Fast Automatic Beam-Based Alignment of the LHC Collimator Jaws

Accelerators & Technology Sector Seminar

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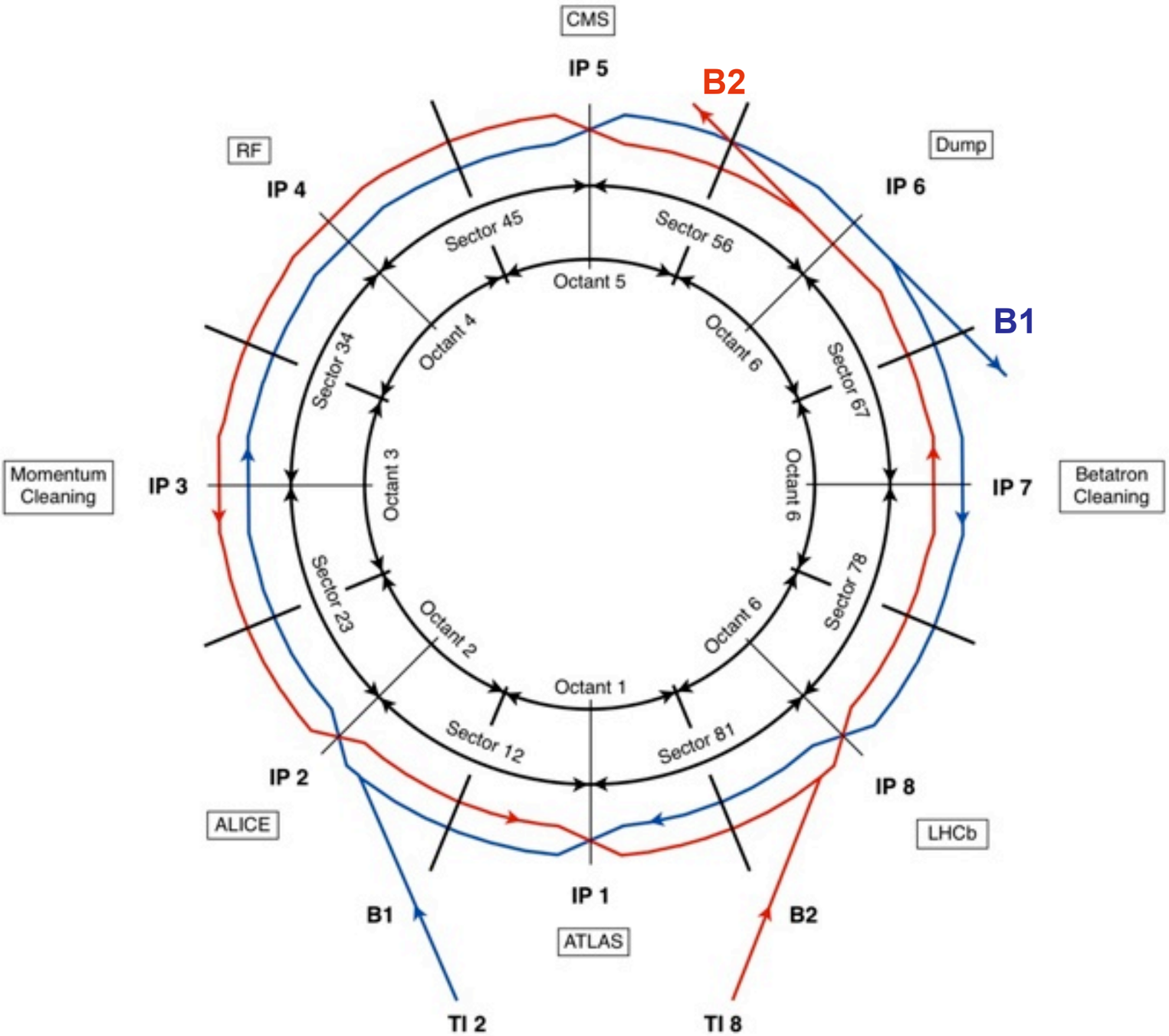
BE-ABP-LCU (CERN)

Main Auditorium, CERN, 19th September 2013

Outline

- The Large Hadron Collider
- LHC Collimation System
- Collimator Beam-Based Alignment
- Alignment Algorithms
- Software Implementation
- Modeling and Simulation of Beam Losses
- Simulation and Operational Results
- Future: BPM-based alignment
- Conclusions

The Large Hadron Collider



LHC Machine Parameters

Circumference: 26650 m

Beam energy: 7 TeV **(4 TeV)**

Particle velocity: 0.999999991c

Bunch intensity: 1.15E11 protons

Bunches per beam: 2808 **(1380)**

Collisions per second: 600 million

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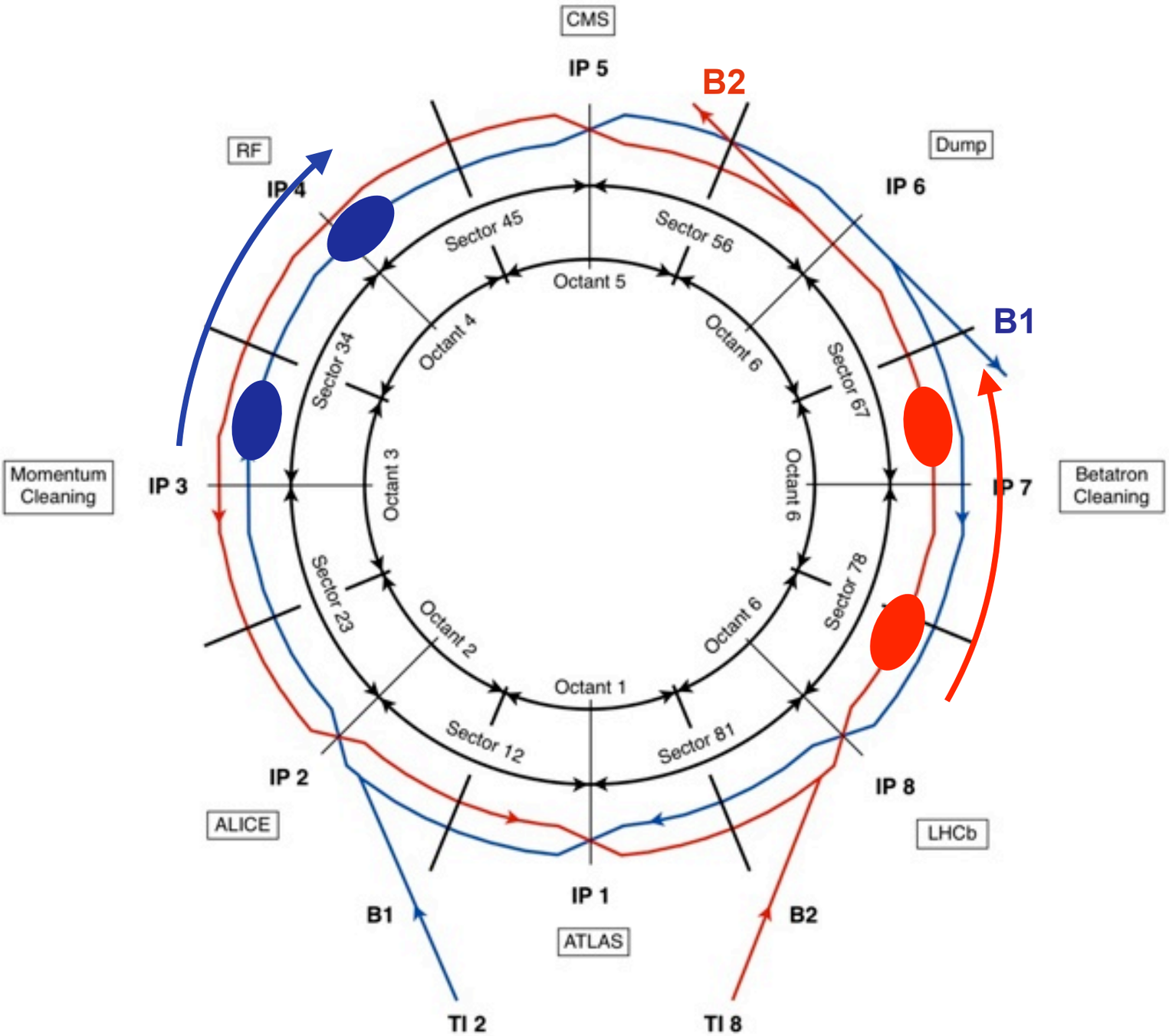

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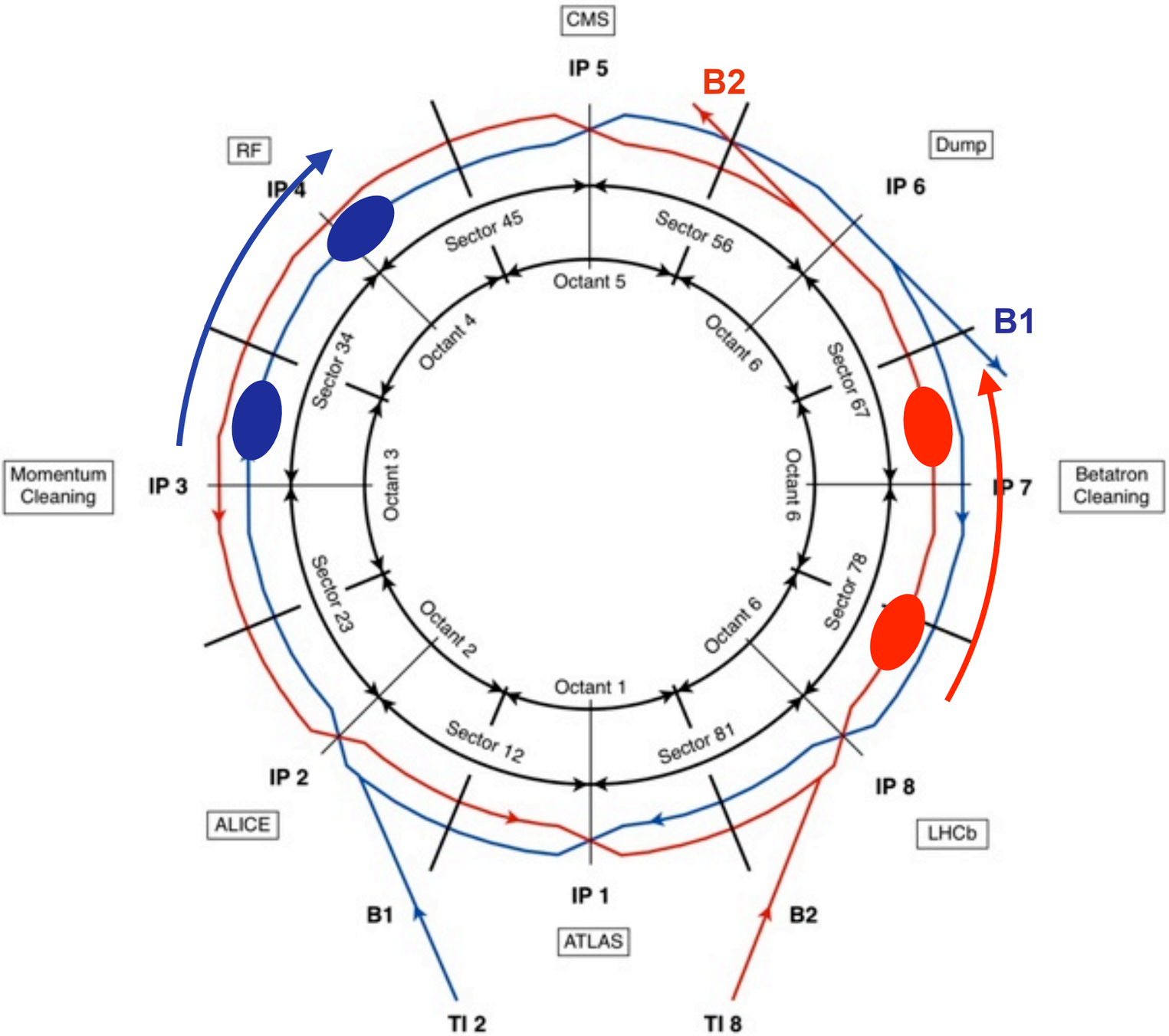

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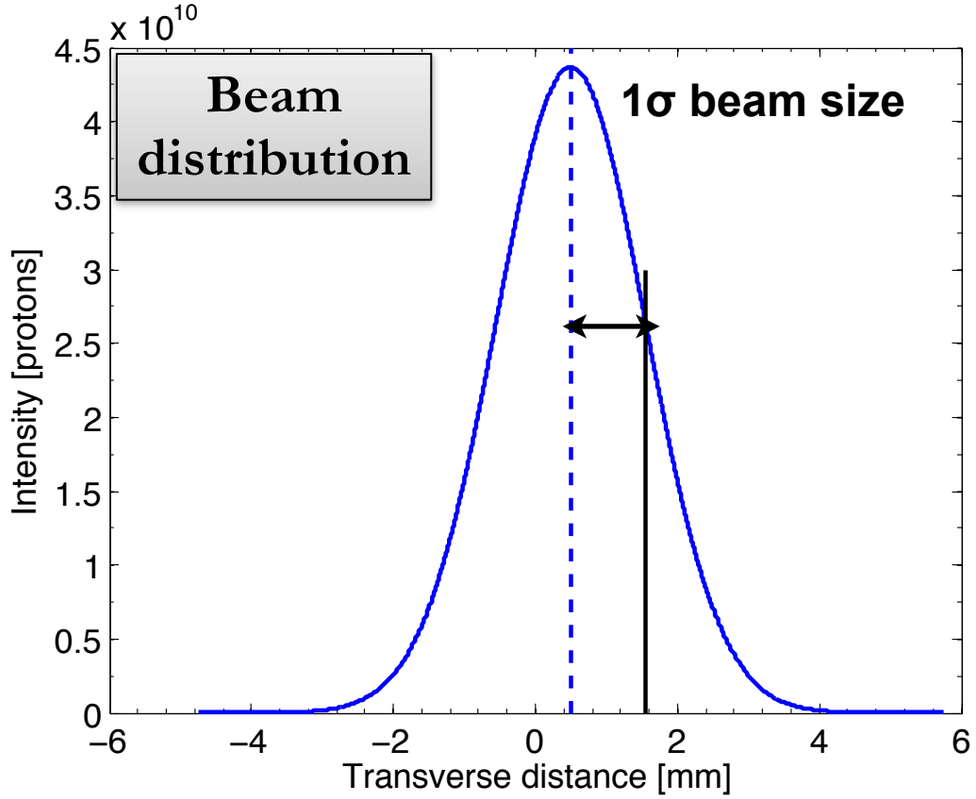

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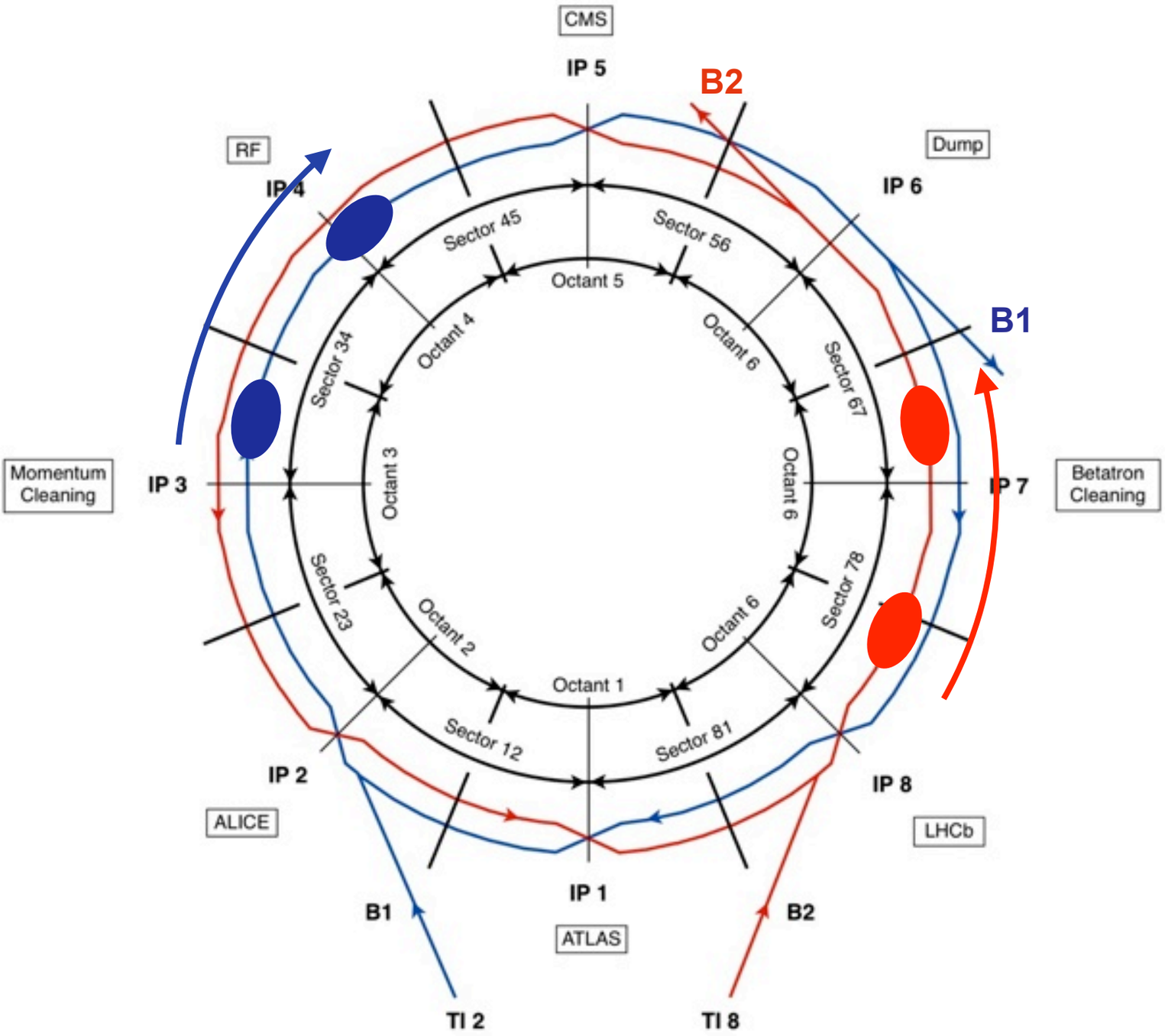

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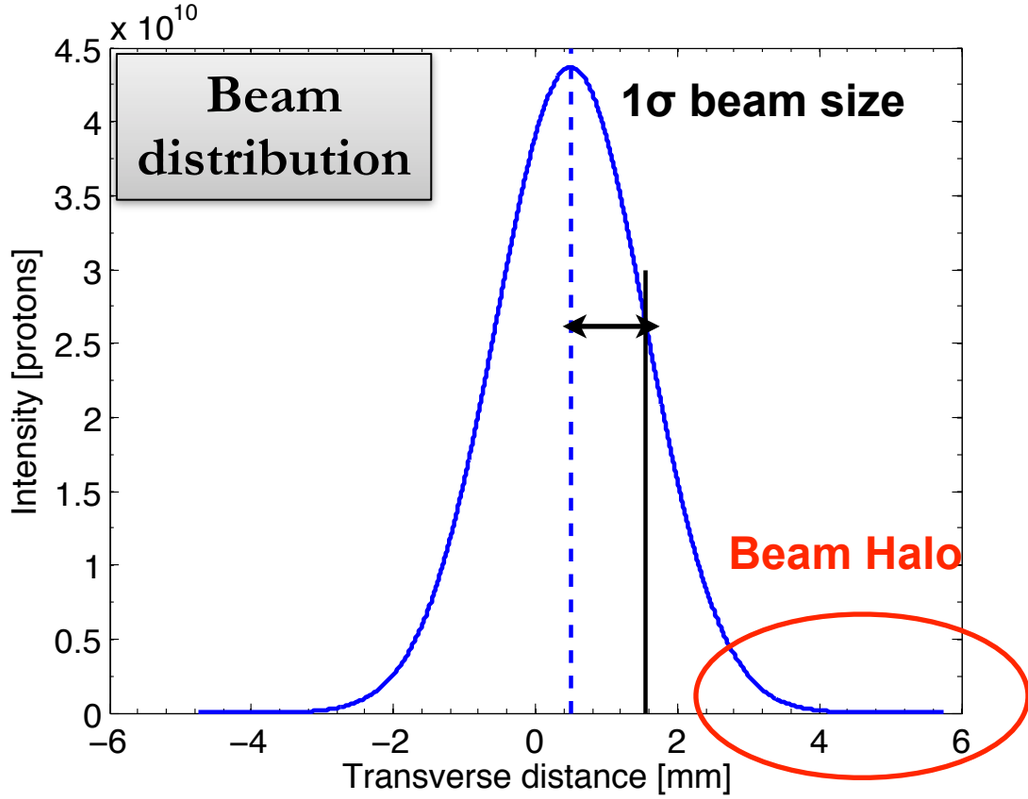

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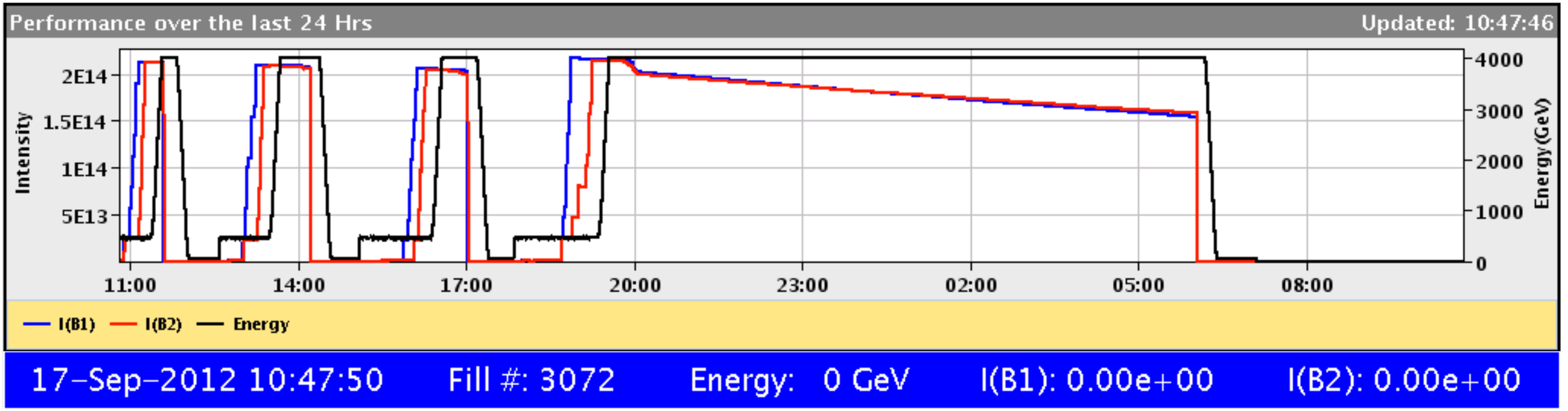

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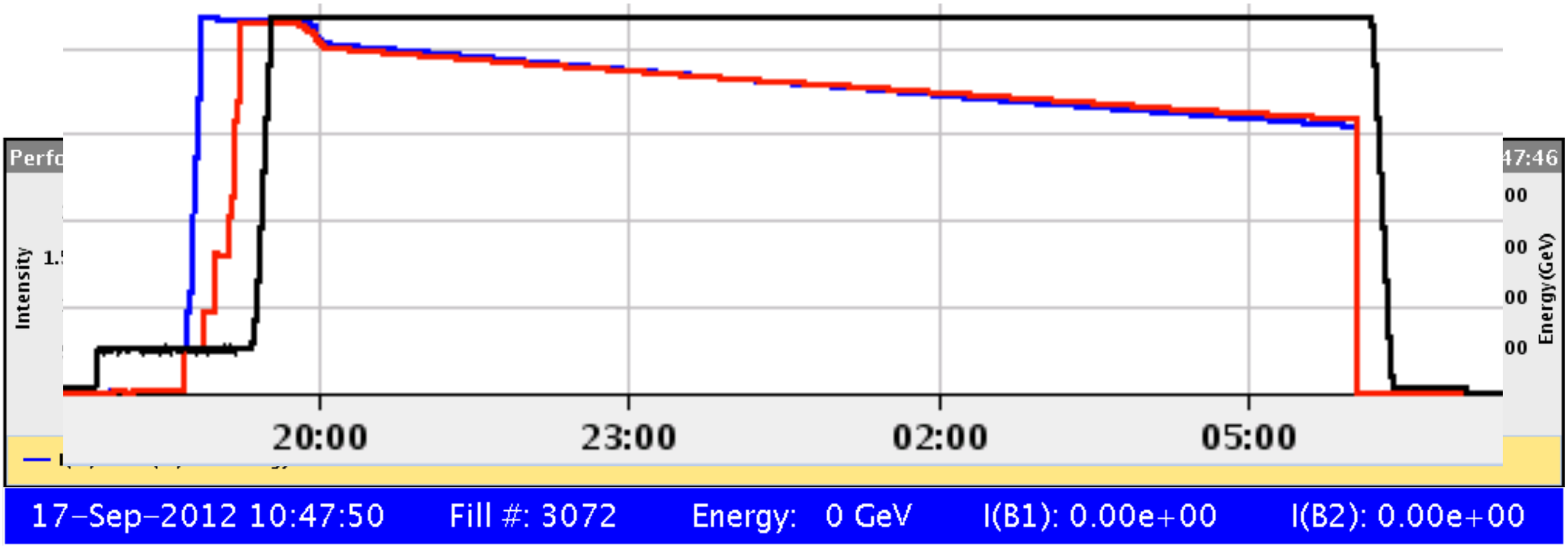

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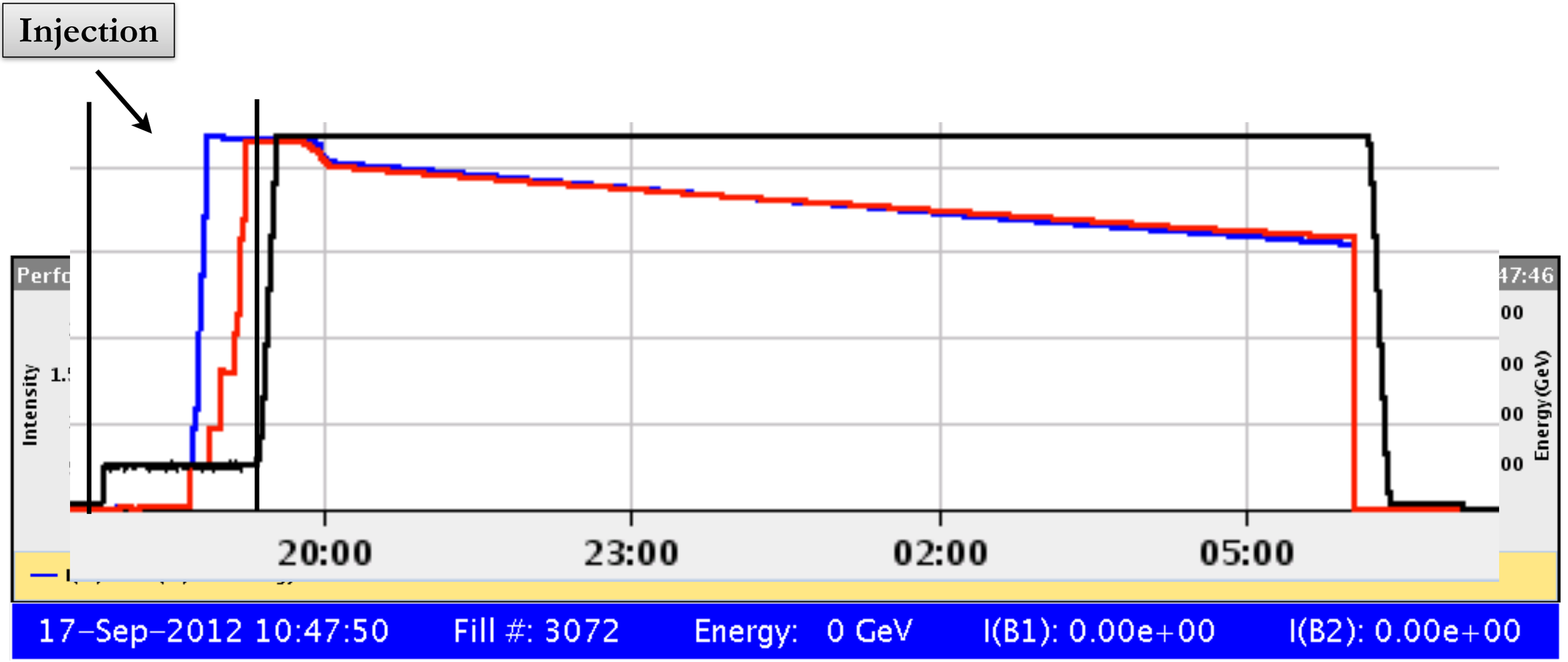

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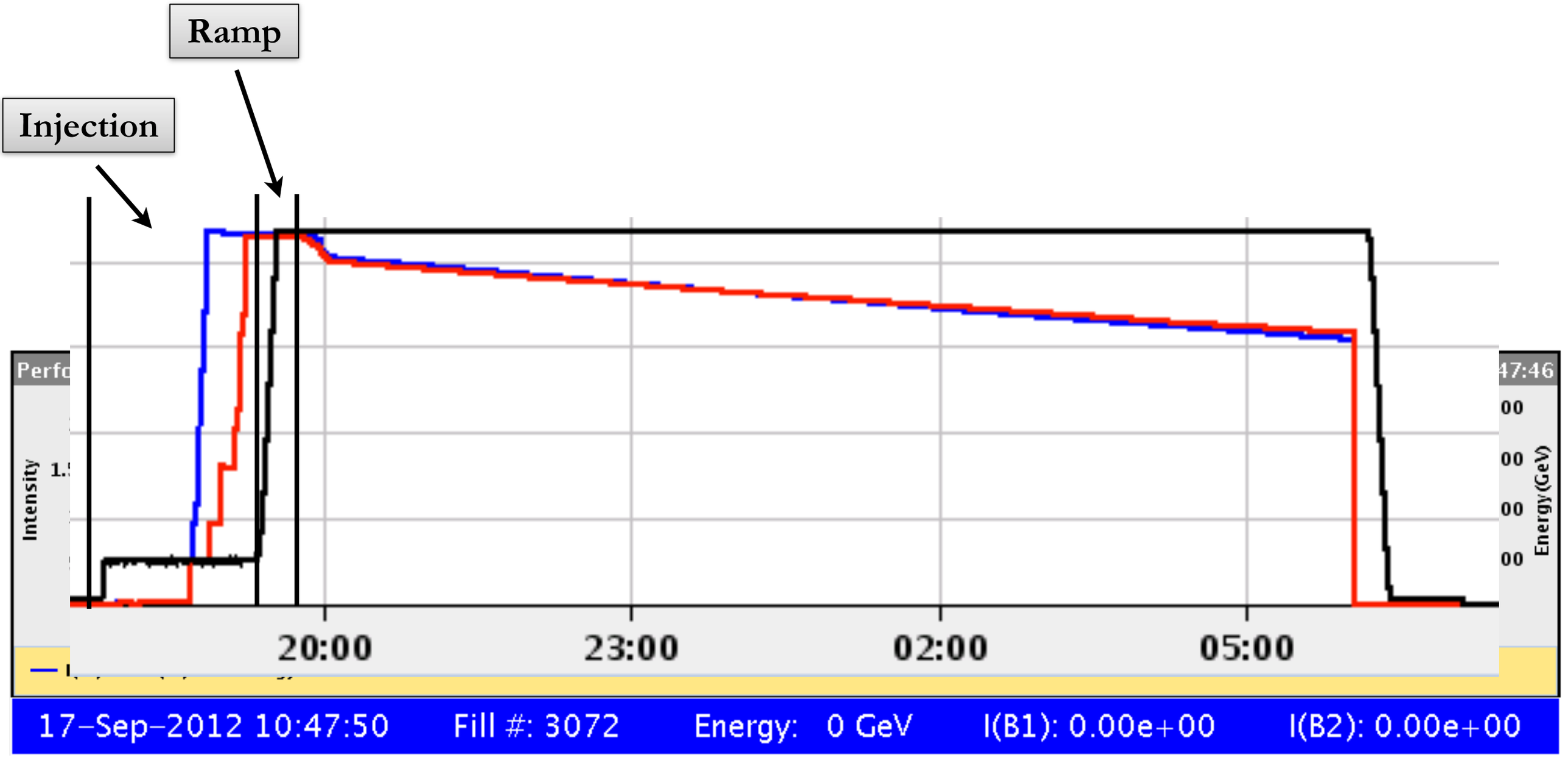

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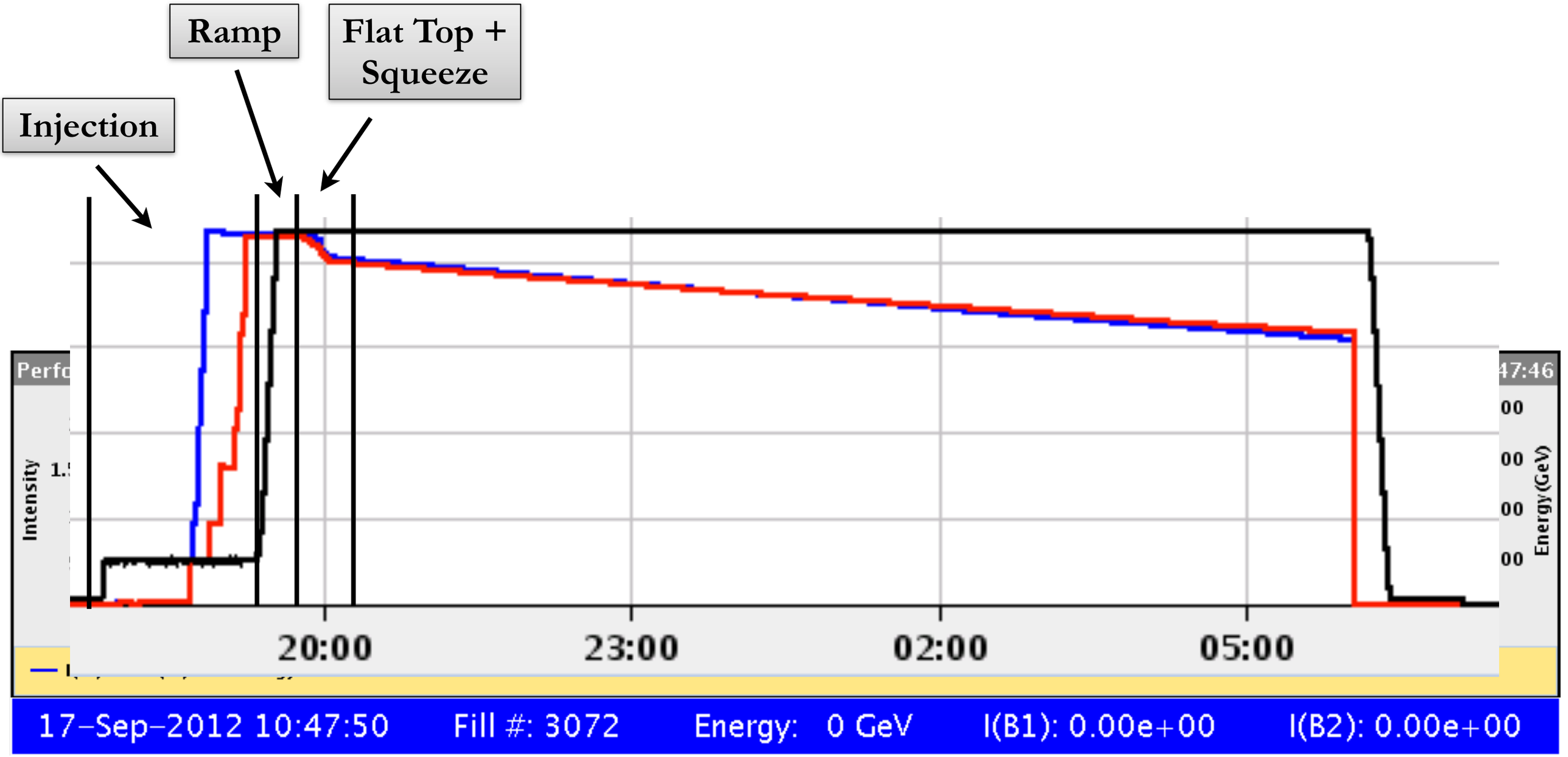

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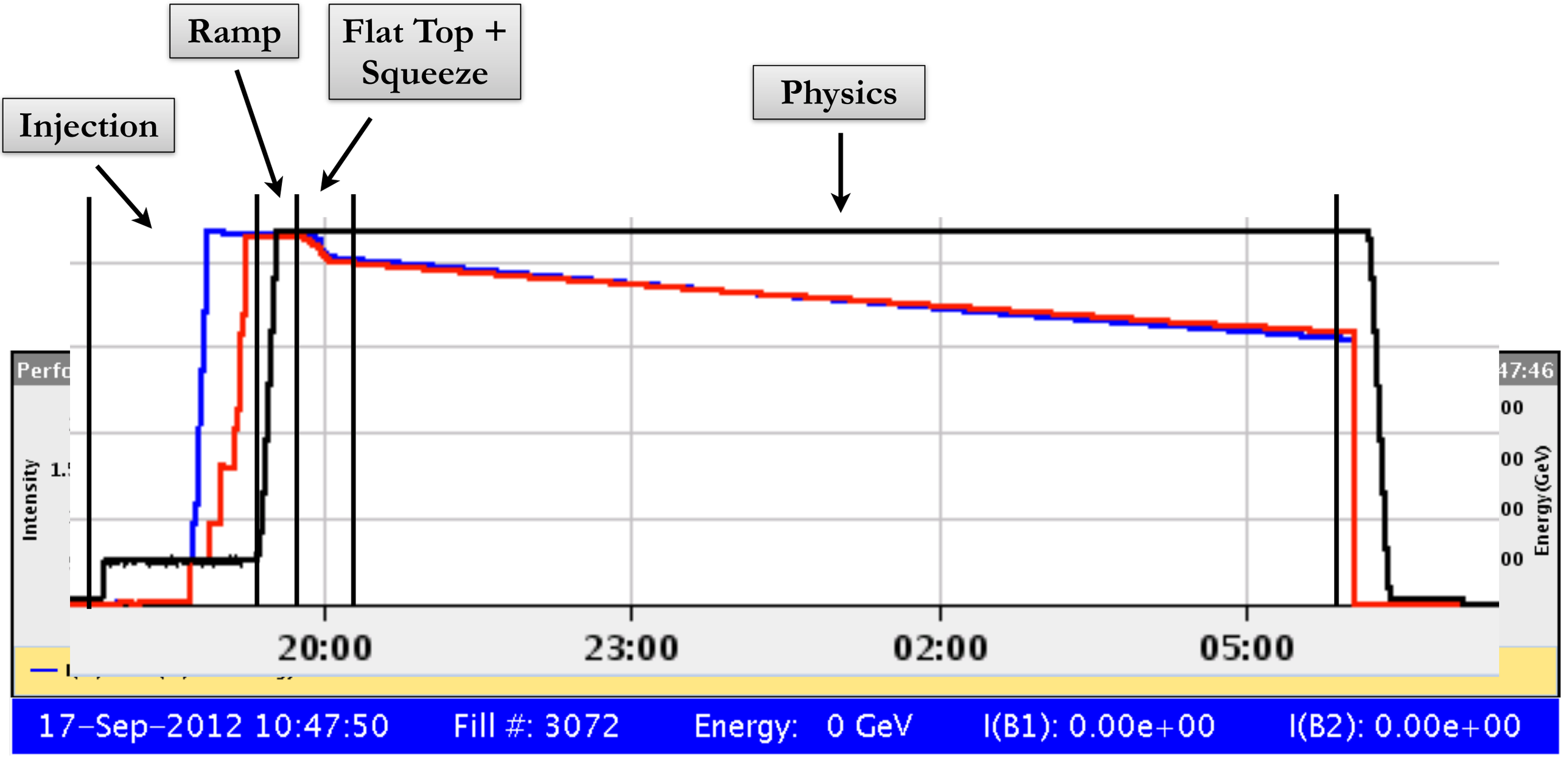

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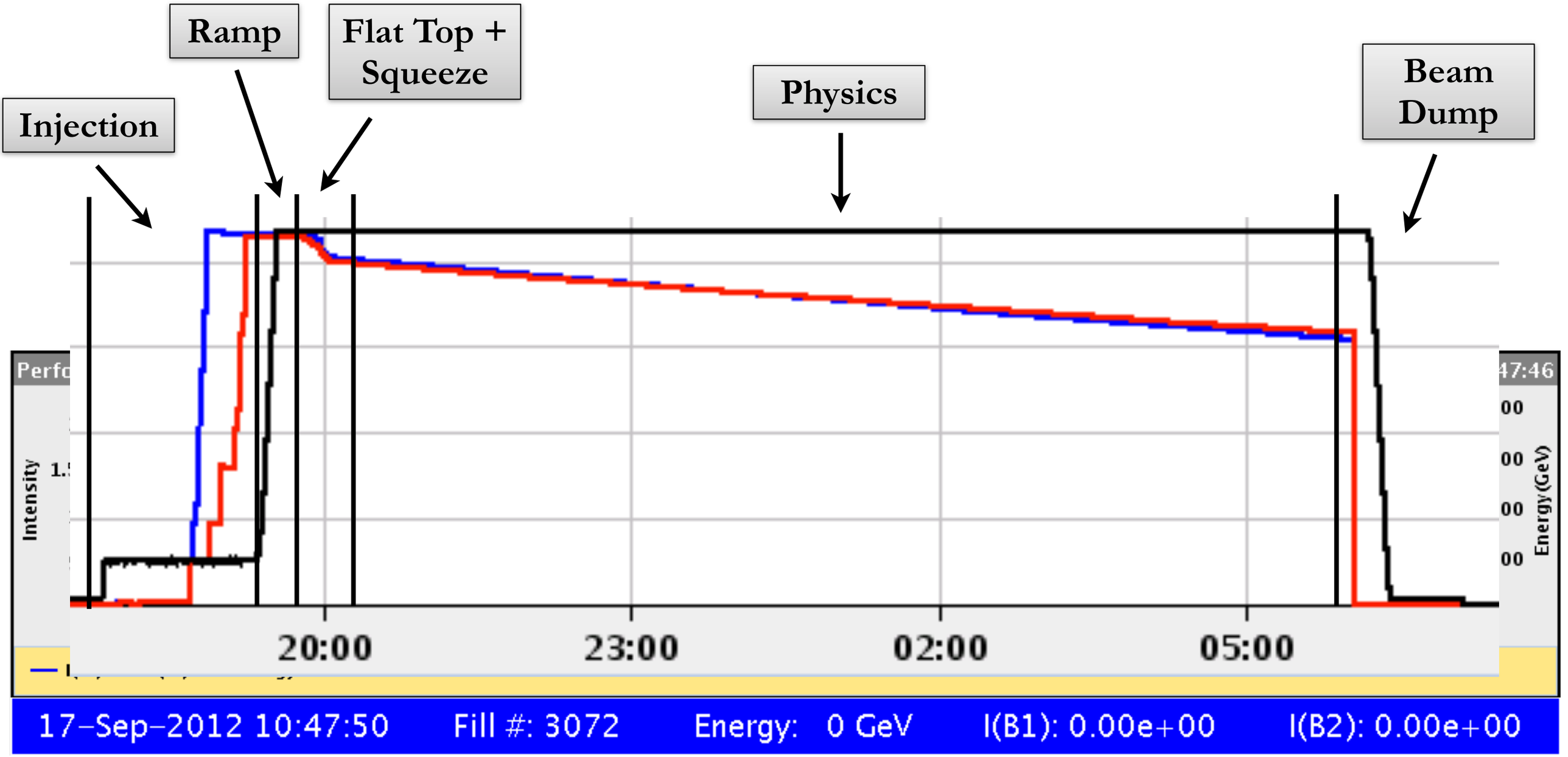

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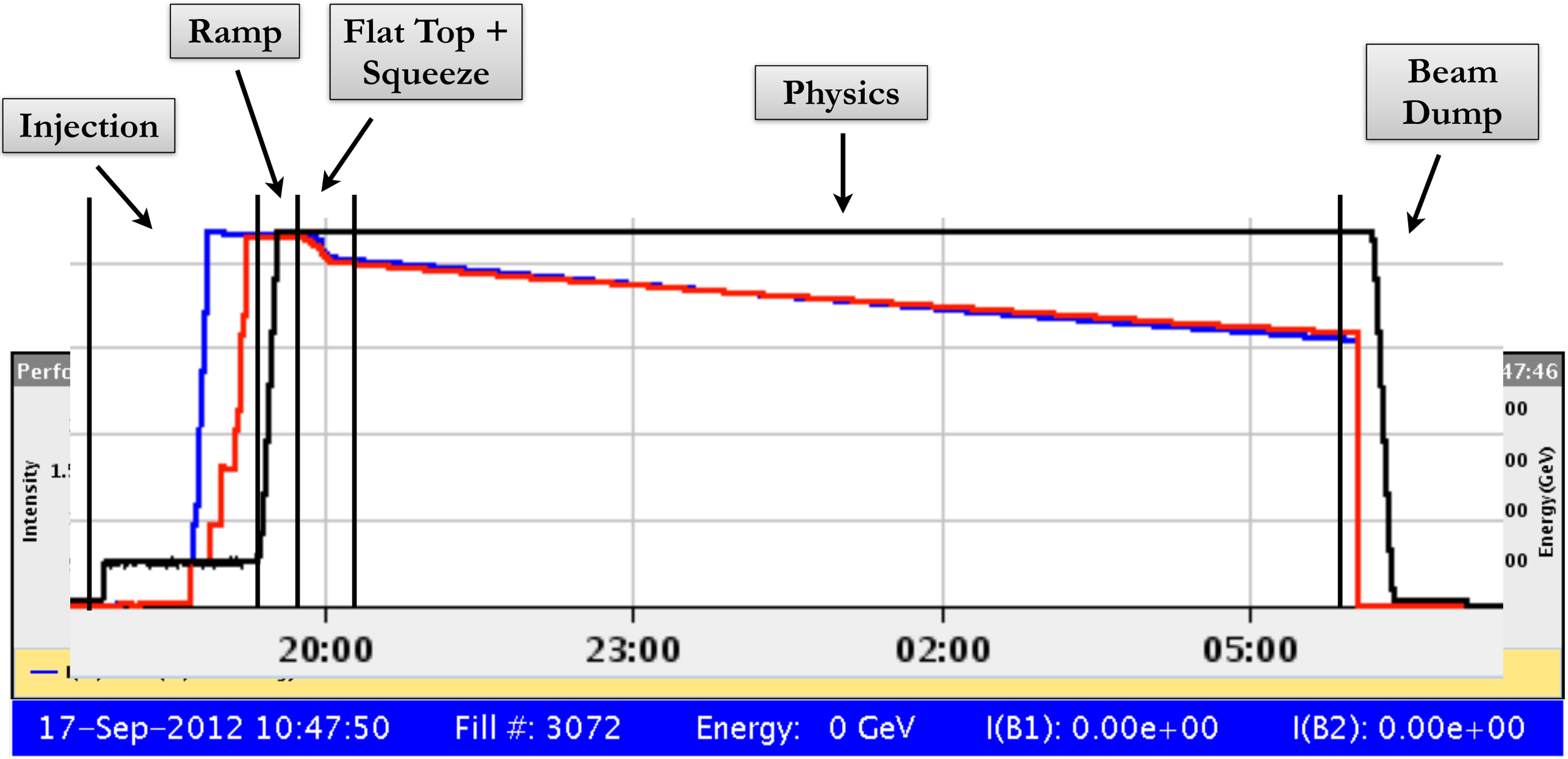

Many settings, including collimators, changed along the machine cycle

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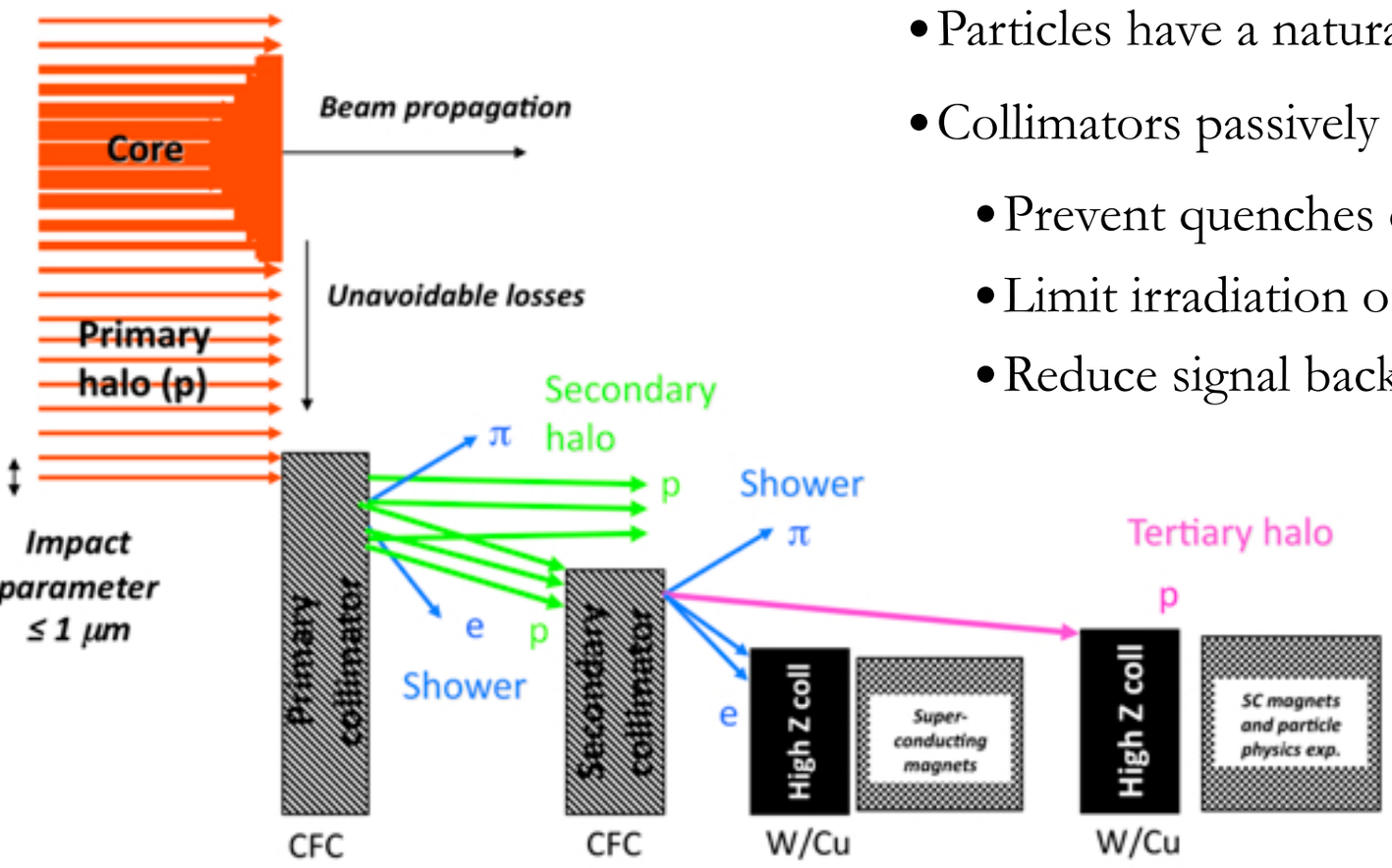
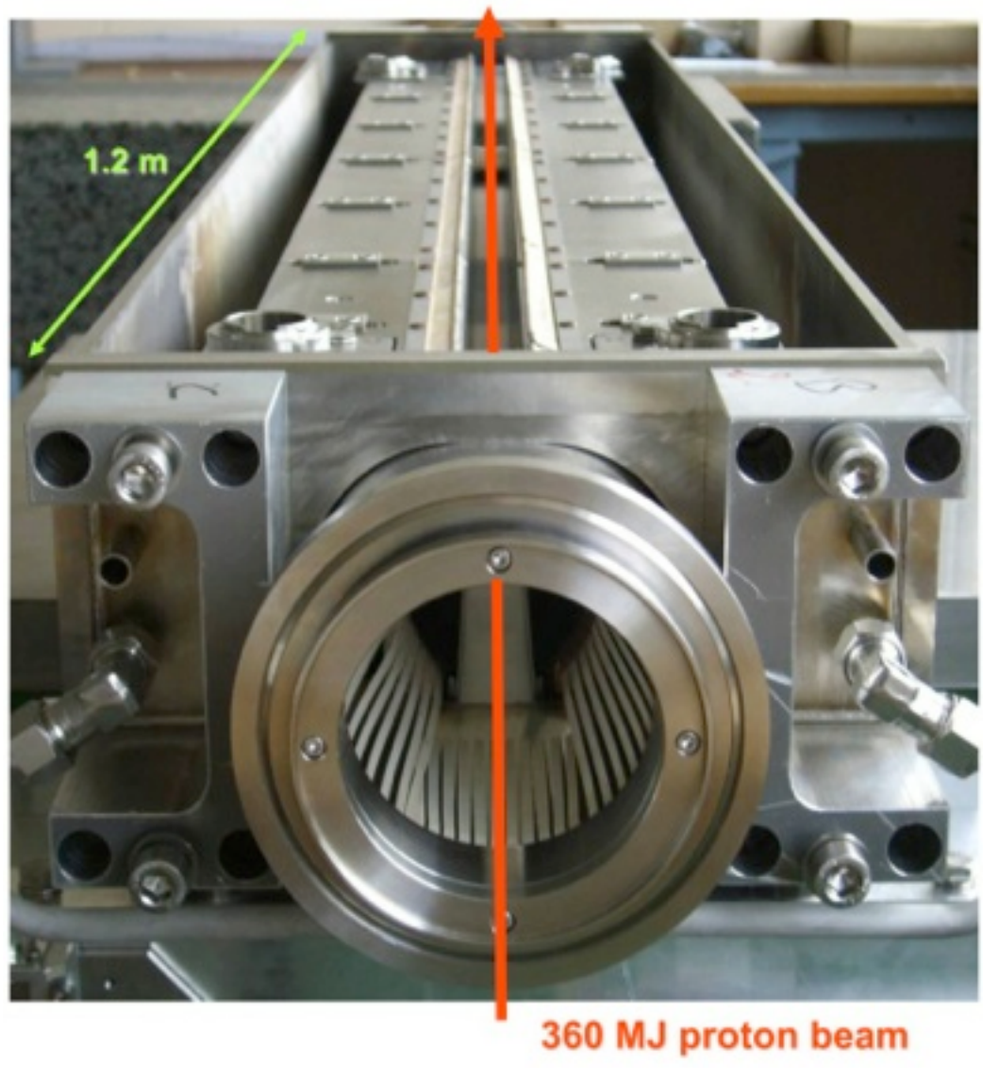
LHC Collimation System



- 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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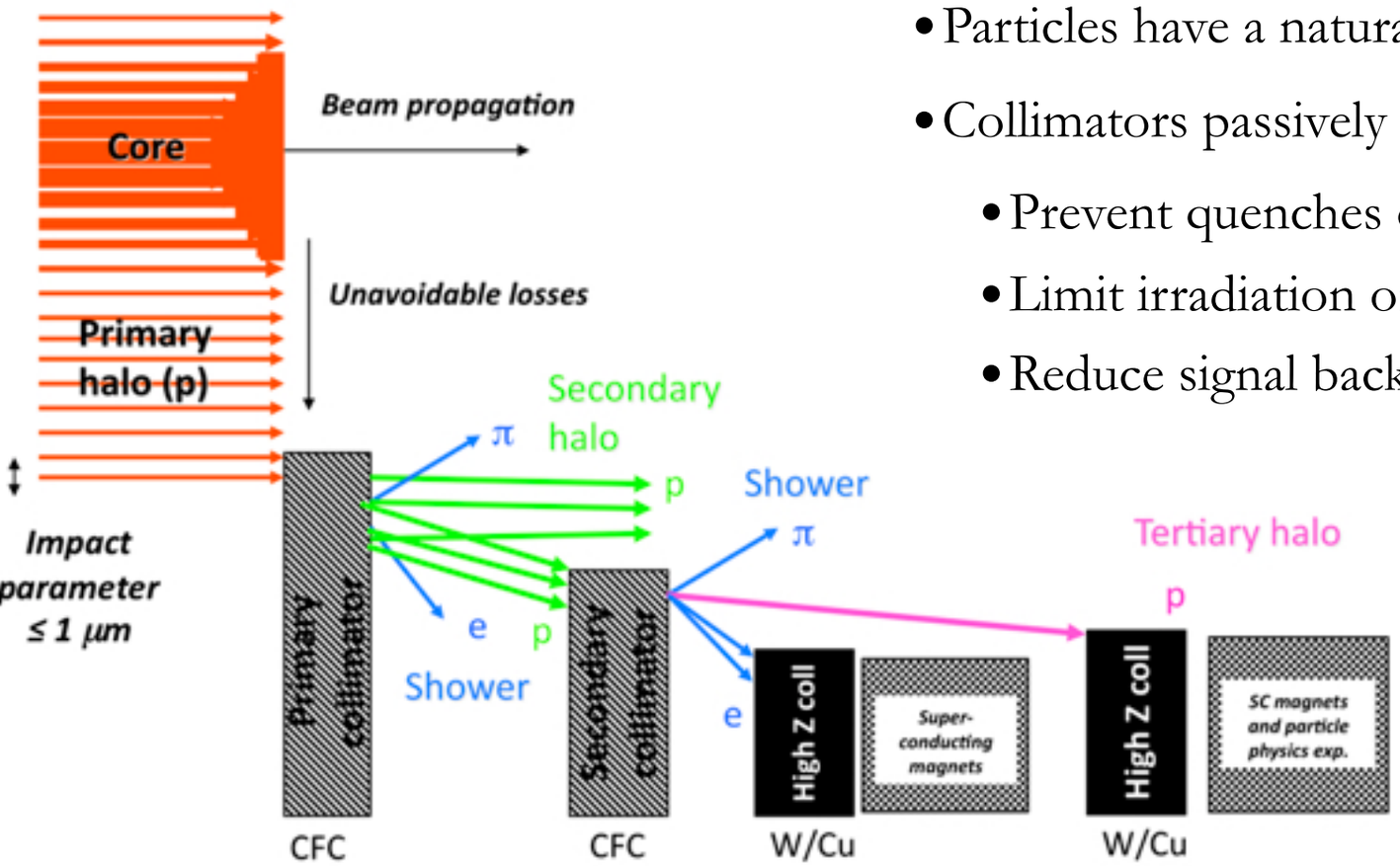

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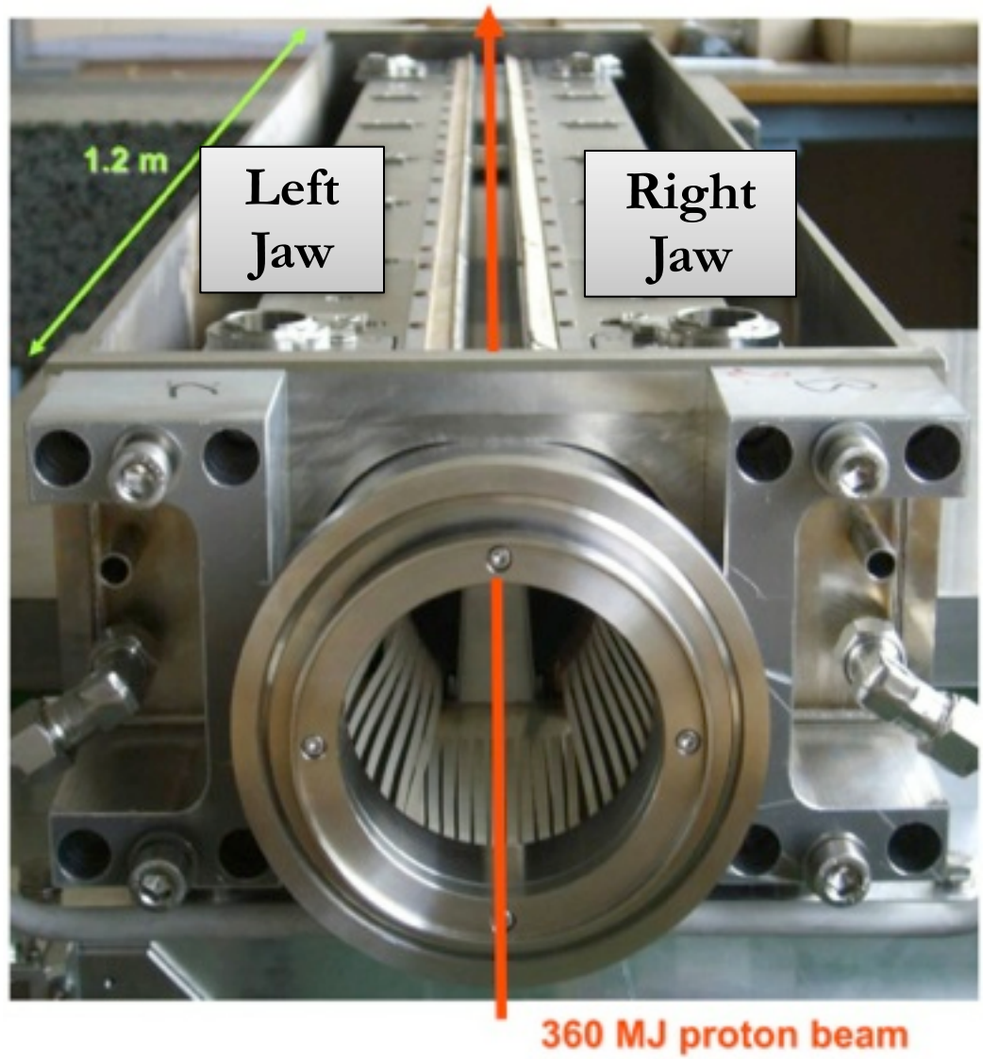

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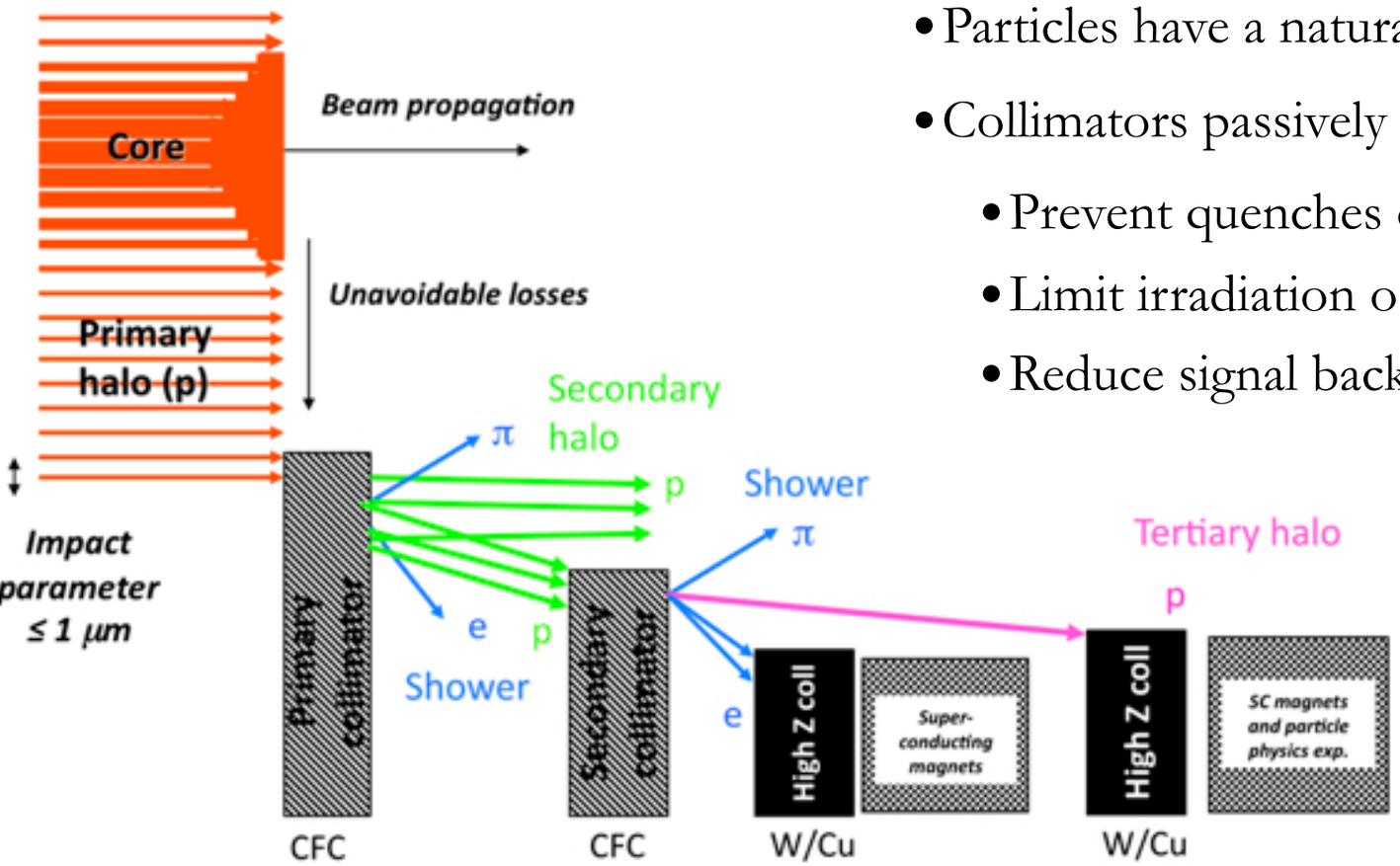

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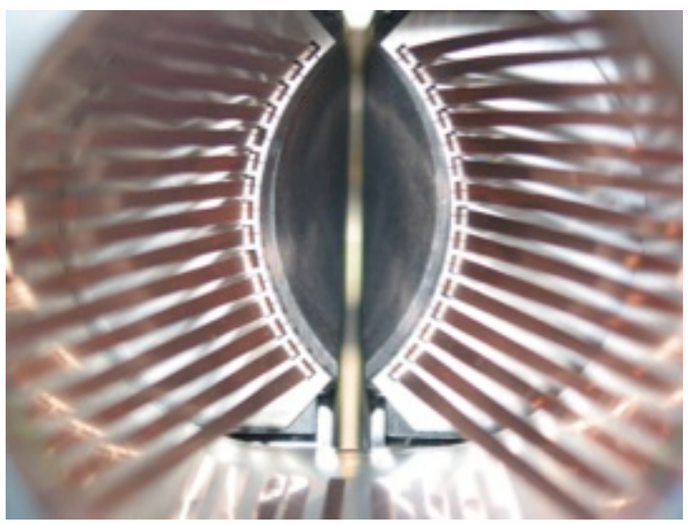

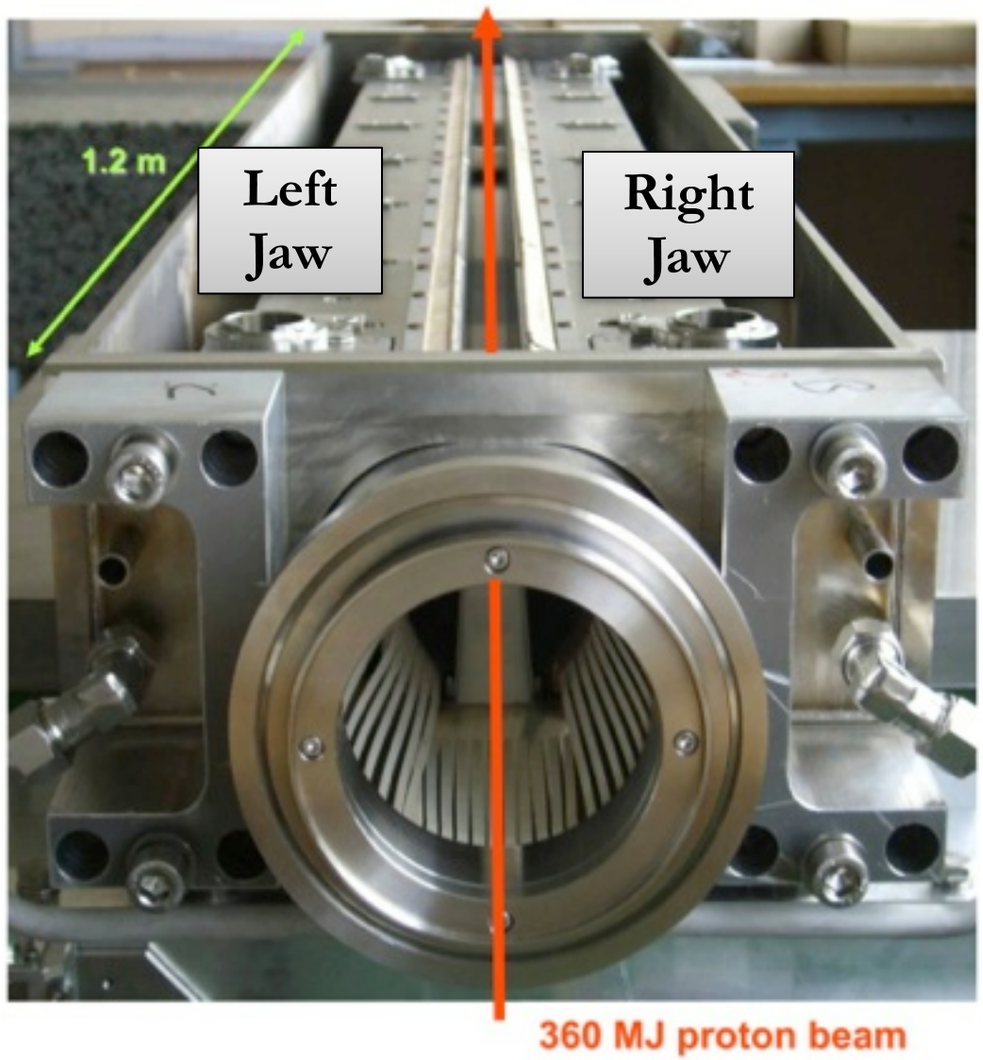

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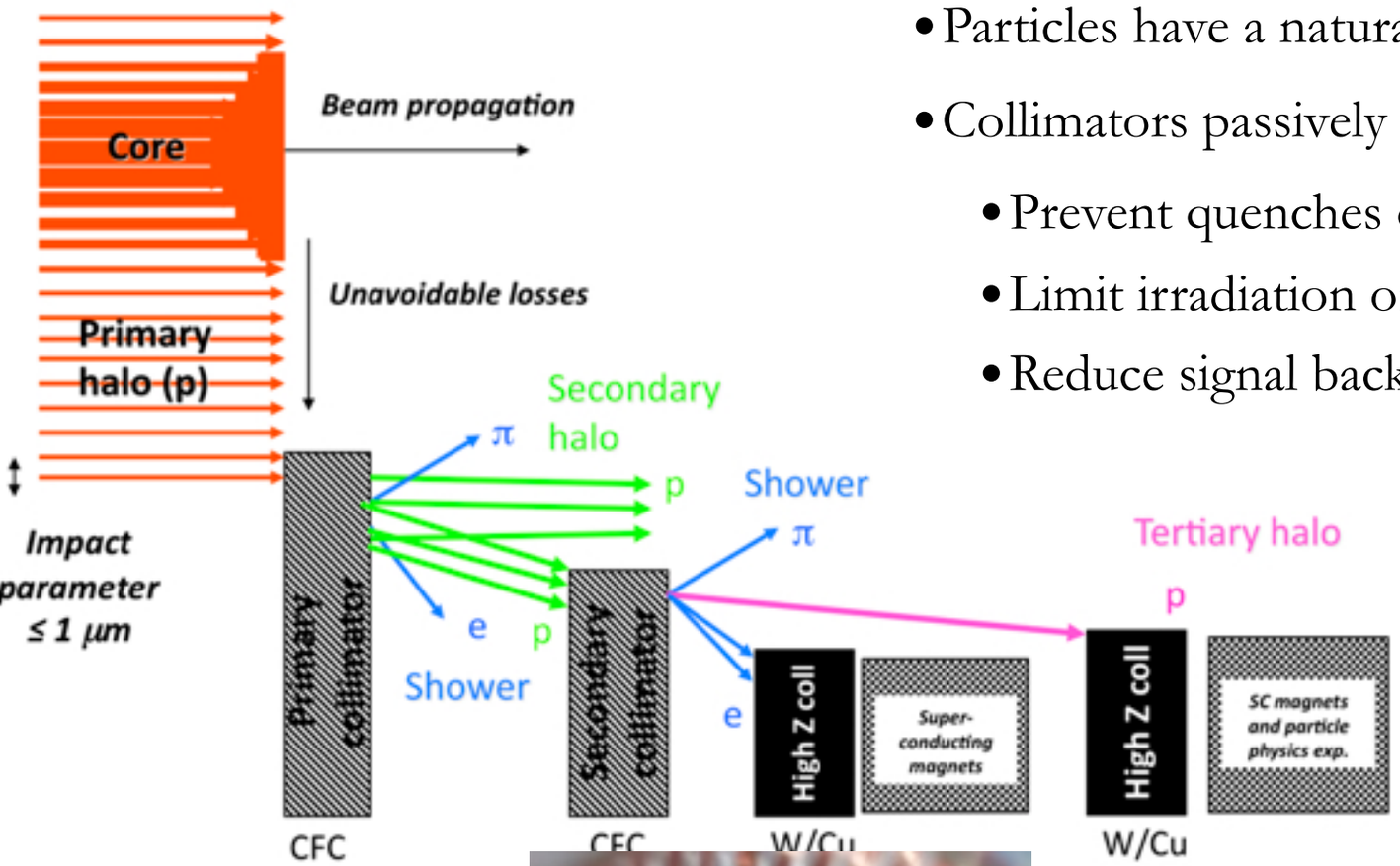

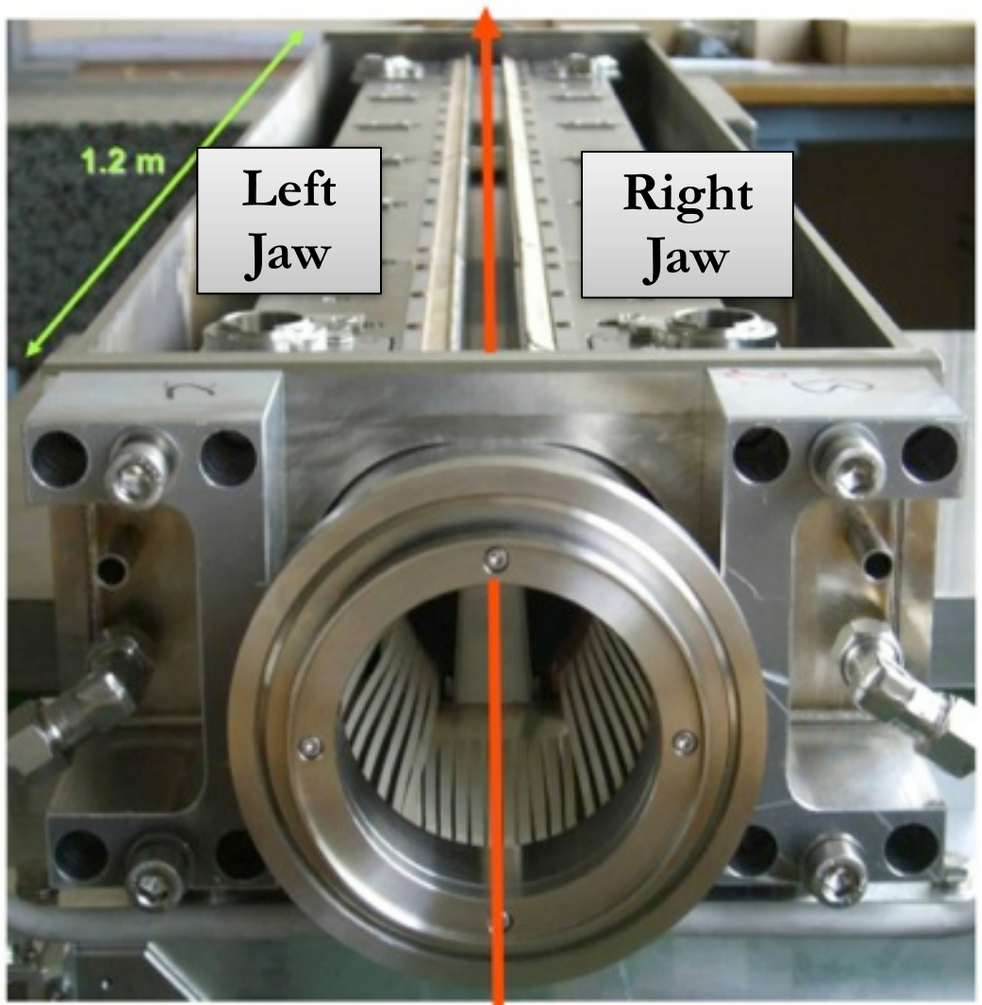

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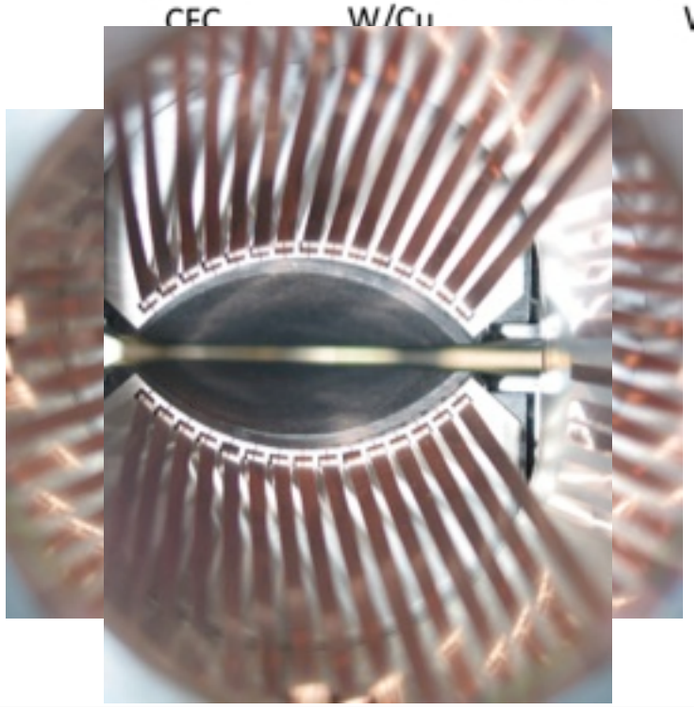

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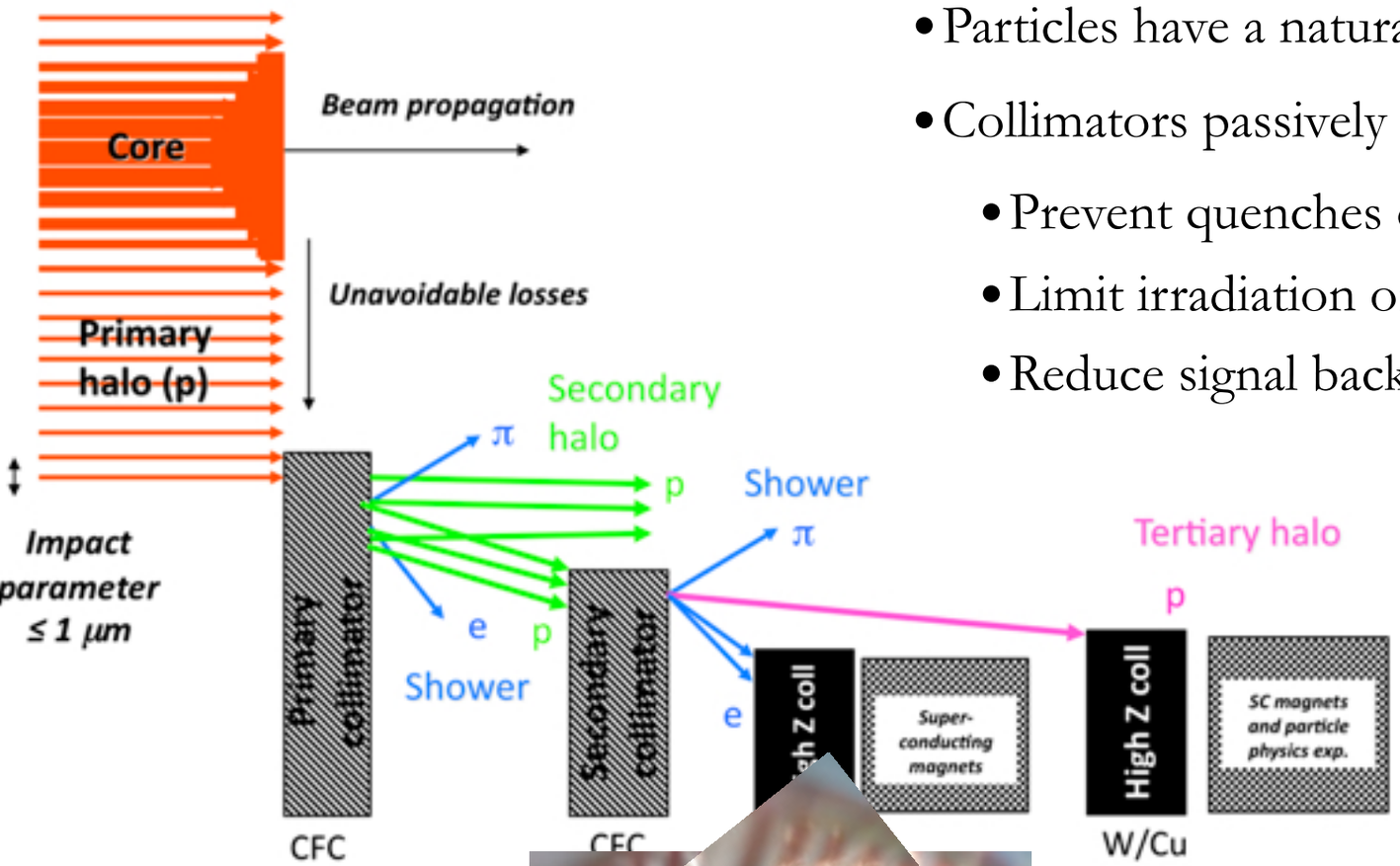

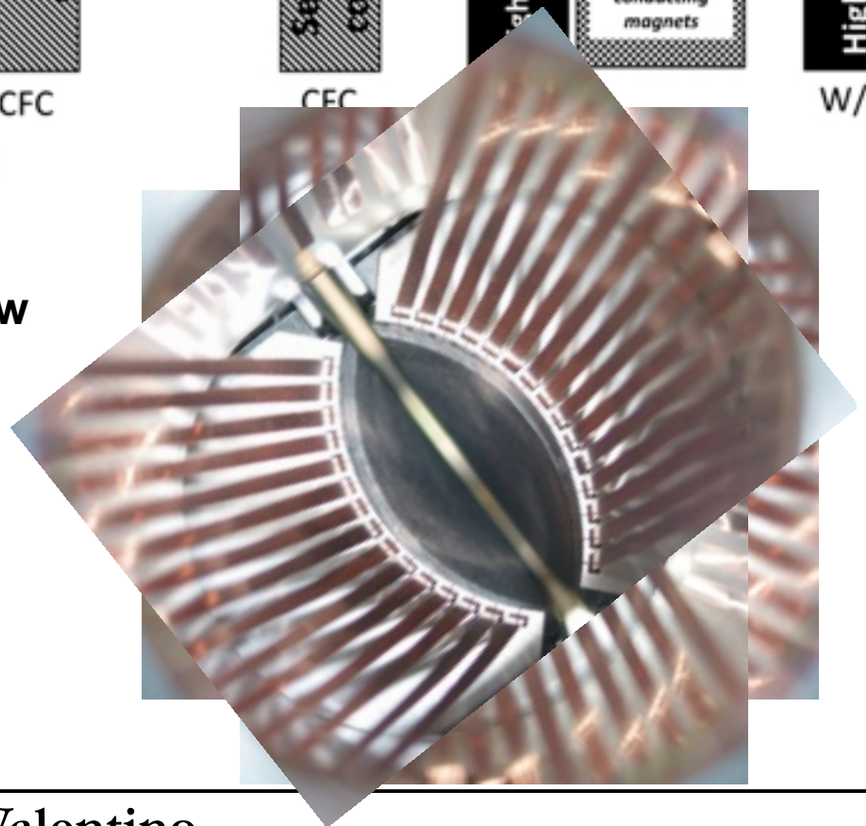

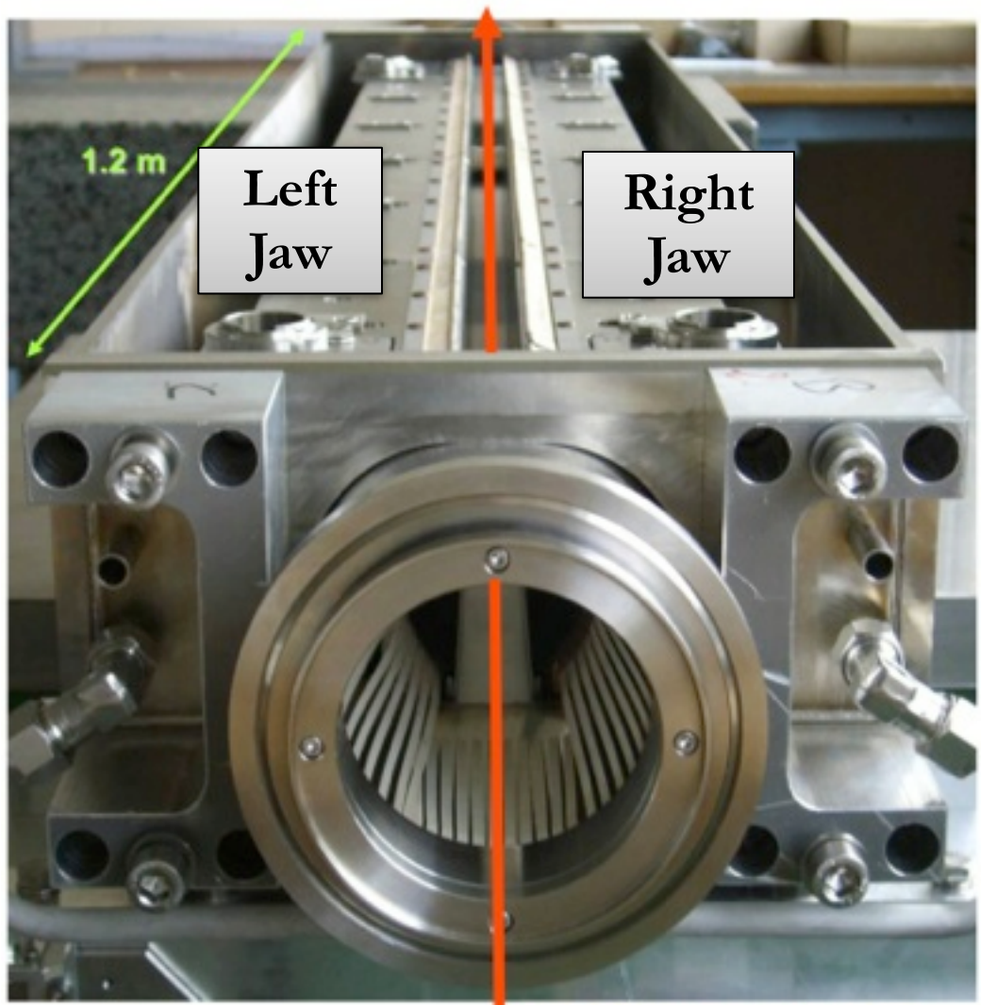

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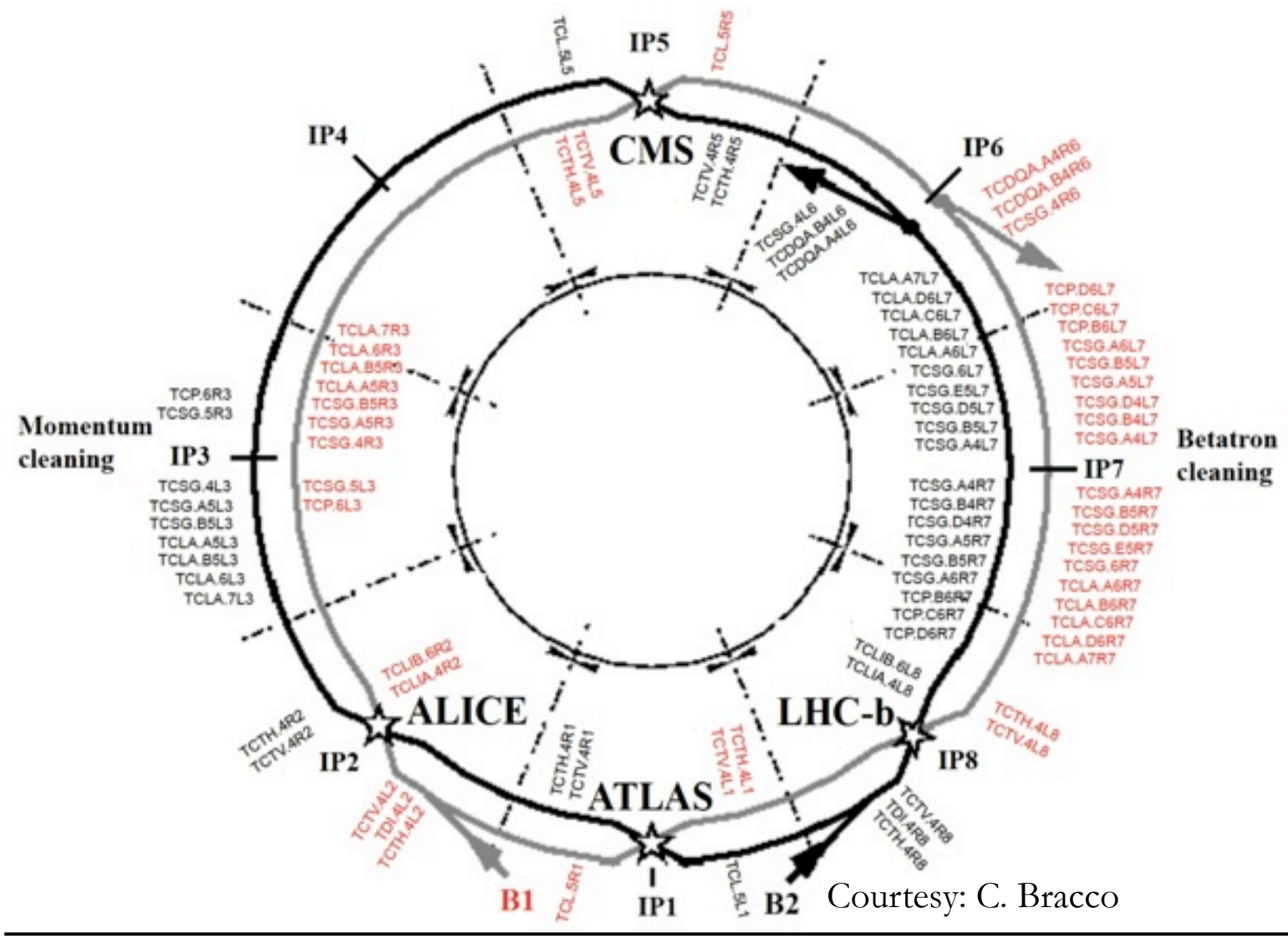
- The LHC is protected by a **collimation system** with 86 collimators (+ 14 transfer line).



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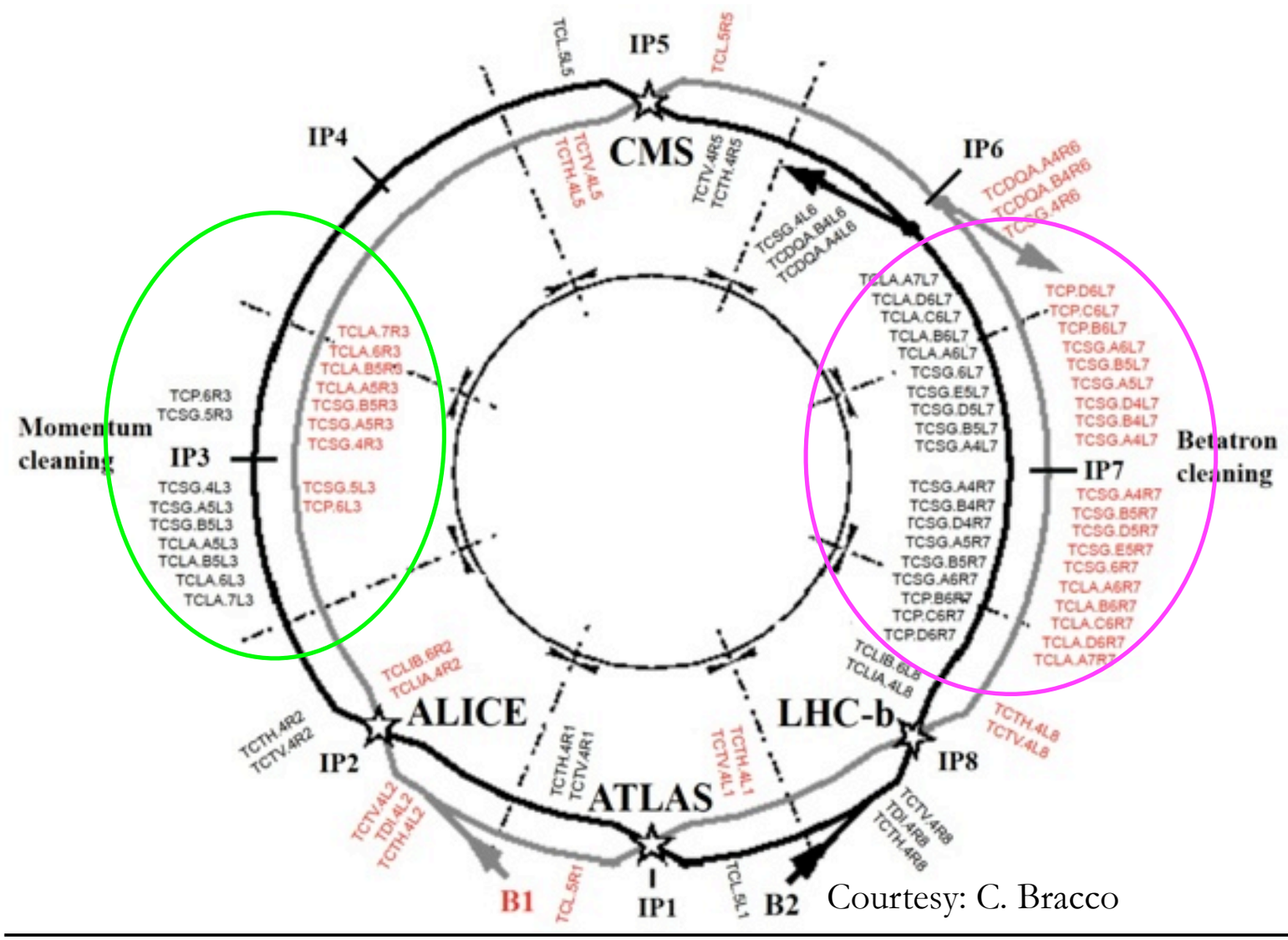

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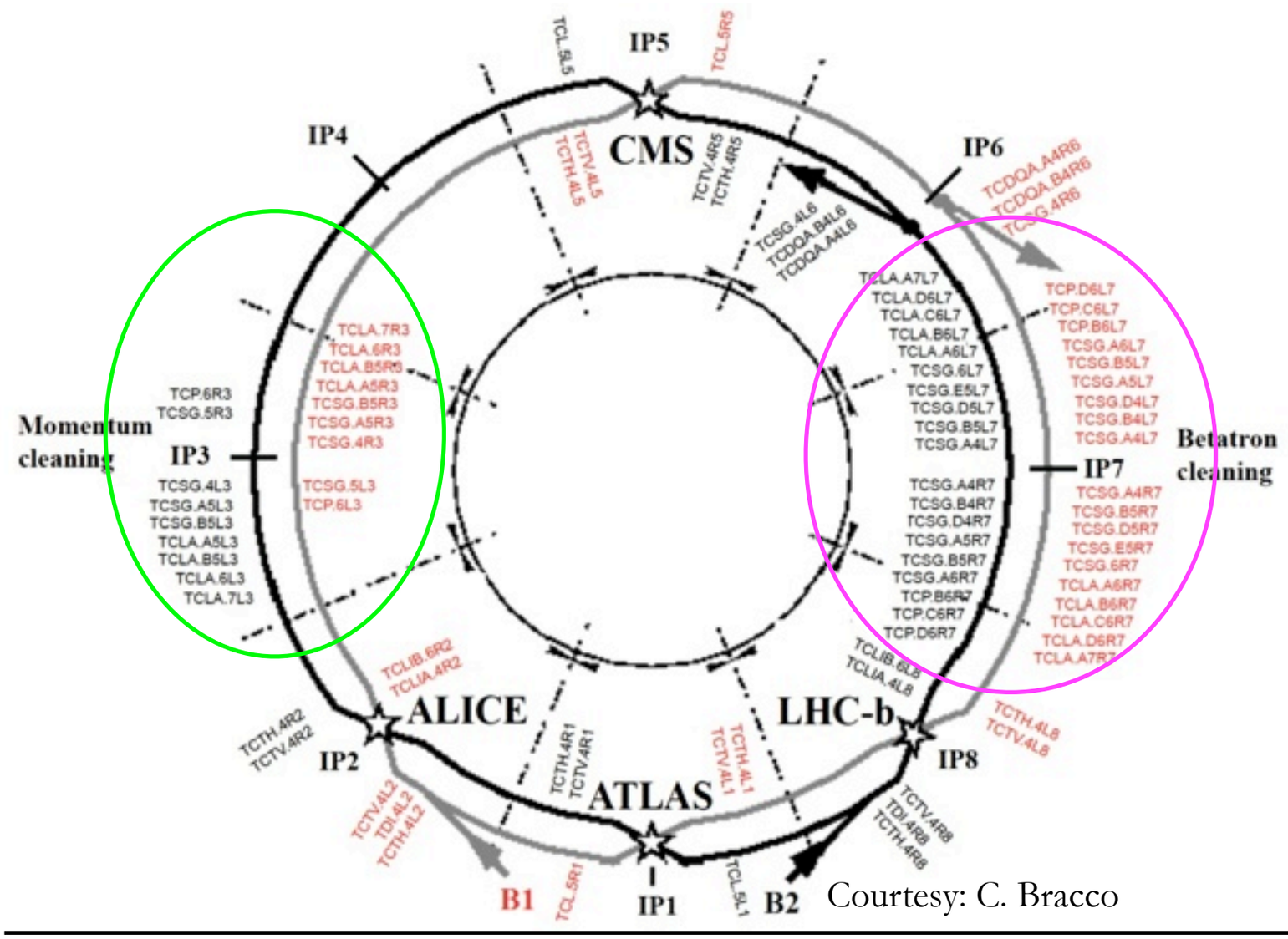
- The LHC is protected by a **collimation system** with 86 collimators (+ 14 transfer line).
- Each cleaning collimator consists of **two moveable 'jaws'** made of carbon, tungsten or copper.
- The jaws are positioned symmetrically around the beam for maximum cleaning efficiency.



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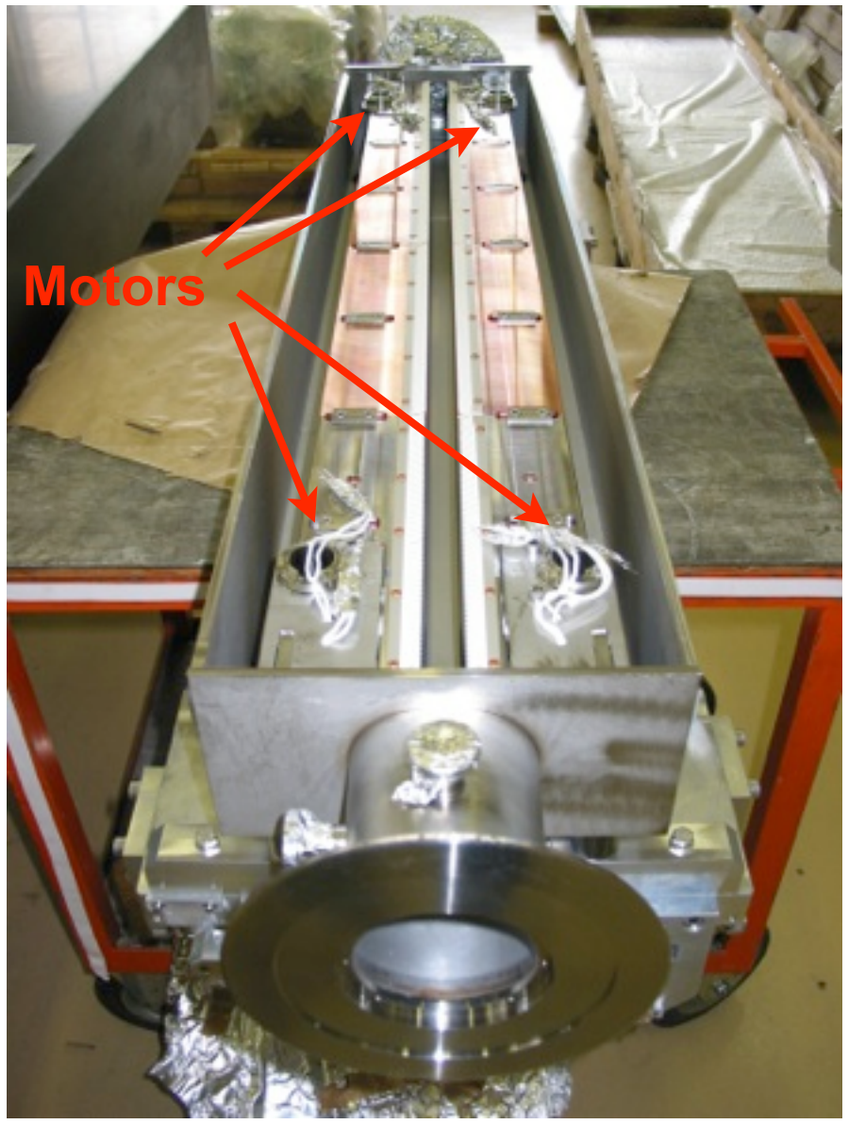

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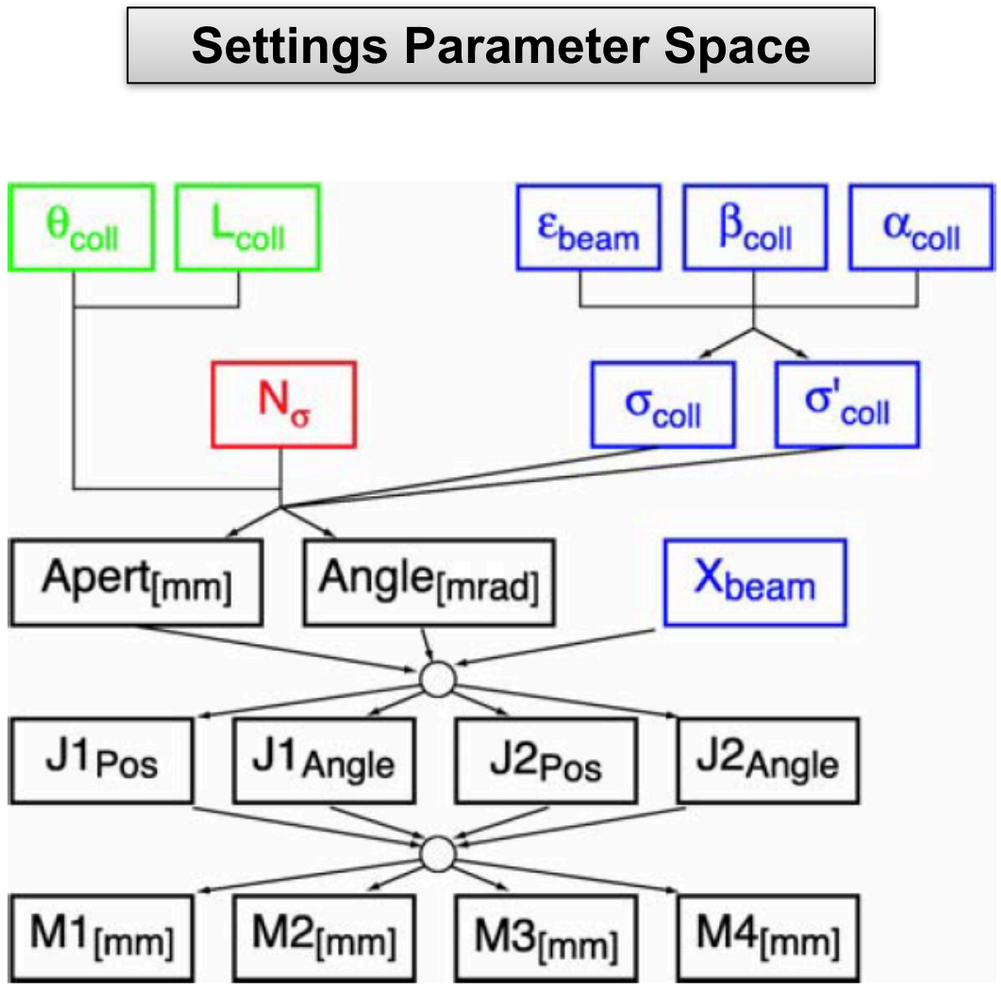
- The collimator settings depend on key beam parameters e.g. **energy, orbit and β-functions** as a function of time, energy and/or β^*.

- Overall system performance depends critically on the correct positioning w.r.t. the beam.

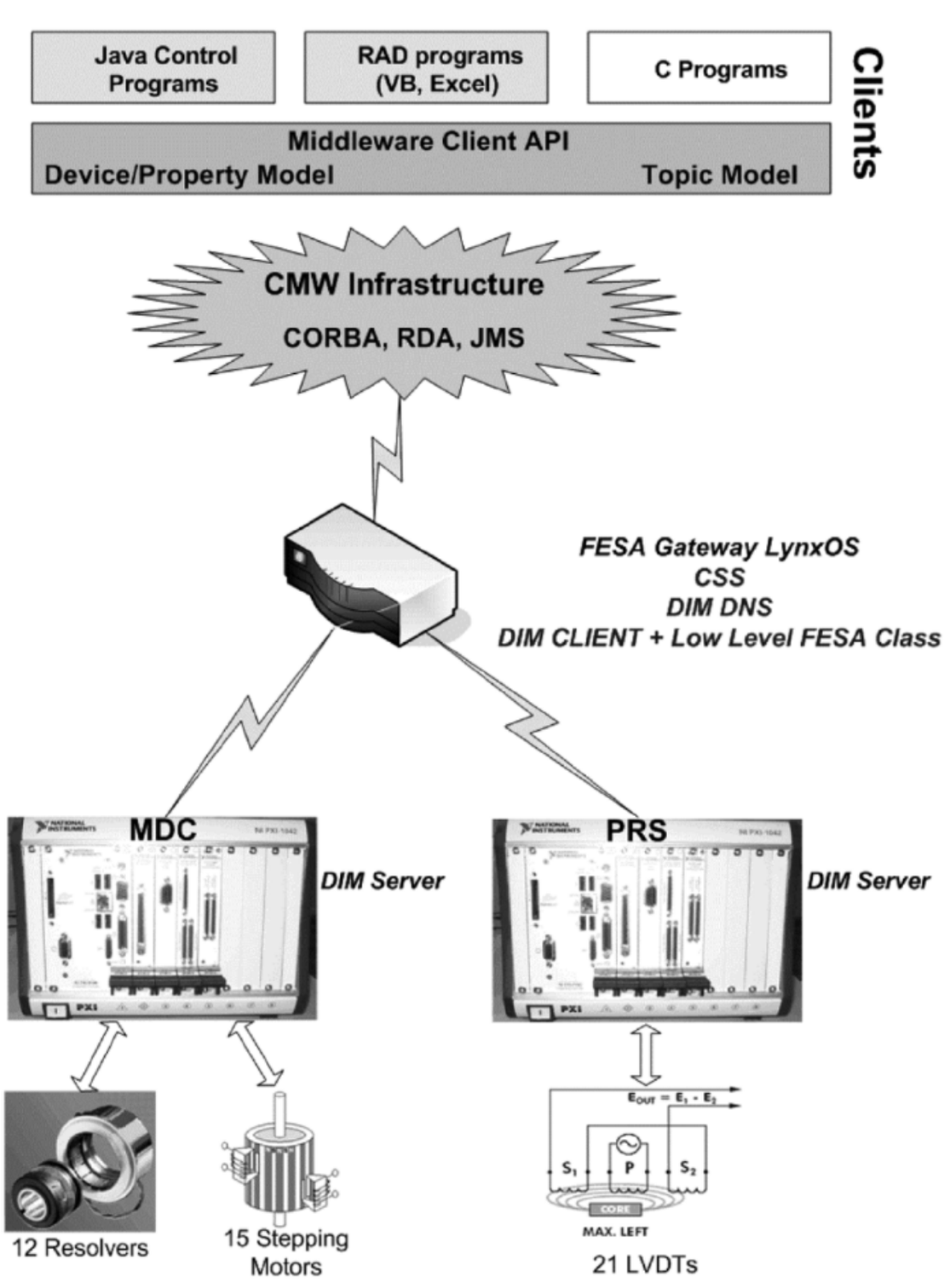
- **Unprecedented complexity:** function-based settings, redundant interlocking strategy that change with time.

- Total of **~400 axes of motion** to be monitored, compared to ~30 at the Tevatron.



S. Redaelli et al.
EDMS LHC-TCT-ES-0001

Collimation System Software Architecture

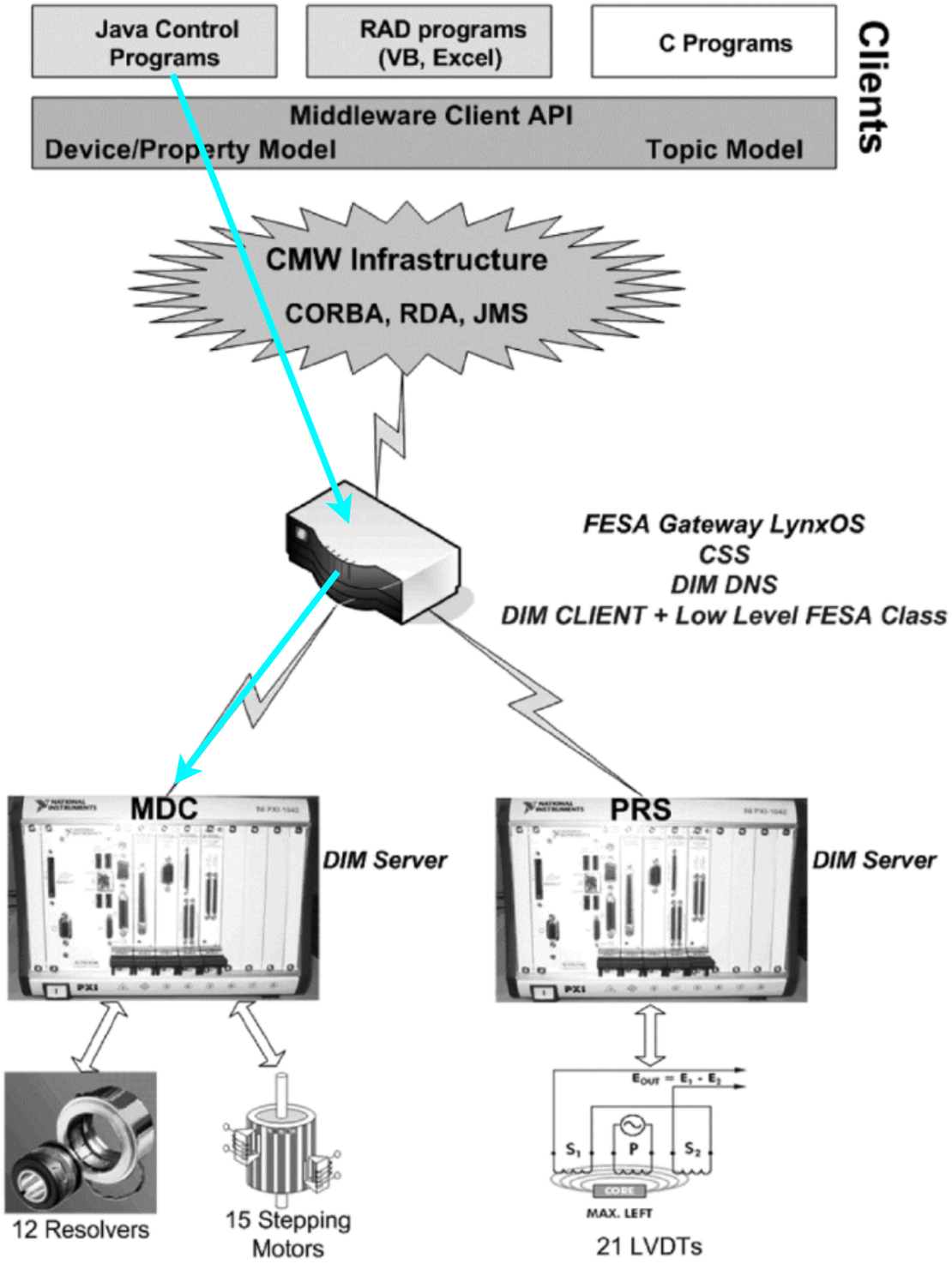


Top-Layer

Middleware Infrastructure

Motors, Position Readout

Collimation System Software Architecture



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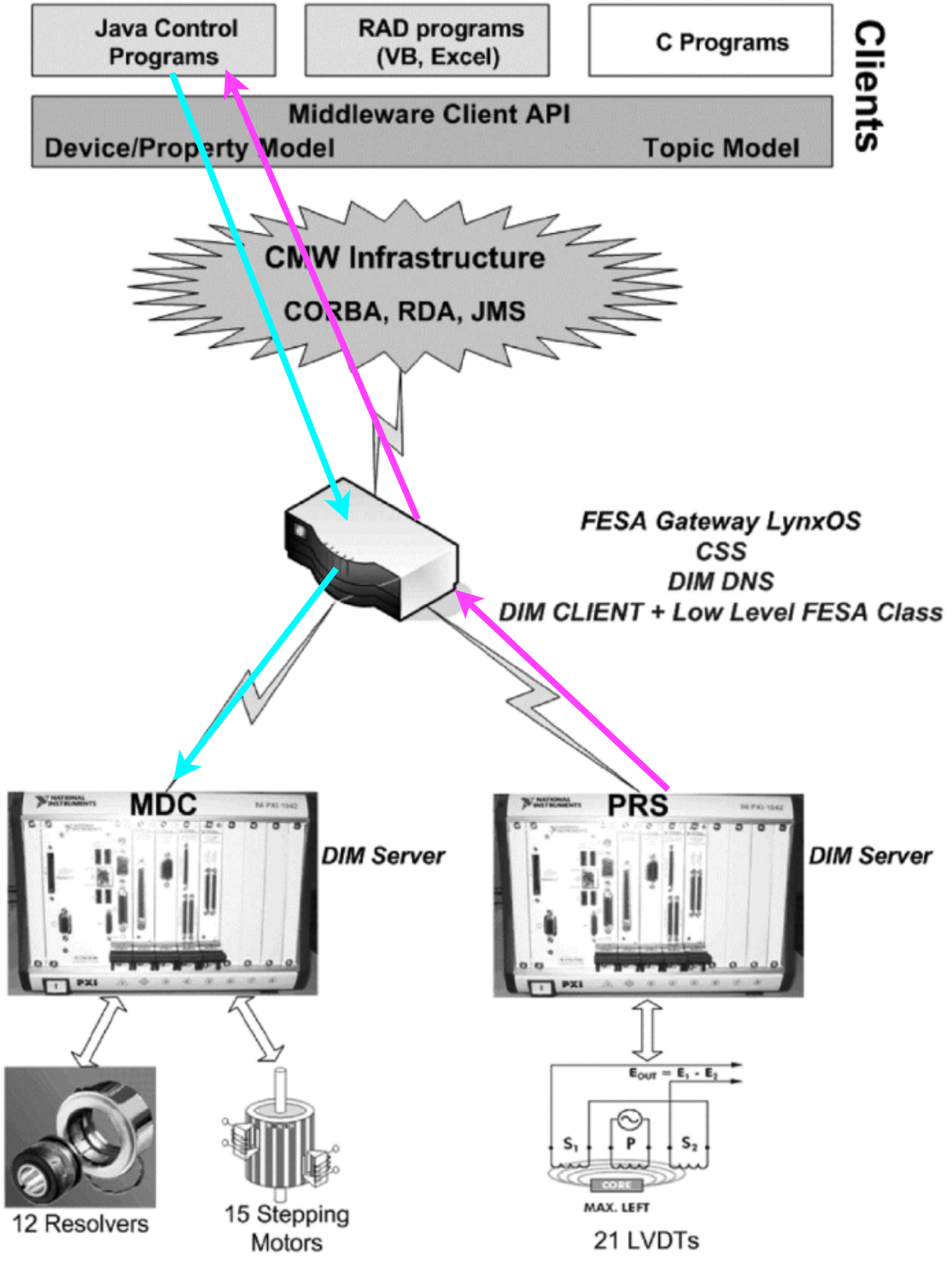

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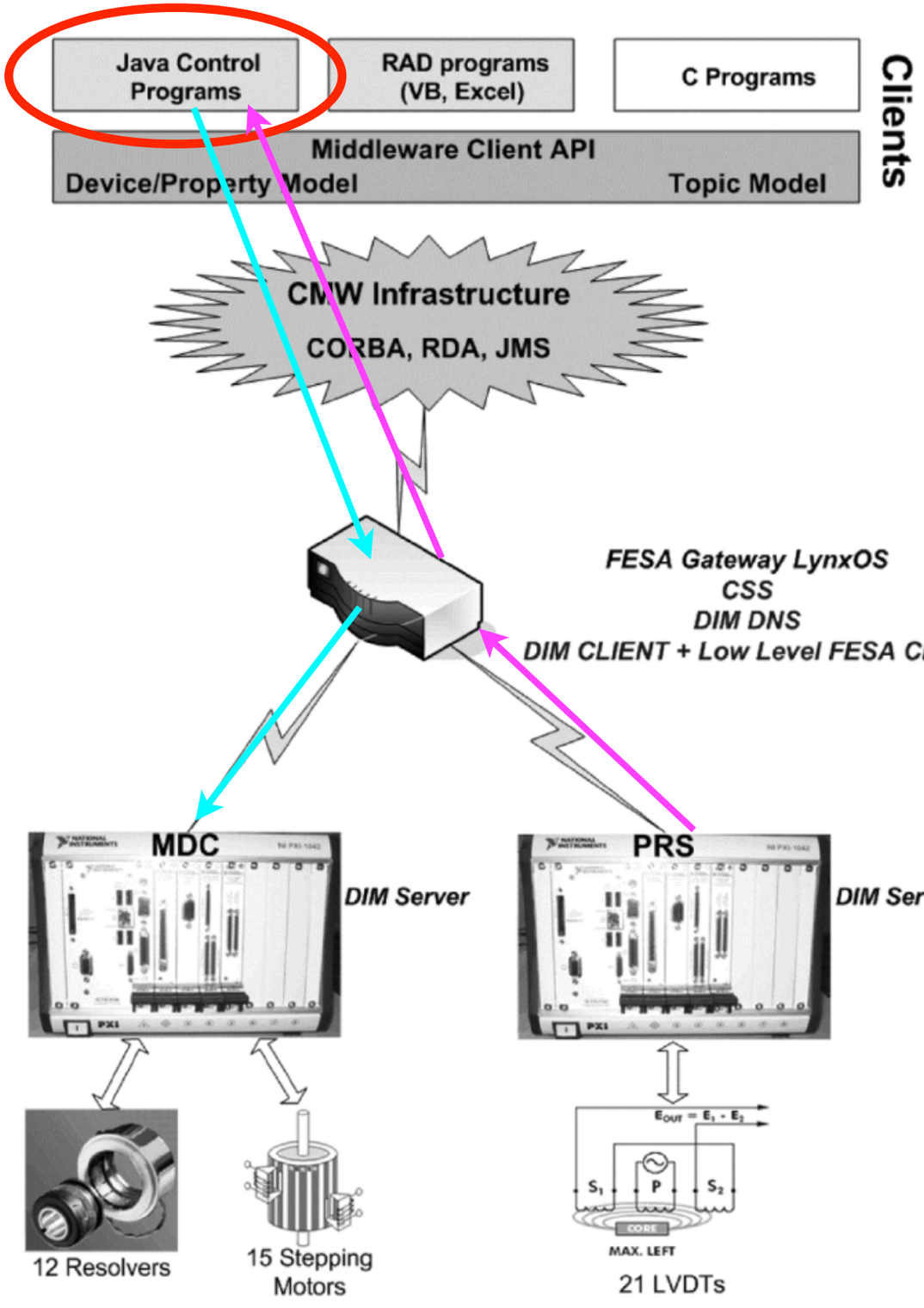

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Beam-Based Collimator Alignment

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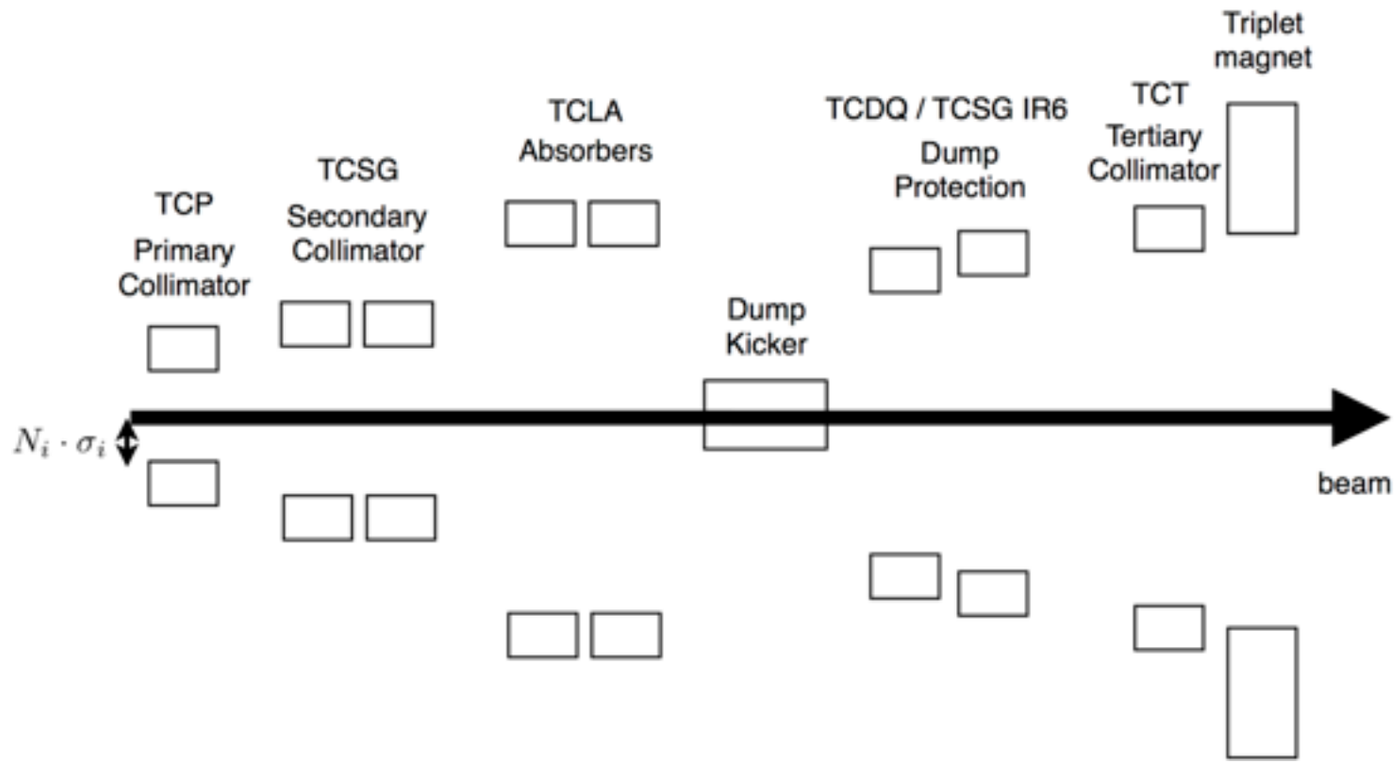

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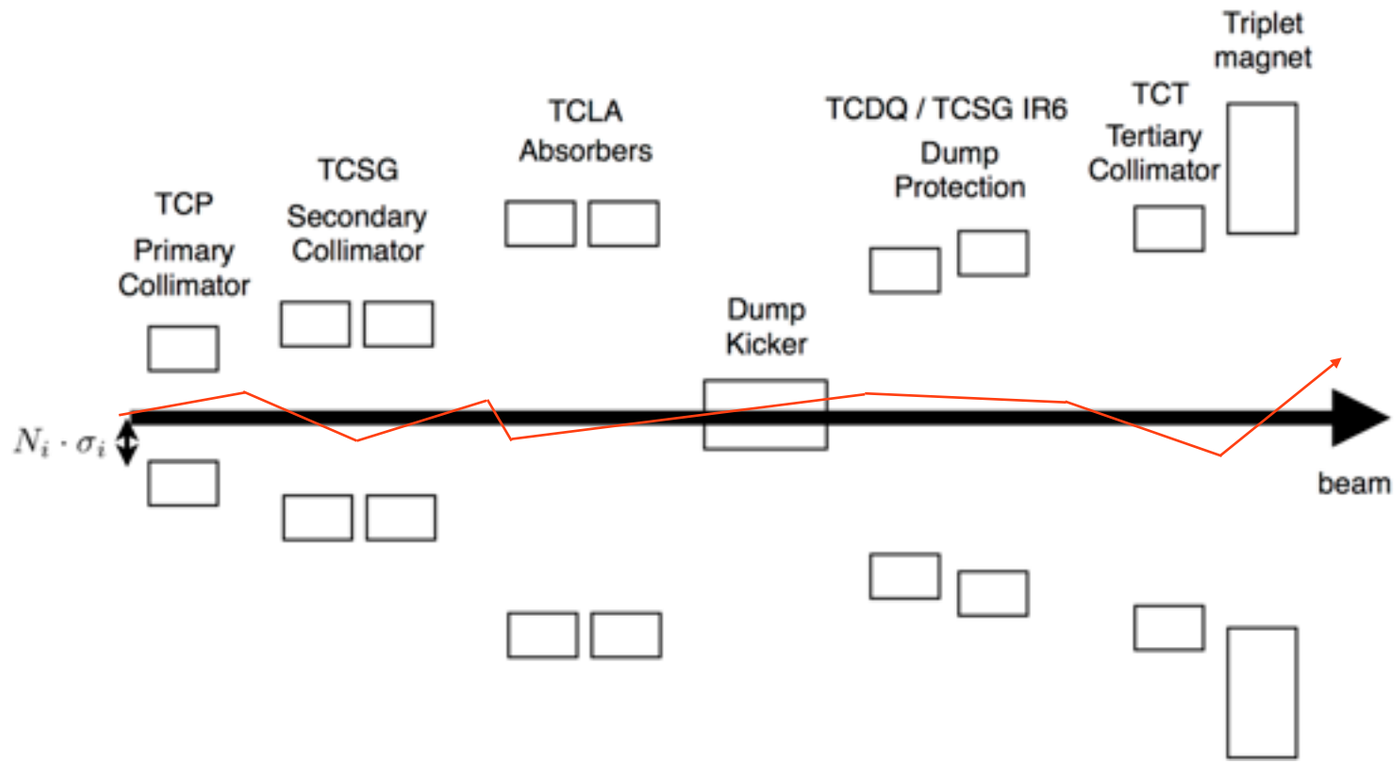

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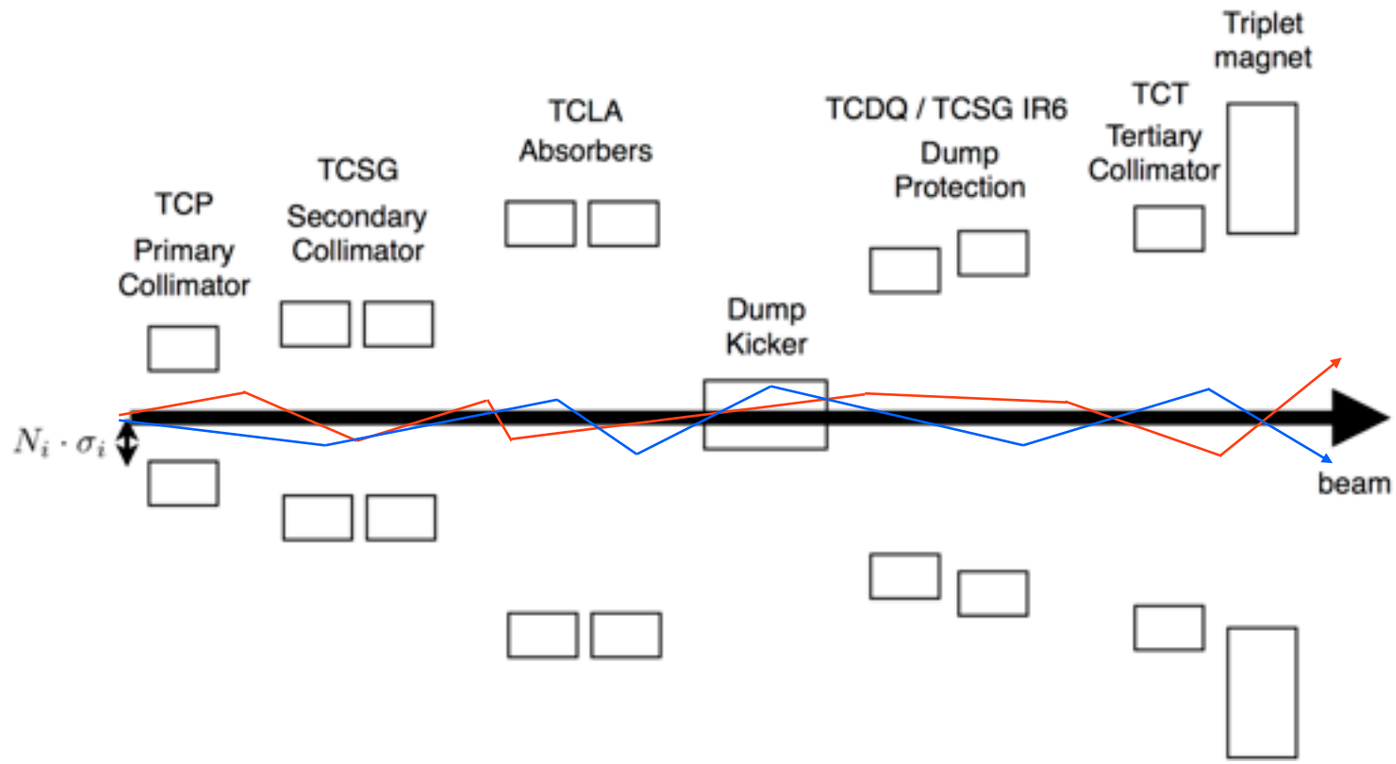

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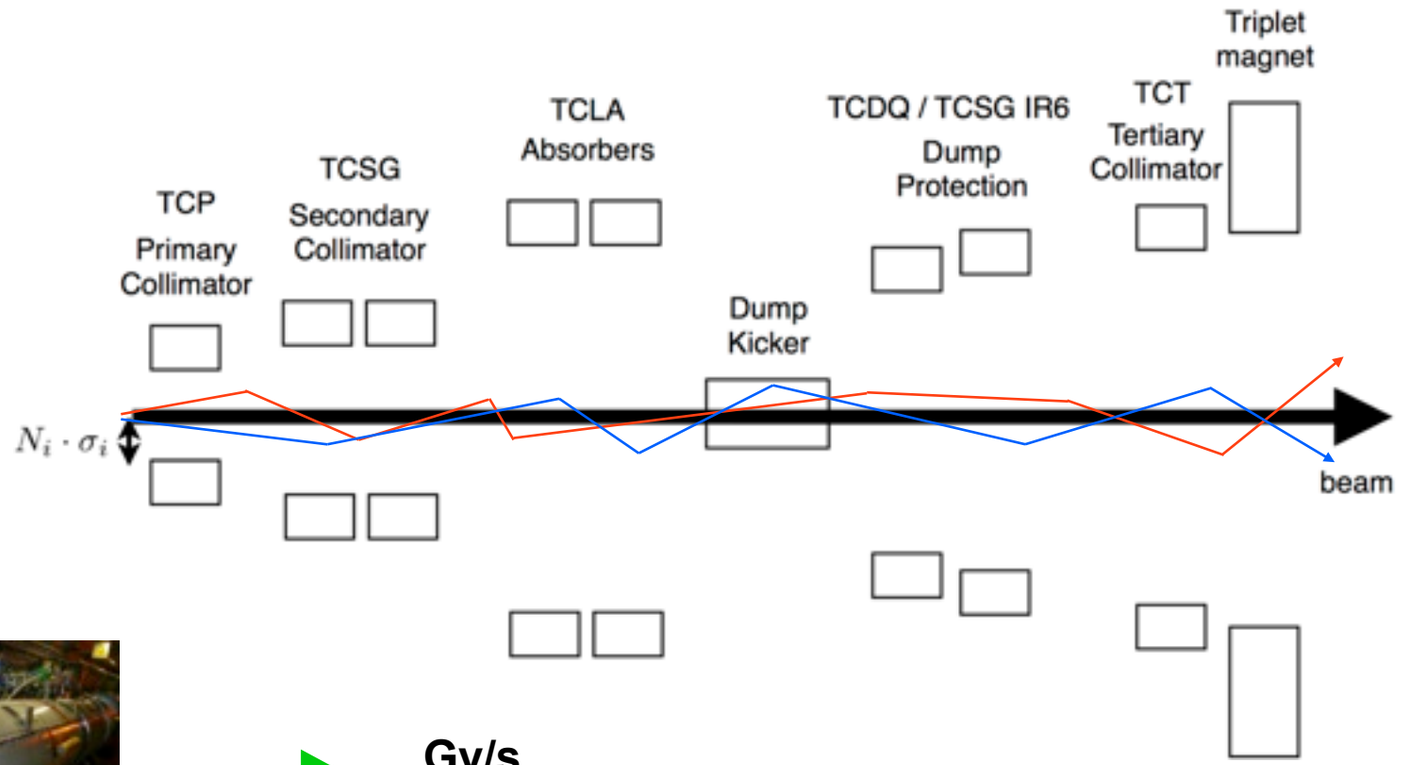
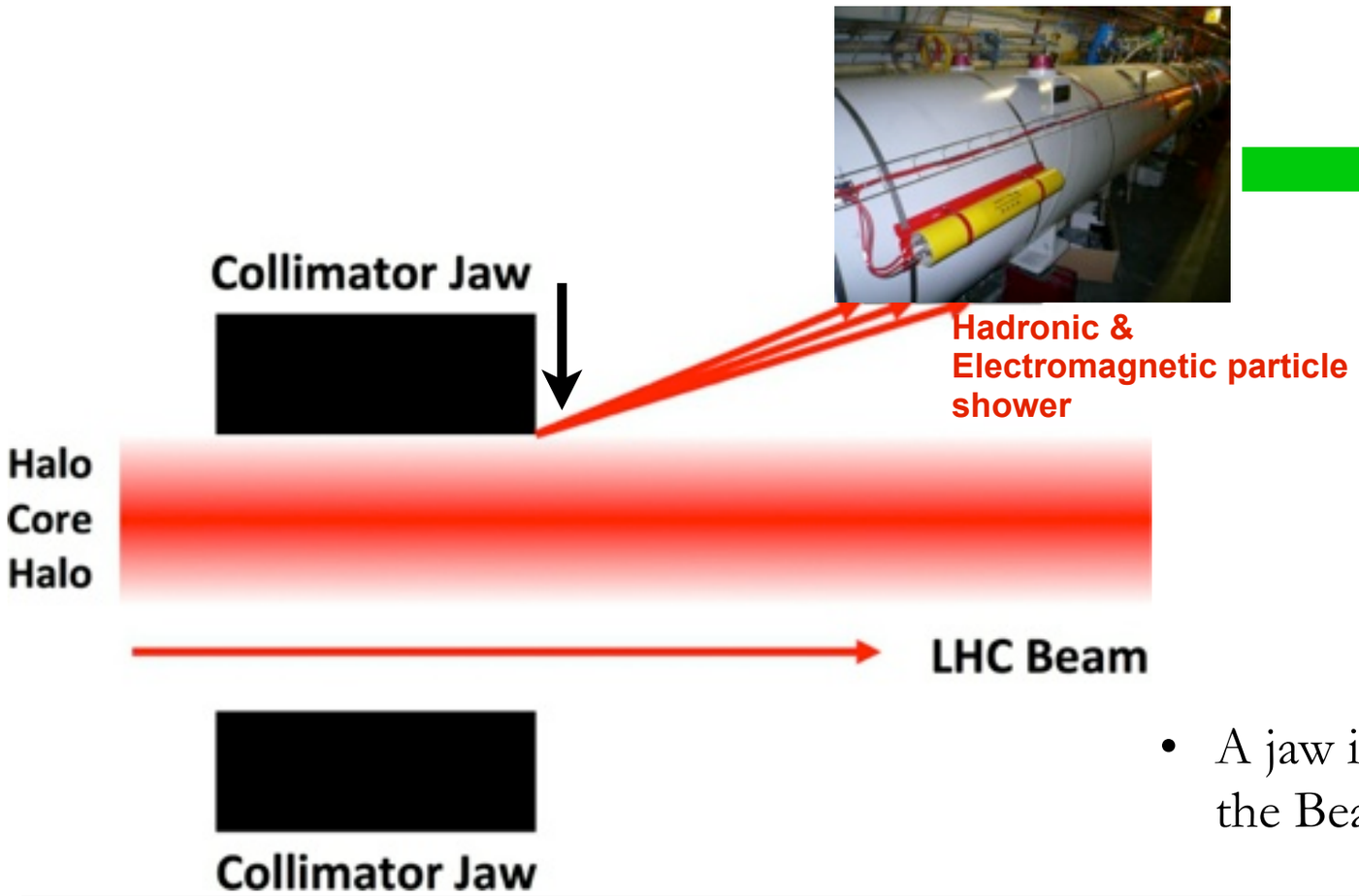
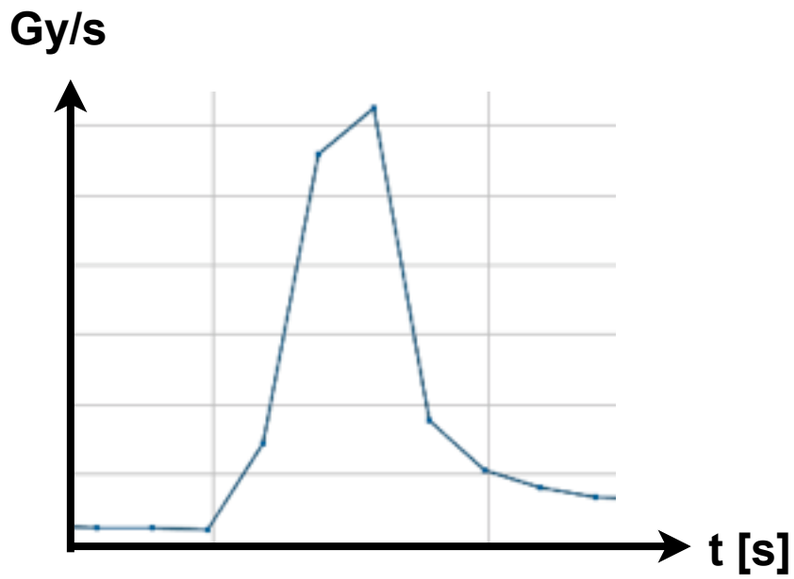
- By touching the beam with each jaw, these values can be determined.







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

Alignment Procedure

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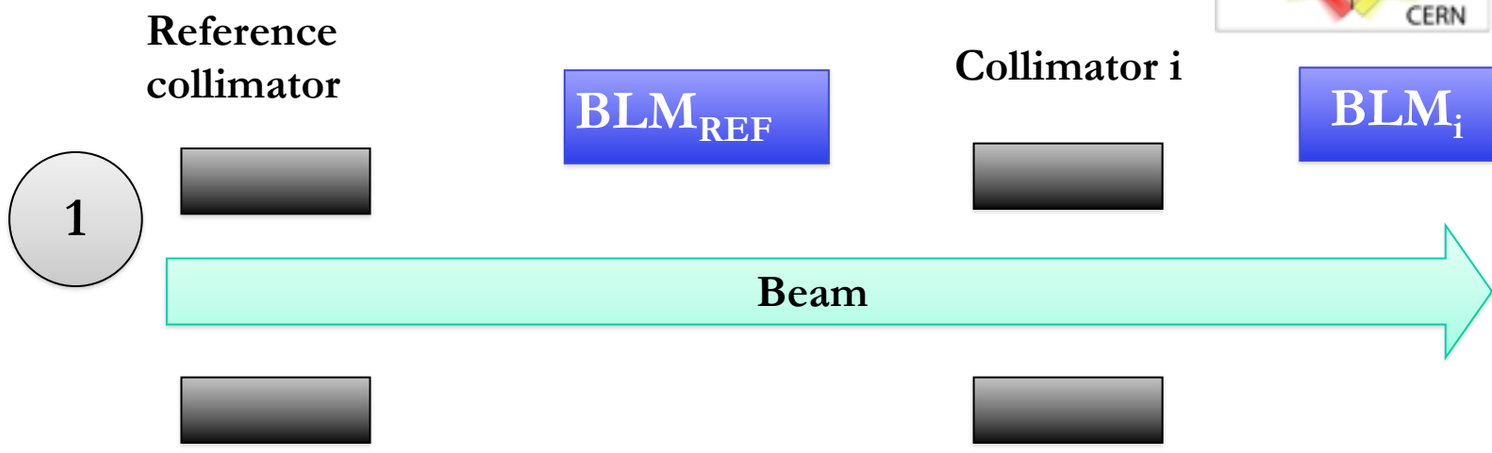

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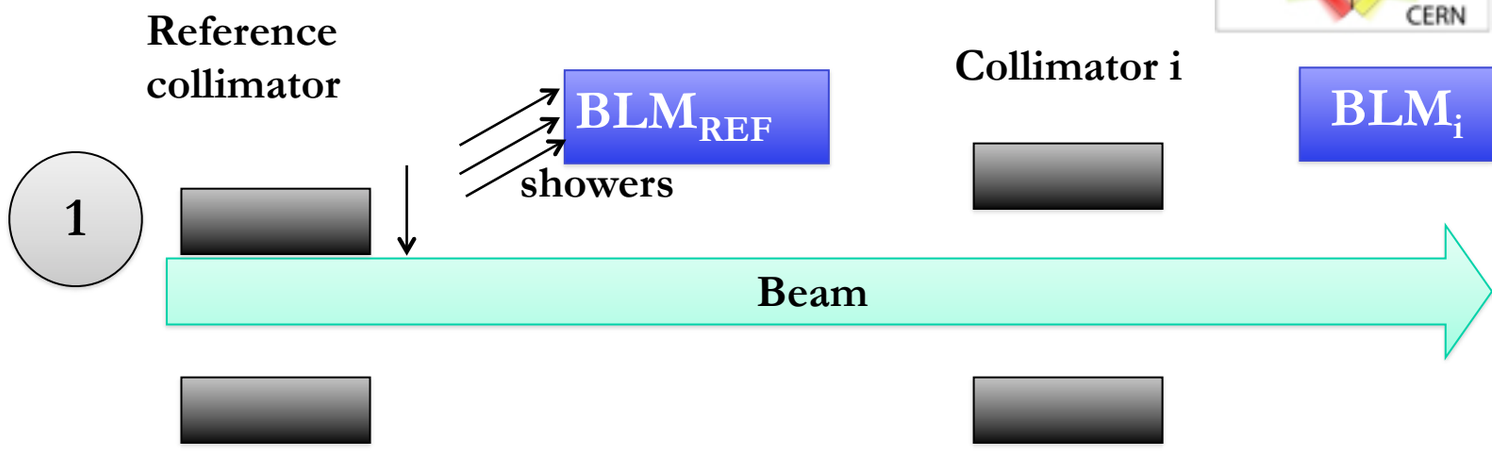

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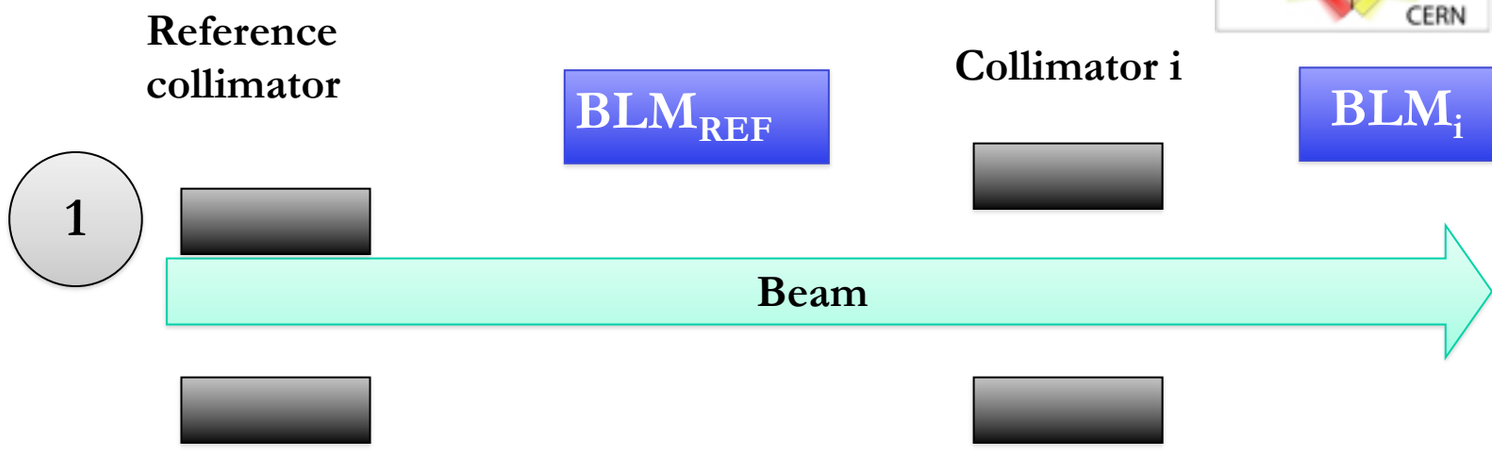

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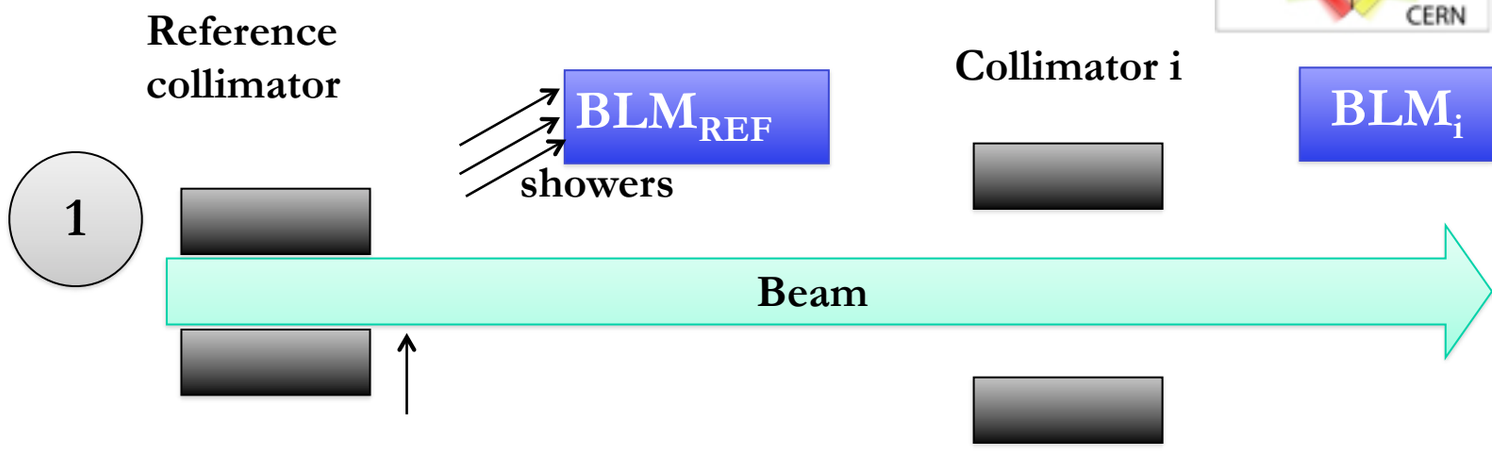

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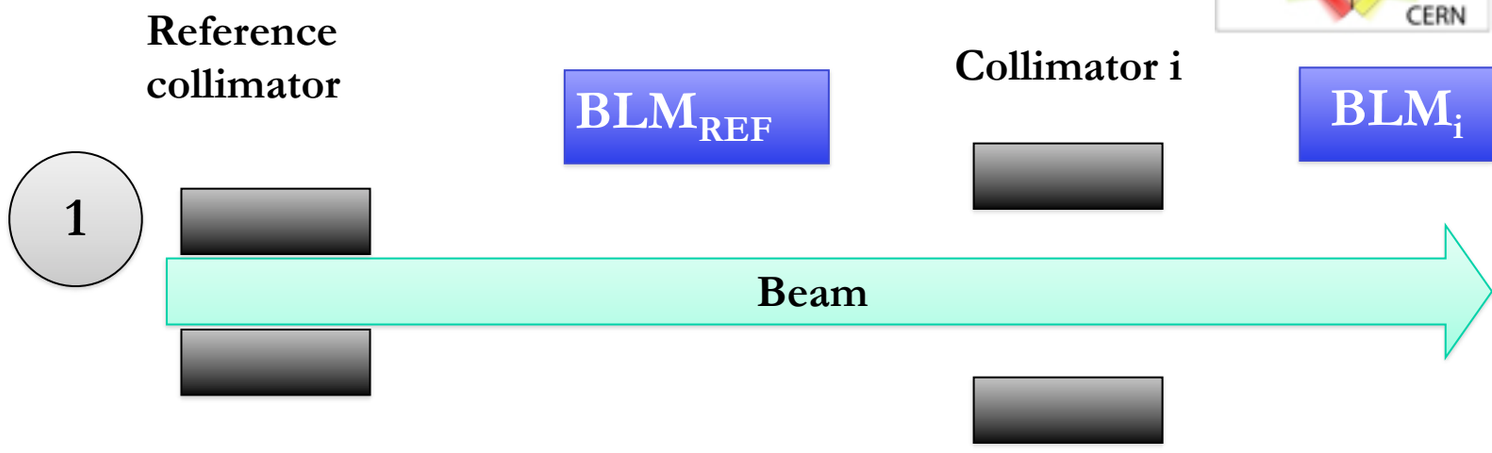

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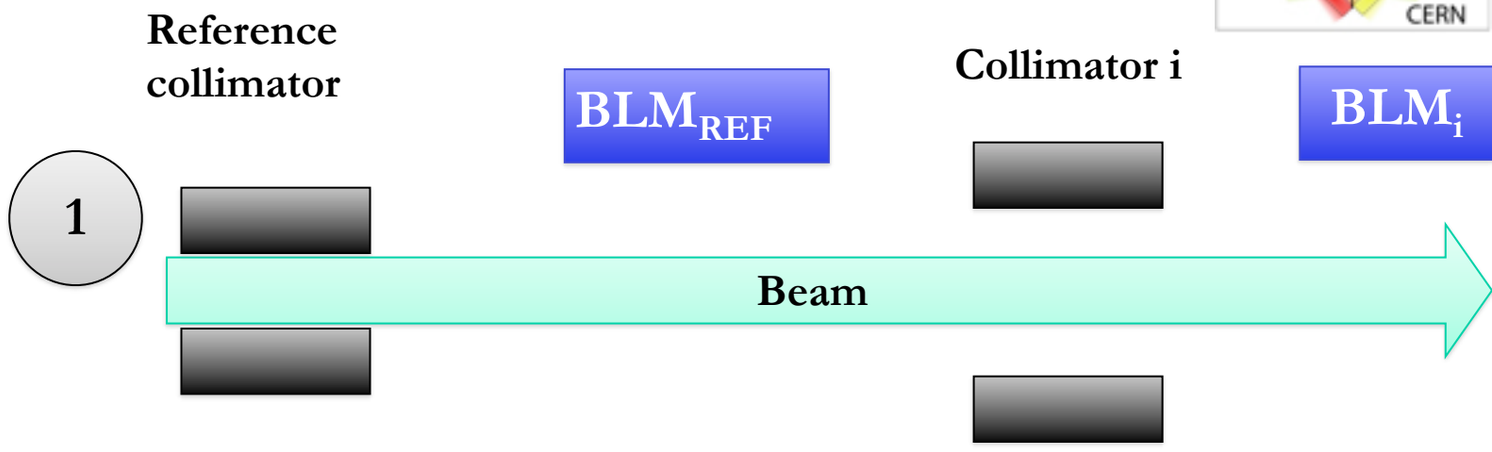

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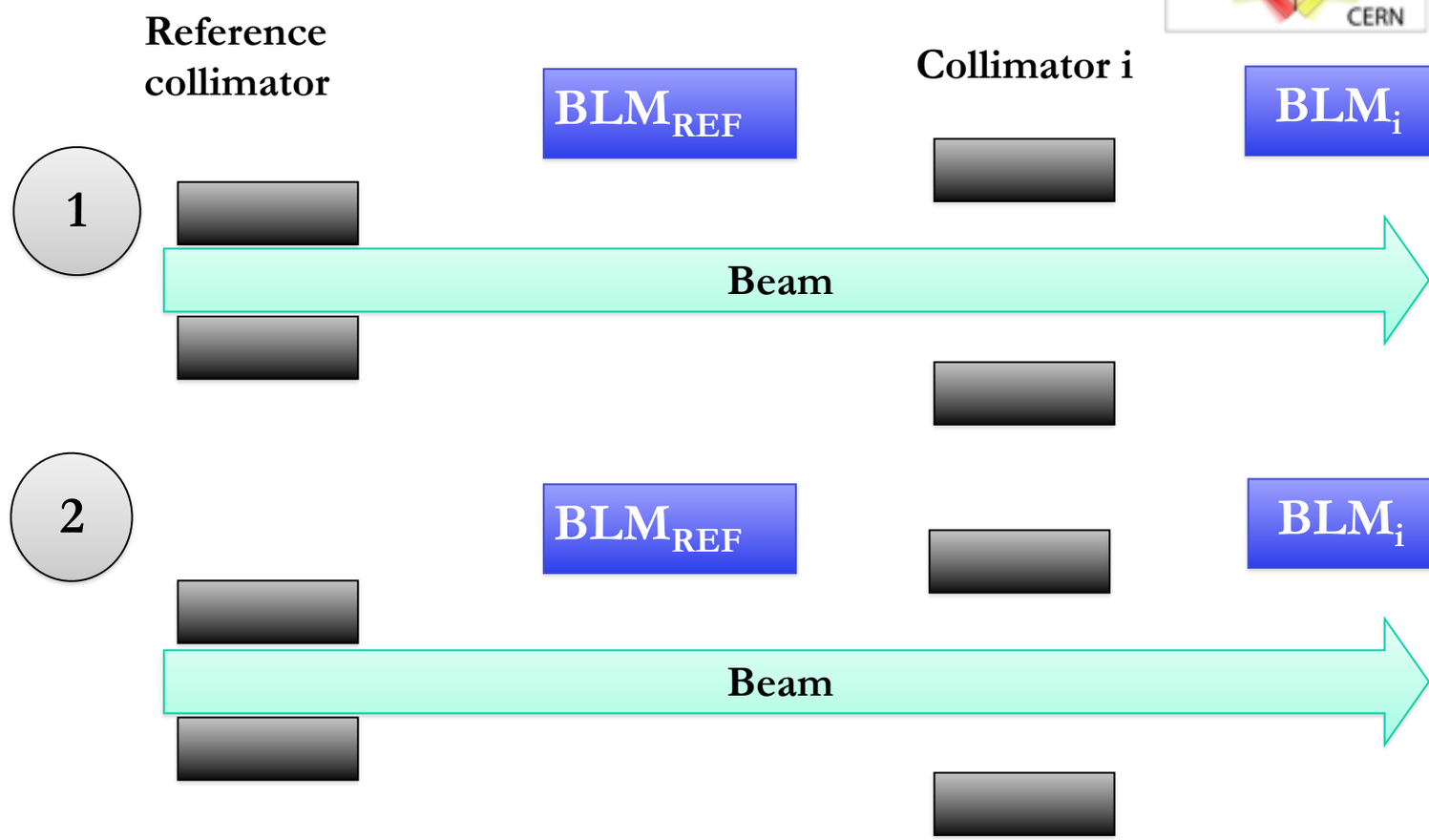

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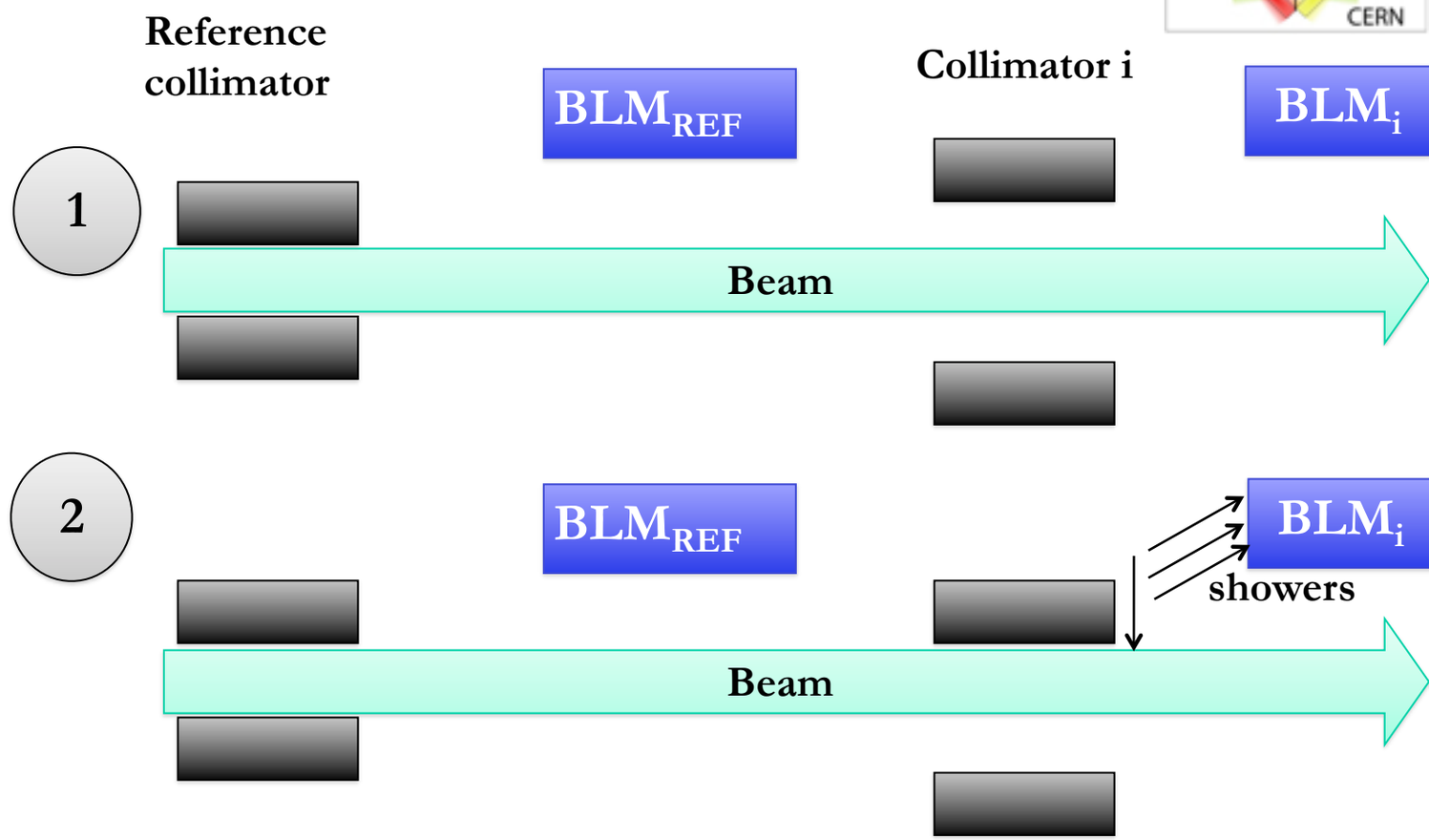

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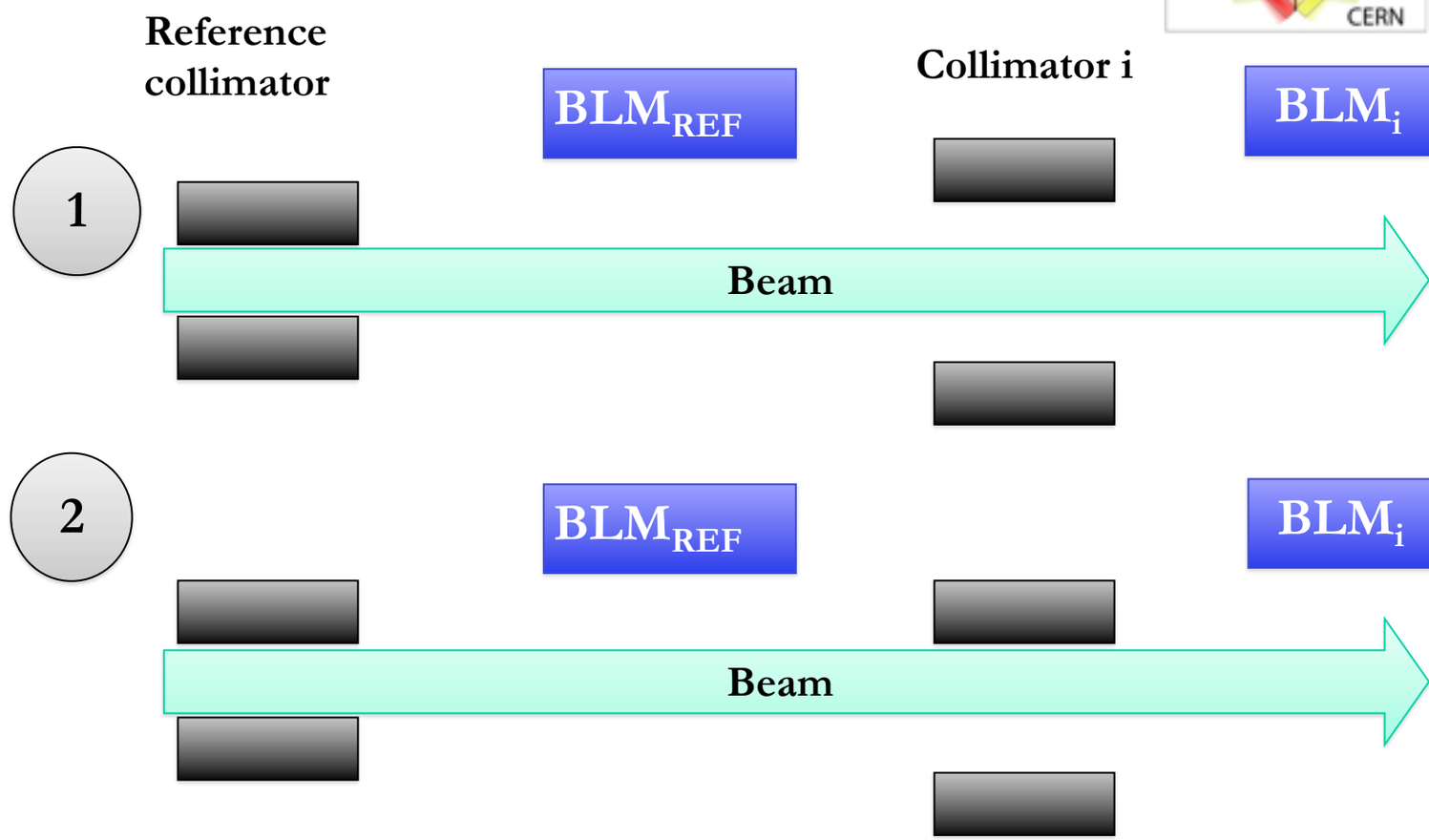

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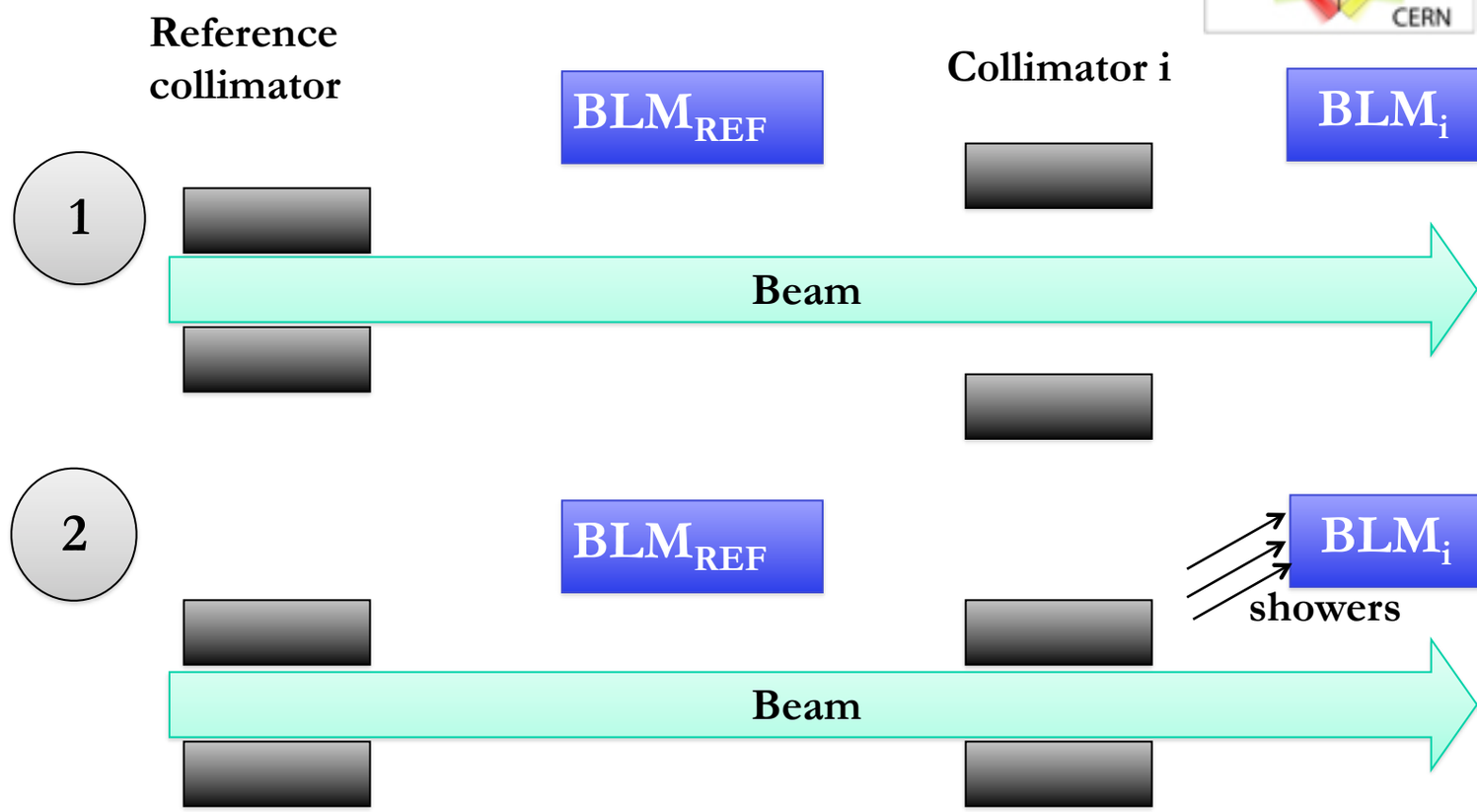

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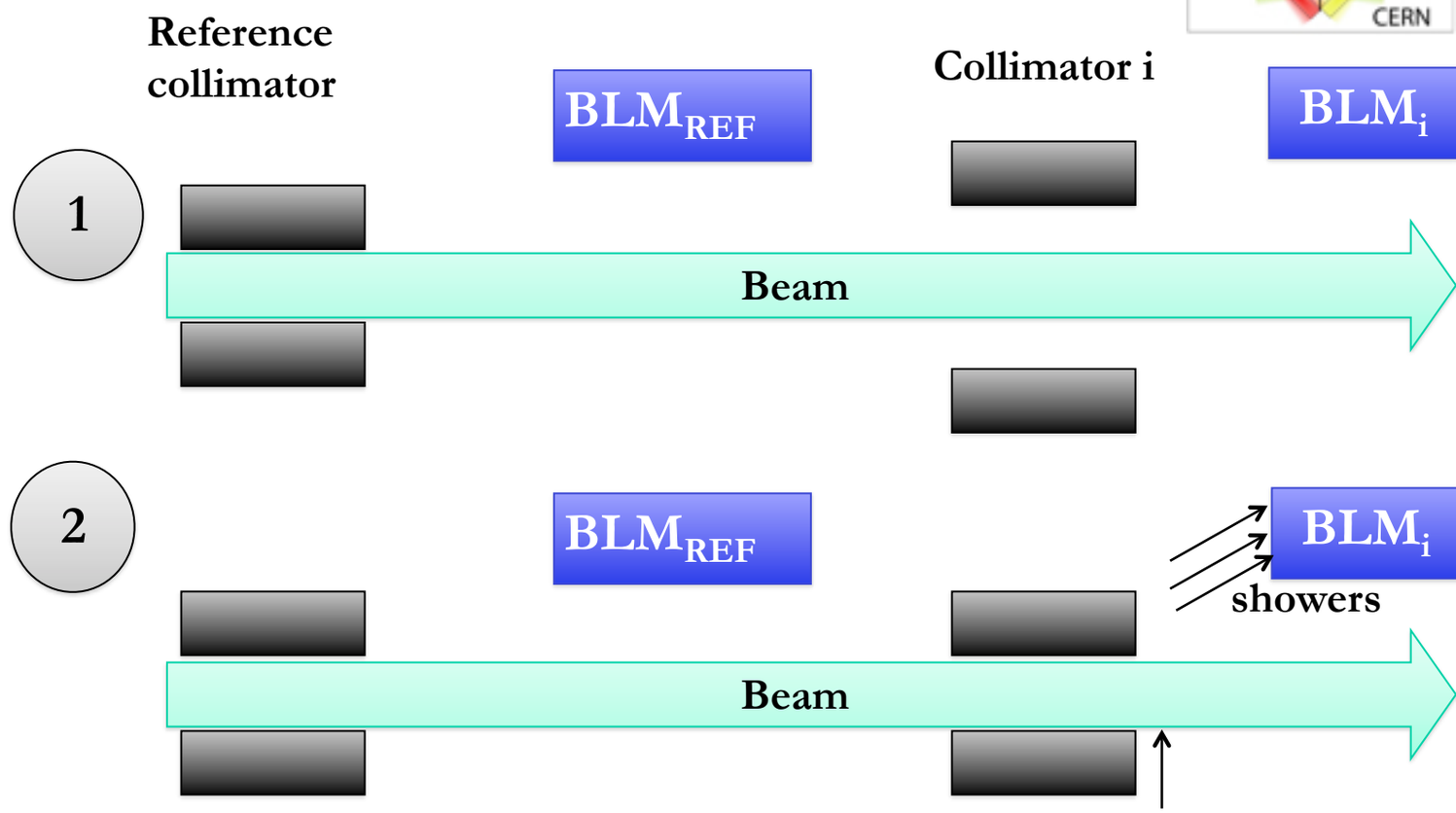

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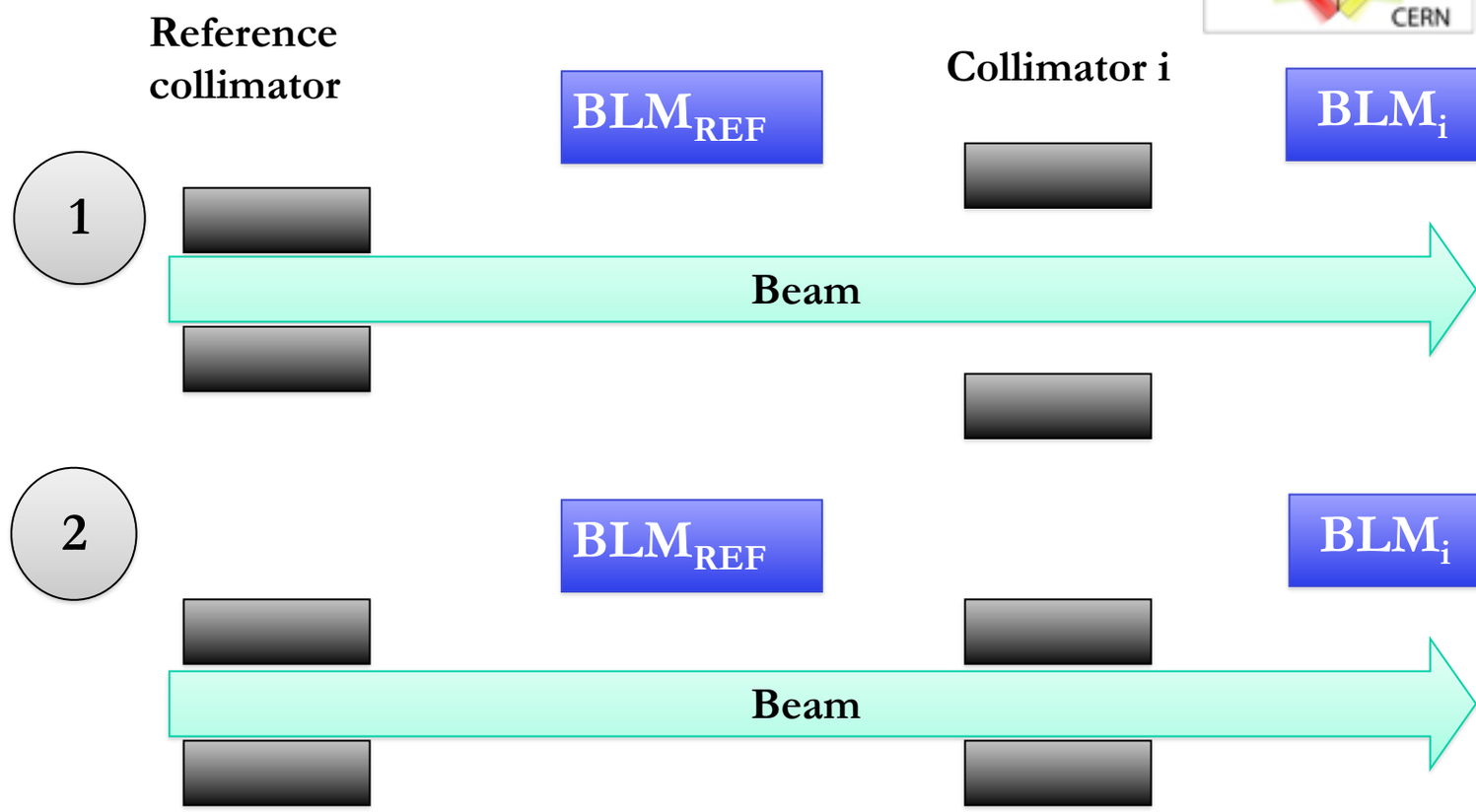

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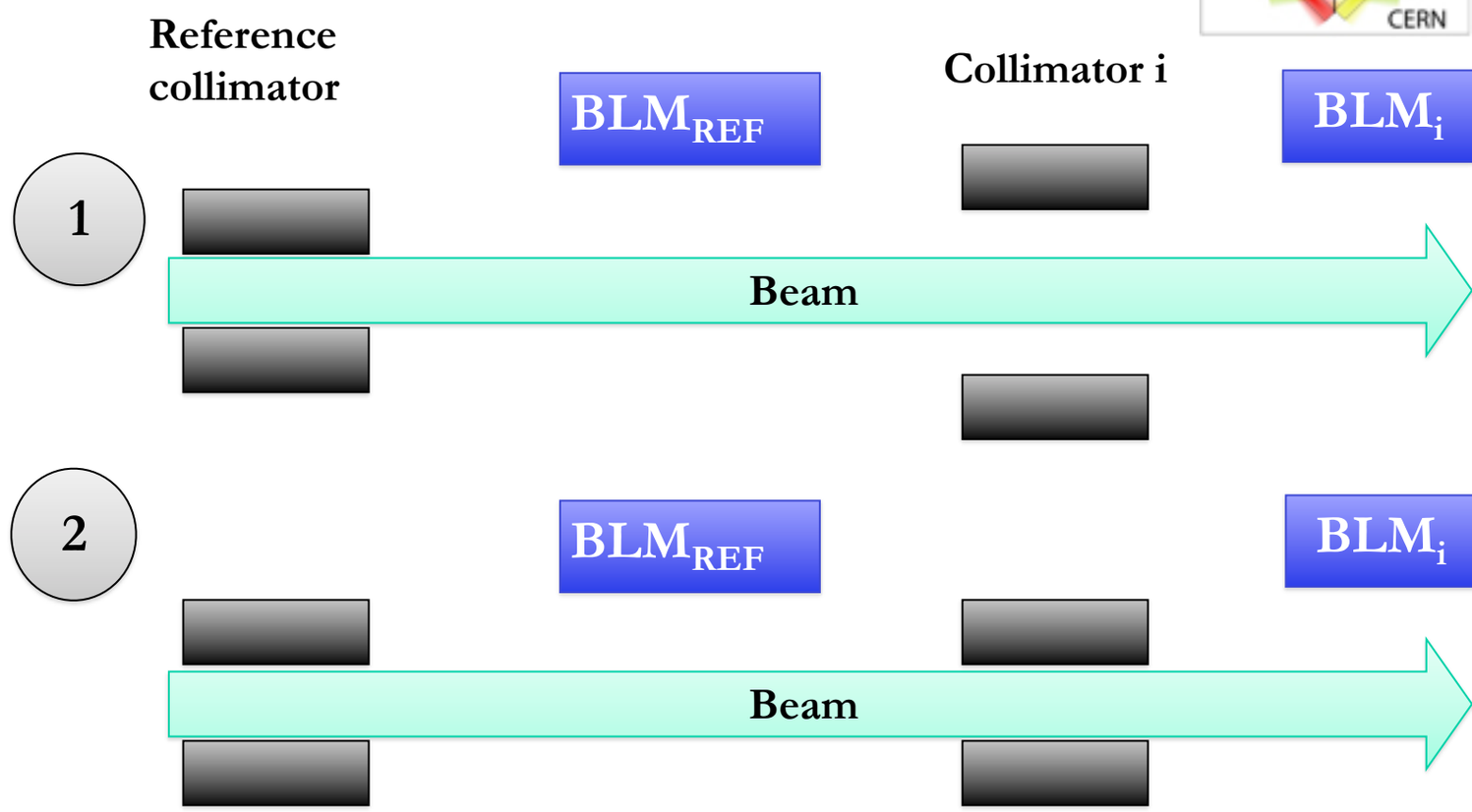

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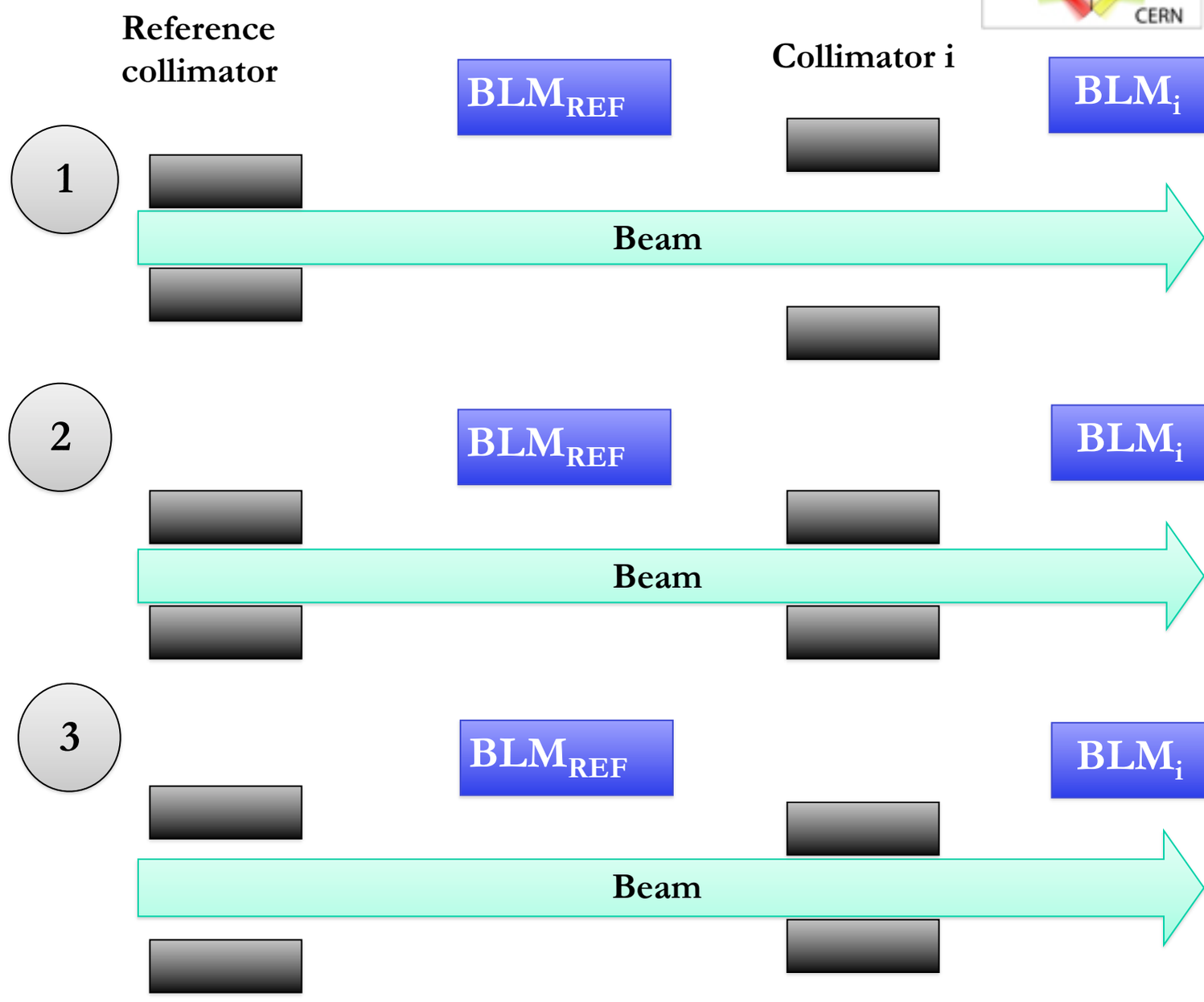

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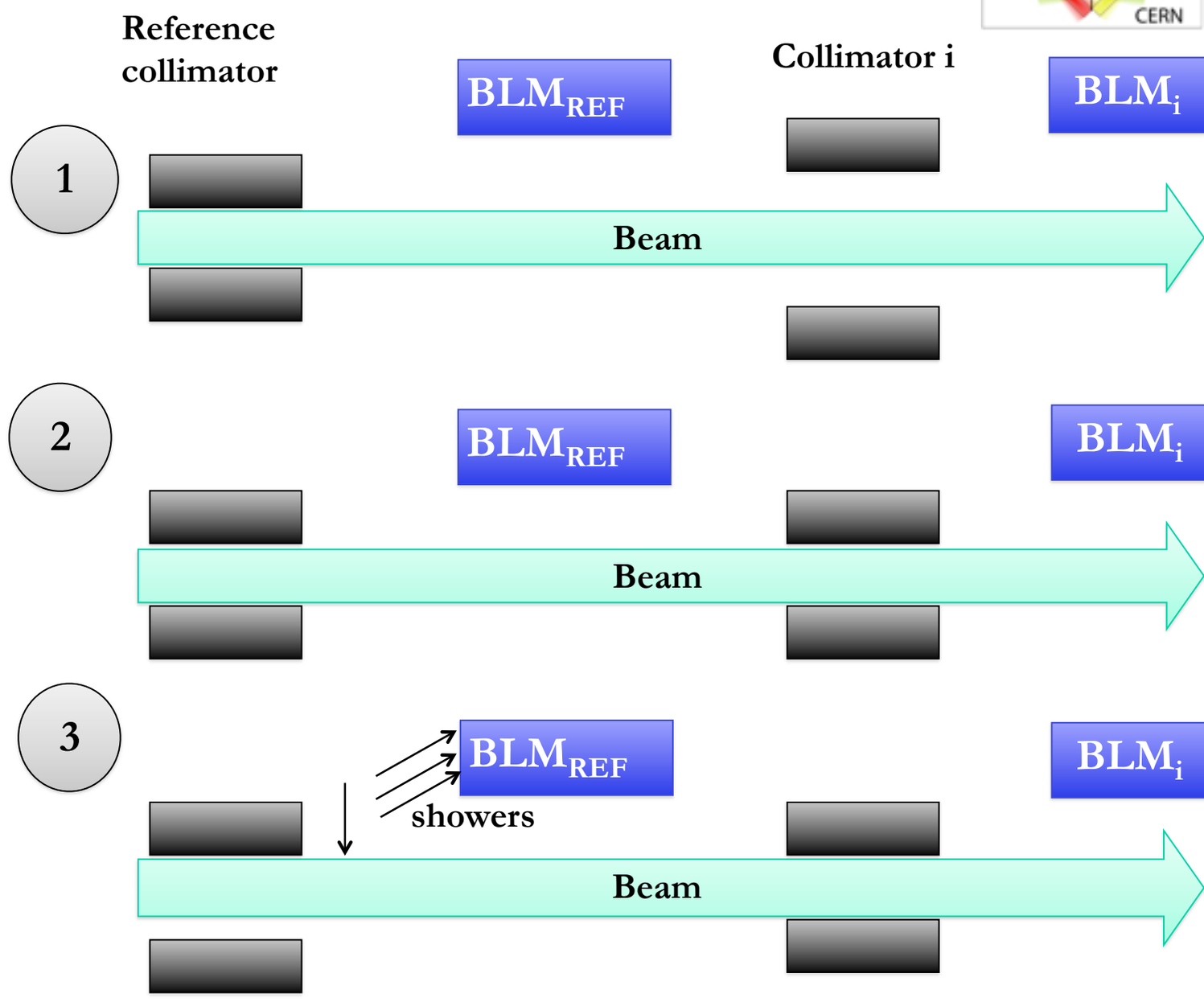

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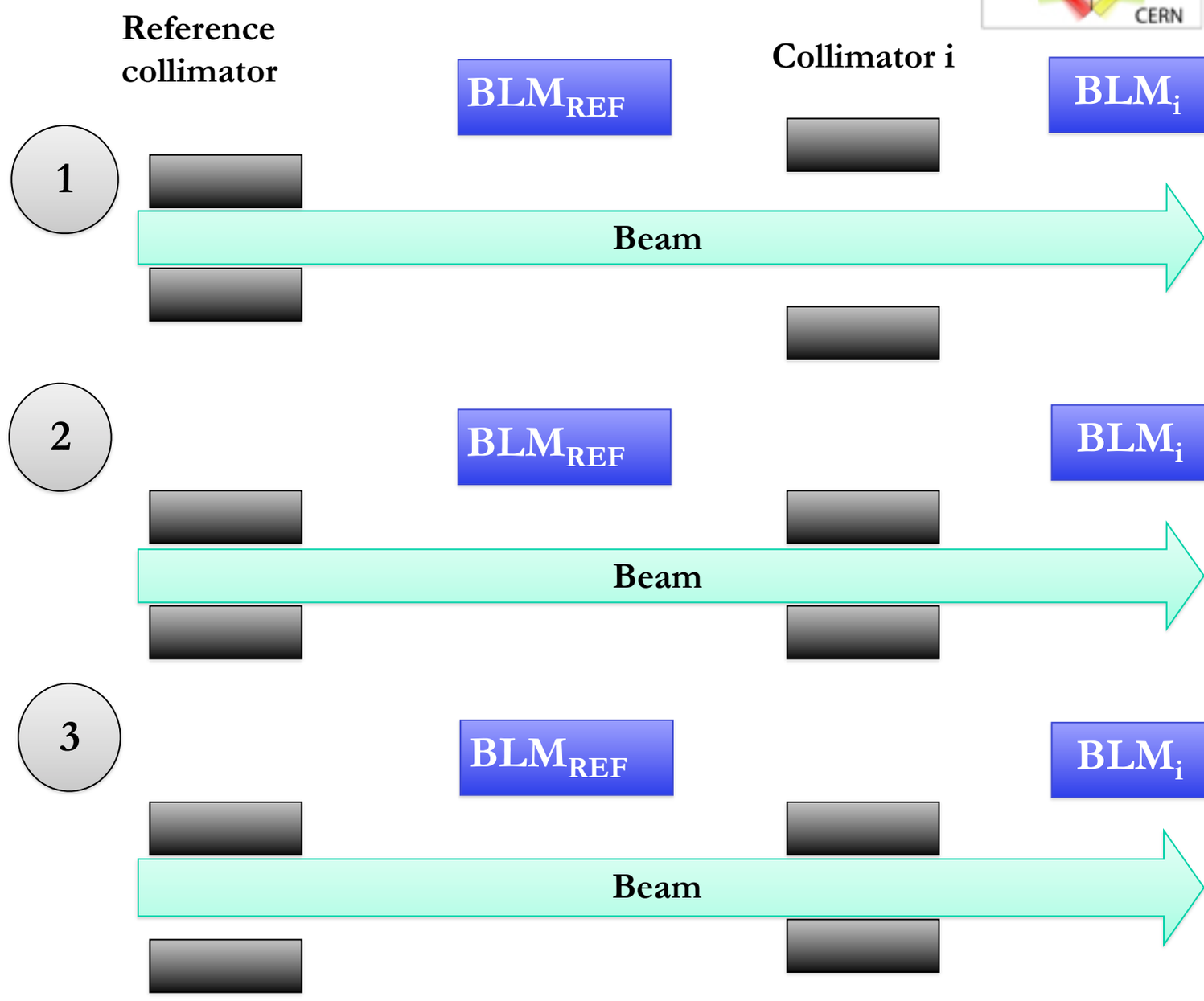

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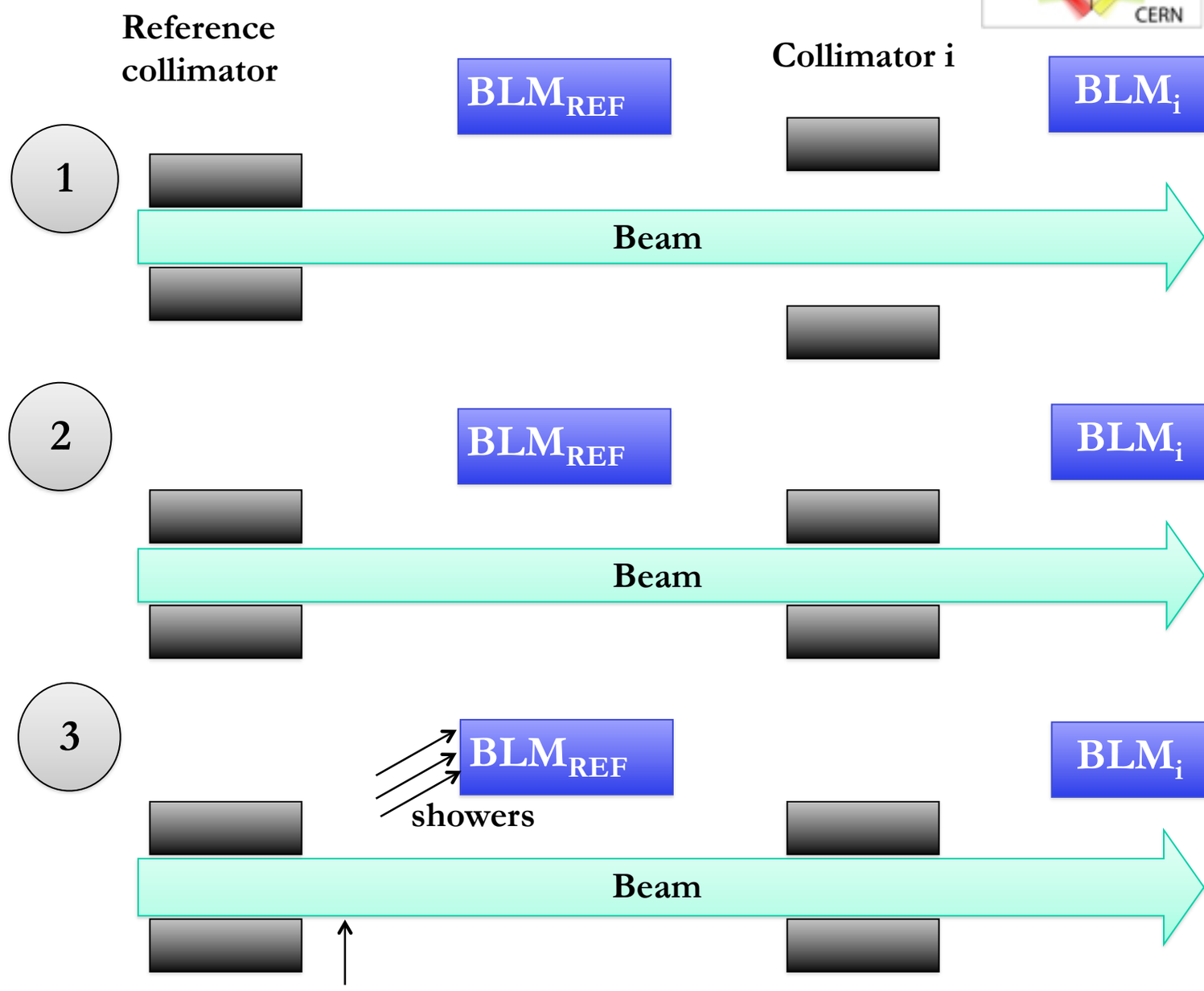

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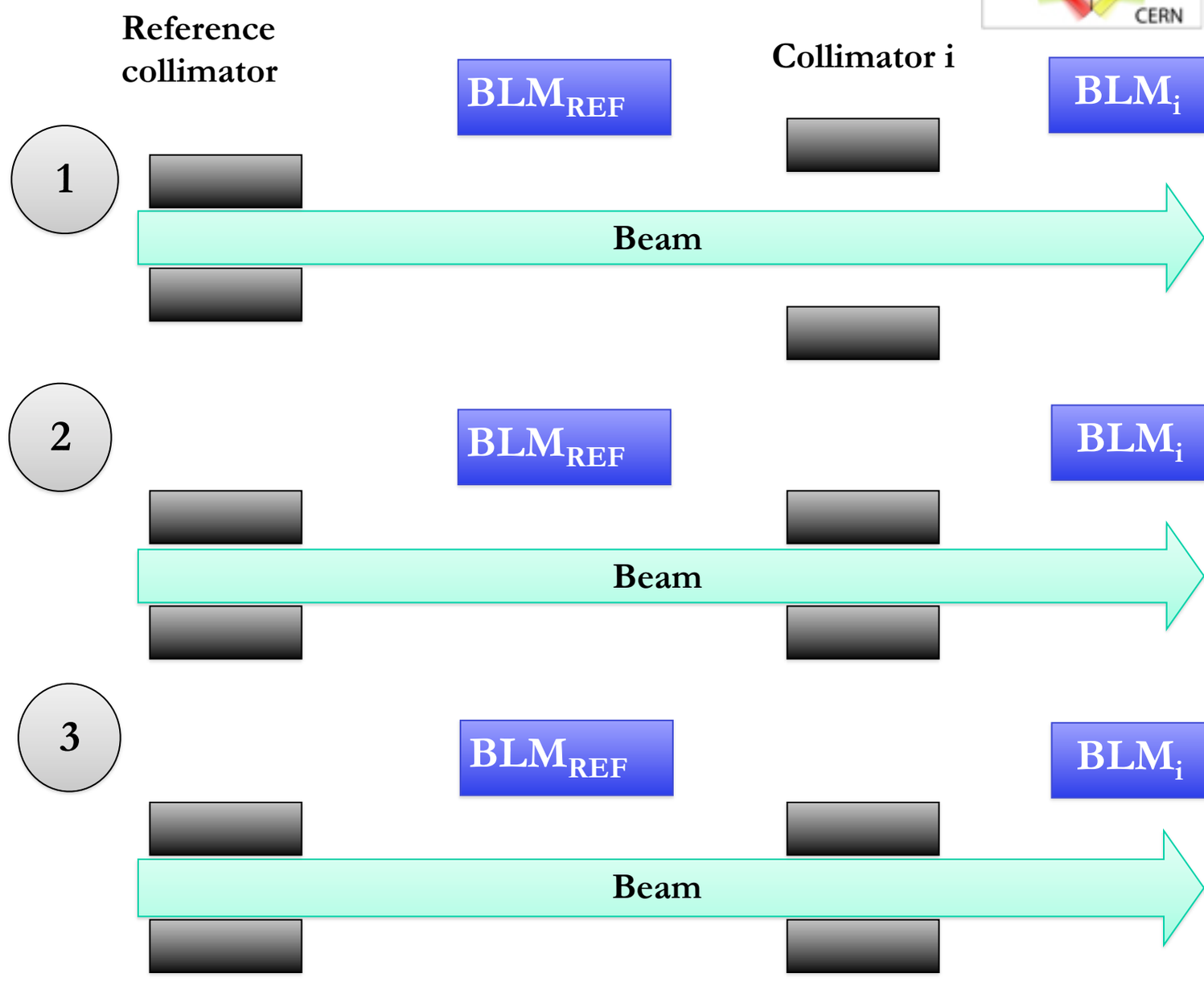

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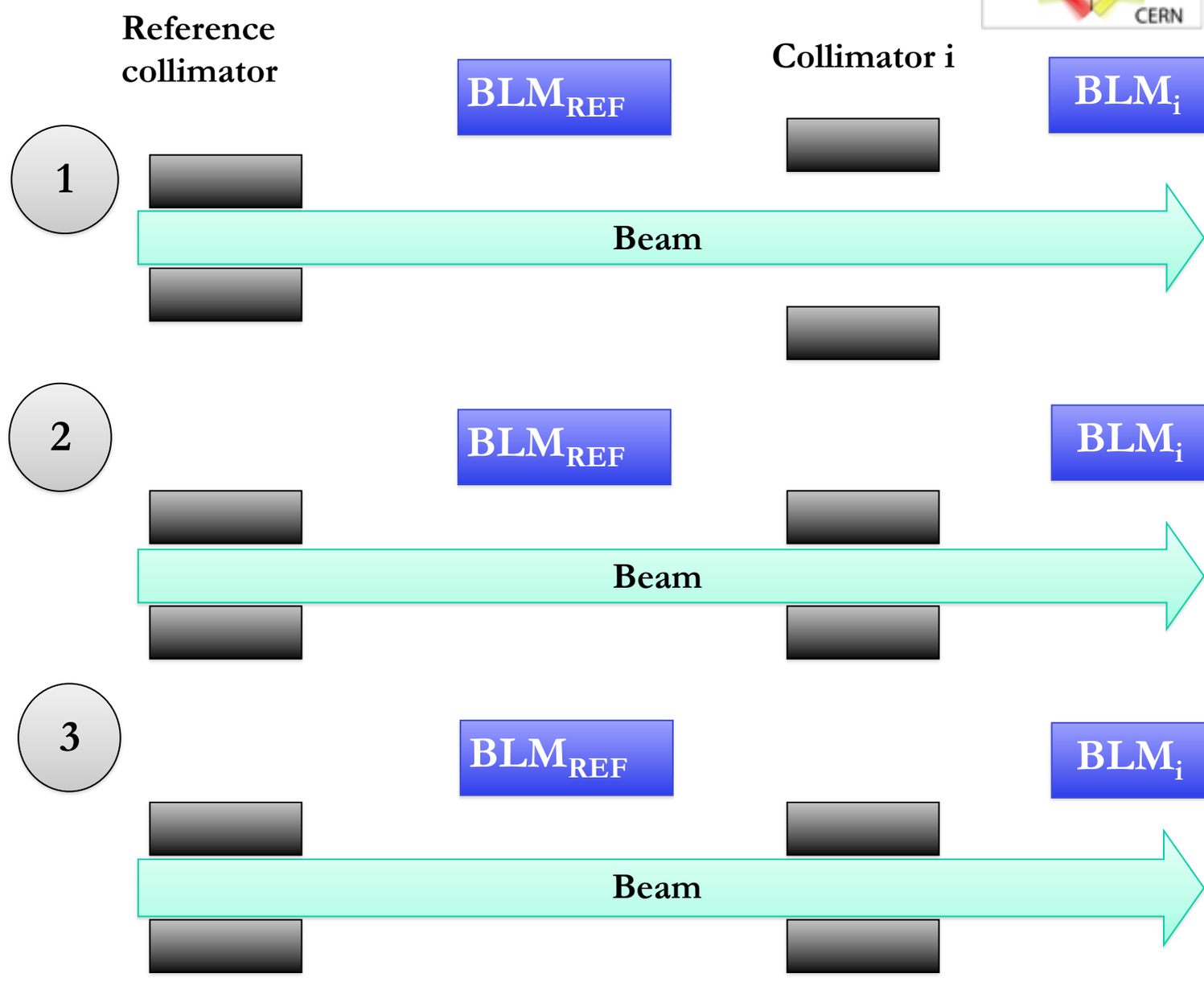

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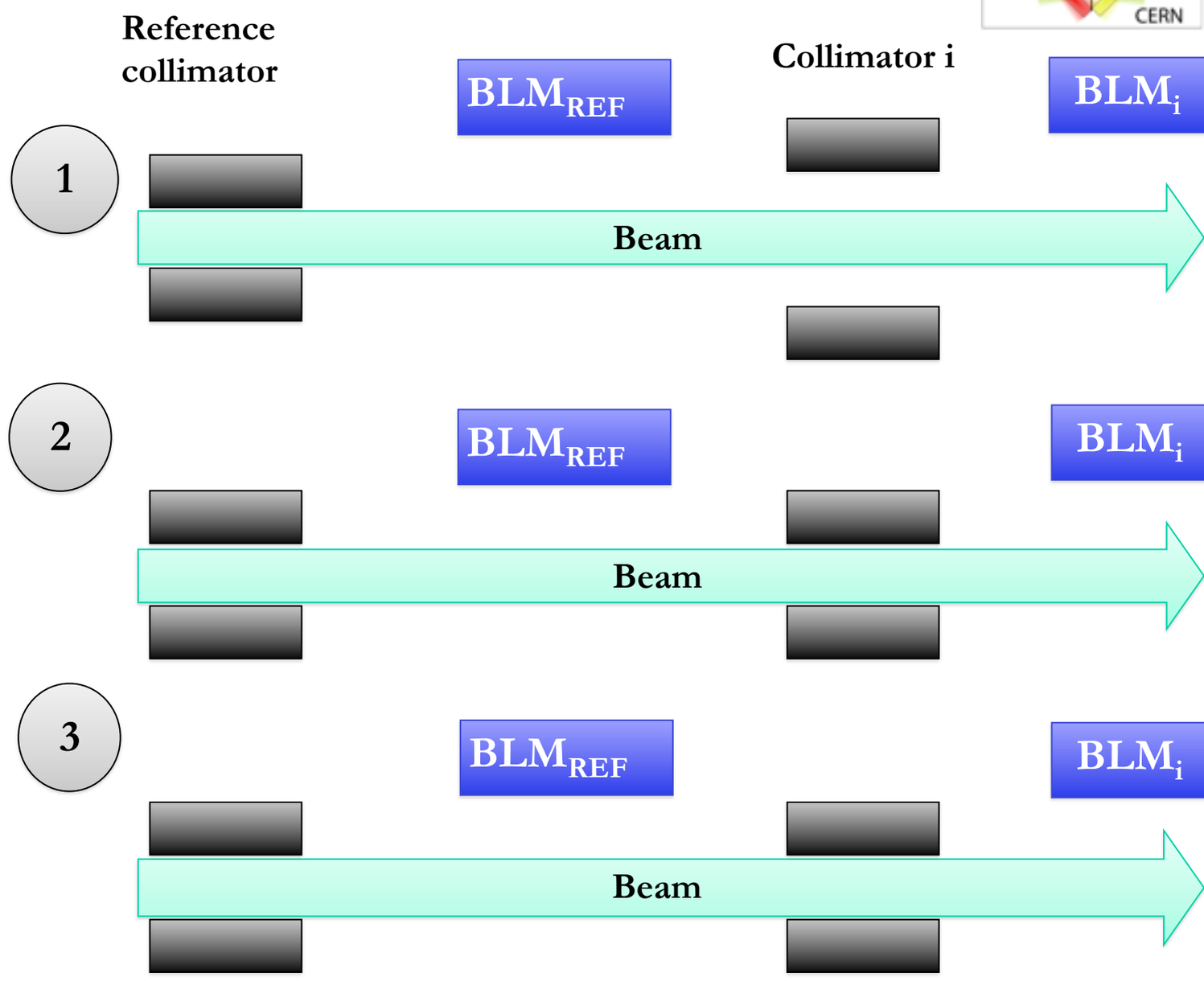

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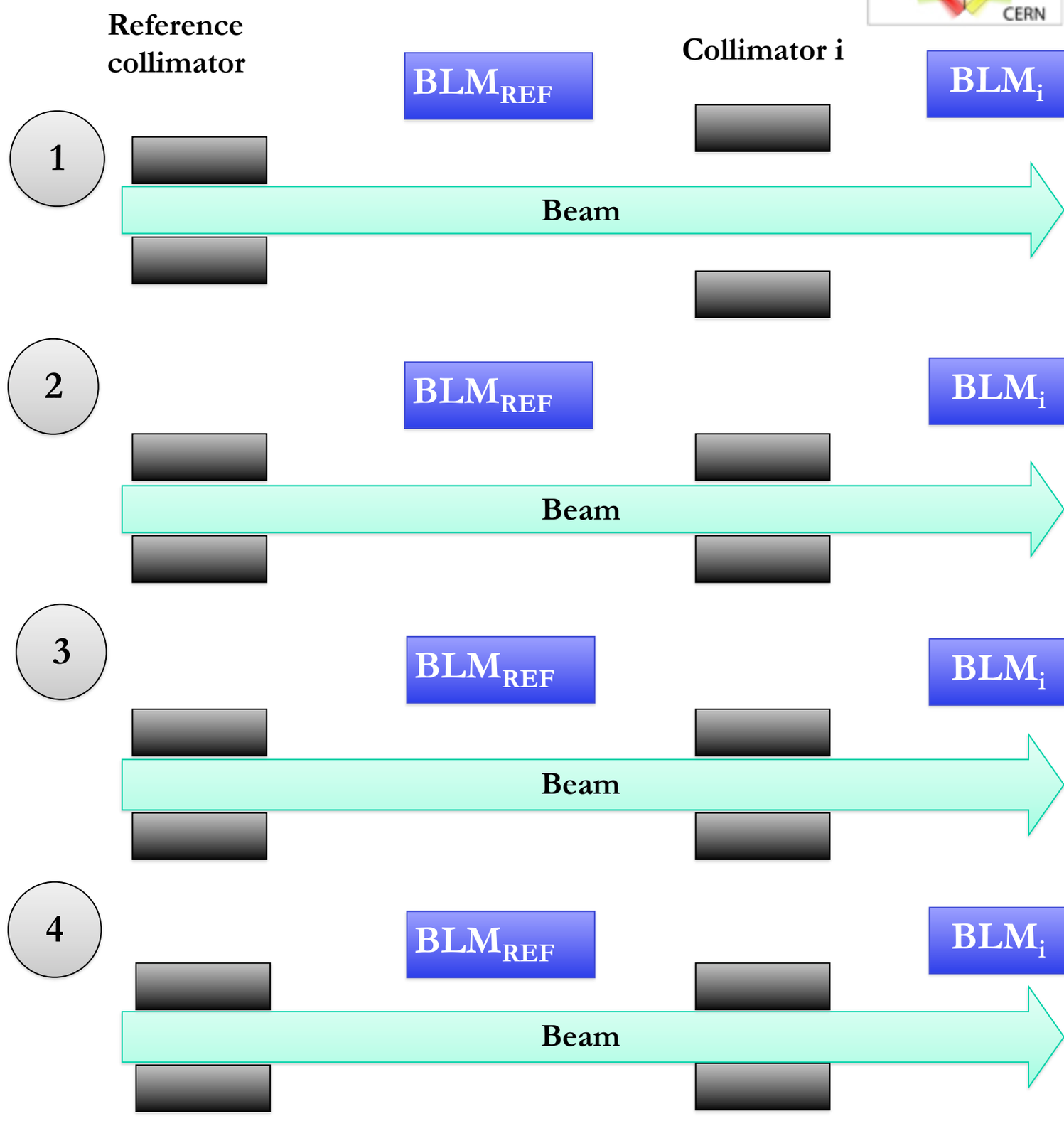

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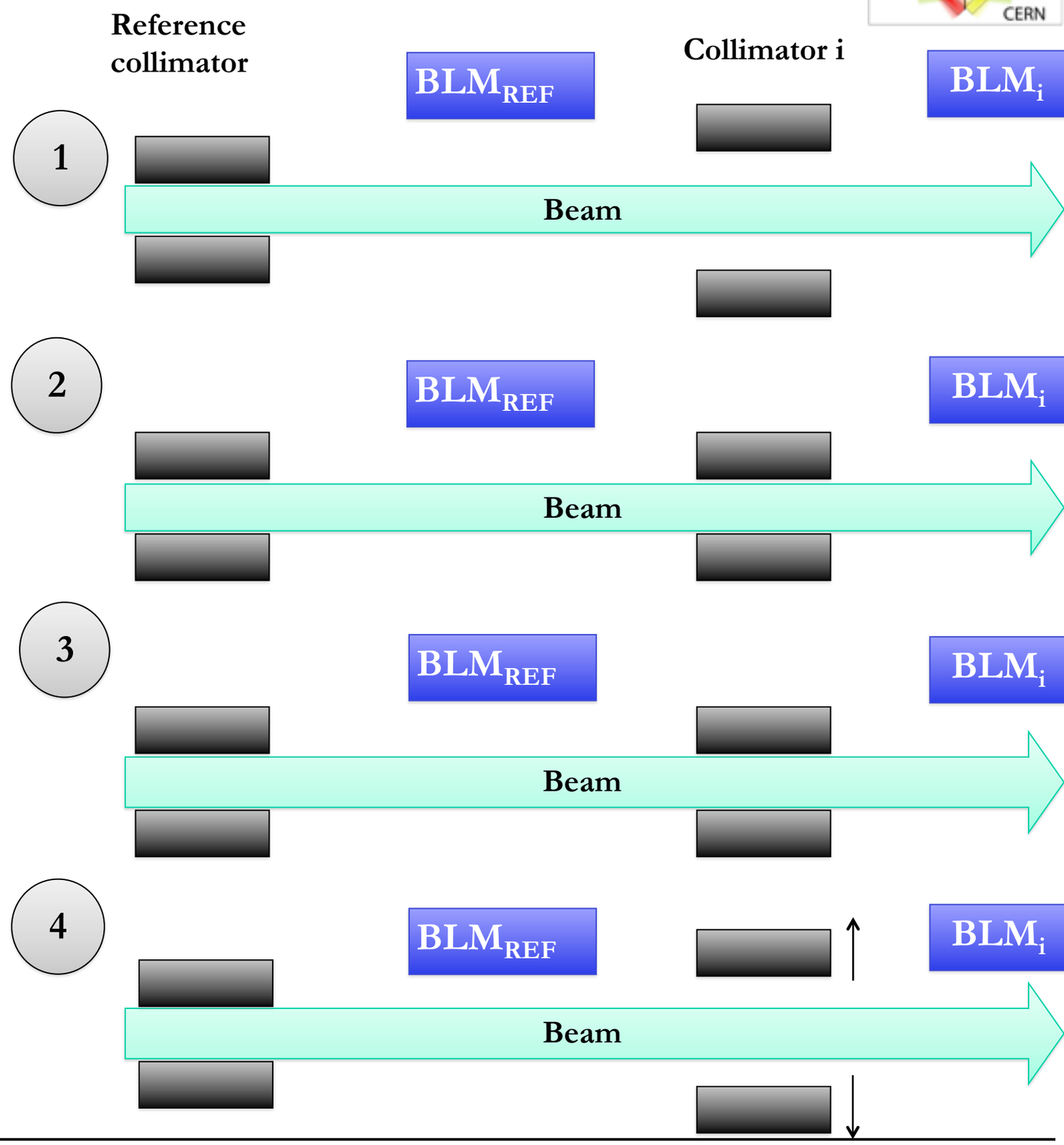

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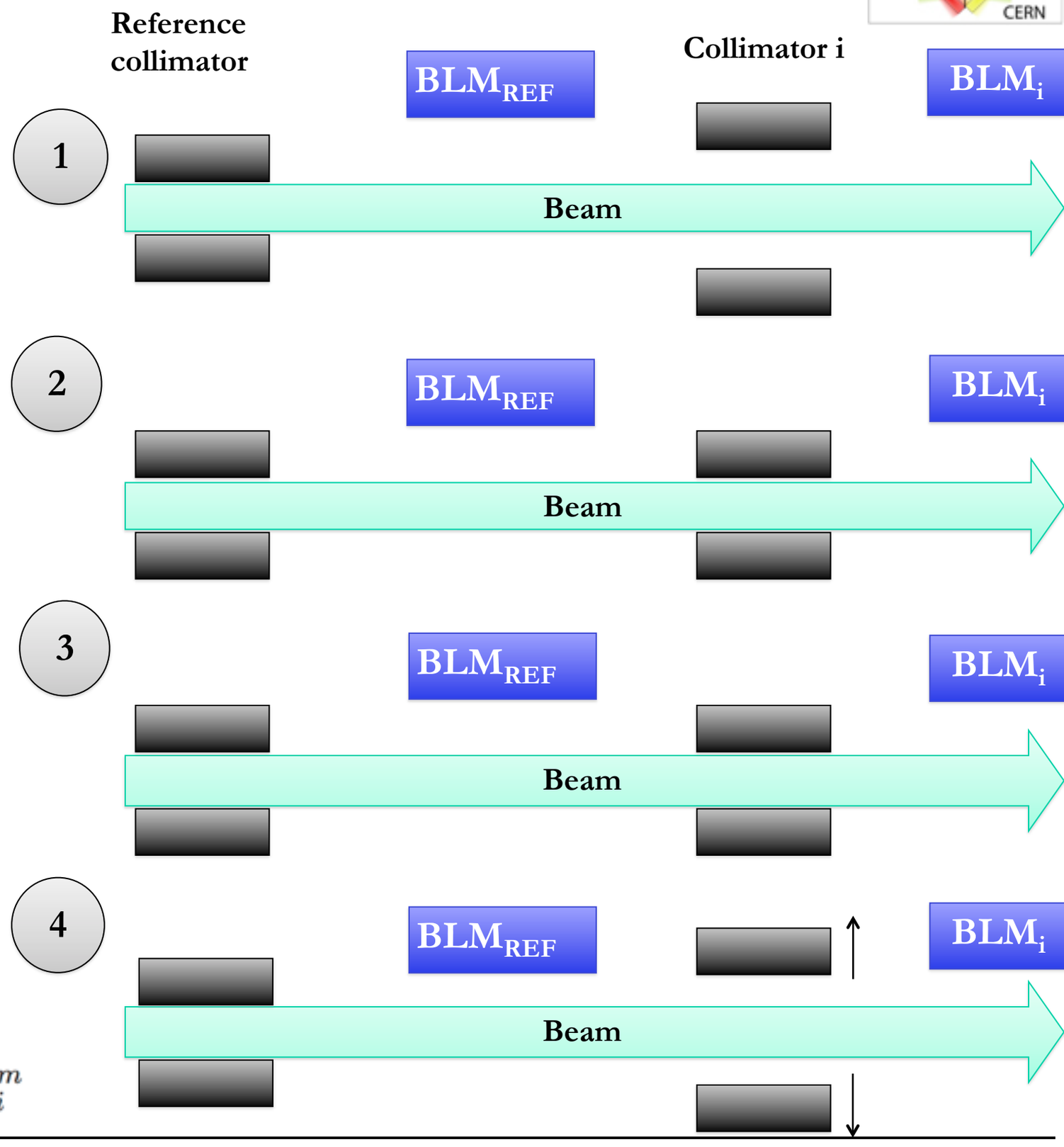
$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^m \qquad x_i^{R,set} = \Delta x_i - N_i \sigma_i^m$$



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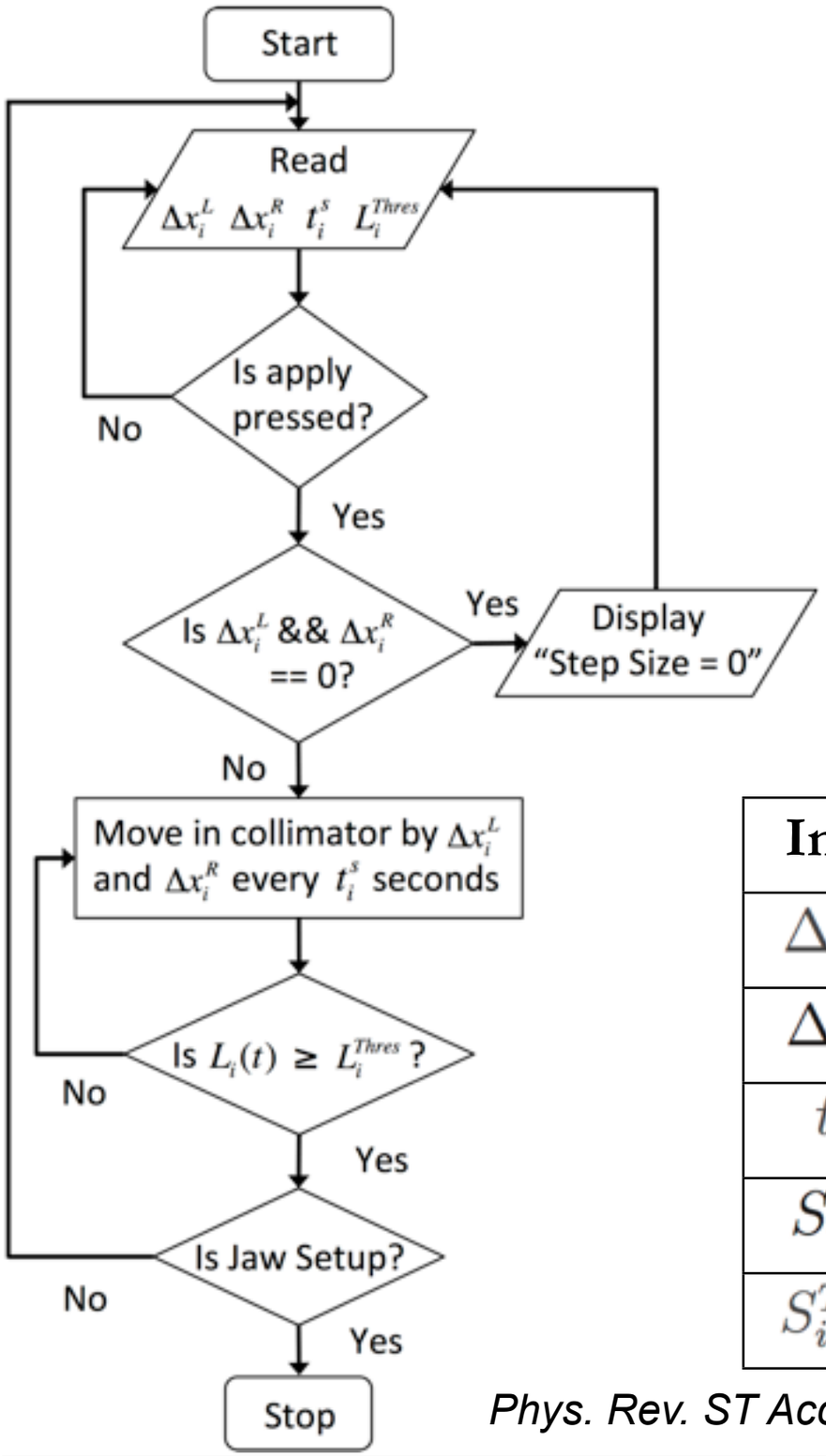
- An intelligent automated system would be able to align the collimators in less time and without human errors.

Outline

- CERN and the Large Hadron Collider
- LHC Collimation System
- Collimator Beam-Based Alignment
- **Alignment Algorithms**
- **Software Implementation**
- **Modeling and Simulation of Beam Losses**
- **Simulation and Operational Results**
- **Future: BPM-based alignment**
- **Conclusions**

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
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

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

Parallel Collimator Alignment

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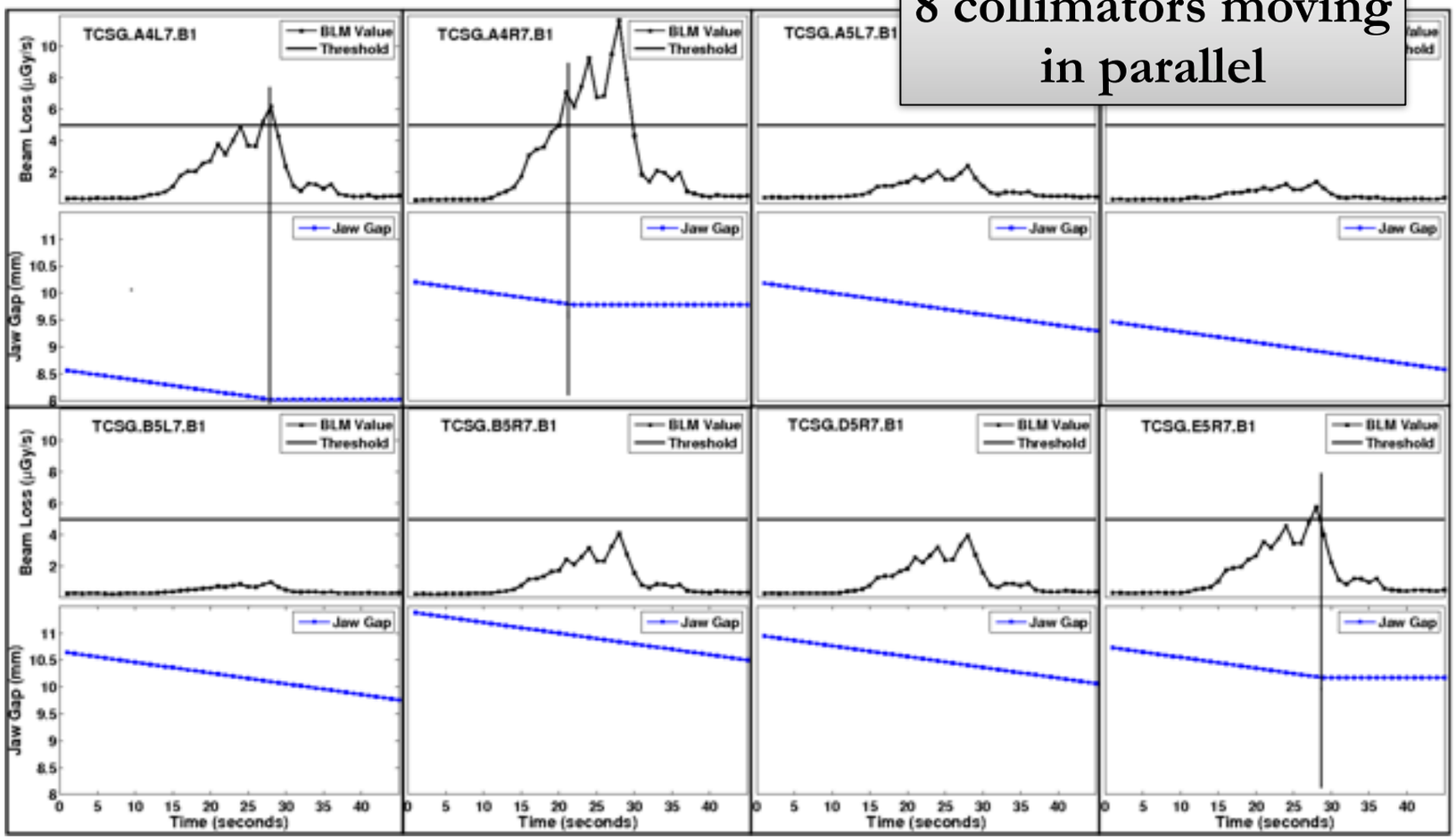
8 collimators moving in parallel



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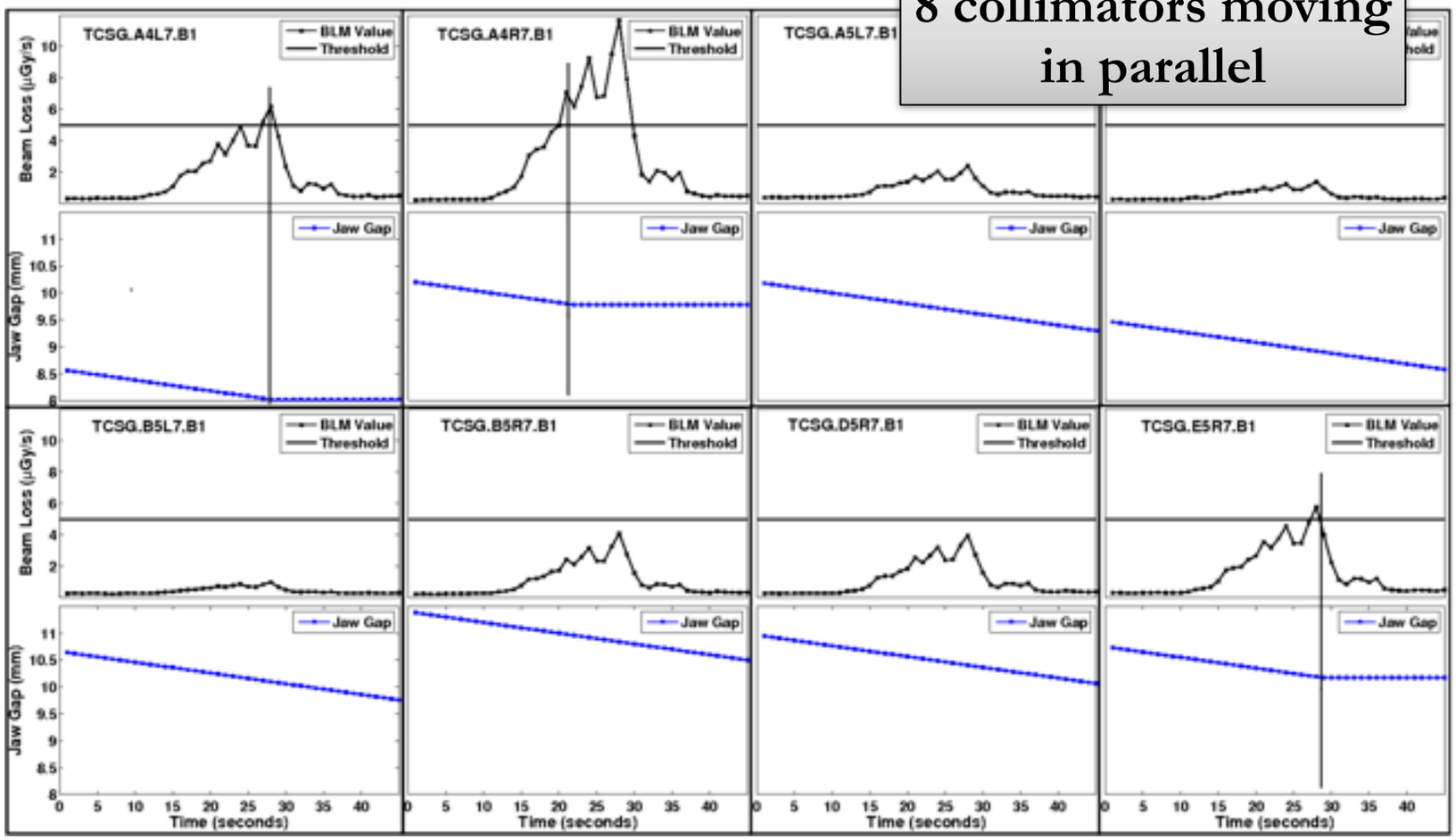

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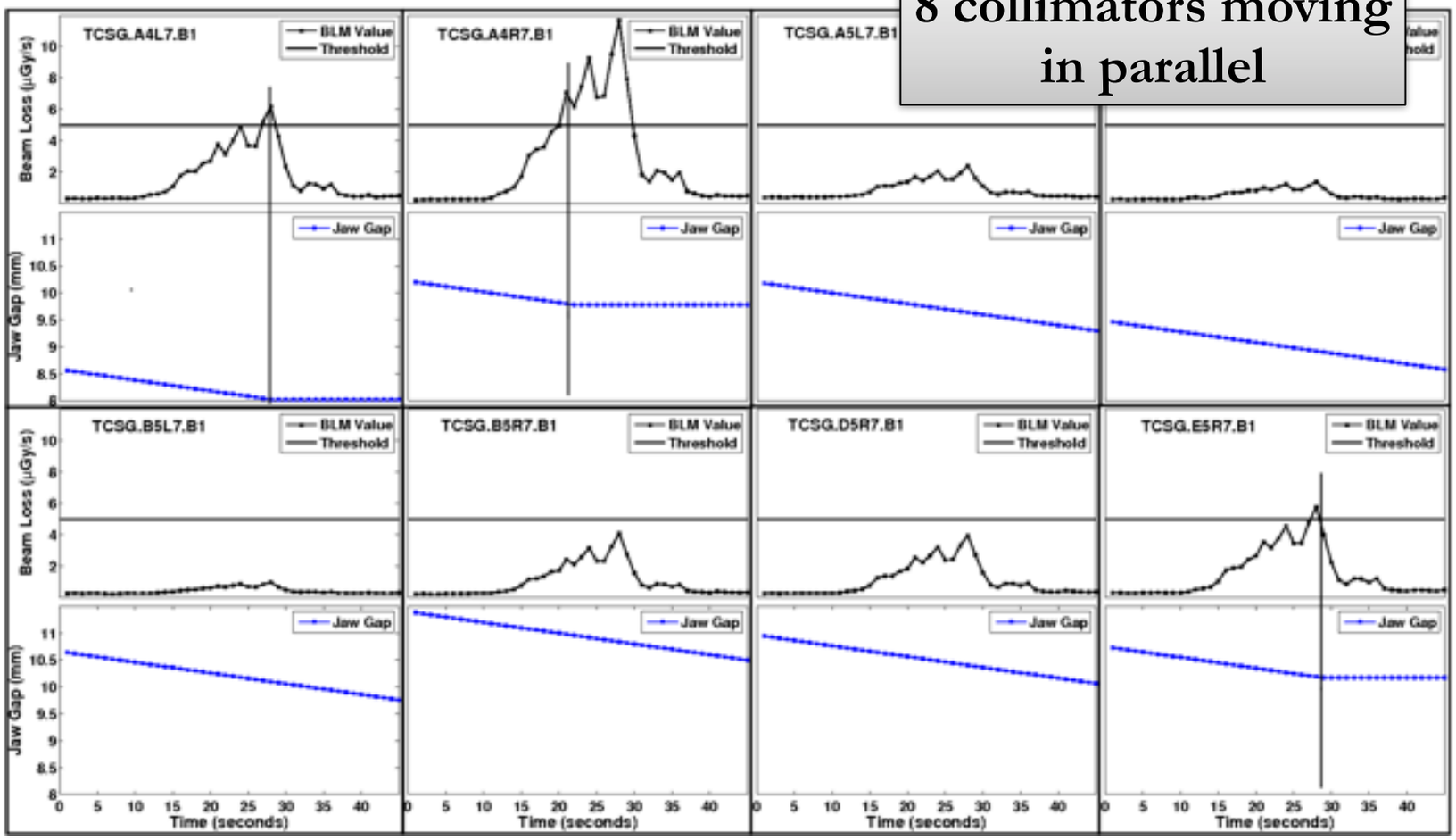

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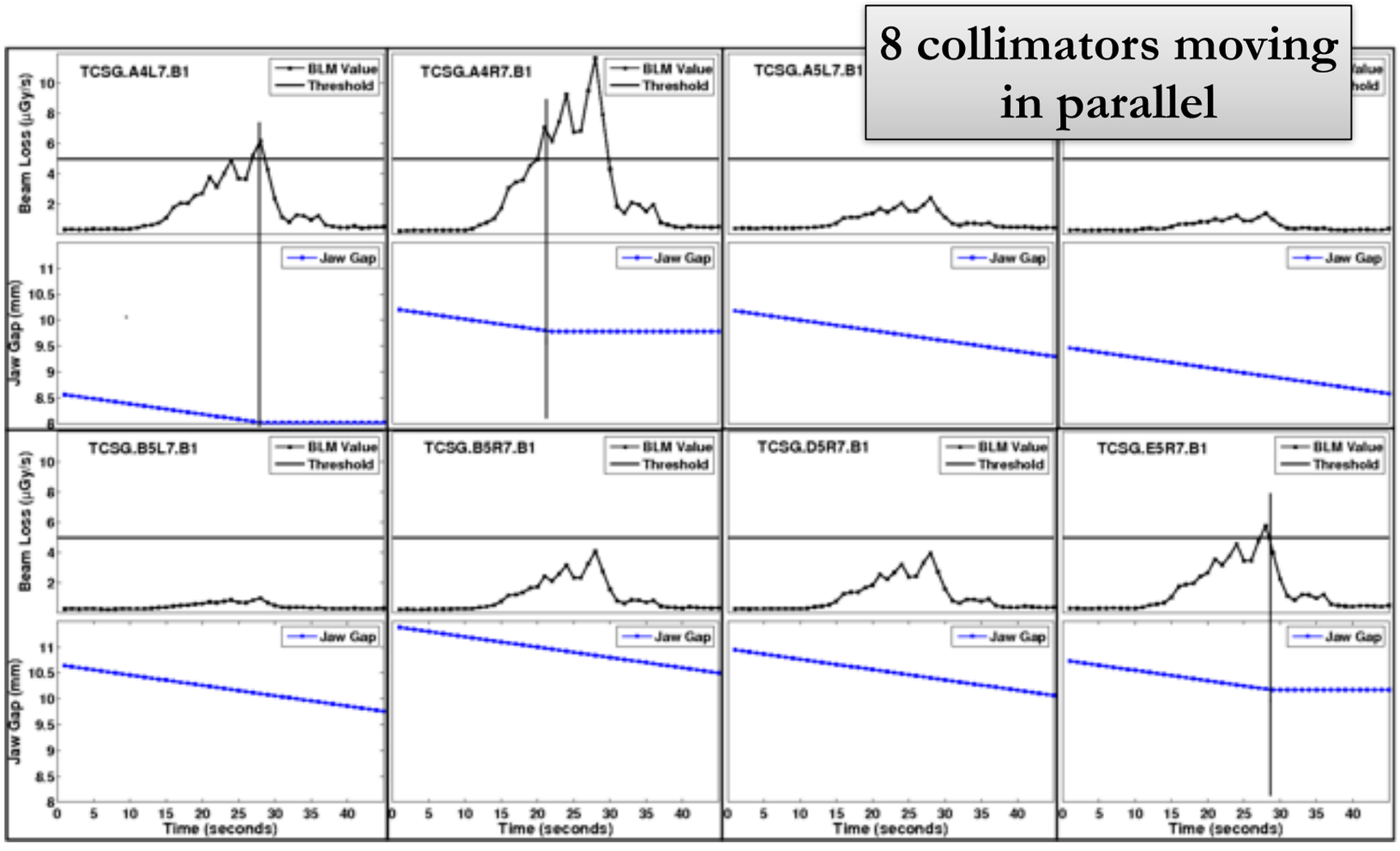

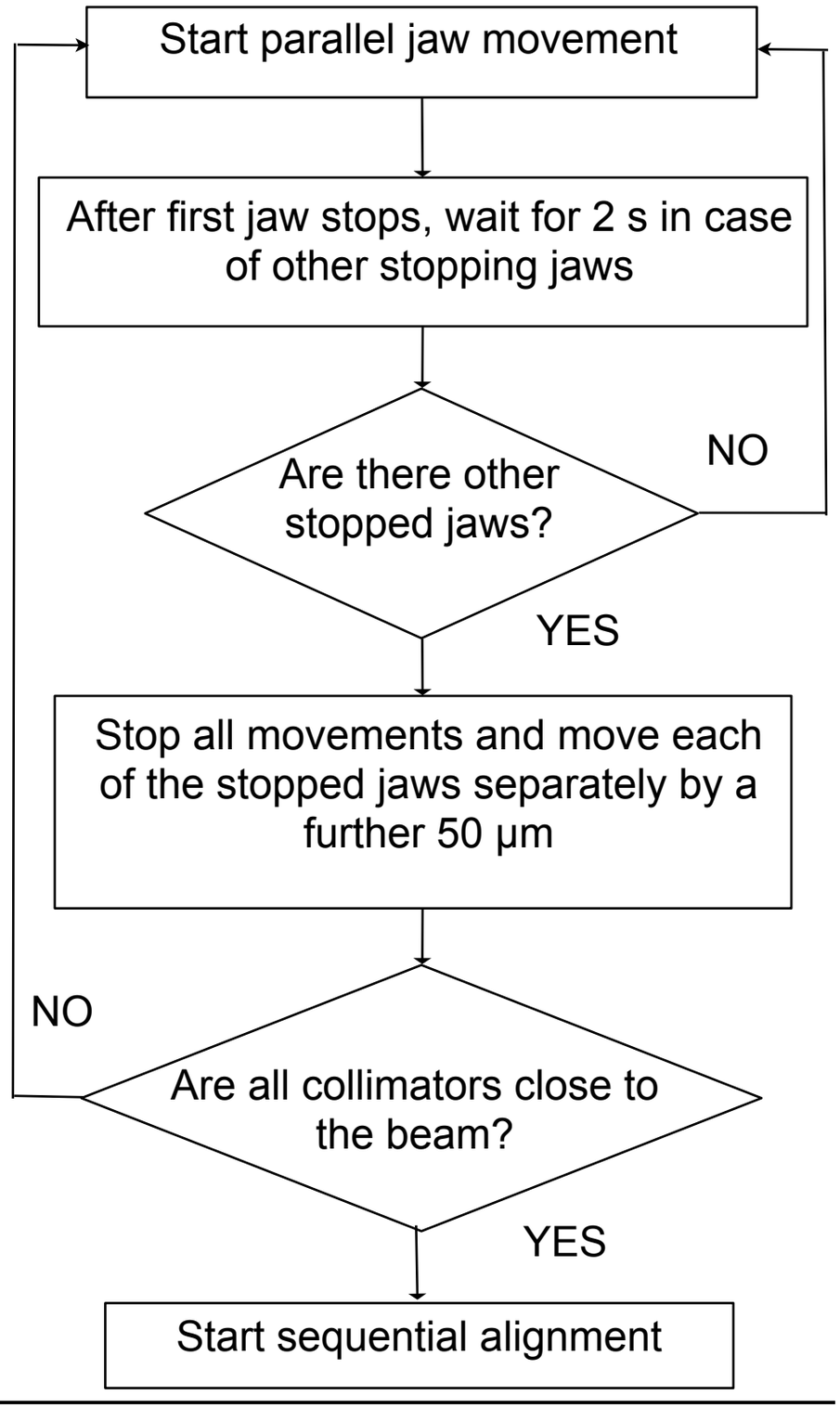

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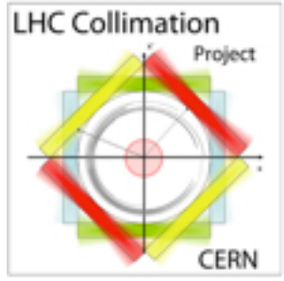
Automatic Threshold Selection



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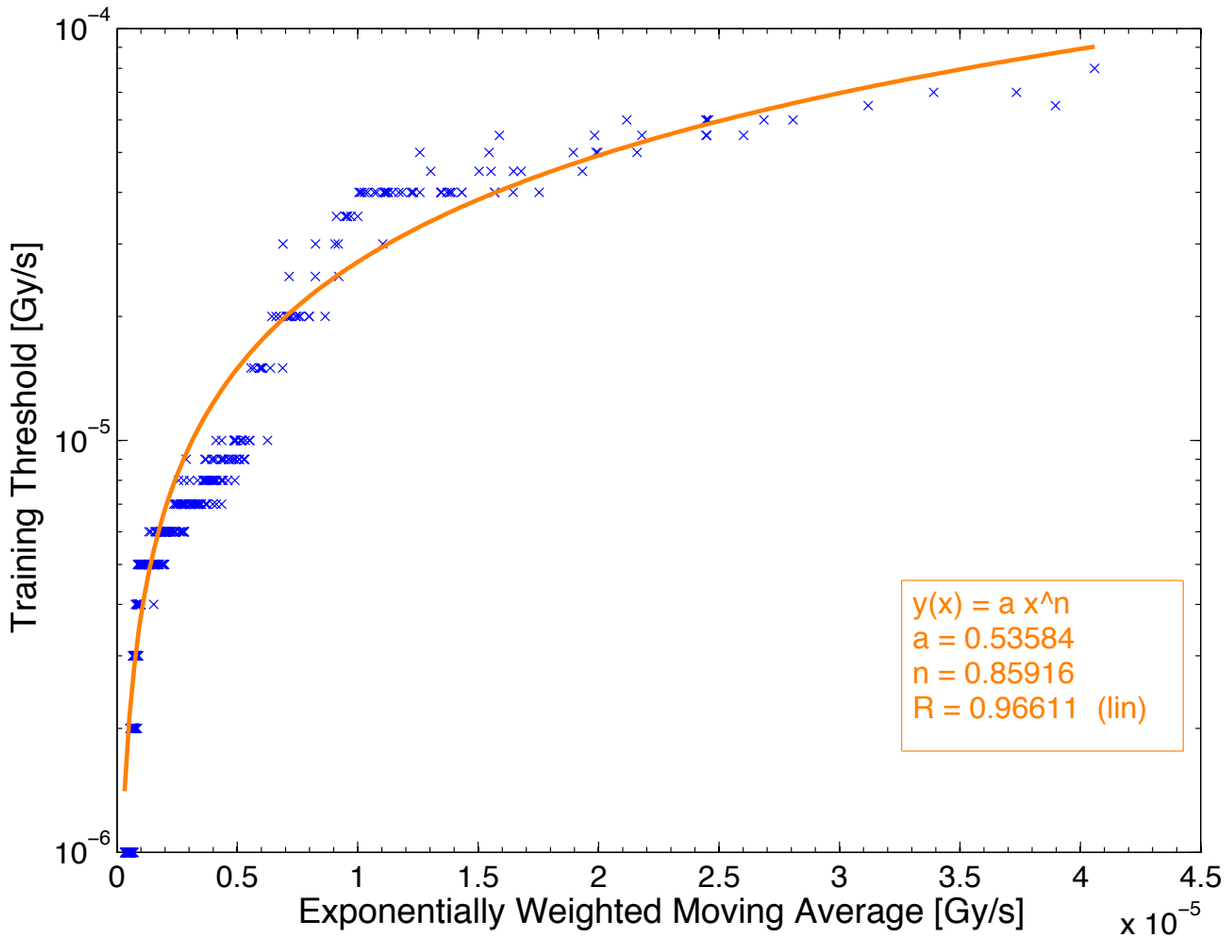
- Samples of the **steady-state BLM signal** in 20 second intervals and the **subsequent threshold** set by operator were collected.

- The **exponentially weighted moving average** of each sample was determined.

- Larger weights assigned to most recent values.

- The threshold can be calculated in terms of the steady-state BLM signal:

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



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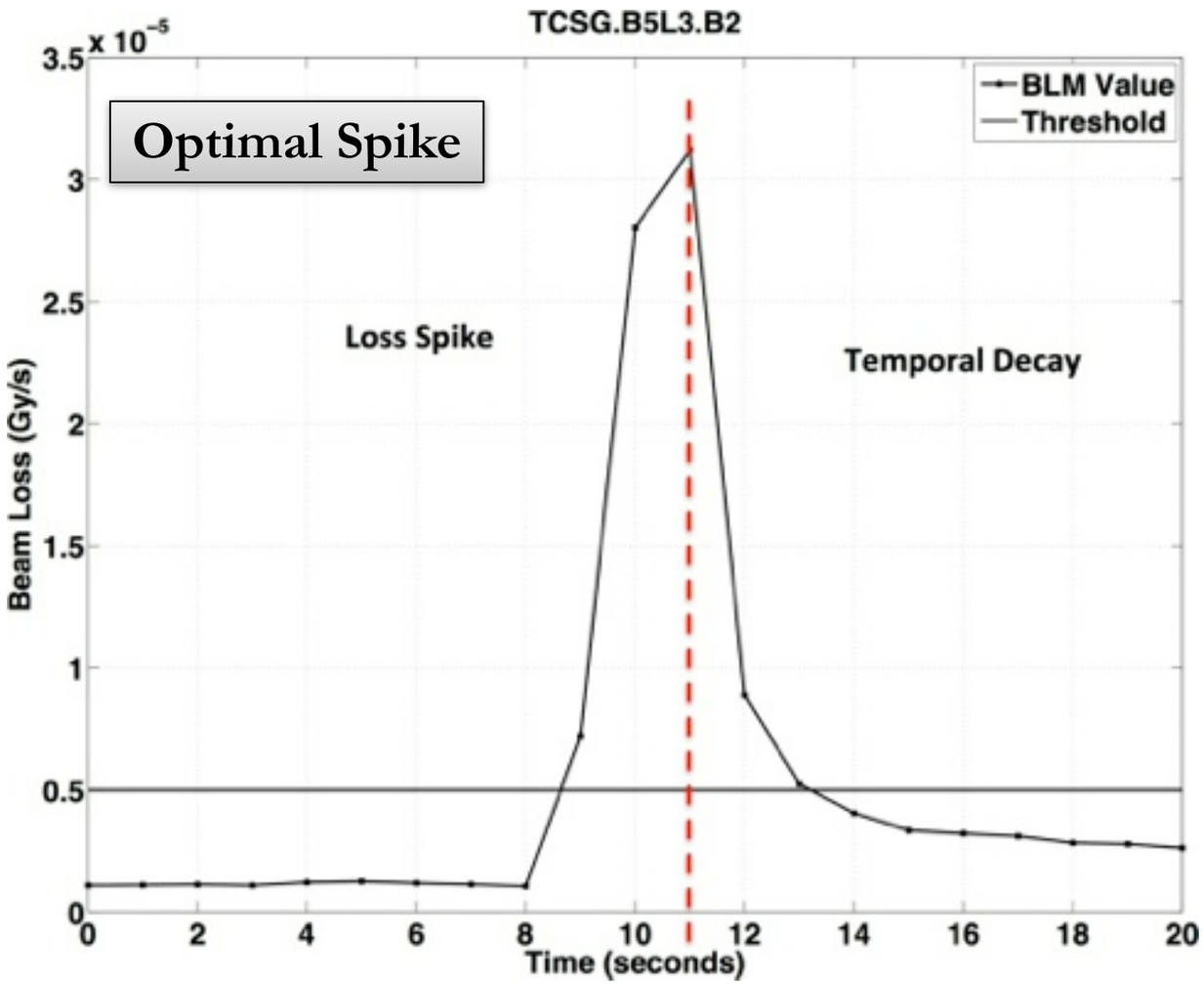
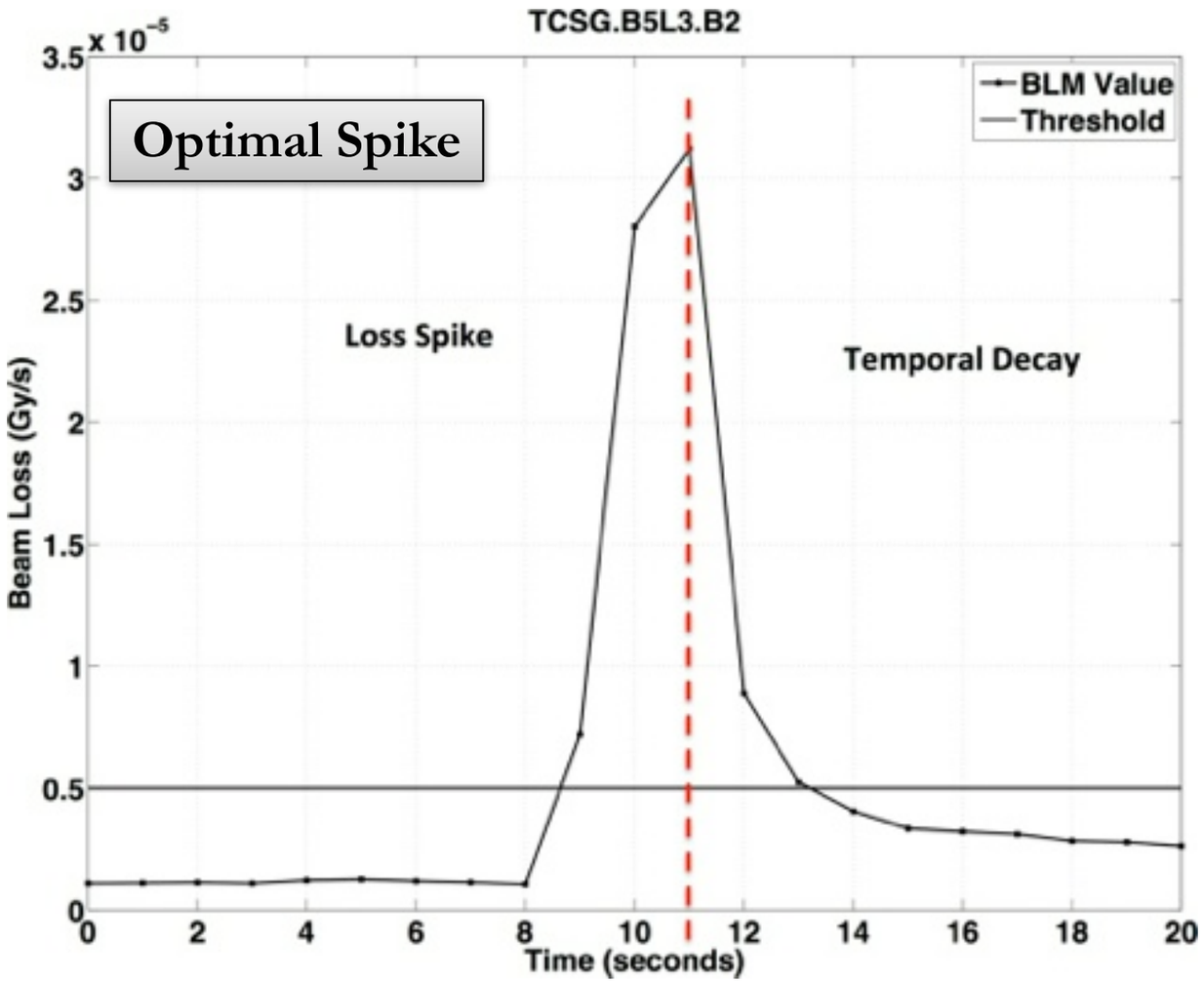
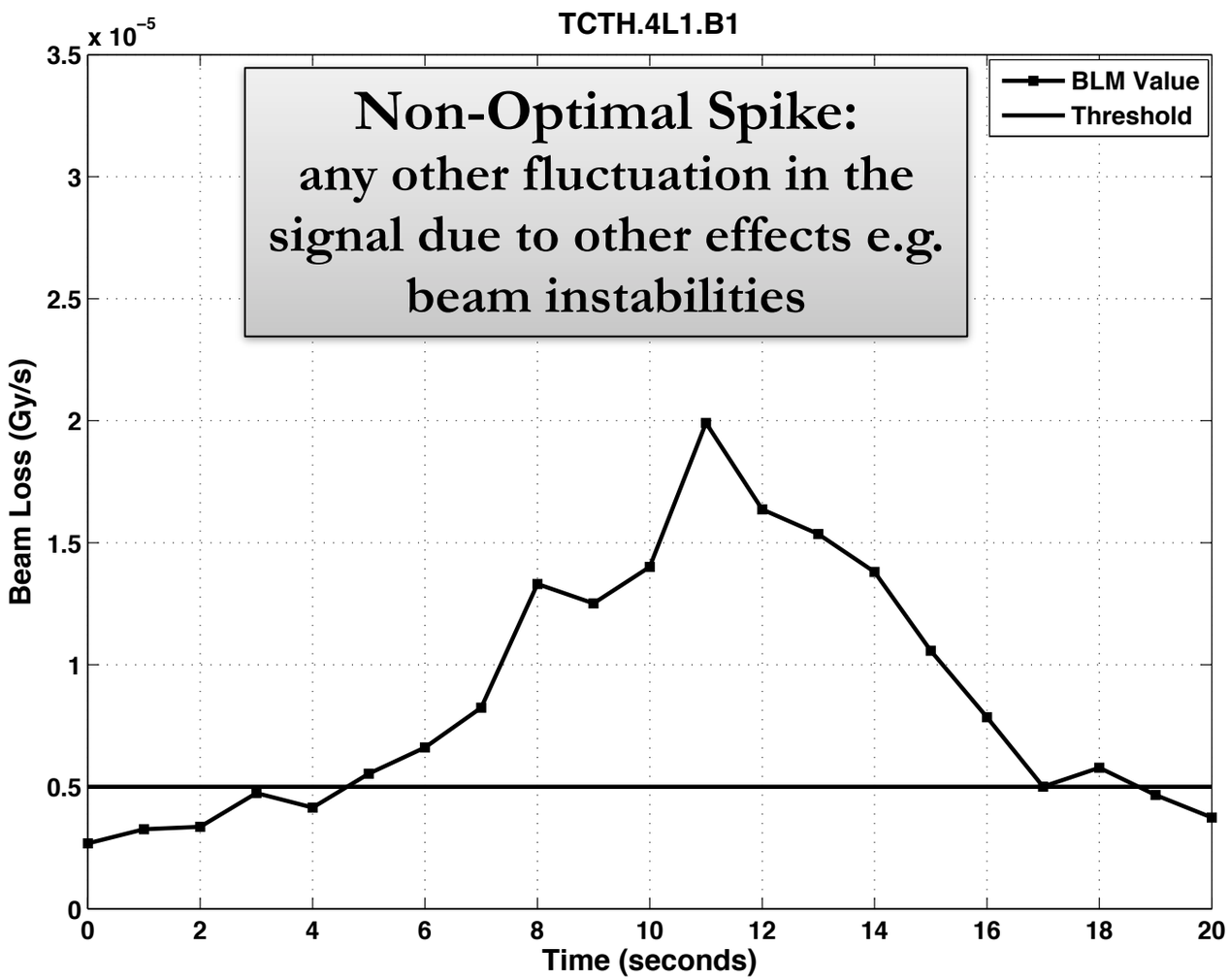
- A jaw is aligned to the beam when an **optimal spike** is observed.



BLM Spike Recognition

- Automatic classification of loss spikes is key to an automated setup procedure.
- **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.

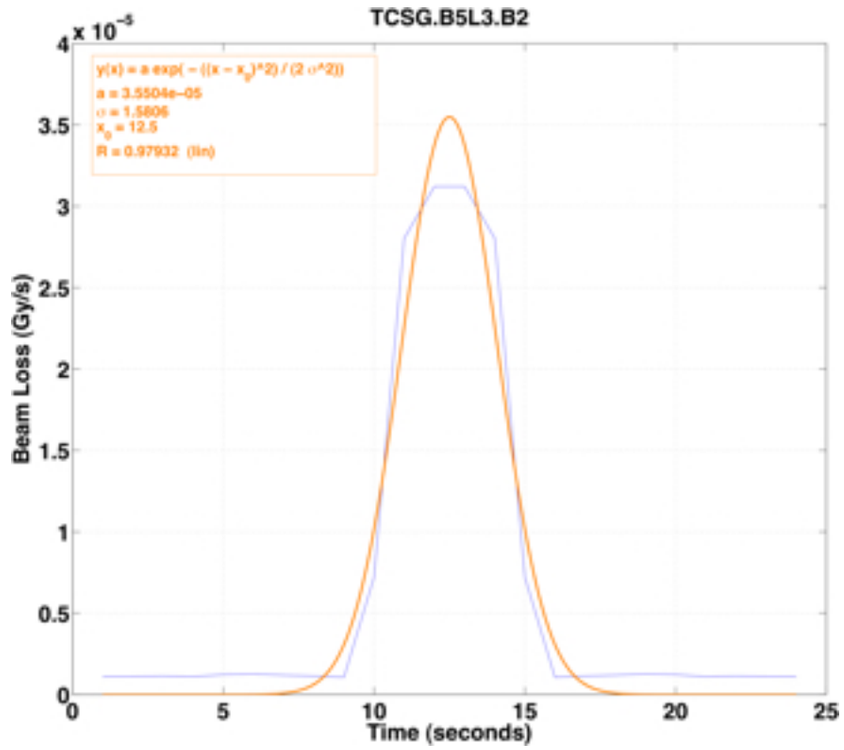


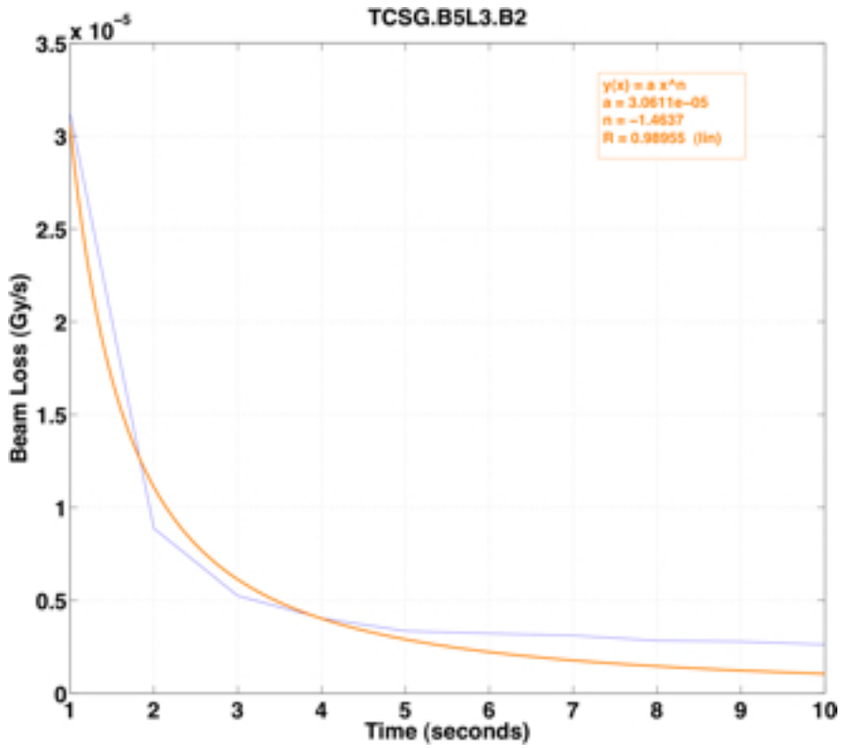


Feature Selection

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

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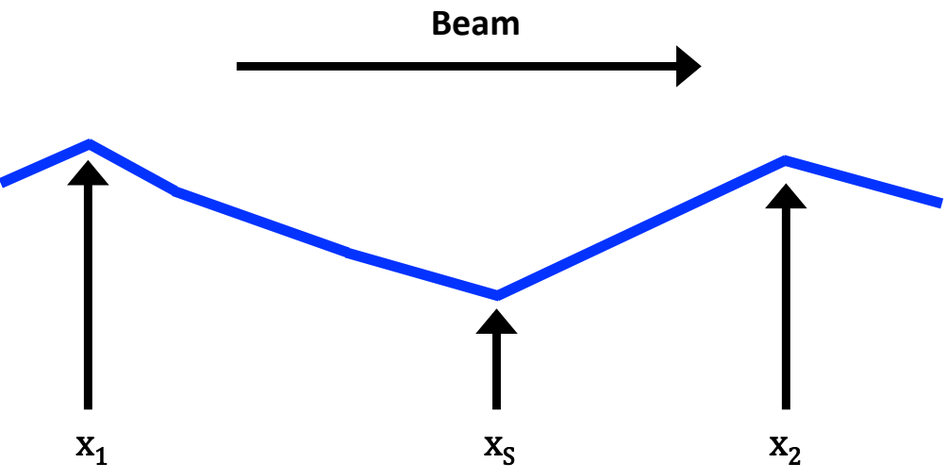
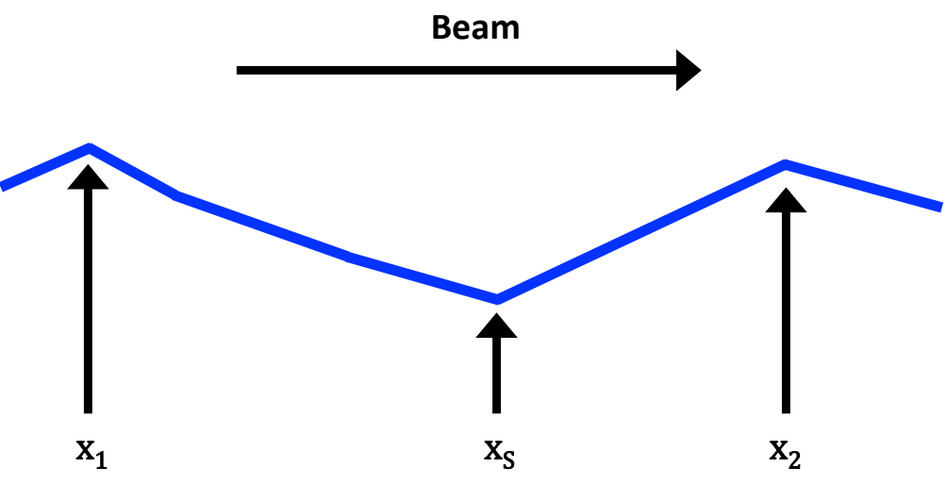
Some unsuccessful classifications due to TCT alignments!

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.

BPM-guided Coarse Alignment



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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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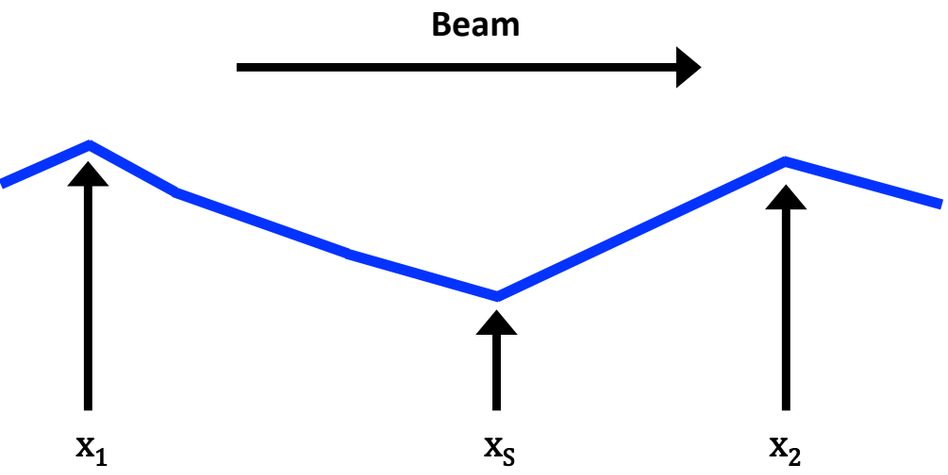

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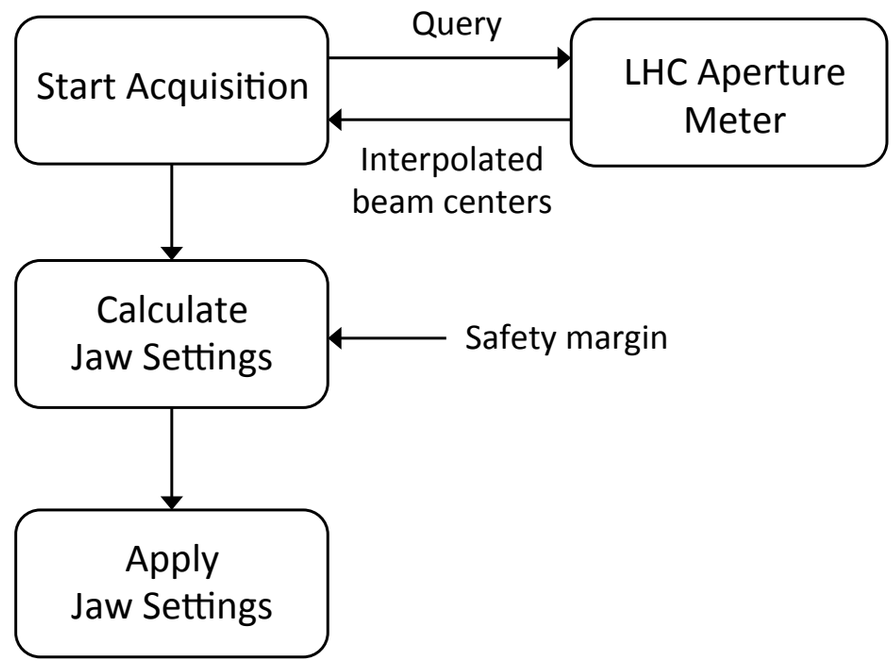

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BPM-guided Coarse Alignment

BPM Initialization

Collimator	BPM Center	Current Left	Current Right	New Left	New Right	
TCSG.A5L7.B1	-0.373	2.105	-2.585	2.112	-2.858	☐
TCP.C6R7.B2	0.150	2.030	-0.990	2.509	-2.210	☐
TCSG.6L7.B2	-0.421	3.180	-3.435	2.979	-3.821	☑
TCLA.7L3.B2	-0.164	5.205	-5.545	1.491	-1.819	☑
TCLA.6L3.B2	0.410	5.350	-6.125	2.616	-1.796	☑
TCLA.B5L3.B2	-0.089	5.055	-7.360	2.278	-2.456	☑
TCSG.B5L3.B2	-0.150	2.940	-3.680	1.374	-1.674	☑
TCSG.A5L3.B2	-0.160	2.510	-3.405	1.227	-1.548	☑
TCSG.4L3.B2	-0.214	1.985	-2.595	0.916	-1.344	☑
TCSG.5R3.B2	-0.168	2.865	-3.740	1.353	-1.688	☑
TCP.6R3.B2	-0.114	3.850	-4.030	2.107	-2.336	☑
TCLA.A7L7.B2	-0.114	2.620	-1.245	1.532	-1.760	☑
TCLA.D6L7.B2	0.328	2.105	-1.730	1.965	-1.308	☑
TCLA.B6L7.B2	-0.032	3.115	-2.890	2.389	-2.454	☑
TCSG.B4R7.B2	-0.268	1.165	-3.280	2.098	-2.635	☑
TCP.B6R7.B2	0.167	1.045	-1.515	2.203	-1.868	☐
TCSG.A5R7.B2	-0.069	2.885	-1.805	2.416	-2.554	☐

☑ Select All

Half Gap (sigma) 6

Center Delta (mm) 0.5

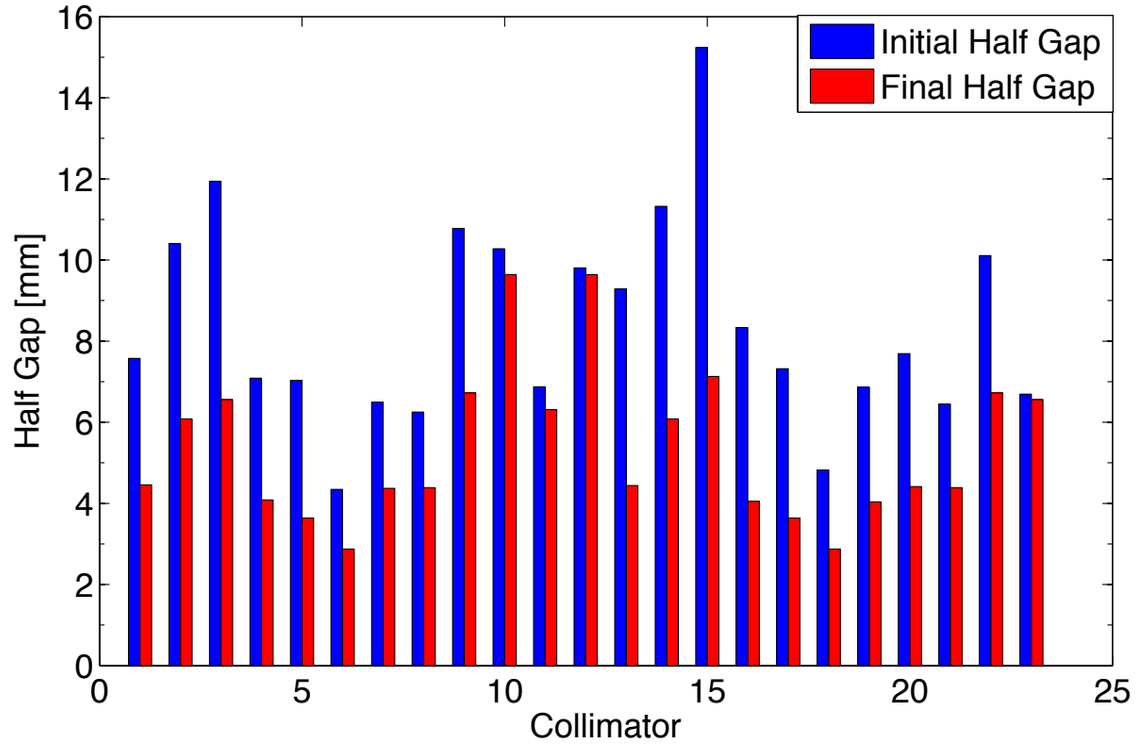
Acquire | Move | Stop

Tool GUI

BPM-guided Coarse Alignment

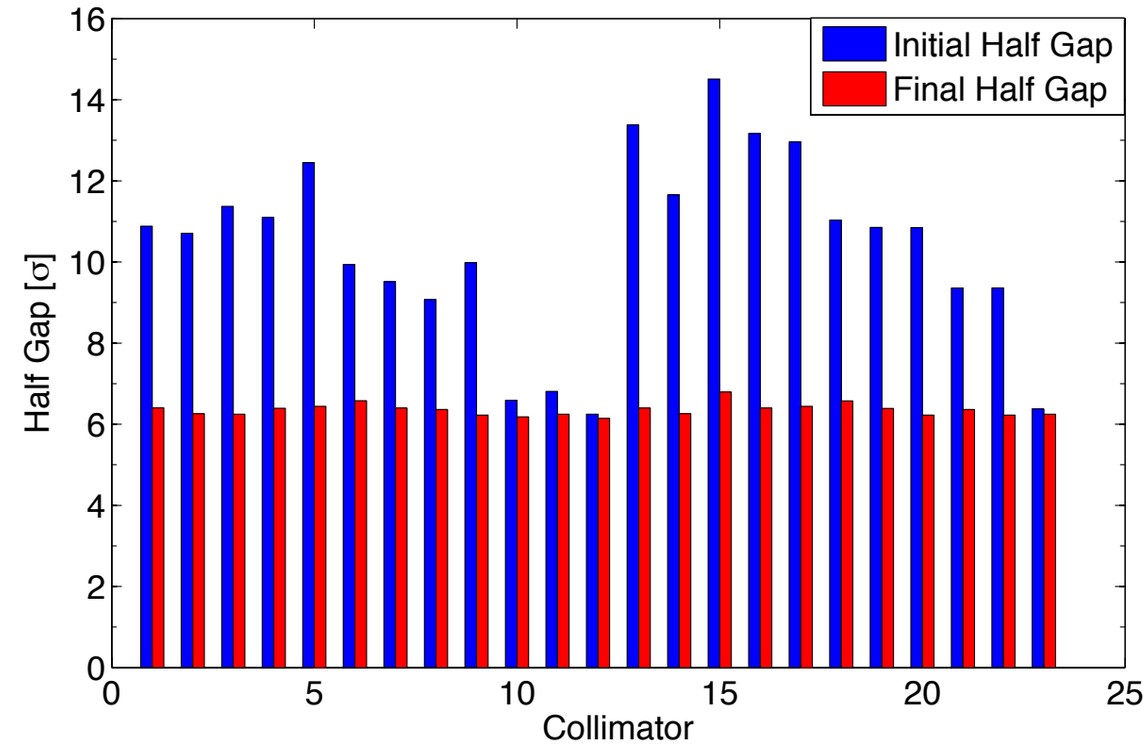
MD 2011 results

Tool GUI



15 σ

6.2 σ



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Data acquisition

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- **Collimator data:** motor positions and LVDT data acquired by subscribing to *RequiredAbsolutePosition* and *MeasuredCornerPositions* parameters. Data published at 1 Hz.
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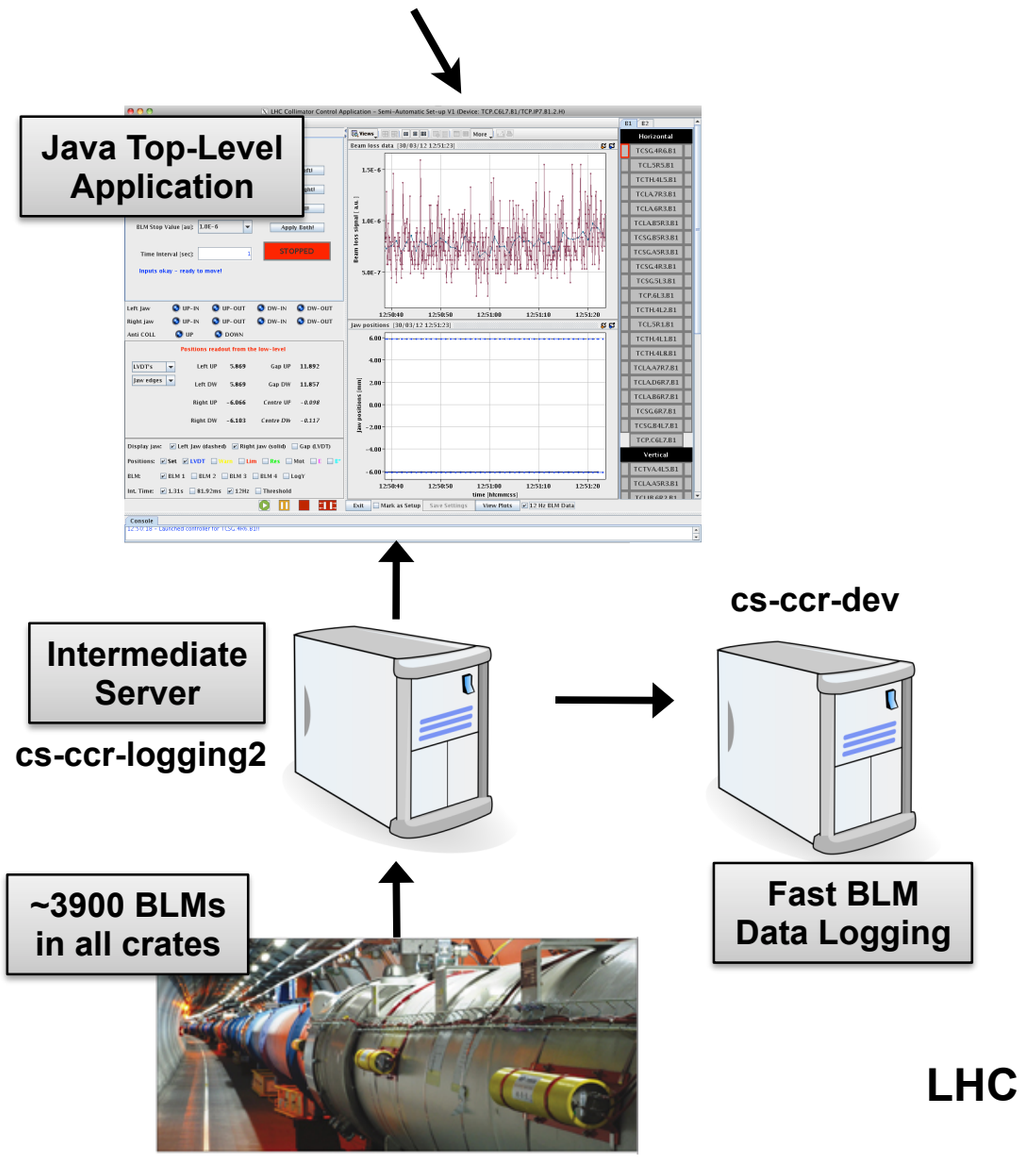

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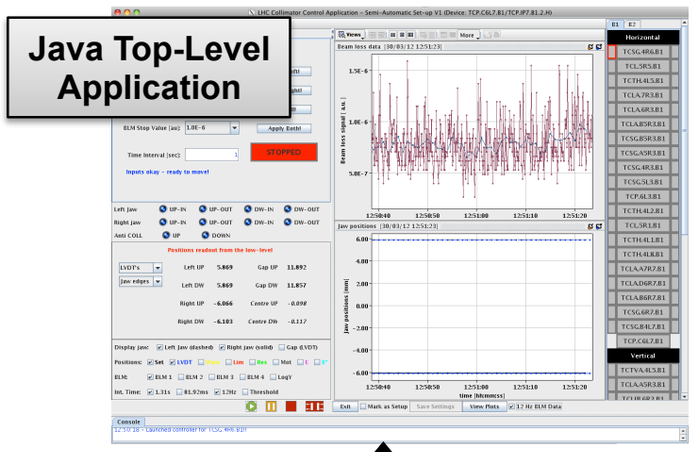
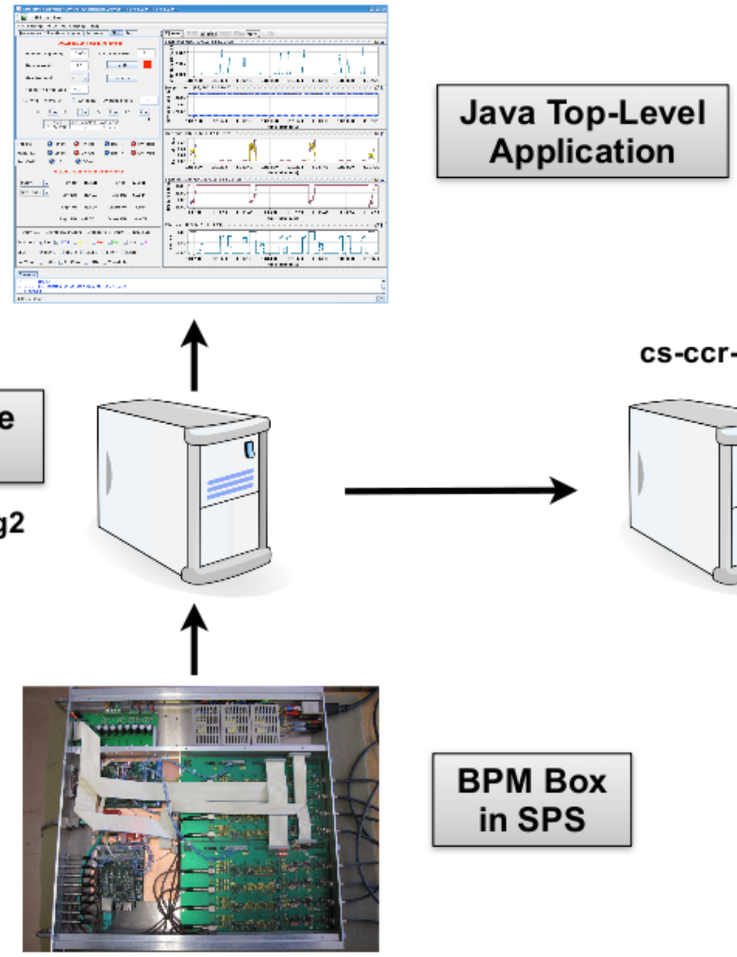
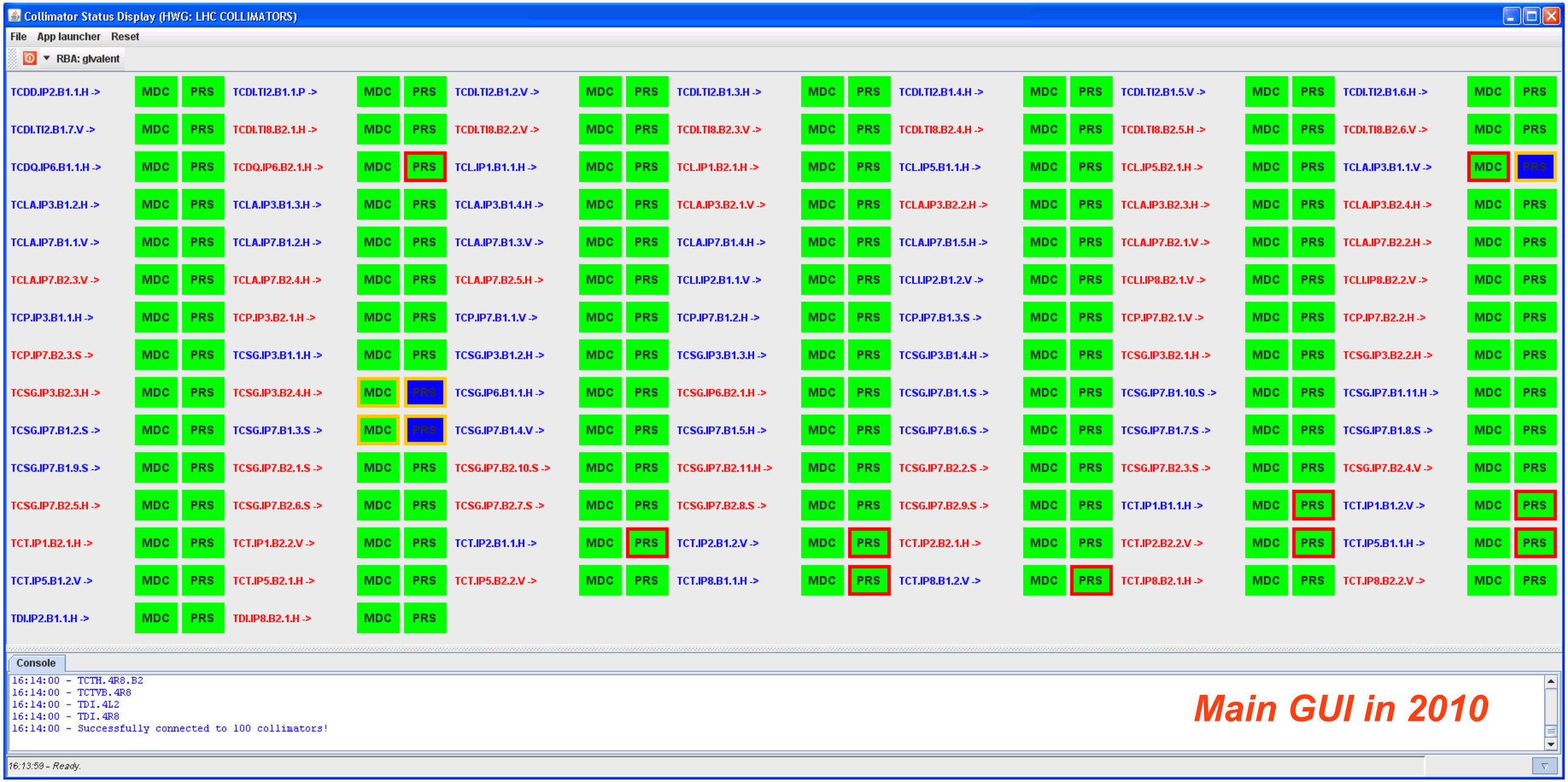


- **10 Hz BPM data:**



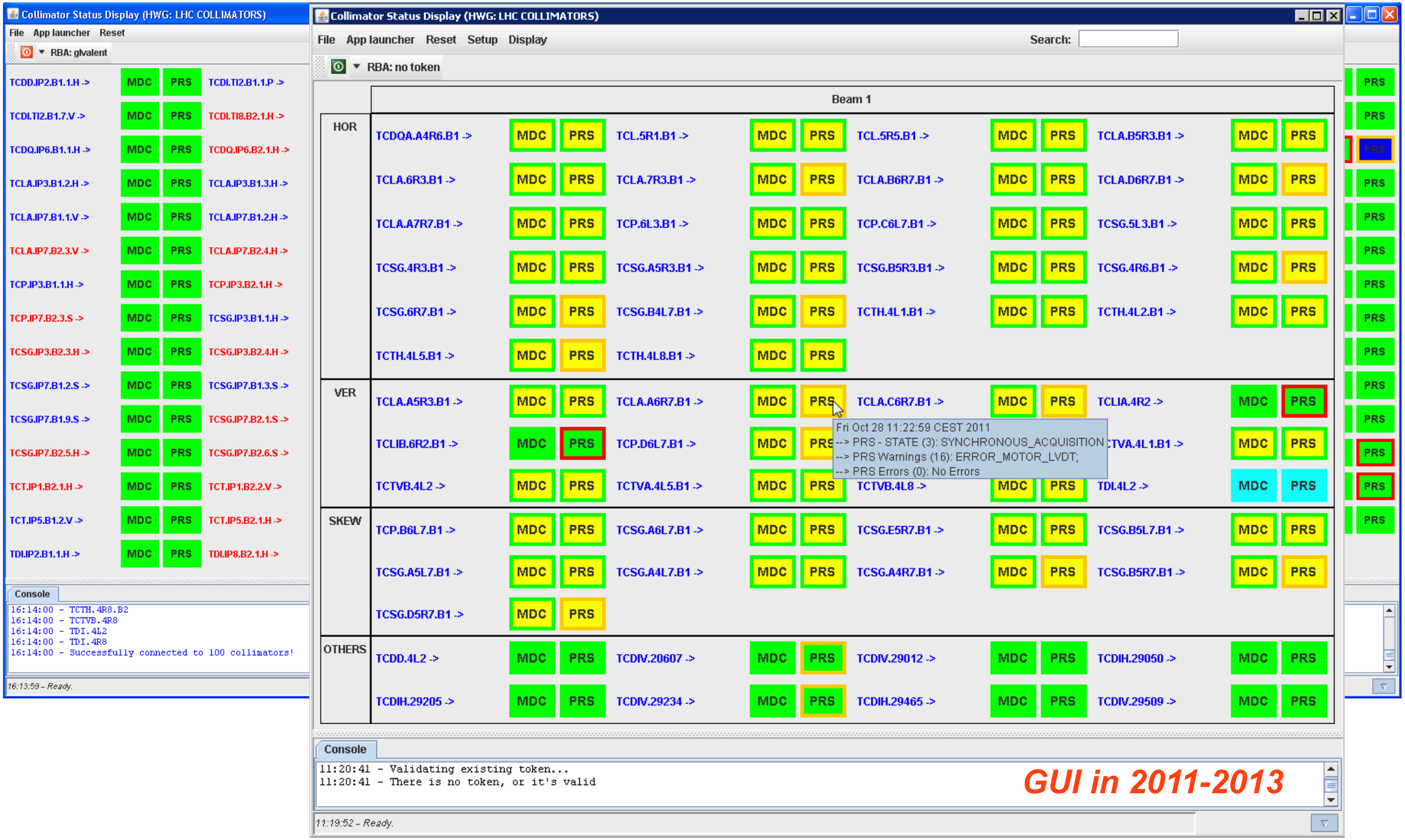
LHC SPS

BLM-based alignment software



Main GUI in 2010

BLM-based alignment software



GUI in 2011-2013

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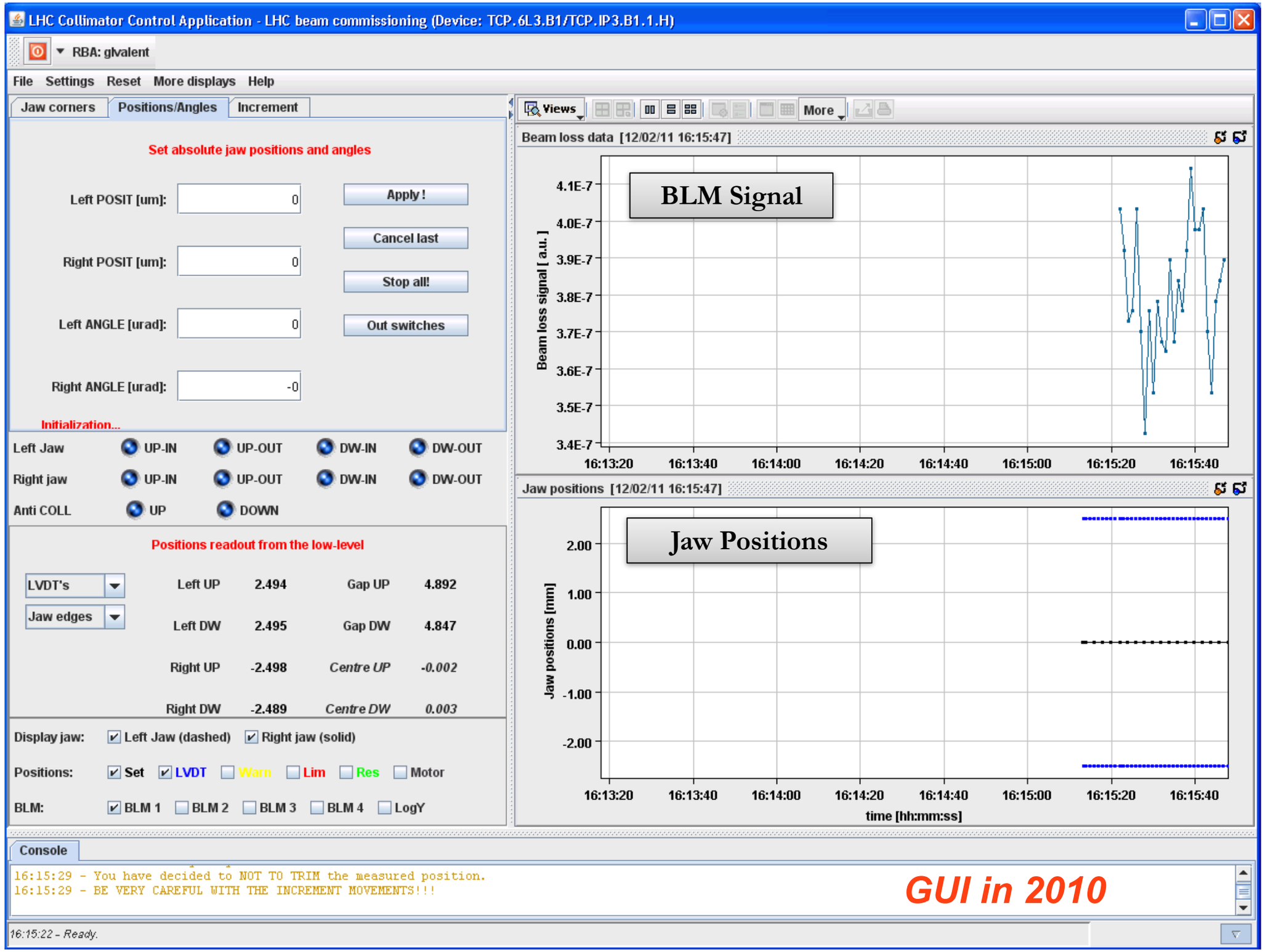

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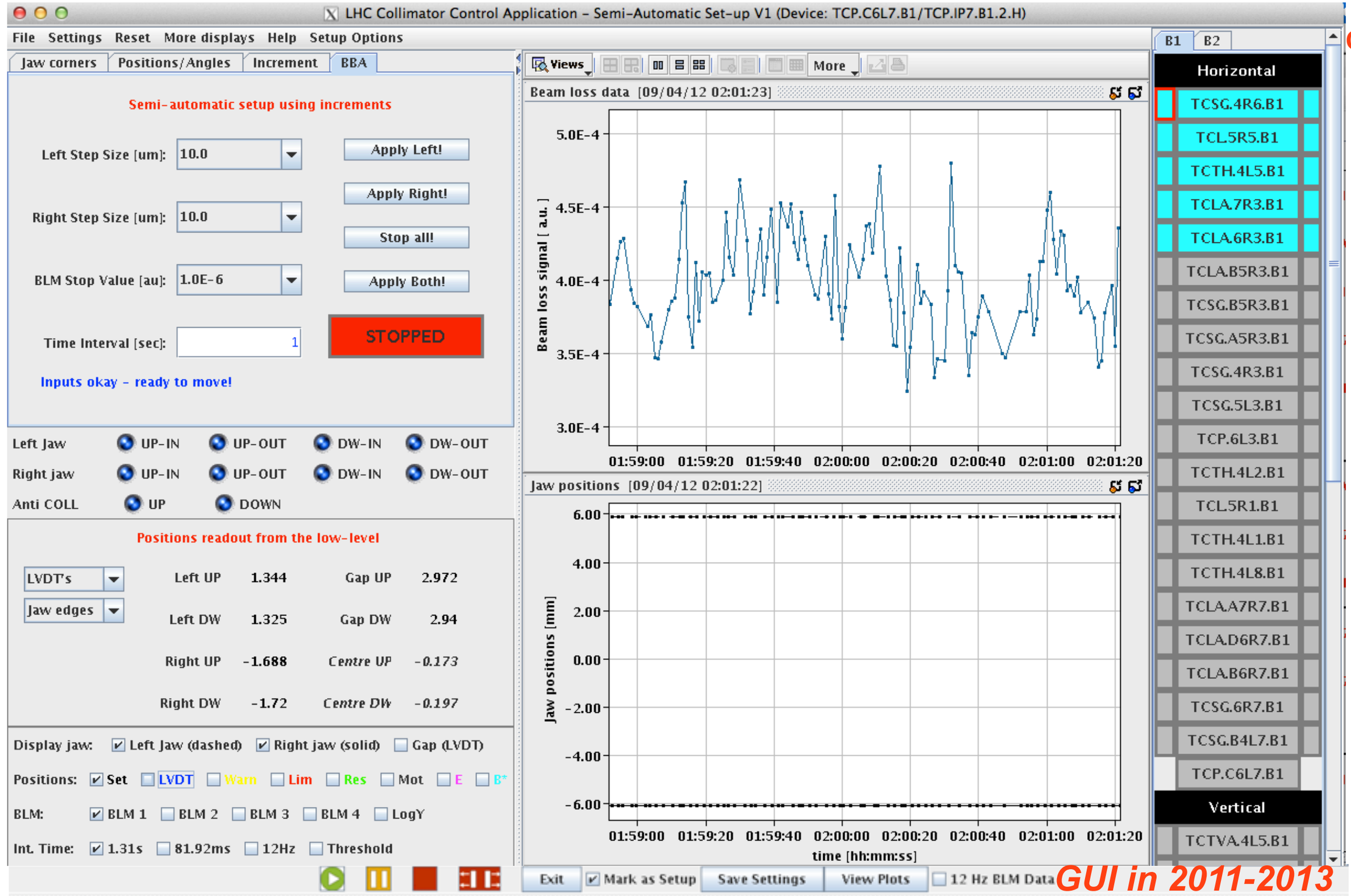
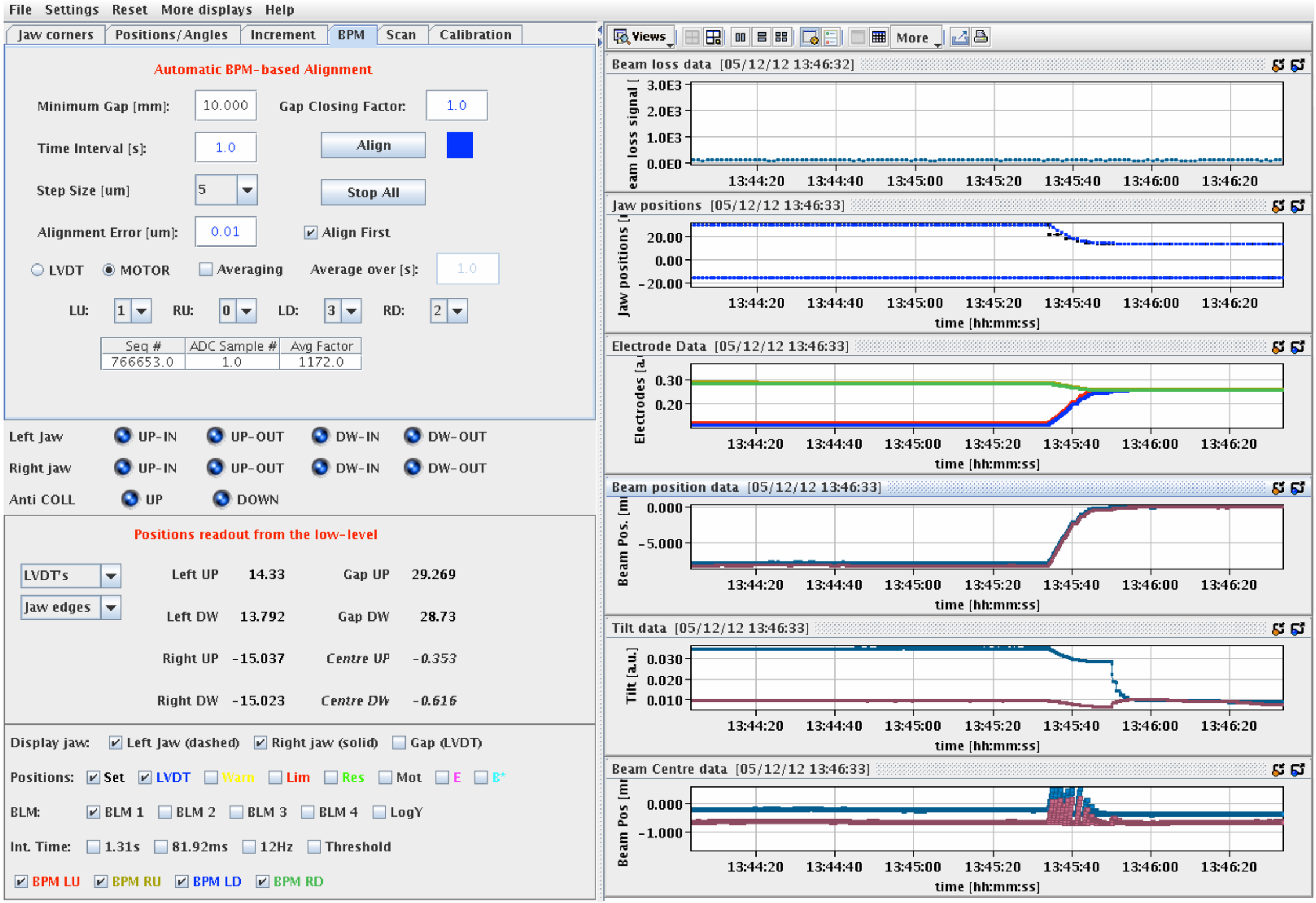


Collimators

GUI in 2011-2013

BPM-based alignment software



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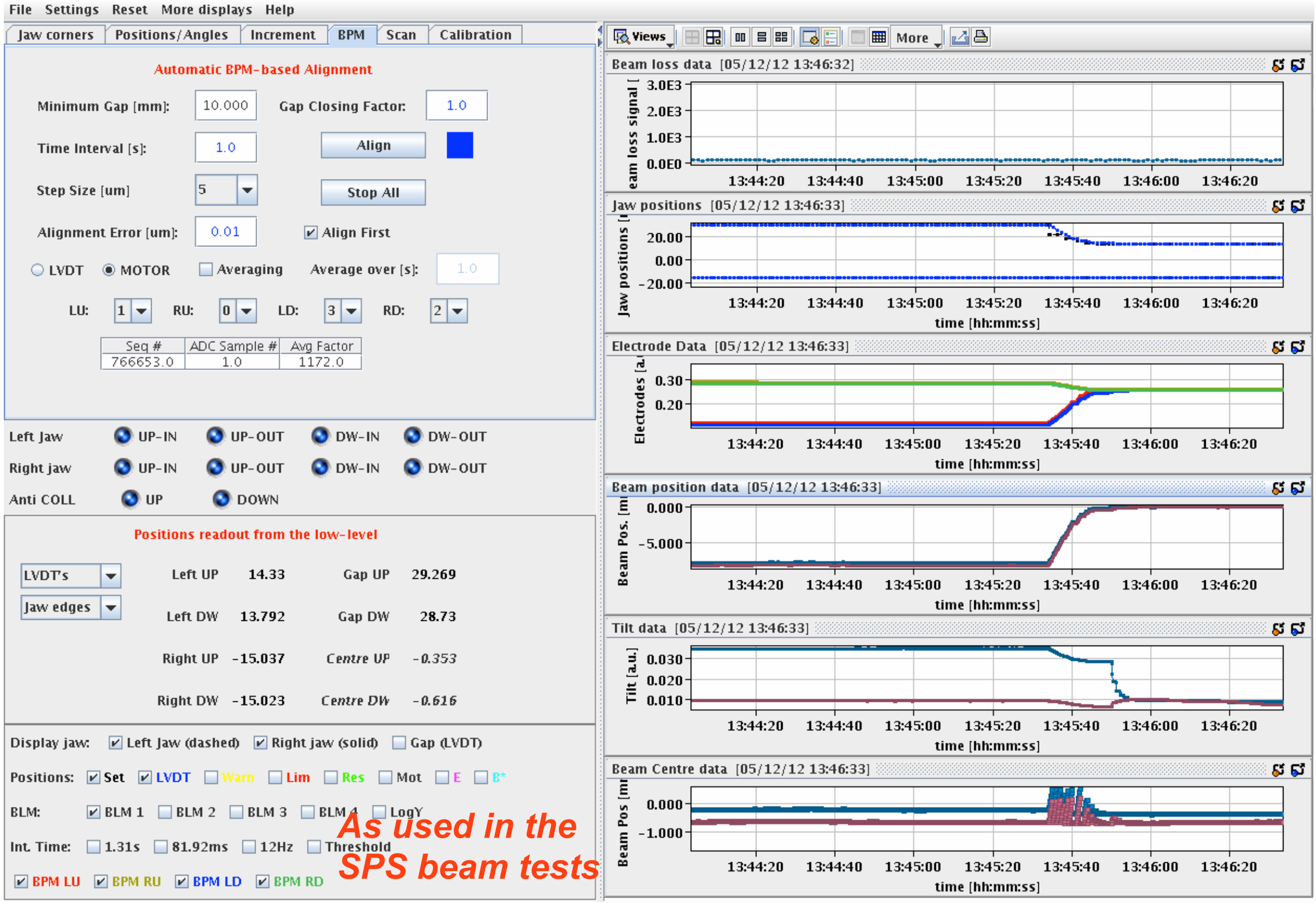

As used in the SPS beam tests

Outline

- CERN and the Large Hadron Collider
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- Software Implementation
- **Modeling and Simulation of Beam Losses**
- **Simulation and Operational Results**
- **Future: BPM-based alignment**
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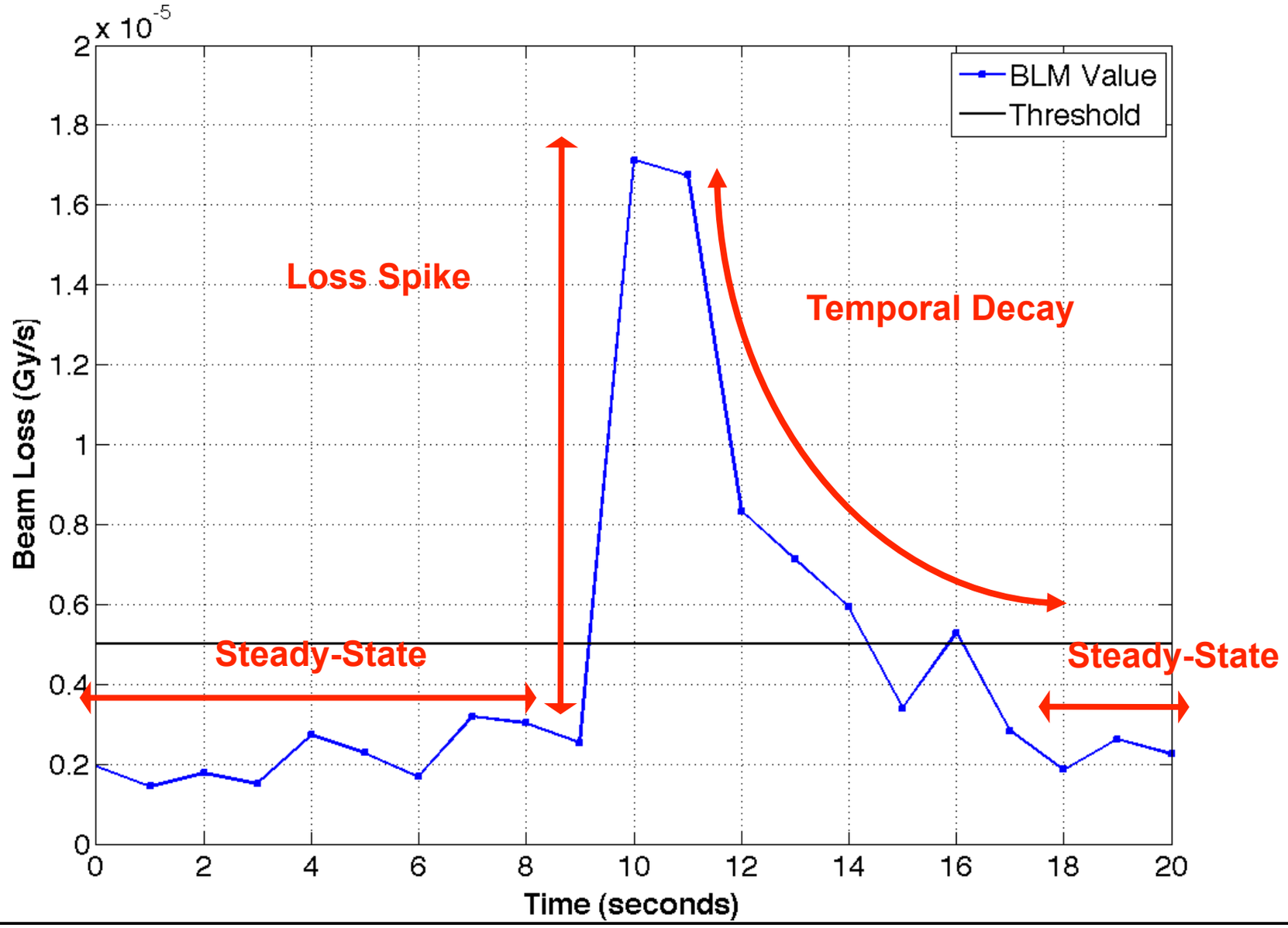
- Loss spike consists of 3 components which have to be understood and modeled:

Typical Optimal Loss Spike



Steady-State BLM Signal

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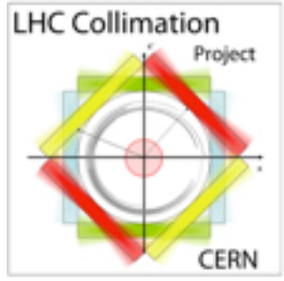

- Empirical model of the BLM steady-state as a function of jaw half gap in σ.
- Four alignment data sets: 450 GeV 2011, 3500 GeV 2011, 450 GeV 2012, 4000 GeV 2012.
- Hundreds of steady-state samples were extracted using a Java application.
- 1 sample = average of last 5 s of data from collimator BLMs when no collimators were moving in the previous 10 s.

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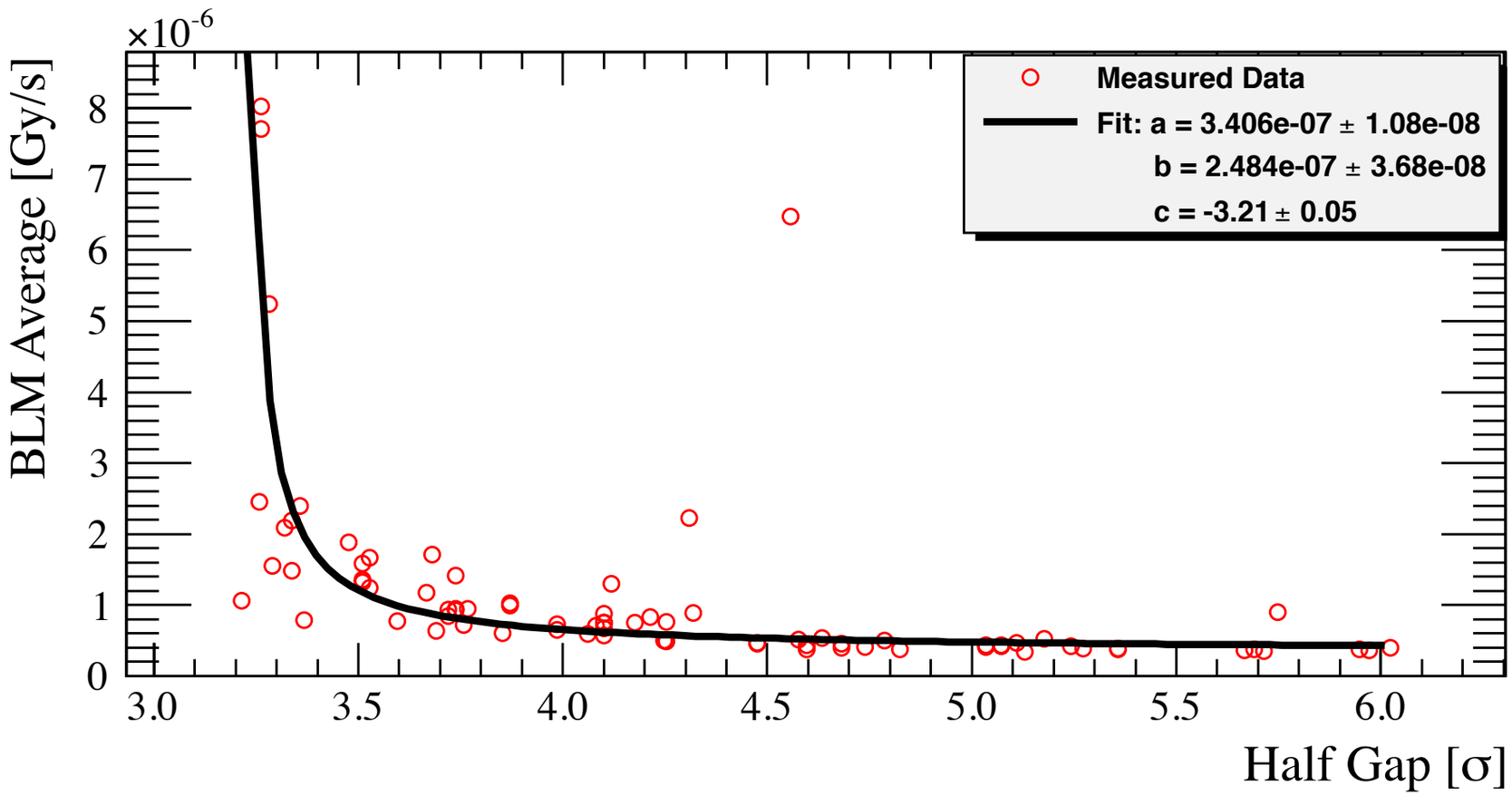
- 1 sample = average of last 5 s of data from collimator BLMs when no collimators were moving in the previous 10 s.
- Polynomial fits of the form $y = a + \frac{b}{x + c}$ e applied, e.g.:



Loss Spike and Decay: Beam Diffusion Measurements

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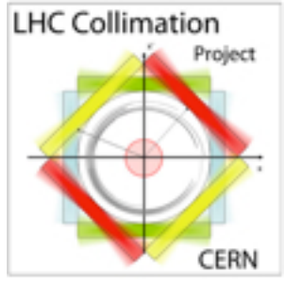

- **Beam diffusion** is the process by which particles are driven from the beam core to the periphery (halo).

- An MD was conducted in on 22nd June 2012 to measure the rate of diffusion in the LHC.

Loss Spike and Decay: Beam Diffusion Measurements

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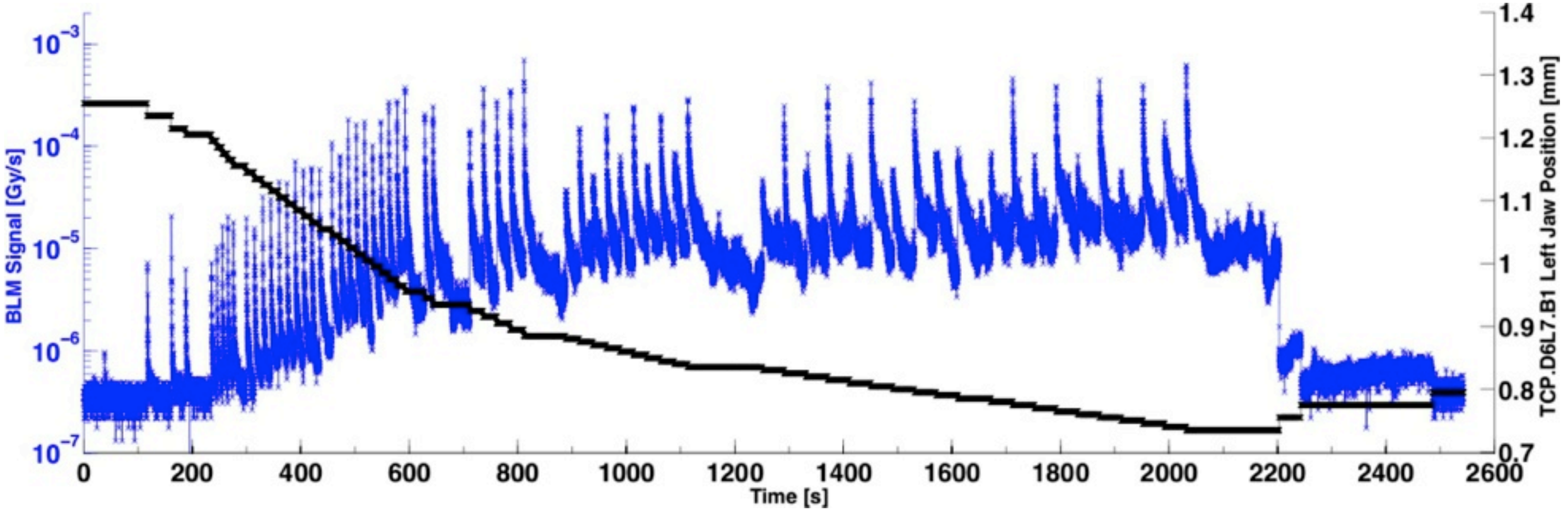
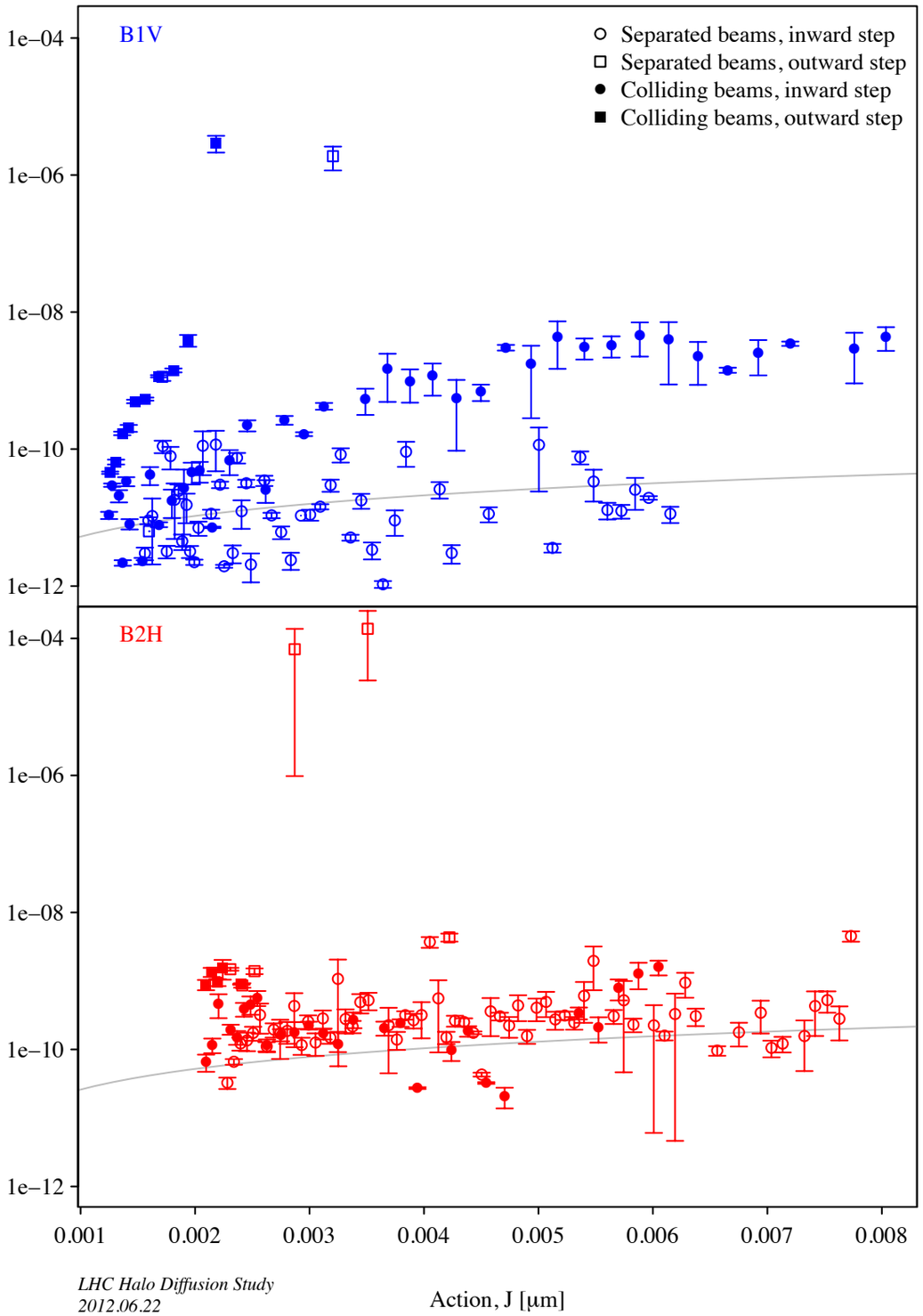
- Collimator jaws used to scrape away the beam halo to observe the response in the BLMs:

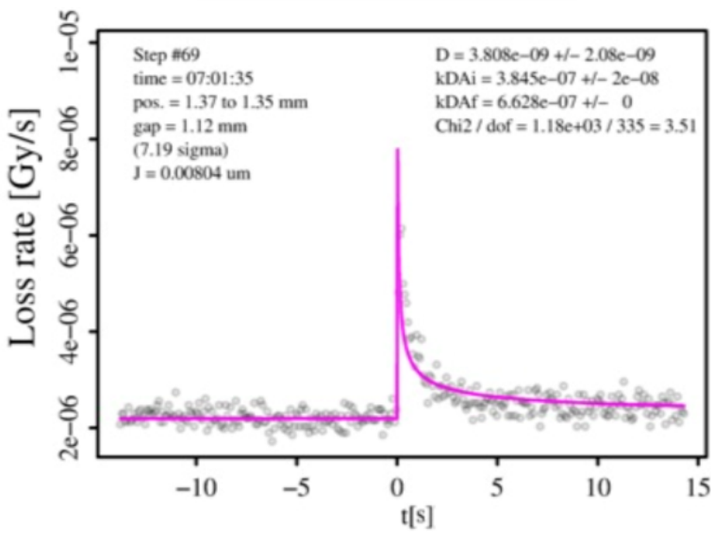


Loss Spike and Decay: Beam Diffusion Measurements (2)

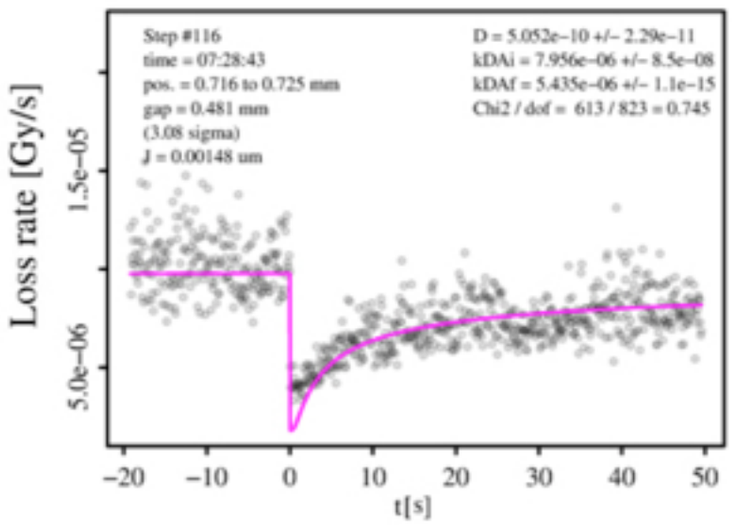


*Phys. Rev. ST Accel. Beams, **16**, 021003 (2013).*

Inward Step



Outward Step



Courtesy of G. Stancari

- Good agreement between diffusion coefficients measured from scraping and from beam emittance growth.
- Larger diffusion rates for colliding beams expected due to luminosity.
- Can be used to simulate spike and decay as a function of jaw position!

BLM Signal Crosstalk

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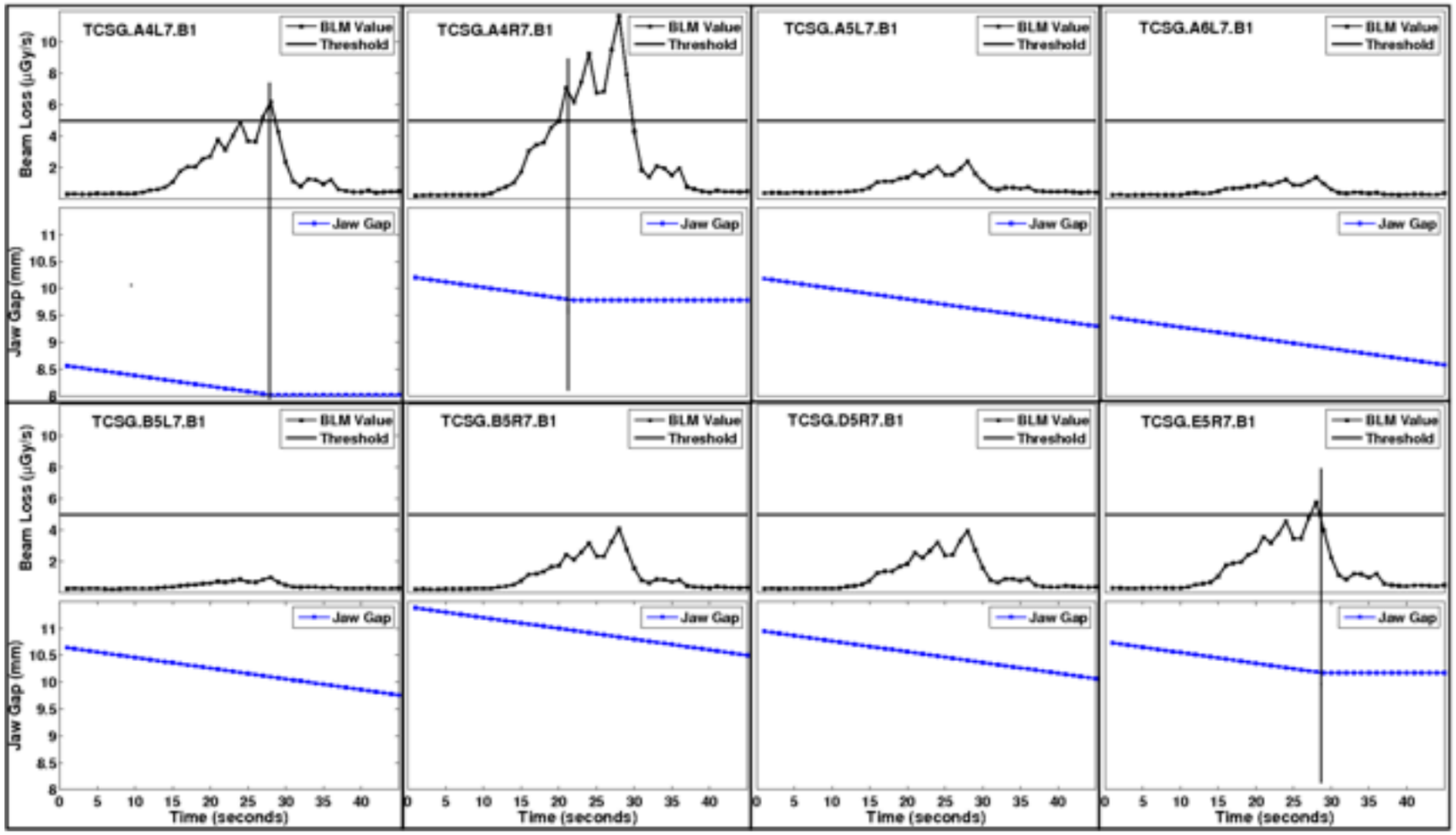

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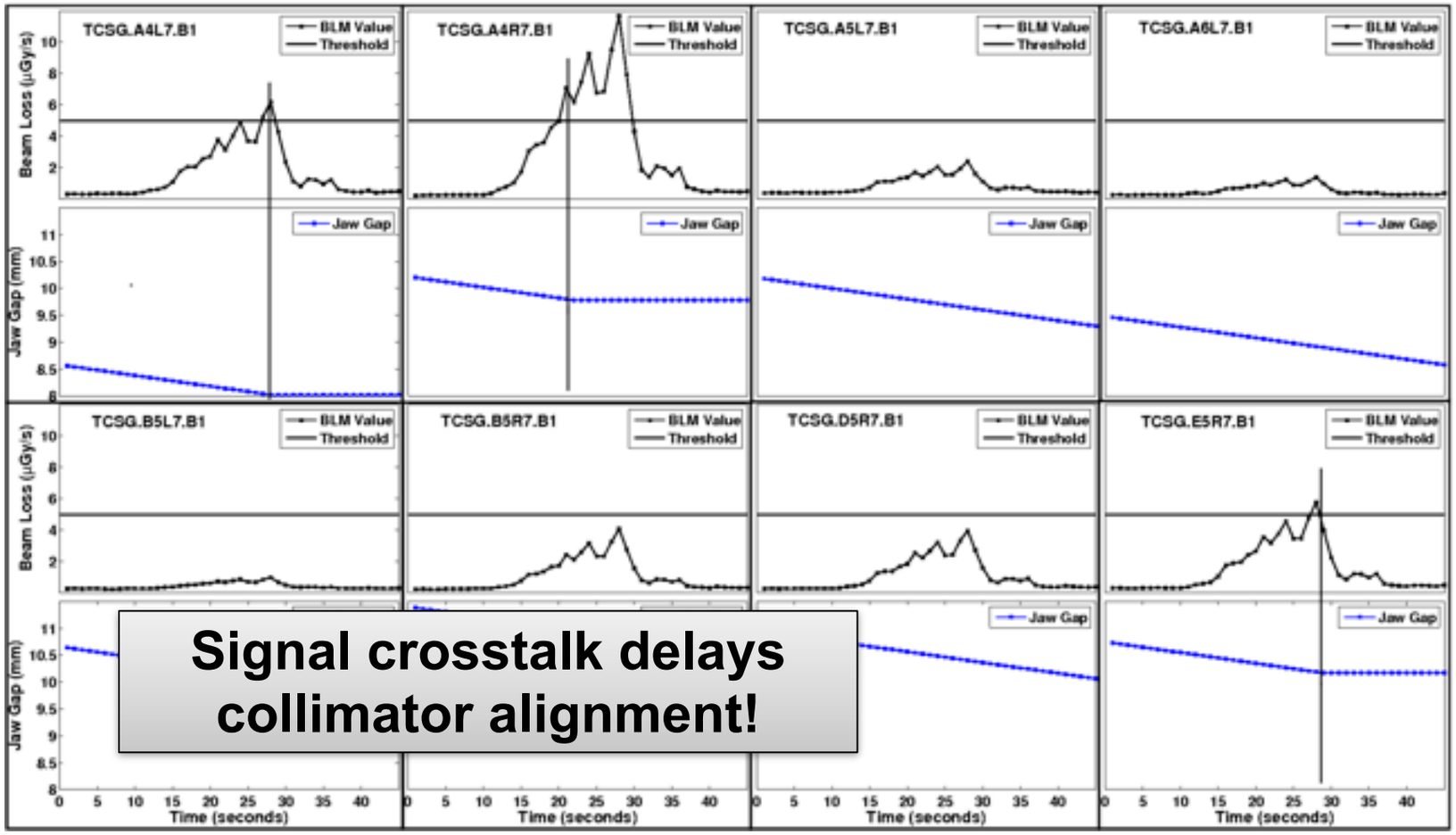
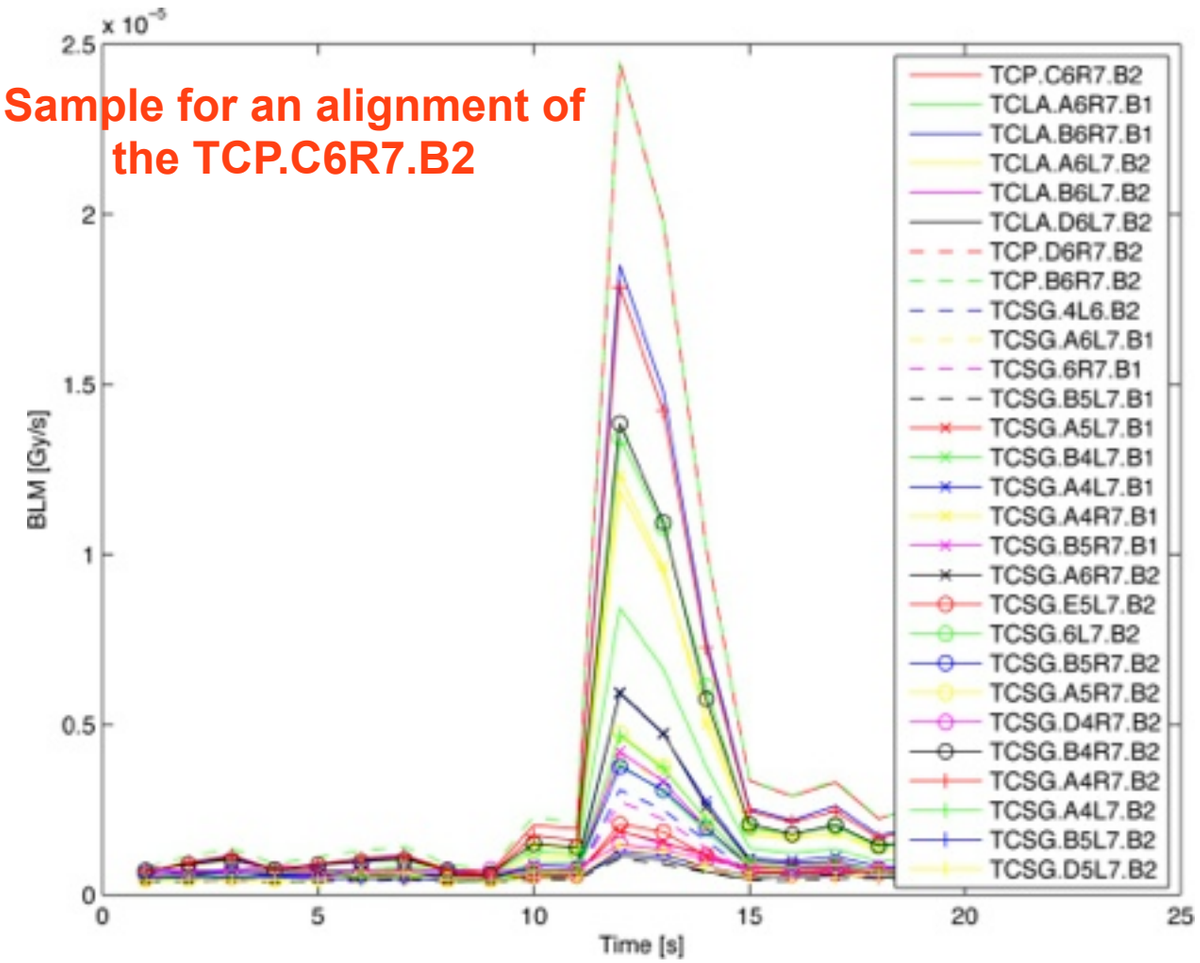


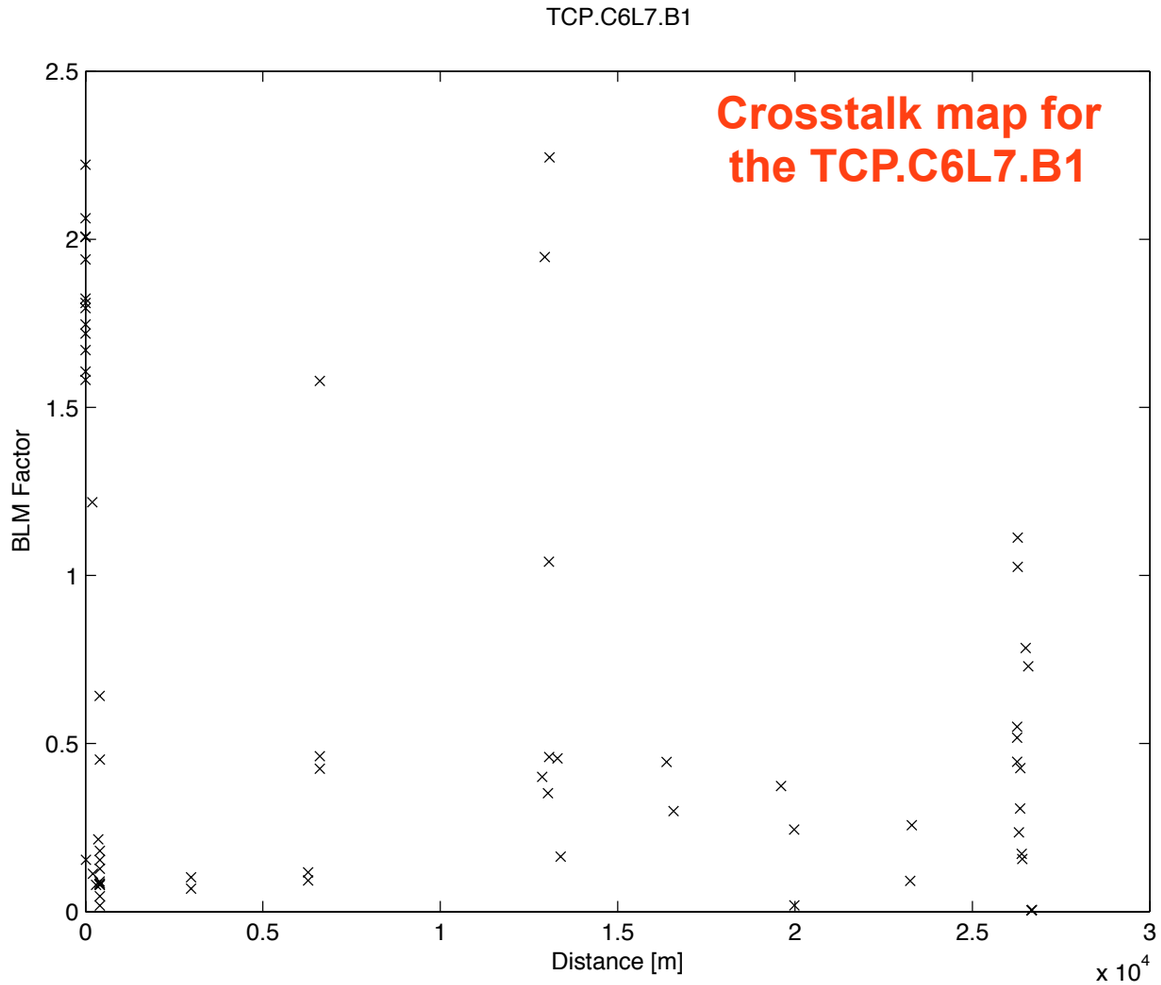
BLM Signal Crosstalk

- 687 21-second samples were extracted, during periods in which only one collimator was moving.

Sample for an alignment of the TCP.C6R7.B2



Crosstalk map for the TCP.C6L7.B1



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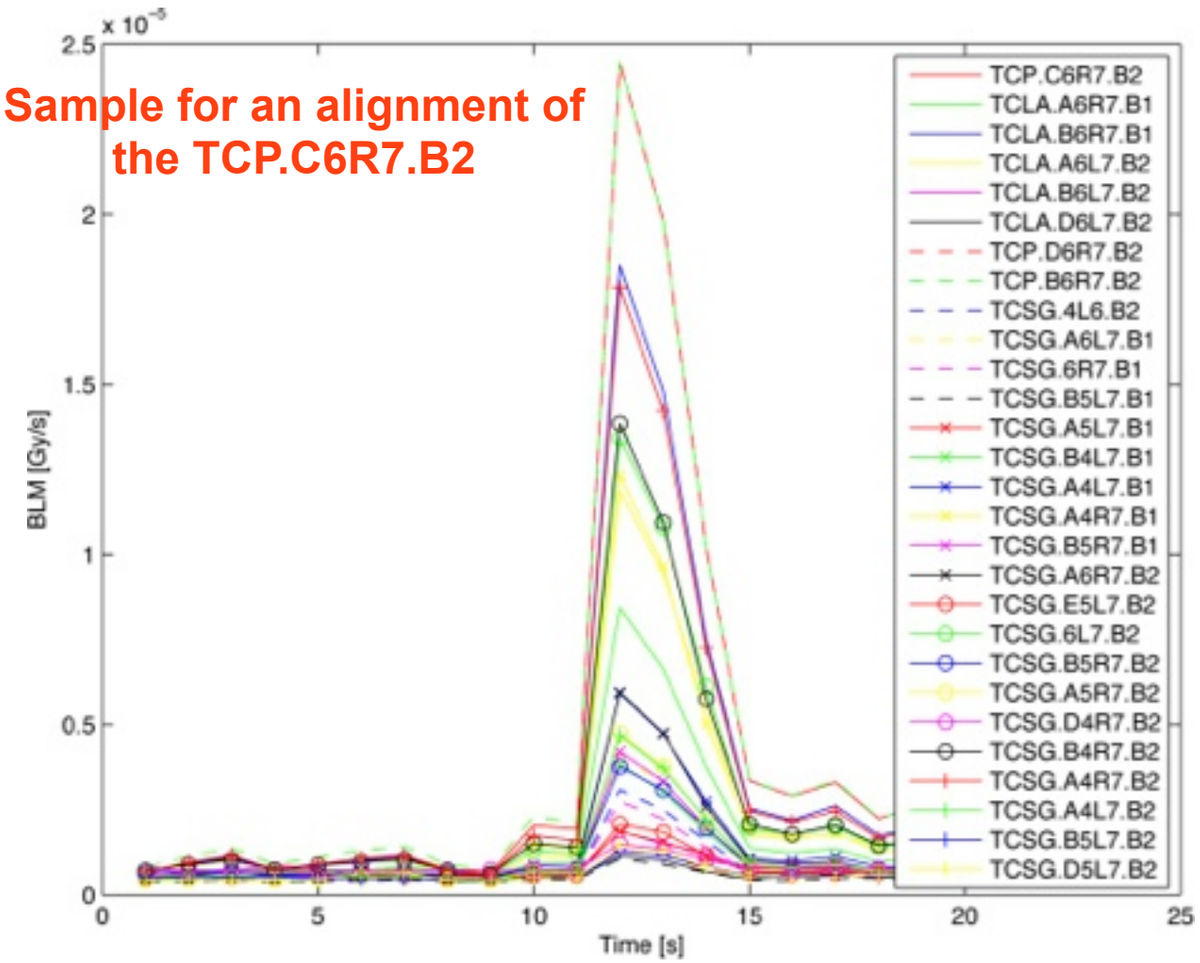

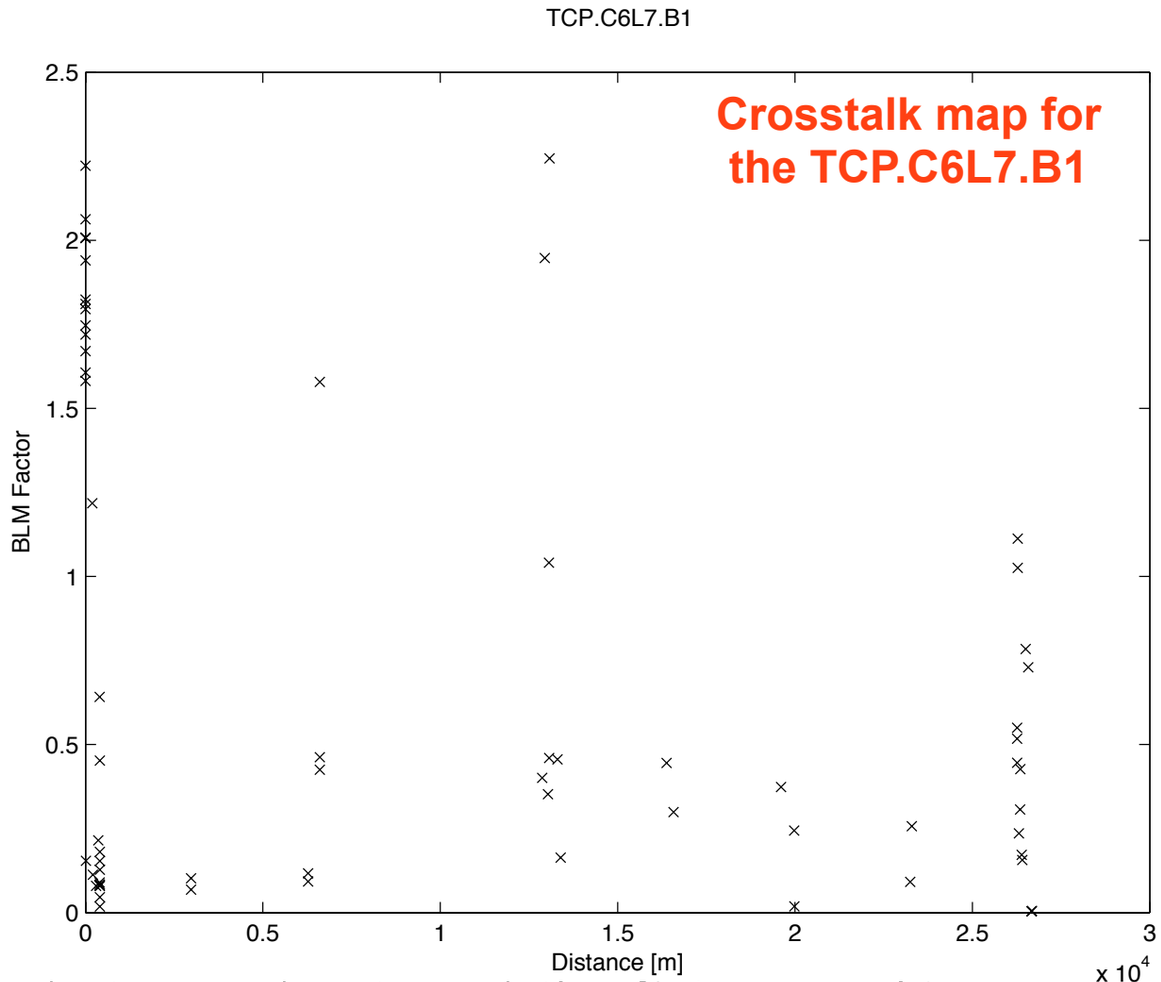

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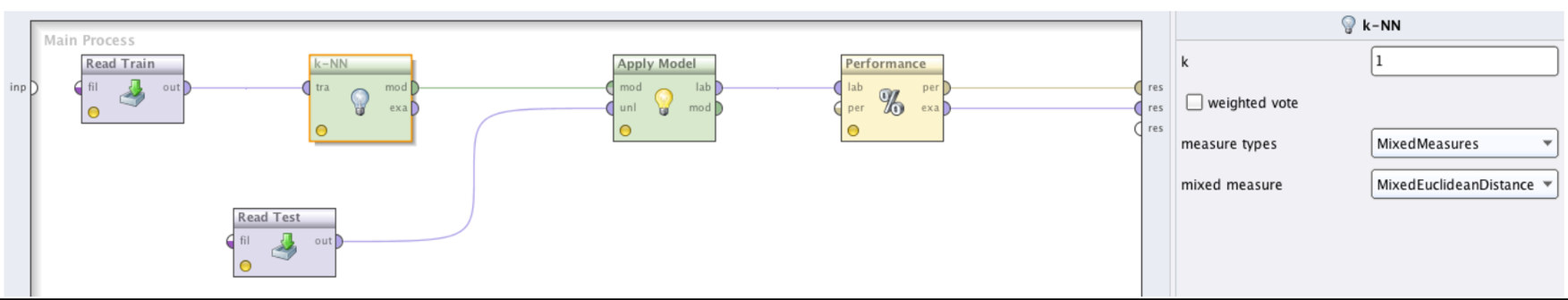
- A separate empirical model was developed for each collimator due to its unique location in the LHC.



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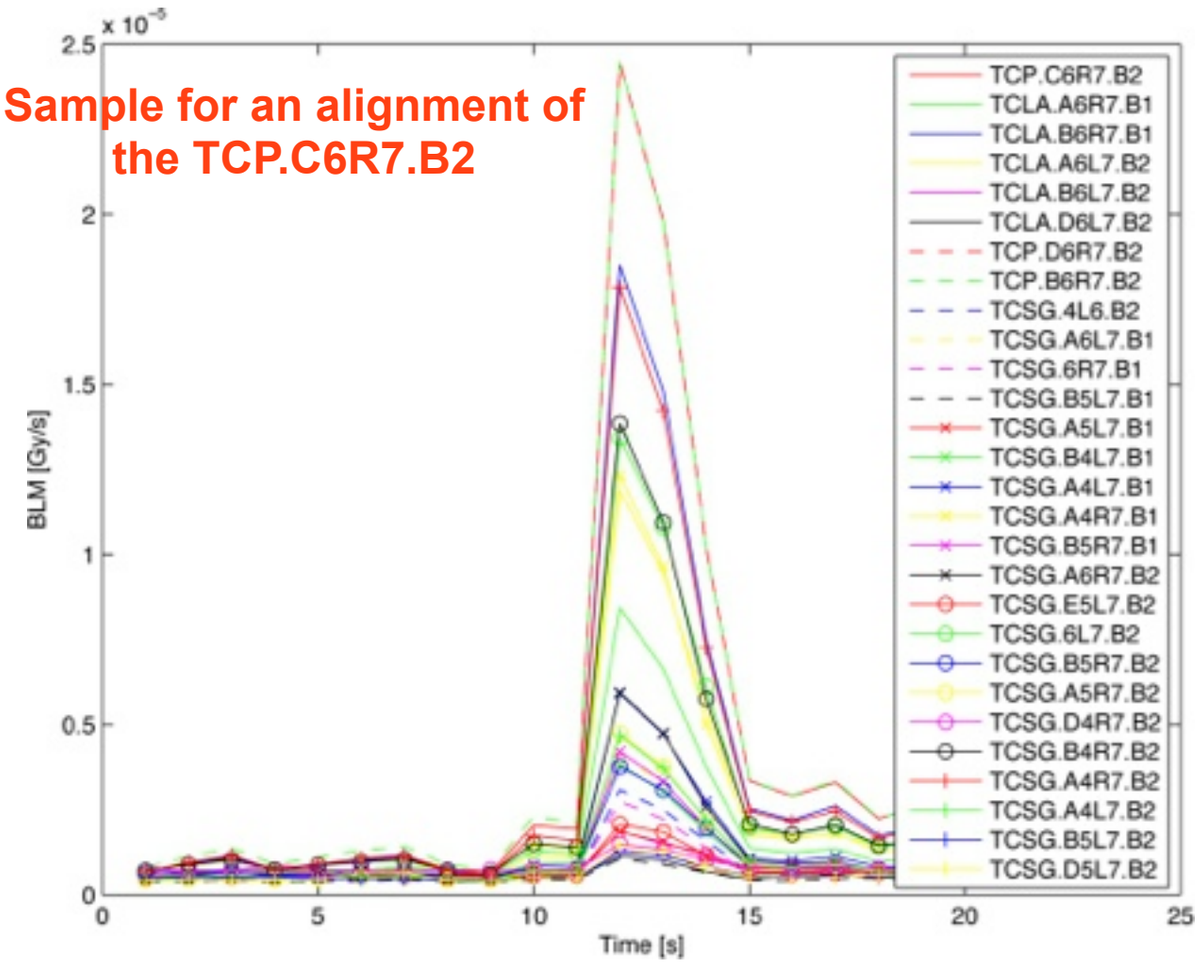

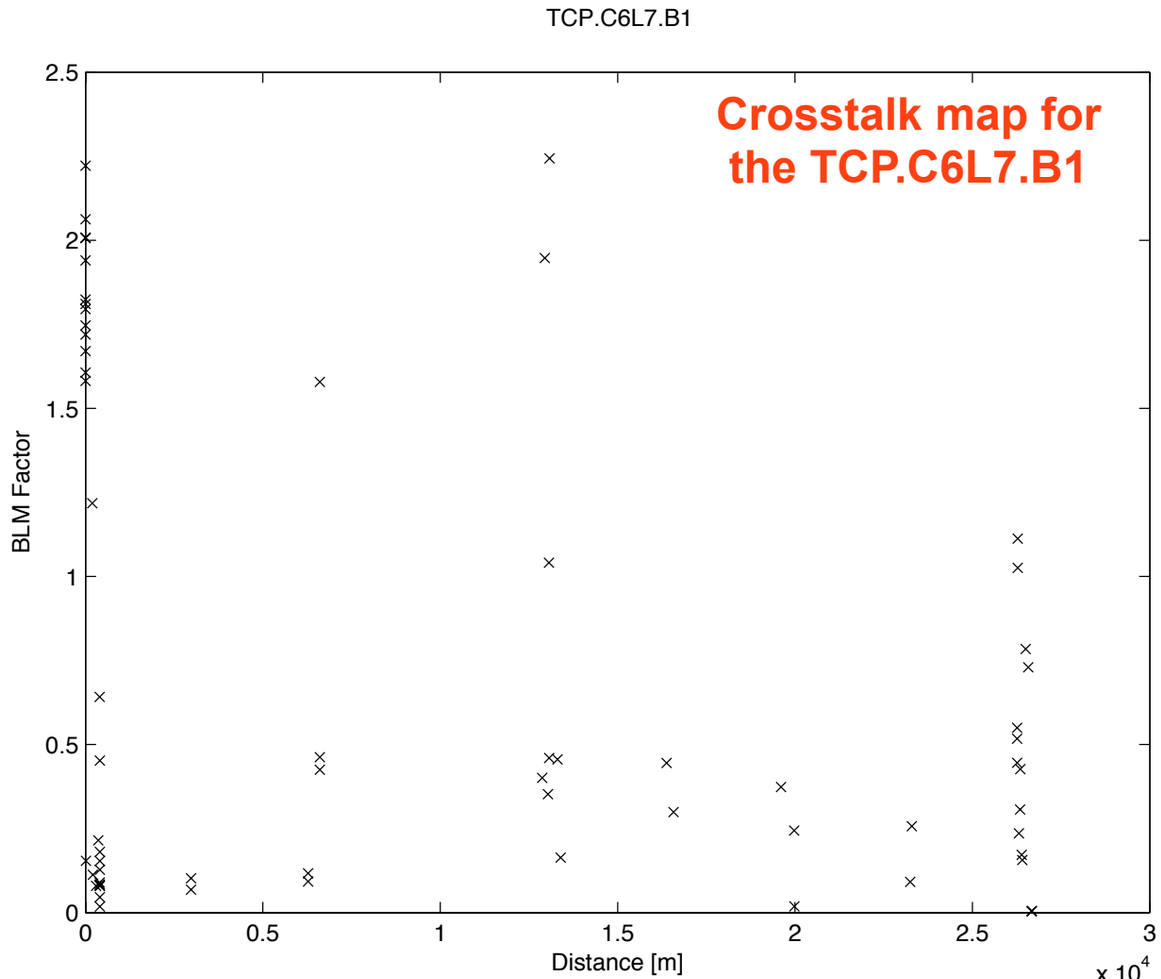

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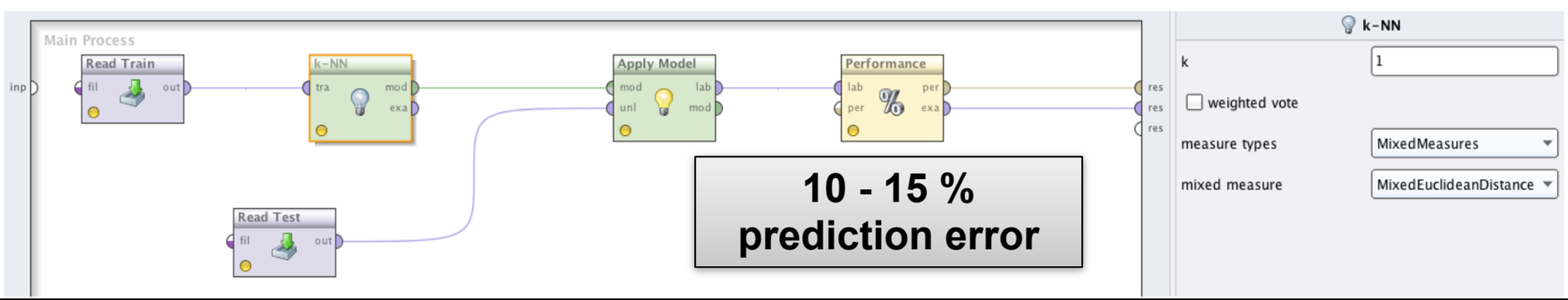

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  - Parallel alignment algorithm utilizing knowledge of crosstalk factors

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2011 onwards

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Collimator Setup Simulator

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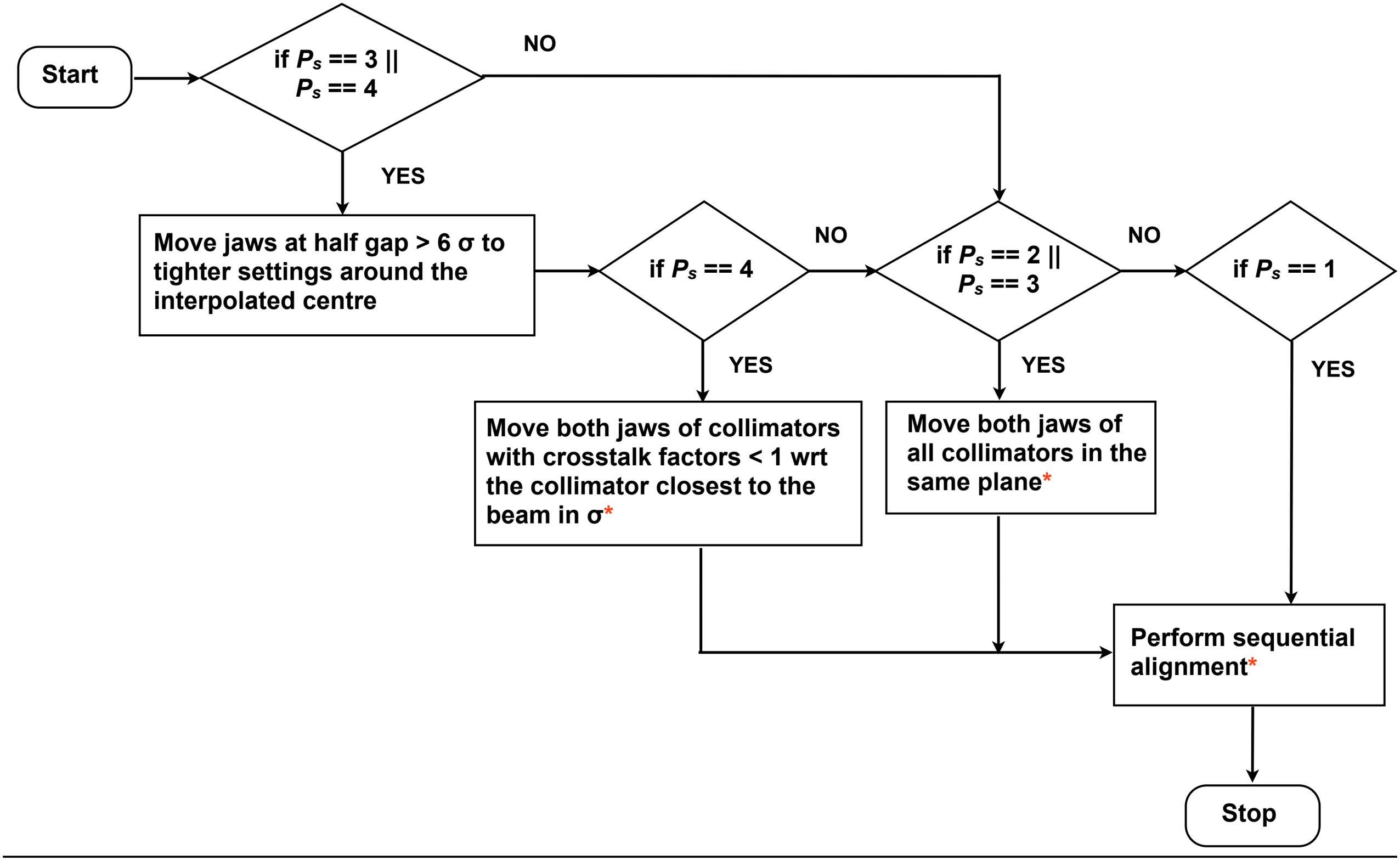

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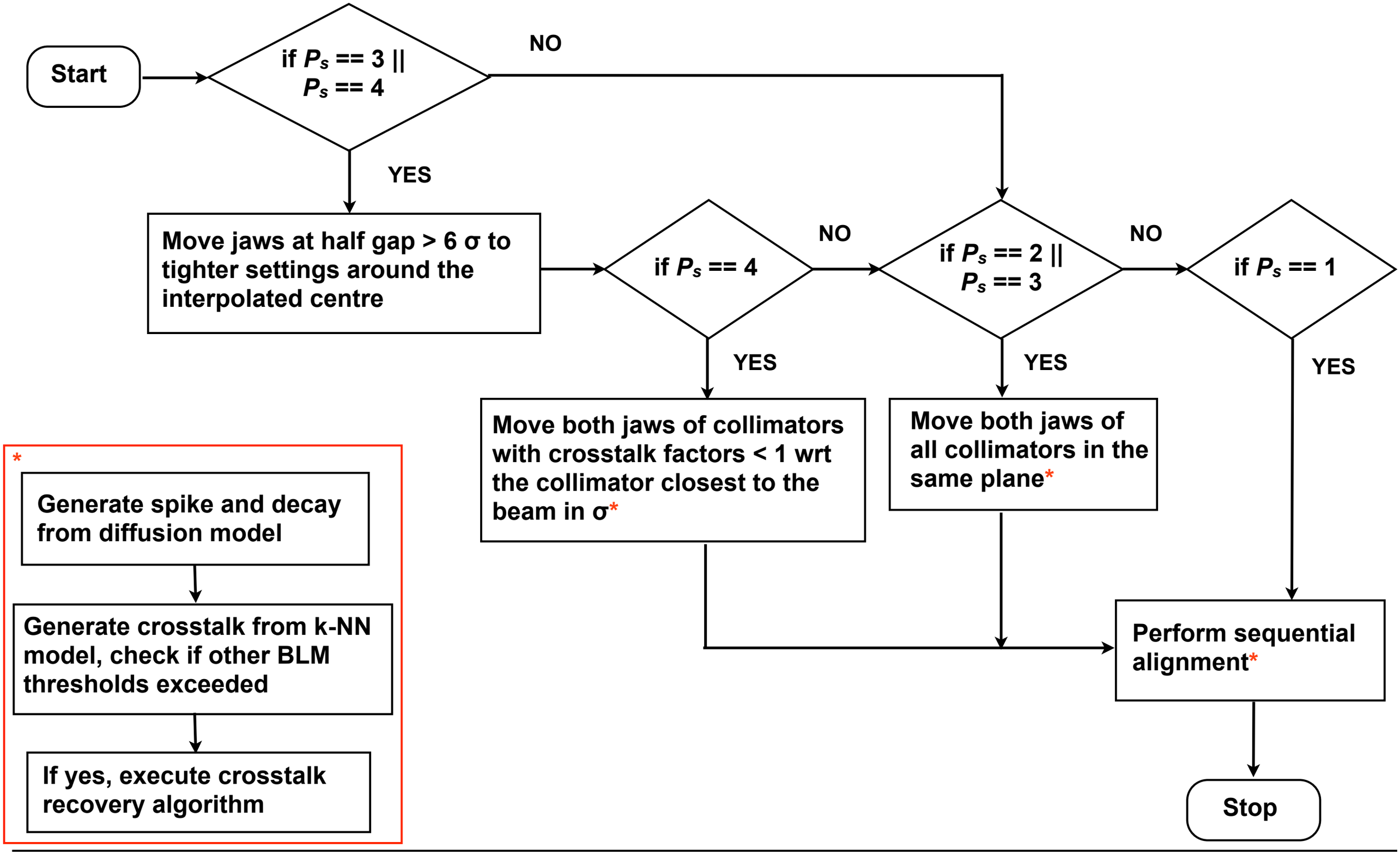

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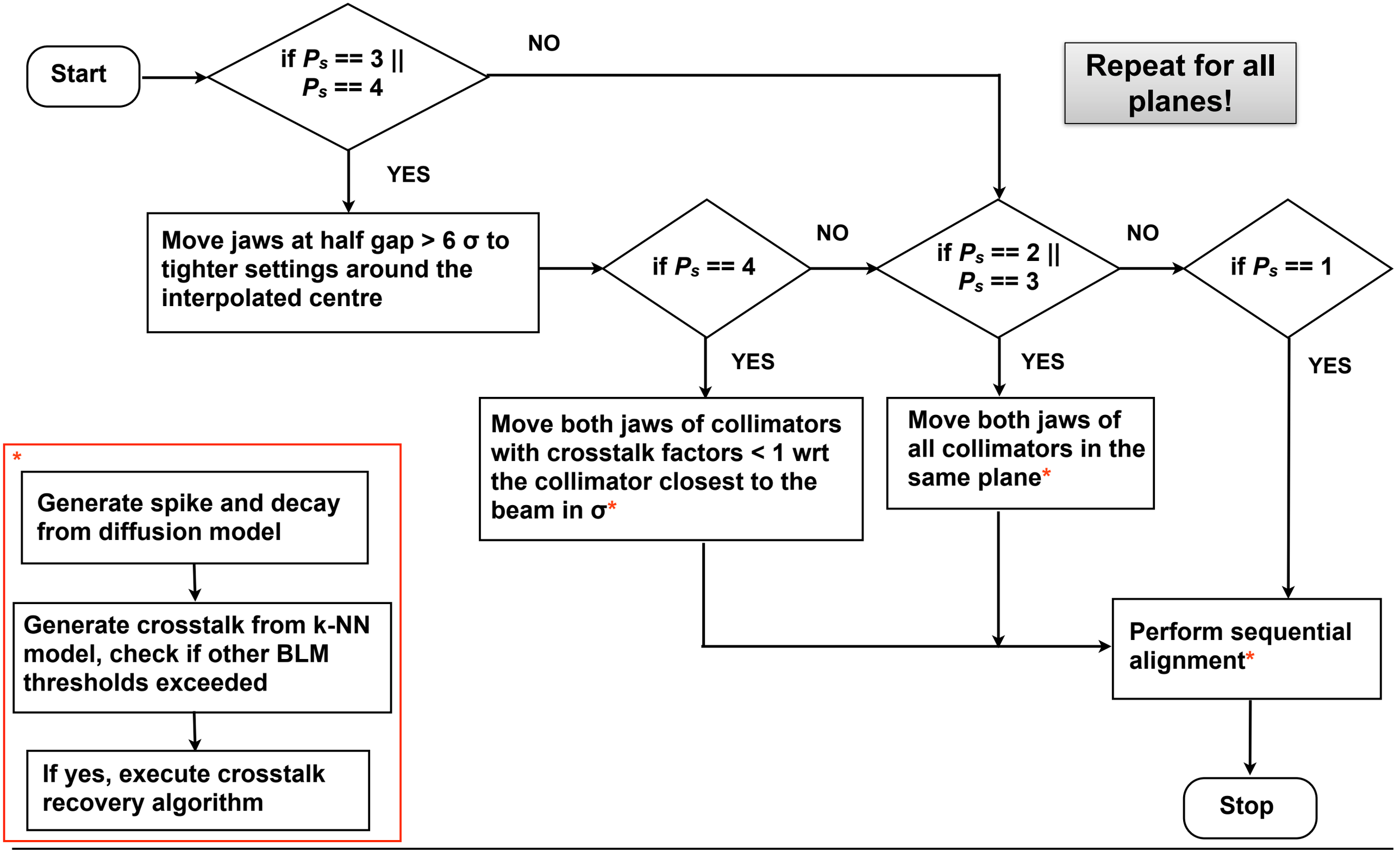
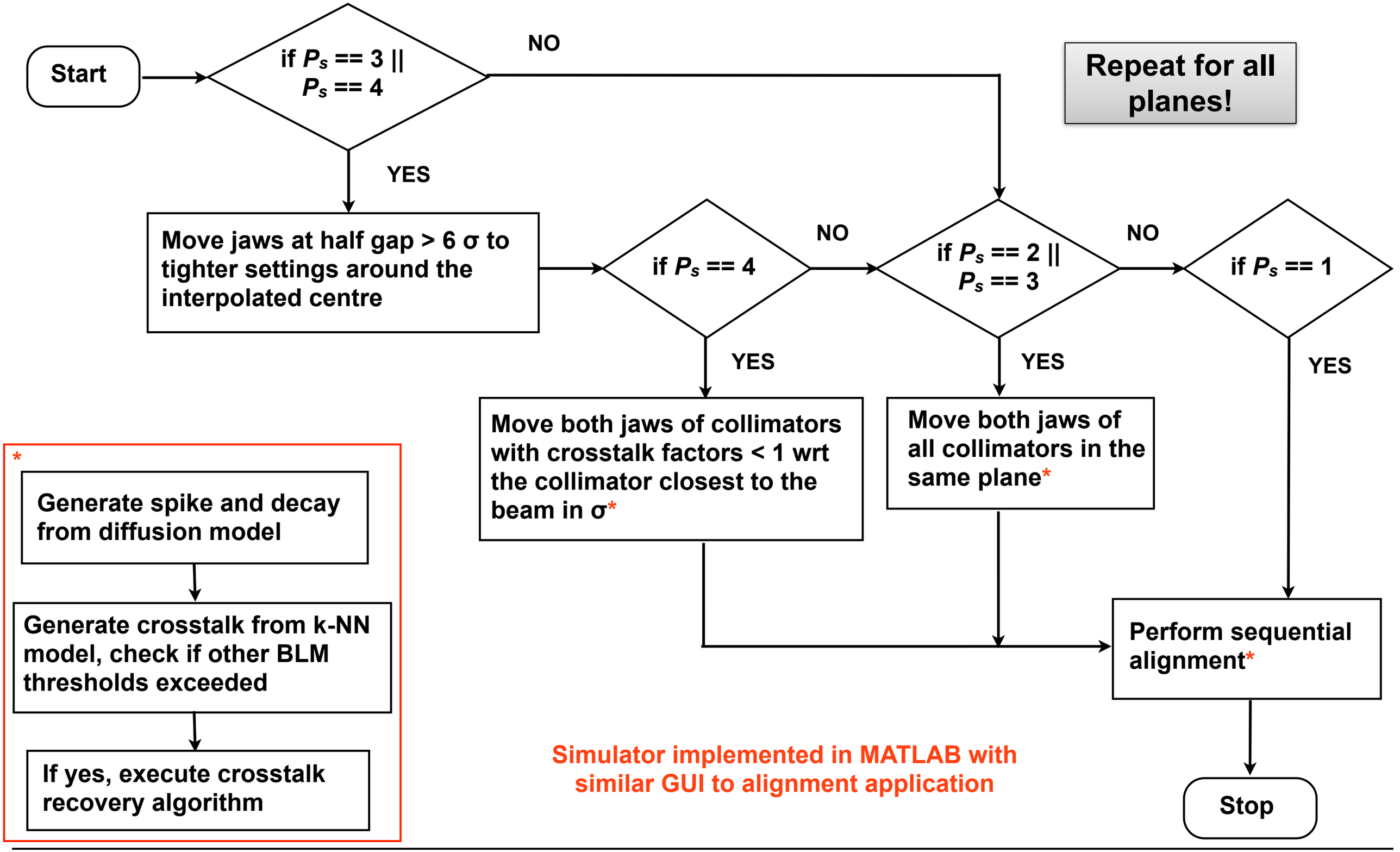


Collimator Setup Simulator



Simulator implemented in MATLAB with similar GUI to alignment application

Outline

- CERN and the Large Hadron Collider
- LHC Collimation System
- Collimator Beam-Based Alignment
- Alignment Algorithms
- Software Implementation
- Modeling and Simulation of Beam Losses
- **Simulation and Operational Results**
- **Future: BPM-based alignment**
- **Conclusions**

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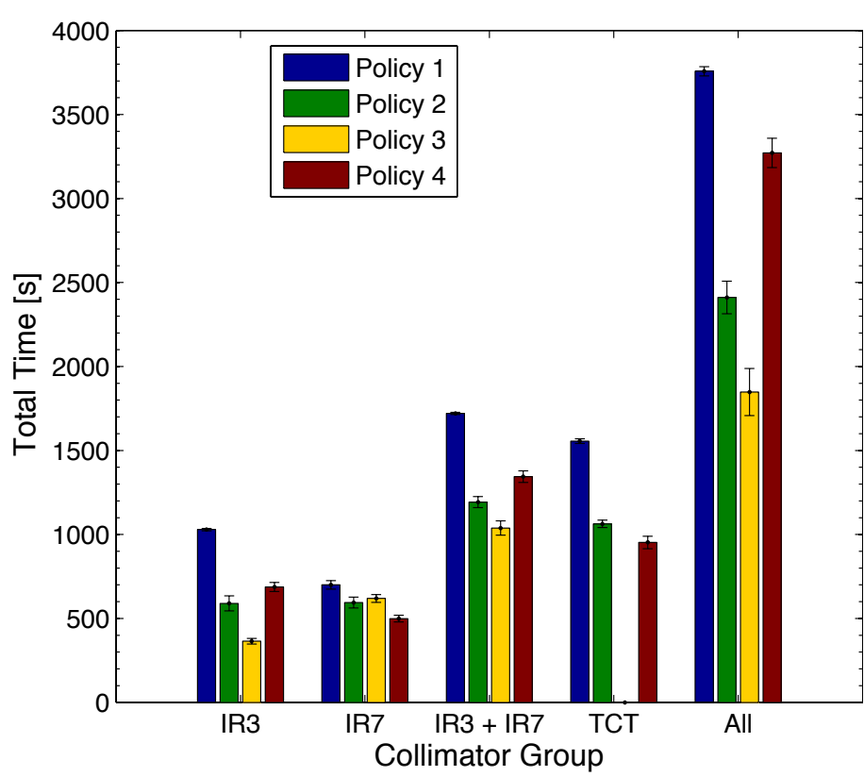

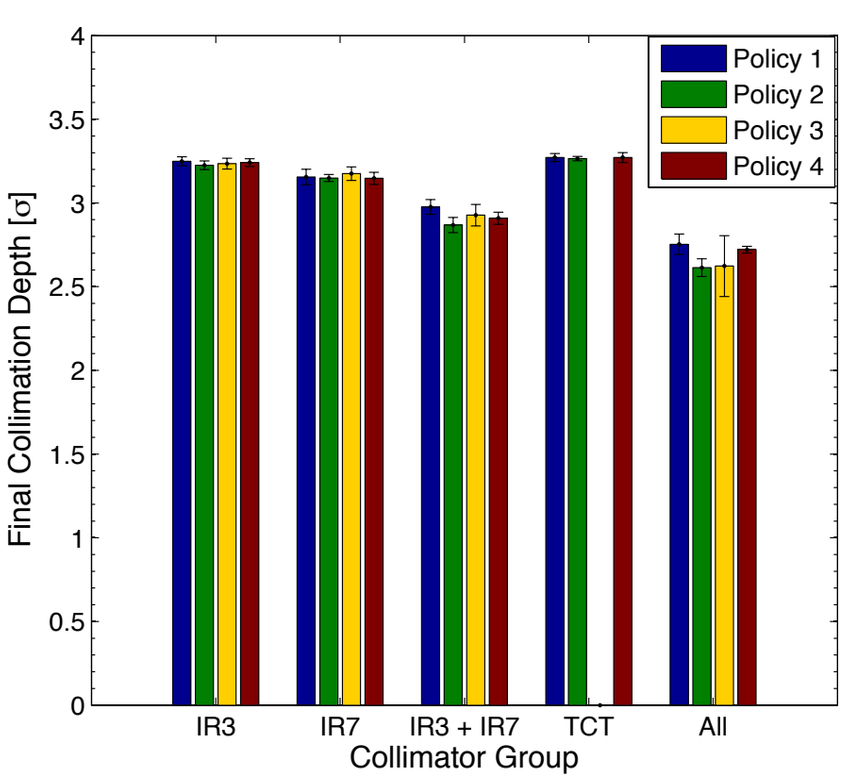

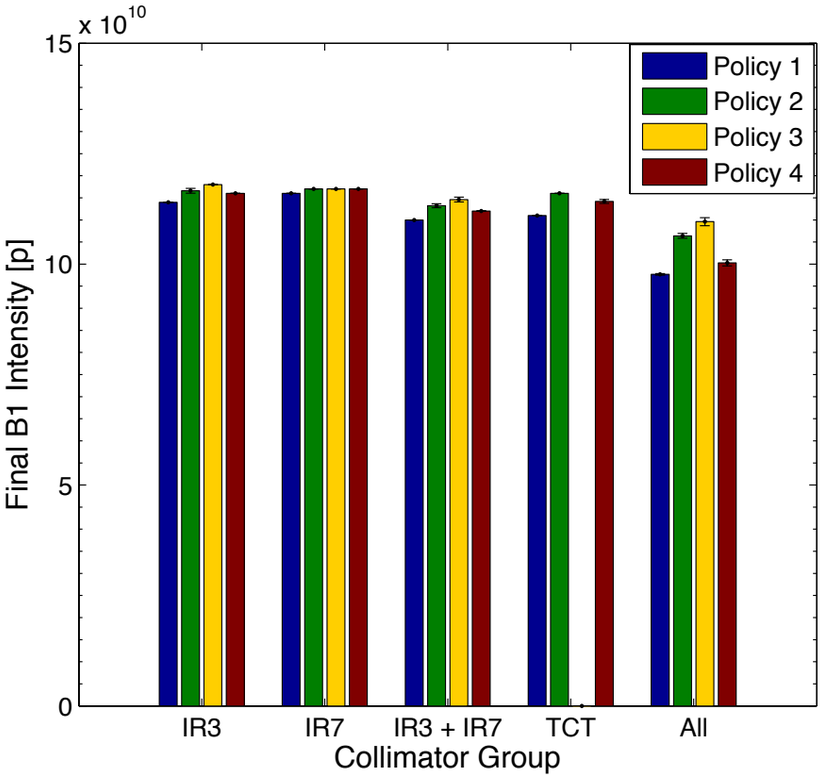

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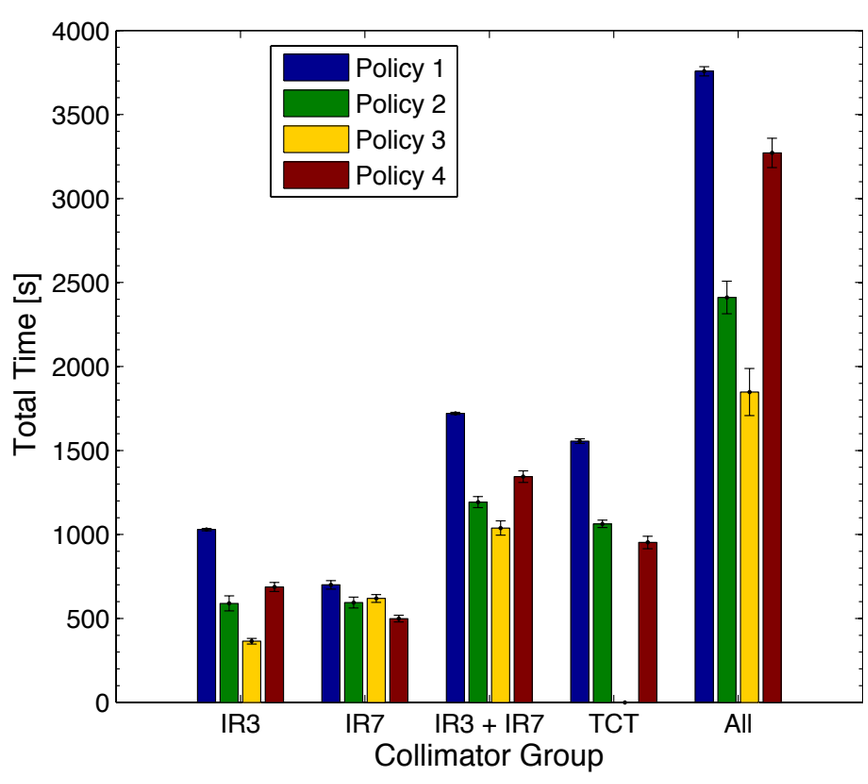

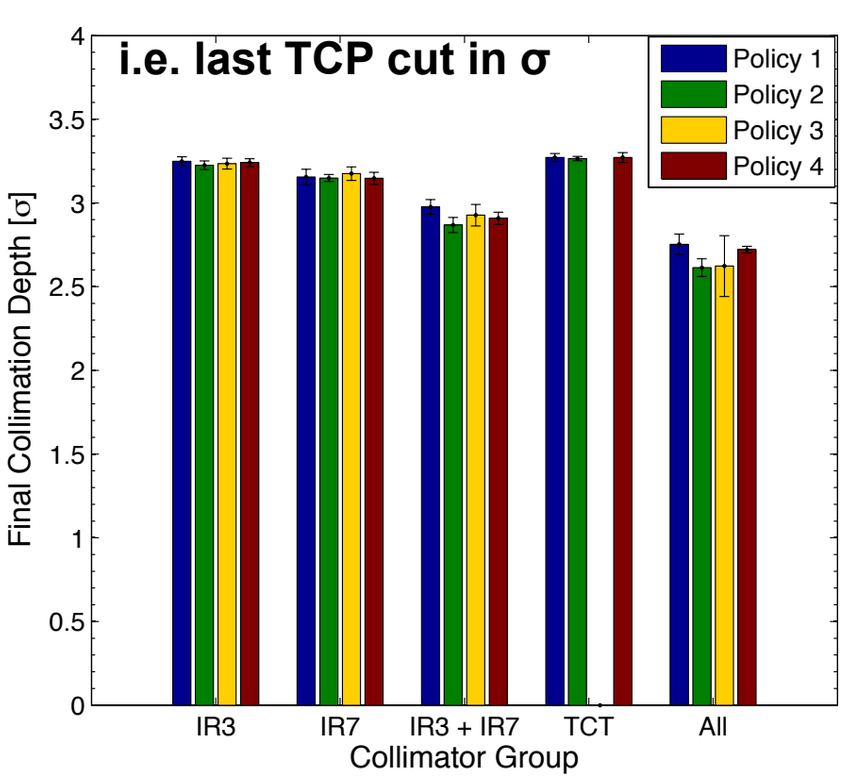

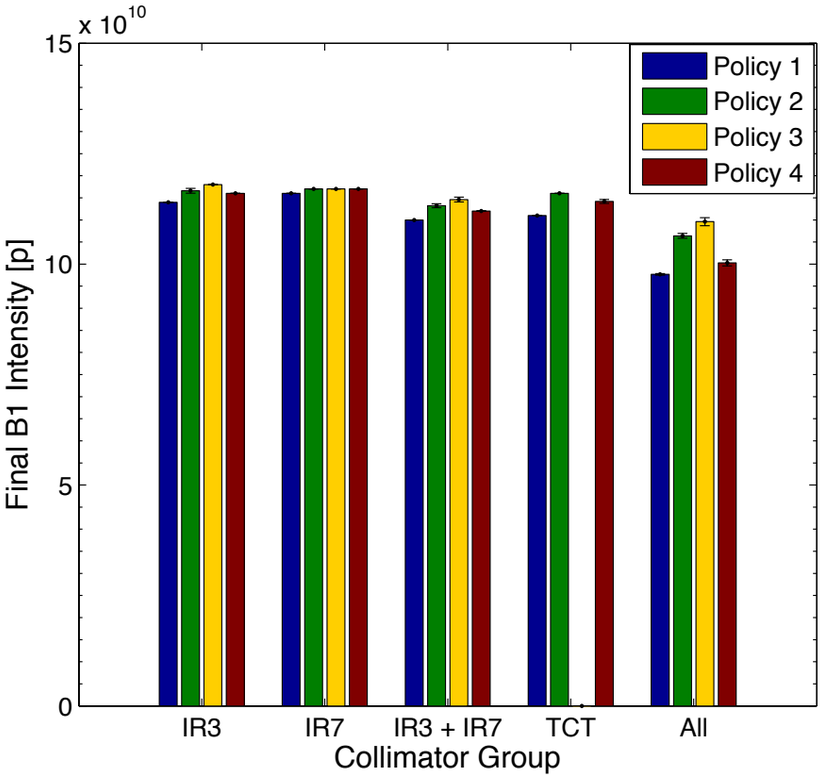

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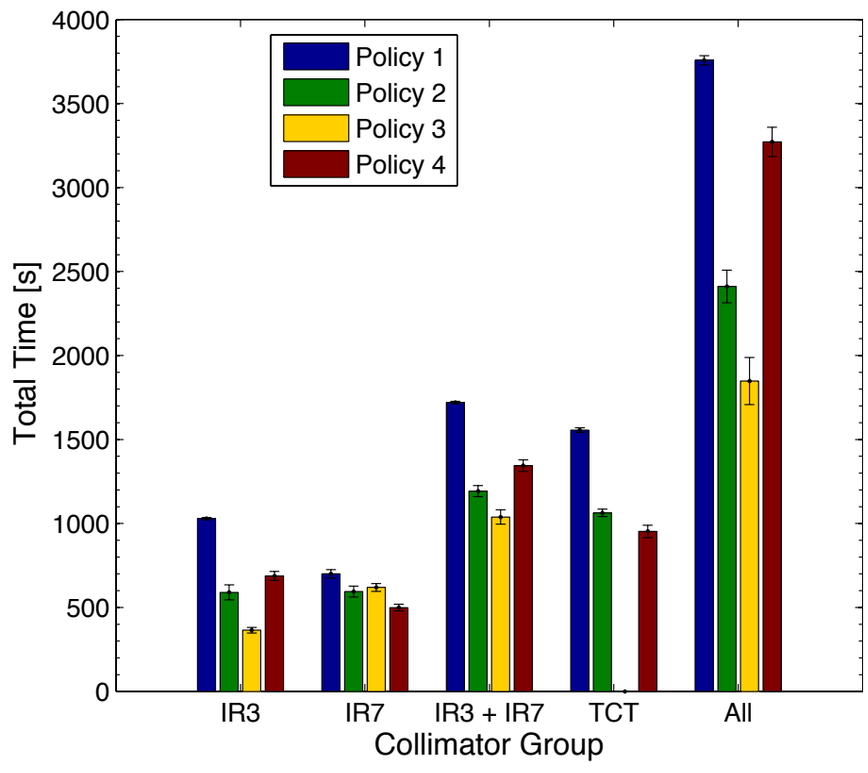

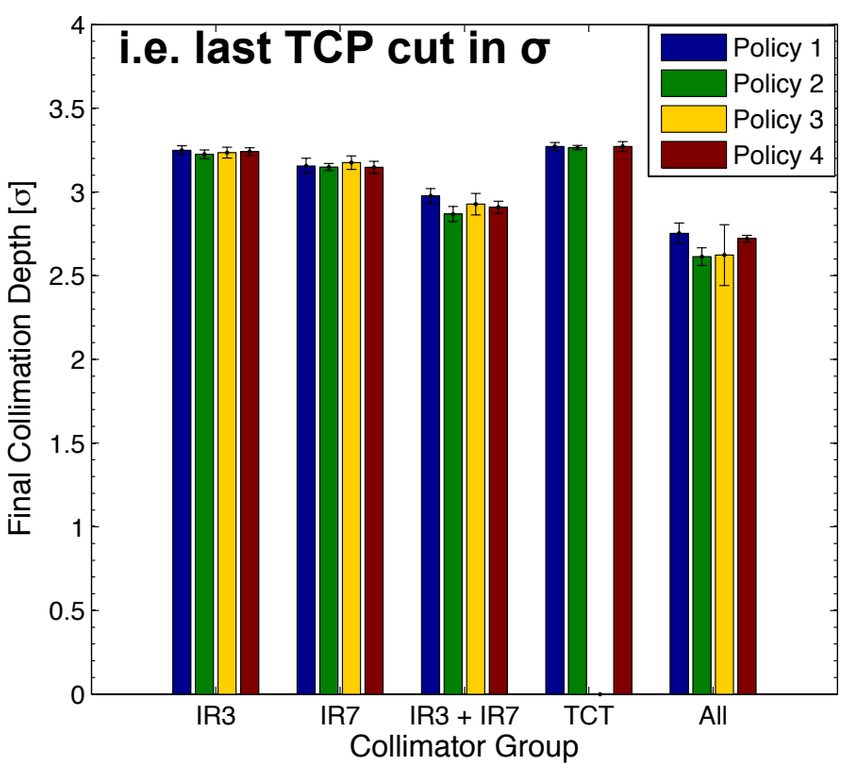

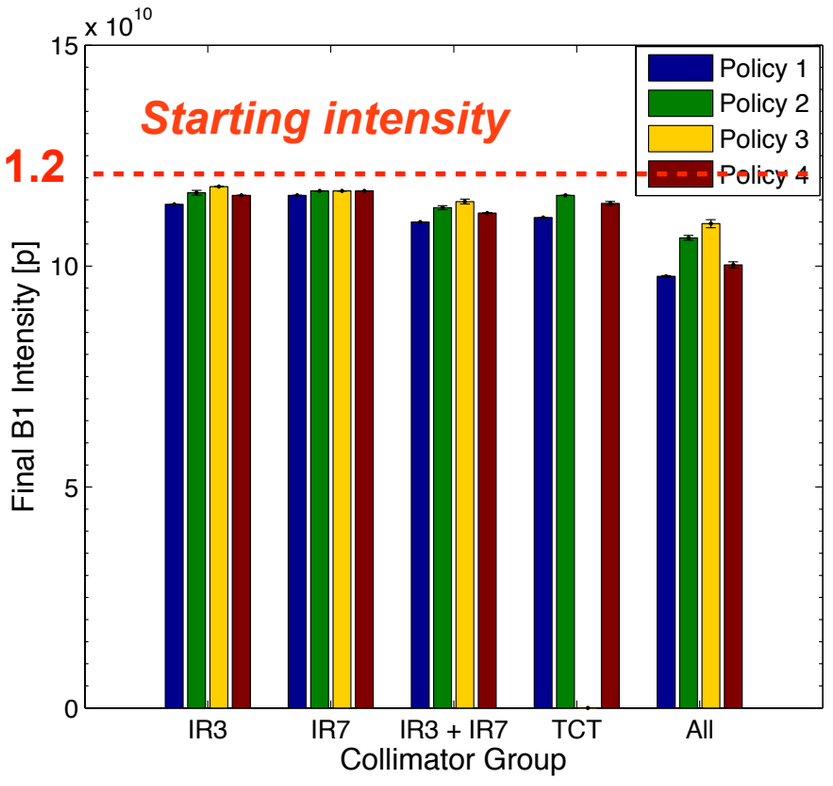

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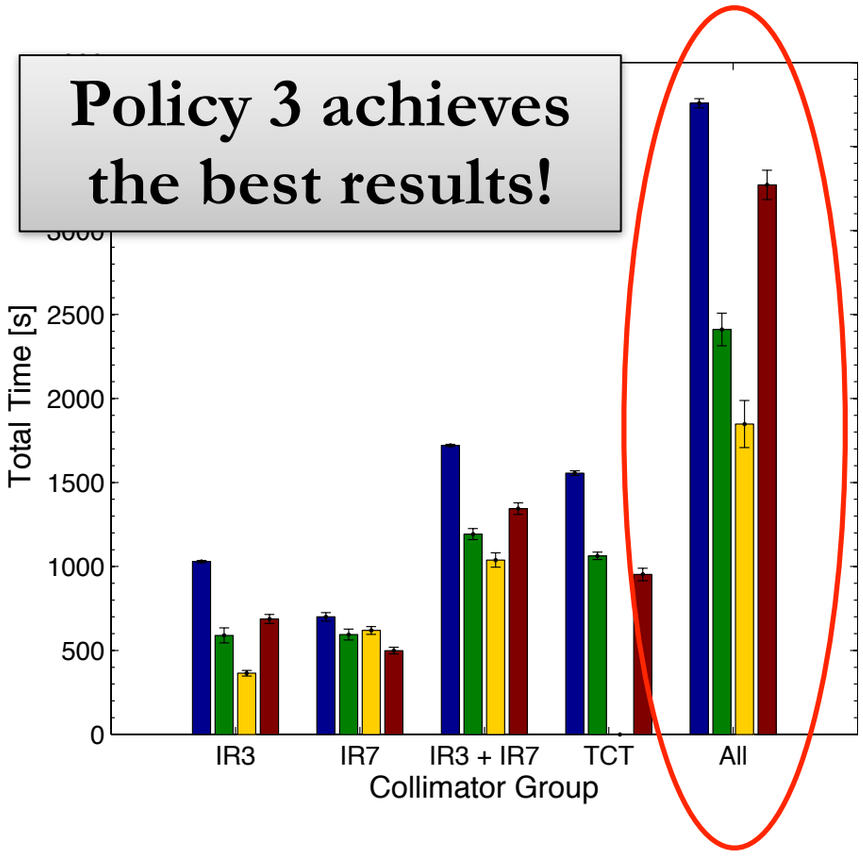

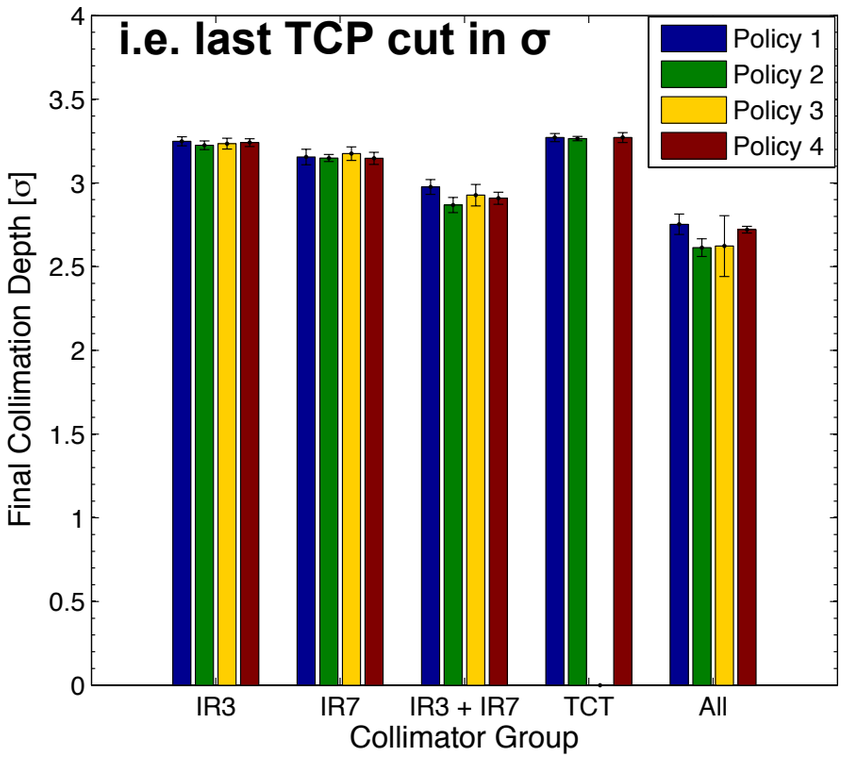

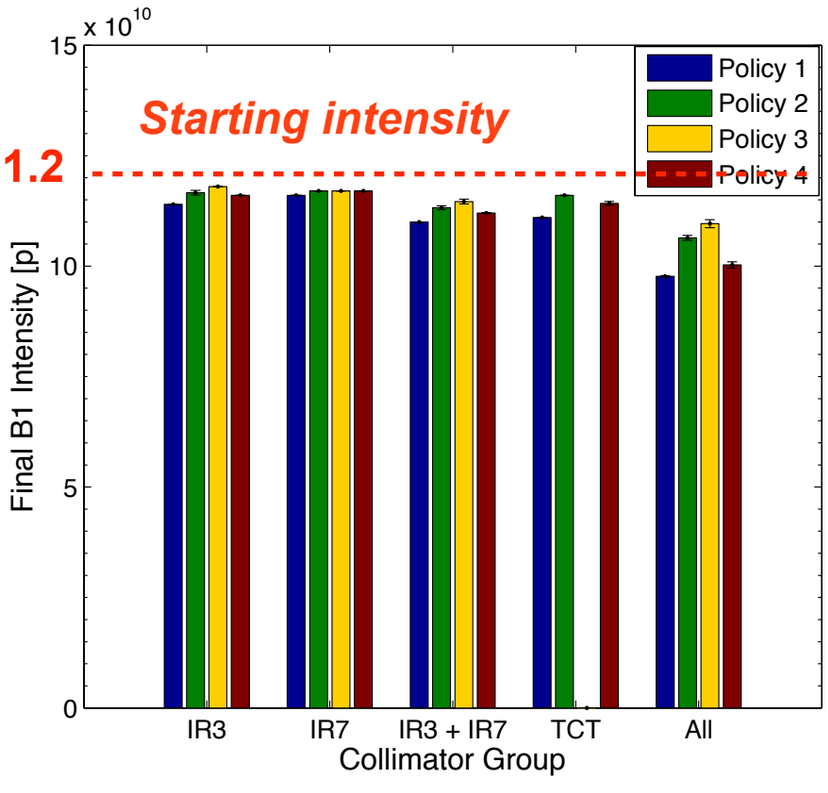

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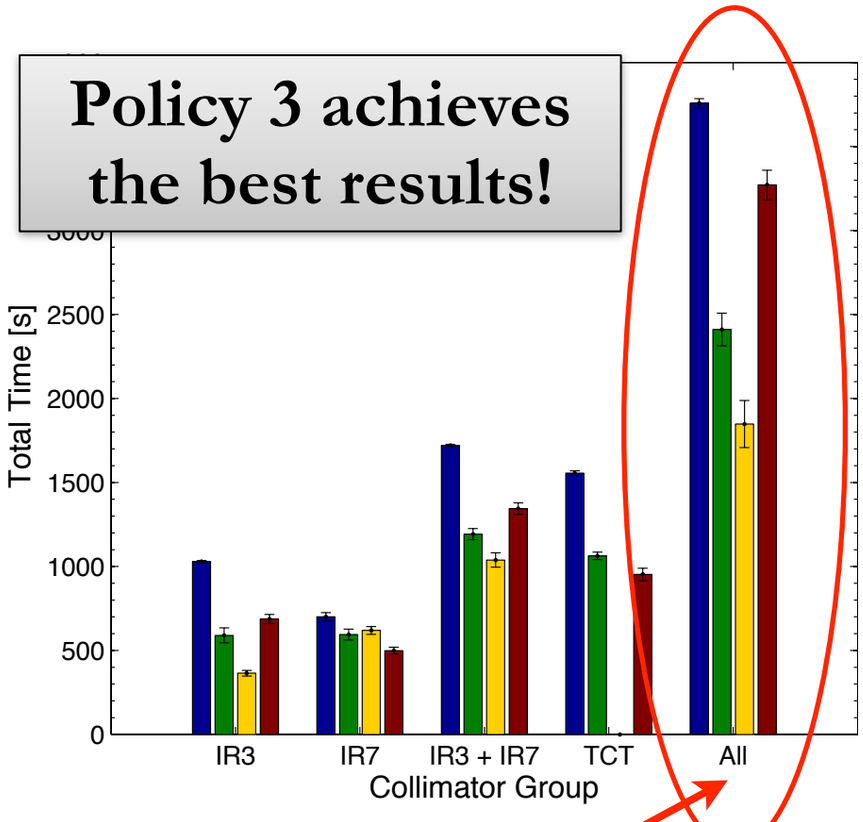
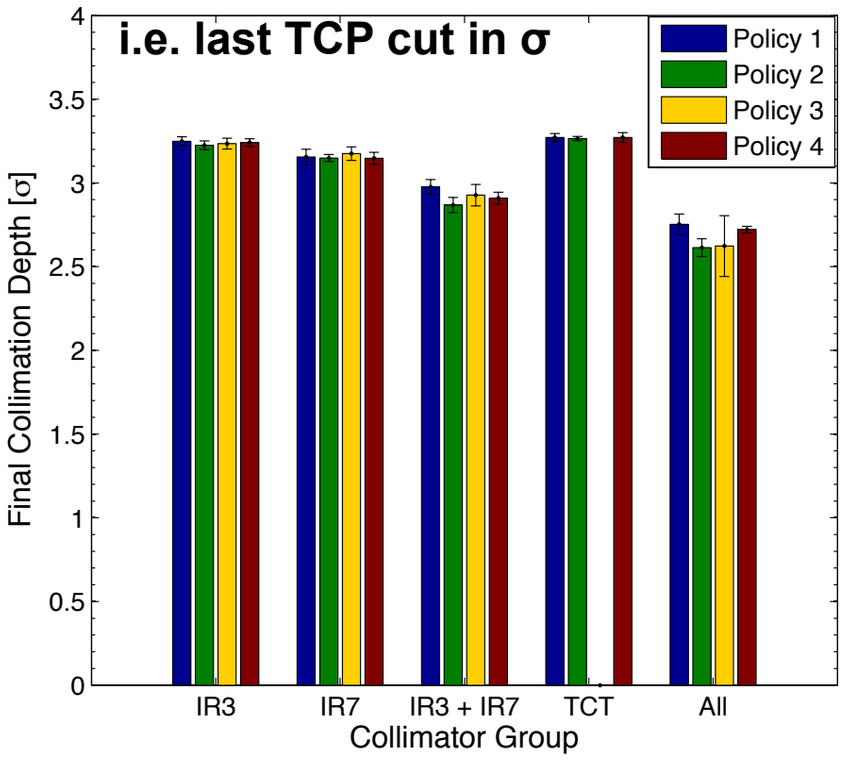
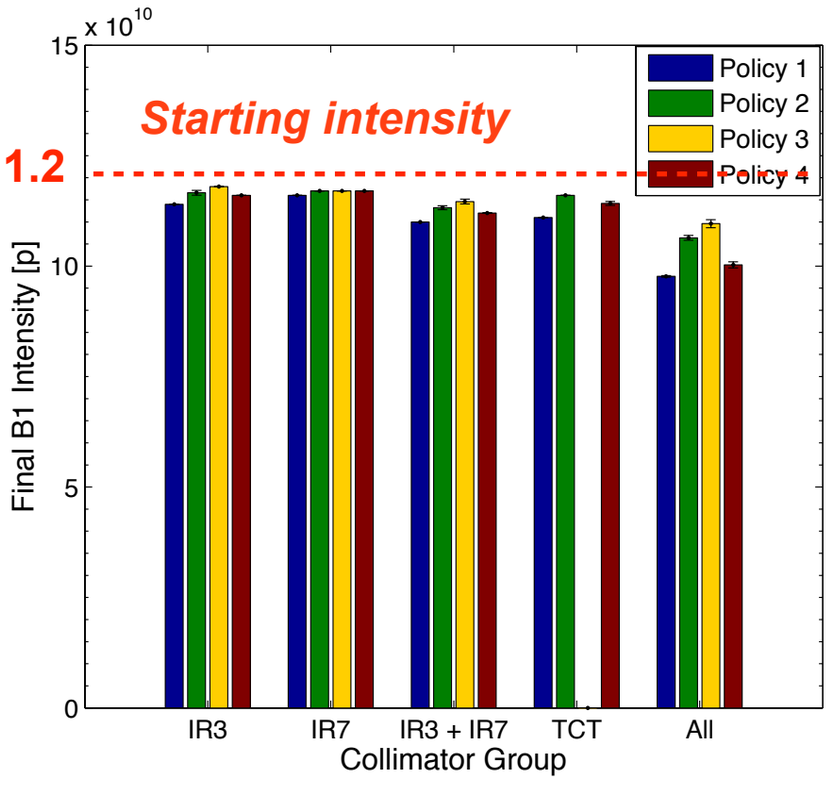






- **Policy 4:** gain in time is **larger** when all collimators are moved simultaneously (**Policy 3**), even though there are more frequent interruptions.

Alignment Results

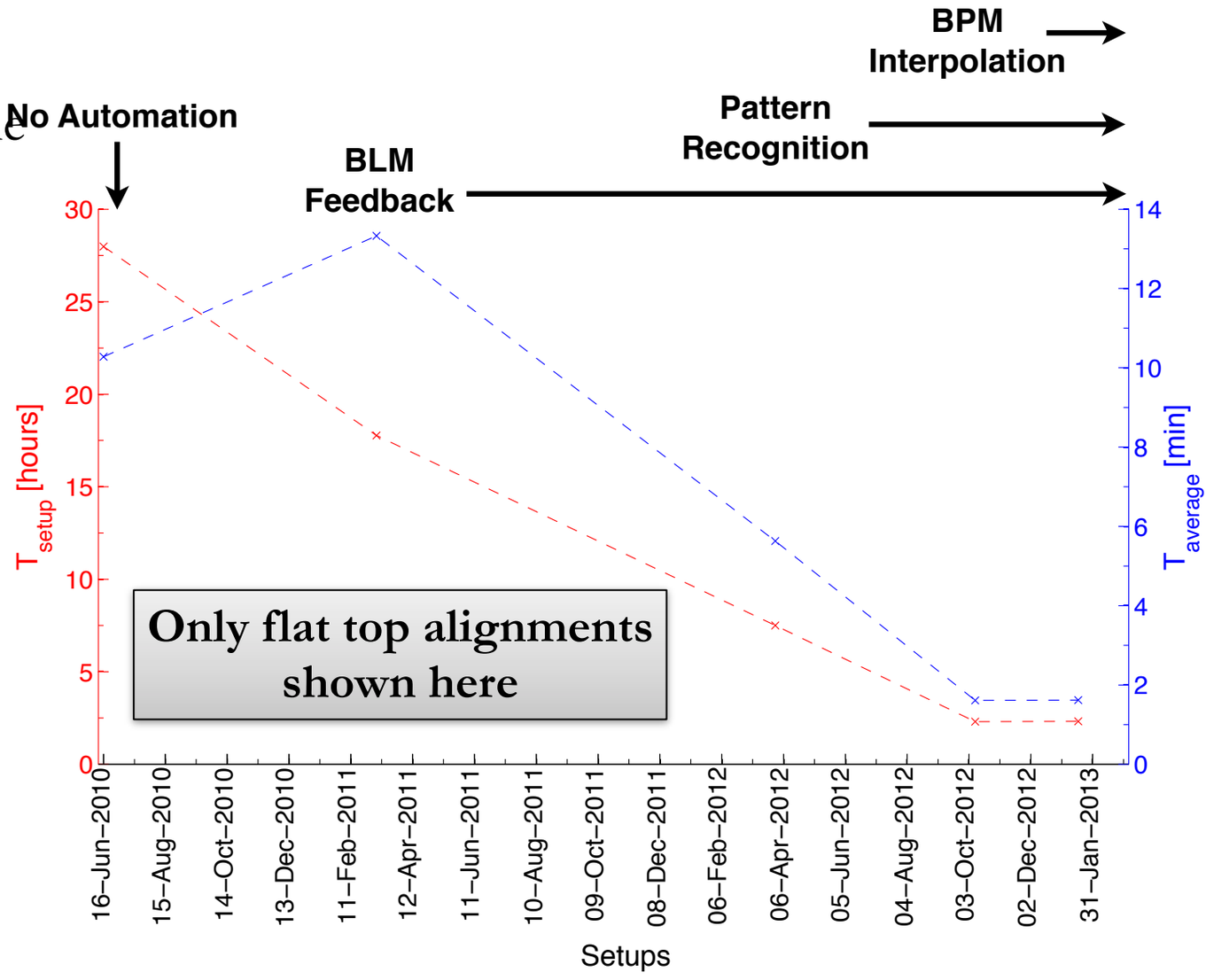
- Total setup time depends on the beam time consumed, the number of beam dumps d and the turnaround time:

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

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

- 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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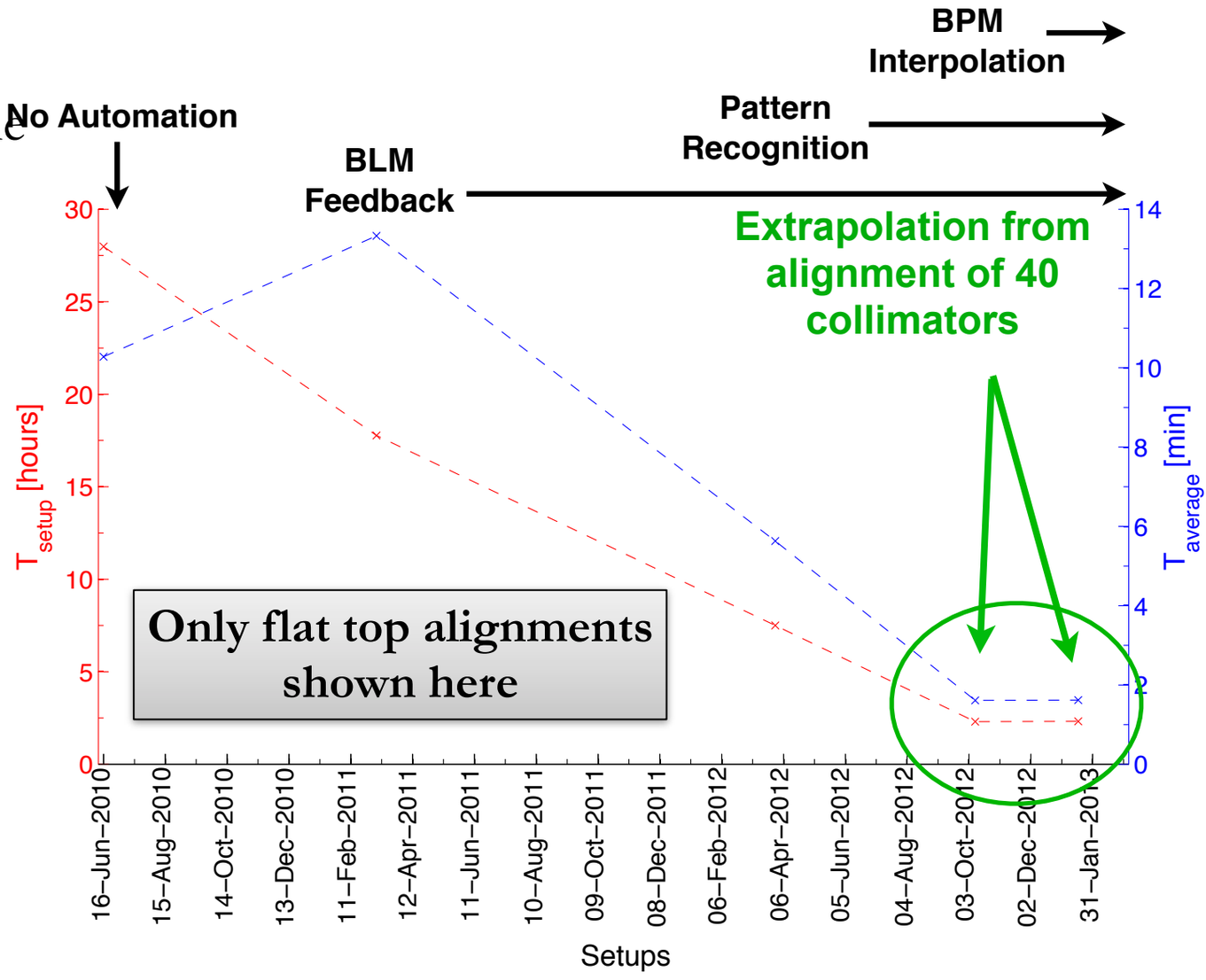

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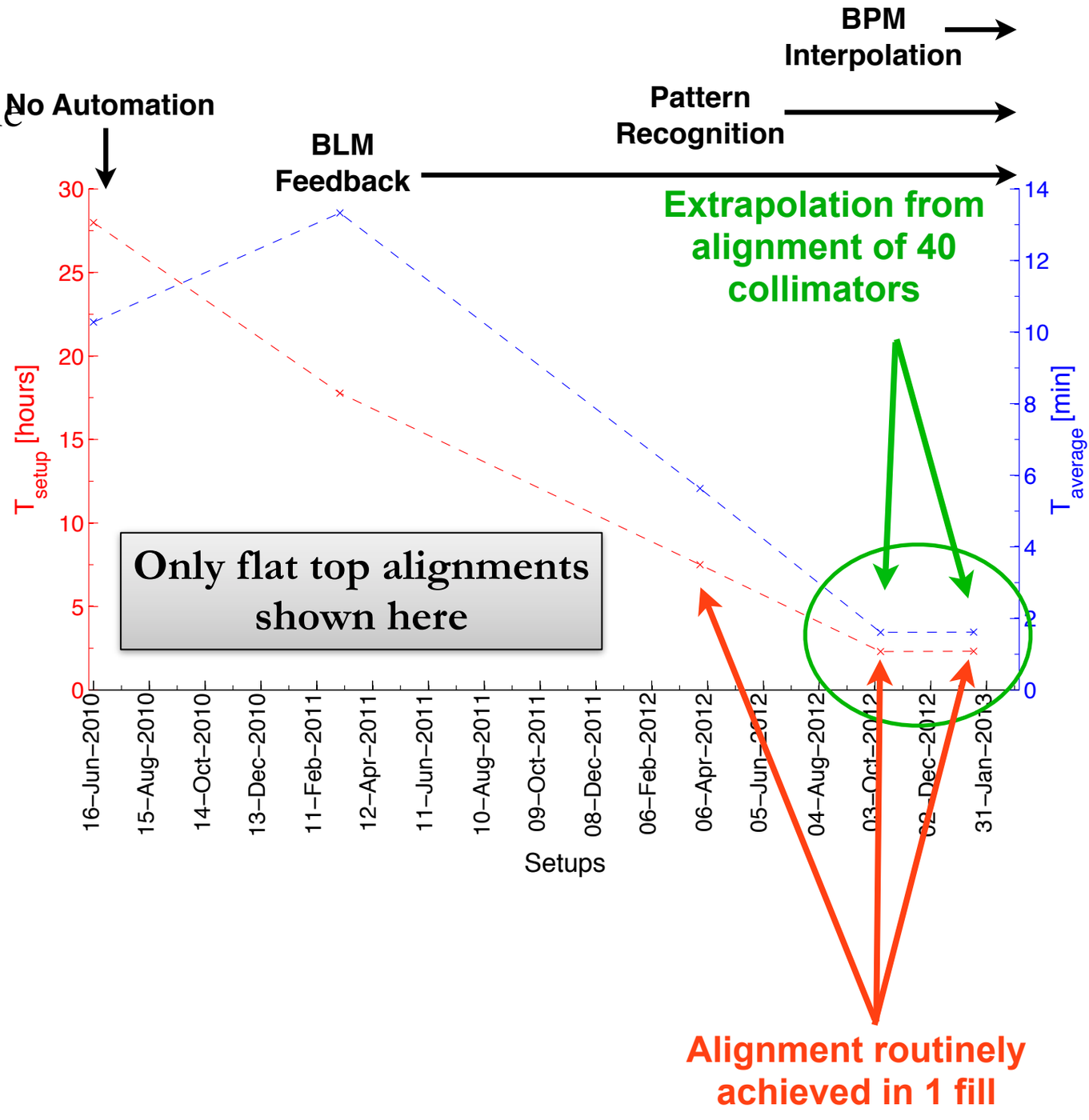

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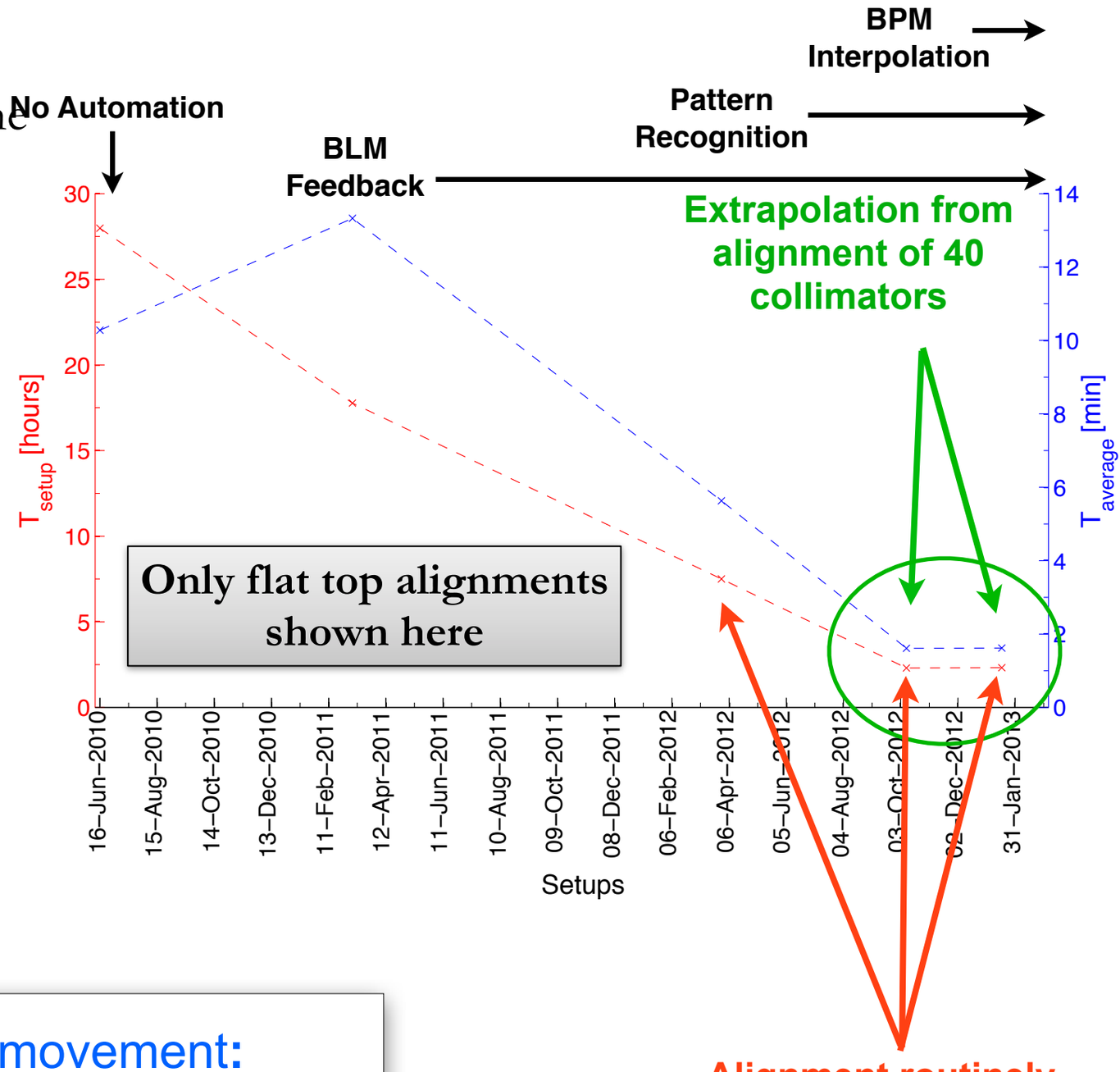

Limitation from loss spikes + jaw movement:

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

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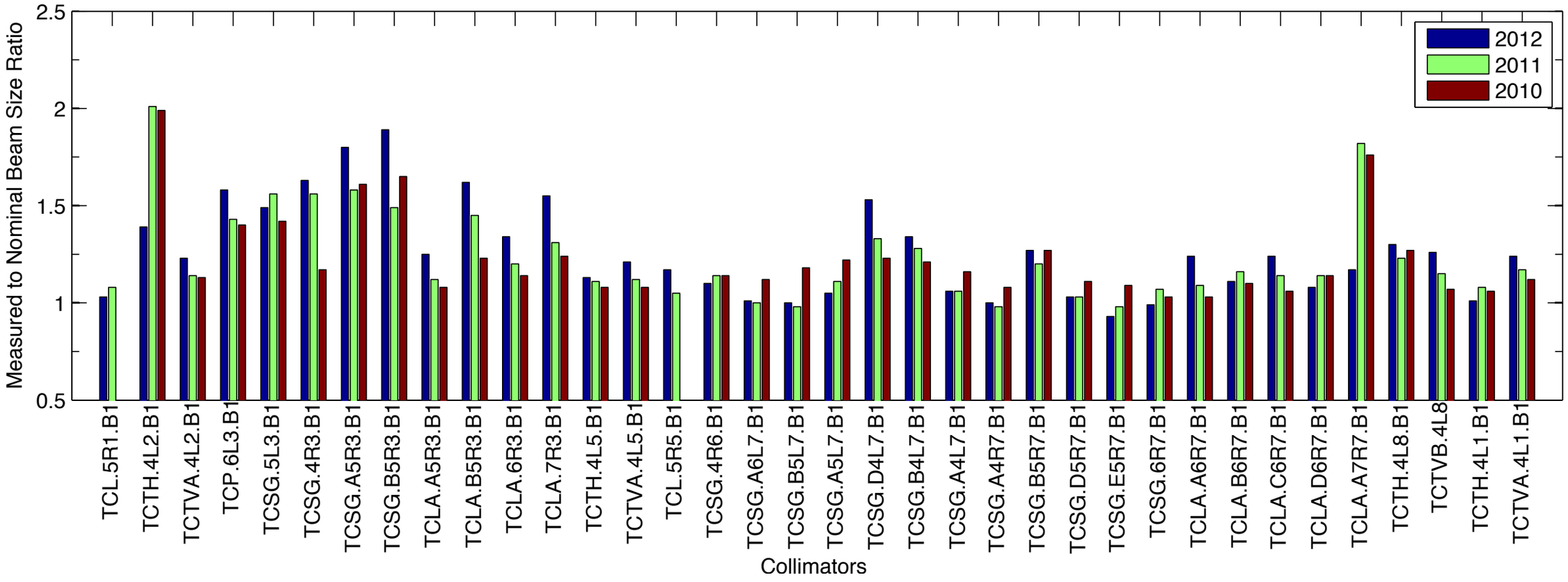
- **Nominal to Measured Beam Size Ratio (B1) at 3.5/4 TeV:**



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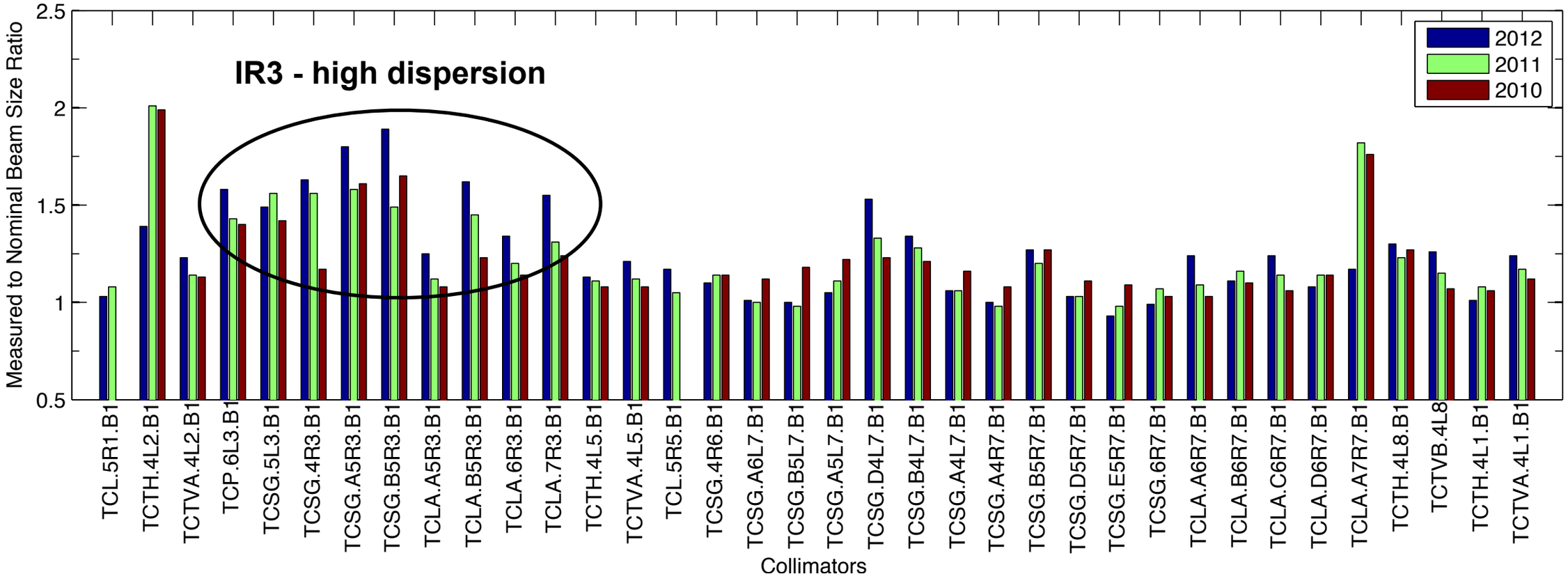

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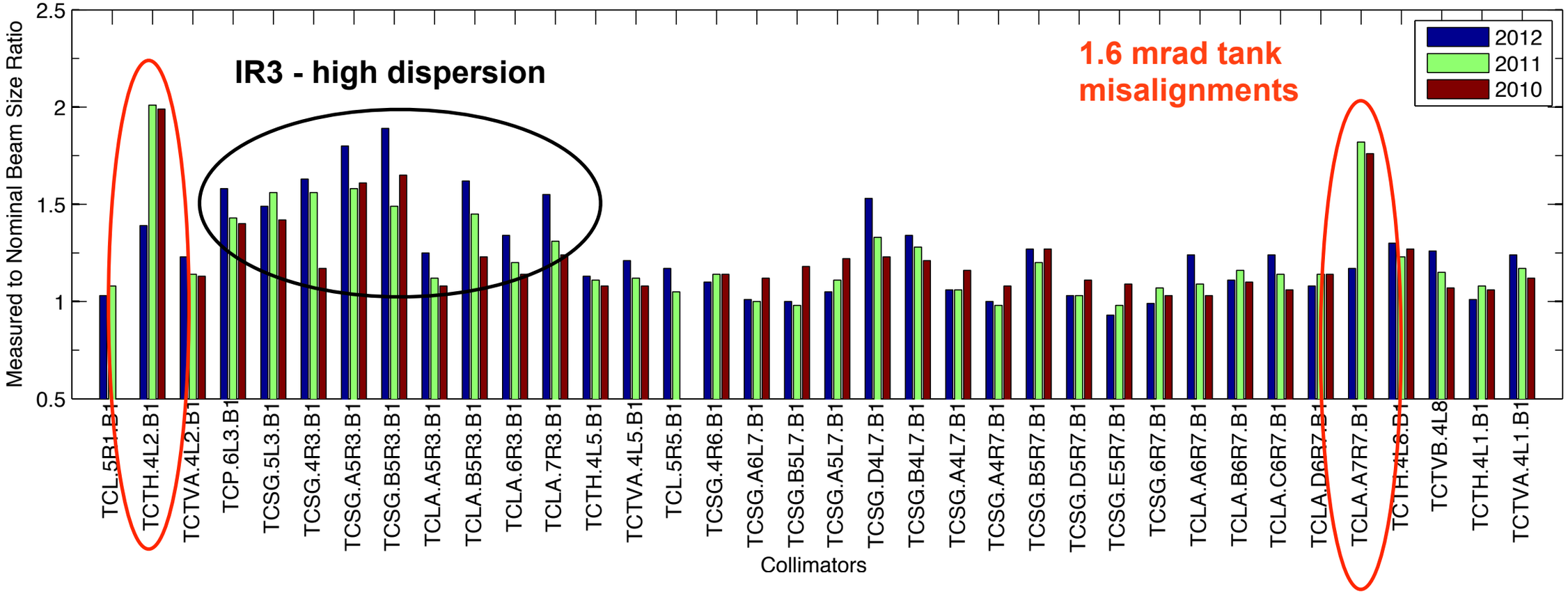

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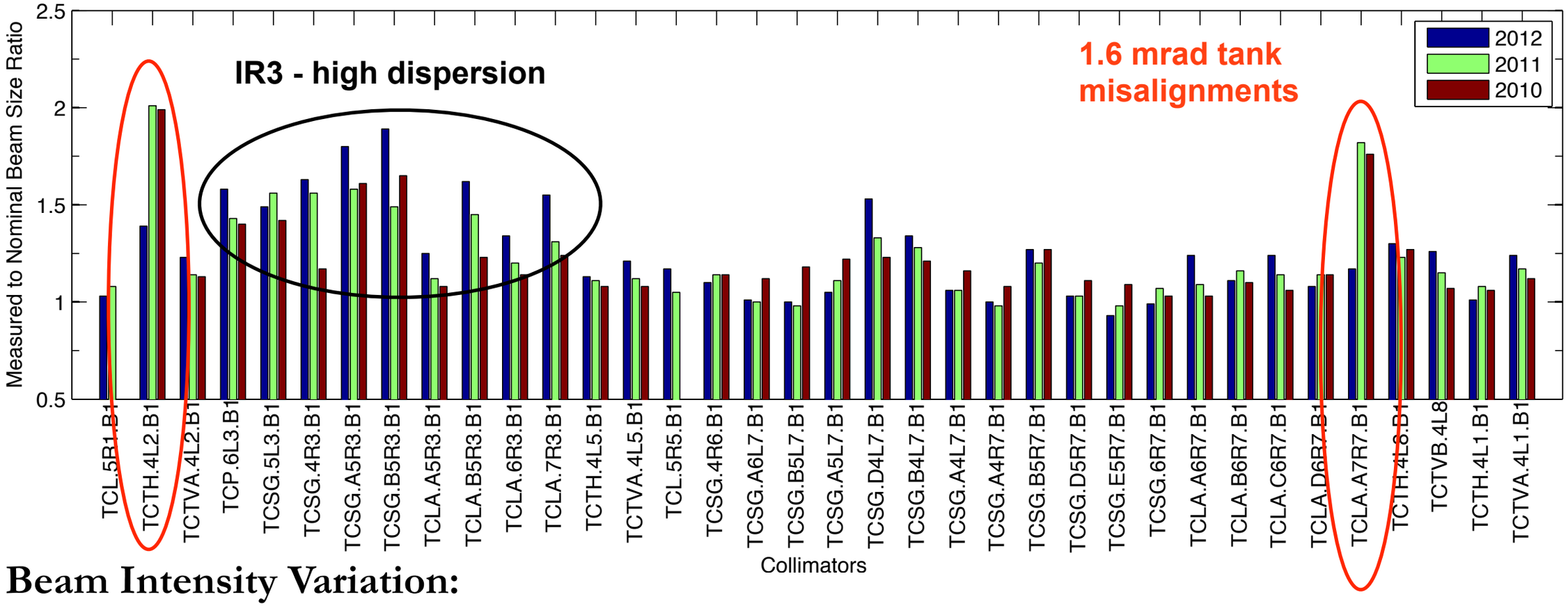

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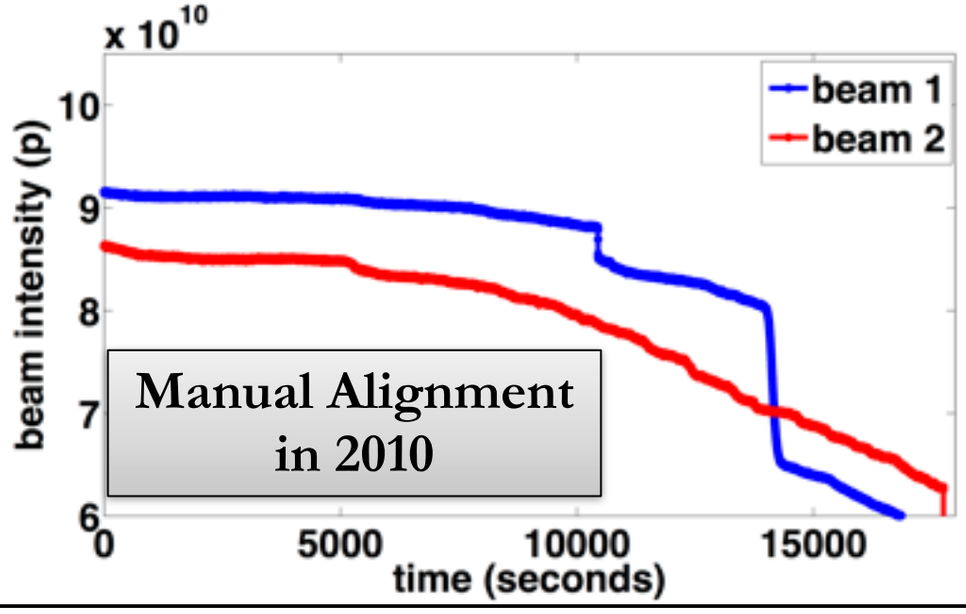
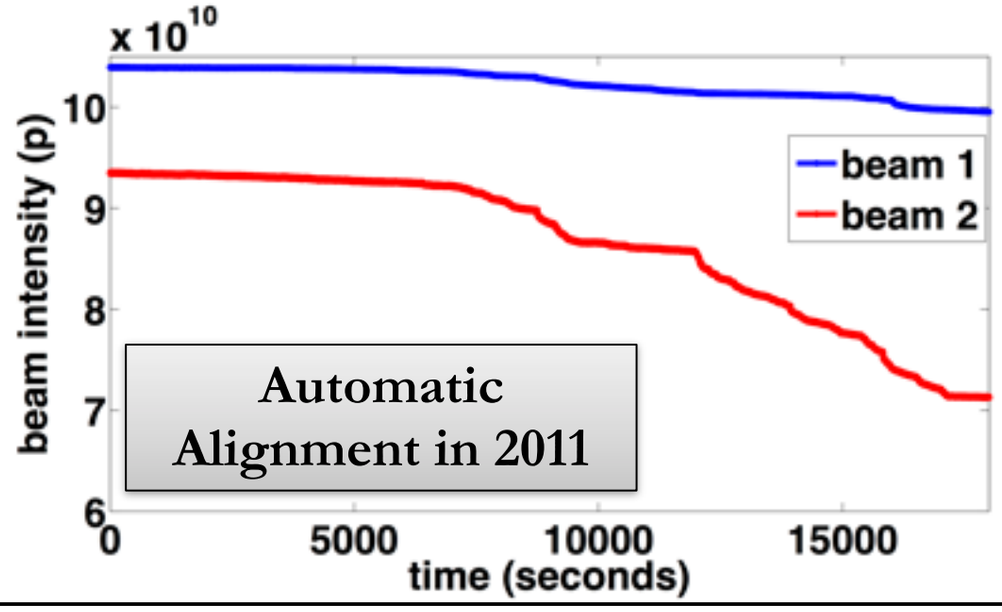
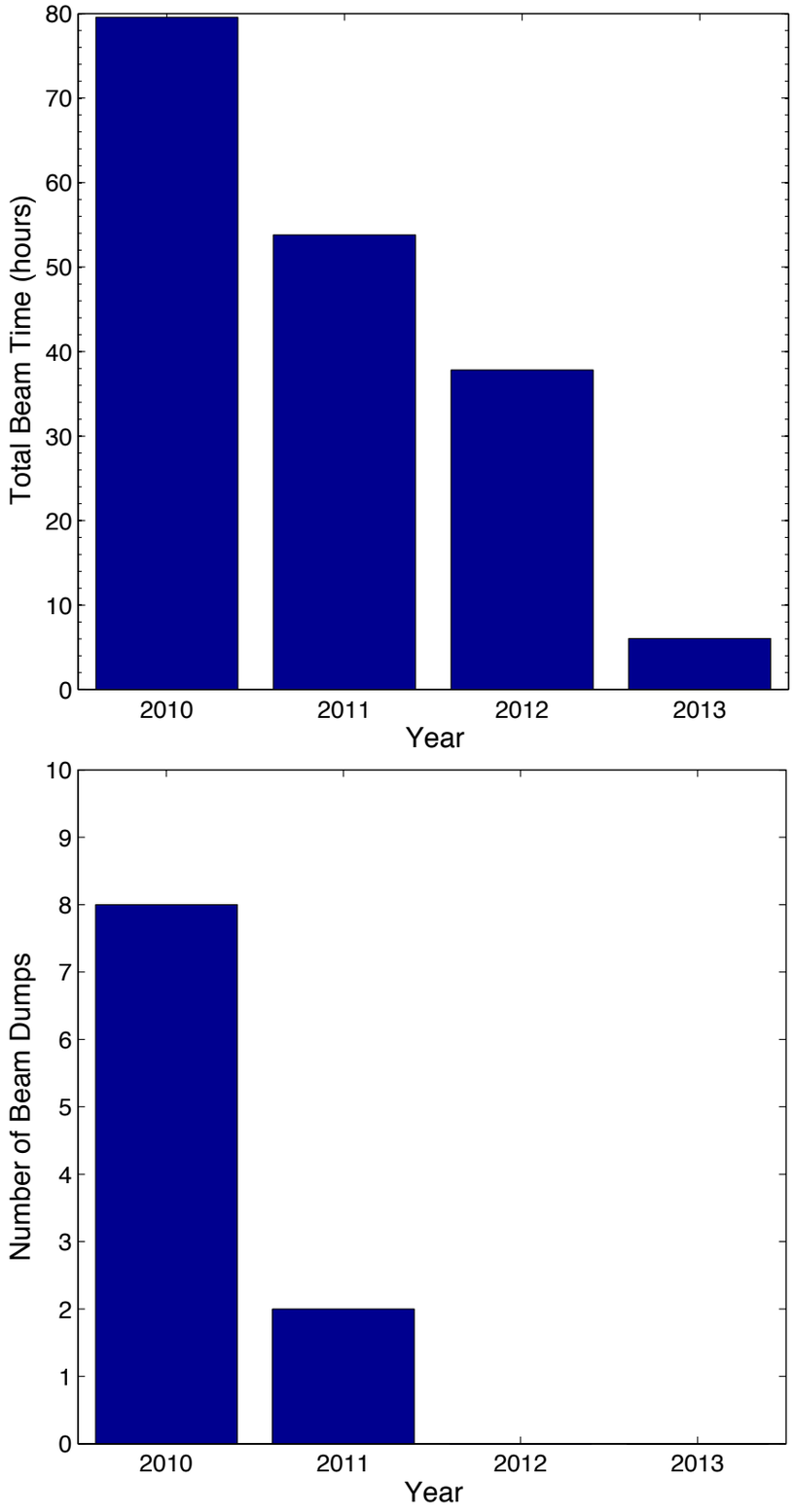
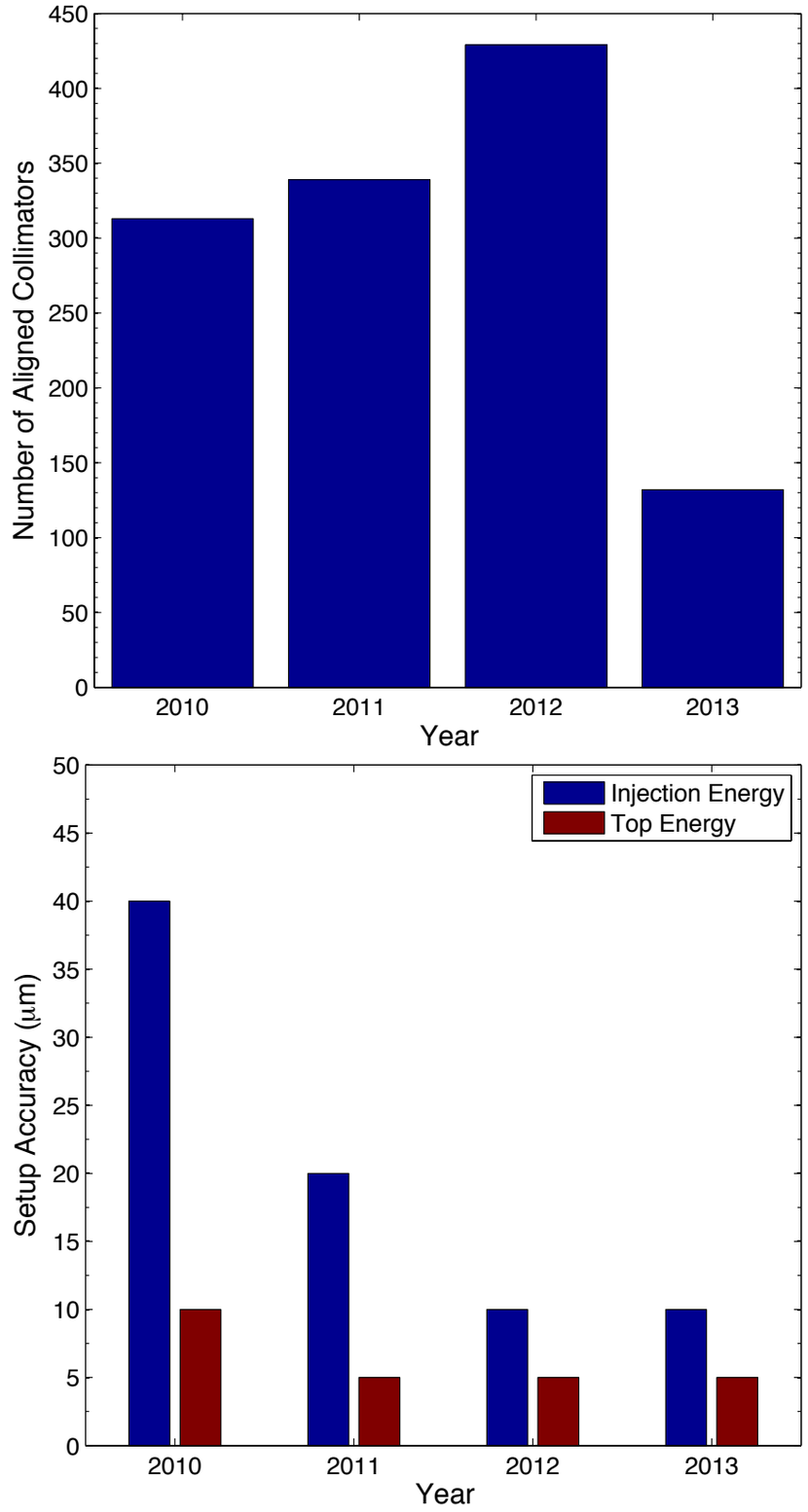




Alignment Performance Overview





Simulations vs. Measurements

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- Policy 4 is not included in the comparison as only simulation results exist.
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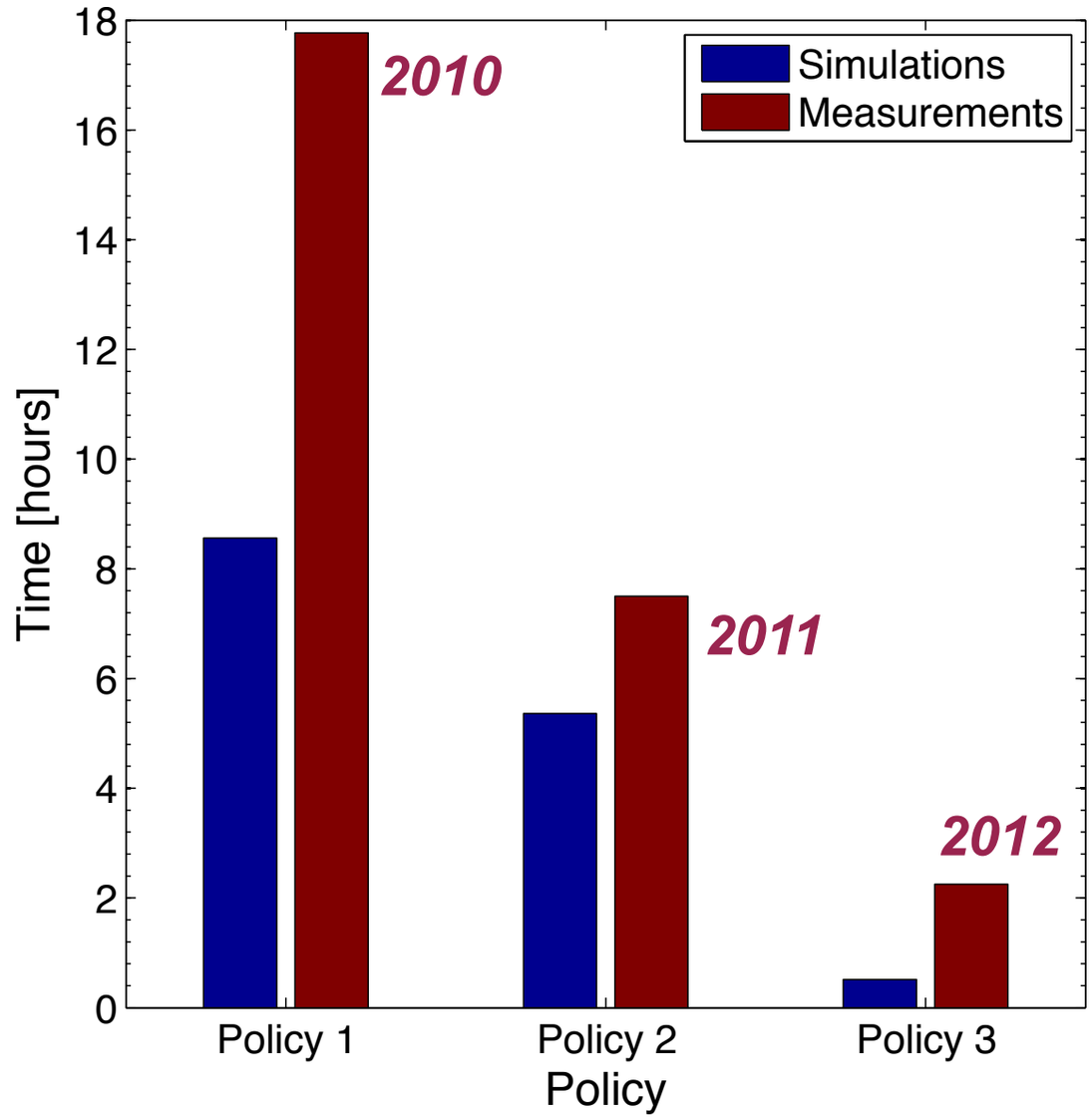

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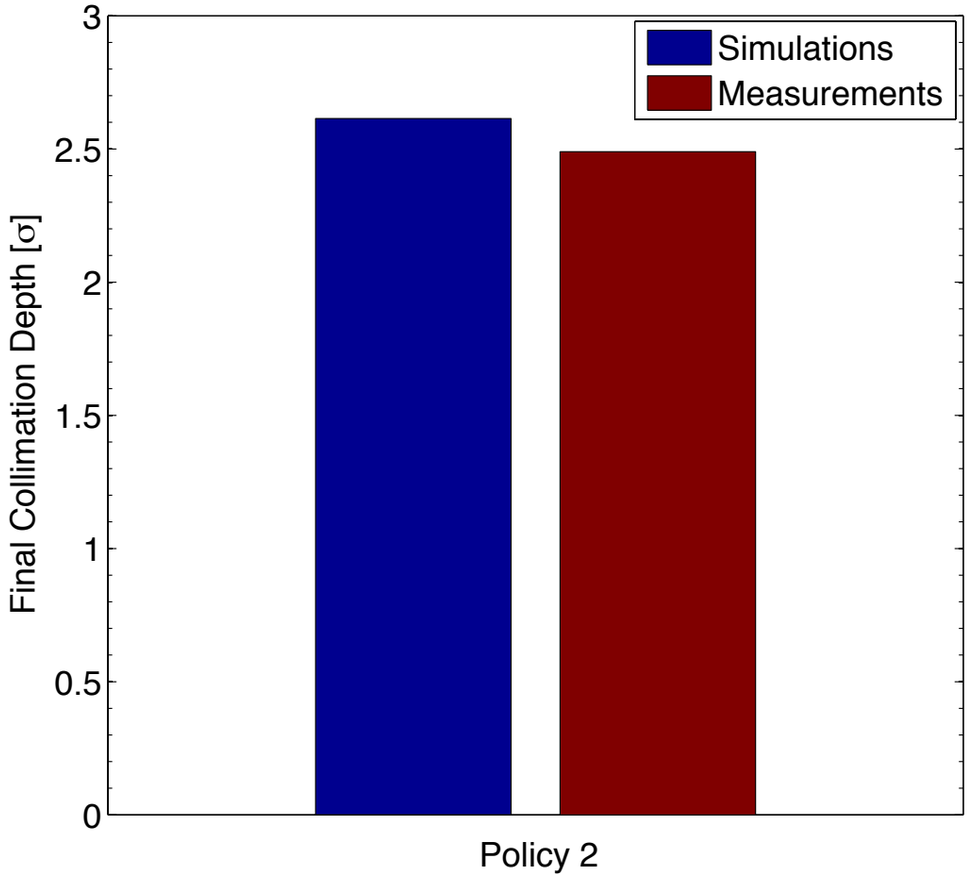

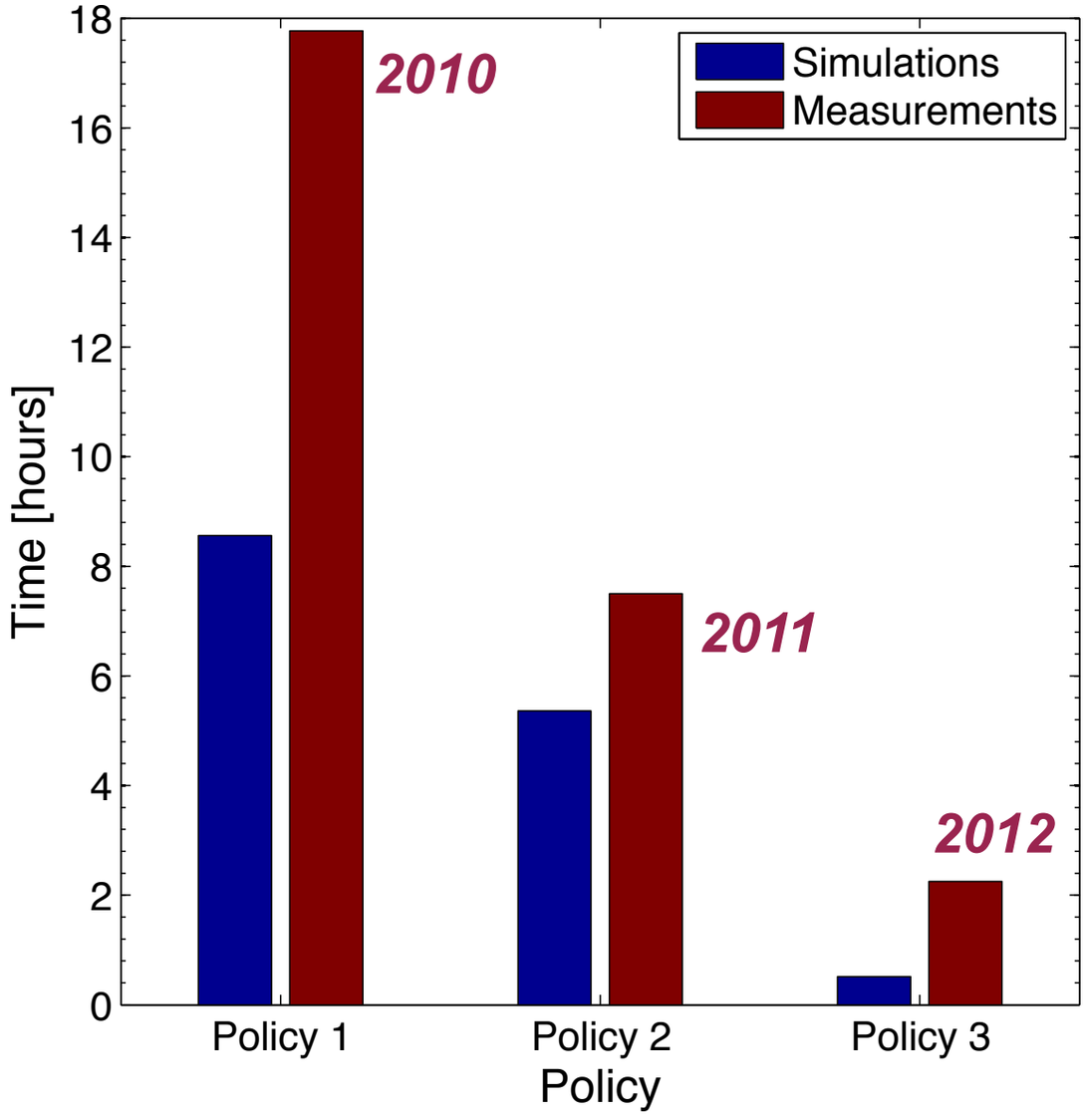

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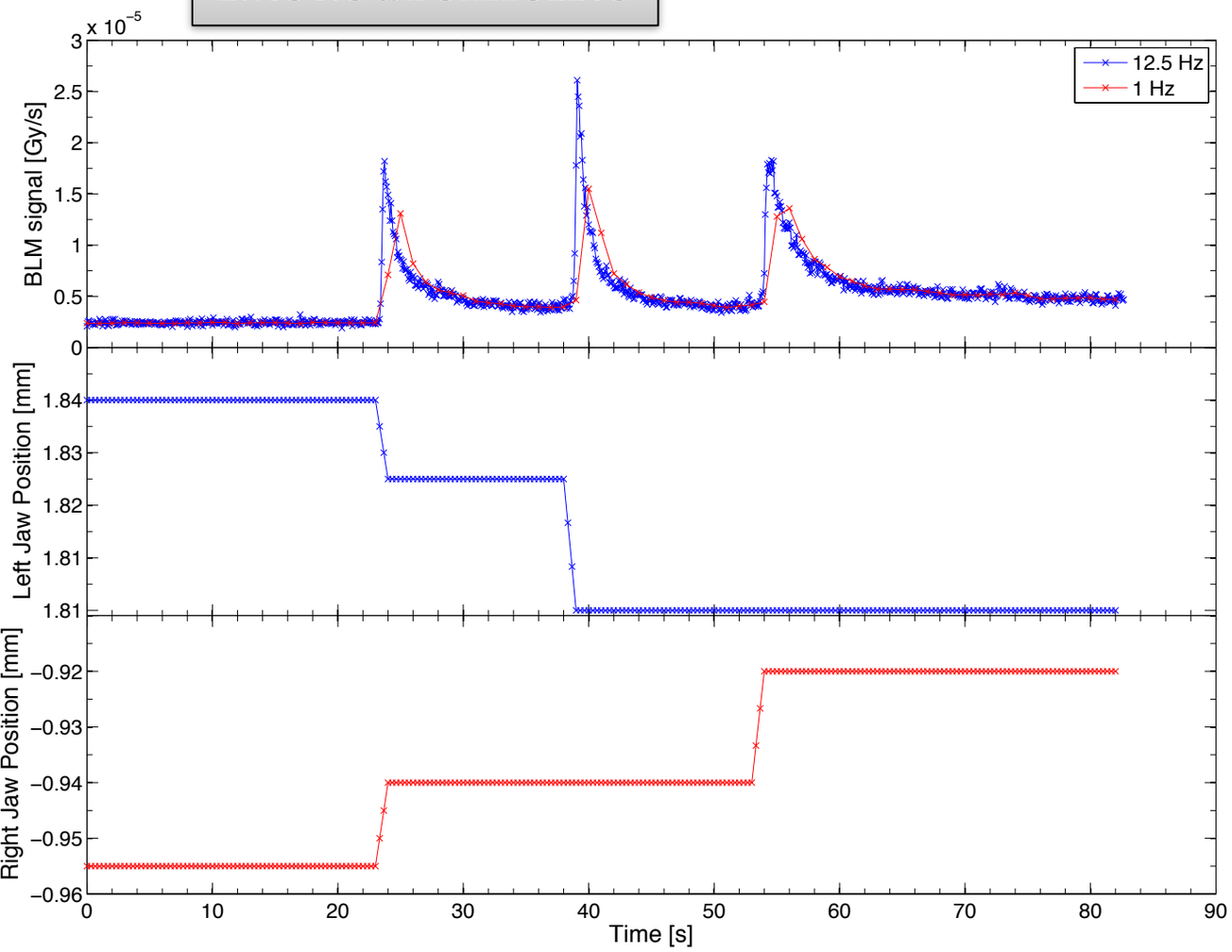

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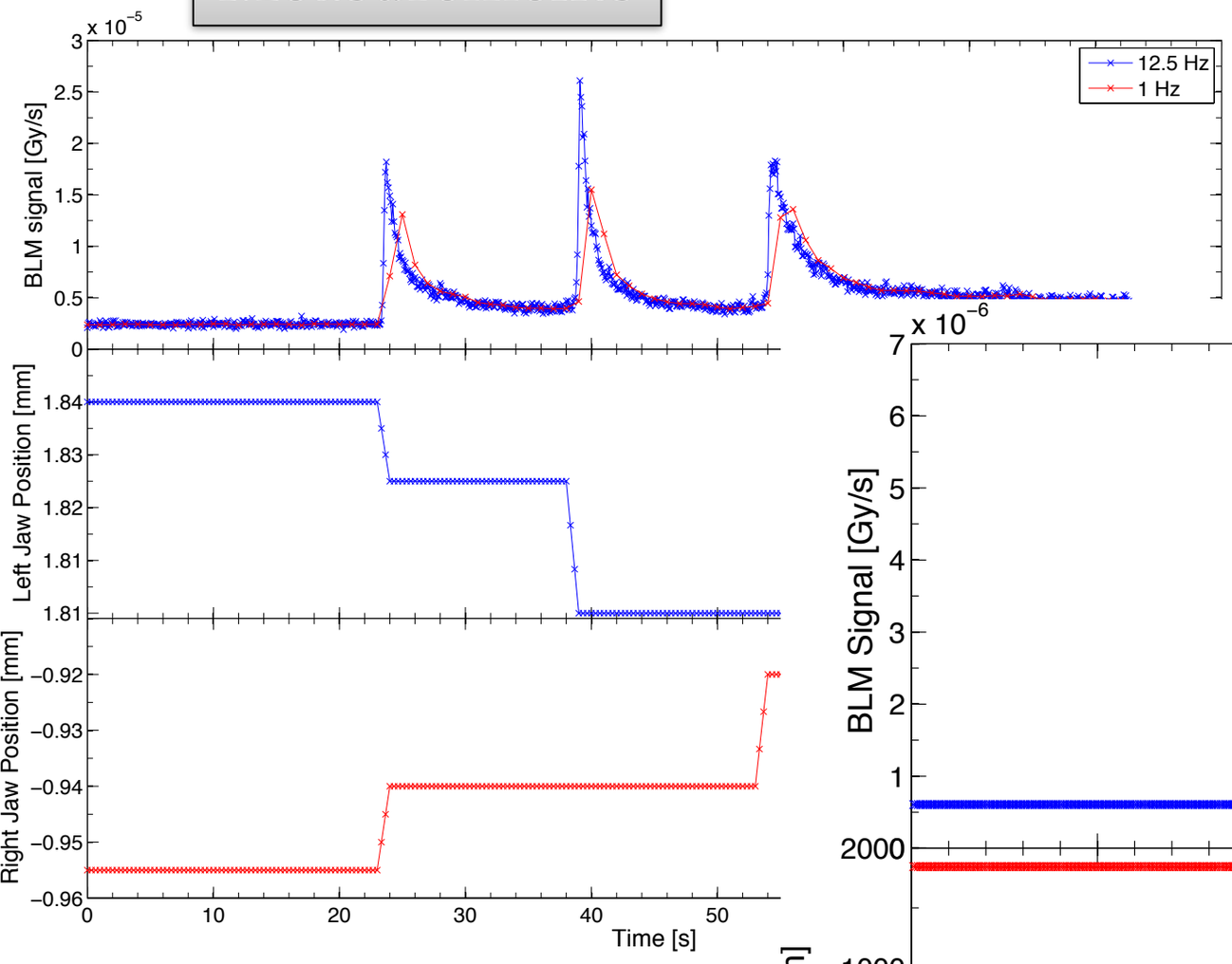

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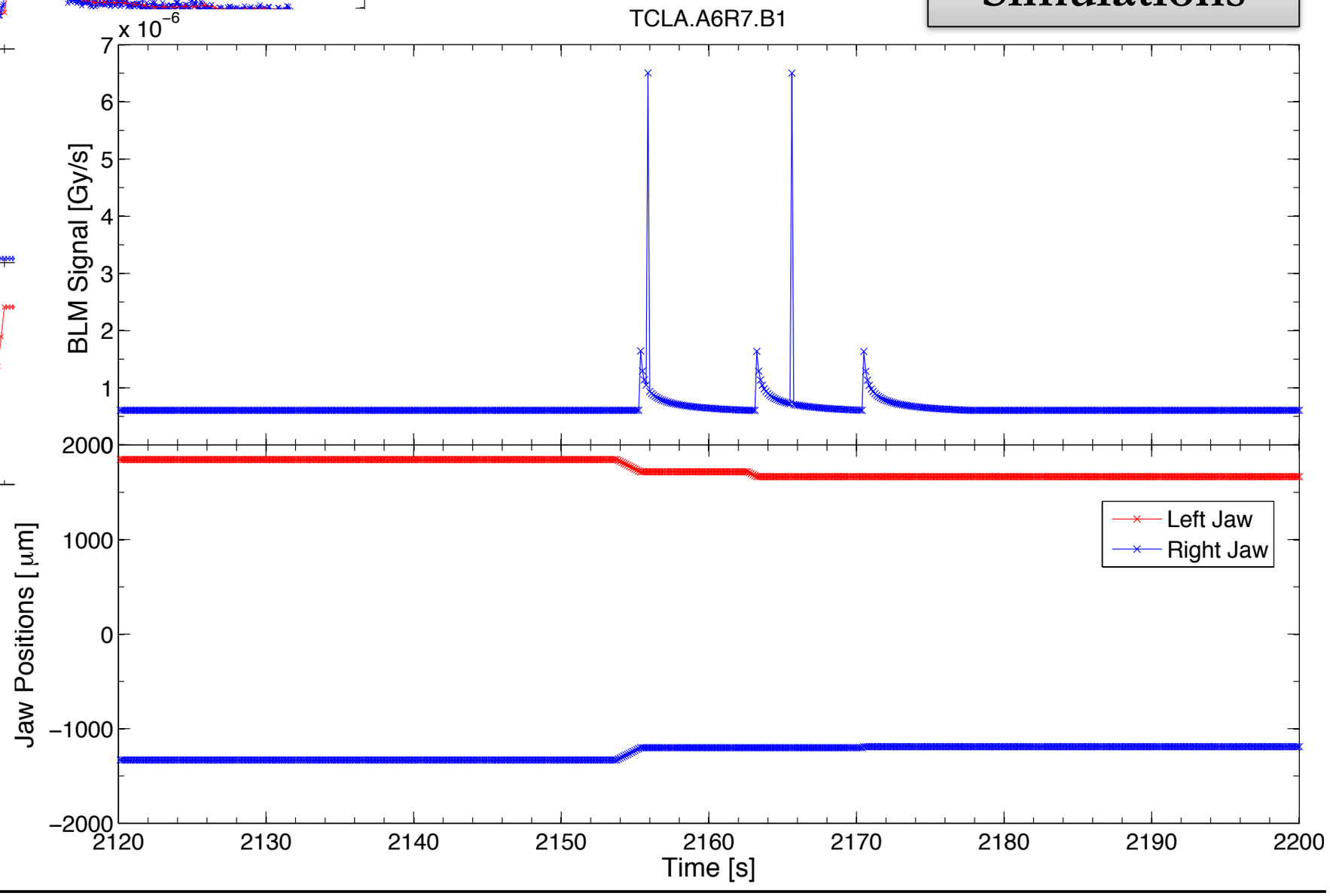

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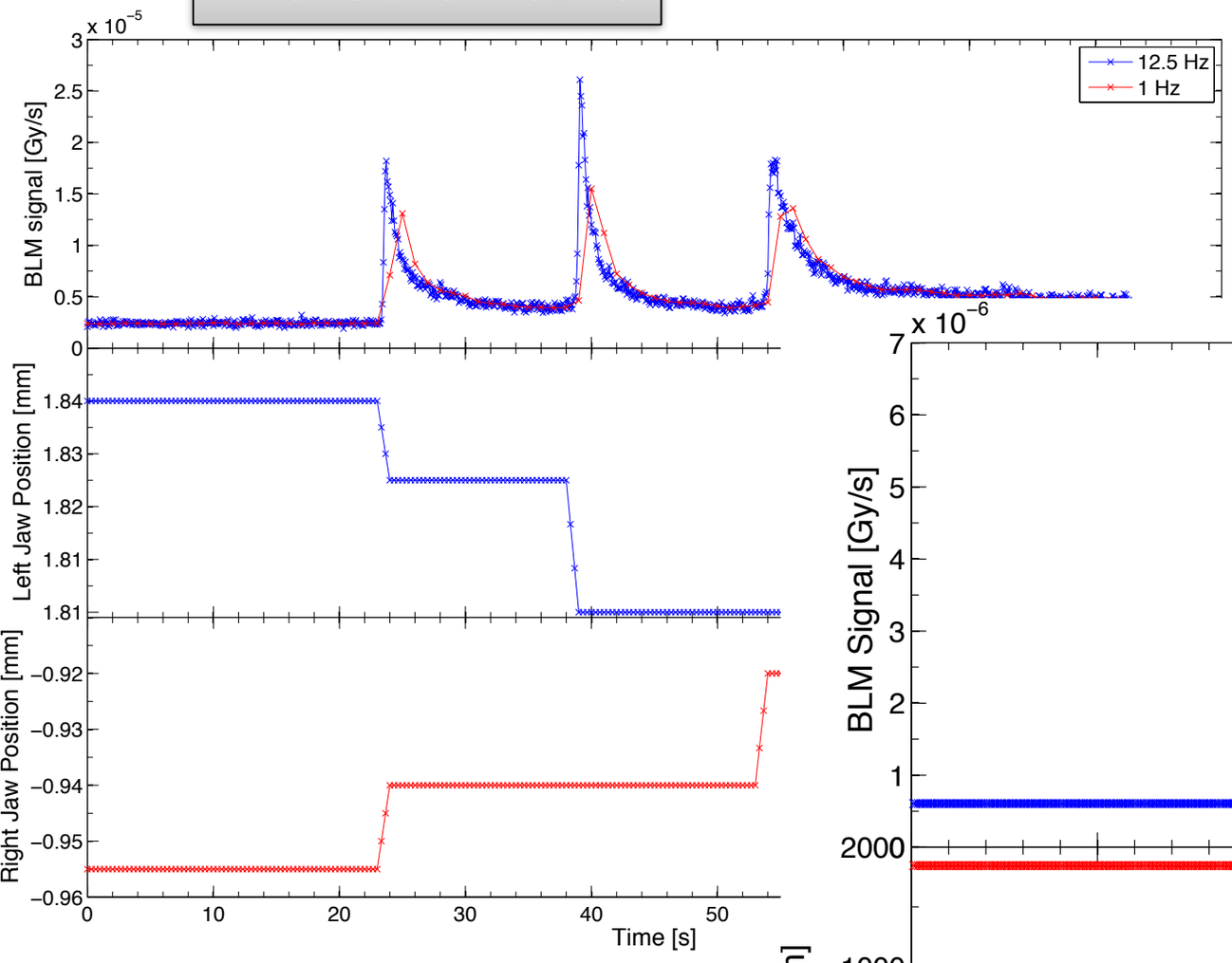
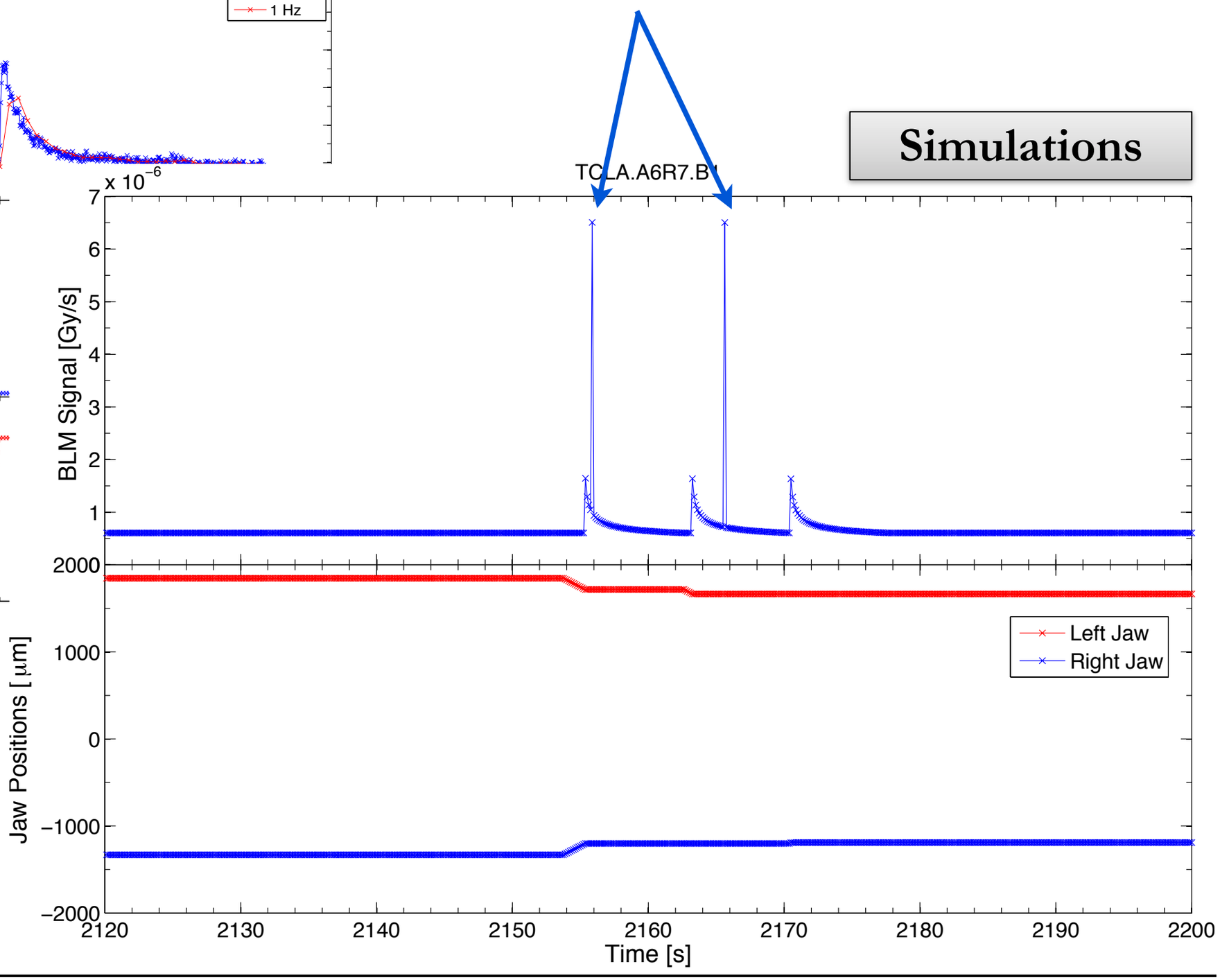


Crosstalk from other beam

Simulations



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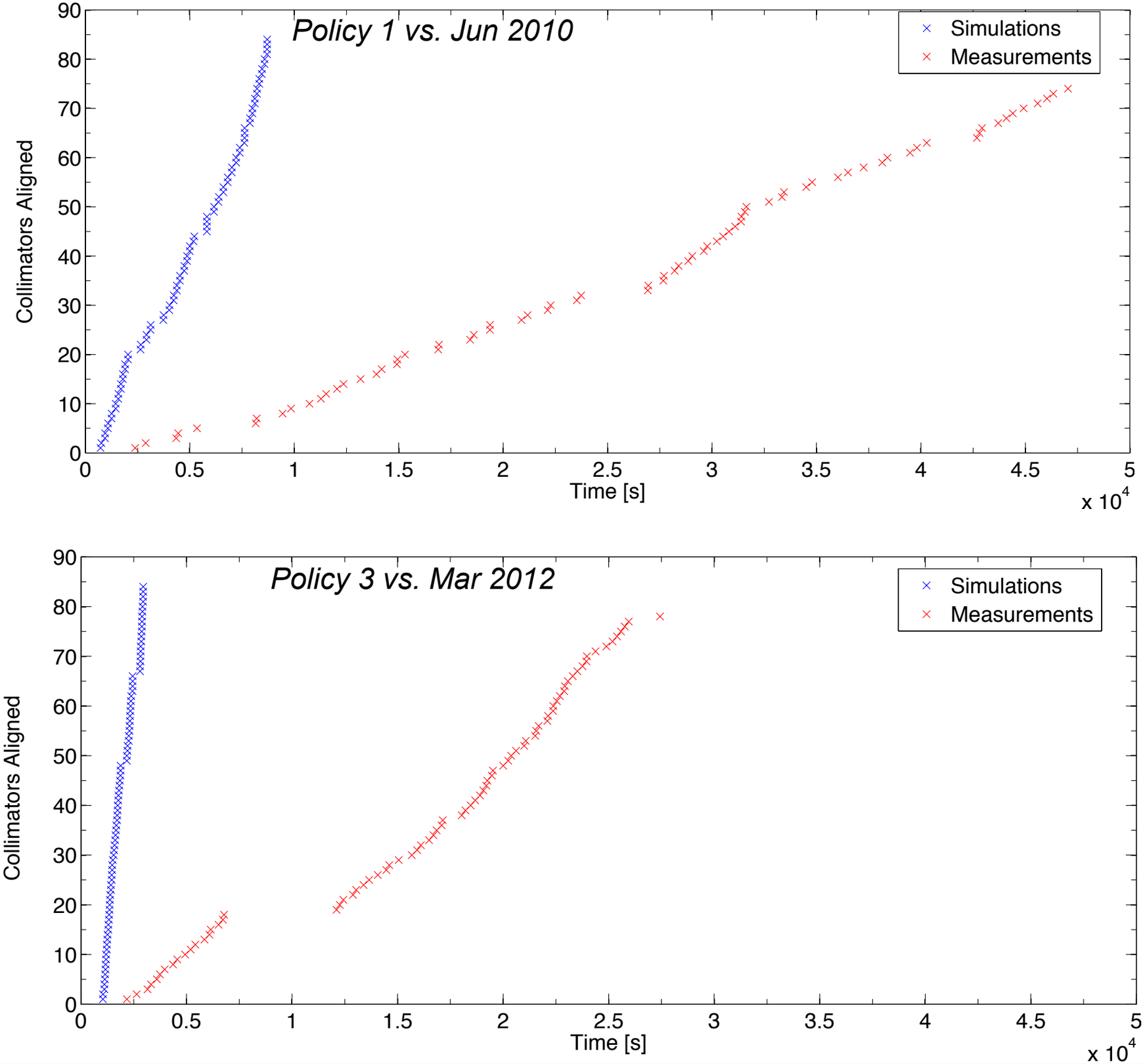

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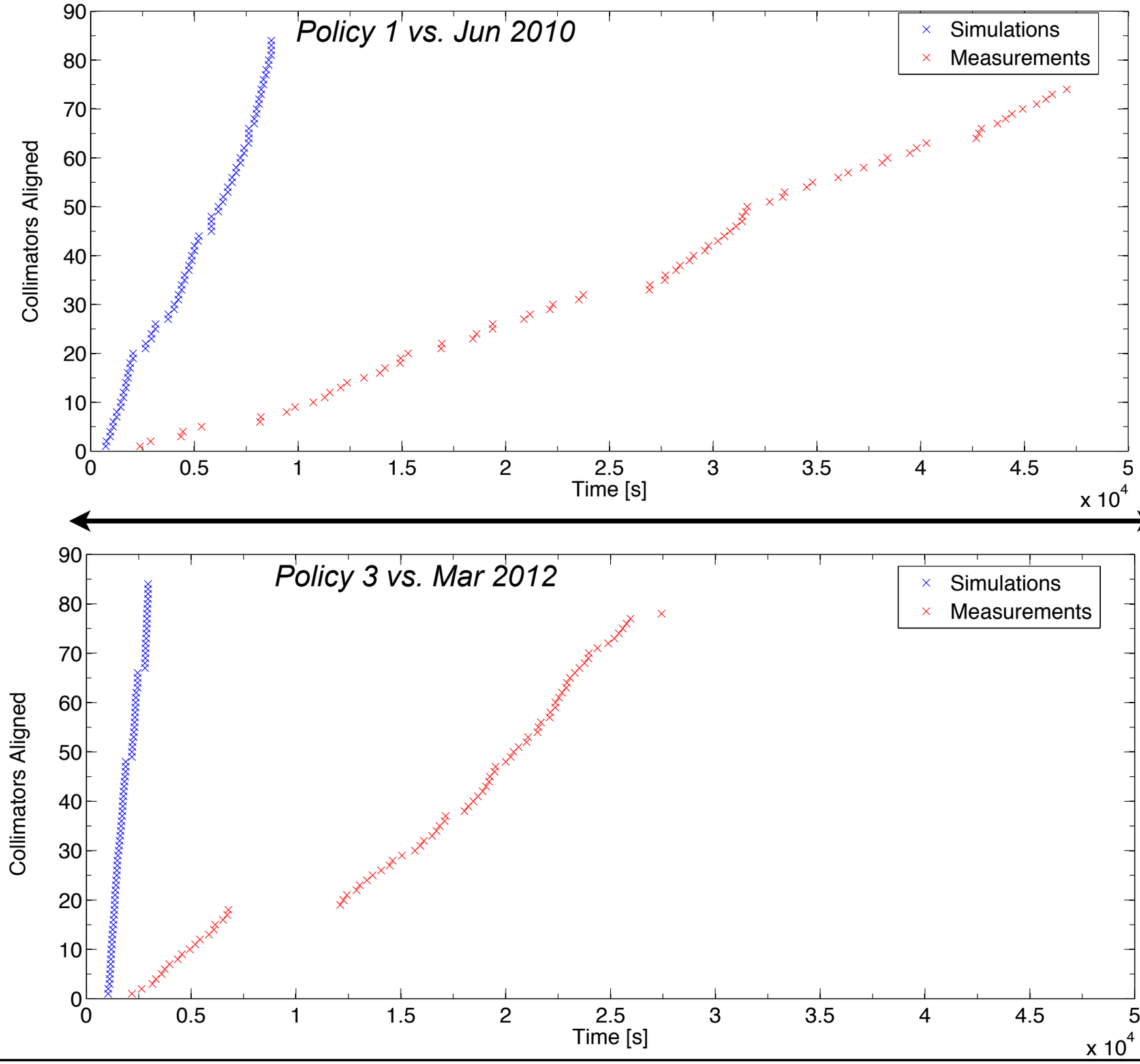

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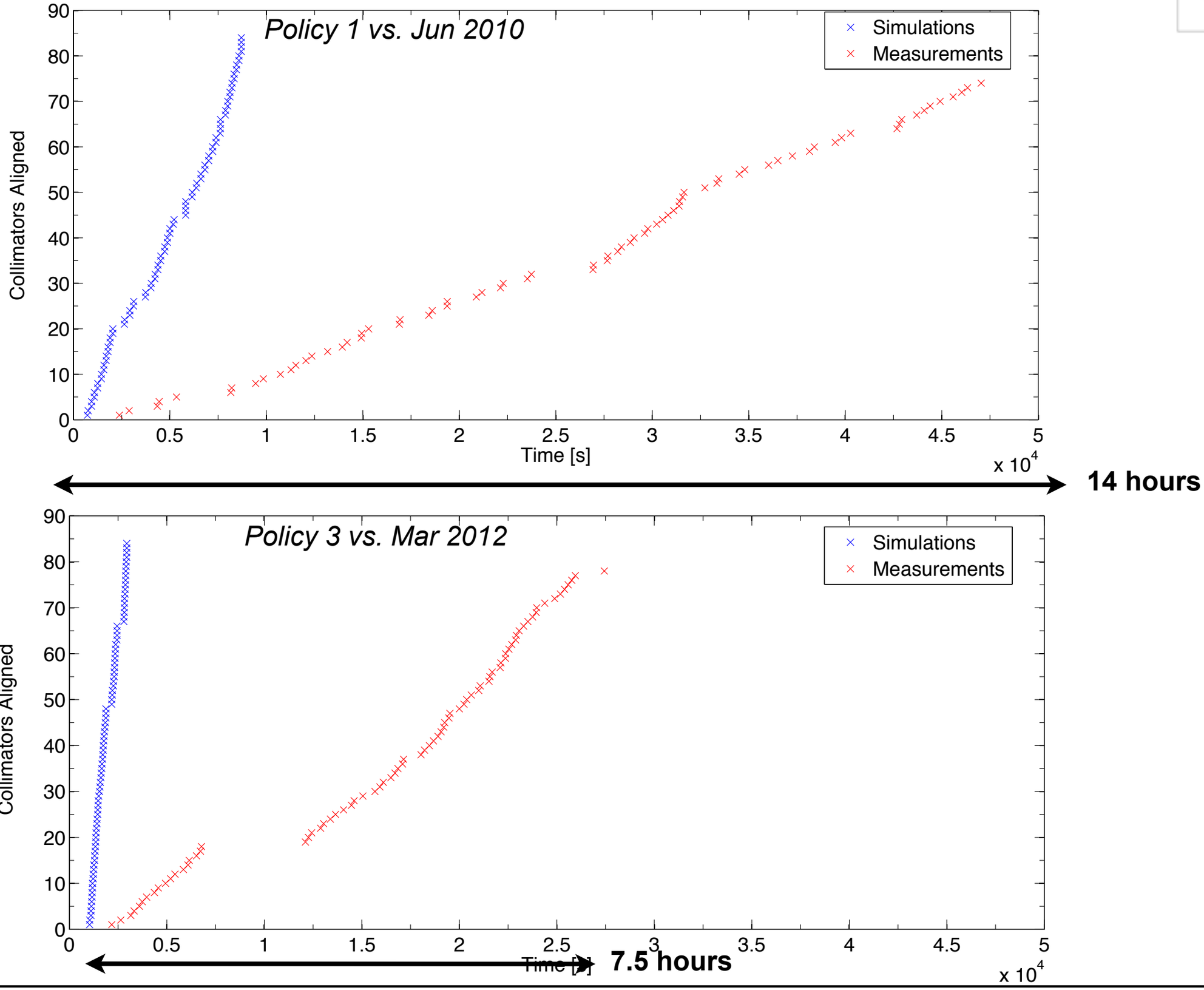

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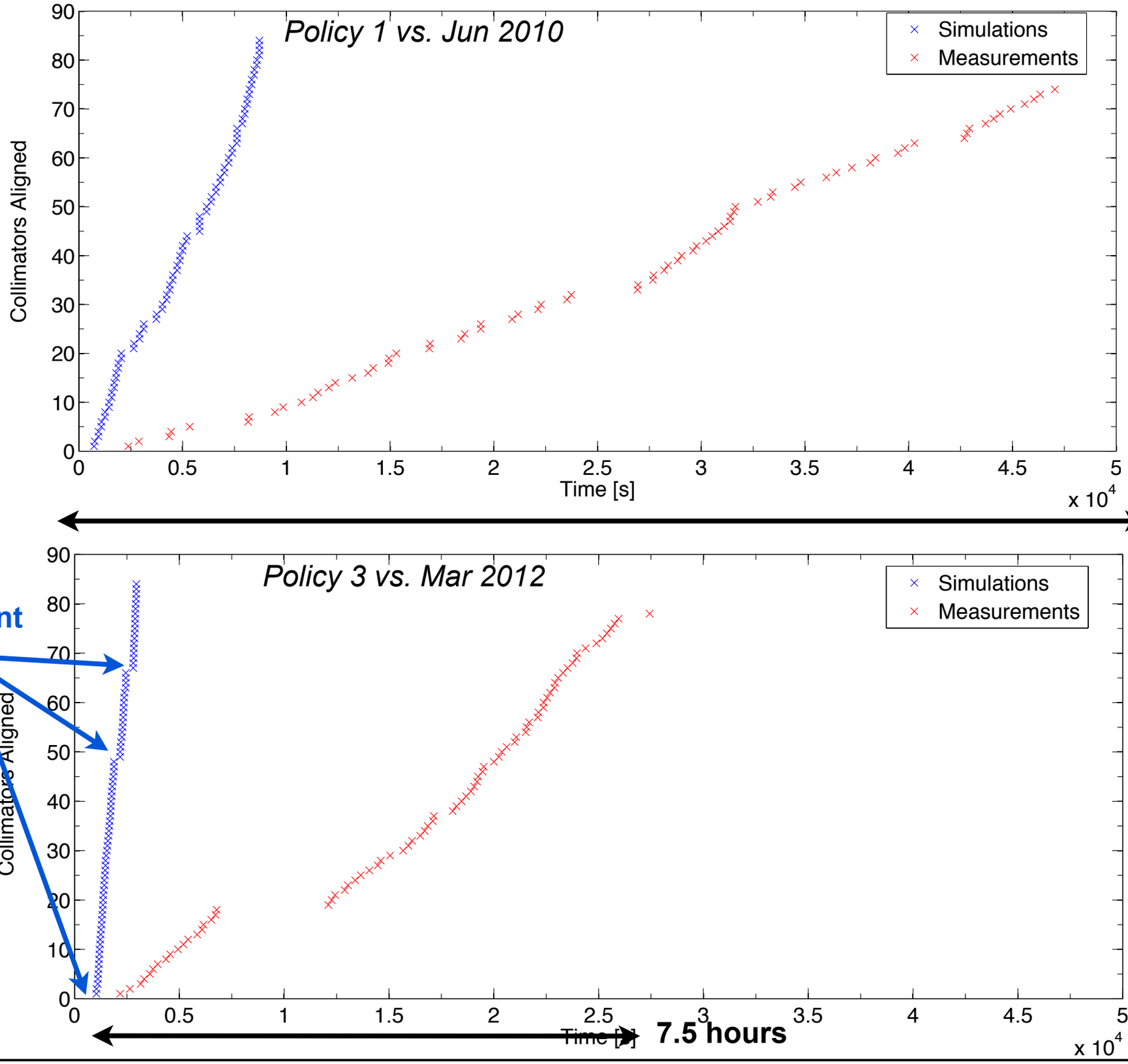
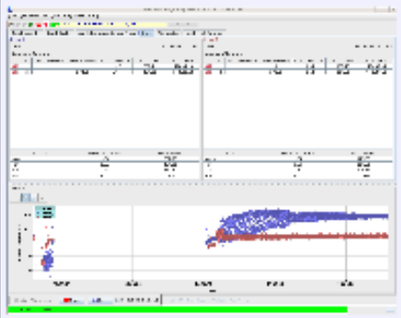
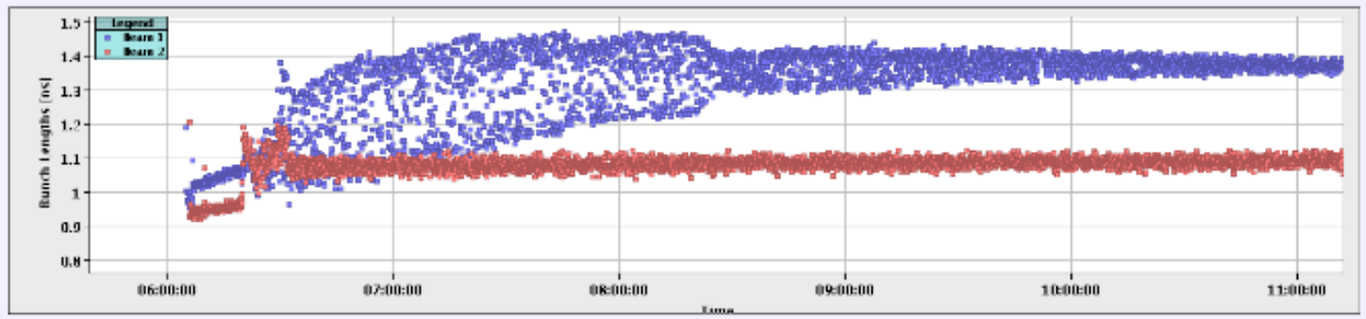


Parallel alignment
H, V, S

Simulations vs. Measurements

6	10:33	NB	RF investigation: The problem observed with the RF blow-up is different from the ramp Wednesday 15:00. The blow-up did work OK, leading to bunch lenght between 1.0 and 1.2 ns for both bunches of each ring. BUT we observe a quadrupole oscillation developping in the last qurarter of the acceleration ramp. At this longitudinal emittance, we did not have single bunch instability last year. So we first want to make sure that it is an instability by ramping same filling pattern with reduced intensity per bunch (7e10 p/bunch). Next fill. Assuming that this gives good results, we would then ramp same filling pattern, nominal intensity with Phase Loop at flat gain. The suspicion is that the phase loop has some influence on stability (even though the mode is quadrupole. That was observed during MDs in 2011).  20120329111108.png  20120329111201.png created by lhcop on cwo-ccc-d4lc

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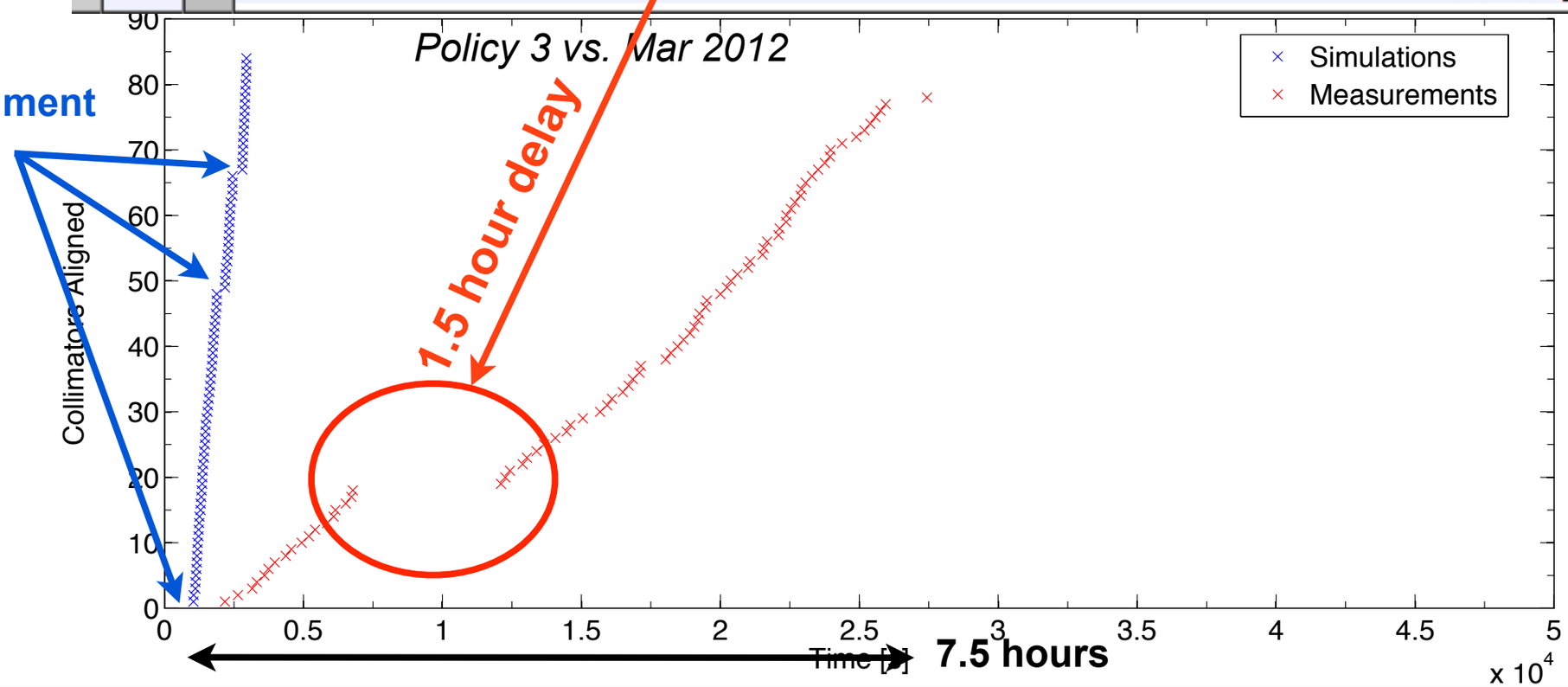

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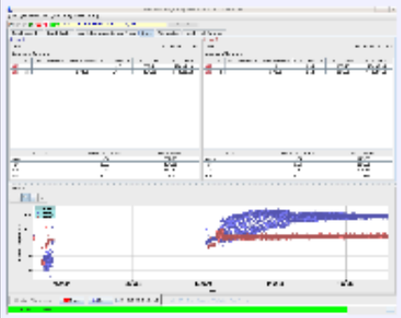
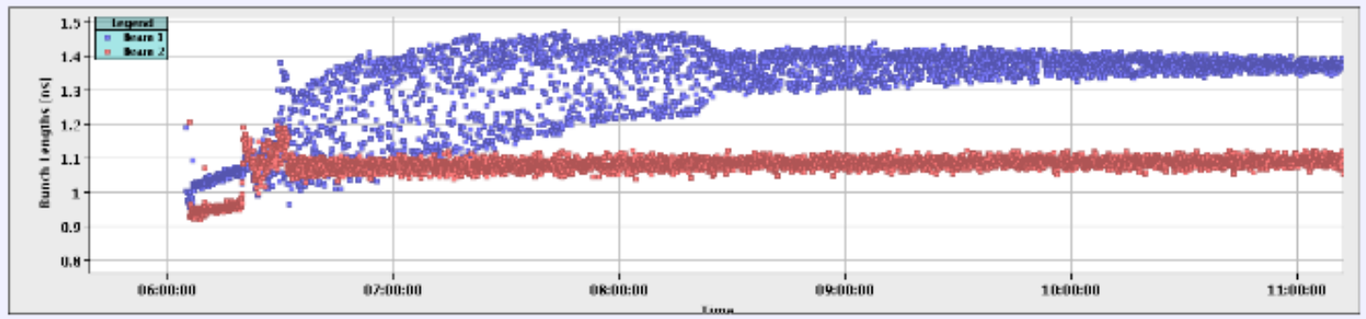
6	10:33	NB	RF investigation: The problem observed with the RF blow-up is different from the ramp Wednesday 15:00. The blow-up did work OK, leading to bunch lenght between 1.0 and 1.2 ns for both bunches of each ring. BUT we observe a quadrupole oscillation developping in the last qurarter of the acceleration ramp. At this longitudinal emittance, we did not have single bunch instability last year. So we first want to make sure that it is an instability by ramping same filling pattern with reduced intensity per bunch (7e10 p/bunch). Next fill. Assuming that this gives good results, we would then ramp same filling pattern, nominal intensity with Phase Loop at flat gain. The suspicion is that the phase loop has some influence on stability (even though the mode is quadrupole. That was observed during MDs in 2011).  20120329111108.png  20120329111201.png created by lhcop on cwo-ccc-d4lc

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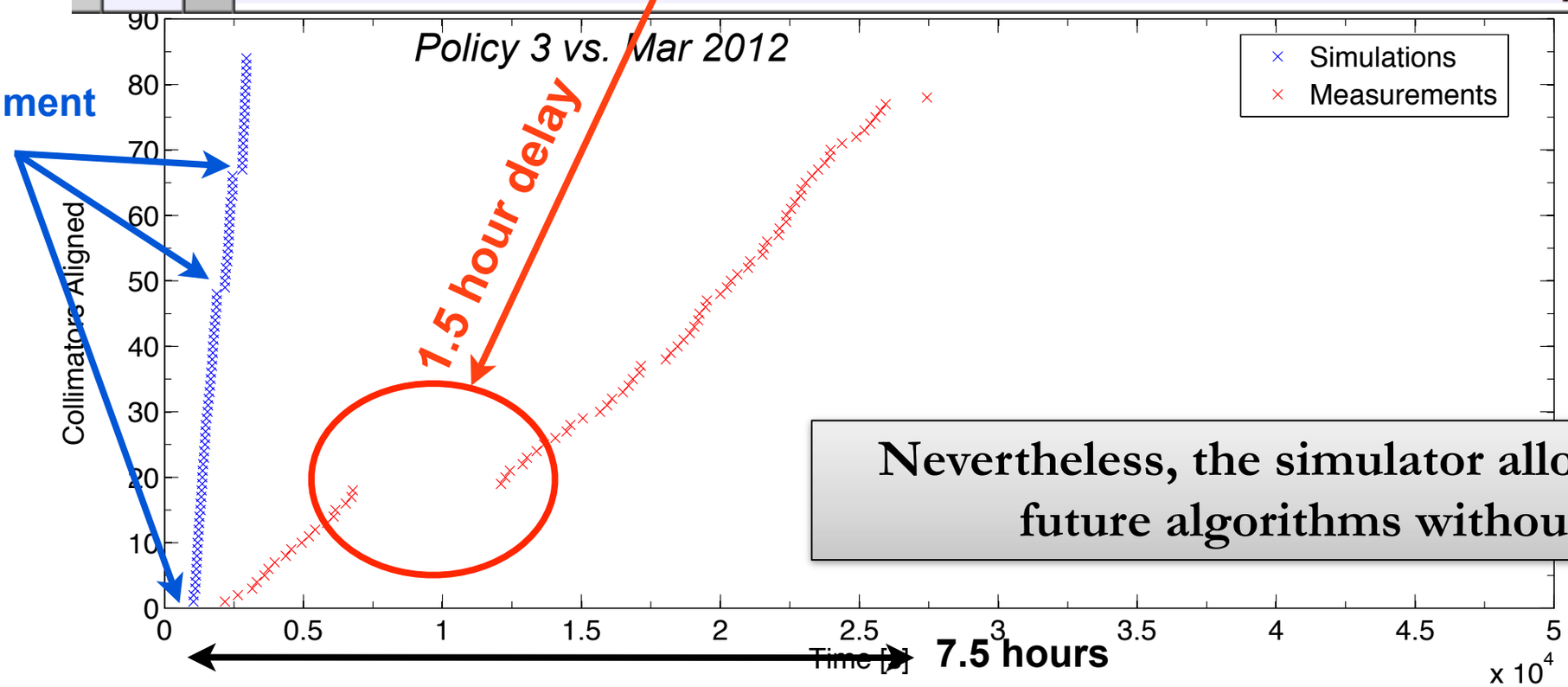

Nevertheless, the simulator allows to validate future algorithms without beam!

Outline

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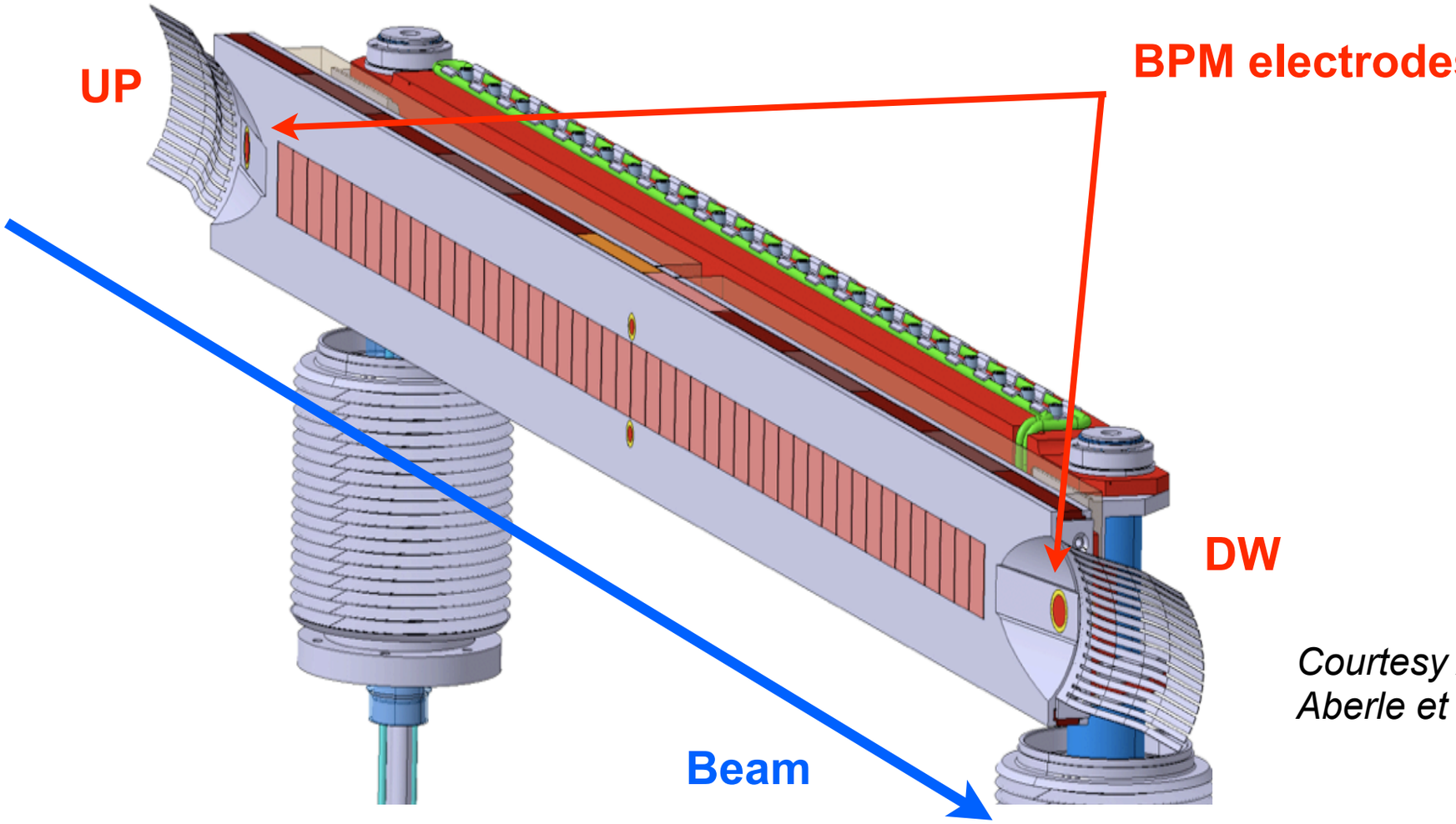
- Collimator Beam-Based Alignment
- Alignment Algorithms
- Software Implementation
- Modeling and Simulation of Beam Losses
- Simulation and Operational Results
- **Future: BPM-based alignment**
- **Conclusions**

BPM-Based Collimator Alignment

- As of 2015, new TCTs with in-built **Beam Position Monitors (BPMs)** will be installed.
- This will provide a **direct measurement of the beam orbit** at the TCT locations.
- Beam centre cannot be measured accurately at large gaps and offsets due to **BPM non-linearities**.
- A mock-up BPM-equipped collimator is currently installed in the SPS for beam tests.



Courtesy A. Dallocchio, A. Bertarelli, O. Aberle et al.

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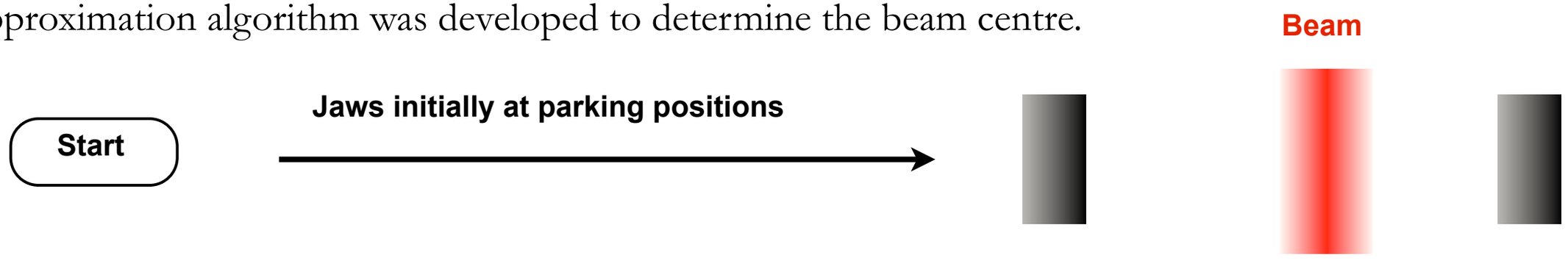

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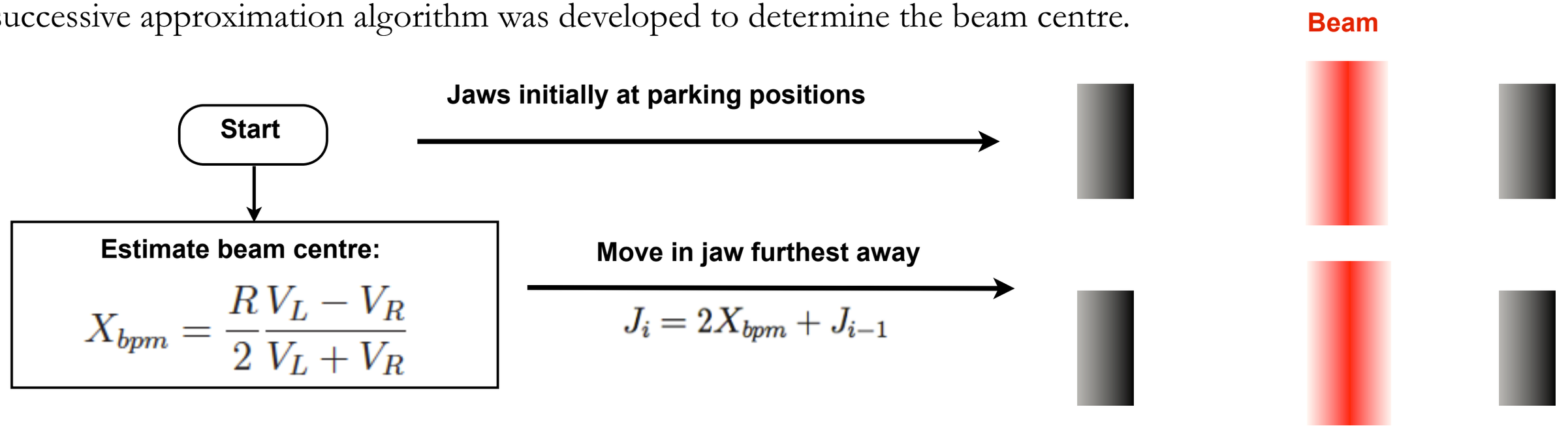

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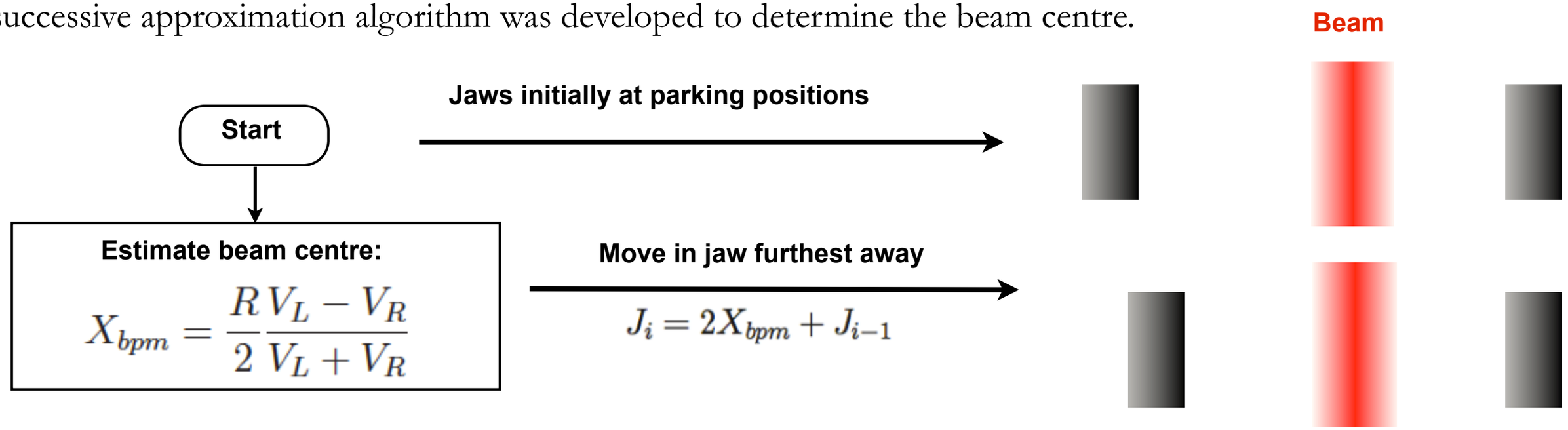

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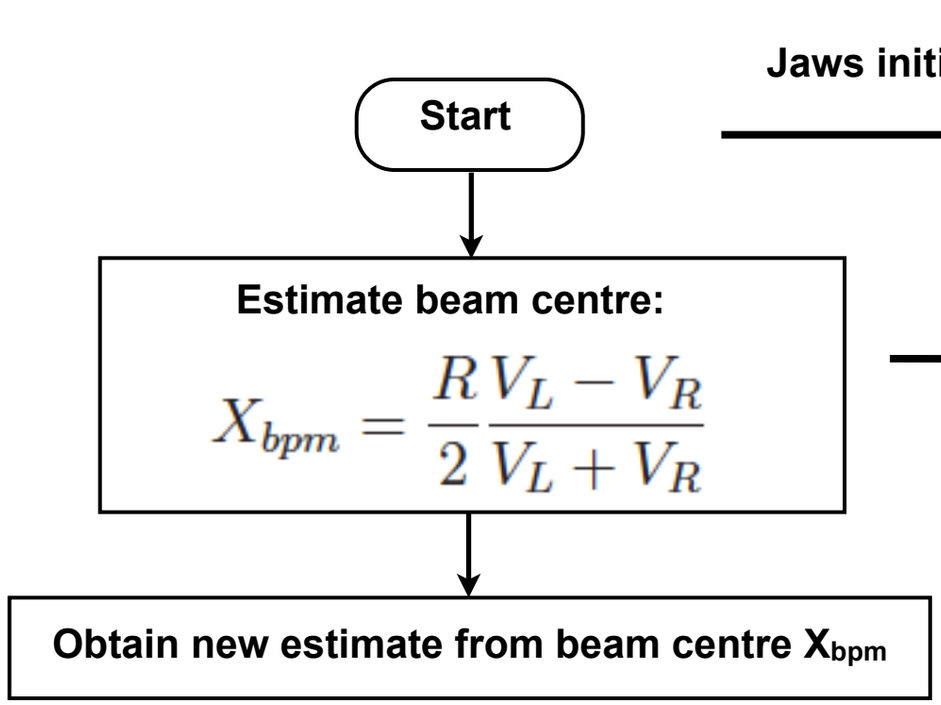

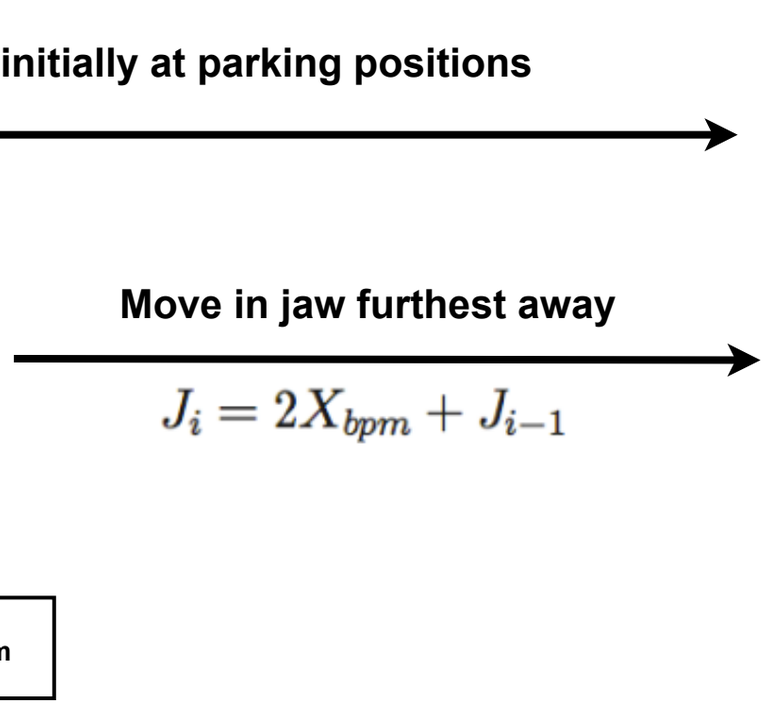

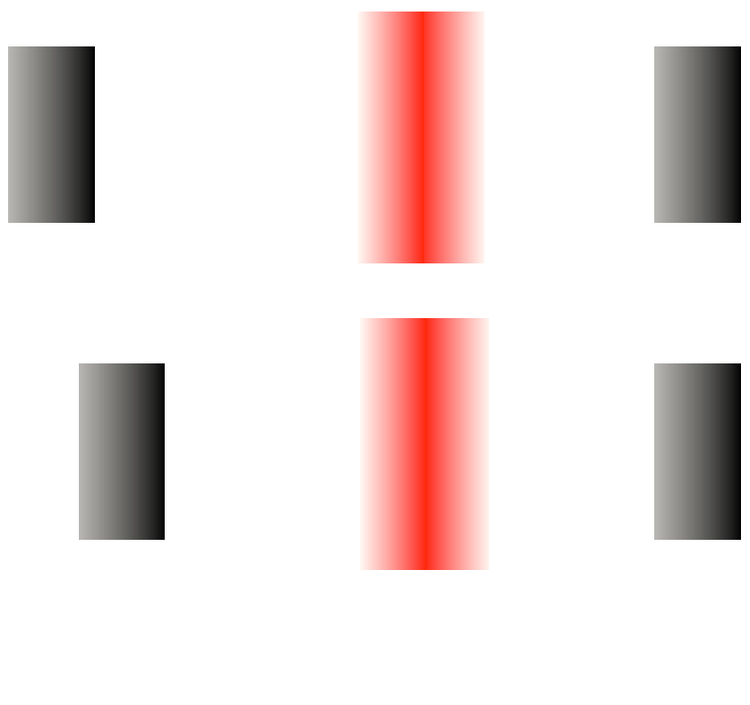

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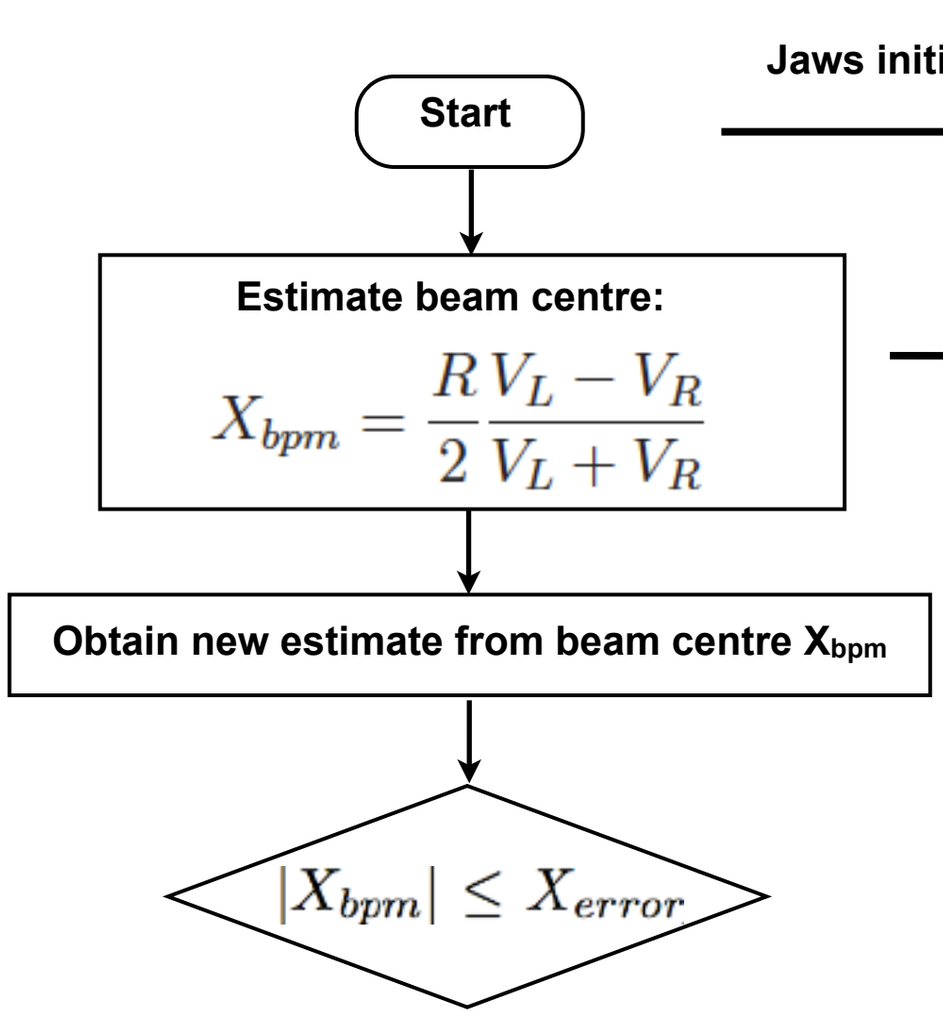

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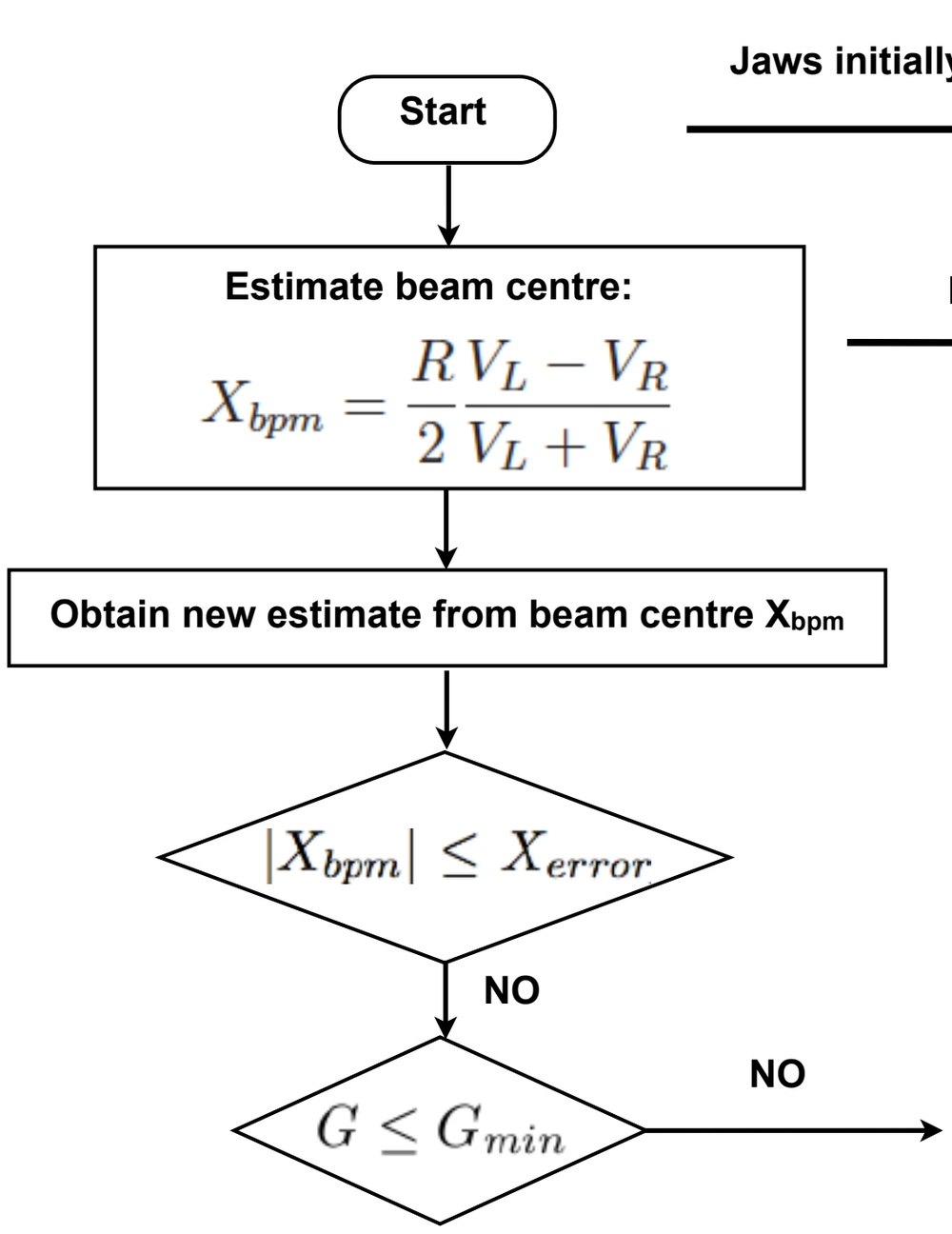

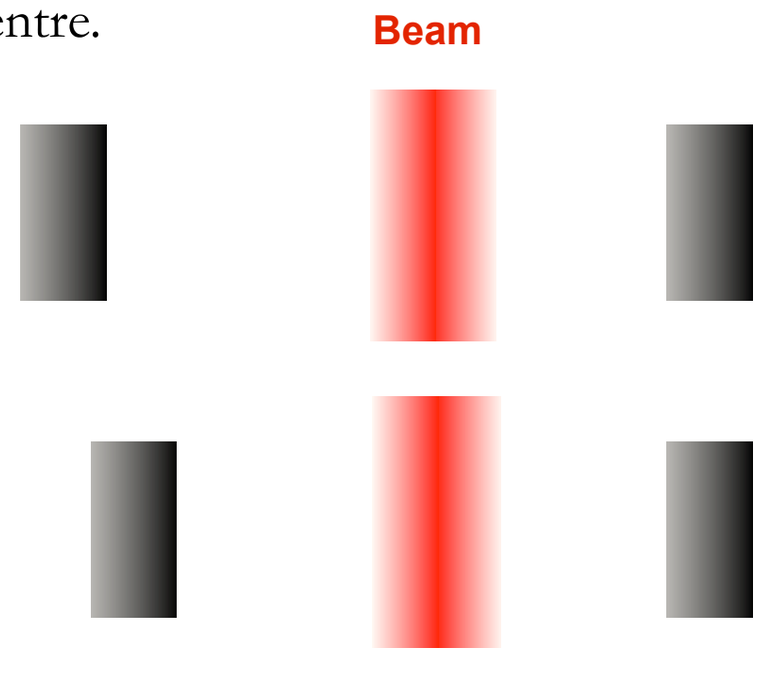

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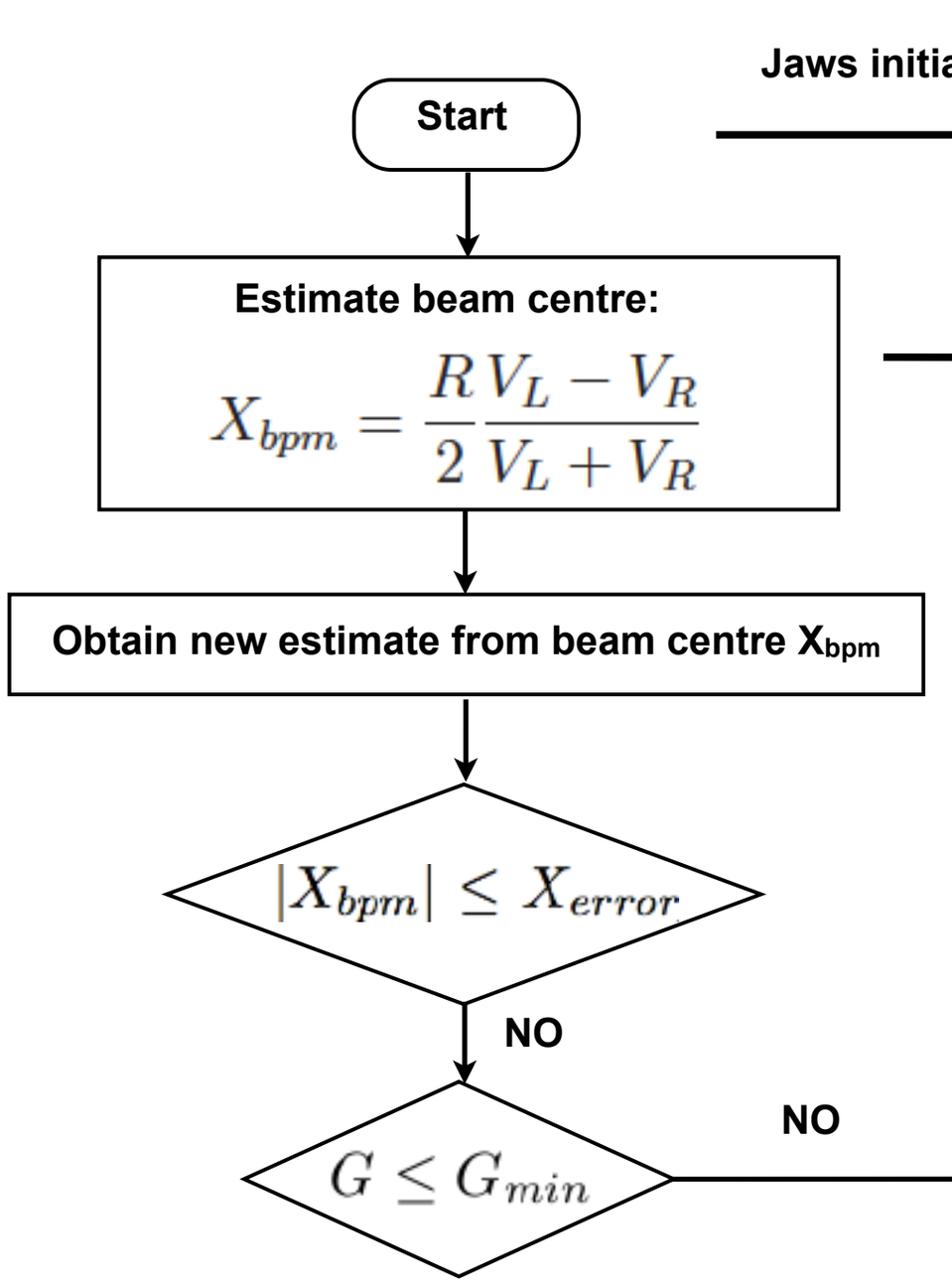

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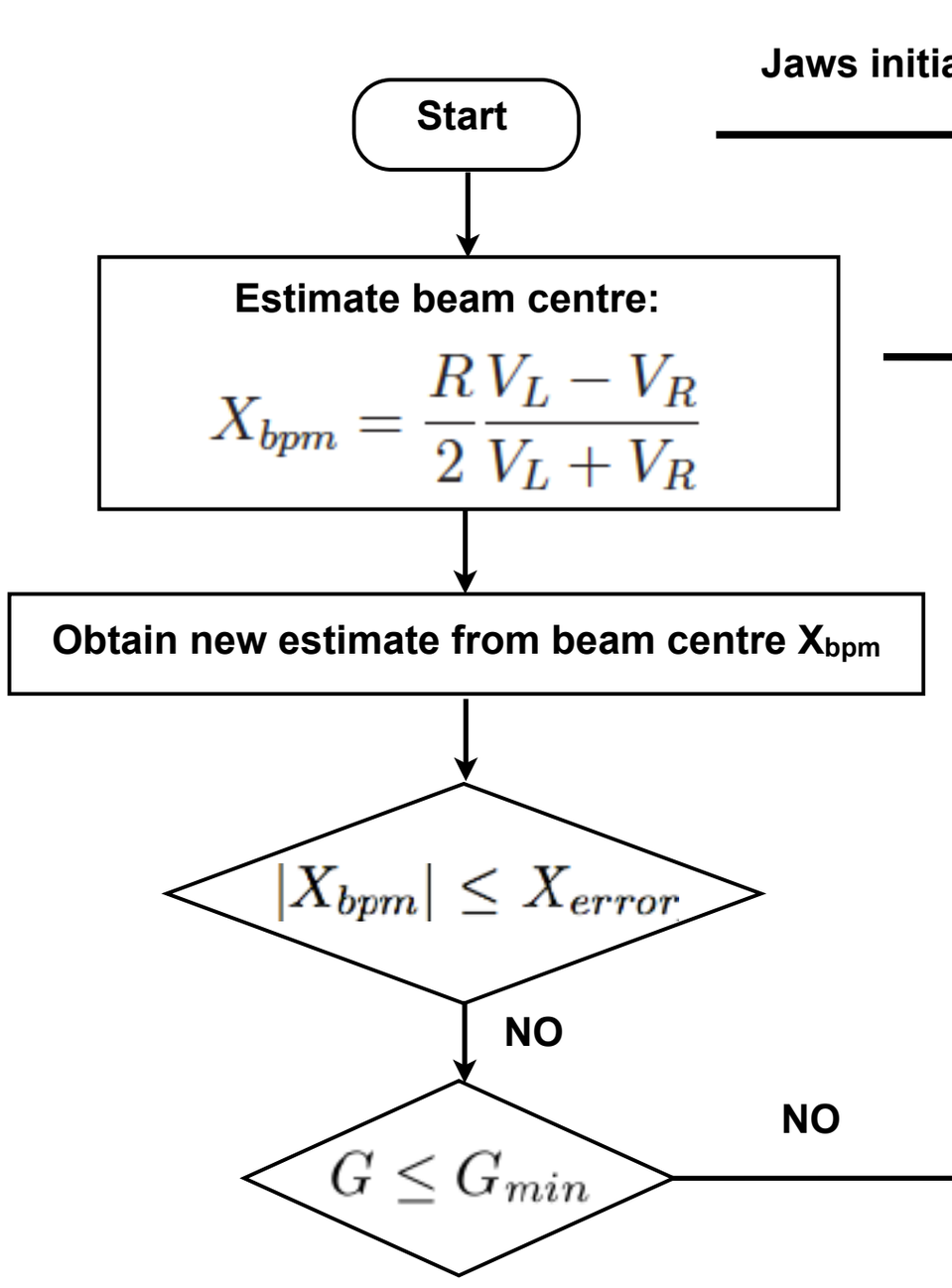

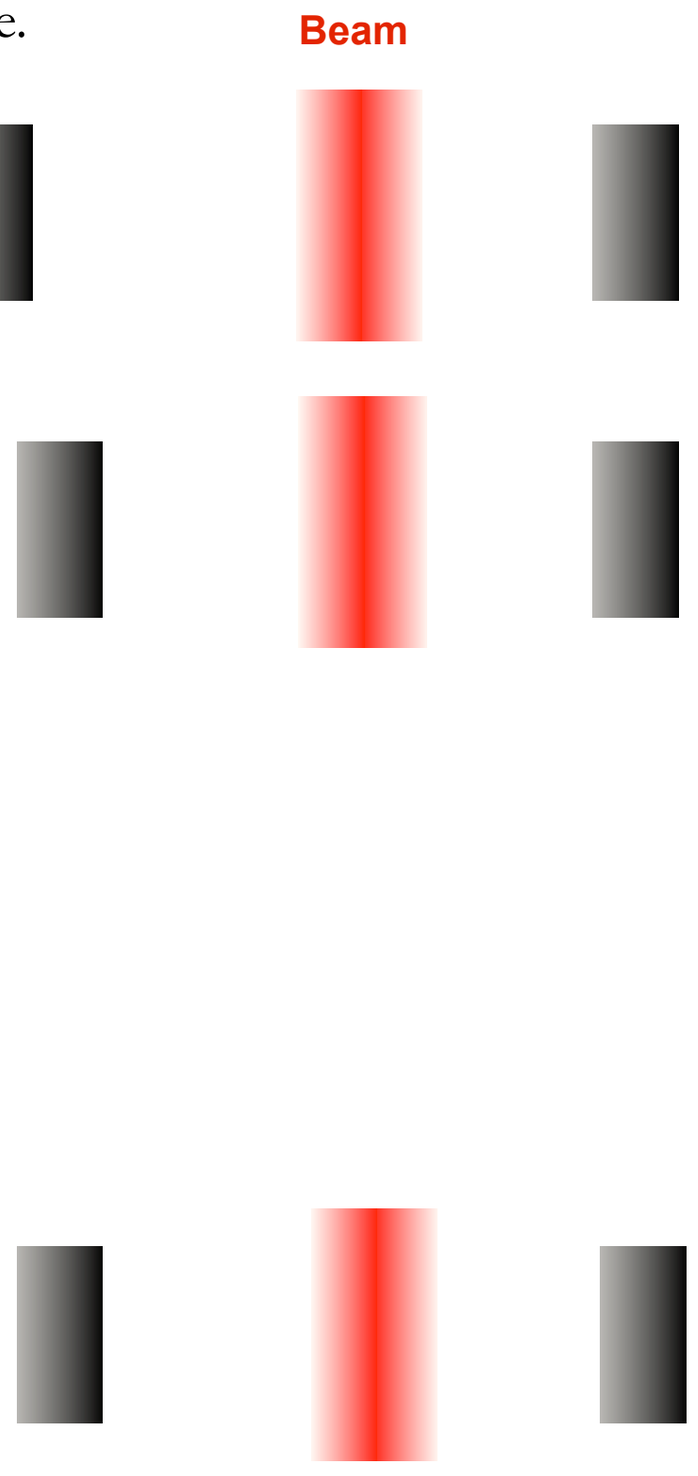

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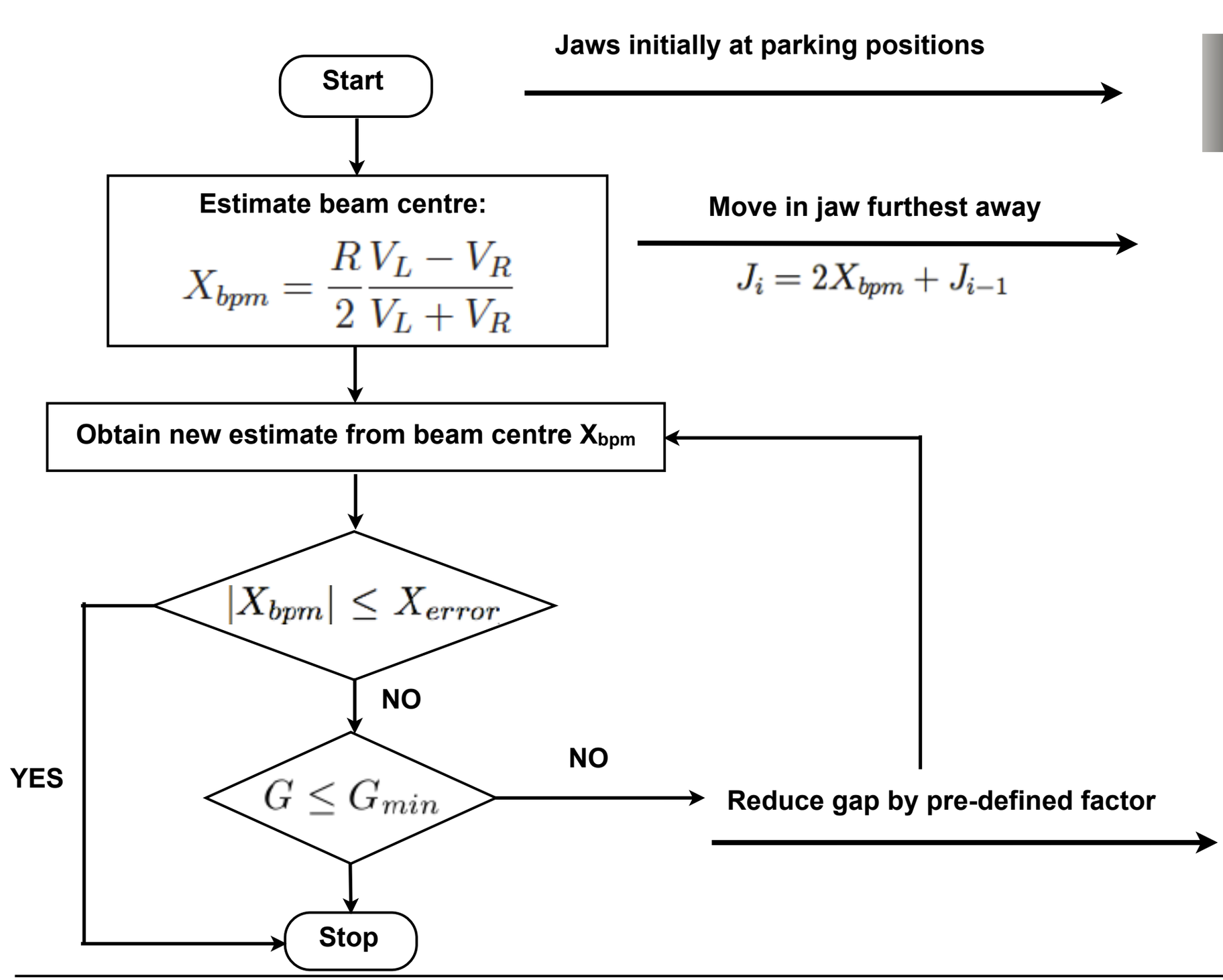

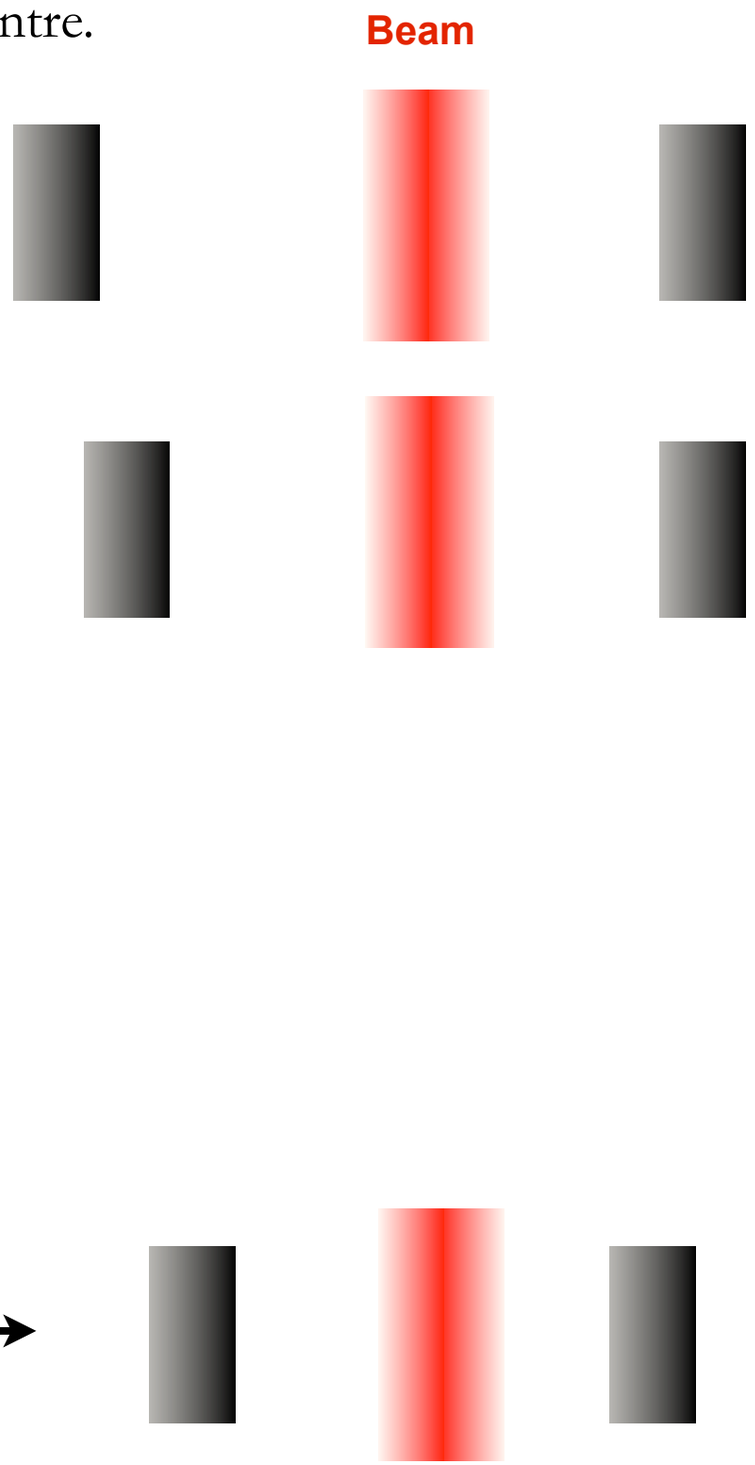

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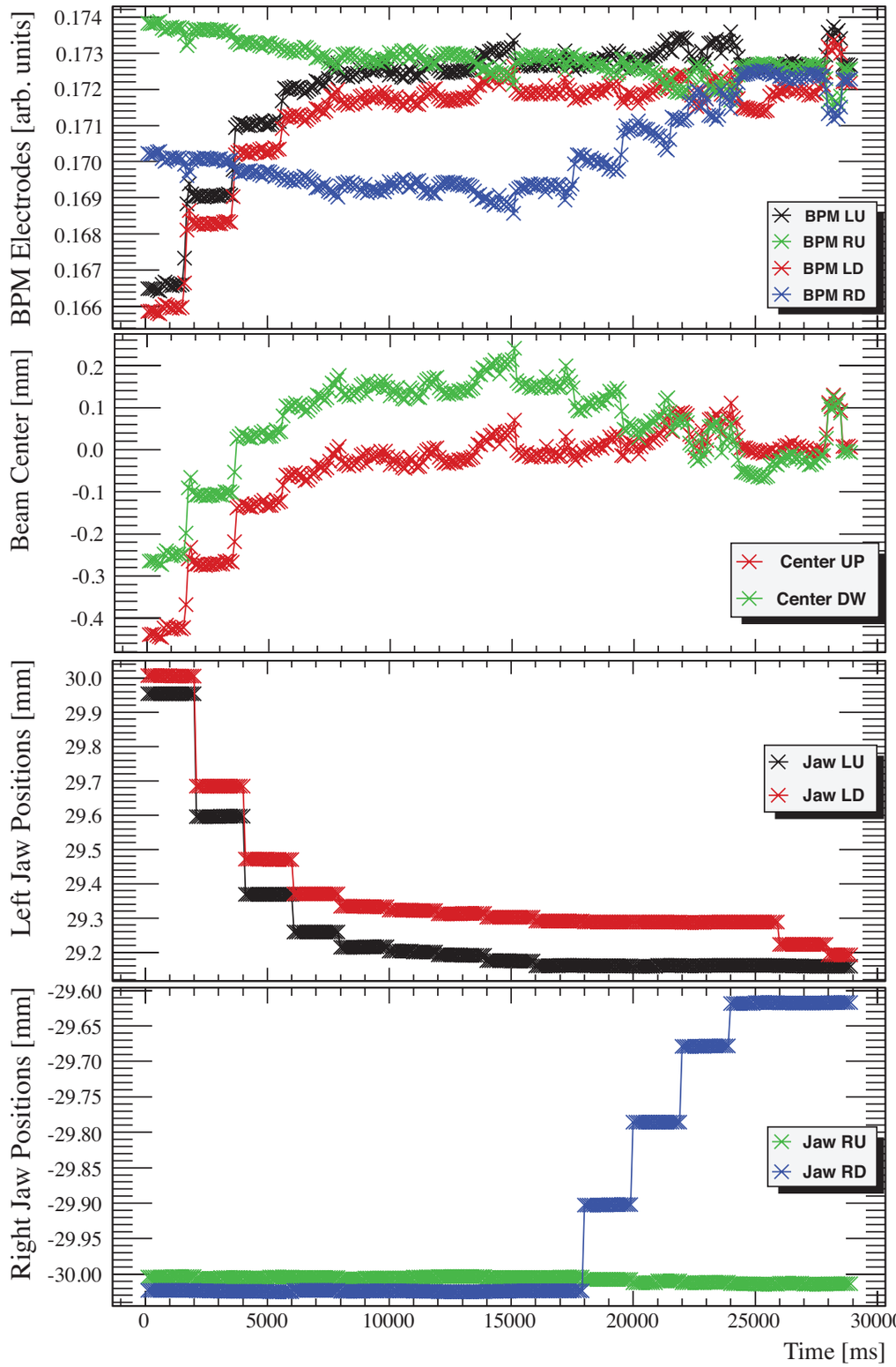

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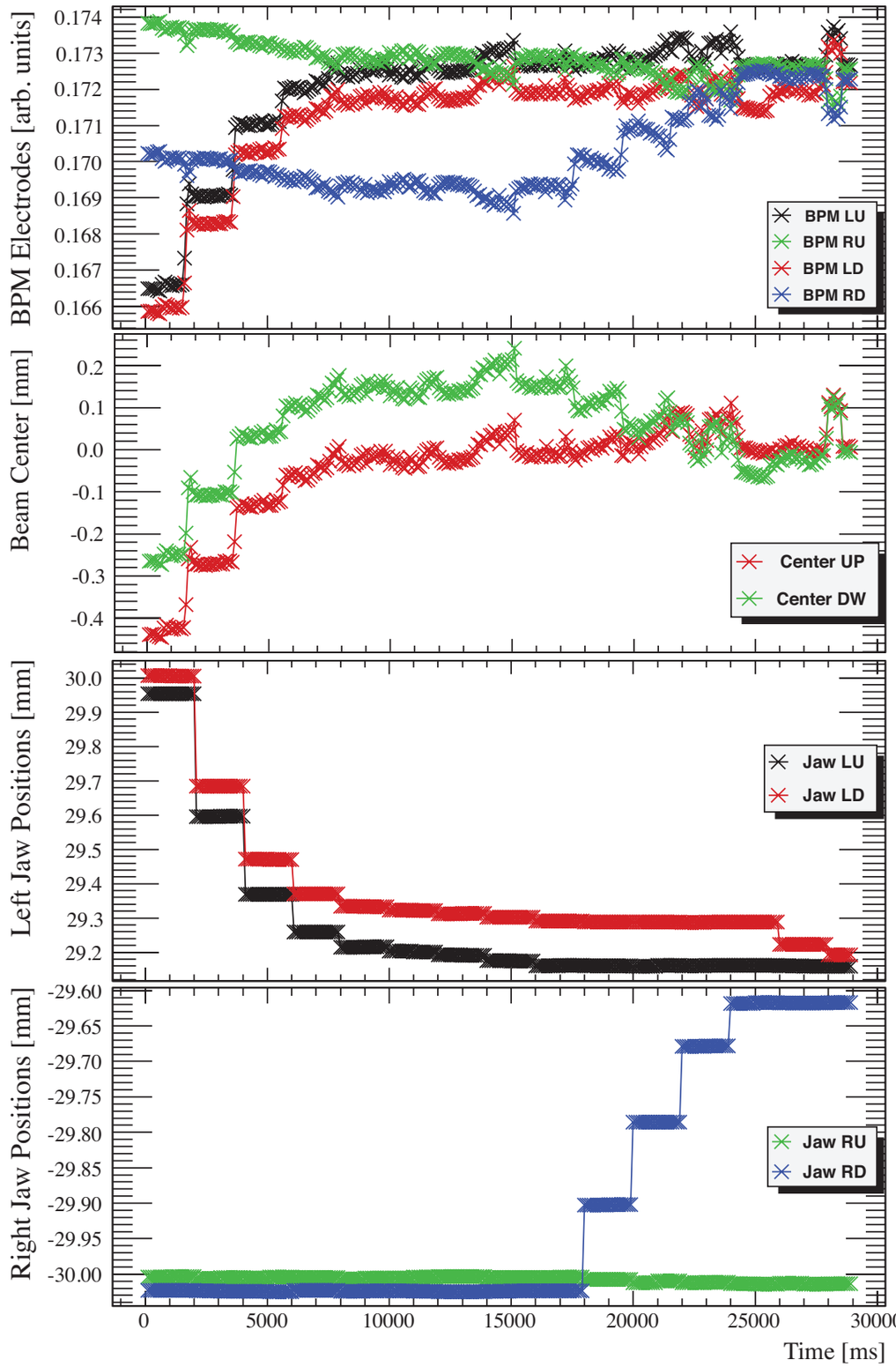

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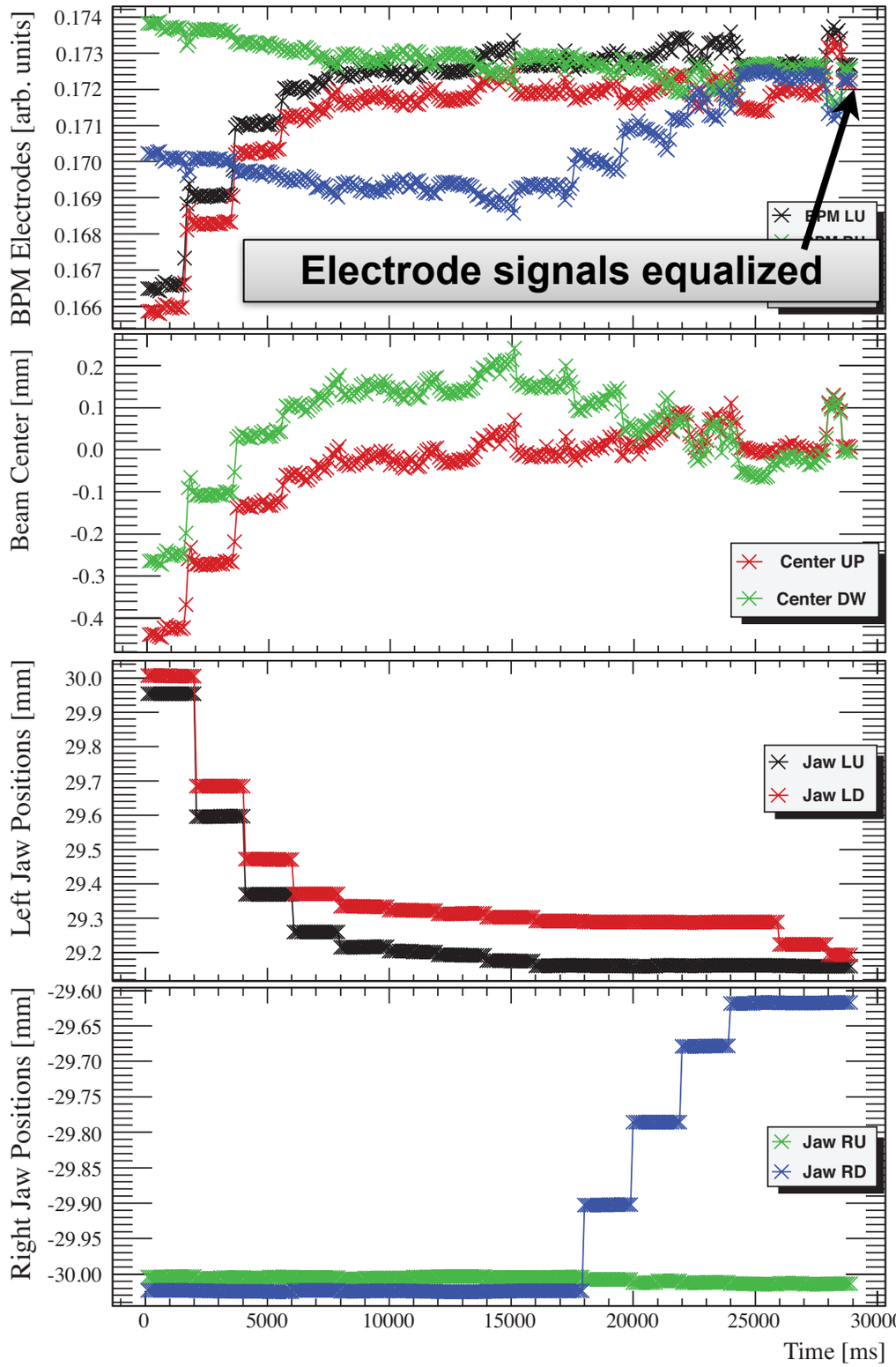

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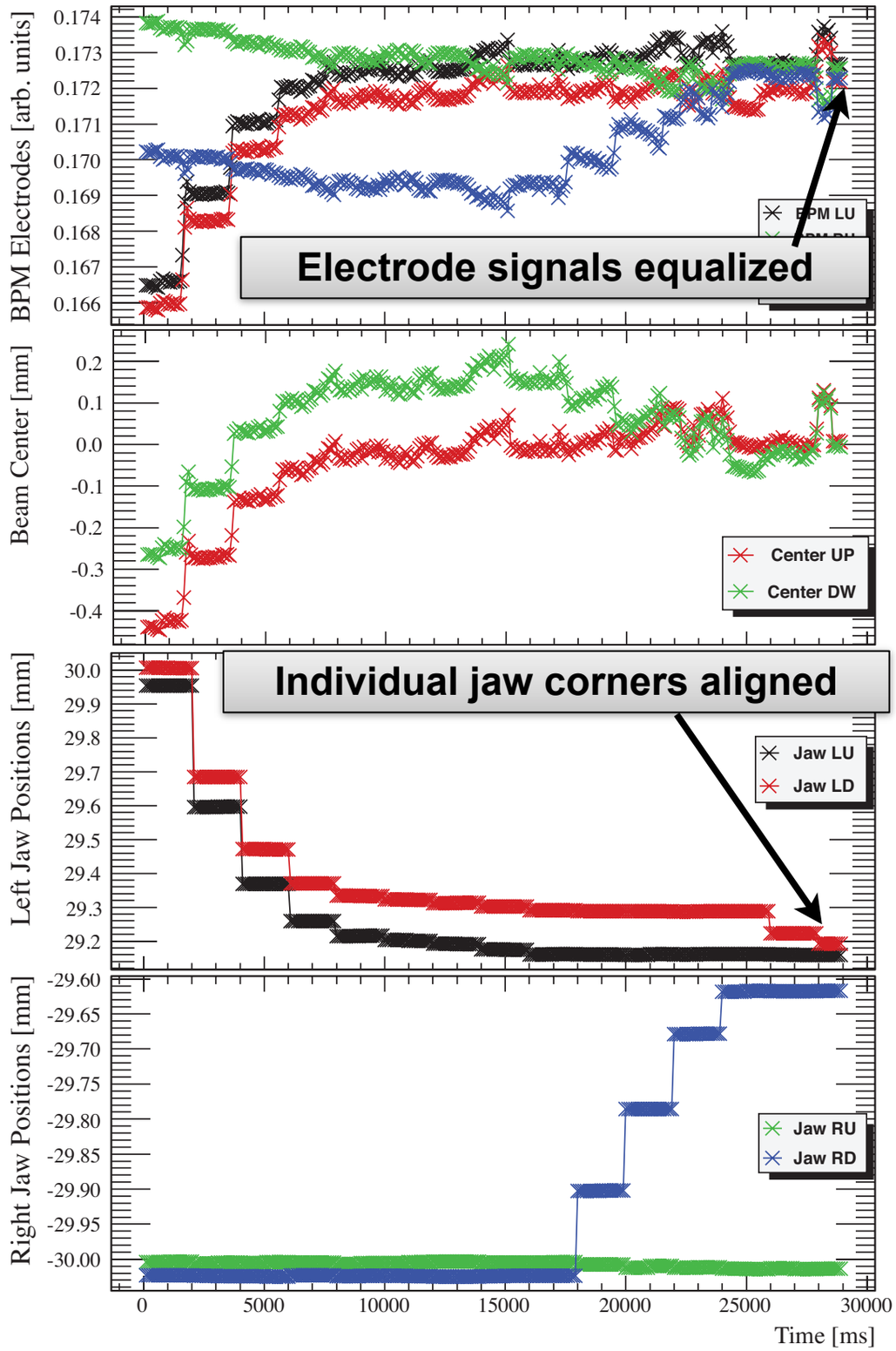

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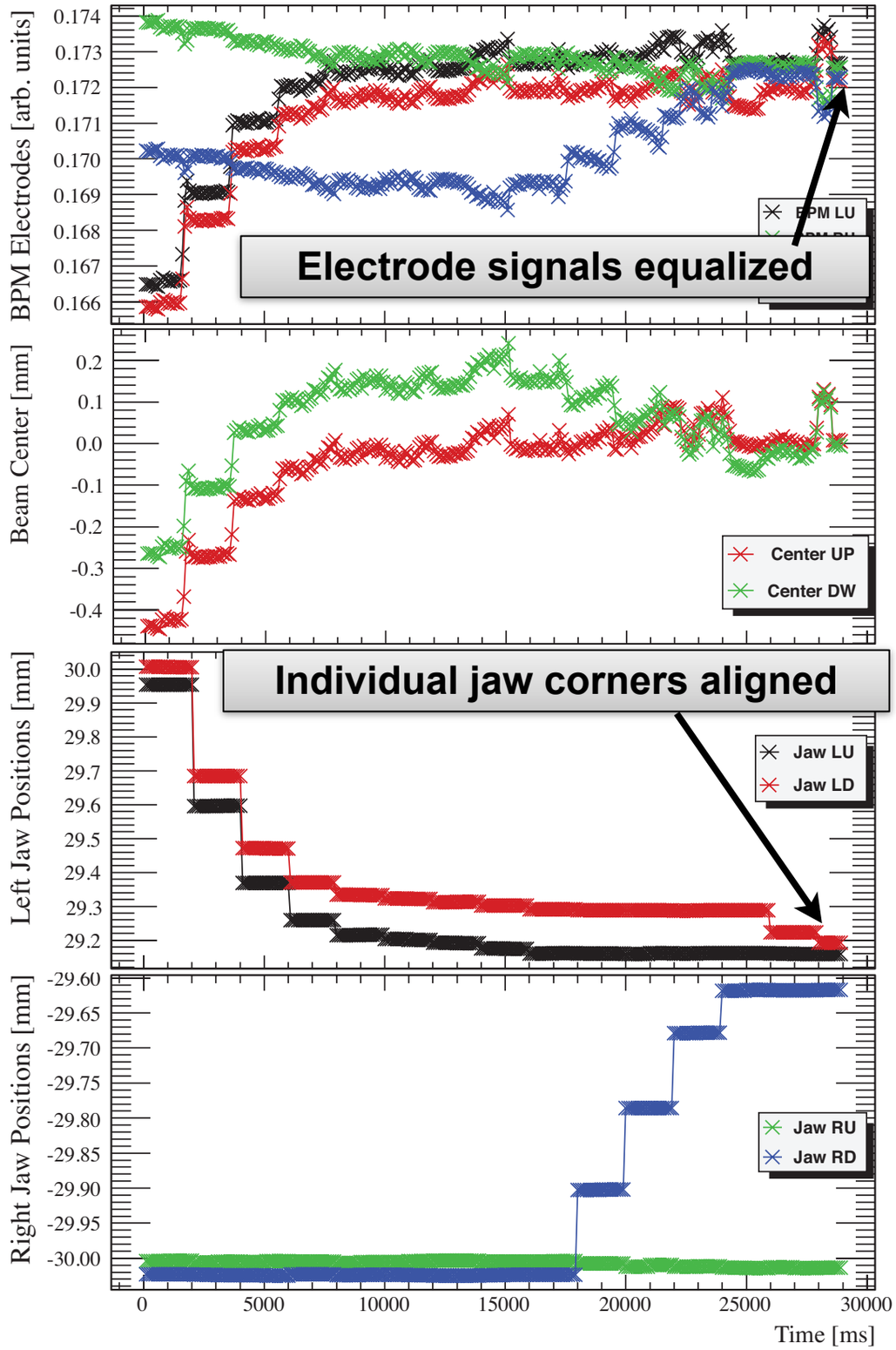

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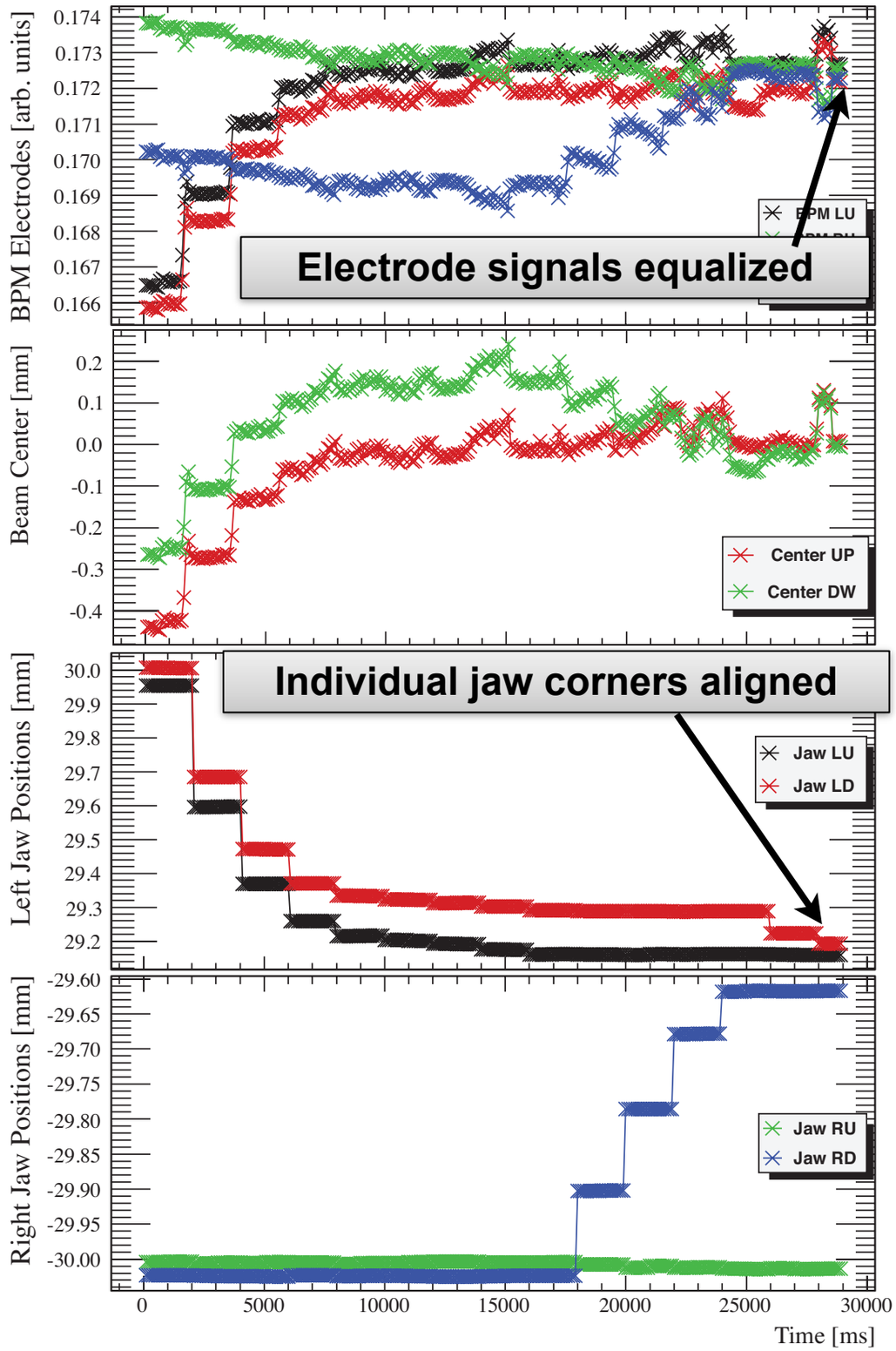

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- BLM vs. BPM centres **agree within 150 µm**
  - BLM jaw step size in the SPS = 50 µm
  - BPM button vs. jaw surface positioning tolerance = 50 µm

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- **Engineering specification** to be drawn up in collaboration with BI team.

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- A new FESA-based software architecture for the embedded collimator BPMs will be defined and implemented during LS1.

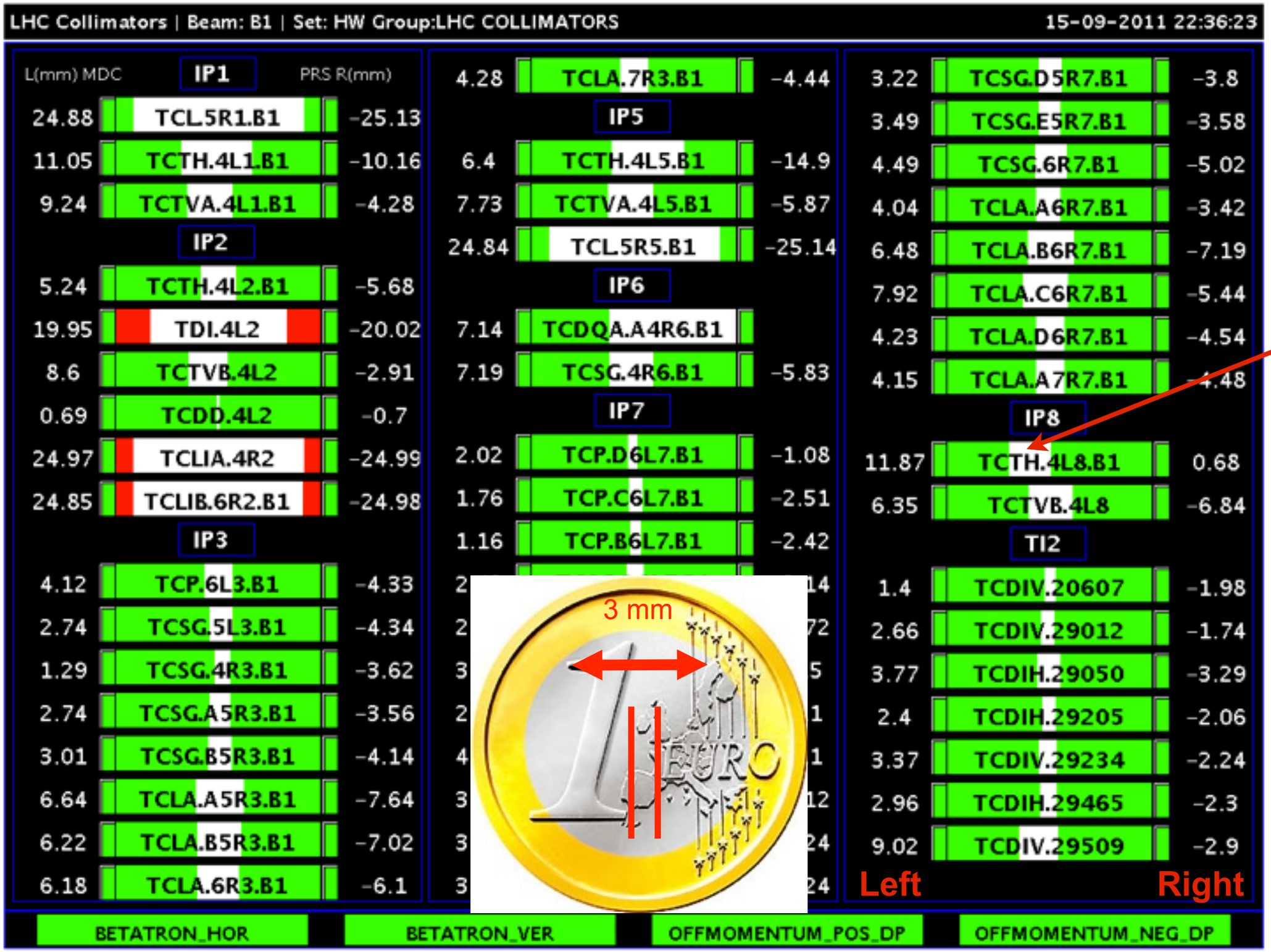
Acknowledgements

- Research funded by **EuCARD ColMat WP8**.
- **PhD supervisors:** Dr. Ralph Assmann (CERN) and Dr. Ing. Nicholas Sammut (UoM).
- **Present + Past collimation team:** Roderik Bruce, Florian Burkart, Marija Cauchi, Daniel Deboy, Luisella Lari, Aurelien Marsili, Daniele Mirarchi, Elena Quaranta, Stefano Redaelli, Adriana Rossi, Belen Salvachua, Daniel Wollmann.
- **Colleagues in BE-BI:** Marek Gasior, Stephen Jackson, Andriy Nosych, Christos Zamantzas.
- **Colleagues in BE-CO:** Vito Baggiolini, Alastair Bland.
- **Colleagues in EN-STI:** Alessandro Masi.
- Giulio Stancari, Fermi National Accelerator Laboratory.
- All LHC + SPS EiCs and operators.


Thank you for your attention!
Any questions?

RESERVE SLIDES

Collimator Status and Positions Display

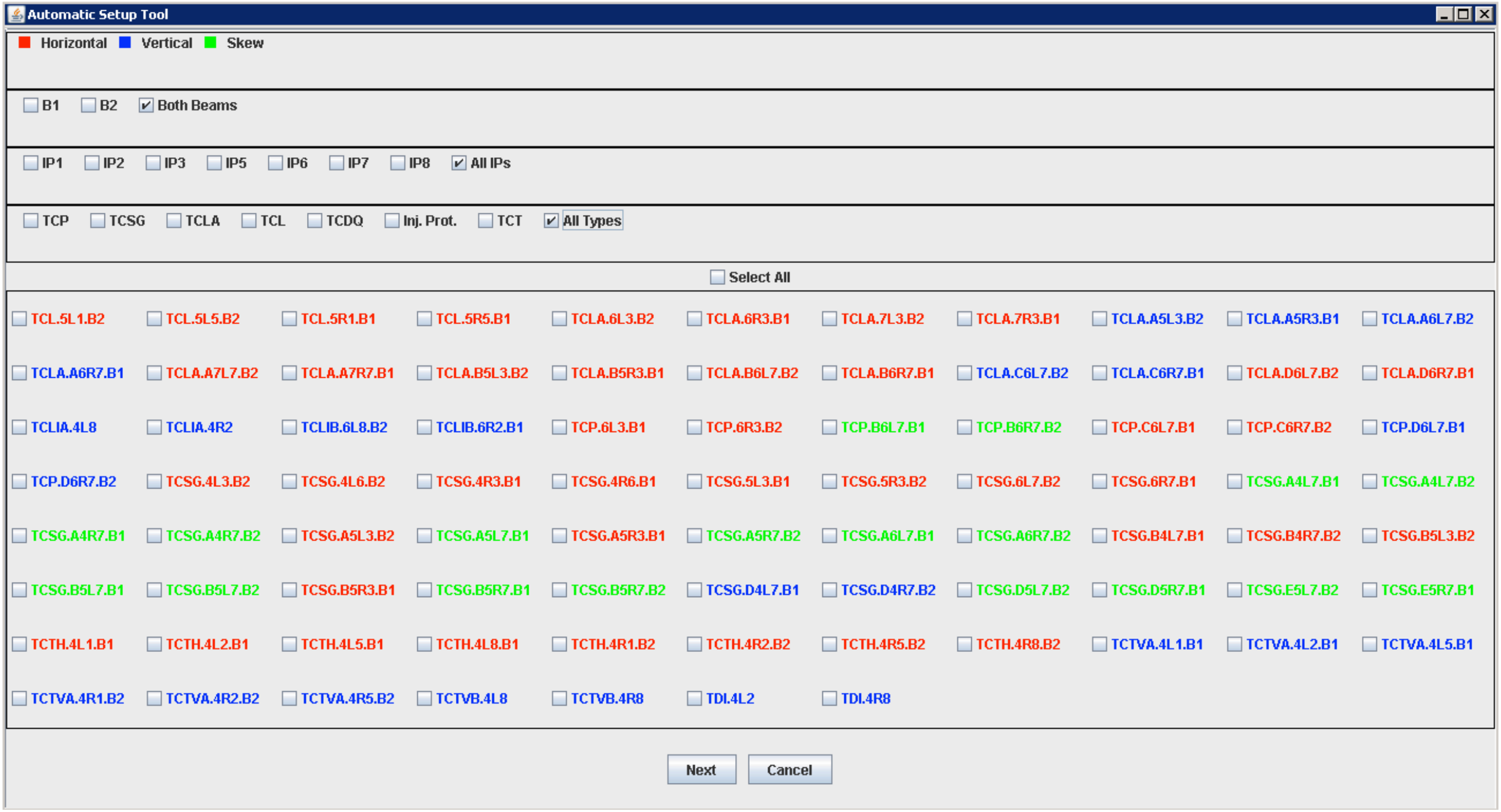


Green: OK

Red: Interlock/Error

Jaw gap indication

BLM-based alignment software



Collimator selector GUI allows the user to include any combination of collimators in the alignment sequence

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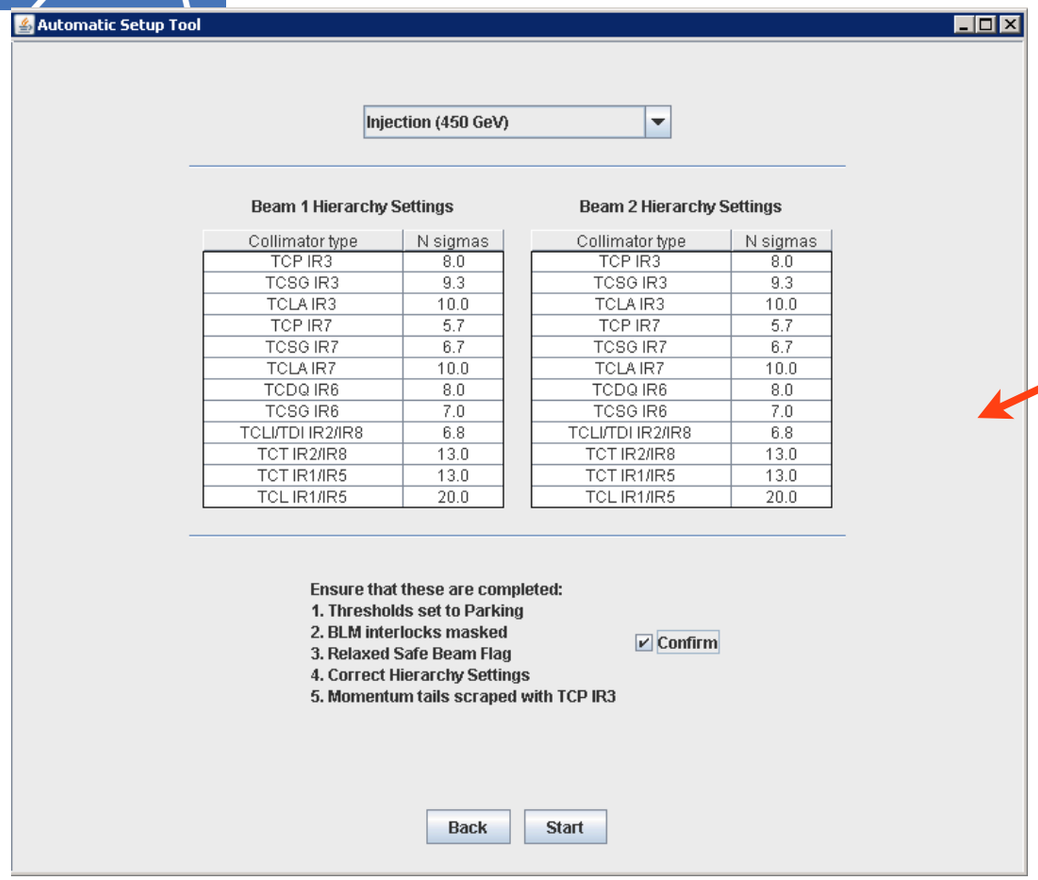
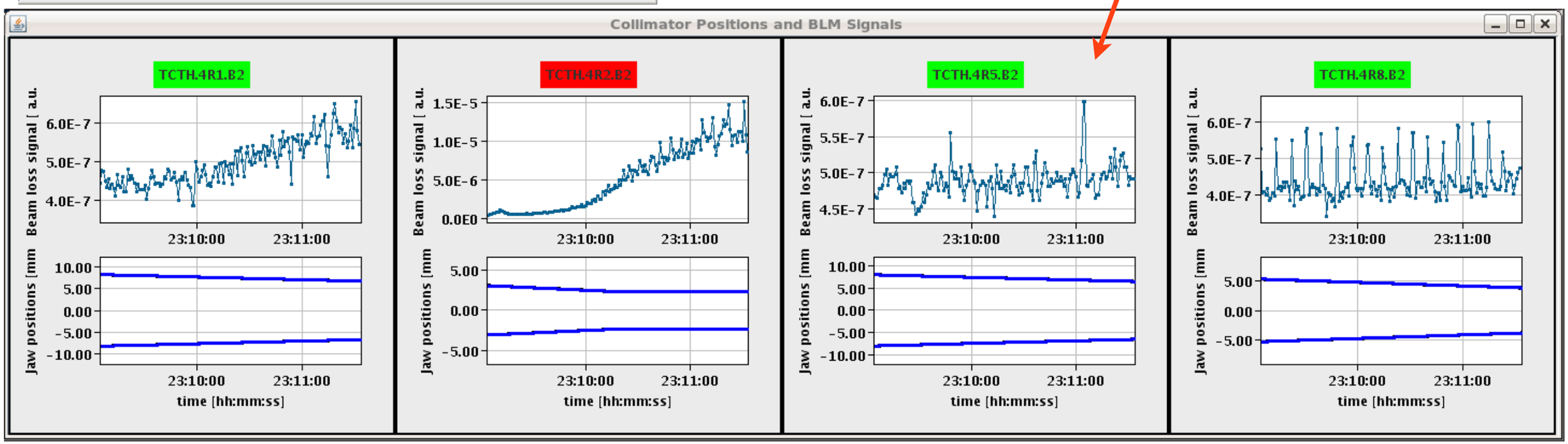


Collimator settings window enables selection of the machine mode and hierarchy settings

Multi-view window showing BLM signals, jaw positions and alignment status for each collimator



BLM-based alignment software

Collimator Setup Sheet - Beam 1 (/user/slops/data/LHC_DATA/OP_DATA/LHCCollimators/Setups/Setup_2013-02-01_1/Collimator_Setup_Sheet_4000GeV-collisions_2013-02-01_19-14-16_B1_ONGOING.txt)

File Edit Options

Geometric Emittance: 8.21E-10

Setup N Sigma: 4.5

RMS Momentum Deviation: 3.06E-4

Number	Status	Collimator Name	Angle (deg)	JAW L Calib (mm)	JAW R Calib (mm)	LVDT gap	Gap Offset (mm)	Half Gap Meas (mm)	Eff sigma in coll plane	JAW L Setting (mm)	JAW R Setting (mm)	Target HALF GAP sigma	Pos
Horizontal													
9	True	TCP.C6L7.B1	0.00	1.020	-1.525	2.474	-0.252	1.272	n/a	n/a	n/a	3.62	197
10	True	TCTH.4L5.B1	0.00	-1.895	-7.975	6.067	-4.935	3.040	0.942	4.482	-14.352	10.00	131
11	True	TCP.C6L7.B1	0.00	0.895	-1.425	2.249	-0.265	1.160	n/a	n/a	n/a	3.30	197
36	True	TCP.C6L7.B1	0.00	0.895	-1.425	2.250	-0.265	1.160	0.352	0.895	-1.425	3.30	197
37	True	TCTH.4L2.B1	0.00	2.950	-2.275	5.191	0.338	2.612	0.791	8.249	-7.574	10.00	321
38	True	TCP.C6L7.B1	0.00	0.855	-1.405	2.190	-0.275	1.130	n/a	n/a	n/a	3.21	197
42	True	TCP.C6L7.B1	0.00	0.855	-1.405	2.189	-0.275	1.130	0.352	0.855	-1.405	3.21	197
43	True	TCTH.4L1.B1	0.00	3.500	-2.115	5.569	0.692	2.808	0.942	10.110	-8.725	10.00	265
44	True	TCP.C6L7.B1	0.00	0.815	-1.365	2.109	-0.275	1.090	n/a	n/a	n/a	3.10	197
45	True	TCP.C6L7.B1	0.00	0.815	-1.365	2.109	-0.275	1.090	0.352	0.815	-1.365	3.10	197
46	True	TCTH.4L8.B1	0.00	7.680	4.260	3.400	5.970	1.710	0.551	12.579	-0.639	12.000	231
47	True	TCP.C6L7.B1	0.00	0.785	-1.325	2.038	-0.270	1.055	n/a	-0.270	-0.270	3.00	197
Vertical													
0	True	TCP.D6L7.B1	90.01	1.035	-0.585	1.596	0.225	0.810	n/a	n/a	n/a	3.20	197
1	True	TCTVA.4L5.B1	90.01	2.505	-1.355	3.852	0.575	1.930	0.600	6.572	-5.422	10.00	131
2	True	TCP.D6L7.B1	90.01	0.980	-0.540	1.496	0.220	0.760	n/a	n/a	n/a	3.00	197
12	True	TCP.D6L7.B1	90.01	0.980	-0.540	1.487	0.220	0.760	n/a	n/a	n/a	3.00	197
13	True	TCTVA.4L2.B1	90.01	0.620	-4.760	5.343	-2.070	2.690	0.840	6.332	-10.472	10.00	325
14	True	TCP.D6L7.B1	90.01	0.965	-0.530	1.464	0.217	0.748	n/a	n/a	n/a	2.95	197
18	True	TCP.D6L7.B1	90.01	0.965	-0.530	1.464	0.217	0.748	n/a	n/a	n/a	2.95	197
19	True	TCTVA.4L1.B1	90.01	4.460	0.450	3.977	2.455	2.005	0.600	8.452	-3.542	10.00	265
20	True	TCP.D6L7.B1	90.01	0.955	-0.520	1.445	0.217	0.738	n/a	n/a	n/a	2.91	197
21	True	TCP.D6L7.B1	90.01	0.955	-0.520	1.445	0.217	0.738	n/a	n/a	n/a	2.91	197
22	True	TCTVB.4L8	90.01	2.025	-1.895	3.883	0.065	1.960	0.650	7.862	-7.732	12.000	232
23	True	TCP.D6L7.B1	90.01	0.940	-0.500	1.405	0.220	0.720	n/a	0.220	0.220	2.84	197
Skew													

Collimator setup sheet after a TCT alignment

TCT collimator alignment results