# Fast Automatic Beam-Based Alignment of the LHC Collimation System

Gianluca Valentino

with contributions from:

R. W. Assmann, R. Bruce, S. Jackson, S. Redaelli,

B. Salvachua, N. Sammut, D. Wollmann, C. Zamantzas

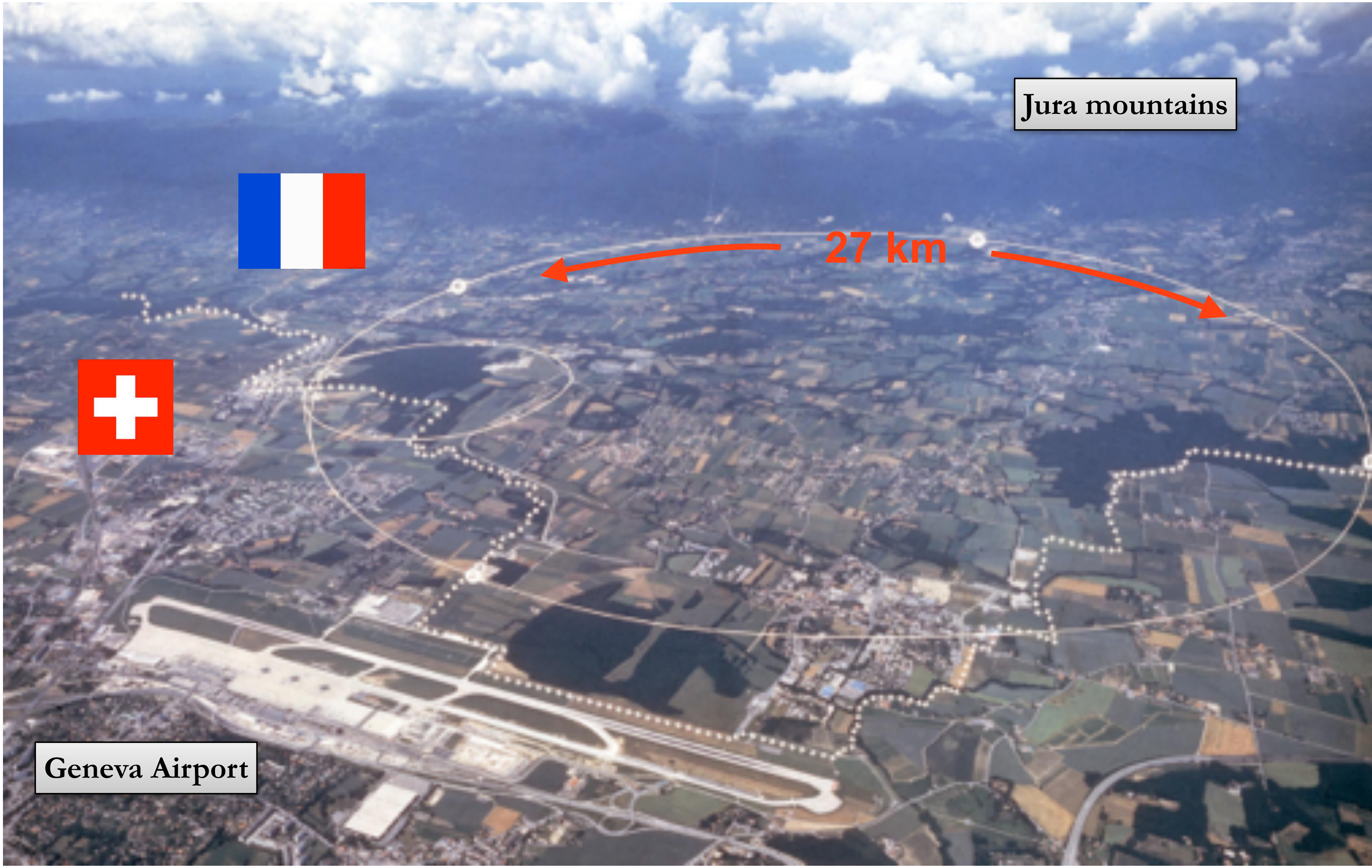
Work supported by:

EuCARD

# Outline

- **LHC Collimation System**
- **Collimator Beam-Based Alignment**
- **Alignment Algorithms**
    - BLM feedback loop
    - Parallel collimator alignment
    - BLM spike recognition
    - BPM-guided coarse alignment
- **Operational Results**
- **Summary**

# The Large Hadron Collider



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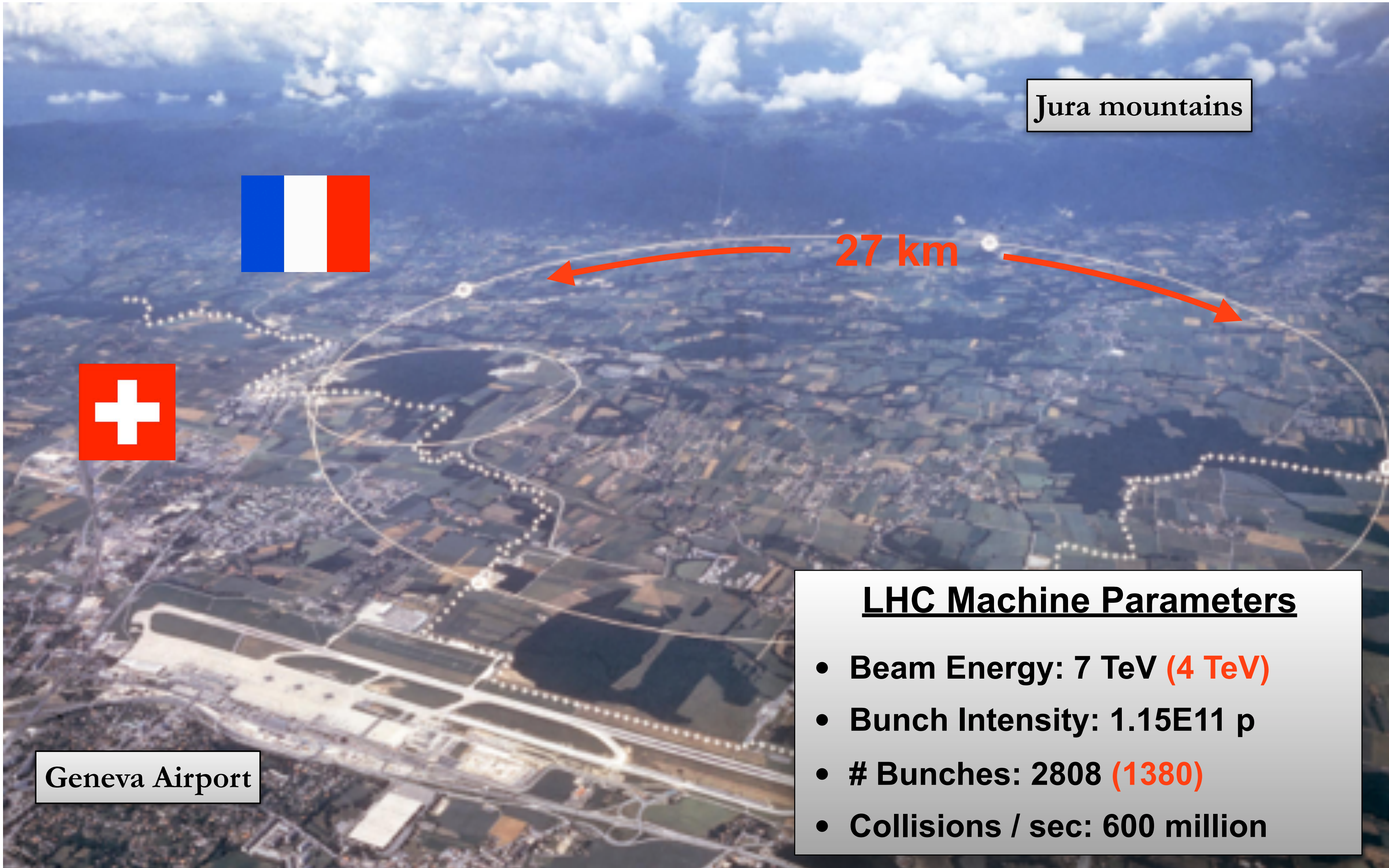
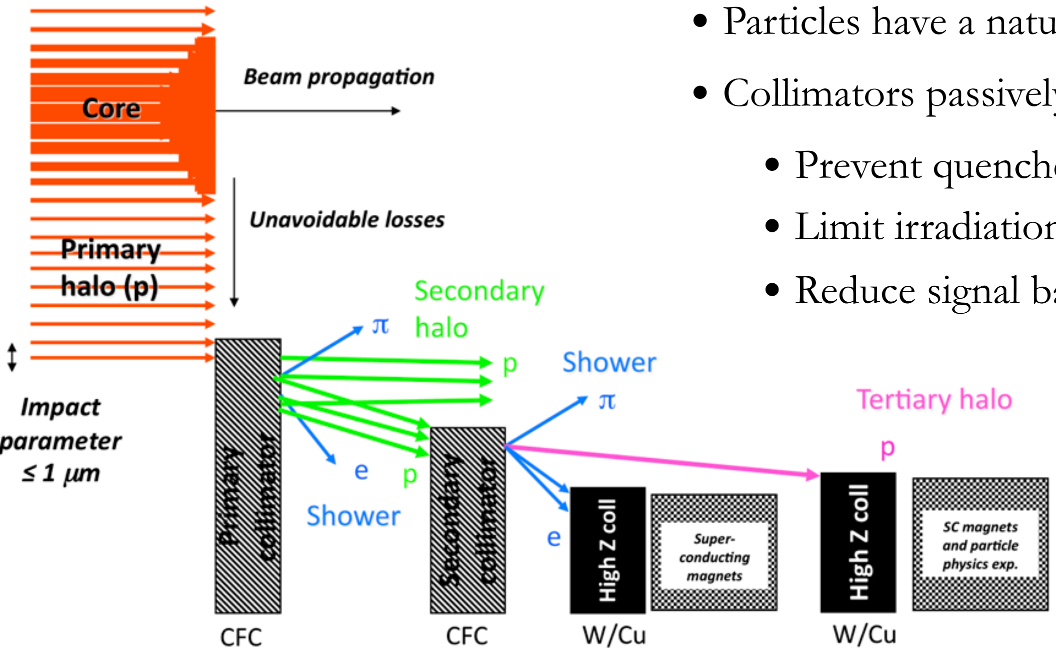



**LHC Machine Parameters**

- Beam Energy: 7 TeV (4 TeV)
- Bunch Intensity: 1.15E11 p
- # Bunches: 2808 (1380)
- Collisions / sec: 600 million

# LHC Collimation System




- Particles have a natural tendency to drift to the beam halo over time.
- Collimators passively scatter and intercept beam halo particles to:
  - Prevent quenches of the super-conducting magnets.
  - Limit irradiation of sensitive devices.
  - Reduce signal background in the experiment detectors.

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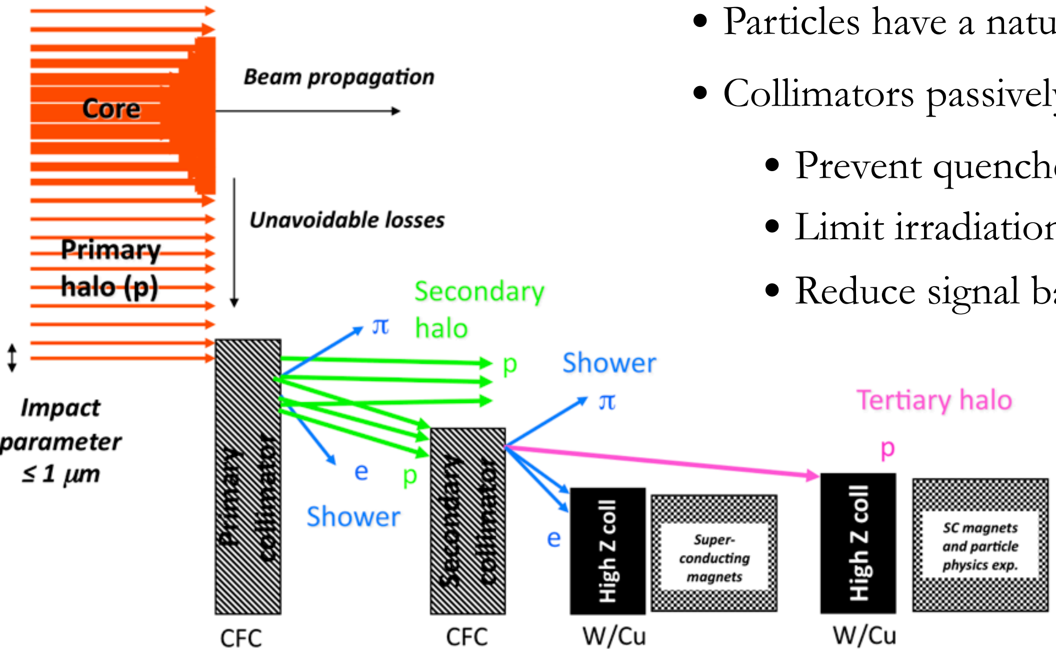


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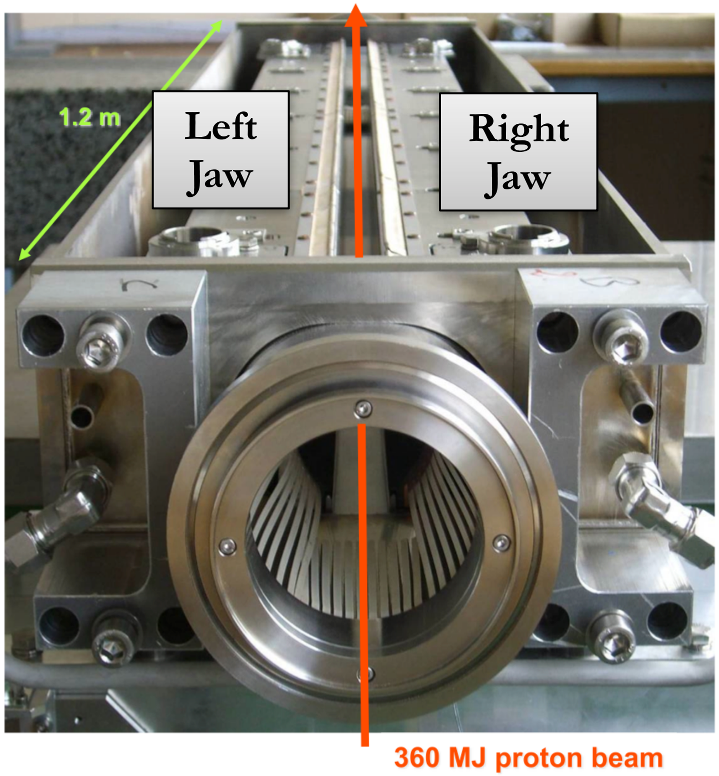

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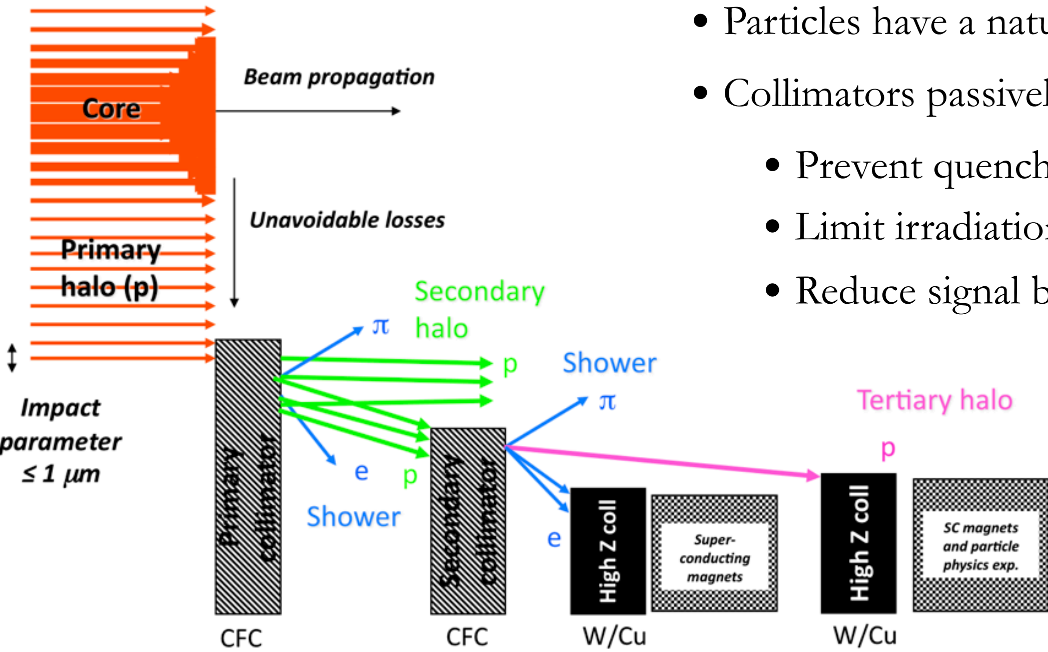


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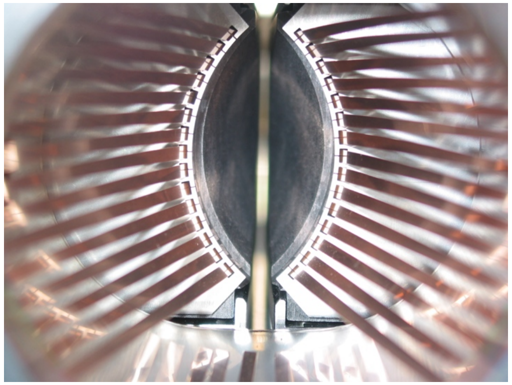

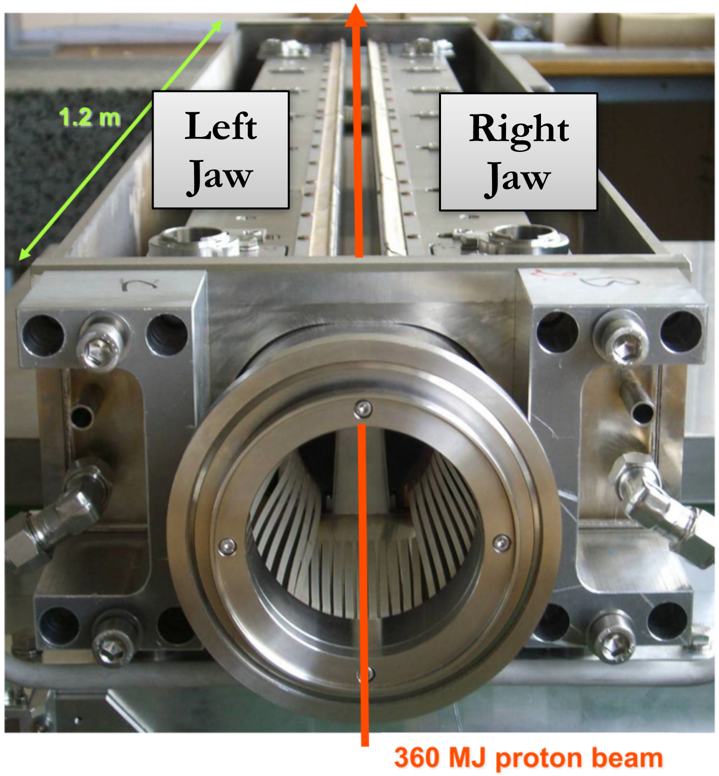

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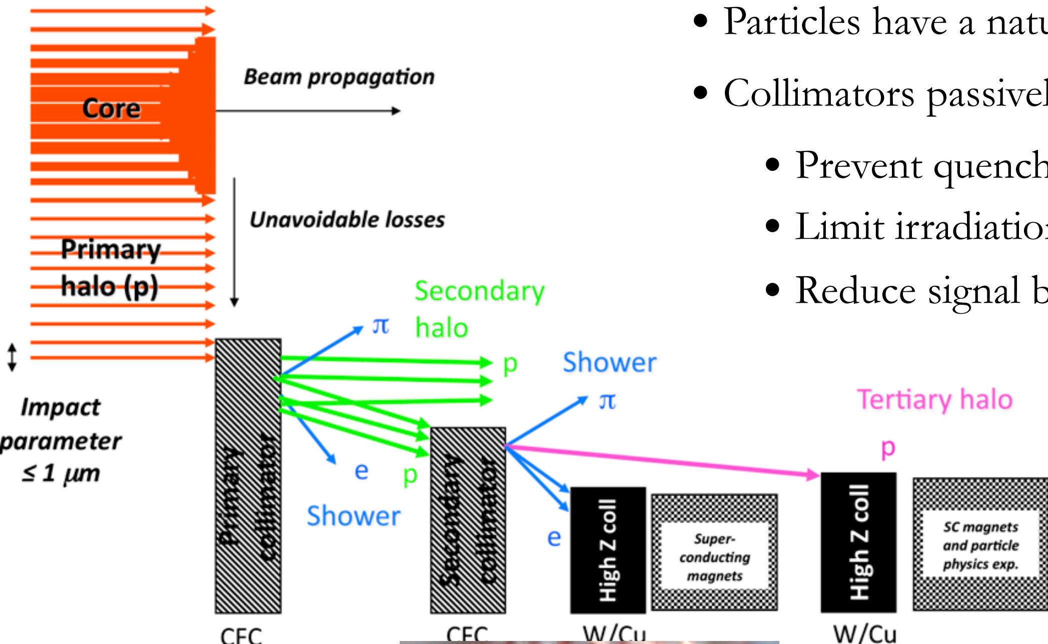
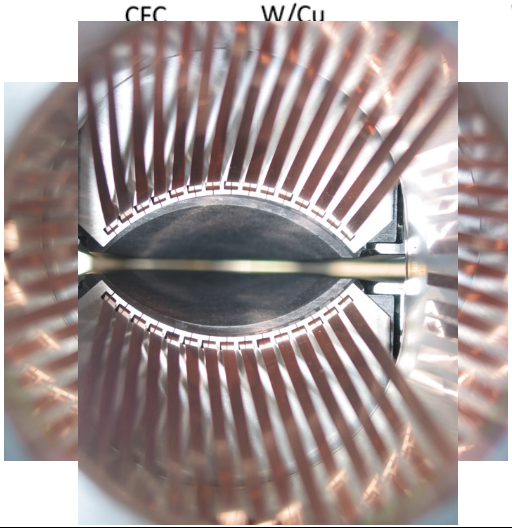
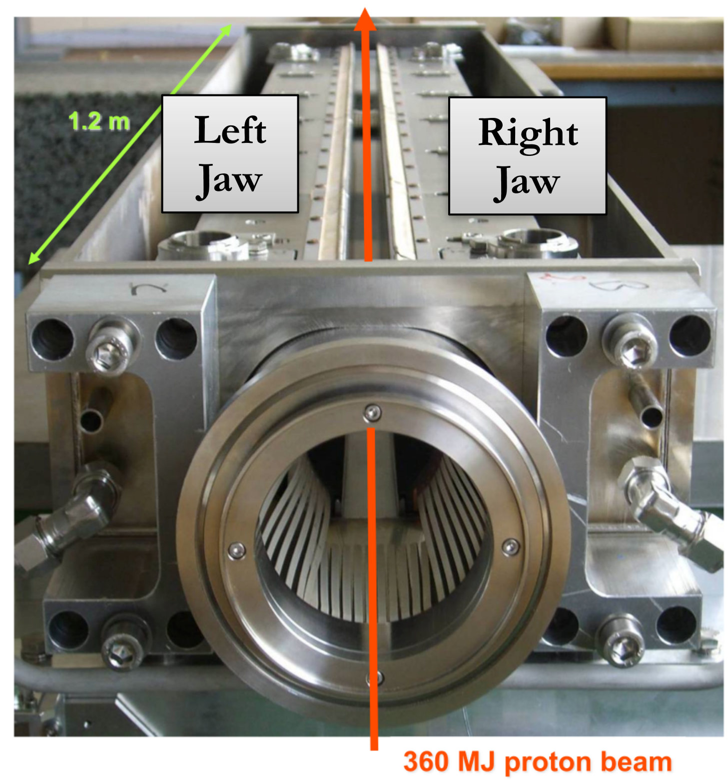



Horizontal

Vertical





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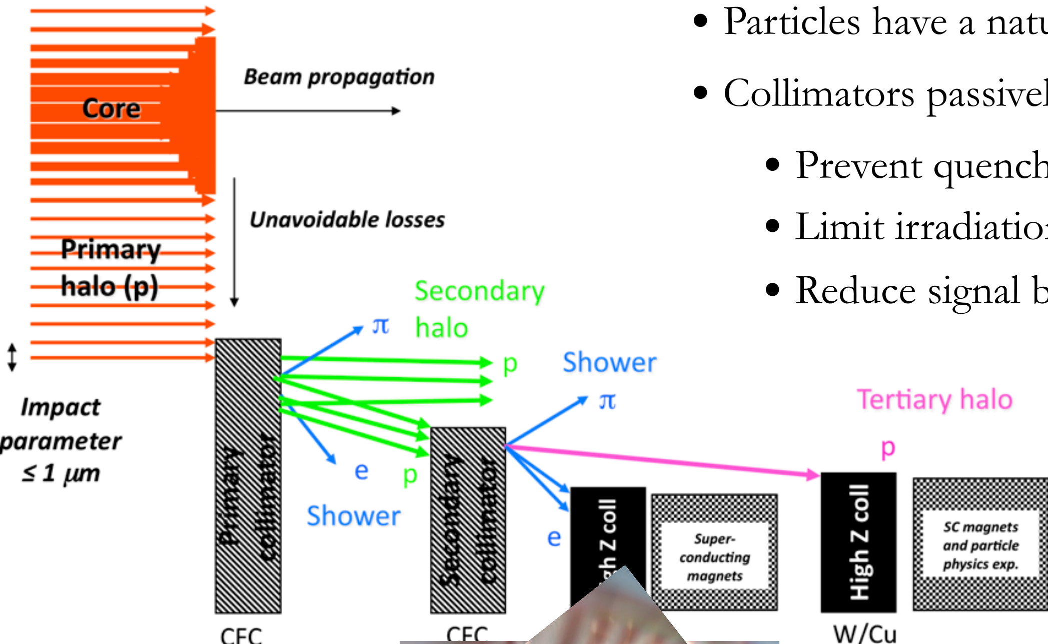
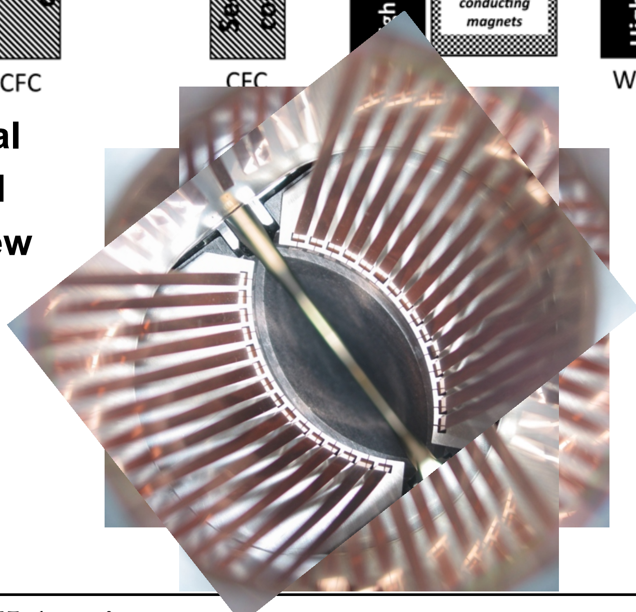
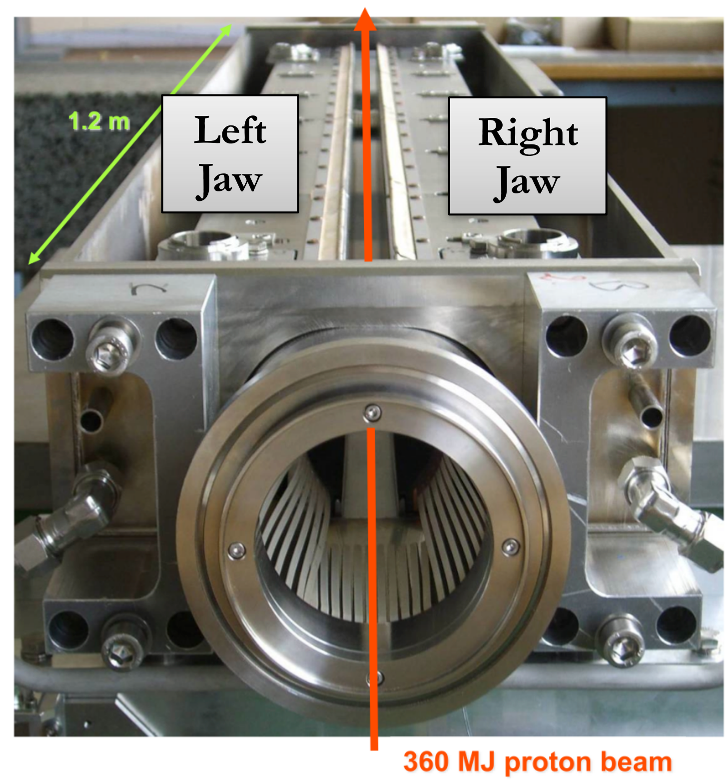



Horizontal
Vertical
Skew





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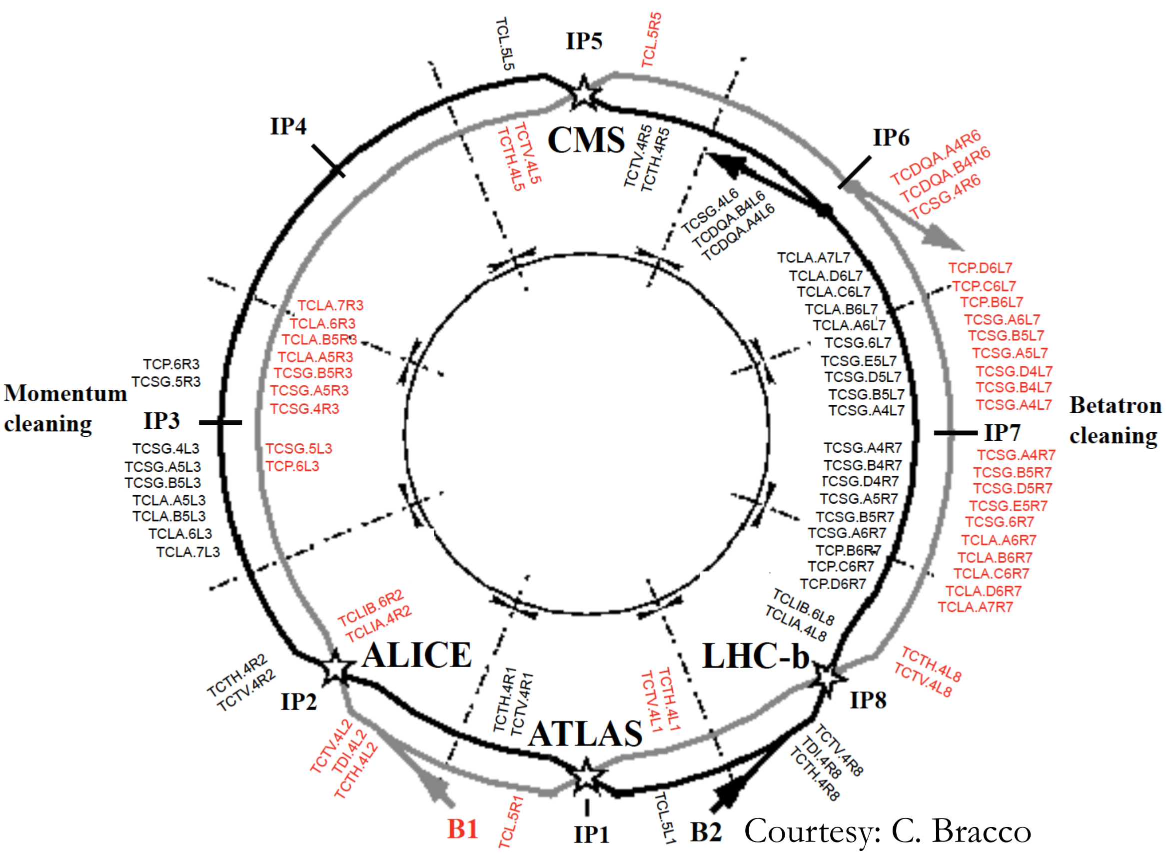


Courtesy: C. Bracco

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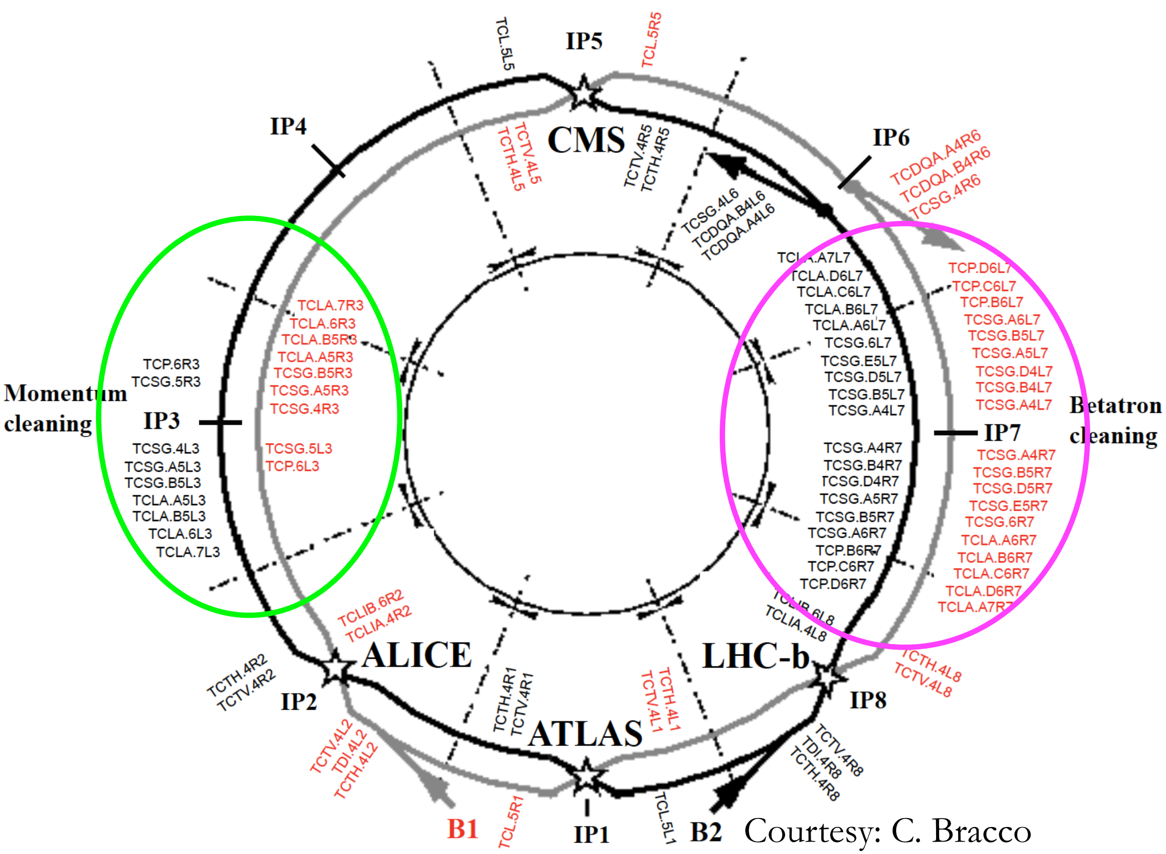


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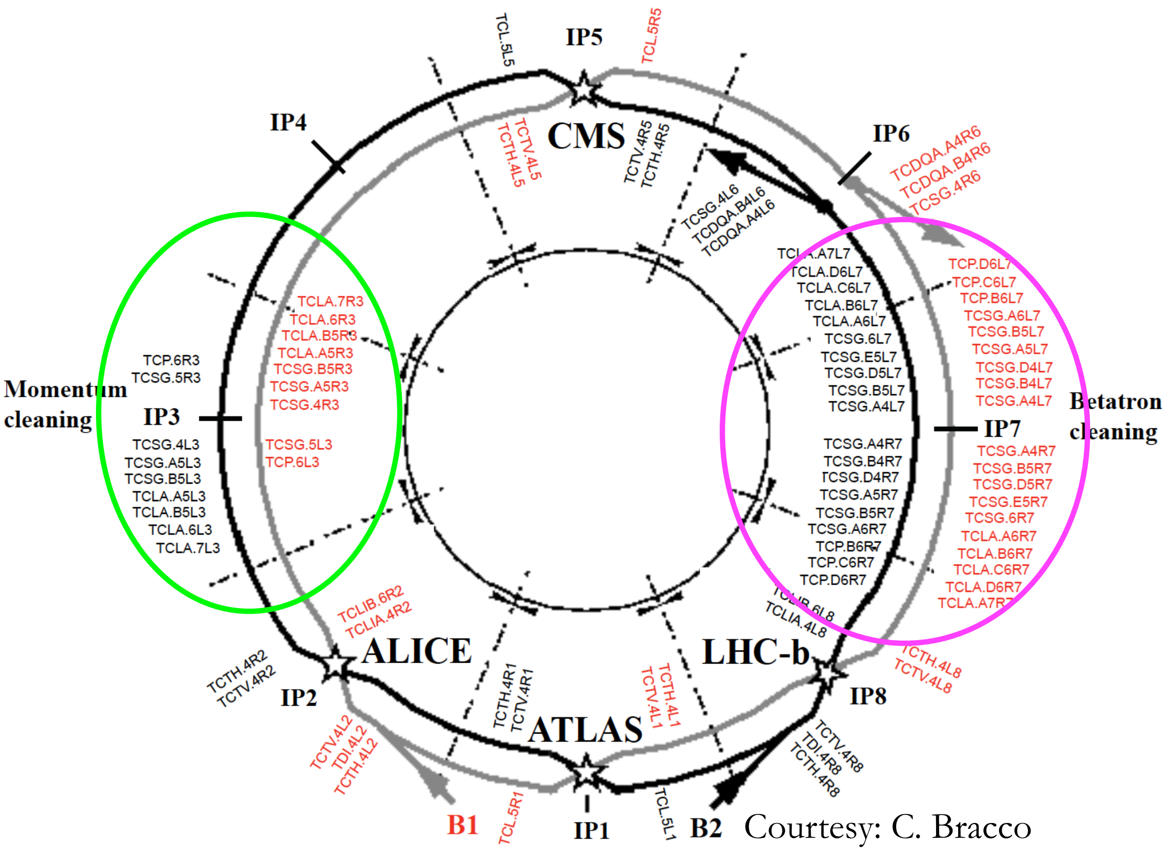
- The LHC is protected by a **collimation system** with 86 collimators (+ 14 transfer line).
- Each cleaning collimator consists of **two moveable 'jaws'** made of carbon, tungsten or copper.
- The jaws are positioned symmetrically around the beam for maximum cleaning efficiency.

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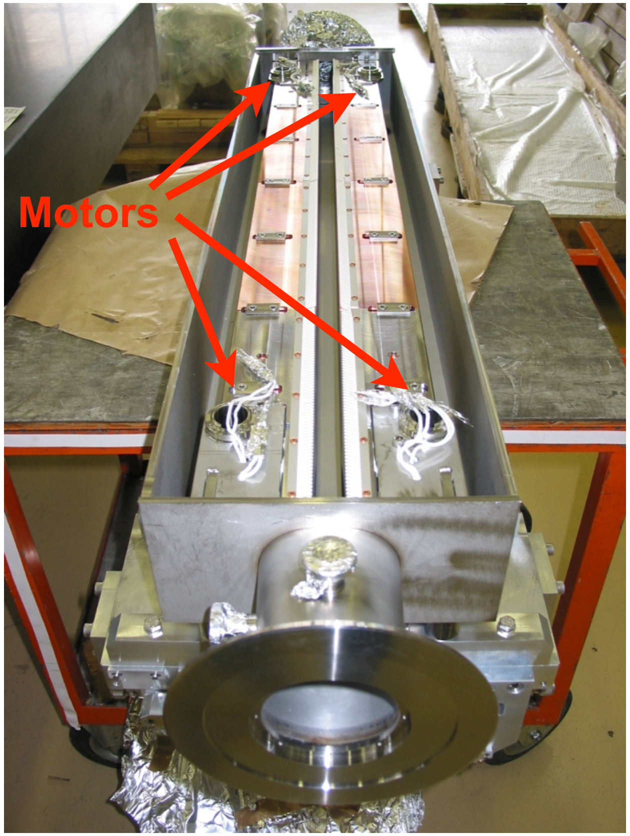

# Collimator Status and Positions Display


**Green: OK**
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**More details in *TUPPC111***

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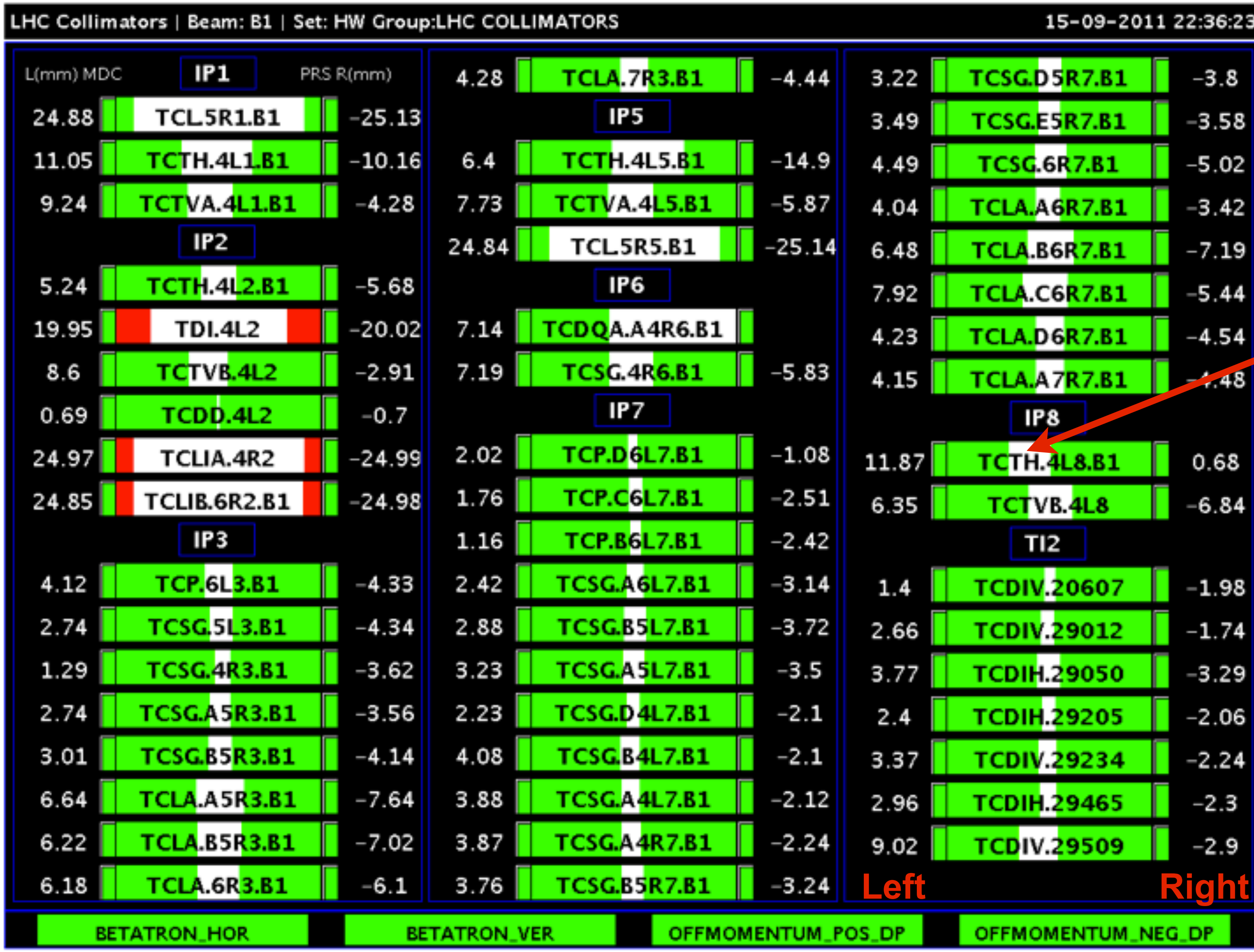


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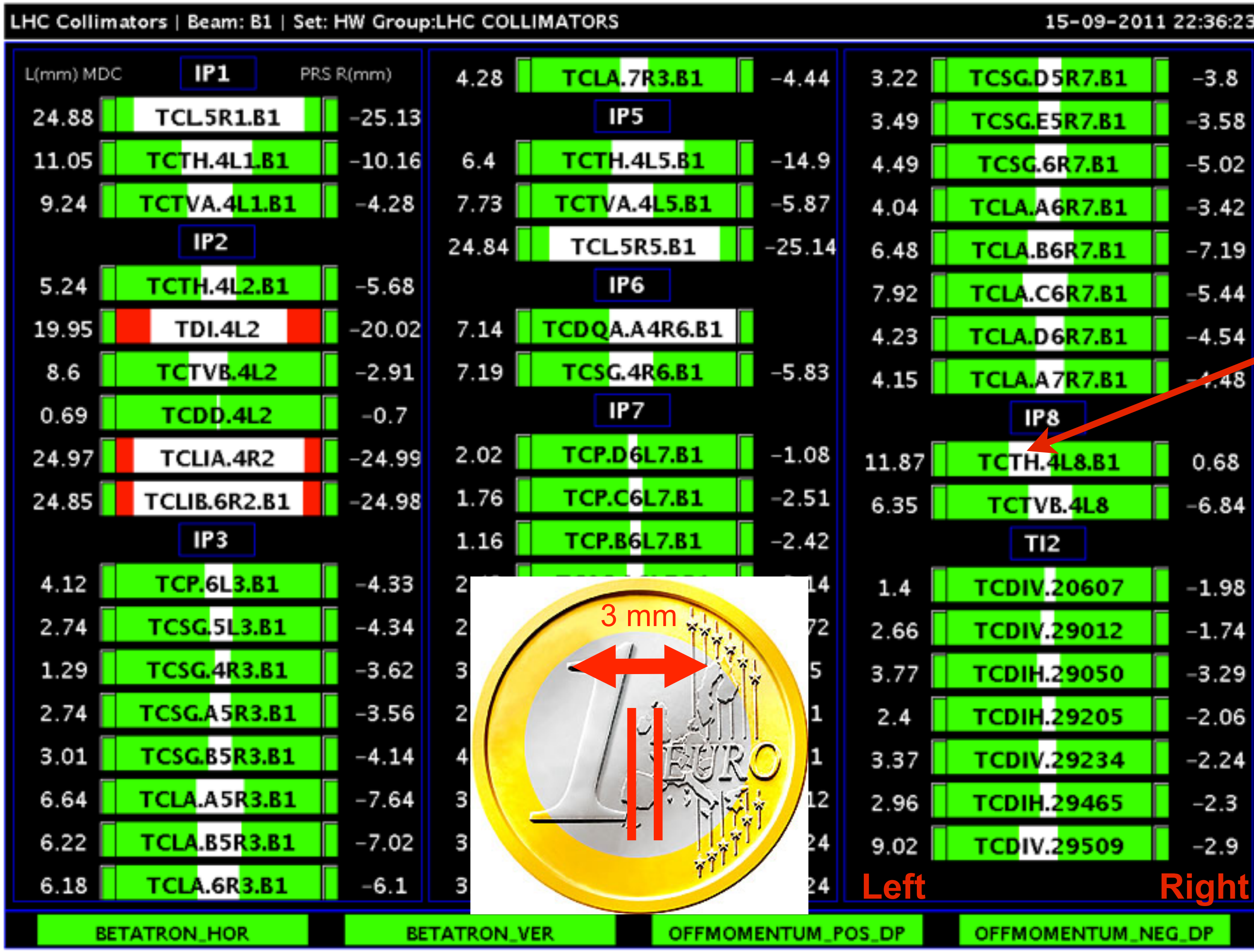


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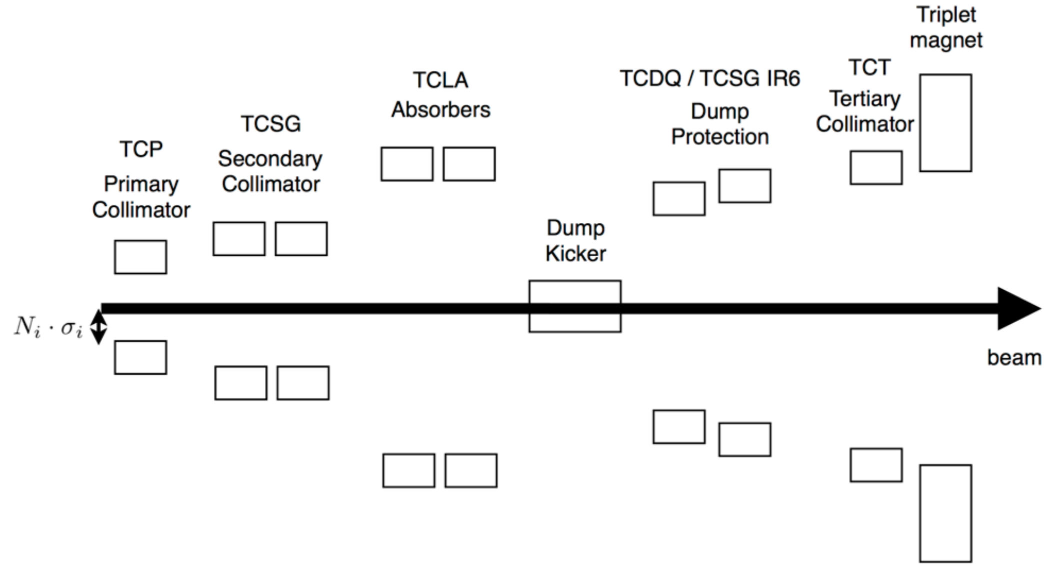
# Beam-Based Collimator Alignment

- The **beam centre** and **beam size** at each collimator location must be measured at **4 points in the machine cycle**.



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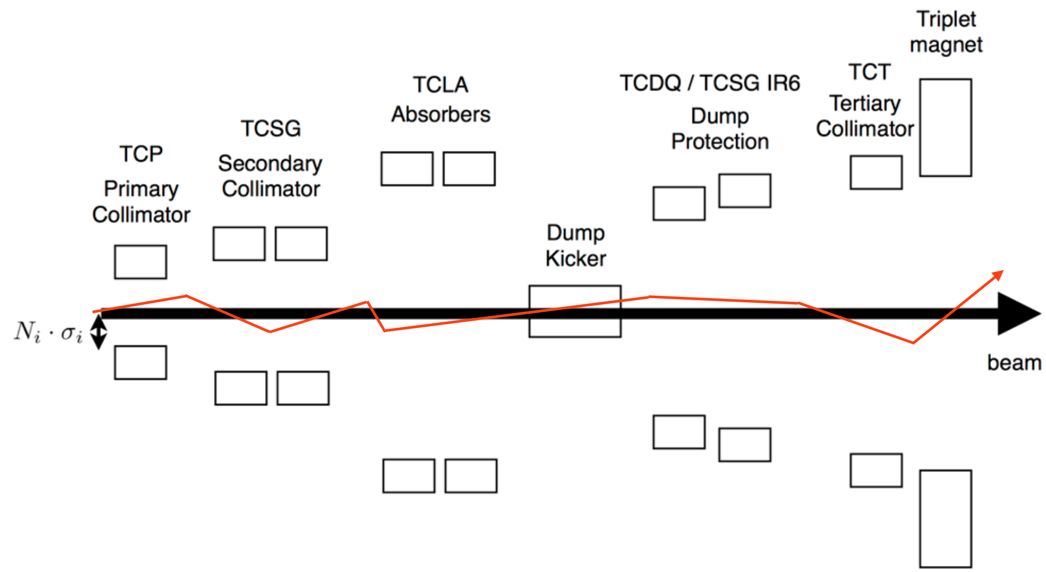

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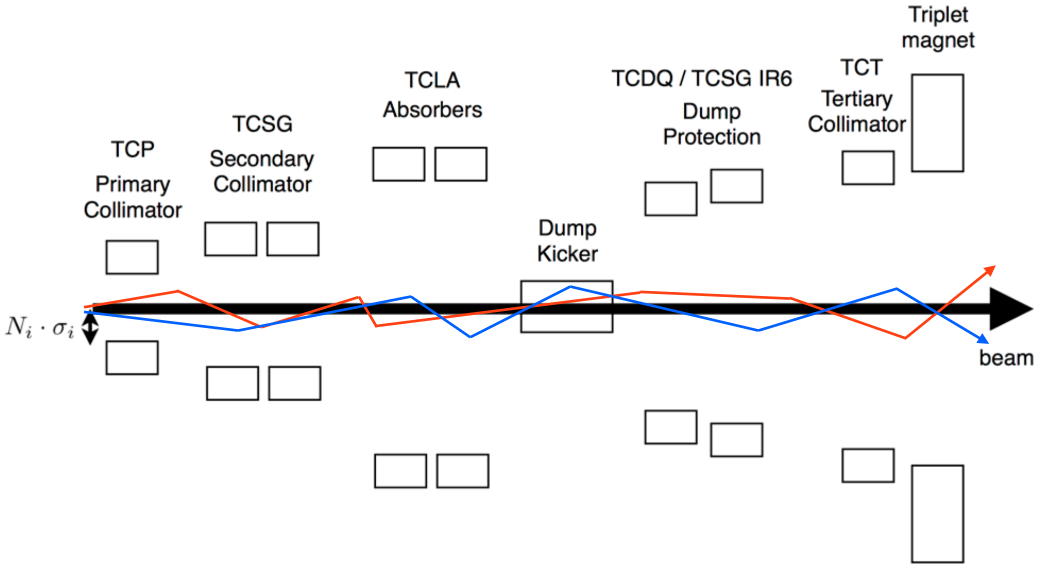

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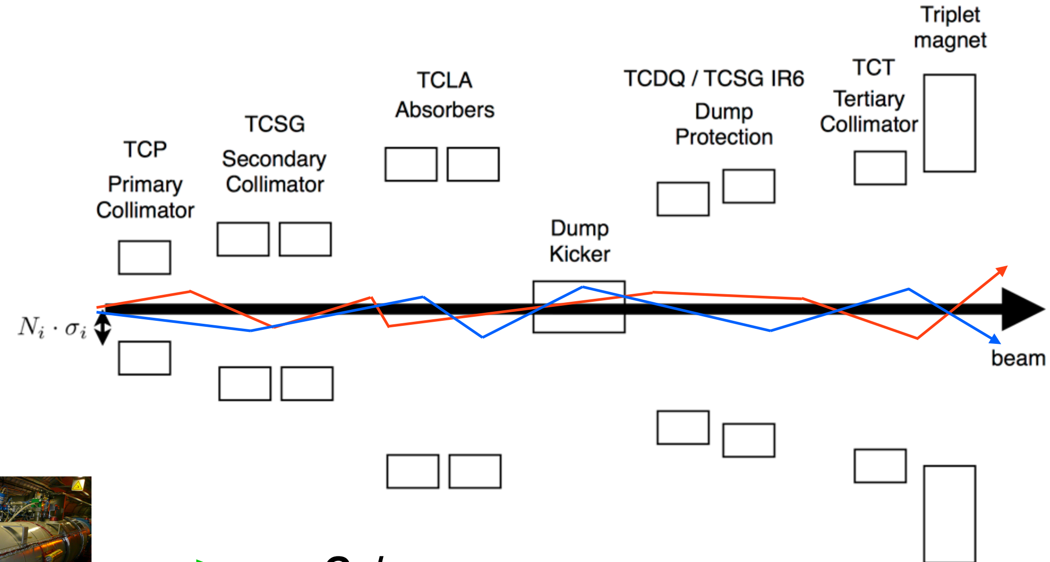
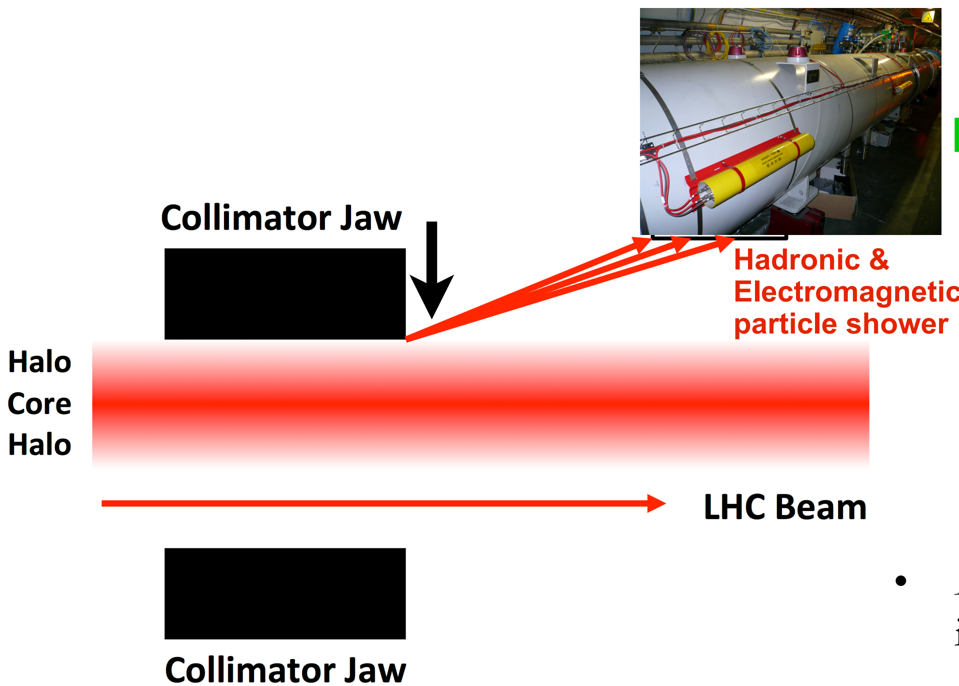
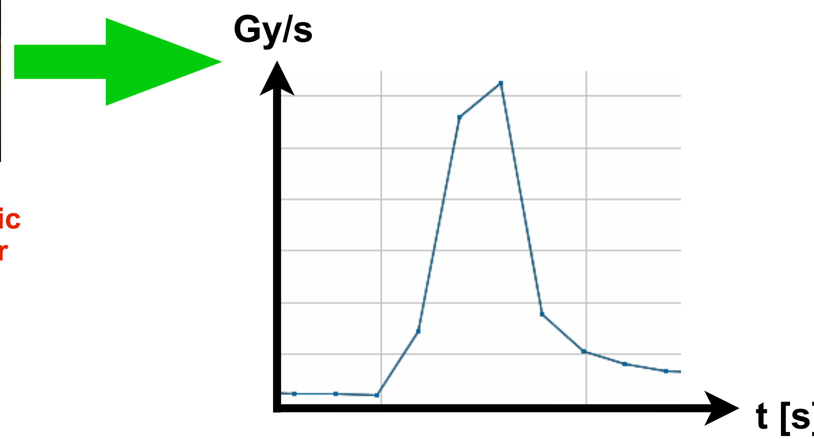
- The **beam centre** and **beam size** at each collimator location must be measured at **4 points in the machine cycle**.

- By touching the beam with each jaw, these values can be determined.




- A jaw is aligned when the characteristic loss spike is seen in the Beam Loss Monitoring (BLM) detector signal.

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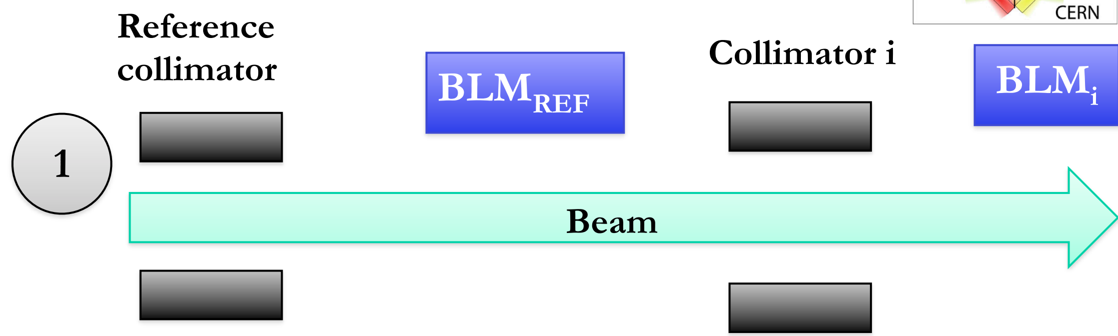


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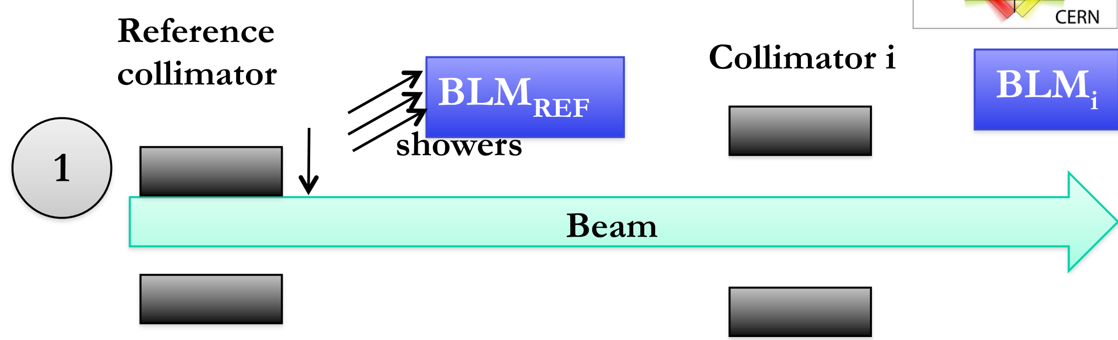

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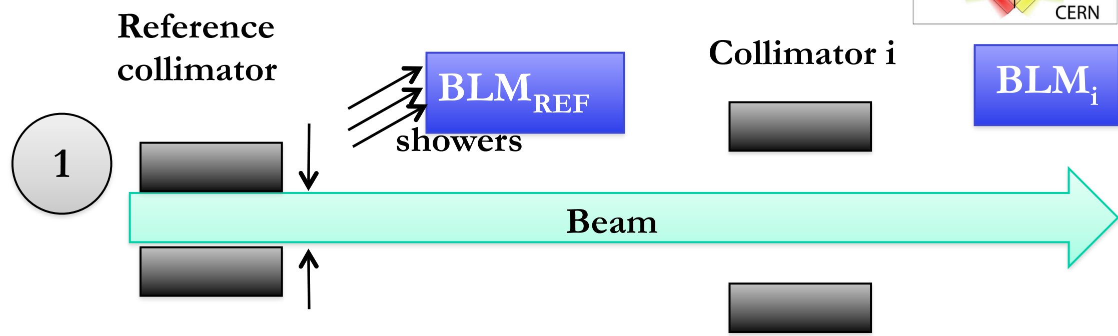

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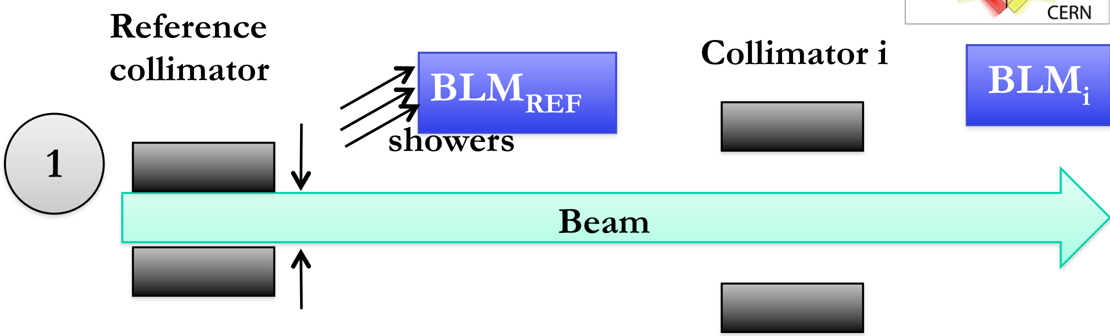


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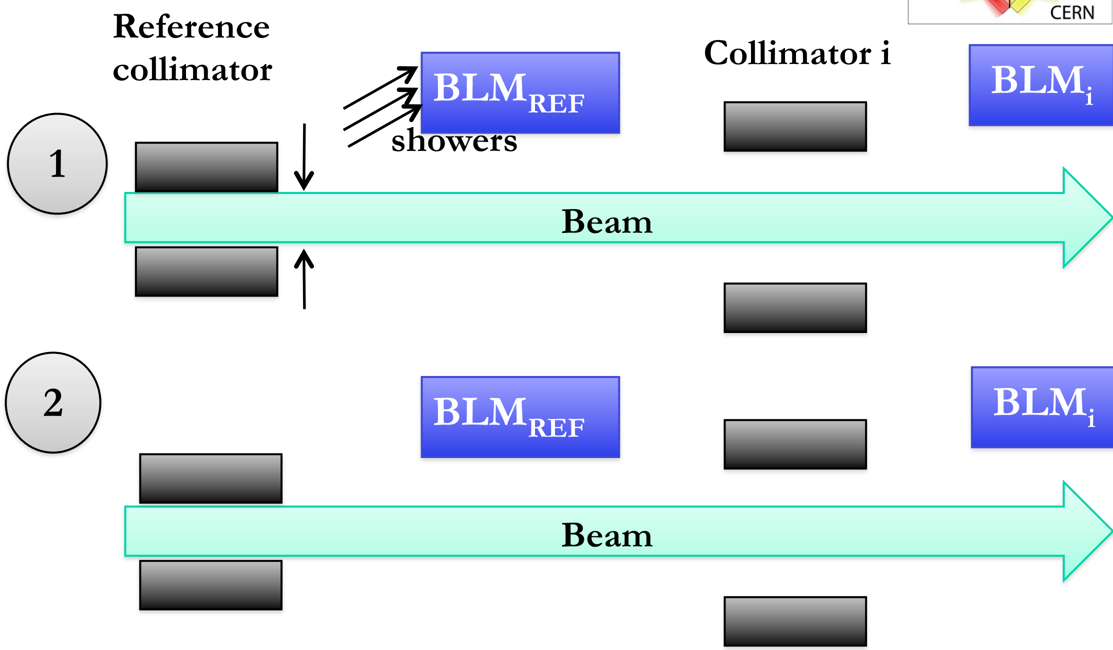

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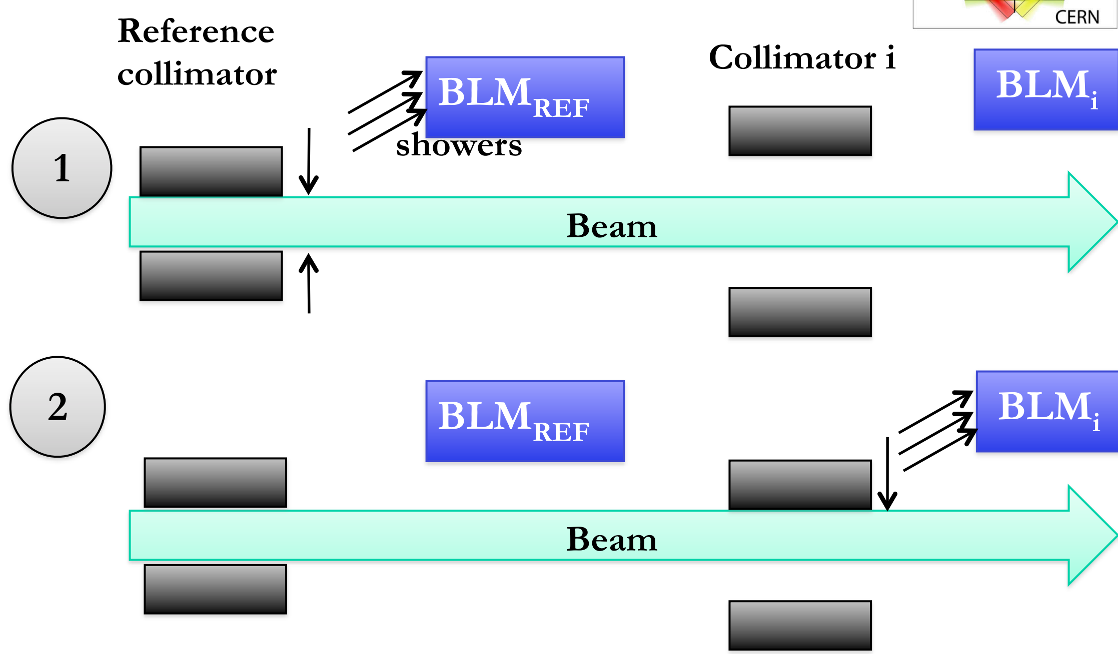

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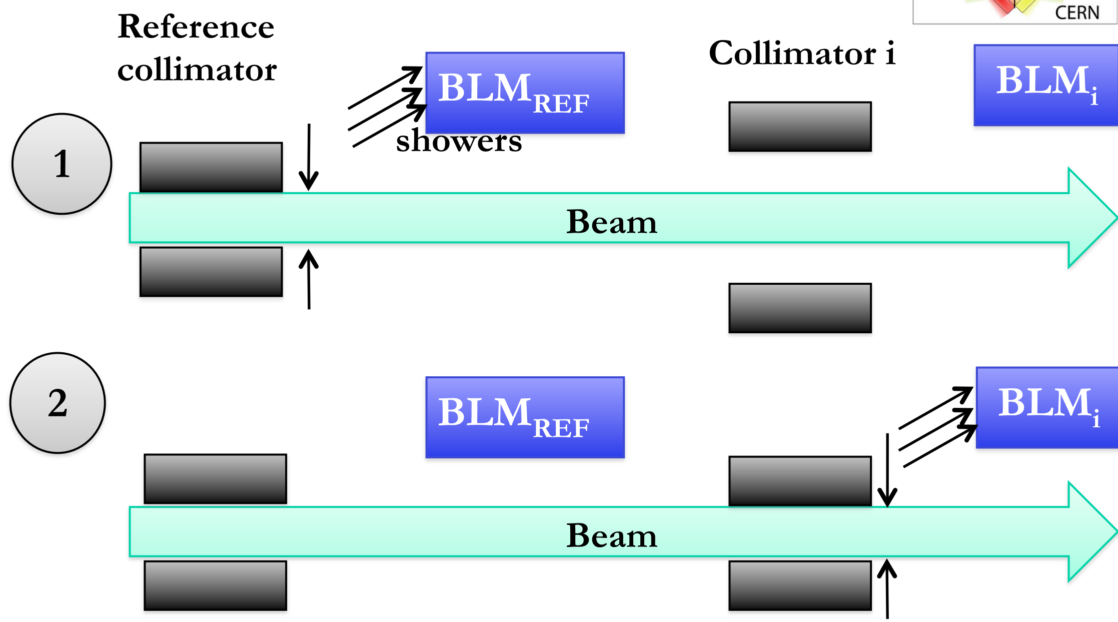

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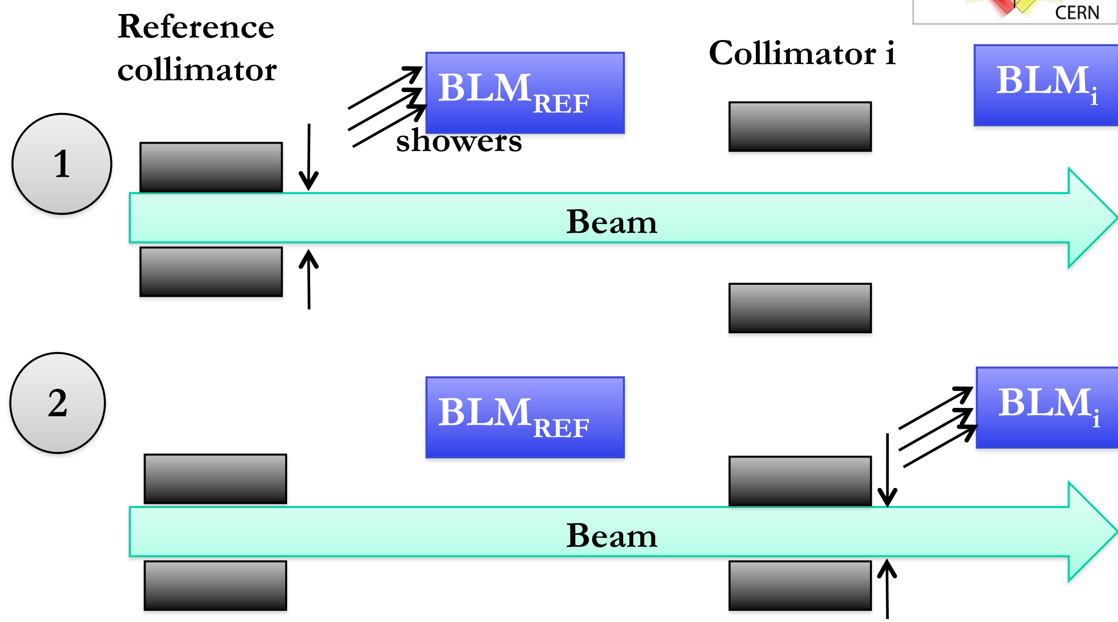

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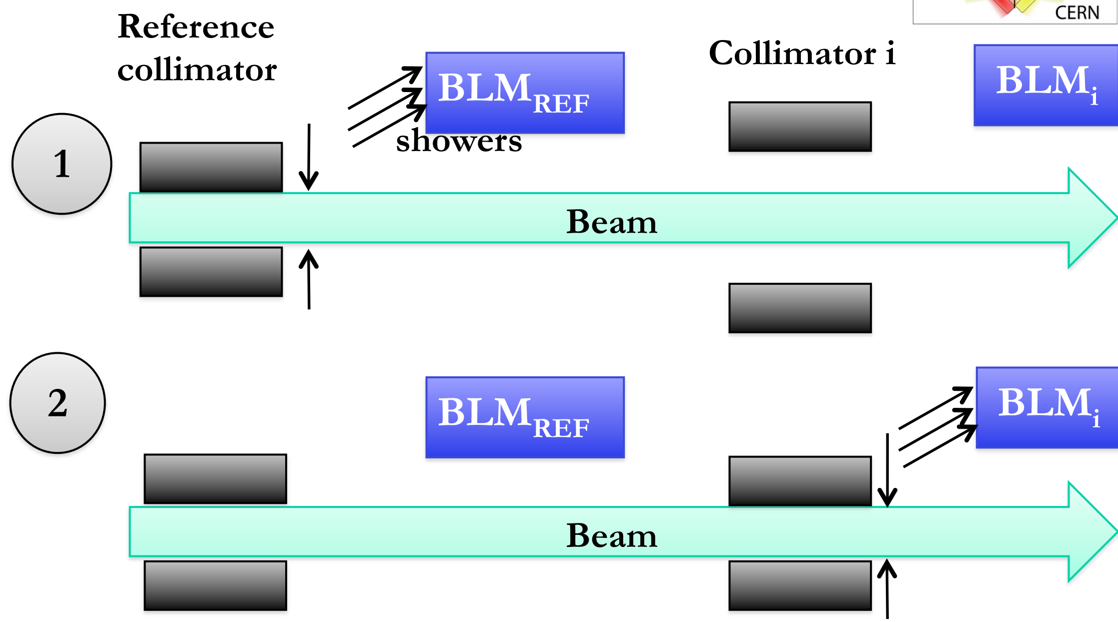

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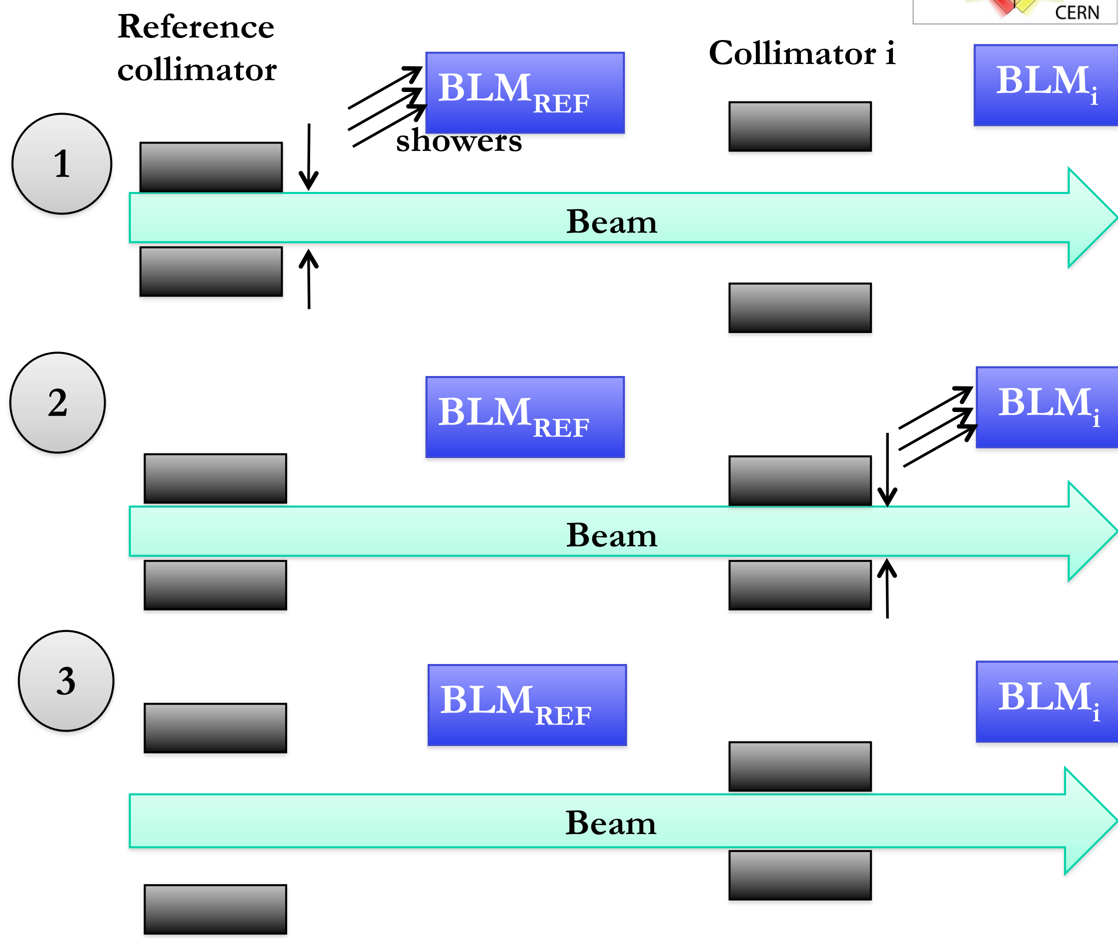

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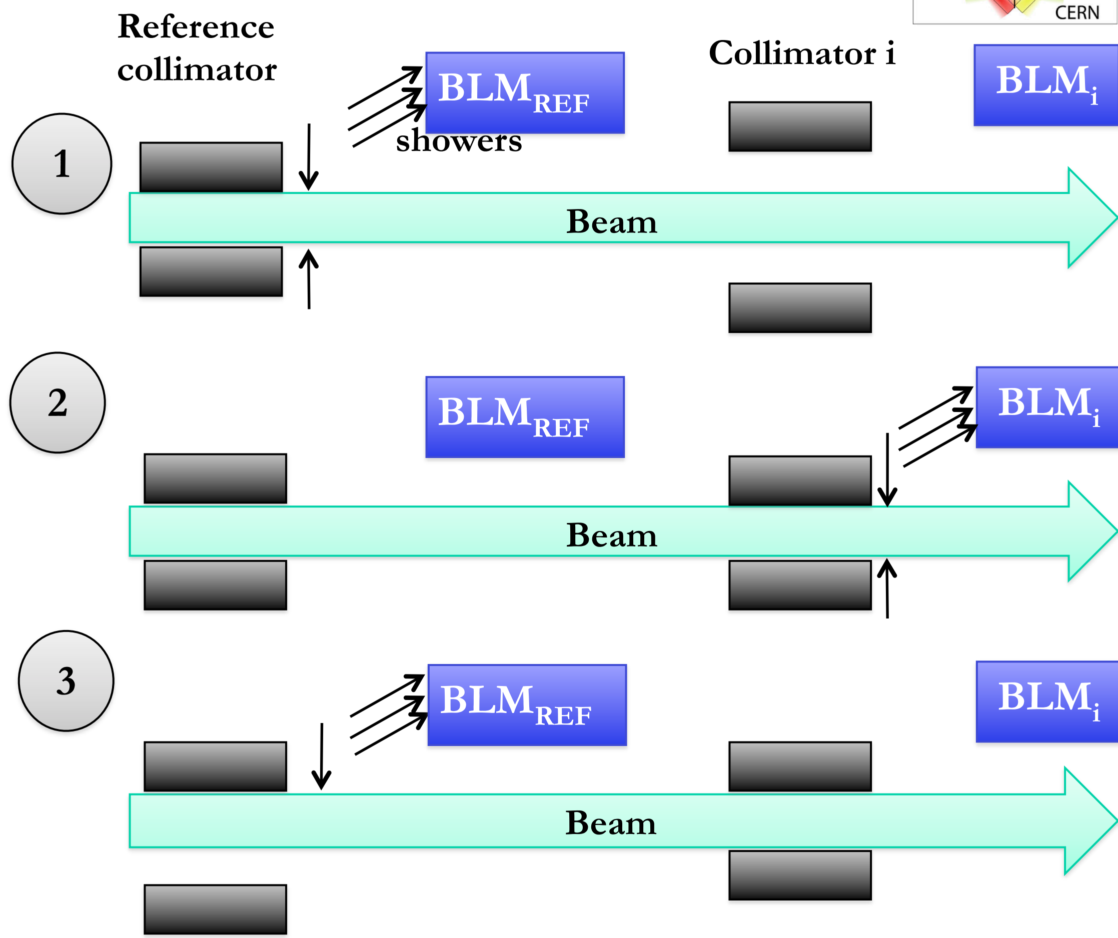

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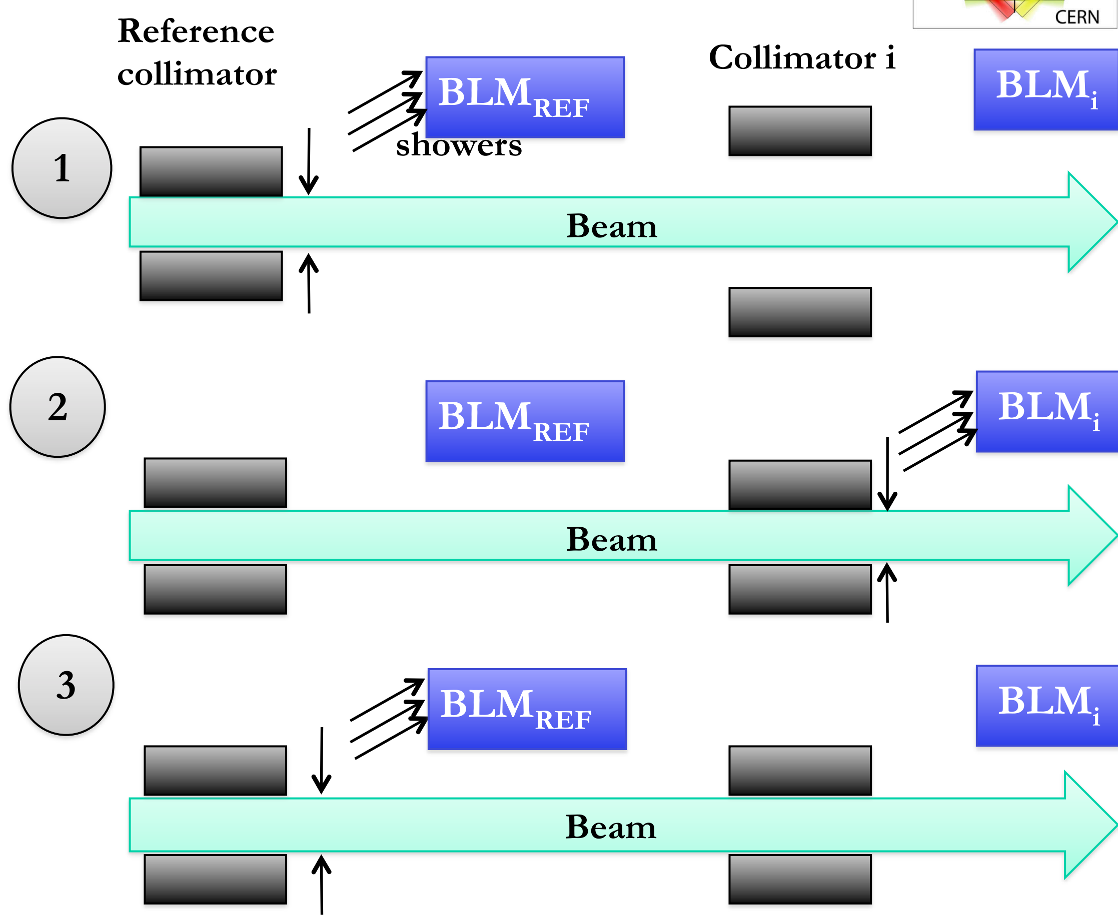

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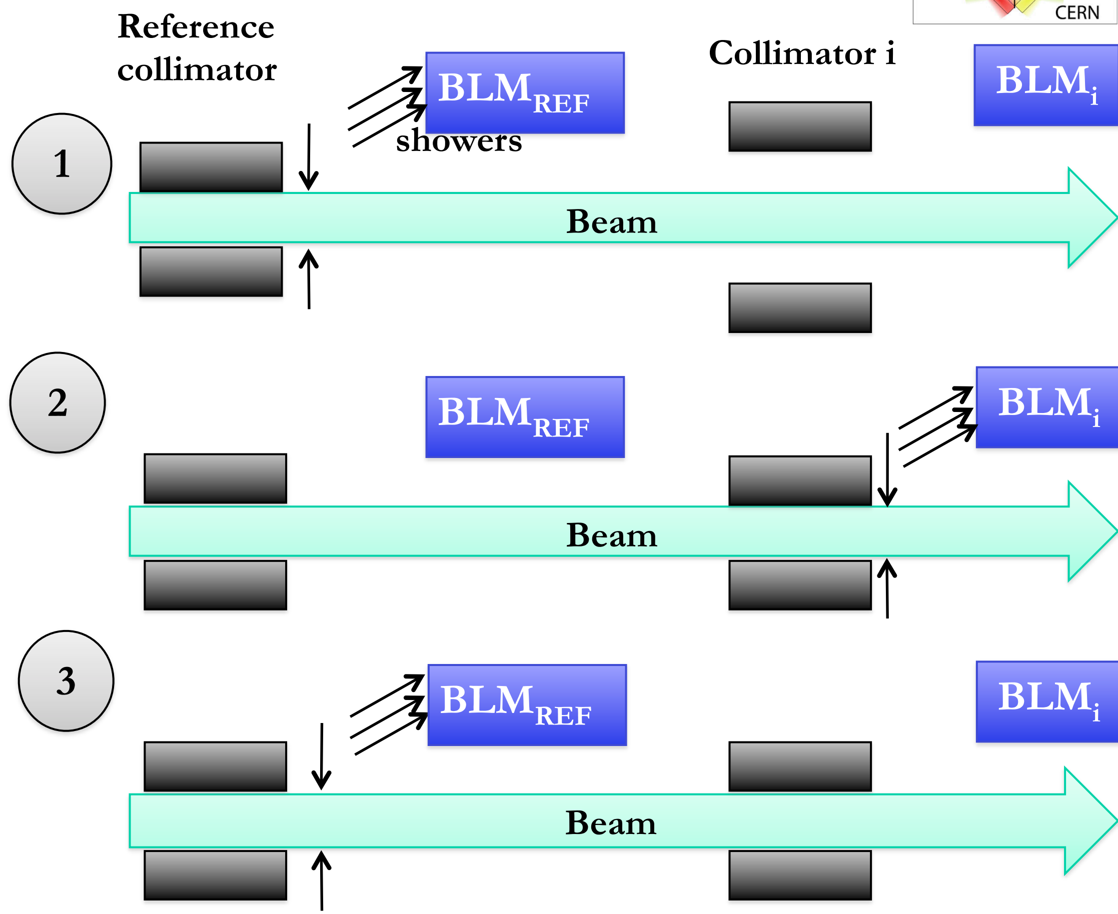

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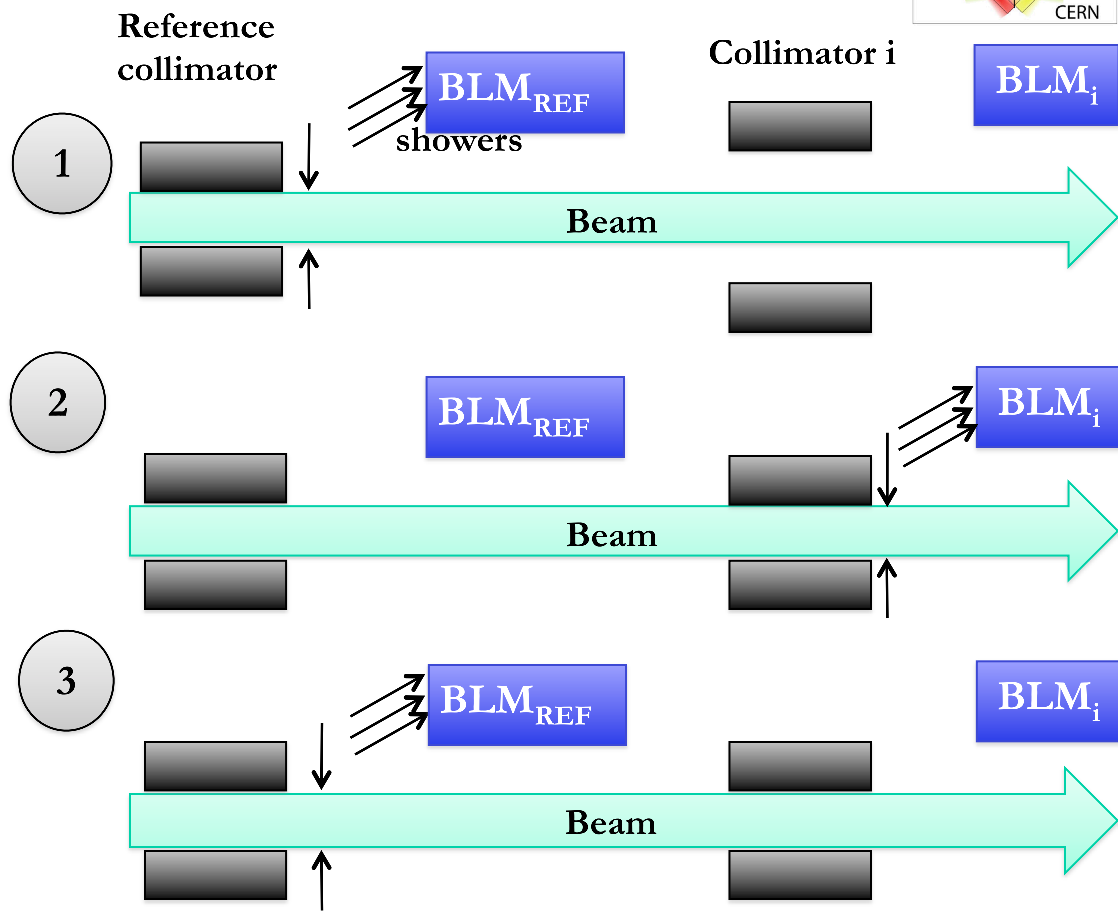

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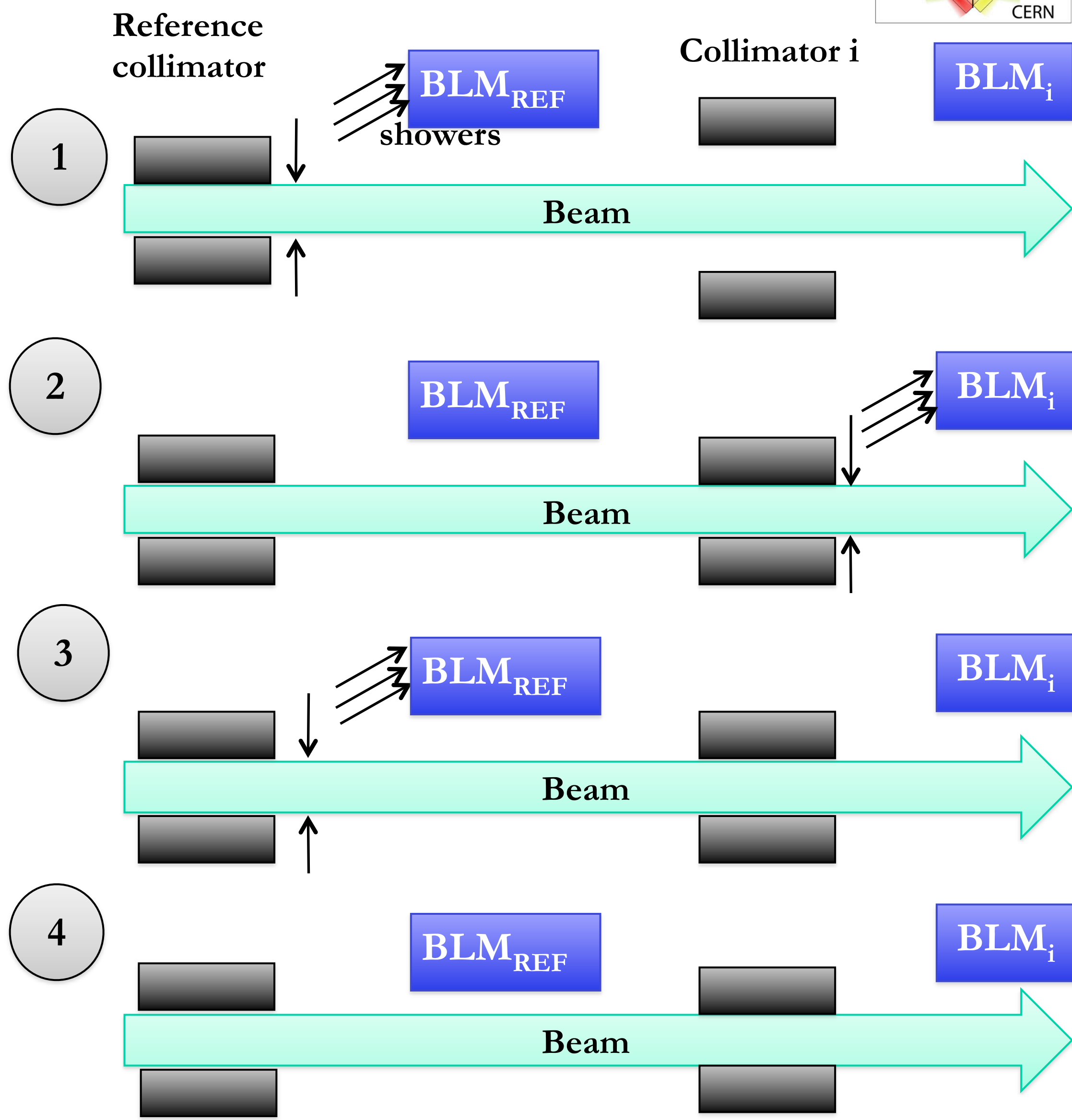

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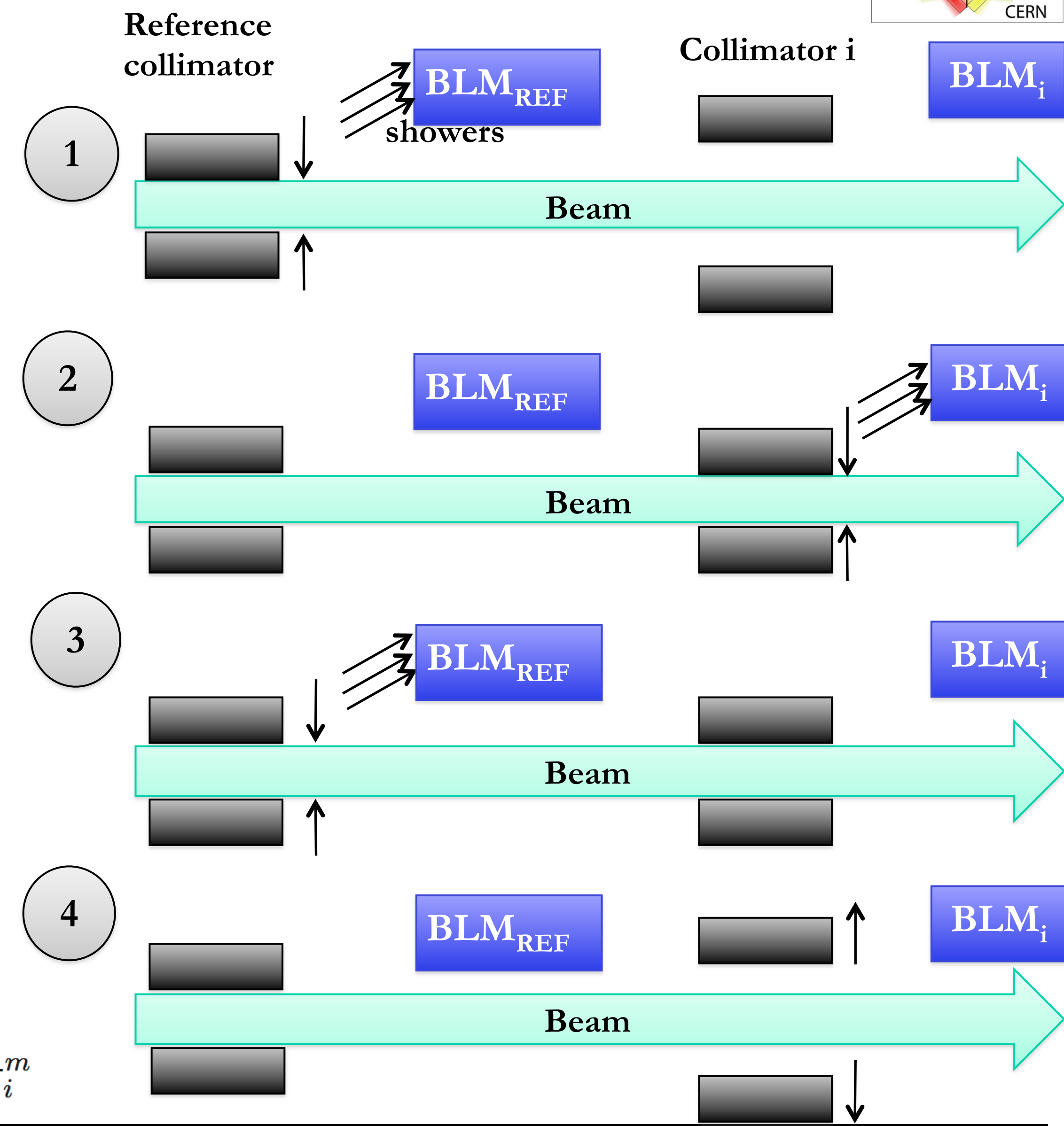
$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^m \qquad x_i^{R,set} = \Delta x_i - N_i \sigma_i^m$$



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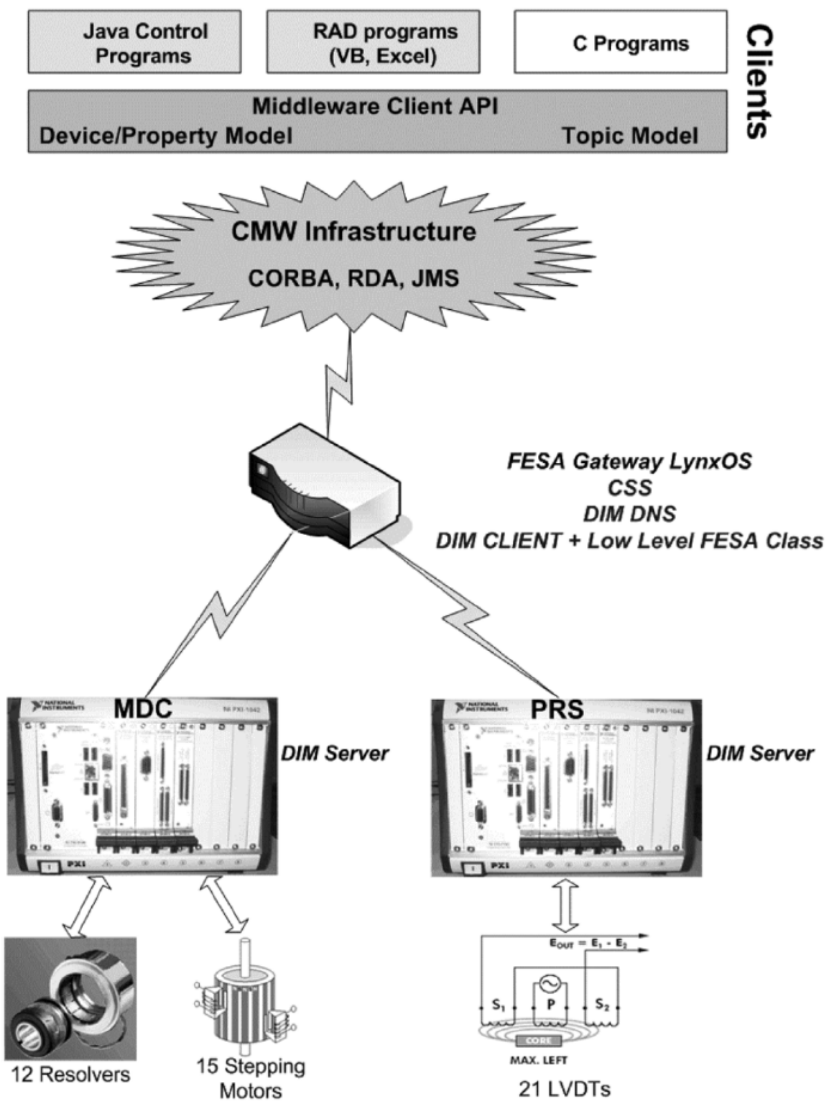
- An intelligent automated system would be able to align the collimators in less time and without human errors.

# Collimation System Software Architecture




Top-Layer

Middleware Infrastructure

Motors, Position Readout

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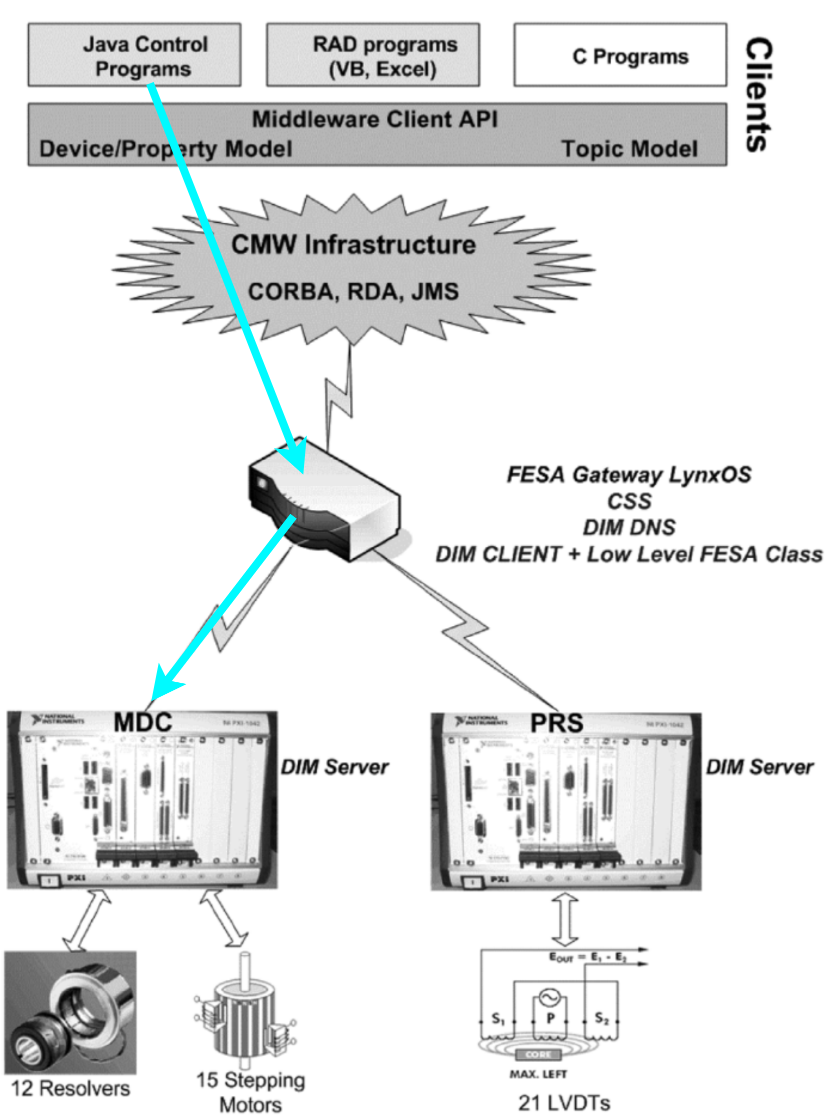


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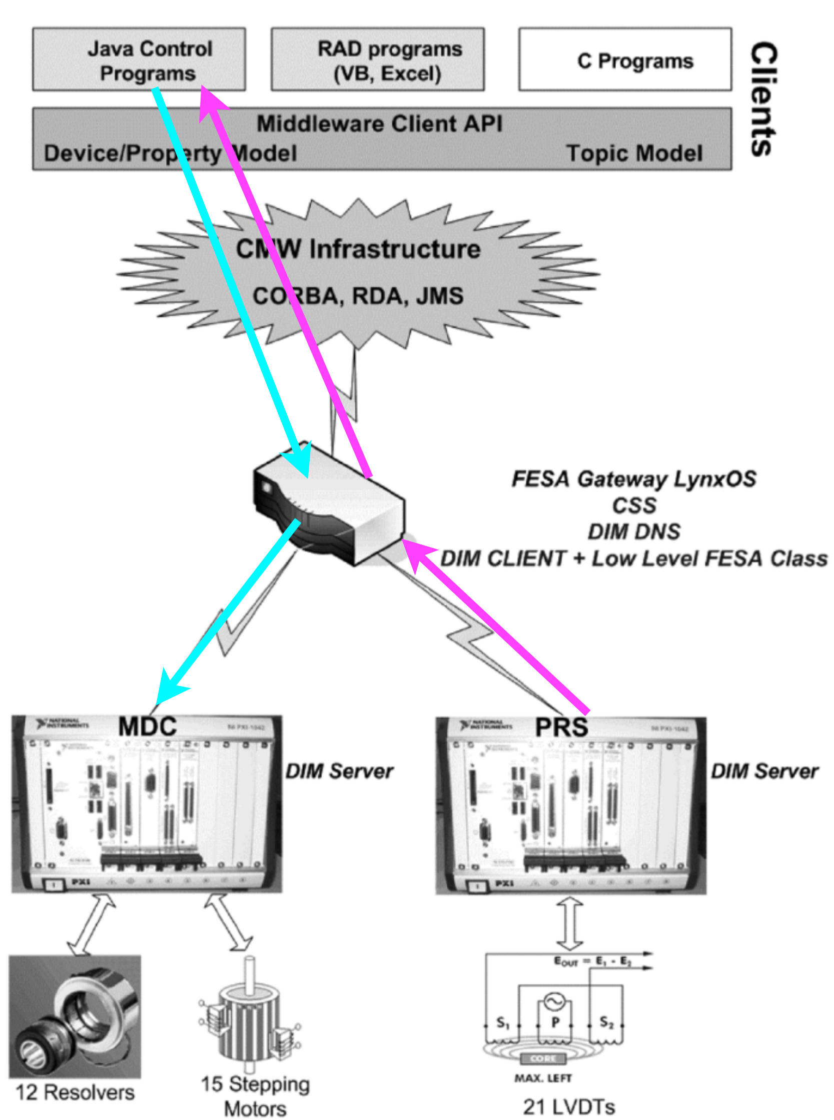


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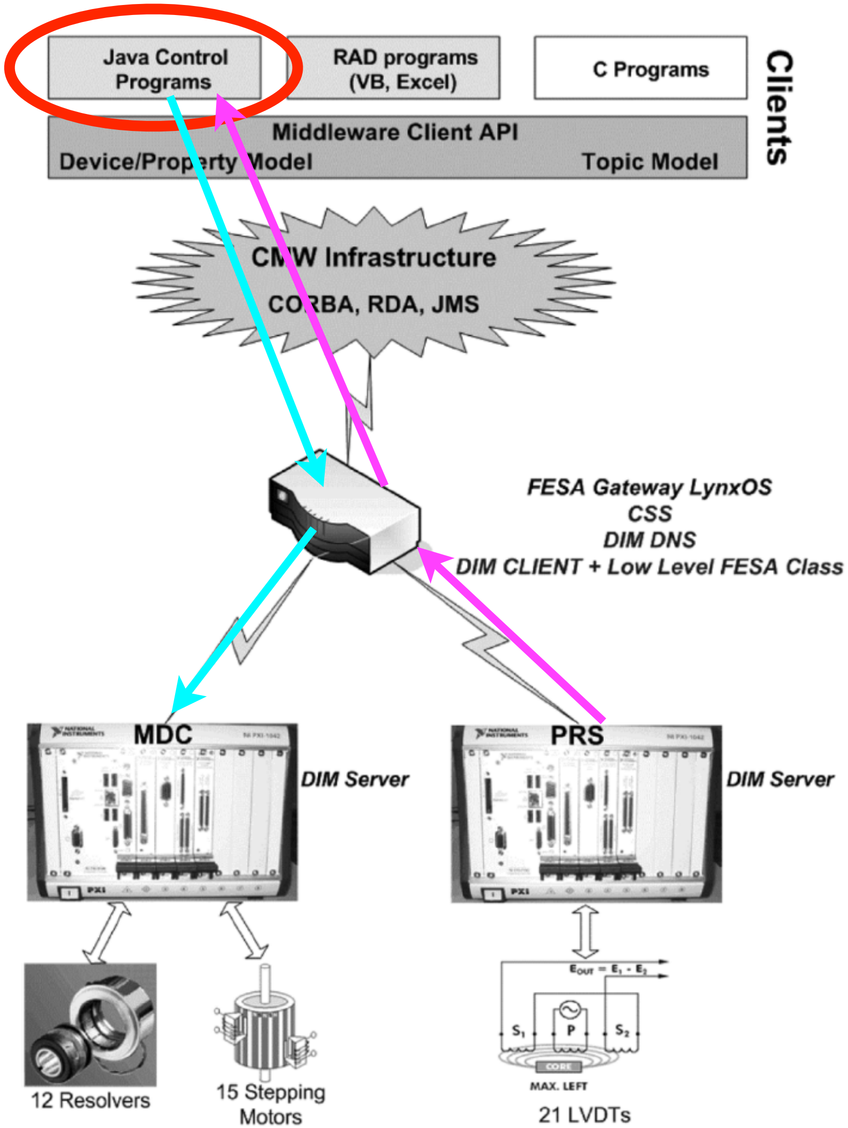


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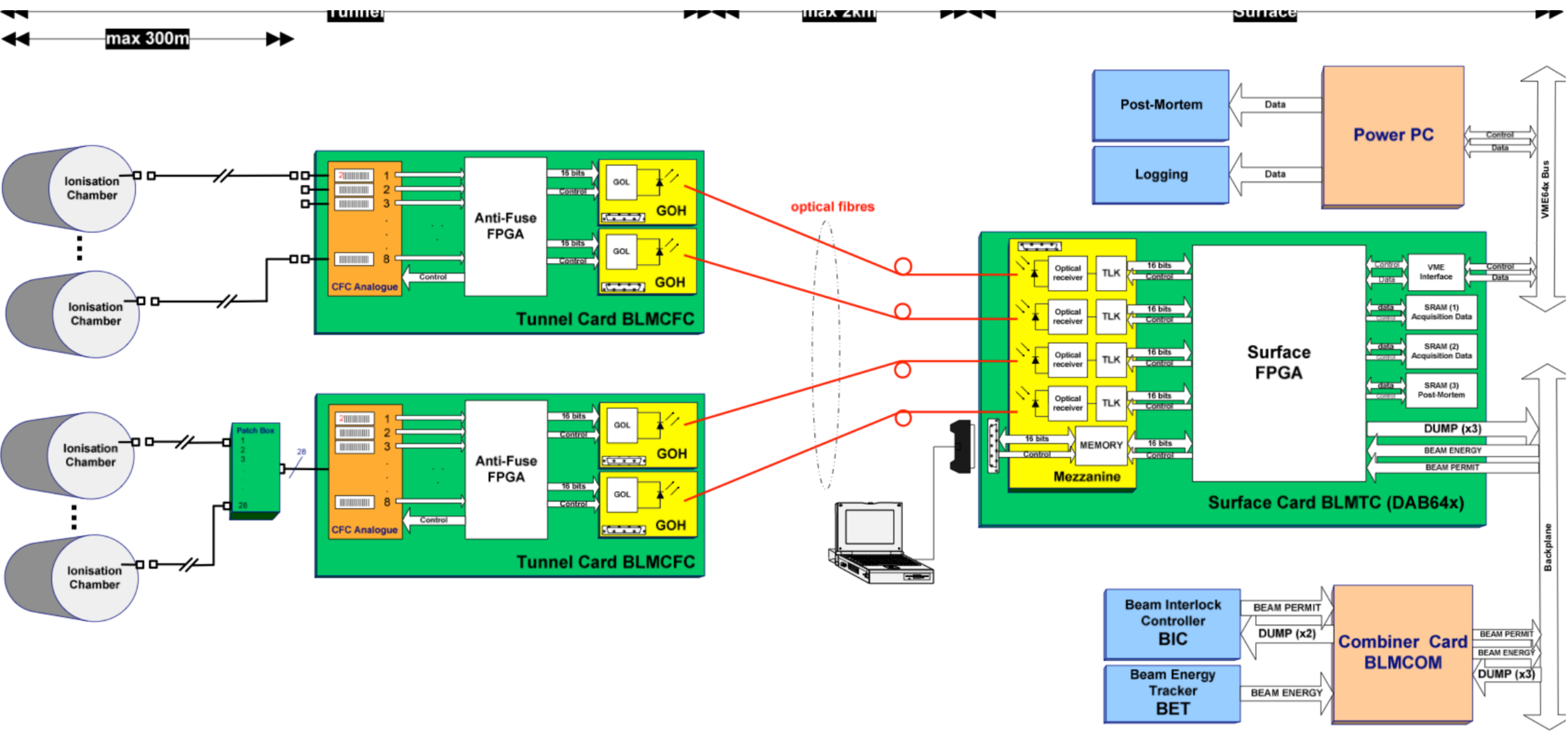
Motors, Position Readout

# BLM Data Acquisition

- Acquired from a data concentrator at **1 Hz, 1.3 s running sum** (2010-2011)...
- ... and via UDP packets at **12.5 Hz, 82 ms running sum** (2012 +).



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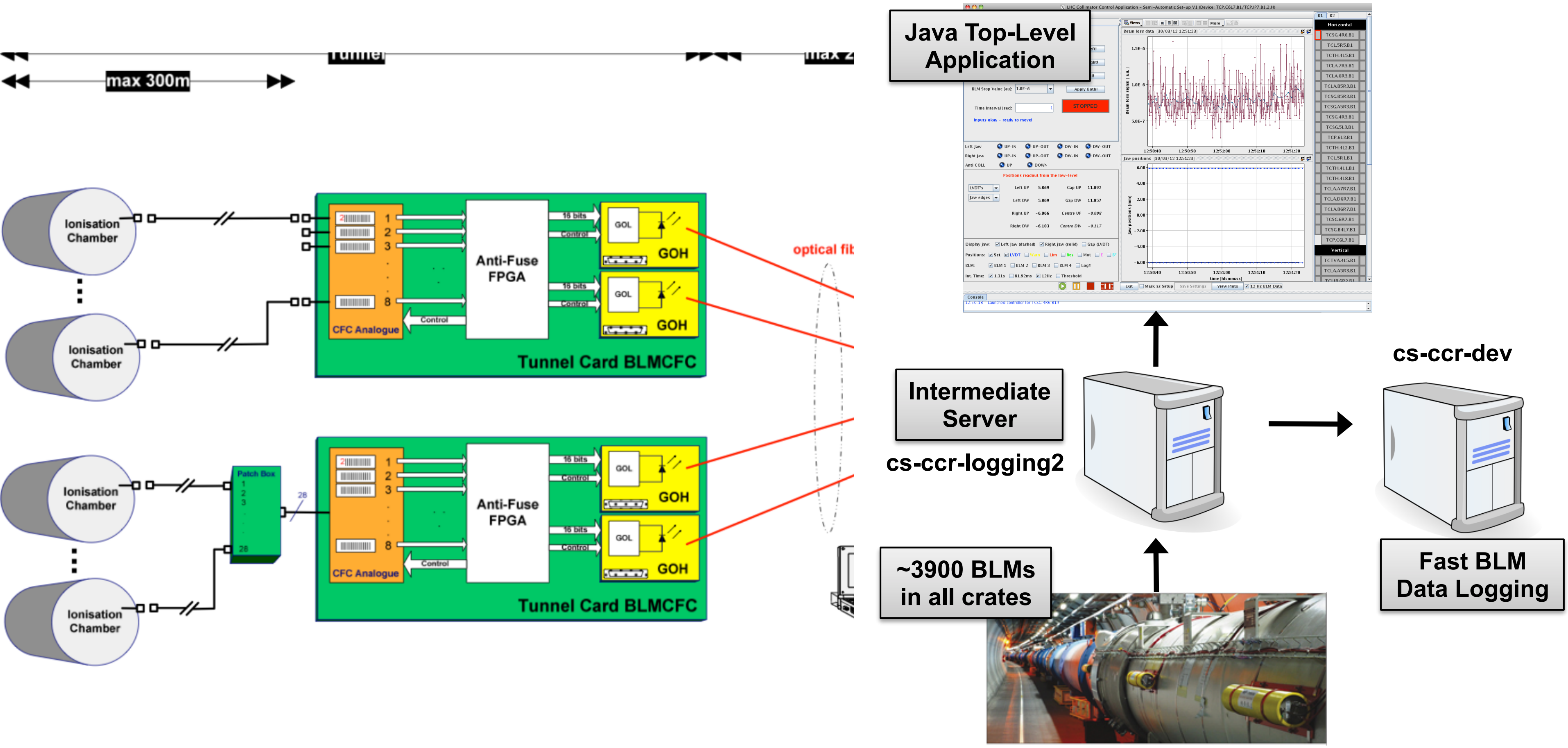
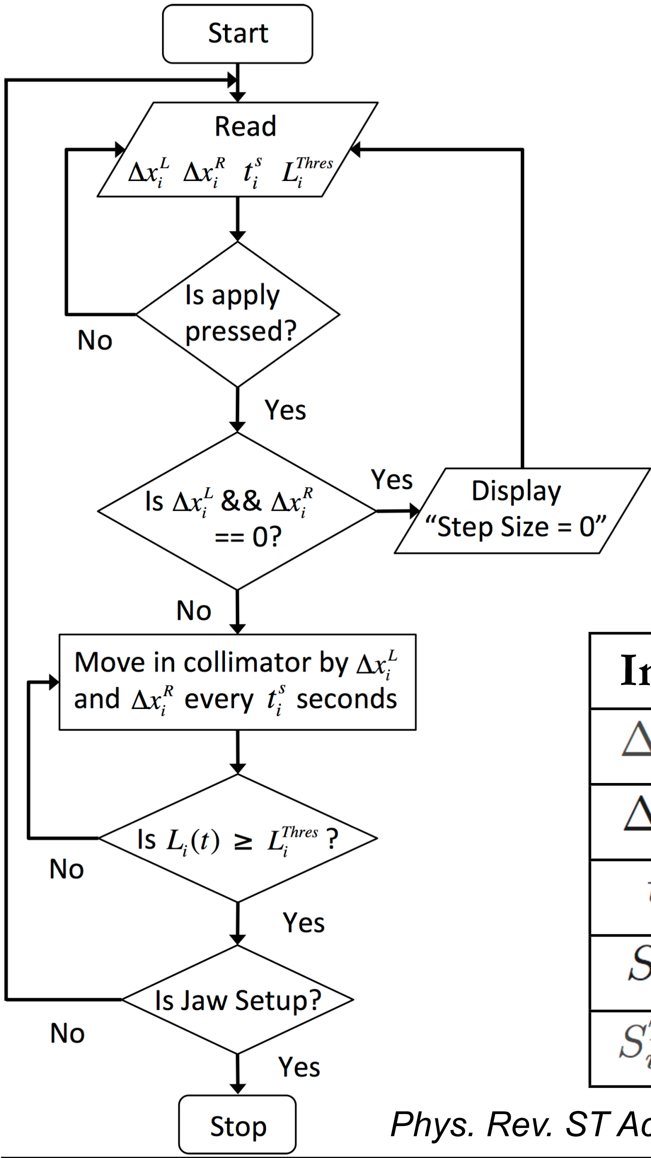


# BLM Feedback Loop




- A **BLM feedback loop** was implemented as a first step in automating the alignment.
- **Input heuristics** developed over 2 years of setups (2009 – 2010) by R. Assmann et al.

| Input | Description | Heuristic |
|---|---|---|
| $\Delta x_i^L$ | Left jaw step size in μm | 5 – 20 |
| $\Delta x_i^R$ | Right jaw step size in μm | 5 – 20 |
| $t_i^s$ | Time interval between each step in seconds | 1 – 3 |
| $S_i(t)$ | BLM signal in Gy/s | 5E-7 – 1E-4 |
| $S_i^{Thres}$ | Loss stop threshold in Gy/s | 1E-6 – 2E-4 |

*Phys. Rev. ST Accel. Beams*, **15**, 051002 (2012).

# Automatic Threshold Selection

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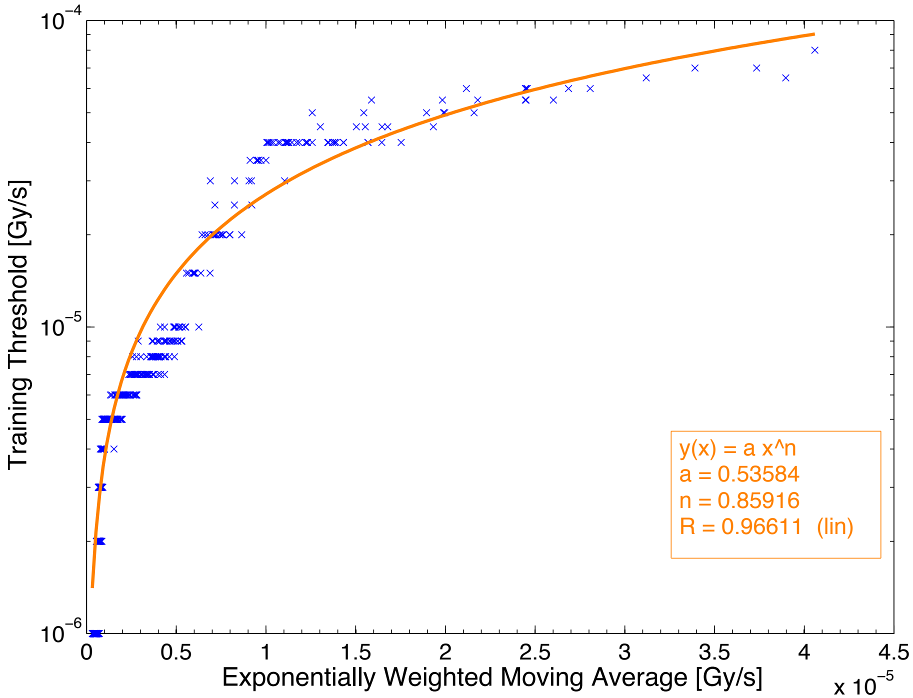
- The **exponentially weighted moving average** of each sample was determined.
- Larger weights assigned to most recent values.
- The threshold can be calculated in terms of the steady-state BLM signal:

$$S_i^{Thres} = 0.53584e^{0.85916x}$$



# Parallel Collimator Alignment

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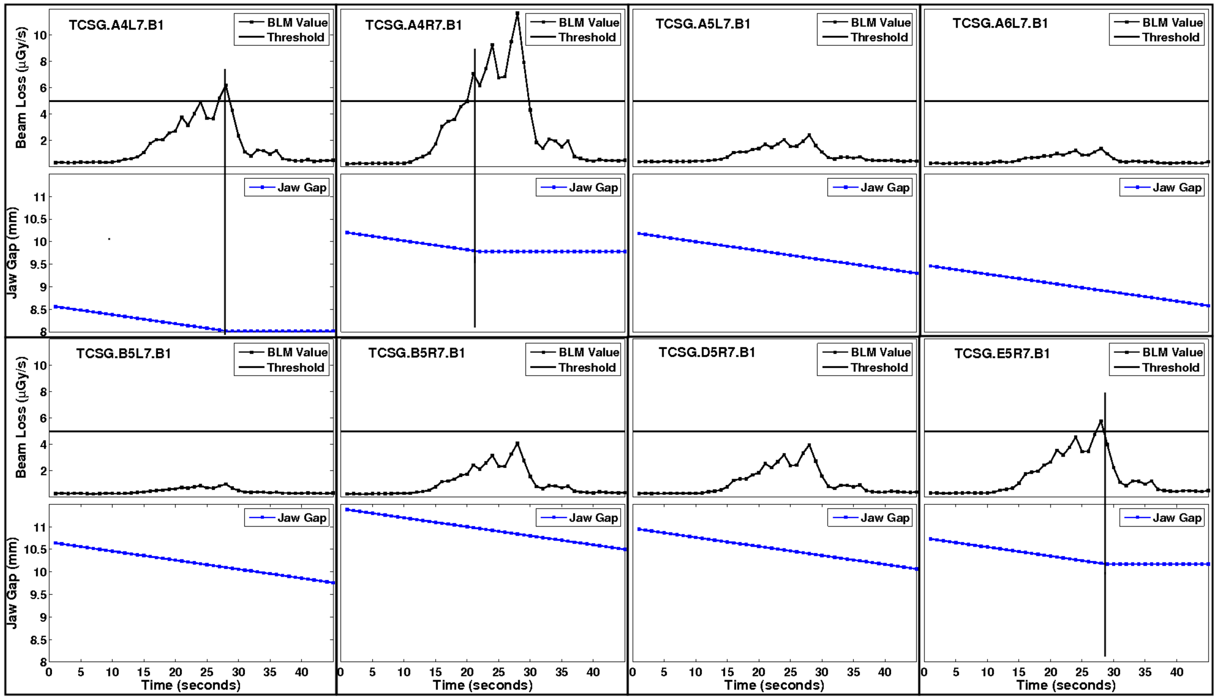

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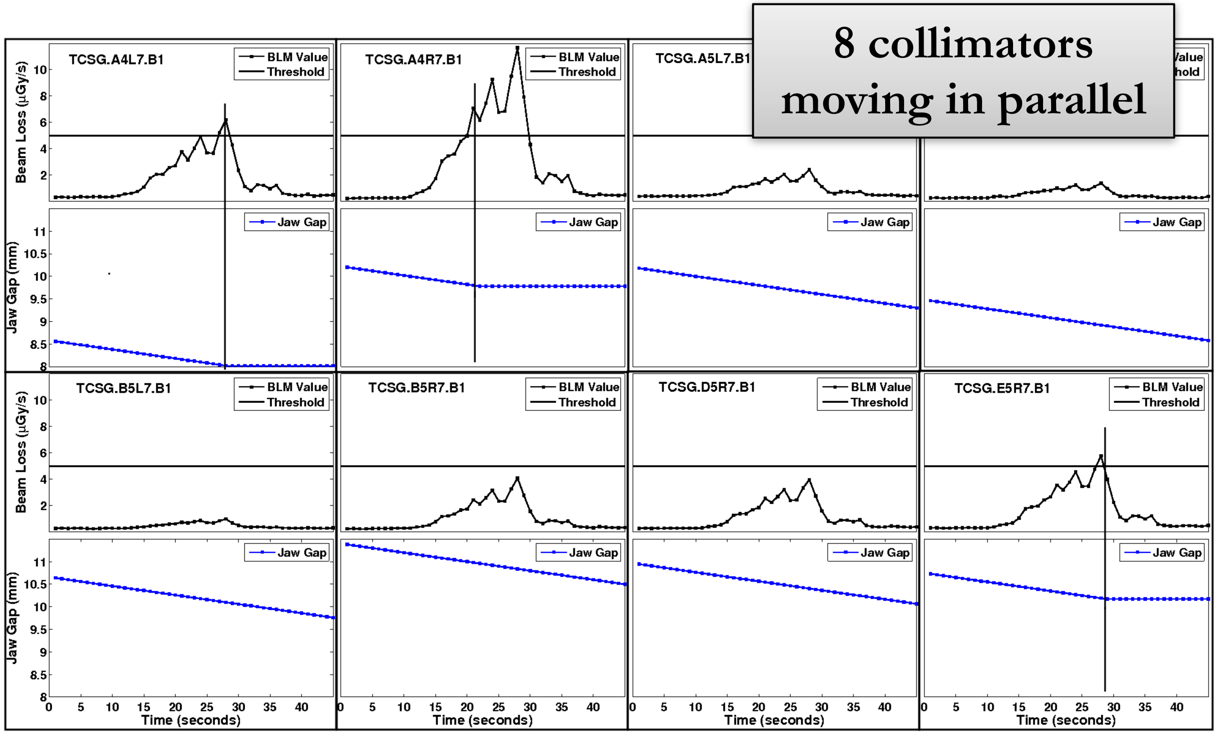
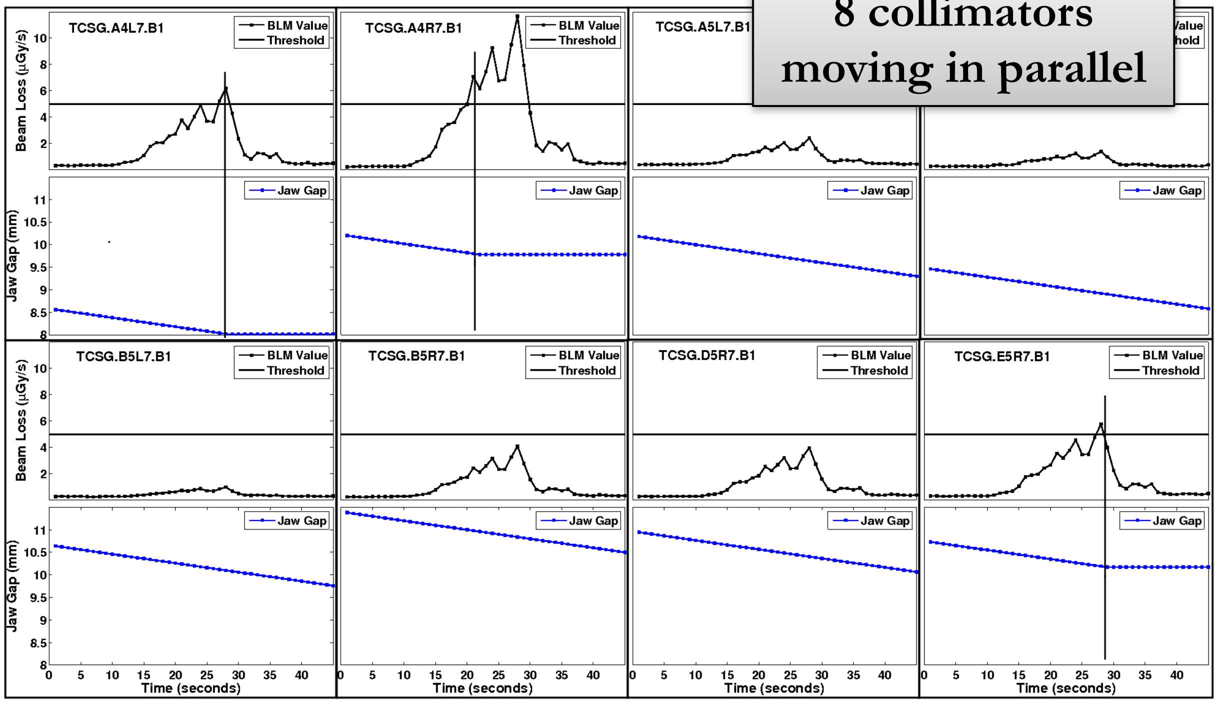


# Parallel Collimator Alignment

LHC Collimation Project CERN

8 collimators moving in parallel

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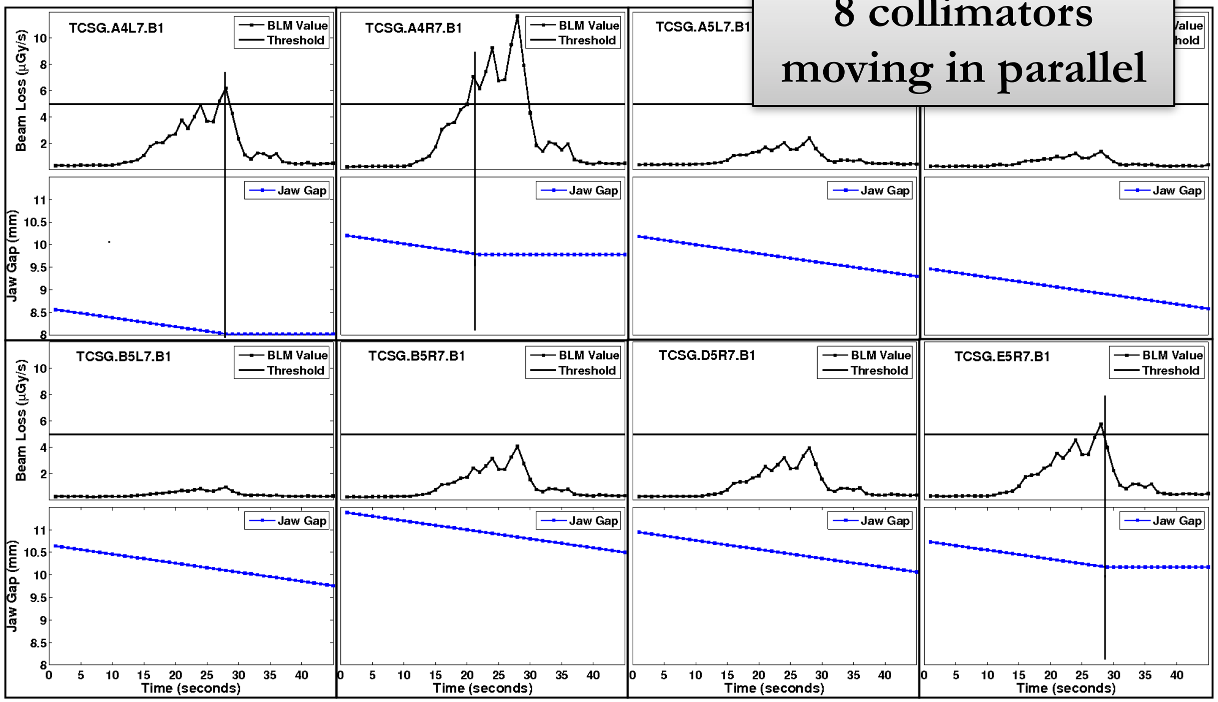


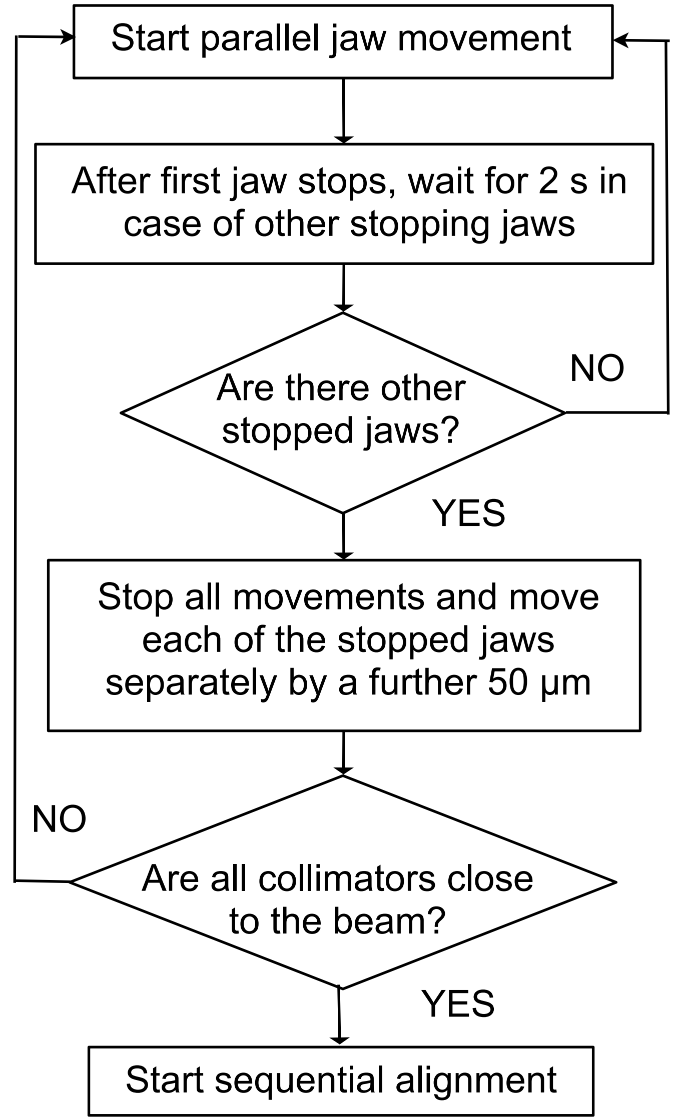


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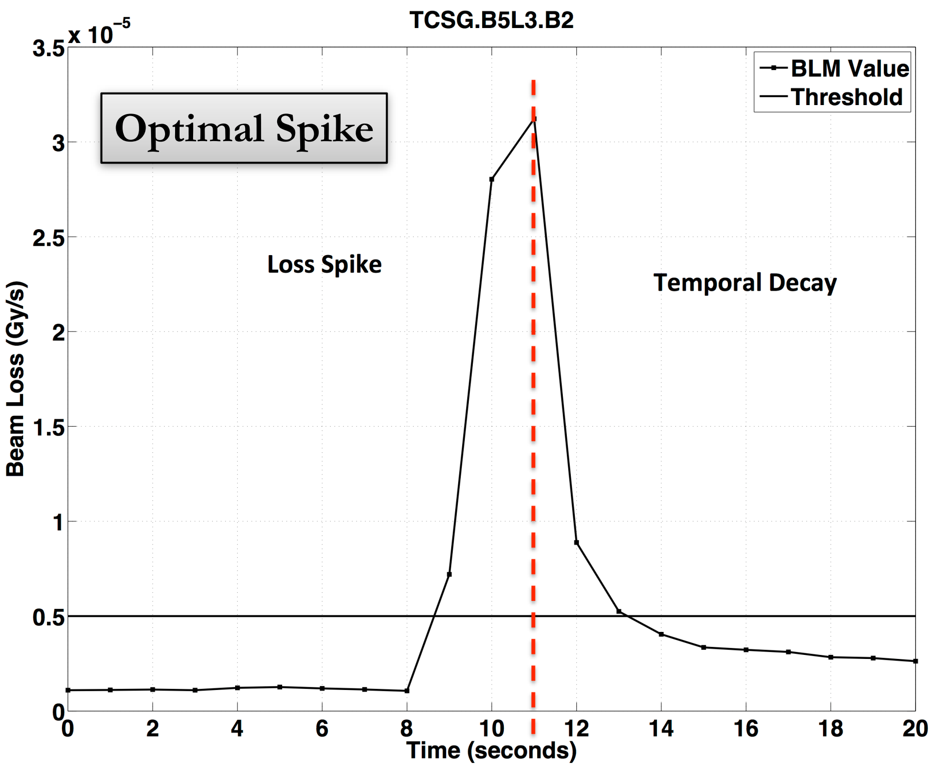

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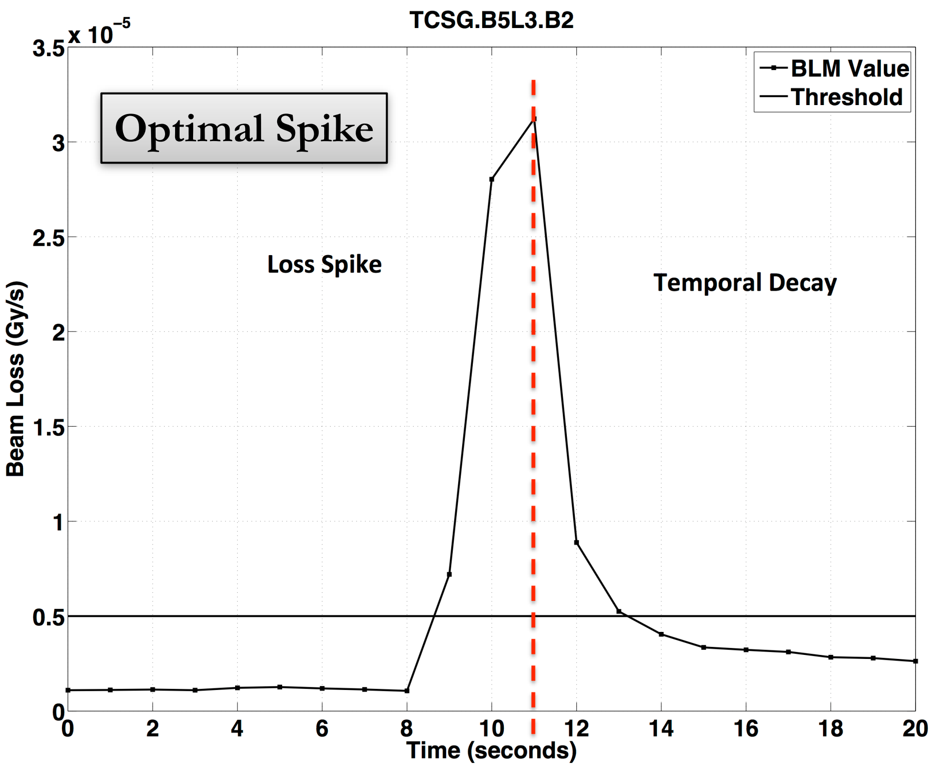
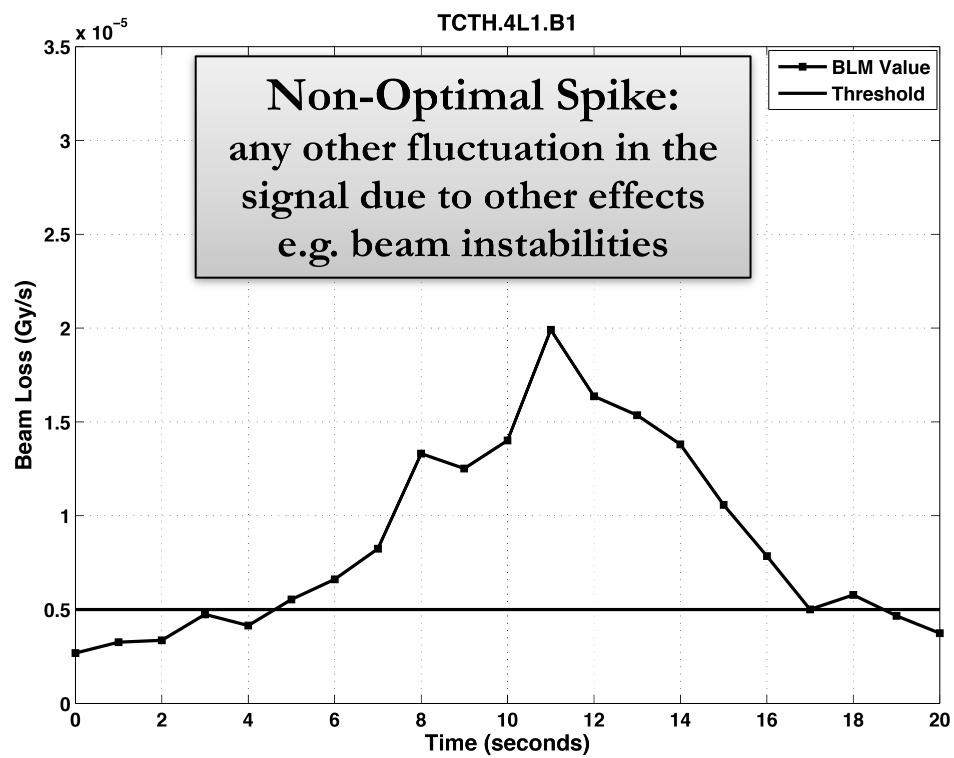
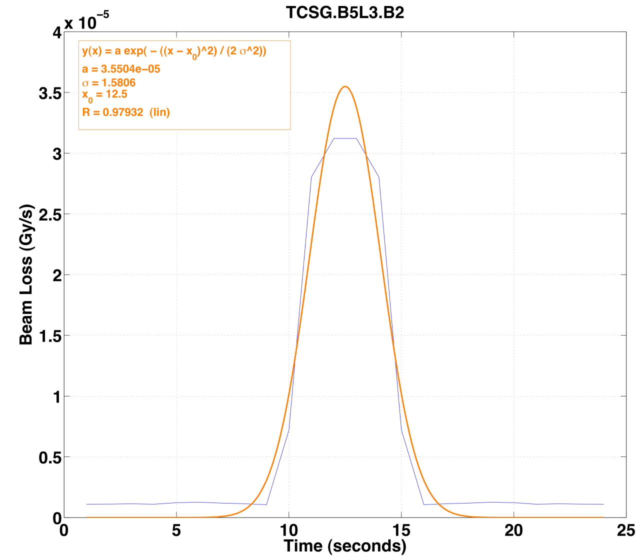


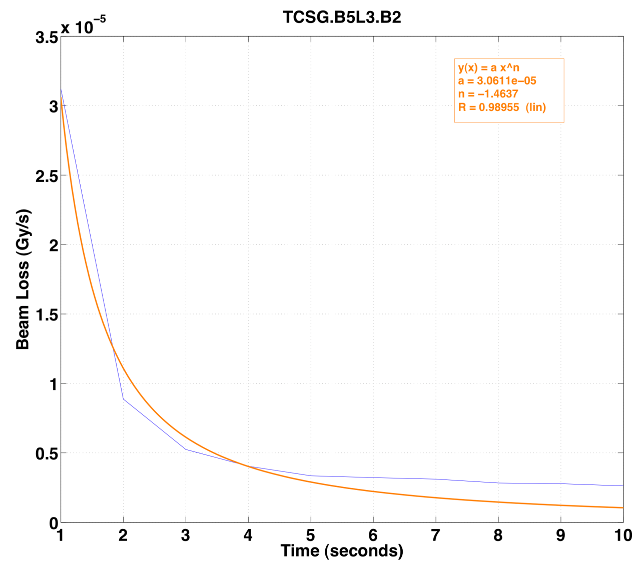
# Feature Selection

- Six features were selected to distinguish between optimal and non-optimal loss spikes.

1. **Maximum BLM value** observed after the threshold is exceeded.
2. **Average** of the 3 smallest loss values of the 7 loss values preceding the maximum value.




3. **Width** of the Gaussian fit applied to the loss spike folded about the maximum value.
4. **Gaussian fit correlation coefficient.**




5. **Power fit exponent.**
6. **Power fit correlation coefficient.**

# SVM Training and Results

- **LIBSVM tool** in MATLAB was used for training and testing the SVM model.
- The data were linearly scaled to [-1, +1] to avoid values in larger numeric ranges dominating those in smaller ranges.
- Grid search performed on C (over-fitting vs. under-fitting penalty factor) and $\gamma$ (width of RBF) using 5-fold cross-validation to determine the optimal values for these parameters.
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| **Parameter** | **Value** |
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| Number of Features | 6 |
| Number of Classes | 2 |
| C | 32768 |
| $\gamma$ | 0.125 |
| Kernel | RBF |
| Training dataset prediction | 97.2973 % |
| Test dataset prediction rate | 82.4324 % |
| **Overall prediction rate** | **89.8649 %** |

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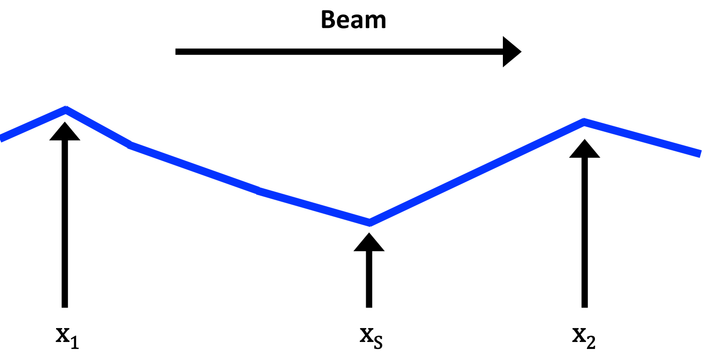
**Some unsuccessful classifications due to TCT alignments!**

# BPM-guided Coarse Alignment




- An approximation to the beam centers at the collimators can be obtained from an interpolation of the orbit measured by the BPMs.
- This was exploited to speed up the alignment, assuming a **reproducible delta** between measurements and interpolation.
- All collimator jaws can be **moved directly to the tighter settings** at a rate of 2 mm/s instead of 0.01 mm/s.

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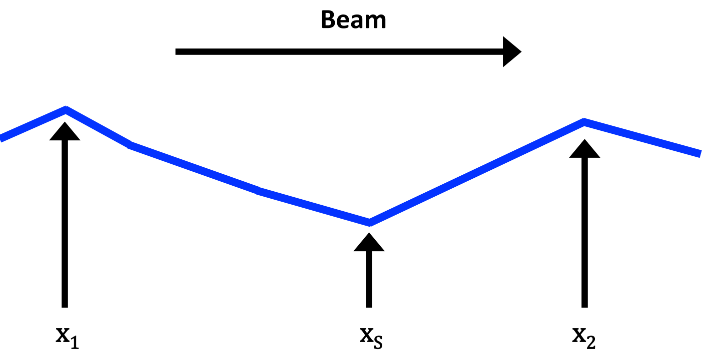


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$$x_i^L = x_i^{int.} + (N_{TCP} + N_{margin}) \times \sigma_i^n + \sigma_i^{m,int.}$$

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Typically
< 1.5 mm

- $x_i^{int.}$ : interpolated beam center at collimator *i*.
- $N_{TCP}$ : half-gap of IR7 TCP in units of sigma.
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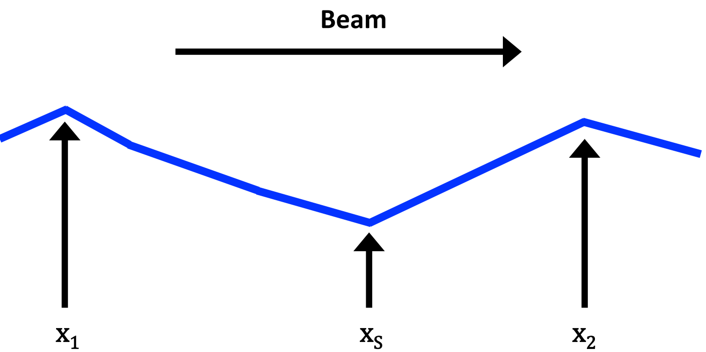


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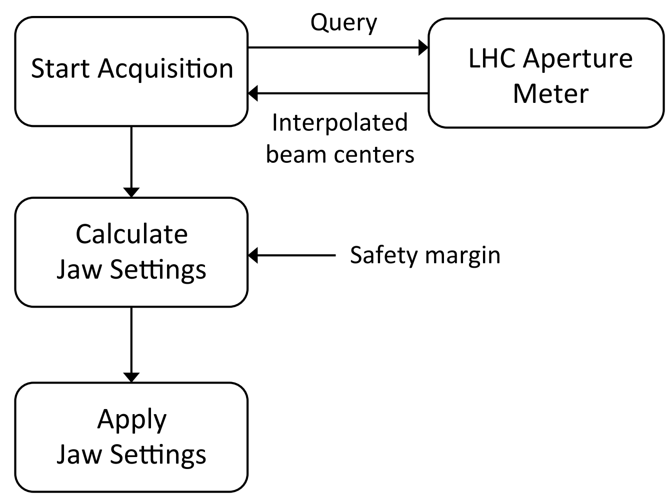


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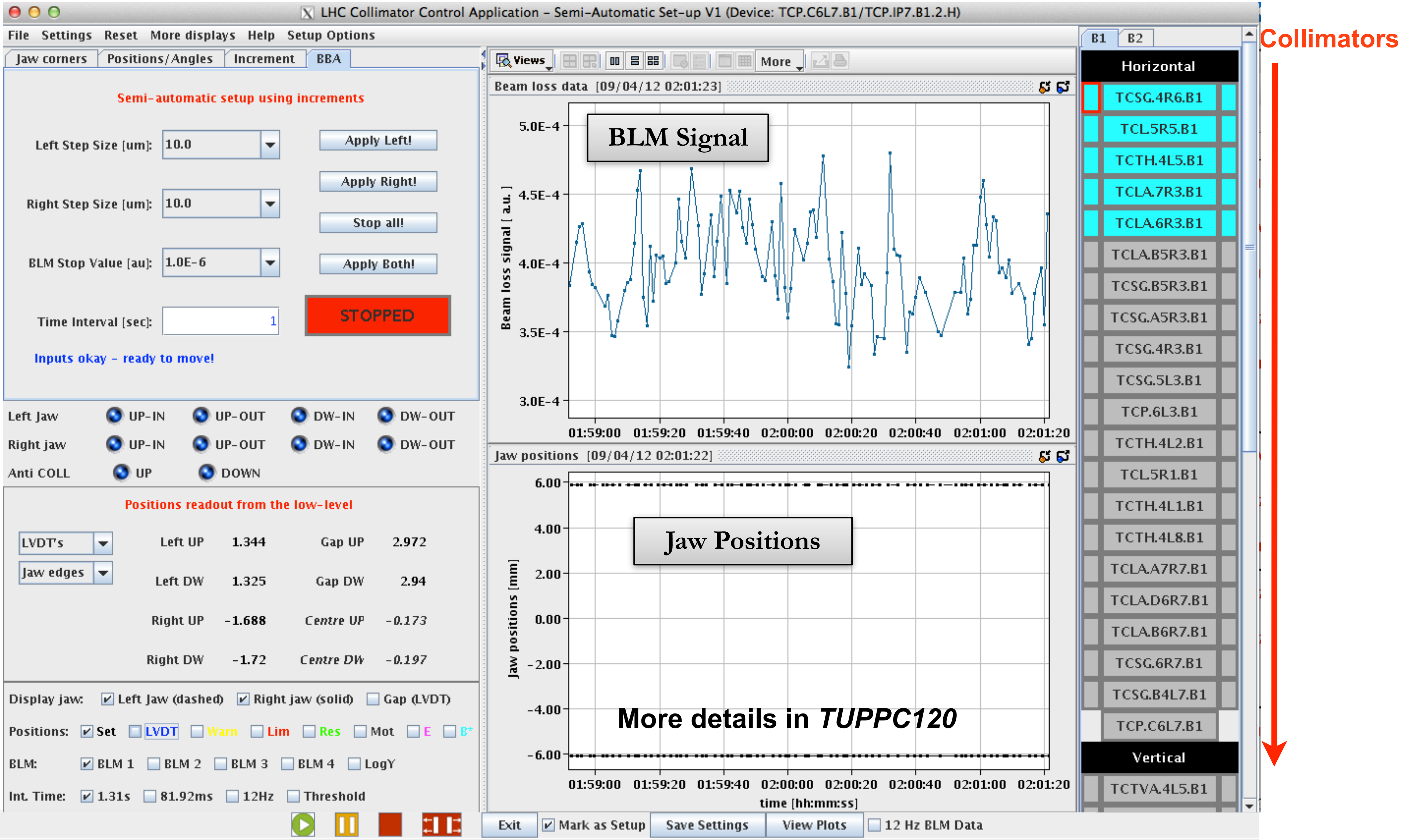
# BLM-based alignment software



# Alignment Results

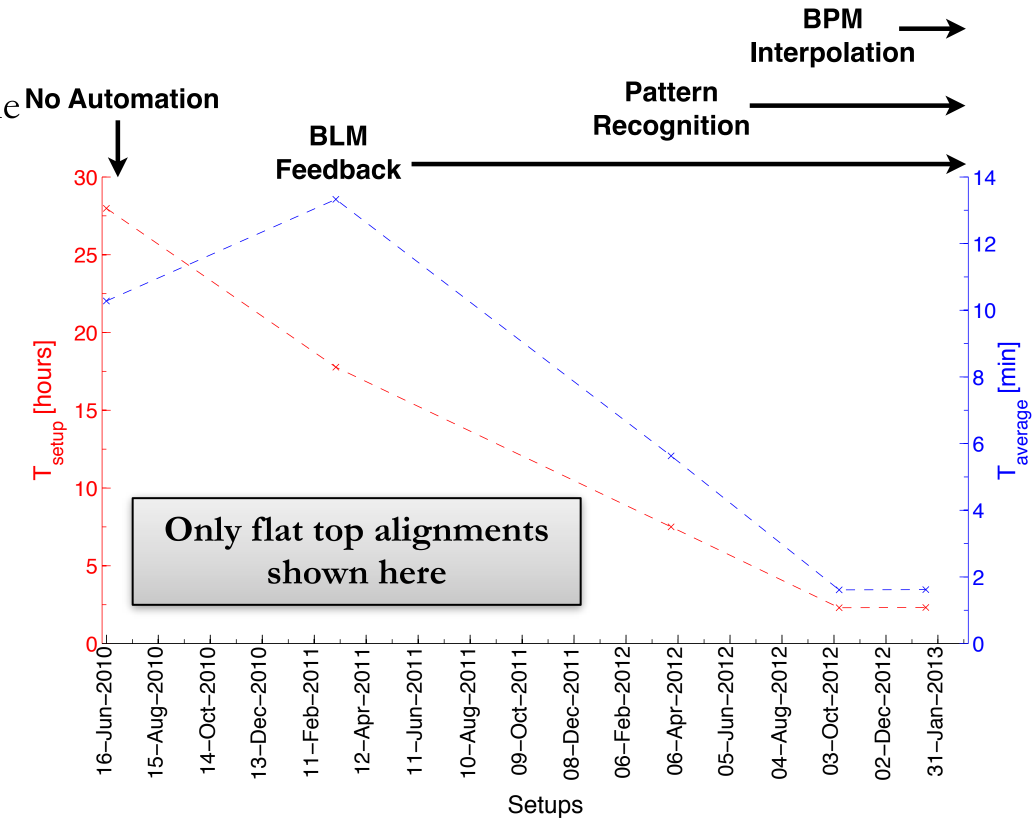
- Total setup time depends on the beam time consumed, the number of beam dumps $d$ and the turnaround time:

$$T_{setup} = T_{beam} + d \times T_{turnaround}$$

$$T_{average} = \frac{T_{beam}}{C}$$

- No costly beam dumps due to high losses from 2011 onwards.

- Use of smaller jaw step size (better accuracy) made easier by automatic alignment.



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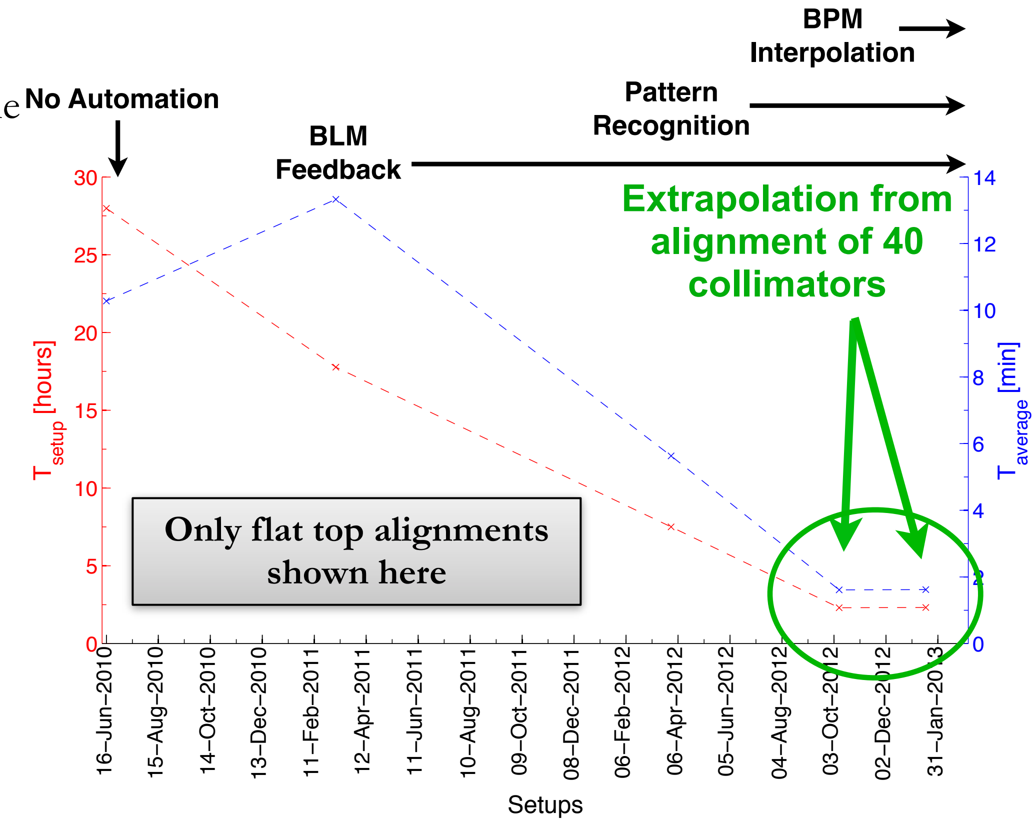

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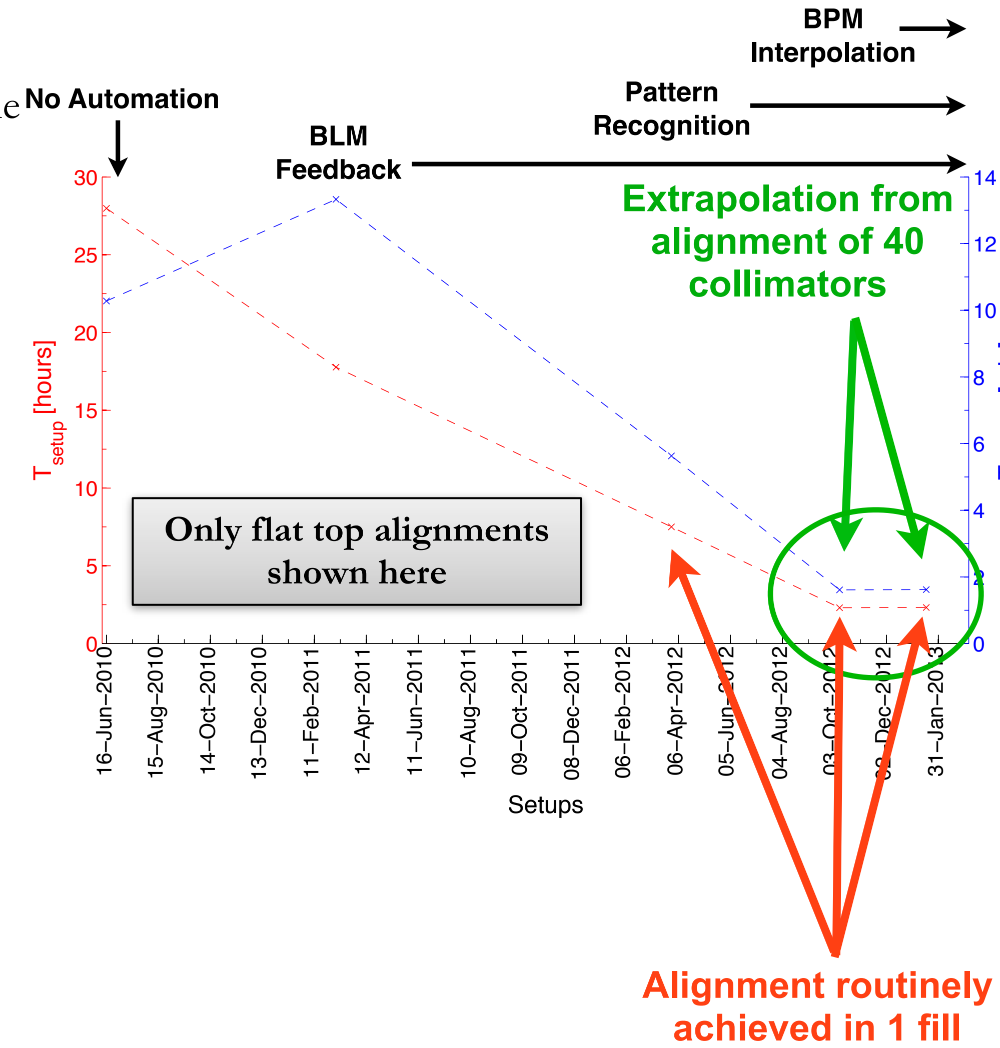

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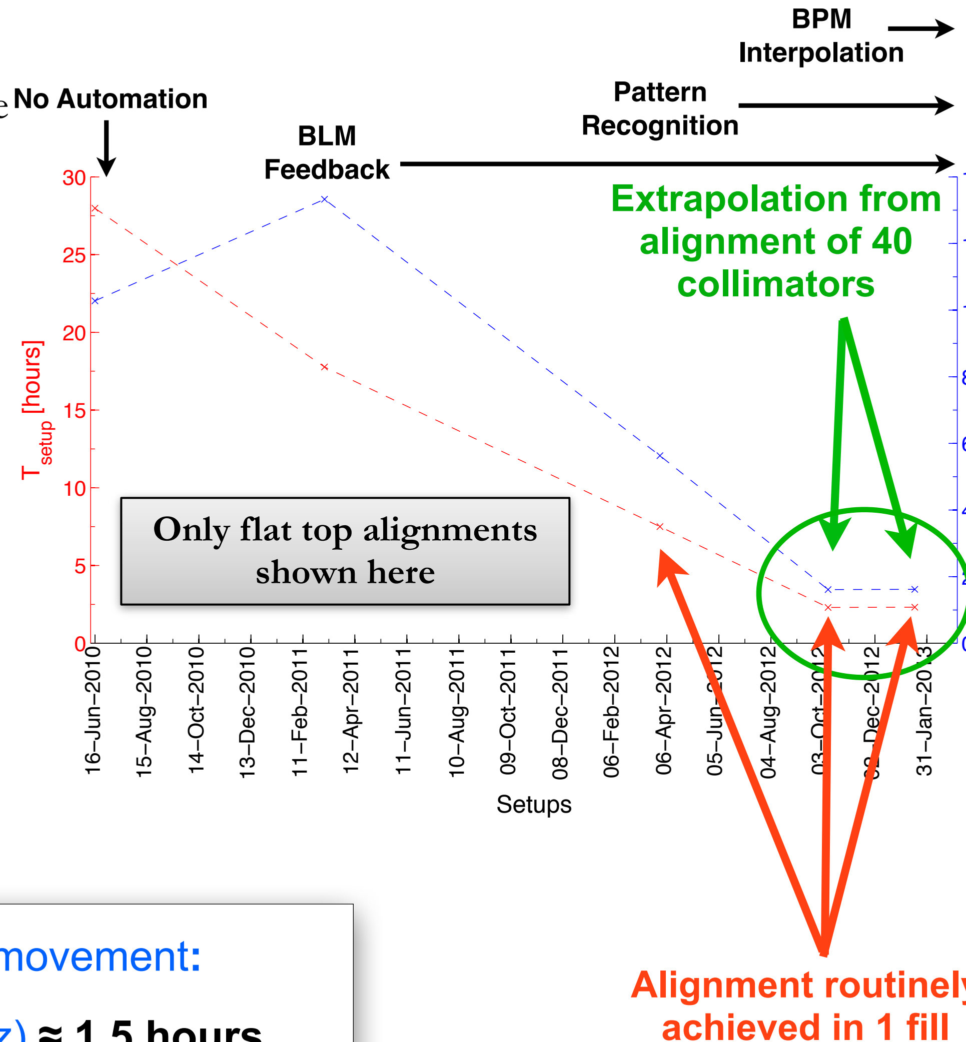
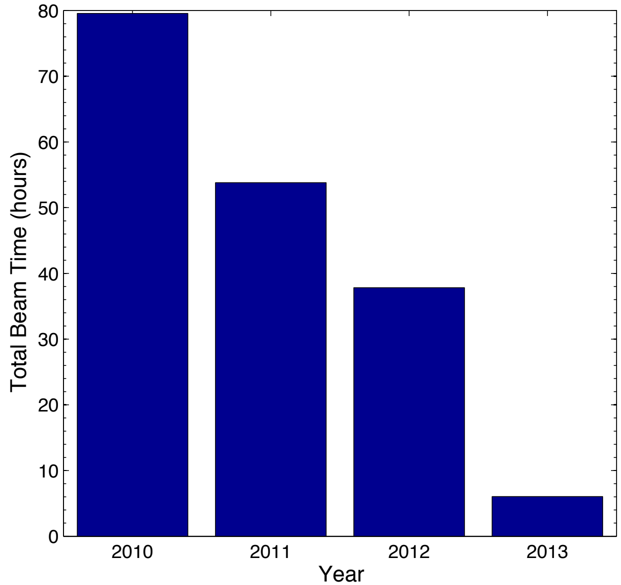
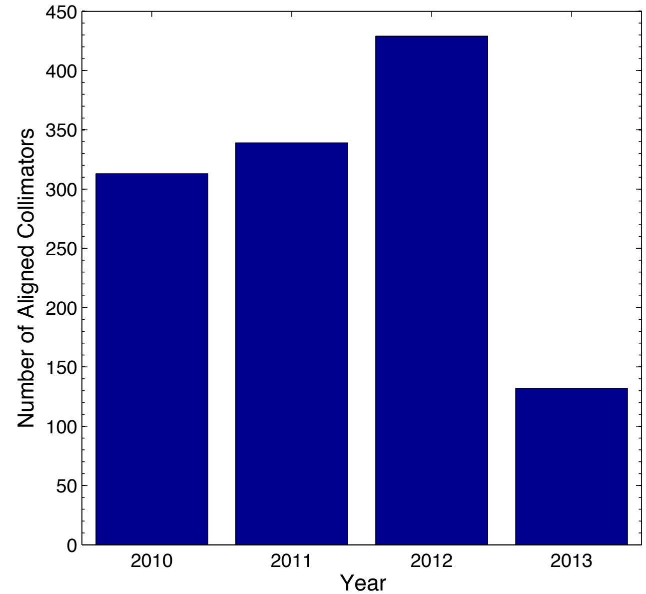


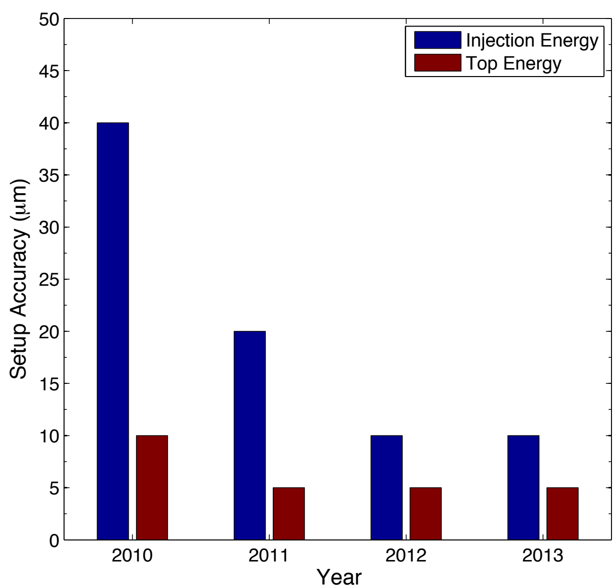

**Limitation from loss spikes + jaw movement:**

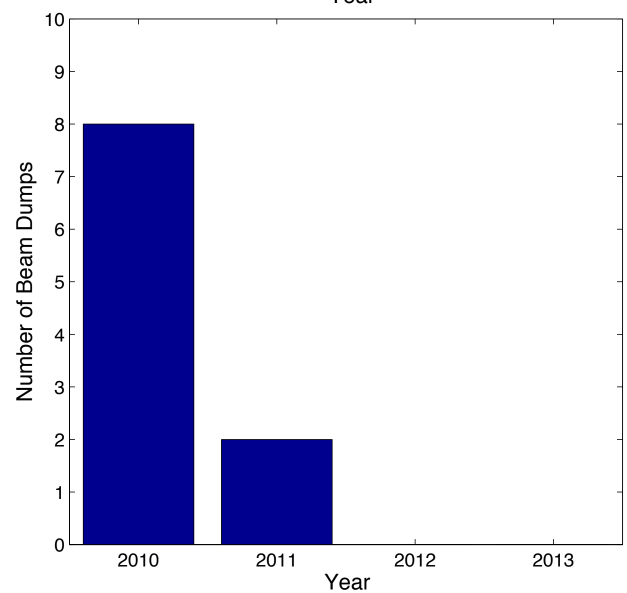
**(86 x 2 x 2 x 15s) + (8 mm / 5 μm / 8 Hz) ≈ 1.5 hours**

# Operational Results



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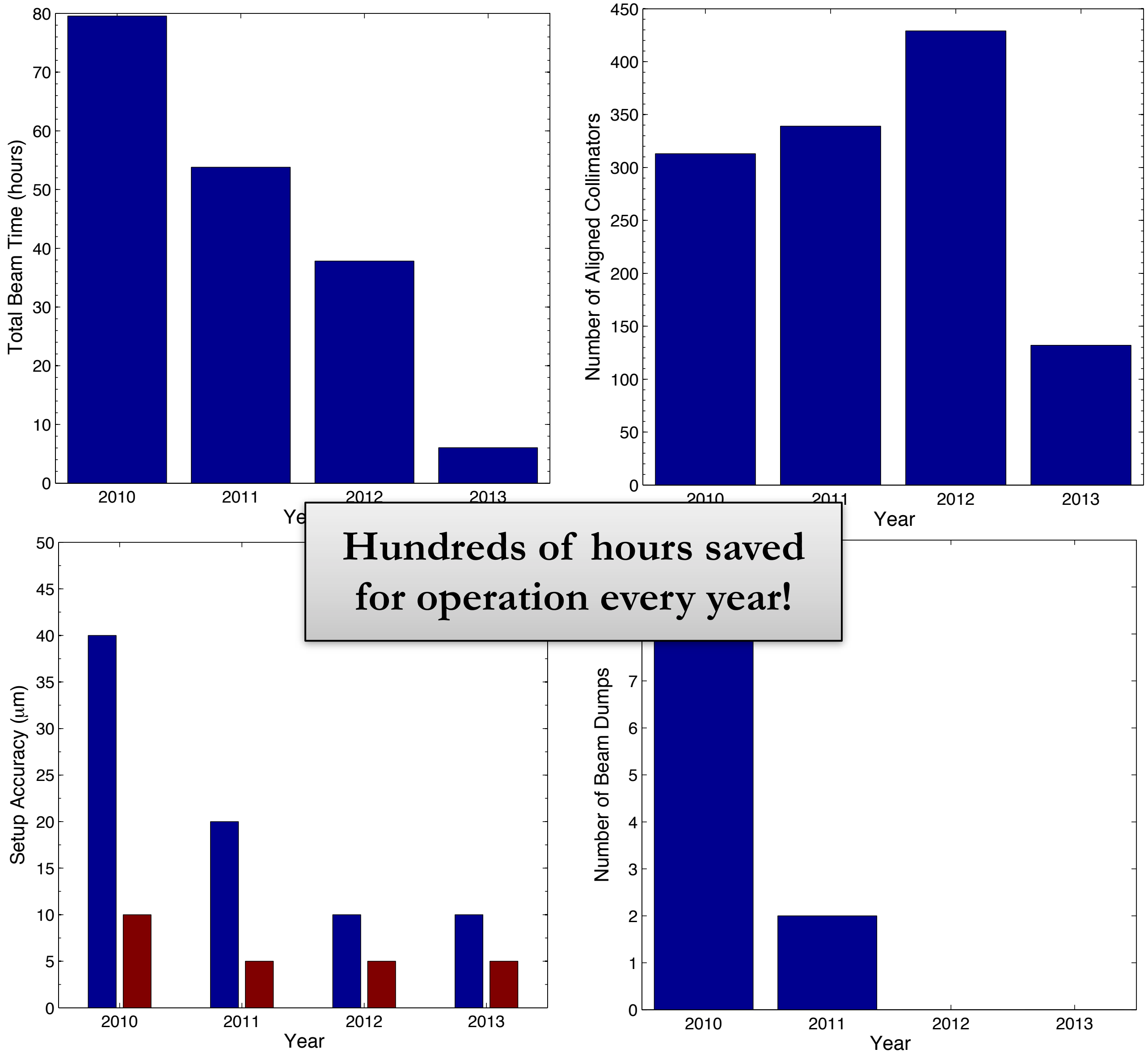



Hundreds of hours saved for operation every year!

# Summary

- LHC collimation system cleaning efficiency is highly dependent on correct collimator positions.
- The jaw positions are determined from beam-based alignment, which can last **> 20 hours when done manually**.
- The BLM signals are used in a **feedback loop to automatically stop the jaw** once the losses exceed a pre-defined threshold, an indication that the jaw has possibly touched the beam halo.
- The **threshold is automatically set depending on the steady-state BLM signal** based on an empirical data analysis.
- **SVM-based loss spike classification** allows the setup software to move in the jaw further to obtain a sharper spike and ensure that the automatic alignment is reliable.
- The **BPM-interpolated orbit** allows for a coarse alignment of the jaws around the beam center with a safety margin to gain time.
- Automatic alignment algorithms have so far reduced the total setup time from 28 hours to 4 hours (**factor 7 improvement**) and minimized the possibility of human error.
- The **robustness of the loss spike classification algorithm** needs to be improved to counter noise in the BLM signal and provide a fully automatic collimator alignment software tool.

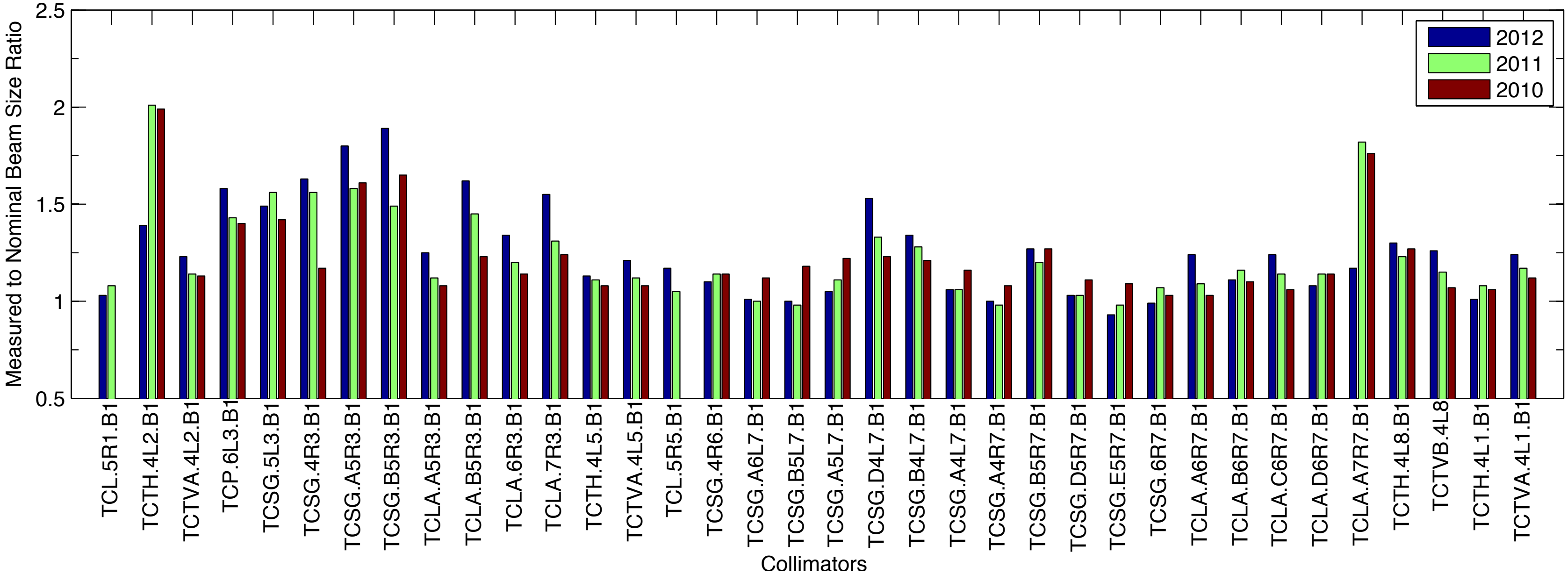
Thank you for your attention!

Any questions?

gianluca.valentino@cern.ch

# RESERVE SLIDES

# Alignment Results (2)



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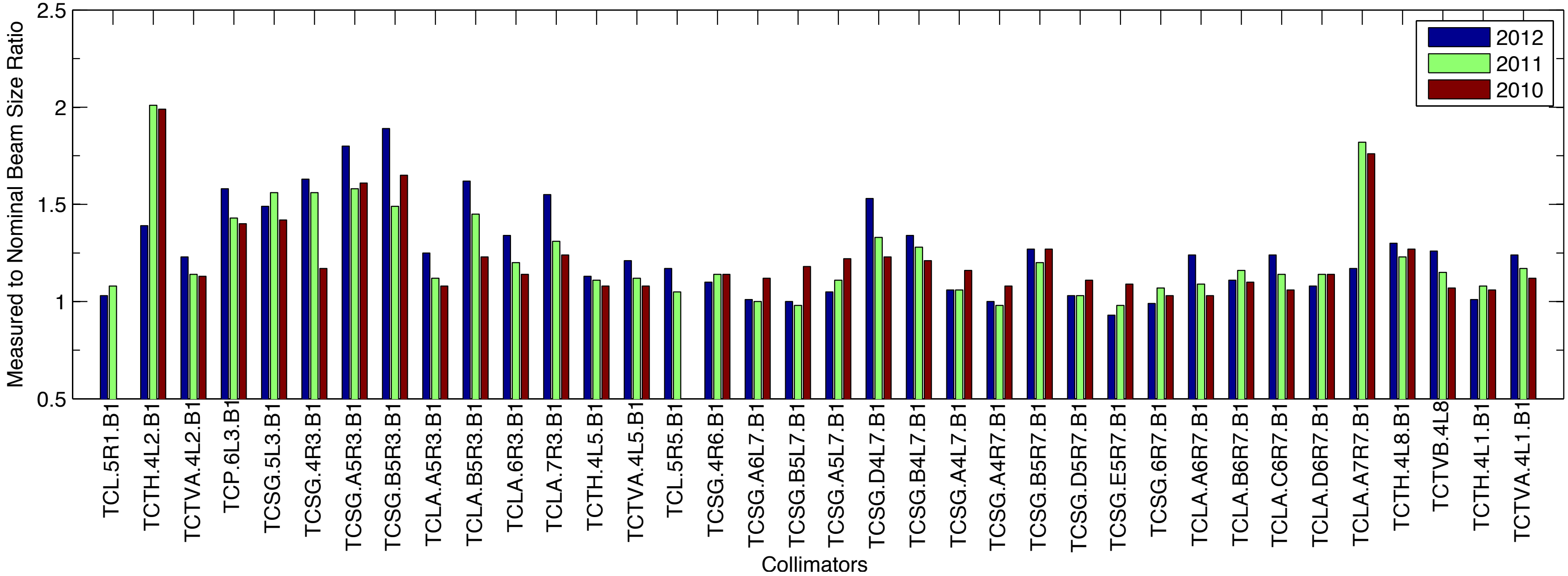

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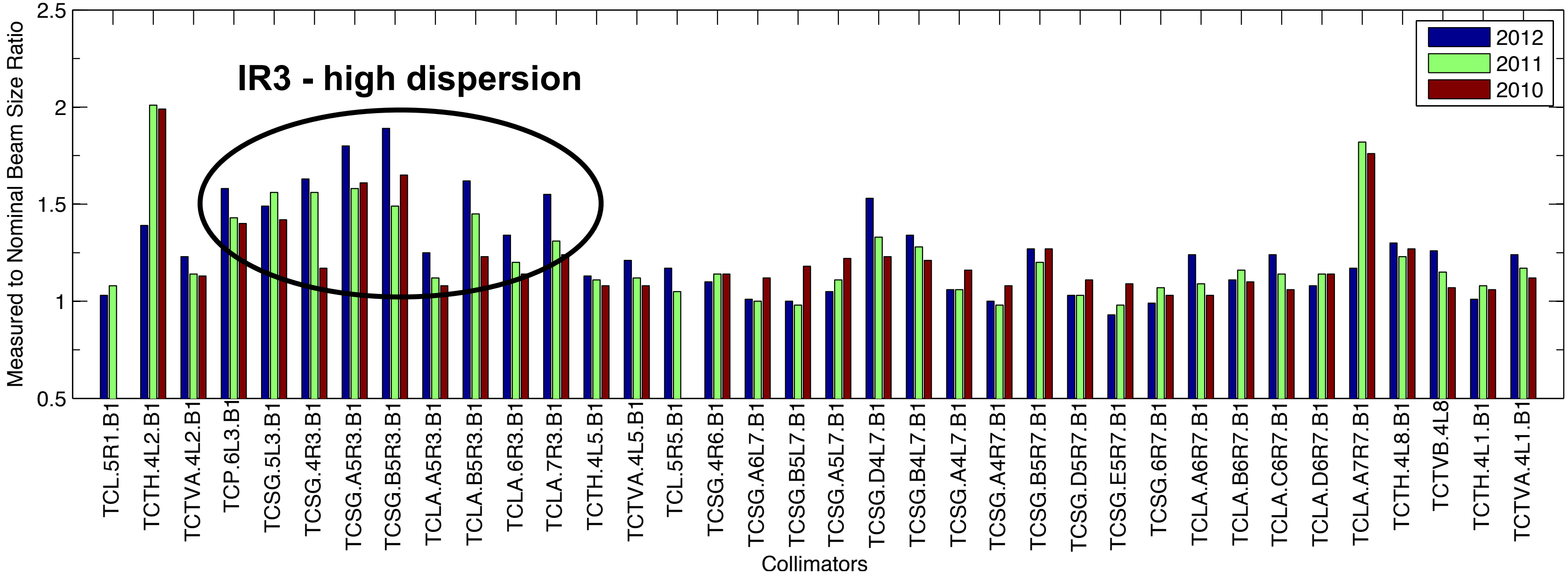

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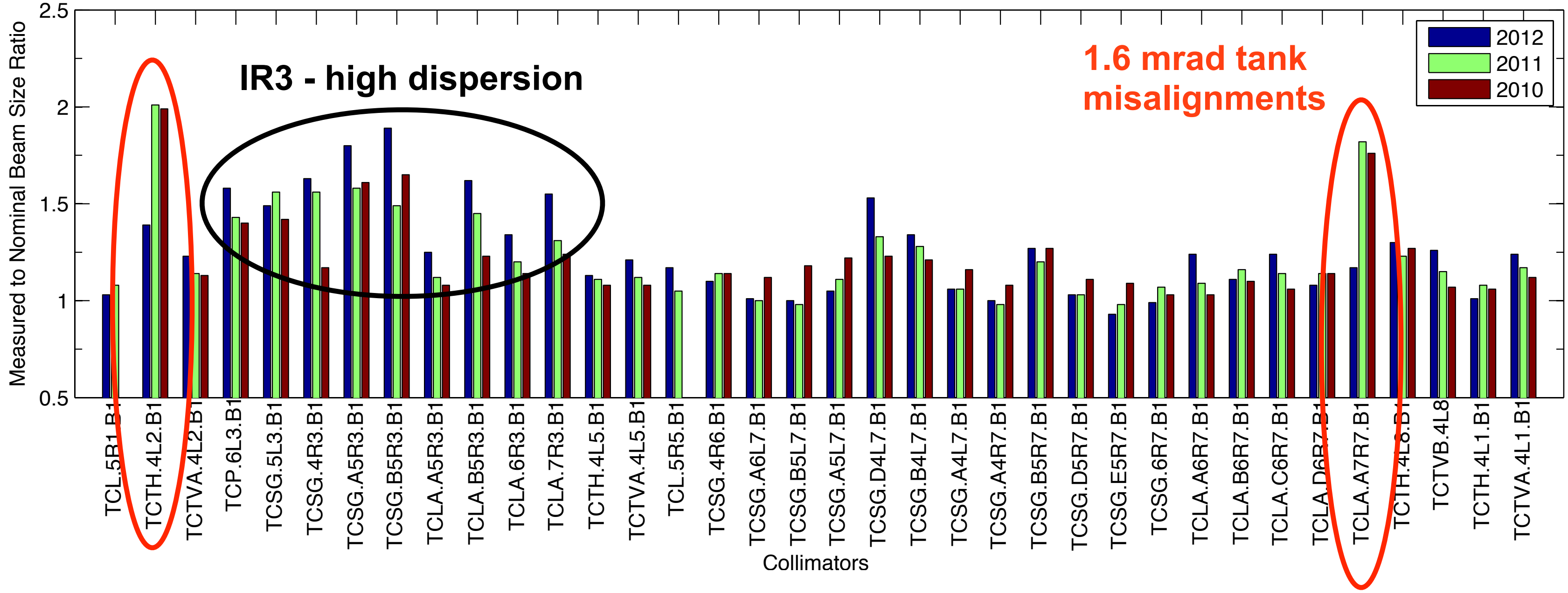

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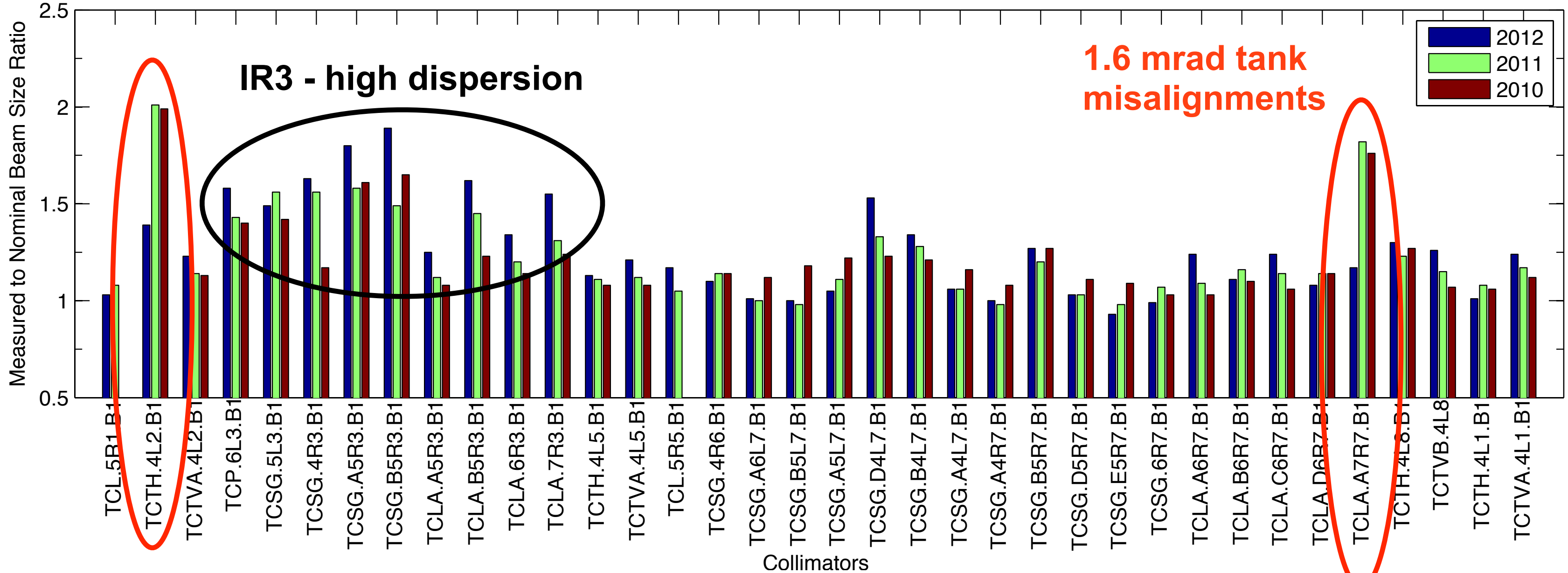
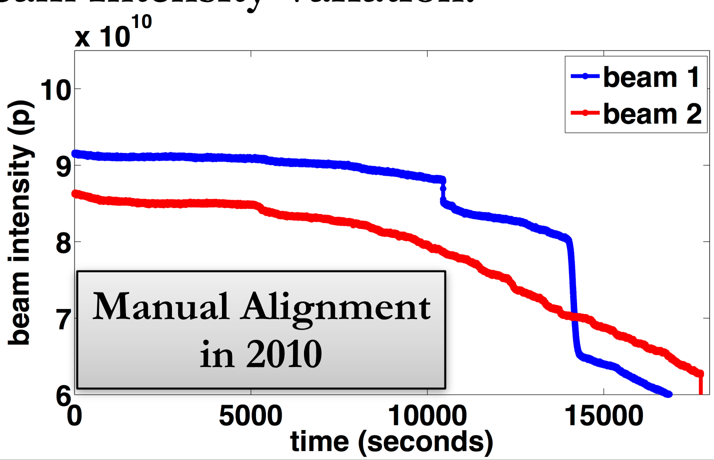
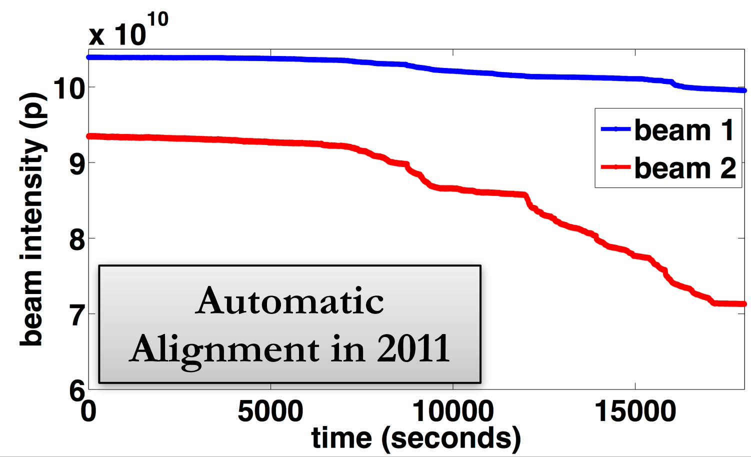
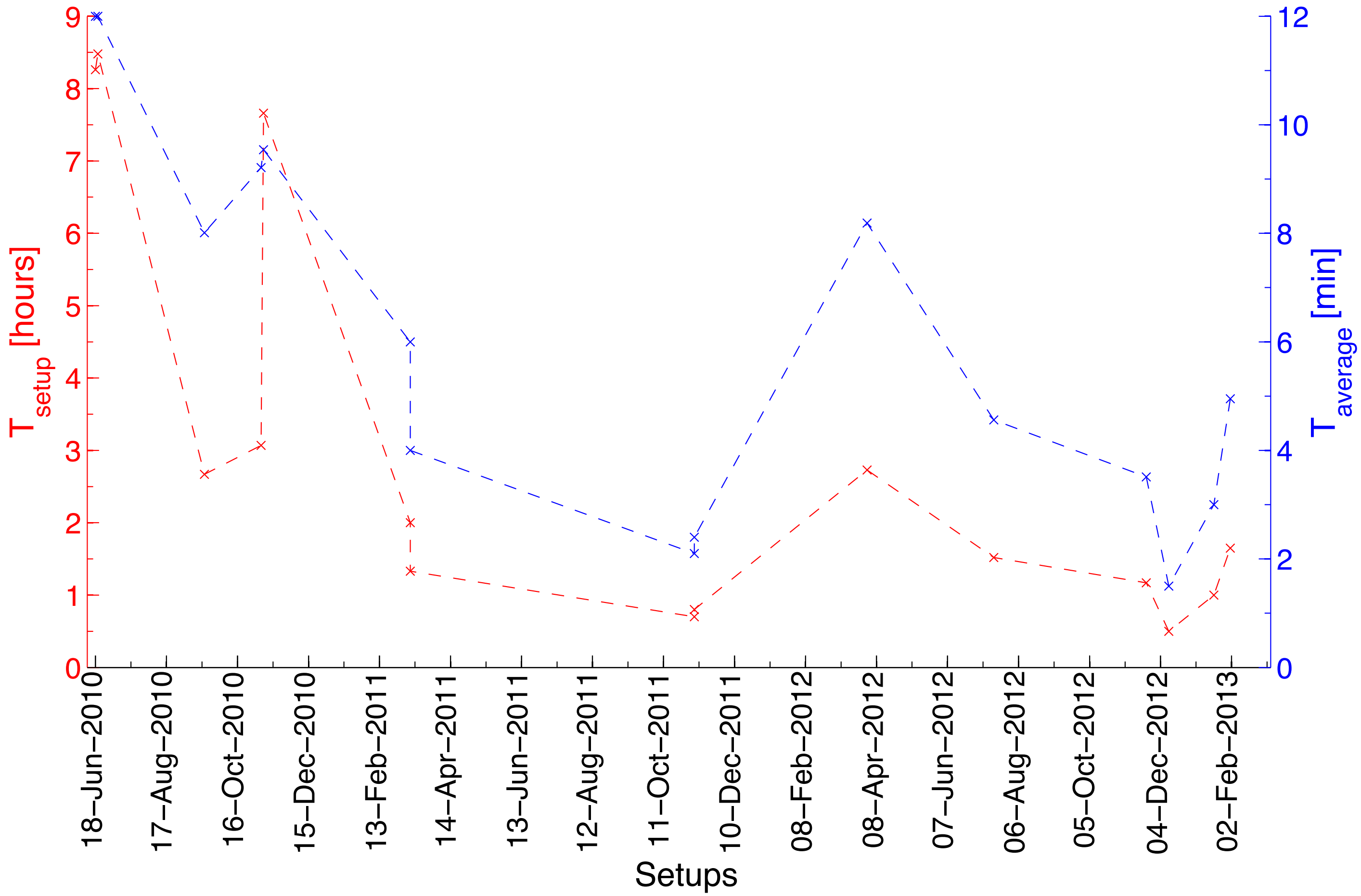



- **Beam Intensity Variation:**

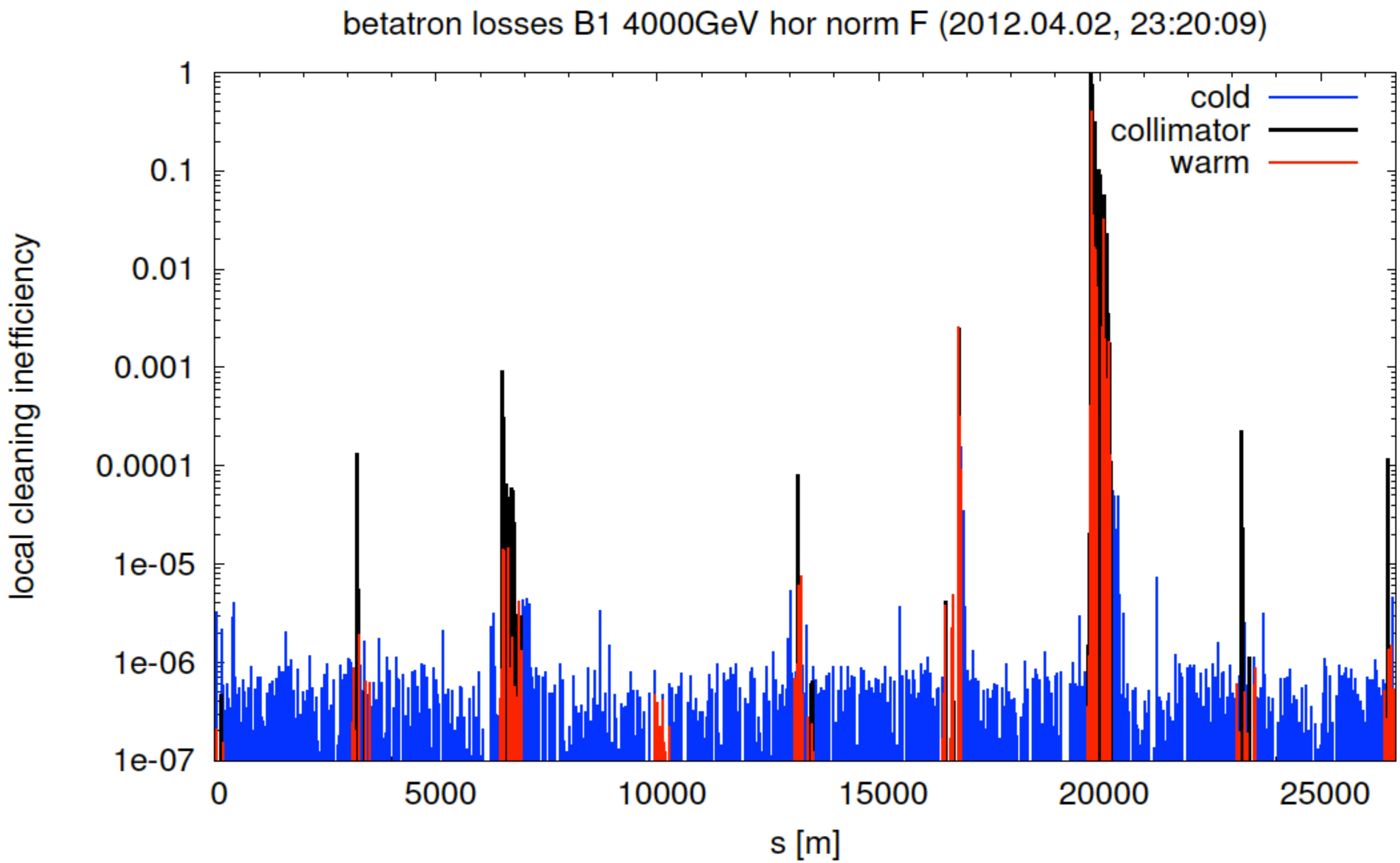


# TCT collimator alignment results



# Collimation System Qualification



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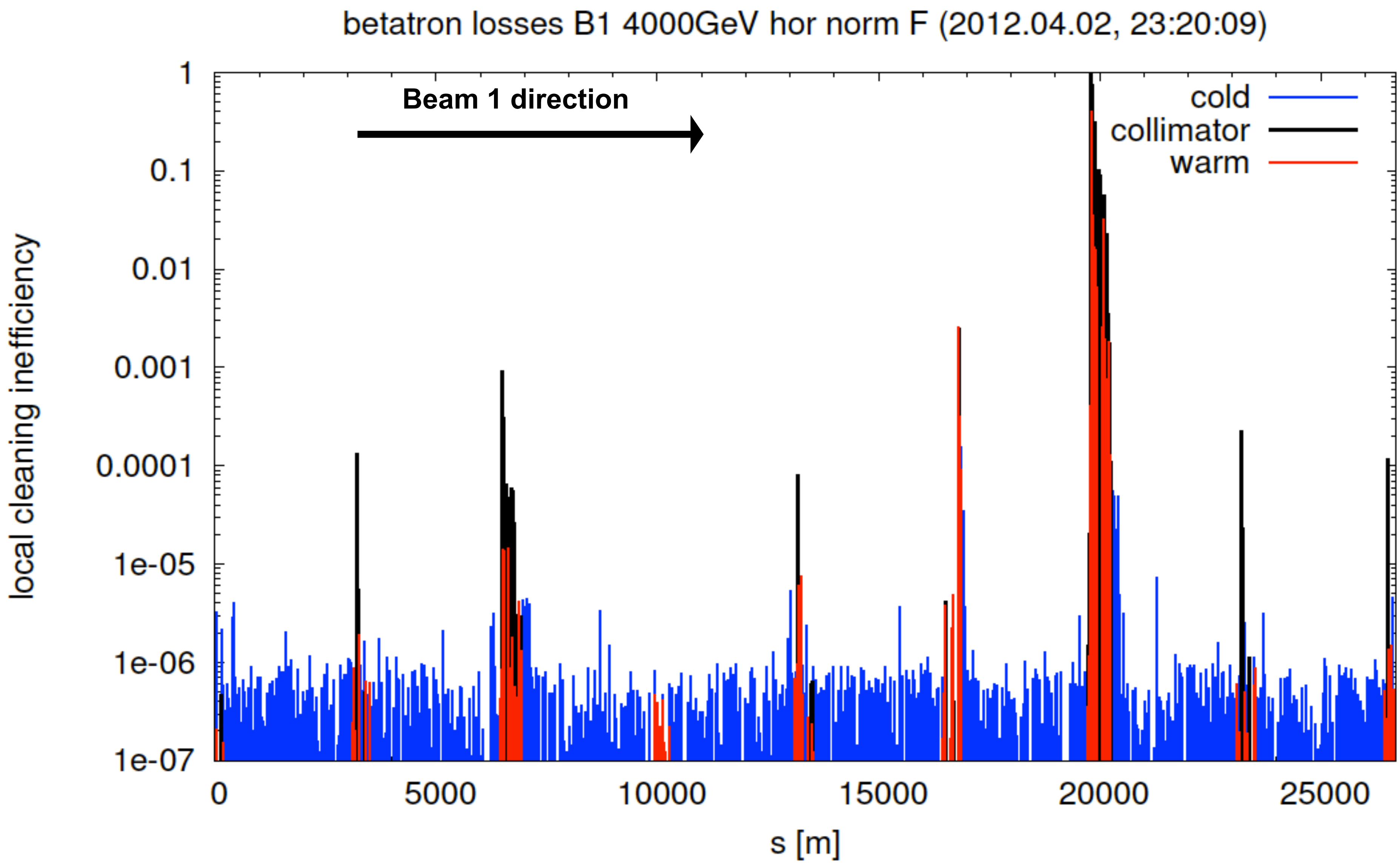

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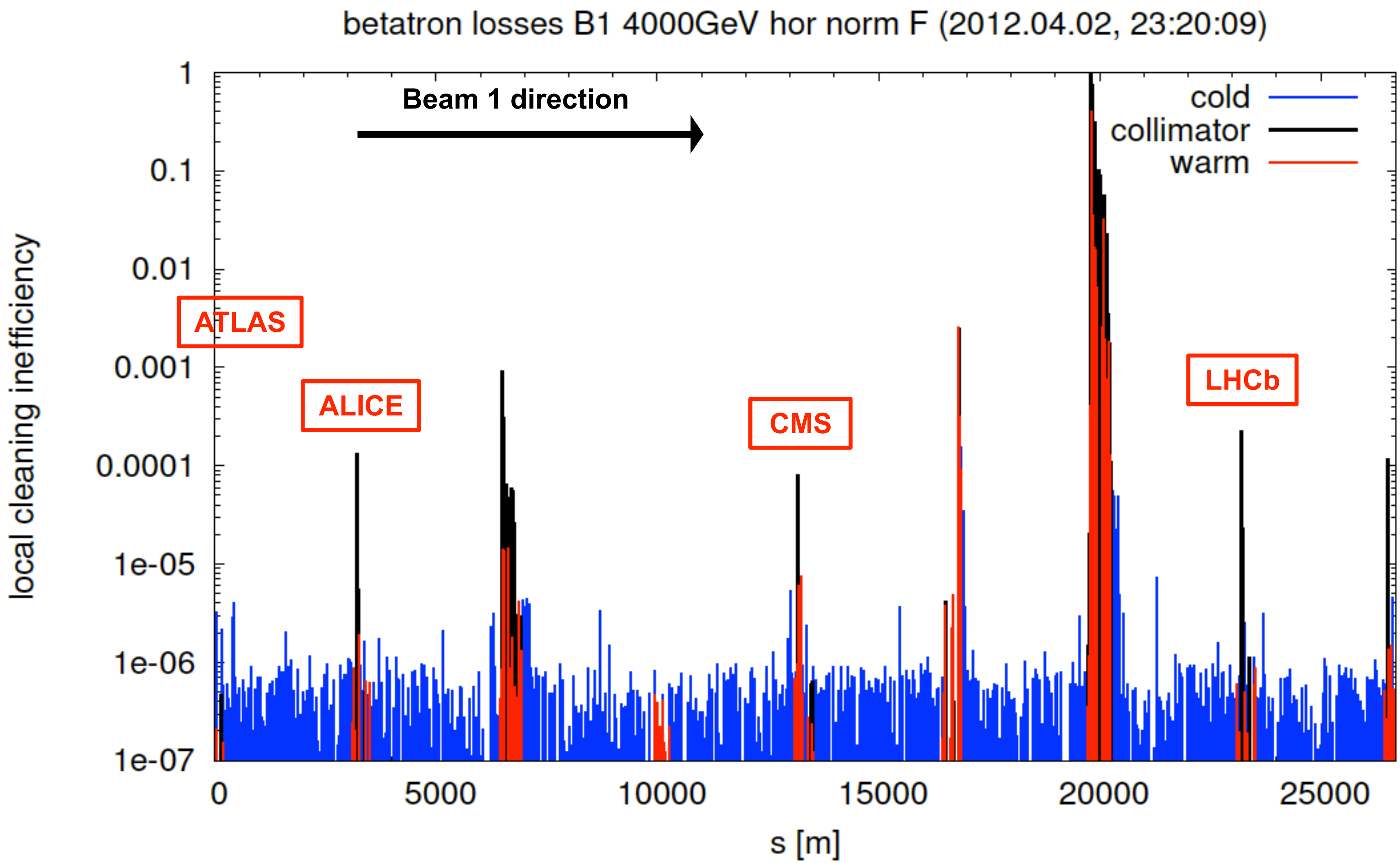

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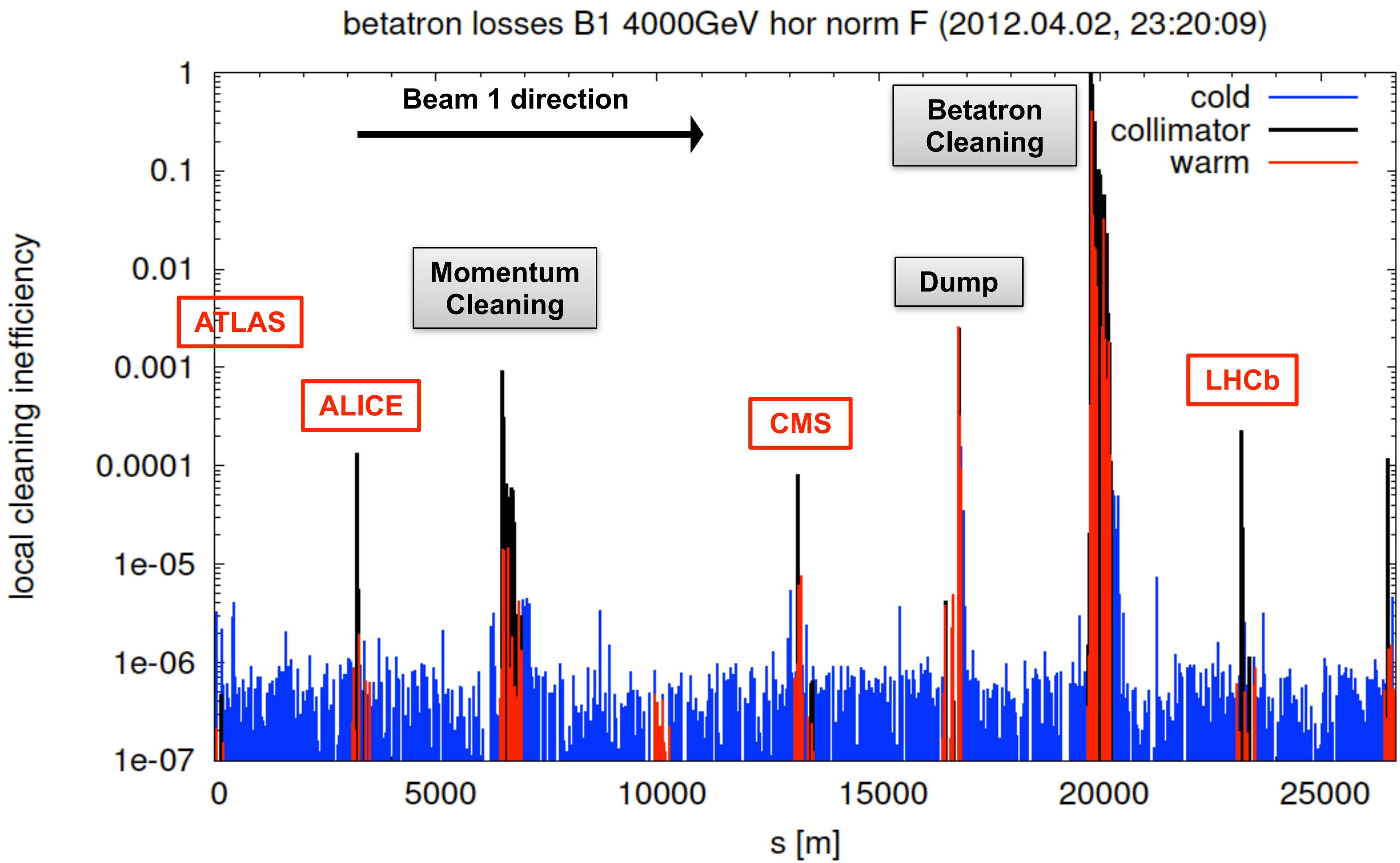

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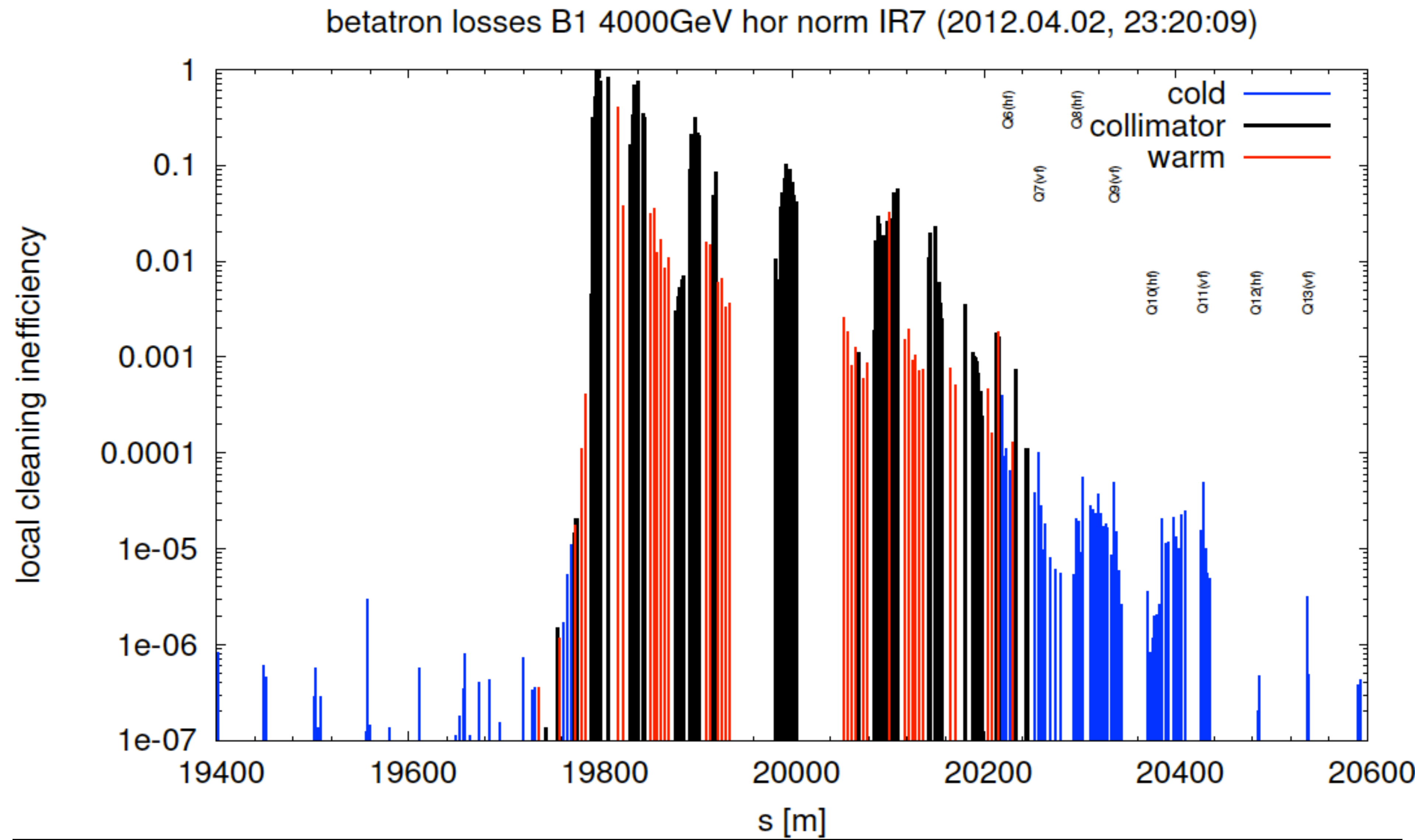

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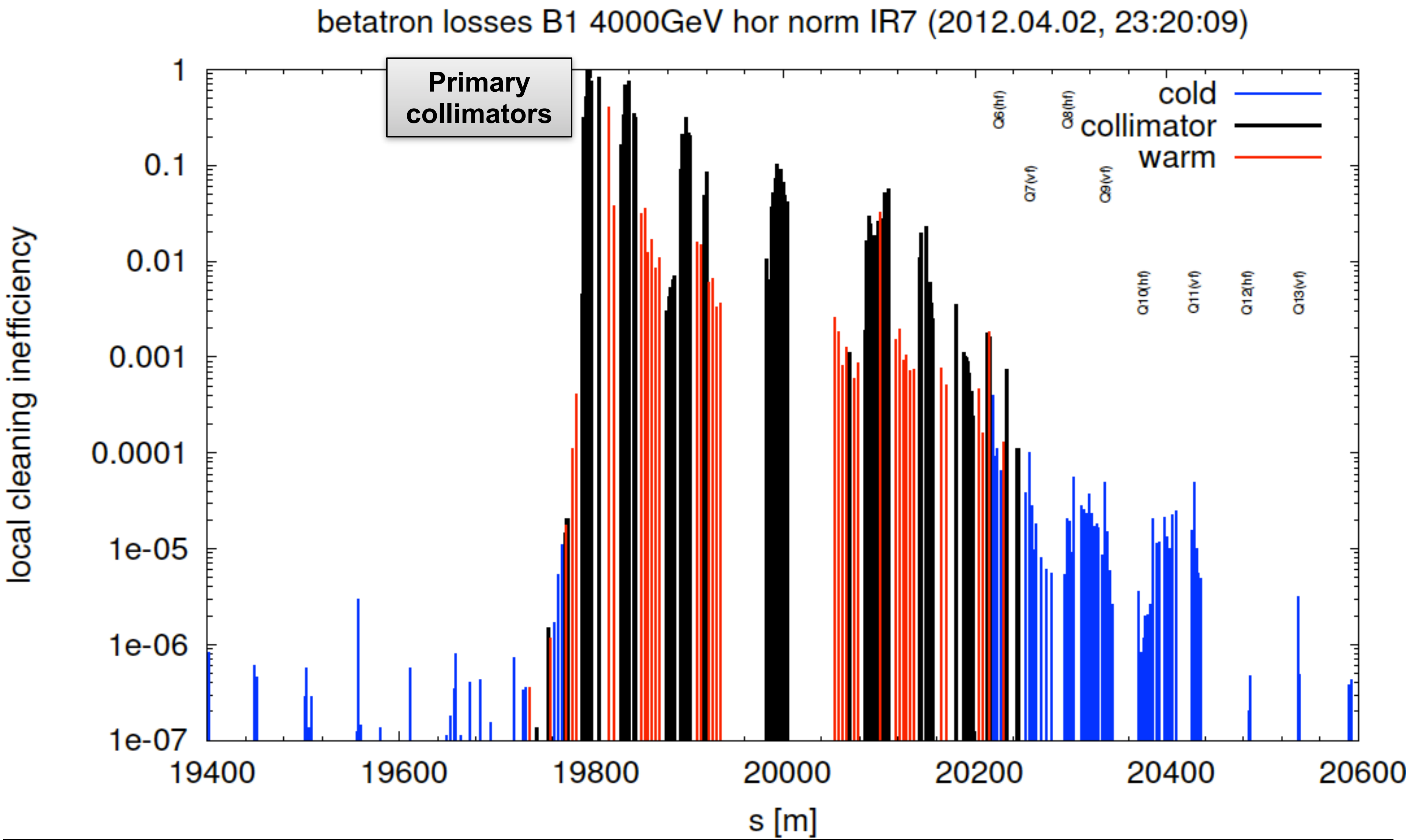

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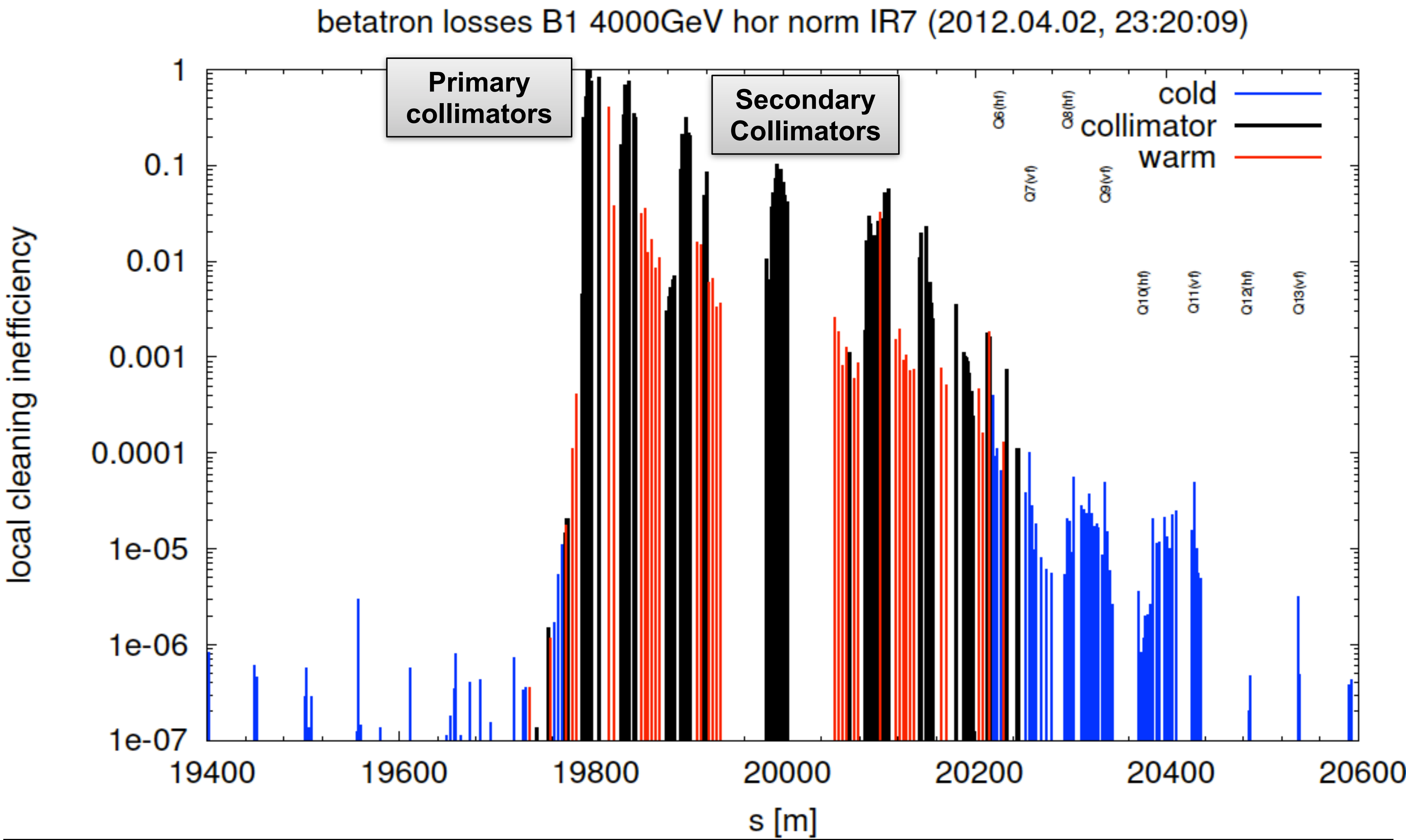

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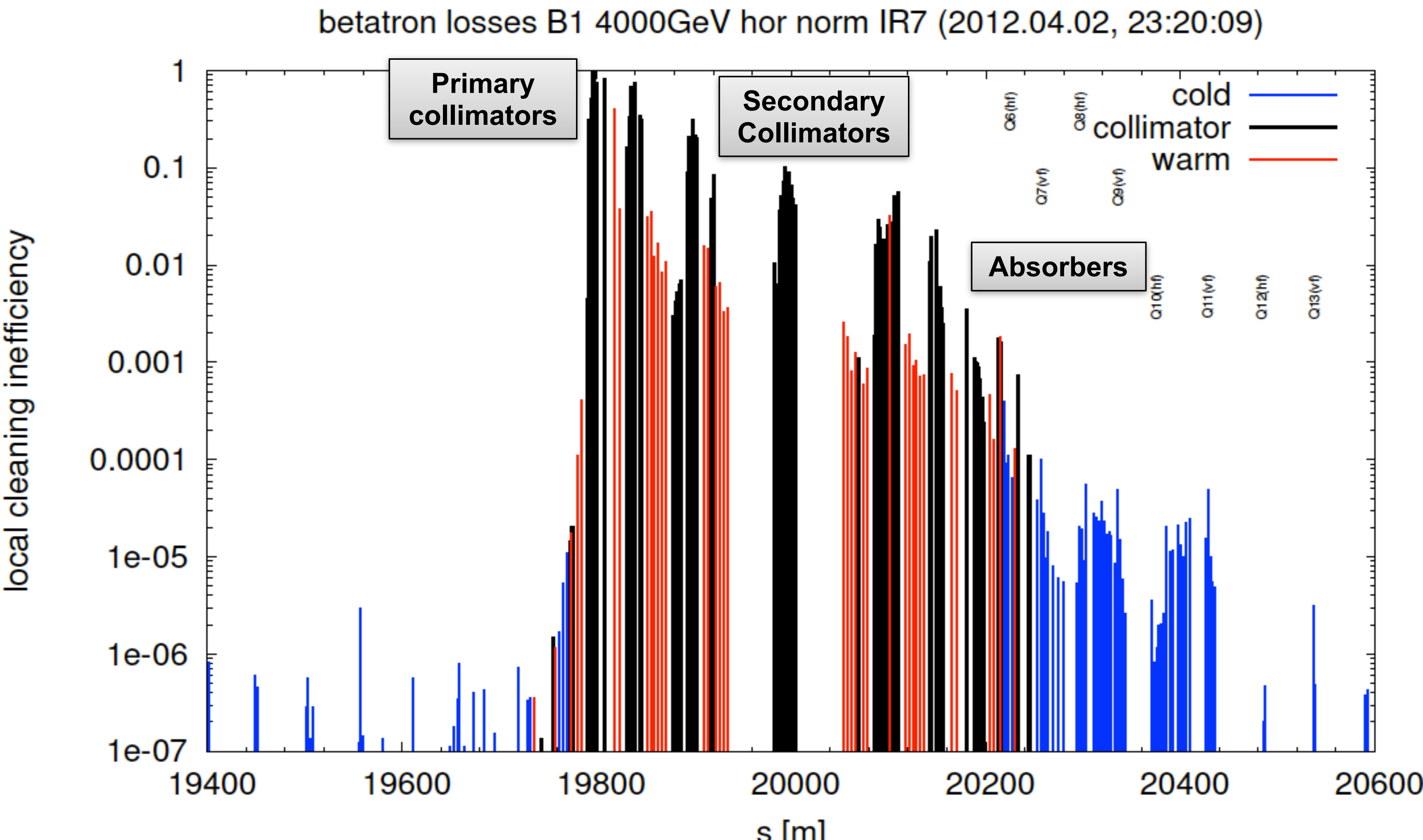

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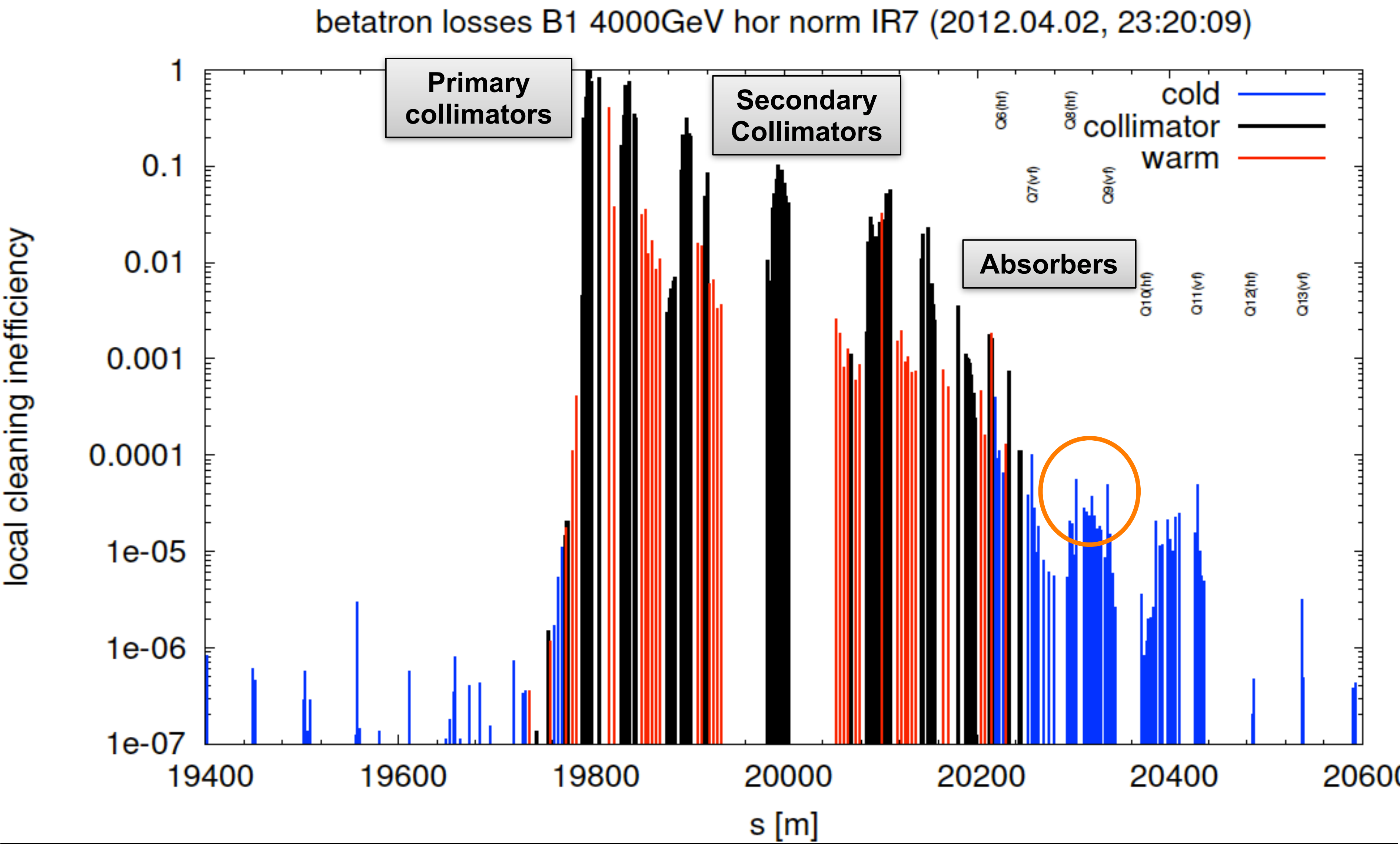
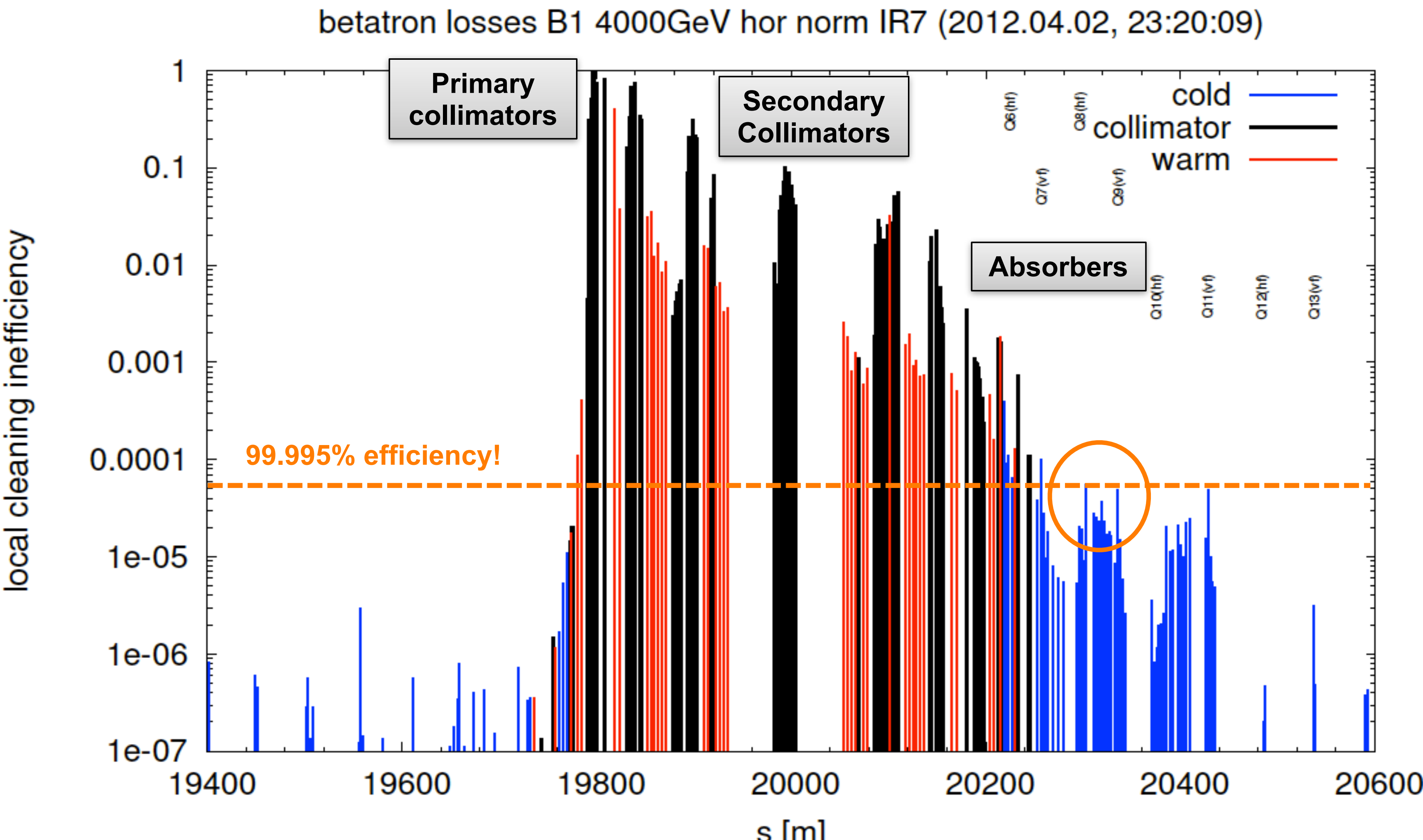


# Collimation System Qualification



# Collimation System Qualification