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Automatic Computer Algorithms for Beam-Based Setup of the LHC Collimators

Gianluca Valentino

with contributions from:

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

B. Salvachua, N. Sammut, D. Wollmann

Outline

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

The Large Hadron Collider

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- The LHC at CERN is the largest and most powerful particle accelerator in the world.
- Nominal parameters:

  Circumference: 27 km, Energy: 7 TeV, Intensity = 3.23E14, Peak Lumi IP1/5 = 1E34 $cm^{-2}sec^{-1}$

LHC Collimation System

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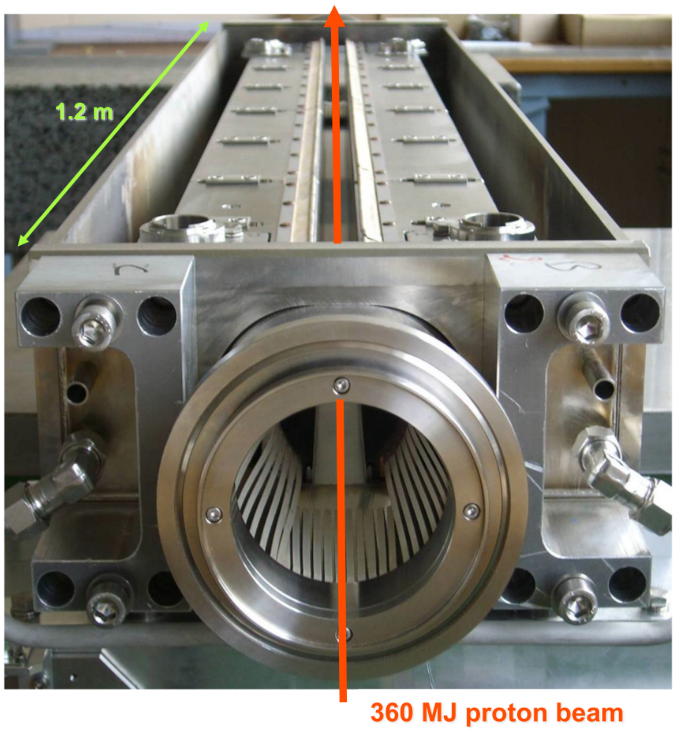
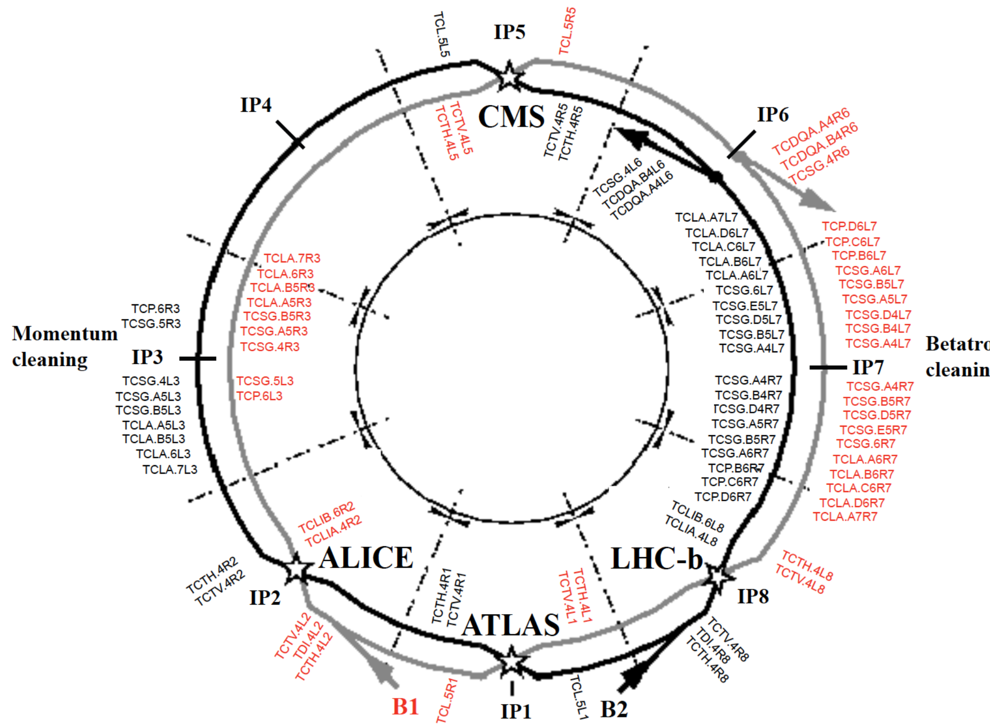
- The LHC is protected by a **collimation system** with 100 collimators.
- Each cleaning collimator consists of **two moveable jaws** made of carbon or tungsten.
- The jaws are positioned symmetrically around the beam.

→ intercept beam halo particles which could quench the super-conducting magnets.





Courtesy: C. Bracco

Collimator Status and Positions Display

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Green: OK
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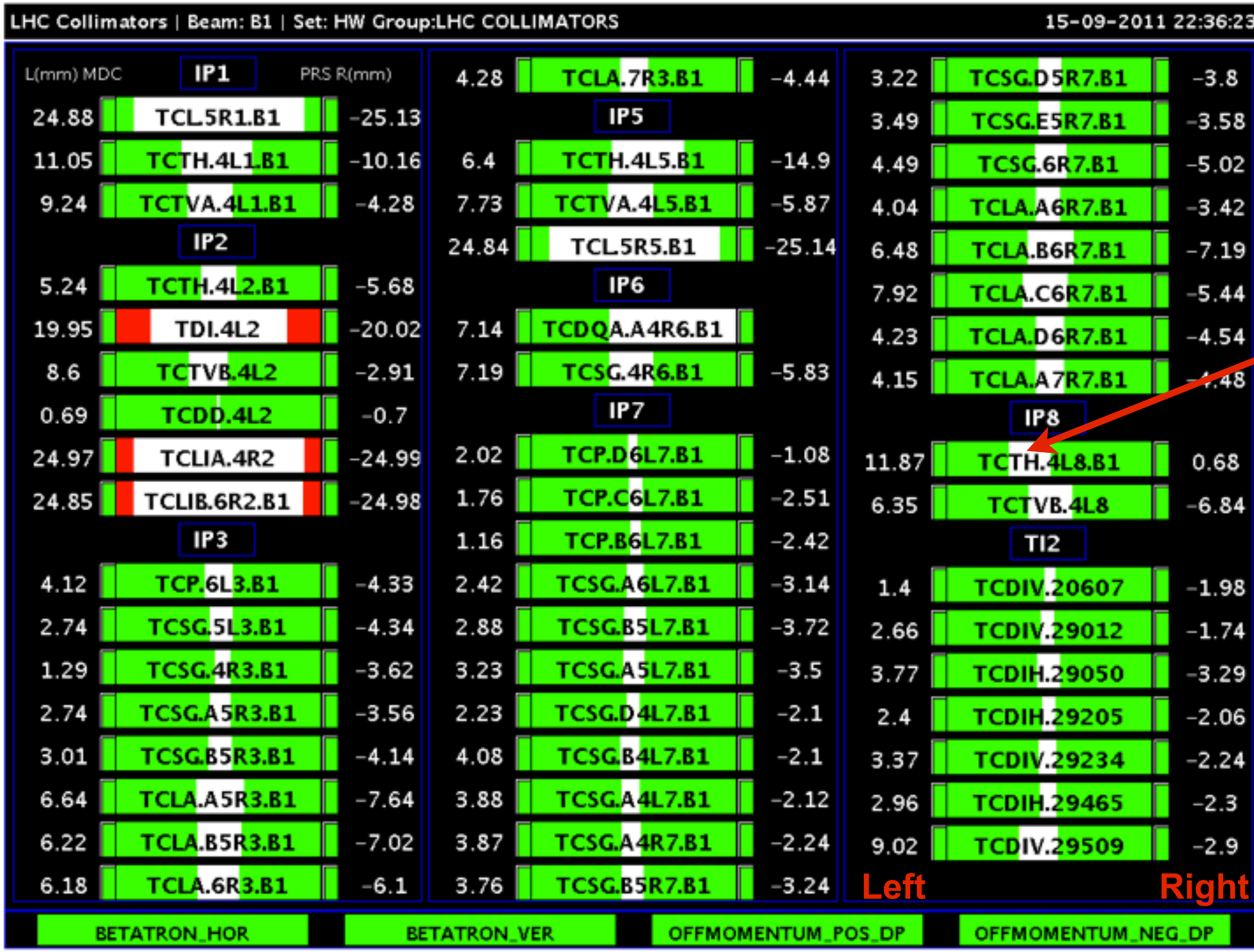

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Jaw gap indication

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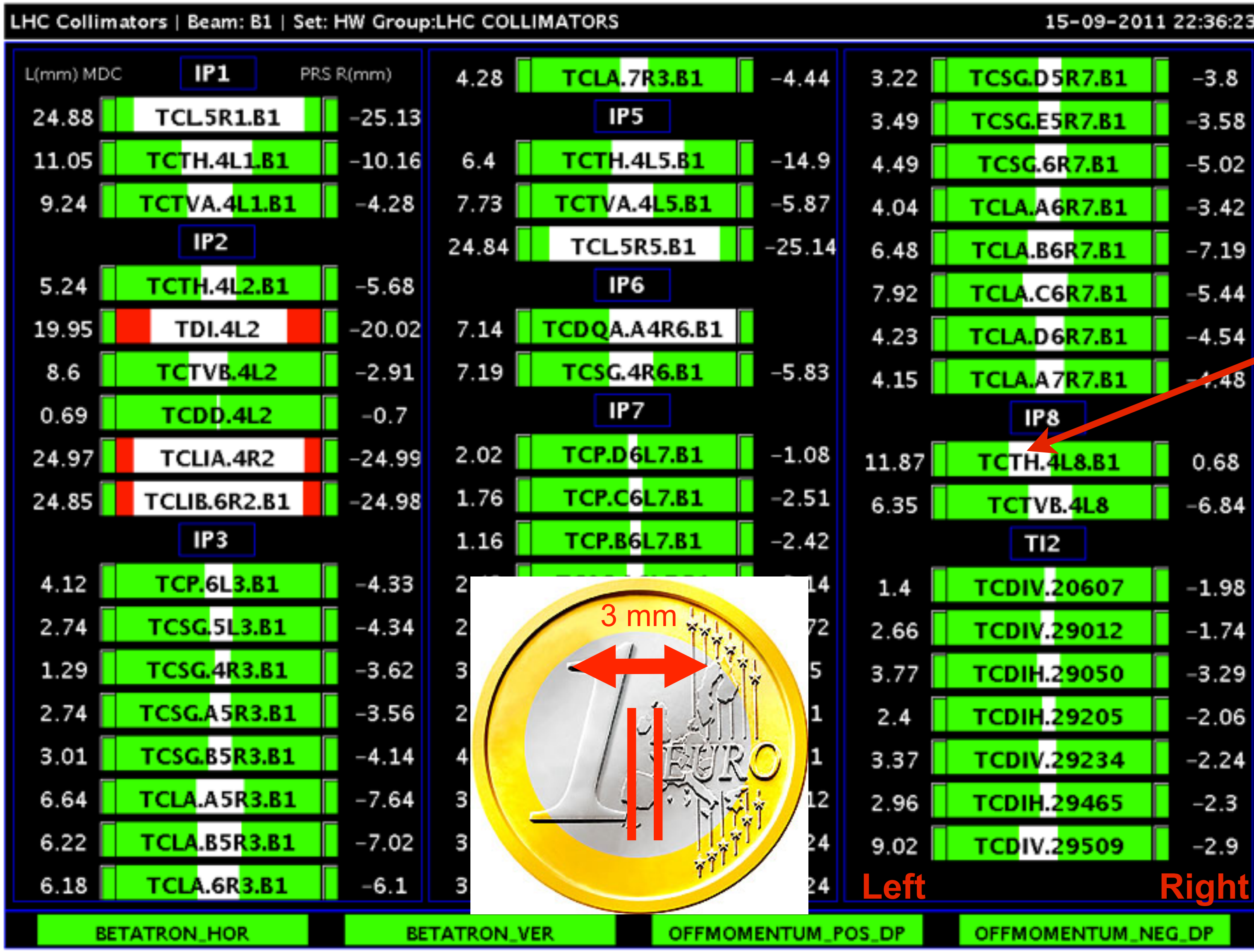

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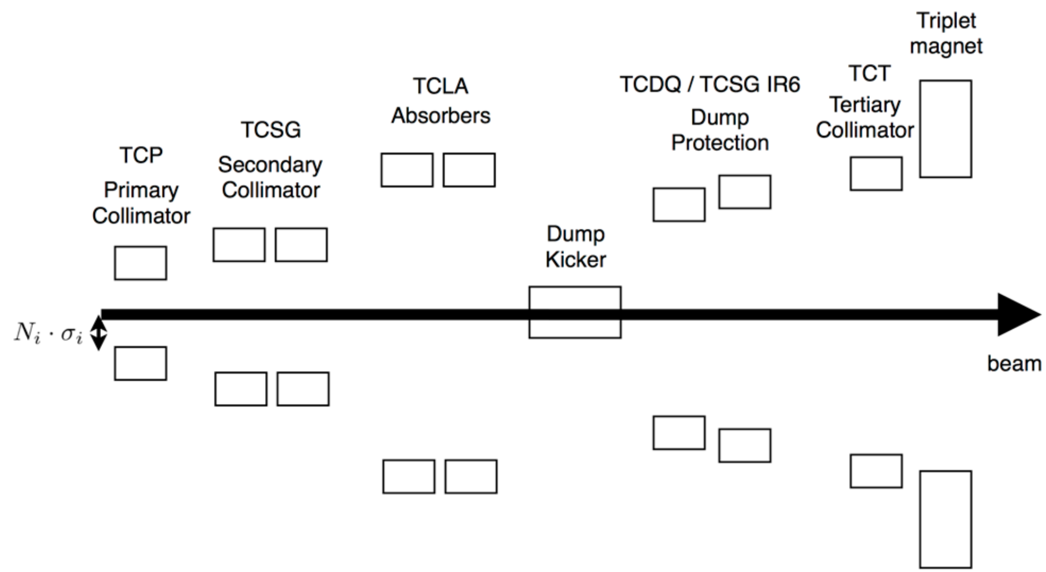
Beam-Based Collimator Alignment

- Collimator jaws are positioned symmetrically around the beam to form a 4-stage hierarchy.

- The beam centre and beam size at each collimator location must be known.



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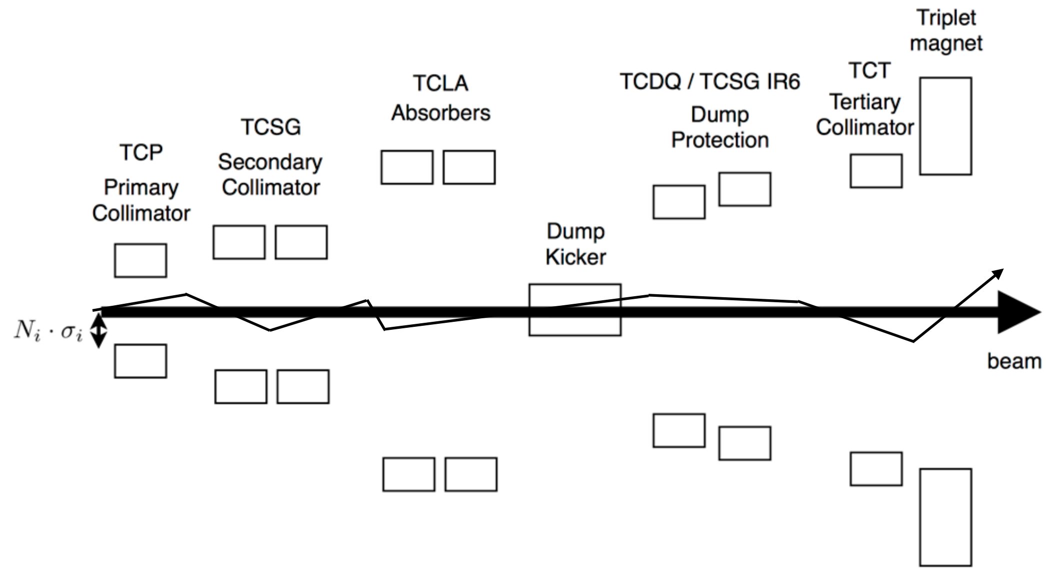

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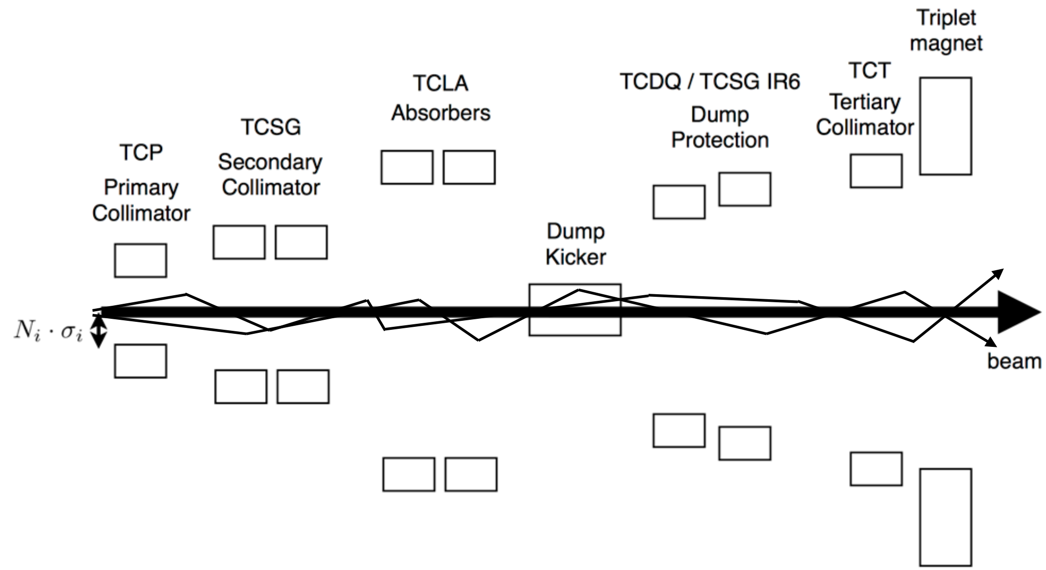

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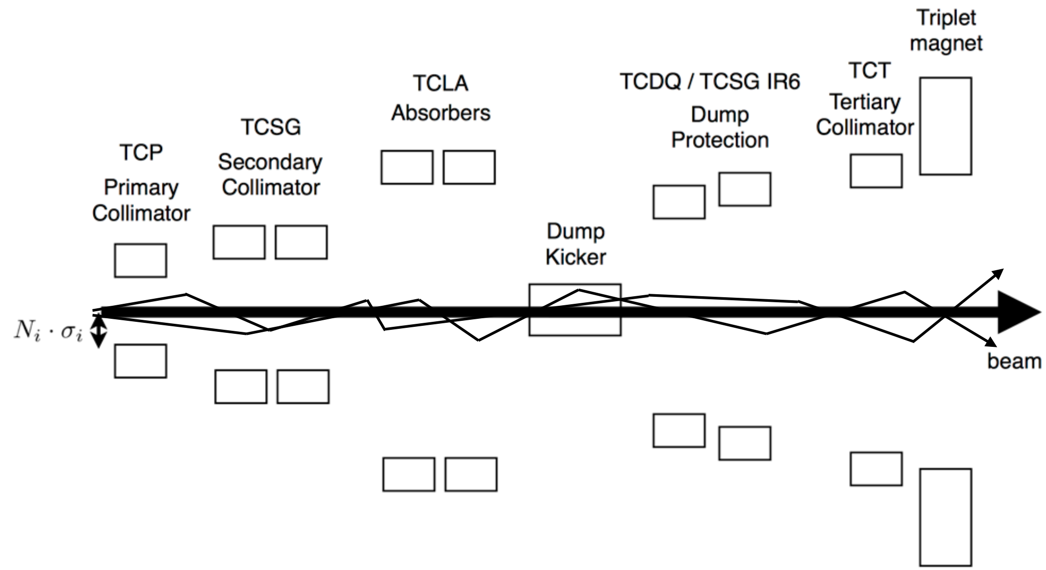
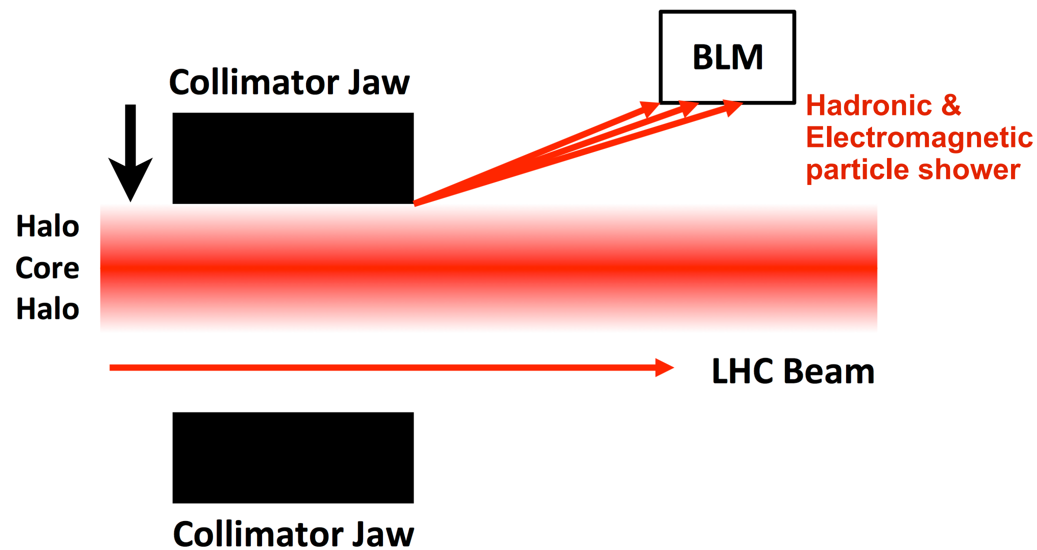


- By touching the beam with each jaw, these values can be determined.

- The jaws moved to beam until a loss spike is seen on the Beam Loss Monitor (BLM).

- Loss spike shape depends on the jaw step size (μm) and the particle distribution in the transverse plane.



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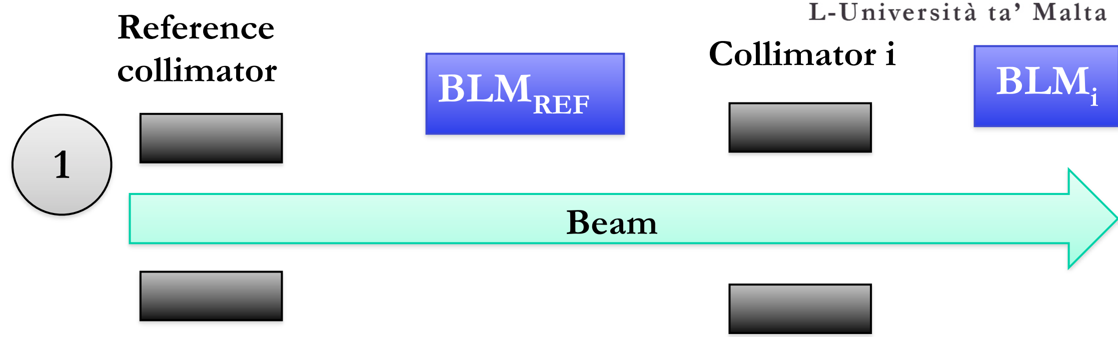

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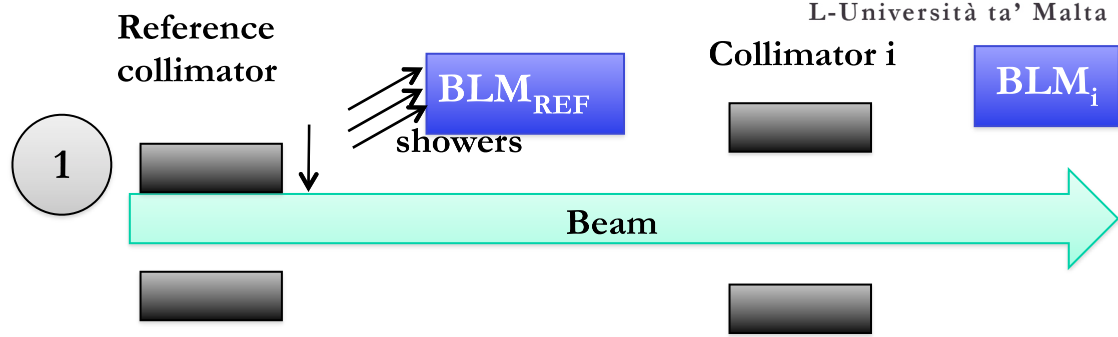

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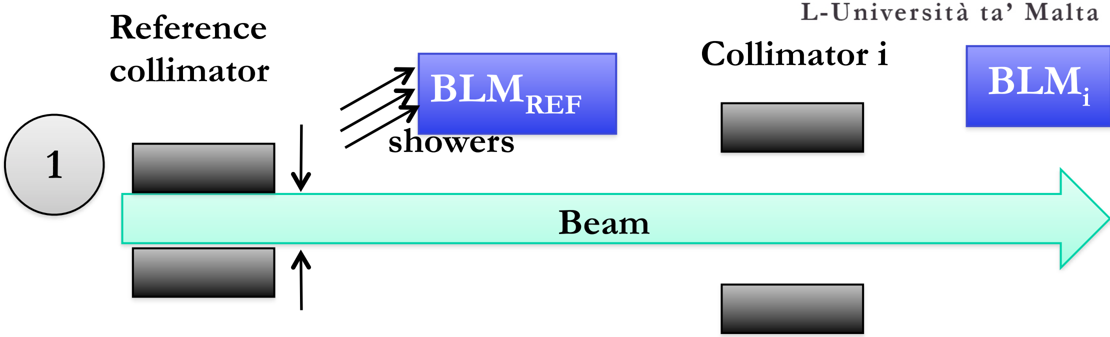

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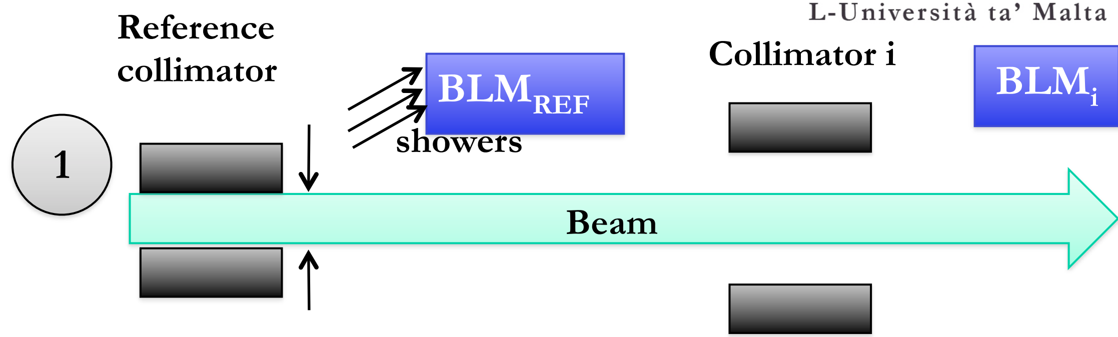

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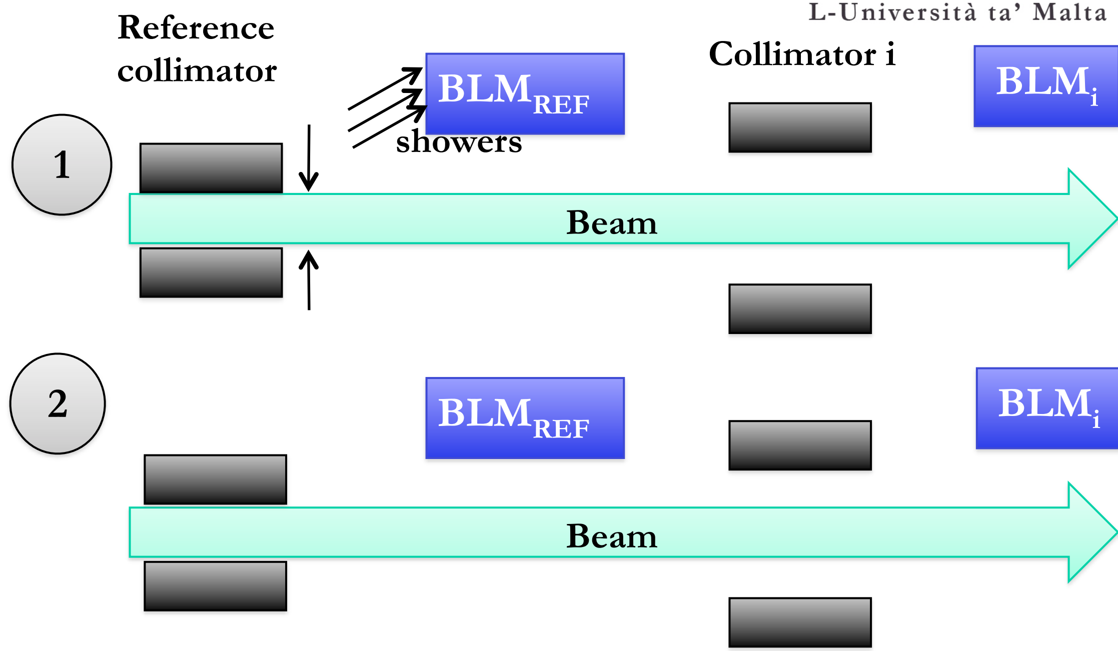

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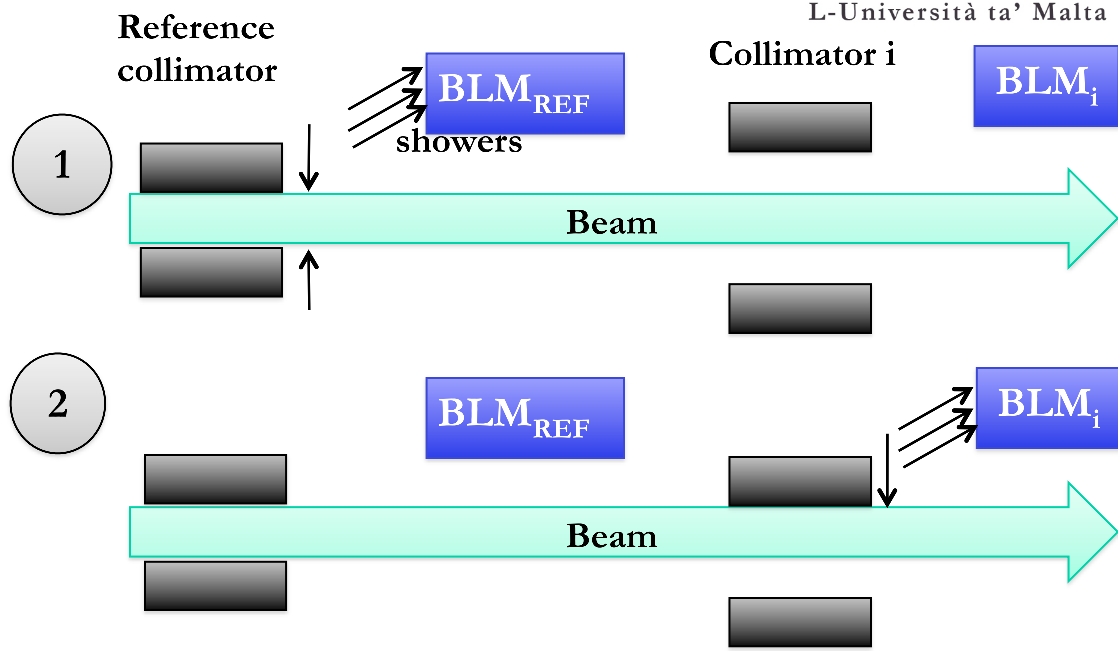

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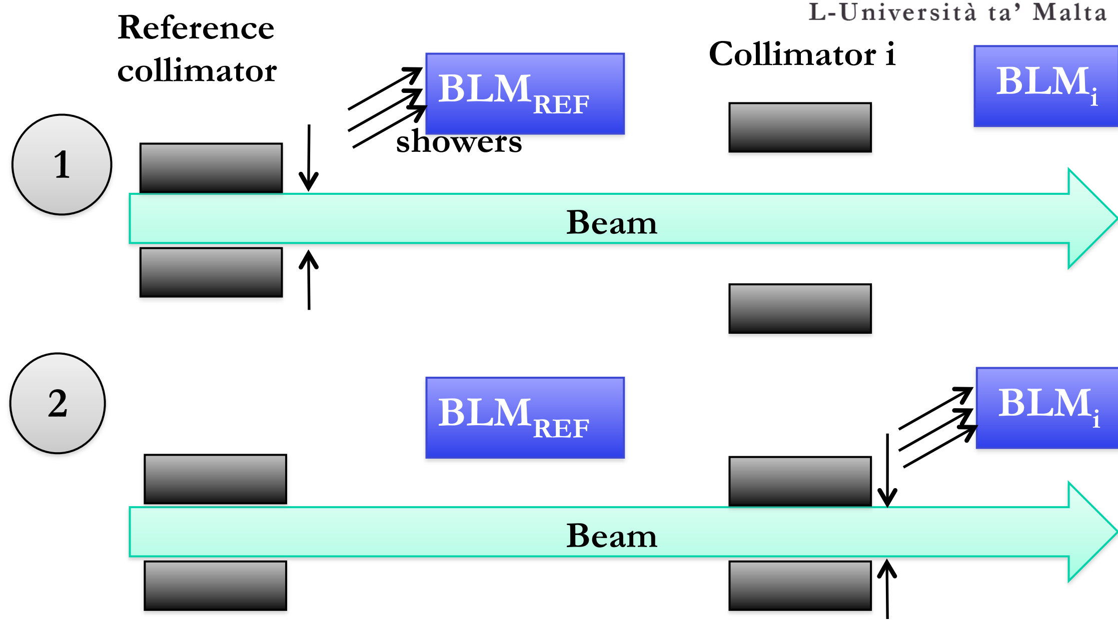

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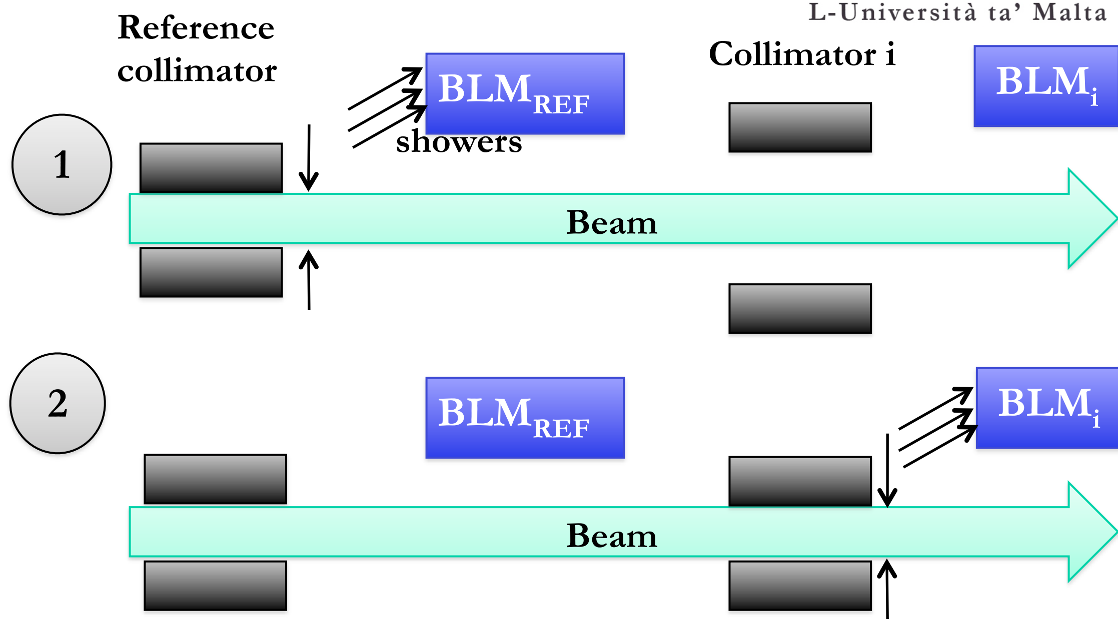

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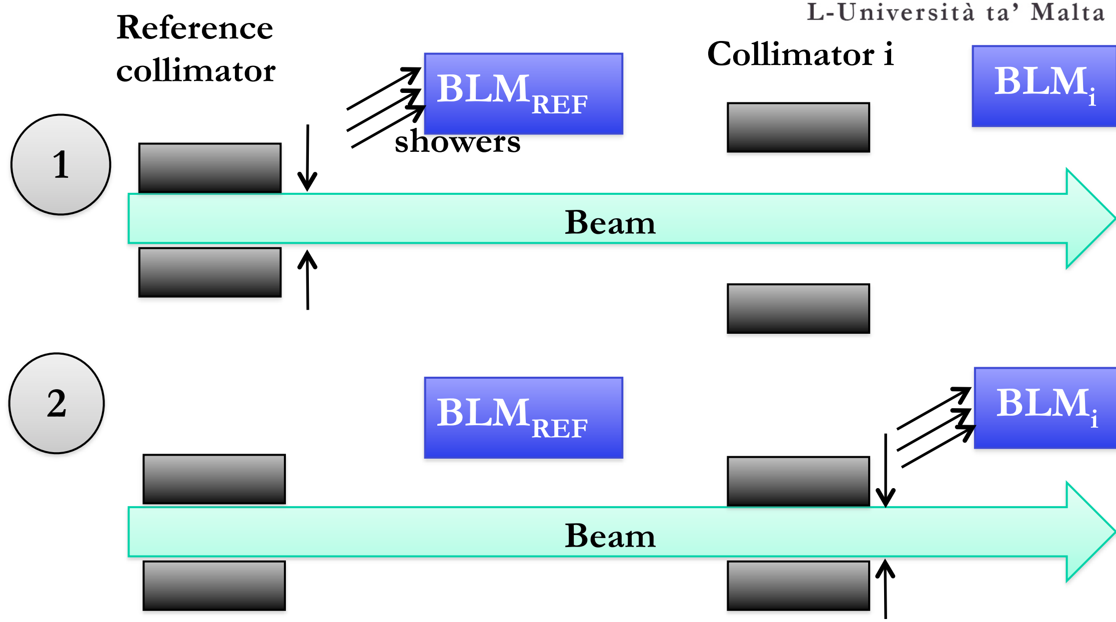

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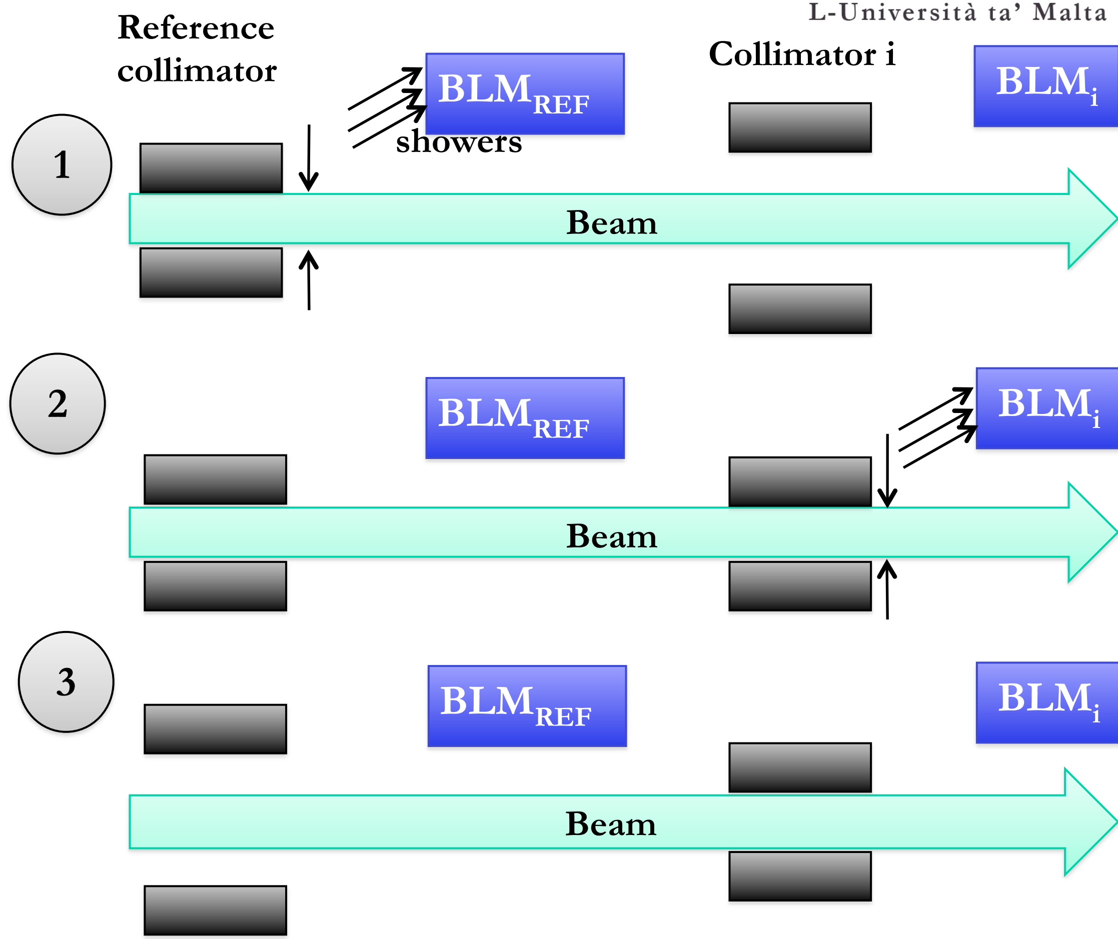

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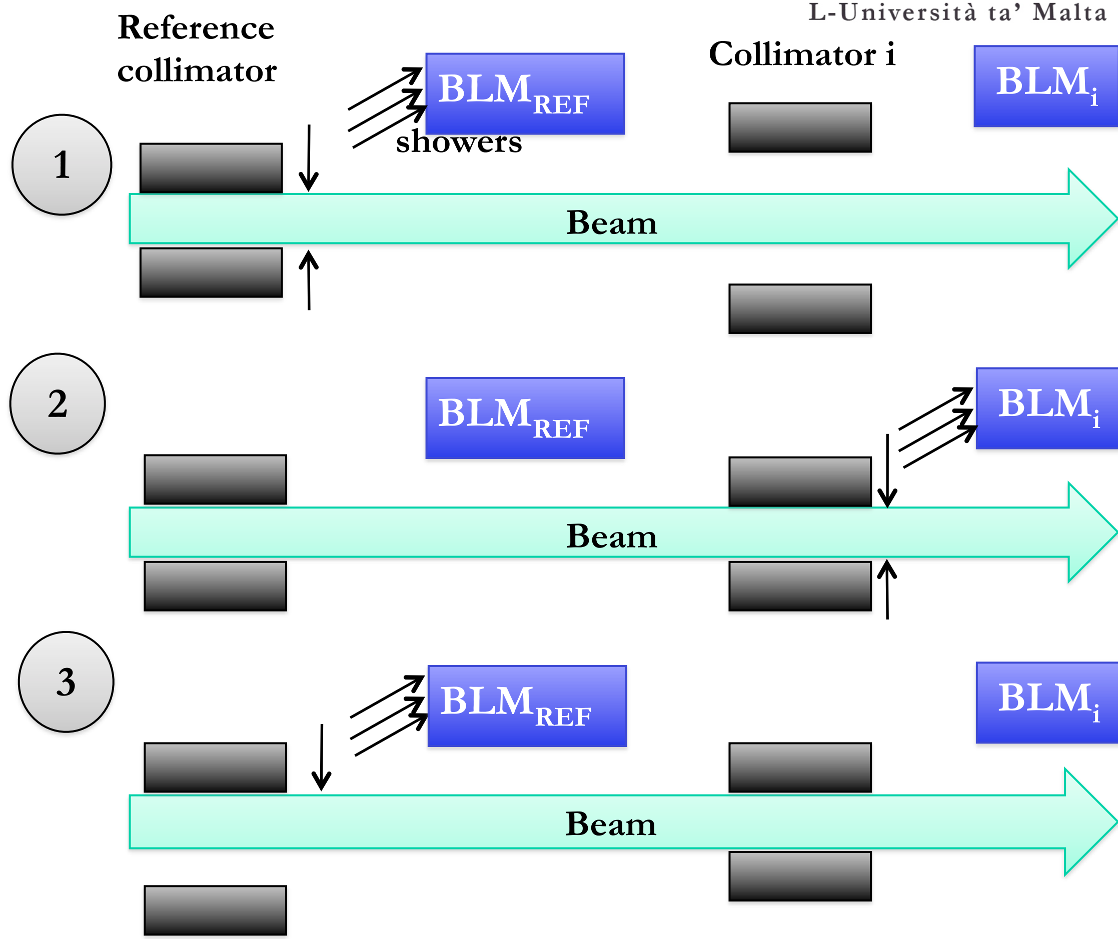

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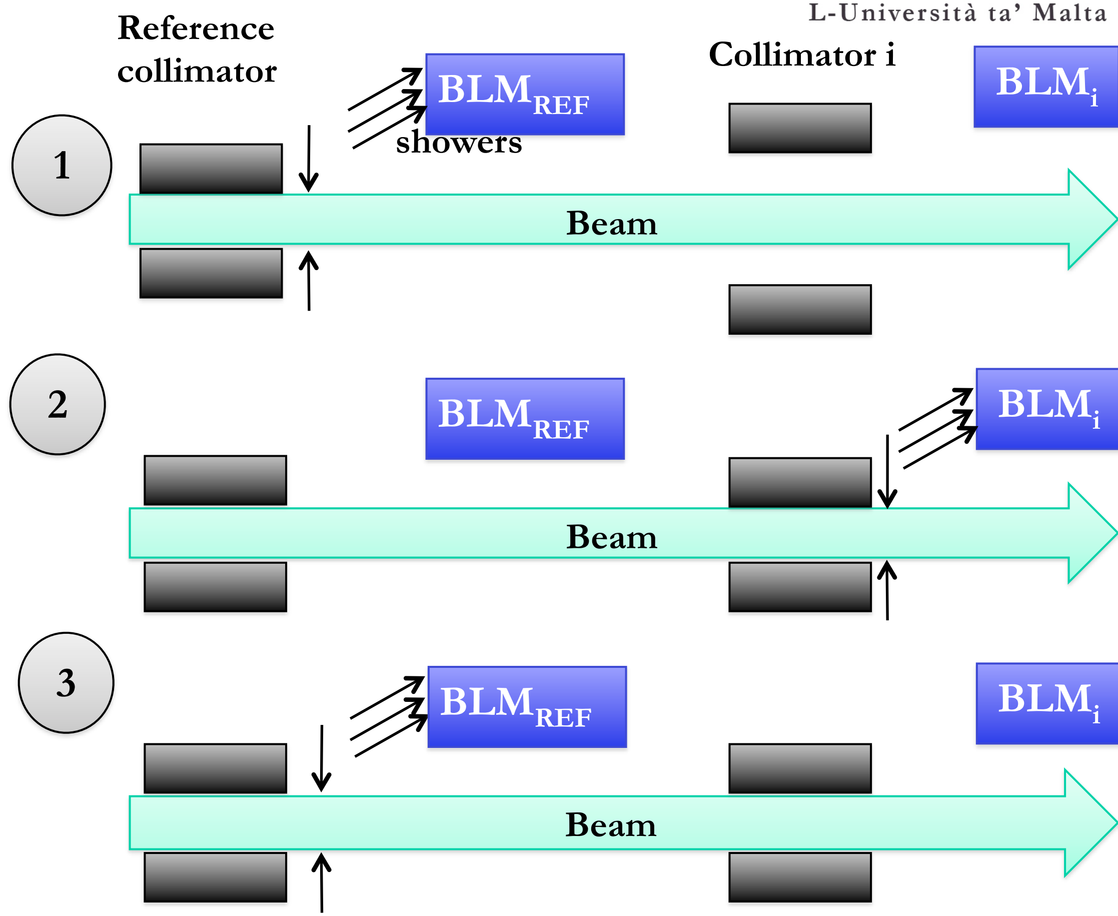

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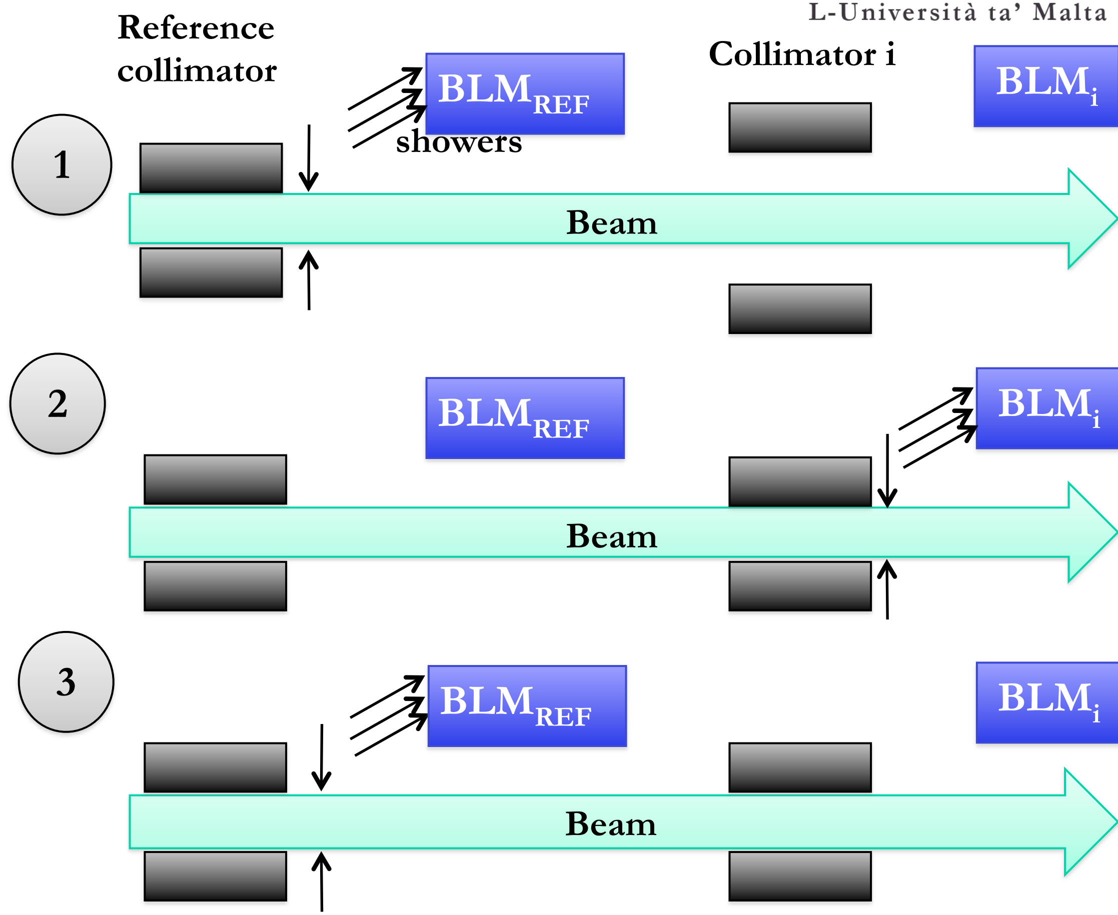

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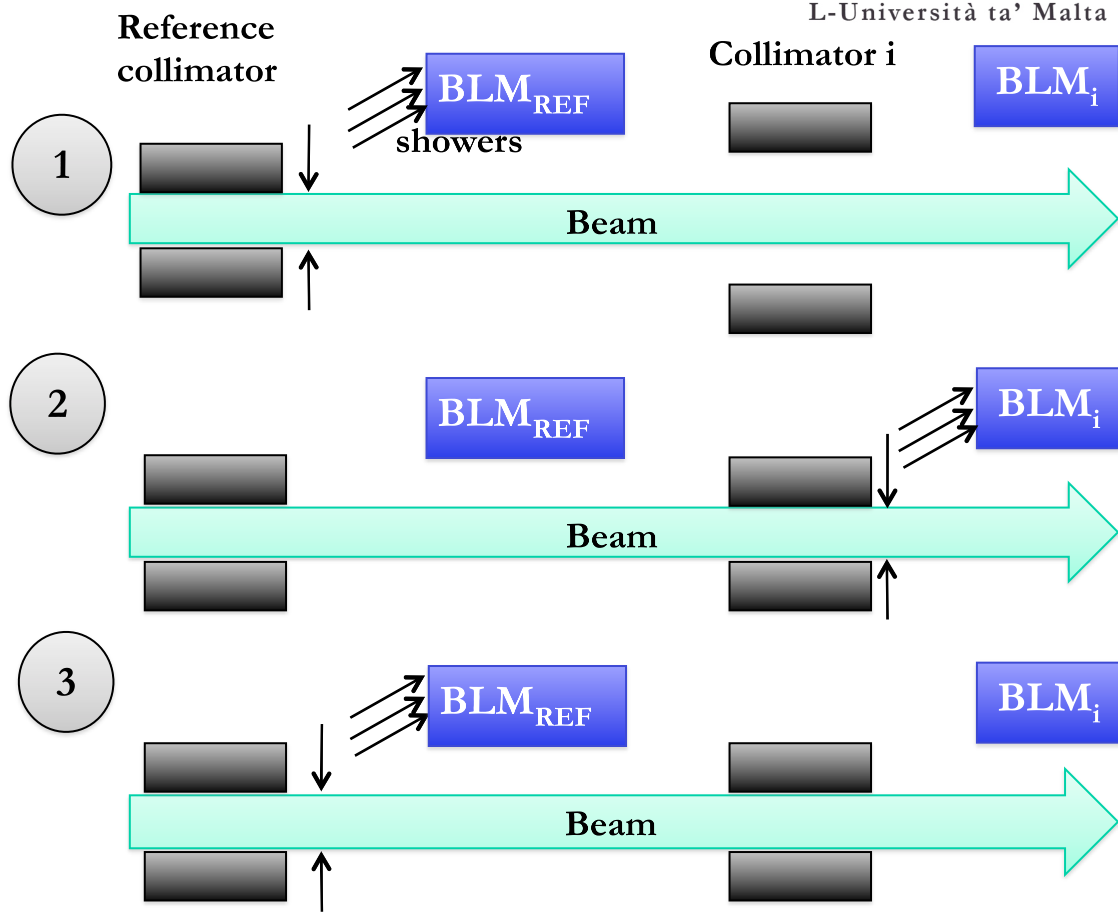

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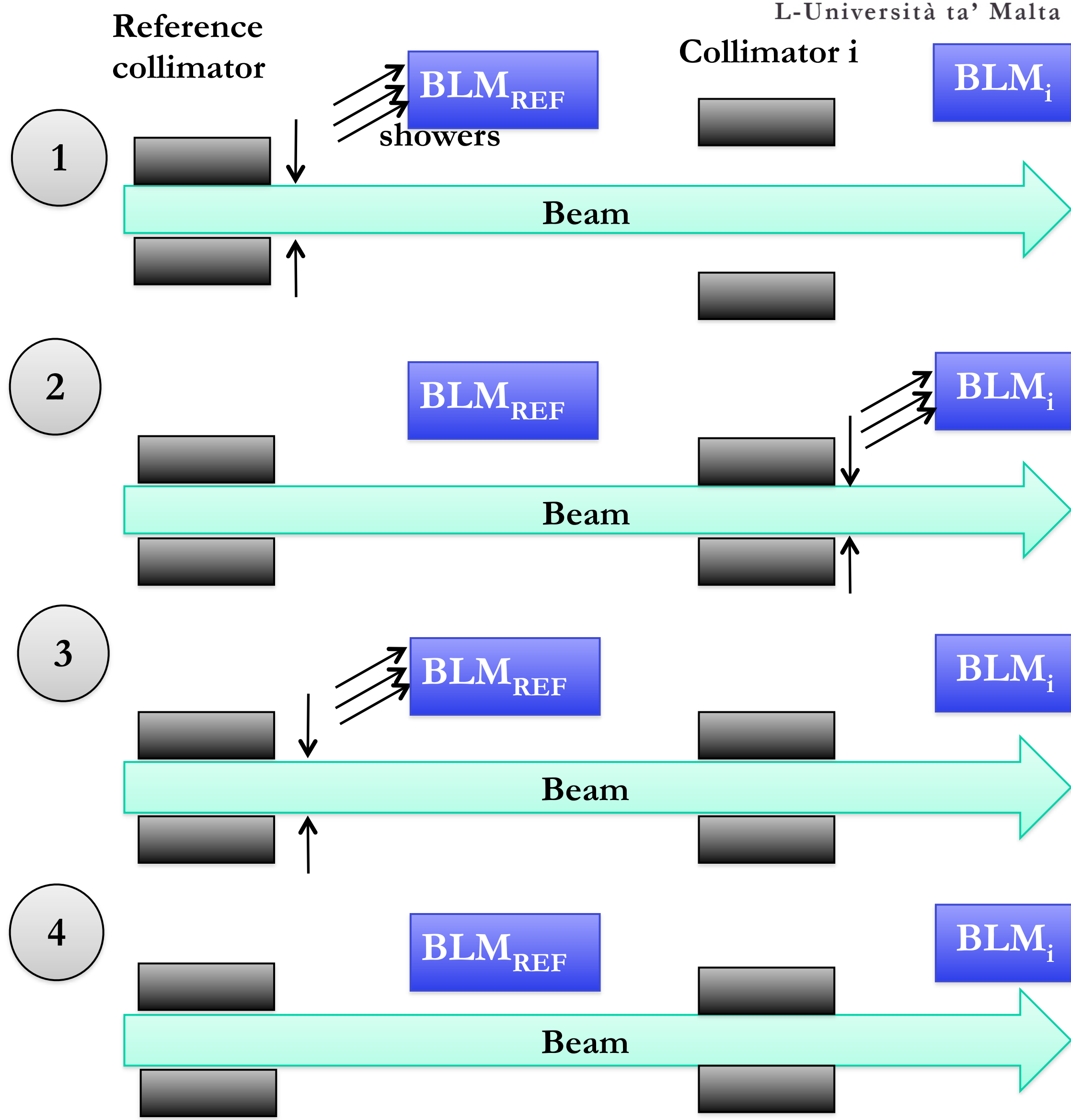

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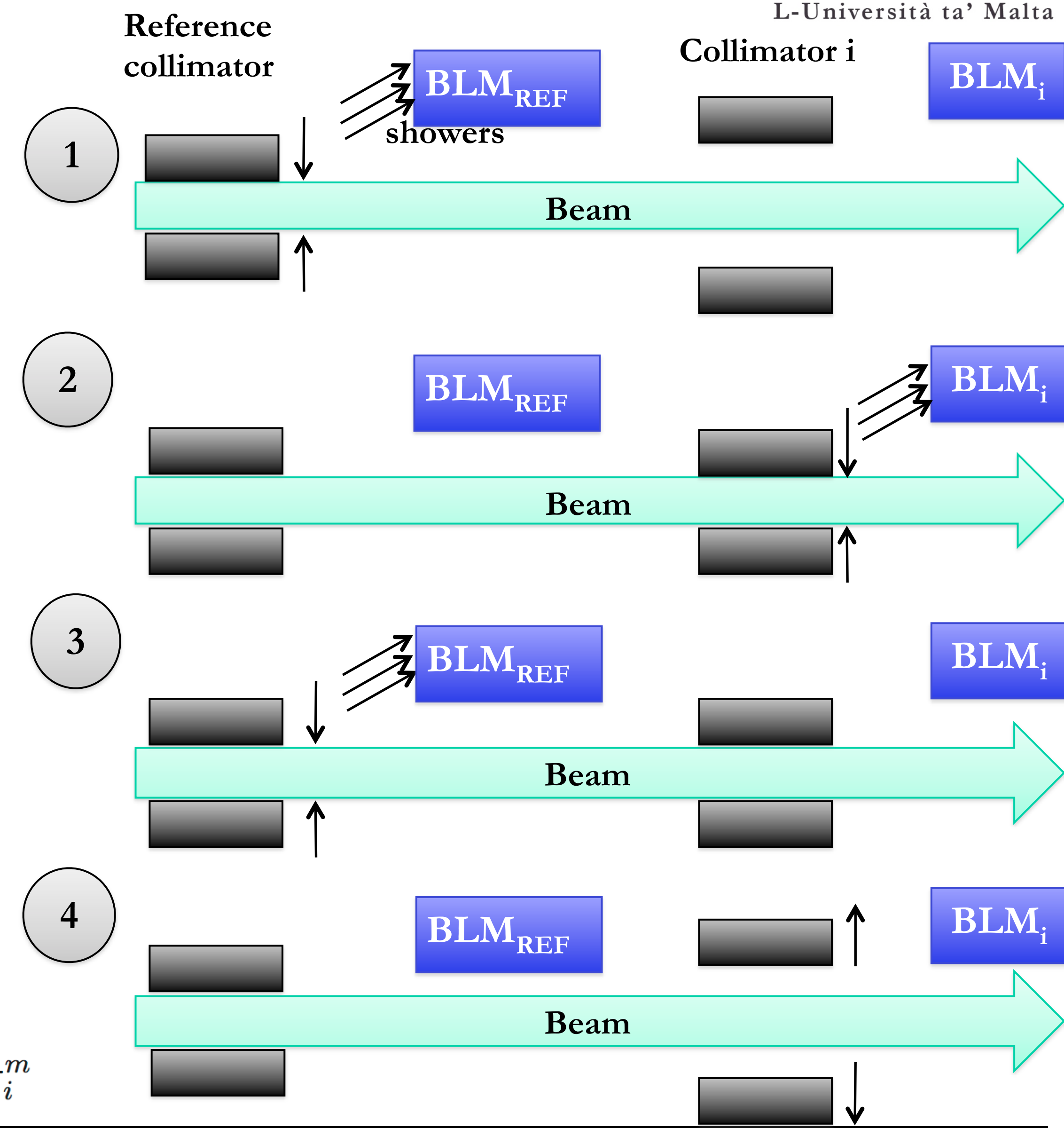
$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^m \qquad x_i^{R,set} = \Delta x_i - N_i \sigma_i^m$$



Automatic Collimator Alignment

- Motivation:
  - Manual collimator alignment is a time-consuming and expensive process (LHC running costs = ~€ 150K / hour).
  - 4 alignments are required for different machine modes:- injection at 450 GeV, flat top, squeezed non-colliding and colliding beams at 4 TeV.
  - Frequent, fast alignments: smaller hierarchy margins (i.e. smaller β^*) + more time for physics = **more luminosity**.
- Alignment algorithms were developed and introduced in an iterative process.
- The work is part of computer science PhD at CERN and the University of Malta.

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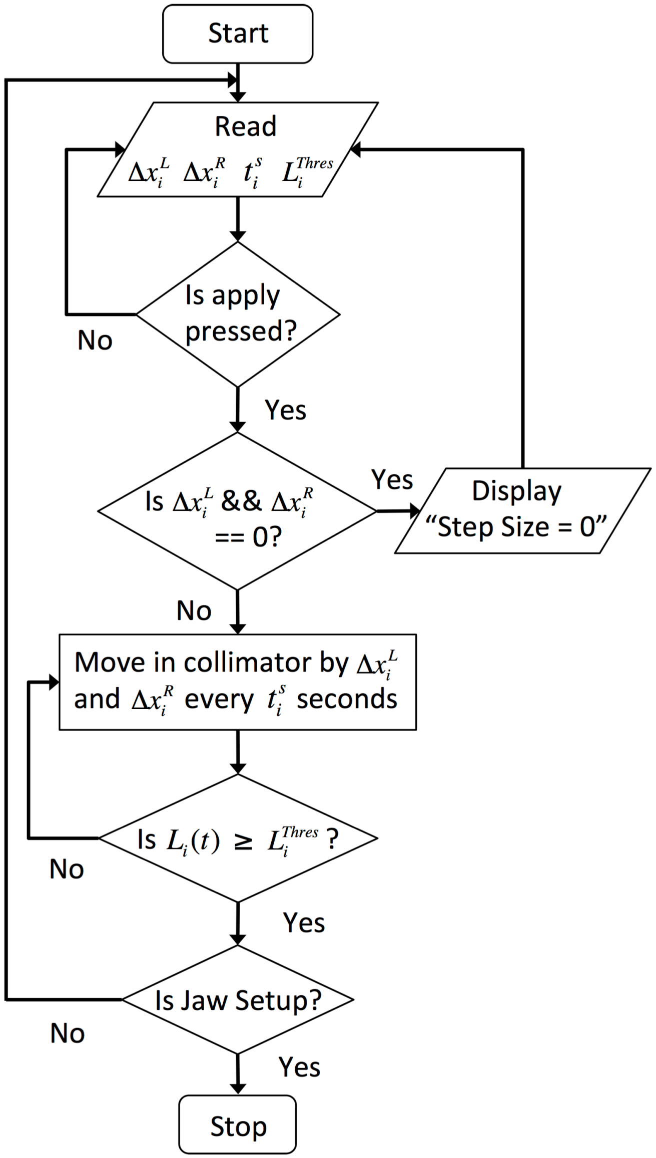

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- Feedback loop implemented in Java application in the top layer of the LHC Software Architecture (LSA).
- The application is operated in the CERN Control Centre (CCC).
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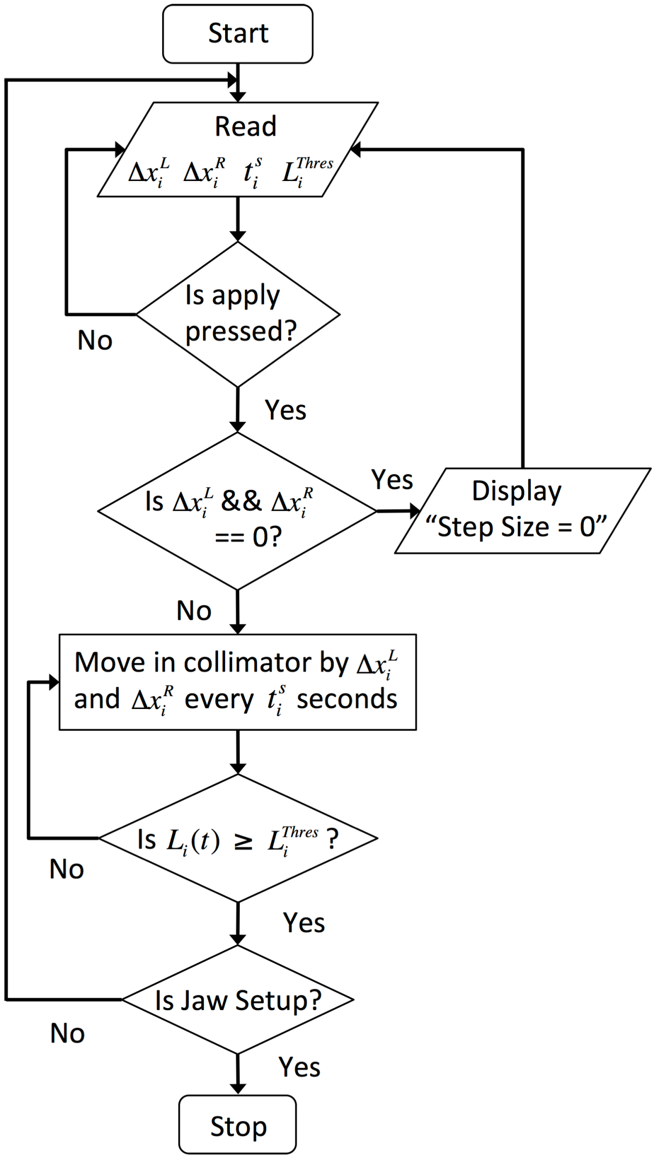

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- Input heuristics developed over 2 years of setups (2009 – 2011) by R. Aβmann et al.

Input	Description	Heuristic
Δx_i^L	Left jaw step size in μm	5 – 20
Δx_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

Parallel Collimator Alignment

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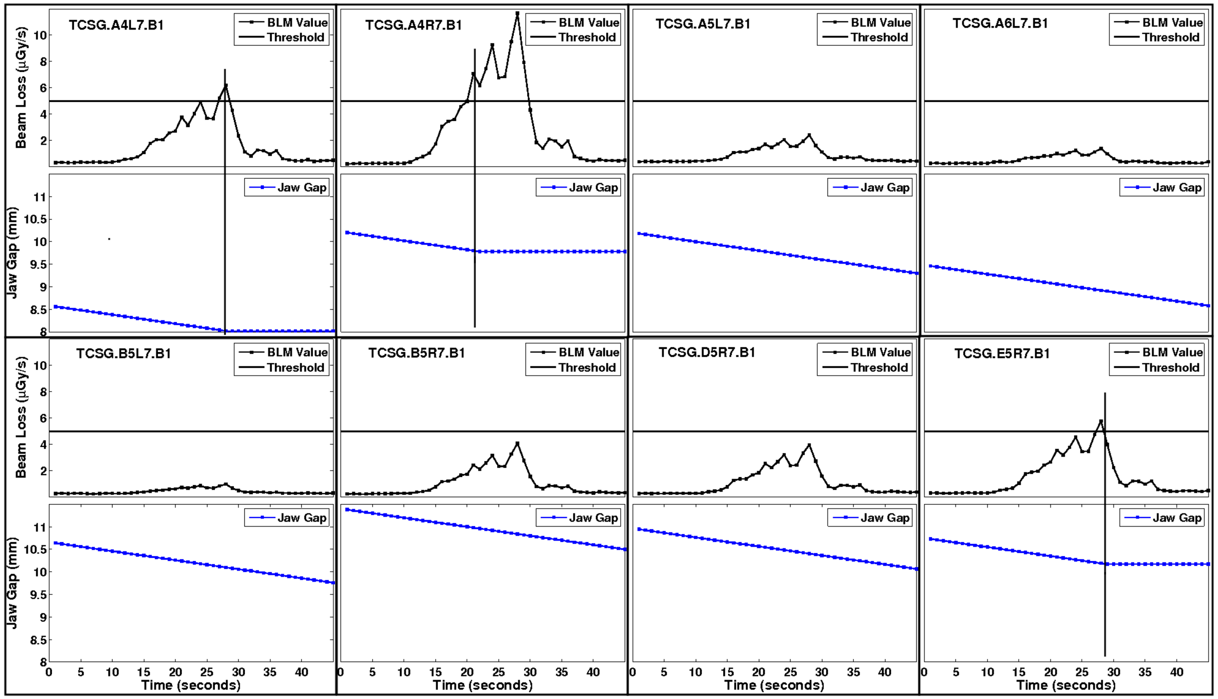

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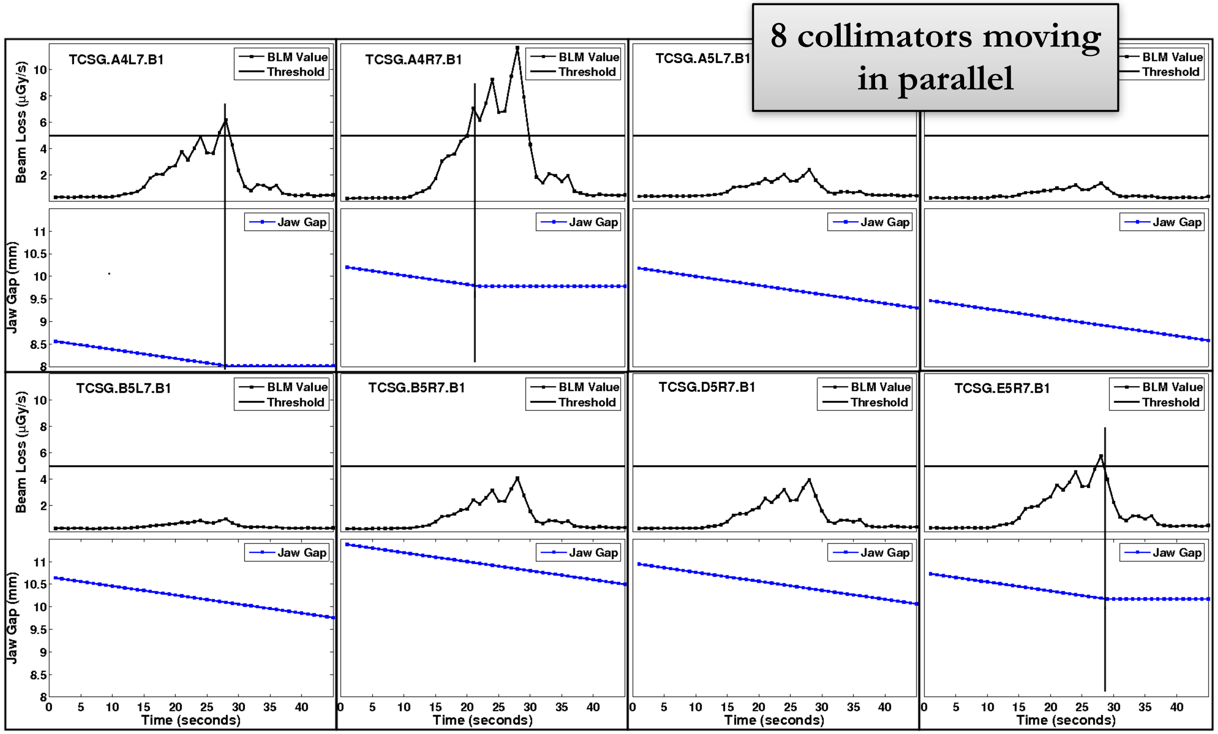

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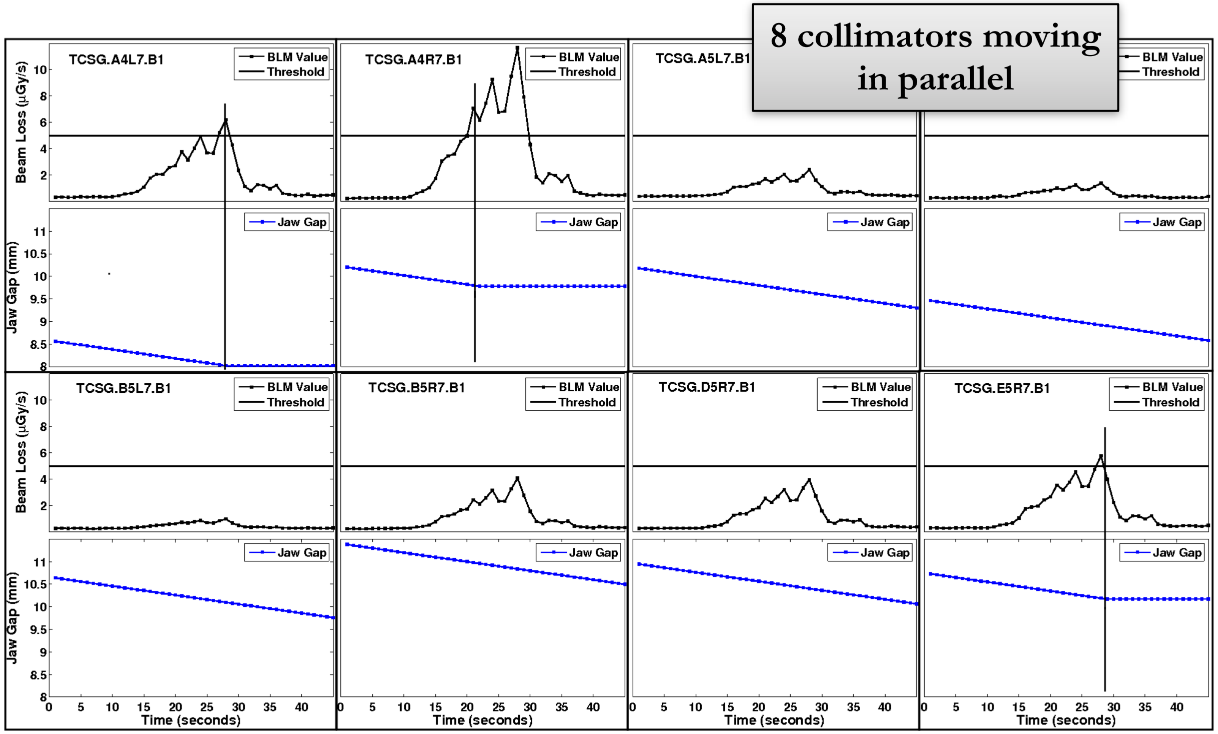

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- Tested in MD (Machine Development) in July 2011.

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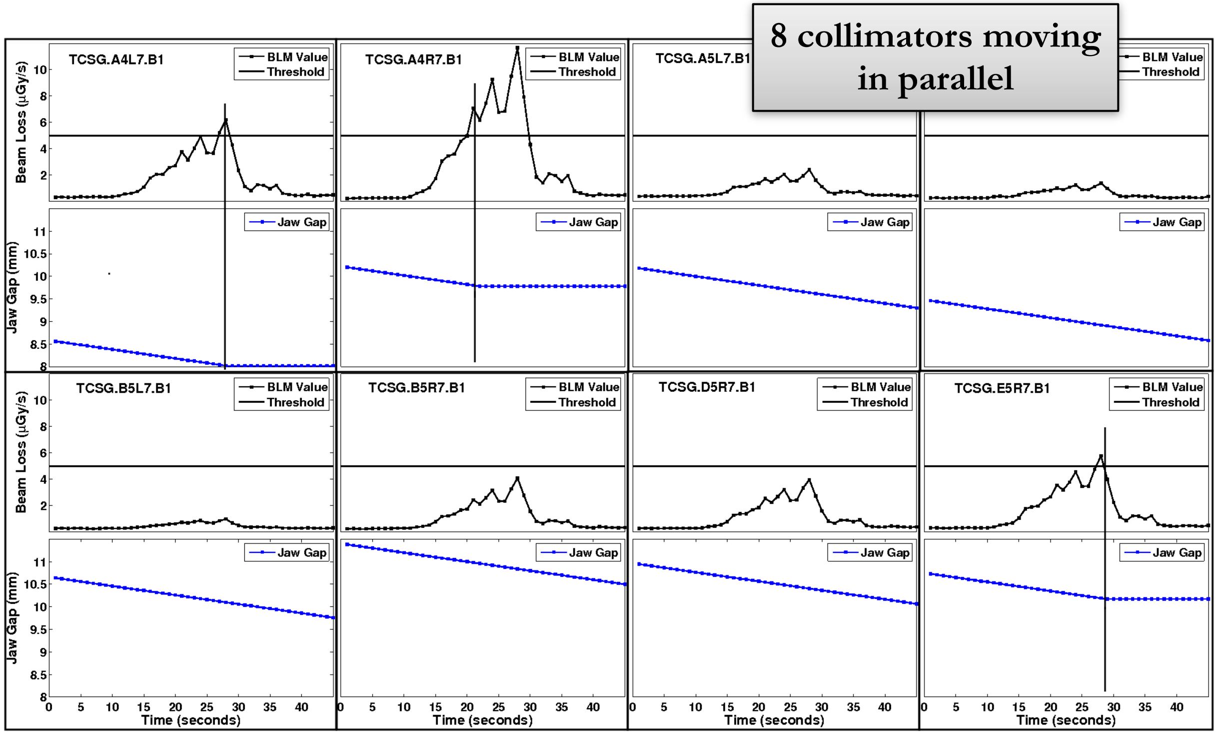

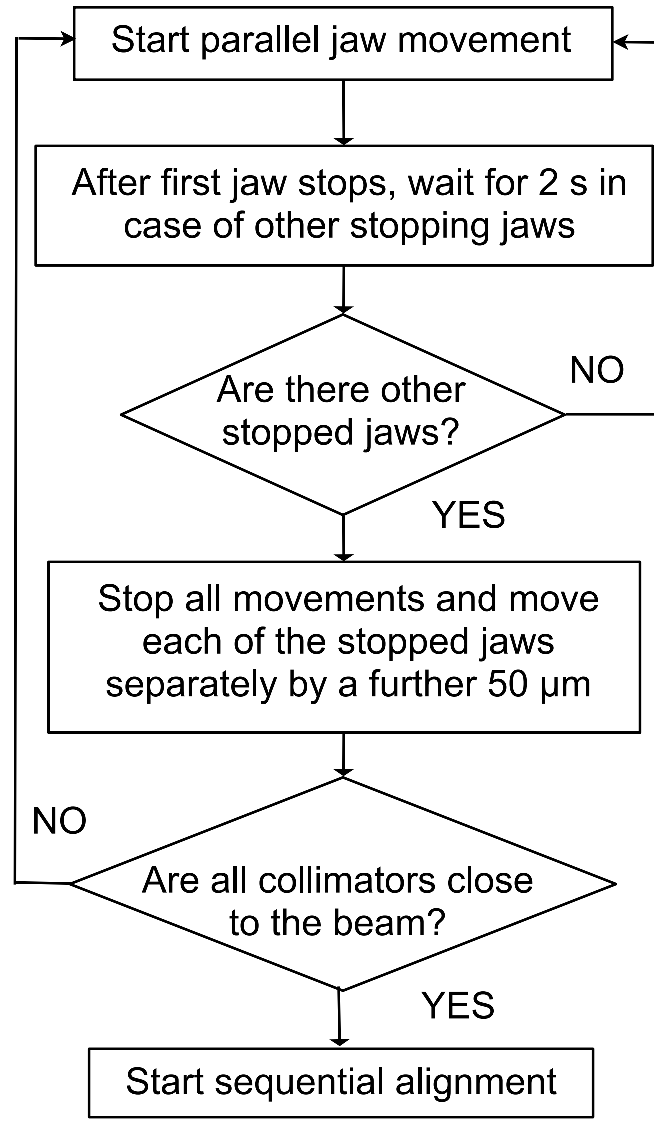

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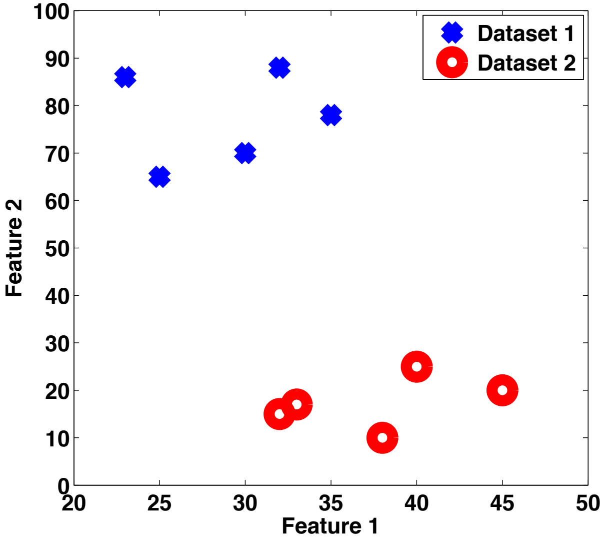

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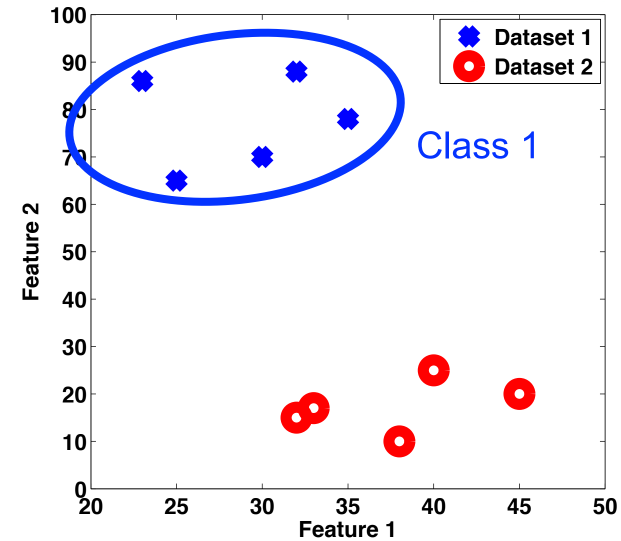

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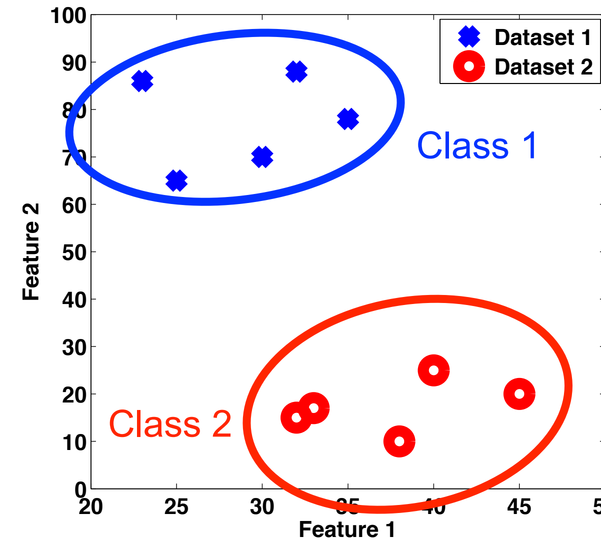

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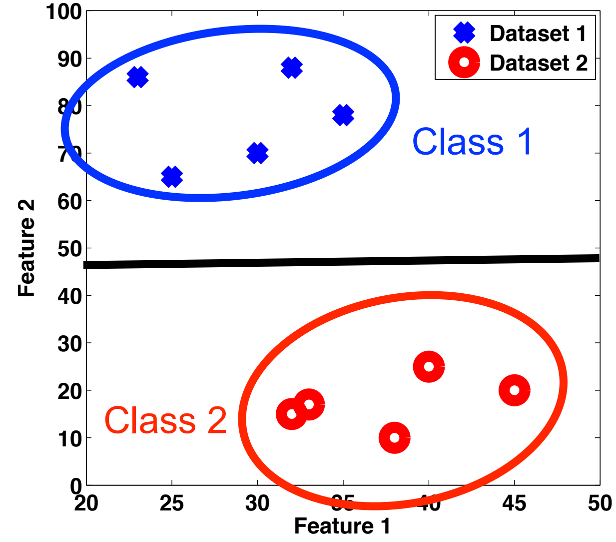

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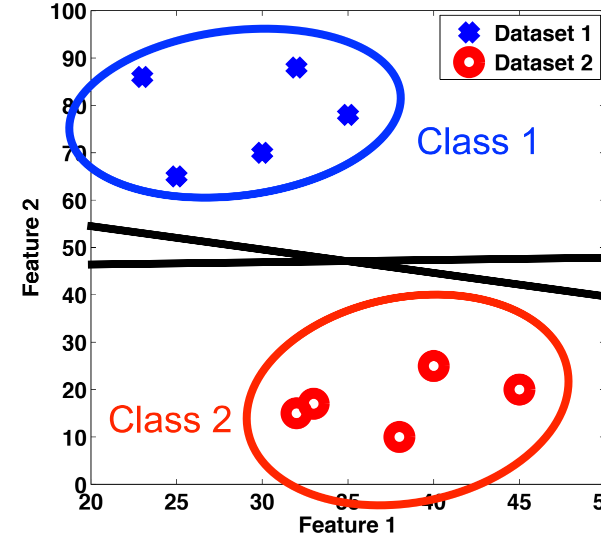

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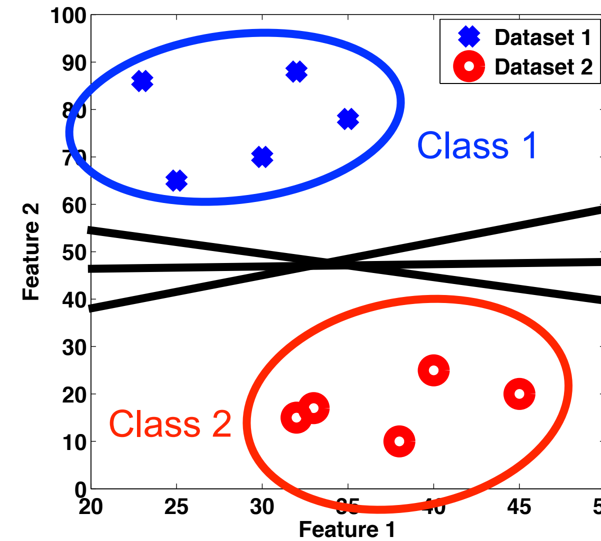

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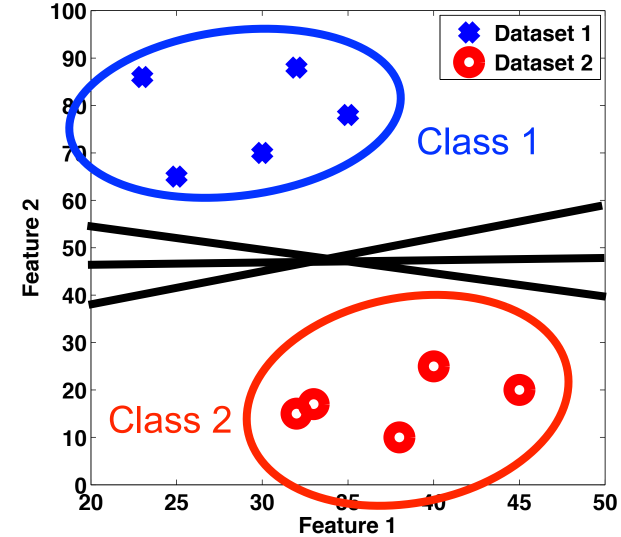

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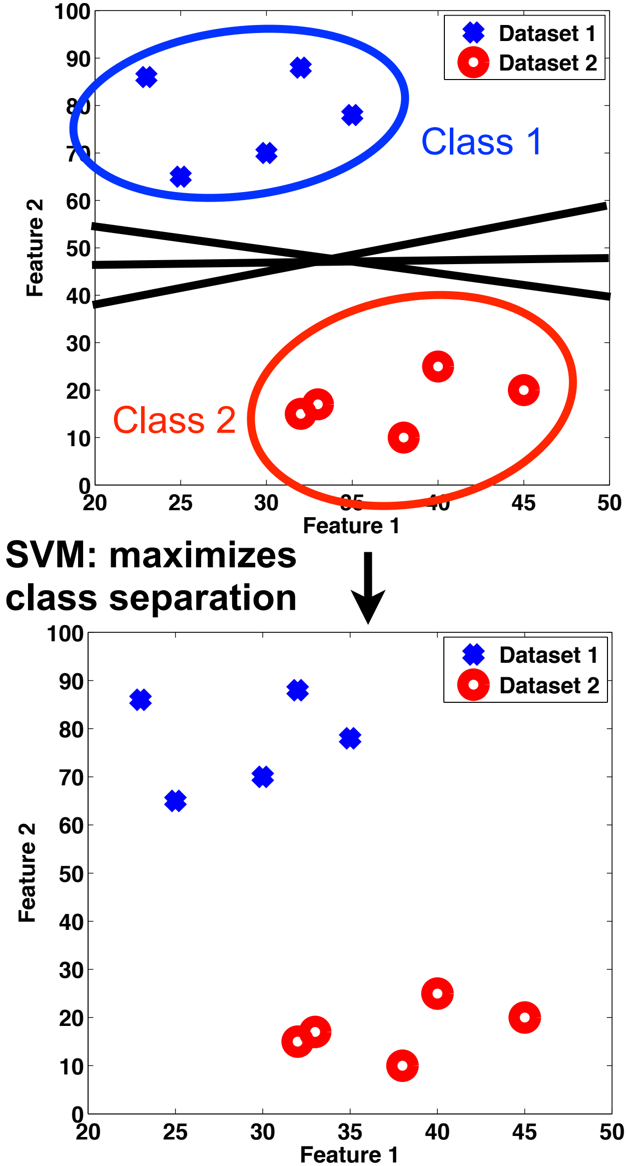

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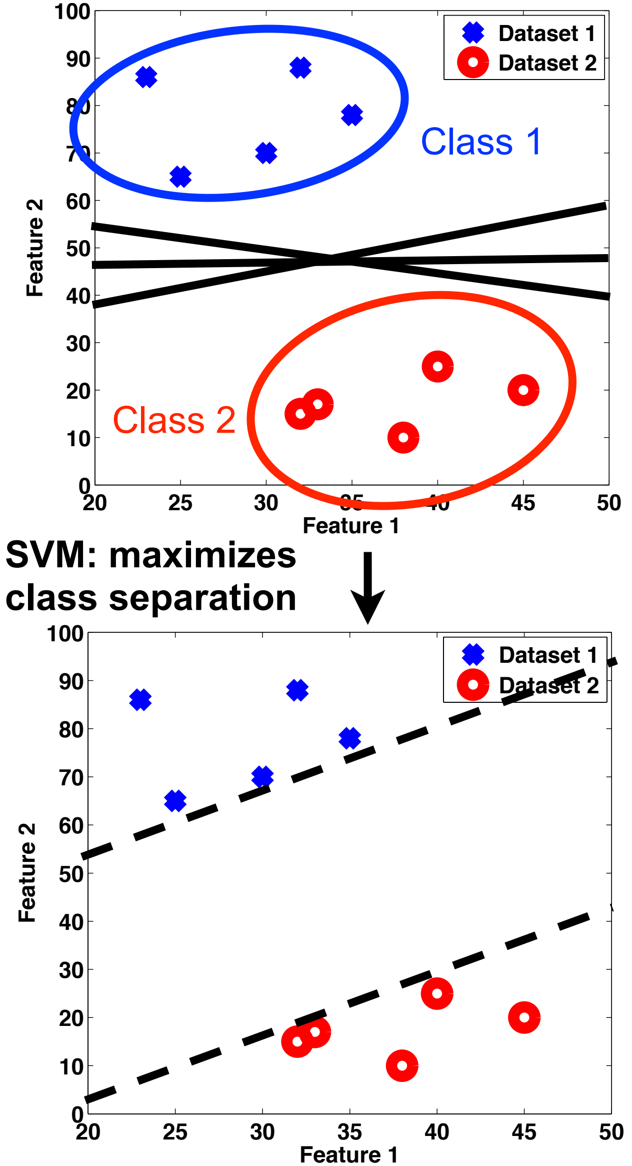

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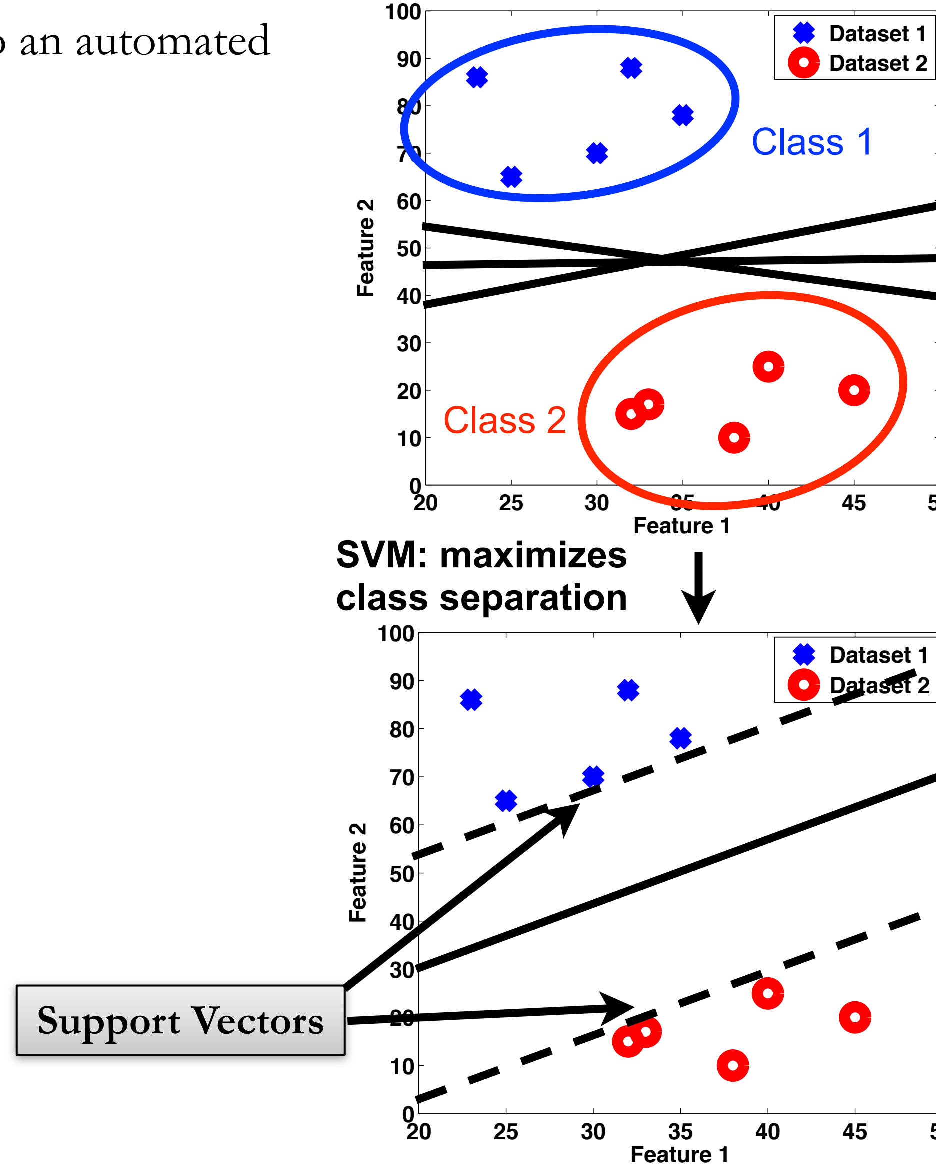

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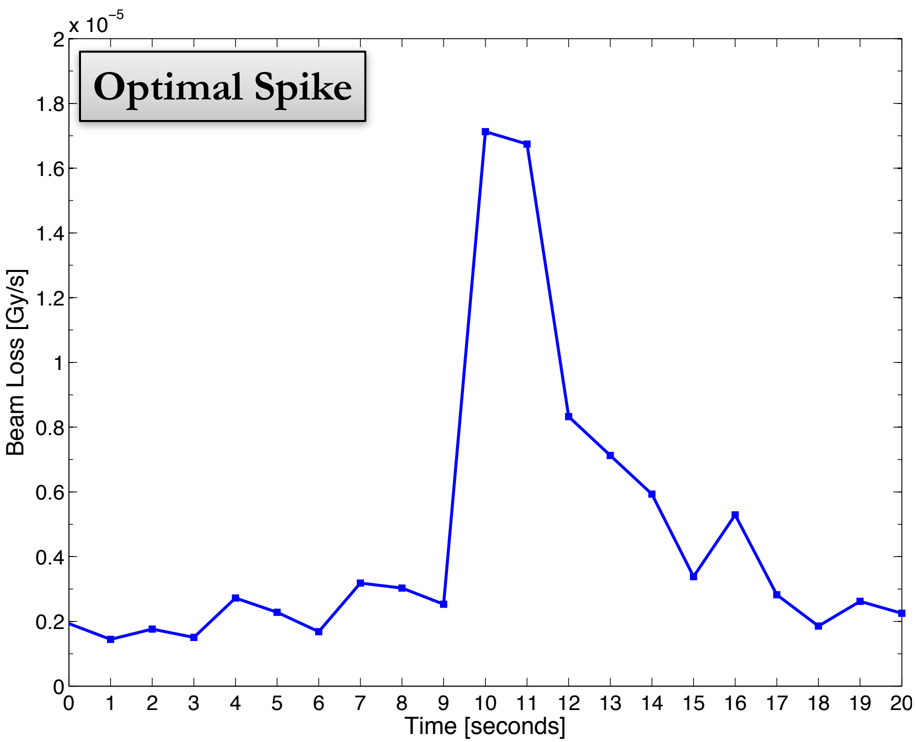
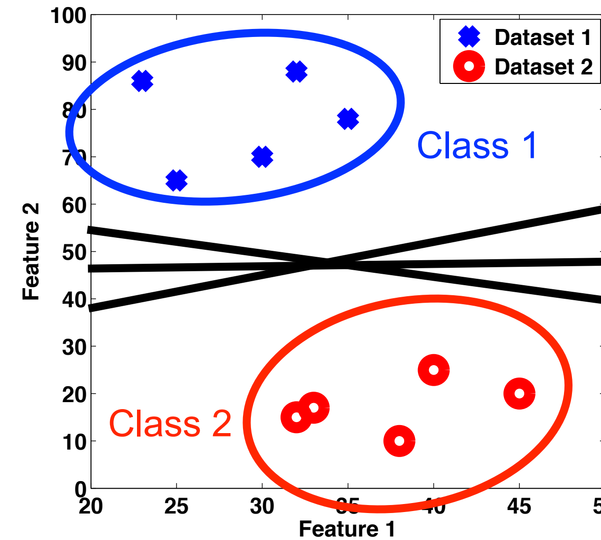
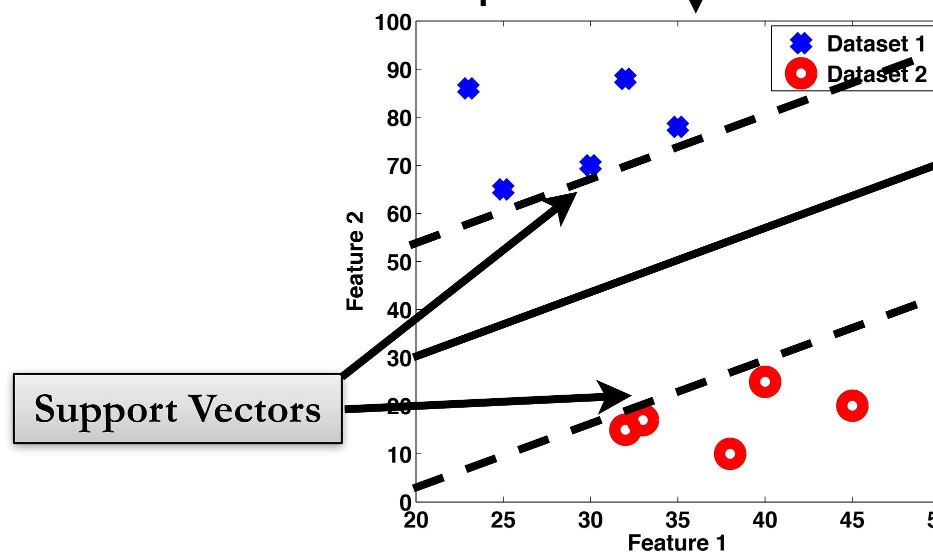
- Support Vector Machines (SVM): **supervised-learning** classification algorithm.
- A jaw is aligned to the beam when an optimal spike is observed. If the spike is non-optimal, the jaw has to be moved in again.



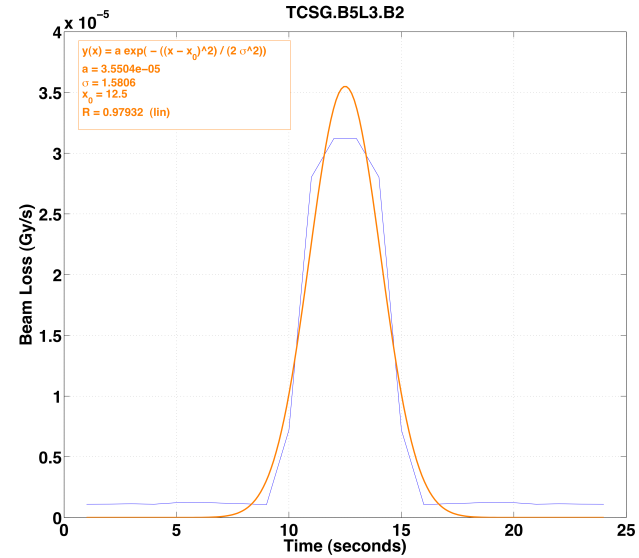


SVM: maximizes class separation

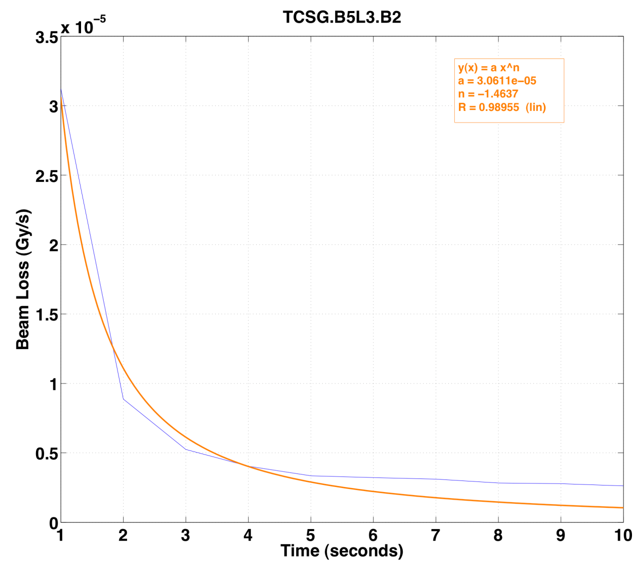


Feature Selection

- 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 γ (width of RBF) using 5-fold cross-validation to determine the optimal values for these parameters.
- 444 samples were used (222 for training and 222 for testing).

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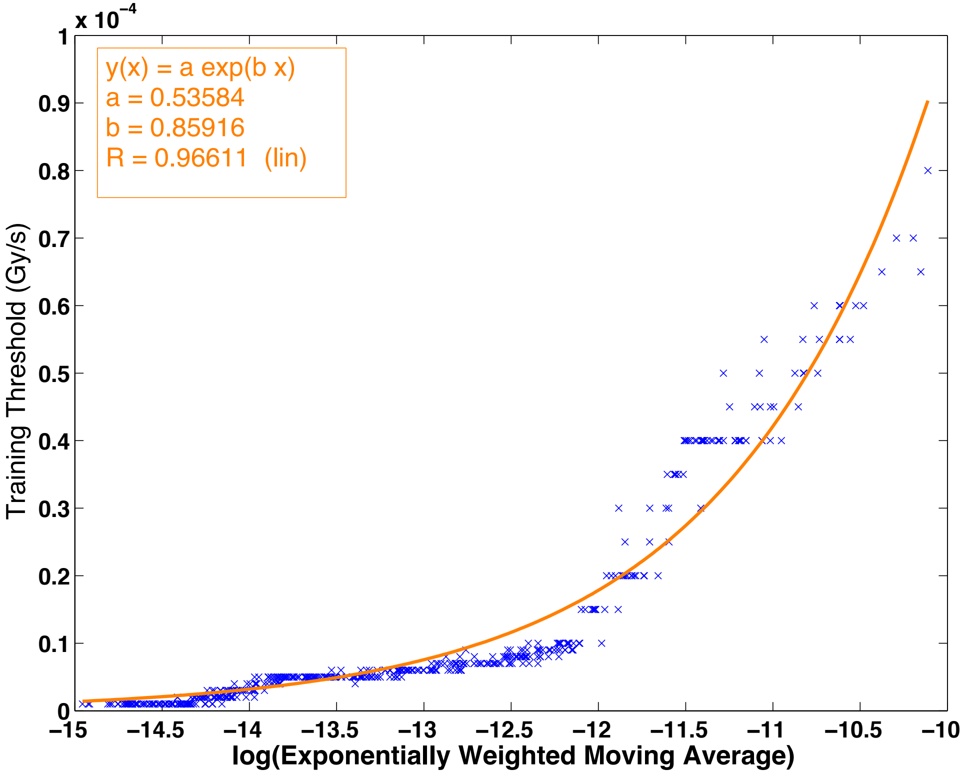
Parameter	Value
Number of Features	6
Number of Classes	2
C	32768
γ	0.125
Kernel	RBF
Training dataset prediction	97.2973 %
Test dataset prediction rate	82.4324 %
Overall prediction rate	**89.8649 %**

Automatic Threshold Selection

- Collimator setup can be automated further if the loss threshold is automatically chosen.
- Samples of the steady-state BLM signal in 20 second intervals and the subsequent threshold set by operator were collected.

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

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



BPM-guided Coarse Alignment

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- An approximation to the beam centers at the collimators can be obtained from an interpolation of the orbit measured by the Beam Position Monitors (BPMs).
- The interpolation can be exploited to speed up the alignment, assuming a measured average delta between beam-based alignment and interpolation of 550 μm.

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- An approximation to the beam centers at the collimators can be obtained from an interpolation of the orbit measured by the Beam Position Monitors (BPMs).
- The interpolation can be exploited to speed up the alignment, assuming a measured average delta between beam-based alignment and interpolation of 550 μm.
- All collimator left and right jaws can be moved directly to the coarse settings at a rate of 2 mm/s instead of 0.01 mm/s:

$$x_i^L = \Delta x_i^{int.} + (N_{TCP} + N_{margin}) \times \sigma_i^n + \frac{\Delta_{m,int.}}{2}$$

$$x_i^R = \Delta x_i^{int.} - (N_{TCP} + N_{margin}) \times \sigma_i^n - \frac{\Delta_{m,int.}}{2}$$

  - $\Delta x_i^{int.}$: interpolated beam center at collimator *i*.
  - N_{TCP} : half-gap of IR7 TCP in units of sigma.
  - N_{margin} : further margin over and above the IR7 TCP cut.
  - σ_i^n : the nominal 1-sigma beam size.
  - $\Delta_{m,int.}$: the expected average delta between the interpolated and the measured center.

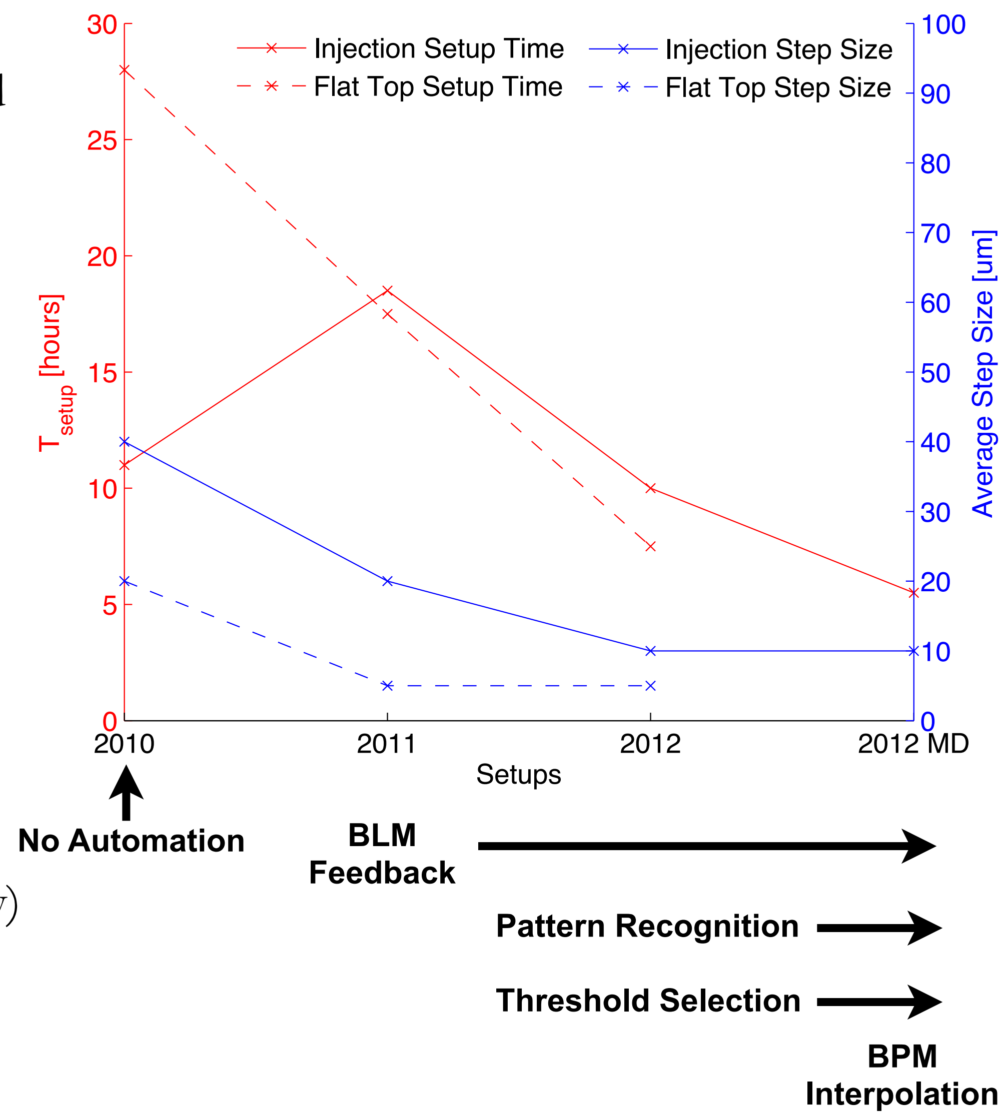
Alignment Results

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

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

- 2010: manual alignment
- 2011: semi-automatic alignment at 1 Hz
- 2012: semi-automatic alignment at 8 Hz

- No costly beam dumps due to high losses from 2011 onwards.
- Use of smaller jaw step size (better accuracy) made easier by semi-automatic alignment.



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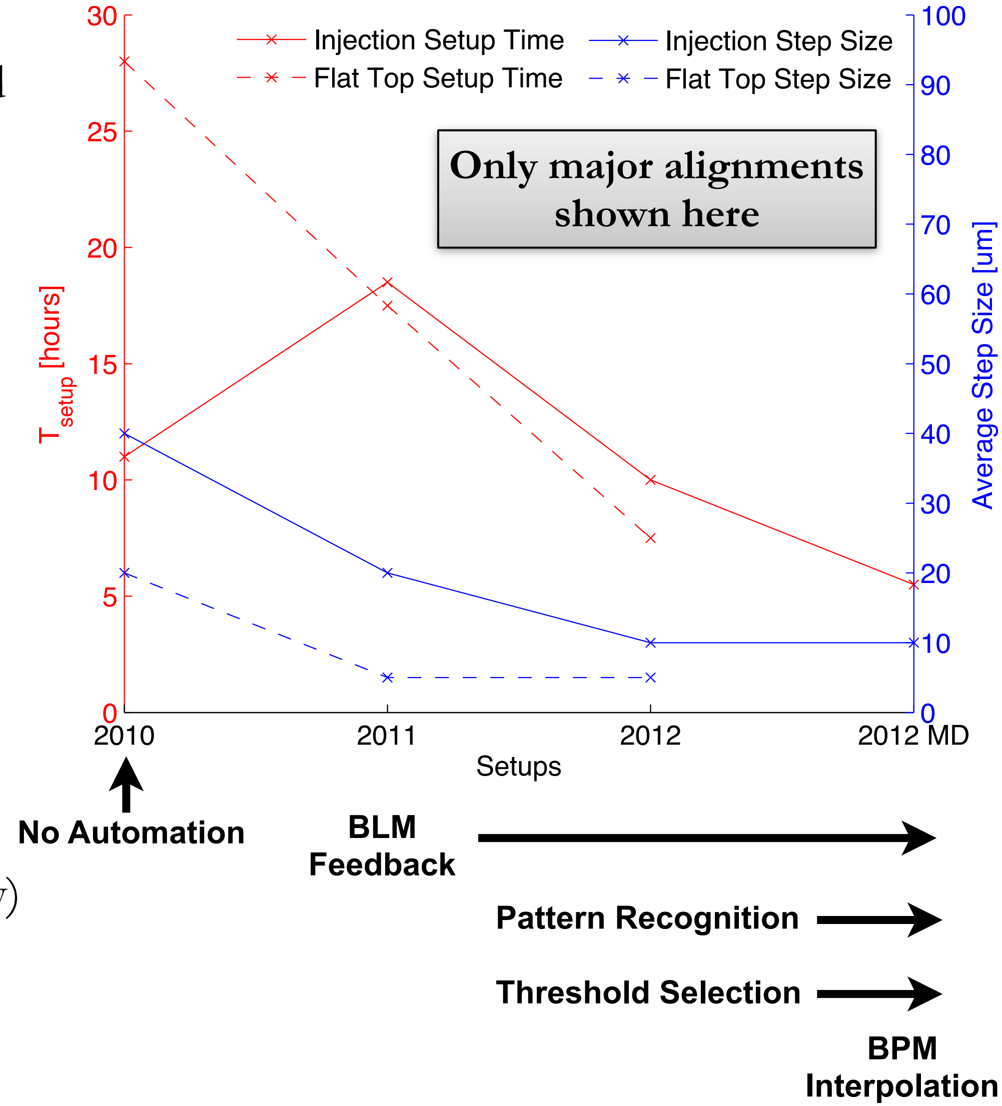

Summary

- 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 5.5 hours (**factor 5 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.

Acknowledgements

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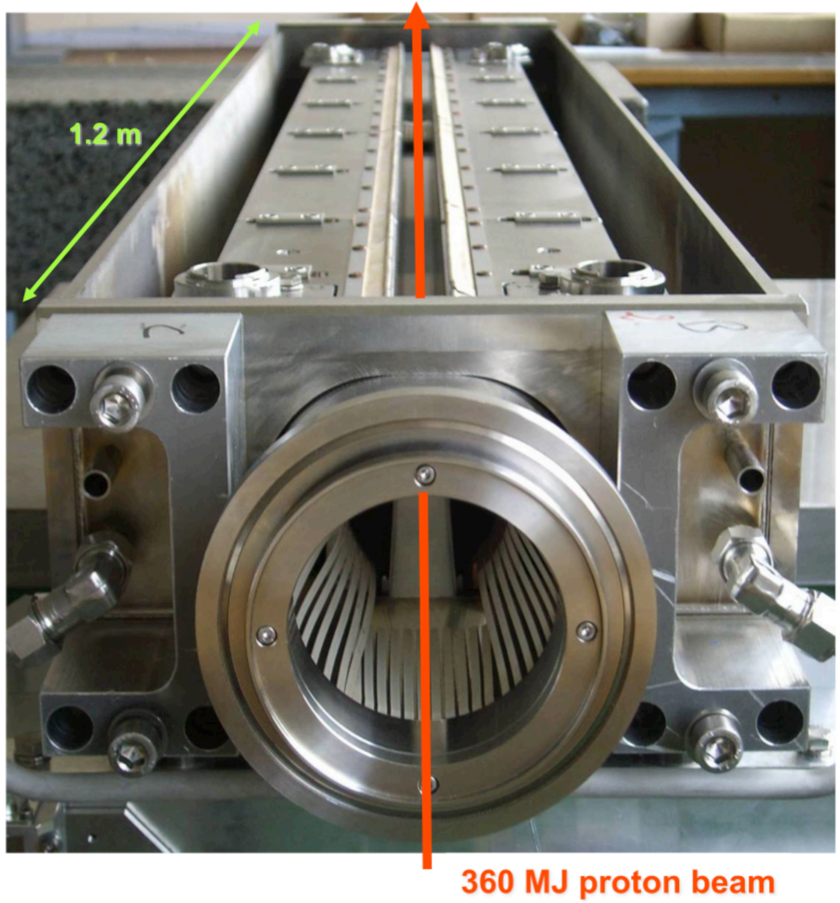
- Research funded by EuCARD ColMat WP8
- LHC Collimation Project at CERN (PhD co-supervisor: Dr. Ralph Assmann)
- University of Malta (PhD co-supervisor: Dr. Ing. Nicholas Sammut)



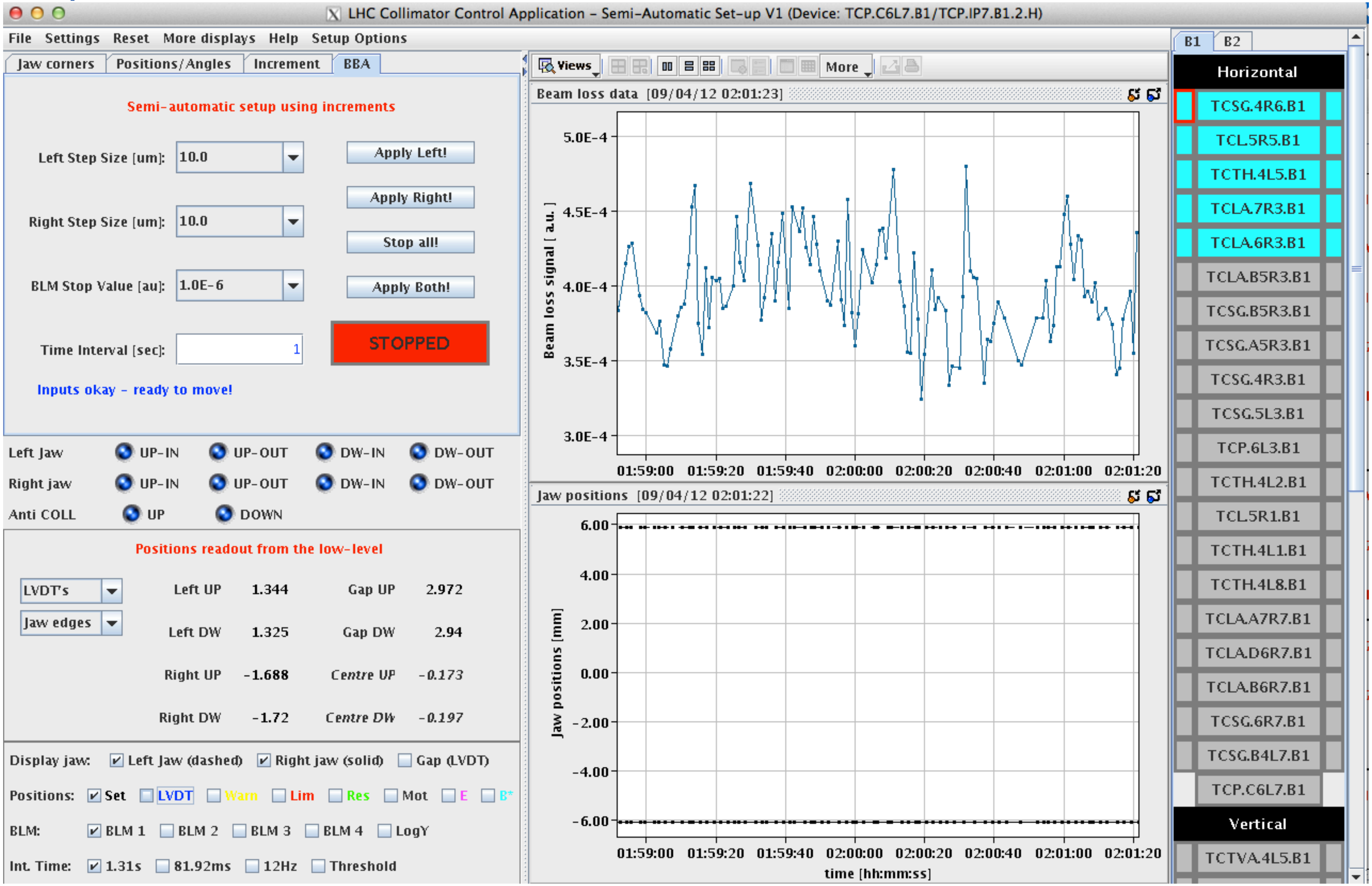
Thank you for your attention!

Contact details:

gianluca.valentino@cern.ch

RESERVE SLIDES

Setup Application GUI



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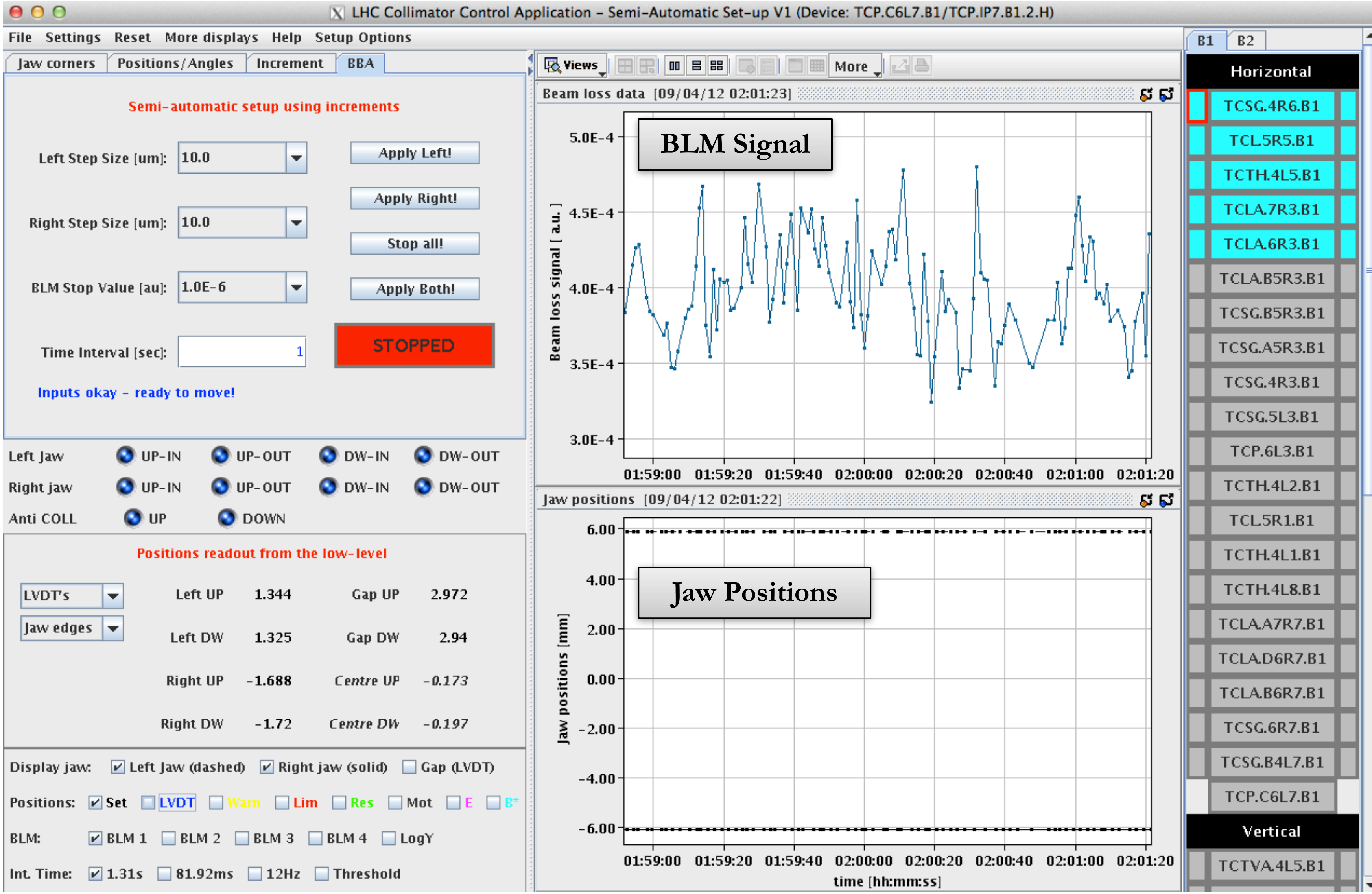

GUI built on S. Redaelli's original single collimator controller

Alignment Results

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- Nominal to Measured Beam Size Ratio (B1 left, B2 right) at 3.5 TeV:

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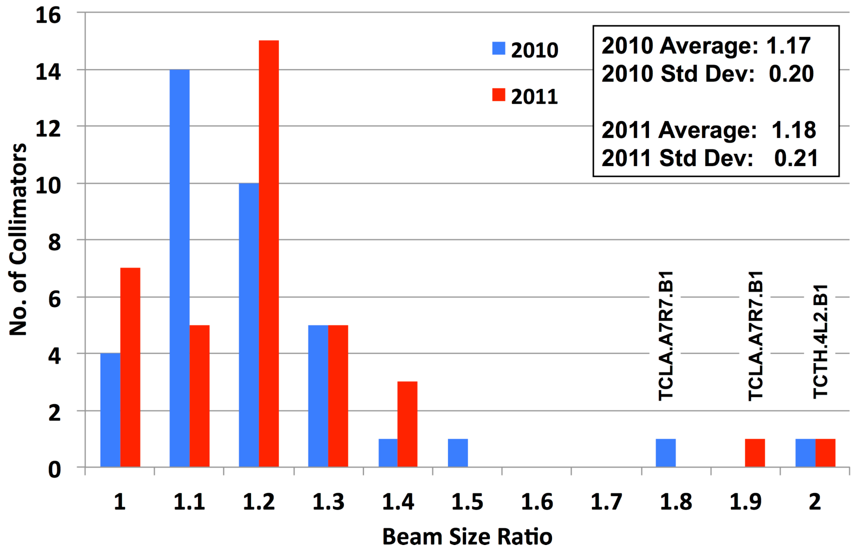

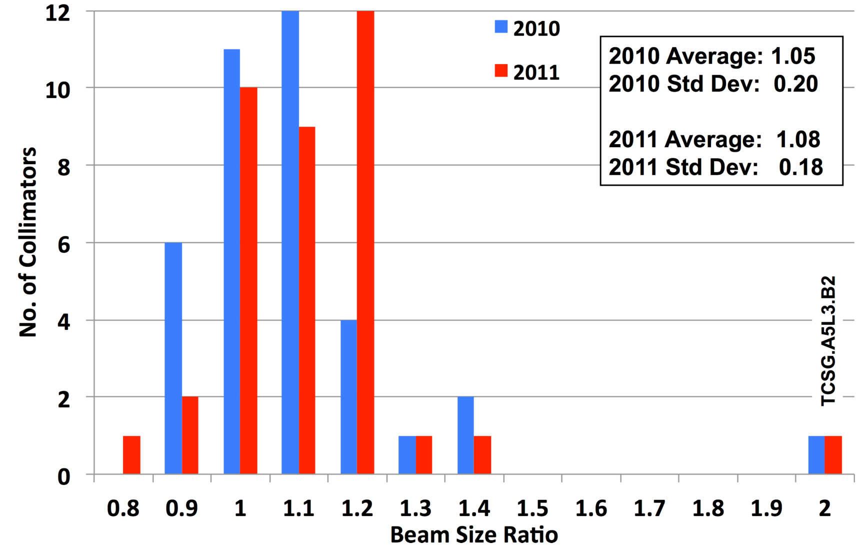

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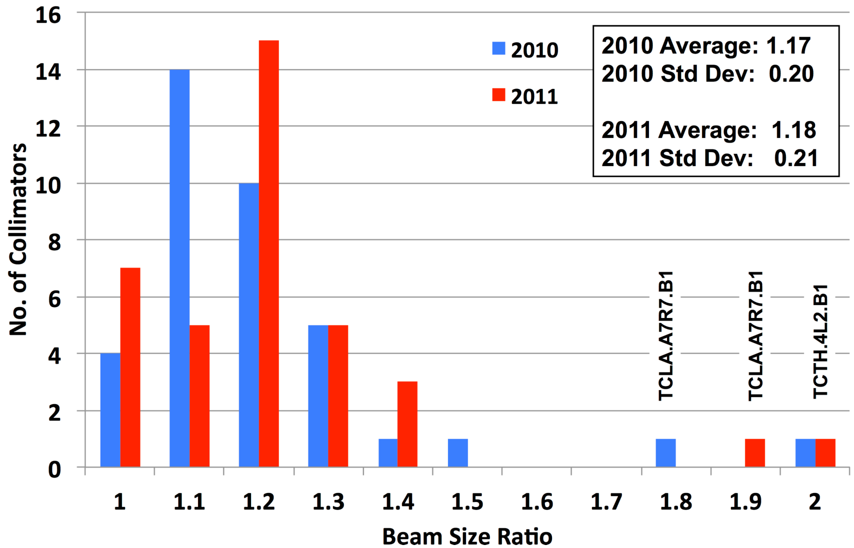

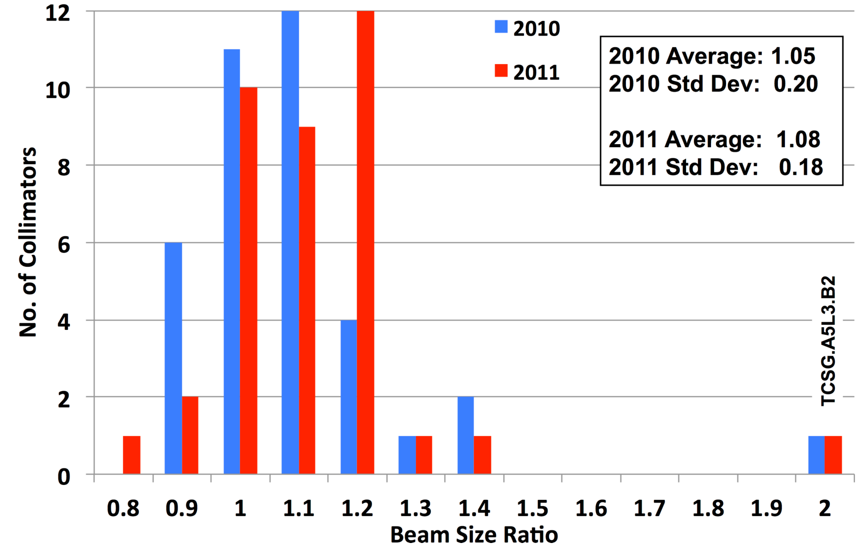

- Beam Intensity Variation:

Alignment Results

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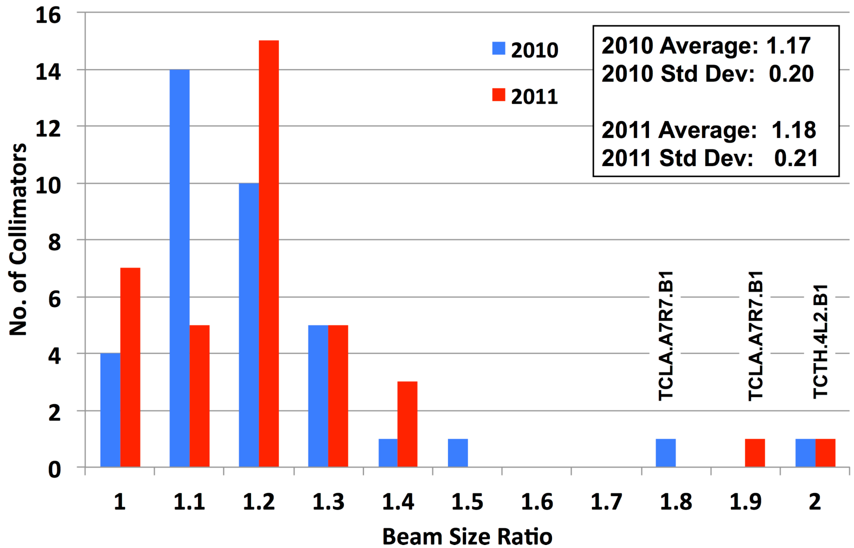

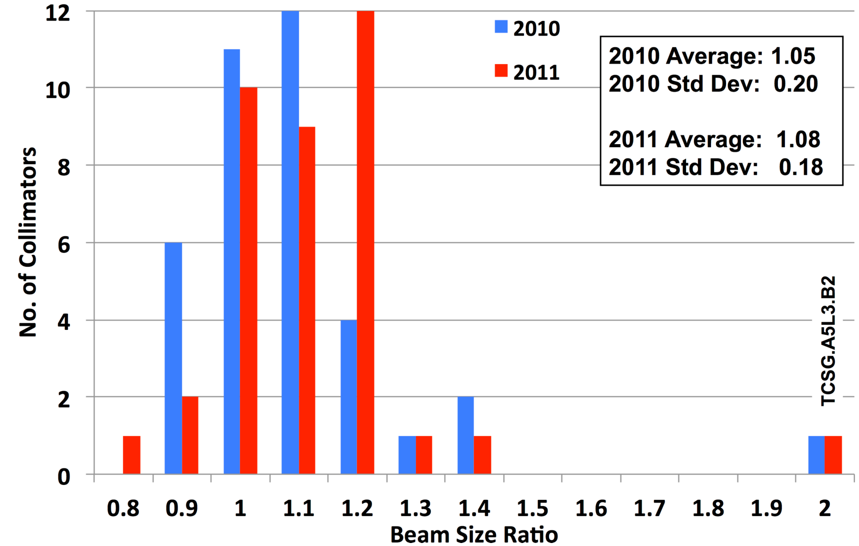

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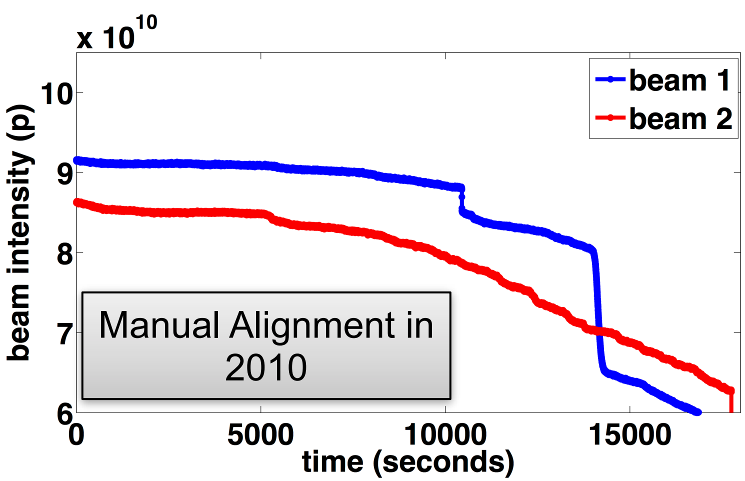

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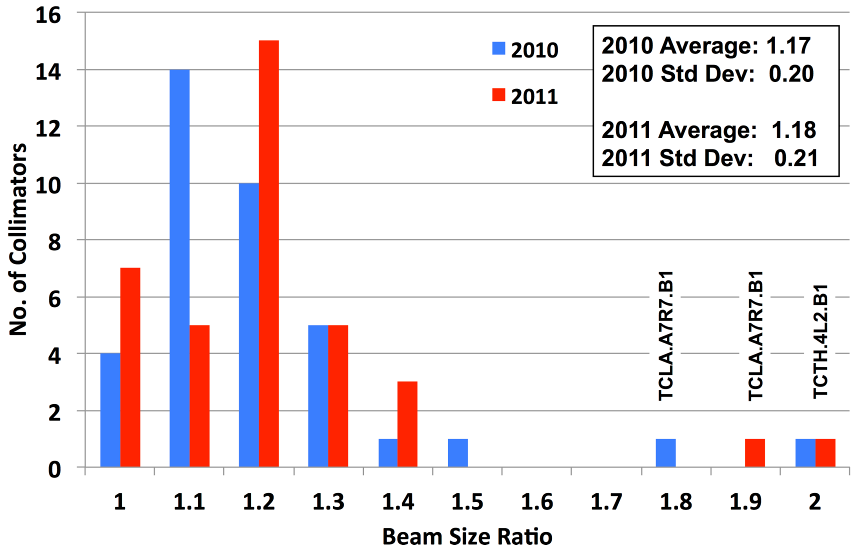

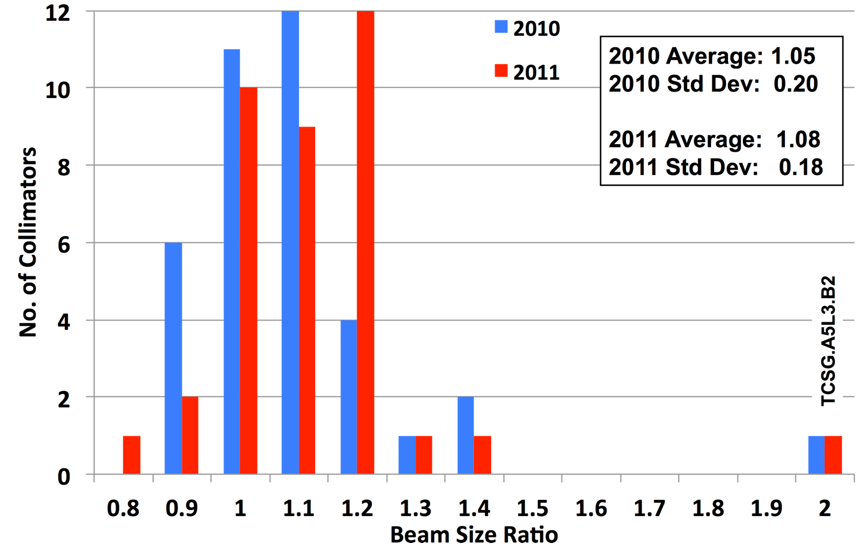

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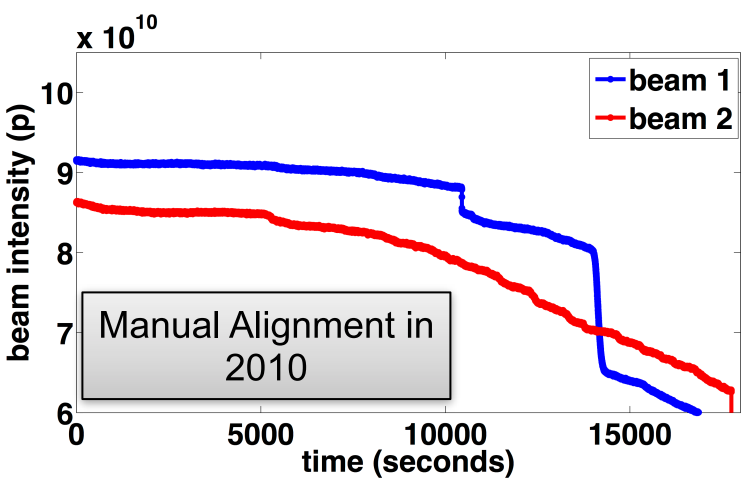
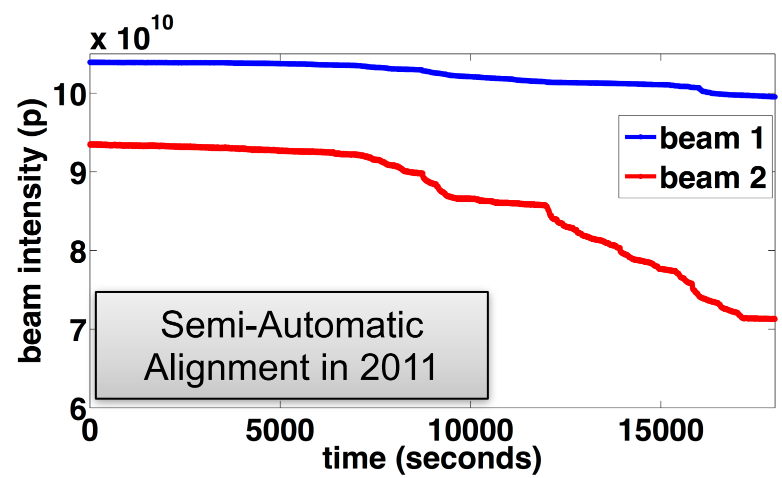
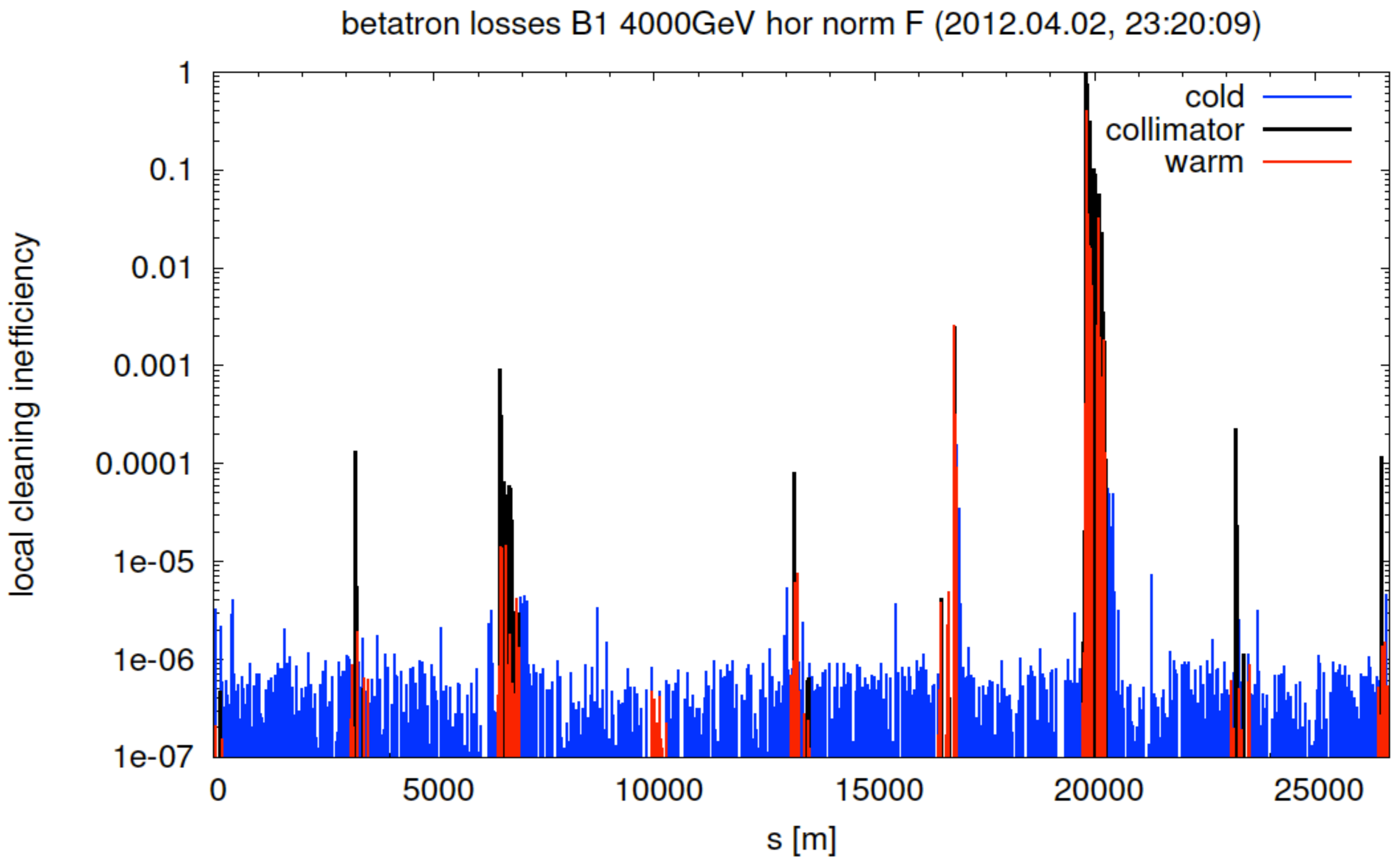




Collimation System Qualification



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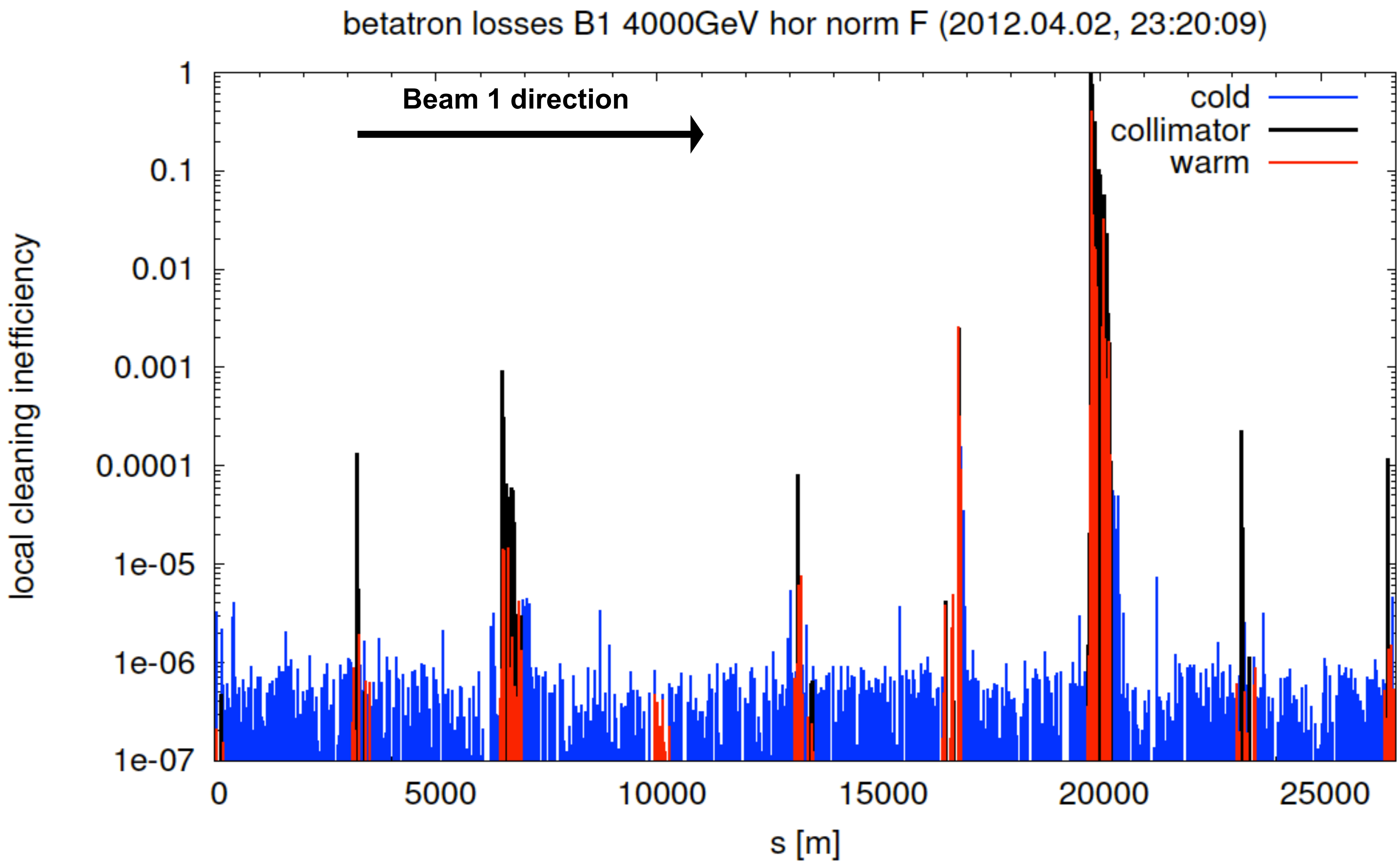

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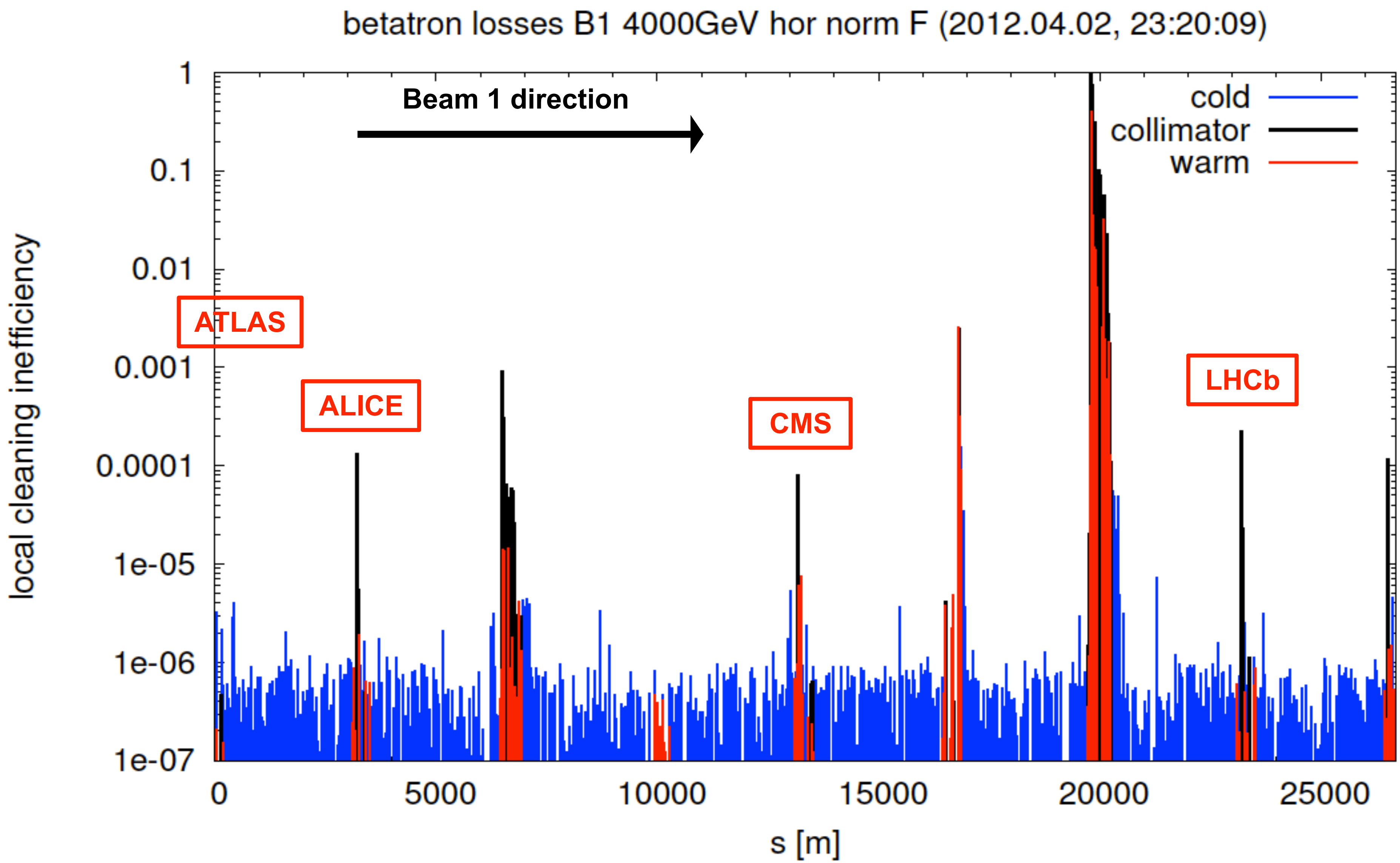

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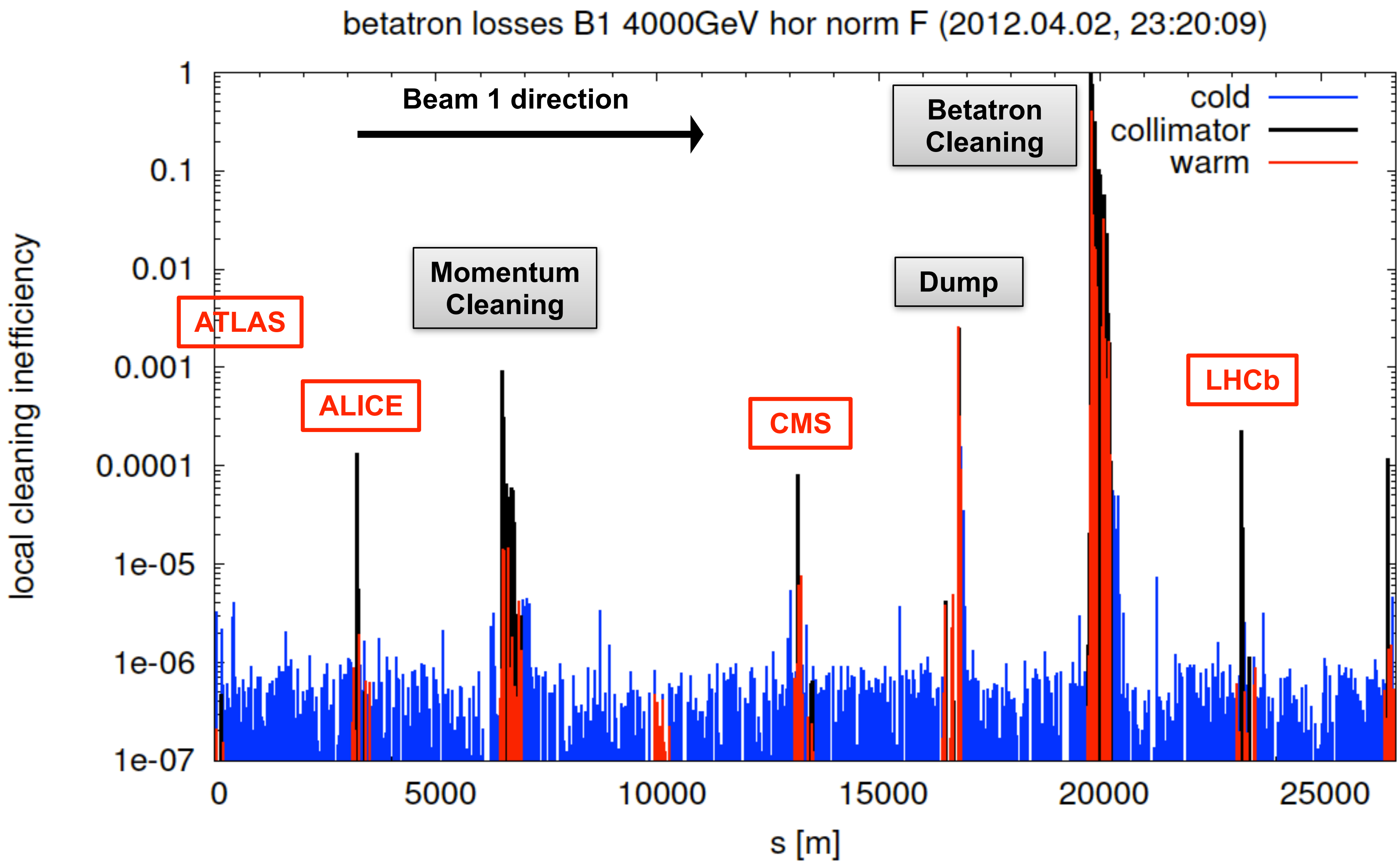

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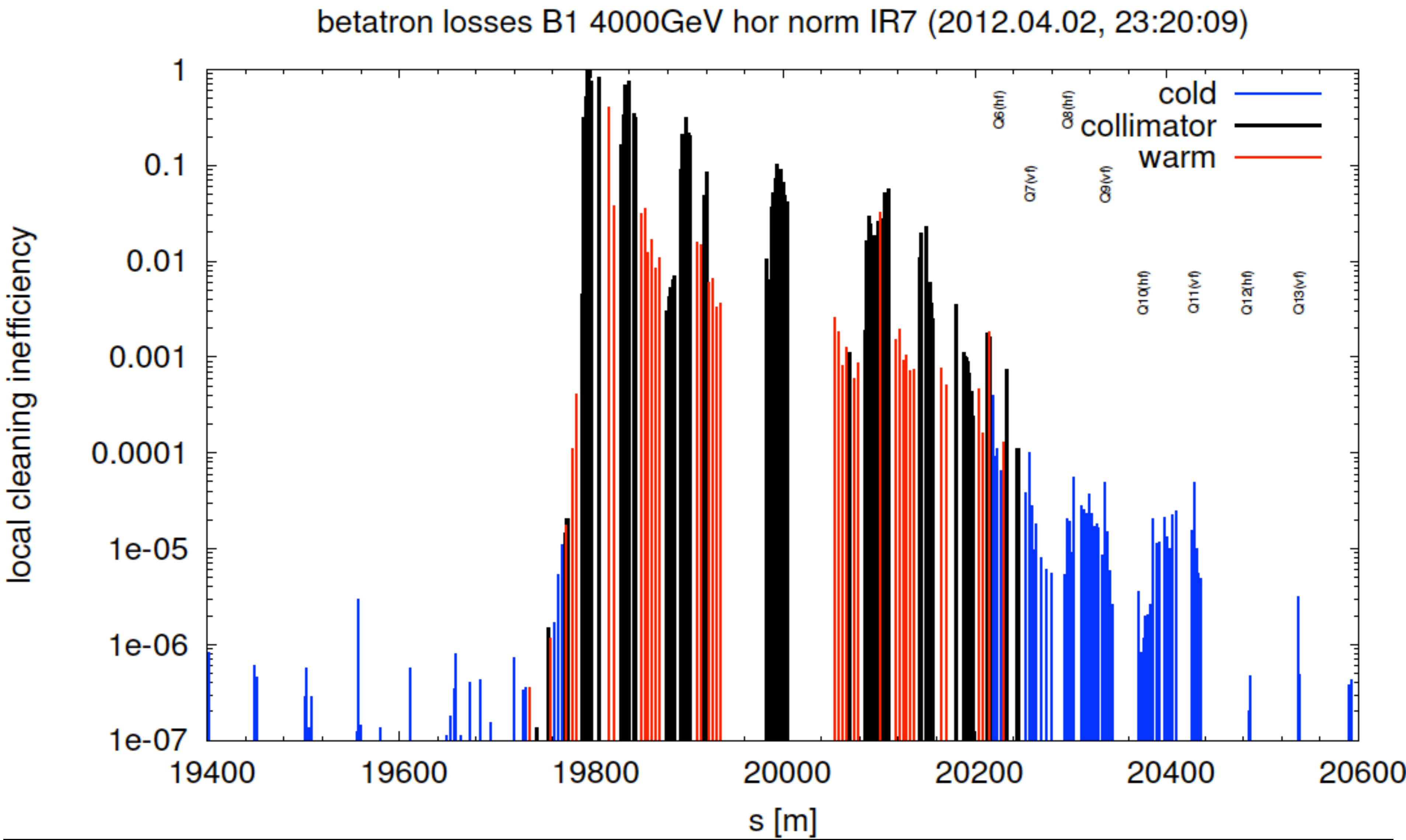

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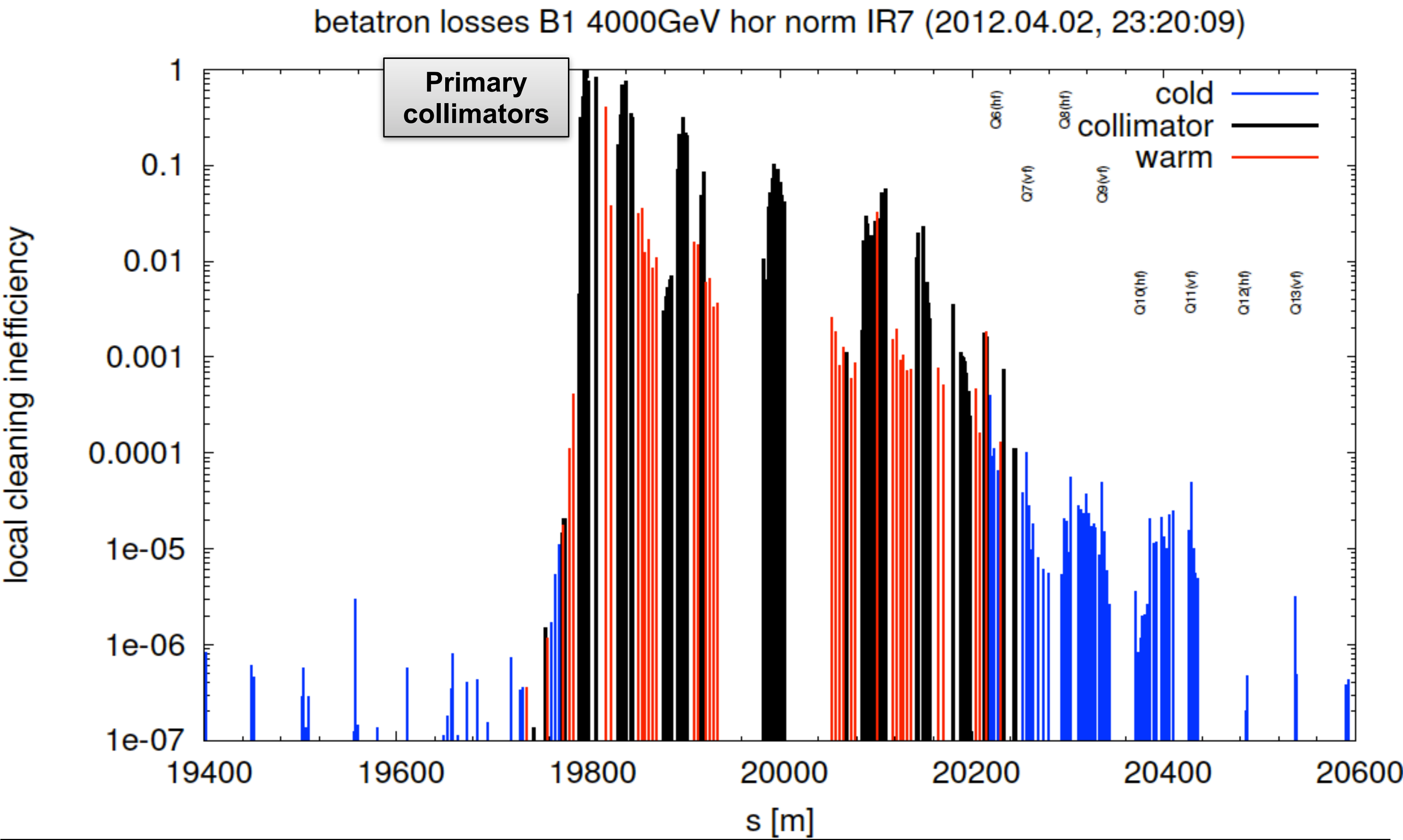

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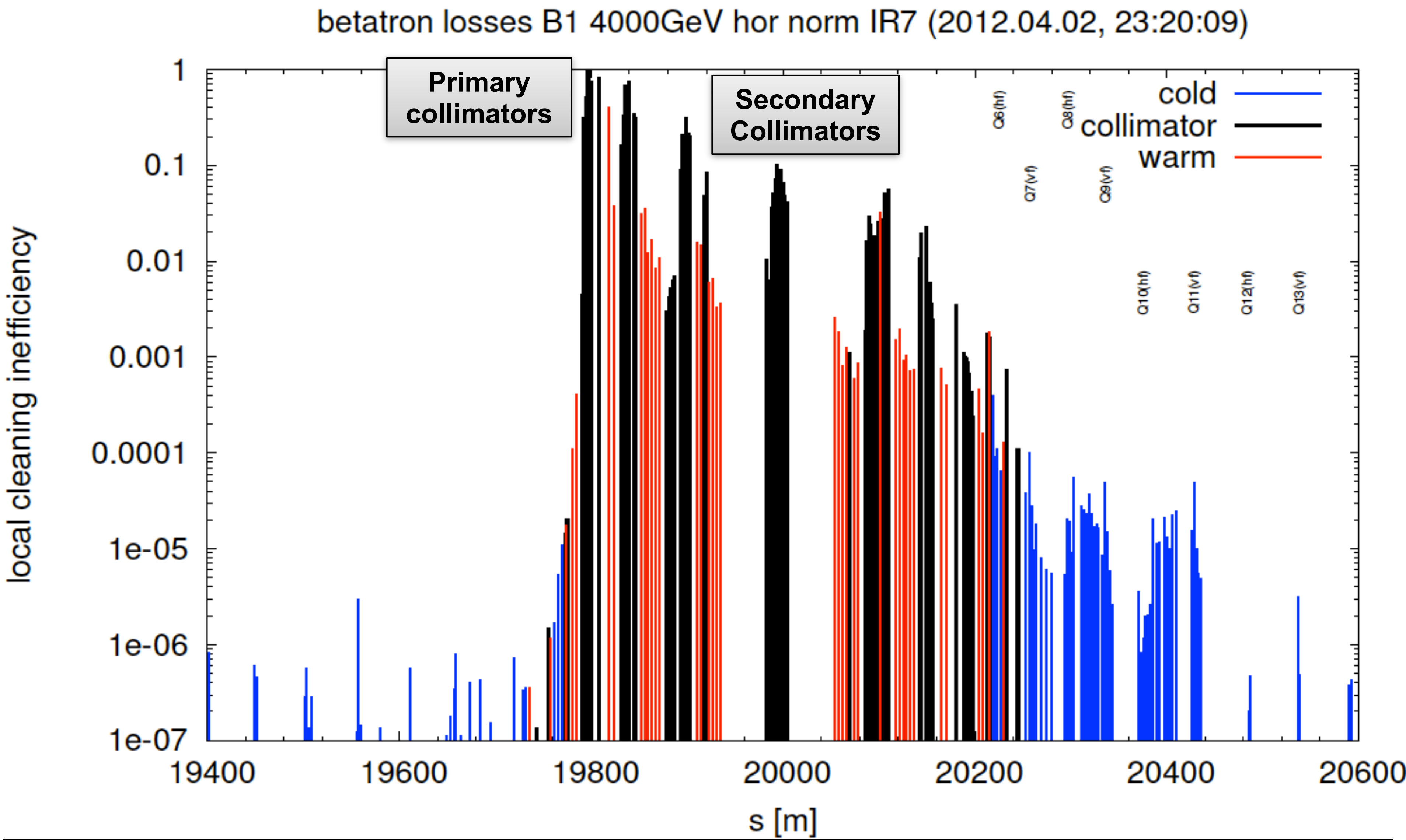

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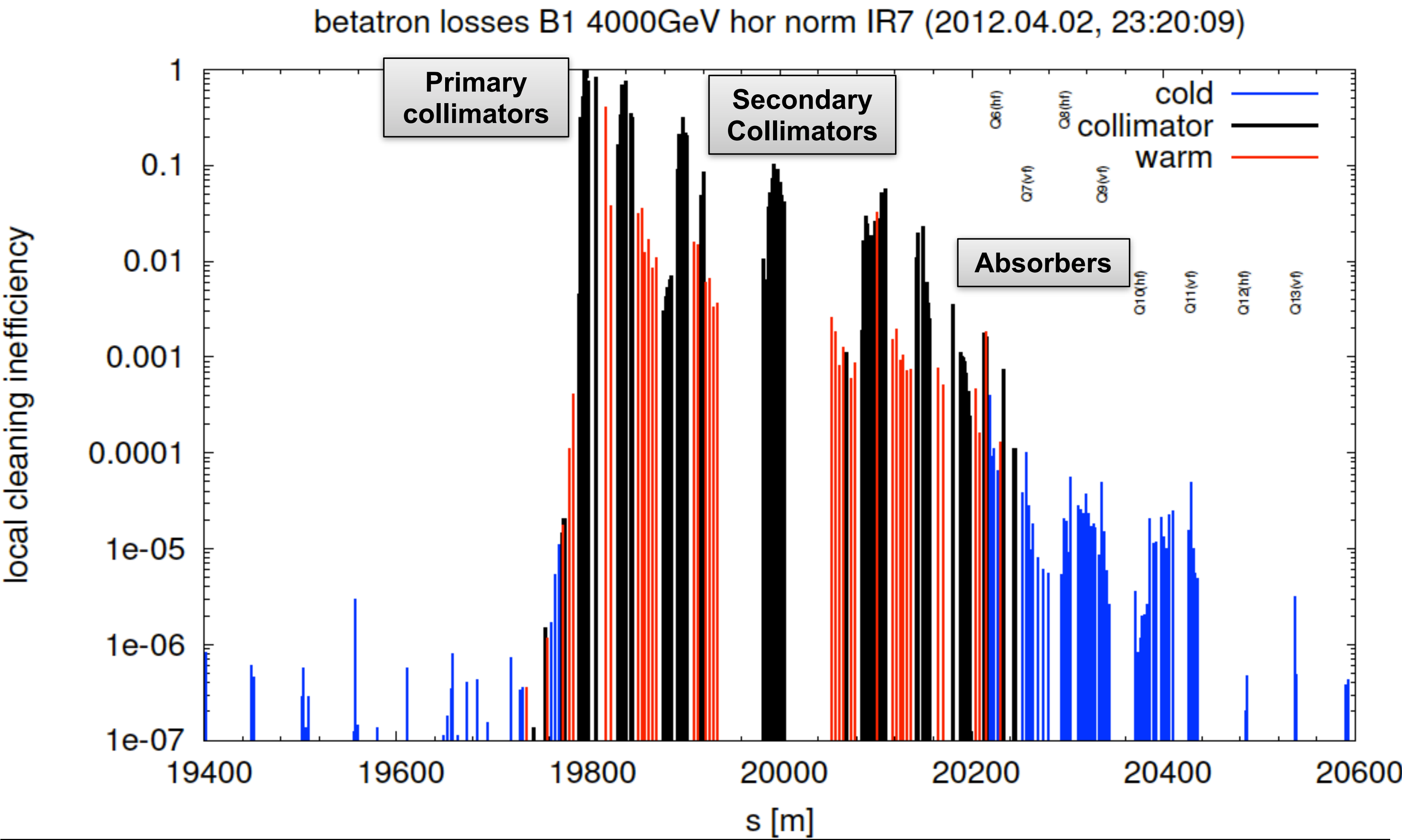

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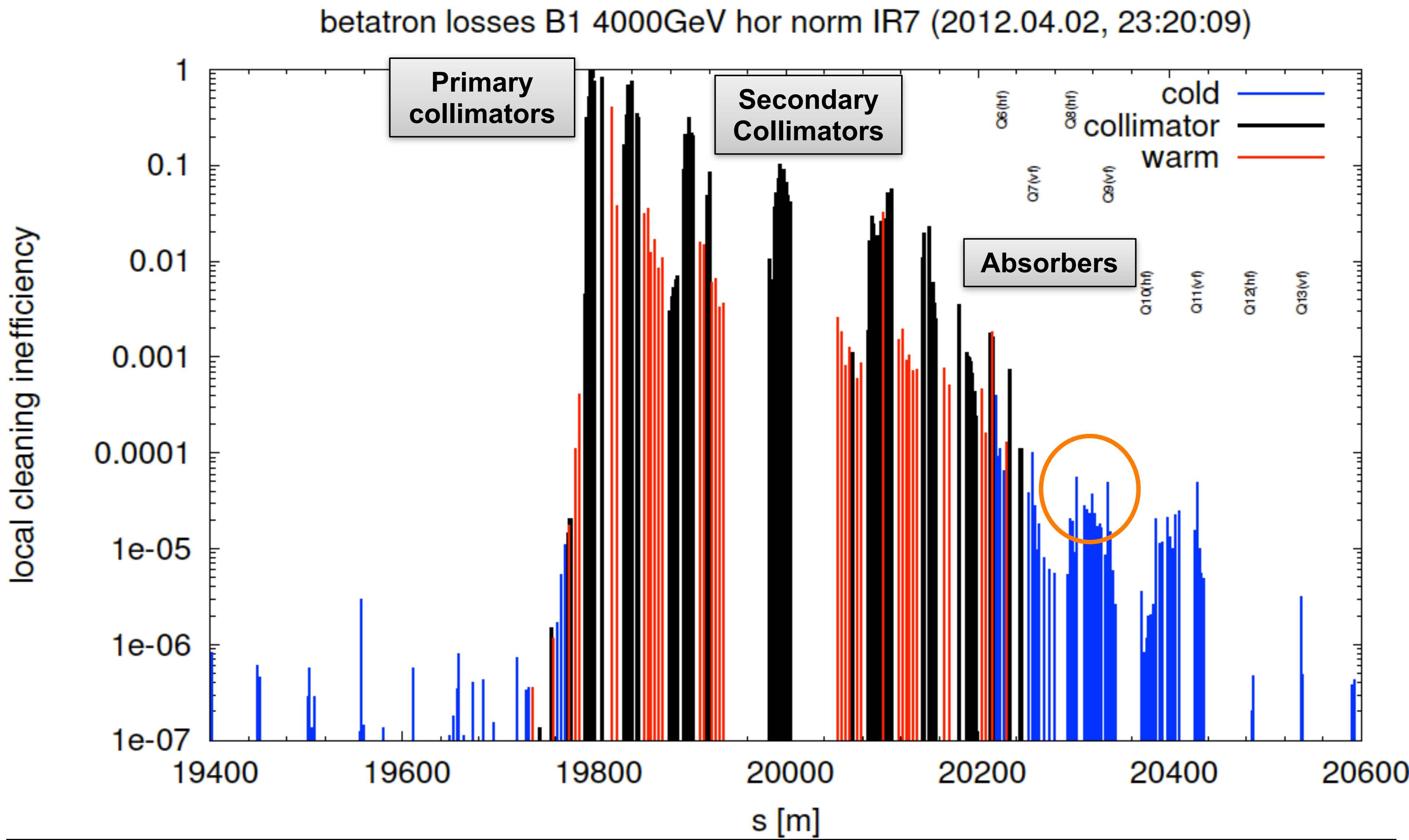

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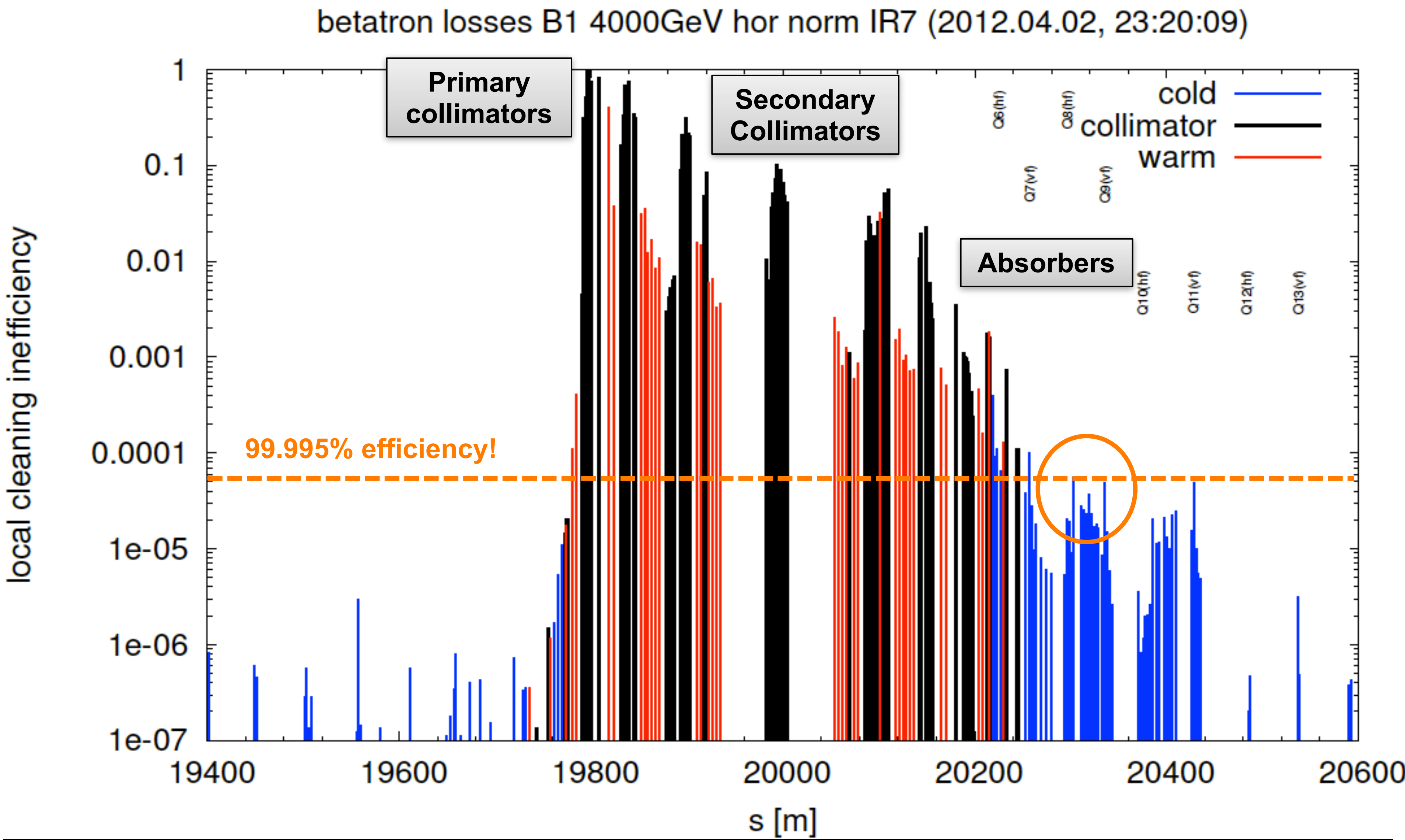

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