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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



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- **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

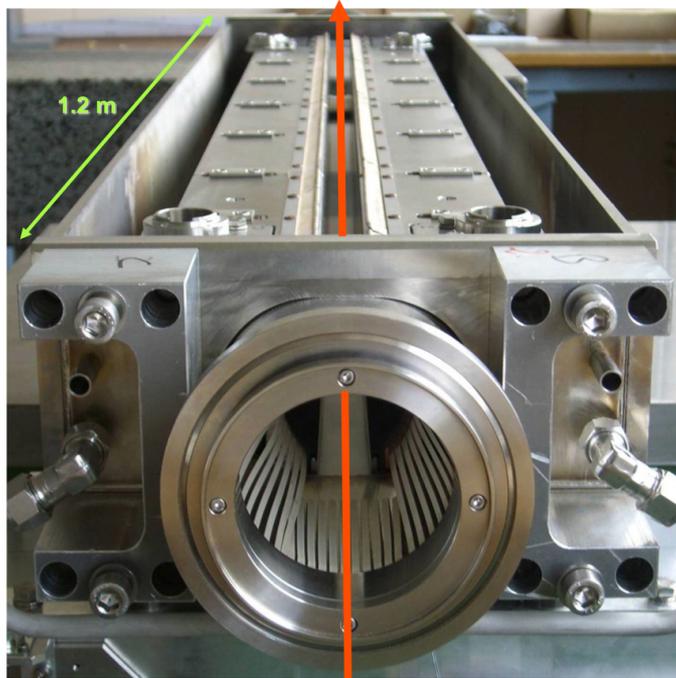


- The LHC at CERN is the largest and most powerful particle accelerator in the world.
- Nominal parameters:

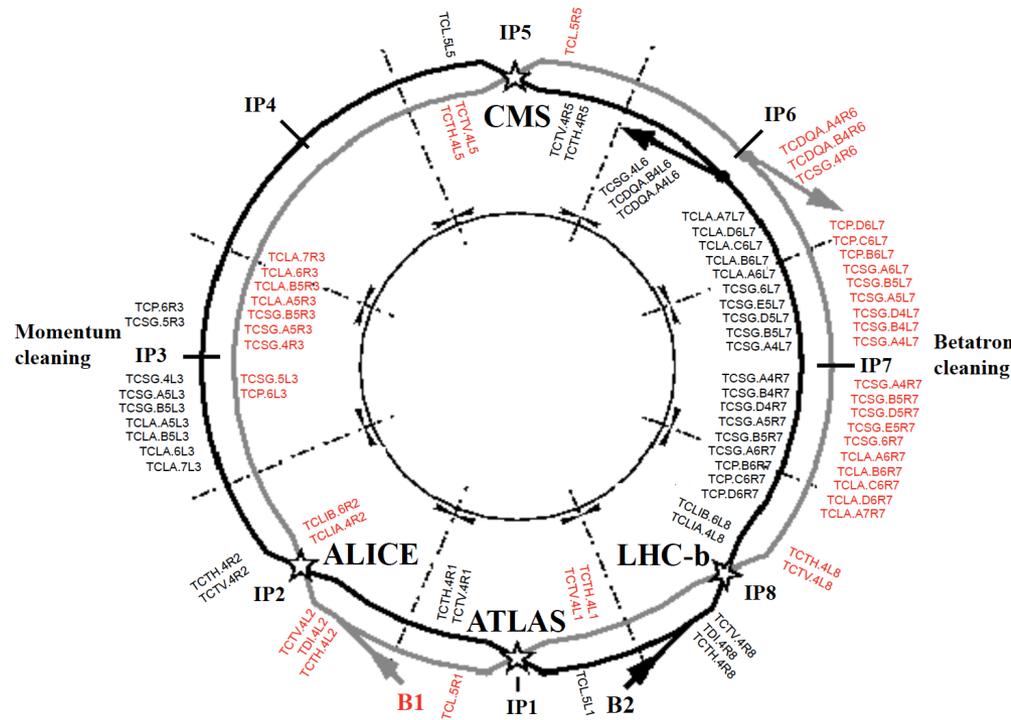
Circumference: 27 km, Energy: 7 TeV, Intensity = $3.23E14$, Peak Lumi IP1/5 = $1E34 \text{ cm}^{-2}\text{sec}^{-1}$

LHC Collimation System

- 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.



360 MJ proton beam



Courtesy: C. Bracco



Collimator Status and Positions Display



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LHC Collimators | Beam: B1 | Set: HW Group:LHC COLLIMATORS 15-09-2011 22:36:23

L(mm) MDC	IP1	PRS R(mm)							
24.88	TCL5R1.B1	-25.13	4.28	TCLA.7R3.B1	-4.44	3.22	TCSG.D5R7.B1	-3.8	
11.05	TCTH.4L1.B1	-10.16	6.4	TCTH.4L5.B1	-14.9	3.49	TCSG.E5R7.B1	-3.58	
9.24	TCTVA.4L1.B1	-4.28	7.73	TCTVA.4L5.B1	-5.87	4.49	TCSG.6R7.B1	-5.02	
	IP2		24.84	TCL5R5.B1	-25.14	4.04	TCLA.A6R7.B1	-3.42	
5.24	TCTH.4L2.B1	-5.68		IP6		6.48	TCLA.B6R7.B1	-7.19	
19.95	TDI.4L2	-20.02	7.14	TCDQA.A4R6.B1		7.92	TCLA.C6R7.B1	-5.44	
8.6	TCTVB.4L2	-2.91	7.19	TCSG.4R6.B1	-5.83	4.23	TCLA.D6R7.B1	-4.54	
0.69	TCDD.4L2	-0.7		IP7		4.15	TCLA.A7R7.B1	-4.48	
24.97	TCLIA.4R2	-24.99	2.02	TCP.D6L7.B1	-1.08	11.87	TCTH.4L8.B1	0.68	
24.85	TCLIB.6R2.B1	-24.98	1.76	TCP.C6L7.B1	-2.51	6.35	TCTVB.4L8	-6.84	
	IP3		1.16	TCP.B6L7.B1	-2.42		TI2		
4.12	TCP.6L3.B1	-4.33	2			1.4	TCDIV.20607	-1.98	
2.74	TCSG.5L3.B1	-4.34	2			2.66	TCDIV.29012	-1.74	
1.29	TCSG.4R3.B1	-3.62	3			3.77	TCDIH.29050	-3.29	
2.74	TCSG.A5R3.B1	-3.56	2			2.4	TCDIH.29205	-2.06	
3.01	TCSG.B5R3.B1	-4.14	4			3.37	TCDIV.29234	-2.24	
6.64	TCLA.A5R3.B1	-7.64	3			2.96	TCDIH.29465	-2.3	
6.22	TCLA.B5R3.B1	-7.02	3			9.02	TCDIV.29509	-2.9	
6.18	TCLA.6R3.B1	-6.1	3						

Green: OK
Red: Interlock/Error

Jaw gap indication

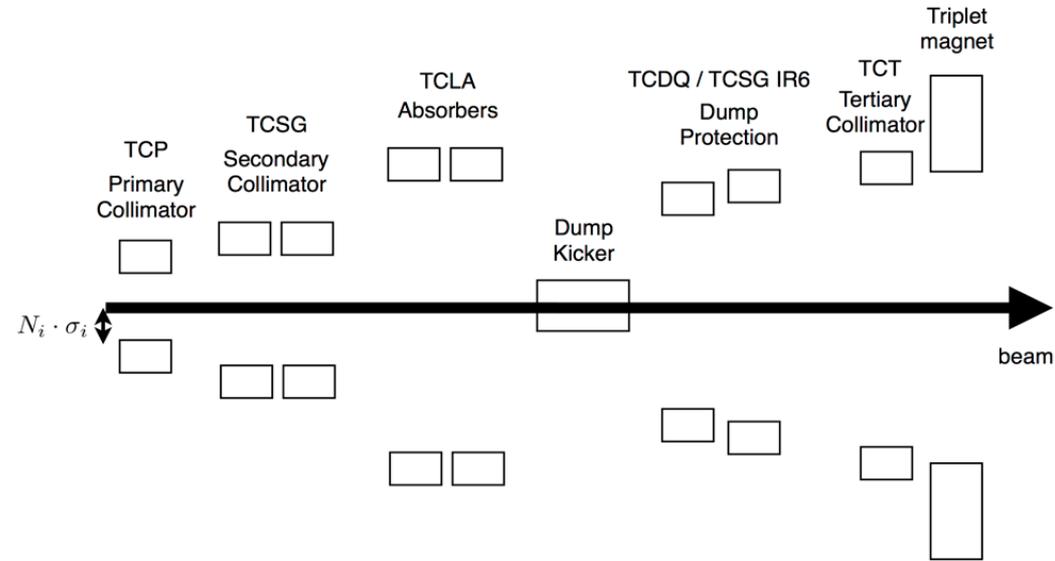


Left Right

Beam-Based Collimator Alignment

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

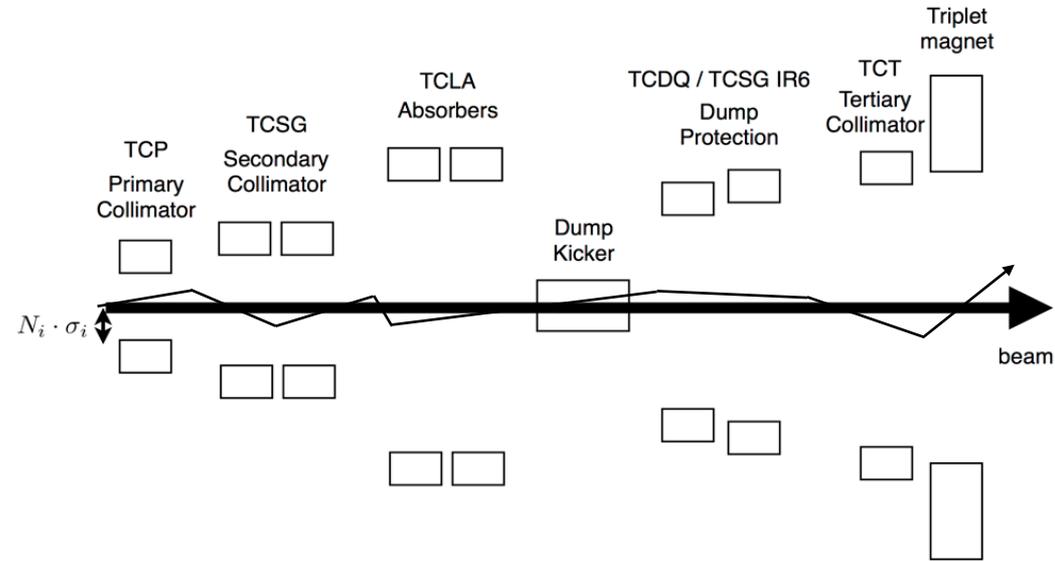
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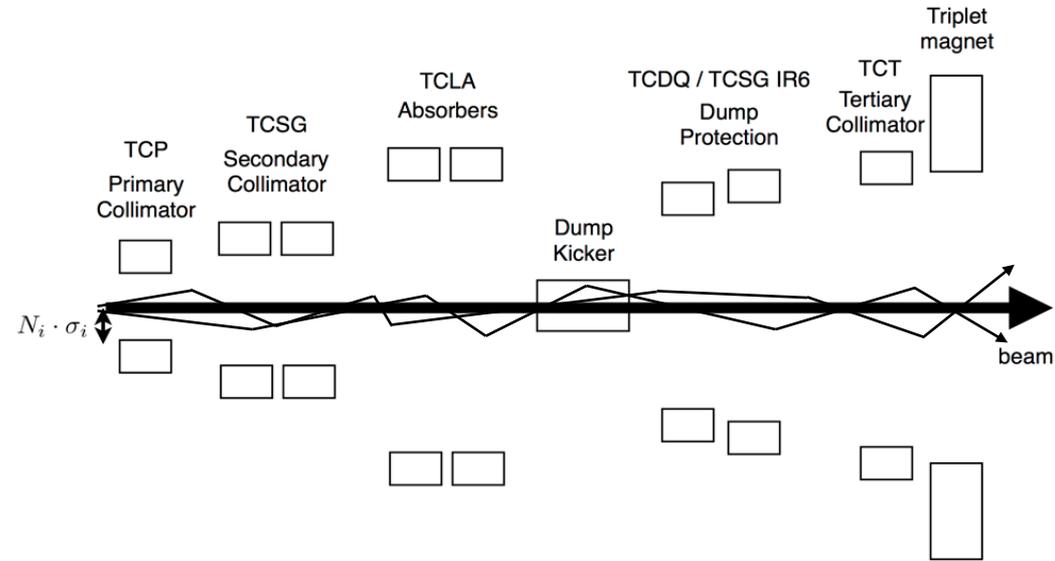
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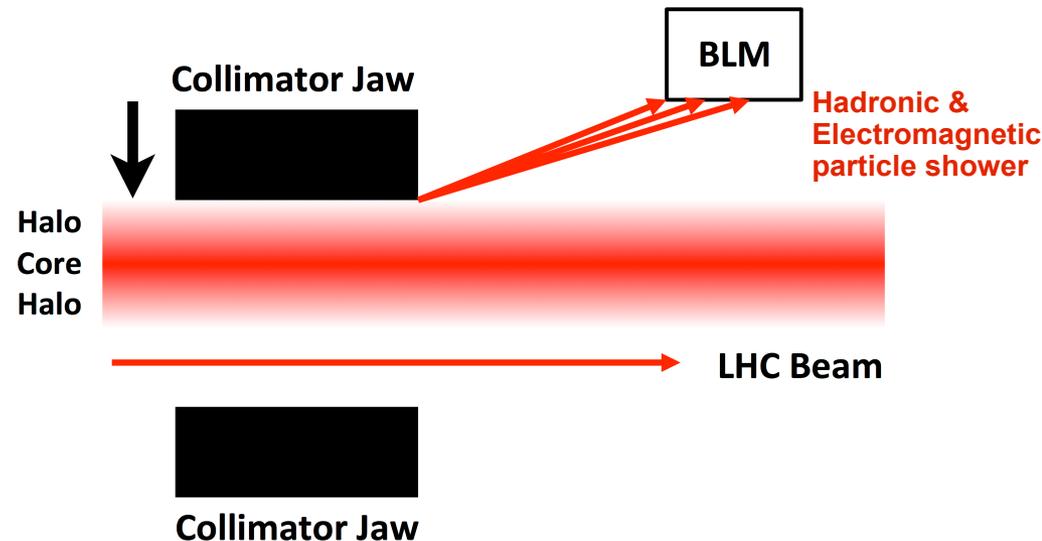
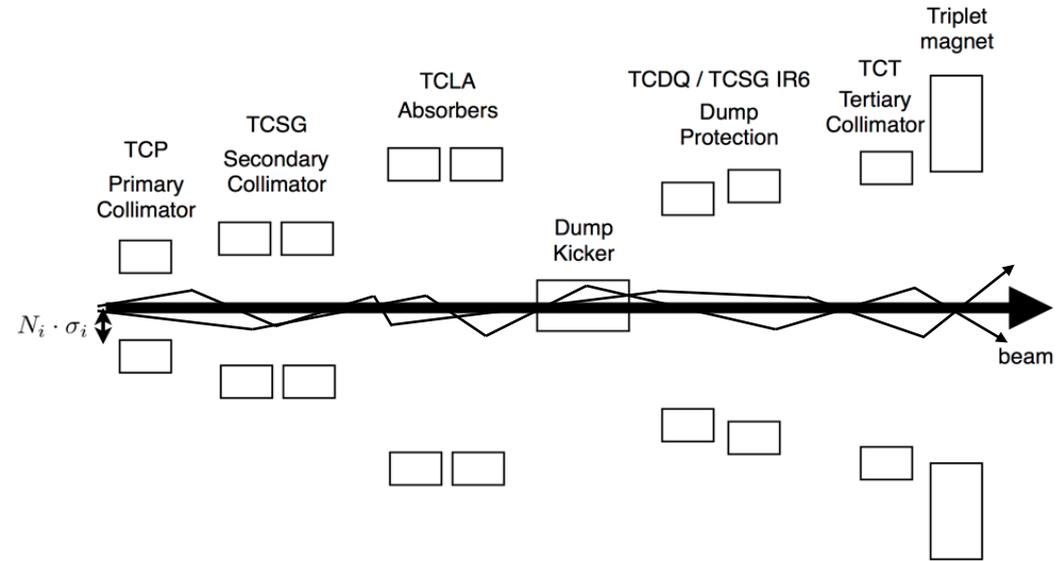
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- The beam centre and beam size at each collimator location must be known.
- By touching the beam with each jaw, these values can be determined.
- The jaws moved to beam until a loss spike is seen on the Beam Loss Monitor (BLM).
- Loss spike shape depends on the jaw step size (μm) and the particle distribution in the transverse plane.





Alignment Procedure



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1. Both jaws of the TCP in the appropriate plane (Hor/Ver/Skew) are aligned to the beam.

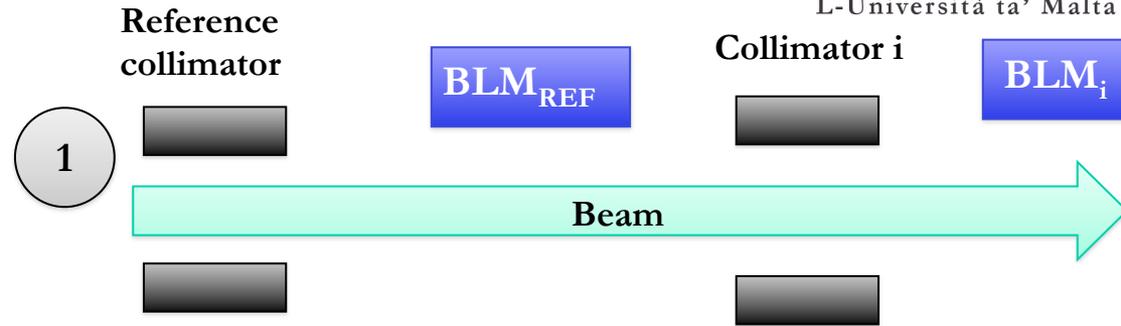


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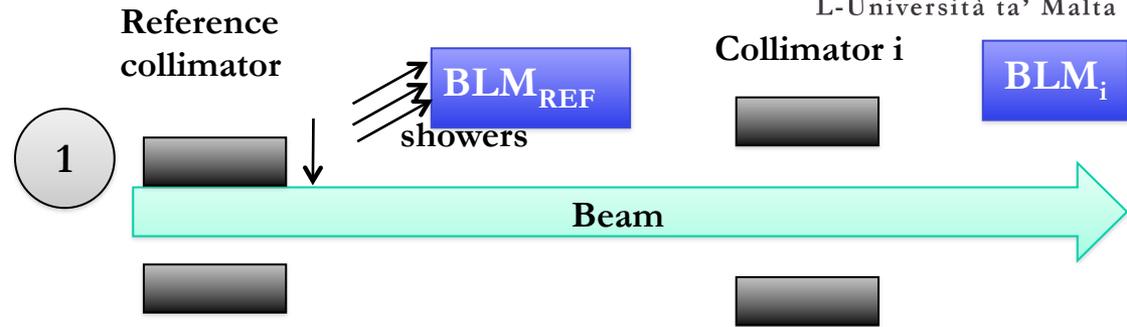


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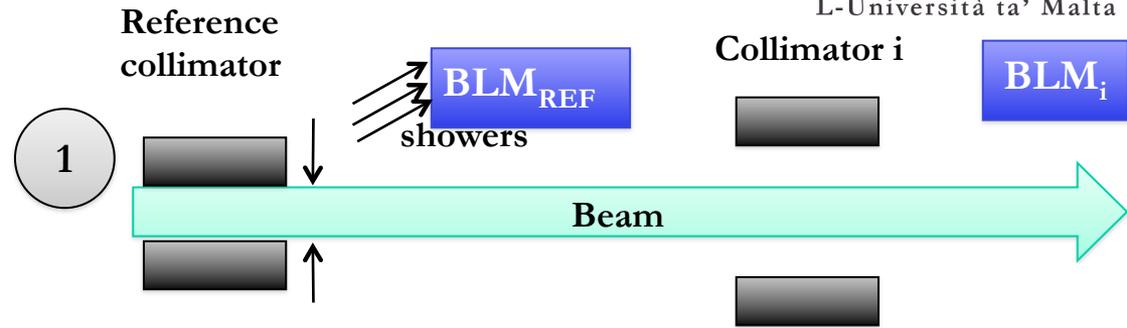
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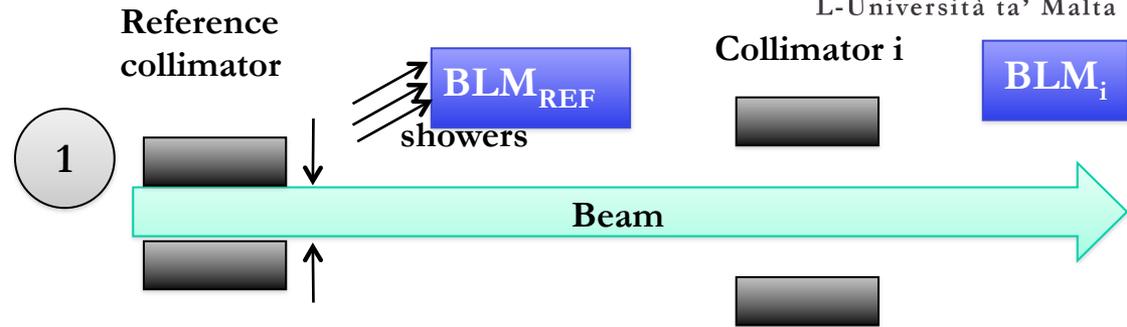
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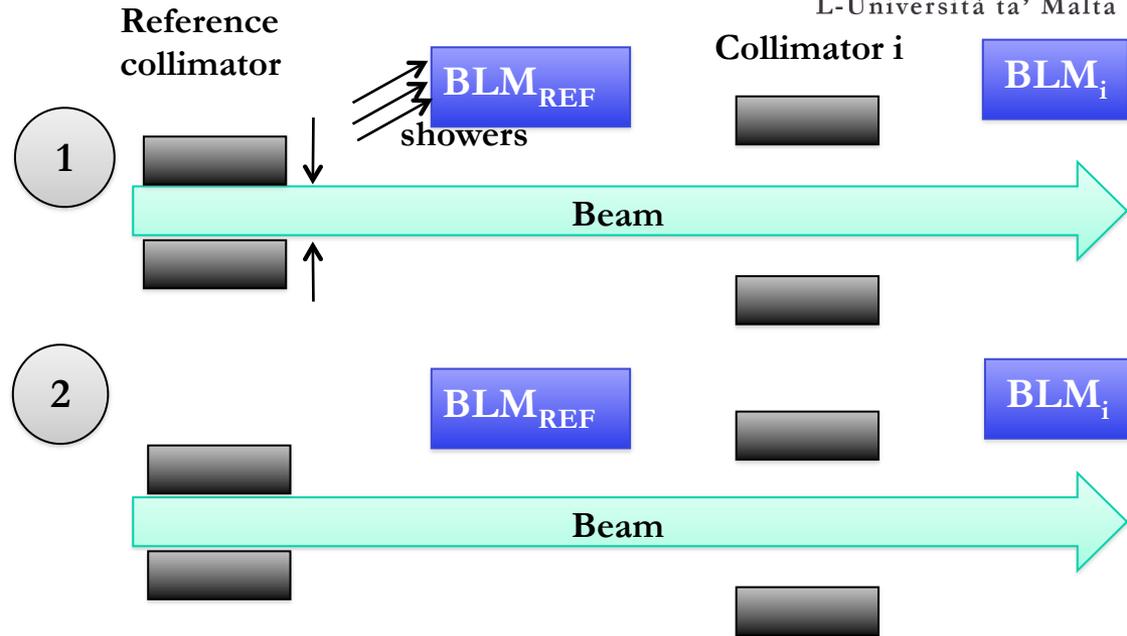
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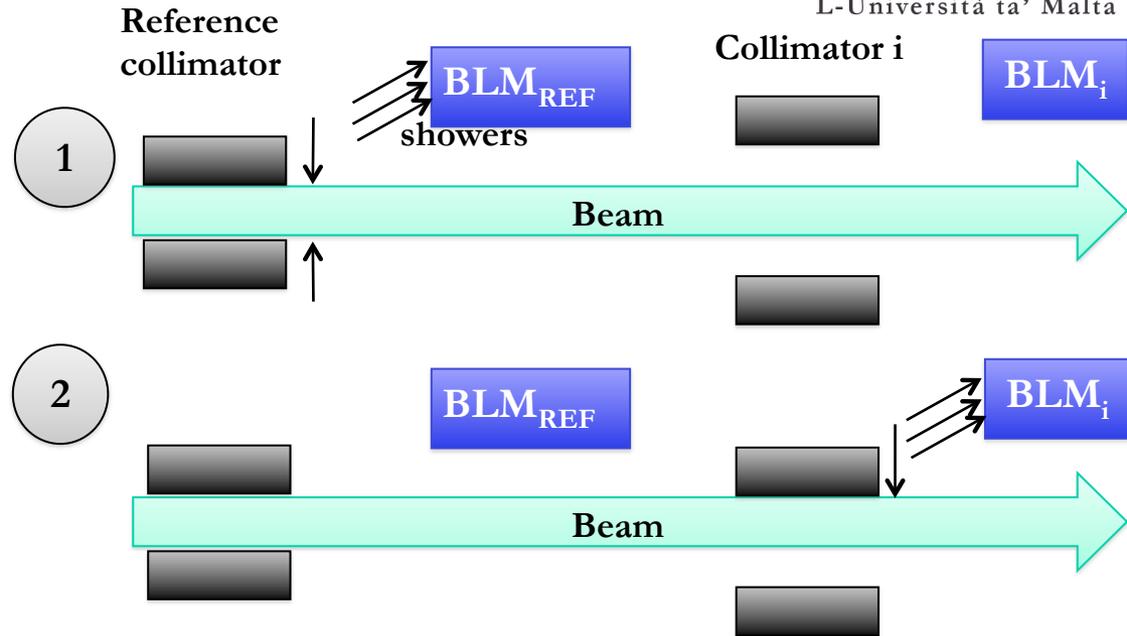
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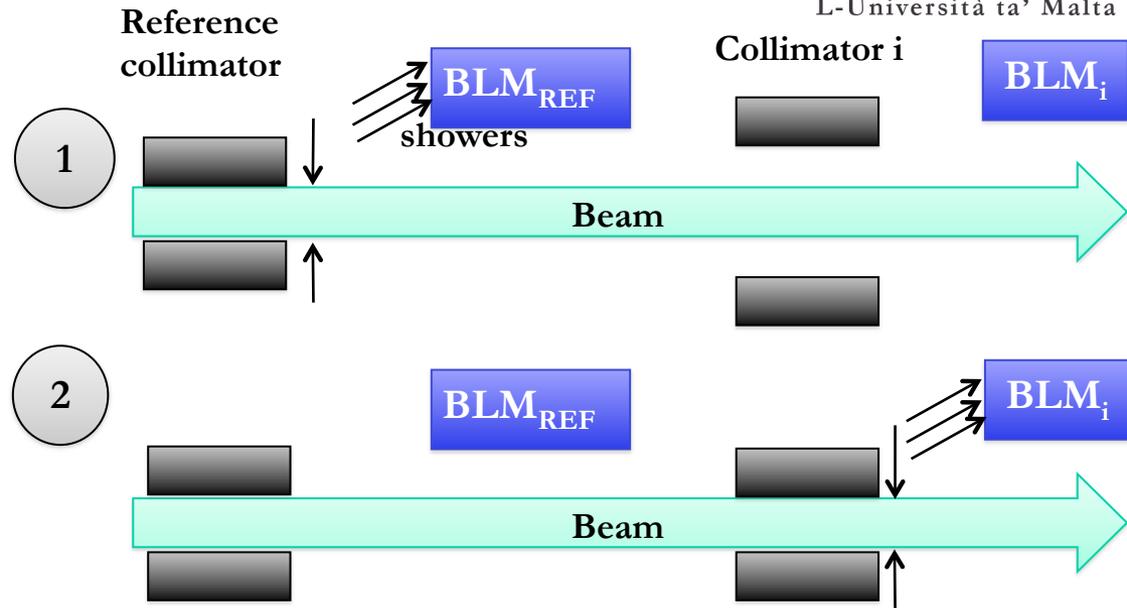
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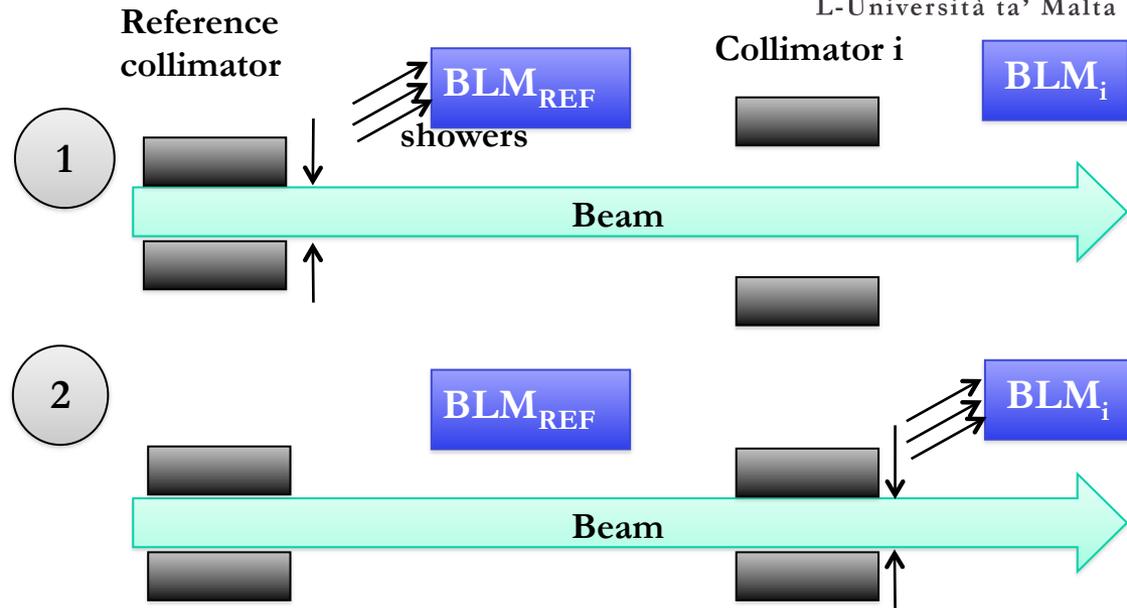


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Beam centre:
$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2}$$



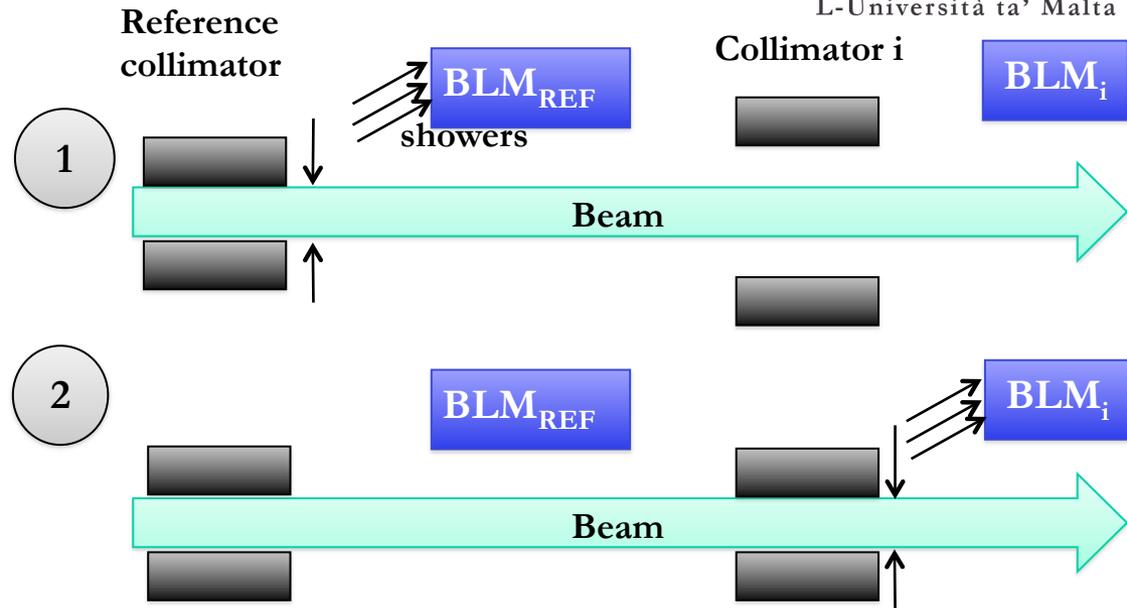
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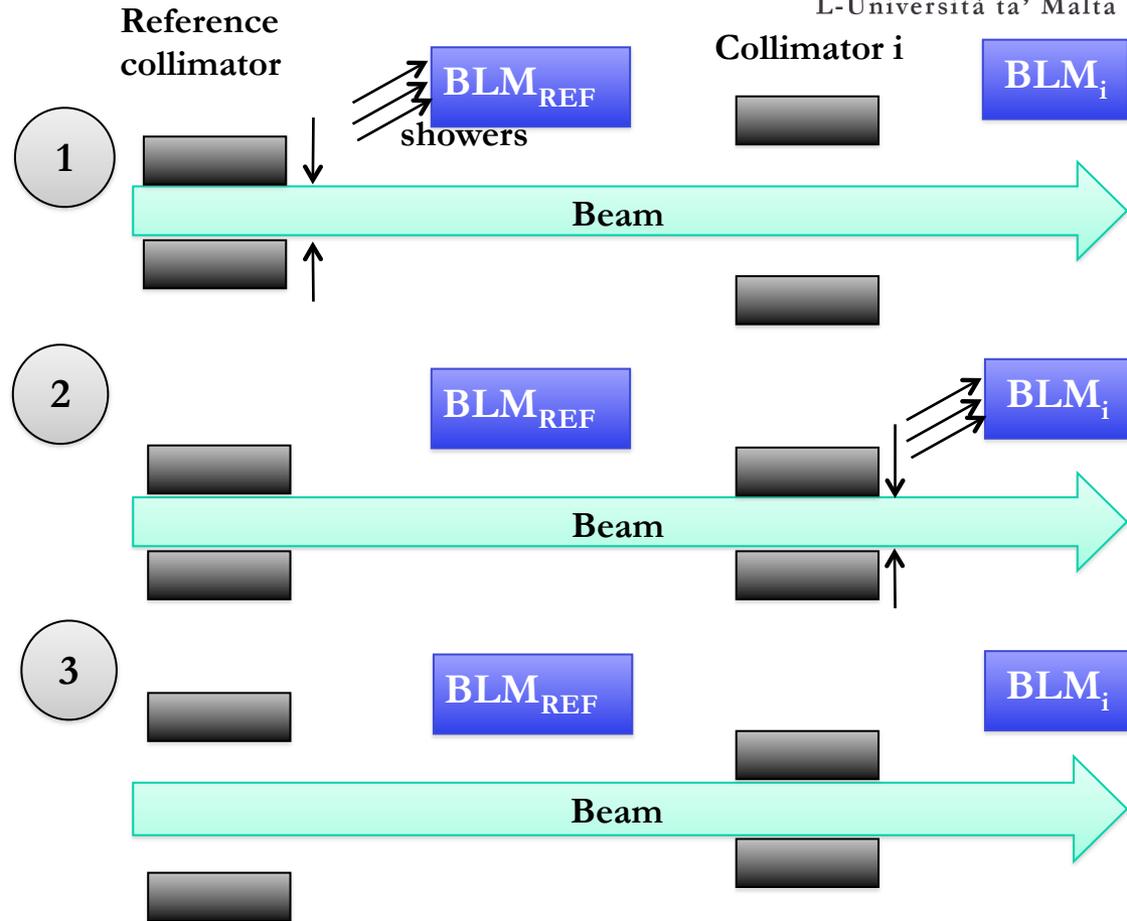
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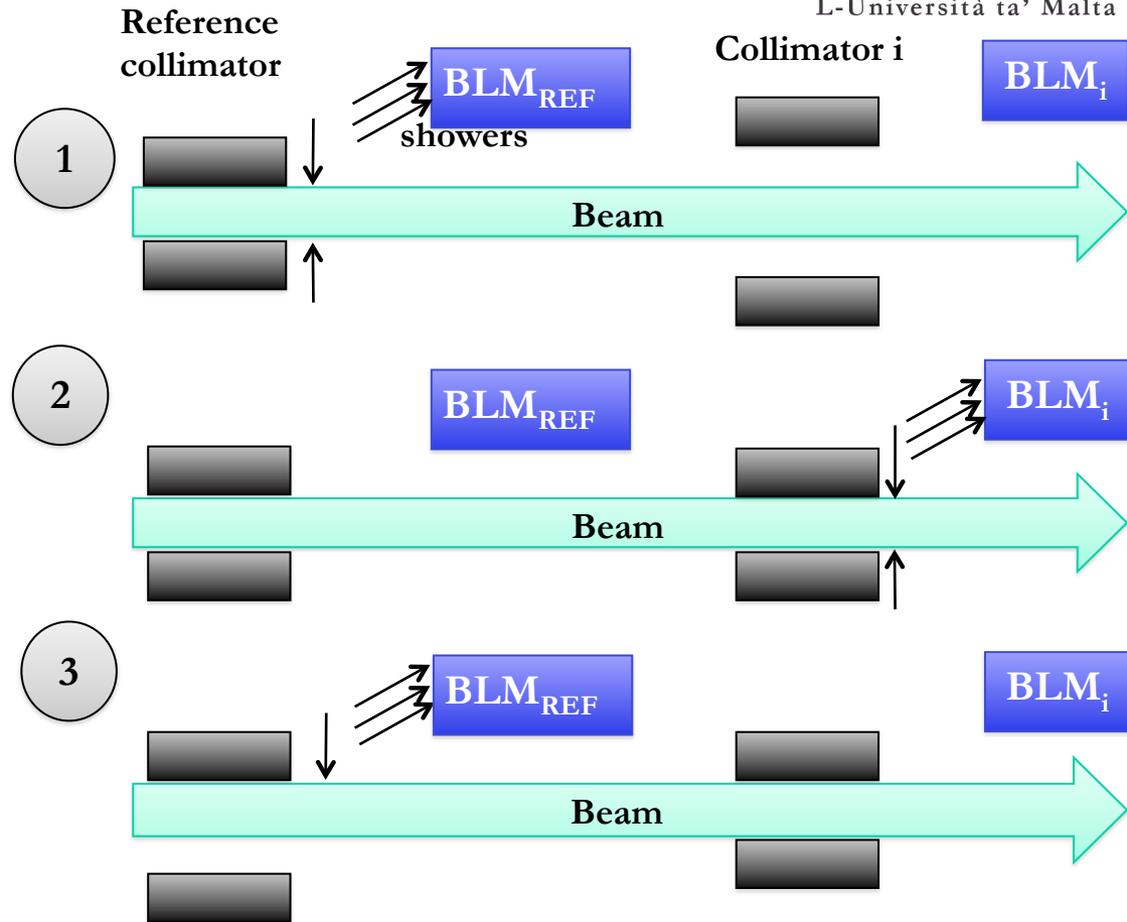
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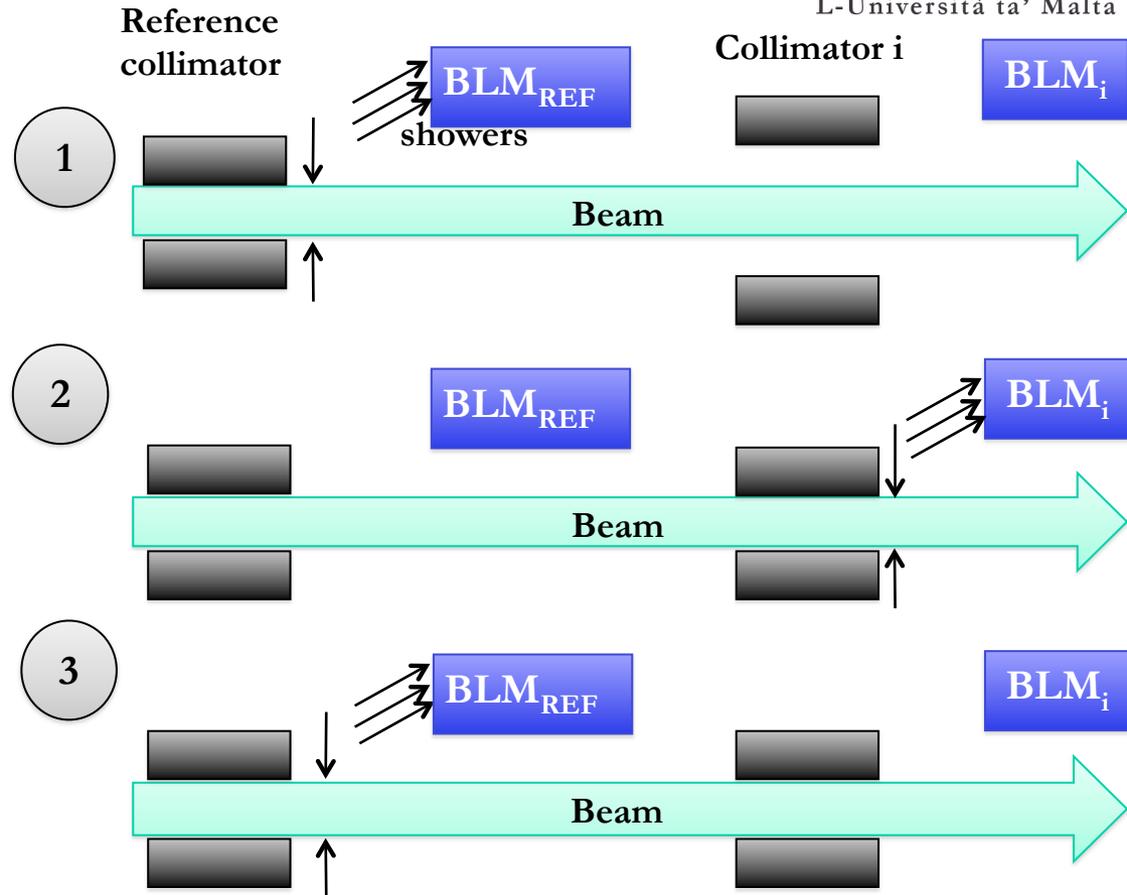
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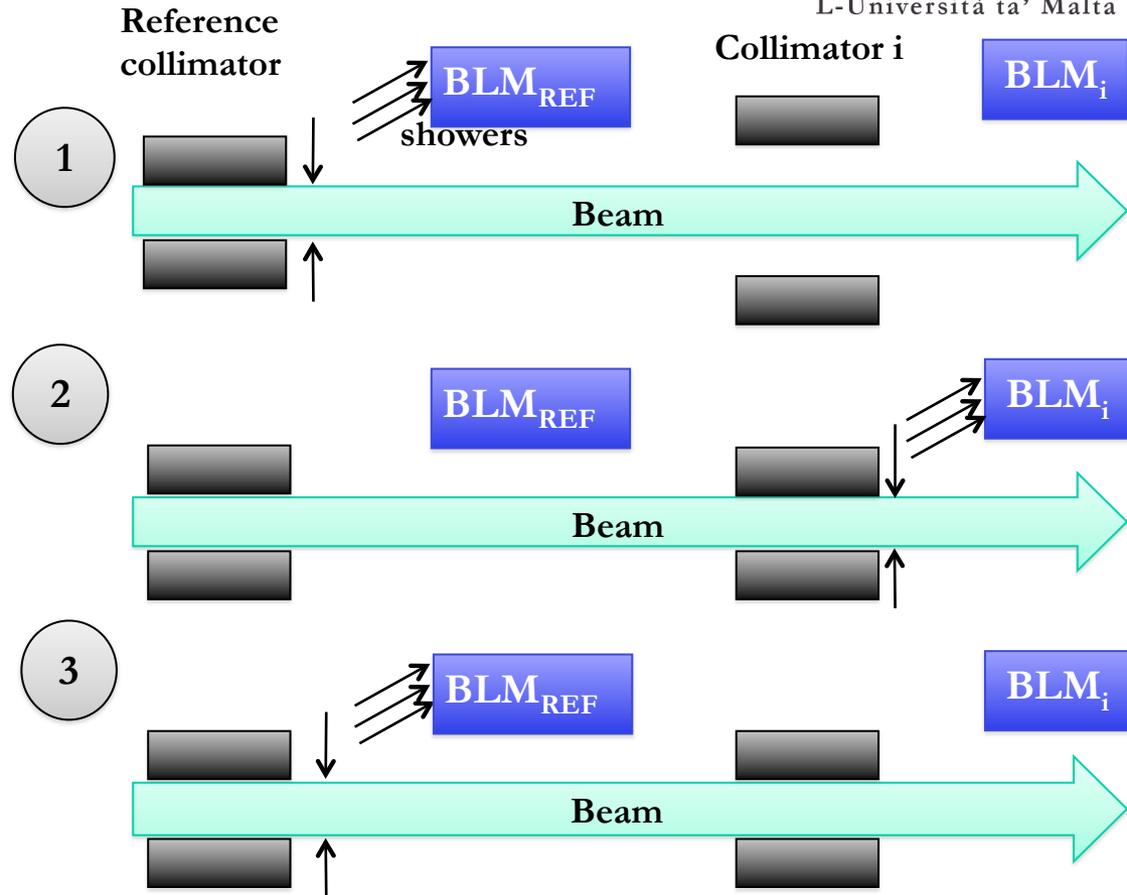
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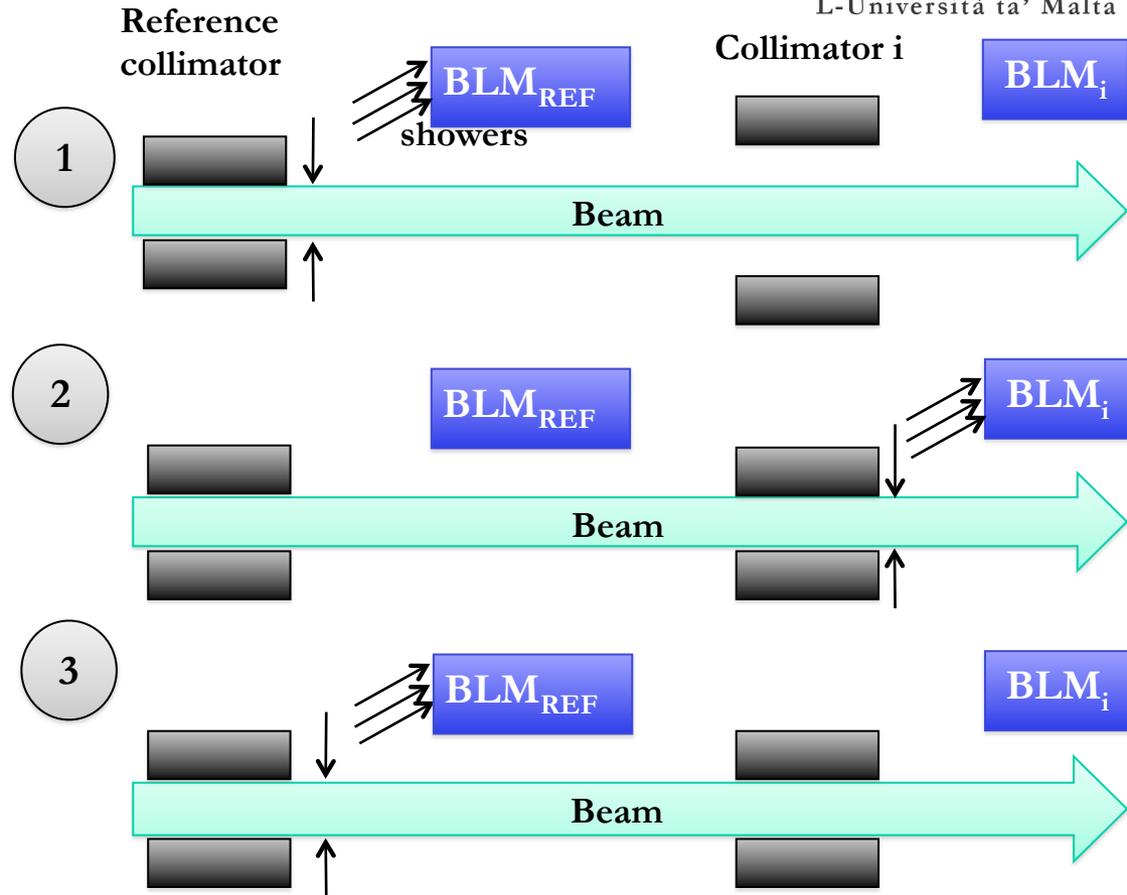
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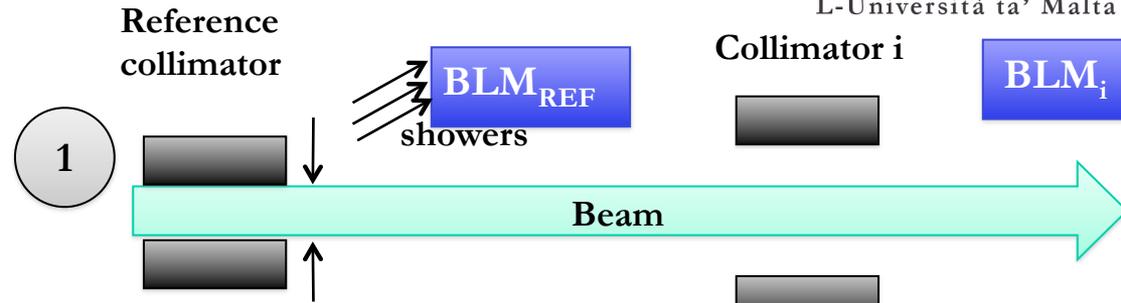
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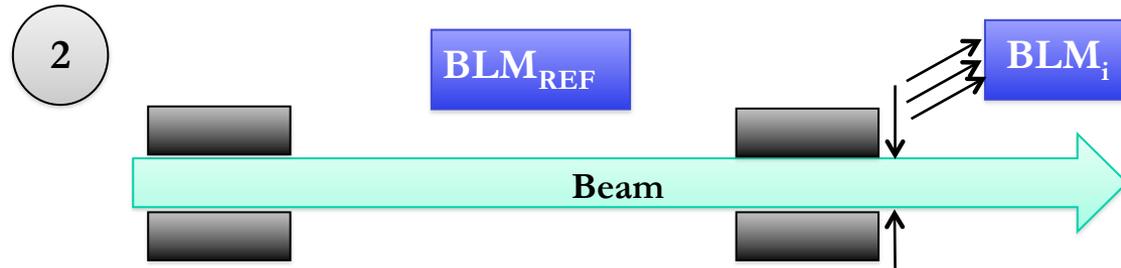
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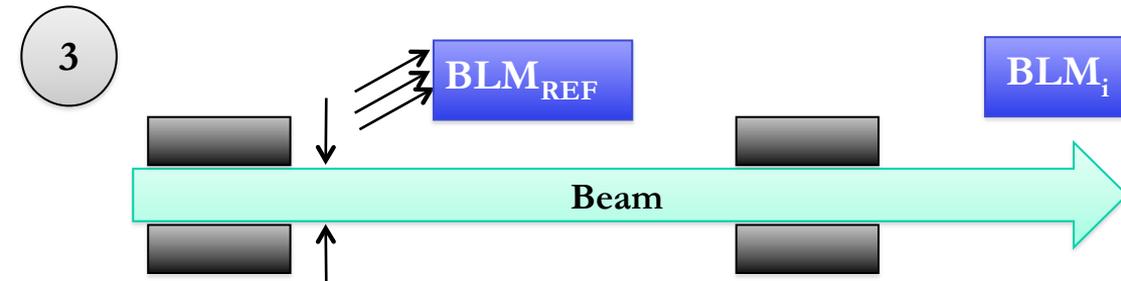
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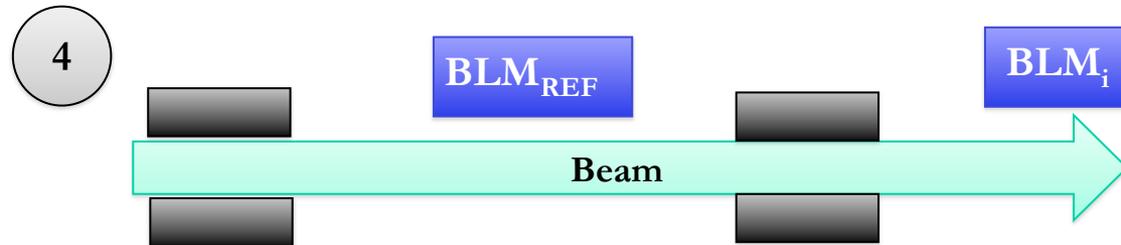


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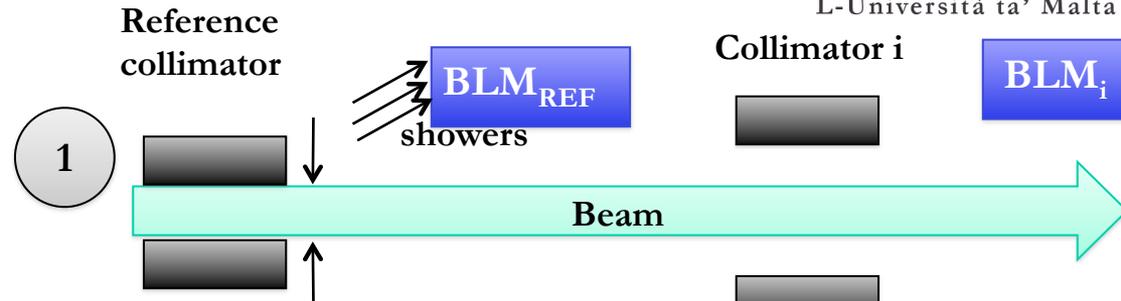


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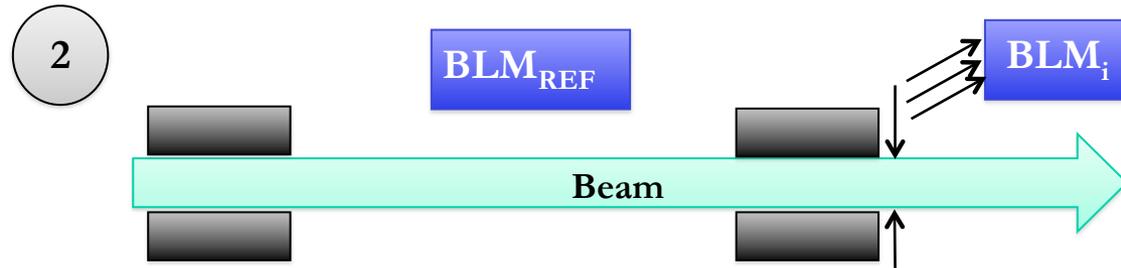
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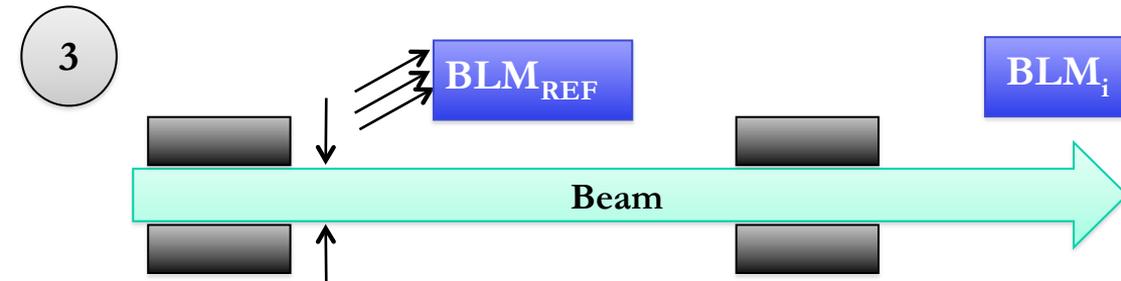
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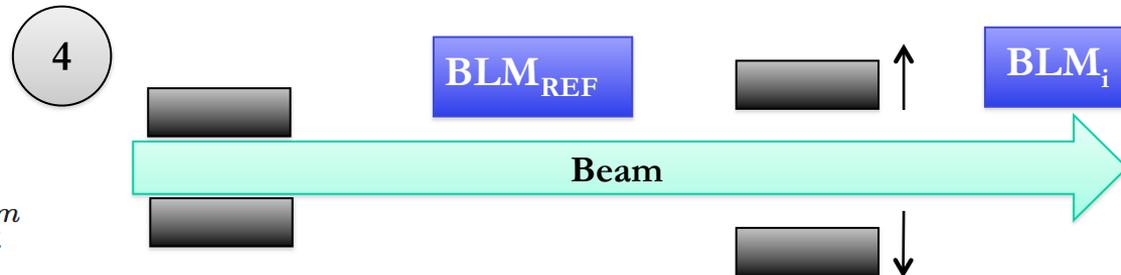
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$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^m \quad x_i^{R,set} = \Delta x_i - N_i \sigma_i^m$$





Automatic Collimator Alignment



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- Motivation:
 - Manual collimator alignment is a time-consuming and expensive process (LHC running costs = $\sim\text{€ } 150\text{K} / \text{hour}$).
 - 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.
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BLM Feedback Loop



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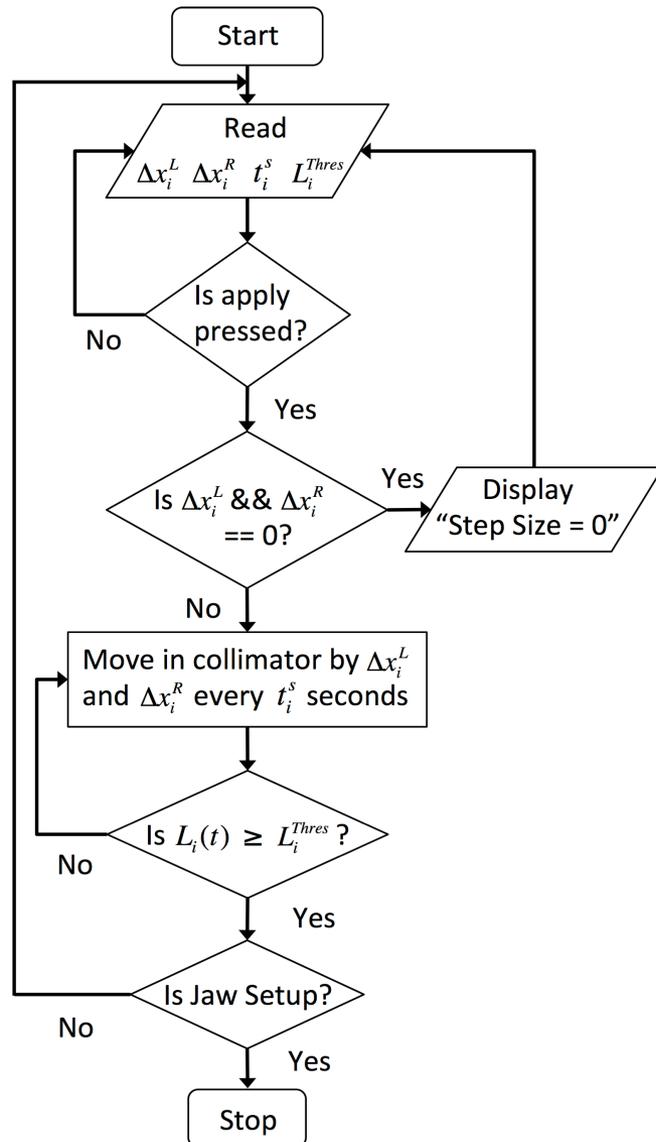


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- A **BLM feedback loop** was implemented as a first step in automating the alignment.

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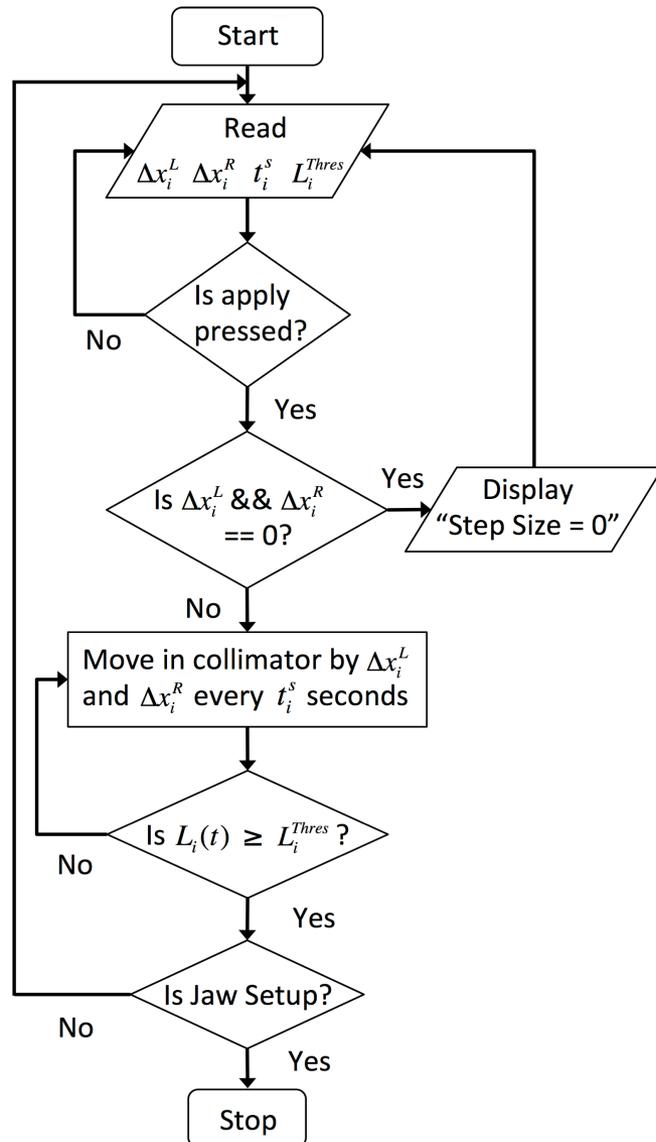
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- Feedback loop implemented in Java application in the top layer of the LHC Software Architecture (LSA).
- The application is operated in the CERN Control Centre (CCC).
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- Semi-automatic alignment results published in PRST-AB.
- Input heuristics developed over 2 years of setups (2009 – 2011) 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



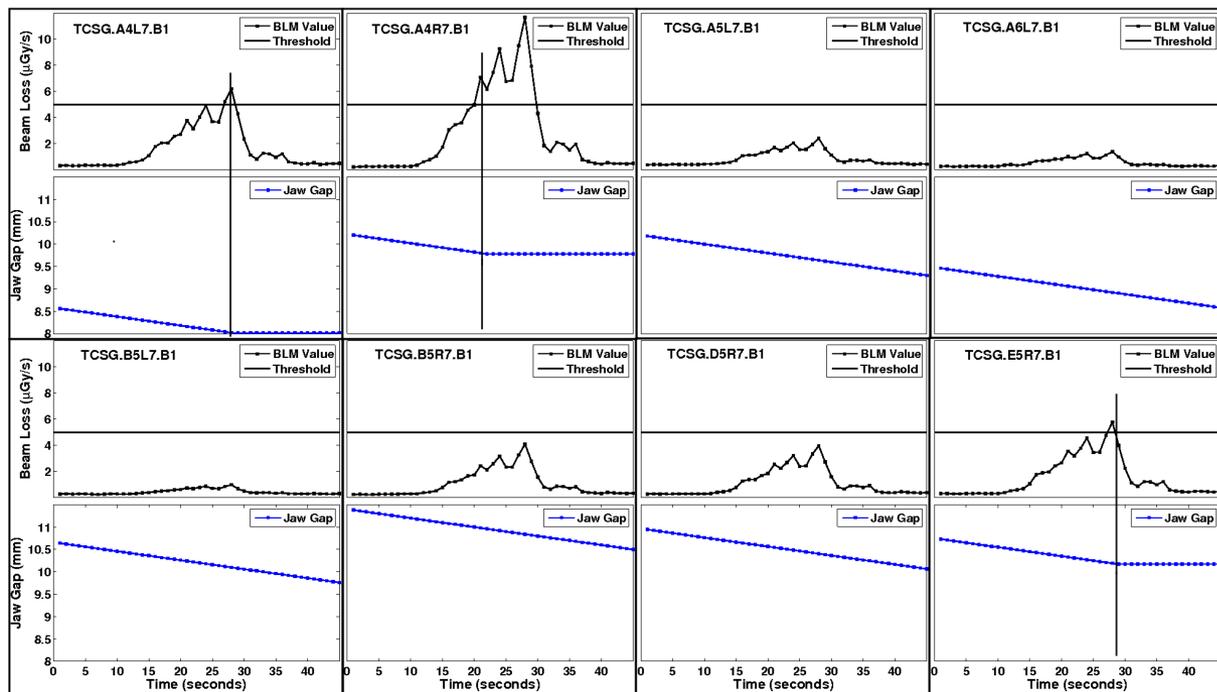


Parallel Collimator Alignment



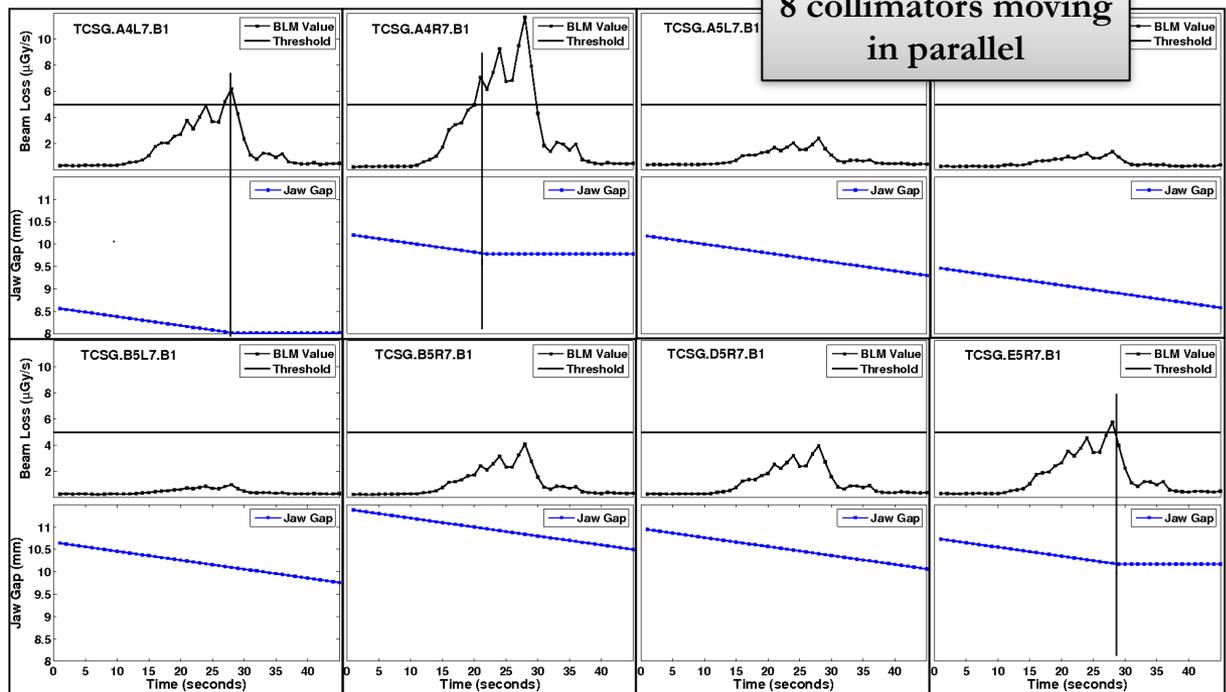
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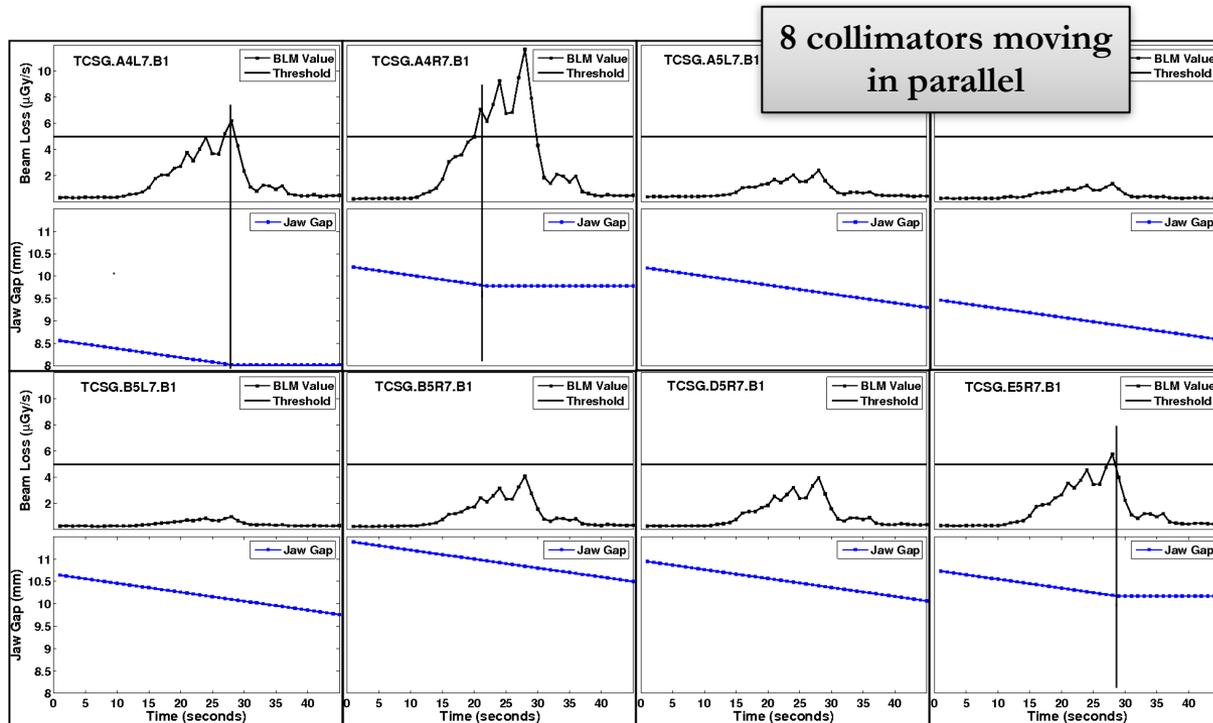
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Parallel Collimator Alignment

8 collimators moving
in parallel

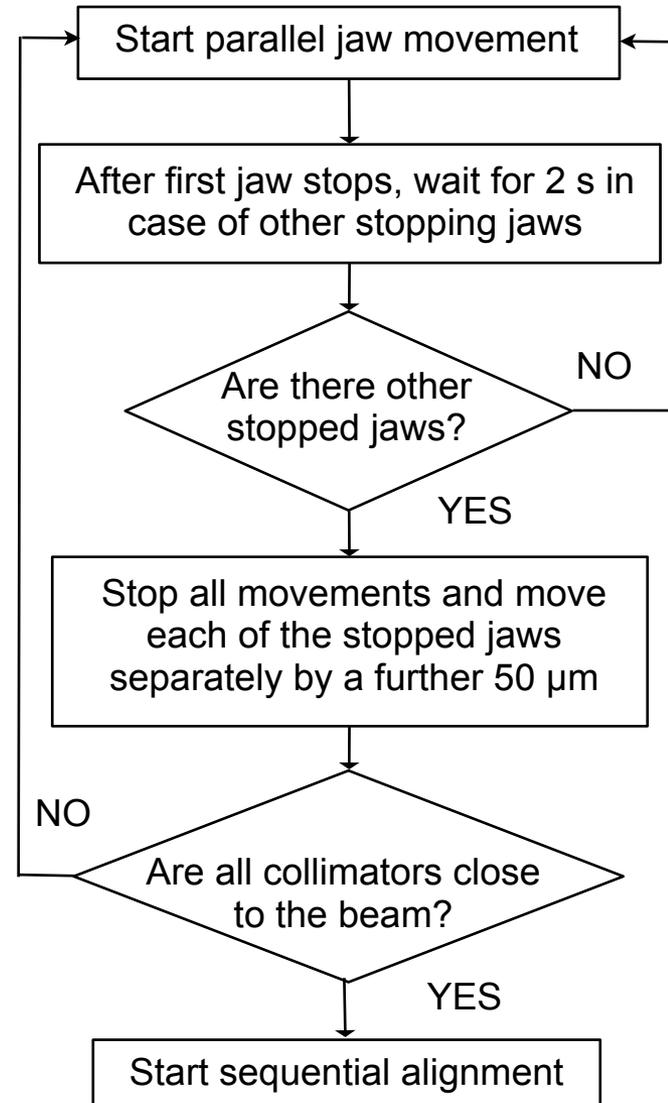
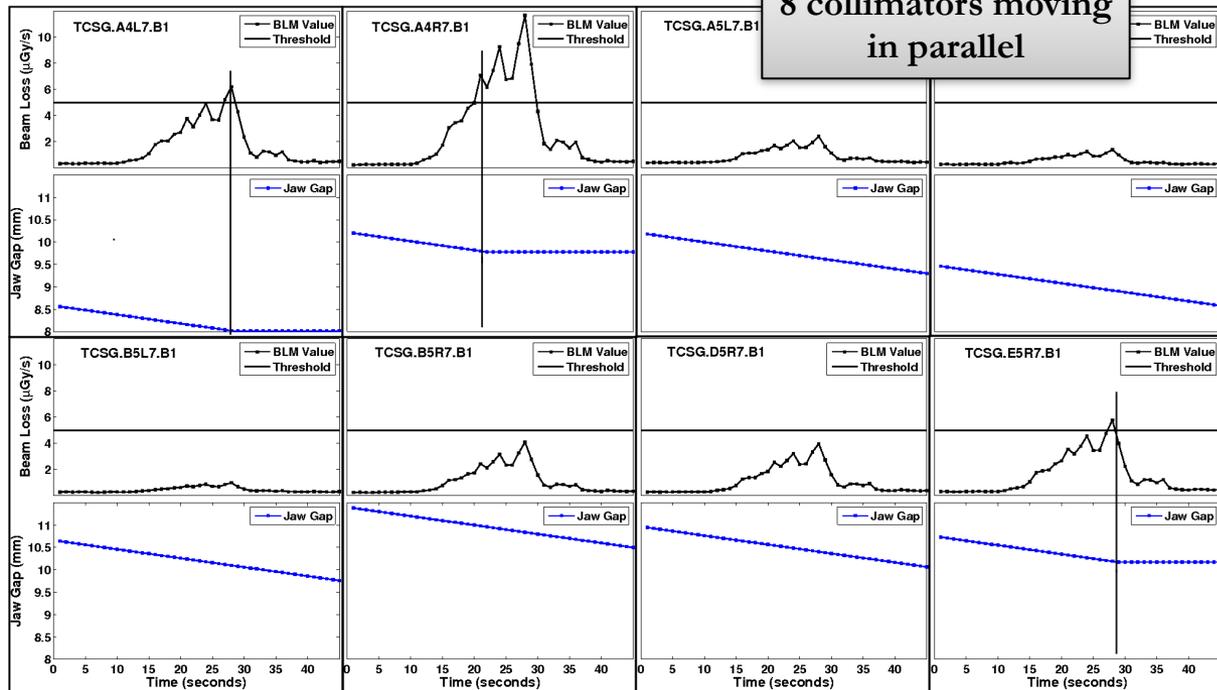




- Iterative algorithm to determine which collimator is at the beam after BLM signal crosstalk.
- Tested in MD (Machine Development) in July 2011.

Parallel Collimator Alignment

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BLM Spike Recognition



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

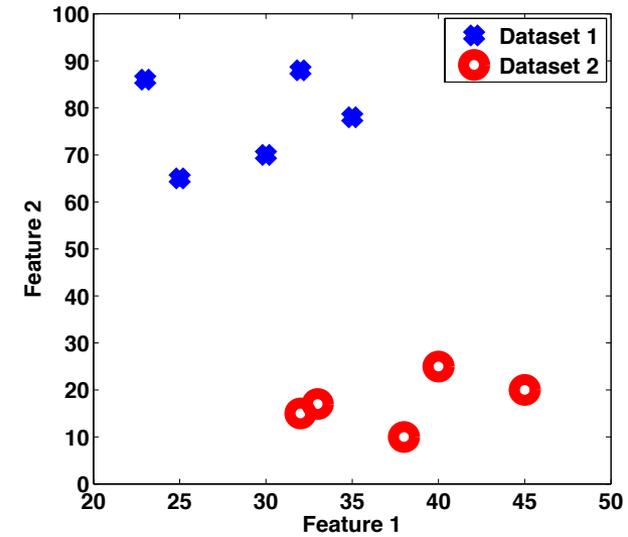


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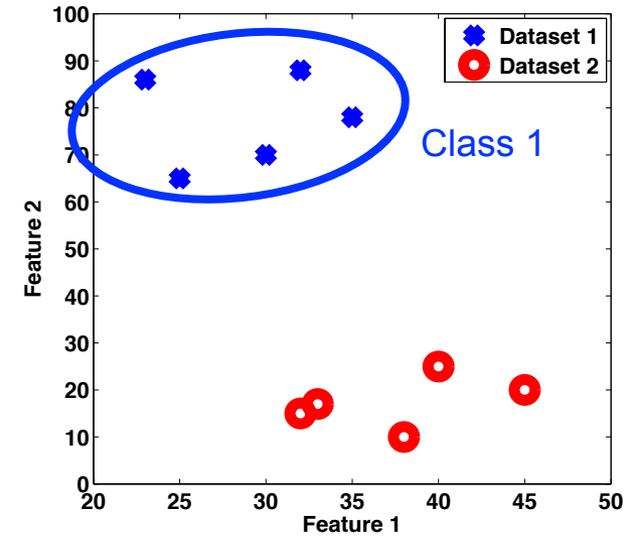


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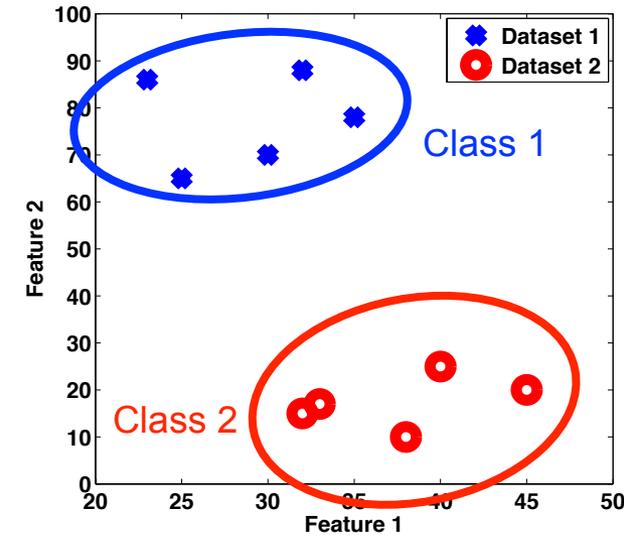
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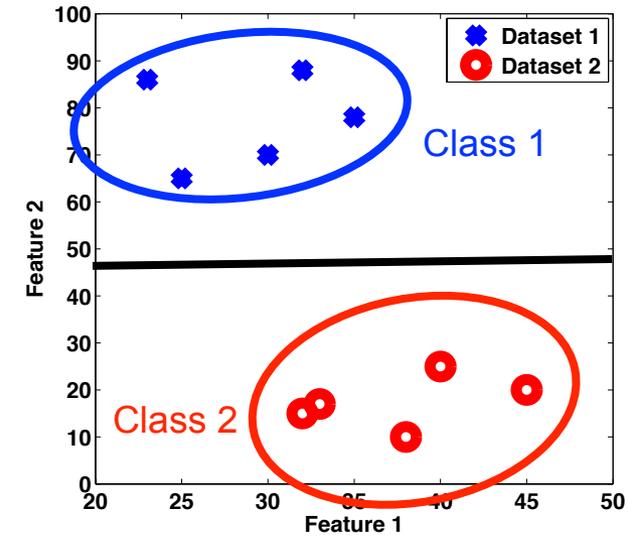
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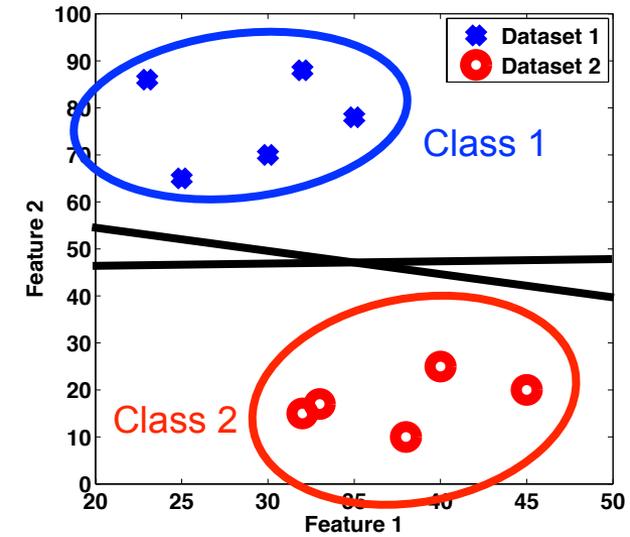
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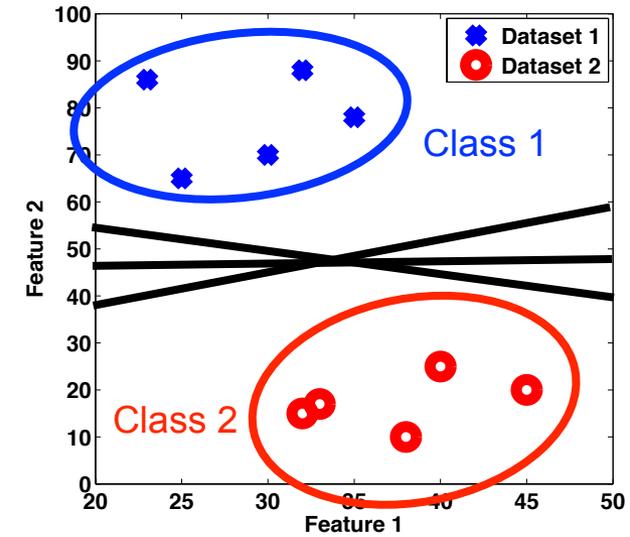
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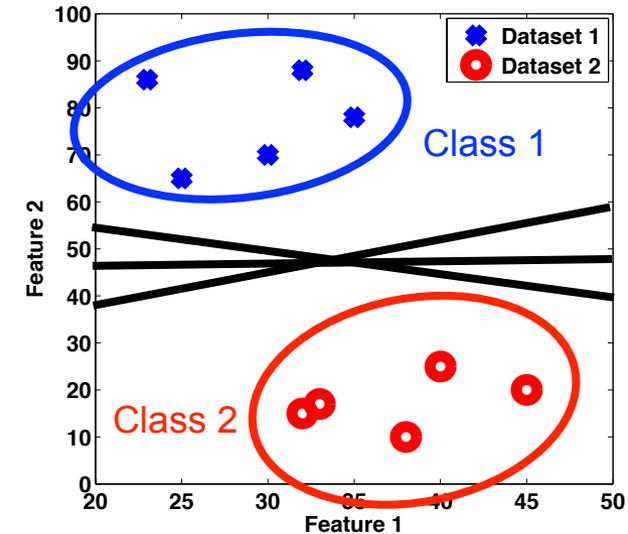
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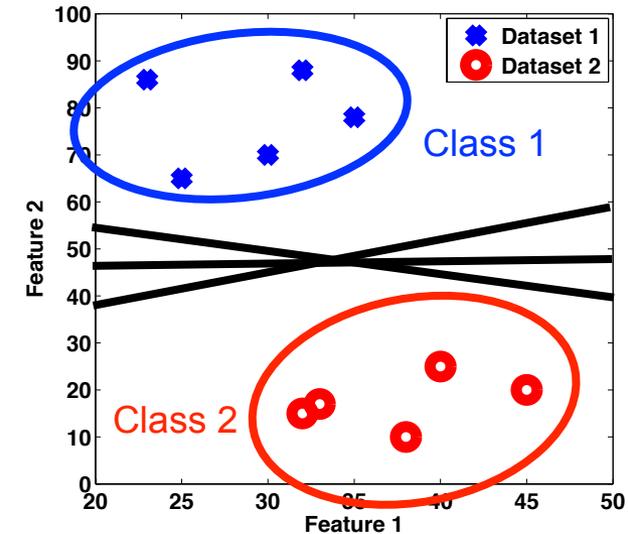
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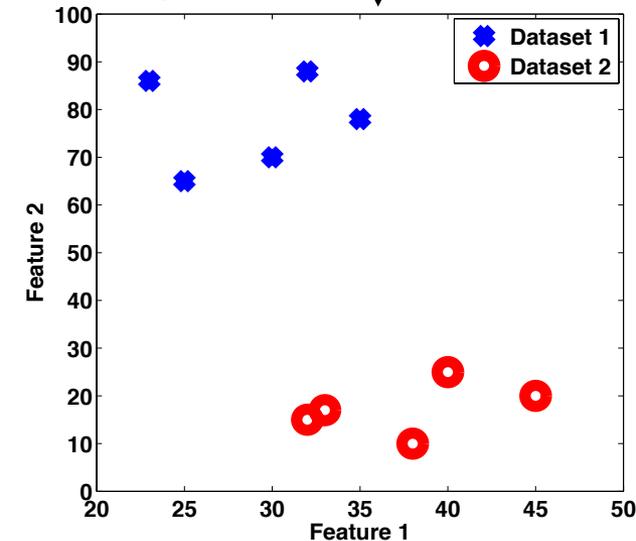


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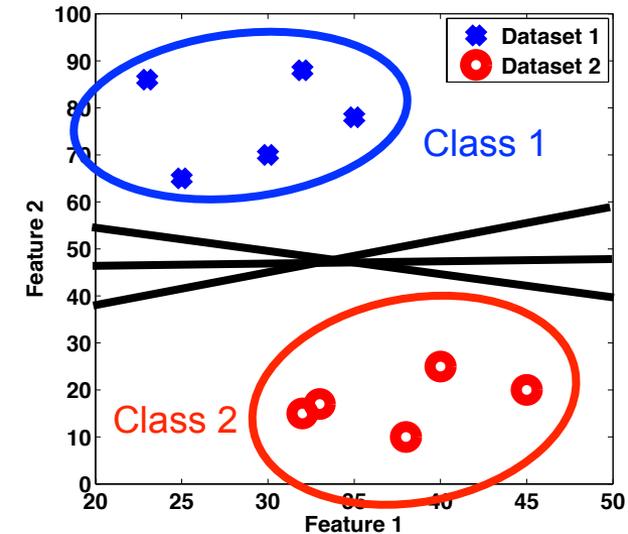


SVM: maximizes
class separation

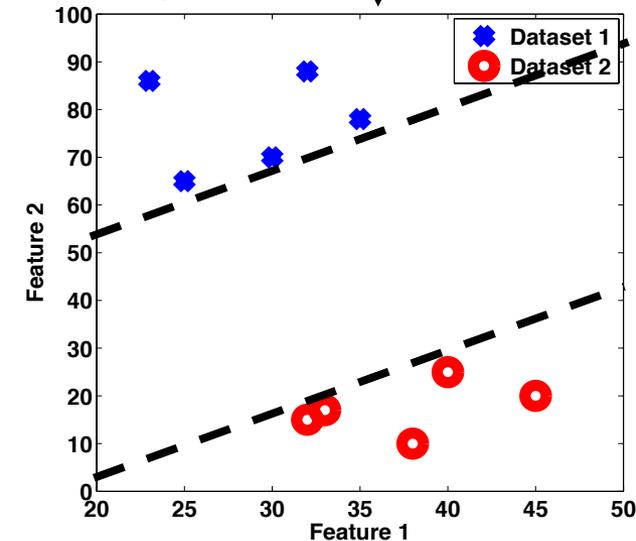


BLM Spike Recognition

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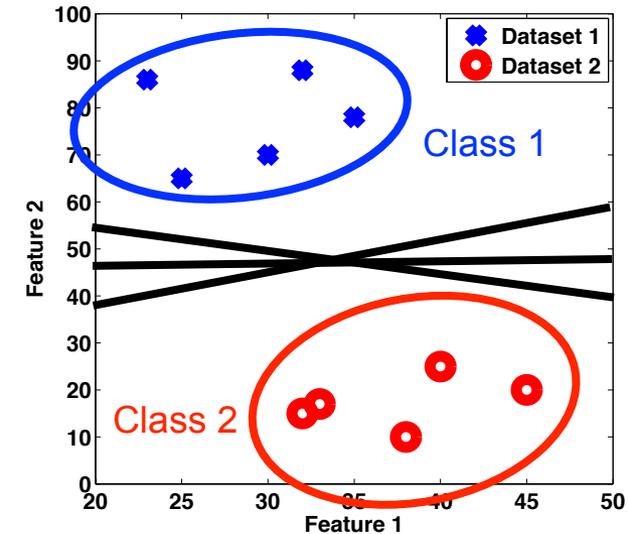


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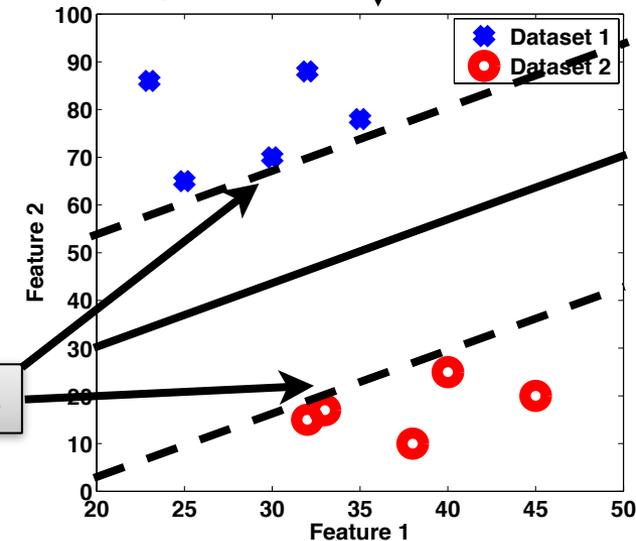


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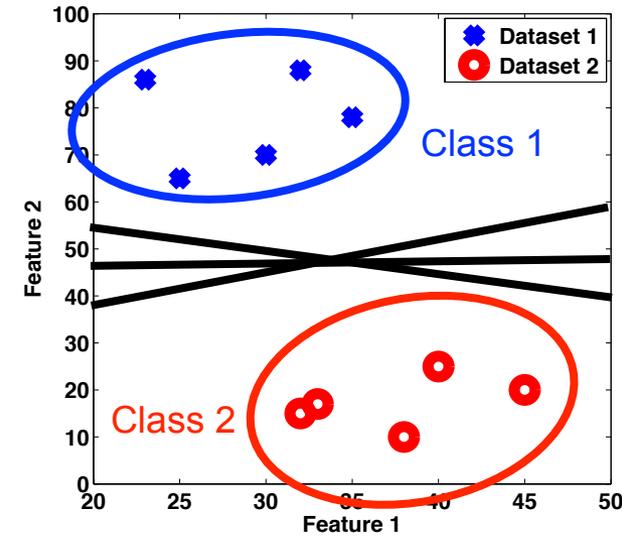
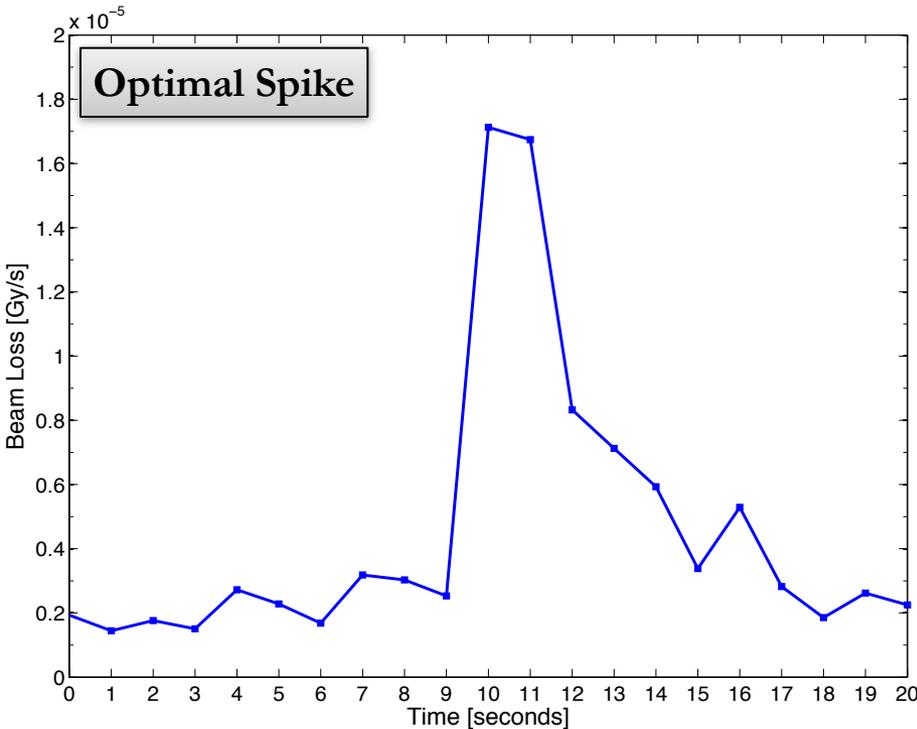


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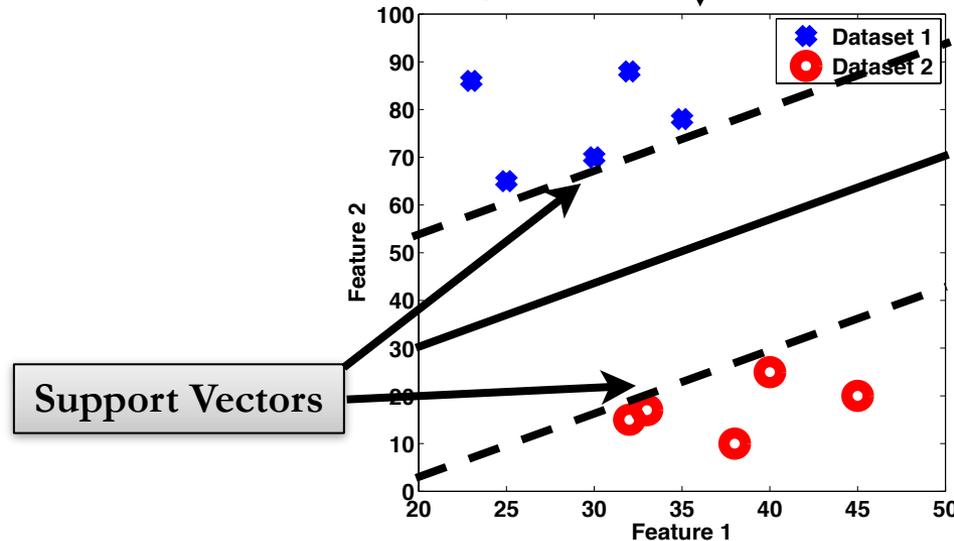


BLM Spike Recognition

- 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.

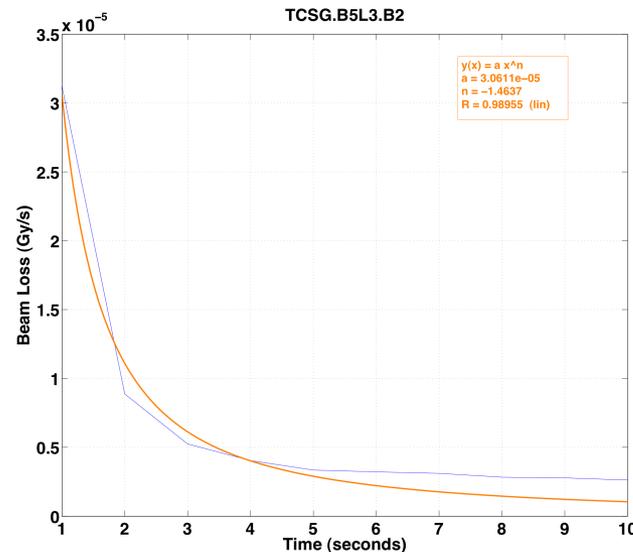
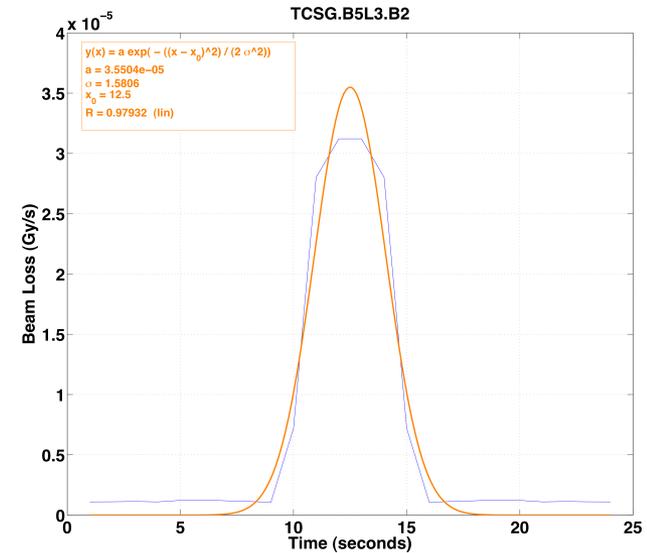


SVM: maximizes class separation



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

- Maximum BLM value** observed after the threshold is exceeded.
- Average** of the 3 smallest loss values of the 7 loss values preceding the maximum value.
- Width** of the Gaussian fit applied to the loss spike folded about the maximum value.
- Gaussian fit correlation coefficient.**
- Power fit exponent.**
- Power fit correlation coefficient.**





SVM Training and Results



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- **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).



SVM Training and Results

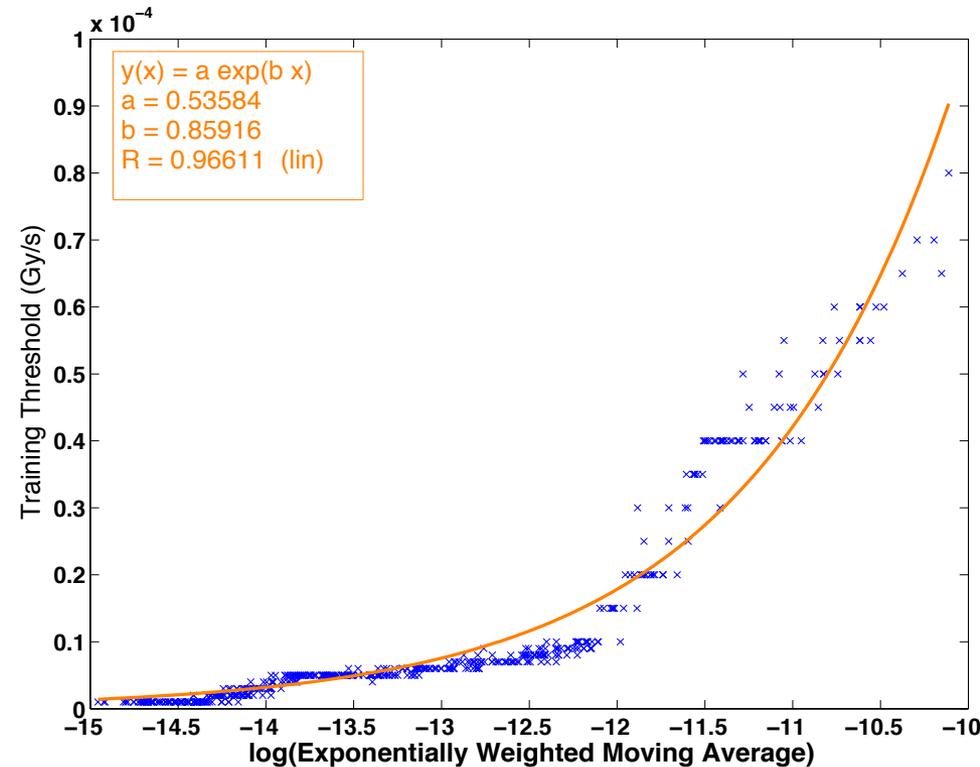


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Parameter	Value
Number of Features	6
Number of Classes	2
C	32768
γ	0.125
Kernel	RBF
Training dataset prediction	97.2973 %
Test dataset prediction rate	82.4324 %
Overall prediction rate	89.8649 %

- 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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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 $550 \mu\text{m}$.

- 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:

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

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

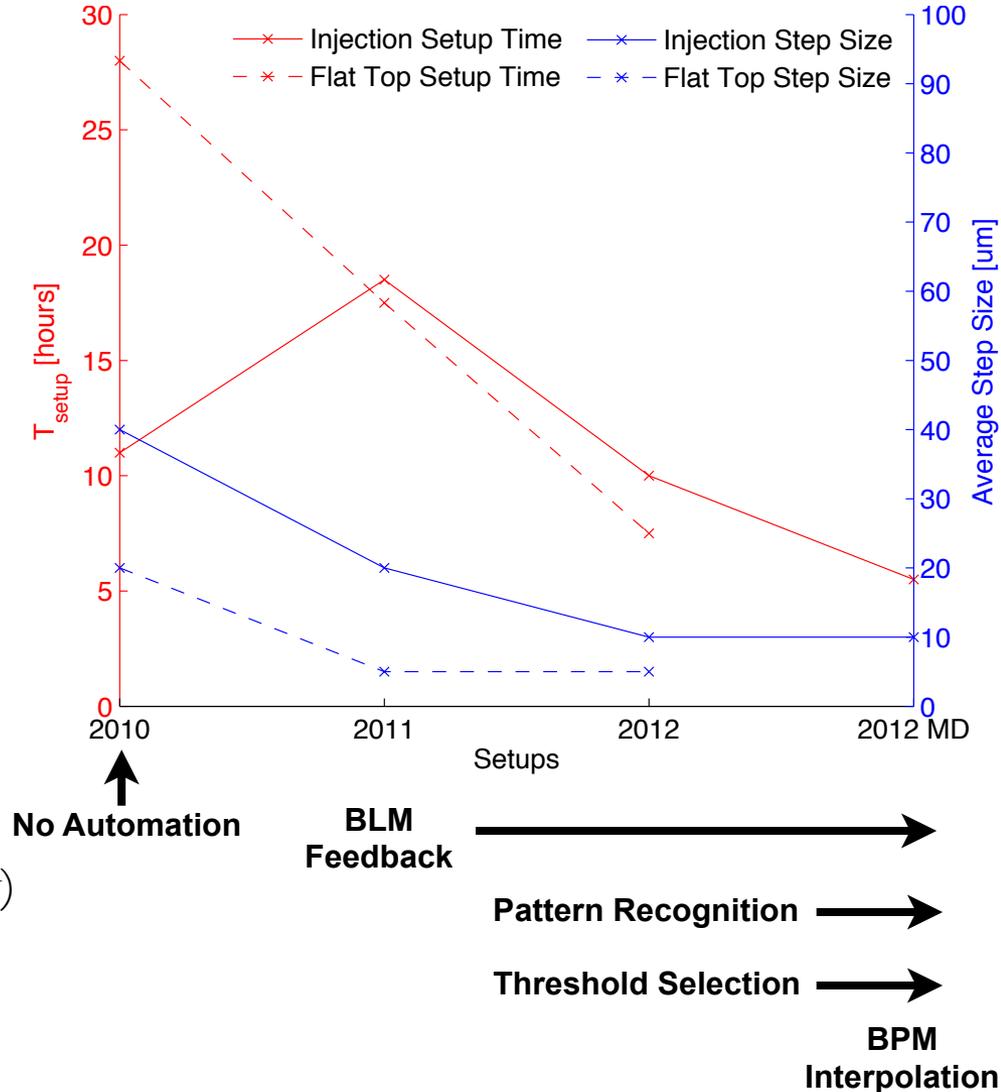
- $\Delta x_i^{int.}$: interpolated beam center at collimator i .
- N_{TCP} : half-gap of IR7 TCP in units of sigma.
- N_{margin} : further margin over and above the IR7 TCP cut.
- σ_i^n : the nominal 1-sigma beam size.
- $\Delta_{m,int.}$: the expected average delta between the interpolated and the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

Alignment Results

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

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

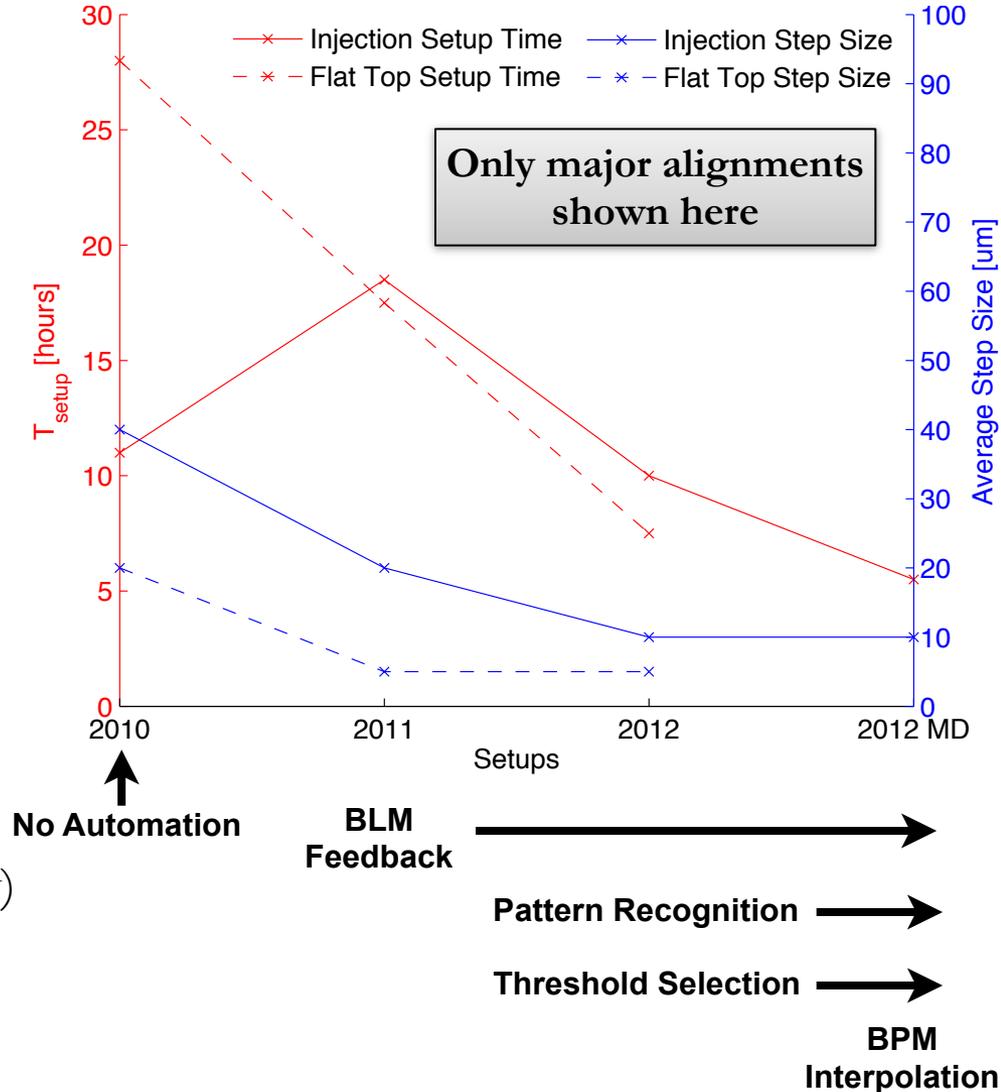
- 2010: manual alignment
- 2011: semi-automatic alignment at 1 Hz
- 2012: semi-automatic alignment at 8 Hz
- No costly beam dumps due to high losses from 2011 onwards.
- Use of smaller jaw step size (better accuracy) made easier by semi-automatic alignment.



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Summary



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- 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.

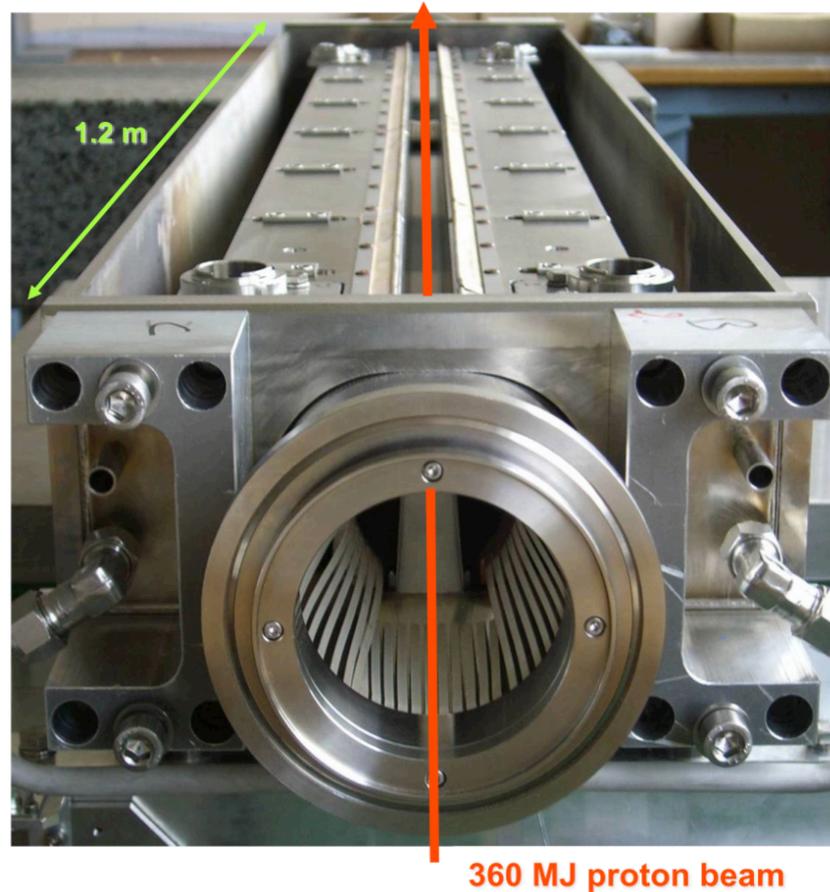


Acknowledgements



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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



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Setup Application GUI



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LHC Collimator Control Application – Semi-Automatic Set-up V1 (Device: TCP.C6L7.B1/TCP.IP7.B1.2.H)

File Settings Reset More displays Help Setup Options

Jaw corners Positions/Angles Increment BBA

Semi-automatic setup using increments

Left Step Size (um): 10.0

Right Step Size (um): 10.0

BLM Stop Value (au): 1.0E-6

Time Interval (sec): 1

STOPPED

Inputs okay - ready to move!

Left Jaw UP-IN UP-OUT DW-IN DW-OUT

Right jaw UP-IN UP-OUT DW-IN DW-OUT

Anti COLL UP DOWN

Positions readout from the low-level

LVDT's 1.344 2.972

Jaw edges 1.325 2.94

-1.688 -0.173

-1.72 -0.197

Display jaw: Left Jaw (dashed) Right jaw (solid) Gap (LVDT)

Positions: Set LVDT Warn Lim Res Mot E B*

BLM: BLM 1 BLM 2 BLM 3 BLM 4 LogY

Int. Time: 1.31s 81.92ms 12Hz Threshold

Views

Beam loss data [09/04/12 02:01:23]

Beam loss signal [a.u.]

01:59:00 01:59:20 01:59:40 02:00:00 02:00:20 02:00:40 02:01:00 02:01:20

Jaw positions [09/04/12 02:01:22]

Jaw positions (mm)

01:59:00 01:59:20 01:59:40 02:00:00 02:00:20 02:00:40 02:01:00 02:01:20

time (hh:mm:ss)

B1 B2

Horizontal

TCSG.4R6.B1

TCL5R5.B1

TCTH.4L5.B1

TCLA.7R3.B1

TCLA.6R3.B1

TCLA.B5R3.B1

TCSG.B5R3.B1

TCSG.A5R3.B1

TCSG.4R3.B1

TCSG.5L3.B1

TCP.6L3.B1

TCTH.4L2.B1

TCL5R1.B1

TCTH.4L1.B1

TCTH.4L8.B1

TCLA.A7R7.B1

TCLAD6R7.B1

TCLA.B6R7.B1

TCSG.6R7.B1

TCSG.B4L7.B1

TCP.C6L7.B1

Vertical

TCTVA.4L5.B1



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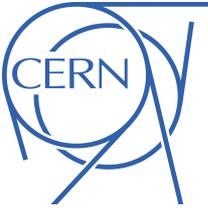
Views



Alignment Results



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Alignment Results

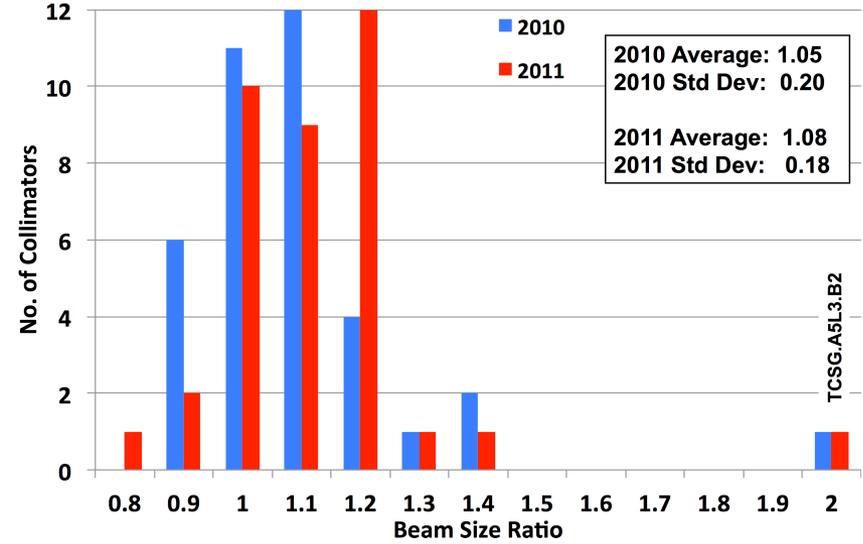
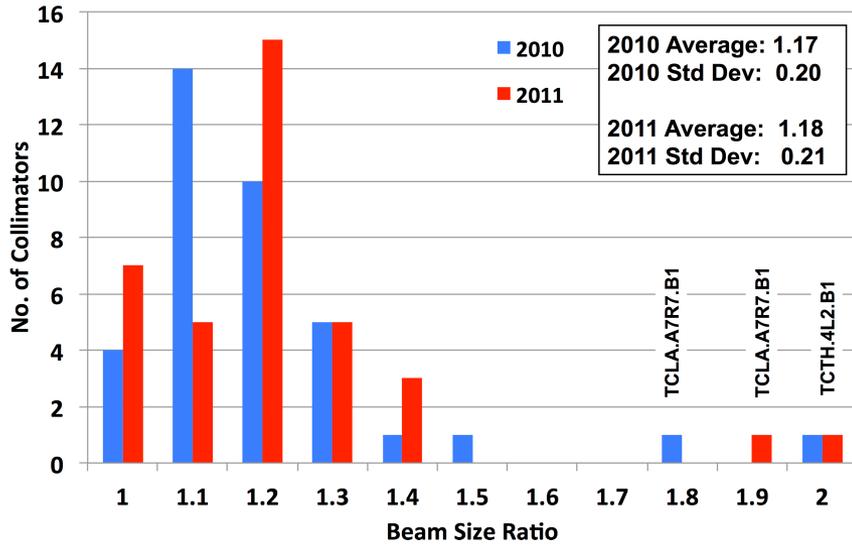


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- Nominal to Measured Beam Size Ratio (B1 left, B2 right) at 3.5 TeV:

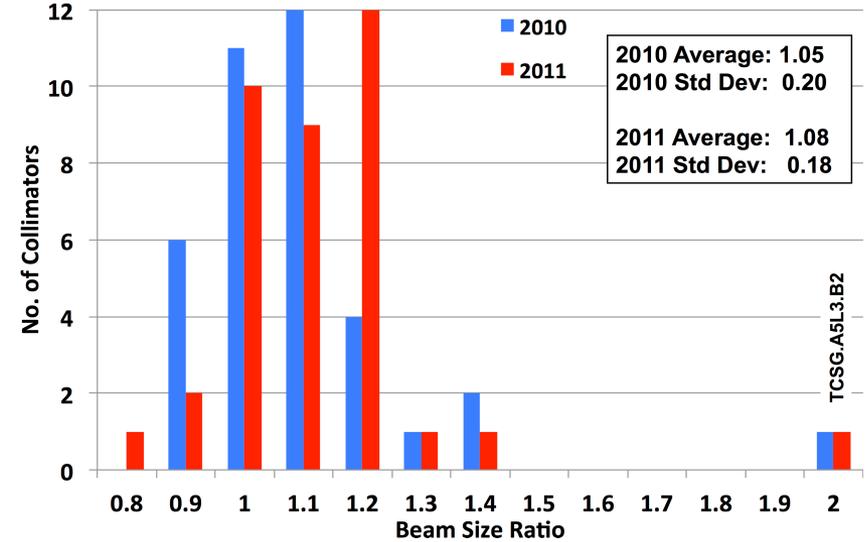
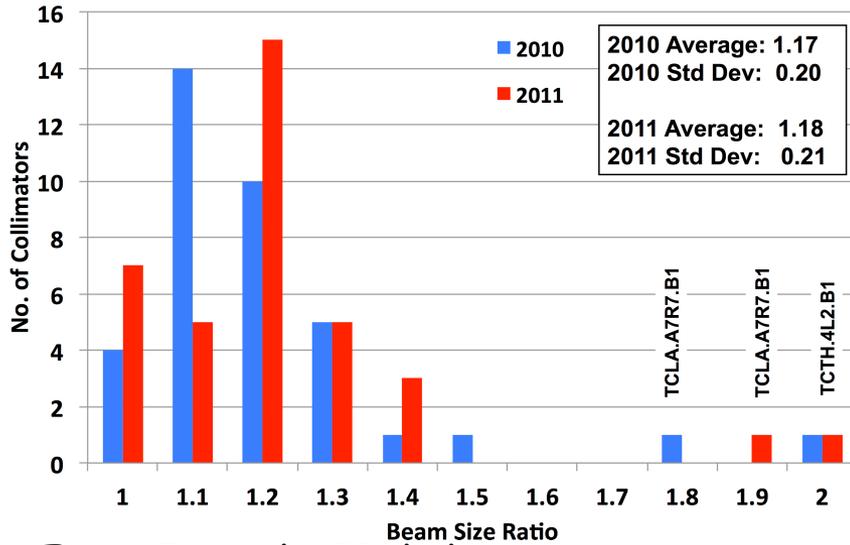
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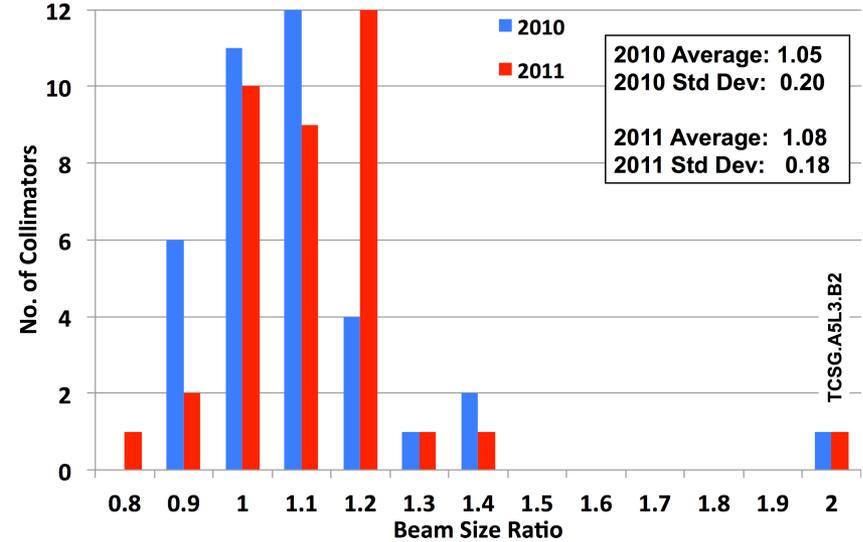
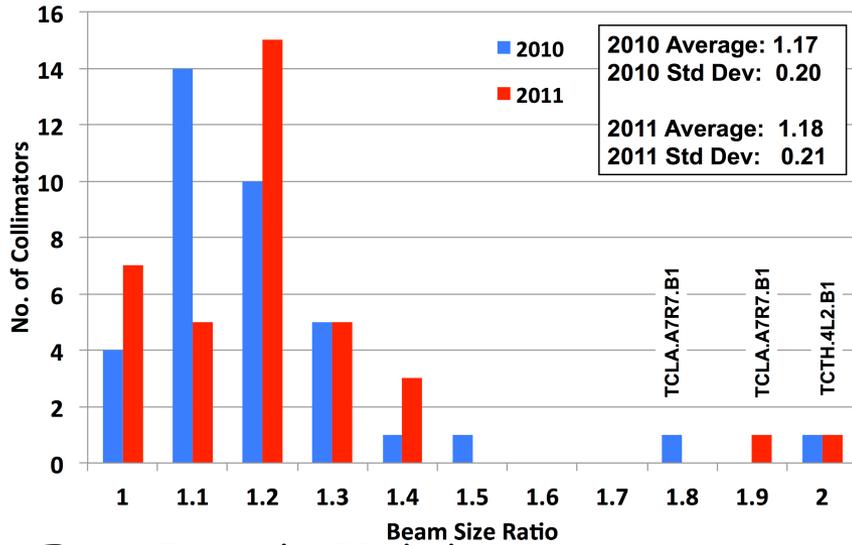
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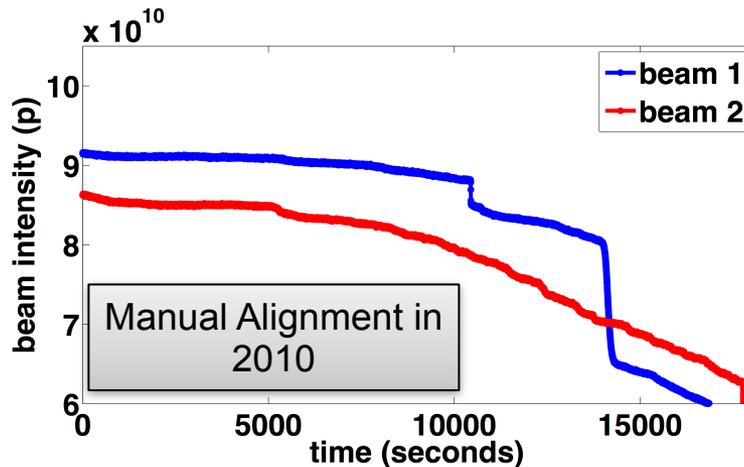


- Beam Intensity Variation:

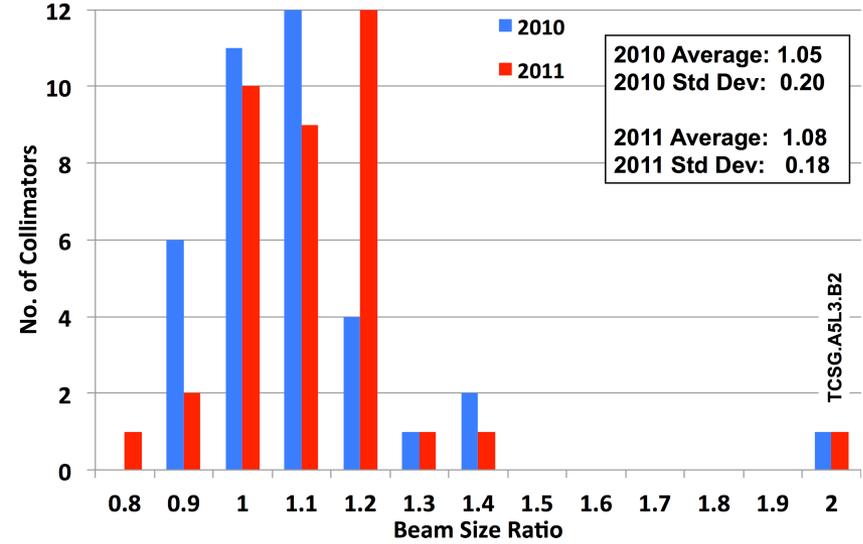
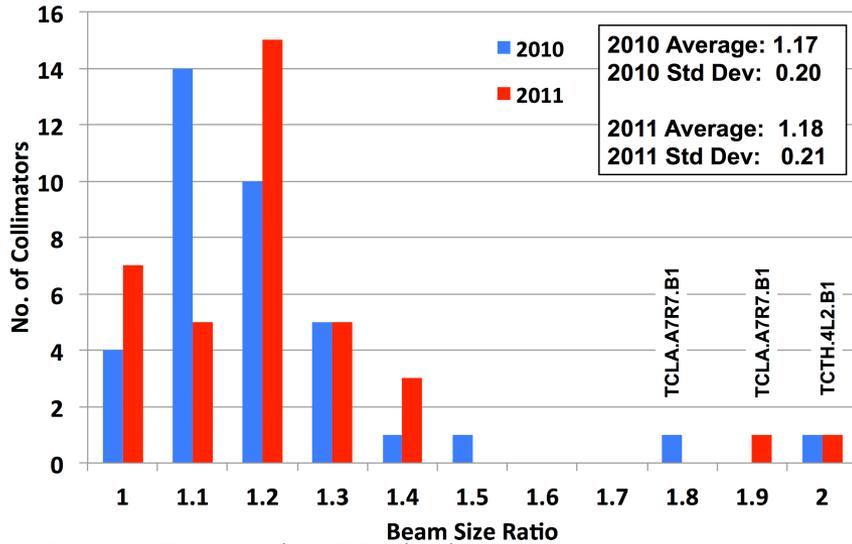
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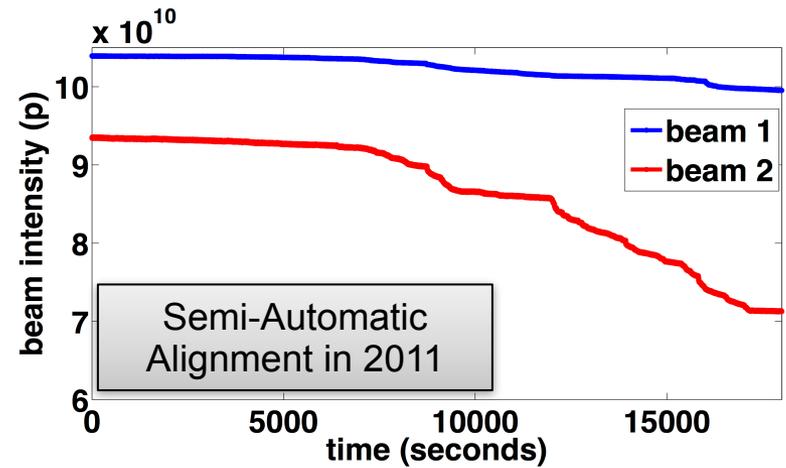
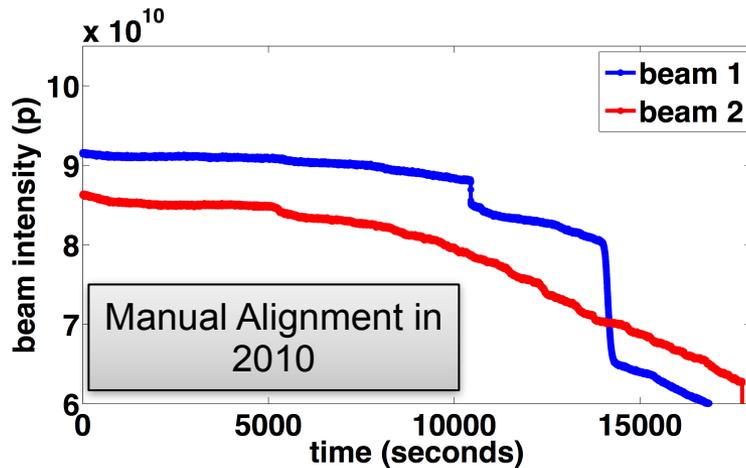
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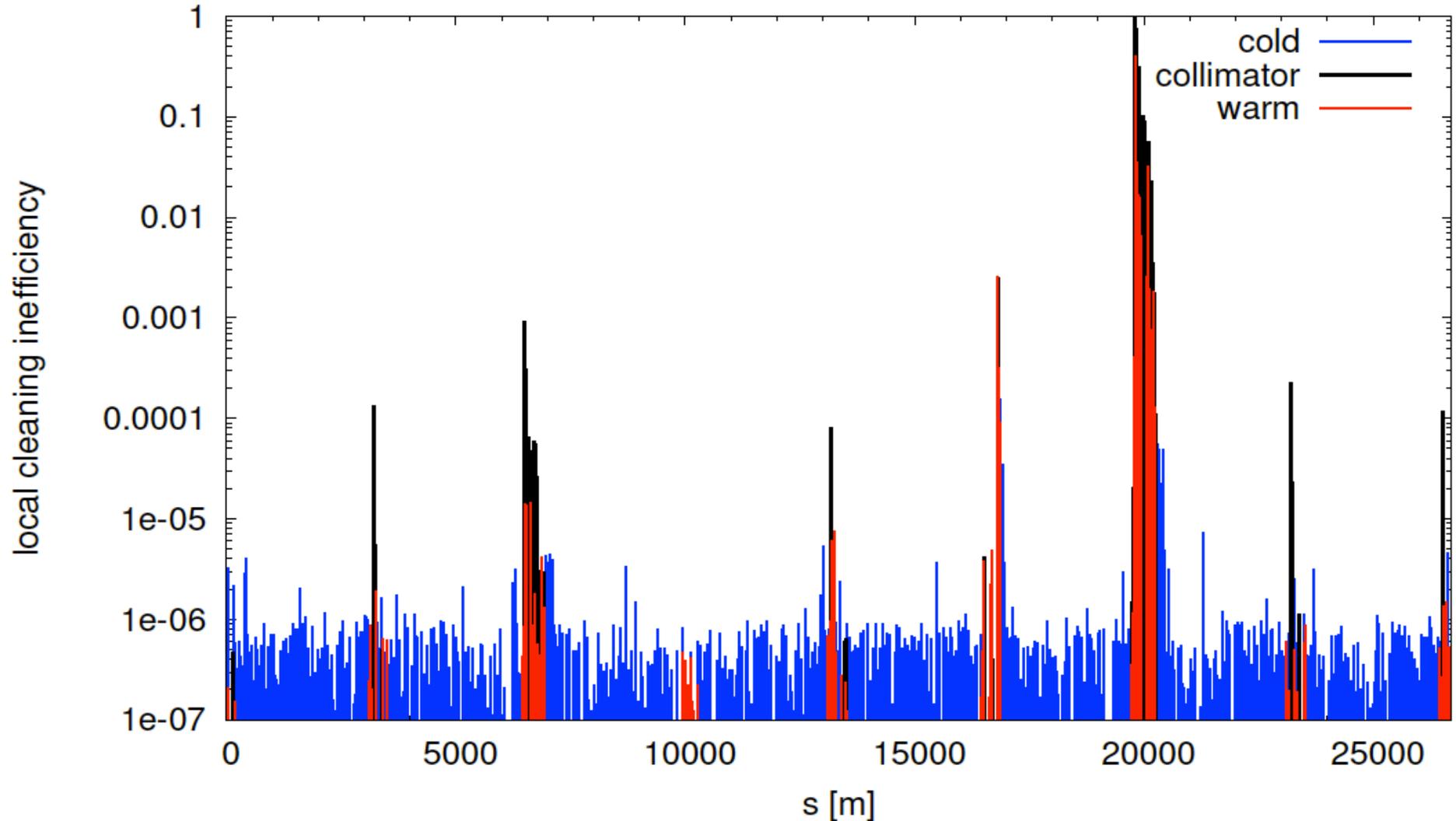


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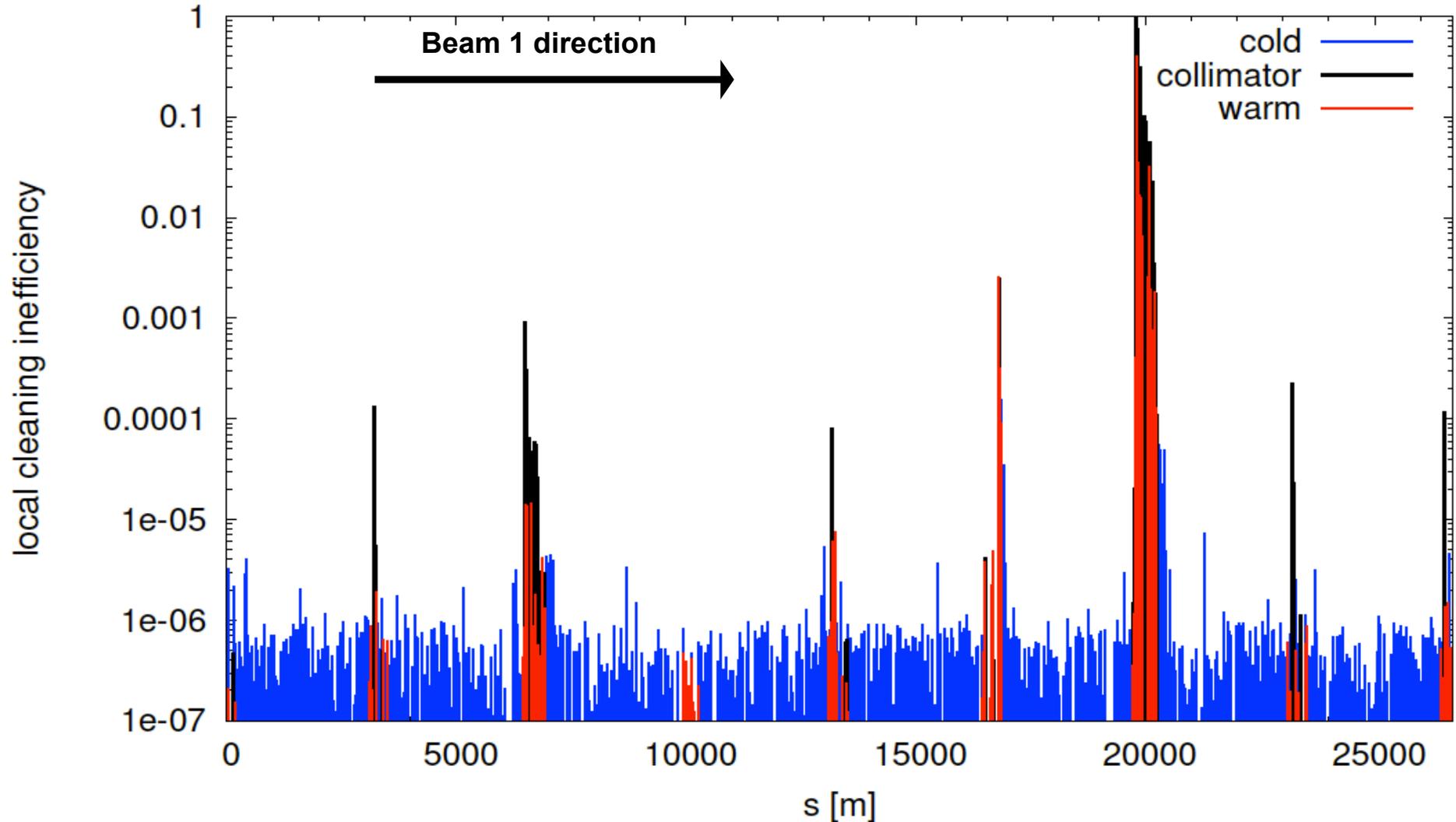
Collimation System Qualification

betatron losses B1 4000GeV hor norm F (2012.04.02, 23:20:09)



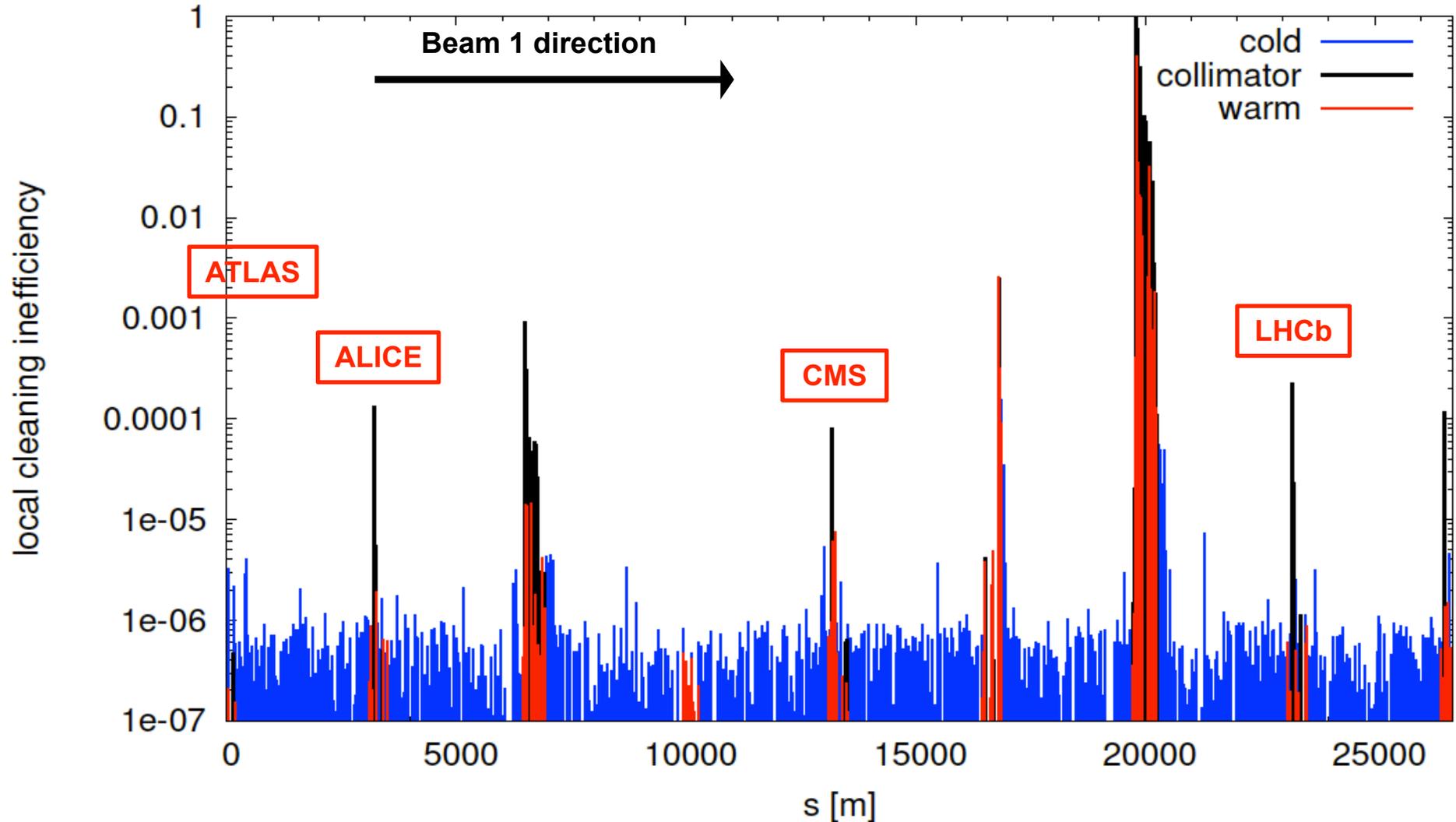
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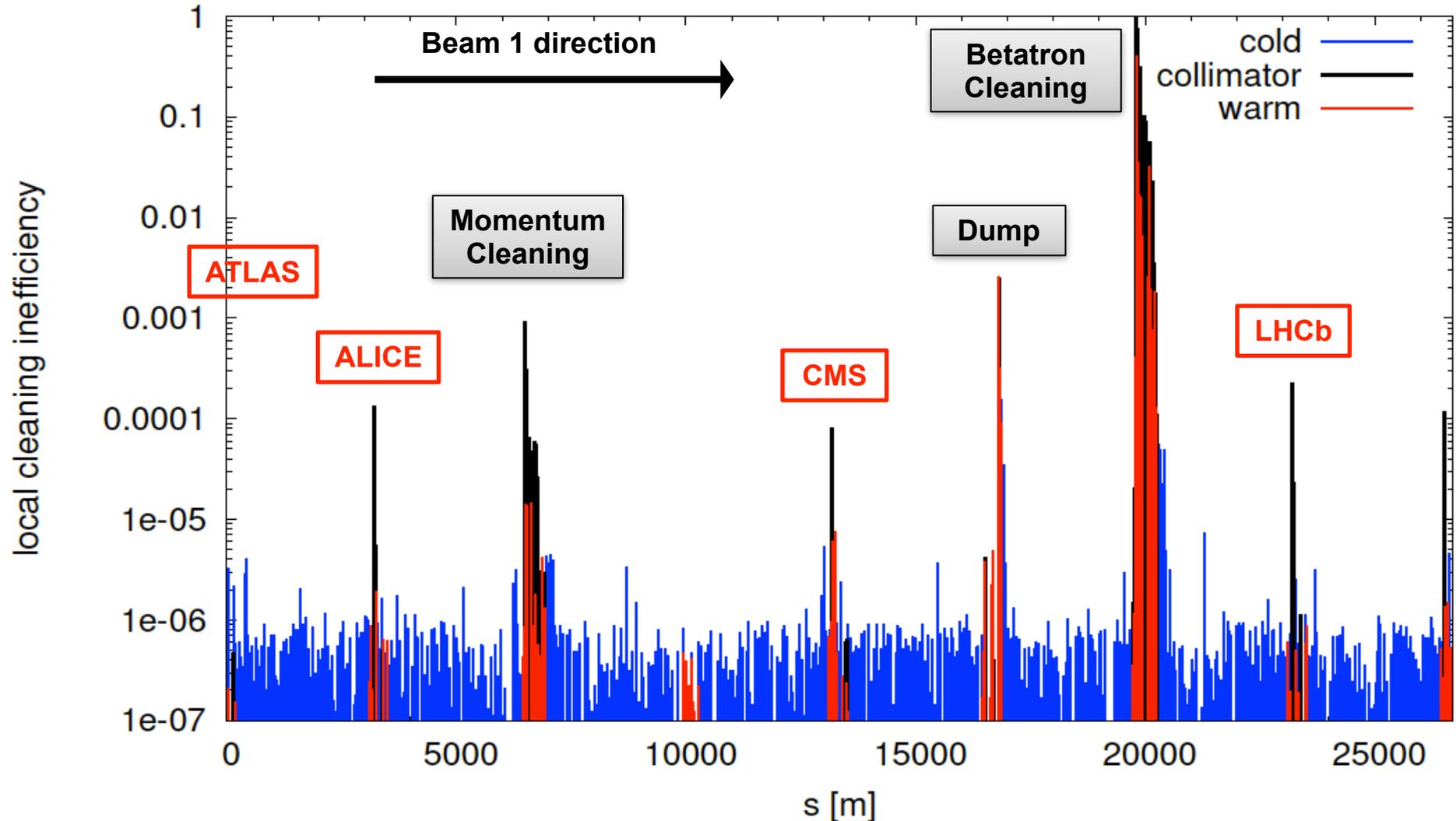
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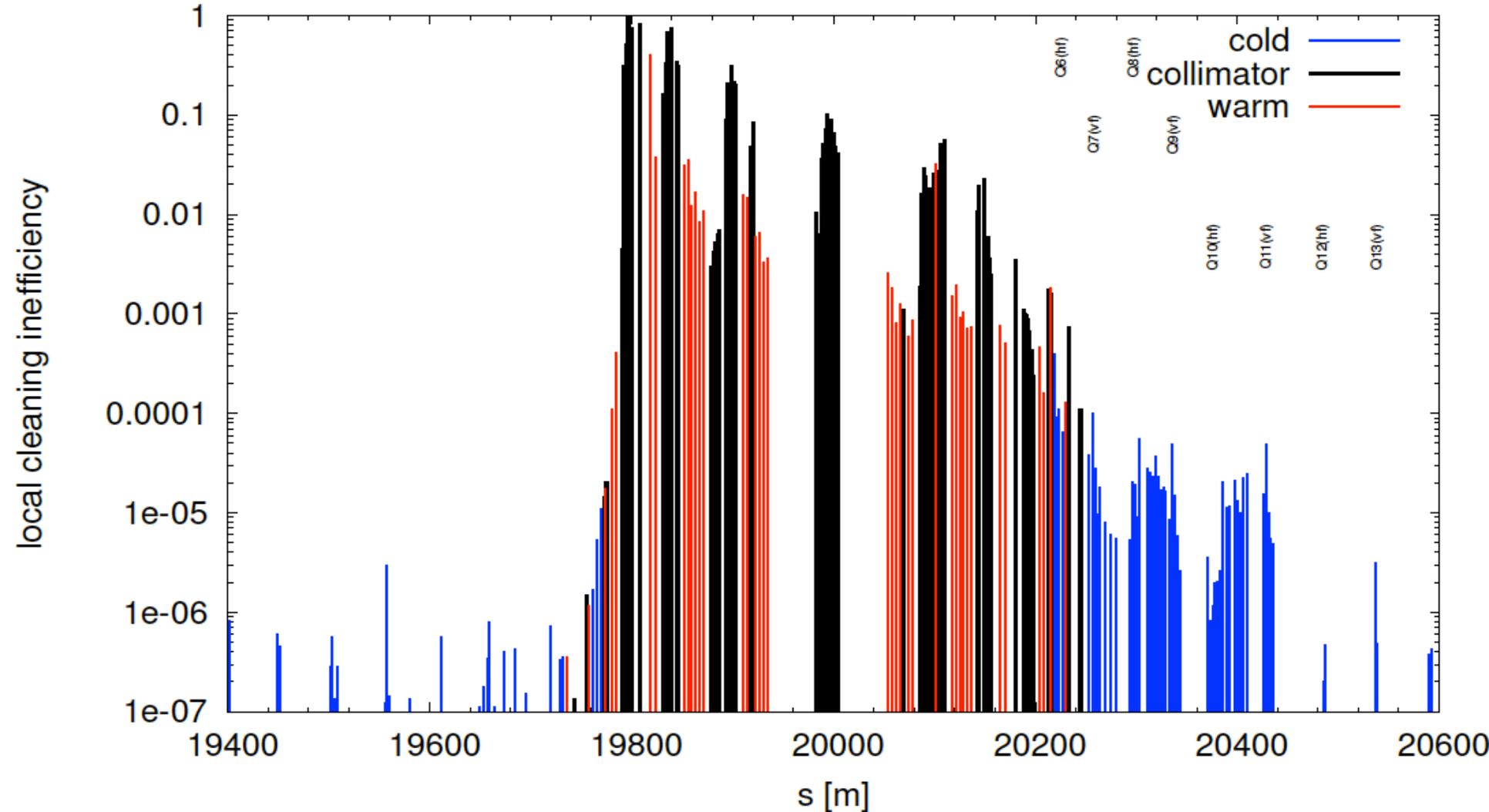
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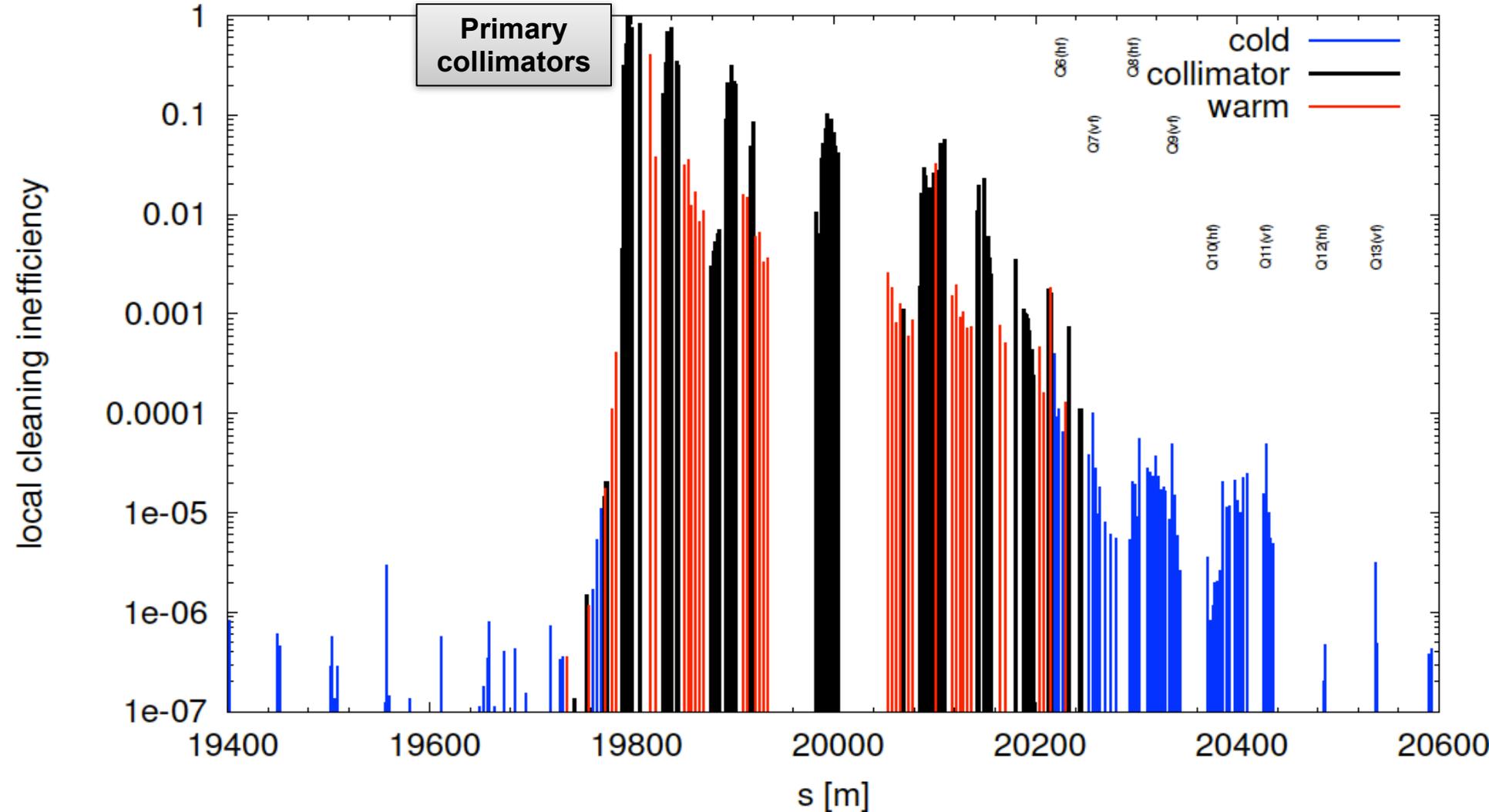
Collimation System Qualification

betatron losses B1 4000GeV hor norm IR7 (2012.04.02, 23:20:09)



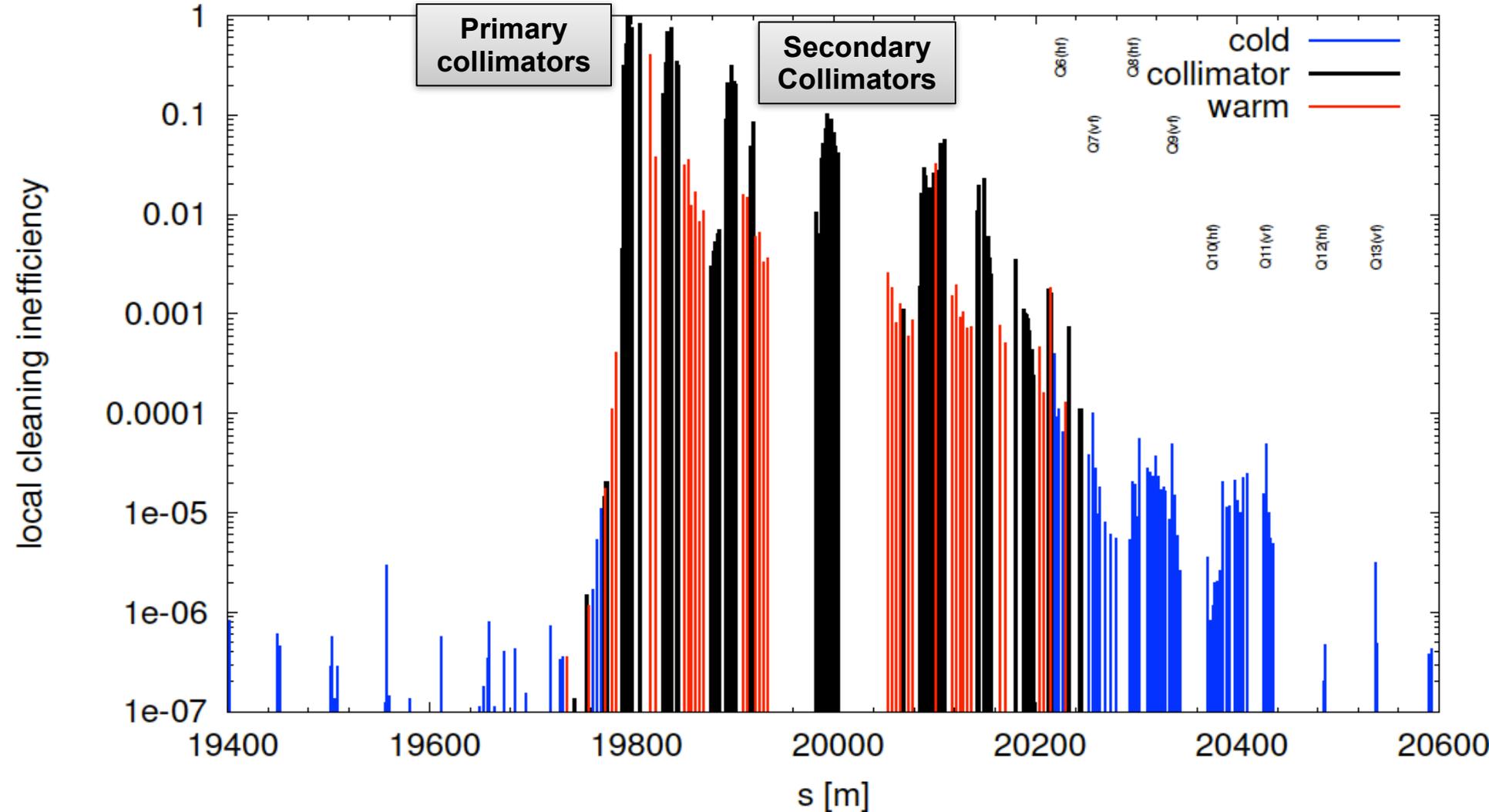
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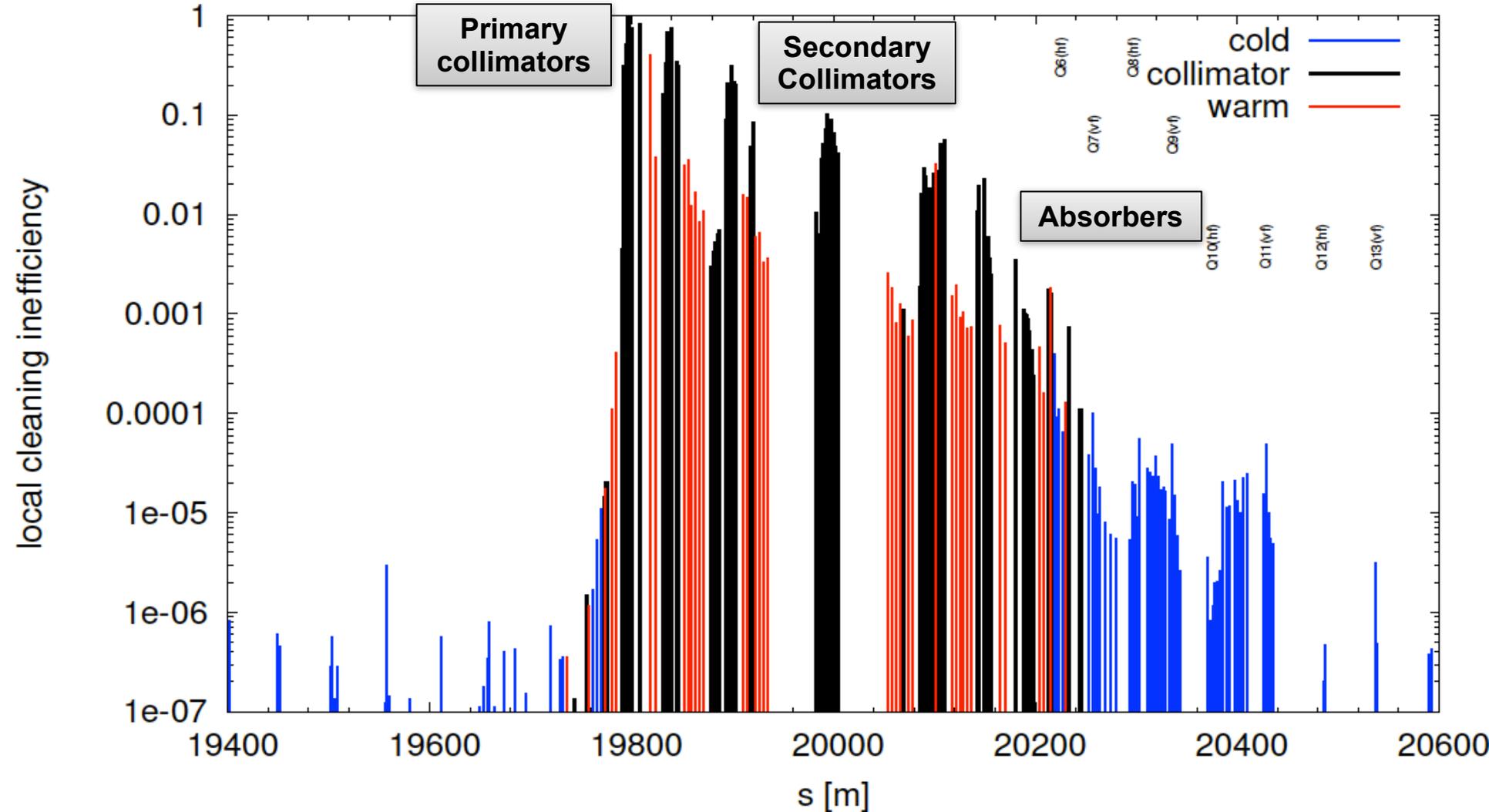
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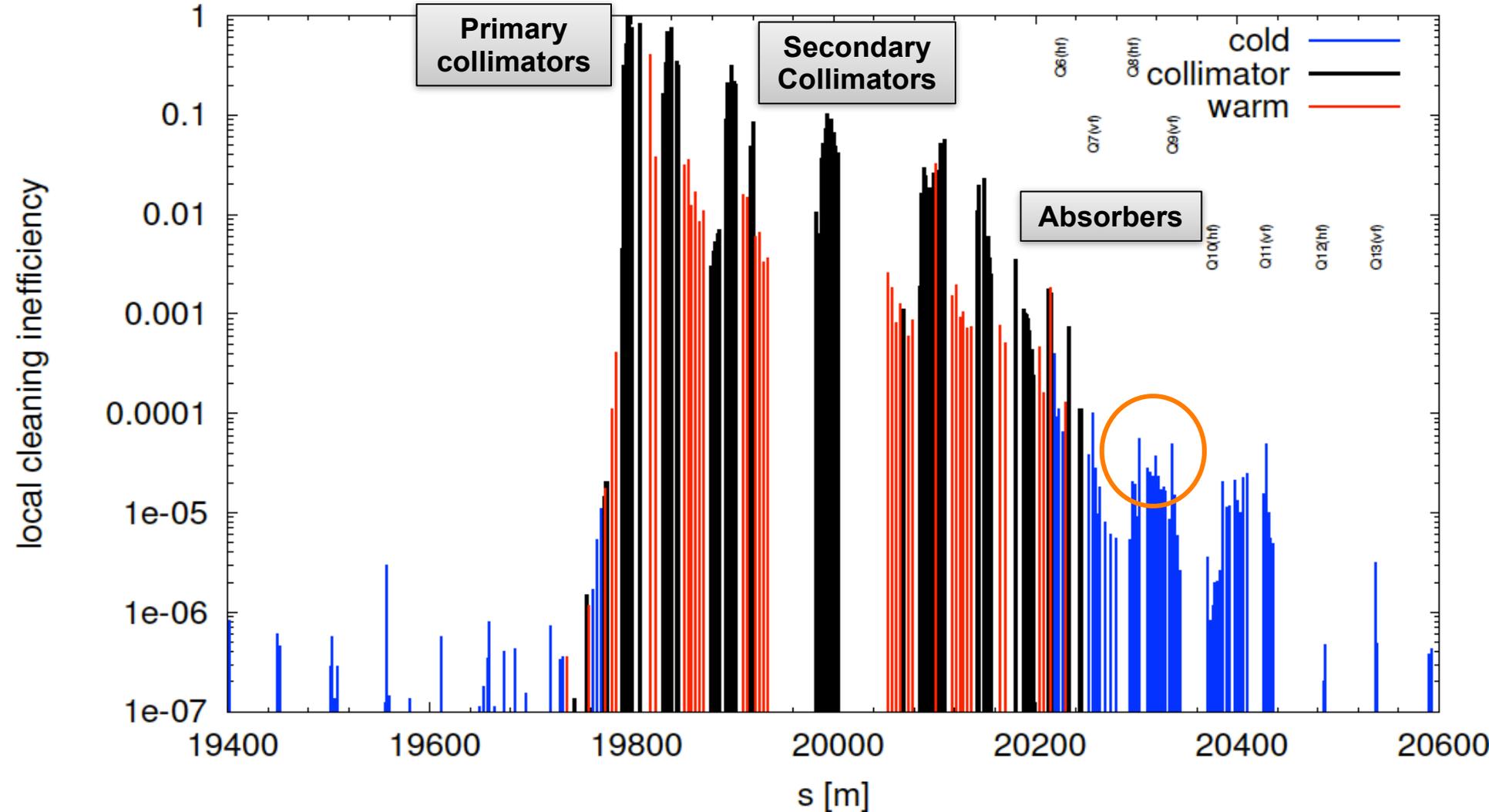
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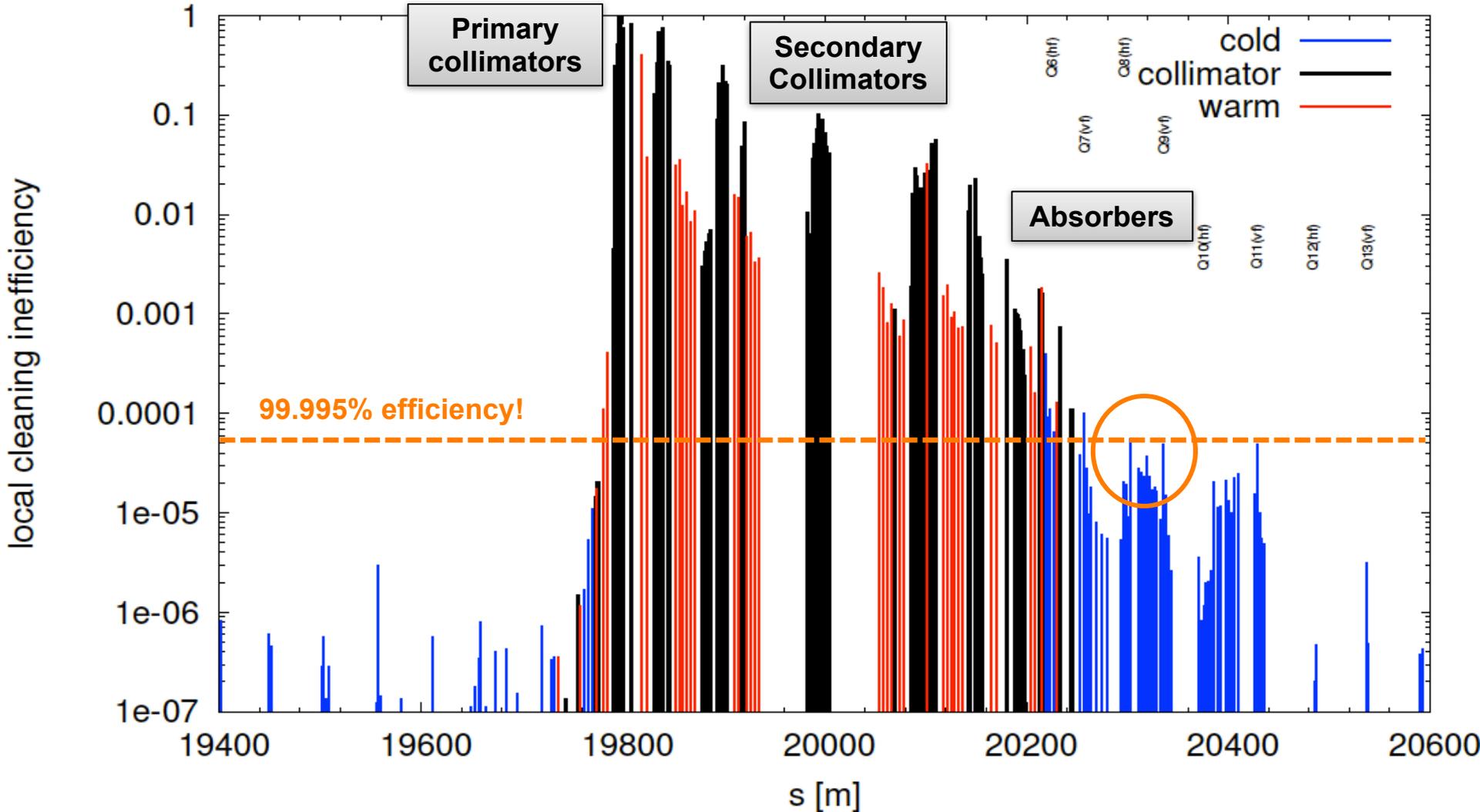
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