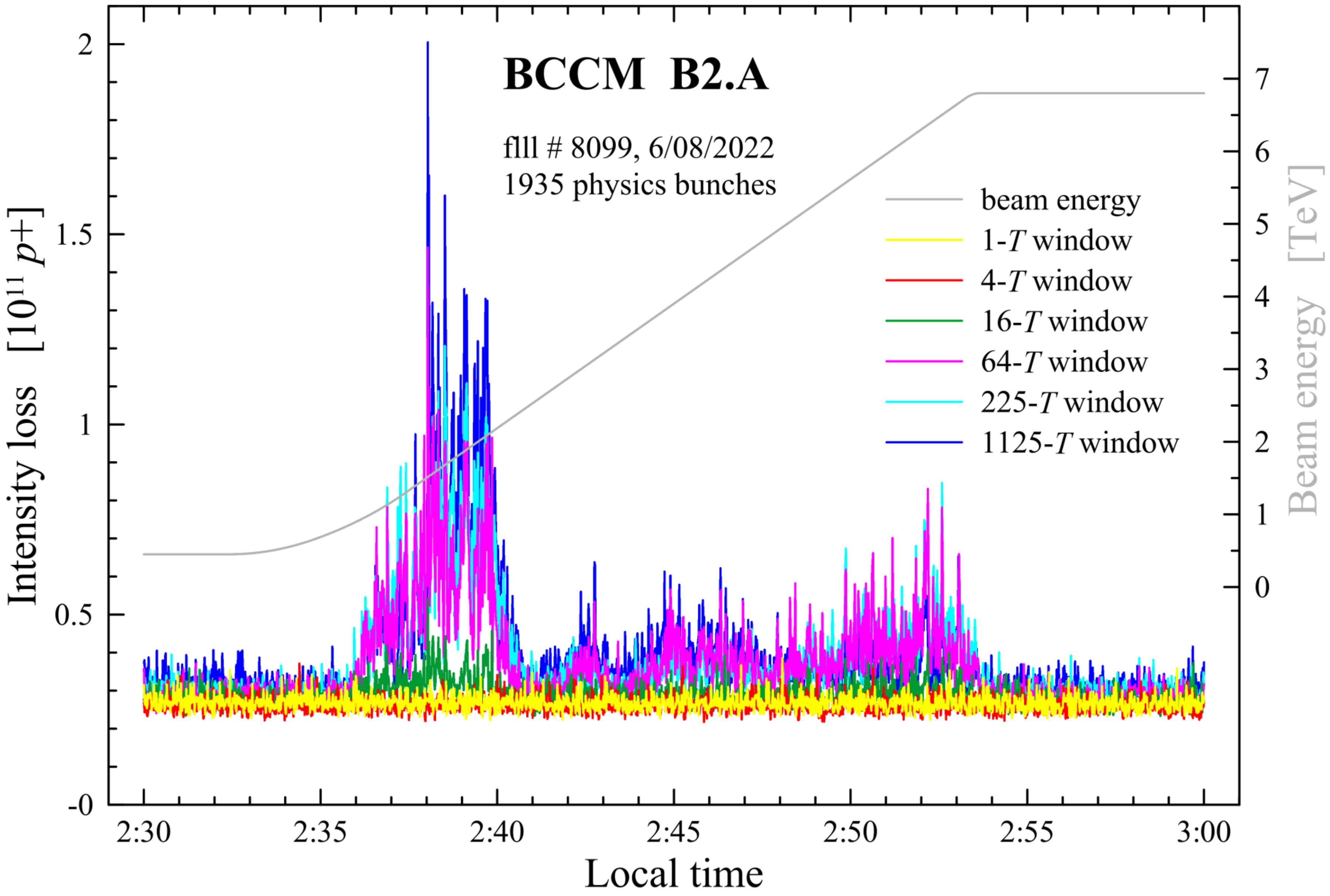
BCCM operation – absolute intensity measurement



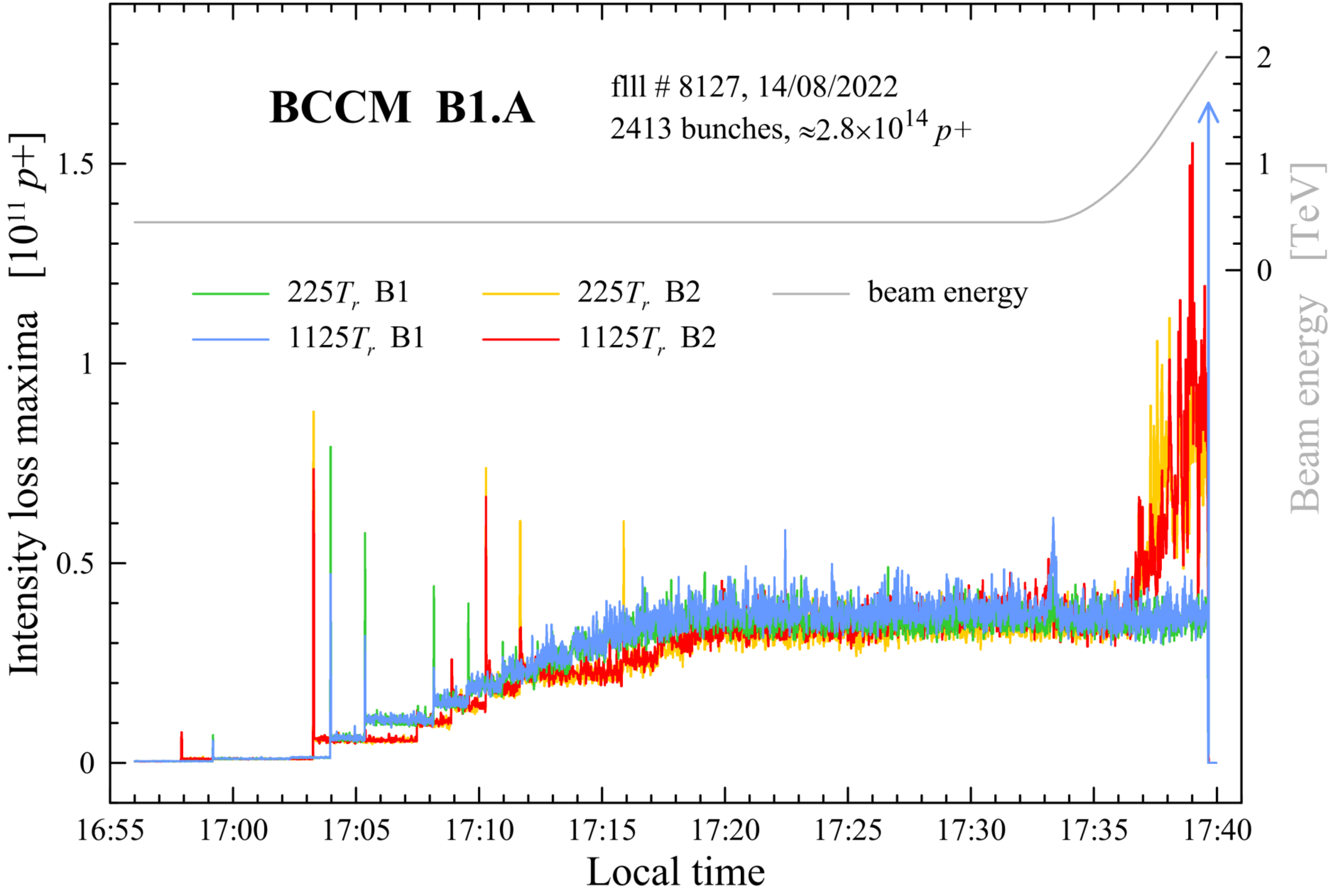
BCCM operation – perturbations during the ramp



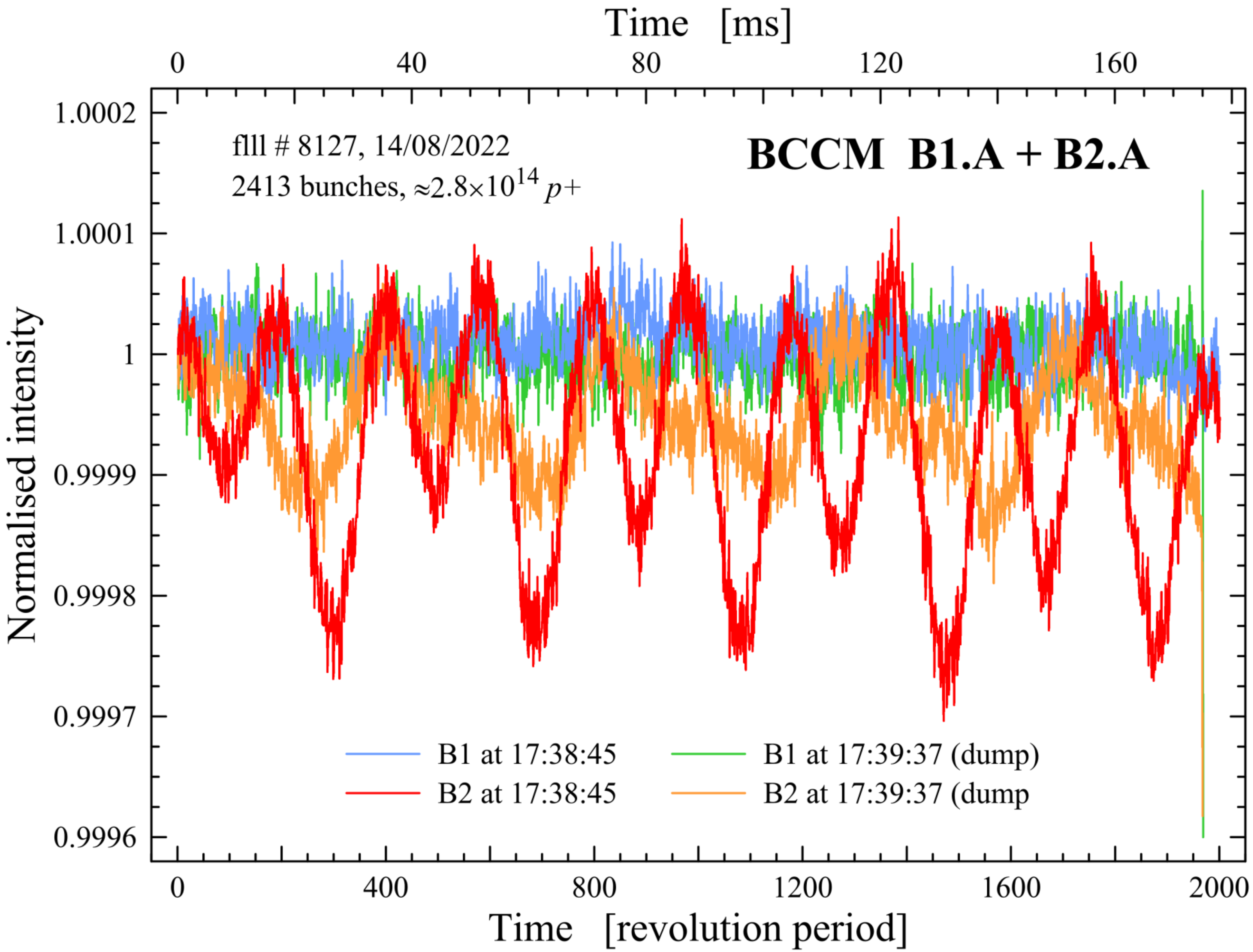
BCCM operation – perturbations during the ramp



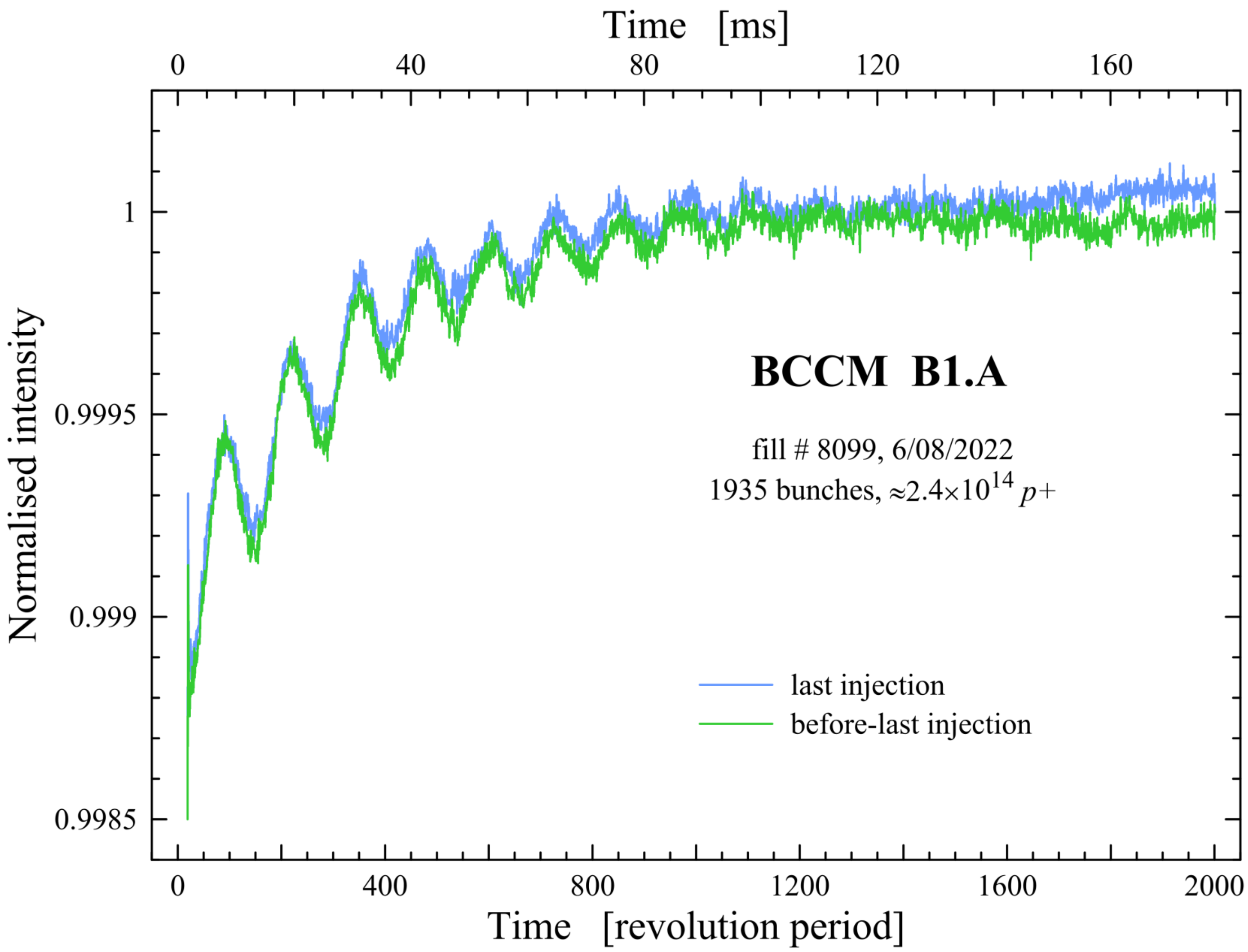
RF longitudinal blow-up: missing on B1, present on B2



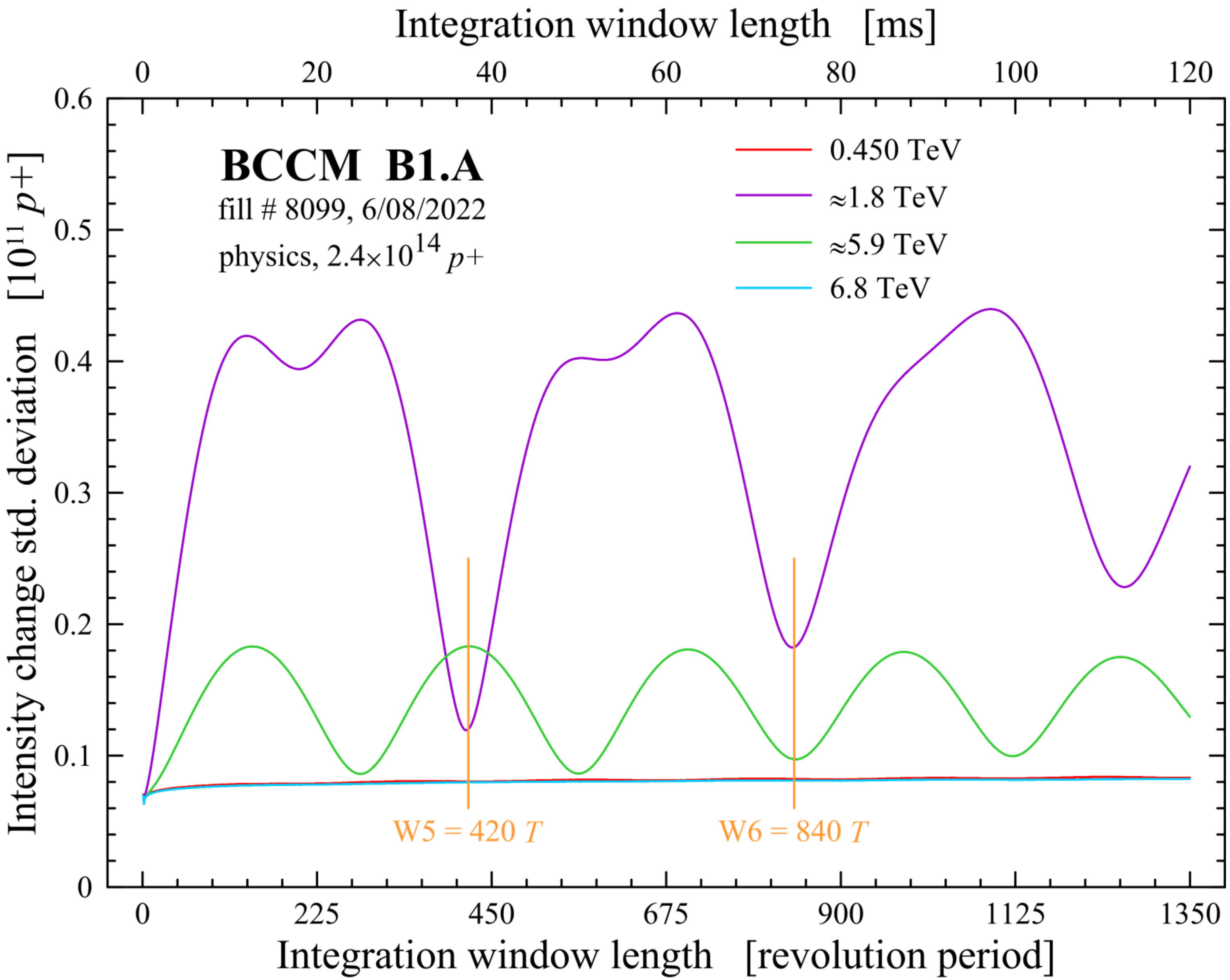
RF longitudinal blow-up: missing on B1, present on B2



Injection longitudinal oscillations



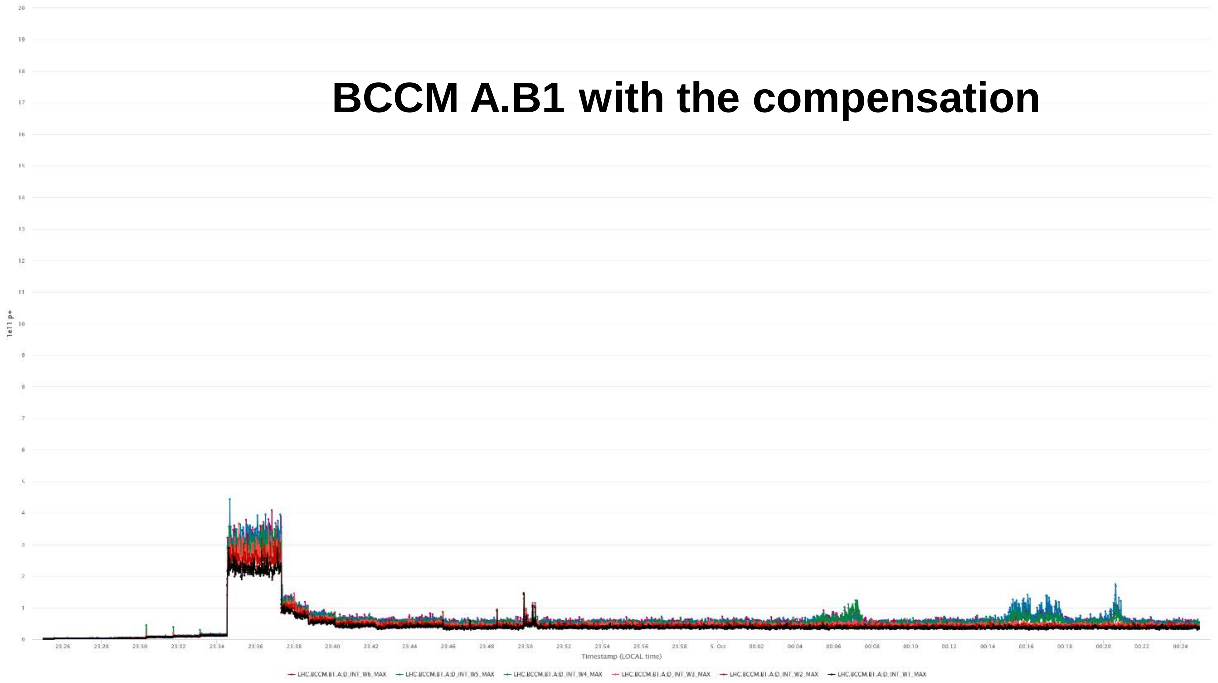
Optimization of the integration window length

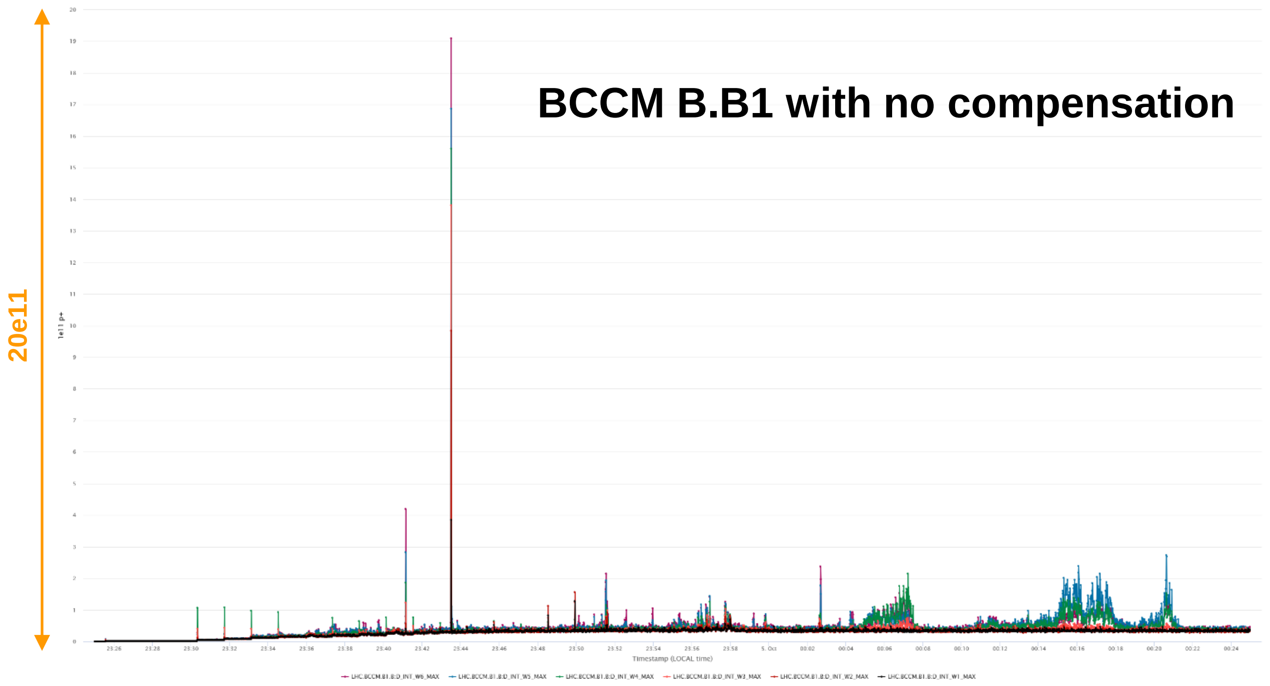


- Two longest integration windows set for tests to 420 and 840 turns since 15/08
- Observed some 30 % reduction of the spurious beam loss maxima during the RF longitudinal blow-up

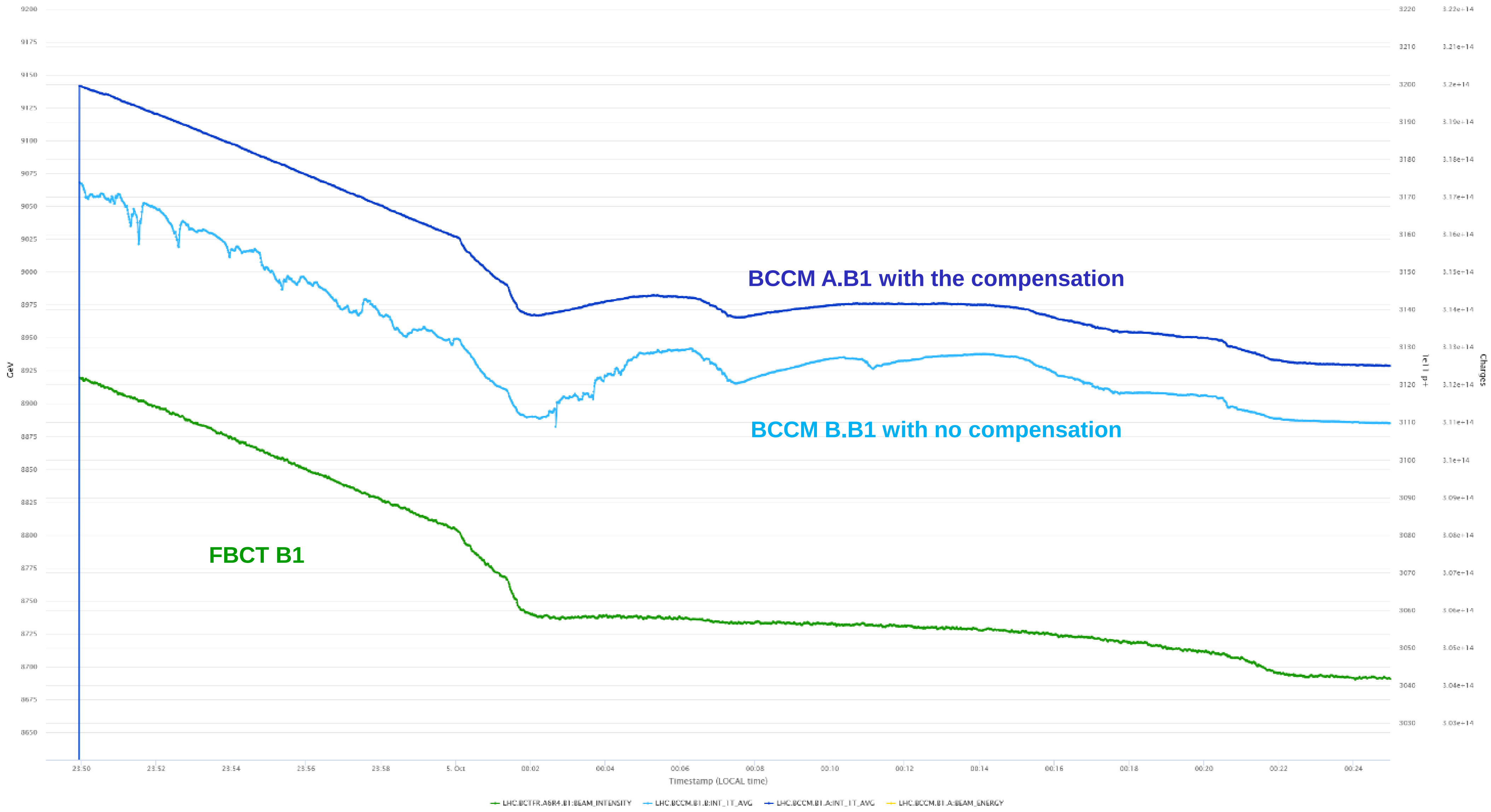
1st order low pass compensation

- The BPMs used by the BCCM are high-pass systems with the cut-off ≈ 200 MHz (16 pF + 50 Ω)
- Their frequency characteristic was flattened by a 1st order low-pass (≈ 12 MHz) at the expense of 80 % signal loss. Ongoing tests of the low-pass on systems A and comparing to systems B without the compensation (since 28/09).
- The low-pass is sometimes very effective
- Some issues with the “stability of the signal baseline”

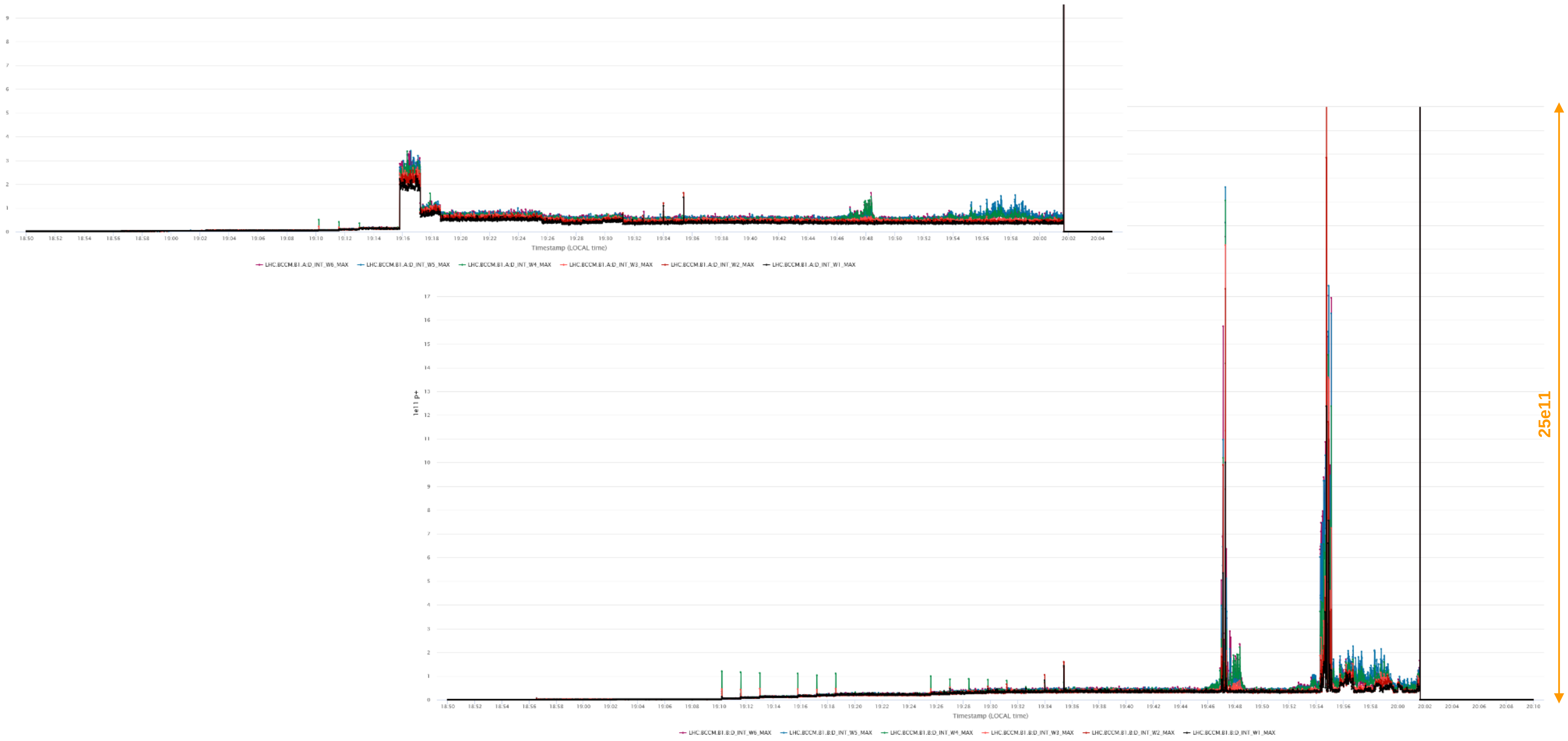




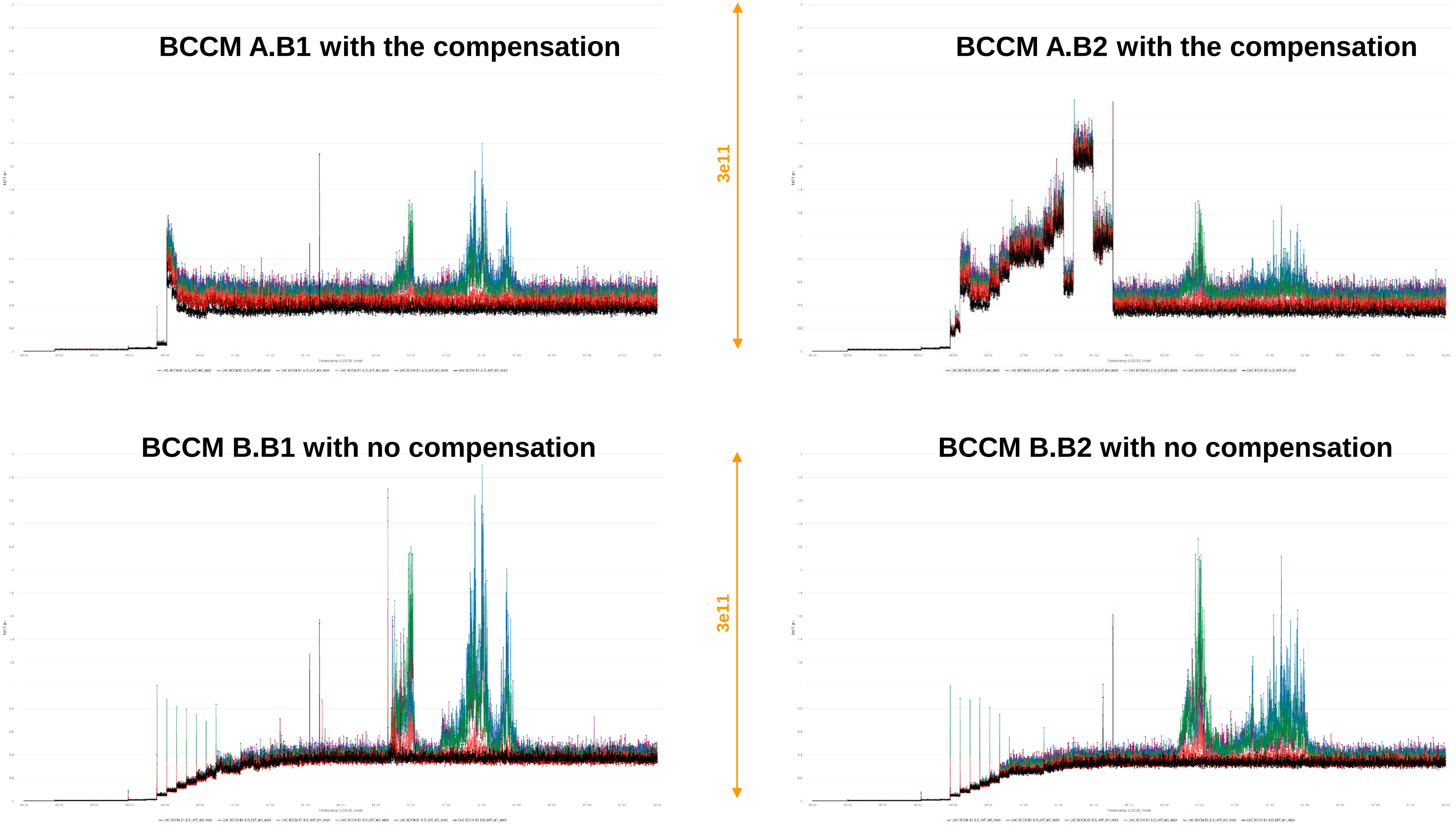
1st order low pass compensation



1st order low pass compensation



1st order low pass compensation



Conclusions and options to investigate

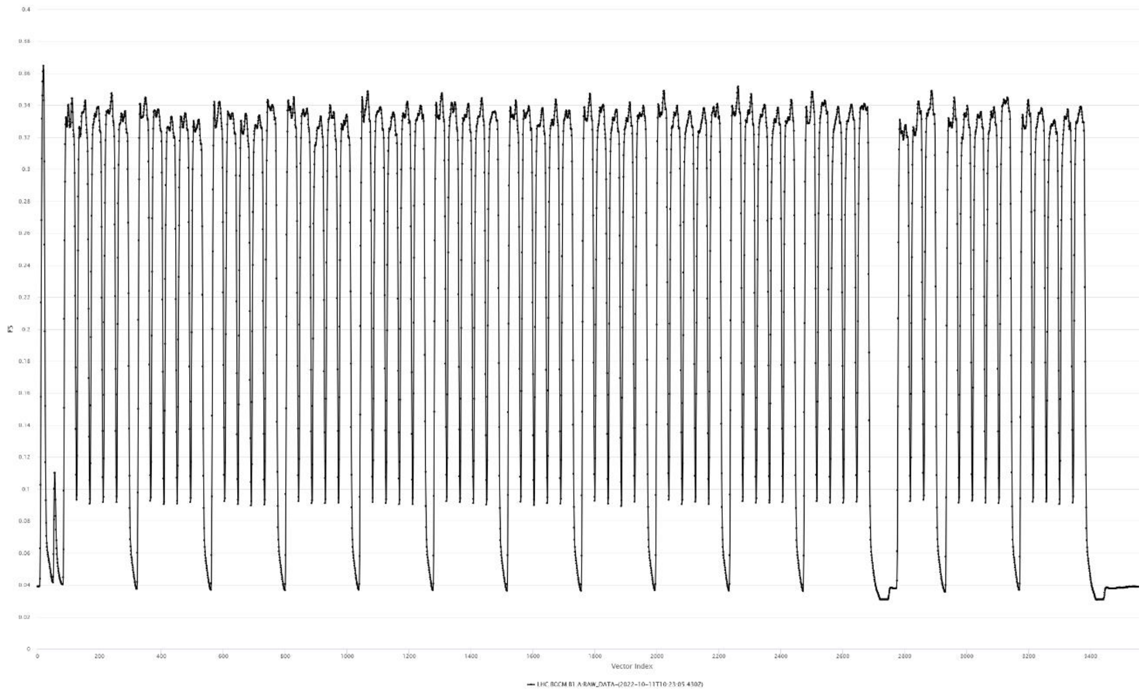
- During the 2022 run the four BCCM systems have been evolving quite a bit and have been continuously tested with beam
- The hardware and FESA are “almost final” and very reliable
- Operational extensive data logging implemented, including continuous turn-by-turn logging of the most important data and on-demand 73-turn snapshots of the 40 MHz raw ADC samples (currently stored also every beam dump)
- The residual bunch length dependence of the BPM signals is the only known problem with the current implementation of the system. The problem shows up during beam injections, the RF longitudinal blow-up and beam instabilities.
- The new dump threshold levels for the two longest integration windows help a lot to fulfil all the system specifications
- New lengths of the two longest integration windows are being tested. Still to be decided whether they are helping enough.
- A 1st order low-pass filter compensating the 1st order high-pass characteristic of the BPM reduces the bunch length dependence. Unfortunately, the low-pass causes issues with the “stability of the signal baseline”.

Options to investigate:

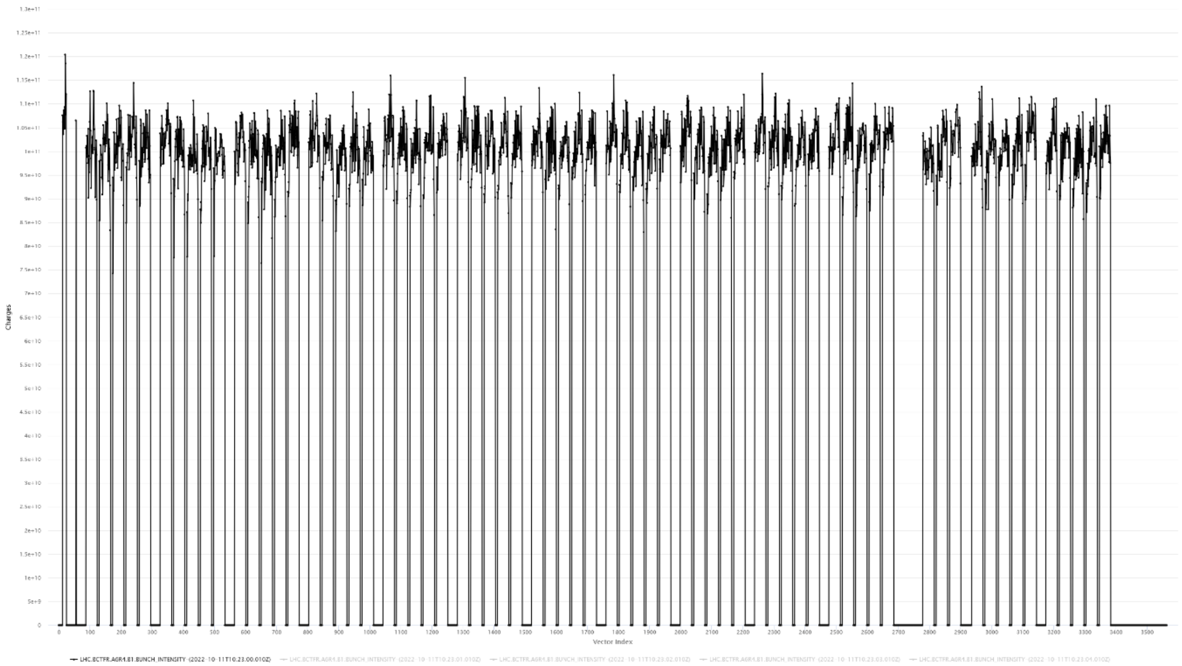
- A less aggressive 1st order low-pass, with the hope to improve the “stability of the signal baseline”
- FBCTs with the flat frequency characteristic as the beam signal source

Spare slides

25 ns data: BCCM vs FBCT



one turn of BCCM data



one turn of FBCT data