Beam Diagnostics for studying Beam Losses in the LHC

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Outline

- Introduction: LHC, BLM
- Machine Protection as Main Functionality
- Alternative Measurements:
  - Beam Lifetime
  - Beam Loss Plane Decomposition
  - Bunch-by-bunch loss pattern
  - Off-momentum feedback
- Summary

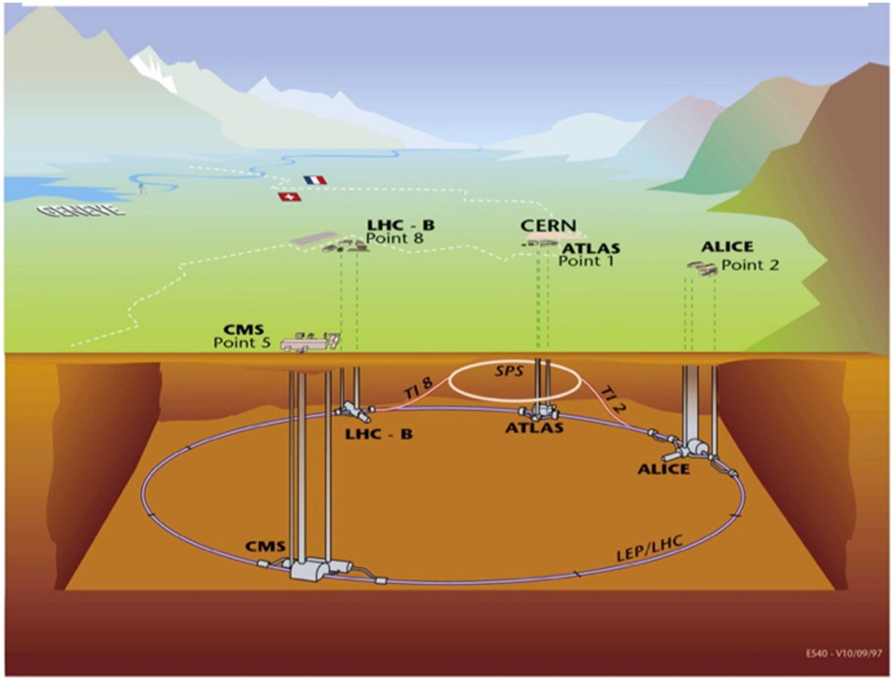
CERN LHC

The LHC is a 26.7 km hadron collider (proton-proton and ion-ion).

Nominal beam energy 7 TeV

Equipped with **super-conducting magnets** cooled down to **1.9K**.

1232 dipole magnets providing a magnetic field of **8.33 T** at nominal current.



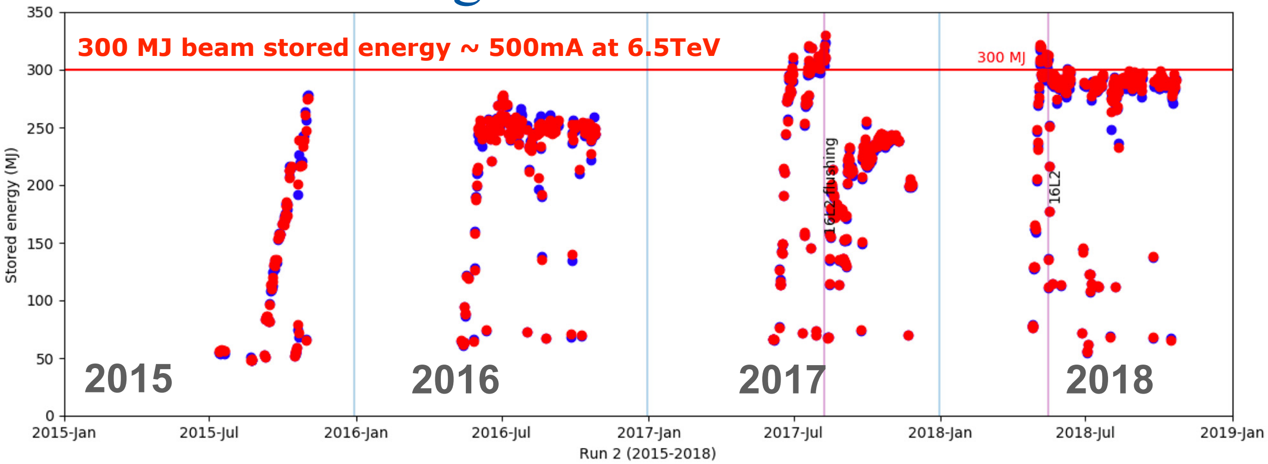
Energy deposition ***at 6.5TeV of ~ 100 mJ/cm3 risk to initiate a quench.***

High current beams (0.5A) are accelerated to near 7 TeV with **very small margin to magnet quench,** meaning that very few particles can be lost in the magnets.

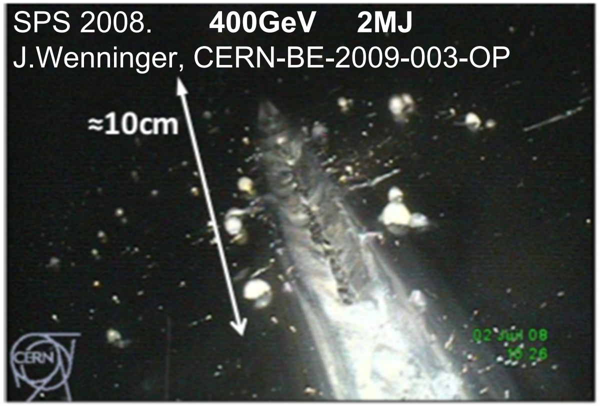
2018 LHC stored energy

*Energy deposition **at 6.5TeV of ~ 100 mJ/cm³ risk to initiate a quench***

Run II circulating beam intensities reached **~300MJ at 6.5TeV**



At 6.5 TeV with about $3x10^{14}$ proton beams, a tiny fraction of beam, 0.00002%, could quench a magnet (~ $6x10^7$ protons)



A quench without damage will require ~ 10 hours of cool down time to recover the cryogenic conditions, impacting on operational efficiency. With damage ~ 3 months

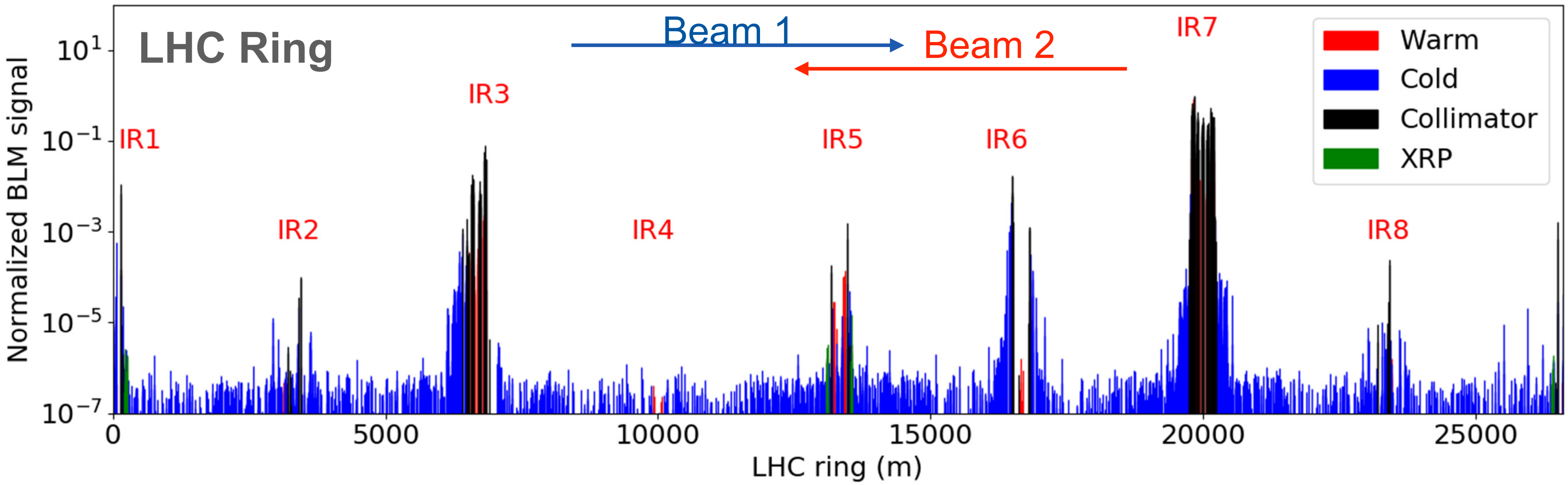
Beam Loss Monitoring for Machine Protection and Operational efficiency

LHC Beam Loss Monitoring

Approximately 4000 Beam Loss Detectors distributed along the LHC covering critical locations:

- ✶Losses in the cold area: dipoles, quadrupoles, etc.
- ✶Losses at injection and extraction: transfer lines
- ✶Losses down stream each collimator.

Losses are concentrated in warm regions



LHC Beam Loss Monitors

Ionisation chamber

About 50cm tube with parallel aluminium electrodes plates (each 0.5 cm)
Filled with N_2 at 100mbar overpressure and HV 1.5kV
1.5L of sensitive volume

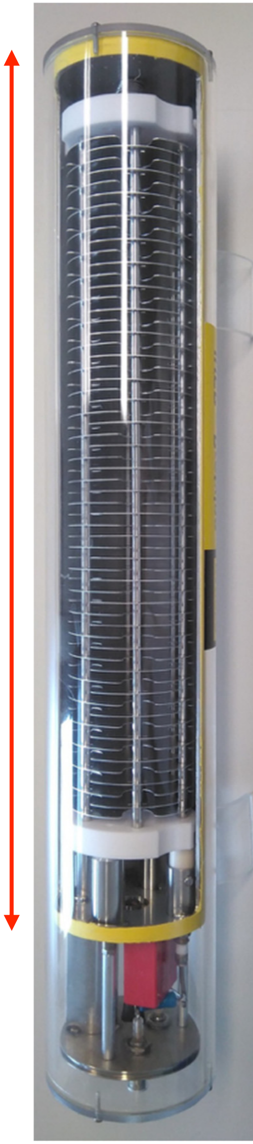
Read out

By charge to frequency conversion using radiation tolerant electronics with dynamic range > 10^8 (10 pA - 1 mA)
Measurement of Gy/s in 12 moving average windows ranging **from 40 μs to 83.9 s**
Allows the setting of unique beam extraction thresholds depending on the duration of the beam loss and beam energy.

LHC turn is 89 μs

Beam extracted in ~ 3 LHC turns

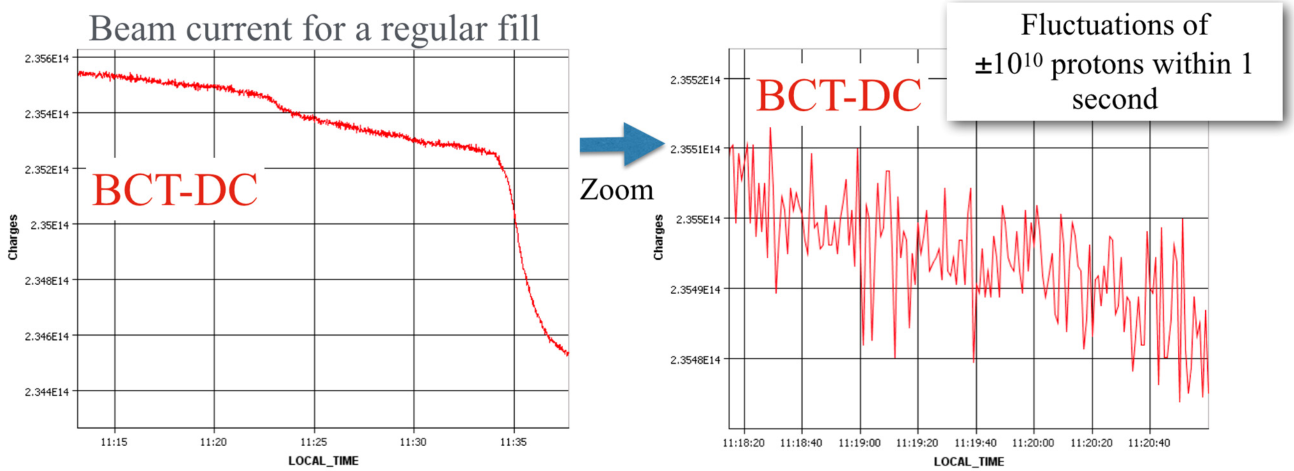
50 cm



Measurement of Beam Losses

Number of particles lost in given time (Beam Lifetime) is typically monitored using DC Beam Current Transformers (**BCT-DC**)**.** However, this method at LHC requires fit over several seconds.

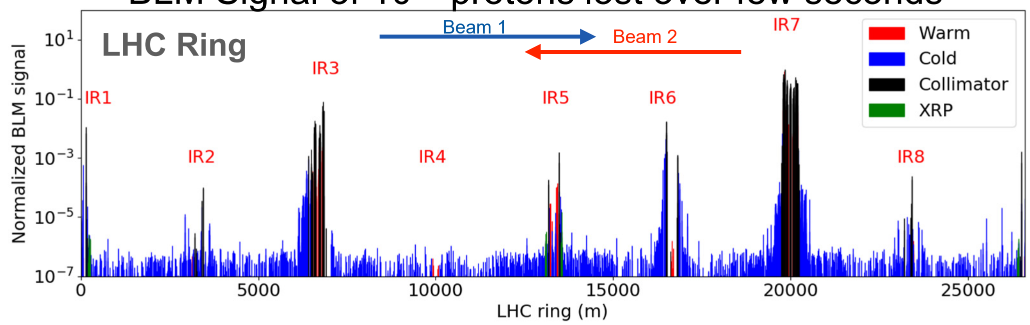
Beam current for a regular fill



10^{10} protons corresponds to: 1µA on 0.5A beam

Other devices such as **beam loss monitors could be used for this measurement** and have additional advantages for the measurement of the proton loss rate.

BLM Signal of 10^{10} protons lost over few seconds



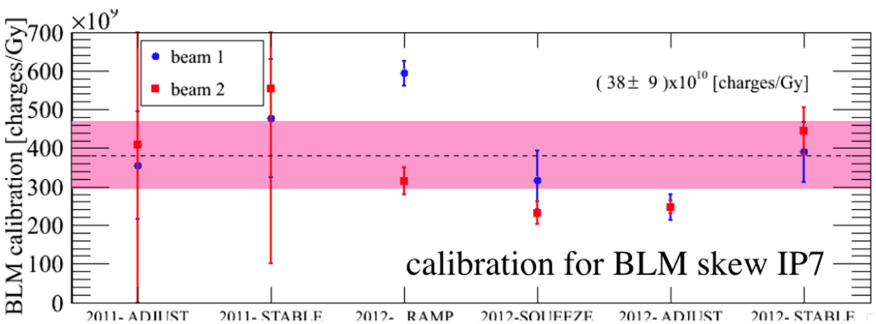
BLM Calibration: Run I

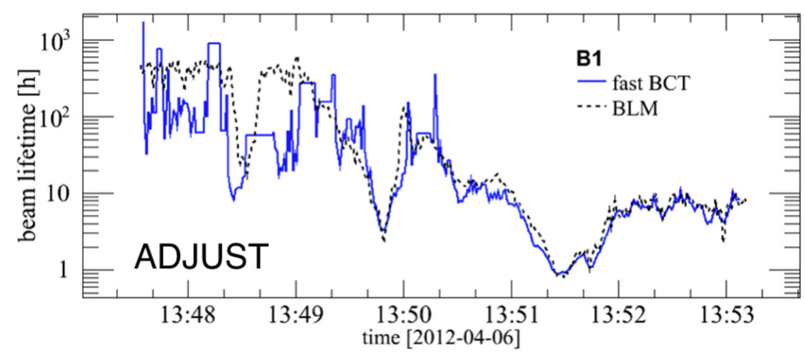
Calibration of BLMs from Gy/s to protons per second

Individual cross-calibration of Beam Loss Detector downstream of primary collimators.

Input data used:

- **Beam scraping studies:** fully scrape low intensity beam with the collimator jaw in steps (*F. Burkart, PhD 2012 CERN-THESIS-2012-046 Beam Loss and Beam Shape at the LHC collimators)*
- **Analysis of beam losses during LHC cycle:** fitting the BLM signal to the derivative of the beam current measurement *(B.Salvachua et al. "Lifetime Analysis at High Intensity Colliders Applied to the LHC", IPAC2013)*





BLM Calibration: Run II

Review the idea of identifying loss patterns (A.Marsili PhD CERN-THESIS-2012-316)

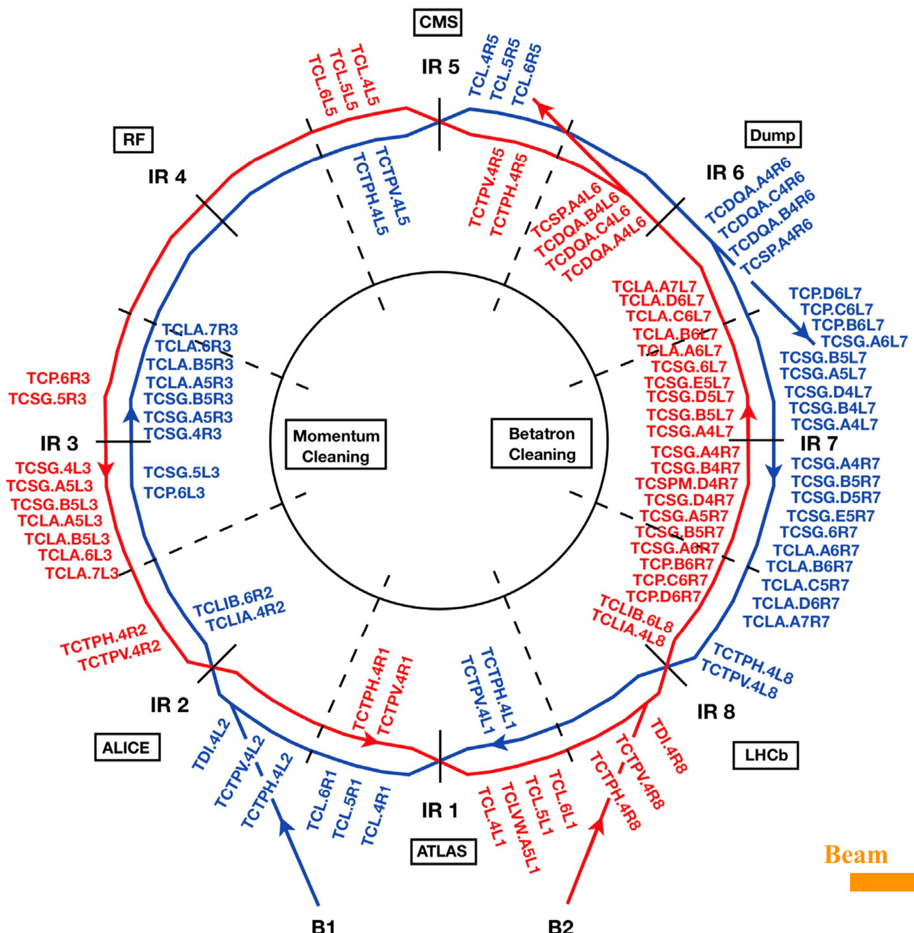
Provide two type of calibrations:

- *Based on few BLMs not sensitive to the plane of losses.*
- *Based on more BLMs combined to get losses with different pattern (SVD).*

ONLINE DIAGNOSTICS
Less sensitive to changes in collimation settings

OFFLINE ANALYSIS
More precise but more sensitive to collimation hierarchy

Concept

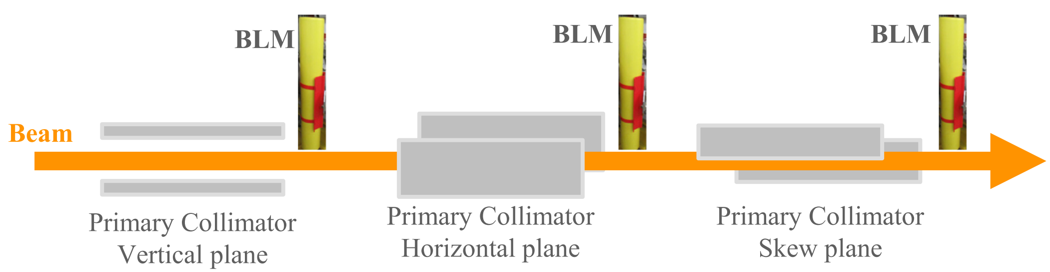


LHC collimation system

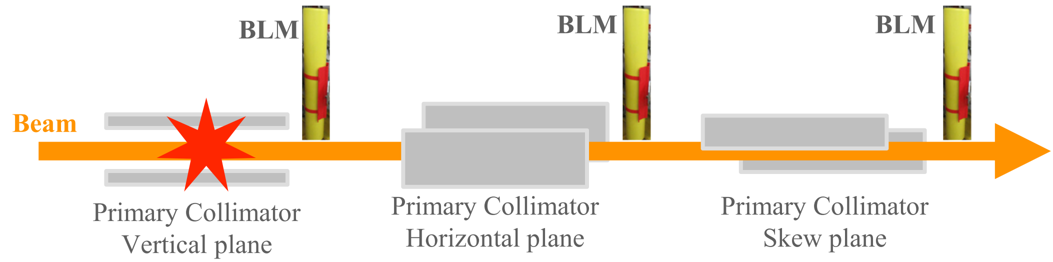
There are about 100 collimators in the LHC, each one with a BLM downstream.

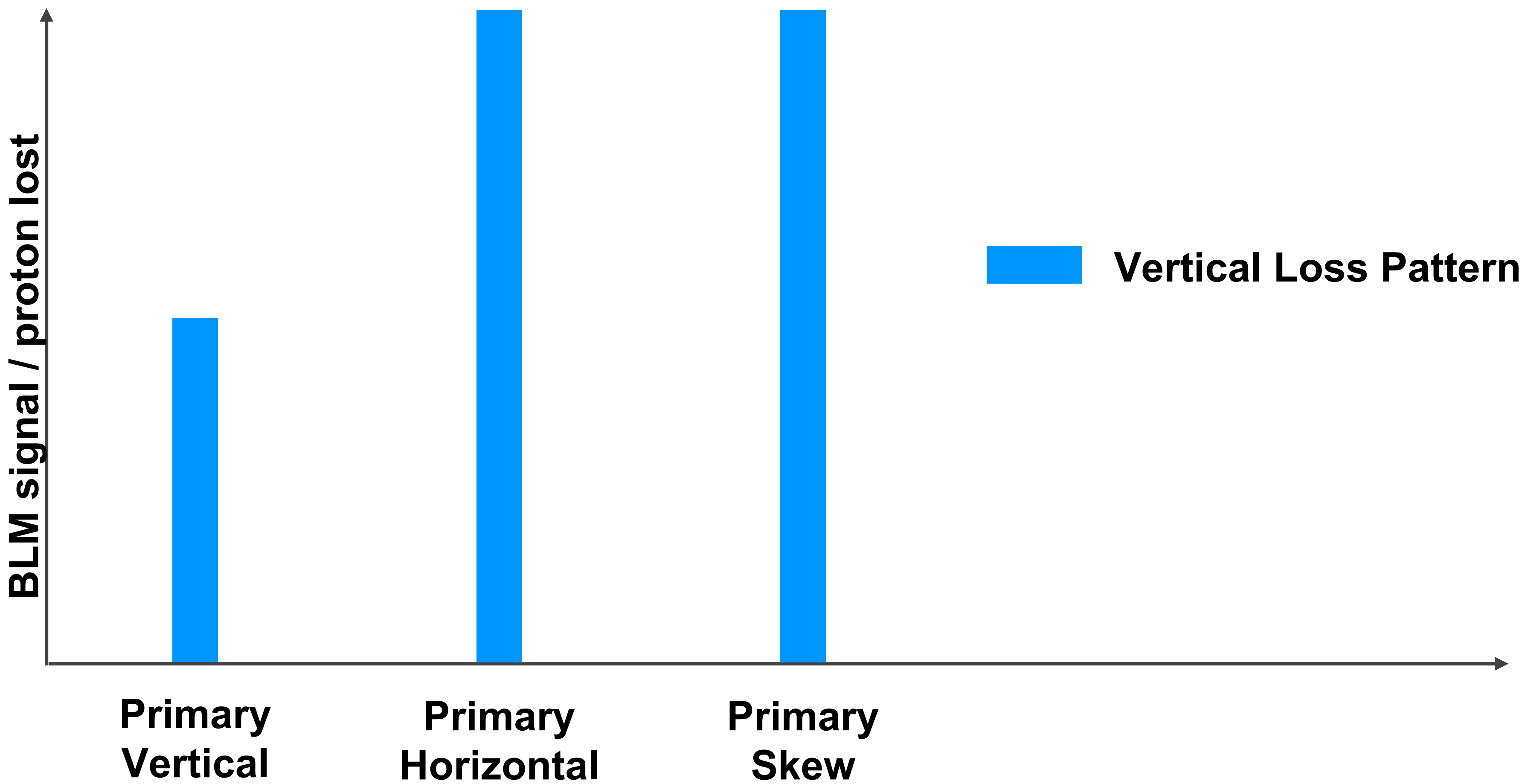
Losses are initiated at the primary collimators. Loss patterns could be observed depending on the type of losses.

Combine information on many BLM
Losses are concentrated in the collimation region (most of the cases).

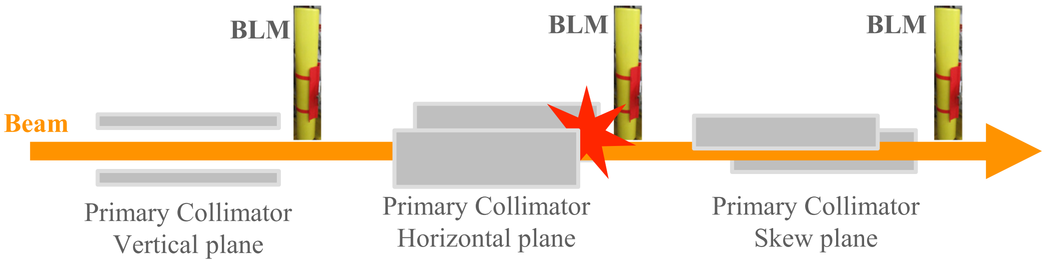


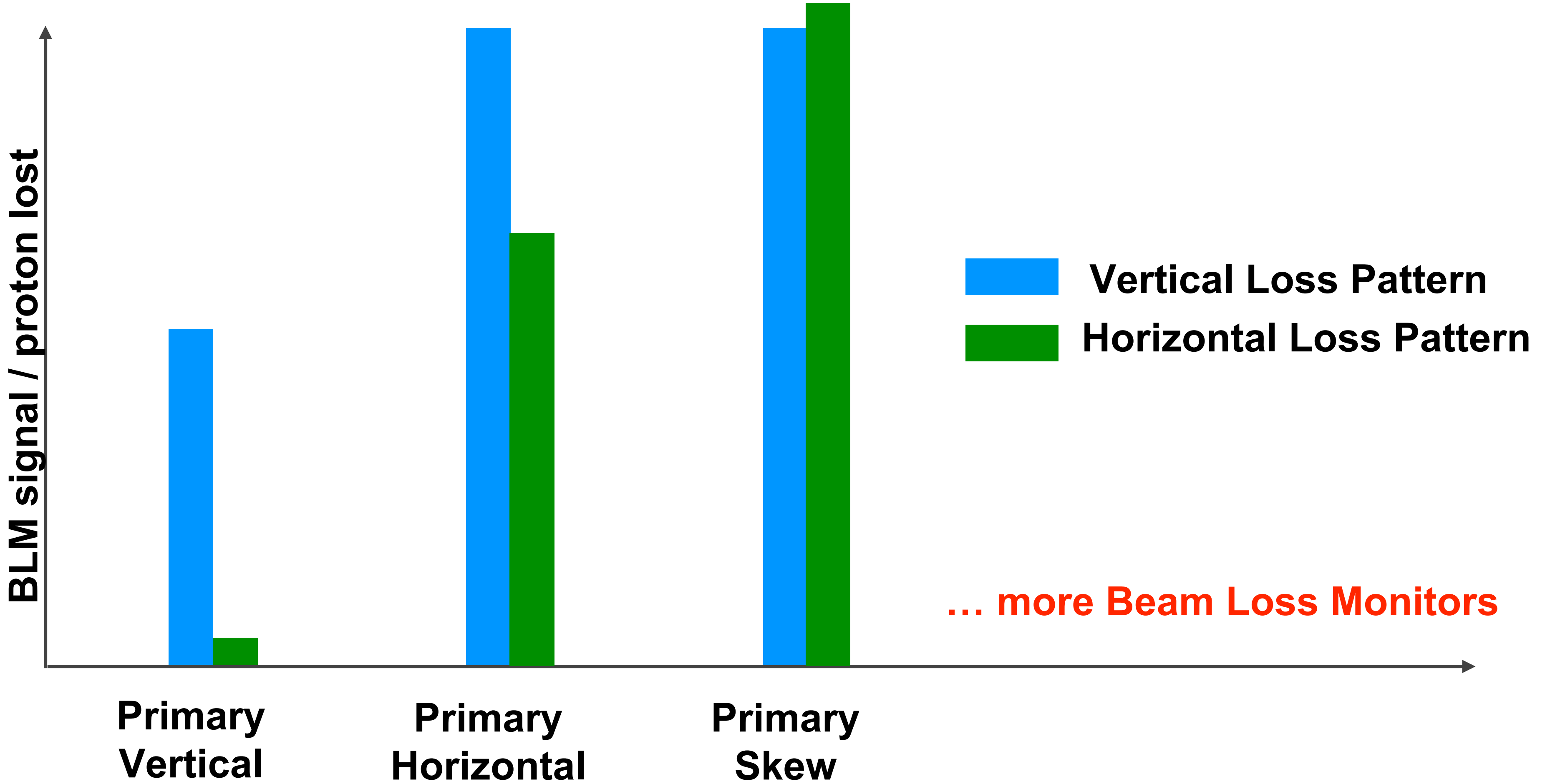
Loss Pattern





Loss Pattern





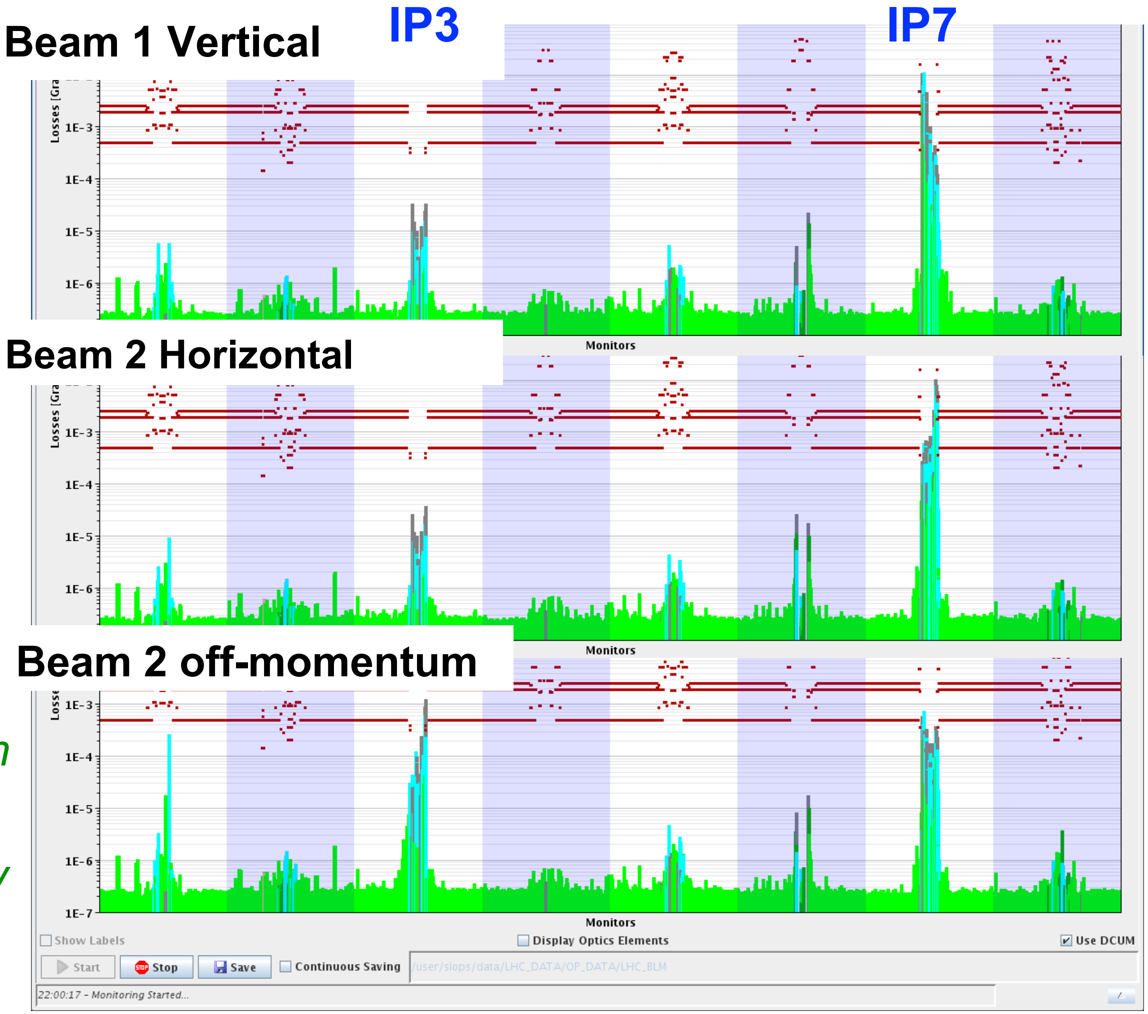
LHC Loss Maps

Well defined loss scenarios were losses in different configuration are created in a controlled way.

- ✶Transverse excitation of the beam at low intensity.
- ✶Beam scraping with different collimators.
- ✶RF frequency shifts at low intensity creating off-momentum losses.

Loss maps are regularly used to validate the LHC machine protection settings.

Performed periodically and after any optics or operational scenario change.



BLM Calibration: Run II

Simple way to re-calibrate the BLMs used for the beam lifetime monitoring in the Control Room that can be re-calibrated quickly if conditions change.

- Select a group of monitors, not too sensitive to the plane of losses
- Cross-Calibrate BLM with BCTs using dedicated loss map data and parasitic physics fill to verify calibration.

BLMEI.06R7.B2I10_TCHSS.6R7.B2	BLMEI.06L7.B1E10_TCHSS.6L7.B1
BLMEI.06R7.B2I10_TCHSH.6R7.B2	BLMEI.06L7.B1E10_TCHSH.6L7.B1
BLMEI.06R7.B2I10_TCHSV.6R7.B2	BLMEI.06L7.B1E10_TCHSV.6L7.B1
BLMEI.06R7.B2I10_TCP.A6R7.B2	BLMEI.06L7.B1E10_TCP.A6L7.B1

$$min\left(\frac{\mathrm{BLM}}{dI/dt}\bigg|_H - \frac{BLM}{dI/dt}\bigg|_V\right)$$

$$\frac{dI}{dt}\bigg|_{loss} = \alpha \cdot \sum_{i=1,4} \mathrm{BLM}_i$$

Calibrate the sum of all the monitors

$$\frac{dI}{dt} = \frac{dI}{dt}\bigg|_{loss} + \mathcal{L} \cdot \sigma_{inelastic}$$

Including protons lost due to luminosity

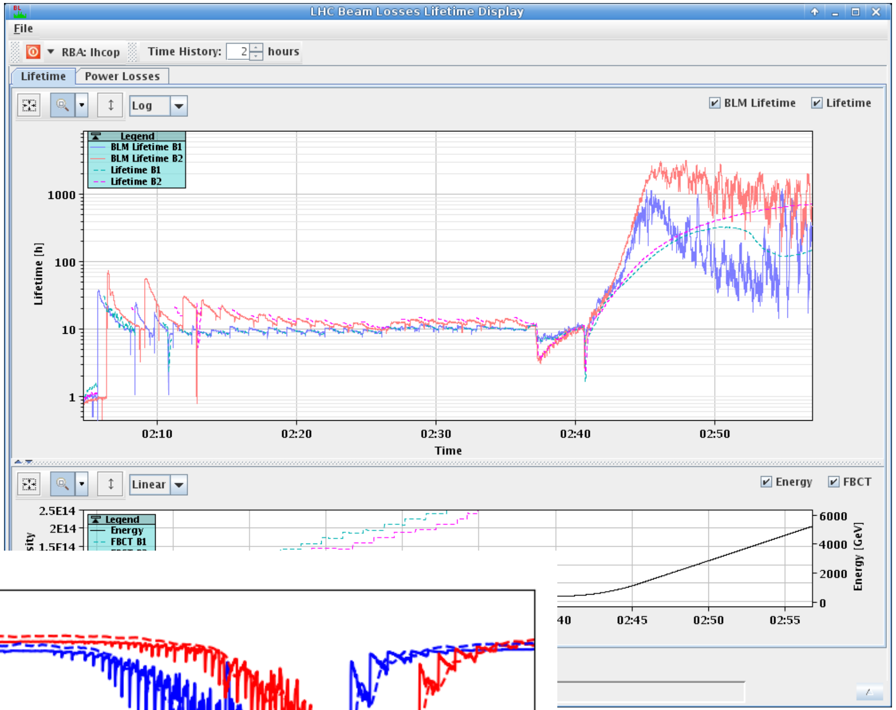
Beam Lifetime

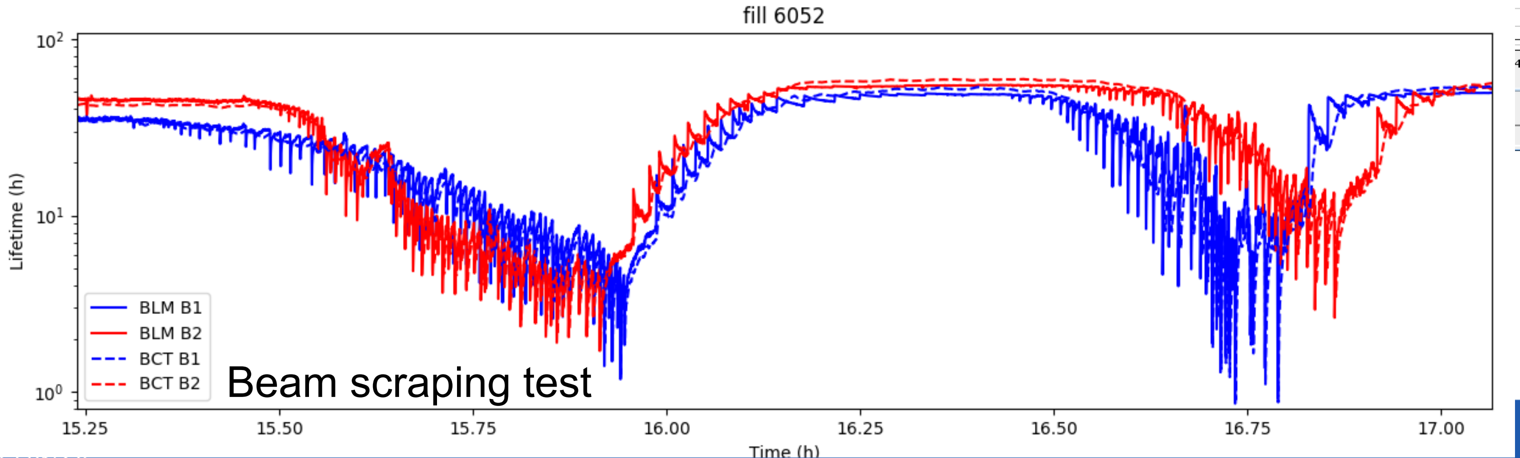
Beam Lifetime is used to monitor the performance of the machine

$$I = I_o e^{\frac{-t}{\tau}} \rightarrow \quad \tau = \frac{-I}{dI/dt}$$ *Beam lifetime*

$$\frac{dI}{dt} = R_{\text{loss}}$$ *Beam loss rate*

Example of beam lifetime online reconstruction and comparison with BCT





SVD Loss Identification

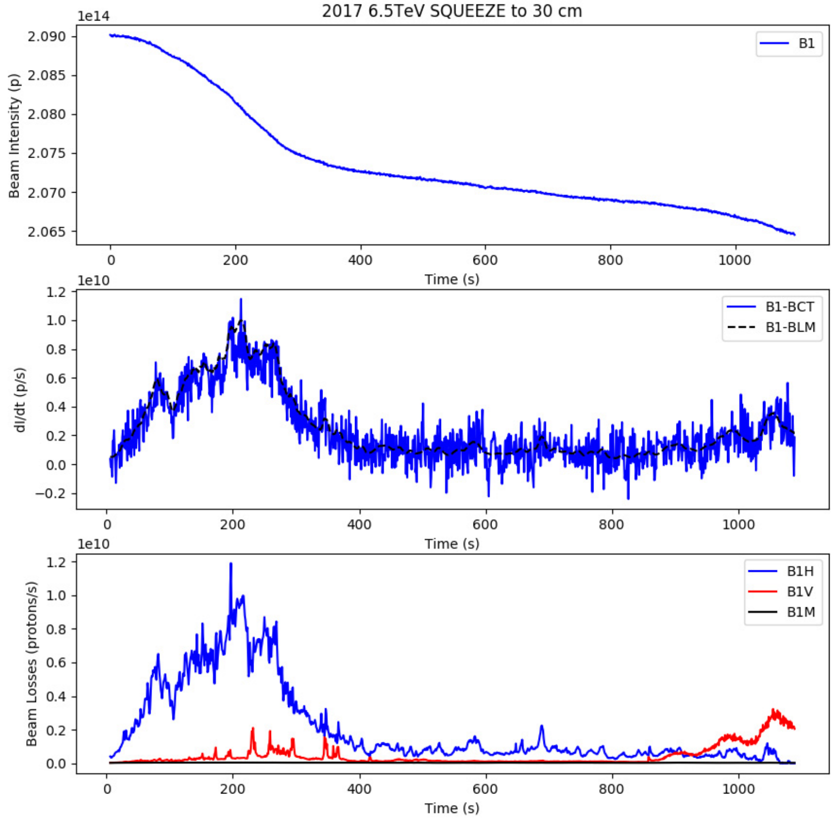
Singular Value Decompositions applied to a BLM matrix to characterised the loss plane:

- **Horizontal losses**
- **Vertical losses**
- **Off-momentum losses**

Input data corresponds to well-defined loss scenarios (pure horizontal losses, etc.)

Result | Matrix built from reference lossmaps | Measurement of BLMs

$$\begin{pmatrix} \text{B1H} \\ \text{B1V} \\ \text{B2H} \\ \text{B2V} \\ \text{B1 off mom.} \\ \text{B2 off mom.} \end{pmatrix} = \left(\dots \right) \begin{pmatrix} \text{BLM 1} \\ \text{BLM 2} \\ \vdots \end{pmatrix}$$

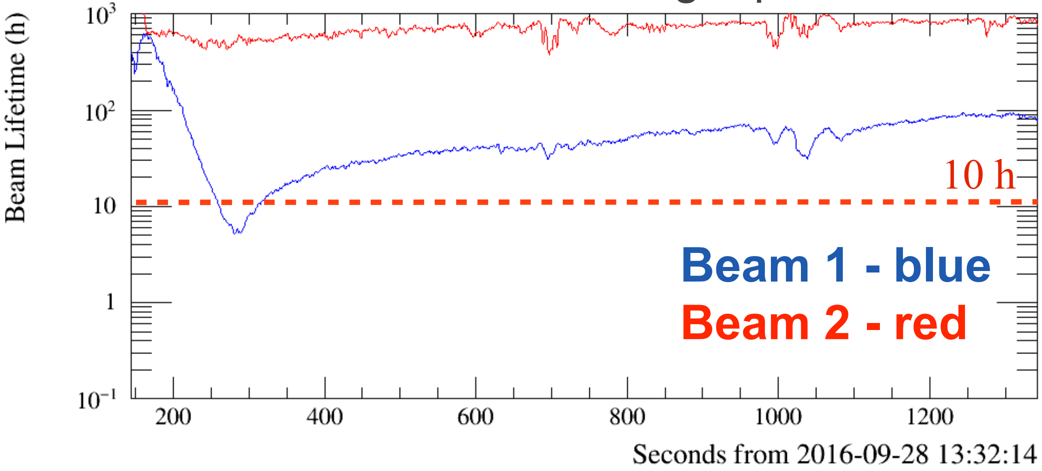


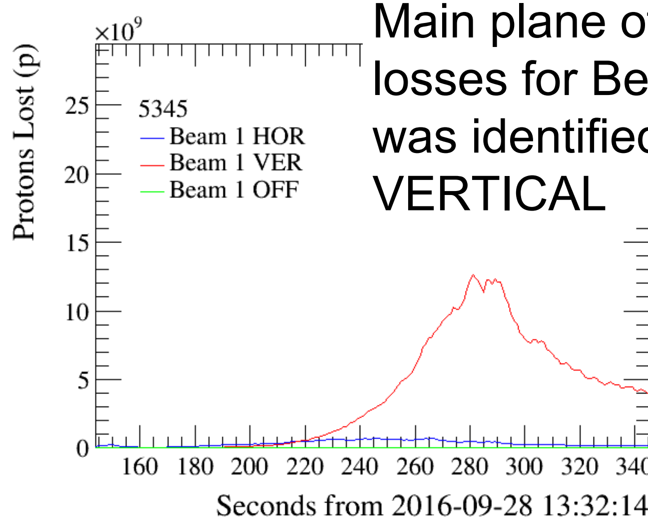
Result is the number of protons lost per second due to each loss scenario

$$\text{BiH} + \text{BiV} + \text{Bi off mom.} \approx -\frac{dI(\text{Bi})}{dt} \qquad i \in \{1, 2\}$$

Usage in operation: beam tune

Beam Lifetime during squeeze

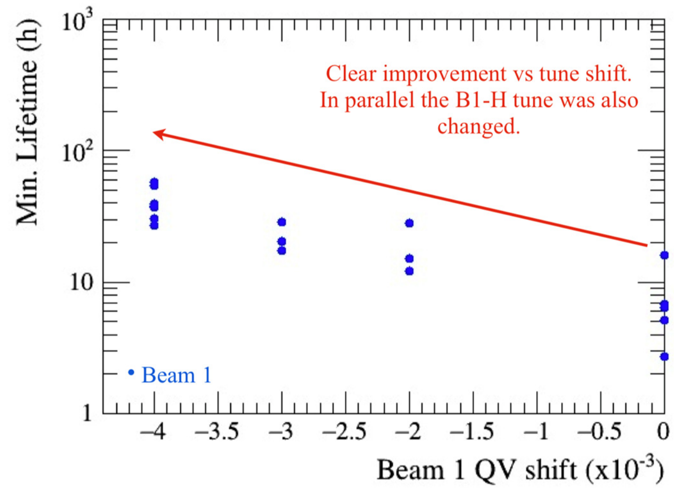




Main plane of losses for Beam 1 was identified as VERTICAL

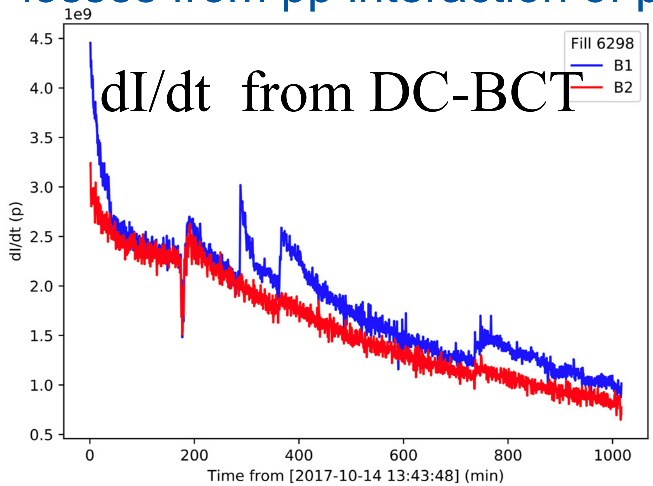
Beam Losses monitored over several LHC fills following changes on the Beam Tune.

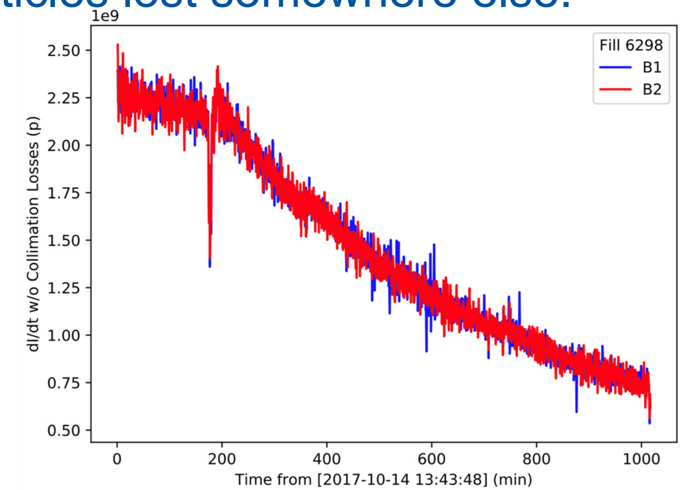
Improvements of losses versus tune trims



Usage in operation: lifetime in collisions

DC-BCT measurement of beam lifetime in collision cannot disentangle beam losses from pp interaction of particles lost somewhere else.

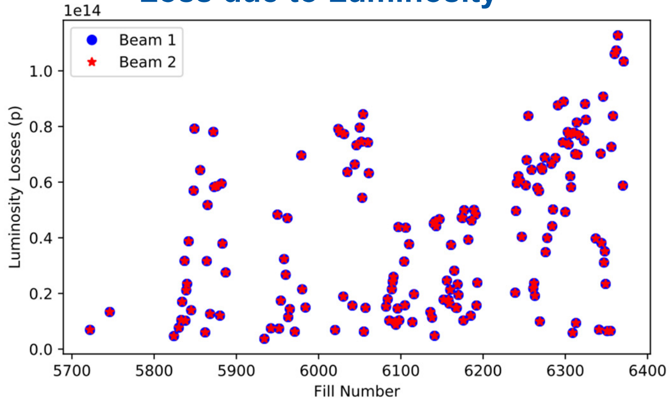




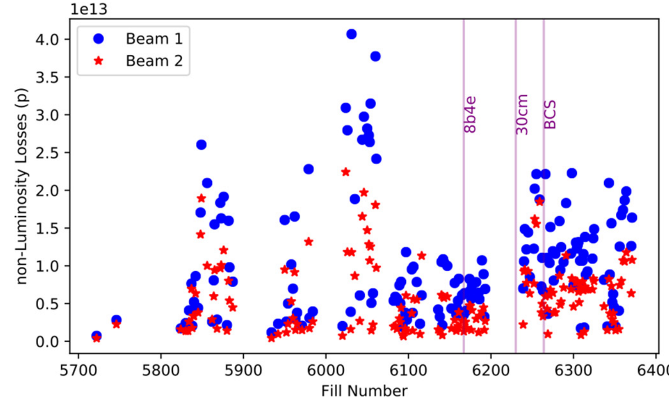
dI/dt corrected from BLM particle lost measurements

BLM provides measurement of machine performance during collisions

Loss due to Luminosity



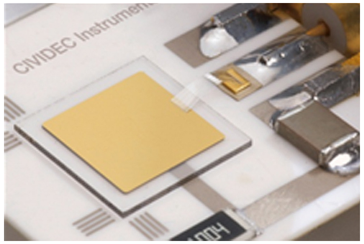
BLM only



Diamond BLM

Complementary devices, solid state ionisation detectors 10 mm x 10mm x 0.5 mm, to provide ns time resolution data

Bunch-by-bunch information!!

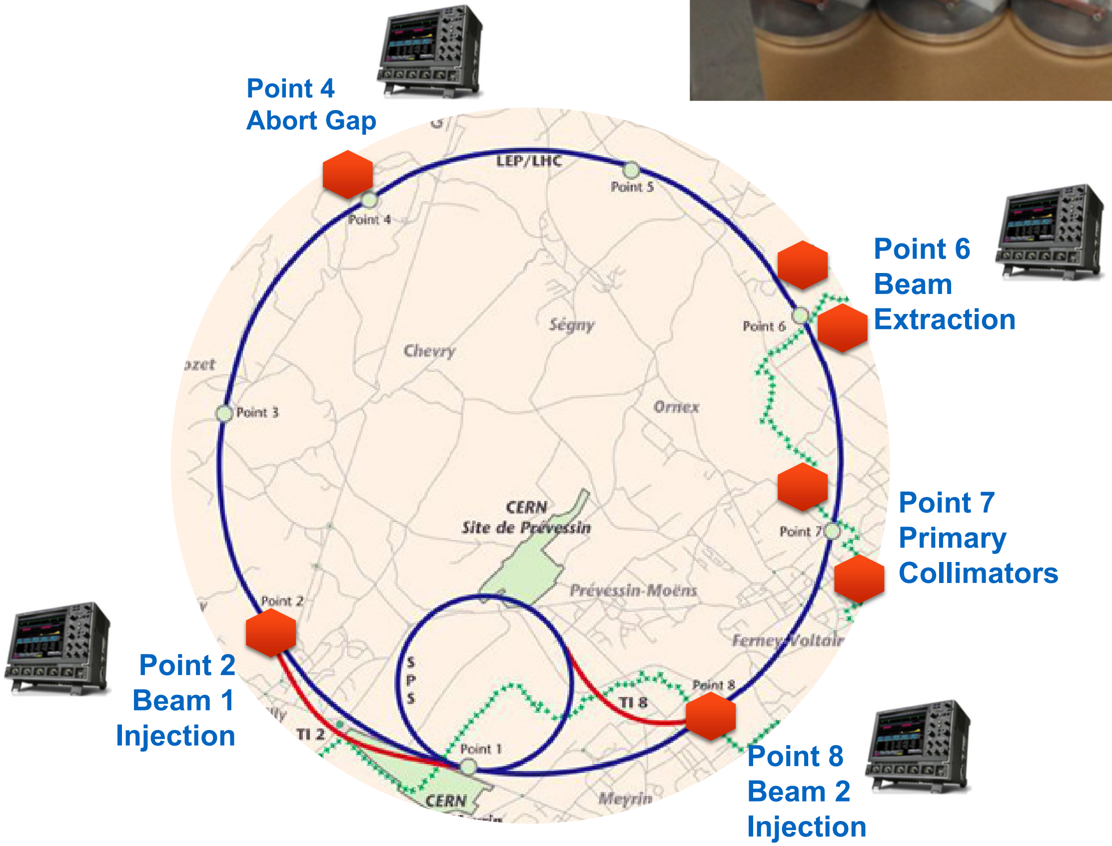


Several units installed in the LHC:

Injection/Extraction and IR7

Point 7, measuring circulating beam losses from collimation:

3 units of dBLM per beam sensitive to primary collimation losses in vertical and horizontal plane.



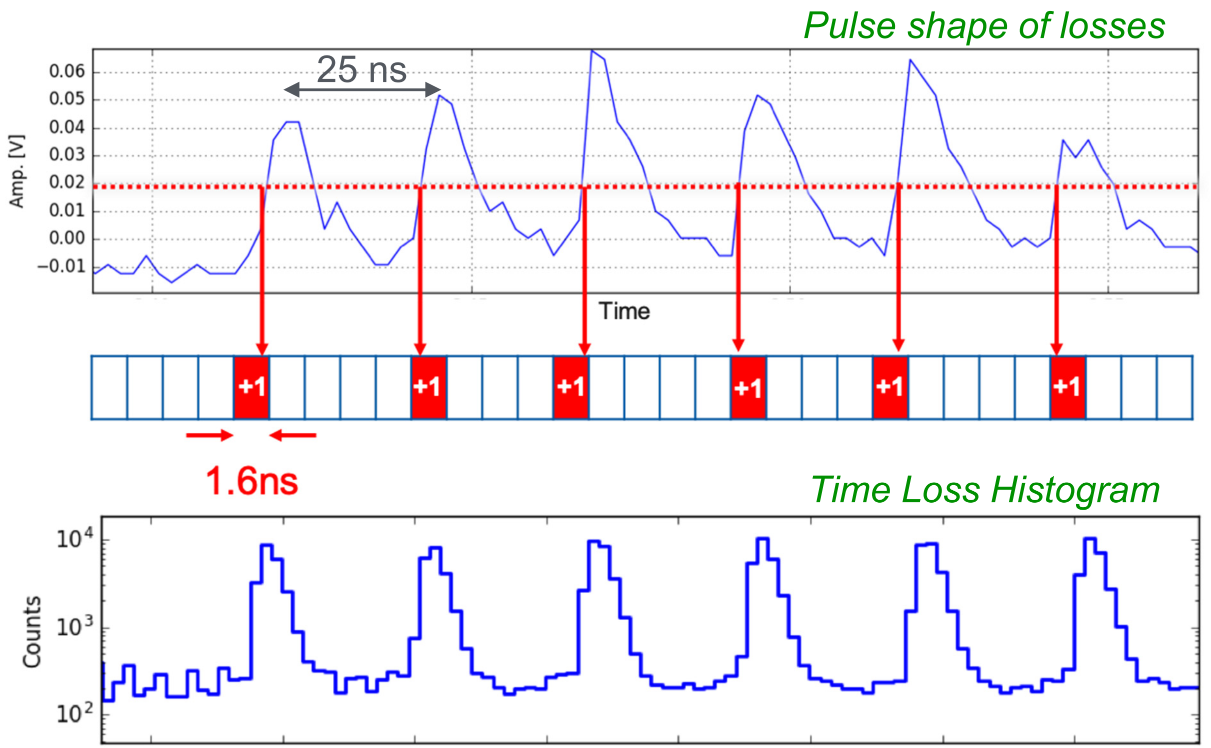
Focusing the rest of the presentation on the Time Loss Histogram read-out

dBLM Read-out

TimeLossHistogram

Precise beam loss timing counts

Threshold of 25mV for histogram data, binning of 1.6 ns, cumulative counts over 1 second.



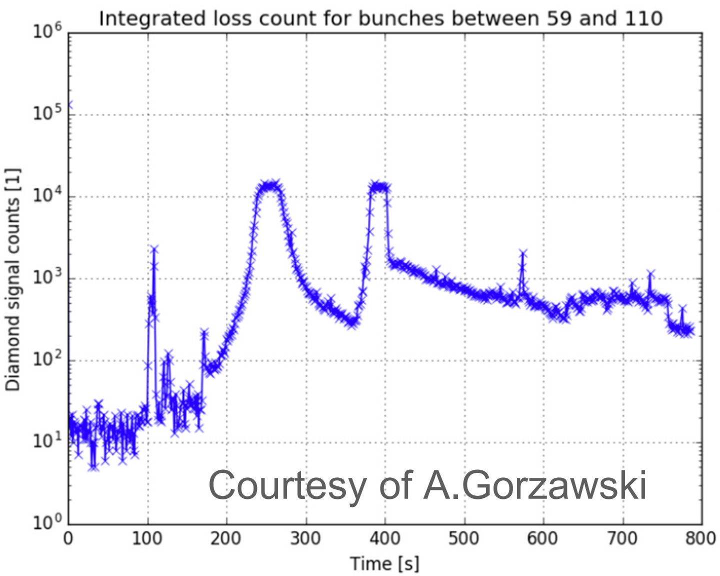
Courtesy of Chen Xu

Bunch-by-bunch: dBLM

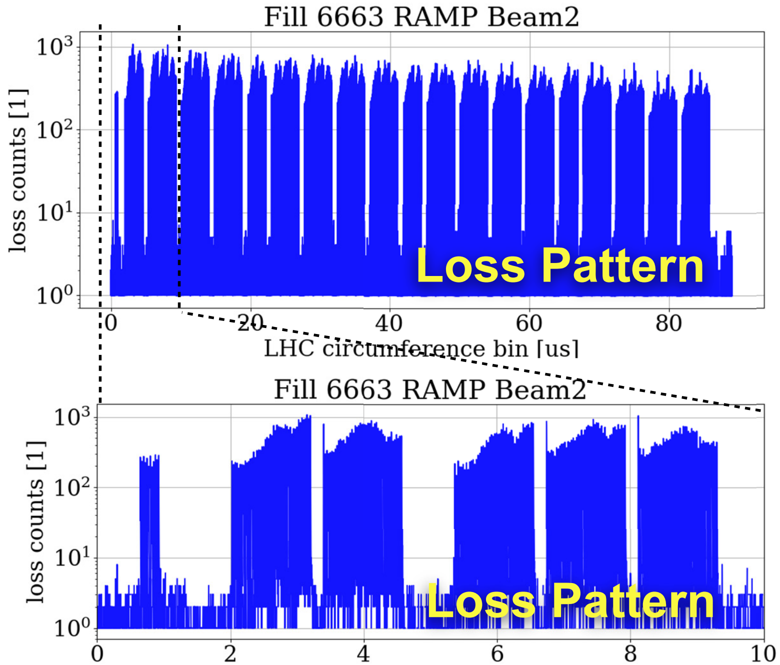
Loss counts can be cumulated over an LHC cycle or specific Beam Mode.

Example of monitoring dBLM counts over the LHC energy RAMP.

Post-processing: dBLM counts summed for all bunches or a selection of bunches as a function of time.



dBLM counts for all bunches accumulated during 1 second.

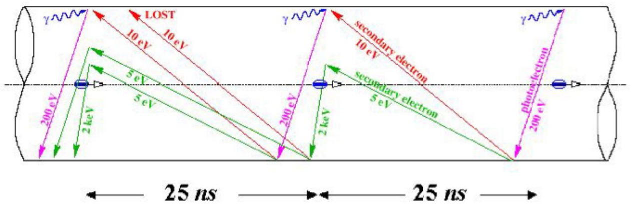


Courtesy of A.Gorzawski

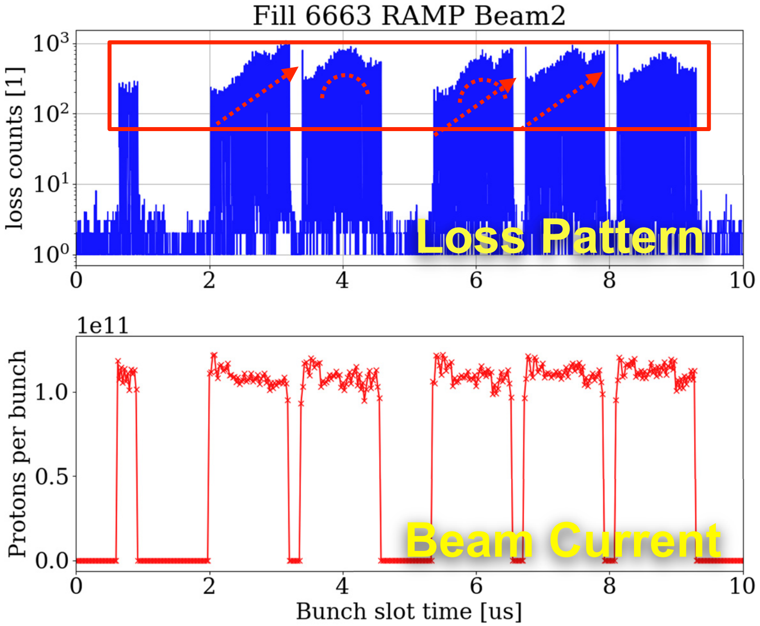
Bunch-by-bunch: dBLM

The structure of losses within the trains can be studied and is reproducible.

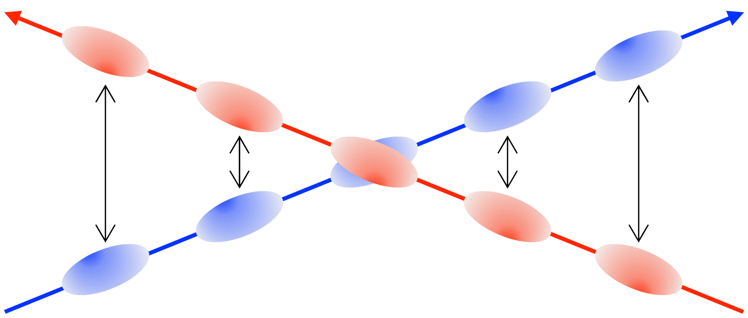
- ***Higher losses in the 1st bunch of second batch****. Could be due to the way the batches are formed in the injector chain.*
- ***Smooth increase of losses from head to tail.*** *This is a typical indication of electron cloud.*



- ***Increase of losses in the middle of the batch.*** *This corresponds to bunches with more long-range beam-beam interactions.*



Courtesy of A.Gorzawski

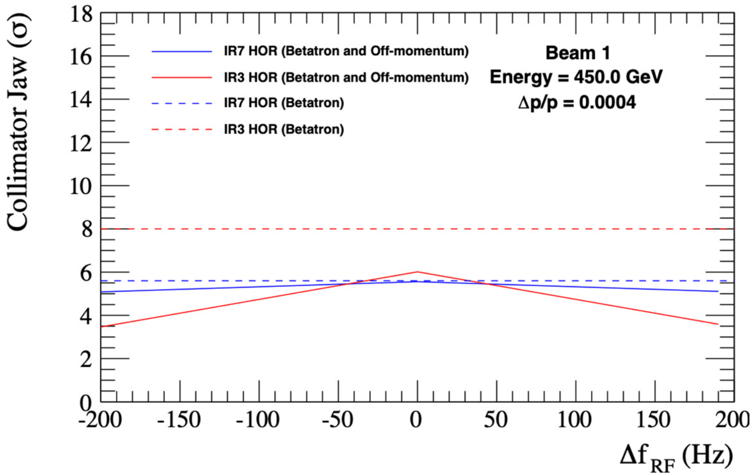


Machine Validation Loss Maps

Beam losses are generated with low intensity beam in different configurations in order to validate the collimation performance → Loss Maps.

In Run I (2010-2012) off-momentum loss maps were done by changing the RF frequency by a fixed amount.

- ✶The effect of this is that losses are shifted from IR7 to IR3 and beam is completely lost in IR3, collimation momentum cleaning region.



Collimator gap as function of Change of RF frequency

Requires re-filling each time which makes it unpractical at top energy

Can we revert the trim when beam losses are high enough to save beam for another measurement?

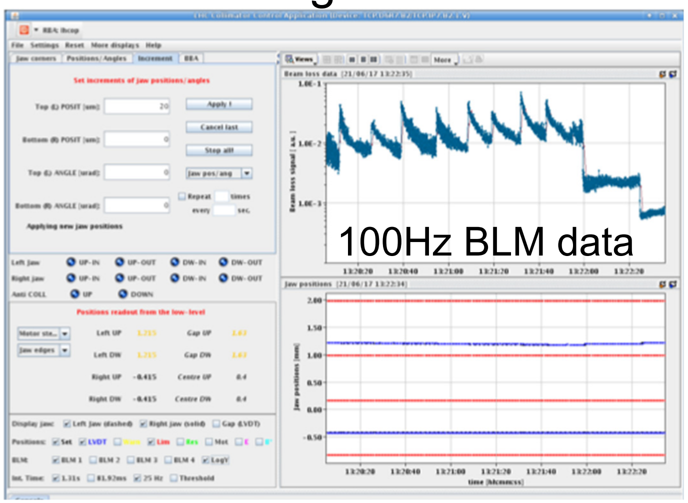
Off-momentum feedback

Beam thresholds are applied at the electronics level. **Measurements data is published with a lower rate (1 Hz)**

In order to provide a feedback on the frequency control of the RF cavities we need faster signals.

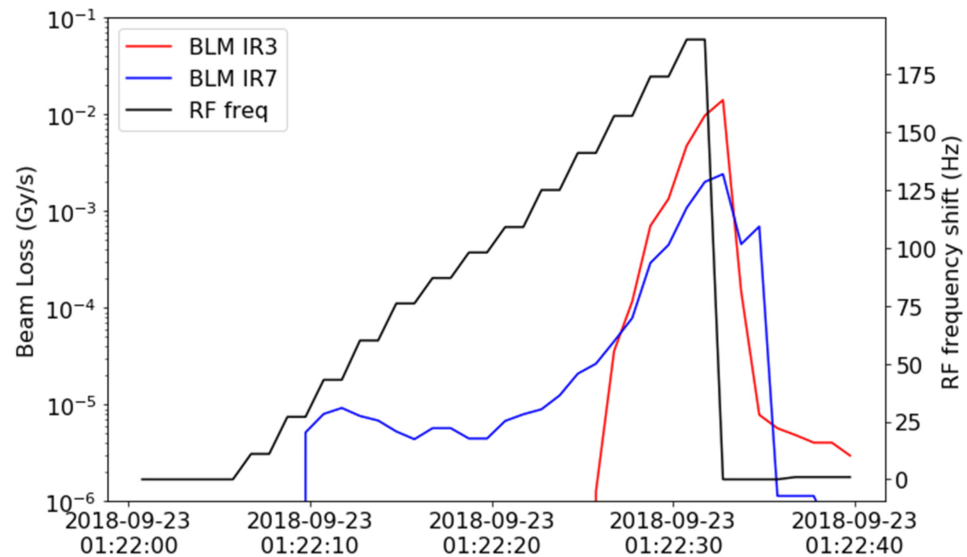
A **dedicated stream of data at 100 Hz** was setup for the collimation alignment purposes and it is now used also for an off-momentum feedback.

Collimation alignment software



Courtesy of G.Azzopardi

BLM signals during off-momentum loss maps

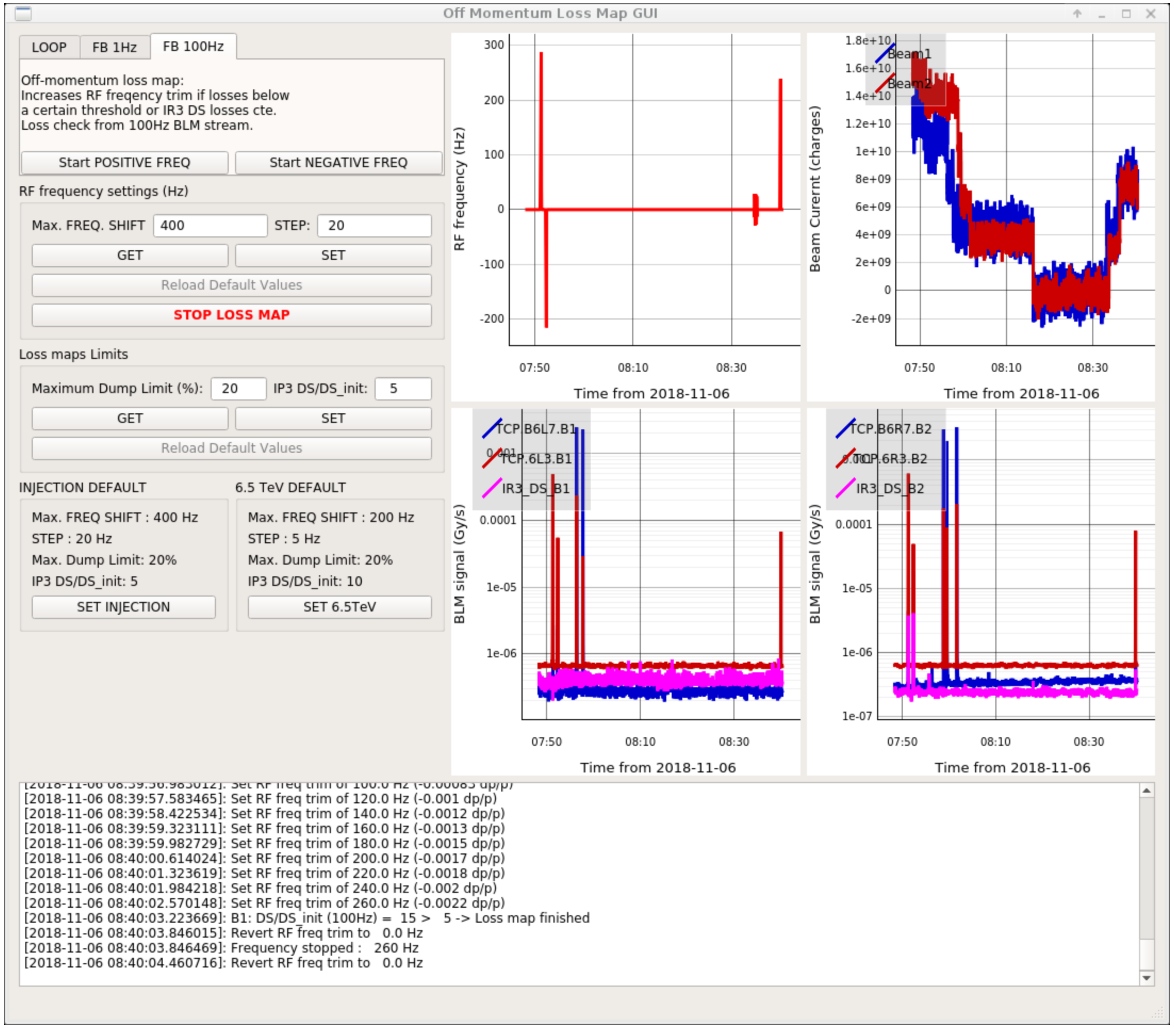


Off-momentum feedback

RF frequency trim is controlled with a python class based on the reading of BLM data.

A GUI was developed to control the FB. Allows to use a slow controller based on 1Hz BLM data and a fast controller based on 100Hz BLM data.

The FB stops when some conditions are reached: maximum losses, ratios between monitors or dump limits.



Summary

- Explore the usage of Beam Loss Monitors to provide different measurements after cross-calibration with other devices:
  - Fast measurement of Beam Lifetime
  - Identify loss patterns to improve machine performance. Number of particles lost by different mechanism (vertical, horizontal and off-momentum halo cleaning).
- Provide loss measurements bunch-by-bunch. Installation of new beam loss devices (dBLM). Similar cross-calibration could follow.
- Flexibility on data rate publication, faster data stream used as part of RF feedback controller.
- Other measurements not covered here: collimation cleaning performance, measurement of tail particles by scraping, experimental background monitoring, etc.