BLM DIAMOND SYSTEM AT LHC AND SPS

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IBIC'22, September 13th, 2022

Kraków

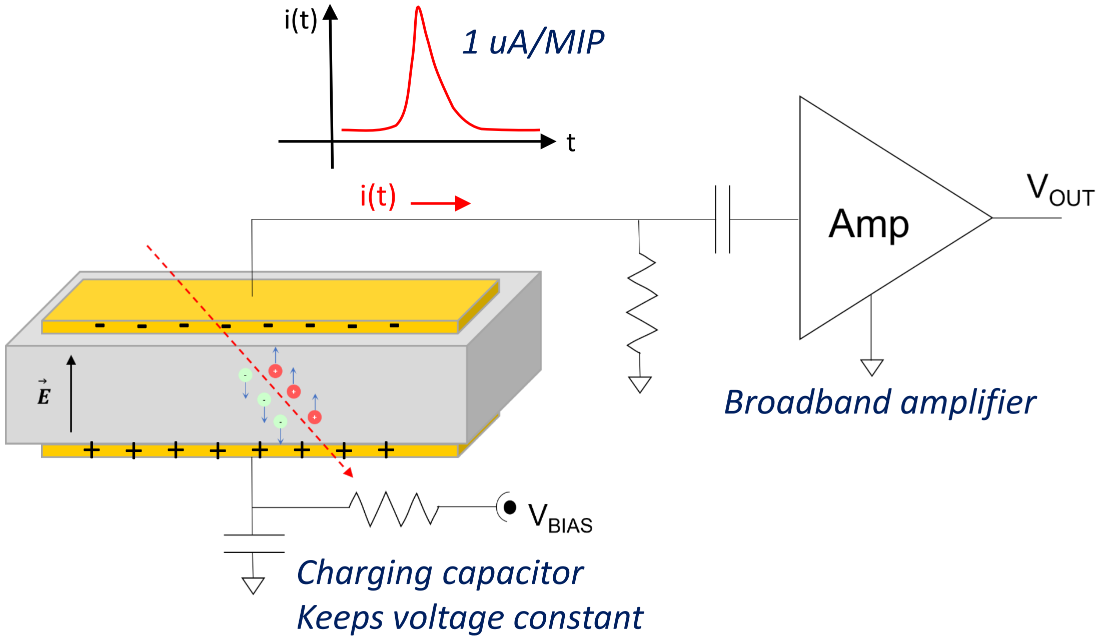
With contributions from E. Effinger, E. Griesmayer, M. Gonzalez-Berges, J. Kral, J. Martinez, S. Morales, B. Salvachua, C. Zamantzas and P. Arrutia

Outline

- Introduction to diamond detectors
- BLM Diamond locations at SPS and LHC
- New hardware platform used since 2018
- Firmware description
- Acquisition modes implemented
- Use case
- Conclusions

Introduction to pCVD diamond detectors

Based on the ionization principle : "Solid state ionization chamber"



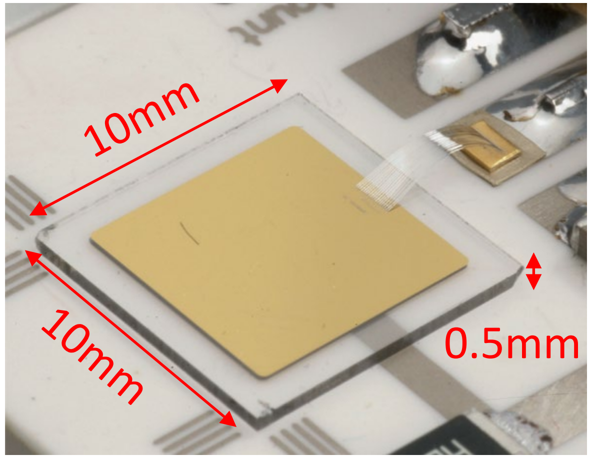


Photo Credit: CIVIDEC Instrumentation
[Proc. DIPAC'11, MOPD41]

Number of electron-hole pairs is proportional to the energy deposited in the material.
Bias voltage should be high enough to minimize recombination.

Synthetically grown by Chemical Vapor Deposition process

500 µm thickness, 10x10 mm^2 surface
Coated on each side with 8x8 mm^2, 200 nm gold electrodes.

pCVD diamond properties

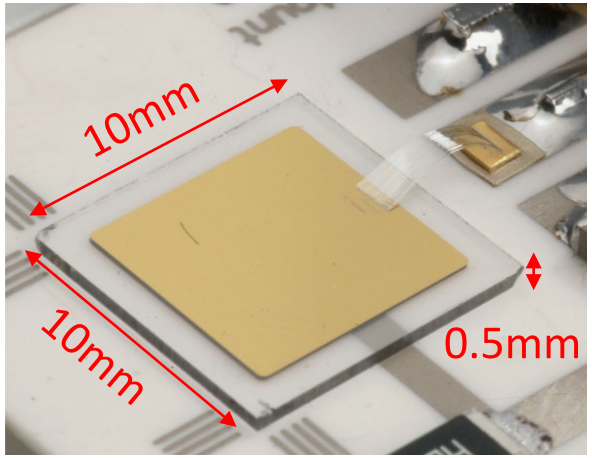
- Very fast response times (pulses < few ns)

  → Allows bunch-by-bunch loss measurements.
- High resistivity (>10^{15} Ωcm)

  → low leakage current (in the order of pA).
- Very radiation resistant material

  → >1 MGy Total Ionizing Dose

  → Suitable as beam loss monitor.
- Negligible temperature dependence.
- High dynamic range.
- Small dimensions → facilitates integration.



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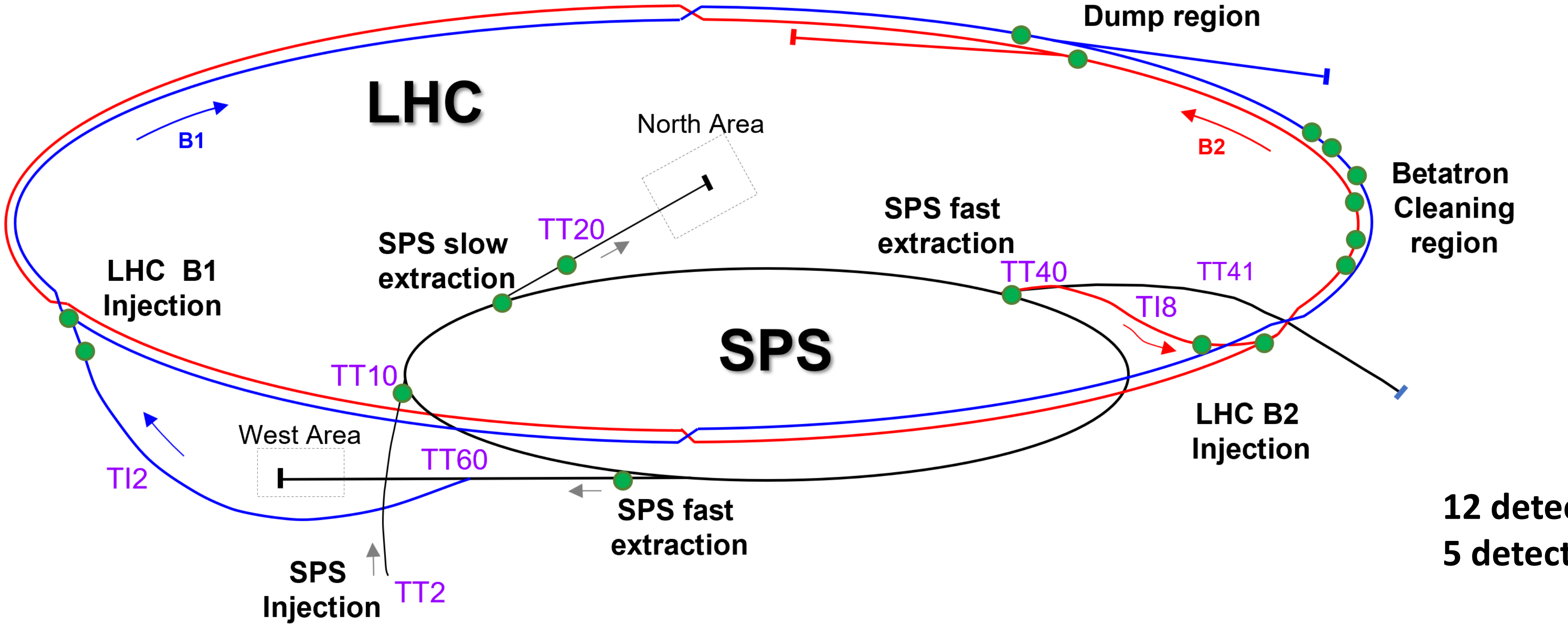
pCVD detector locations at SPS and LHC

- ICs are used as the main protection system, as well as for optimizing the machine operation.
- Diamonds detectors are often used for analyzing injections and extractions and to perform losses studies where the fast response is of main importance.
- Often located downstream of collimators, or near elements susceptible of produce beam losses.



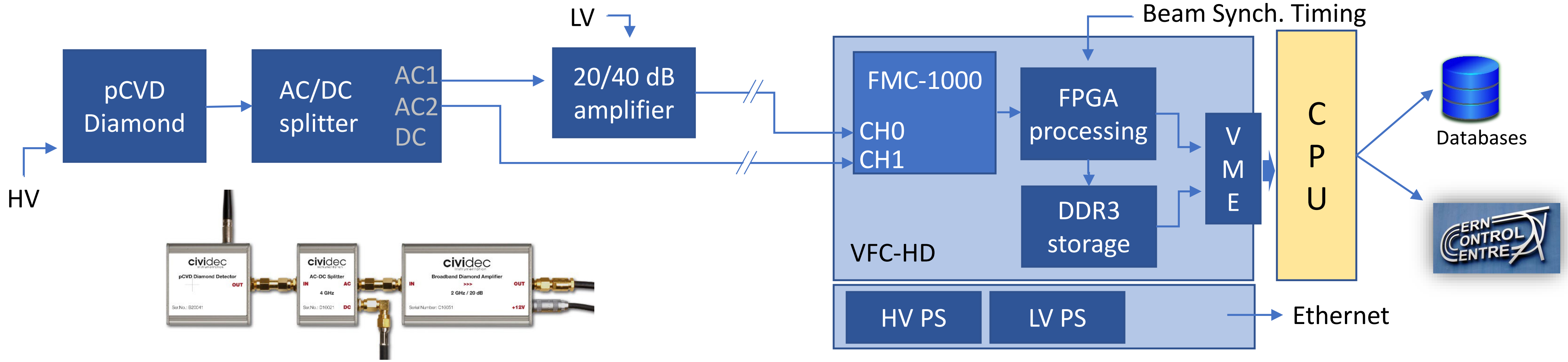
12 detectors in LHC
5 detectors in SPS

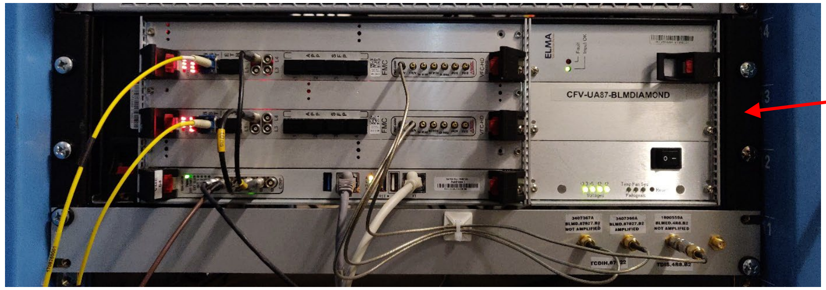
The acquisition chain : Evolution

- CERN uses those detectors since ~2010.
- Acquired through fast oscilloscopes or Cividec ROSY DAQ for many years.
- During 2018, the readout and SW migrated to CERN proprietary tools :

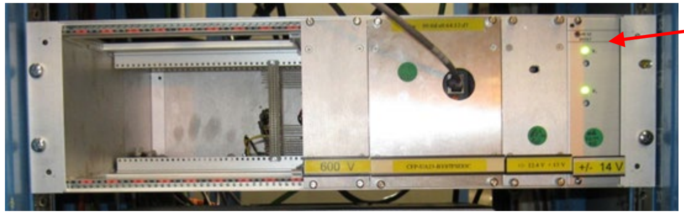
  - Uses CERN Beam Instrumentation standard FMC carrier card (VFC-HD).
    → Used by many other beam instrumentation devices → Facilitates maintenance and integration.
  - Integration CERN controls SW layers.
    → Data publication (FESA servers), logging databases, etc.
  - Increased flexibility on the signal processing:
    → Quick adaptation to user requirements.
    → Increased number of acquisition modes.
    → Data pattern recognition auto-triggering.
    → Capture on selection of bunches.
  - Increased ADC number of bits (14 vs 8)
  - Reduced sampling speed (650 MSPS vs 1.25GSPS or 5 GSPS) and input range (±0.45V vs ±10V)

The acquisition chain





ELMA VME crate
+ MEN A25 CPUs
+ VFC-HD
+ FMC-1000



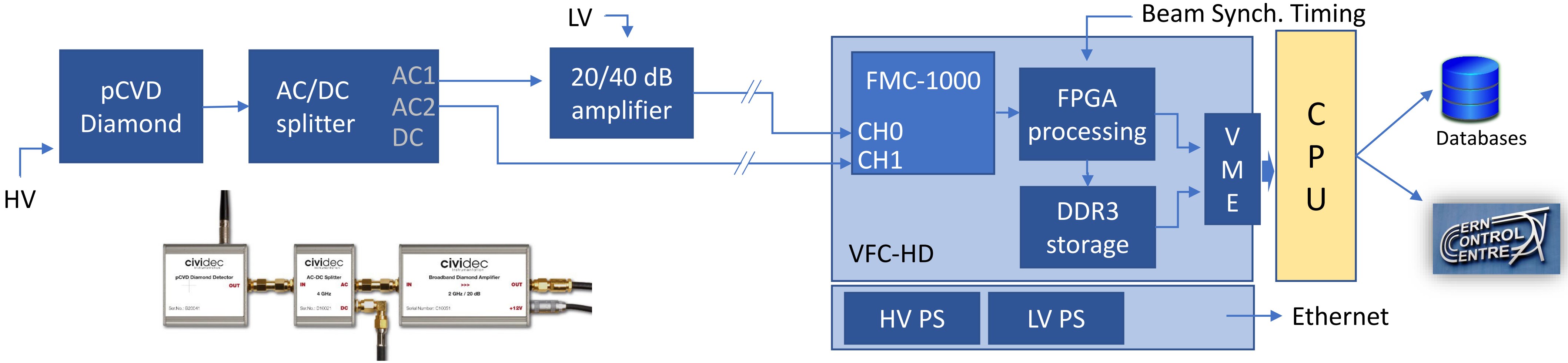
High and Low Voltage Supply
Controlled via an Ethernet Controller

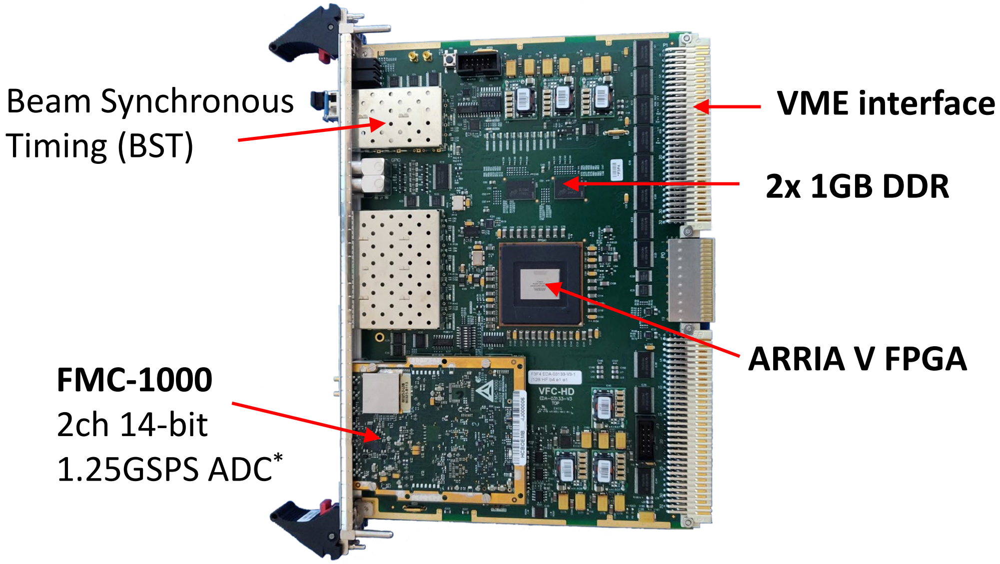
Detector + Analog Front-end
(Near observed element)

Cabling
(hundreds m)

Digital Back End
(In service tunnel)

The acquisition chain





Detector + Analog Front-end
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Cabling
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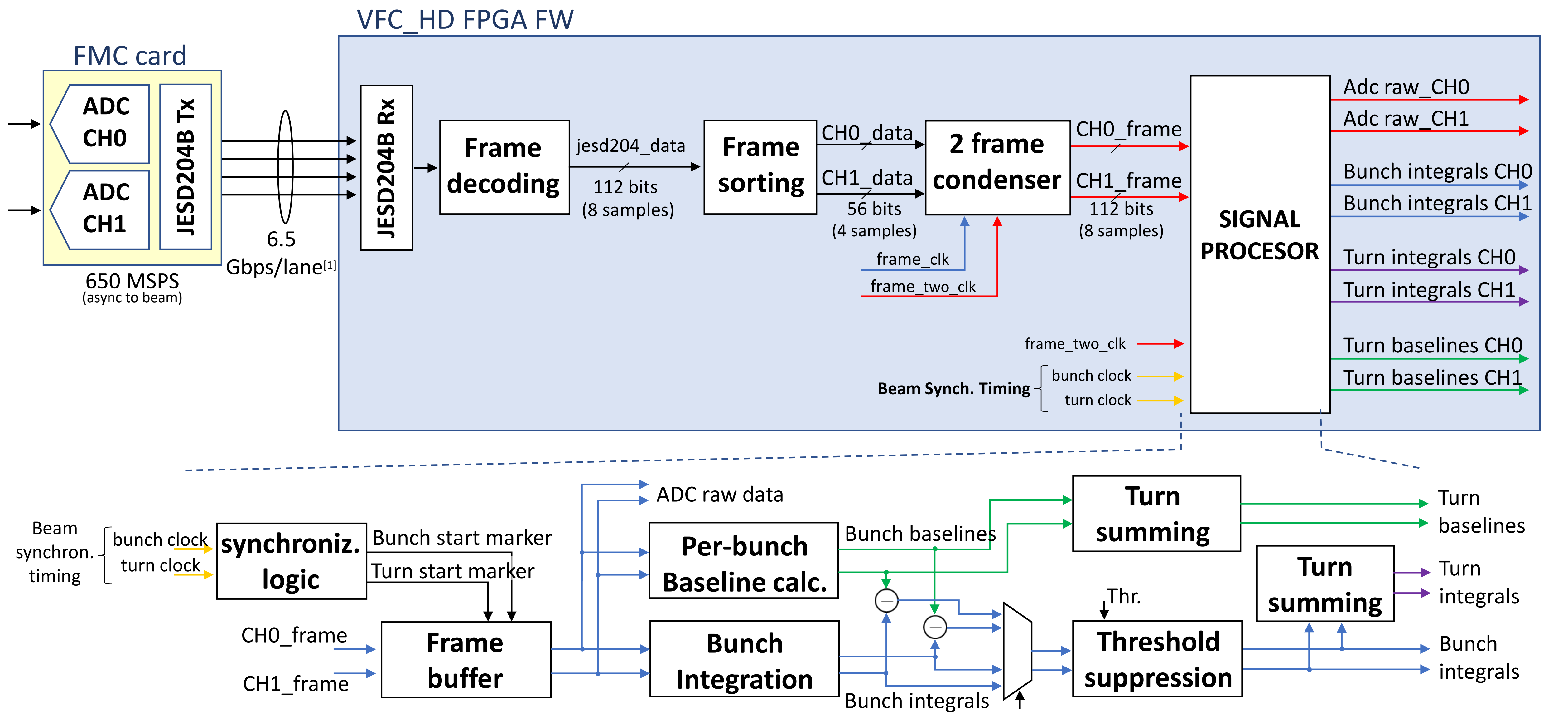
Digital Back End
(In service tunnel)

* Operated at 650MSP

Diamond BLM FW functional block



[1] 2 ADC x 650MS/s / ADC x 2 bytes / sample x (10bit/8bit) / 4 lanes = 6.5Gpbs

Measurement modes (I)

- **2 types of measurements : 1 single shot and 5 continuous**

  → Continuous modes only used with the detectors at the LHC betatron cleaning region

1) Capture (Snapshot)

→ ADC raw data is dumped in 2 circular buffers (one per channel) → ~500 Msamples @ 650MS/s

→ Samples can previously be reduced by averaging or using different gating mechanisms (front-panel, a sequence of counters, selection of consecutive bunches)

→ Very flexible freeze mechanism (front panel, BST, pattern recognition auto-triggering, etc.)

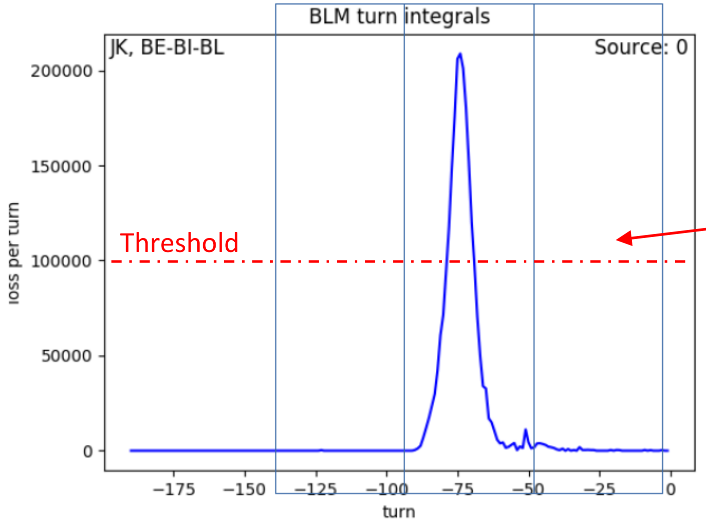


Figure CREDIT : J. Kral

Auto-trigger pattern recognition examples:

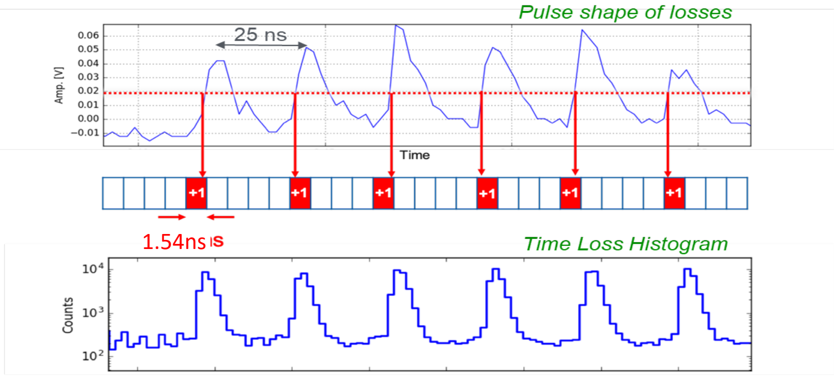
- Detect N bunch loss integrals above threshold within turn
- Take 3 consecutive 5 ms windows and check for total loss in the middle one being higher than a configurable threshold while the two adjacent are lower

Measurement modes (II)

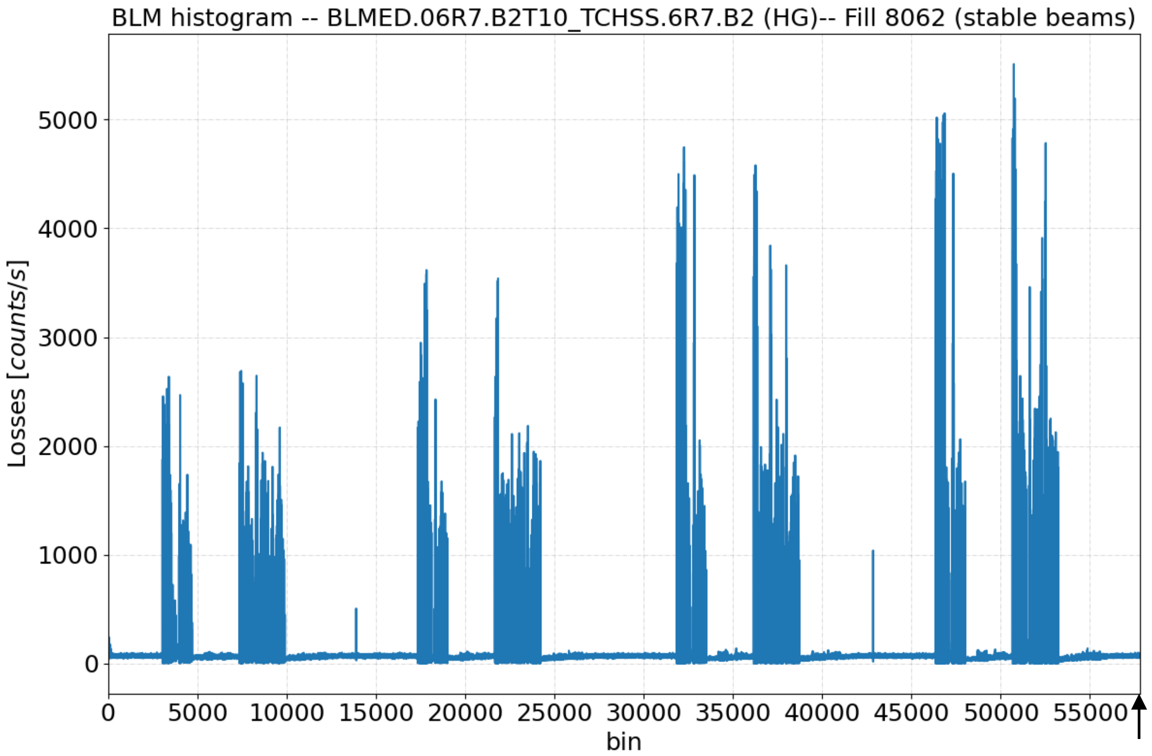
Continuous measurements

2) Beam Loss arrival time histogram

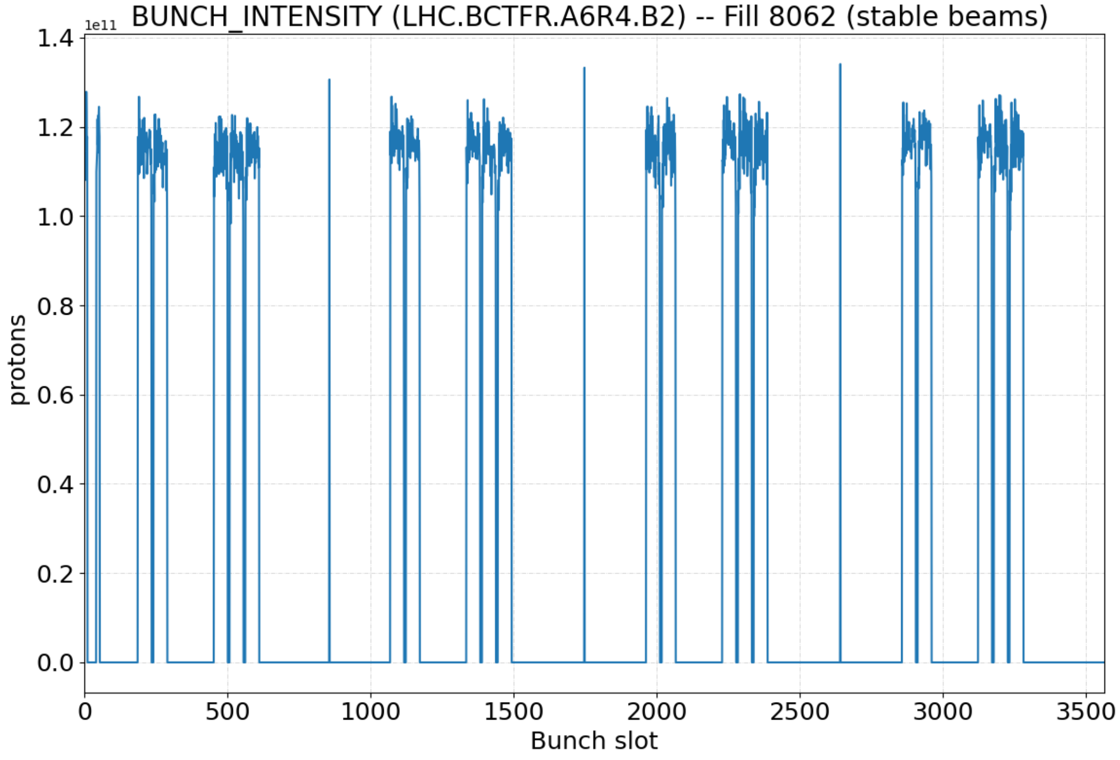
An LHC turn (89 us) is divided in bins of 1.54 ns (1/650 MSPS).
Histogram which counts how many times the diamond BLM signal rising edge crosses a configurable threshold over a configurable period of time (1 s).



Courtesy of Chen Xu



57803 hist. bins



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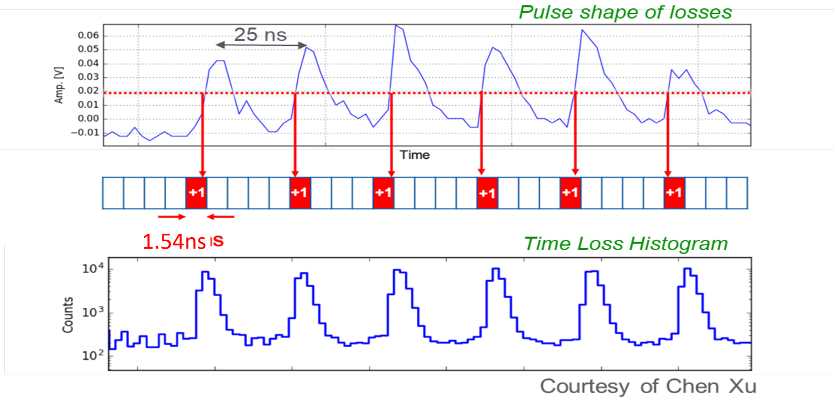

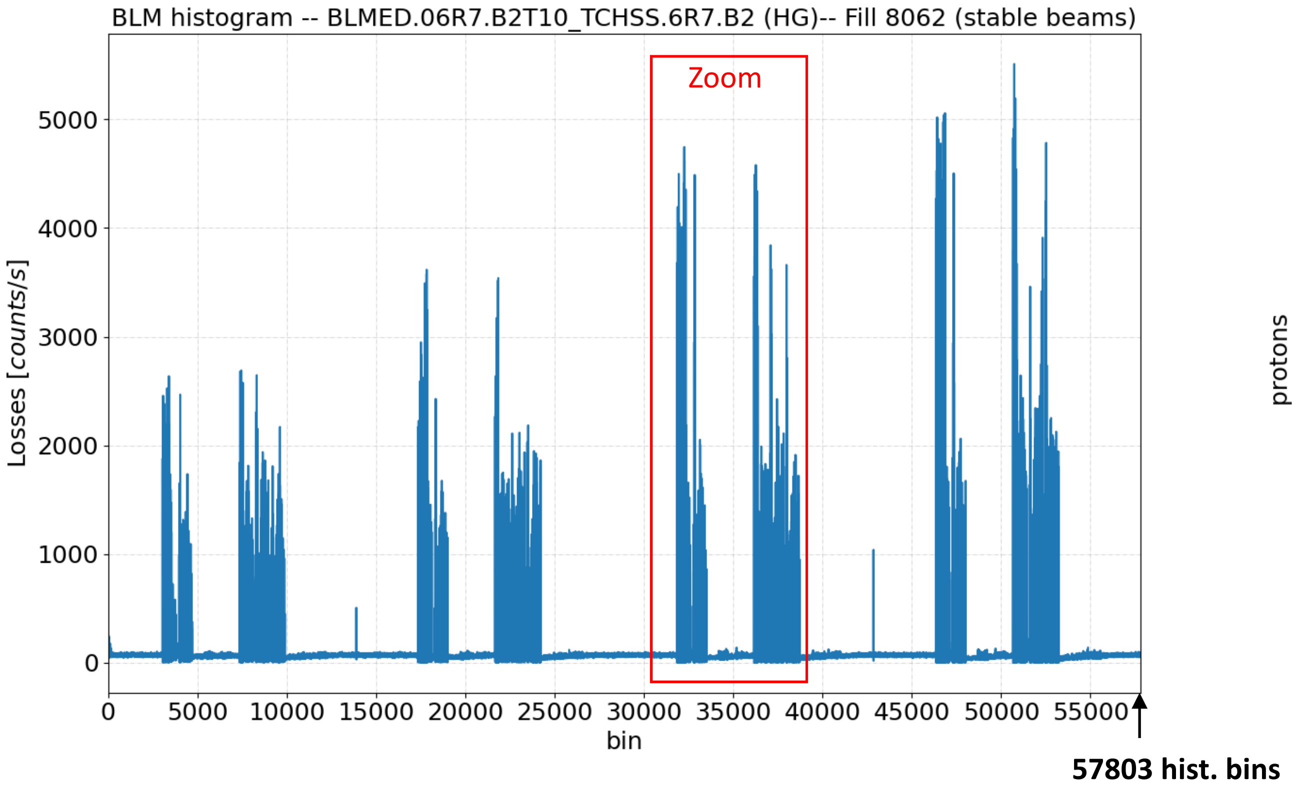

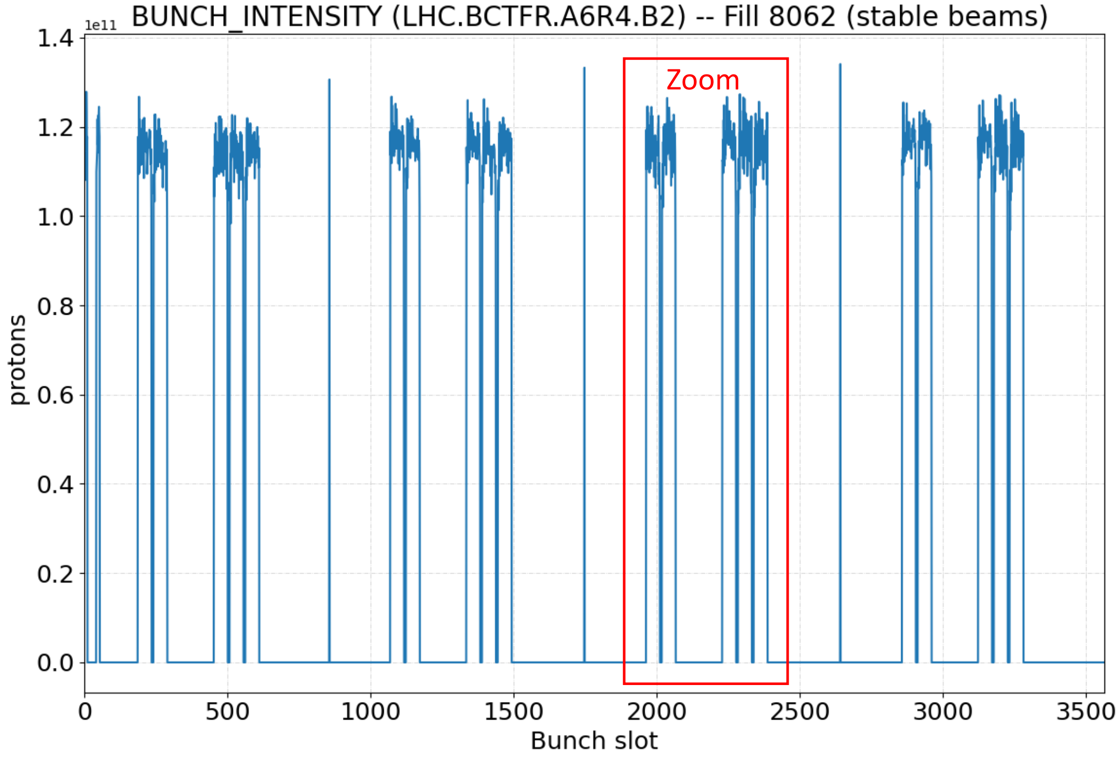

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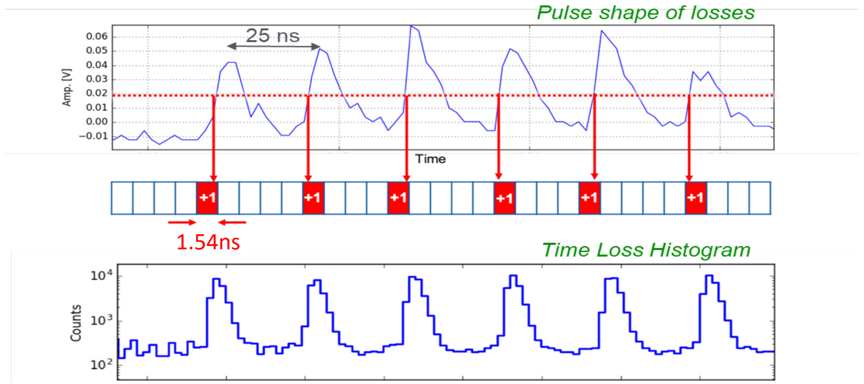

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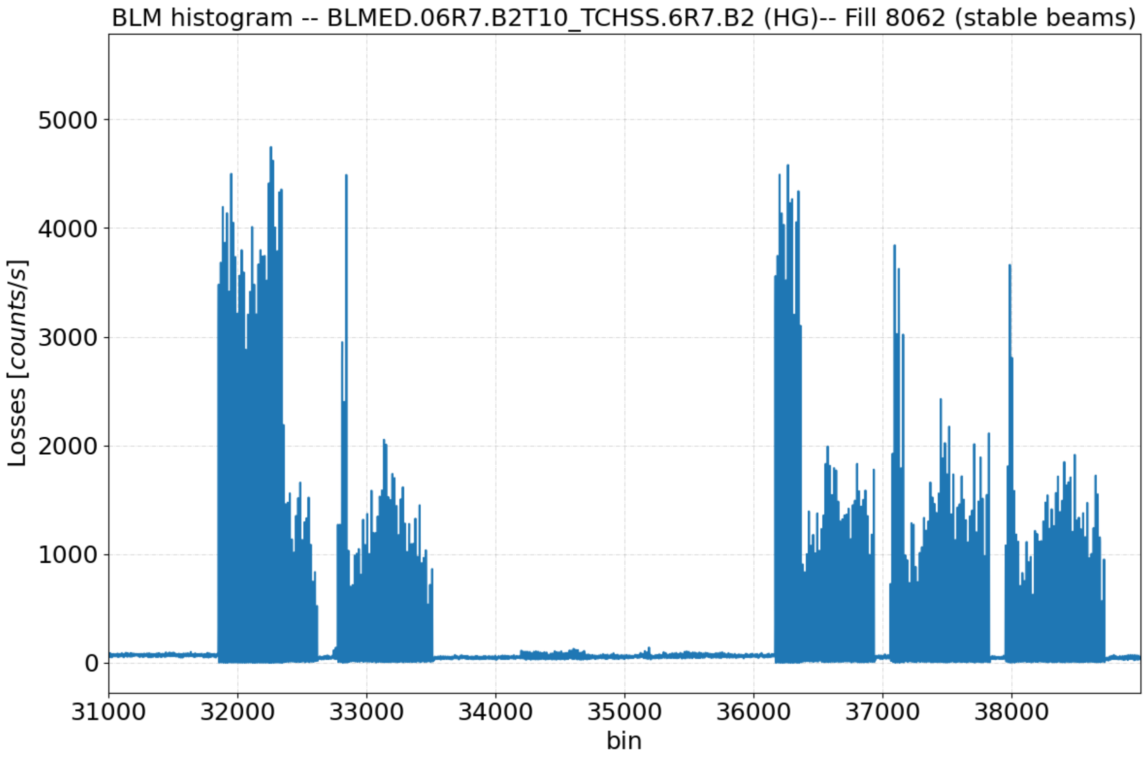

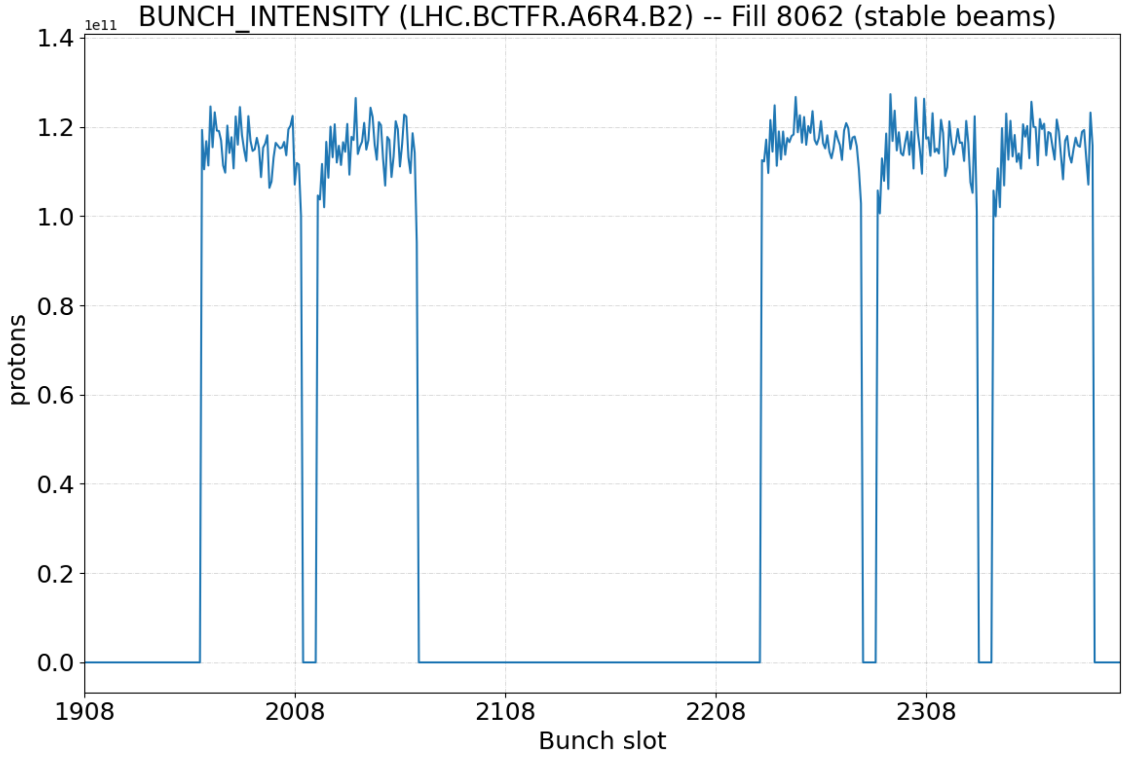

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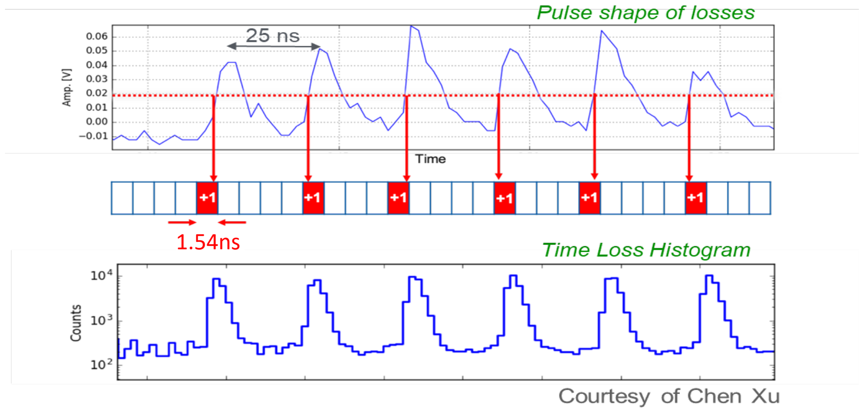

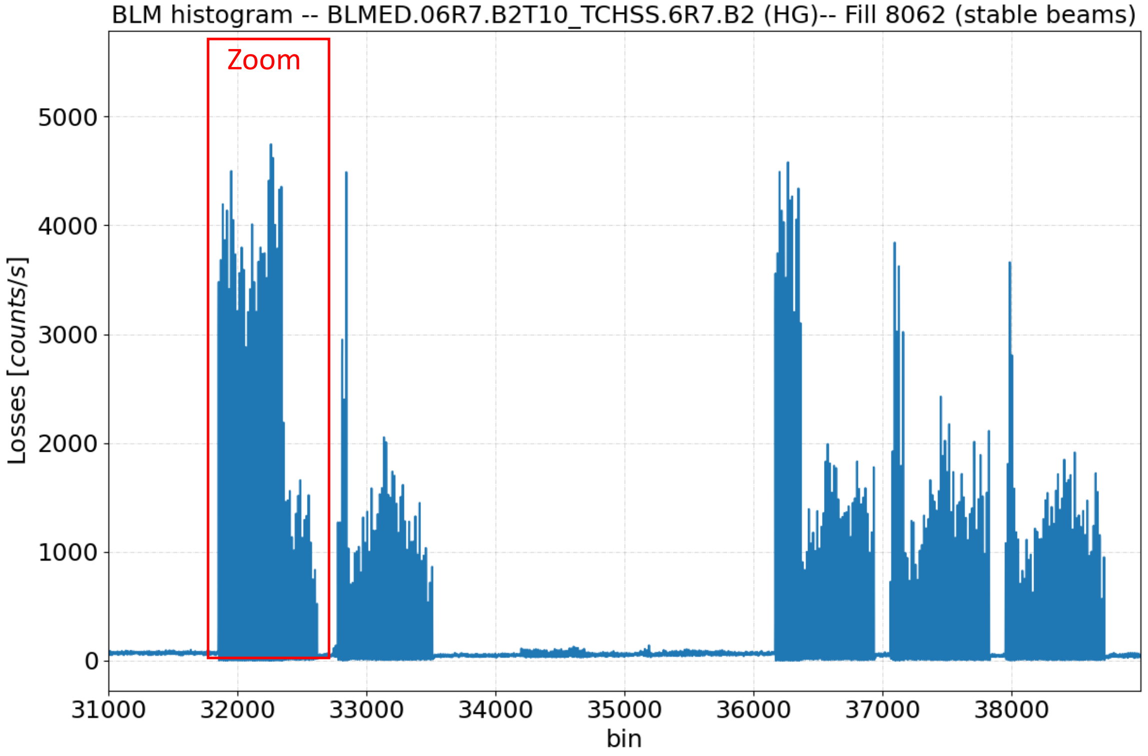

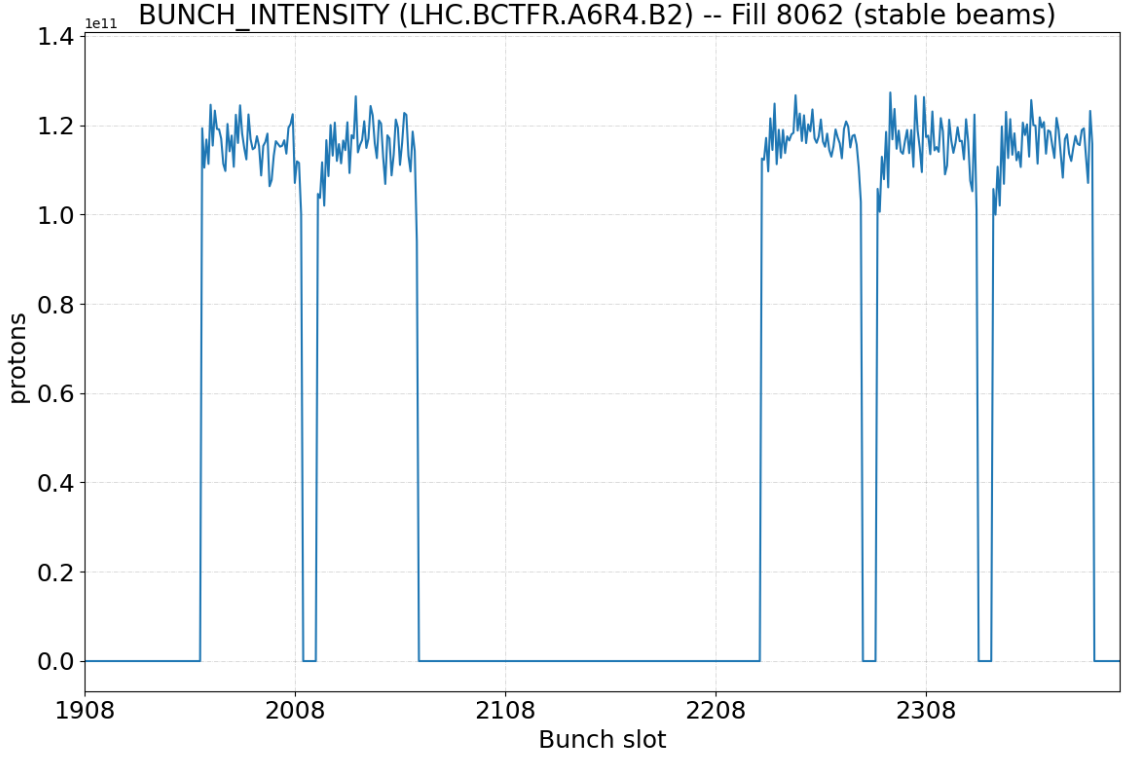

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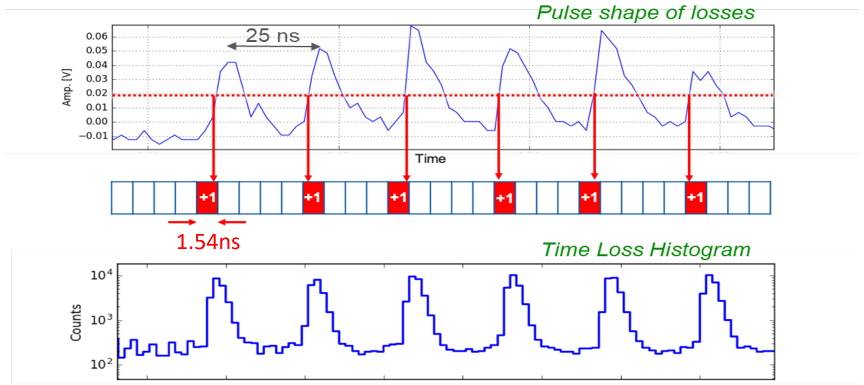

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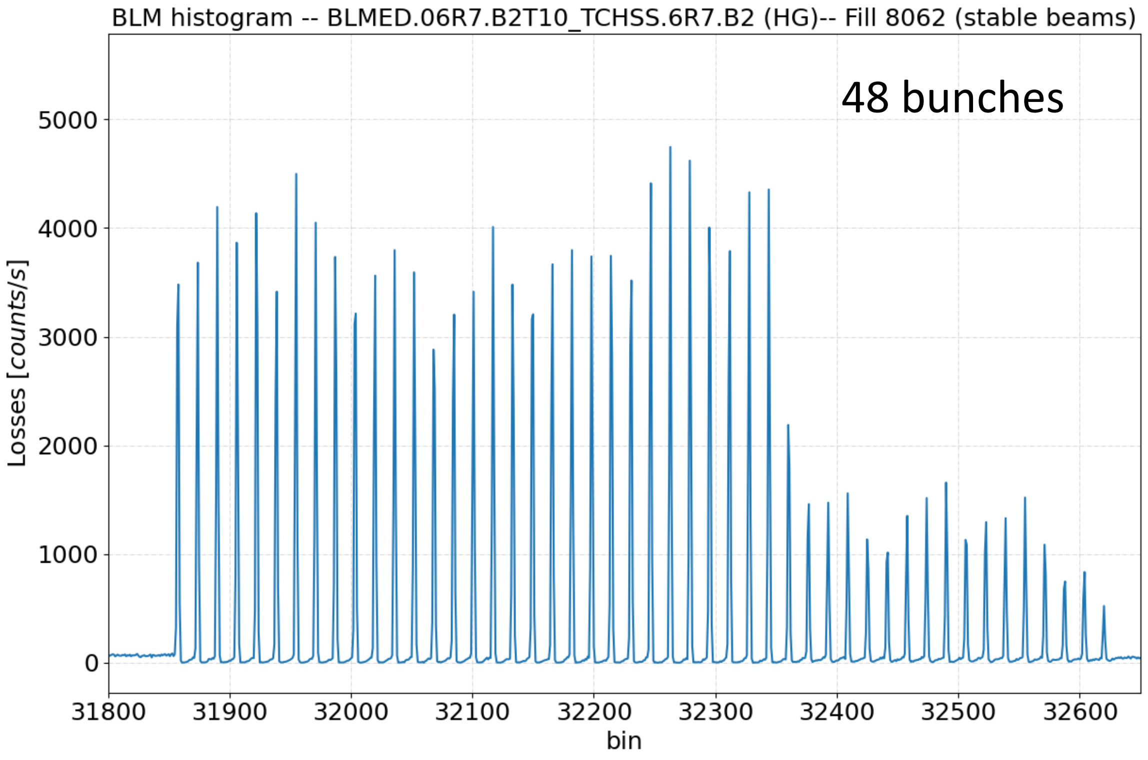
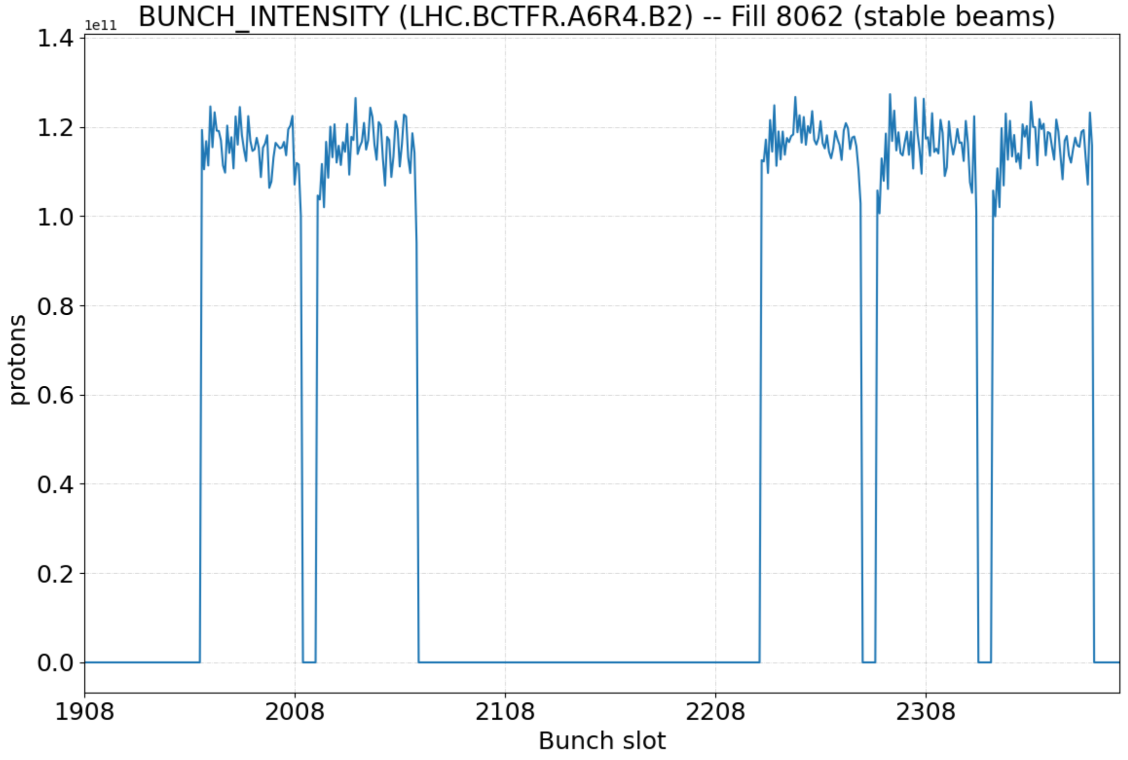




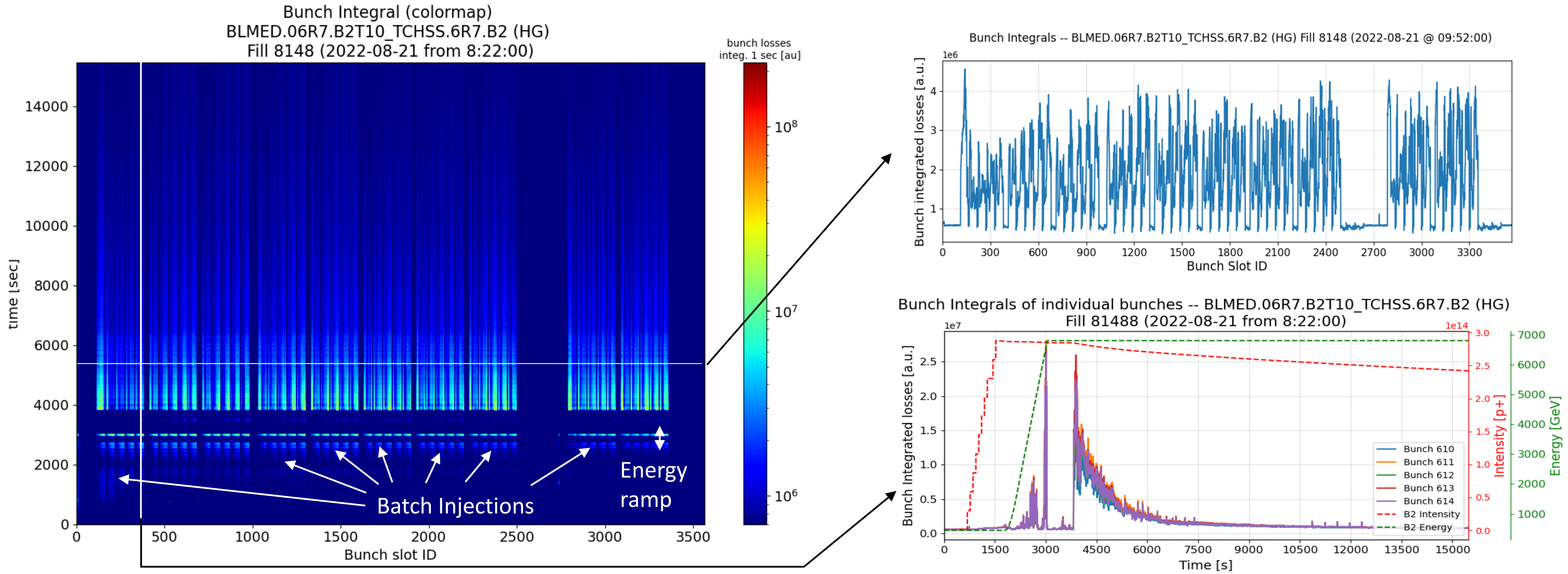
Measurement modes (III)

Continuous measurements

3) Beam loss integral (bunch-by-bunch losses)

Integrate loss magnitudes within a bunch slot using baseline restitution.

Accumulates bunch loss integrals for a configurable number of turns



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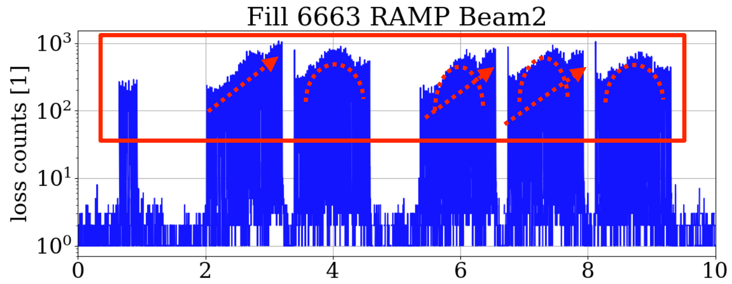
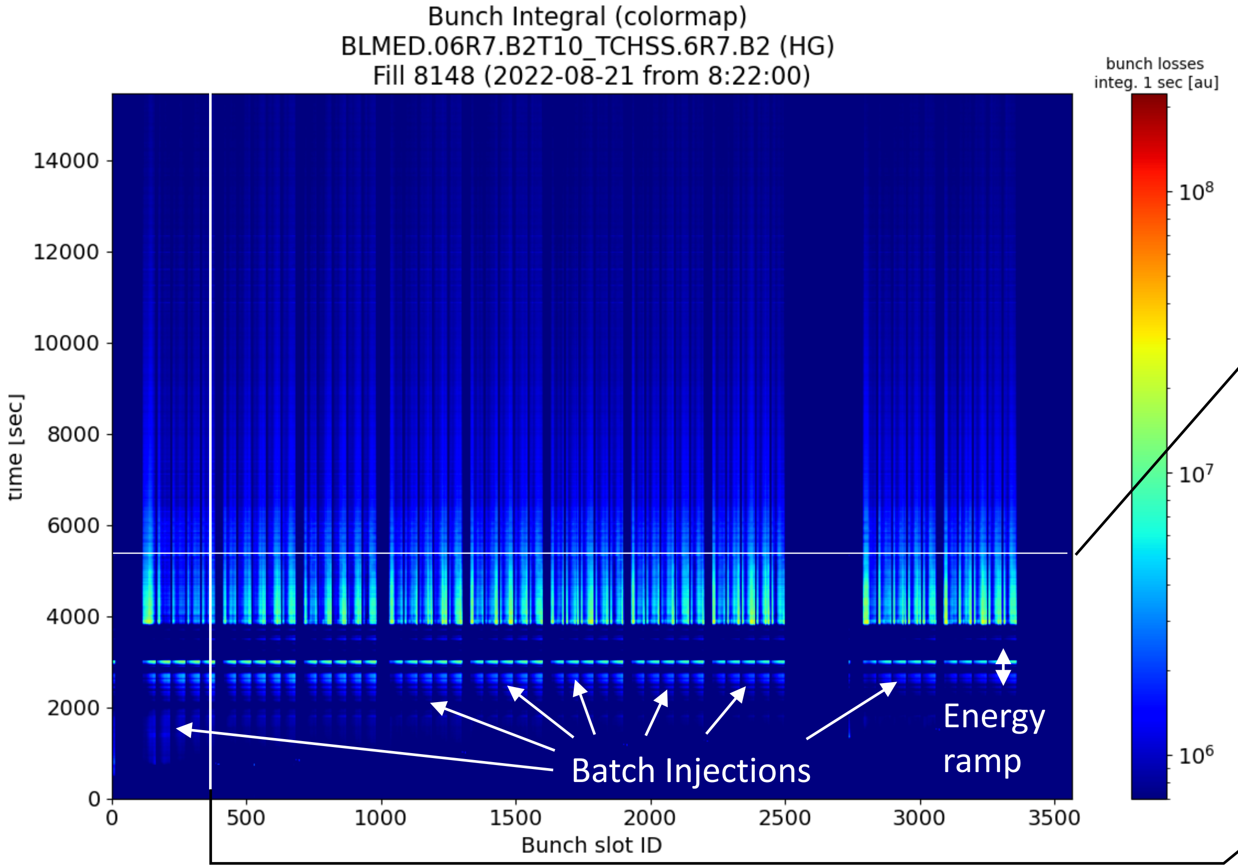
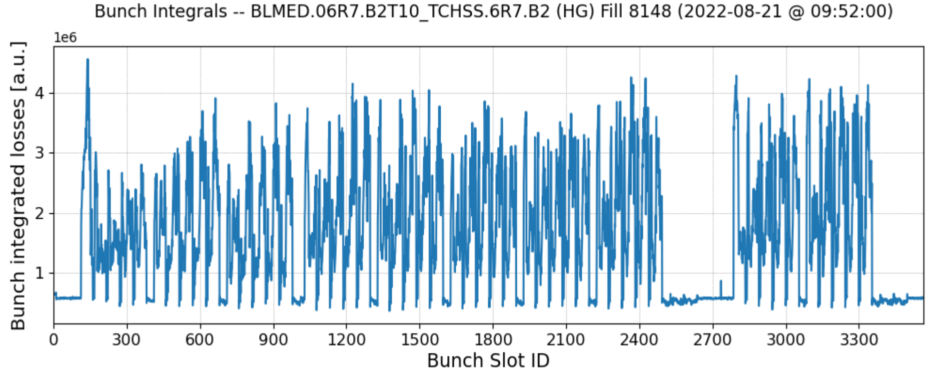
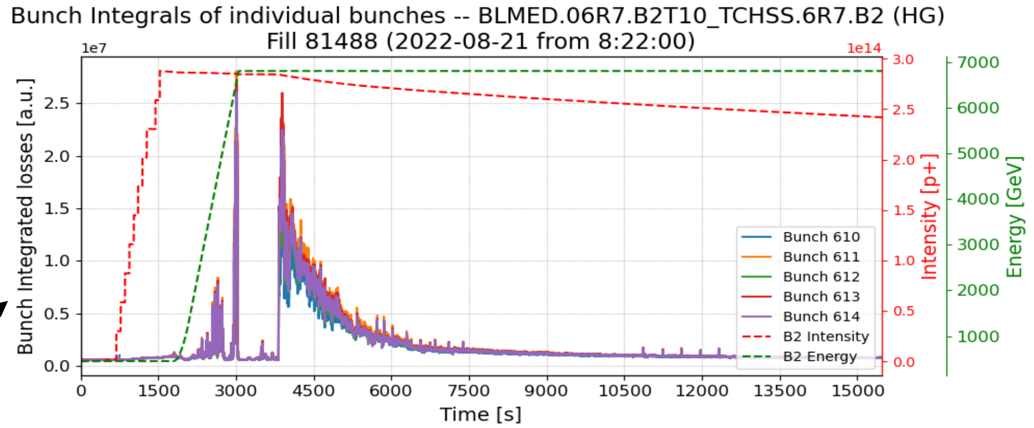


Figure CREDIT: A. Gorzawski

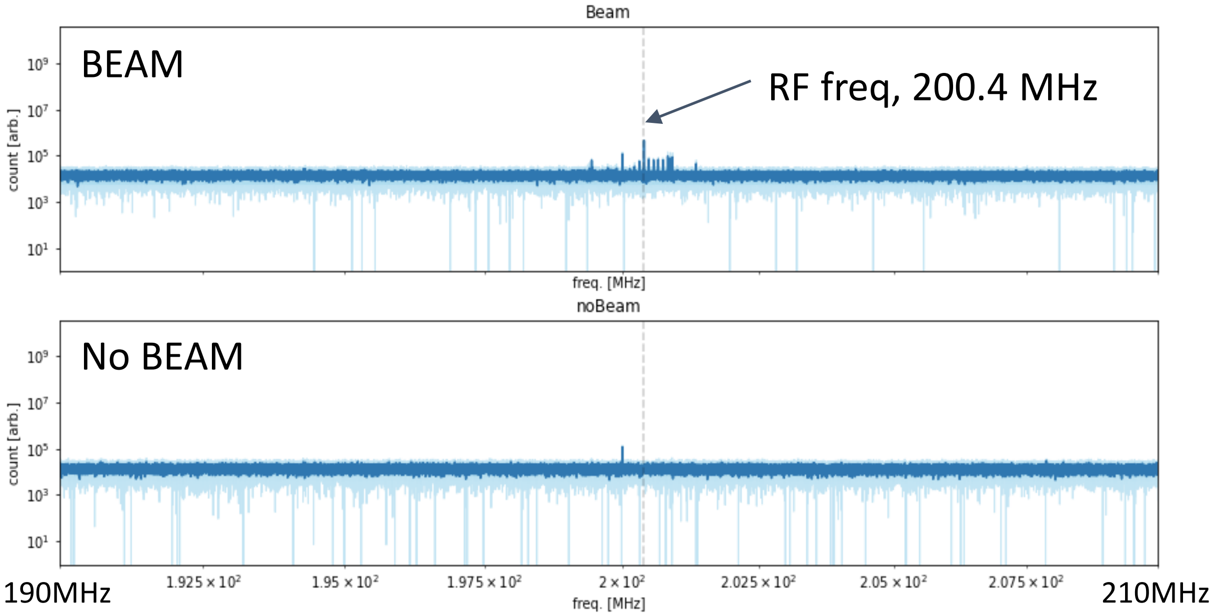




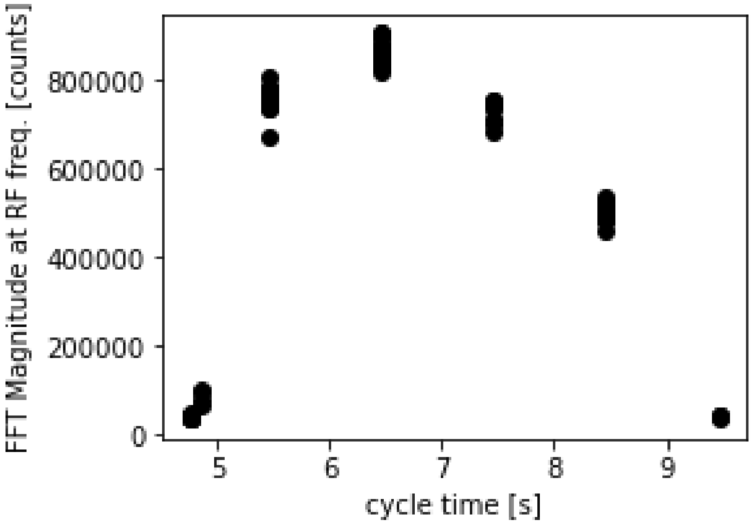


Use case: Spectrum analysis of Slow extractions

- Diamonds BLMs were explored to monitor remaining SPS RF component of the extracted unbunched beam on the SPS slow extraction line
- Several acquisitions on different extractions with and without beam (to subtract background interferences)
- SPS RF component was visible and monitored during machine adjustments to reduce it
- Acquisitions done on different moments along the cycle (which takes 4.8s) to observe the full variation



FFT data from dBLM detector under extraction septum 4



Evolution of remaining RF component along the cycle

Figures
CREDIT : P. A. Arrutia (CERN)

Conclusions

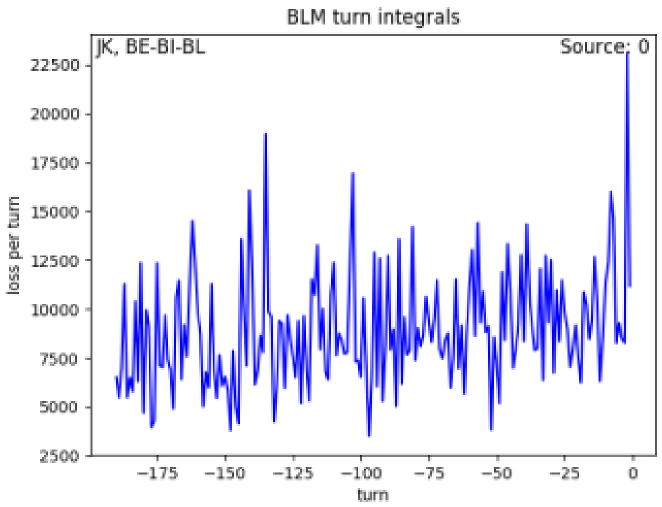
- LHC and SPS BLM diamond acquisition system has been migrated from fast oscilloscopes and Cividec ROSY DAQs to FMC digitisers equipped in the standard CERN BI VME FMC carrier card (VFC-HD).
- The new platform has allowed to integrate new acquisition modes, and trigger mechanisms.
- It also facilitates the SW development, maintenance and integration with the rest of CERN SW control layers.
- The new system provides larger number of bits.
- The reduced input range of the digitizer has required duplicate the number of channels and it is being considered to upgrade the front-ends with remotely controllable gains.
- The system is being commissioned (after the LHC second long shutdown) and will continue being further characterised and optimised in the months to come.

Thank you

Measurement modes (IV)

Continuous measurements

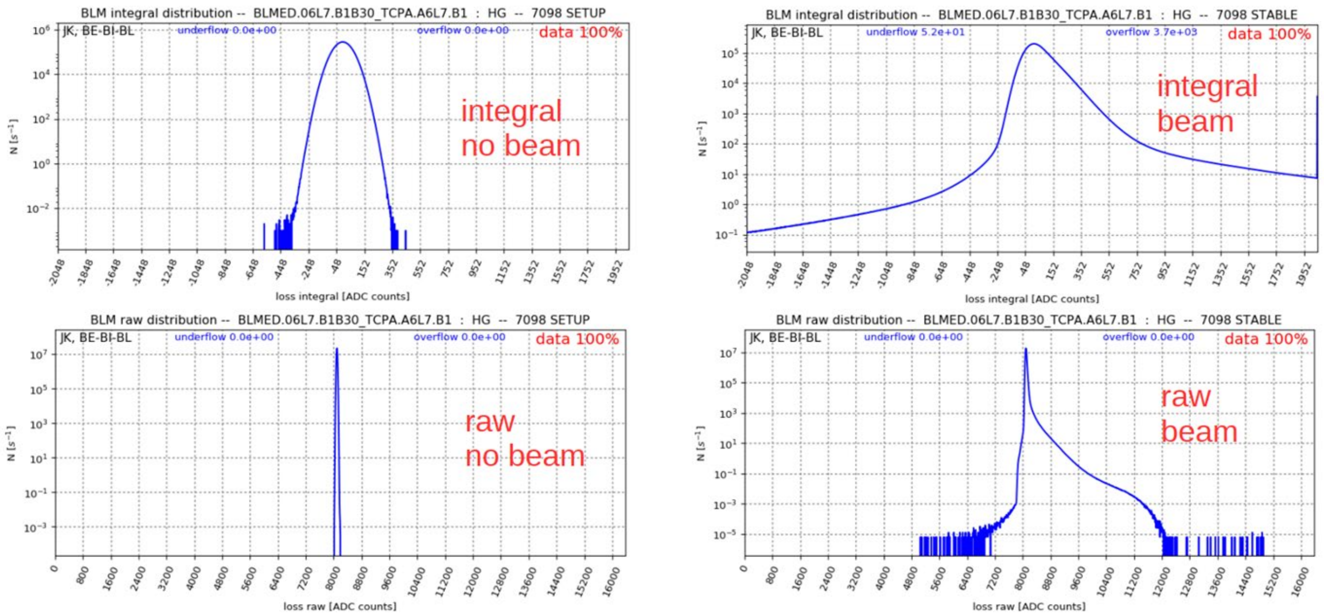
3) Turn-by-turn loss measurement :
Constructs turn-by-turn integrals by summing single bunch losses within a turn



4) Raw data distribution
Distribution of raw ADC values integrated over 1s

5) Integral data distribution
Distribution of bunch-by-bunch losses integrated over 1s

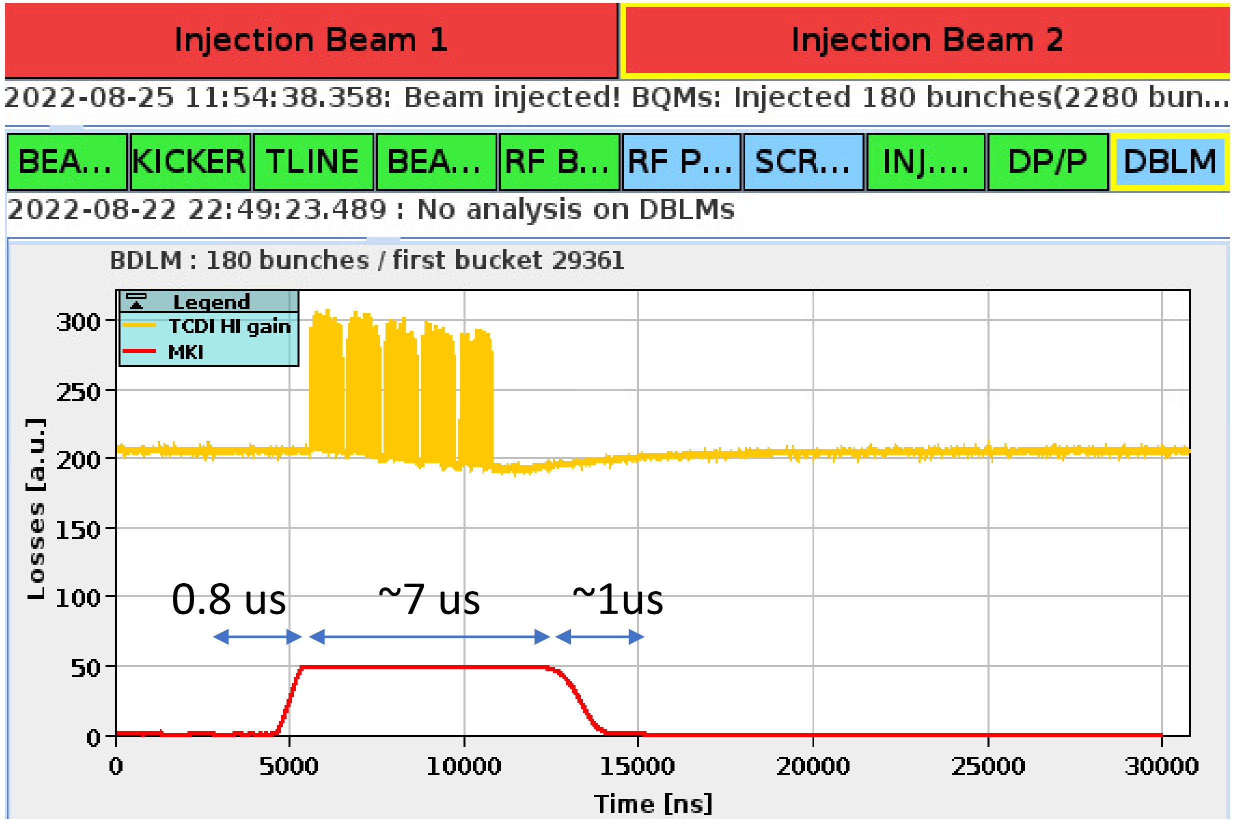
Diagnostic for equipment experts



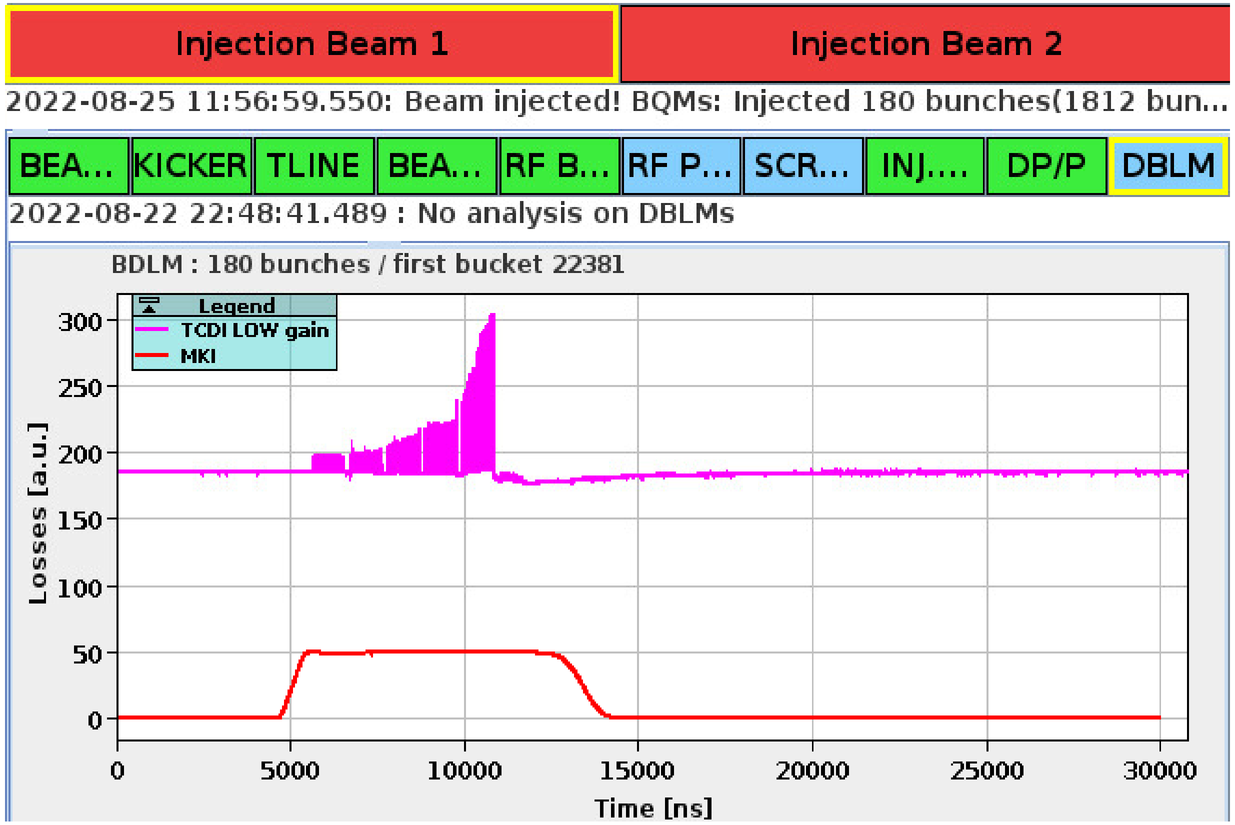
Figures
CREDIT : J. Kral

Use cases: Injection Quality checker

Detectors in injectors lines are used in the IQC application that monitors the quality of each injection



Injection of 5 batches with 36 bunches each
Uniform losses along the train



Injection of 5 batches with 36 bunches each
Increasing losses along the train

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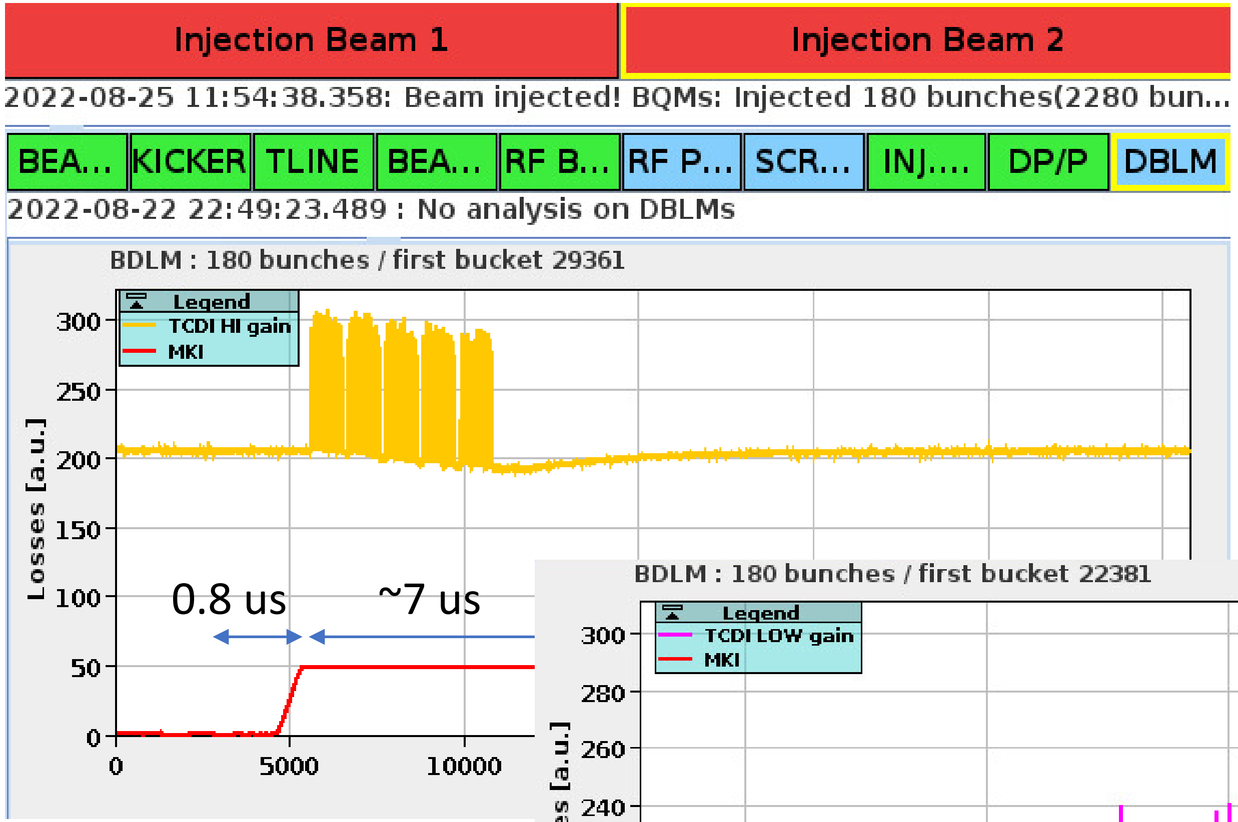

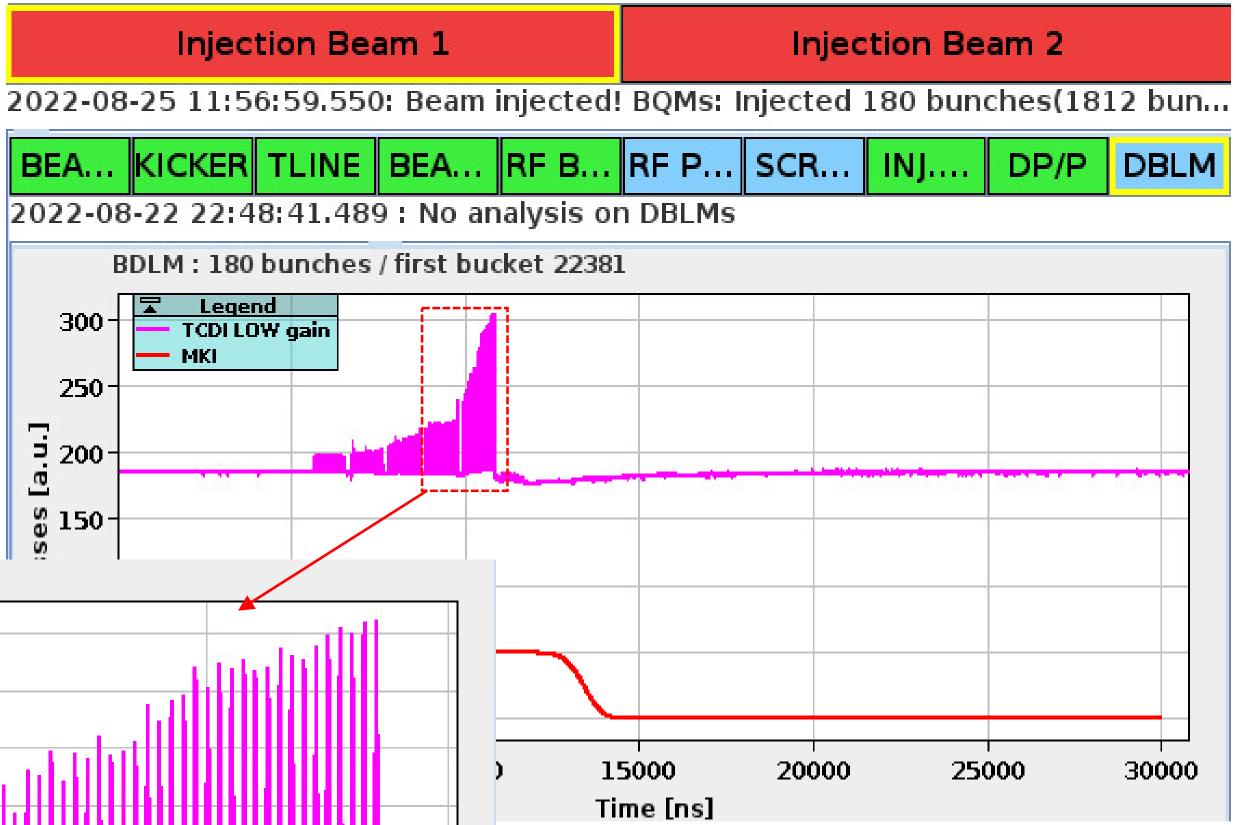

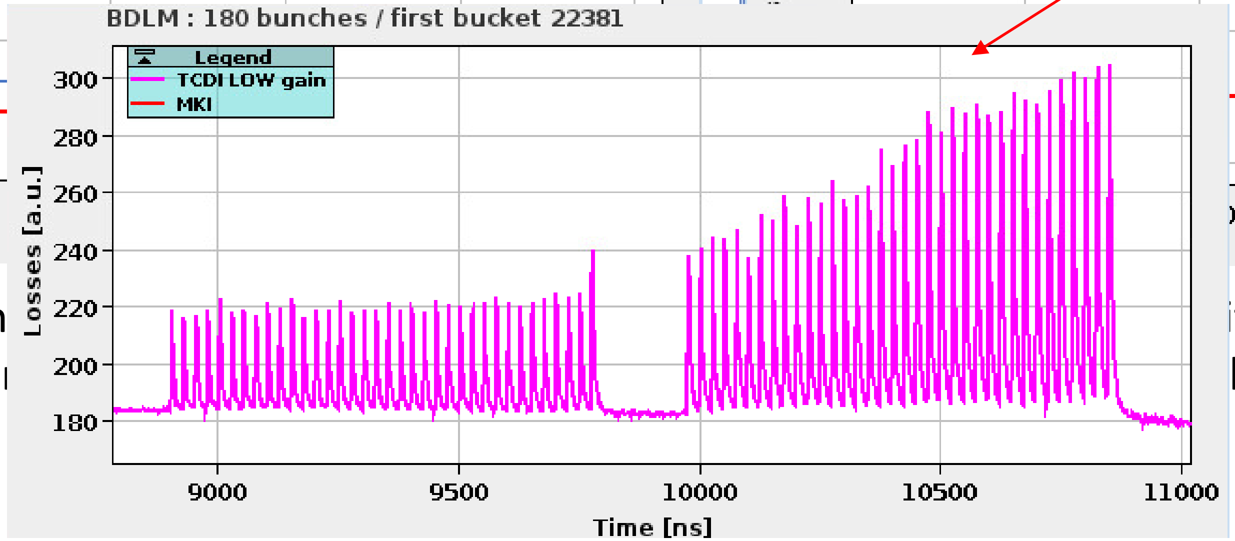

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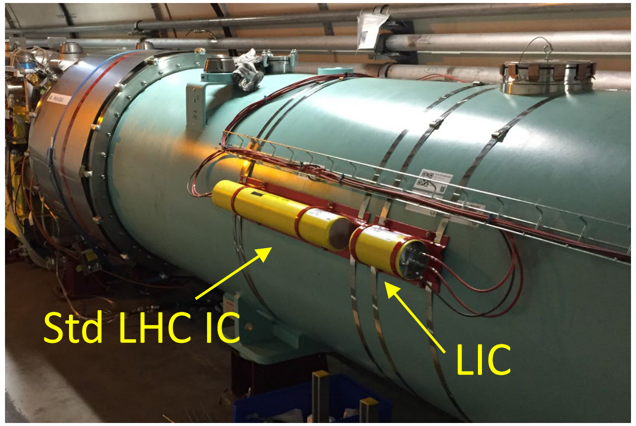
Beam loss detectors types at CERN

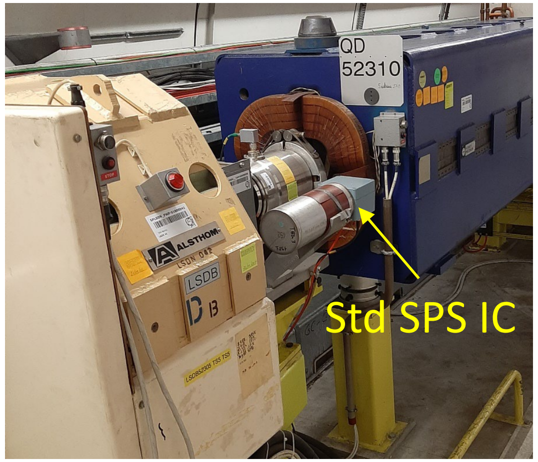
- Beam losses are monitored in the CERN accelerator complex using a several kind of detectors : Ionization chambers (different sizes), SEM, diamonds, etc.
- This allows to cover larger requirements : dynamic range, bandwidth, radiation tolerance or even mechanical constraints

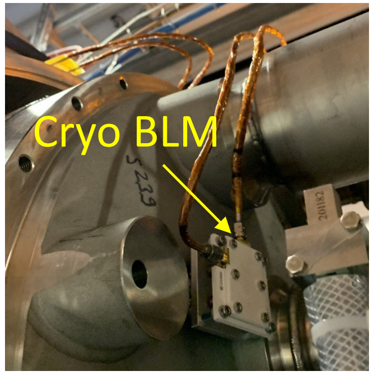
At LHC:
- 3600 ionization chambers (IC)
- 130 secondary emission detectors (SEM)
- 12 diamond detectors
- 4 cryo-BLMs

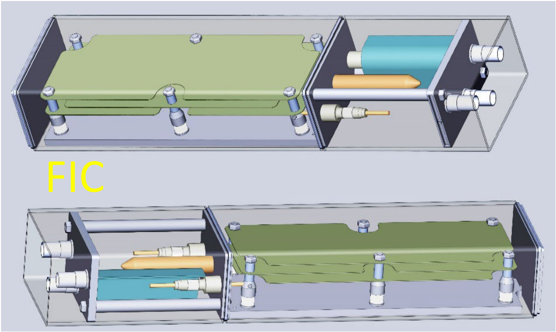
At SPS:
- 456 ionization chambers
- 5 diamonds
- 1 Optical BLM prototype

At injectors:
- 230 flat ionization chambers
- 25 diamonds









Introduction to pCVD diamond detectors

- Very large electron and hole mobilities (1700 and 2100 cm^2/Vs for e^- and holes)

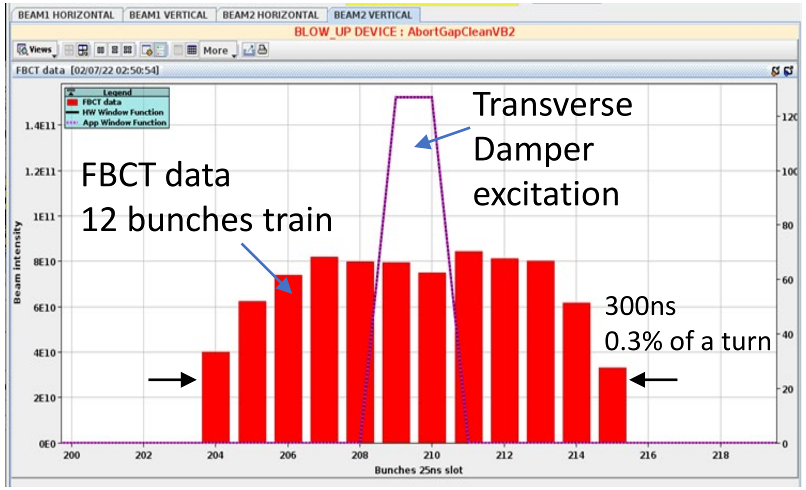
  → Very fast response times, pulses < few ns → Allows bunch-by-bunch losses measurement.
- Large band gap (~5.45eV)

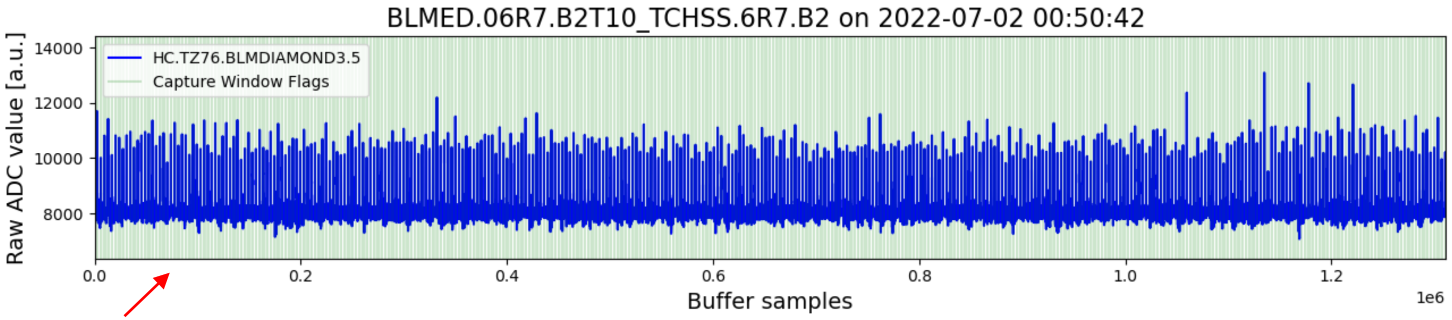
  → high resistivity (>10^{15} Ωcm) → low leakage current (in the order of pA).

  → it allows the application of electric fields ~1-2 V/µm.
- Large displacement threshold energy (43 eV/atom).

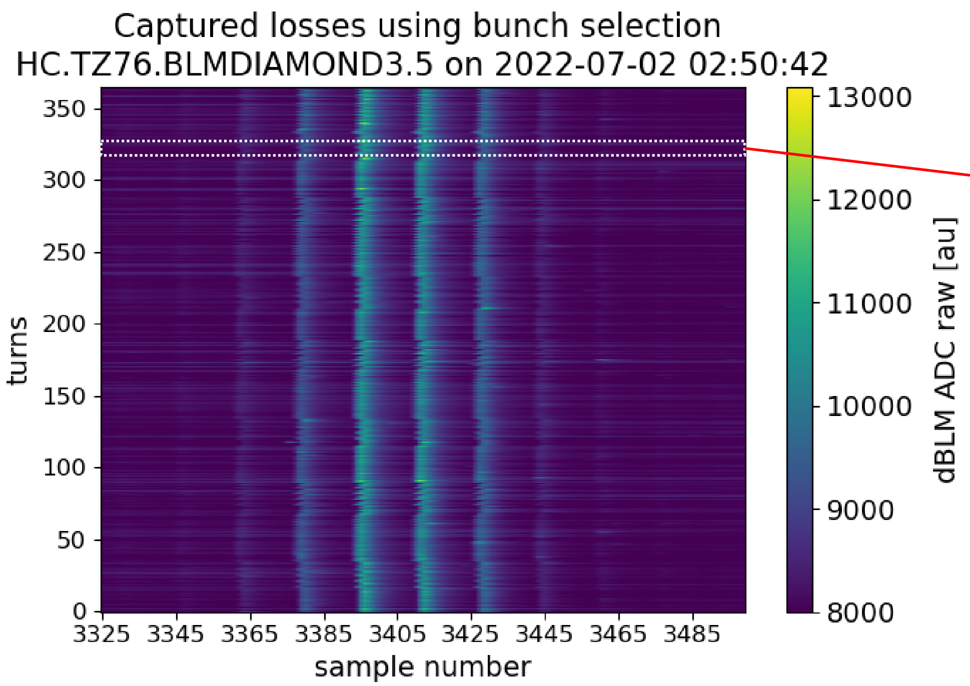
  → Very radiation resistant material (>1MGy Total Ionizing Dose) → Suitable as beam loss monitor.
- Negligible temperature dependence.
- High dynamic range.
- Small dimensions → facilitates integration.

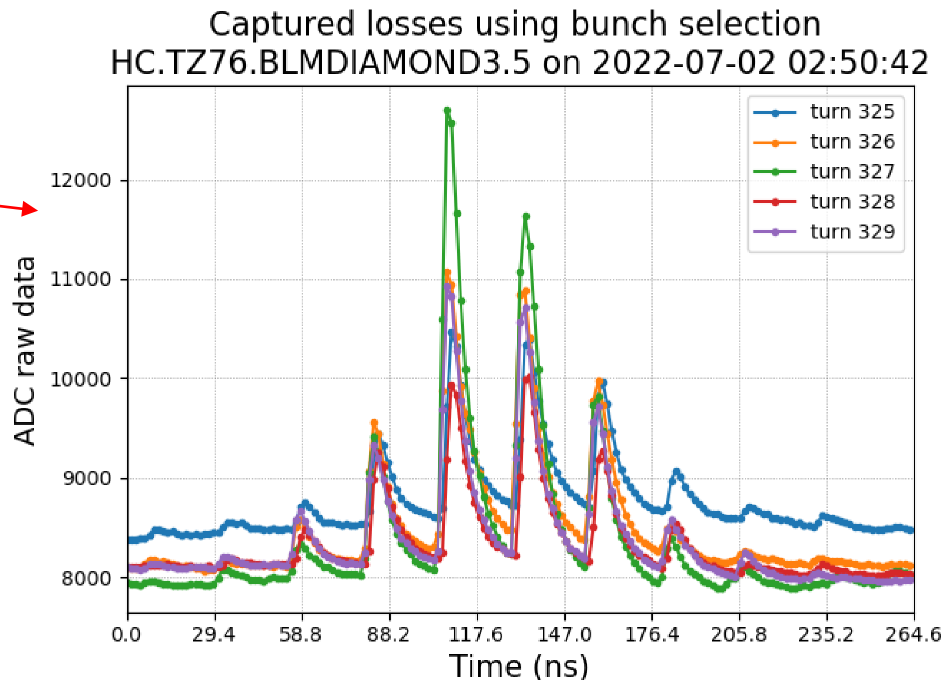
Measurements : Capture on selected bunches





Capture buffer only records selected bunches on successive turns (no data from empty bunch slots)



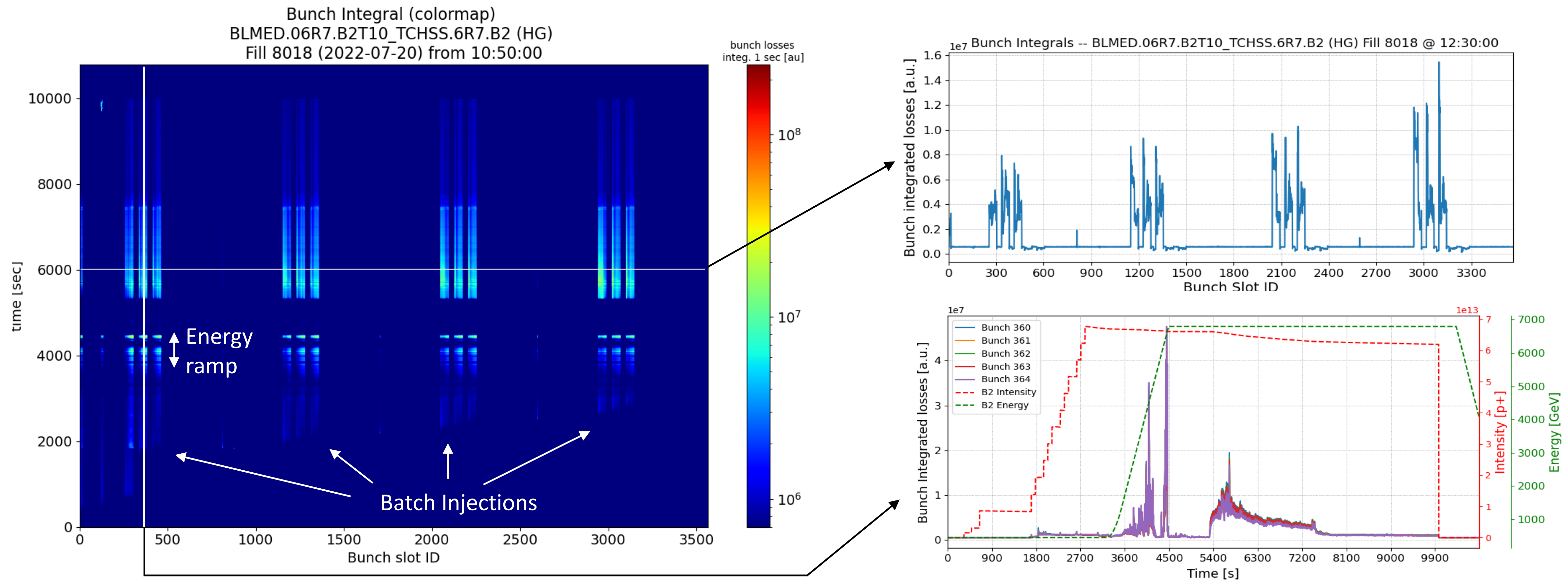


Measurement modes (II)

Continuous measurements

3) Beam loss integral (bunch-by-bunch losses)

Integrate loss magnitudes within a bunch slot using baseline restitution.
Accumulates bunch losses for a configurable number of turns



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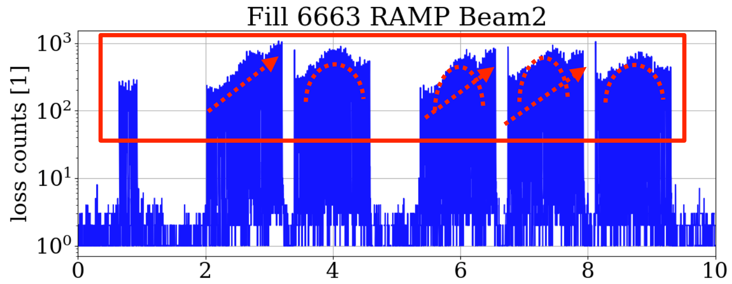
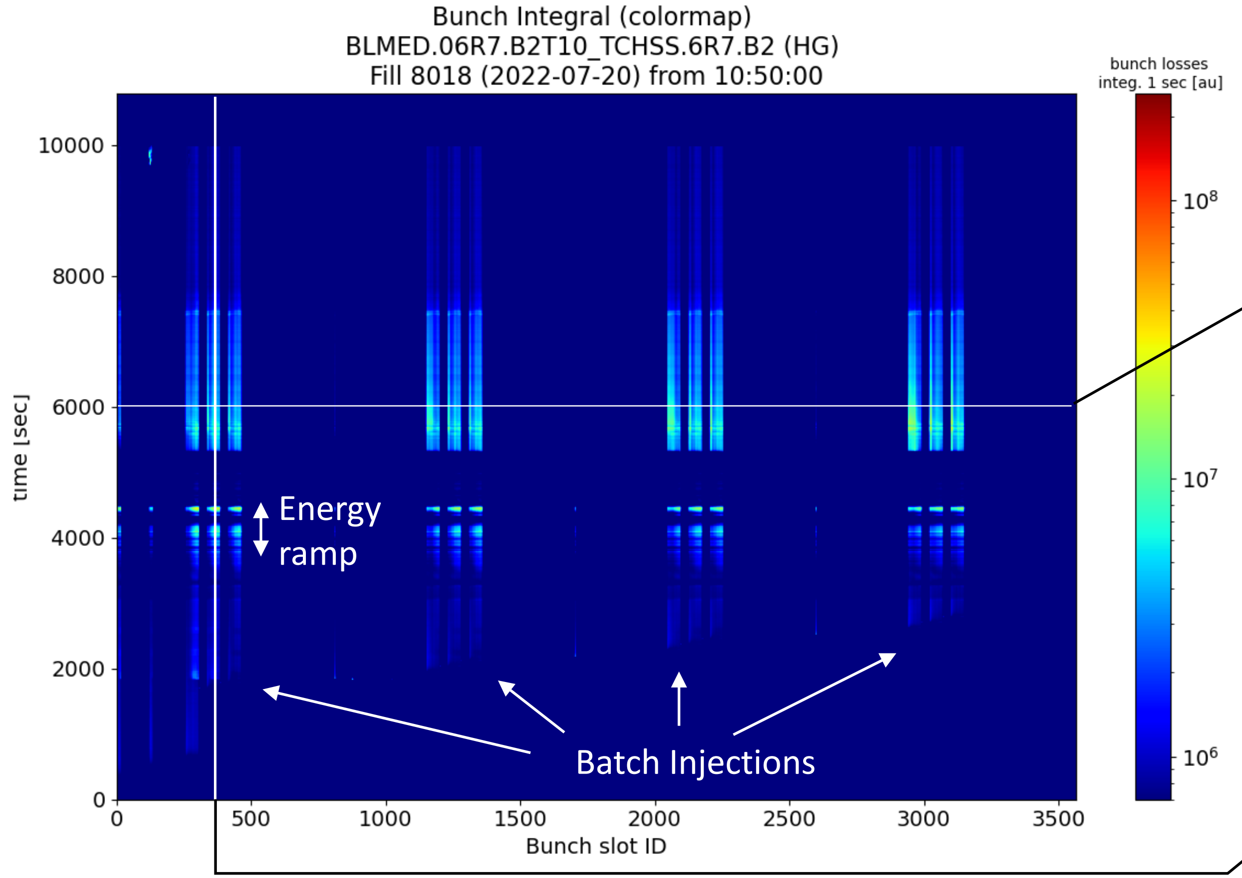
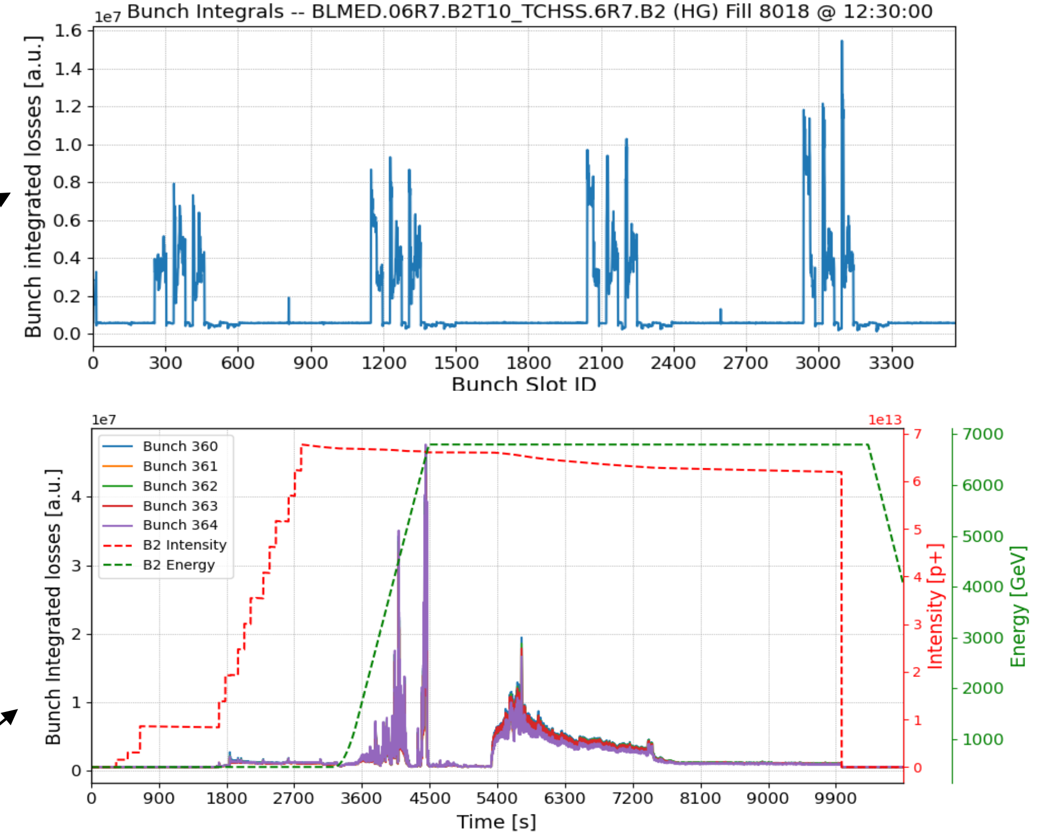
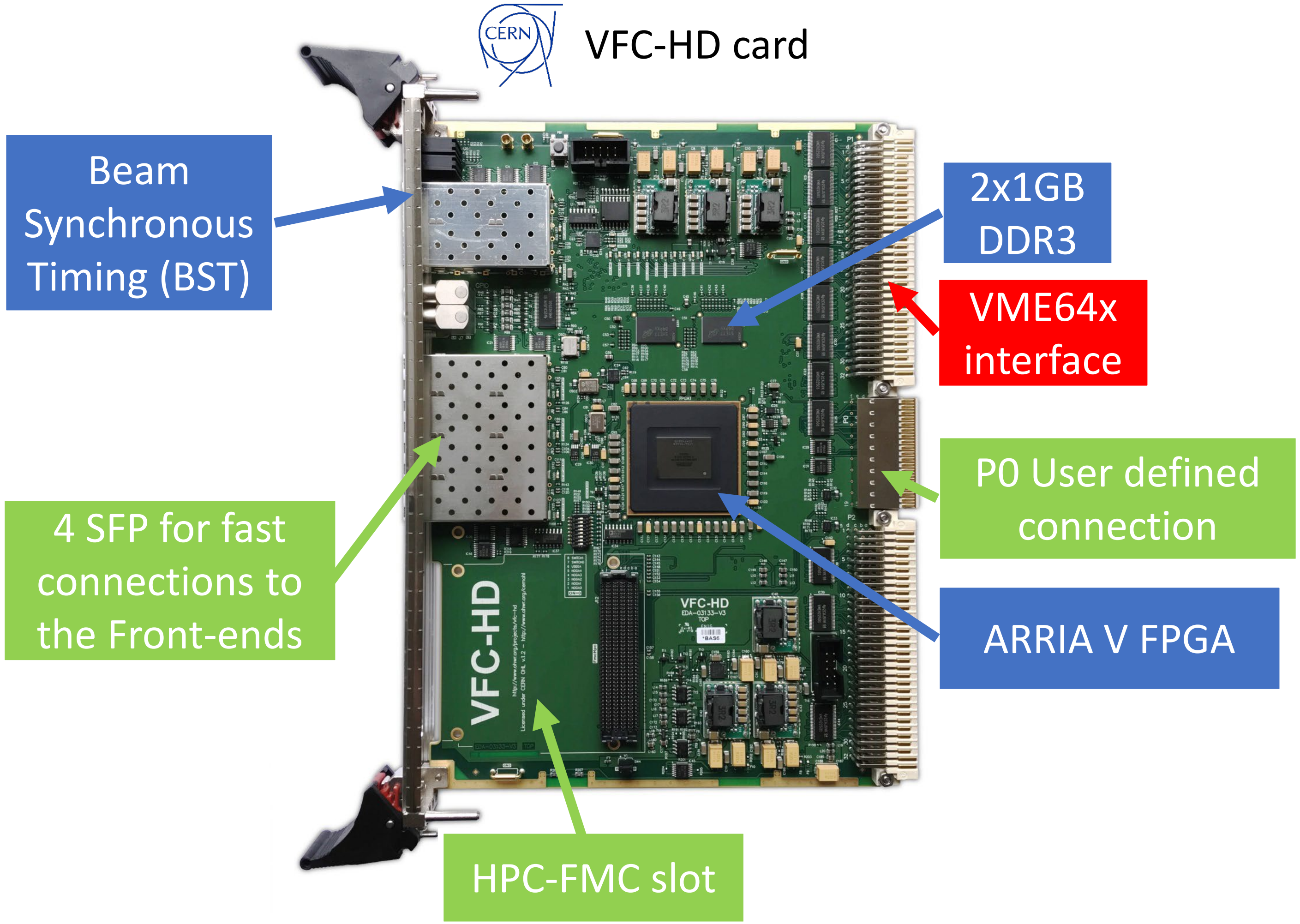


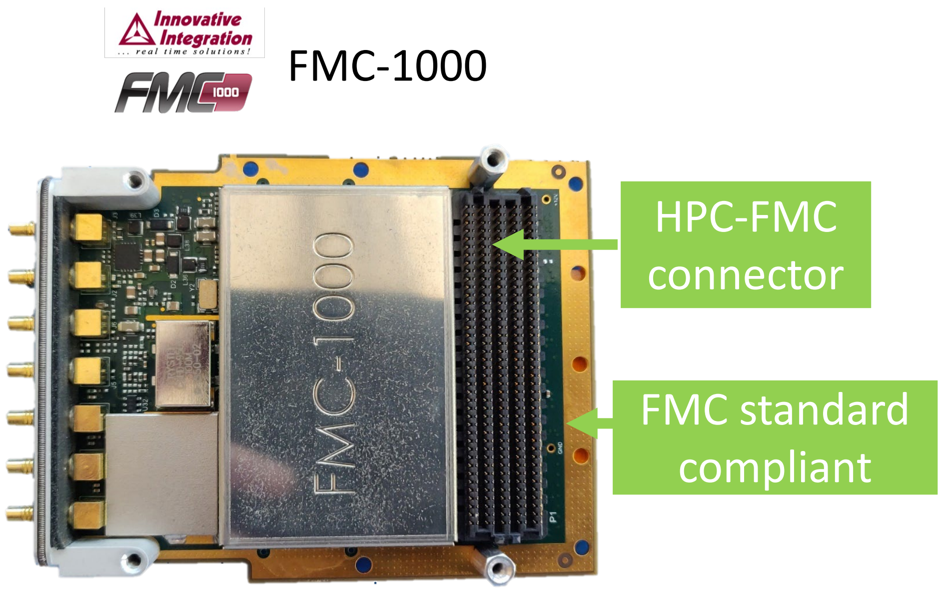
Figure CREDIT: A. Gorzawski





The acquisition chain : Data read-out





1x 2 channel, 14 bit, 1250 MSPS ADC
DC coupled

Currently used at a Max. speed of 650 MSPS due to Arria V transceiver limit of 6.5 Gbps

Silicon vs Diamond properties

Property		Silicon		Diamond	
Proton number		14	[10]	6	[10]
Atomic number	[u]	28.0855(3)	[10]	12.010(7)	[10]
Mass density ρ	[g/cm^3]	2.329	[10]	3.520	[10]
Lattice constant	[angstrom]	5.430 95	[85]	3.567	[85]
Melting point	[K]	1687	[86]	4713	[86]
indirect Band gap	[eV]	1.12	[87]	5.46 to 5.6	[87]
Rel. dielectric constant		5.7	[88]	11.9	[89]
Resistivity	[Ω cm]	2.3×10^5	[90]	10^{16}	[91]
Breakdown field	[V/cm]	$\approx 3 \times 10^5$	[87]	10^6 to 10^7	[87]
e mobility μ_e	[cm^2/(V s)]	≤ 1400	[87]	≤ 2200	[87]
h mobility μ_h	[cm^2/(V s)]	≤ 450	[87]	≤ 1800	[87]
e saturation velocity	[10^7 cm/s]	0.86	[92]	9.6	[93]
h saturation velocity	[10^7 cm/s]	0.8	[92]	1.4	[93]
Thermal conductivity	[W/(K cm)]	1.3	[87]	6 to 20	[87]
Energy to create eh-pair	[eV]	3.6	[94]	13	[95]
Radiation length X_0	[cm]	9.370	[10]	12.13	[10]
no. of eh-pairs/MIP	[e/µm]	80	[94]	36	[96]
Displacement energy	[eV]	13 – 20	[97]	37 – 47	[98]

Table 2.2.: Material properties of diamond and silicon. Properties, which depend on the temperature, are given for room temperature and atmospheric pressure.

Table from : "CVD Diamond Sensors In Detectors For High Energy Physics", Felix Bachmair PhD Thesis (DISS. ETH NO. 23725)