CARE-HHH-APD BEAM’07 workshop
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CERN, Geneva, Switzerland

Simulated and Measured Loss Maps with LHC collimators at the SPS and LHC

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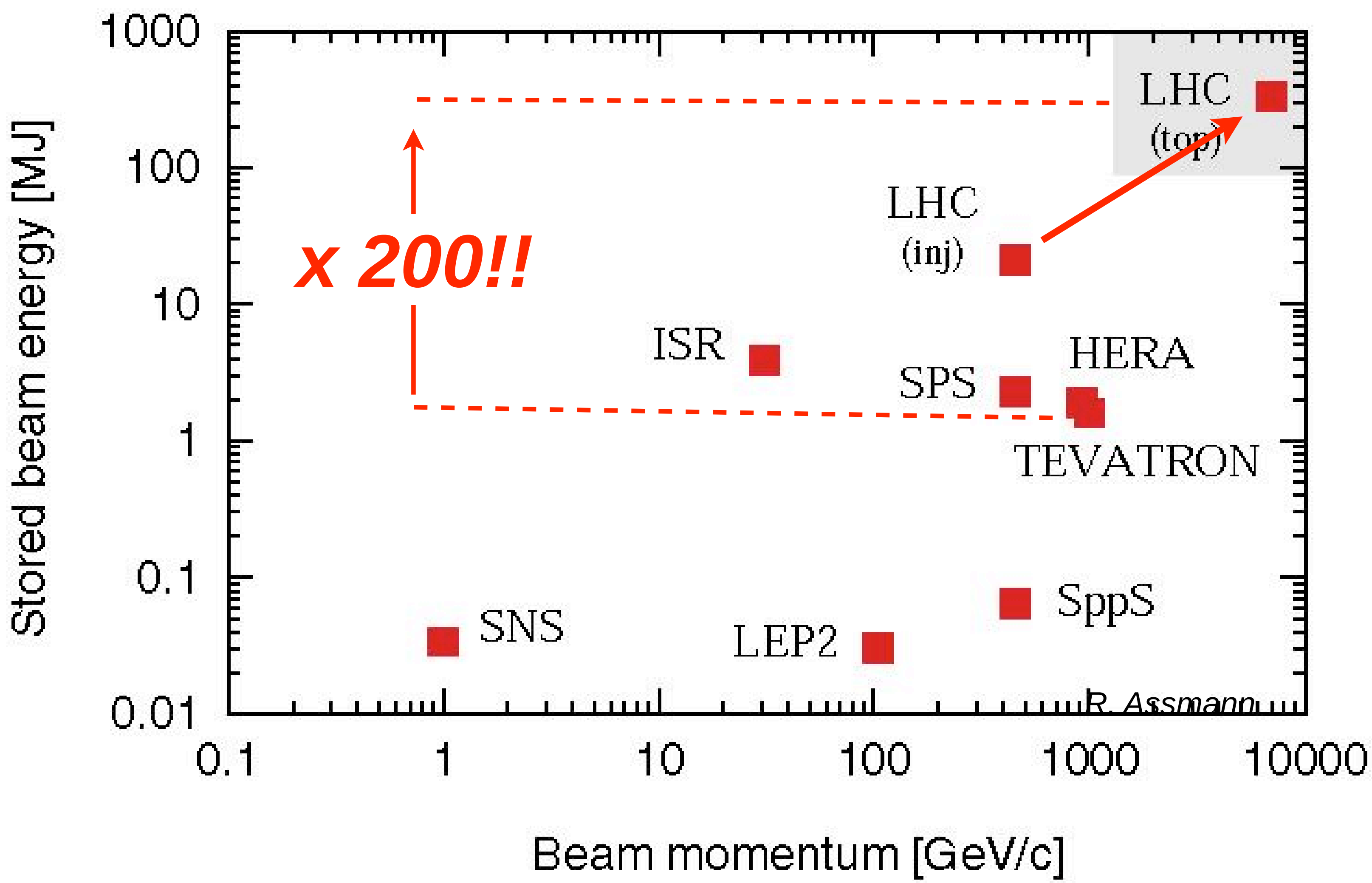
CERN, AB department

Outline of my talk

- **Introduction**
- **Loss studies for the LHC**
  - Simulation tools
  - Performance of a perfect system
  - Energy deposition studies
- **Imperfection models**
  - Jaw surface deformations
  - Aperture alignment errors
- **Loss studies at the SPS**
  - Experimental layout
  - Simulated versus measured losses
- **Conclusions**

Introduction

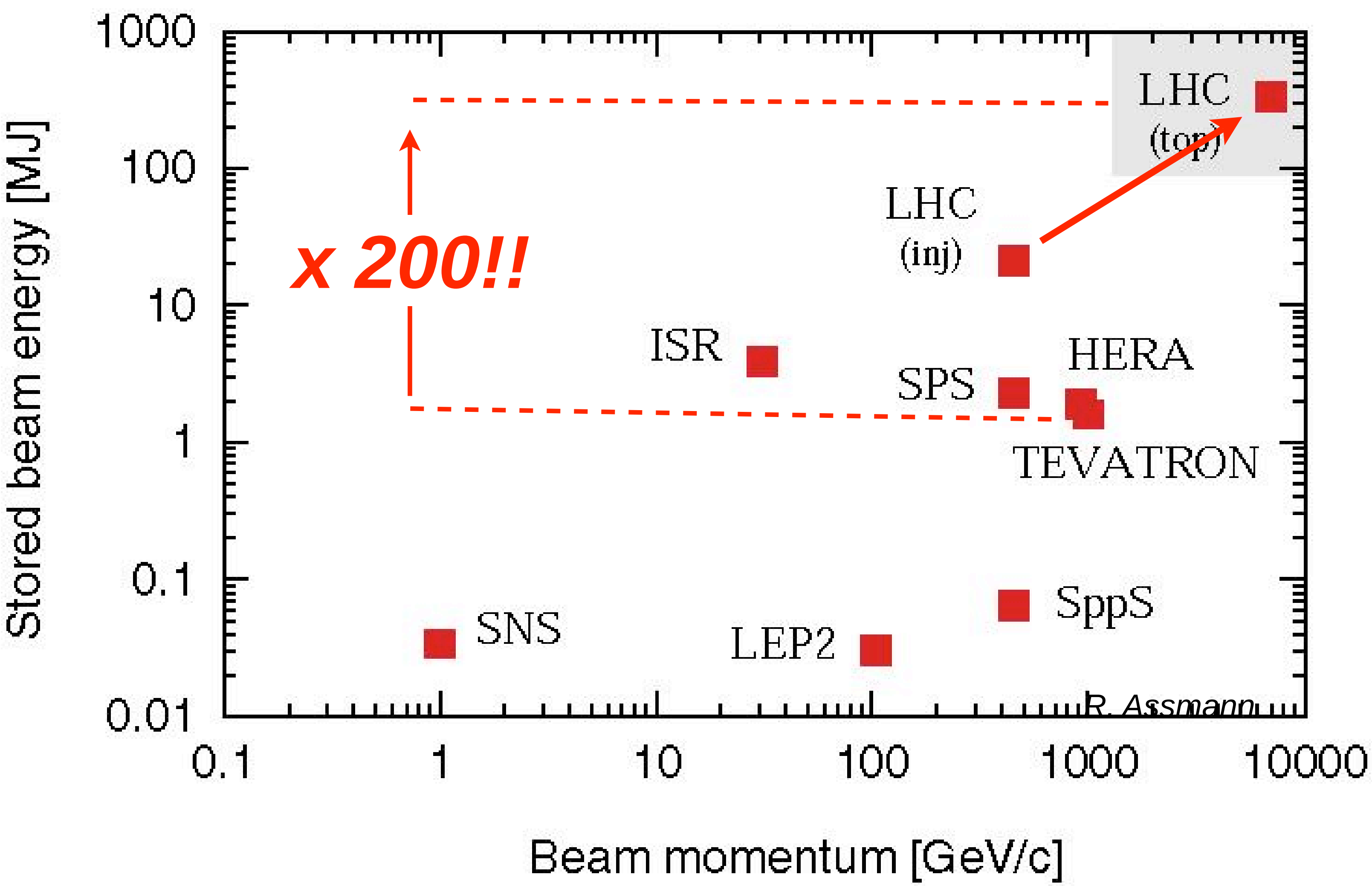


E_b = 7 TeV - I_b = 3.4x10^{14}

Stored energy	**~ 2 x 360 MJ**
Quench limit	~ 10 mJ / cm^3
Damage (metal)	~ 50 kJ / mm^2

- → *Control losses 1000 time better than the state-of-the-art!*
- → *Need collimation at all machine states: injection, ramp, squeeze, physics*
- → *Important role of collimation system for machine protection*

Introduction



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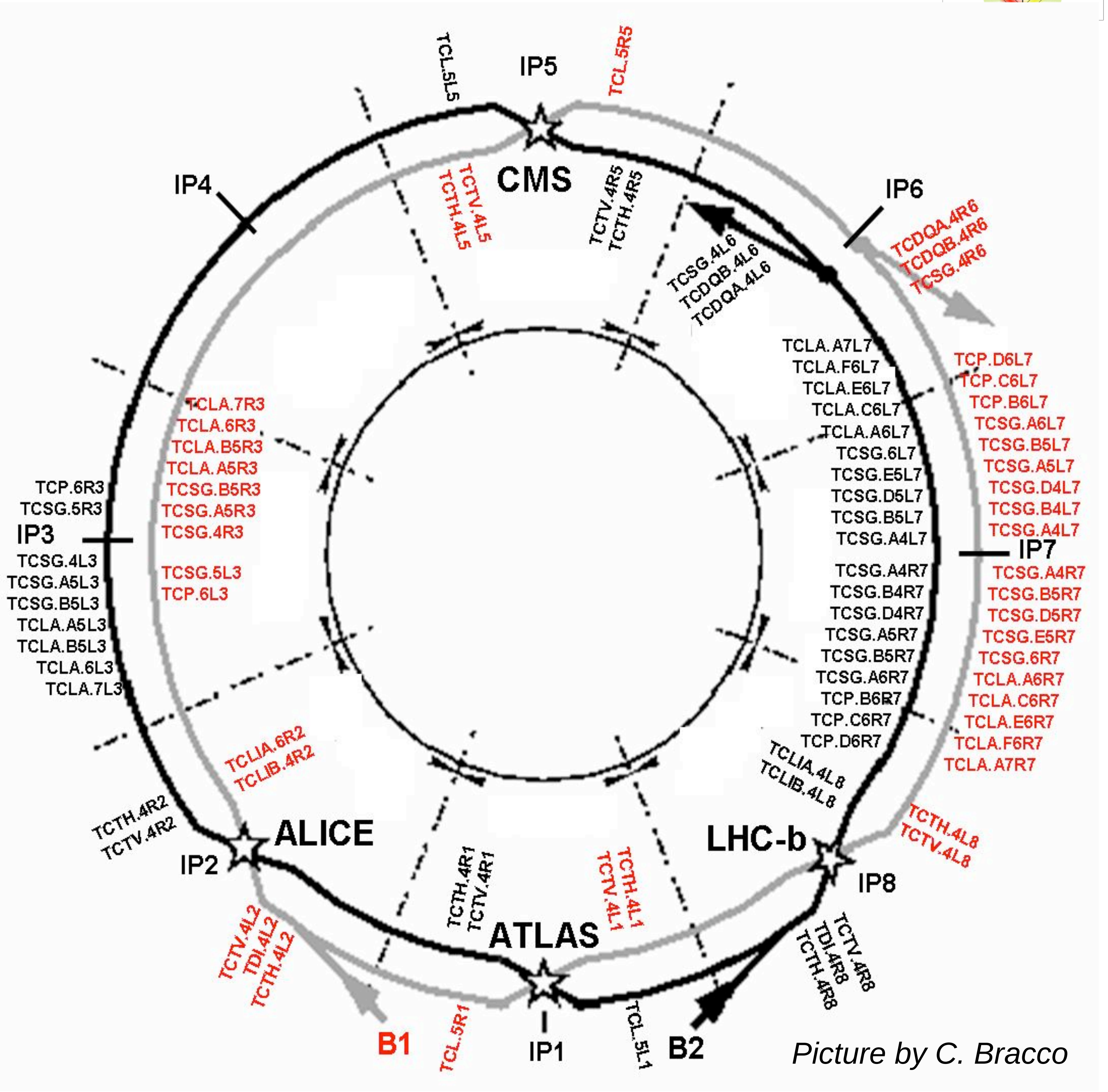
LHC enters in a ***new territory*** for handling ultra-intense beams in a super-conducting environment!

Correspondingly, we need appropriate tools to understand the system performance!

- *Control losses 1000 time better than the state-of-the-art!*
- *Need collimation at all machine states: injection, ramp, squeeze, physics*
- *Important role of collimation system for machine protection*

The Phase I LHC collimation system



Picture by C. Bracco

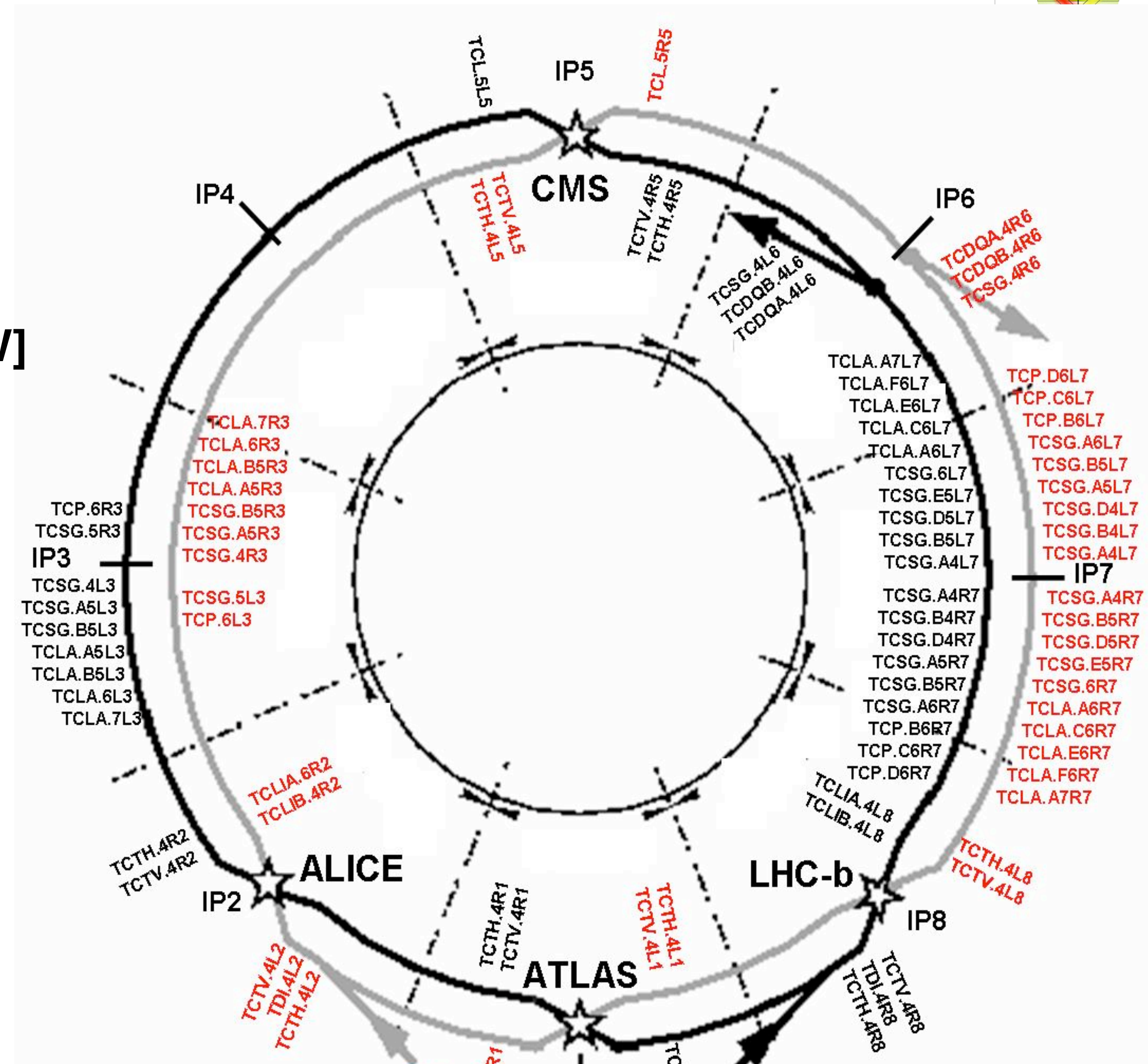
The Phase I LHC collimation system

LHC Collimation Project

Two warm cleaning insertions

IR3: Momentum cleaning
- 1 primary (H) → TCP [C]
- 4 secondary (H,S) → TCS [C]
- 4 shower abs. (H,V) → TCLA [W]

IR7: Betatron cleaning
- 3 primary (H,V,S)
- 11 secondary (H,V,S)
- 5 shower abs. (H,V)
- 3 beam scrapers (H,V,S)



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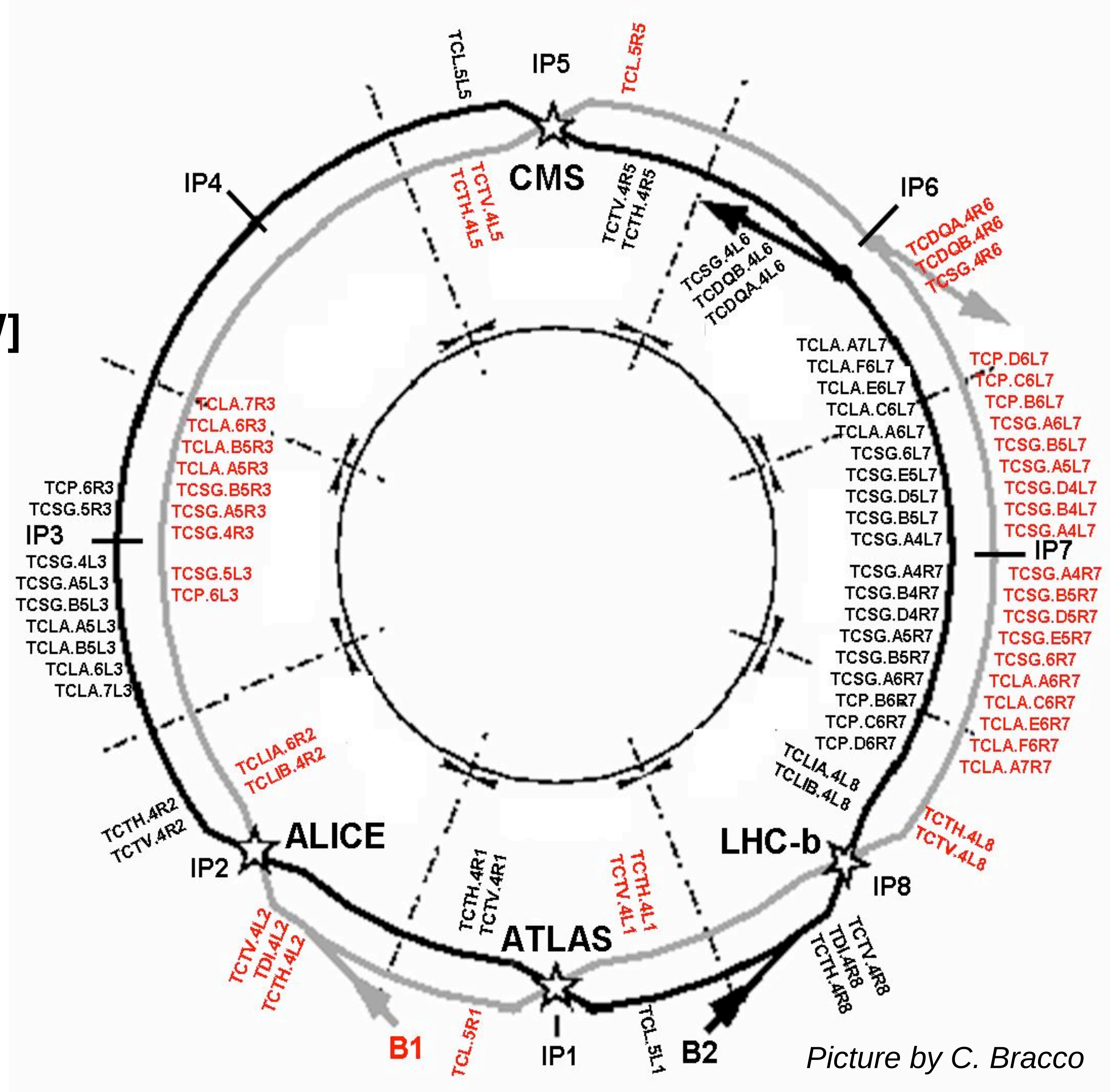
Local cleaning at triplets

- 8 tertiary (2 per IP)→ TCT [W]



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Multi-stage halo cleaning

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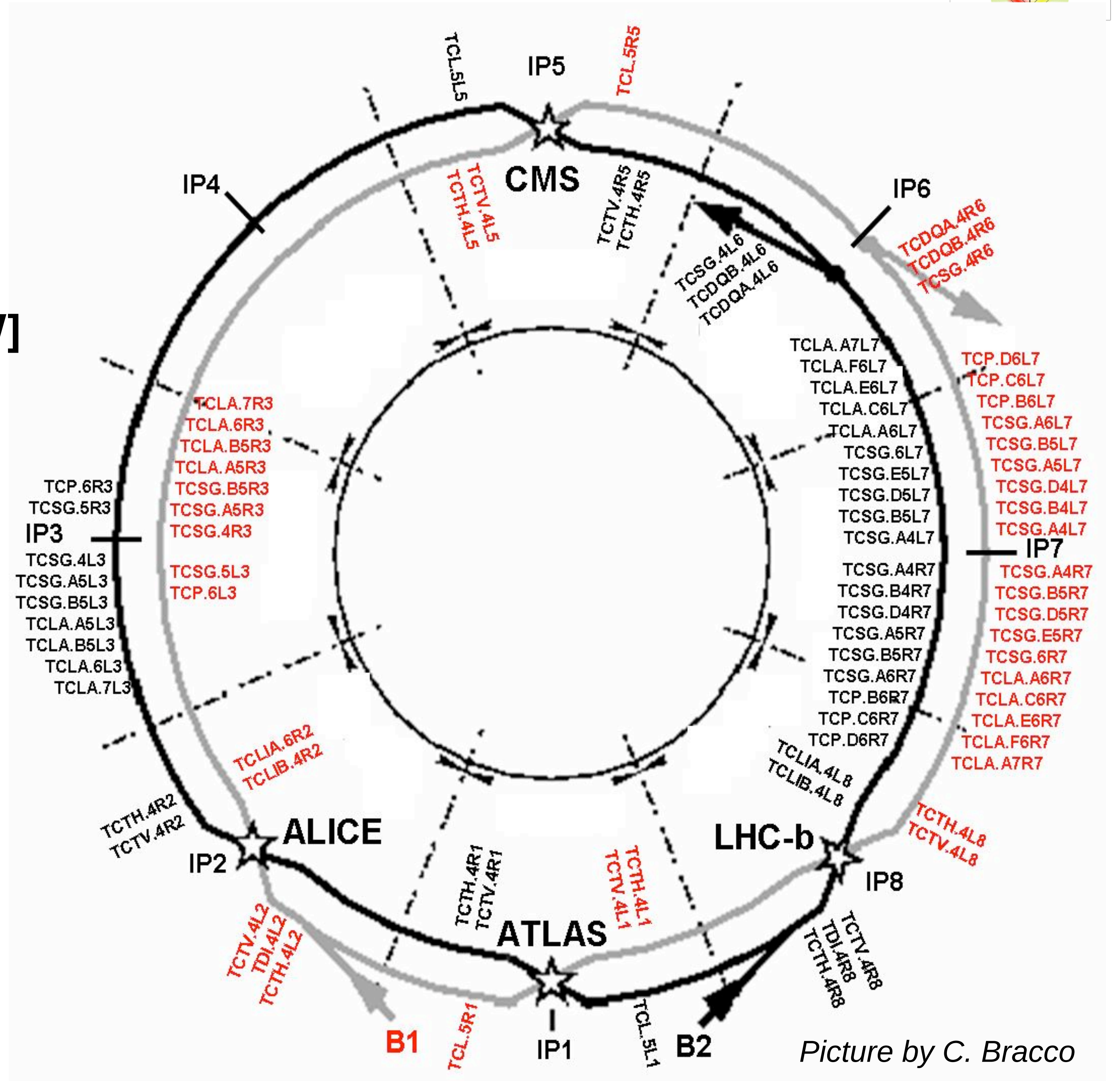

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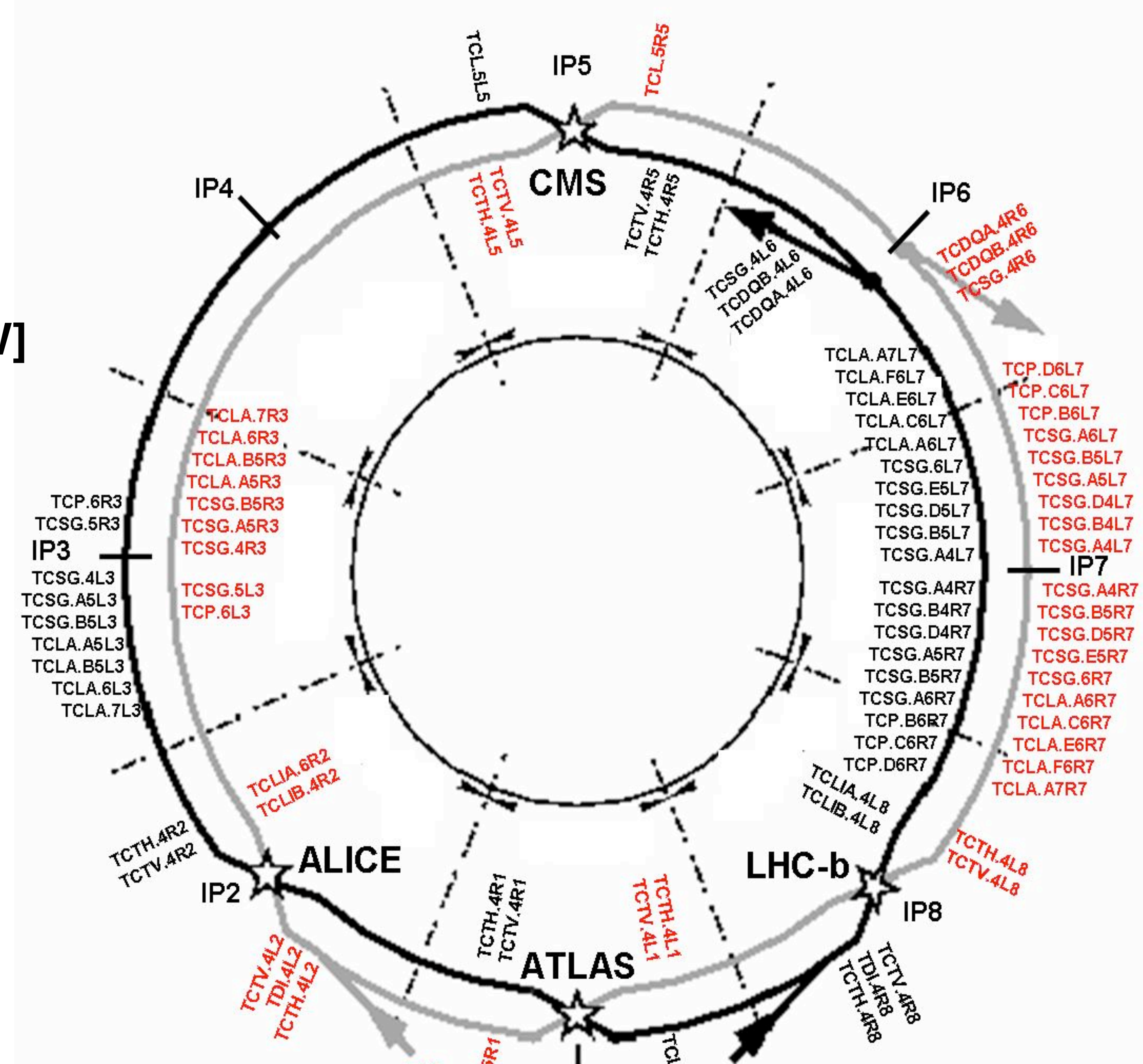

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Physics debris absorbers [Cu]

2 TCLP's (IP1/IP5)

Protection (injection/dump)

10 elements →TCLI/TCDQ [C]

Transfer lines

13 collimators → TCDI [C]

Passive absorbers for warm magnets

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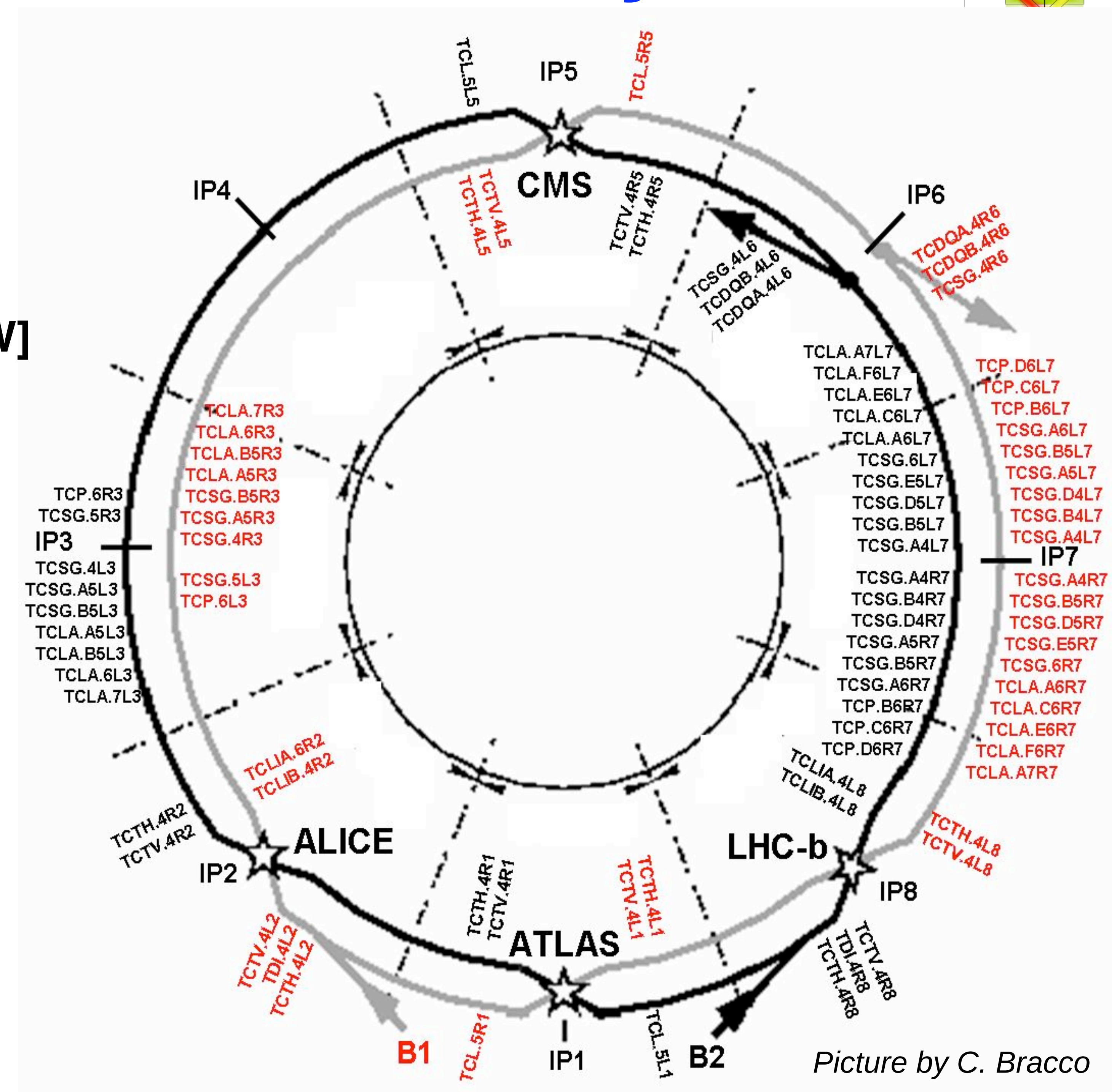
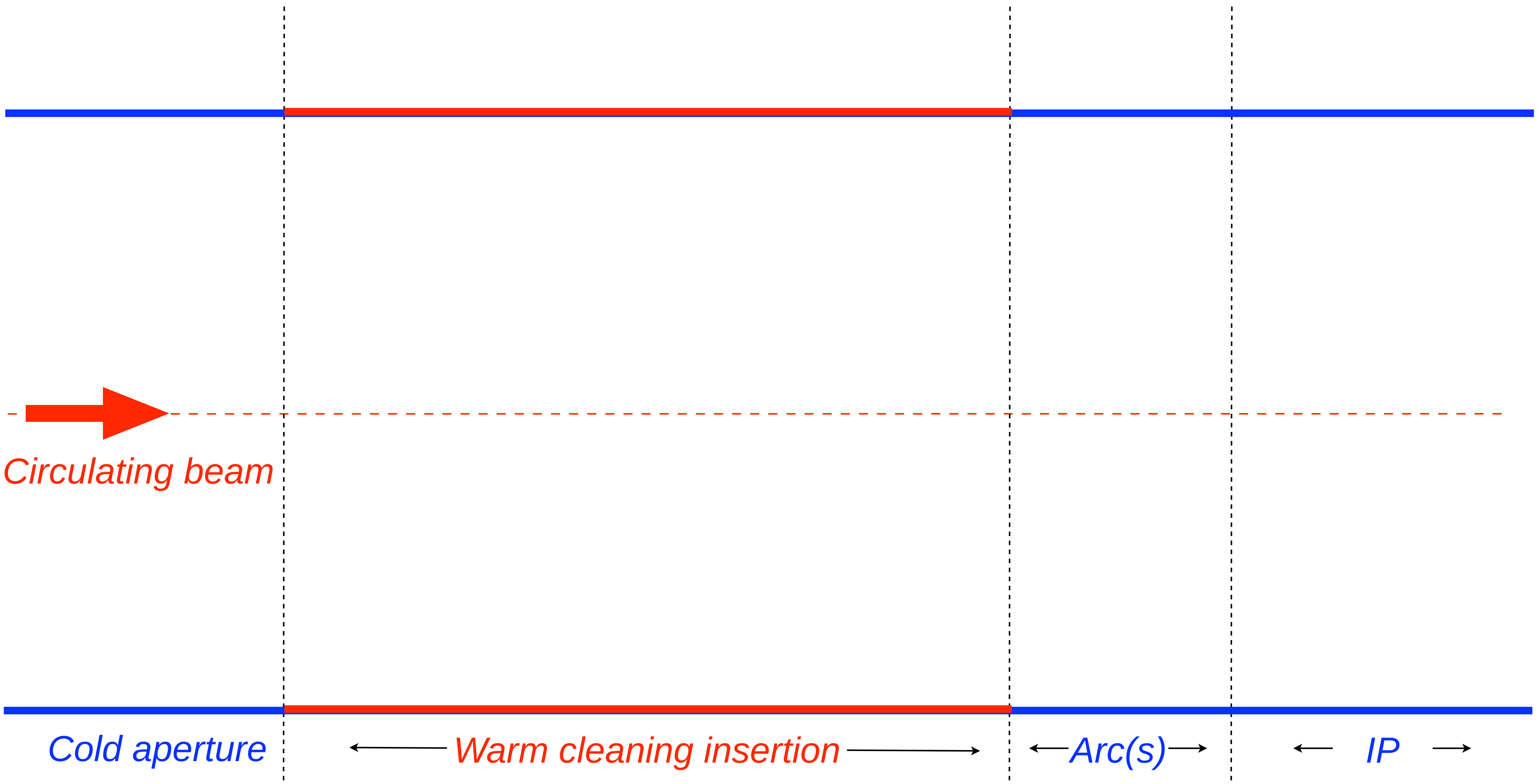


44 movable ring collimators per beam for the Phase I system!

Multi-stage collimation at the LHC

(An illustrative scheme)



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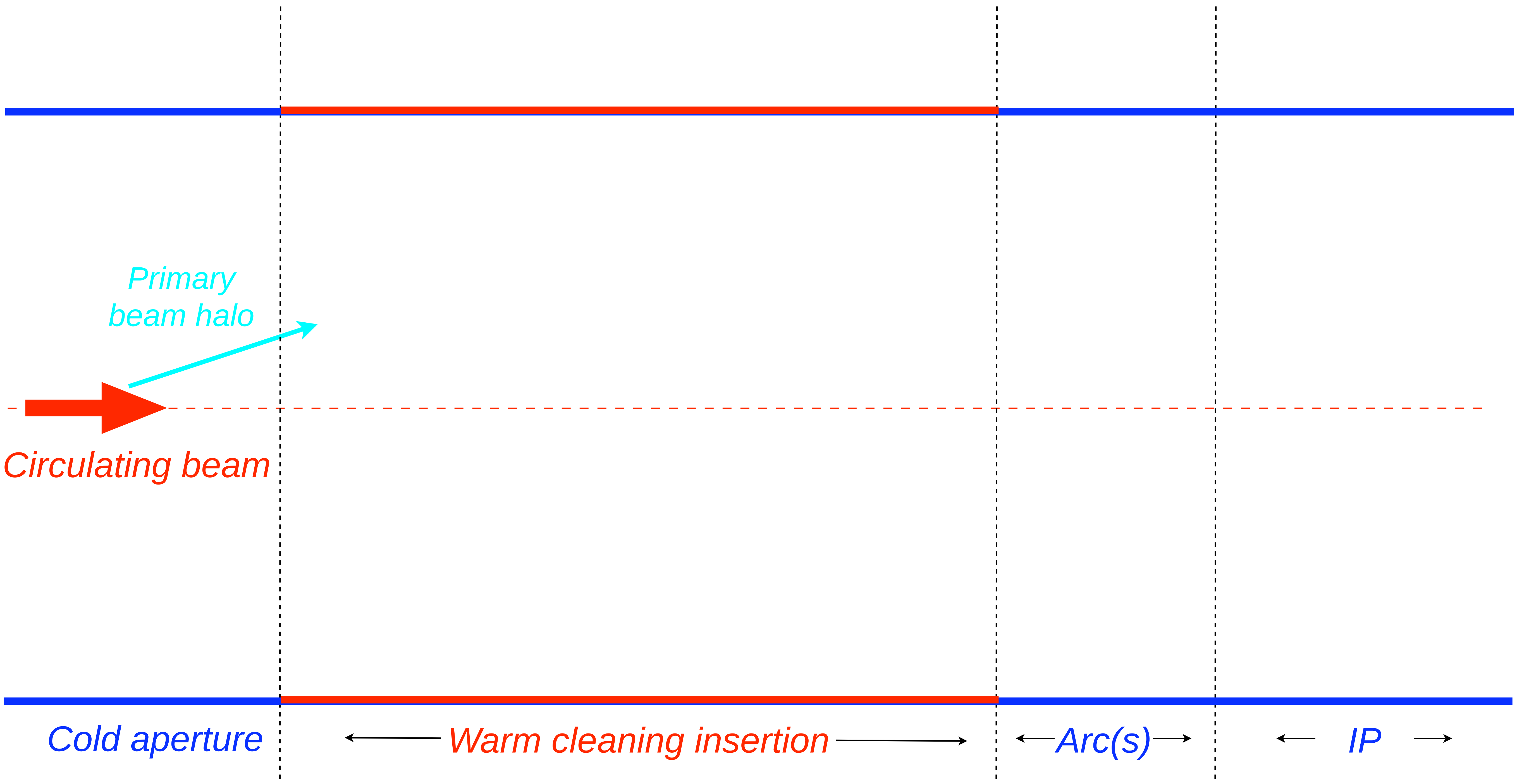

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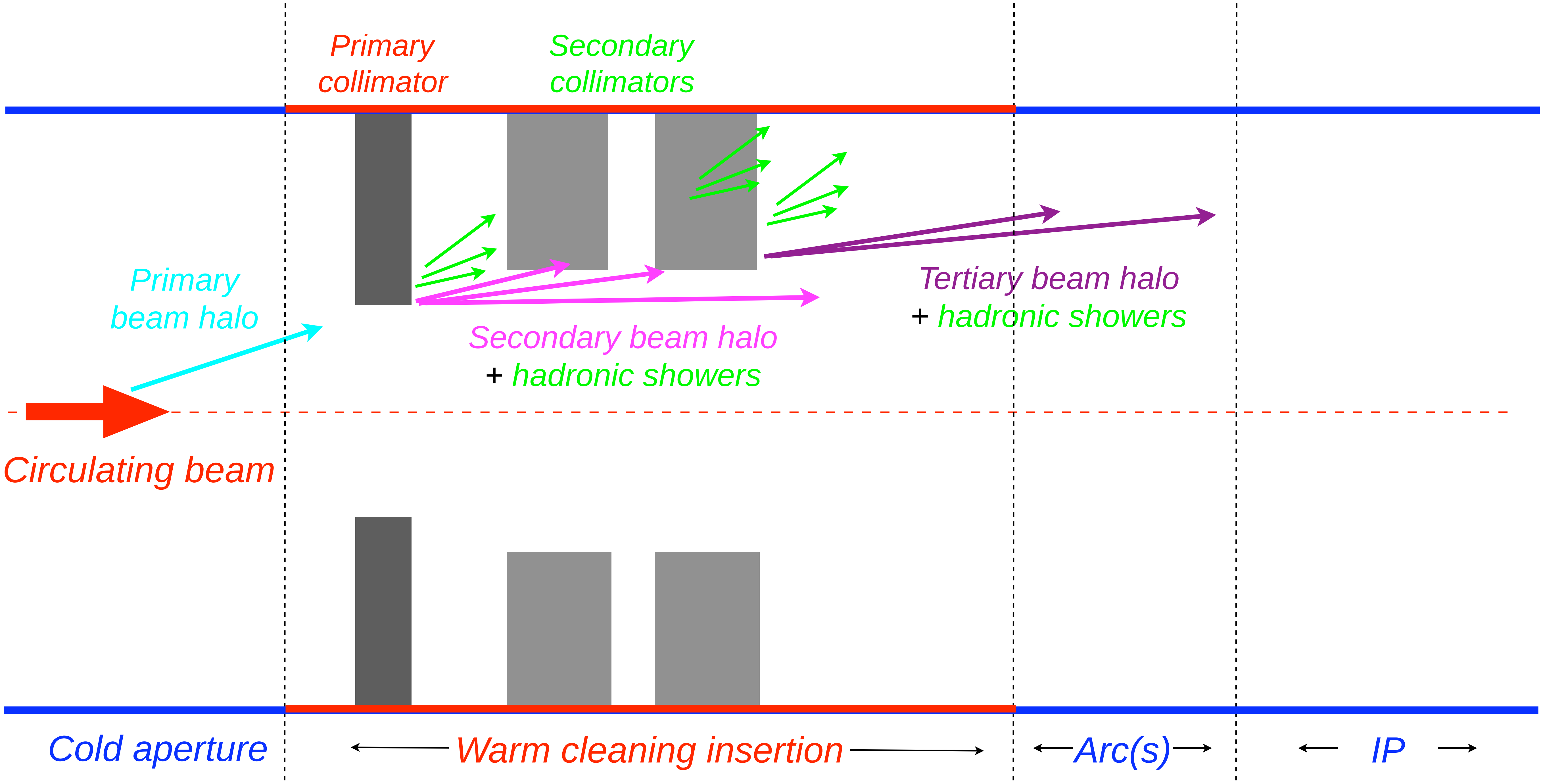

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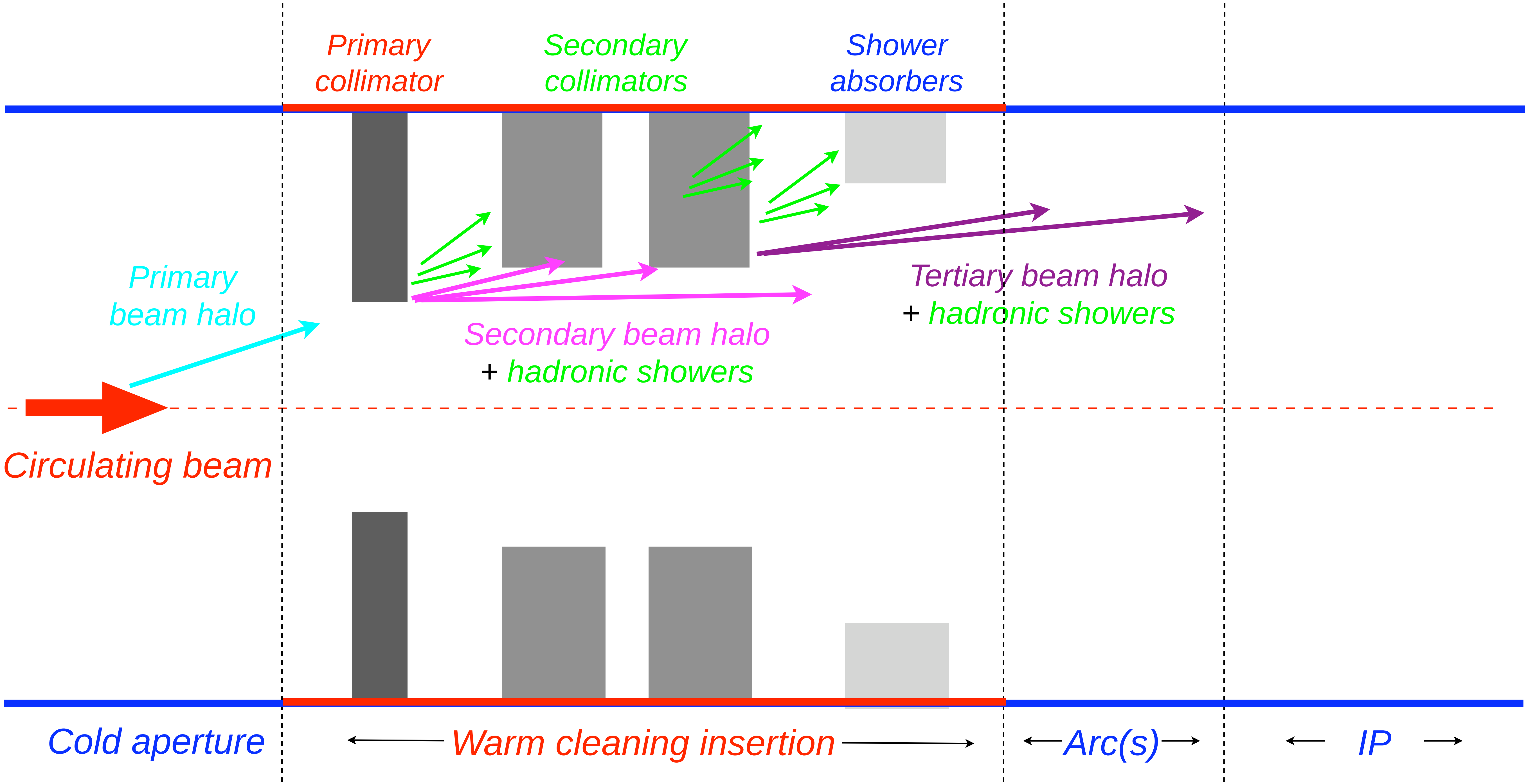

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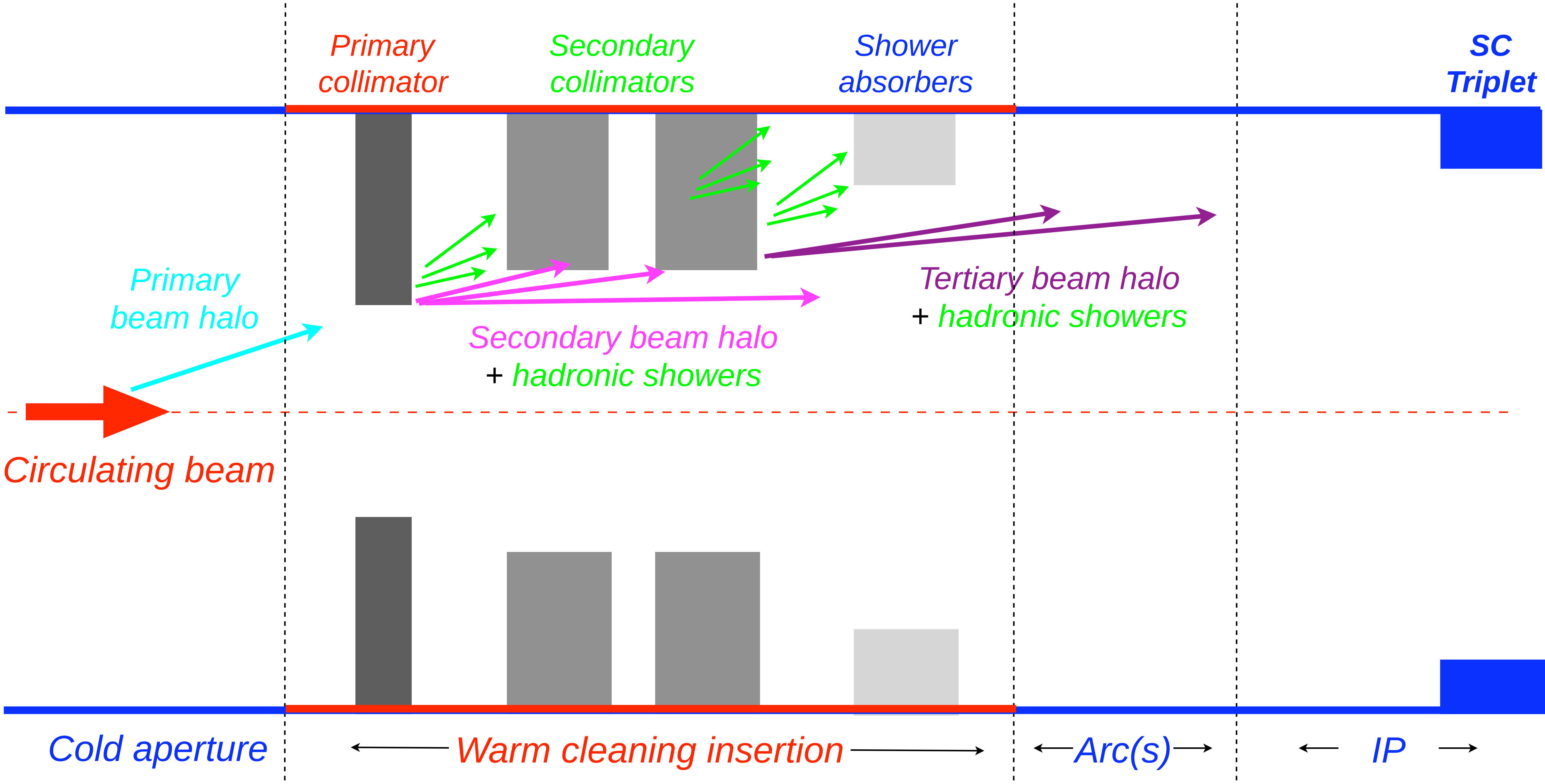

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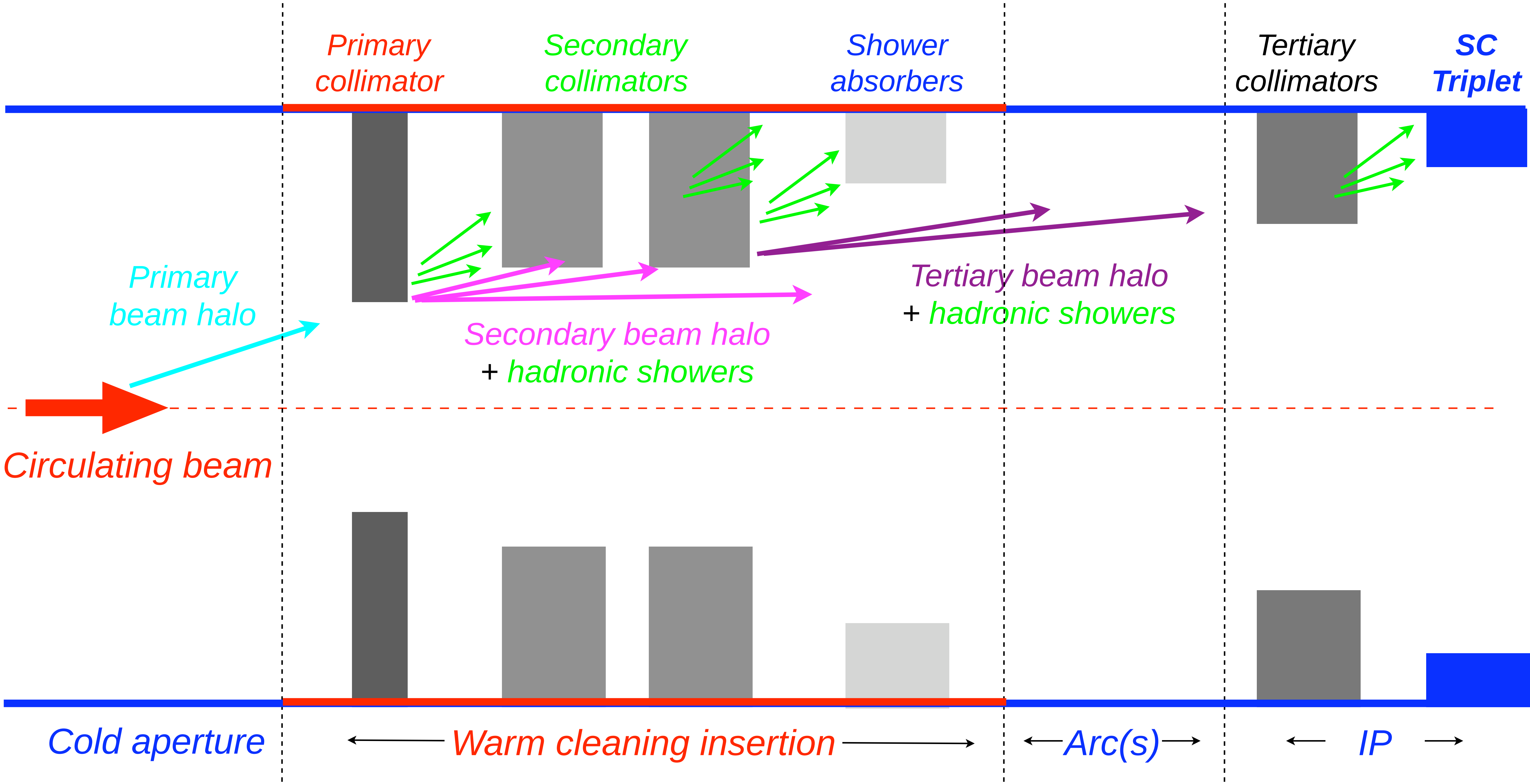

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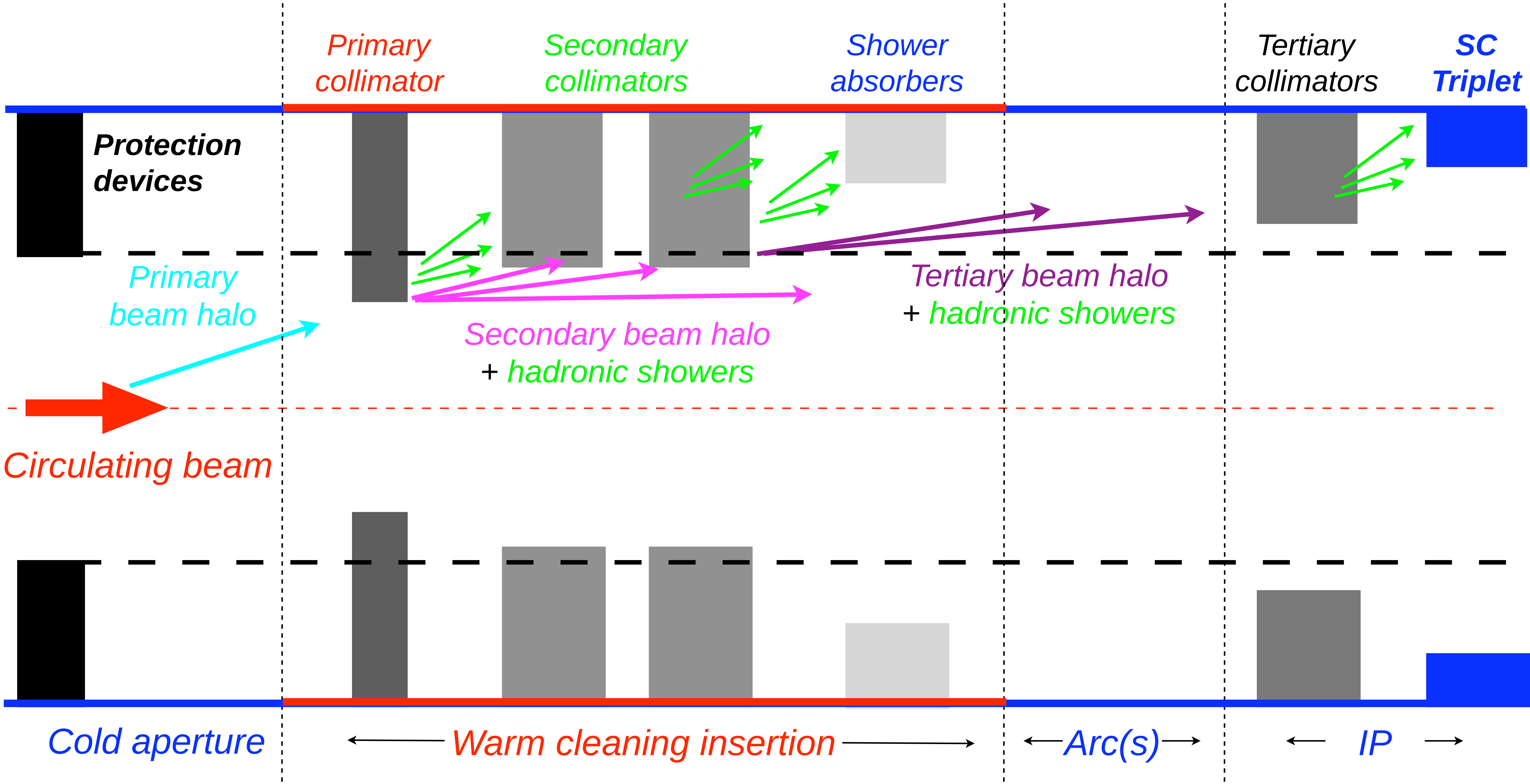

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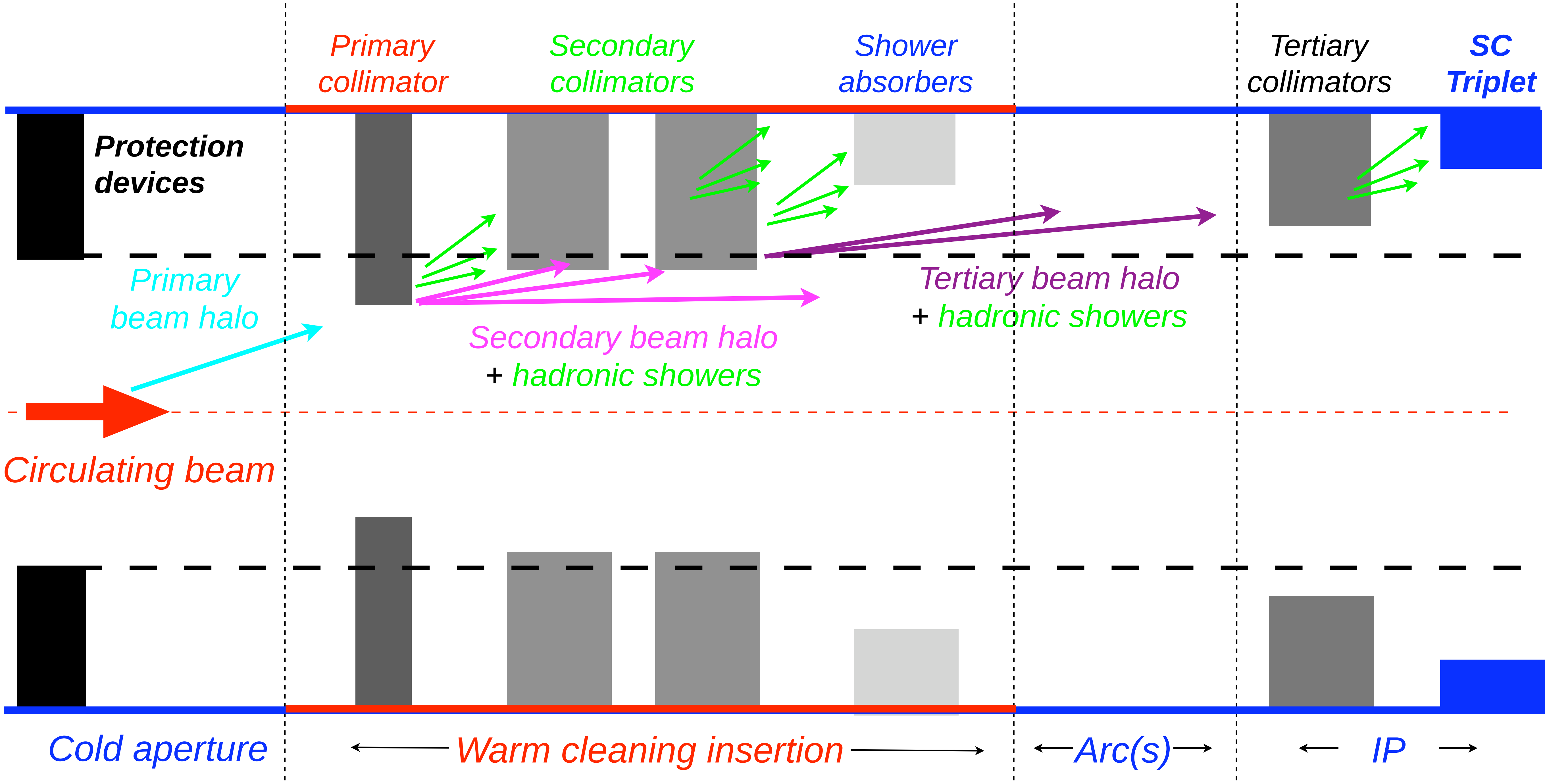

All cleaning + protection devices must be included in simulations!

Collimation needed from injection to collision!

Simulation tools for loss maps

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Accurate tracking of halo particles 6D dynamics, chromatic effects, δp/p, high order field errors, ...	**`SixTrack`**

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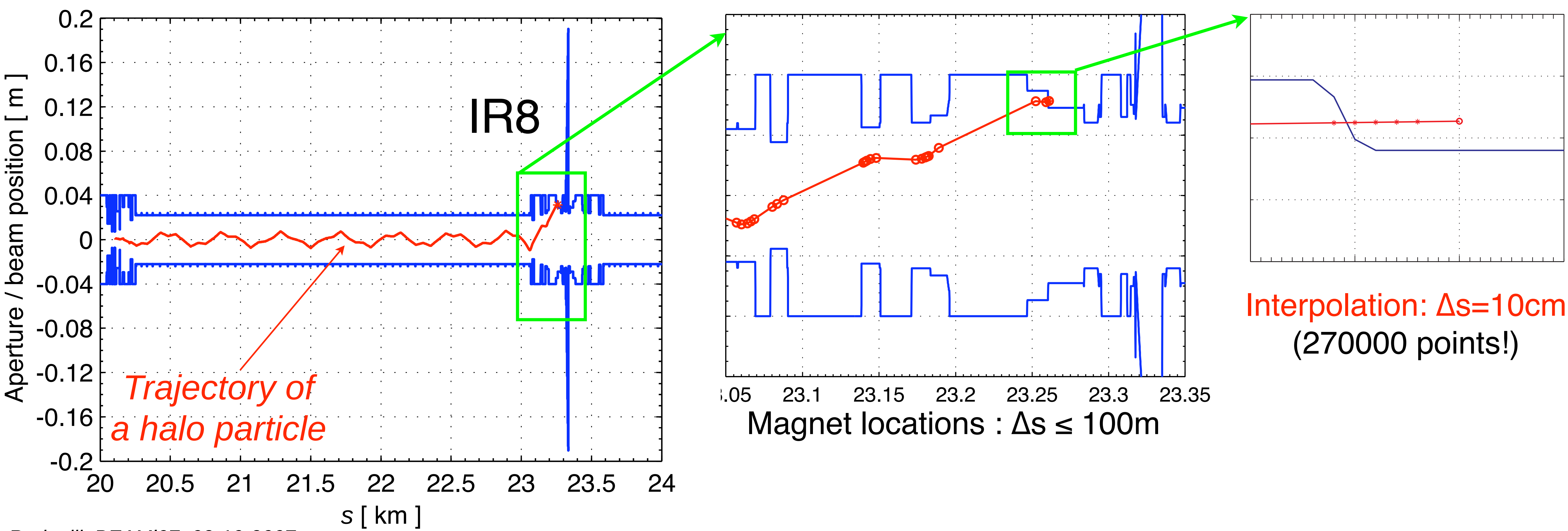
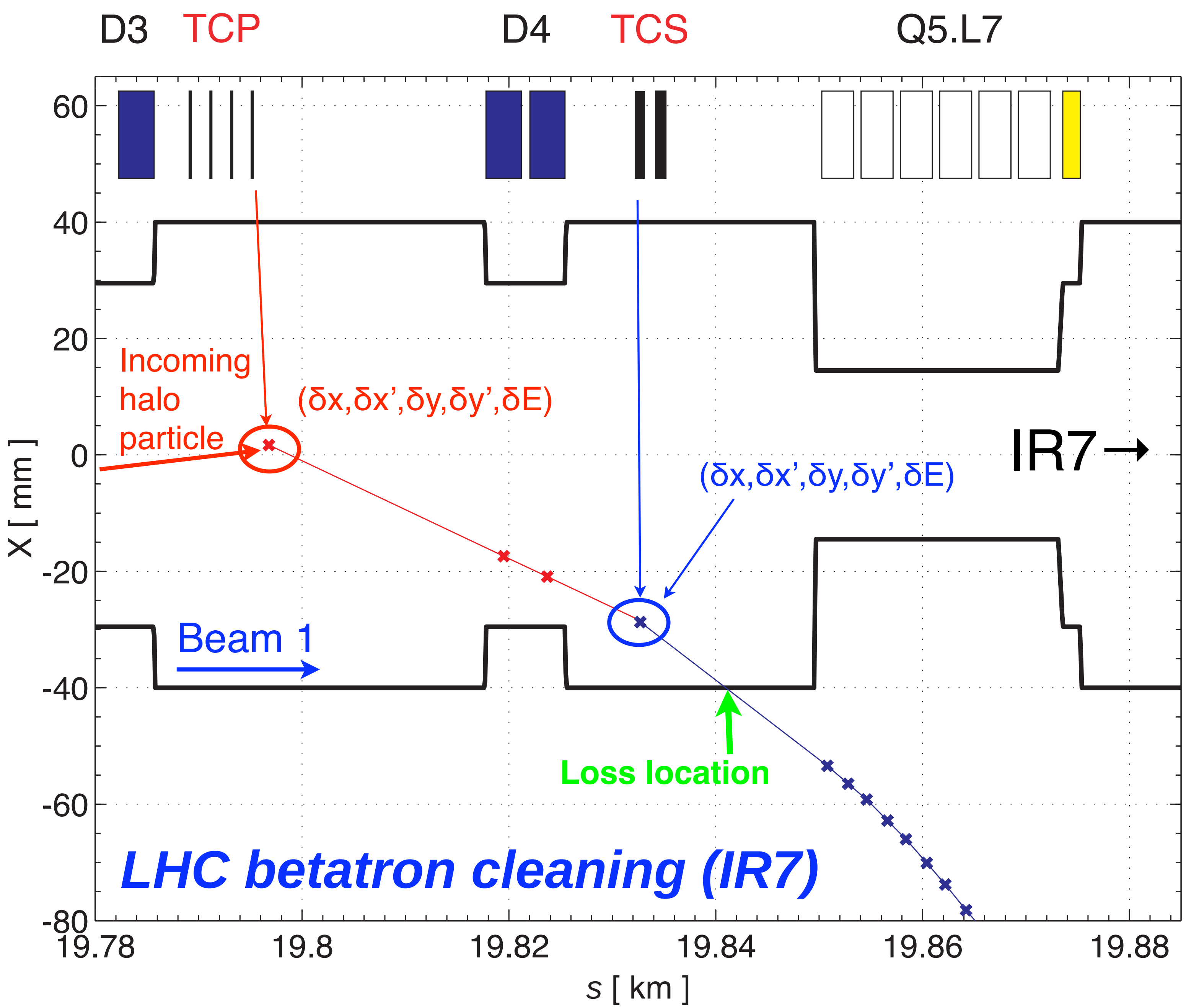


Example - one particle's trajectory



- *Scattering routine called within tracking at each collimator*
- *If particle touches jaw, calculate absorption, offsets, scattering angles and energy error*
- *Trajectories of halo particles saved for off-line aperture analysis (Δs < 10 cm)*

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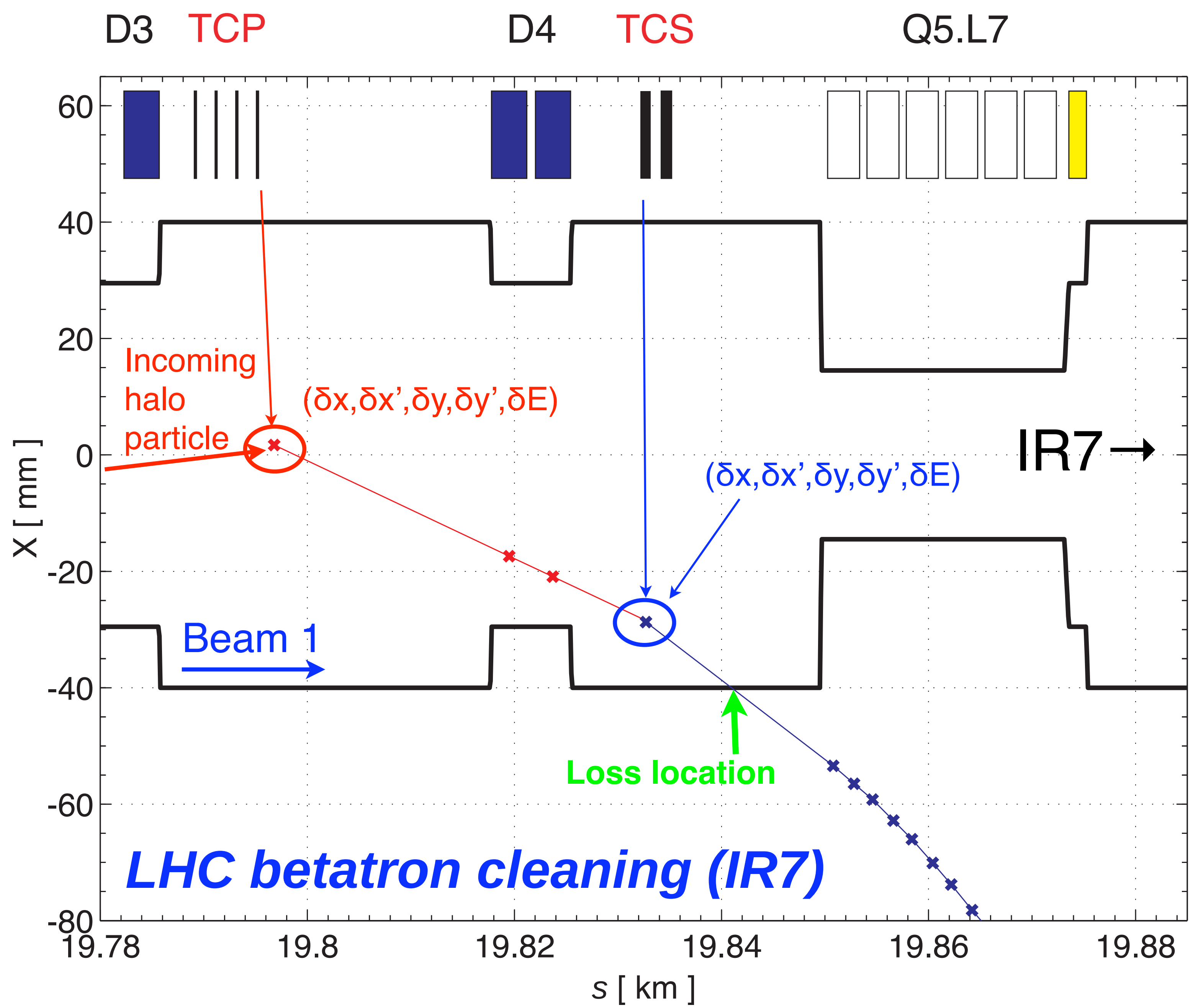

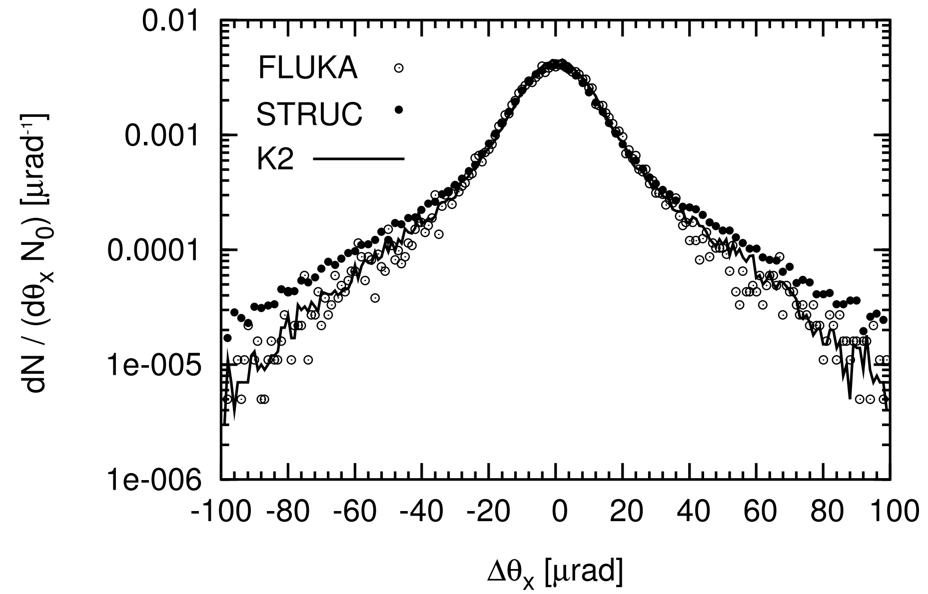

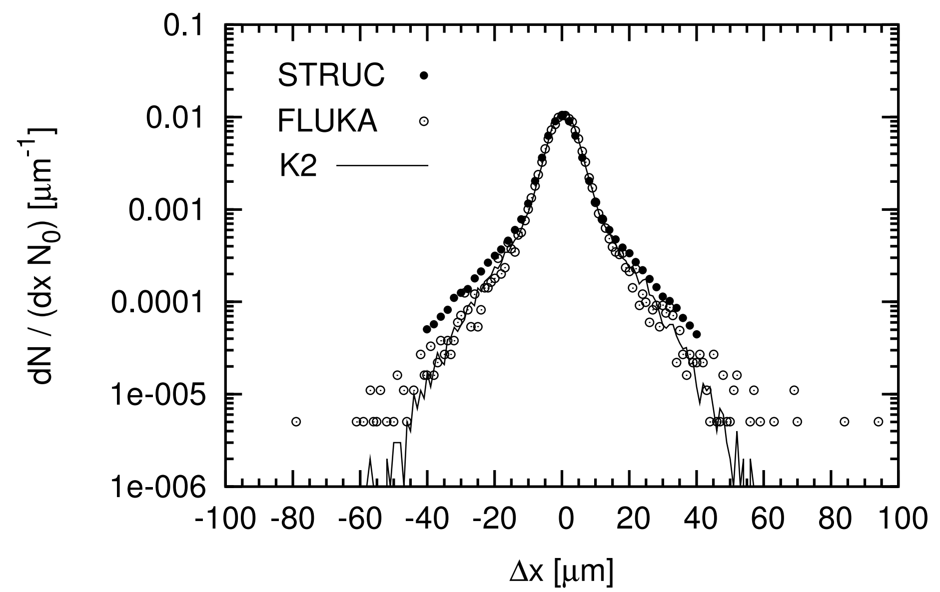

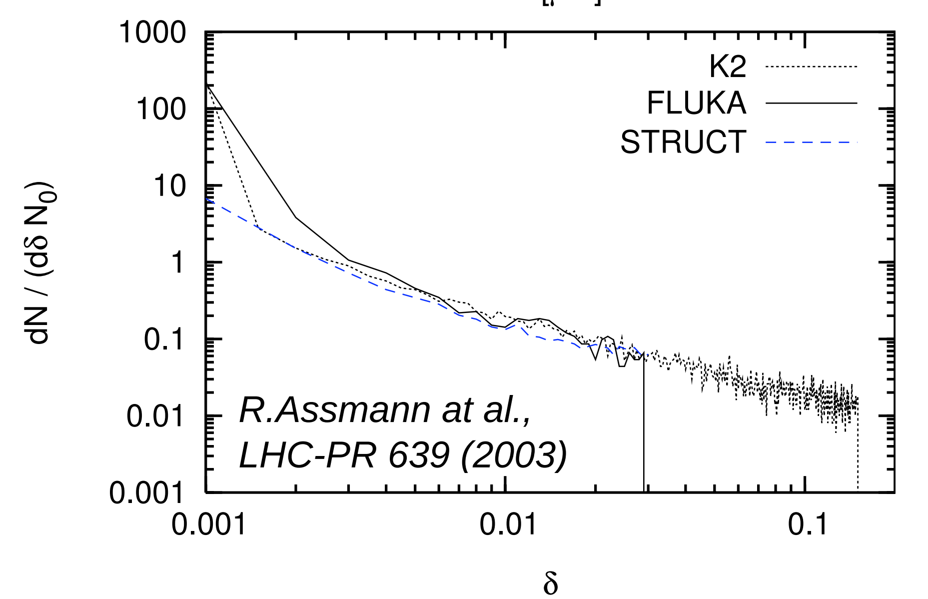

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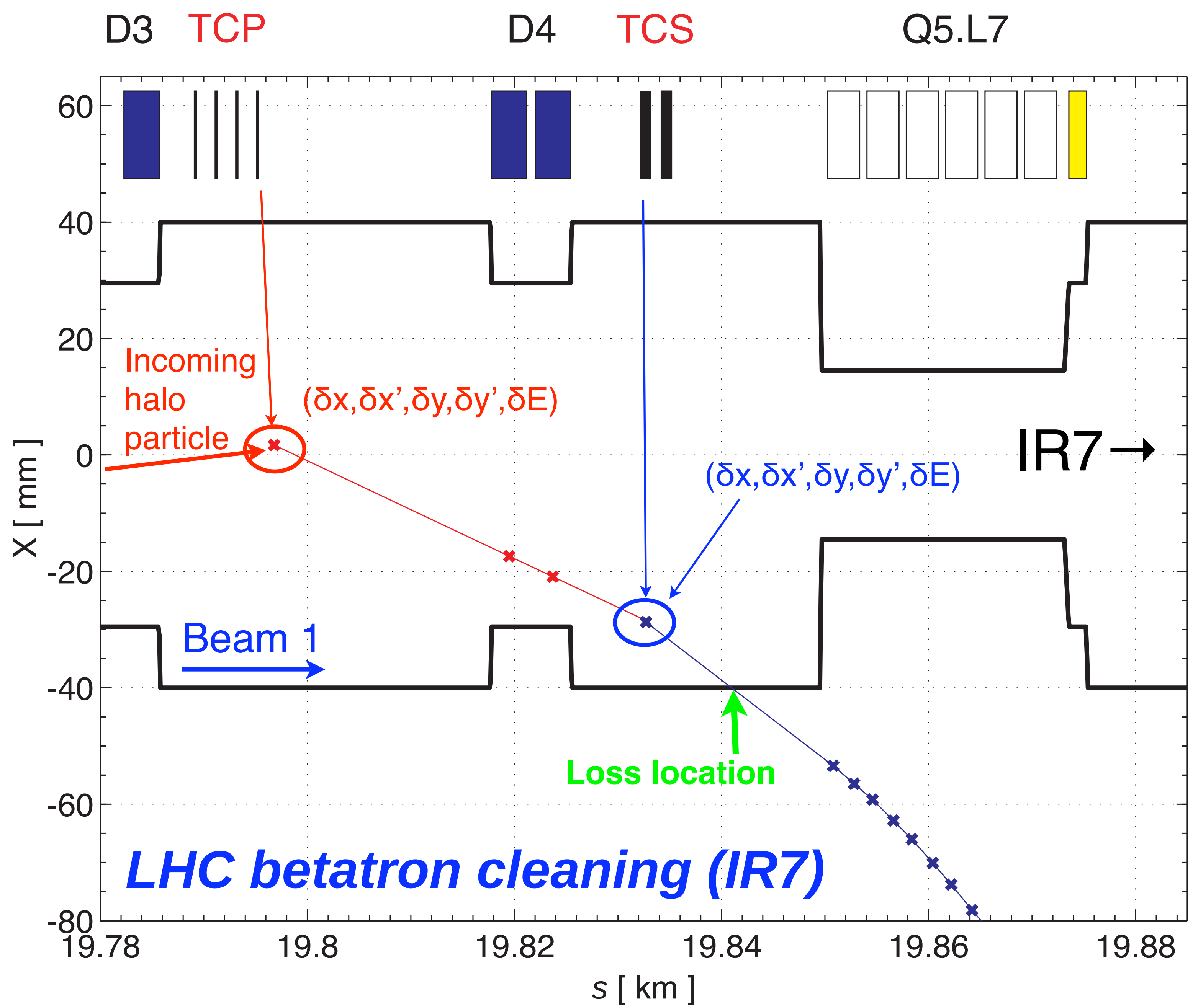
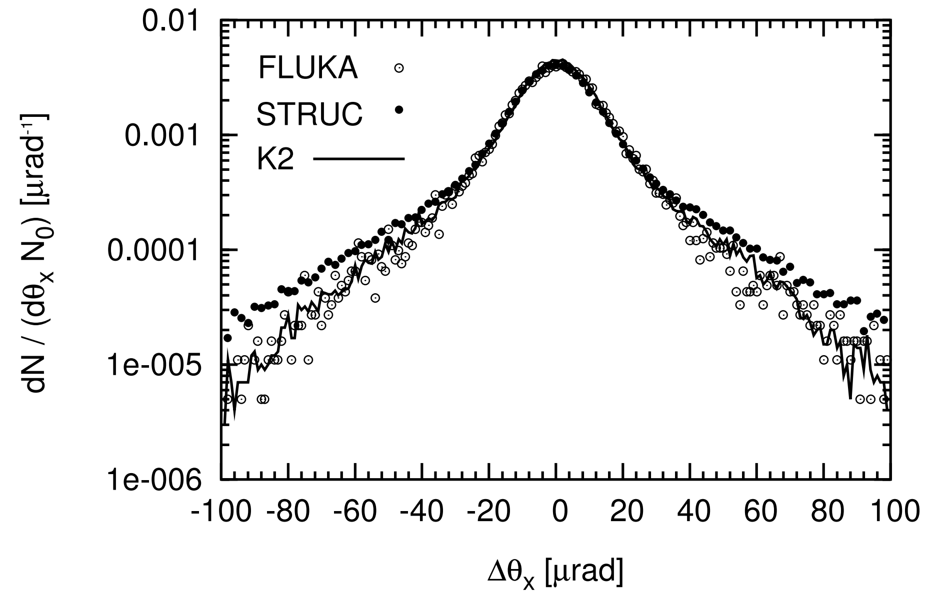
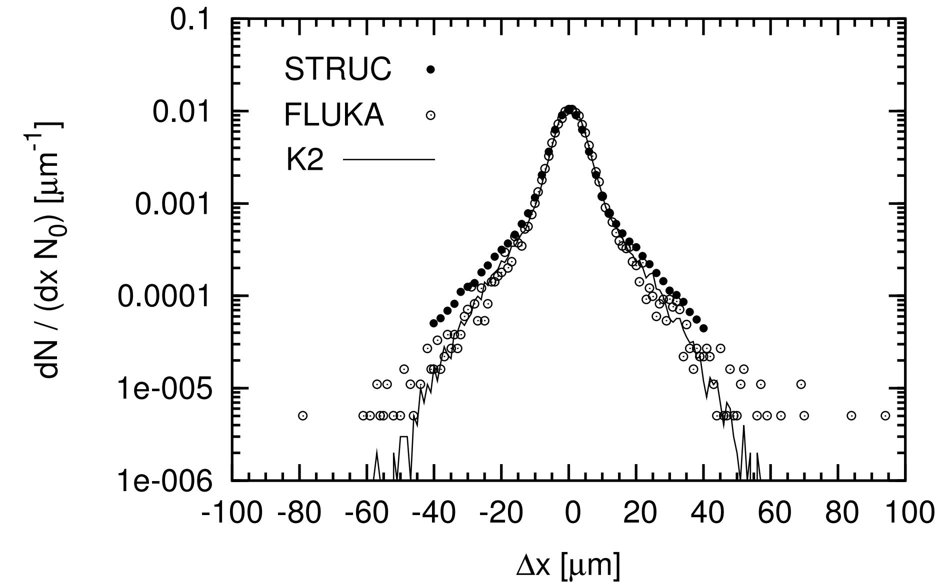
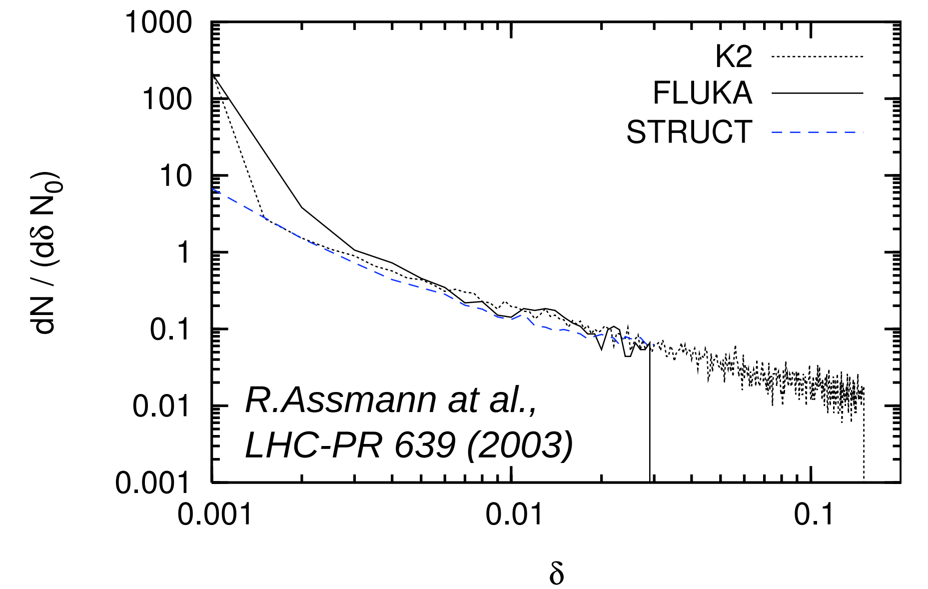








1 case study:

Three halo planes (Hori., vert. and skew); both beams.

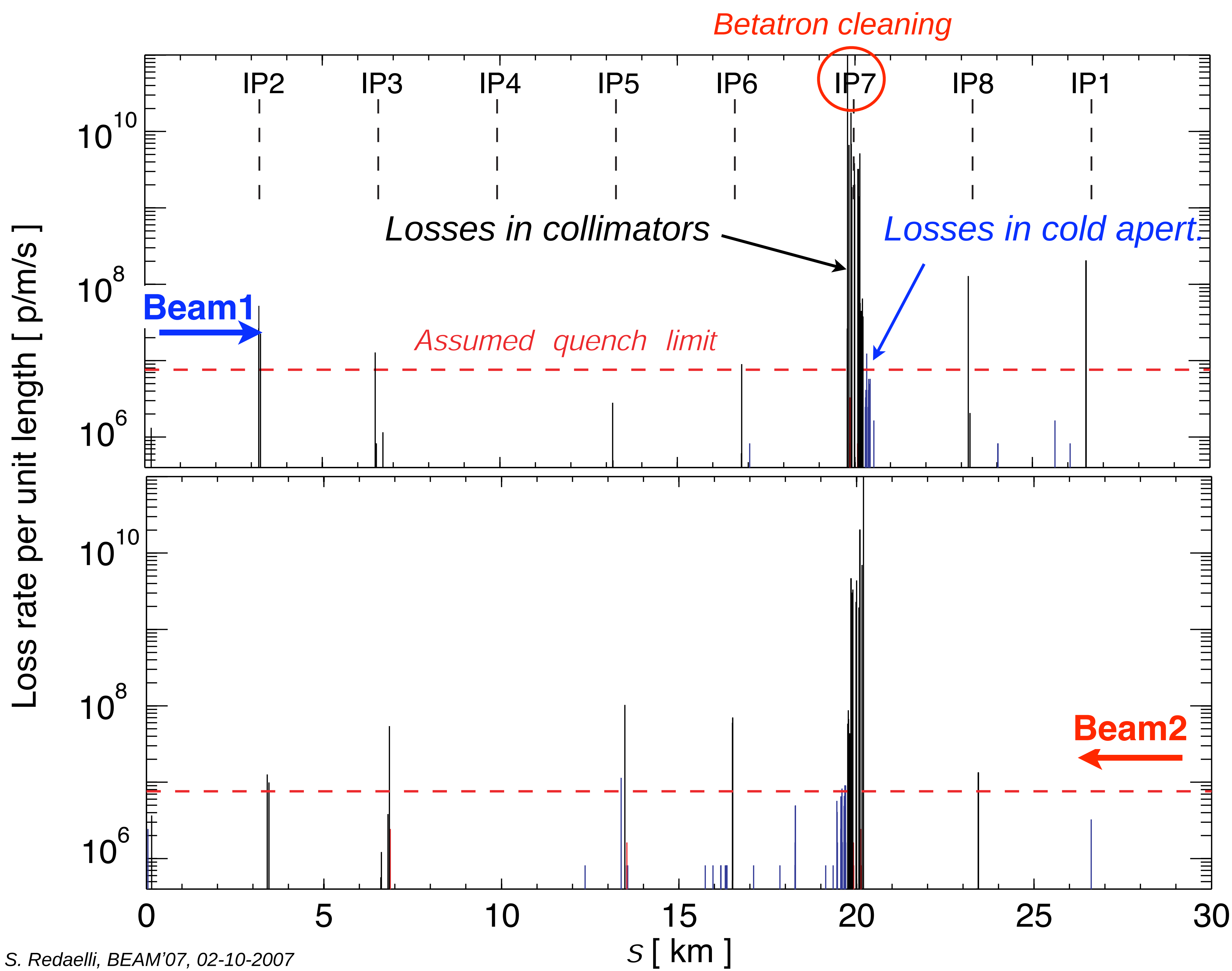
Track 5000000 particles for 200 turns.

Scattering in 44 collimators at each turn.

Check the trajectory in 270000 aperture locations!

Cleaning performance at 7 TeV

(Nominal intensity, ideal performance, τ_b=0.2h)



Legend:

Black = okay

Controlled losses at the collimators

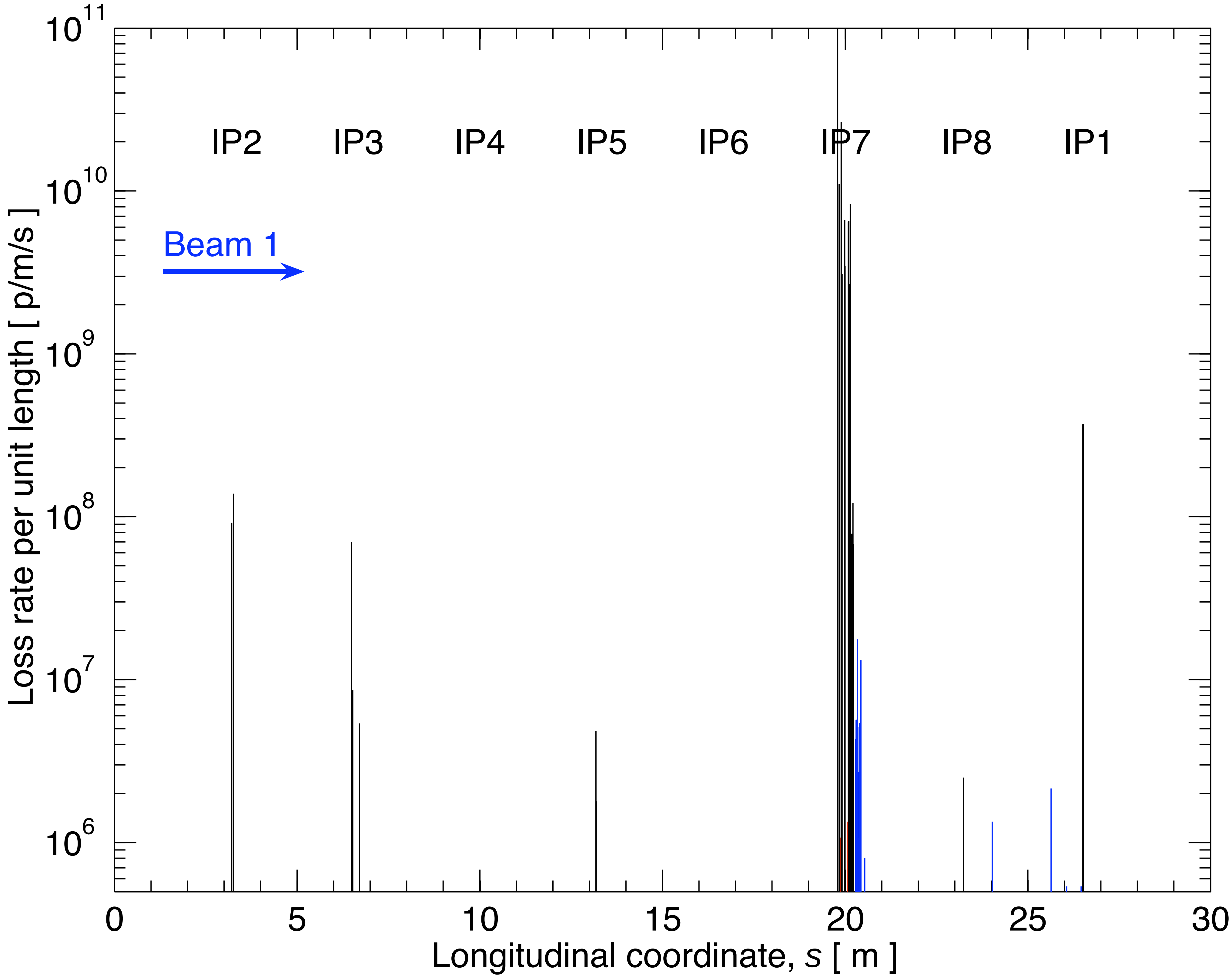
Blue = BAD!

Losses in cold aperture →quench

*Only a few loss locations outside the collimators **(ideal performance)***

Details of beam 1 losses, 7 TeV

(Nominal intensity, ideal performance, τ_b=0.2h)



By design, losses are concentrated in the warm insertion.

However, there is some leakage (~10^{-4}): losses in the dispersion suppressor from single diffractive interaction with primary collimators.

This limits the Phase I performance.

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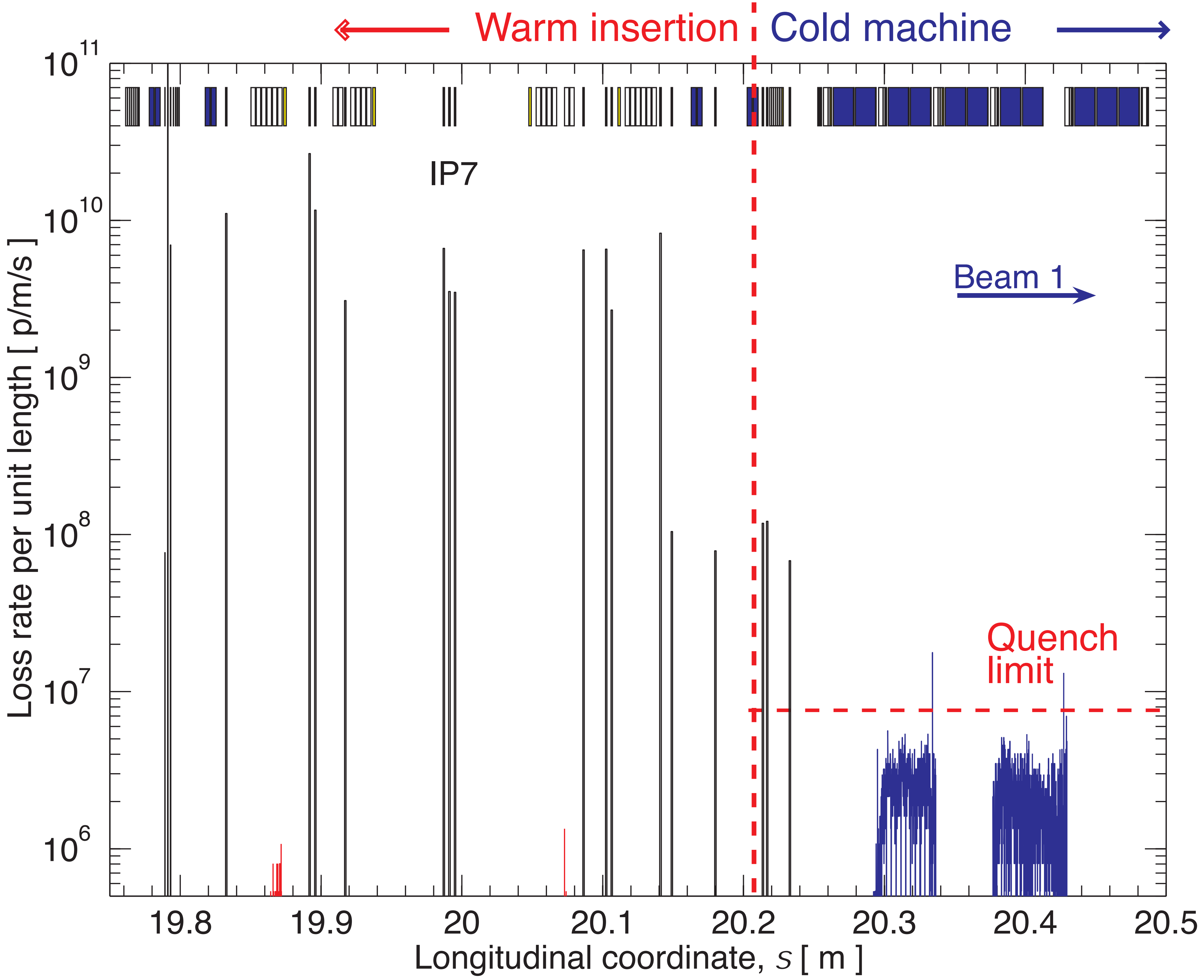

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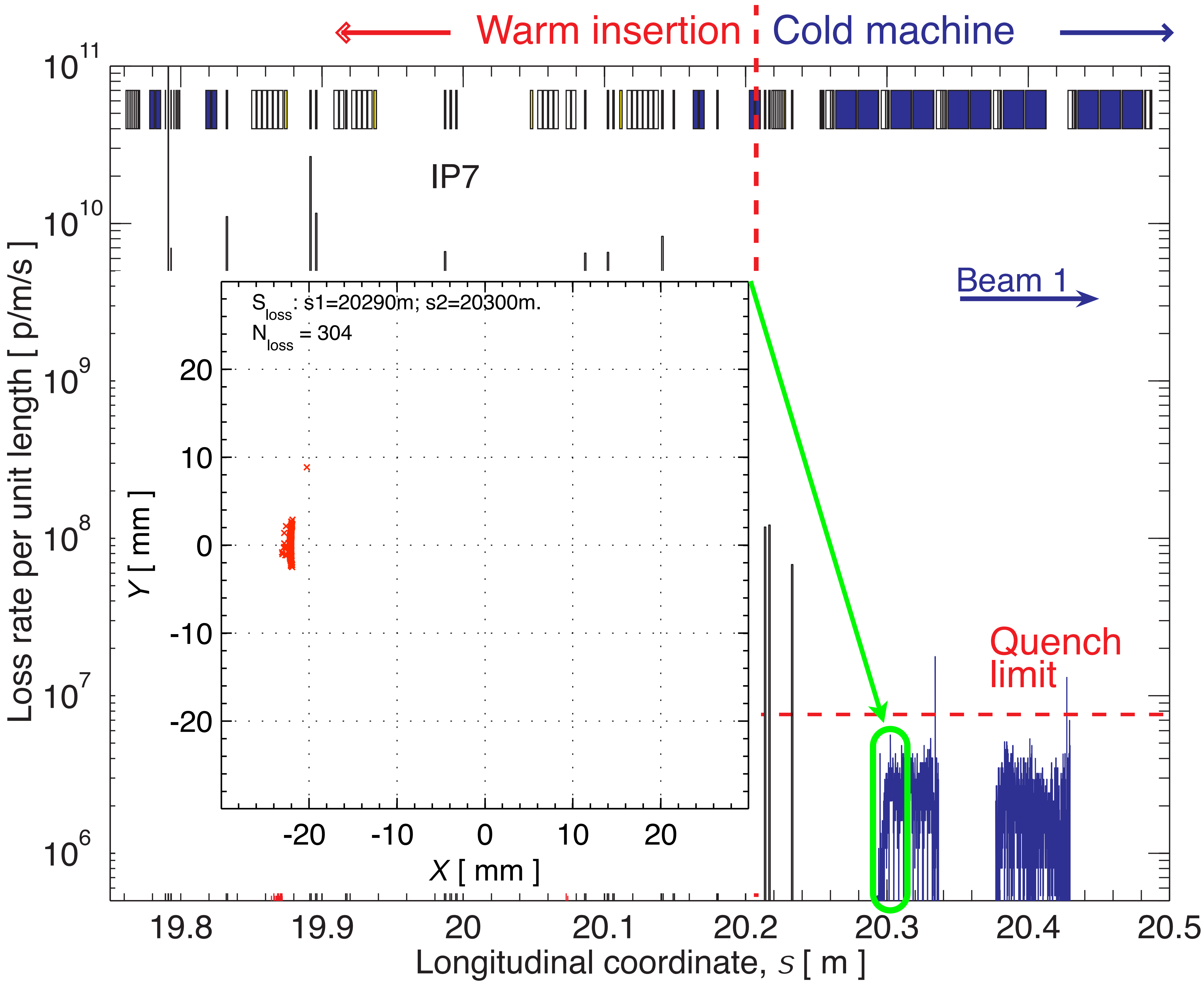

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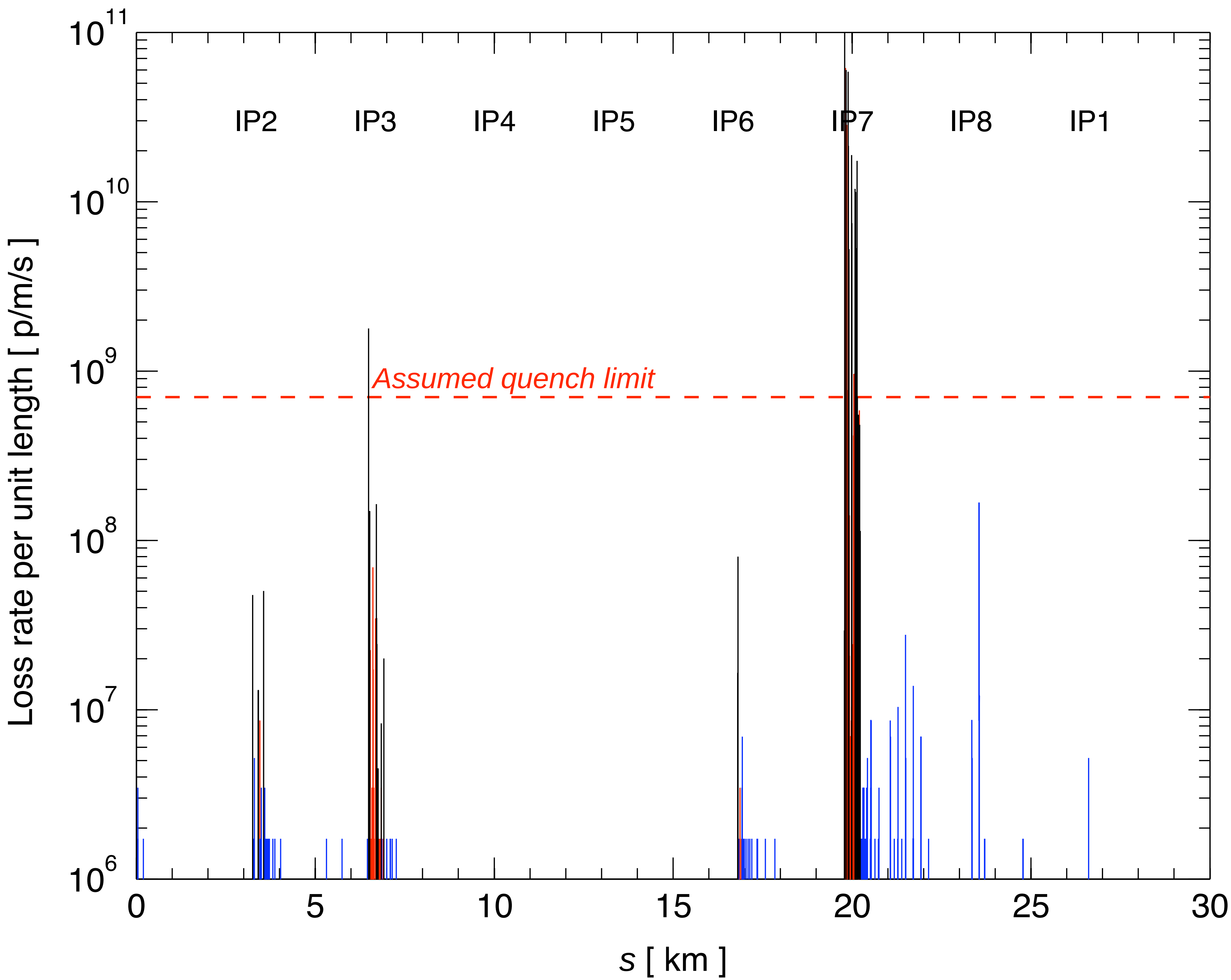
Cleaning performance at 450 GeV

(Nominal intensity, ideal performance, τ_b=0.1h)



Larger losses (larger betatron amplitudes at lower energy) but also larger quench limits.

Below the assumed quench limits!

Cleaning during energy ramp

Beam cleaning needed throughout the ramp!

Collimator settings: trade off between

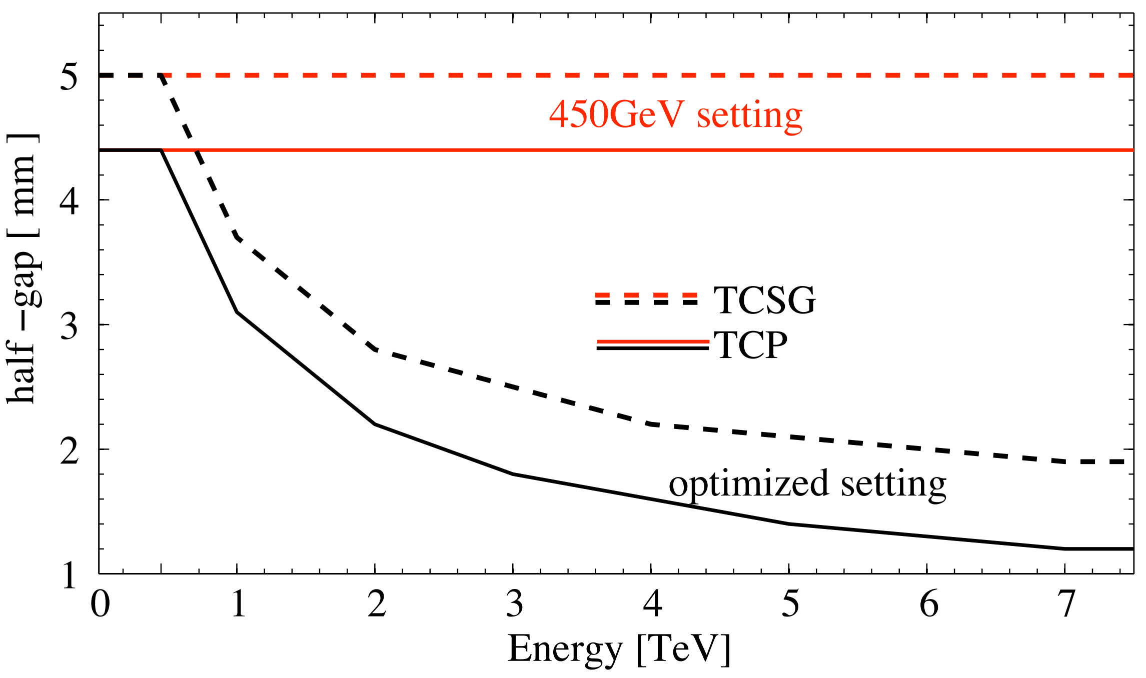
- Optimum cleaning

    Maintain canonical 6/7σ settings!

    $\sigma_{Inj} \approx 1$ mm → $\sigma_{7TeV} \approx 0.25$ mm

- Ease operation in early commissioning

    Keep injection settings until β-squeeze!



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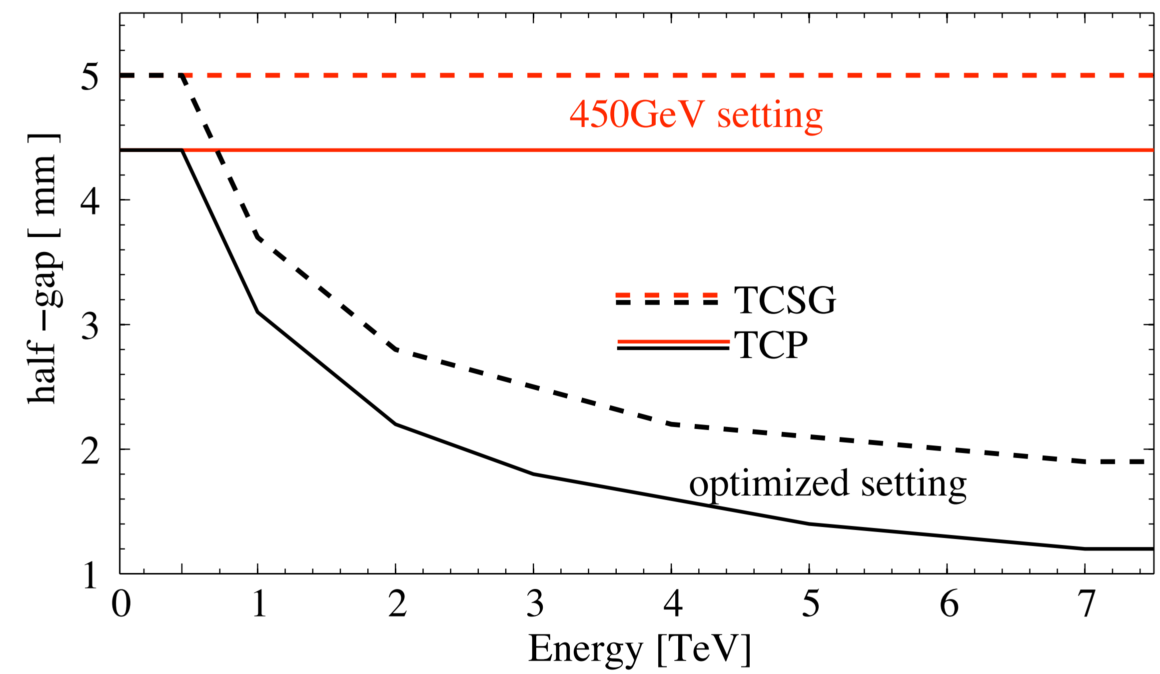

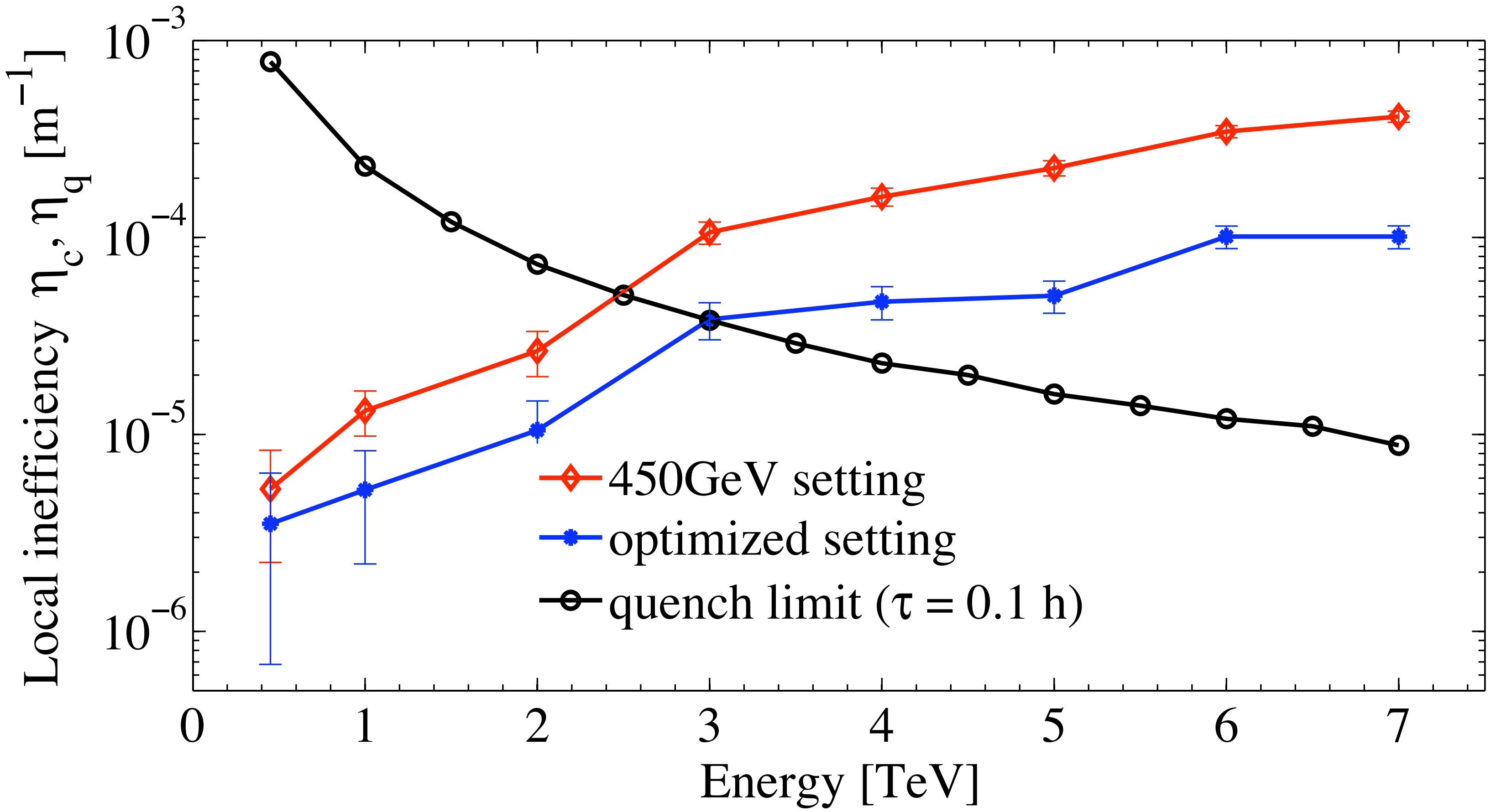

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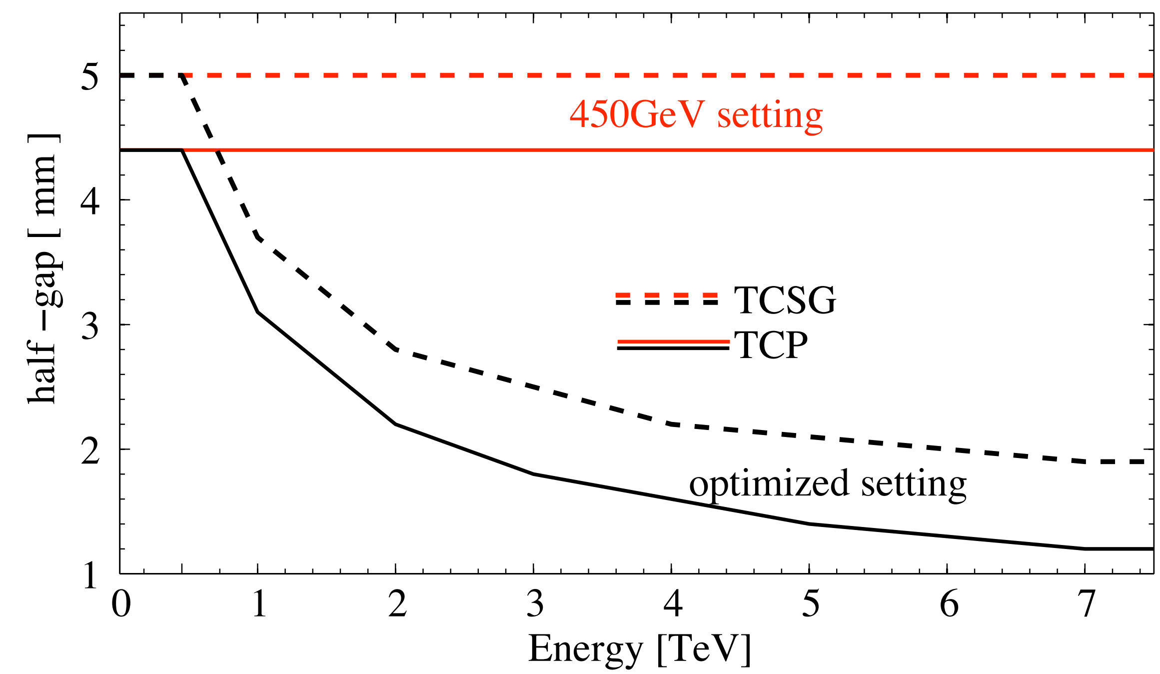

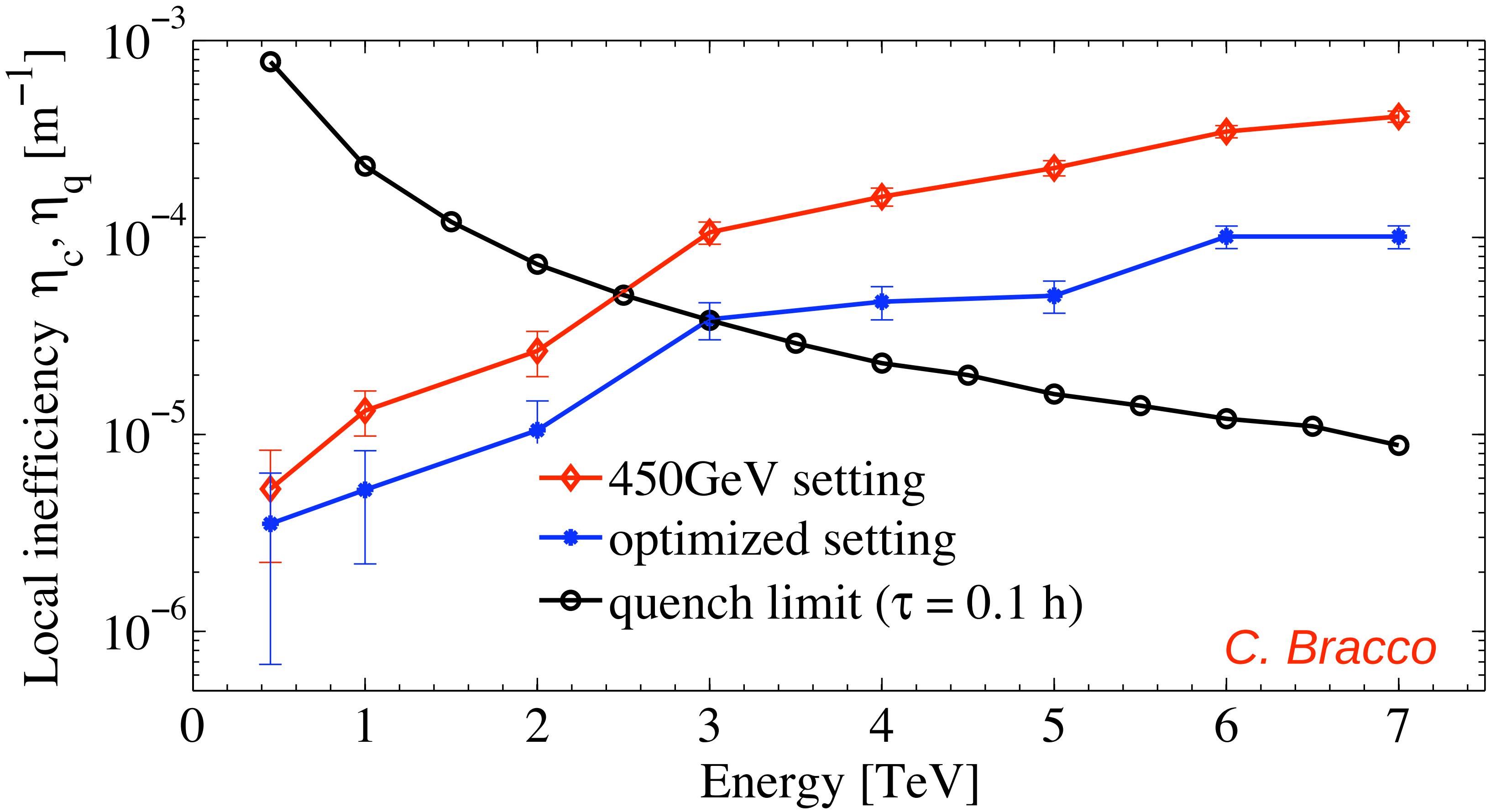

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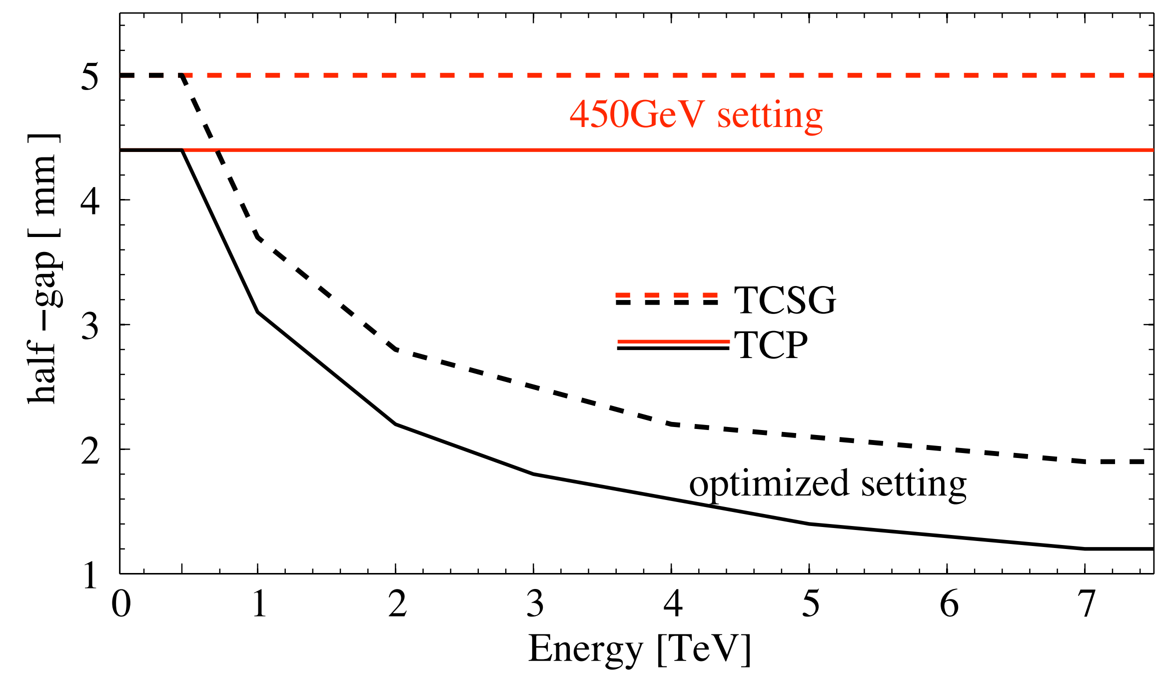
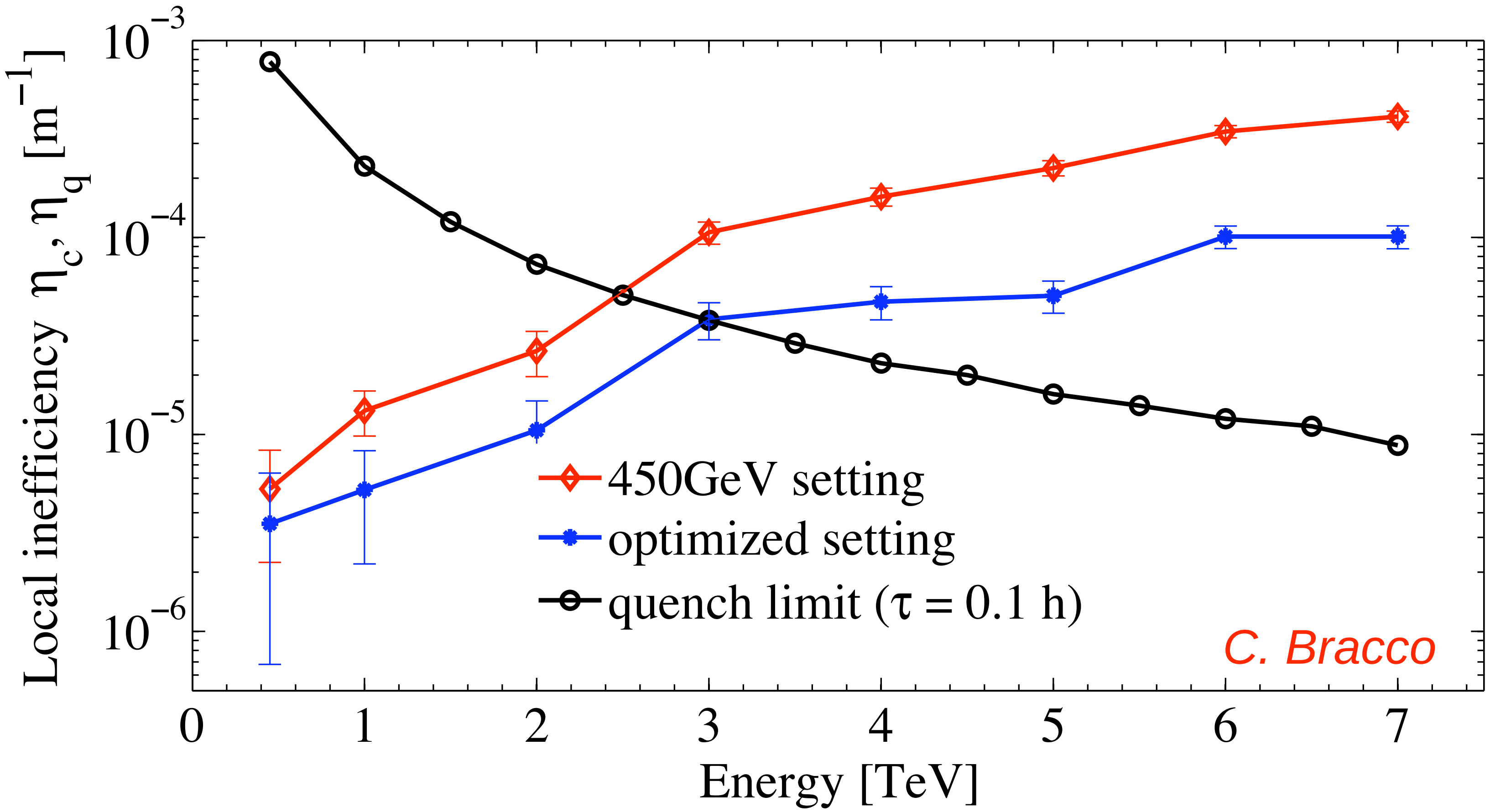




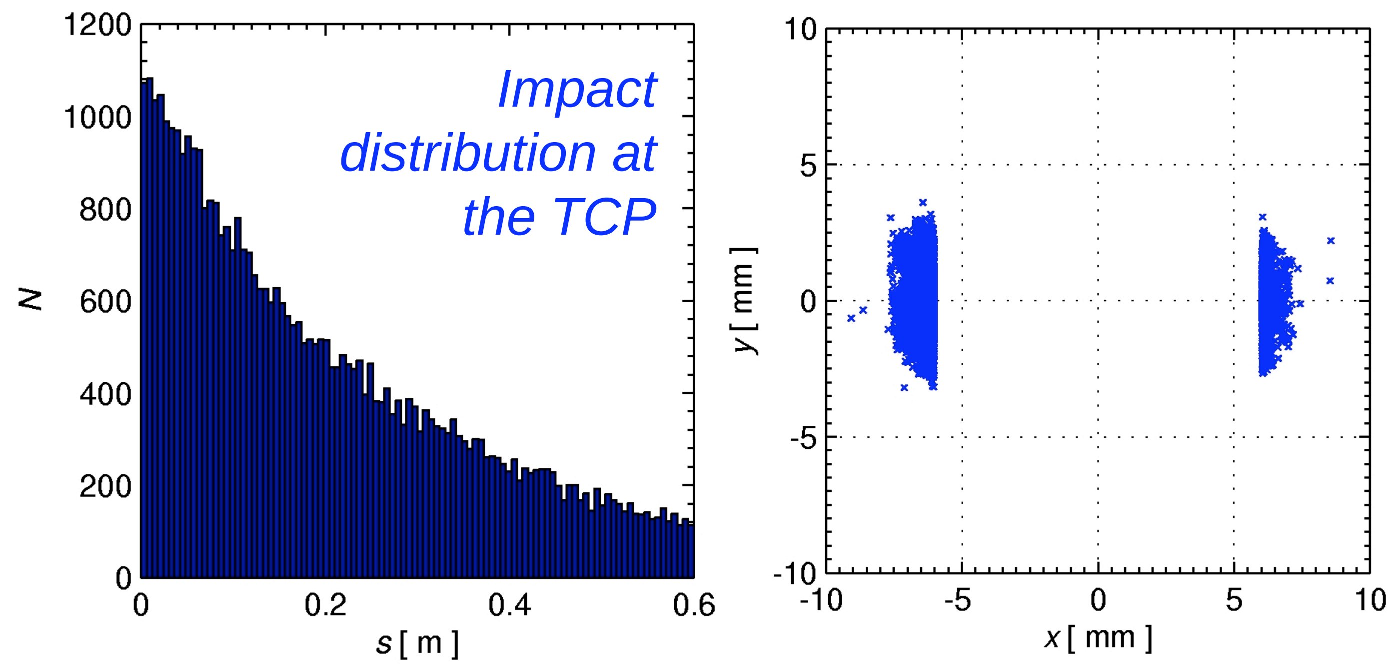
Proposed optimized setting during energy ramp:

Constant retraction in millimeters: easy tolerances + sufficient cleaning at startup with reduced intensities.

Detailed commissioning scenarios worked out by C. Bracco (PhD work).

Overview of energy deposition studies

Distribution of inelastic interactions within collimator jaw material is used as an input for energy deposition studies (collaboration with the CERN FLUKA team).



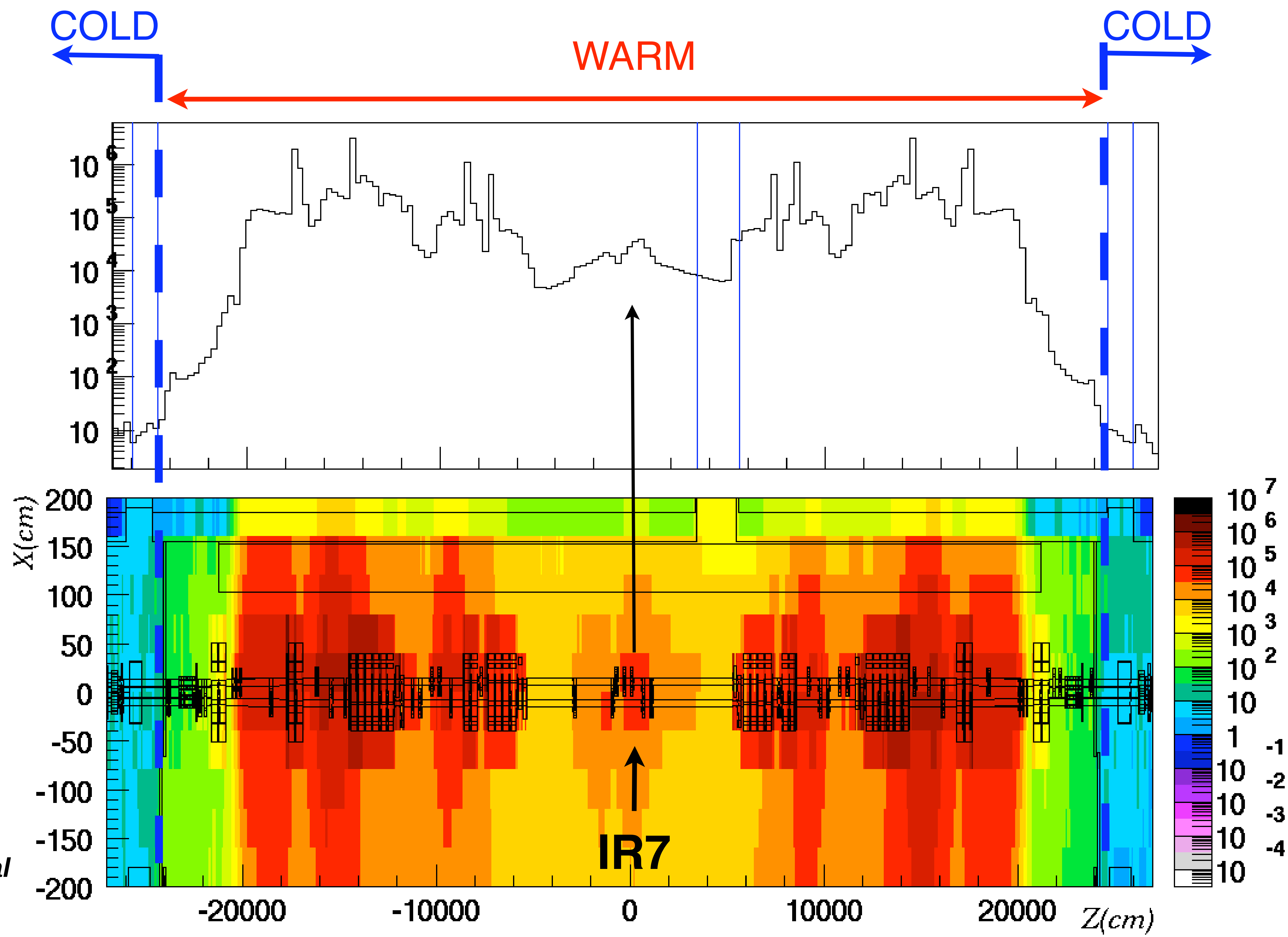
Energy deposition studies play a major role in the system design!

- → Energy in the super-conducting magnets versus quench limit
- → Determine the BLM locations for optimum response (BI team)
- → Estimate life time of warm magnets/electronics (passive absorbers)
- → Quantify dose to personnel and impact on the environment
- → Optimize layout of insertion (shielding design)
- → Calculate heating of critical components
- → Beam halo loads in specific locations (e.g., LHC beam dump)
- → Detector background from tertiary collimators (IHPE + US-LARP)

All these studies for the LHC rely on the results of our simulations!

See overview talk by M. Brugger at the recent Collimator Material workshop at CERN.

Radiation doses in IR7



K. Tsoulou et al

Radiation is confined within the warm insertions!

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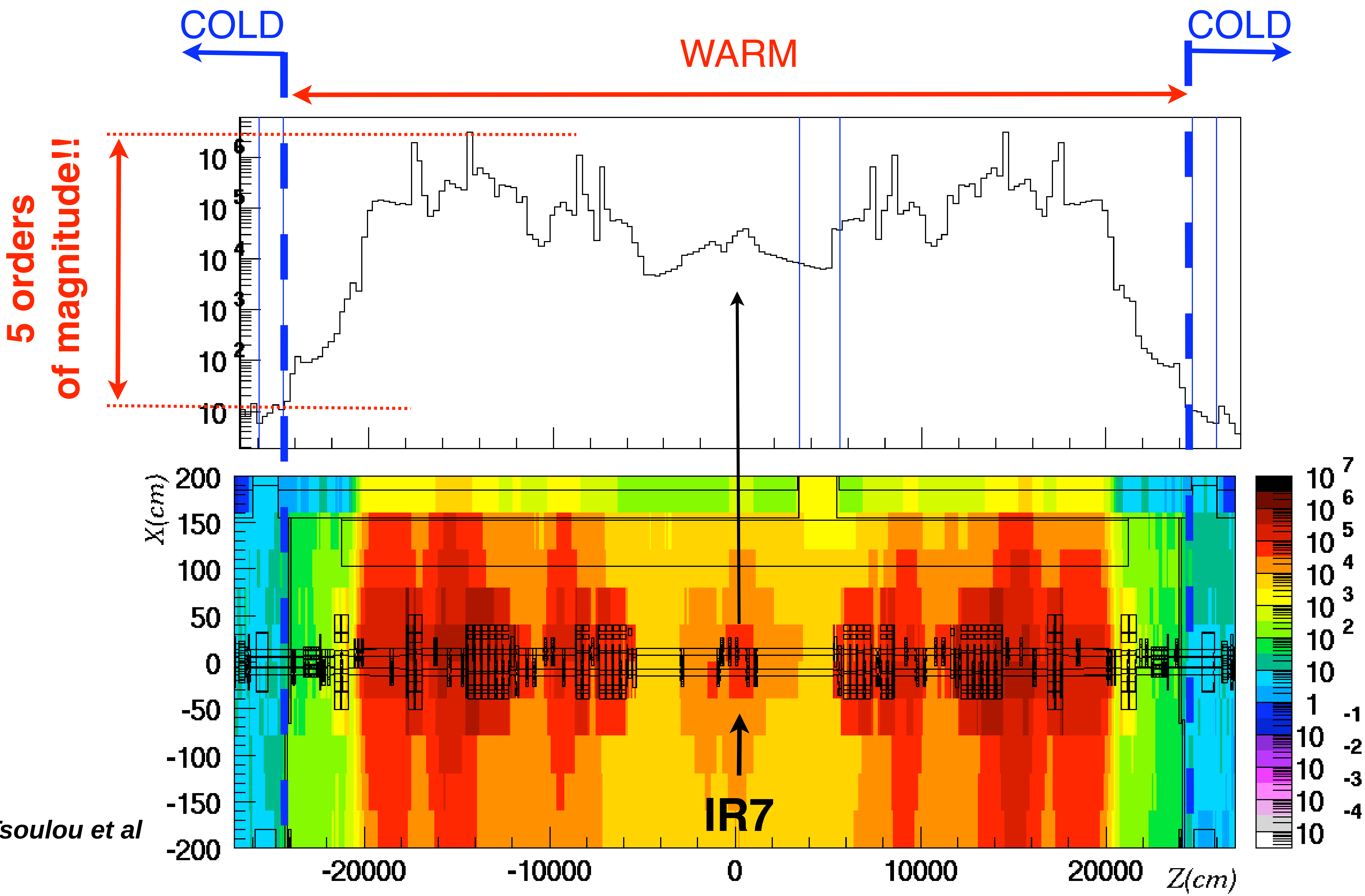

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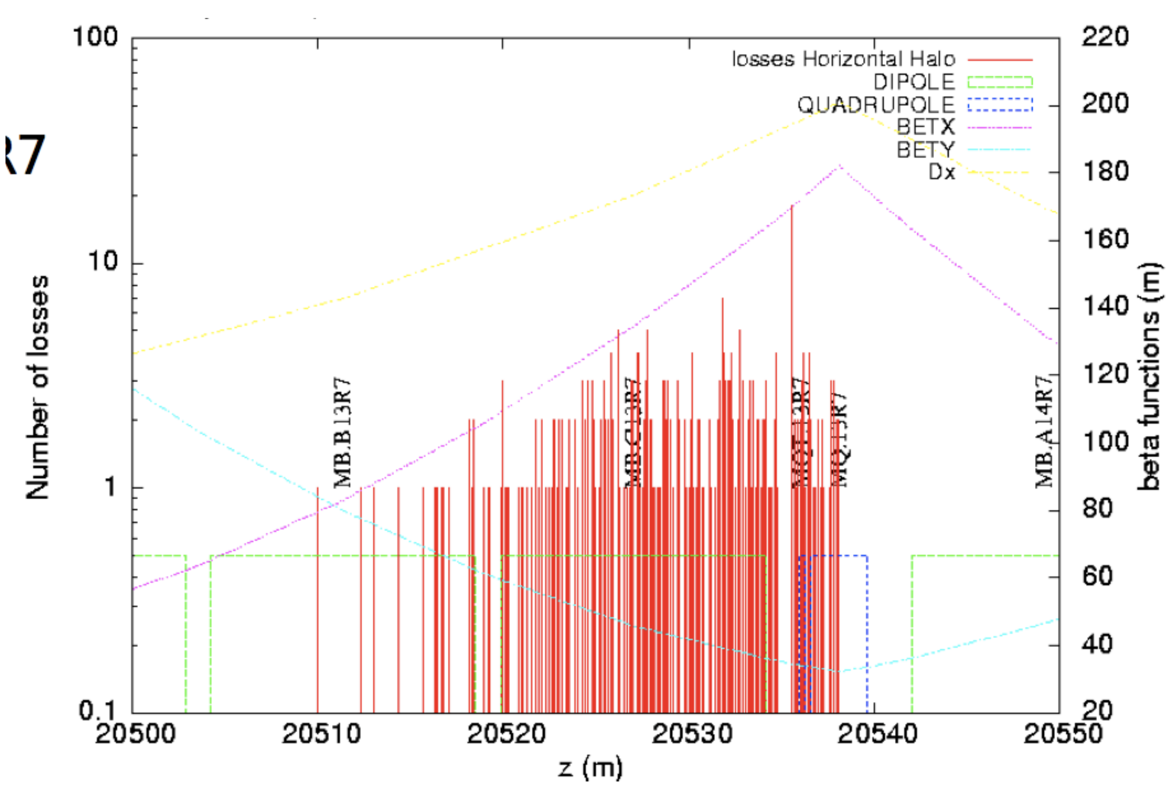
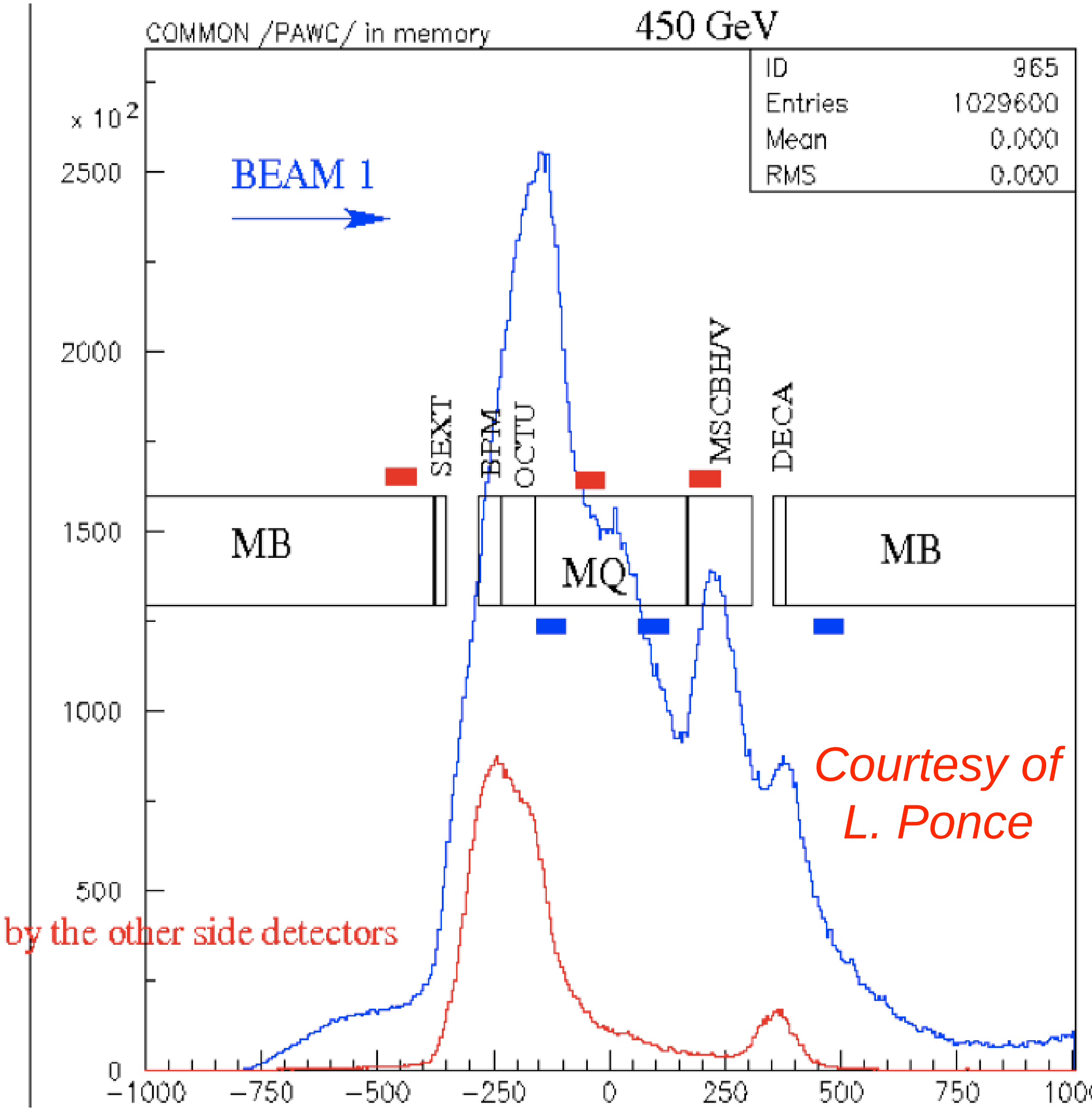
Optimization of the BLM locations





Detailed loss maps around the ring used to determine the location of the beam loss monitors (BLM's)

Critical elements for active machine protection: trigger dump in case of abnormal losses

Final layout: 6 monitors per quadrupole + dedicated monitor (dispersion suppressor downstream of IR7)

Outline of my talk

- Introduction
- Loss studies for the LHC

    Simulation tools

    Performance of a perfect system

    Energy deposition studies

- **Imperfection models**

    Jaw surface deformations

    Aperture alignment errors

- Loss studies at the SPS

    Experimental layout

    Simulated versus measured losses

- Conclusions

Imperfection models - what can be wrong?

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- **Optics errors**

  Closed orbit distortion, coupling, static and dynamic beta-beat (on- and off-momentum), non-linear field errors, feed-down from alignment errors, ...

Imperfection models - what can be wrong?

- ## Optics errors

  Closed orbit distortion, coupling, static and dynamic beta-beat (on- and off-momentum), non-linear field errors, feed-down from alignment errors, ...

- ## Collimator errors

  Alignment (set-up) errors, tilts, surface flatness

Imperfection models - what can be wrong?

- ## Optics errors
  Closed orbit distortion, coupling, static and dynamic beta-beat (on- and off-momentum), non-linear field errors, feed-down from alignment errors, ...

- ## Collimator errors
  Alignment (set-up) errors, tilts, surface flatness

- ## Aperture imperfections
  Statistical errors, manufacturing errors, measured alignment, ...

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Full MADX optics model implemented in SixTrack

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  Detailed collimator geometry in our scattering routine

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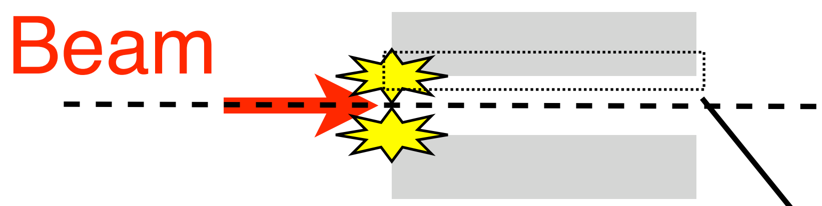
  Statistical errors, manufacturing errors, measured alignment, ...

  Dedicated tools in aperture program

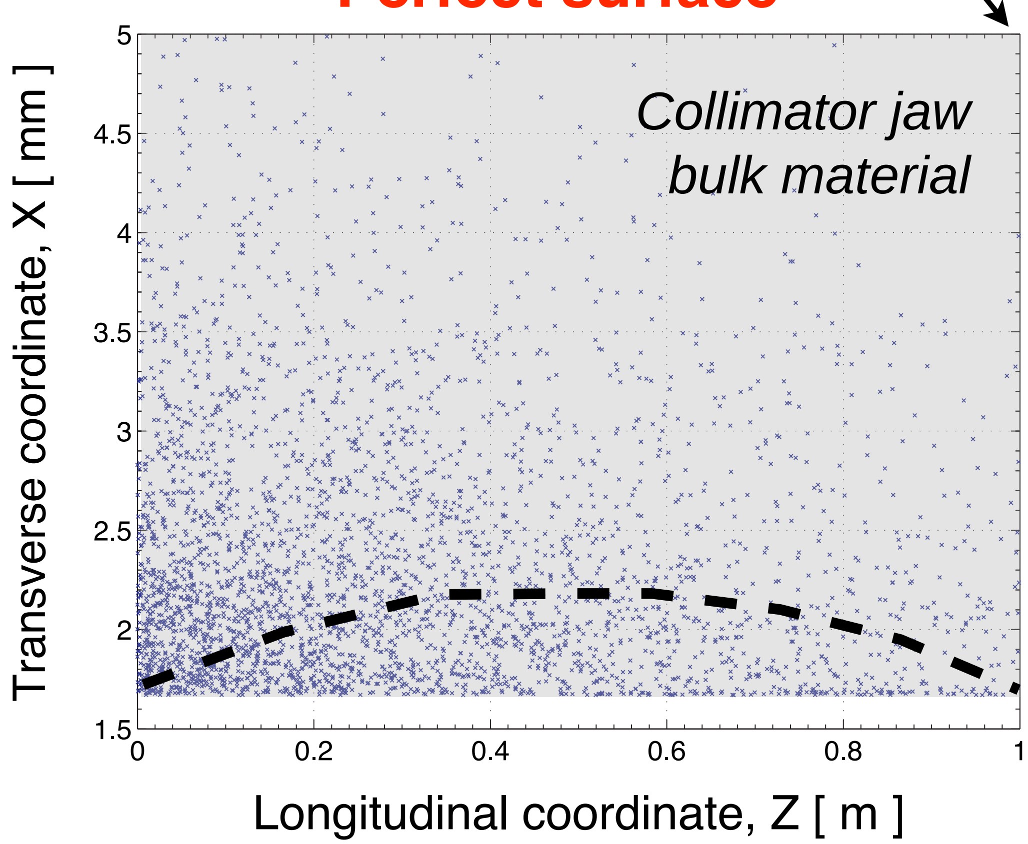
Jaw flatness errors



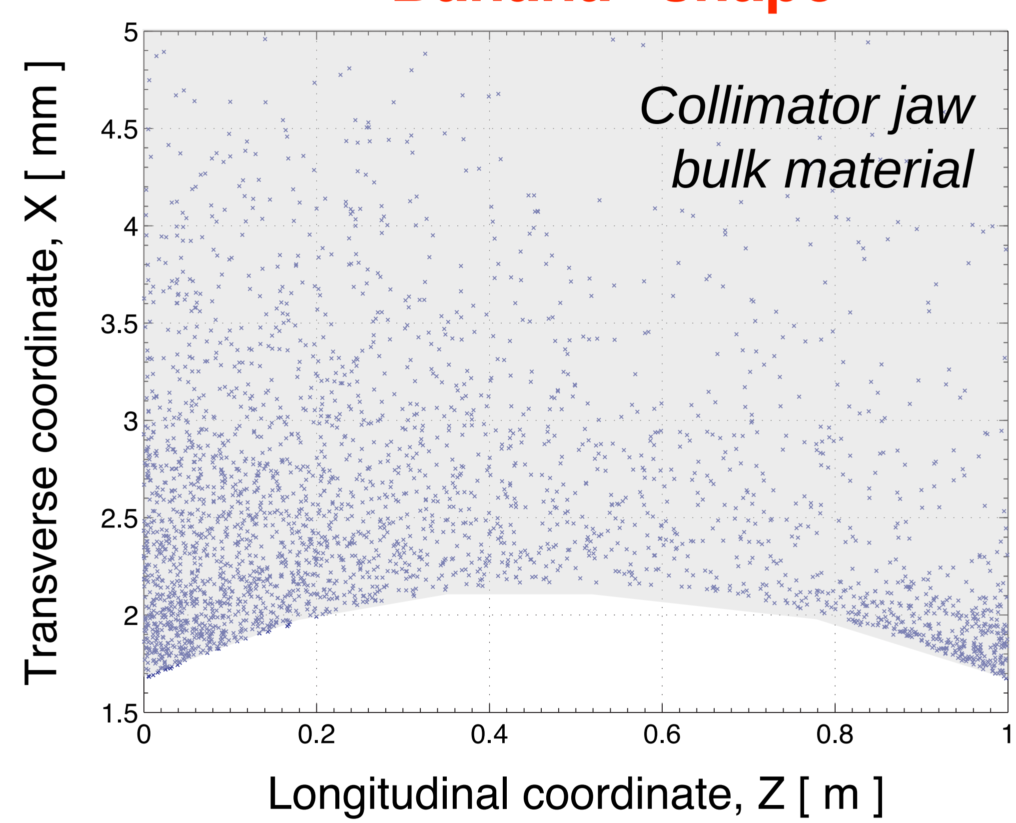
1m jaw (TCSG)

<u>Effect of flatness errors</u>:
- Halo particles interact with less material:
  → Reduced absorption!
- More losses close to the downstream edge
  → More particles/showers escape
- Higher deposited energy *density*

Perfect surface



"Banana" shape



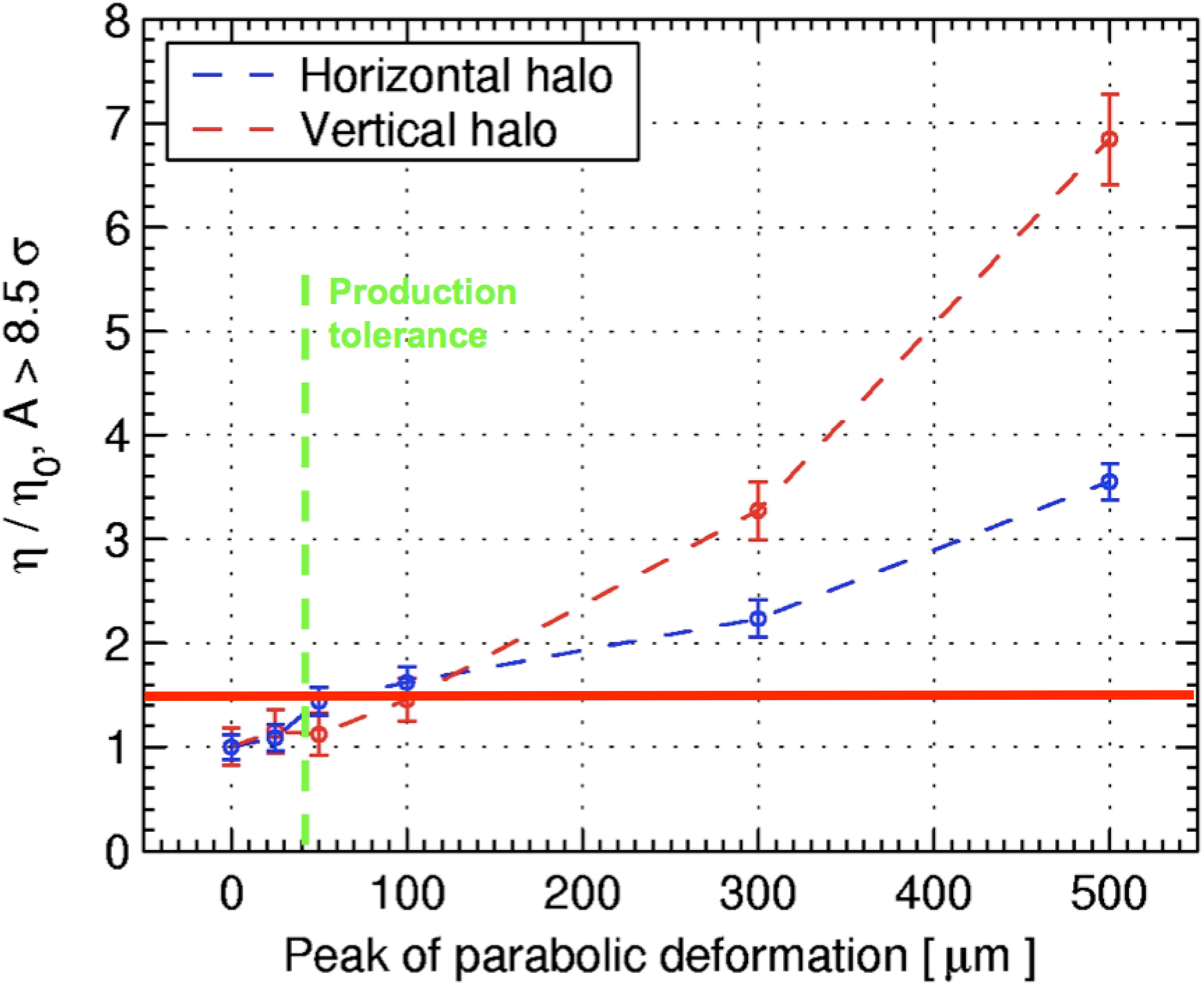
Error: 250 µm

Simulations: can slice each collimator and assign any shape (polynomial fit)

Sensitivity studies + measured flatness from production

Sensitivity on flatness errors

(parabolic "banana" deformation of all secondary collimators)



Based on these studies, the production tolerance was set to **40 μm**.

Tolerance achieved in production.
Database of flatness data being prepared to study the performance of the "as-built" system.

50 % lost of cleaning efficiency for errors of ~ 50 μm
Factor 2-3 for errors above 250 μm

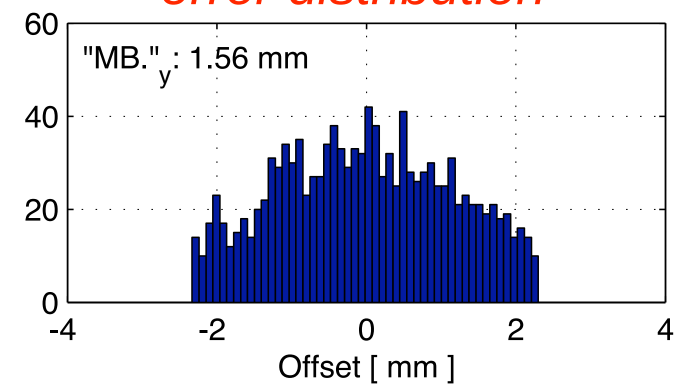
Random aperture alignment errors

- Alignment errors in the aperture model: many “machines” for one tracking run!
- Random errors (H+V) applied to relevant elements per type: MB’s, MQ’s, MQX’s, BPM’s, ...

Ex.: 2250 elements moved; 20 random seeds

```
************************************
* Definition of alignment errors:  *
************************************
*   TYPE *  Dx [ m ]  *  Dy [ m ]  *
*MB.     *    0.0024  *   0.00156  *
*MQ.     *     0.002  *    0.0012  *
*MQX     *     0.001  *     0.001  *
*MQWA    *     0.002  *    0.0012  *
*MQWB    *     0.002  *    0.0012  *
*MBW.    *    0.0015  *    0.0015  *
*BPM     *    0.0005  *    0.0005  *
************************************
* SigmaCut:         1.5            *
************************************
```

Vertical dipole error distribution



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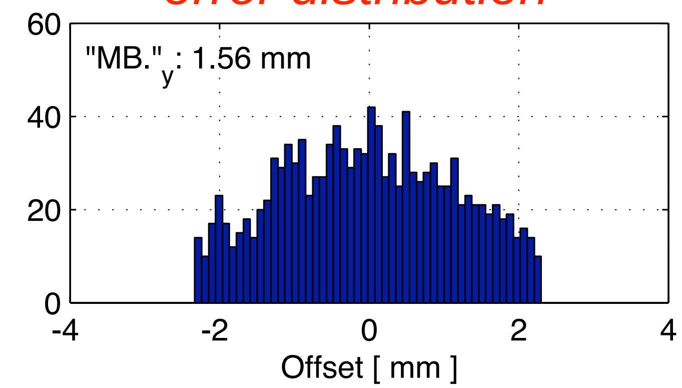

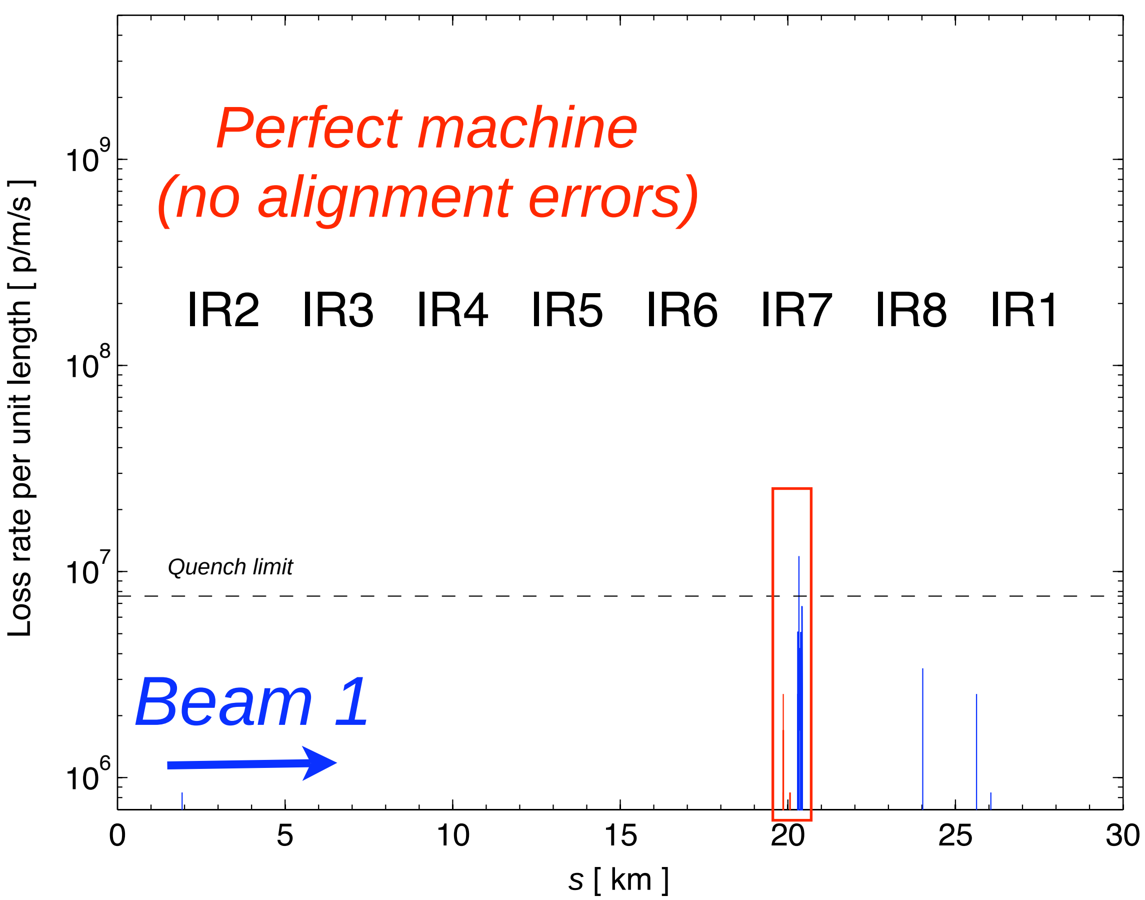

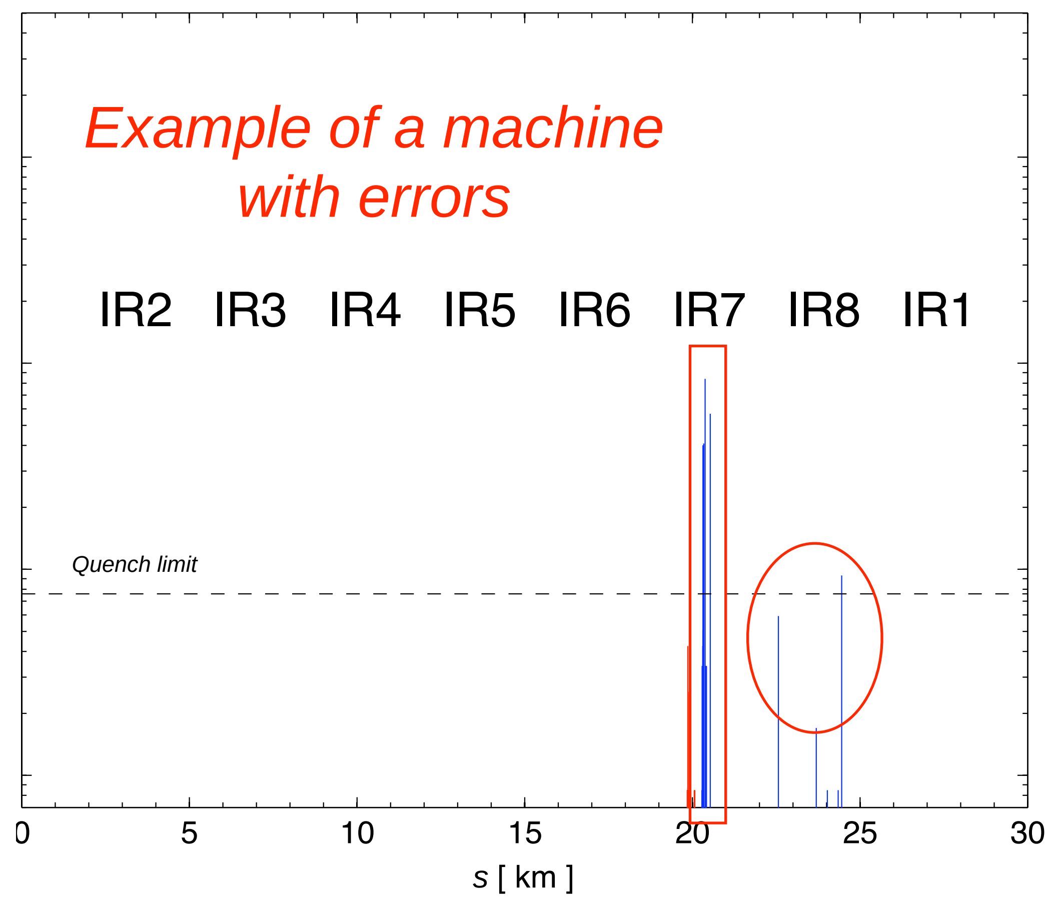

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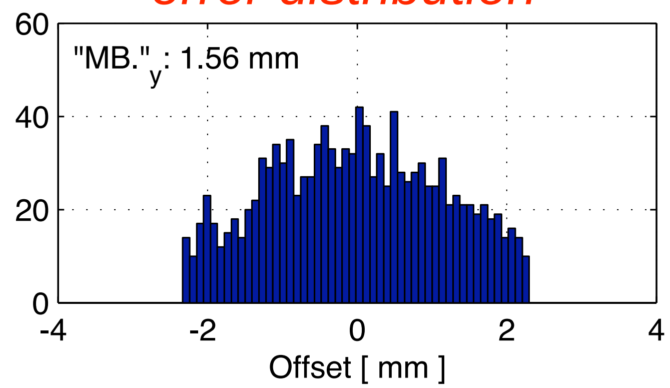
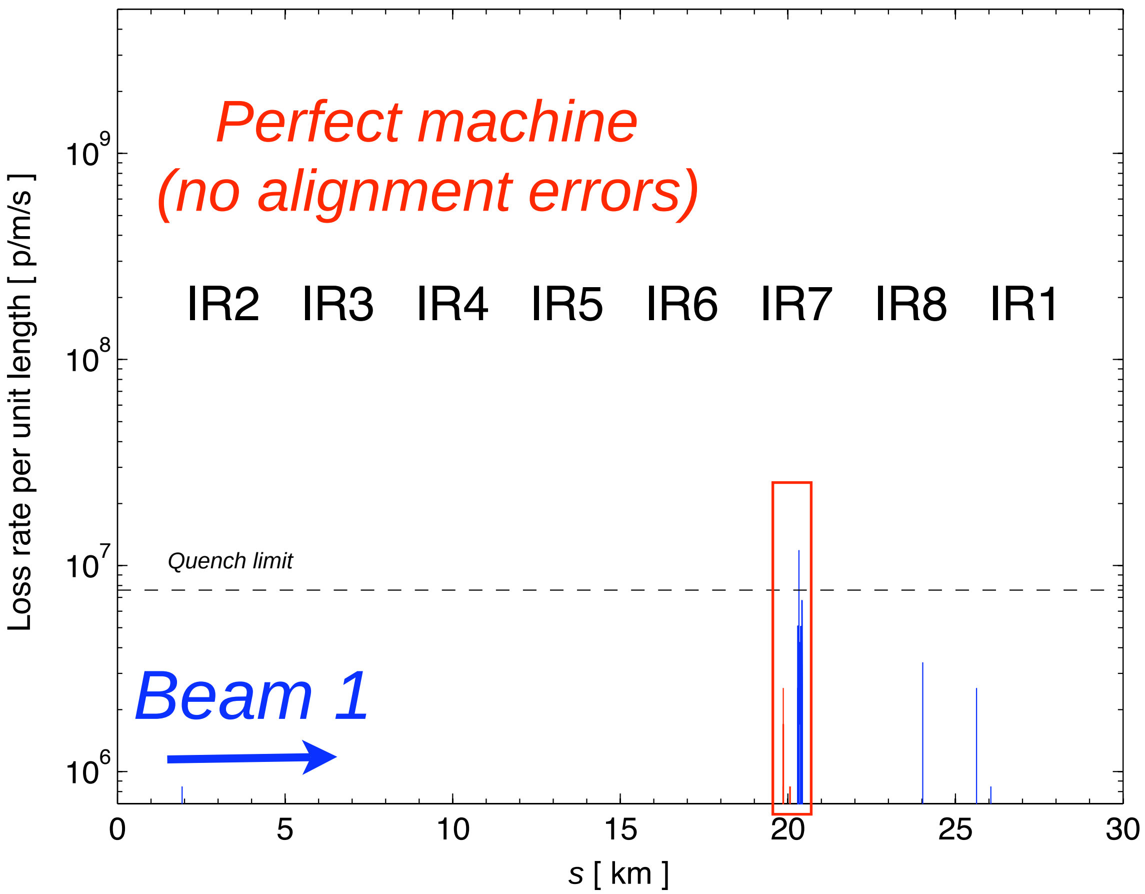
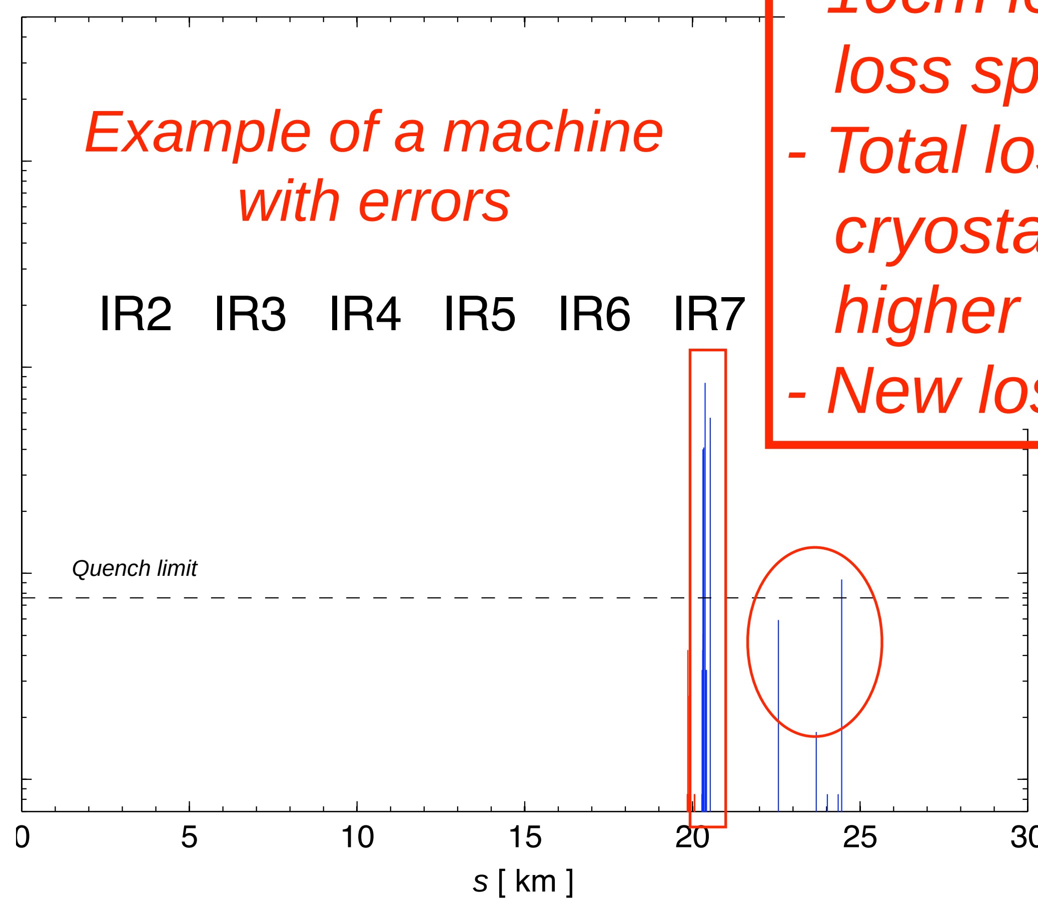






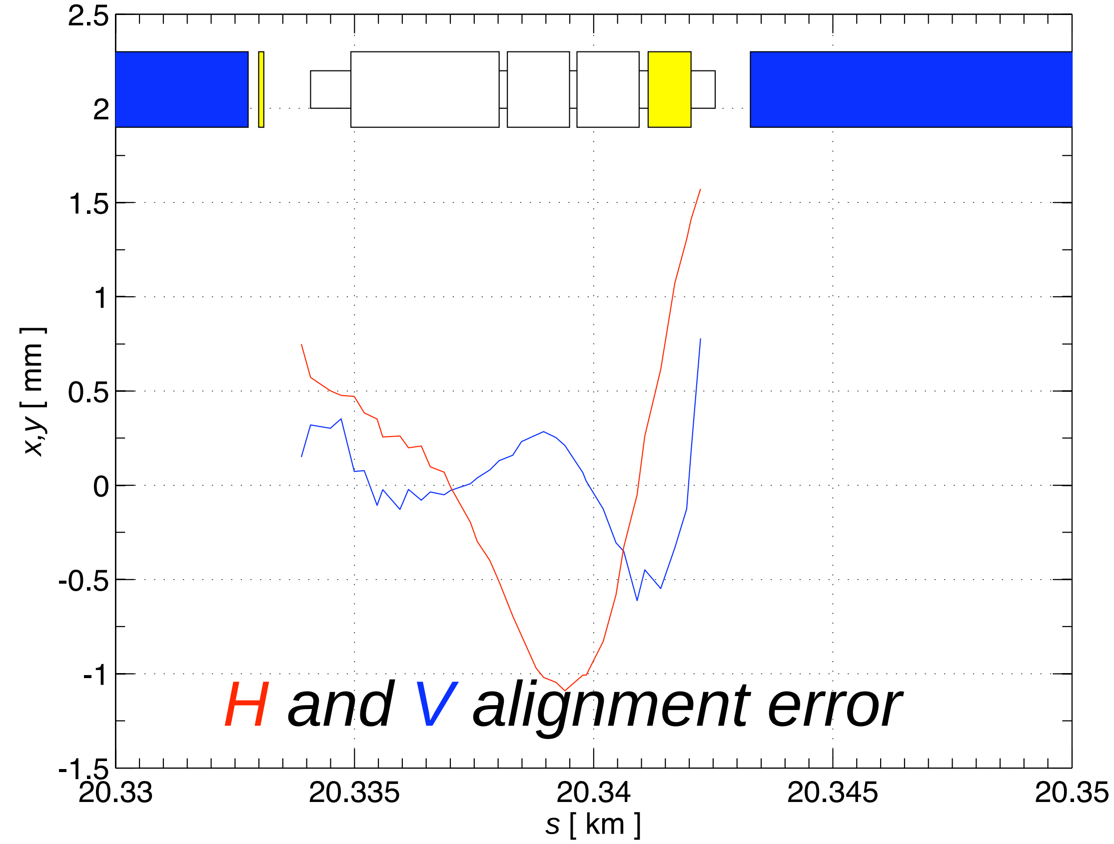
- *10cm level: higher loss spikes!*
- *Total losses in single cryostat 15-20% higher*
- *New loss locations!*

Measured alignment errors

Work in progress: apply measured alignment error along magnet cold bore (~10 cm level) → "as-built" aperture model

Database of measured alignment errors being setup/interfaced to code (ABP/LCU +AT/MCS)

Example: Q9 downstream of betatron cleaning at injection *(data from M. Giovannozzi)*



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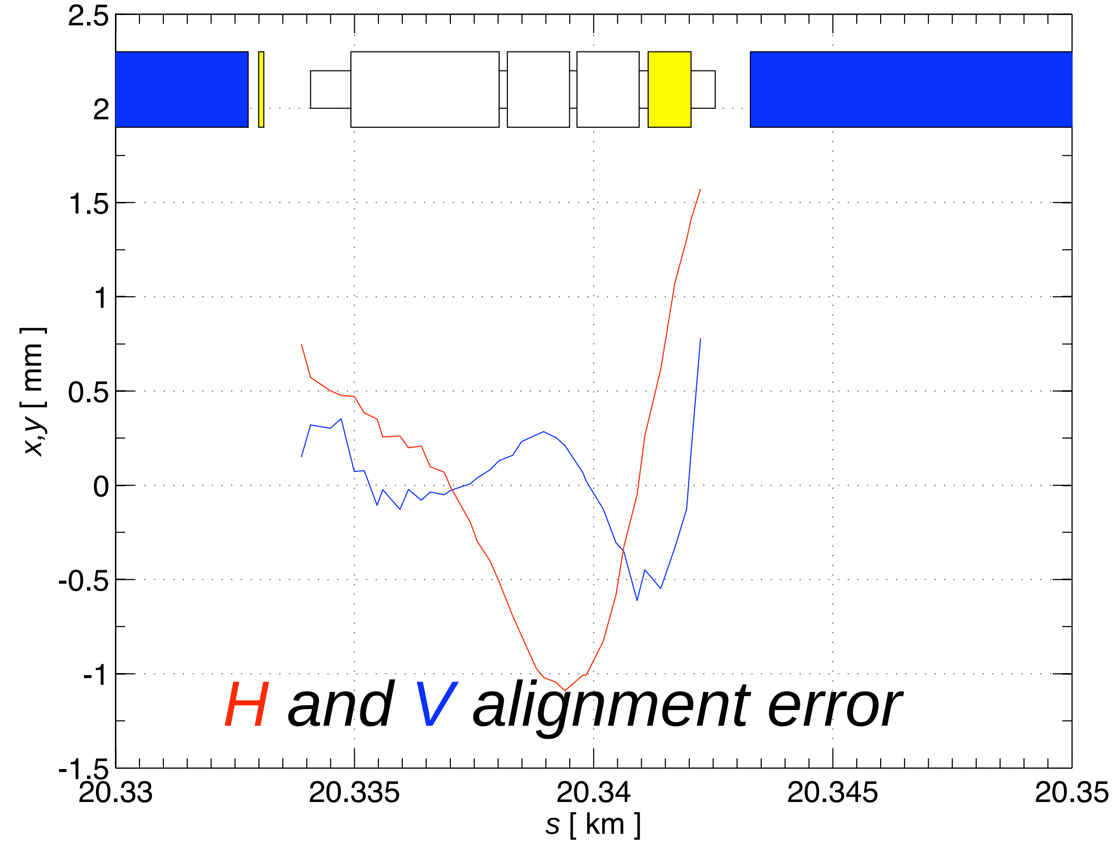
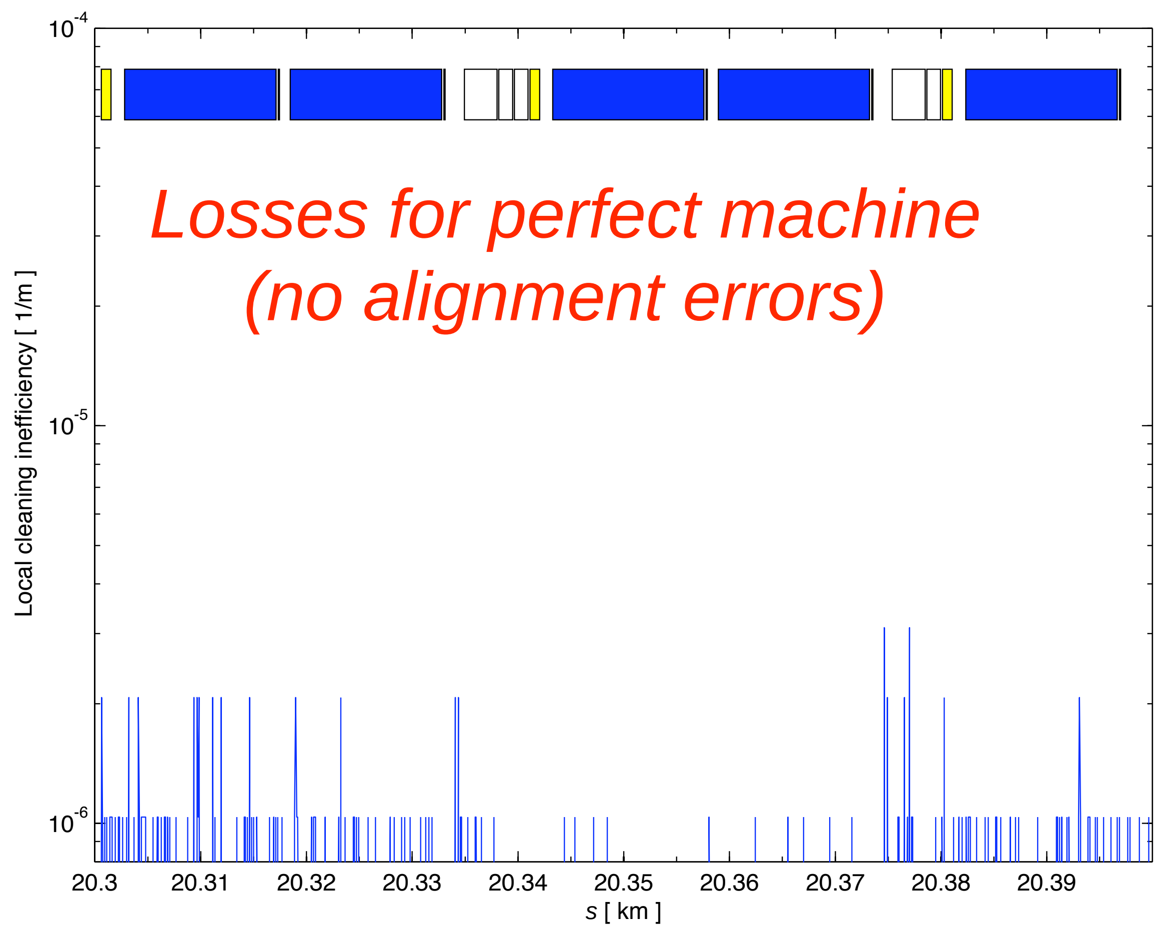
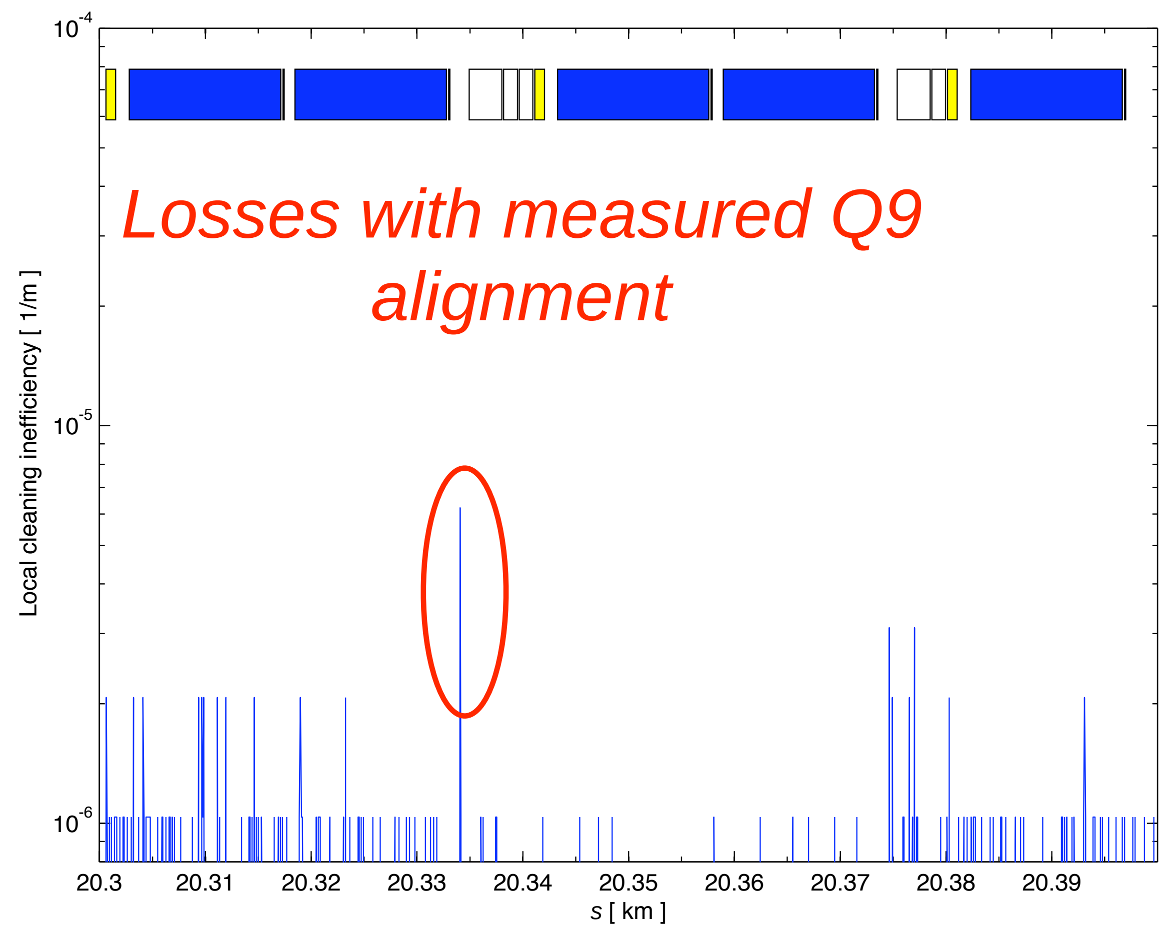






Outline of my talk

- Introduction
- Loss studies for the LHC

  Simulation tools

  Performance of a perfect system

  Energy deposition studies
- Imperfection models

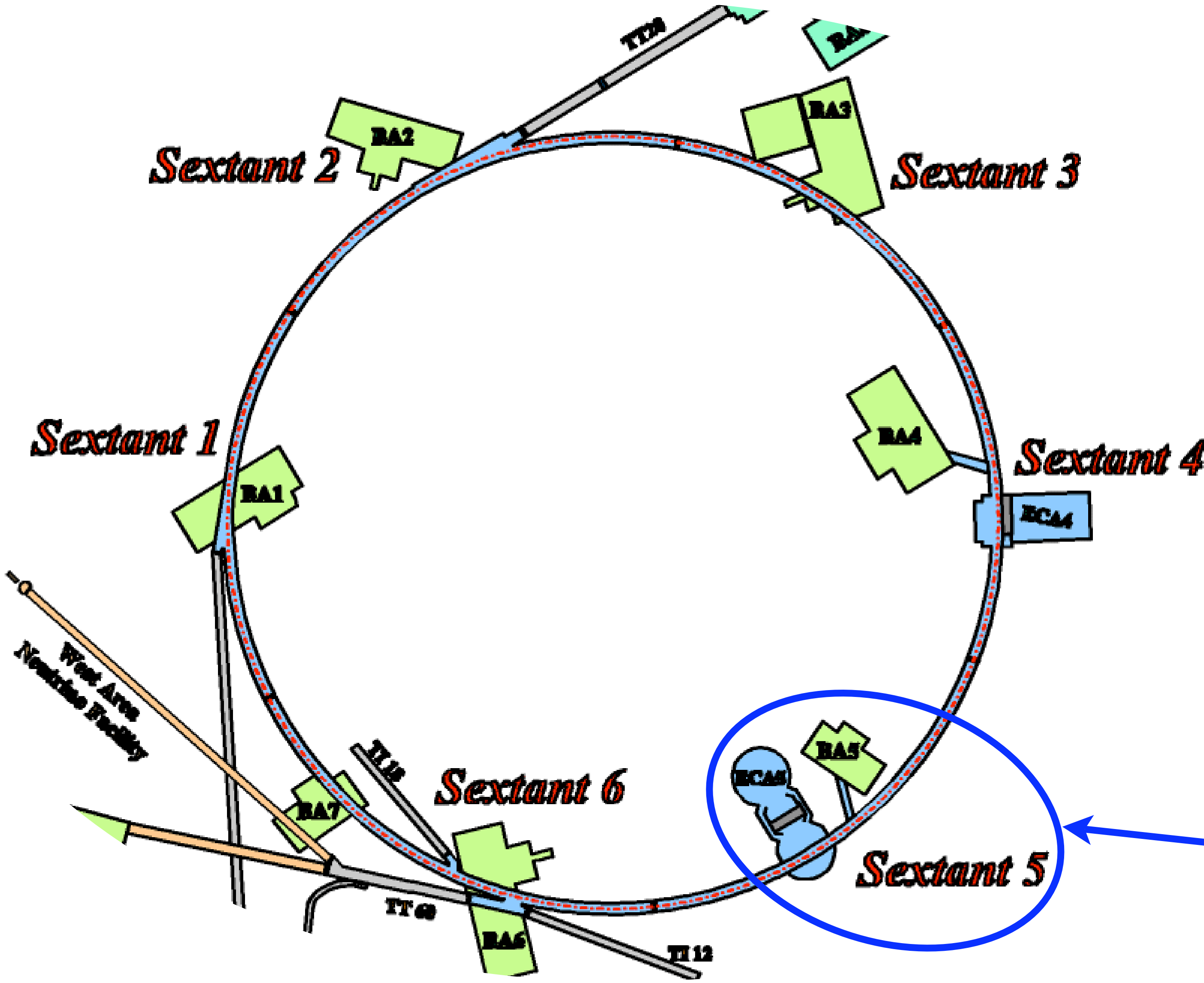
  Jaw surface deformations

  Aperture alignment errors
- **Loss studies at the SPS**

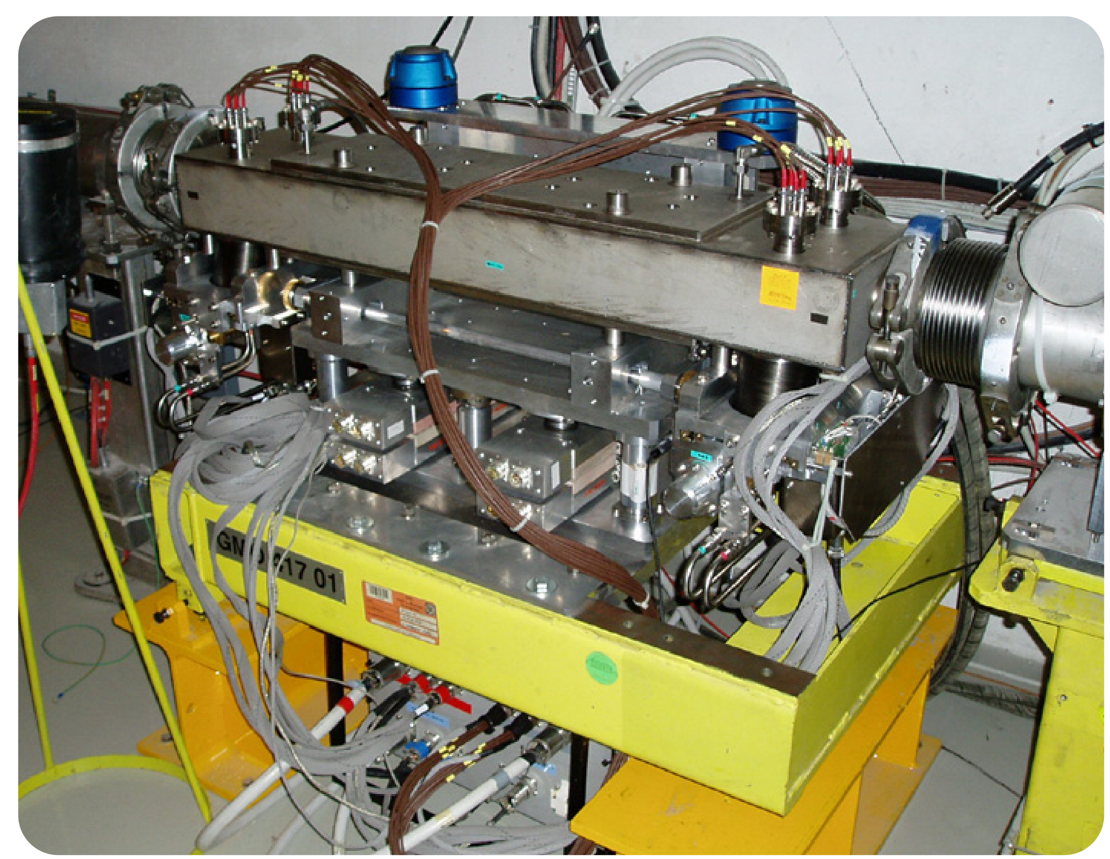
  Experimental layout

  Simulated versus measured losses
- **Conclusions**

Layout of collimator tests at the SPS



A horizontal LHC collimator prototype (full mechanical functionalities) installed in SS5 for beam tests.



SPS optics and aperture

Main beam parameters

βx = 24.9m

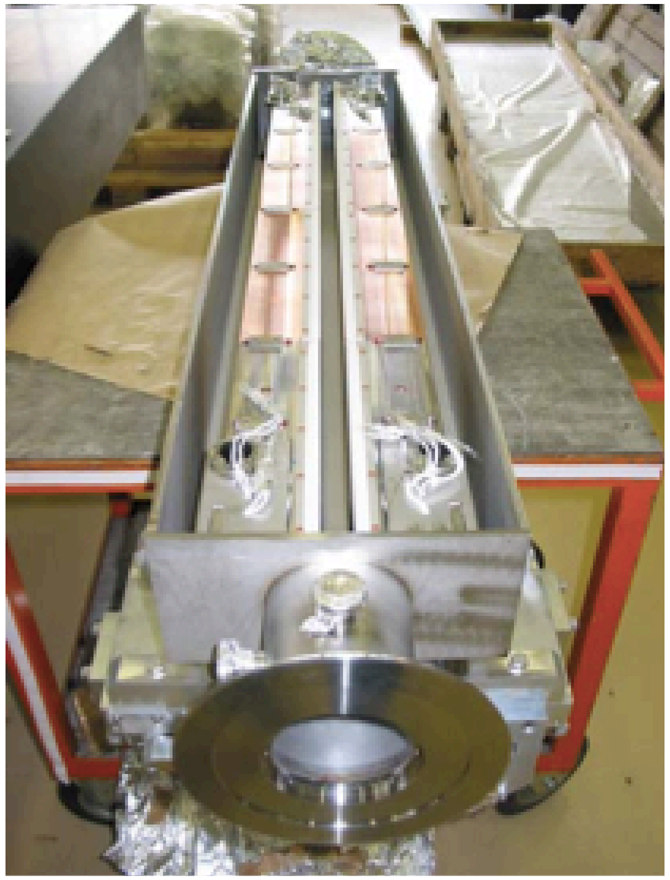
➘ $\sigma x \approx$ 0.7mm

βy = 89.9m

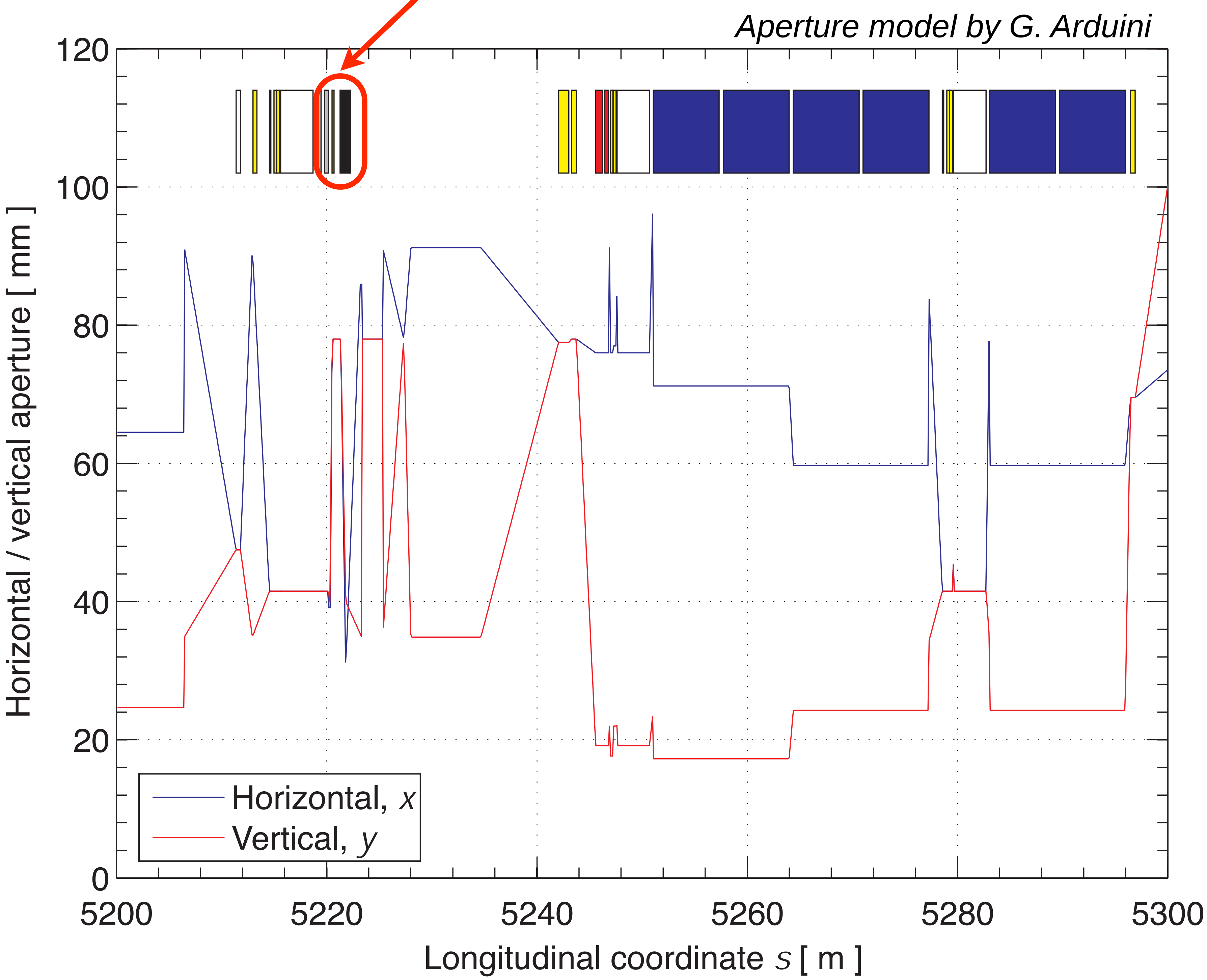
➘ $\sigma y \approx$ 1.3mm

En = 270 GeV / *c*

$\varepsilon \approx$ 1-3 μm



Prototype LHC collimator



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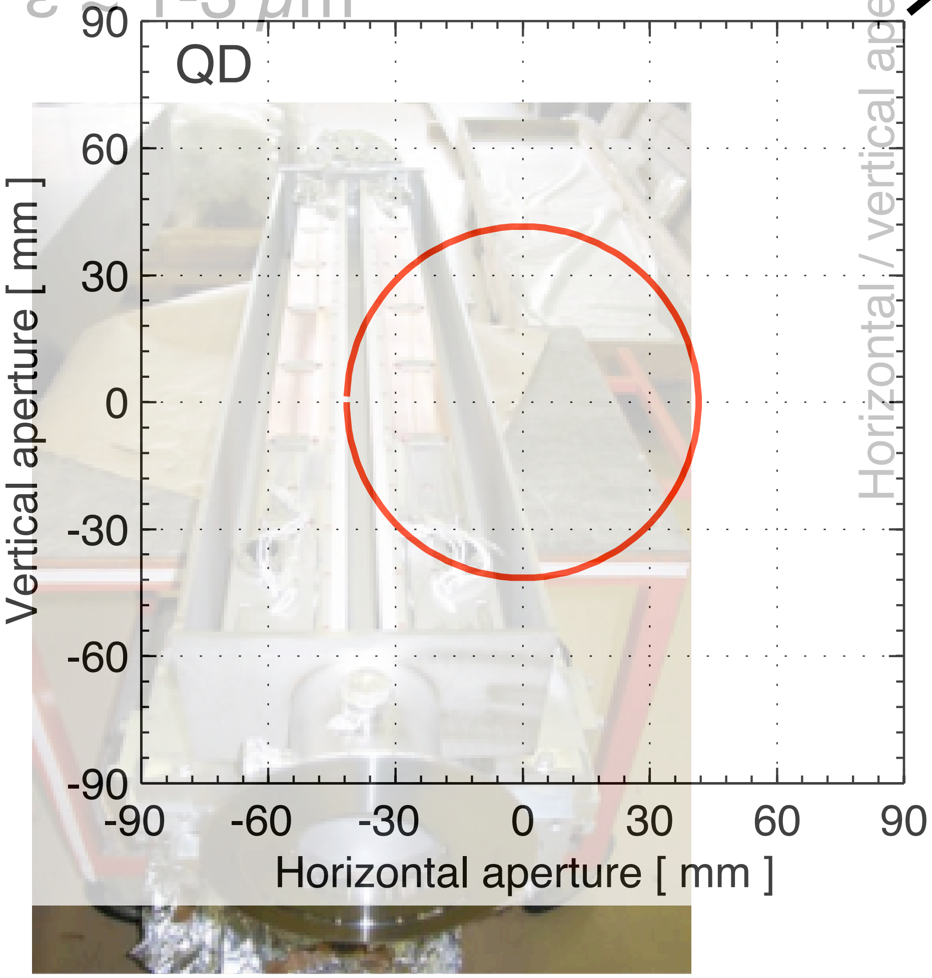

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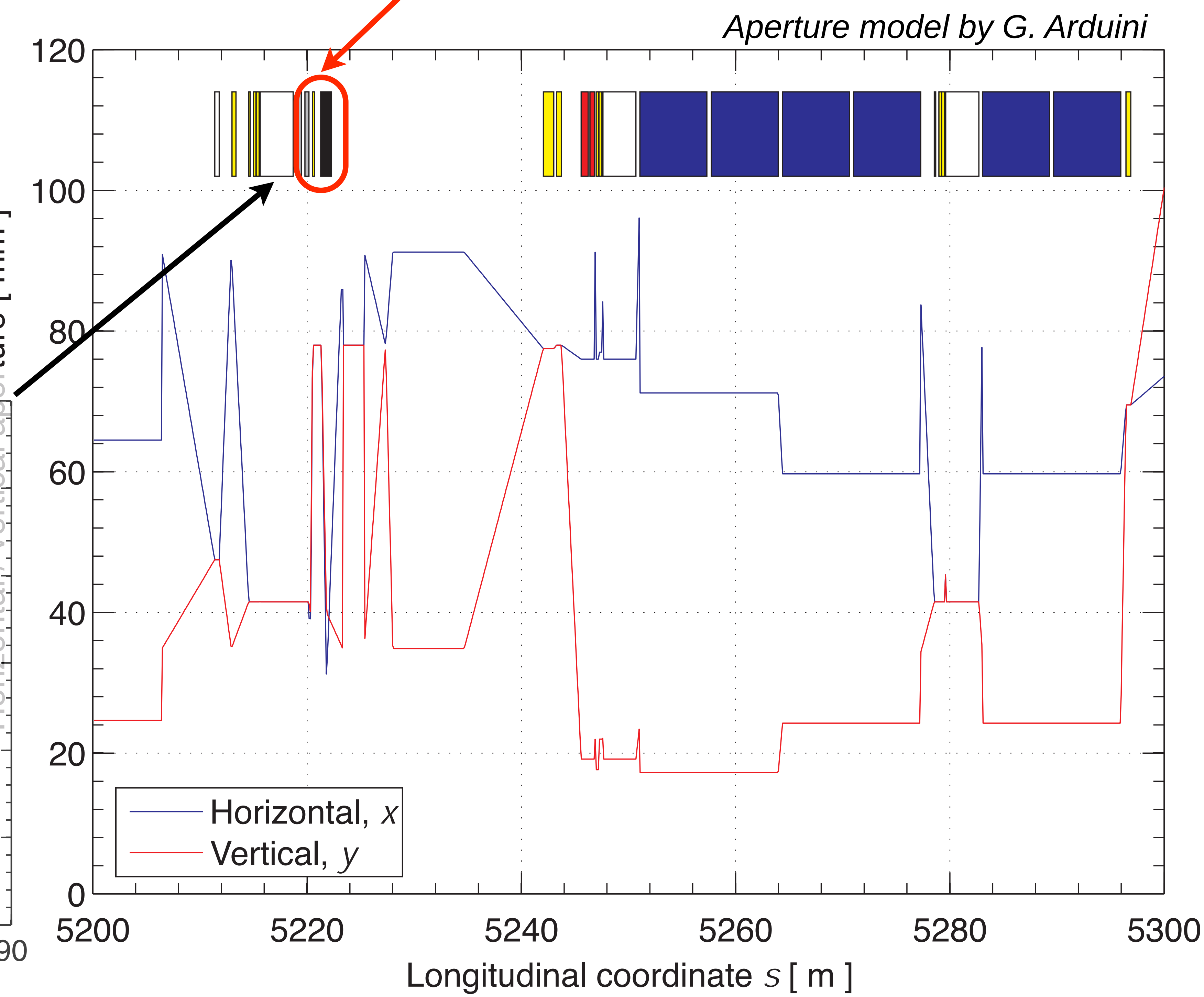

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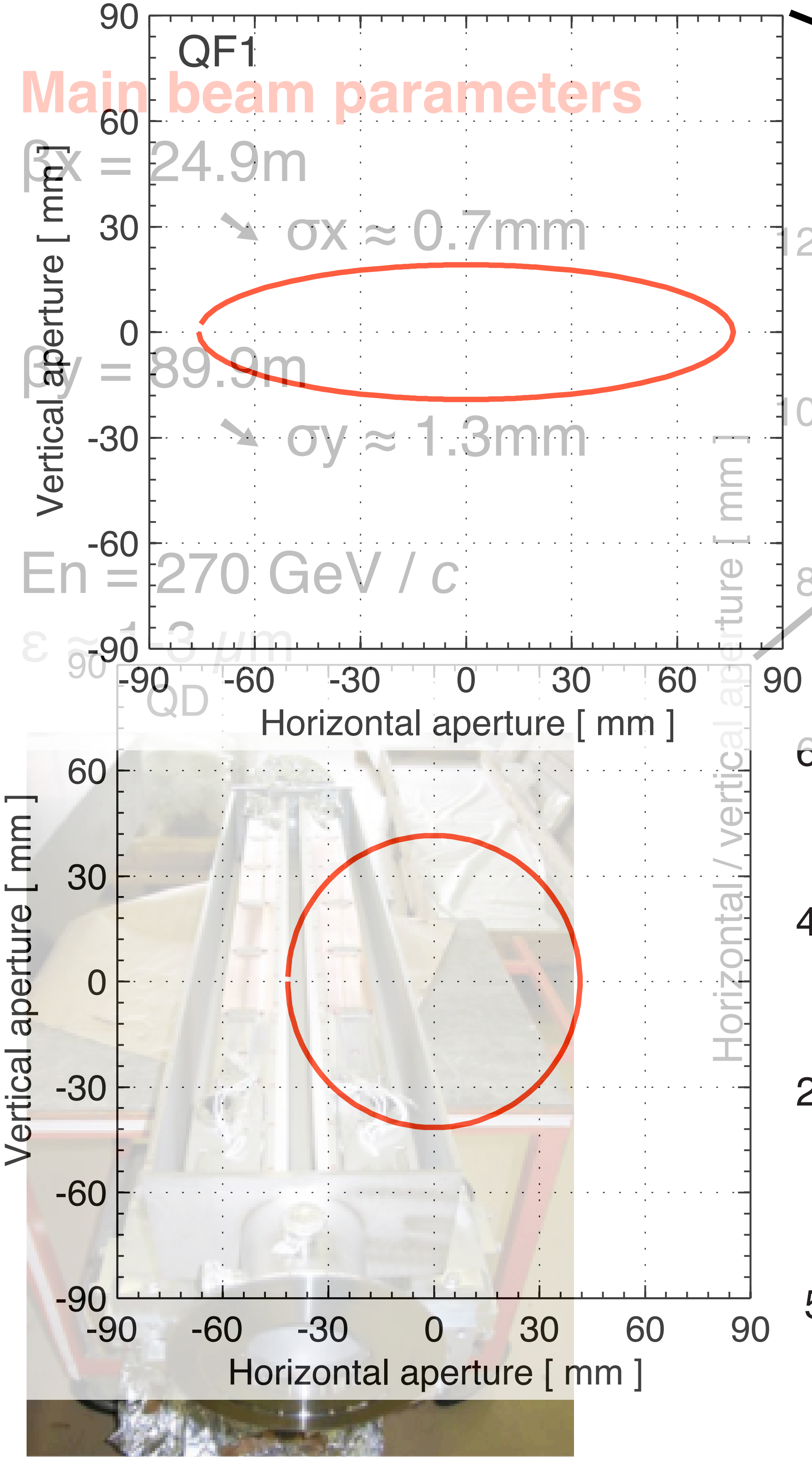

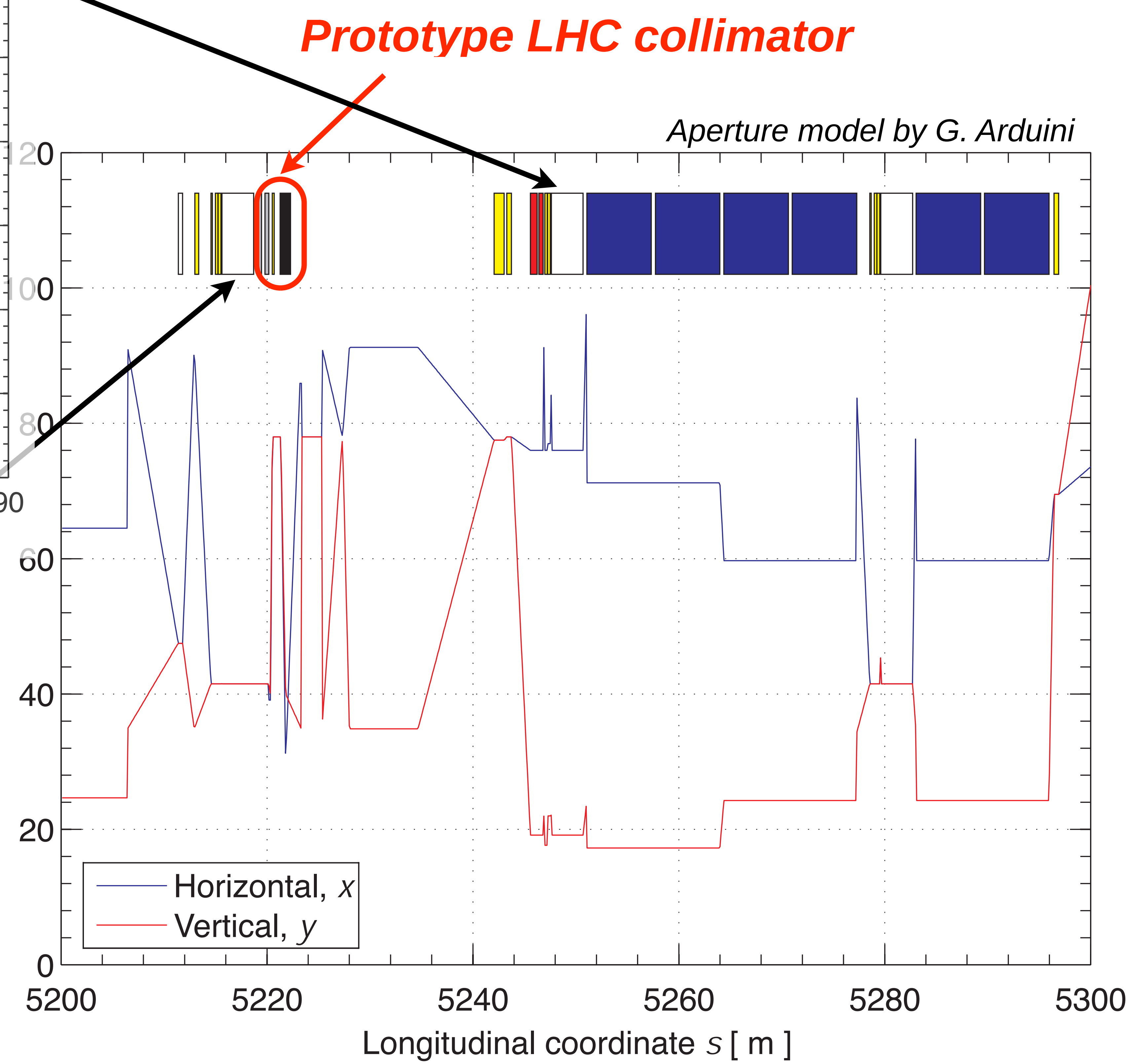

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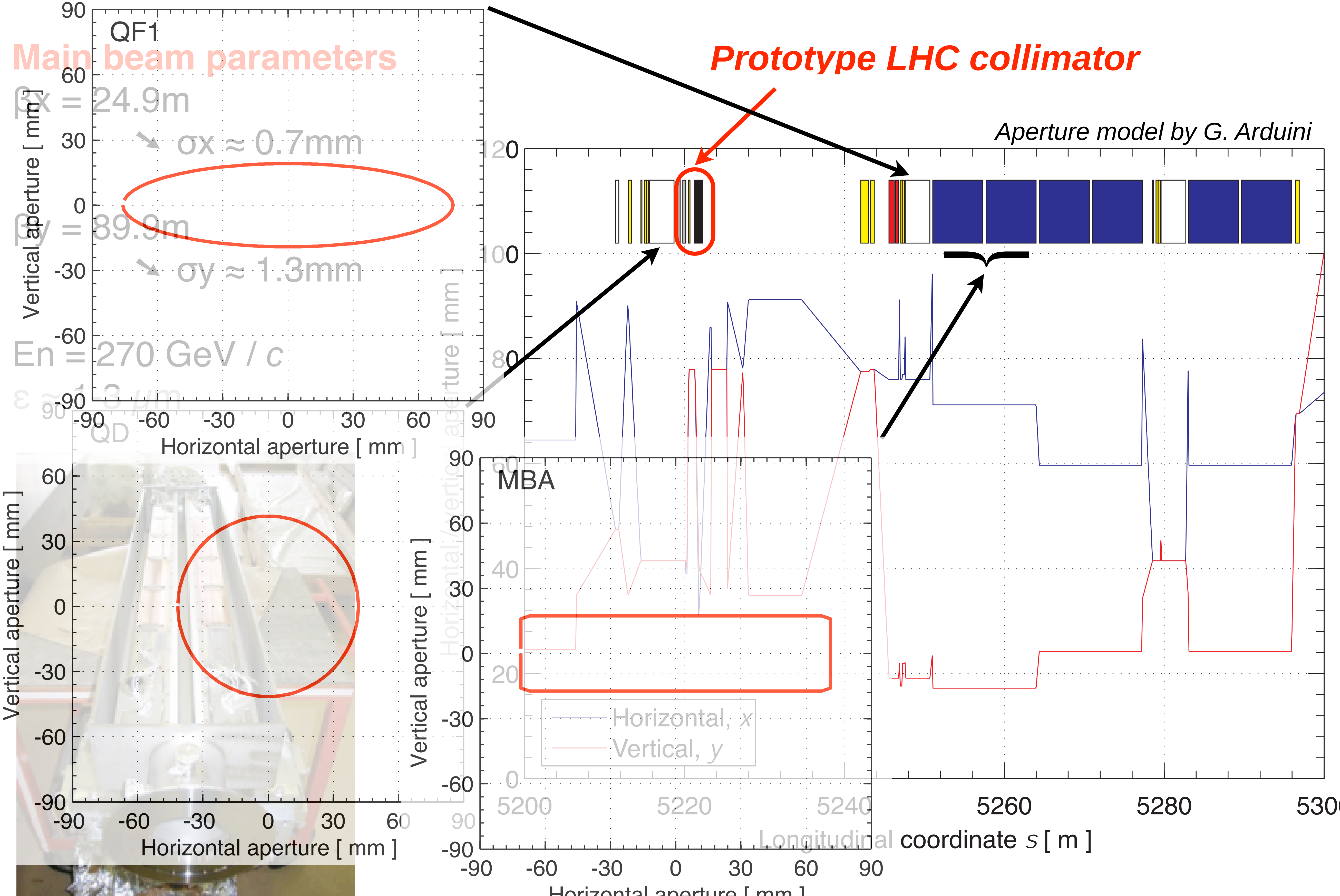

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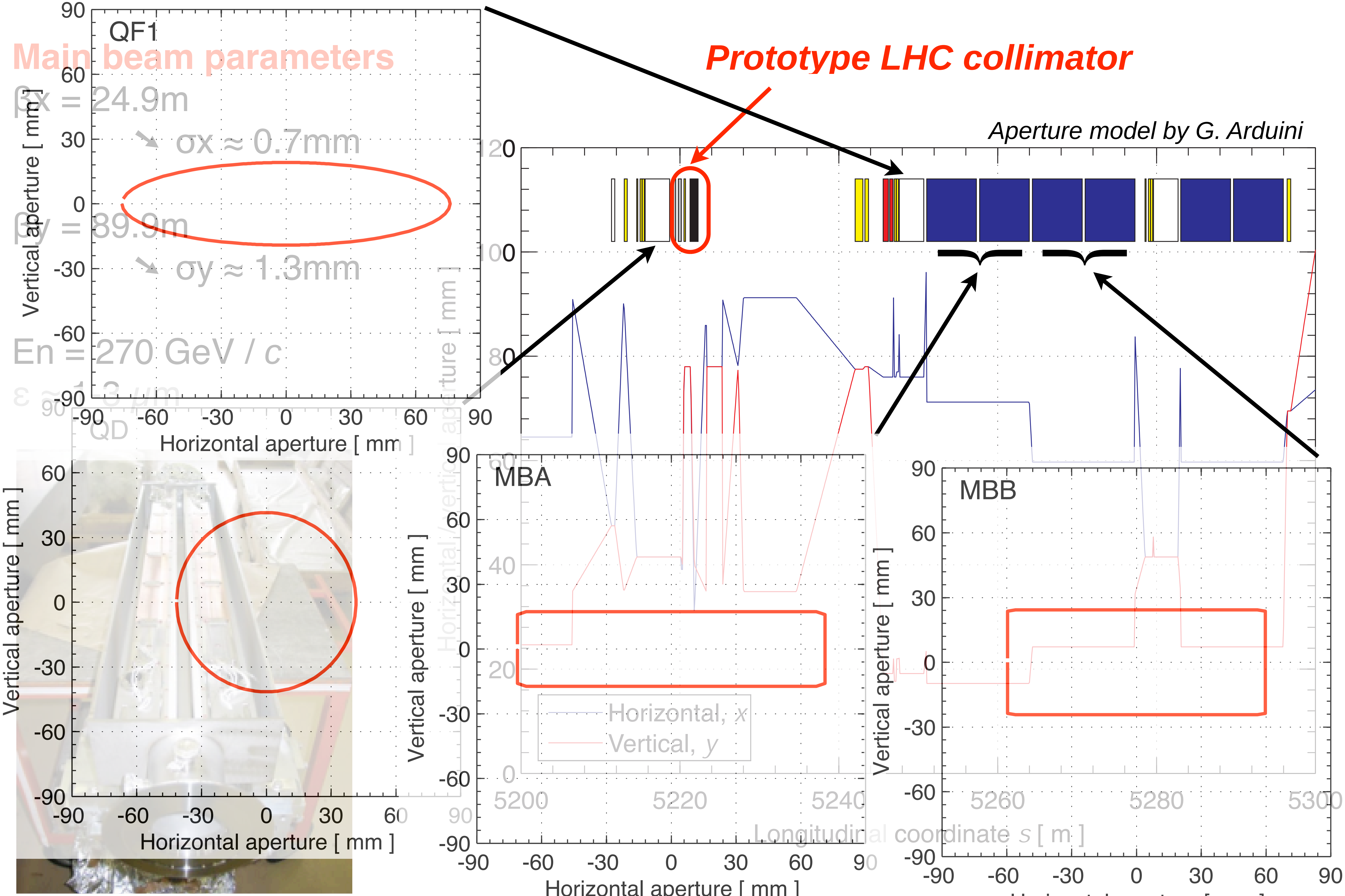
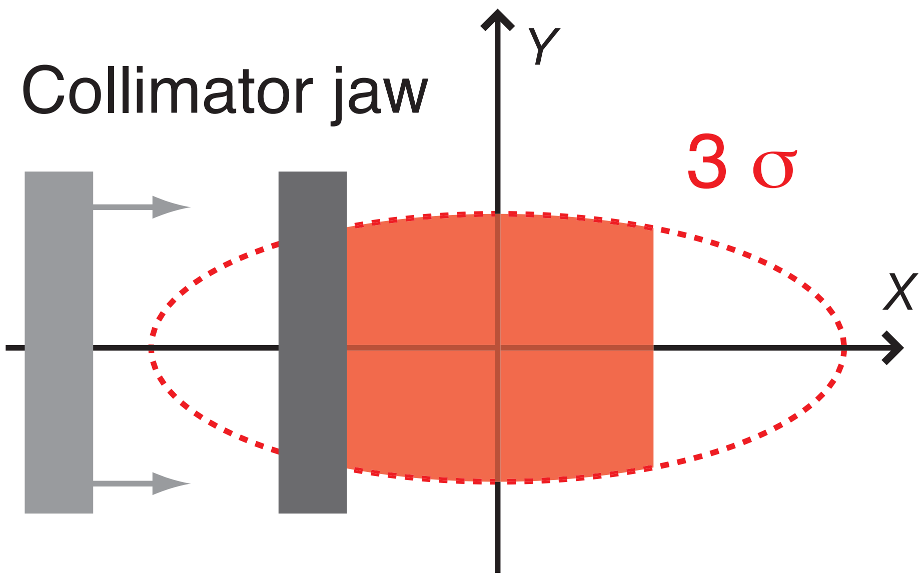


Generation and measurement of losses

Lifetime of SPS coasting beam: ***> 100h****! How do we generate proton losses?*

→ *Full or partial* ***beam scraping*** *with the collimator jaw!*



Simulations were updated to include ***time-dependent jaw movements****:*

- 1 or 2 jaws can be moved at a speed of 2 mm/s
- **20000 turns** for the sweep across the beam

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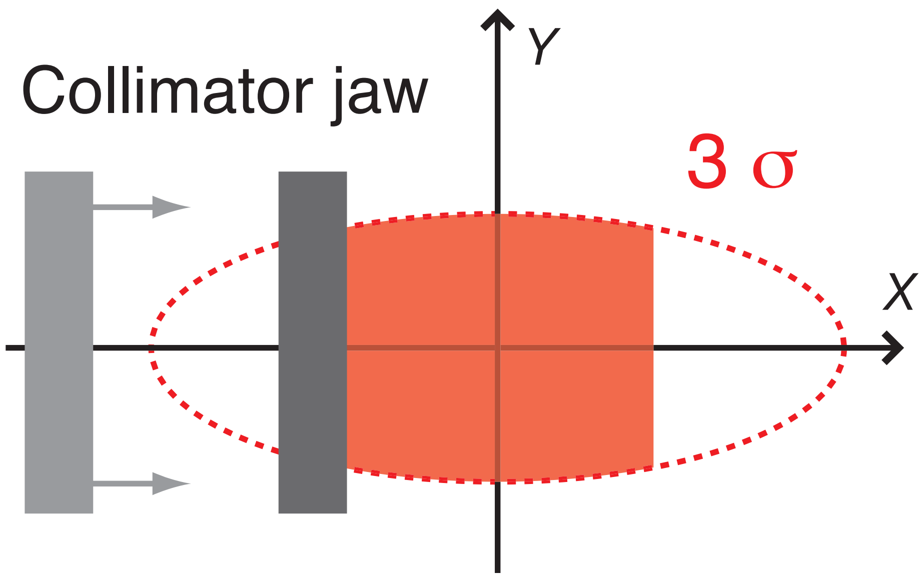

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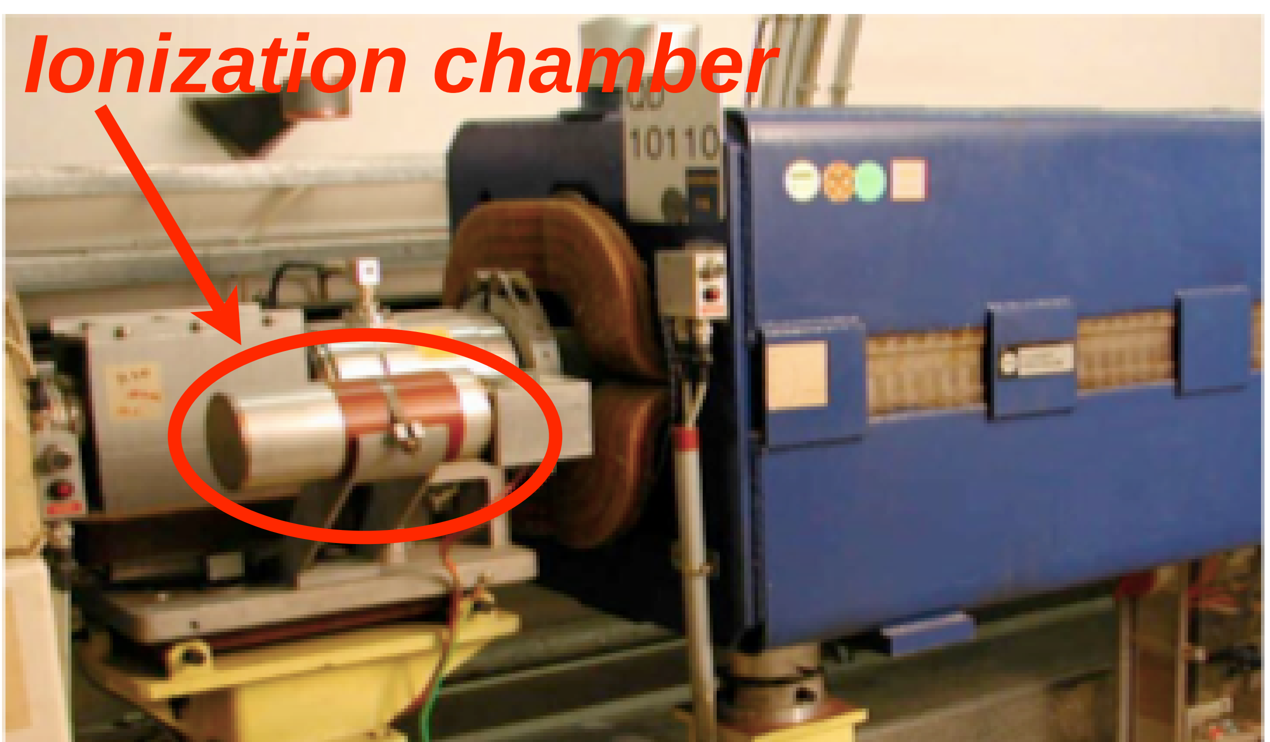
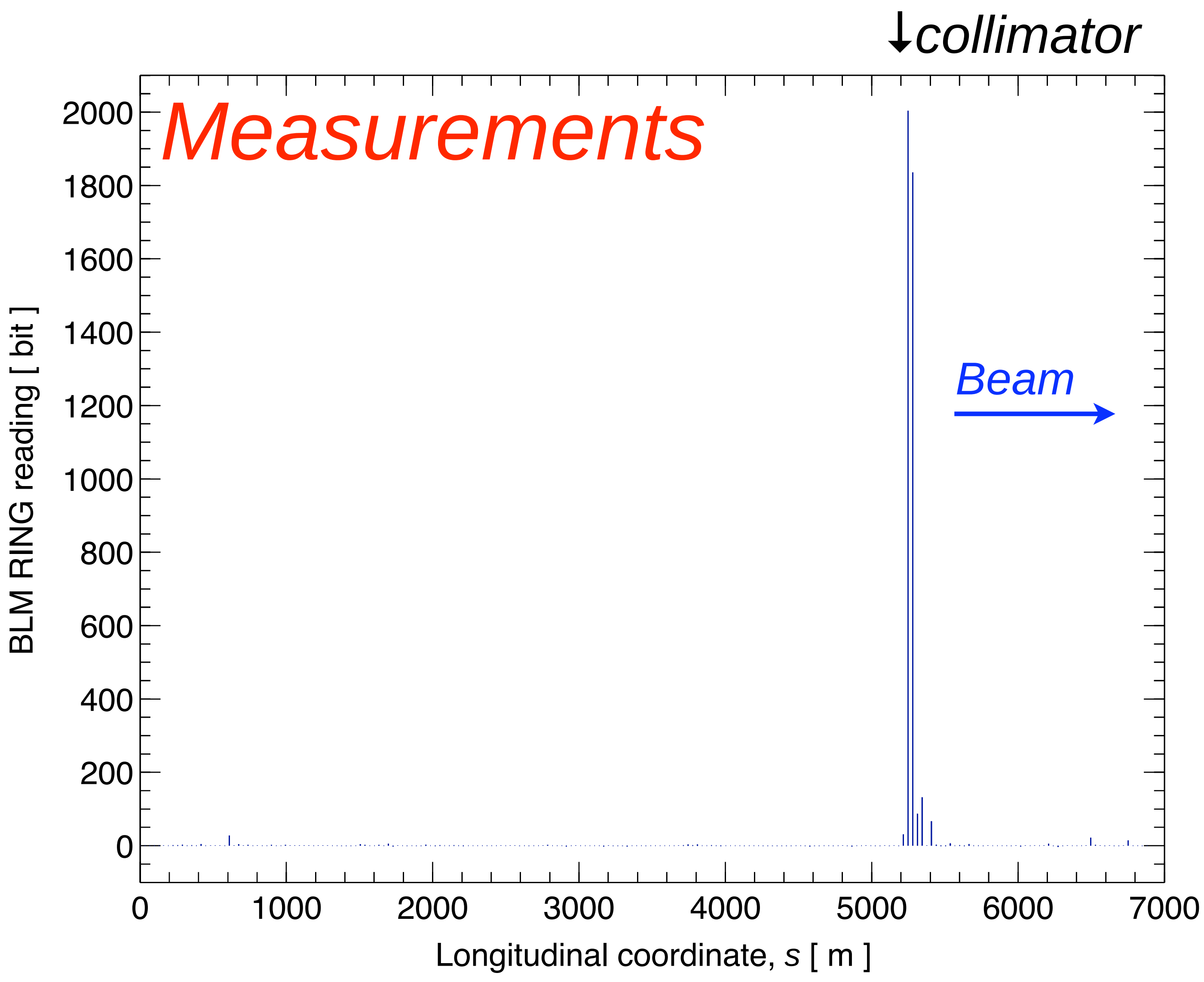
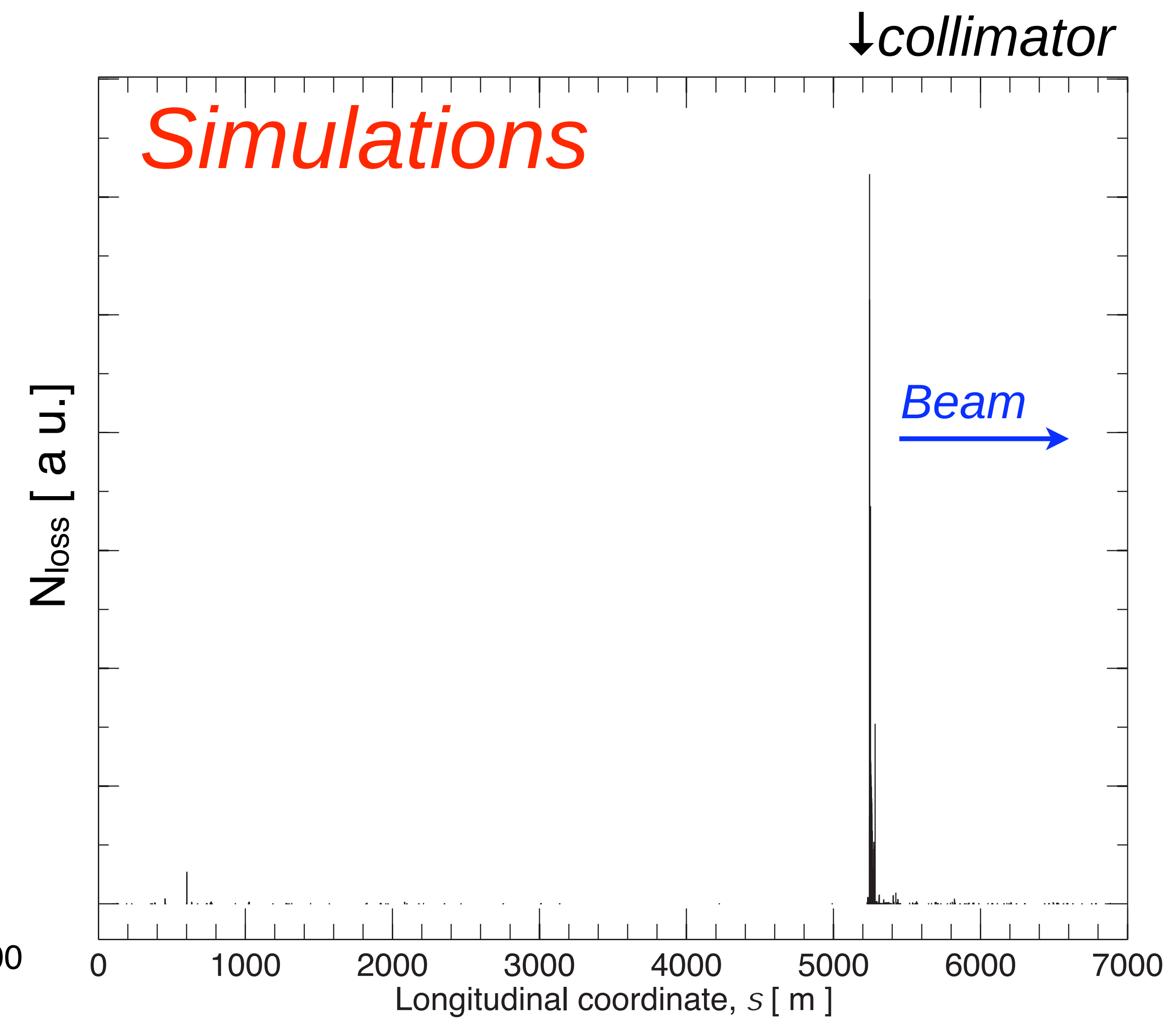


- One ionization chamber per quadrupole
  - → Total of 36x6=216 BLM's
- QD (smaller σ_x) have one H monitor and vice-versa
- Losses integrated over 1 super-cycle of ~ 25 s

Comparison of overall loss pattern





Overall loss pattern along the full ring is correctly predicted!

- Main losses immediately downstream of the collimator
- Next significant peak at an SPS collimator, >2.5km downstream!

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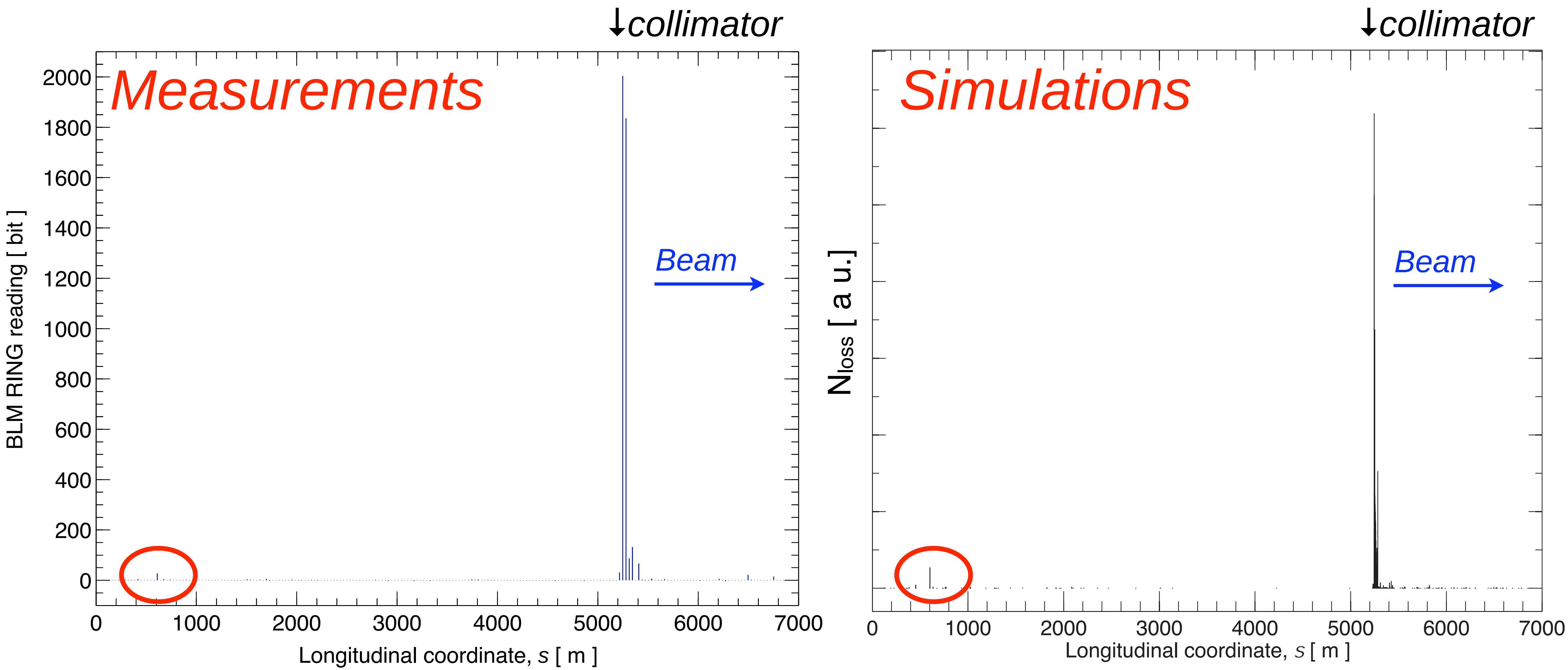

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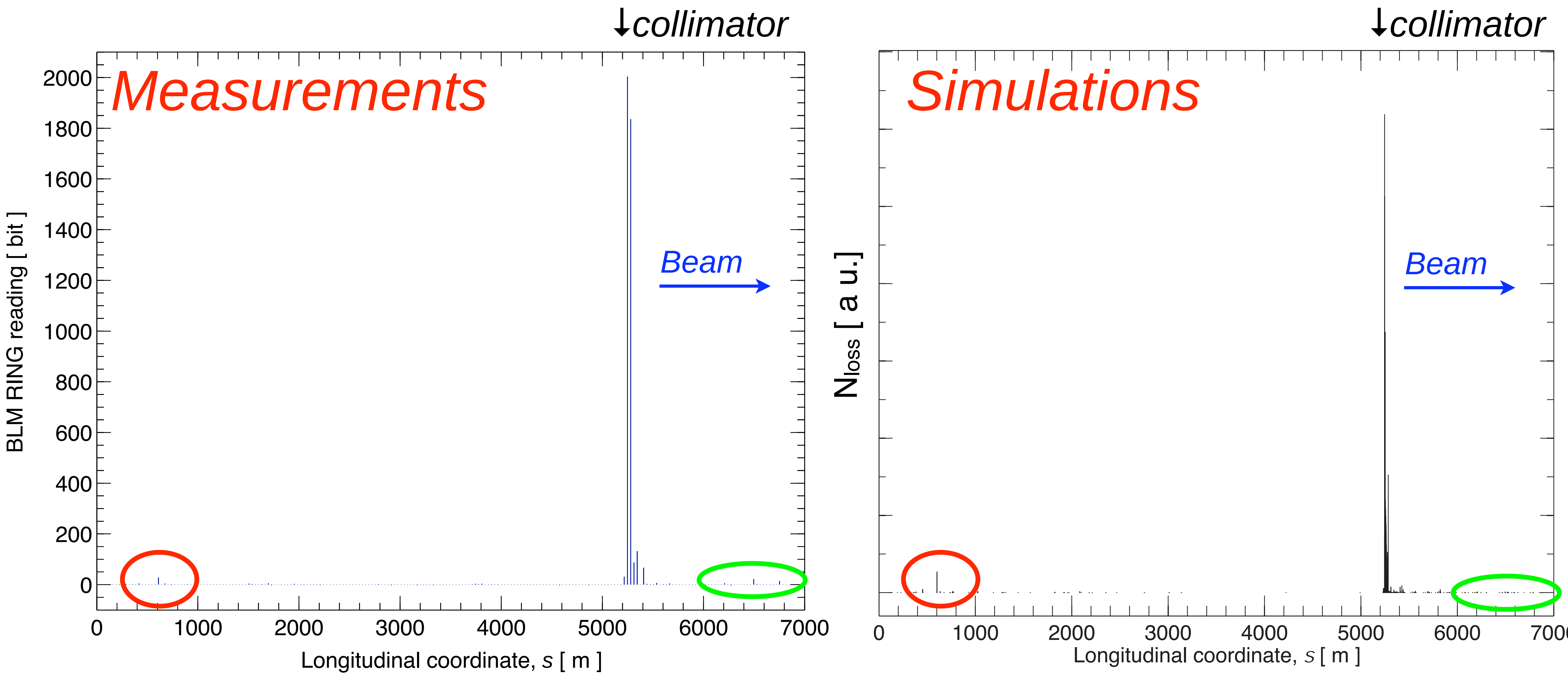

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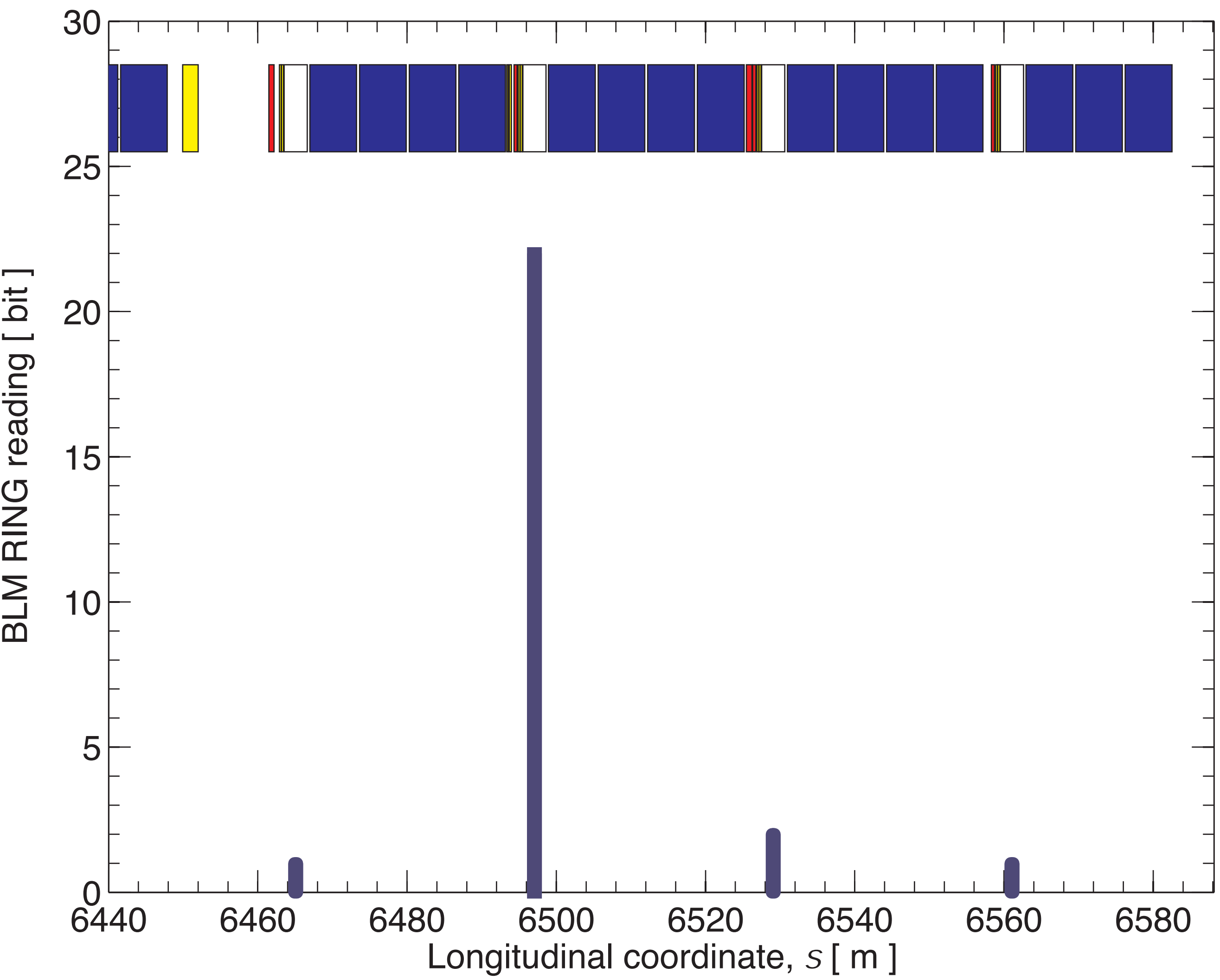
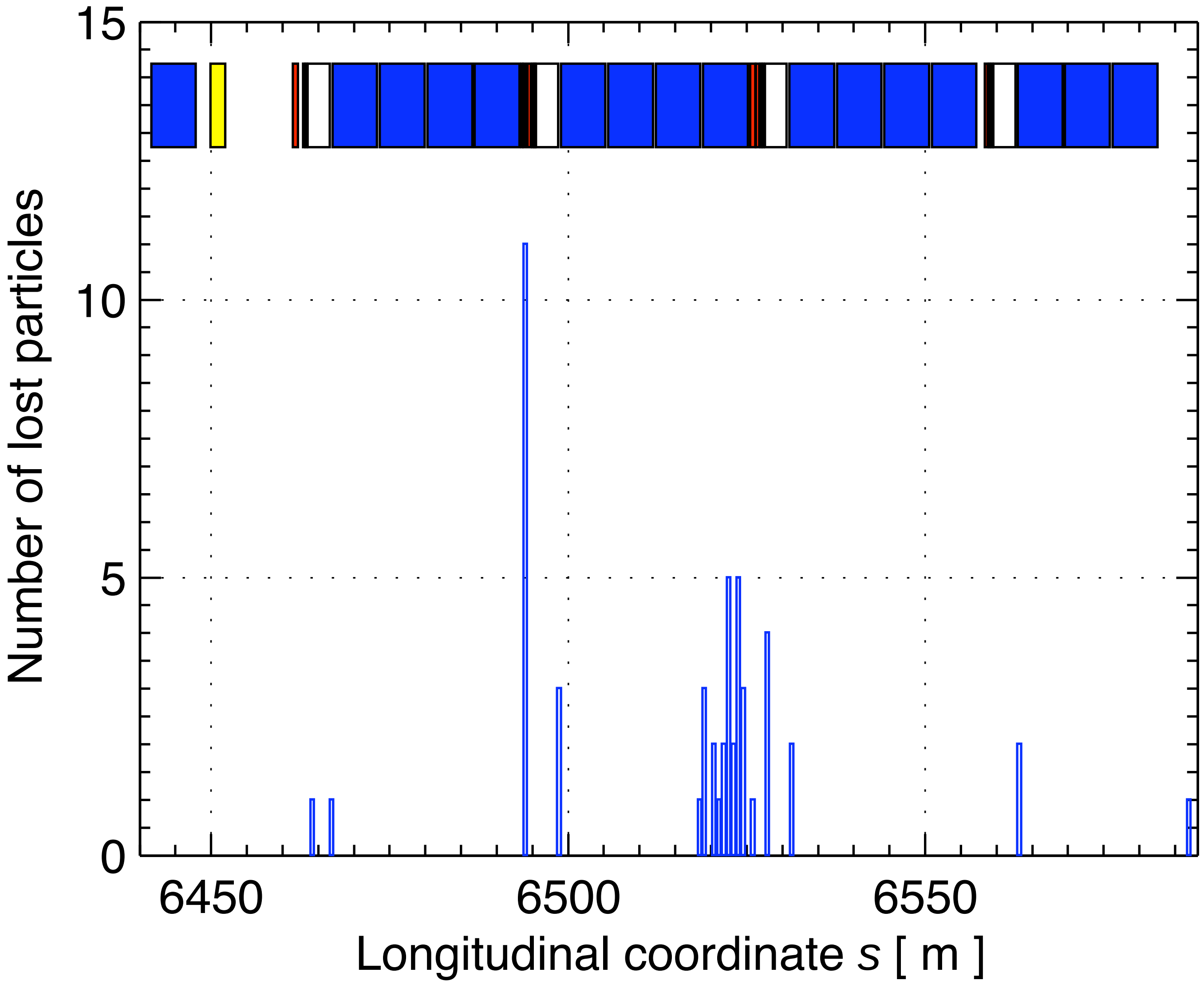
We look at small loss peaks in regions with no collimators:

Measurements



Simulations



Simulations agree qualitatively with measurements also at locations without collimators!

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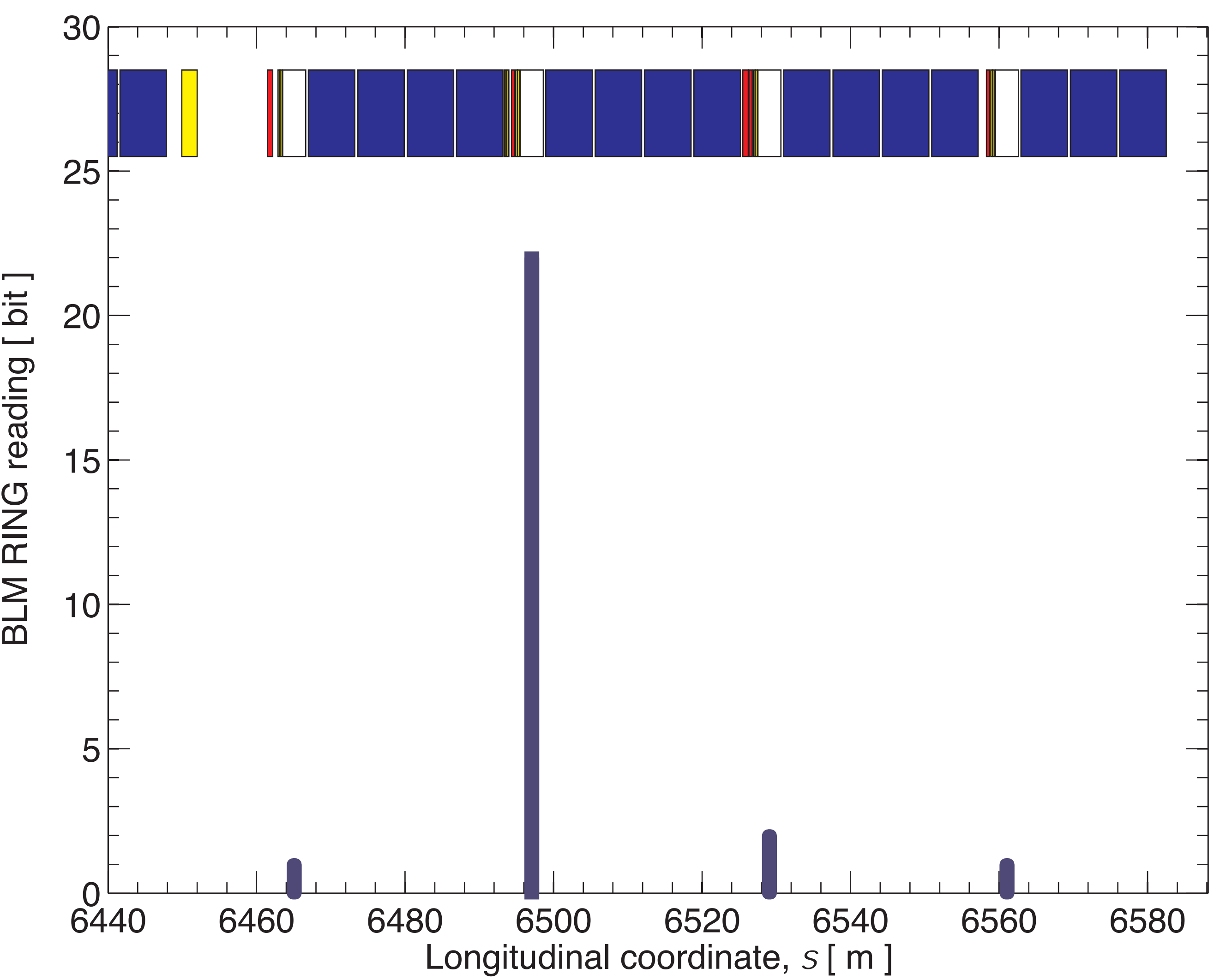

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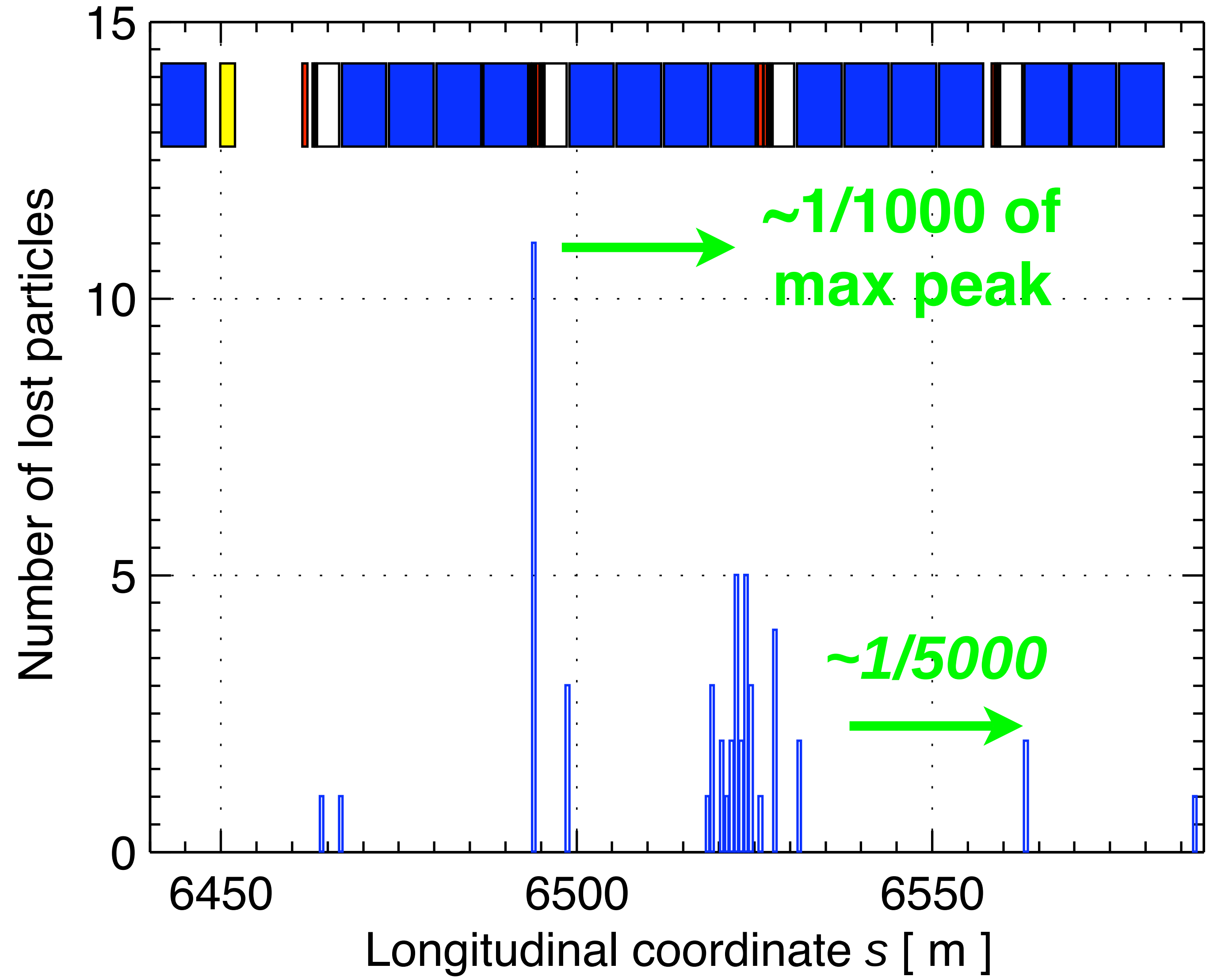

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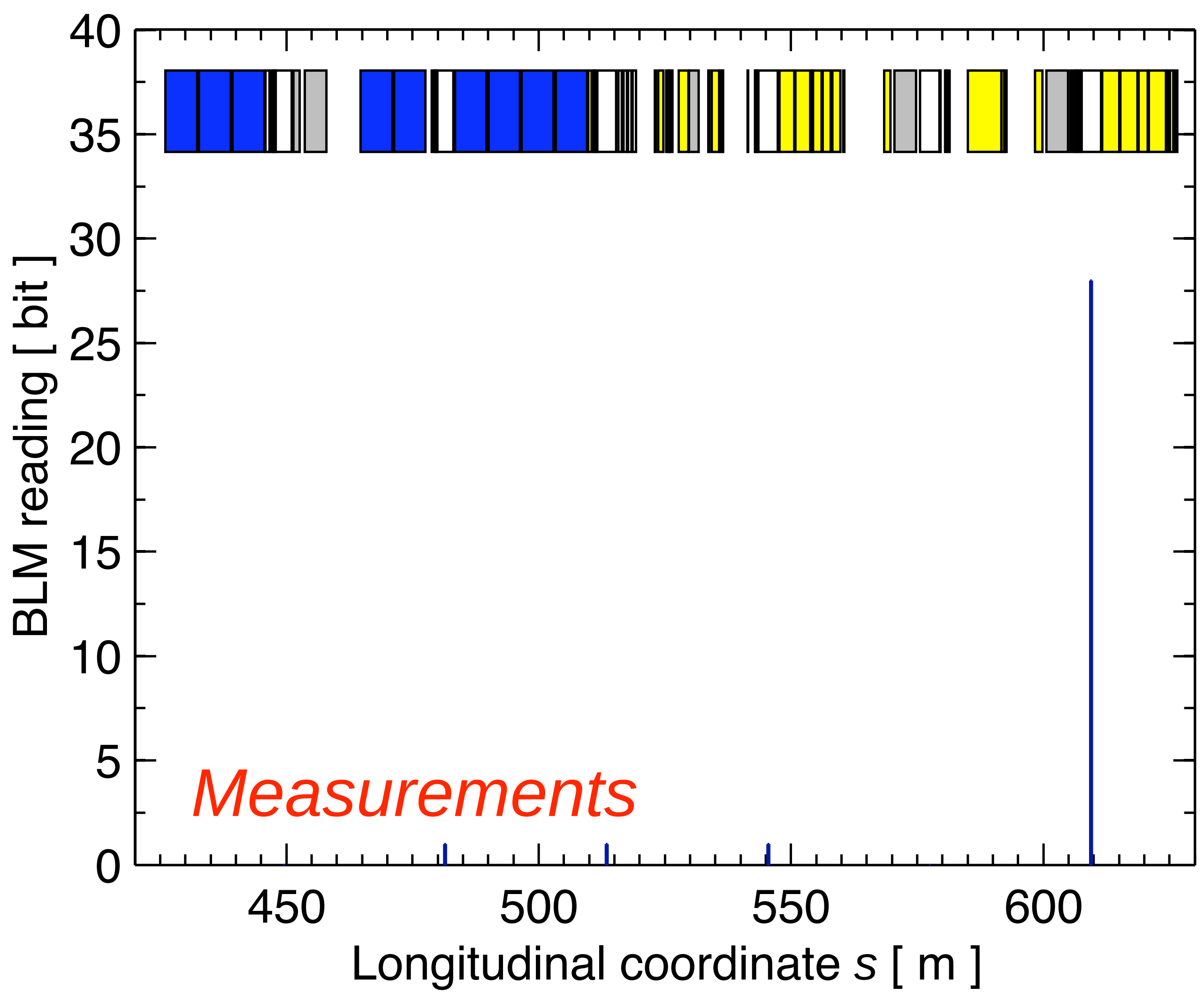
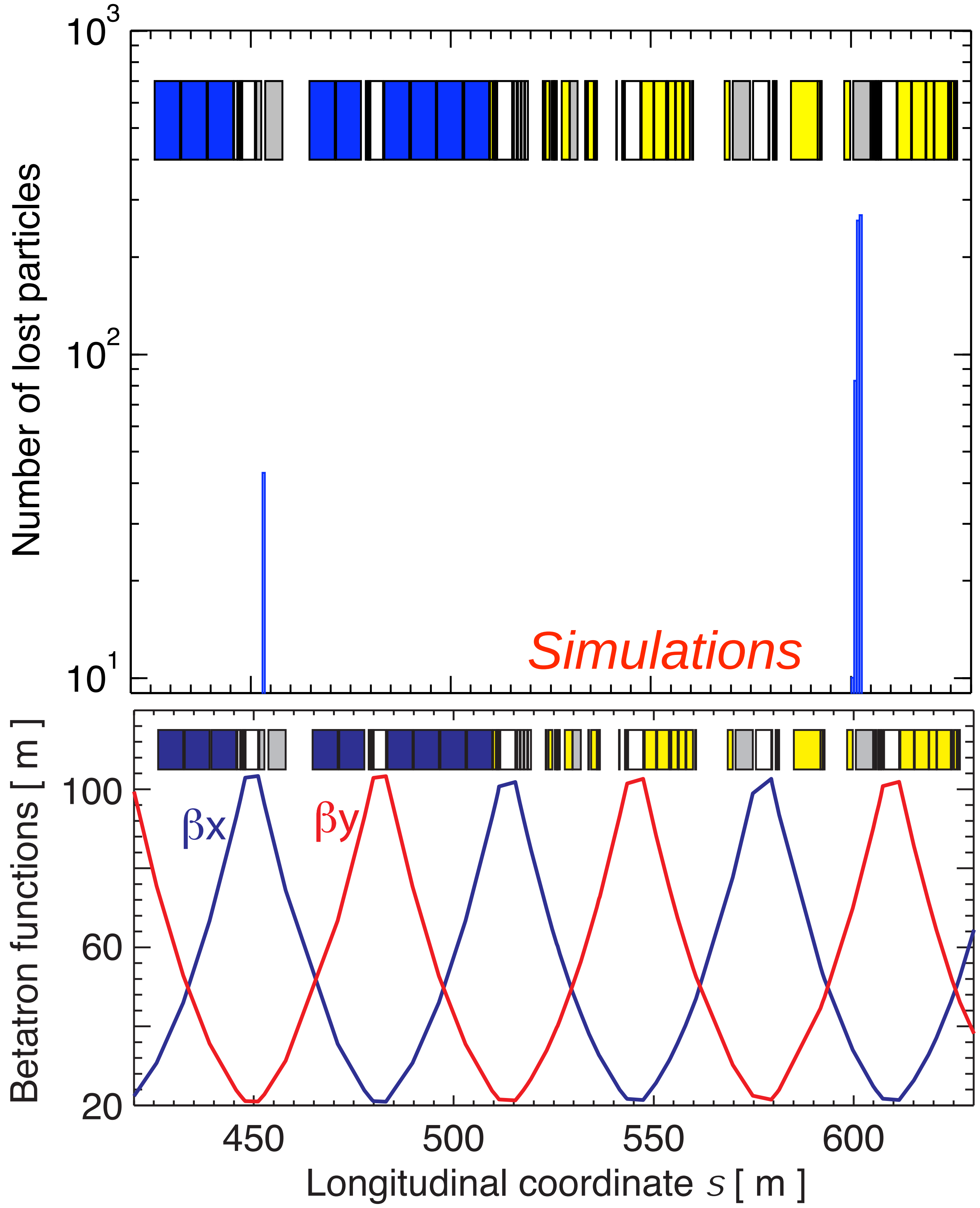
Simulation further downstream





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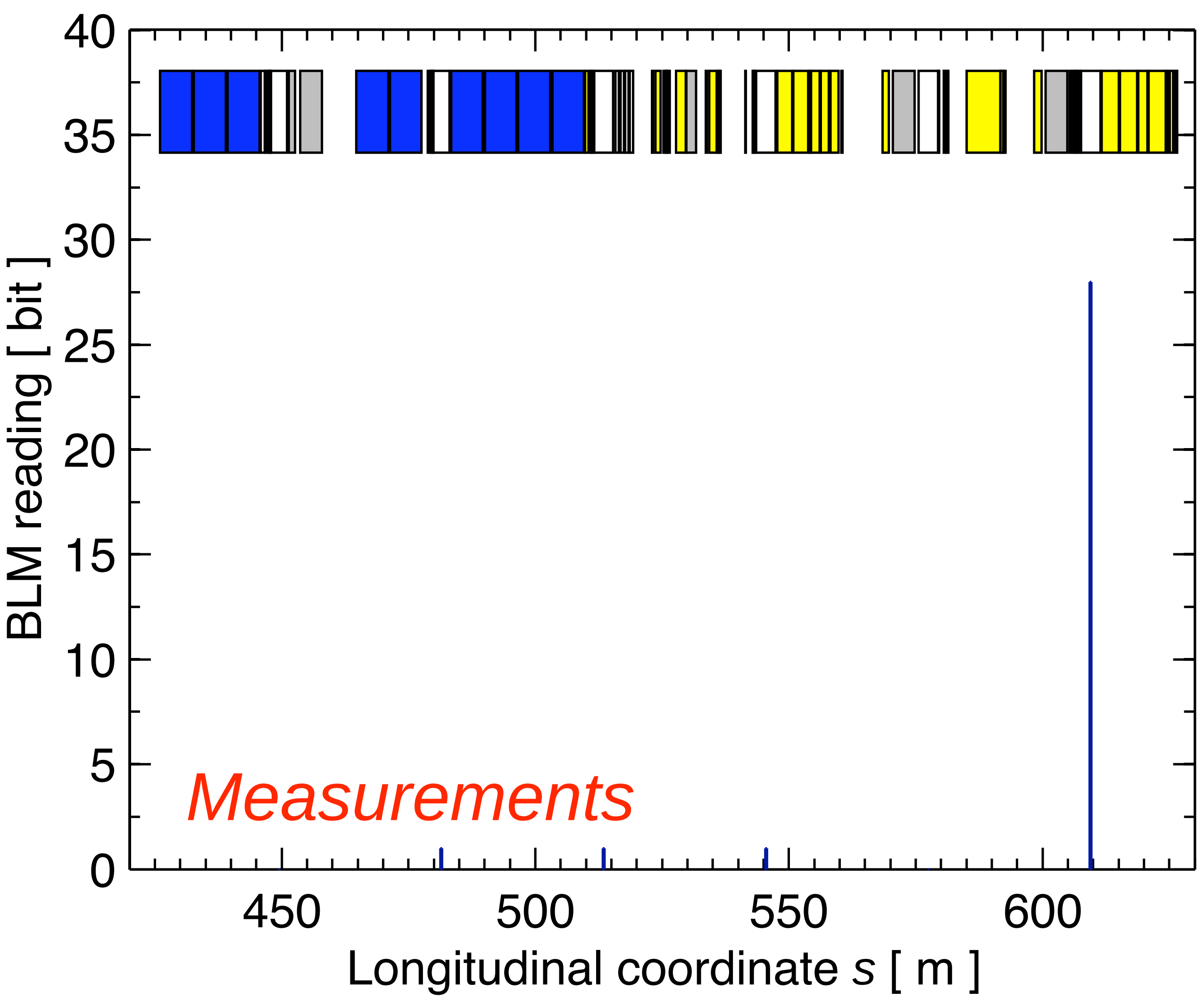

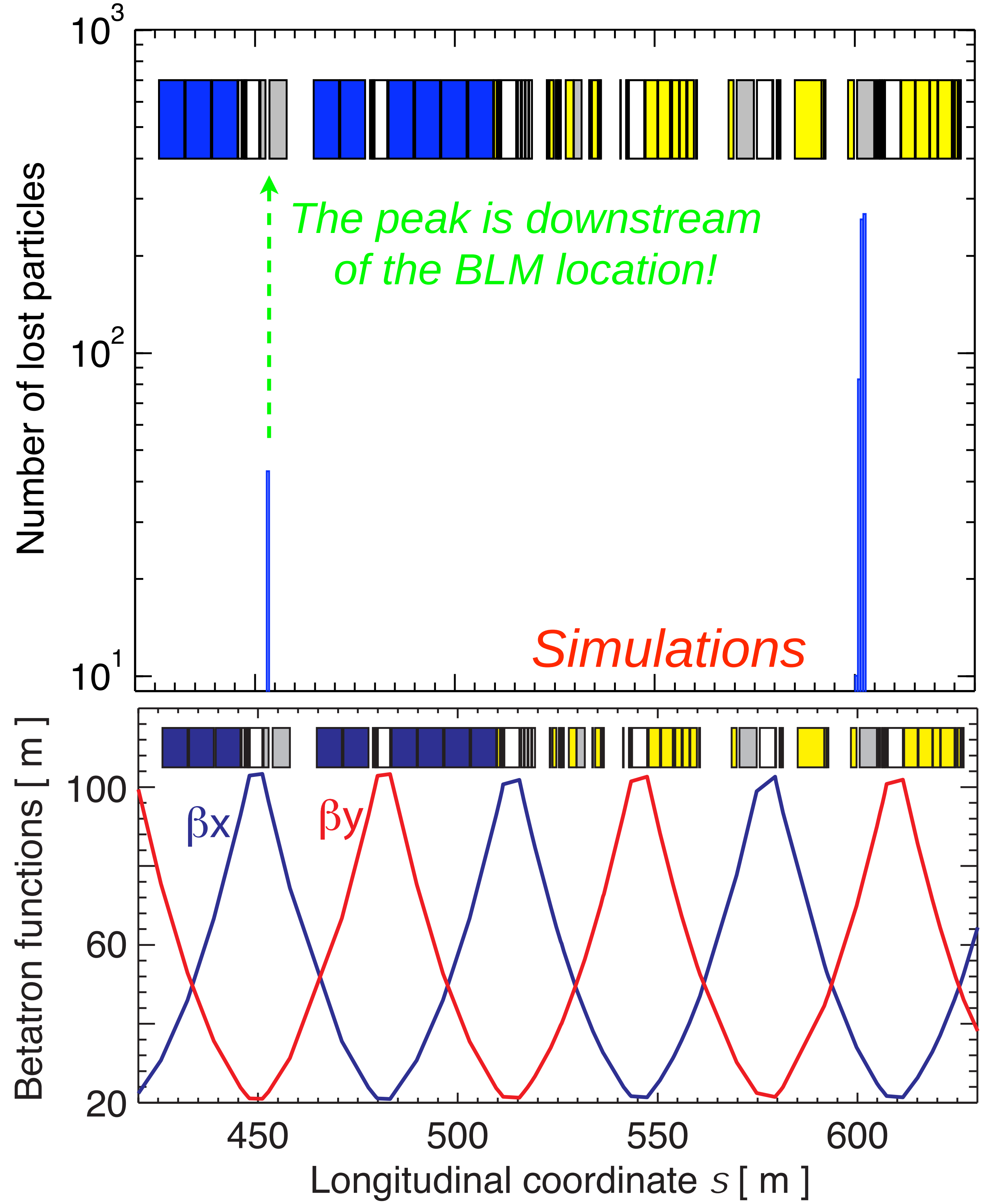

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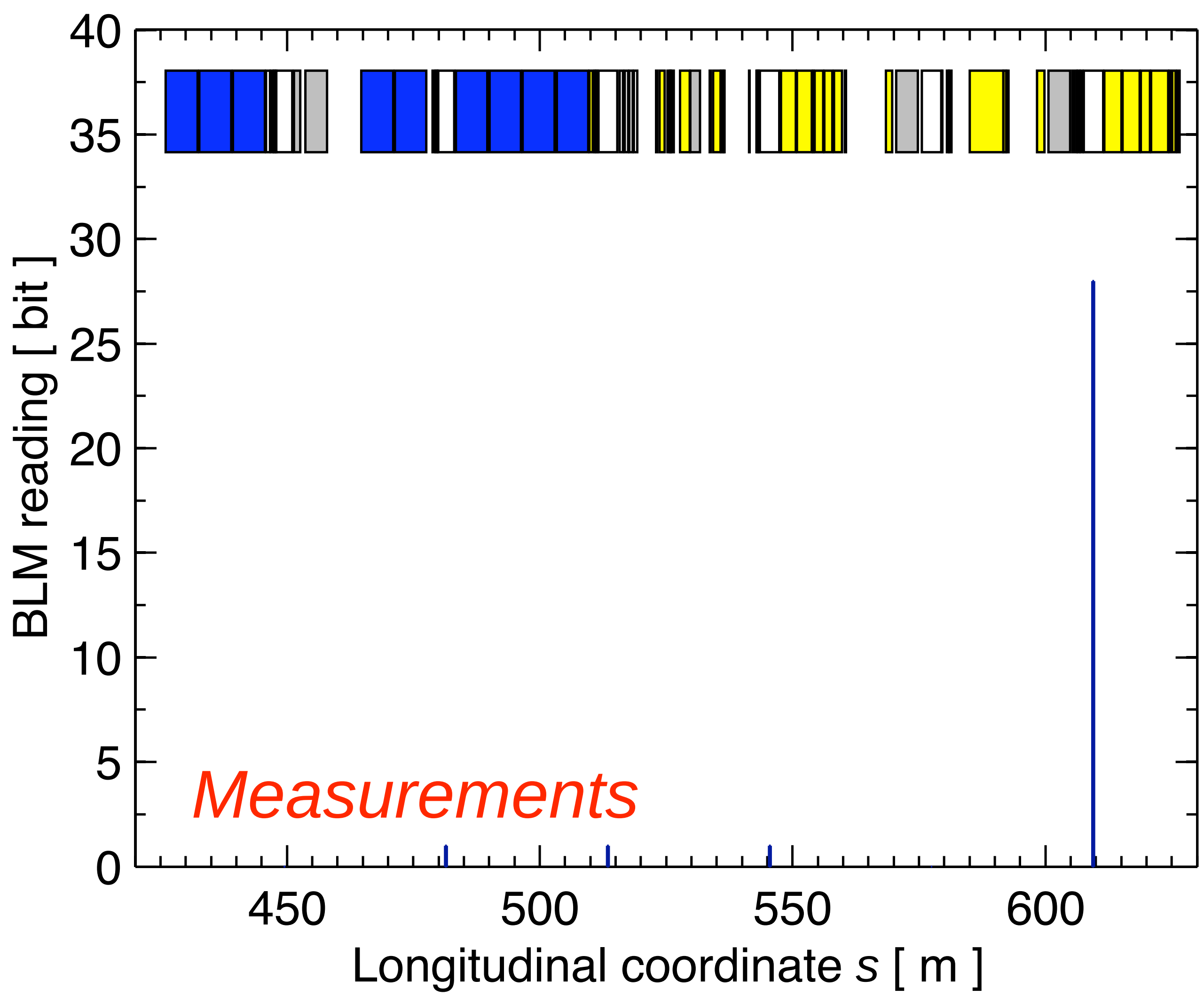
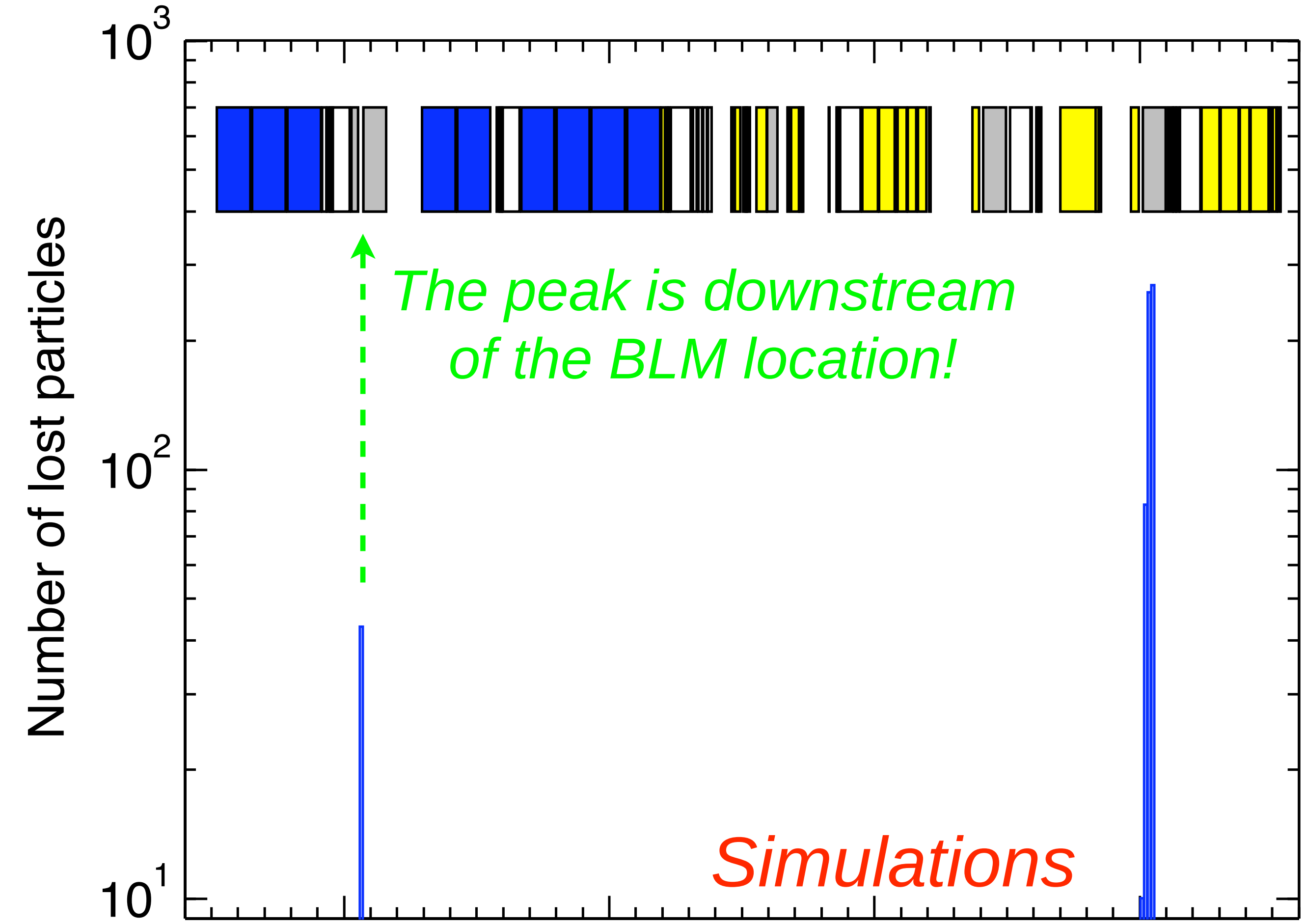
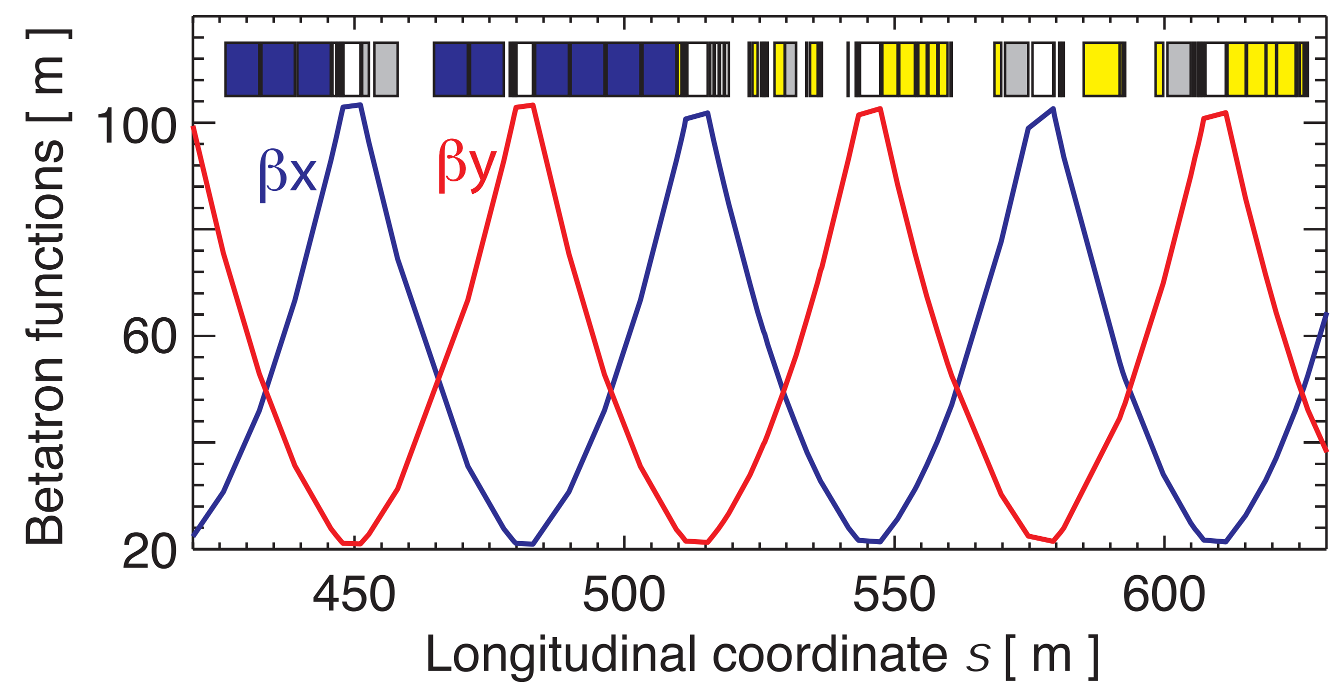


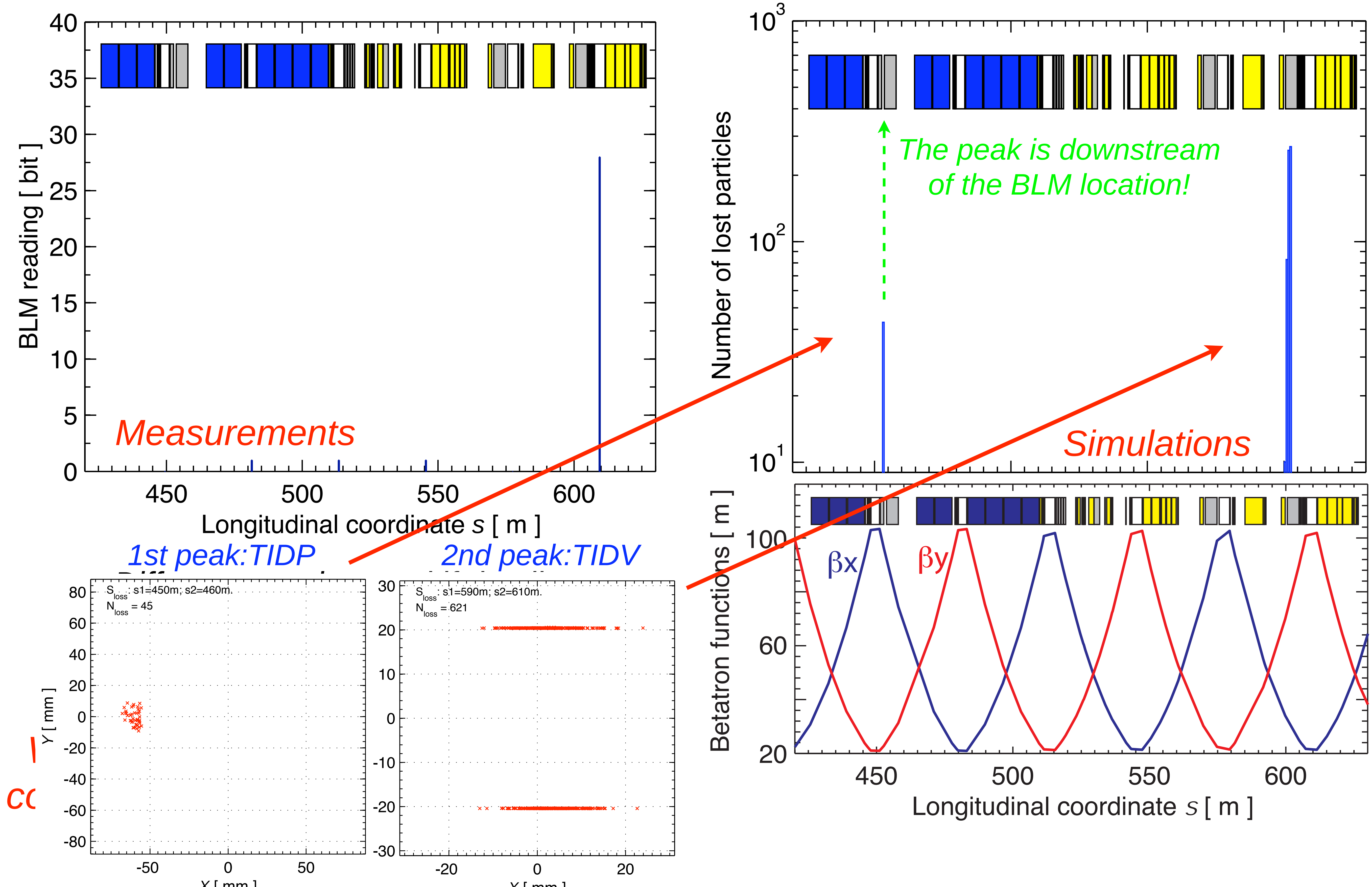




Difference understood if details of BLM mounting are taken into account!

We can nicely simulate losses but, of course, cannot measure without BLM's!

Simulation further downstream



Conclusions

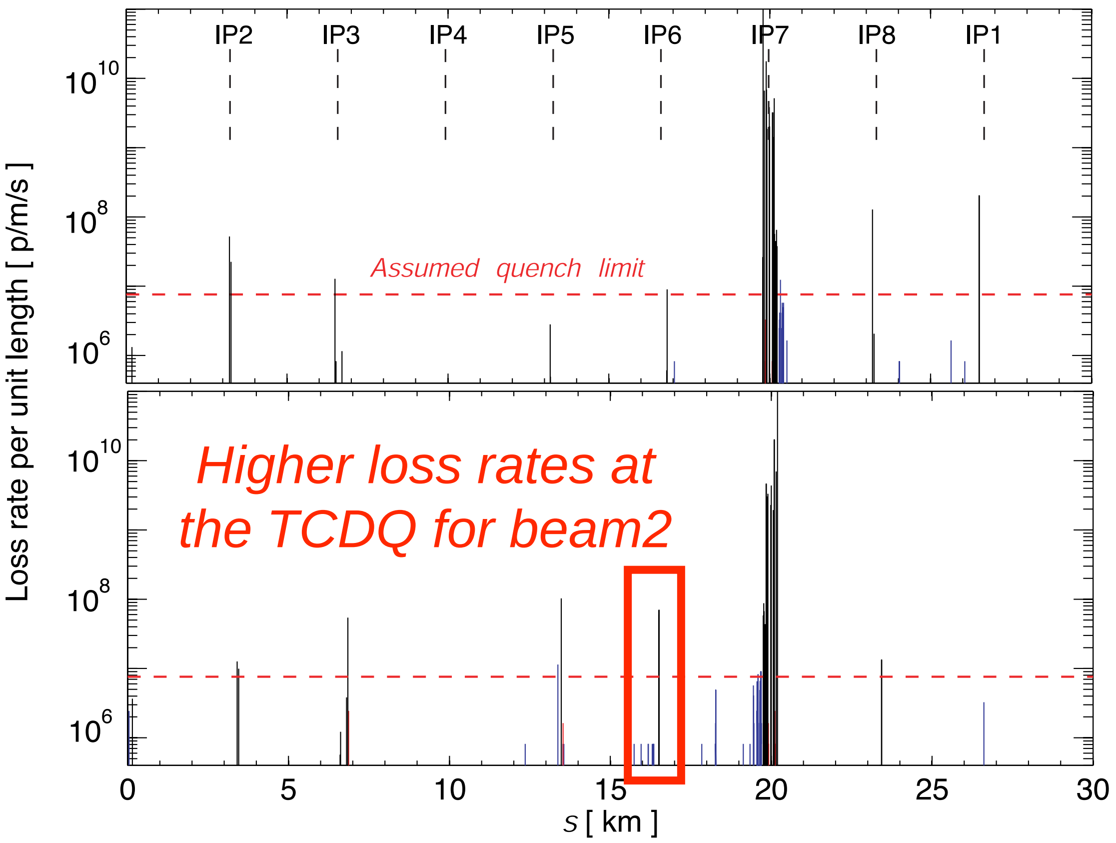
- The simulation tools for LHC beam loss studies were presented
- Codes evolved during the years to match the increasing complexity of the LHC collimation system
- Played a major role in the improvement of the final multi-stage system from the original 2-stage cleaning
- Detailed error models developed to understand the performance of the realistic and “as-built” machine
- Crucial importance for energy deposition and background studies
- Tools are portable end documented on the web - extension to other machines is straightforward!
- Application to collimator induced beam loss at the SPS showed a good agreement between simulations and measurements

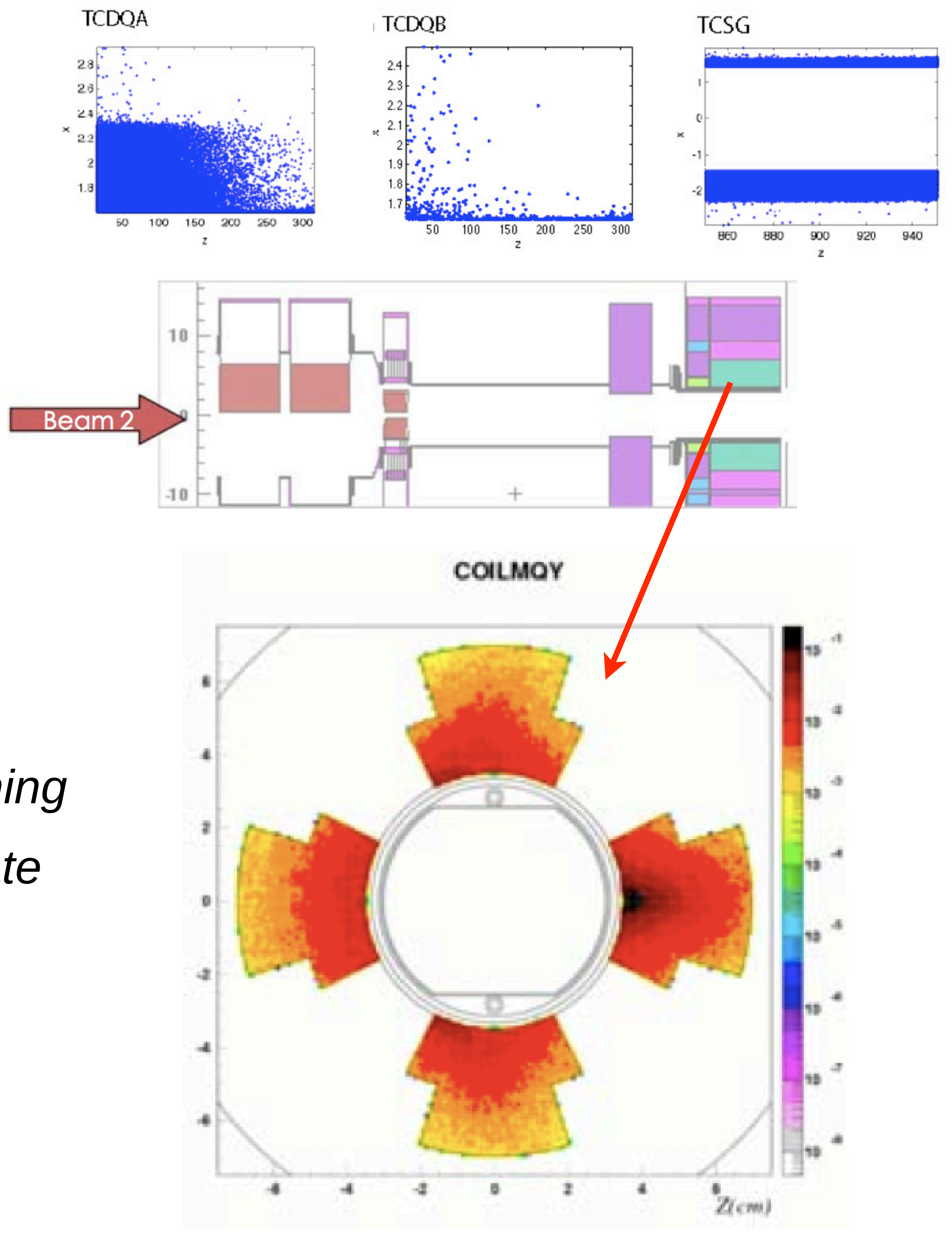
Acknowledgments

- AB-ABP-LCU members
  (M. Giovannozzi, W. Herr, S. Fartouhk)
- AB/ATB members
- F. Schimdt
- J.B. Jeanneret
- CERN BLM team
- M. Jonker
- SPS operation crew (G. Arduini, J. Wenninger)

Reserve slides

Beam halo loads in the dump region

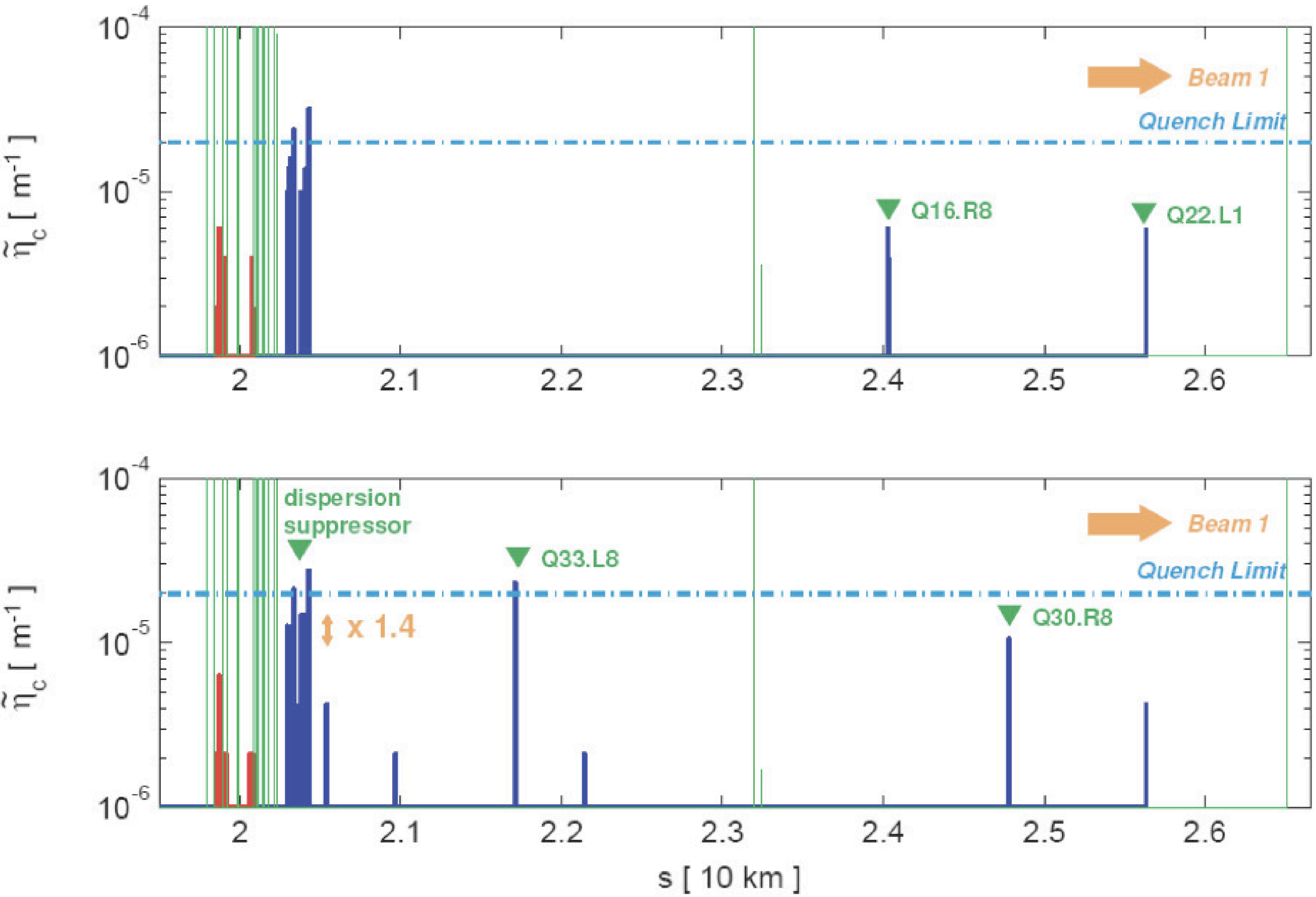




- *Critical loss rates for beam 2: dump region immediately downstream of betatron cleaning*
- *Detailed simulation campaigns to investigate commissioning scenarios with reduced collimation system (C. Bracco, T. Weiler)*
- *Proposed additional shielding to achieve ultimate intensities*

Energy deposition studies by L. Sarchiapone

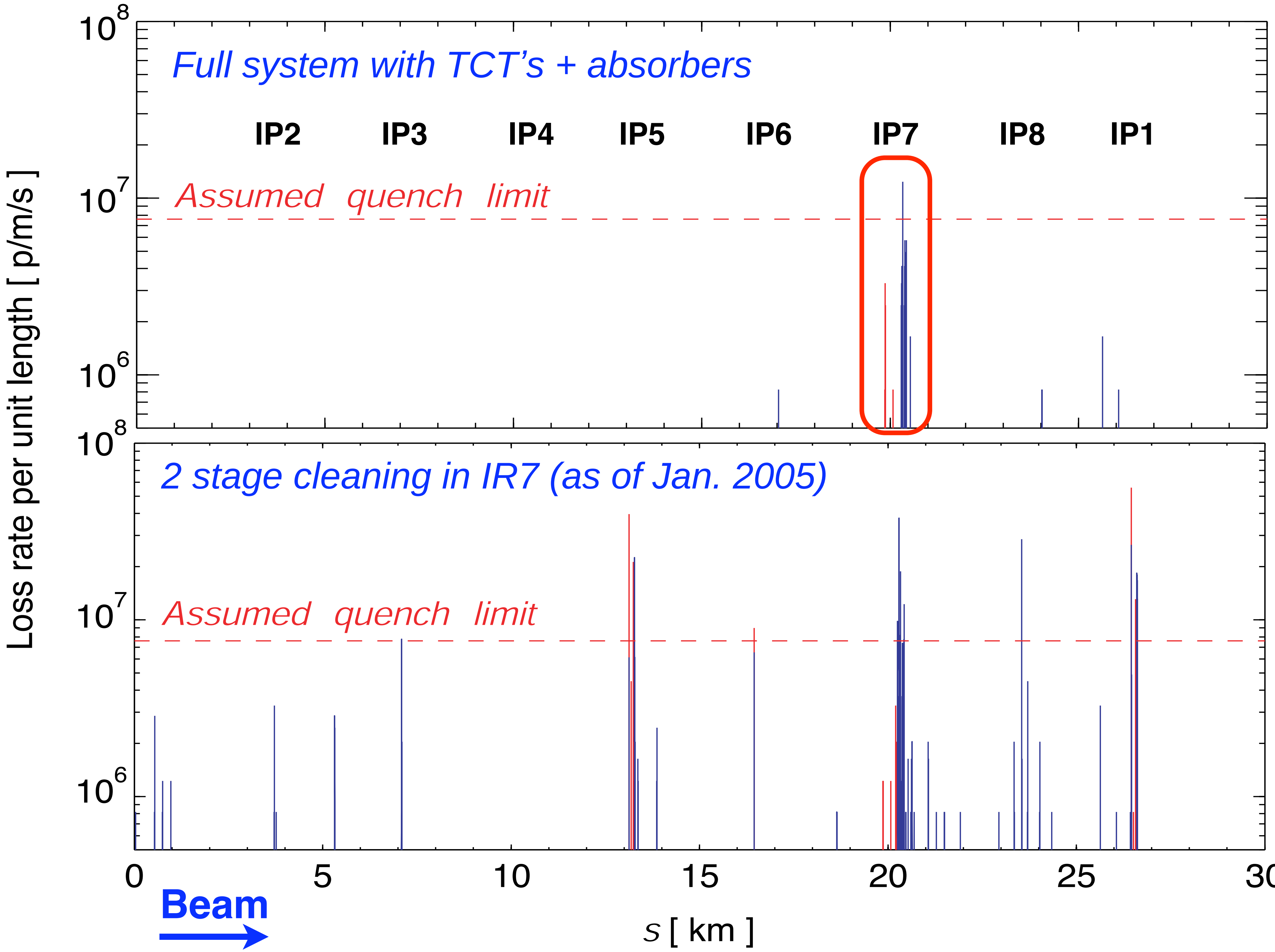
Closed-orbit distortions



Scenario	Energy [TeV]	$\tilde{\eta}^{cold}_{c,peak}$ [10^{-5} m^{-1}]	τ [h]	I_{max}/I_{nom}	R^{max}_{loss} [10^{10} protons/s]
Ideal machine	0.45	18.65 ± 1.96	0.1	5.38 ± 0.57	376.34 ± 39.72
	7.00	4.60 ± 0.96	0.2	0.43 ± 0.09	16.52 ± 3.44
Ideal machine with nominal orbit	0.45	40.60 ± 2.95	0.1	2.46 ± 0.18	172.41 ± 12.51
	7.00	7.45 ± 1.21	0.2	0.27 ± 0.04	10.20 ± 1.66

LHC tolerance: ± 4mm in arcs, ± 3mm in insertions. Scans of amplitude and phase of orbit errors to find critical spots. Extensive studies by G. Robert-Demolaize (PhD work).

Improvements of the system

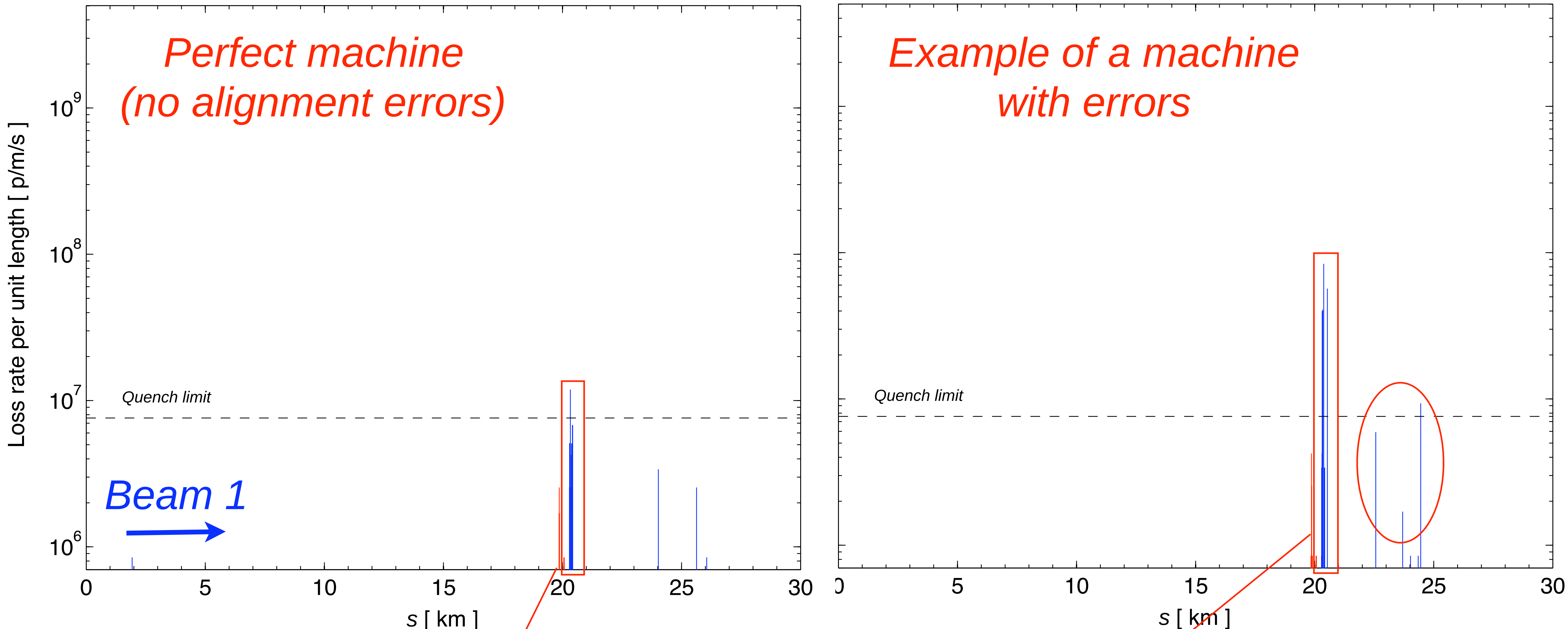


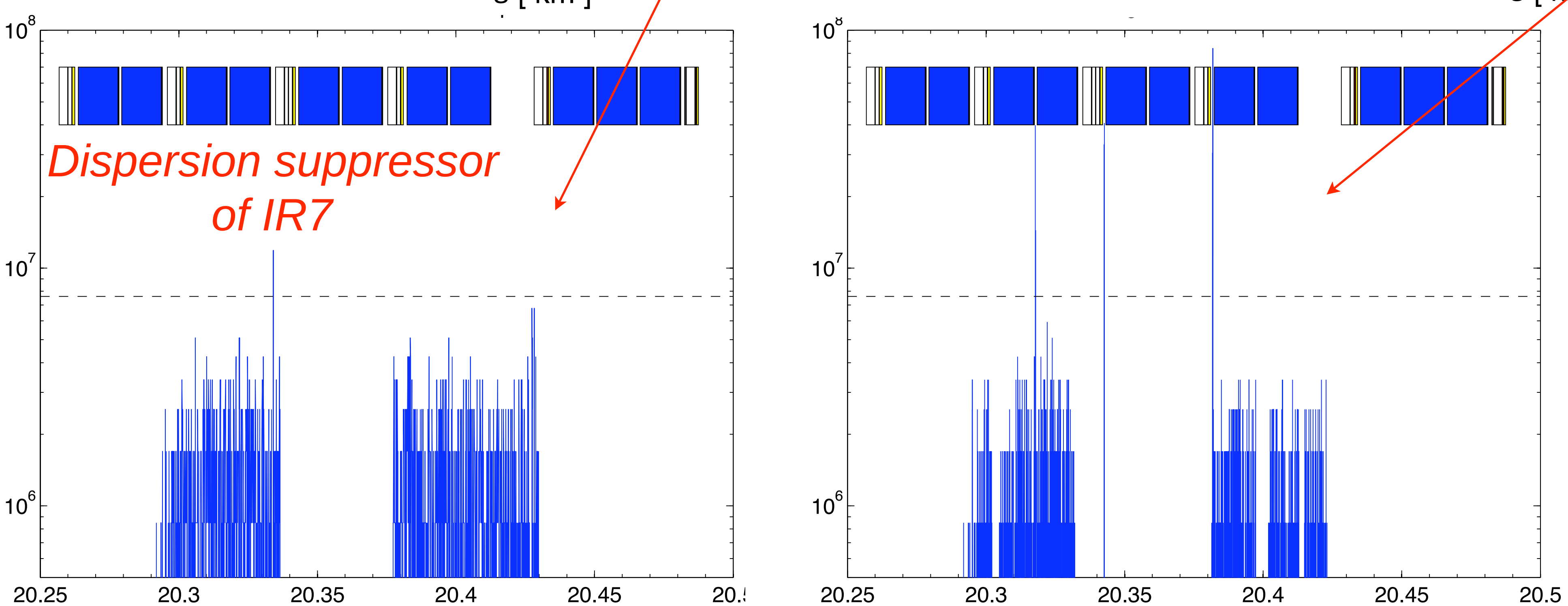
TCLA + TCT
→ Significant improvement in the IR's

Before
→ many losses outside collimators!

There are still losses above the quench limit!

Random aperture alignment errors



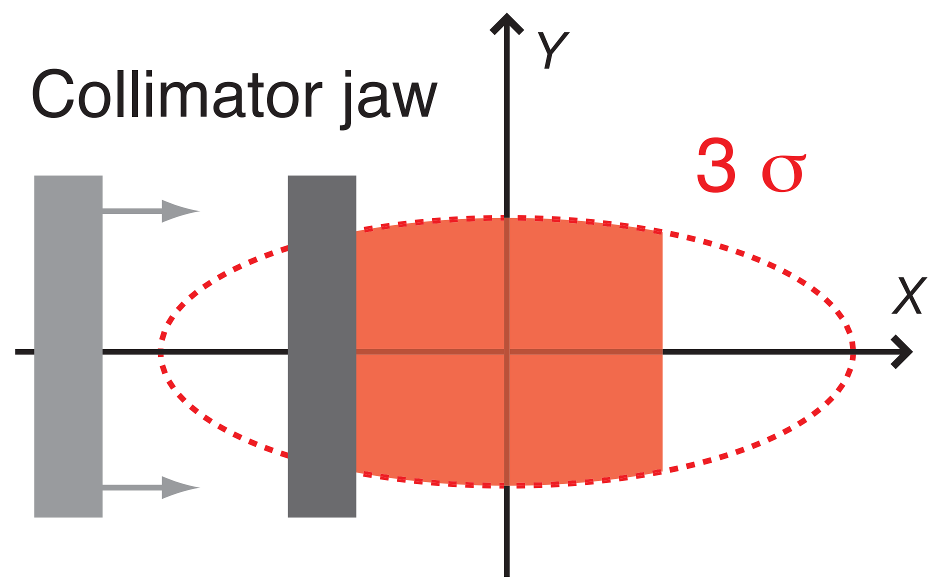


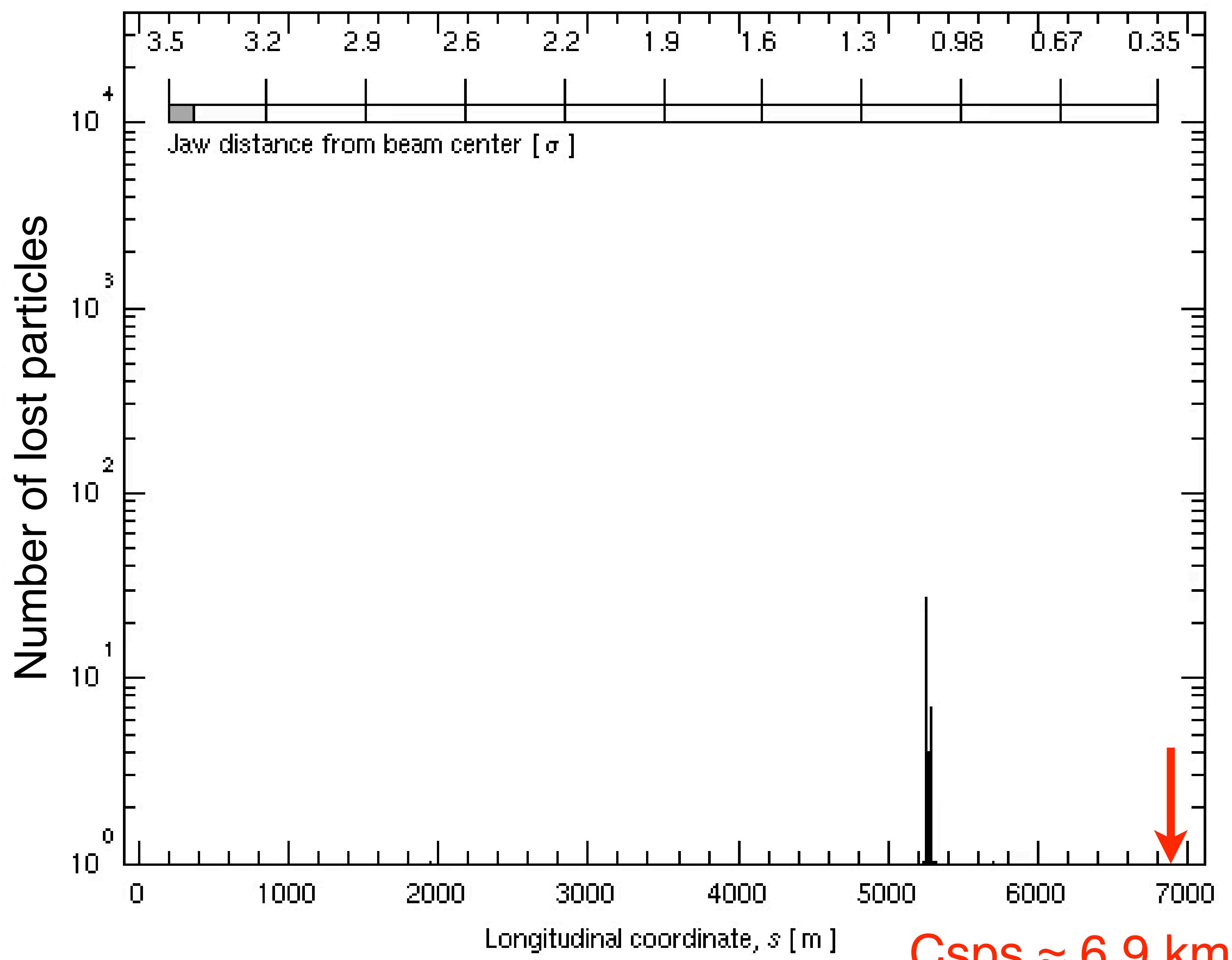
1. Loss spikes at the 10cm level much higher (effect on quench performance to be understood)
2. Total losses in single cryostat up to 15-20% higher
3 .New loss locations!

Time-dependent jaw movements

Simulations include time-dependent jaw movements (new feature)

- Single or both jaws can be moved at their real speed
- Long tracking runs ~ 20000 turns to simulate the full sweep across the beam





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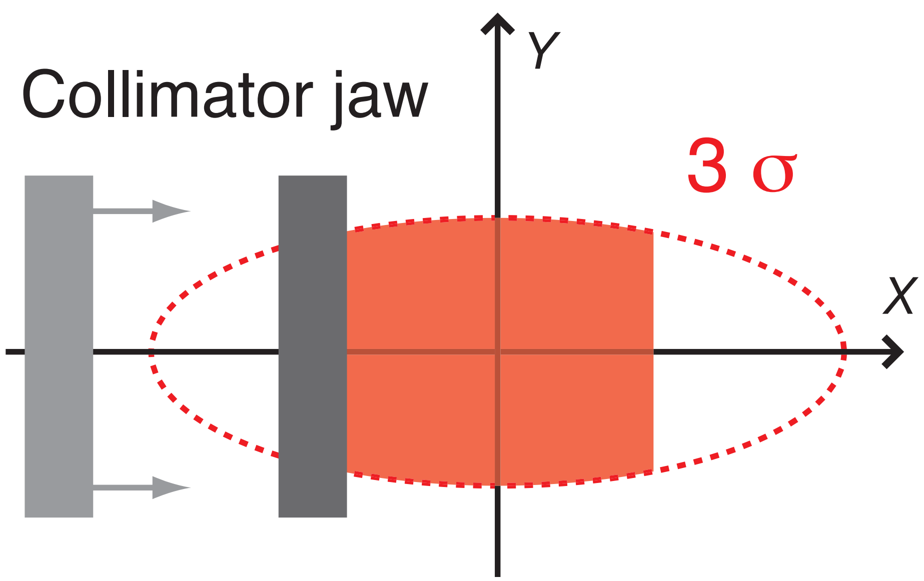
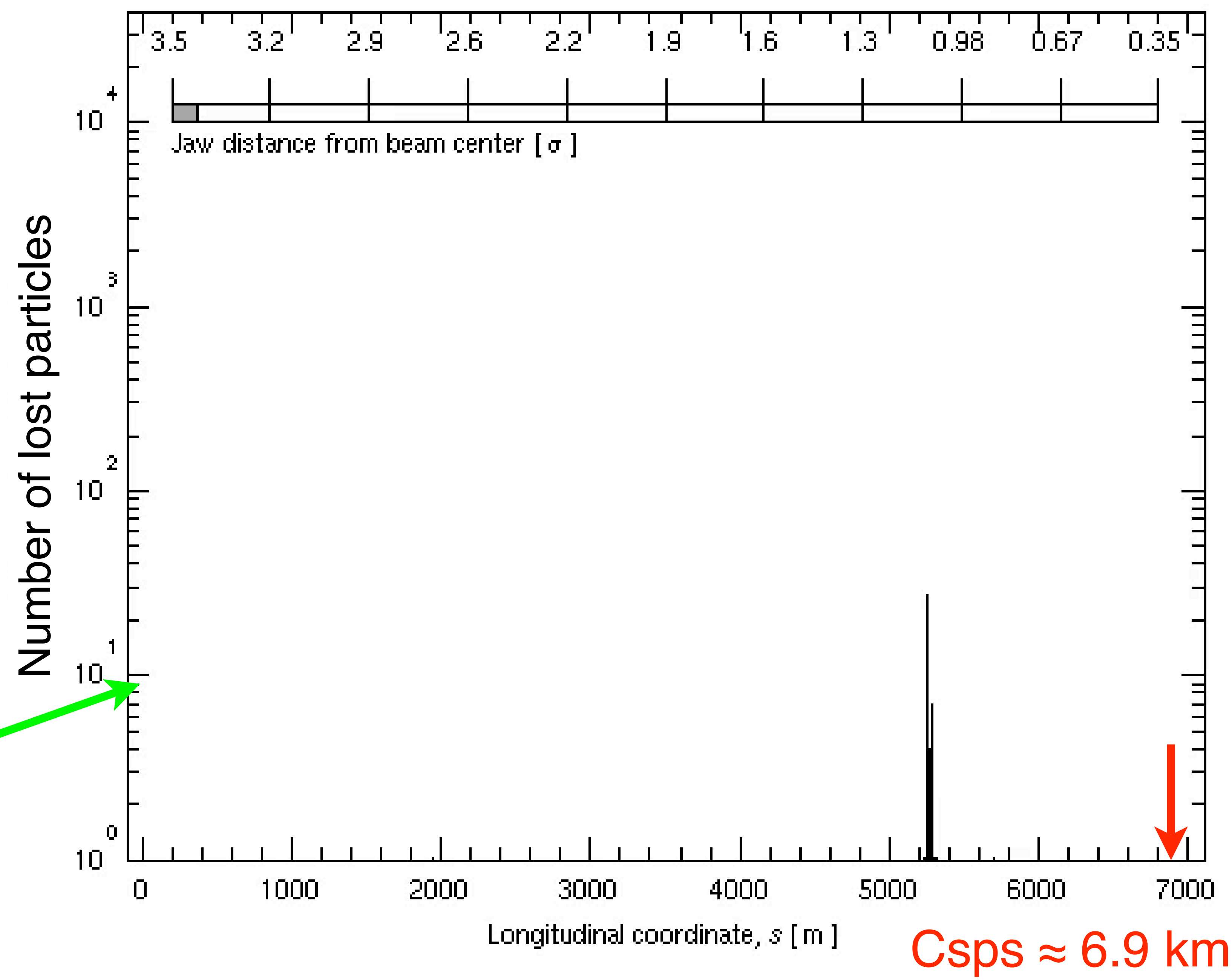
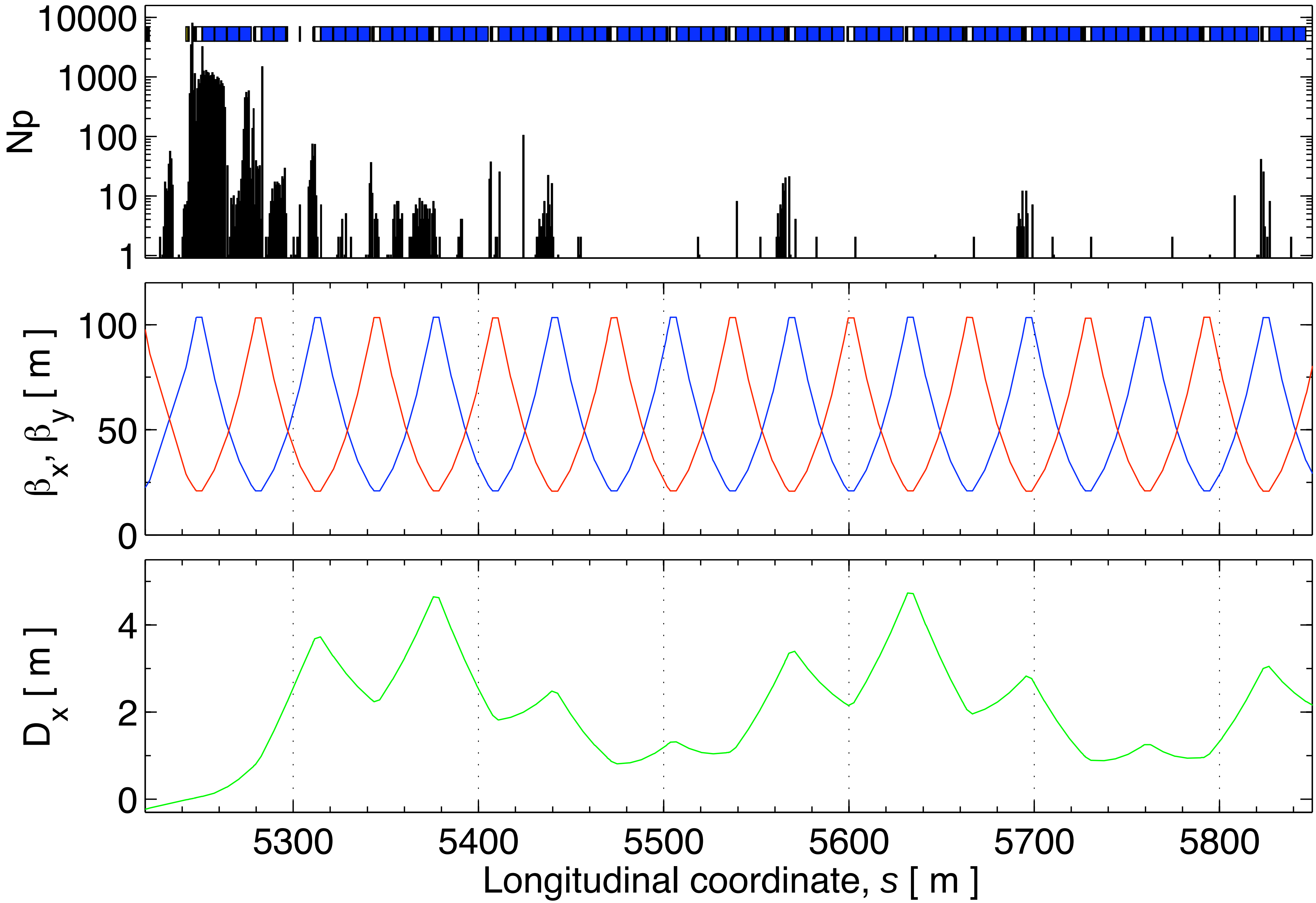


Model accurate to the < 1e-4 level

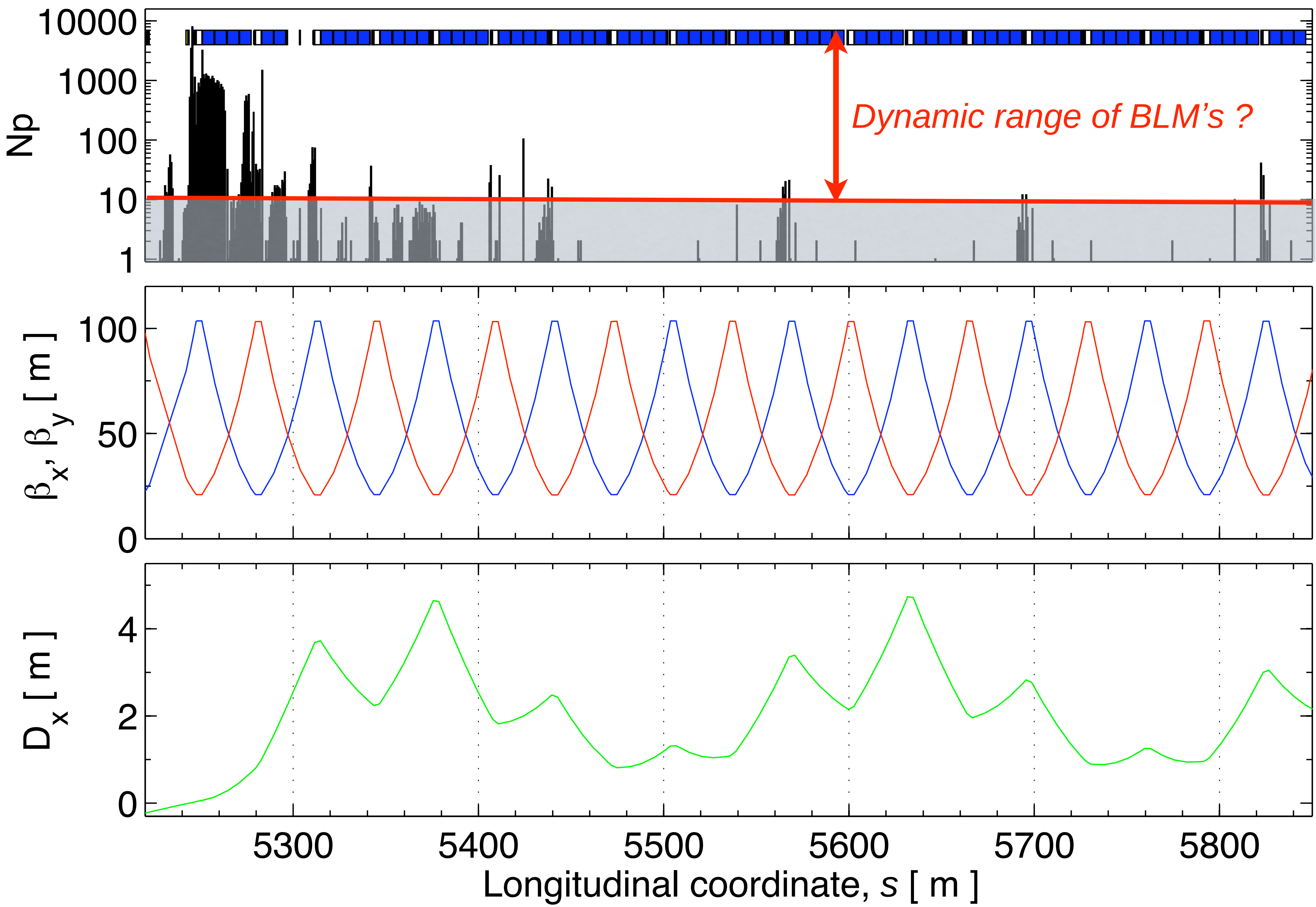
Can the BLM's measure this wide dynamic range?



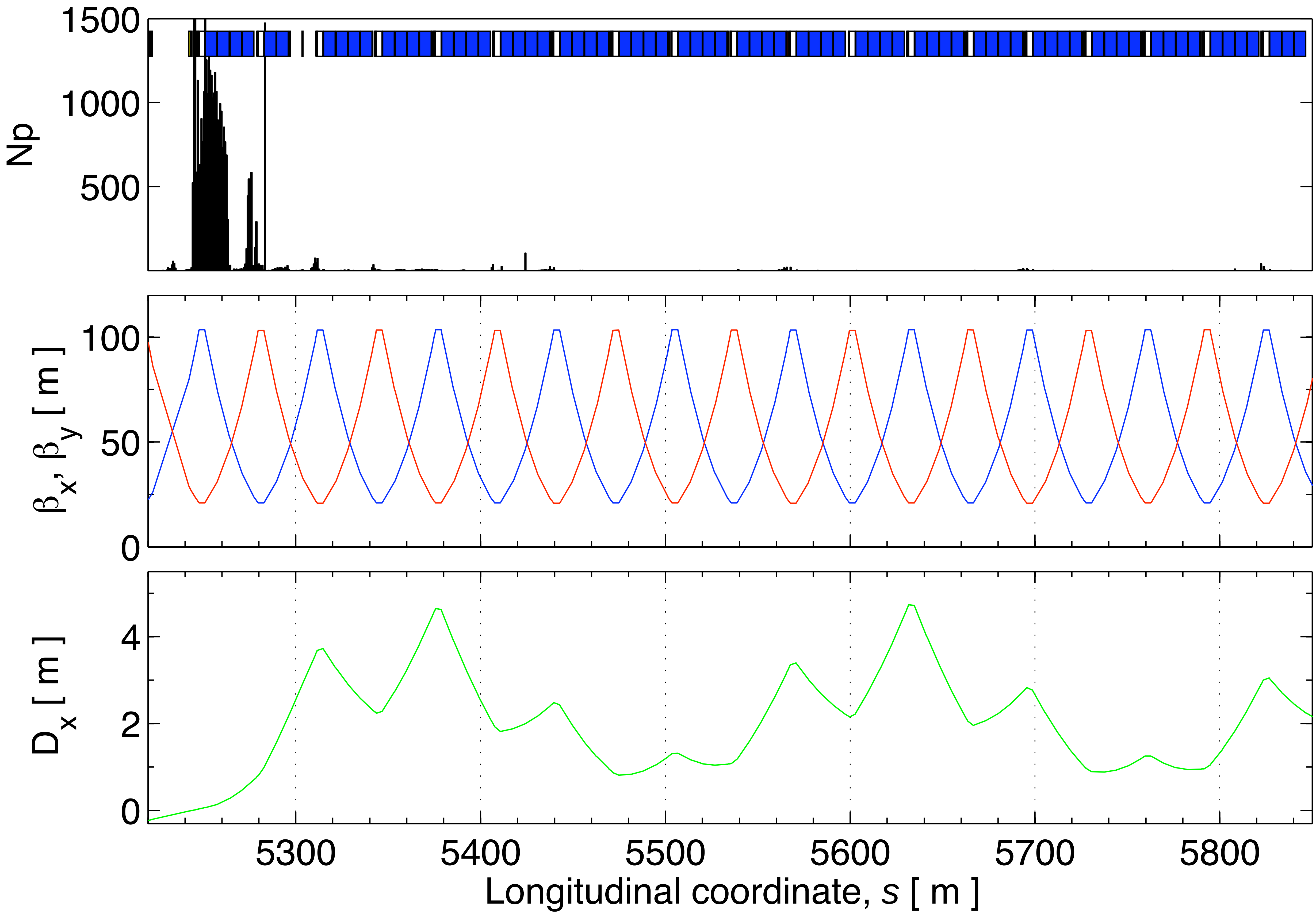
More details of the SPS simulations



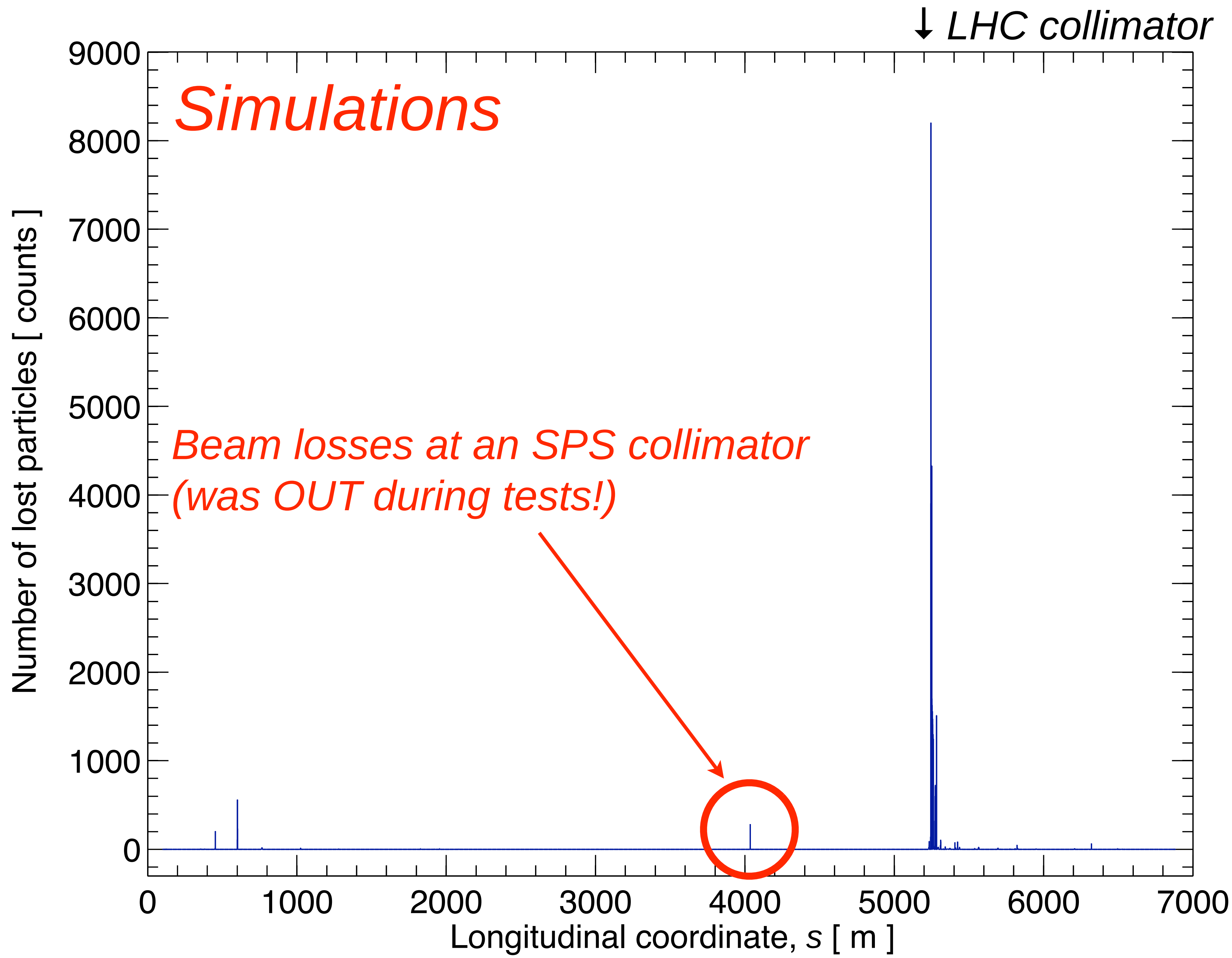
More details of the SPS simulations



More details of the SPS simulations



The comparison showed that the correct settings of septum collimator were **missing** in first simulation runs!



Prediction power: We found that the TPSG was OUT and not IN!