FCC-pp Design meeting
June 12th, 2014
CERN, Geneva, CH

LHC Collimation
Challenges and Work-plan

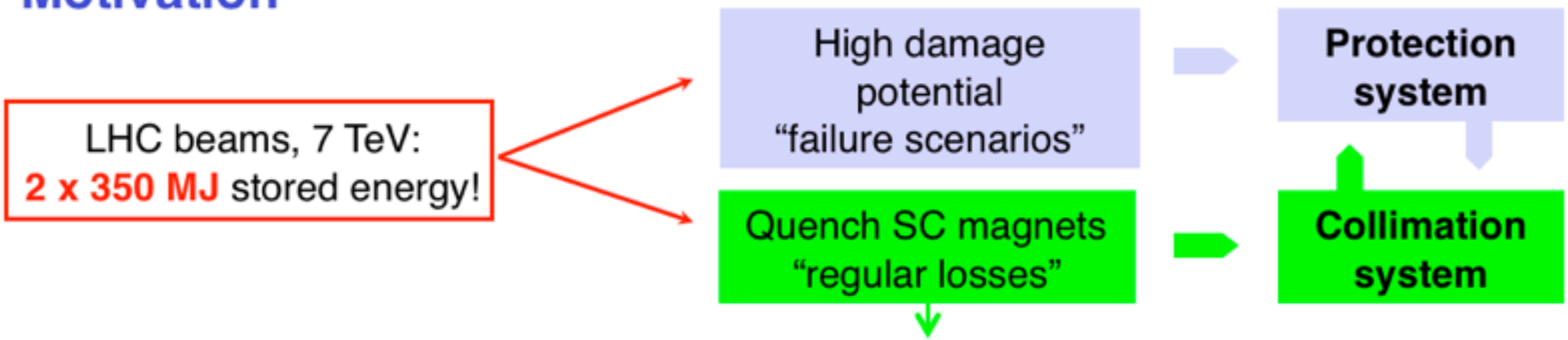
Stefano Redaelli, BE-ABP

Acknowledgments: O. Brüning, D. Schulte, R. Tomas.

Outline

- Introduction
- LHC design challenges
- Present system performance
- Limitations and upgrade plans
- FCC challenges and workplan
- Conclusions

Motivation



Local losses in cold magnets < 10^{-7}-10^{-9} of beam intensity!

How do we prevent particles from touching the aperture?

1. **Good aperture design!** → *Leave enough space to the beam!*
2. **Efficient collimation system!** → *Clean-up the beam halo!*
3. Additional local protection → *Shade sensitive equipment!*

→ The cleaning system is not perfect and hence we must understand:

⇒ *How many particle escape?*
⇒ *Where are they lost in the ring?*
⇒ *Can they quench the magnets?*

} *Take correction actions before it is too late…*

An old slides from Chamonix 2005, when we were in full design phase for the LHC collimation...

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Clearly, it's long way to achieve all of that for FCC!
First studies must be targeted to achieve a conceptual design that addresses the main cleaning challenge, taking into account impedance and machine protection aspects.
Do not discuss today other collimation roles!

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  Avoid many hot locations around the 27km-long tunnel

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Cleaning challenge

LHC total intensity reach from collimation

$$N_{\rm tot} = \frac{\tau R_q}{\tilde{\eta}_c}$$

Minimum (assumed) beam lifetime → τ

Quench limit of SC magnets (in number of protons) → R_q

Collimation cleaning at limiting cold location → $\tilde{\eta}_c$

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Key parameters that determine the intensity reach in a collider:

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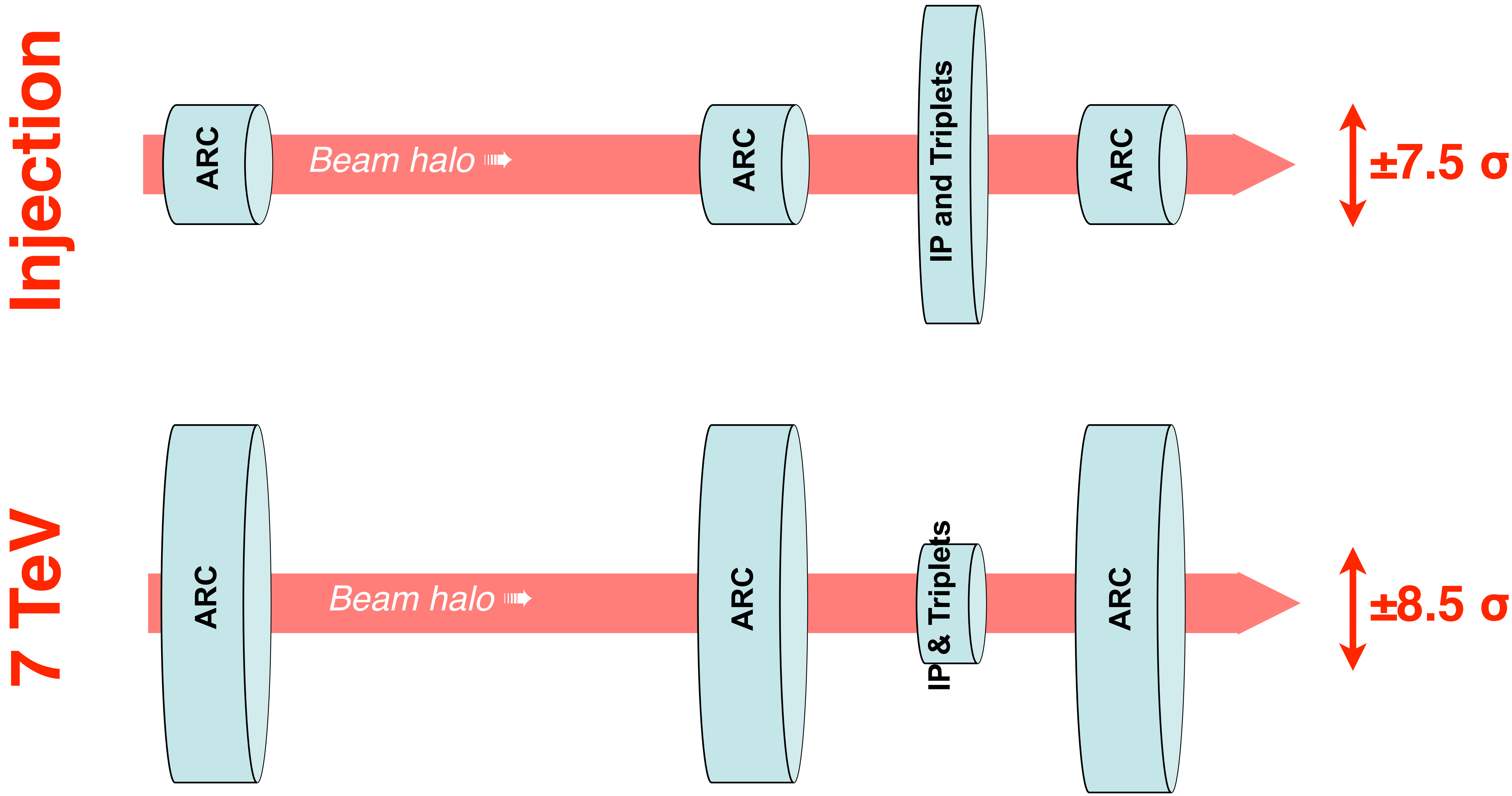
- **Beam lifetime assumptions**

  This is a crucial parameter for the design, but difficult to "guess"
  → determines the total losses in cold magnets for given cleaning;
  → determines the power loads on the collimators, input to the mechanical design.
  No need for collimation system if lifetime is infinite, but...
  LHC design: assumed a transient "minimum allowed lifetime" of 0.2 hours

Aperture challenge



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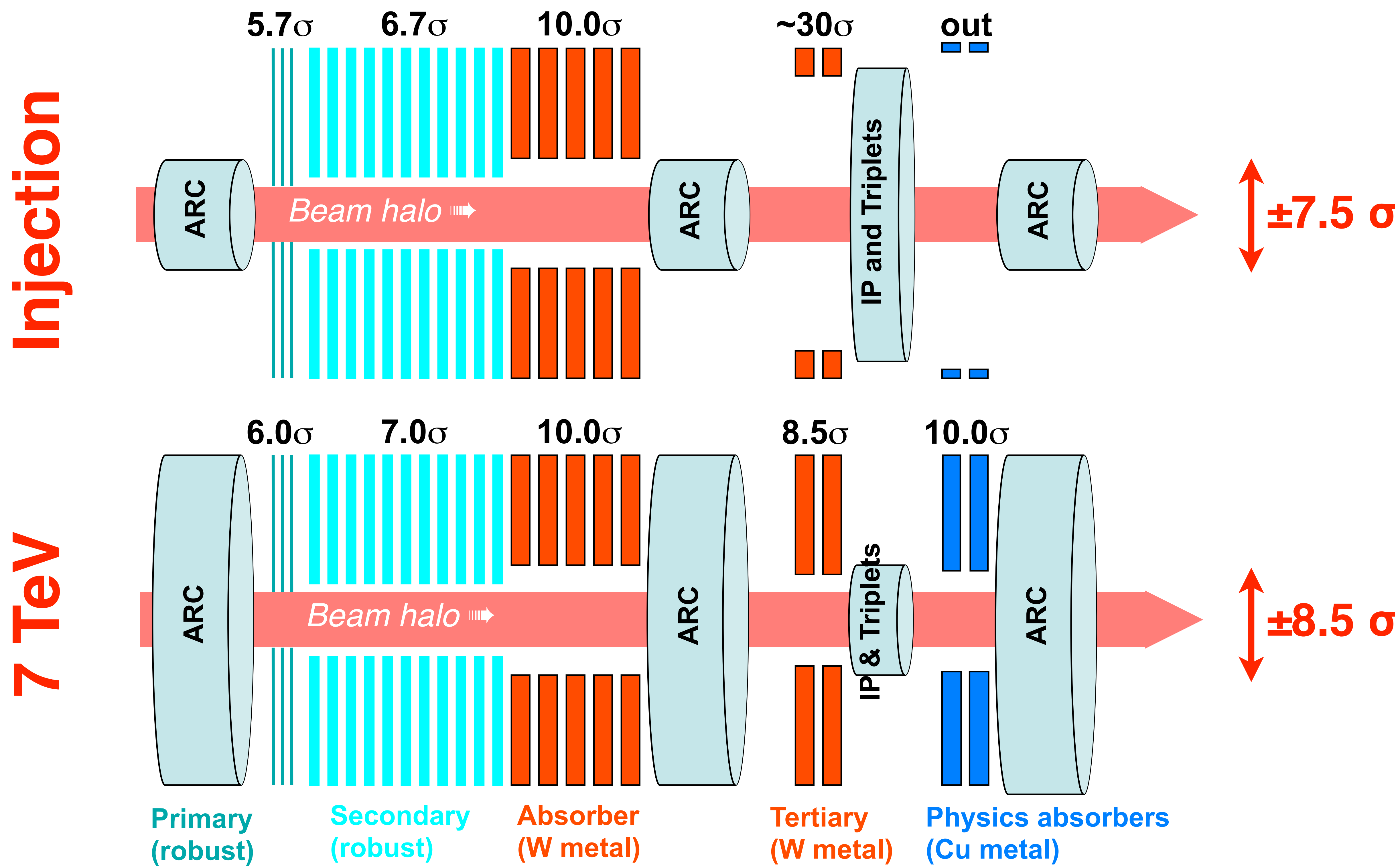

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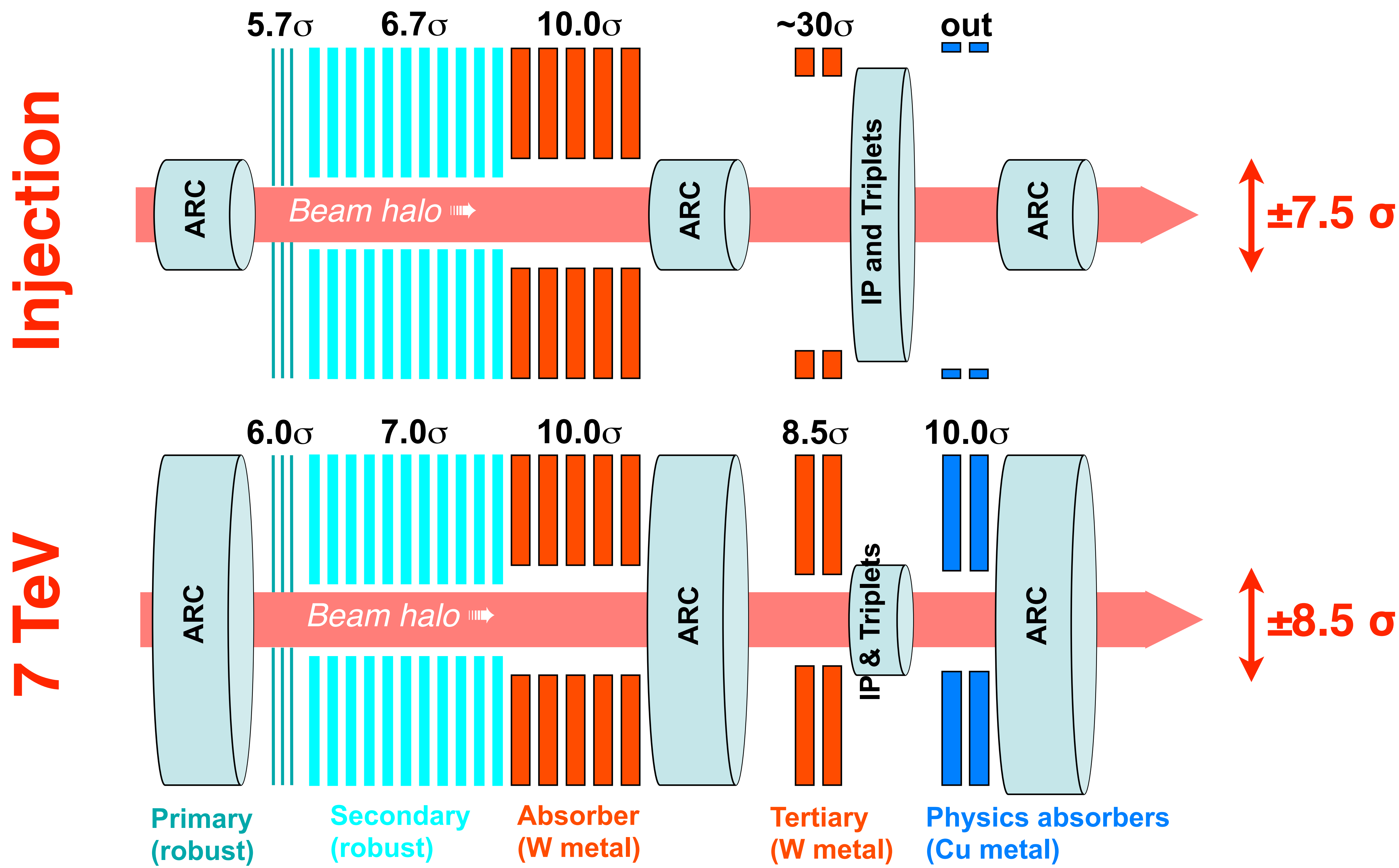

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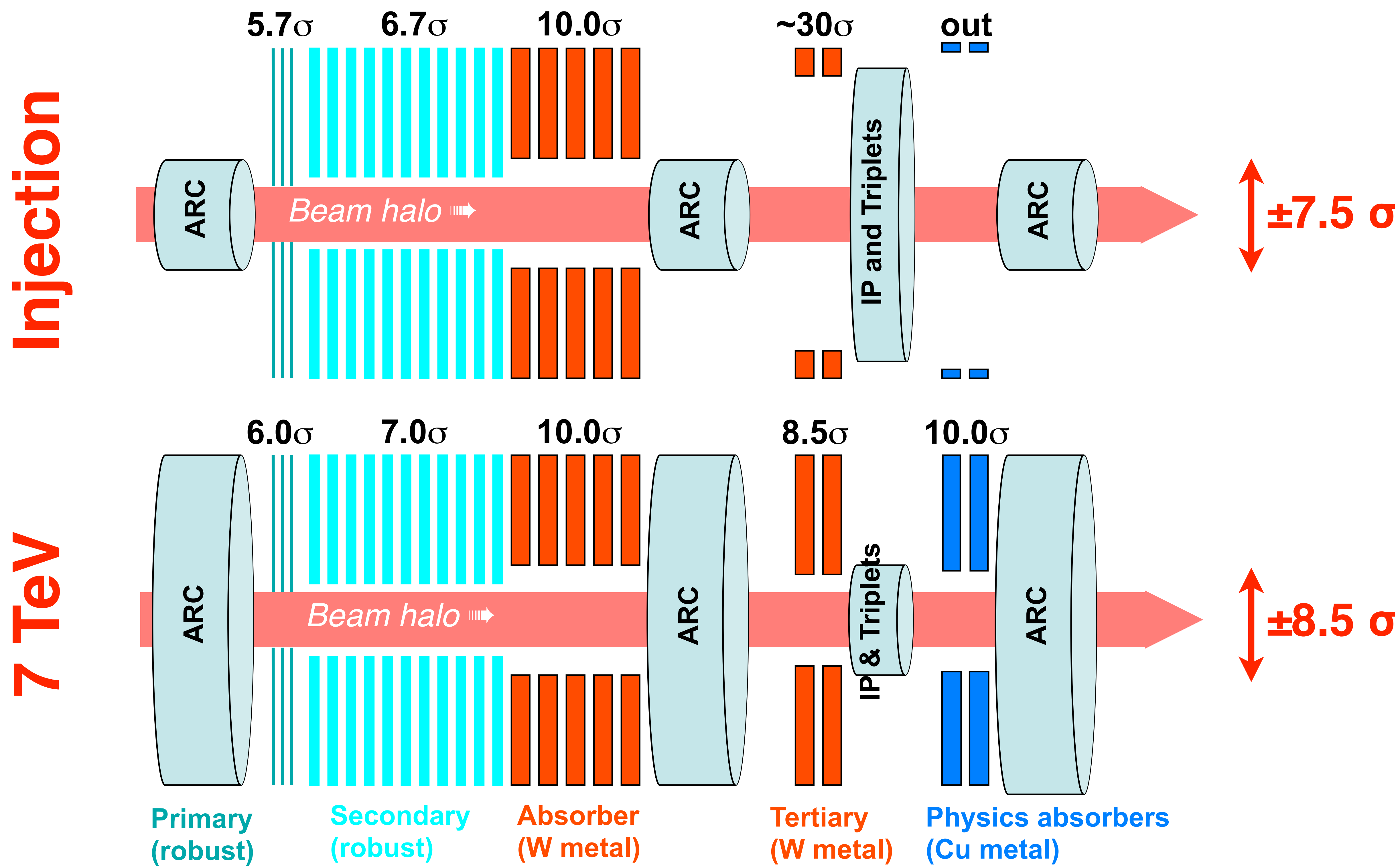


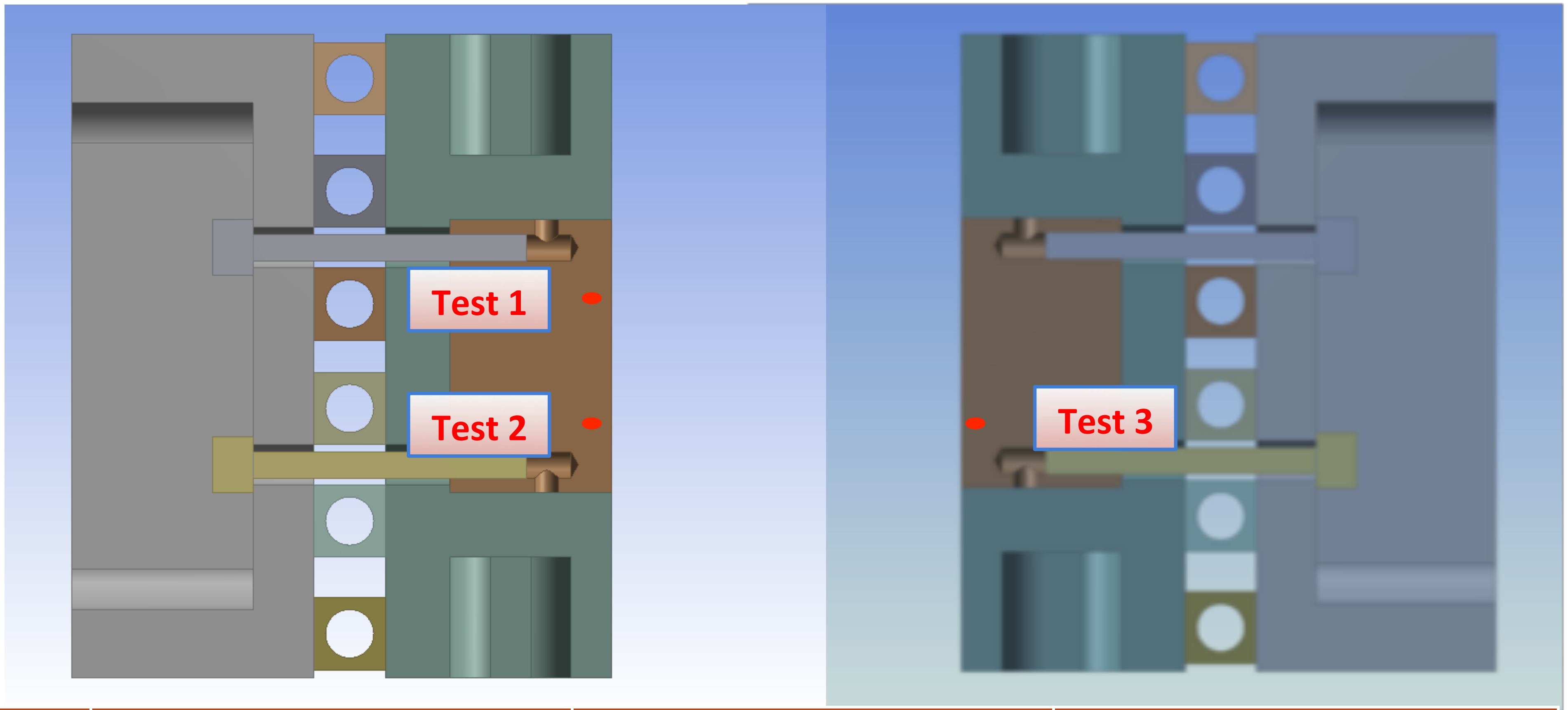
Collimation hierarchy determines the β* reach!

Collimation hierarchy is determined by the available aperture that must be protected in all operational phases.

The material challenge

- Beam energy: **440 GeV**
- Impact depth: **2mm**
- Jaws half-gap: **14 mm**

A. Bertarelli, *et al*



	Test 1	Test 2	Test 3
Goal	**Beam impact equivalent to 1 LHC bunch @ 7TeV**	**Identify onset of plastic damage**	**Induce severe damage on the collimator jaw**
Impact location	Left jaw, up (+10 mm)	Left jaw, down (-8.3 mm)	Right jaw, down (-8.3 mm)
Pulse intensity [p]	3.36×10^{12}	1.04×10^{12}	9.34×10^{12}
Number of bunches	24	6	72
Bunch spacing [ns]	50	50	50
Beam size [σ_x - σ_y mm]	0.53 x 0.36	0.53 x 0.36	0.53 x 0.36

One LHC bunch of 10^{11}p at 7 TeV causes un-recoverable damage to the present metallic collimators!

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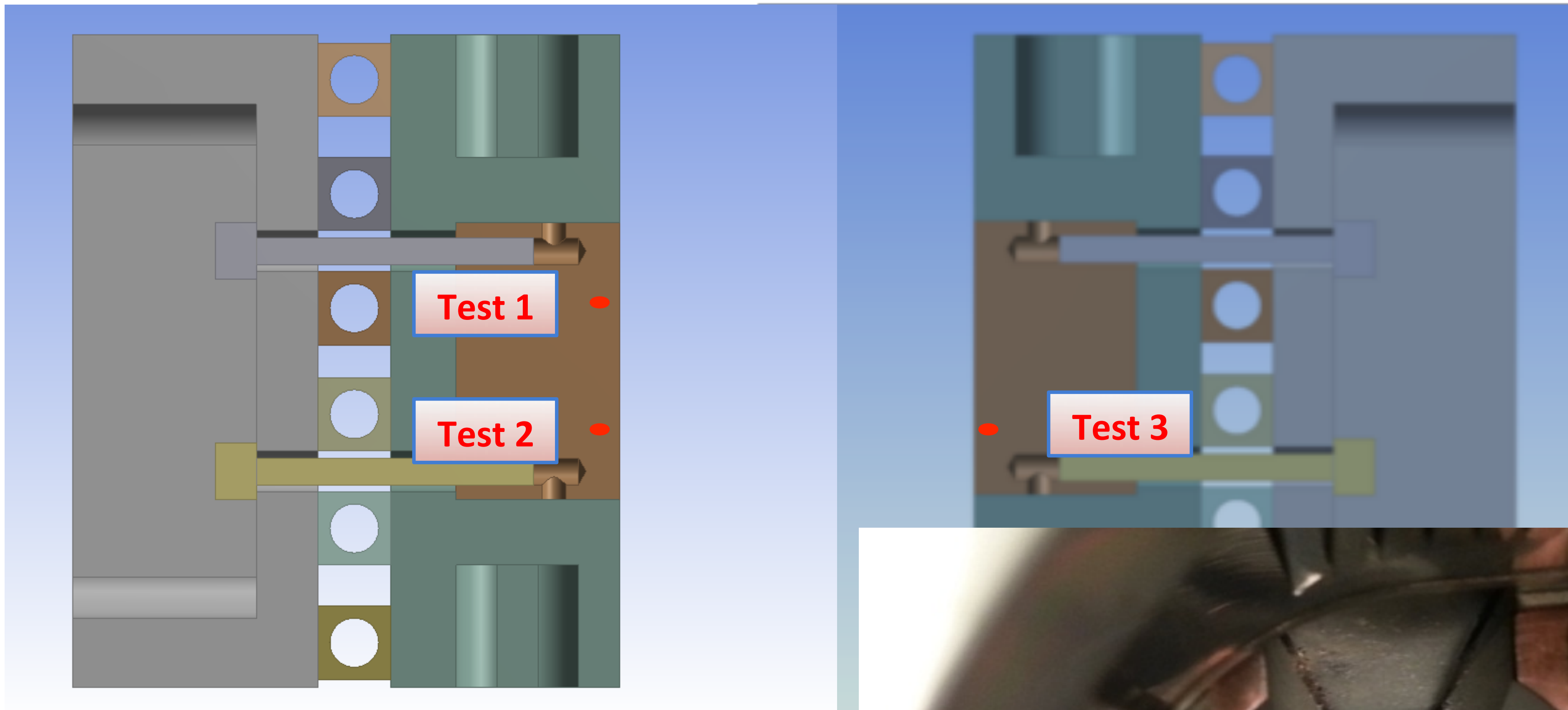

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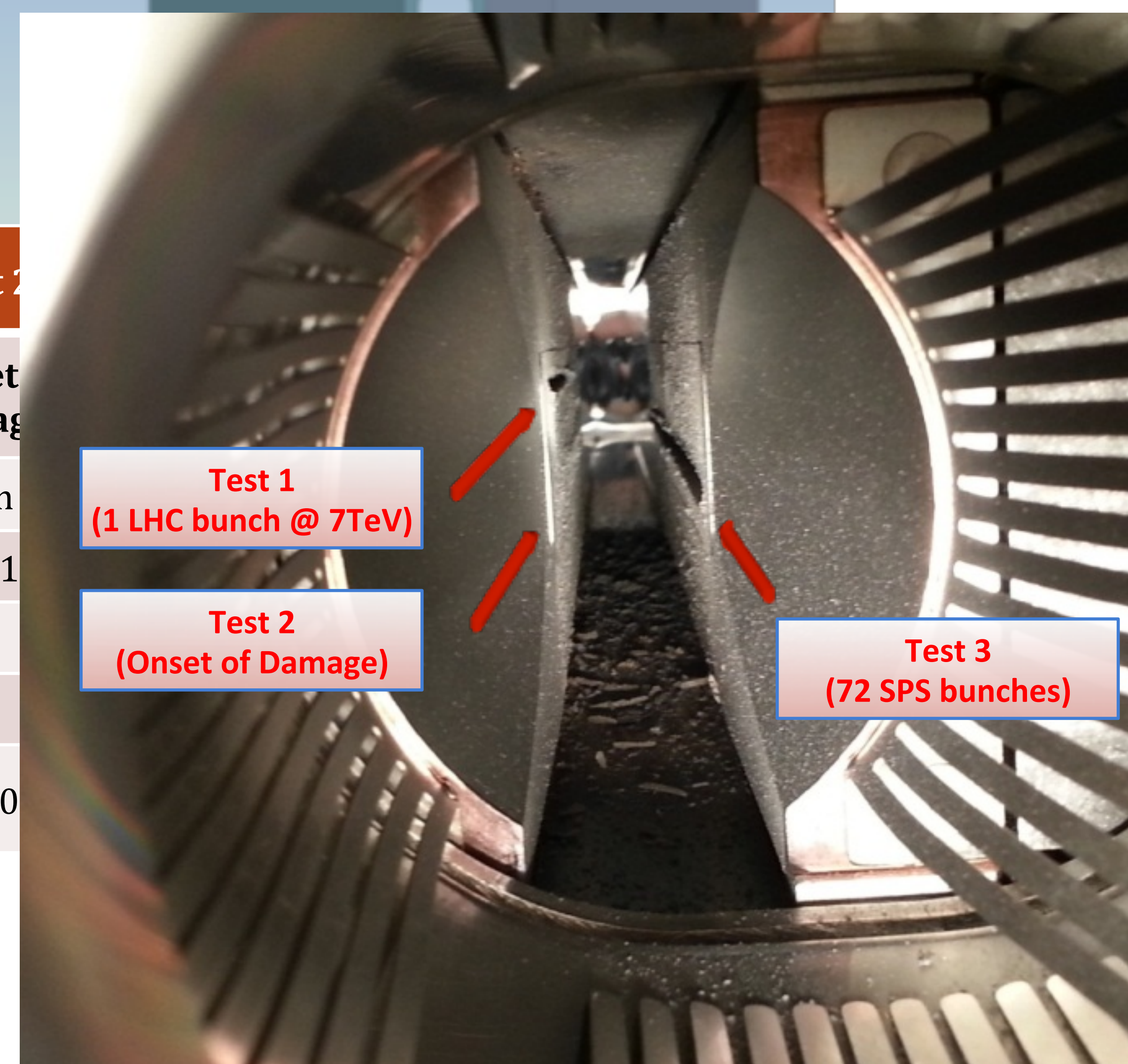
Beam size [σ_x - σ_y mm]	0.53 x 0.36	0.53 x 0



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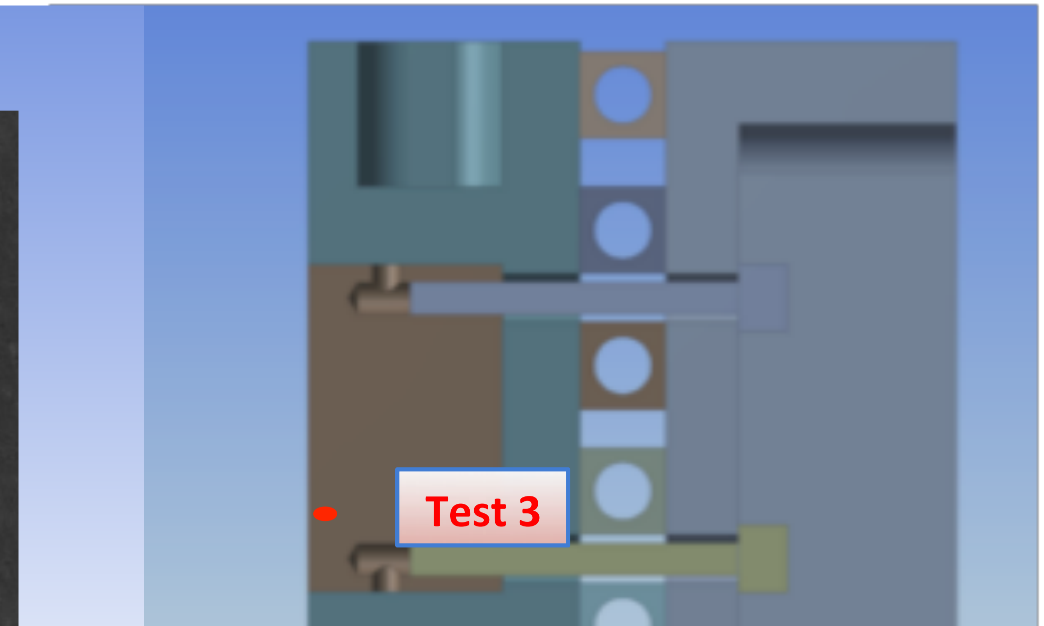
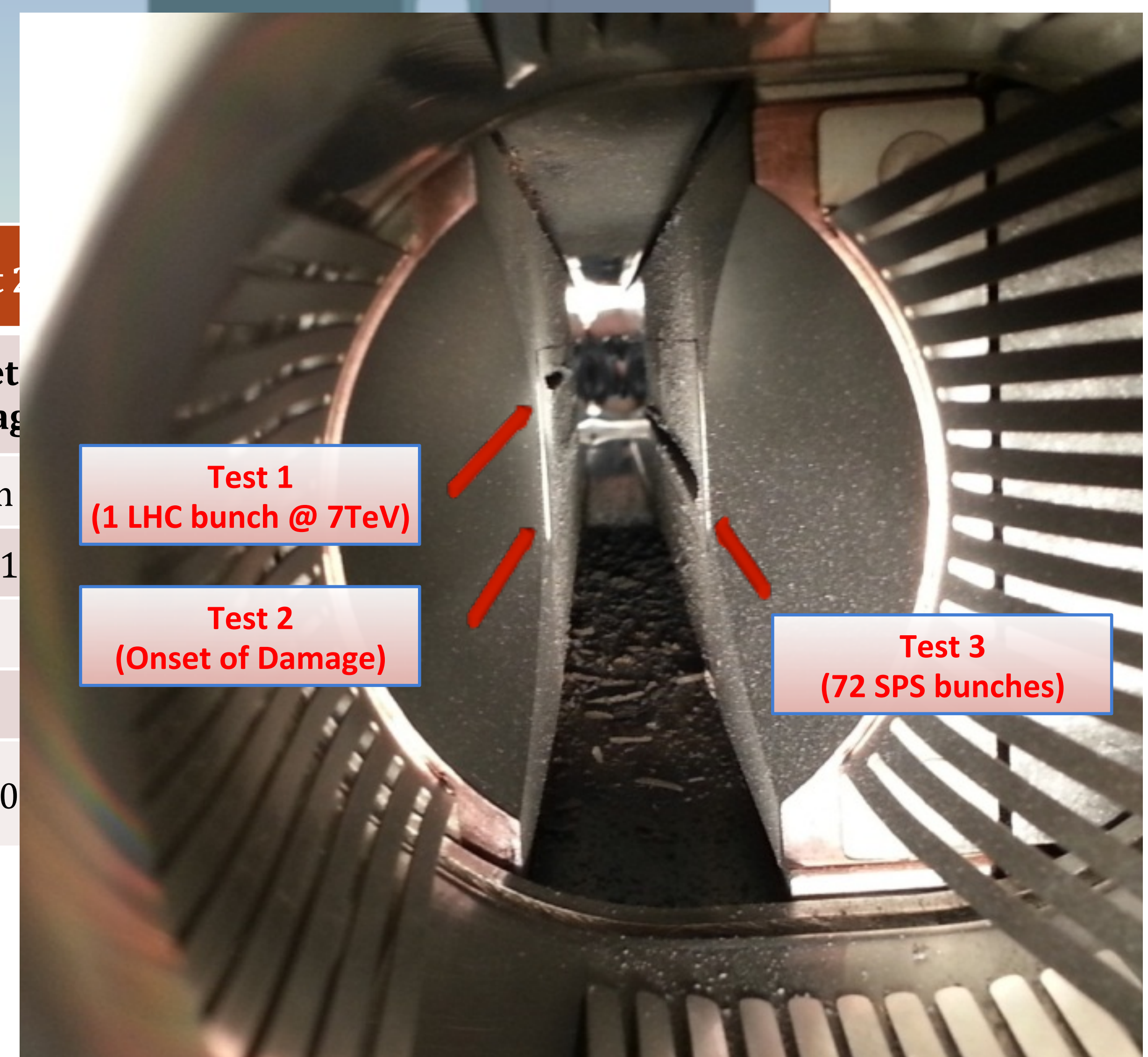


		Test 2
Goal		ify onset damag
Impact location		w, down
Pulse intensity [p		1.04 x 1
Number of bunch		6
Bunch spacing [n		50
Beam size [σ_x - σ_y mm]	0.53 x 0.36	0.53 x 0

12



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LHC collimation challenges

High stored beam energy (melt 500 kg Cu, required for 10^{34} cm^{-2} s^{-1} luminosity)	**~ 360 MJ/beam**
Large transverse energy density (beam is destructive, 3 orders beyond Tevatron/HERA)	**1 GJ/mm^2**
High required cleaning efficiency (clean lost protons to avoid SC magnet quenches)	**99.998 % (~10^{-5}p/m)**
Activation of collimation insertions (good reliability required, very restricted access)	**~ 1-15 mSv/h**
Small spot sizes at high energy (small 7 TeV emittance, no large beta in restricted space)	**~ 200 µm**
Collimation close to beam (available mechanical aperture is at ~10 σ)	**6-7 σ**
Small collimator gaps (impedance problem, tight tolerances: ~ 10 µm)	**< 3 mm (at 7 TeV)**
Big and distributed system (coupled with mach. protection / dump)	**~100 locations ~500 deg. of freedom**

Quench
Damage
Heating
Activation
Stability
Impedance
Precision

*How can we meet all these **challenging** (and sometimes **conflicting**) requirements?*

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LHC collimation layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

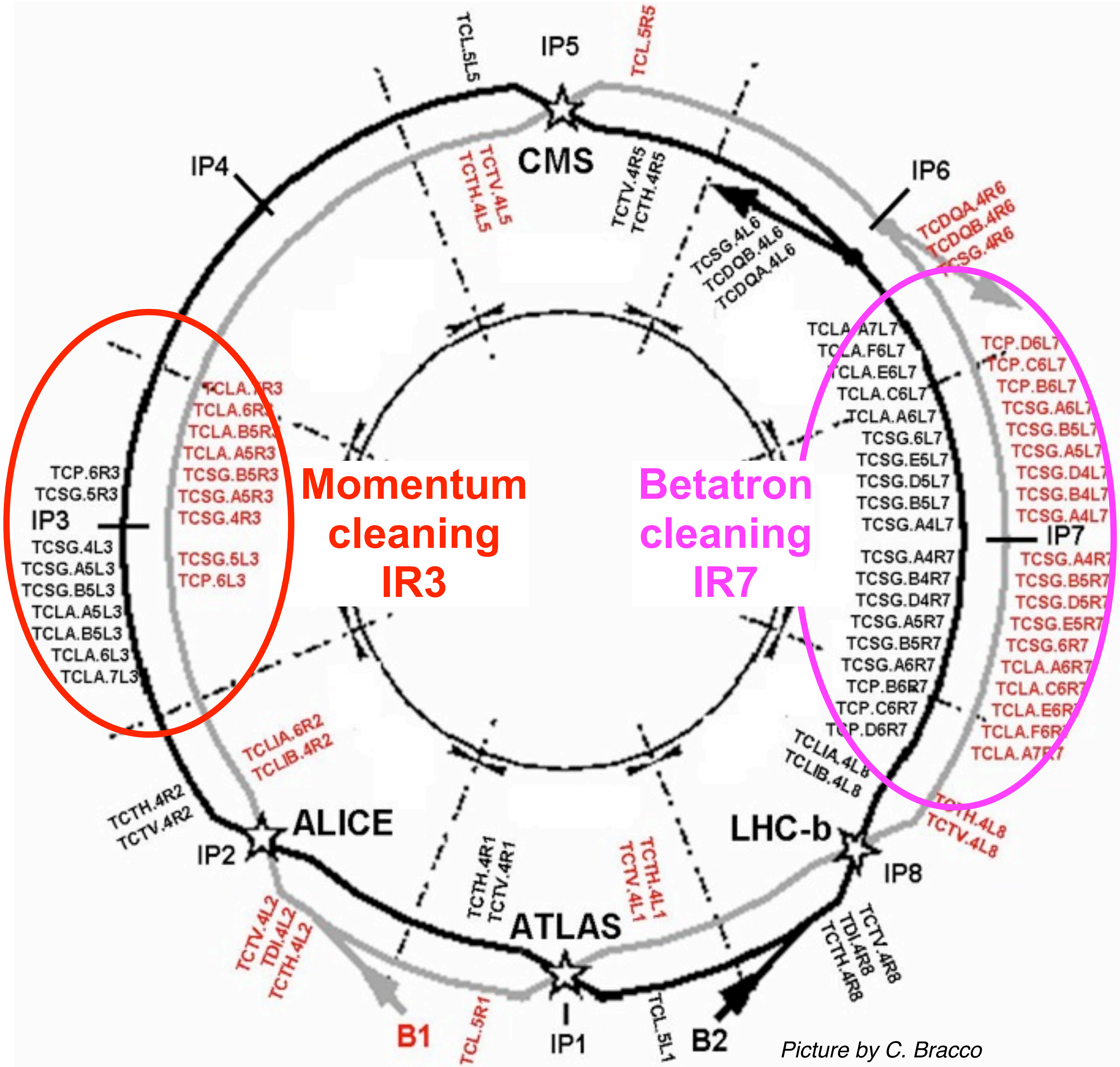
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

Physics debris absorbers

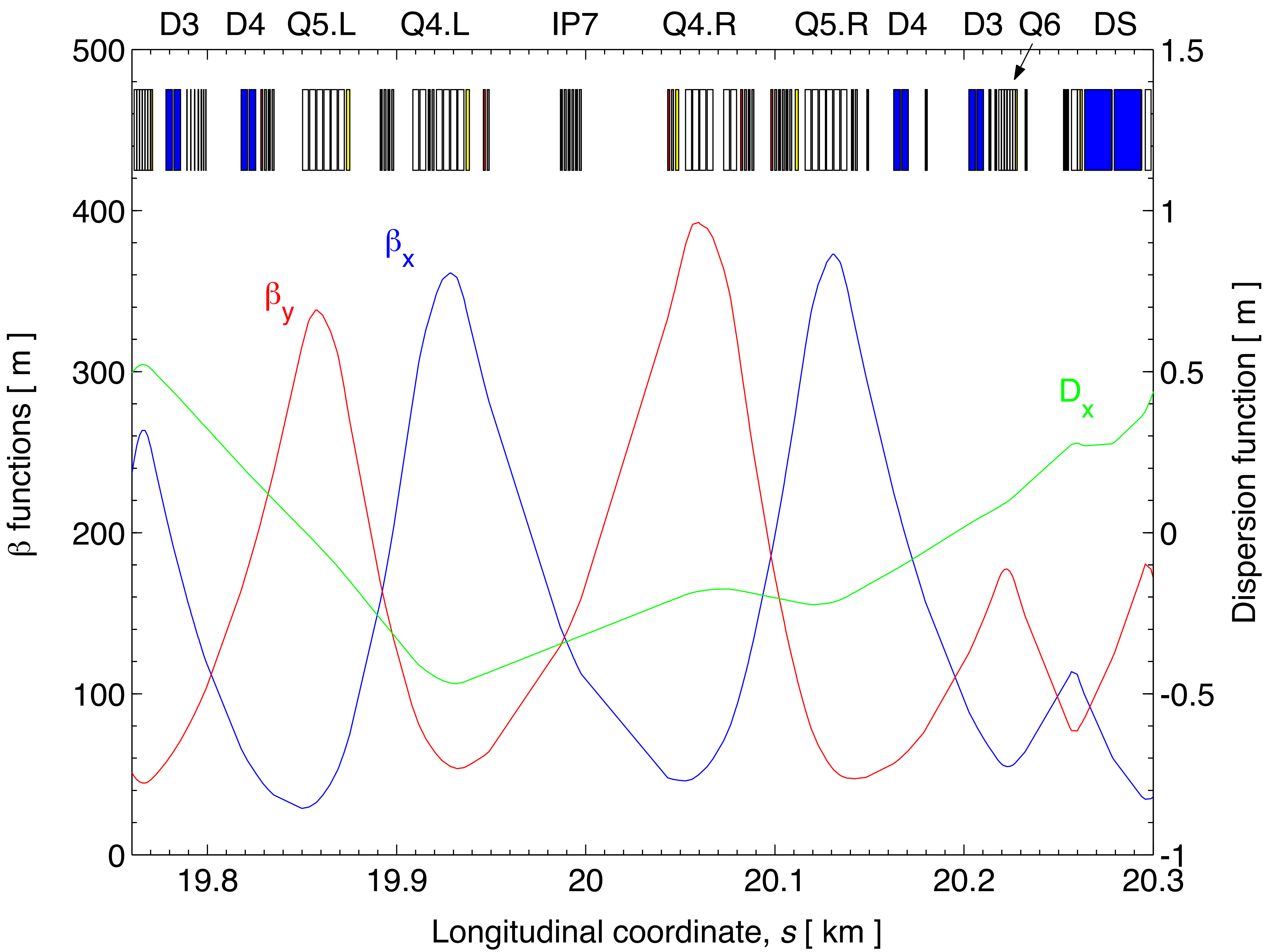
Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 108 collimators (100 movable). Two jaws (4 motors) per collimator!



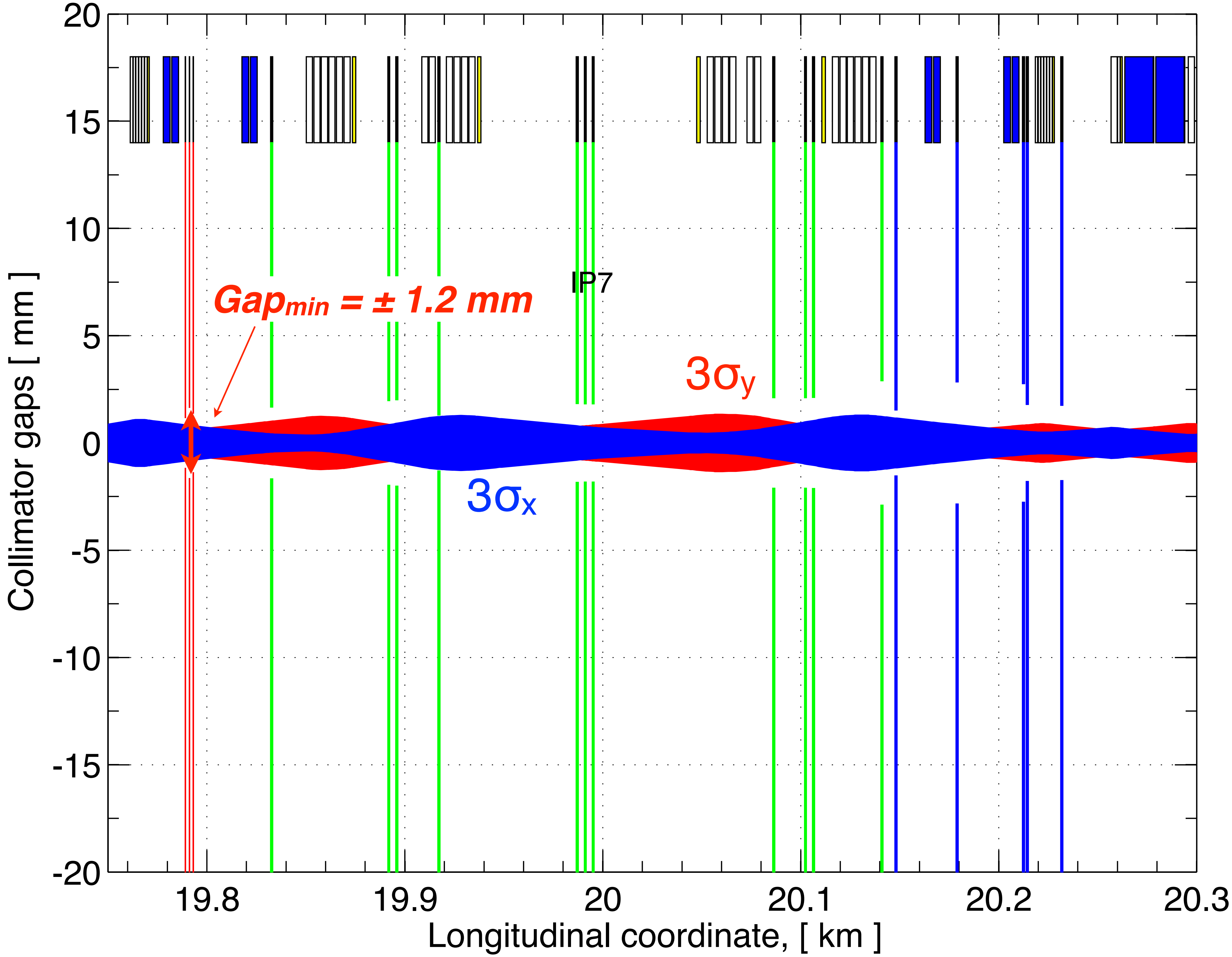
Picture by C. Bracco

IR7 optics and layouts (i)



IR7 optics and layouts (i)

$A_{TCP} = 6\ \sigma$ $A_{TCS} = 7\ \sigma$ $A_{TCLA} = 10\ \sigma$



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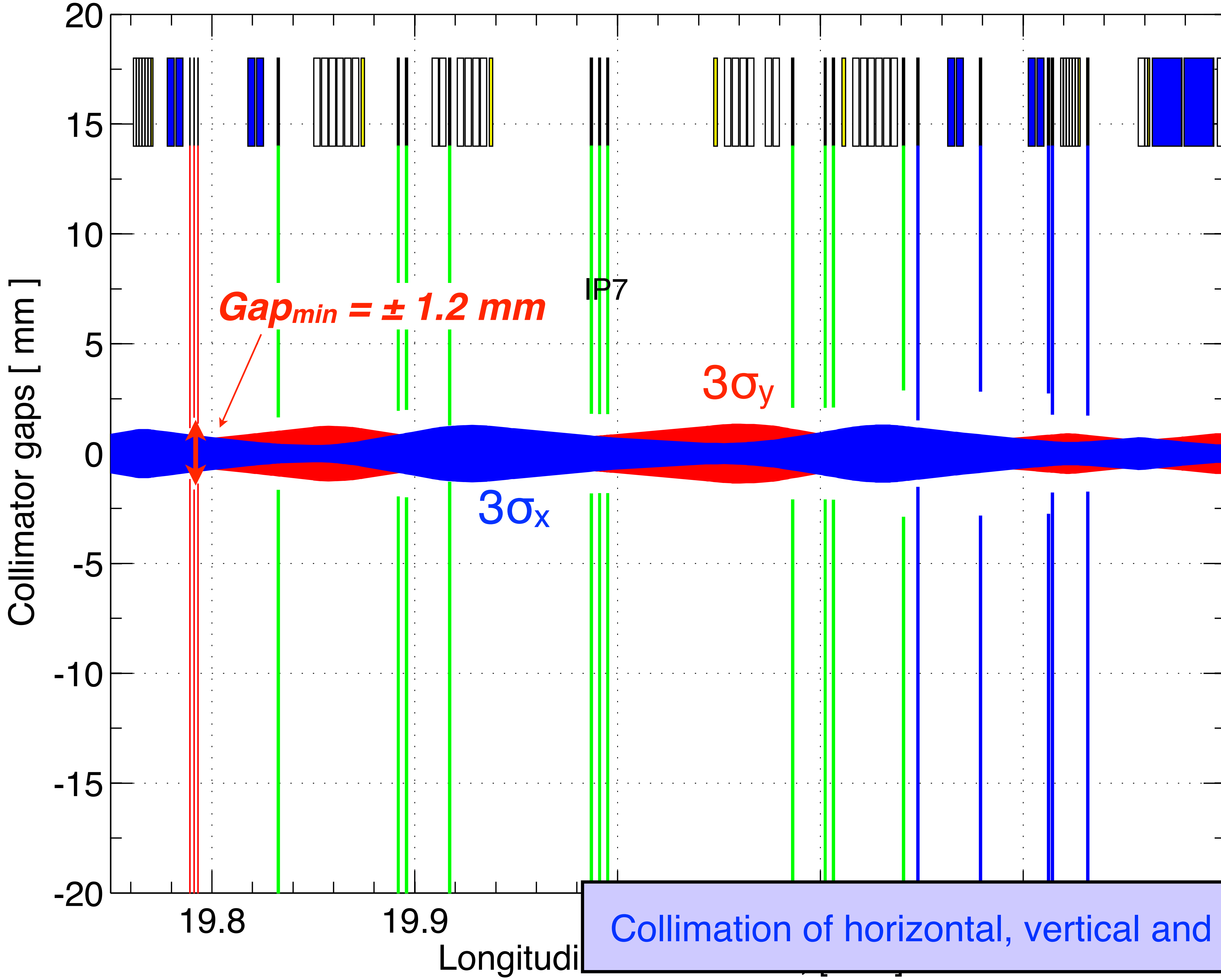
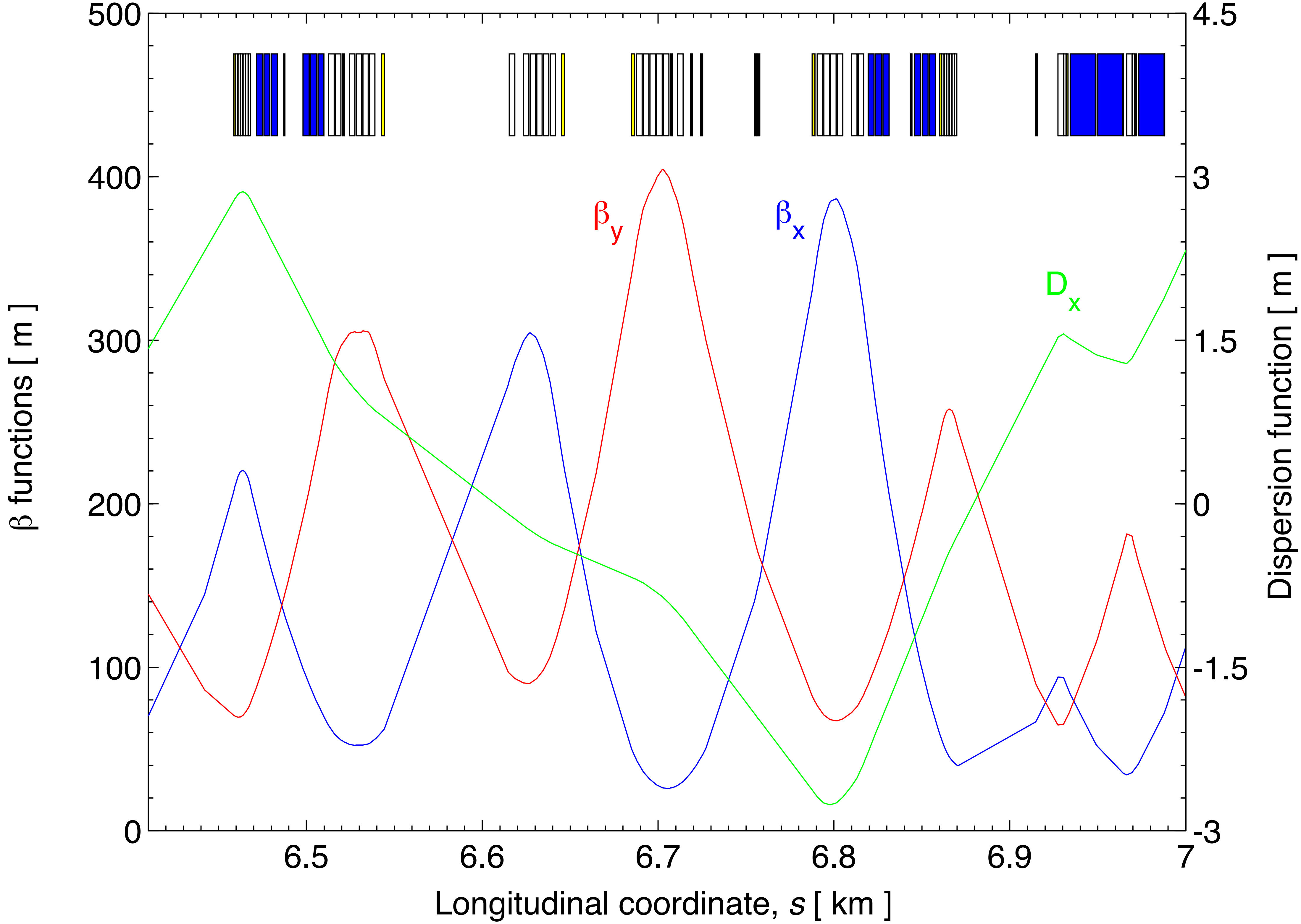


Collimation of horizontal, vertical and skew halos.

Momentum cleaning optics



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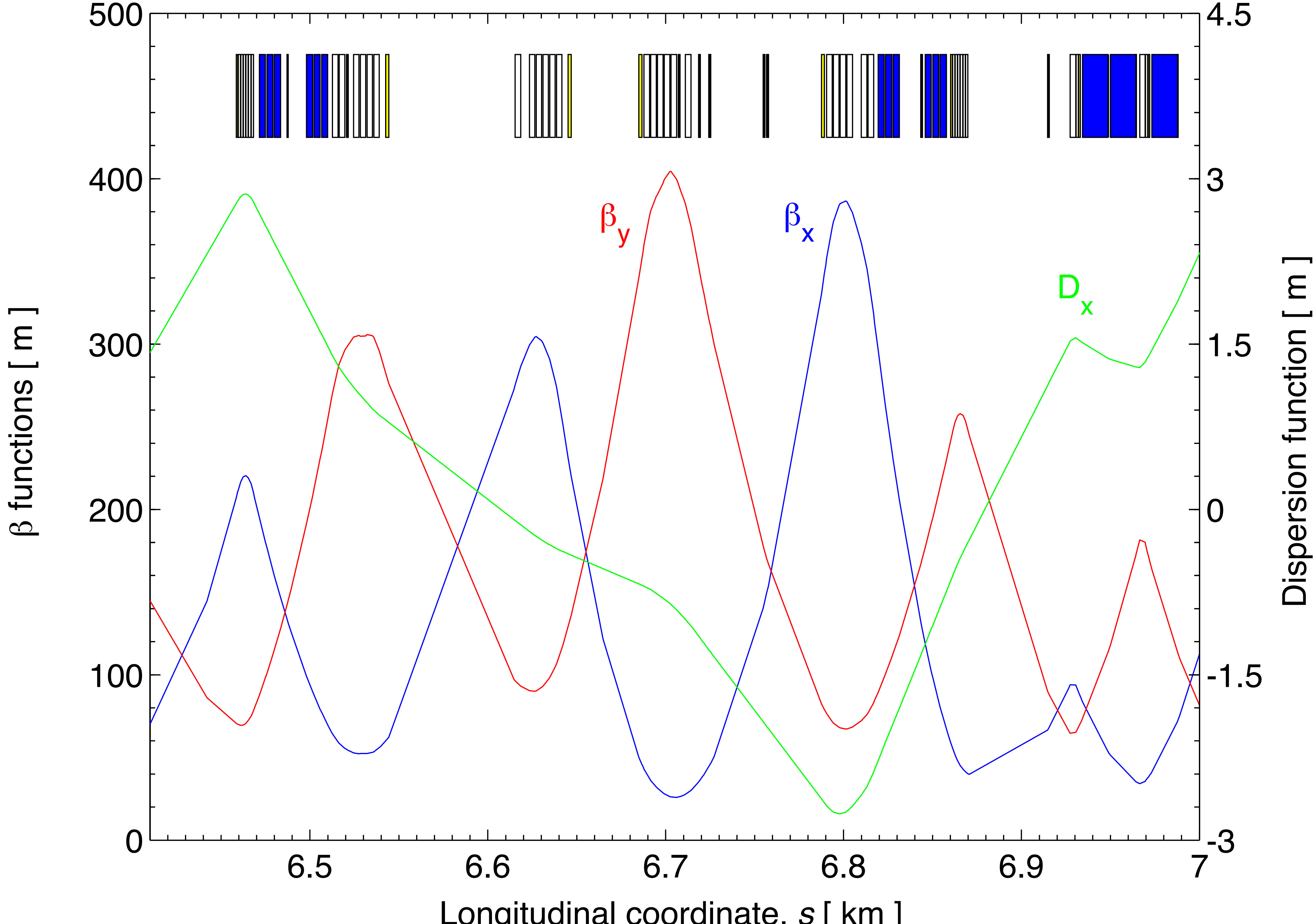
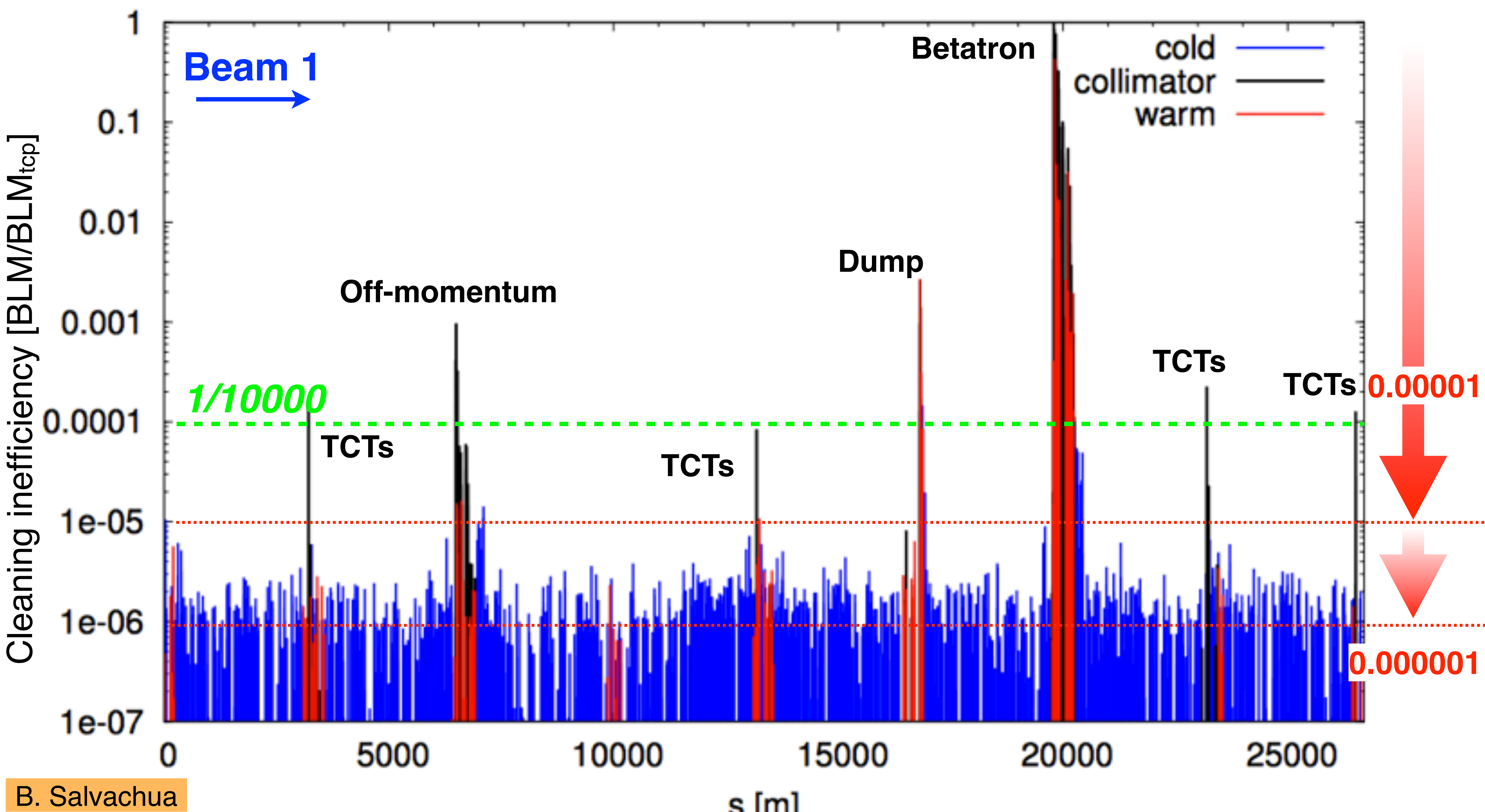


Three-stage cleaning for horizontal losses only
(9 collimators per beam, including vertical absorbers).

Collimation cleaning at 4 TeV (β^*=60cm)



B. Salvachua

2012-13: "tight" collimator settings (TCP gaps as at 7 TeV) for higher beta*!
60 cm for protons, 80cm for ions.

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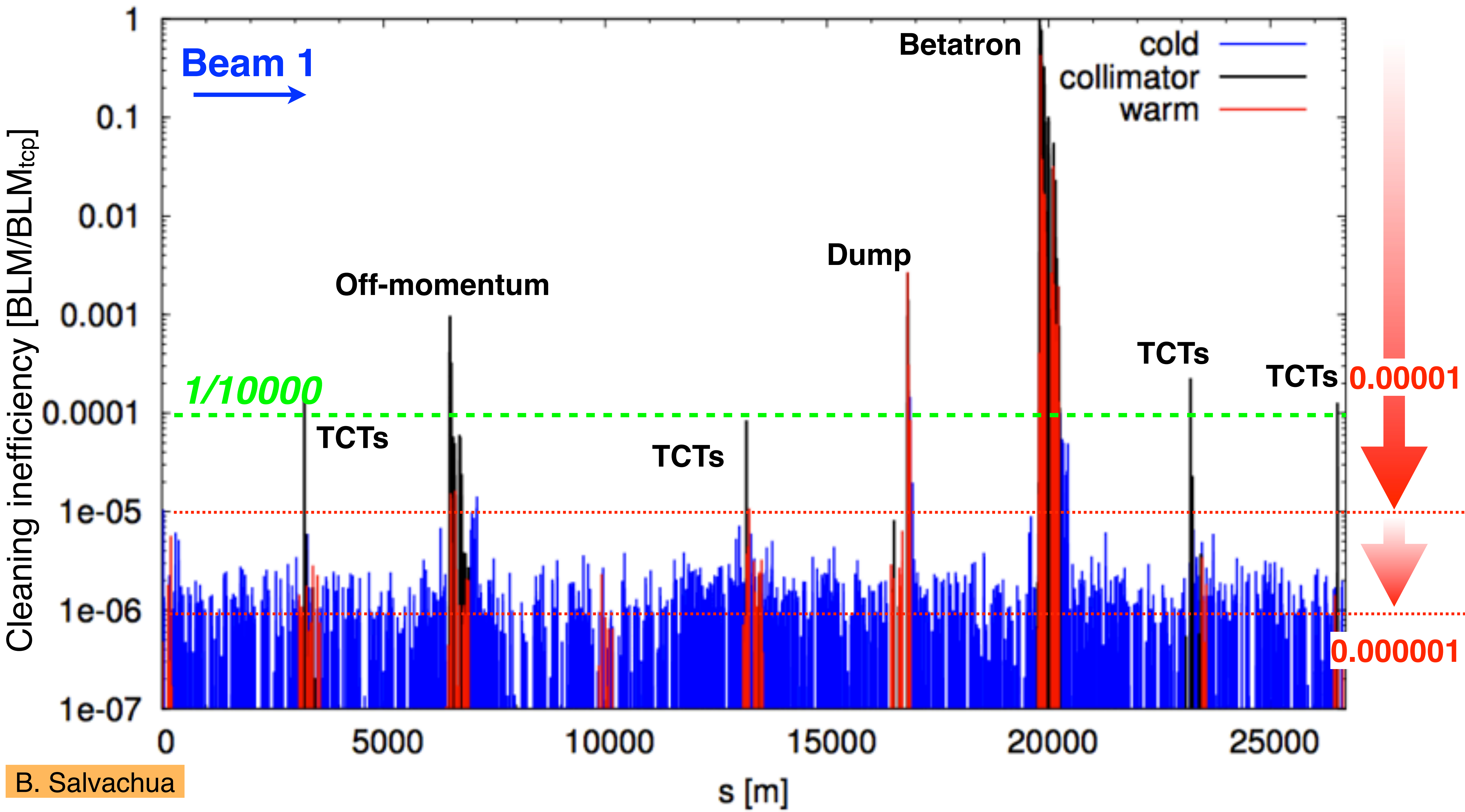
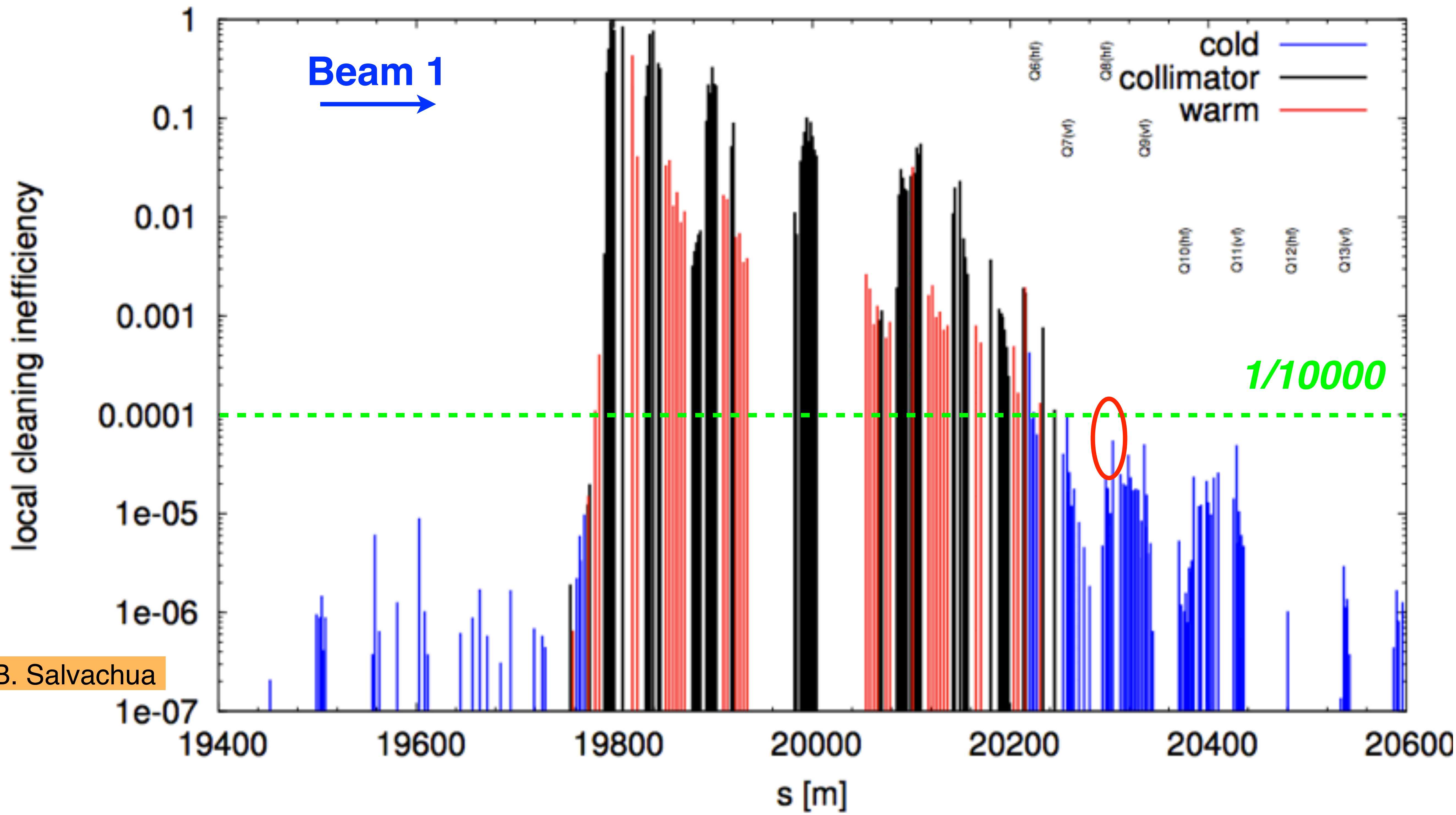


2012-13: “tight” collima

60

Highest COLD loss location: efficiency of > 99.99% !
Most of the ring actually > 99.999%

Loss maps in IR7



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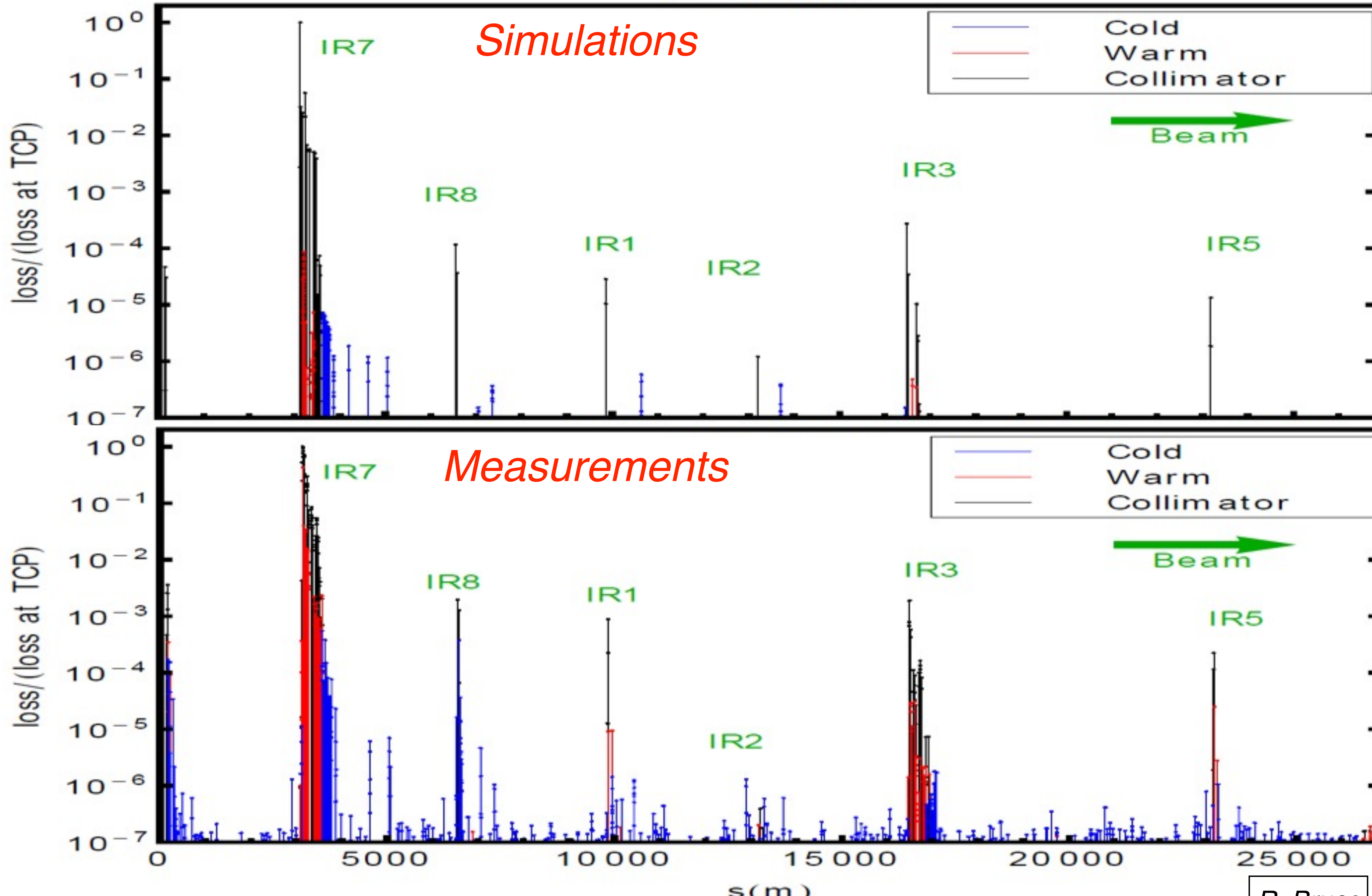
Critical location (both beams): losses in the dispersion suppressor (Q8) from single diffractive interactions with the primary collimators. No other significant limitations observed.

Accuracy of simulation predictions (i)



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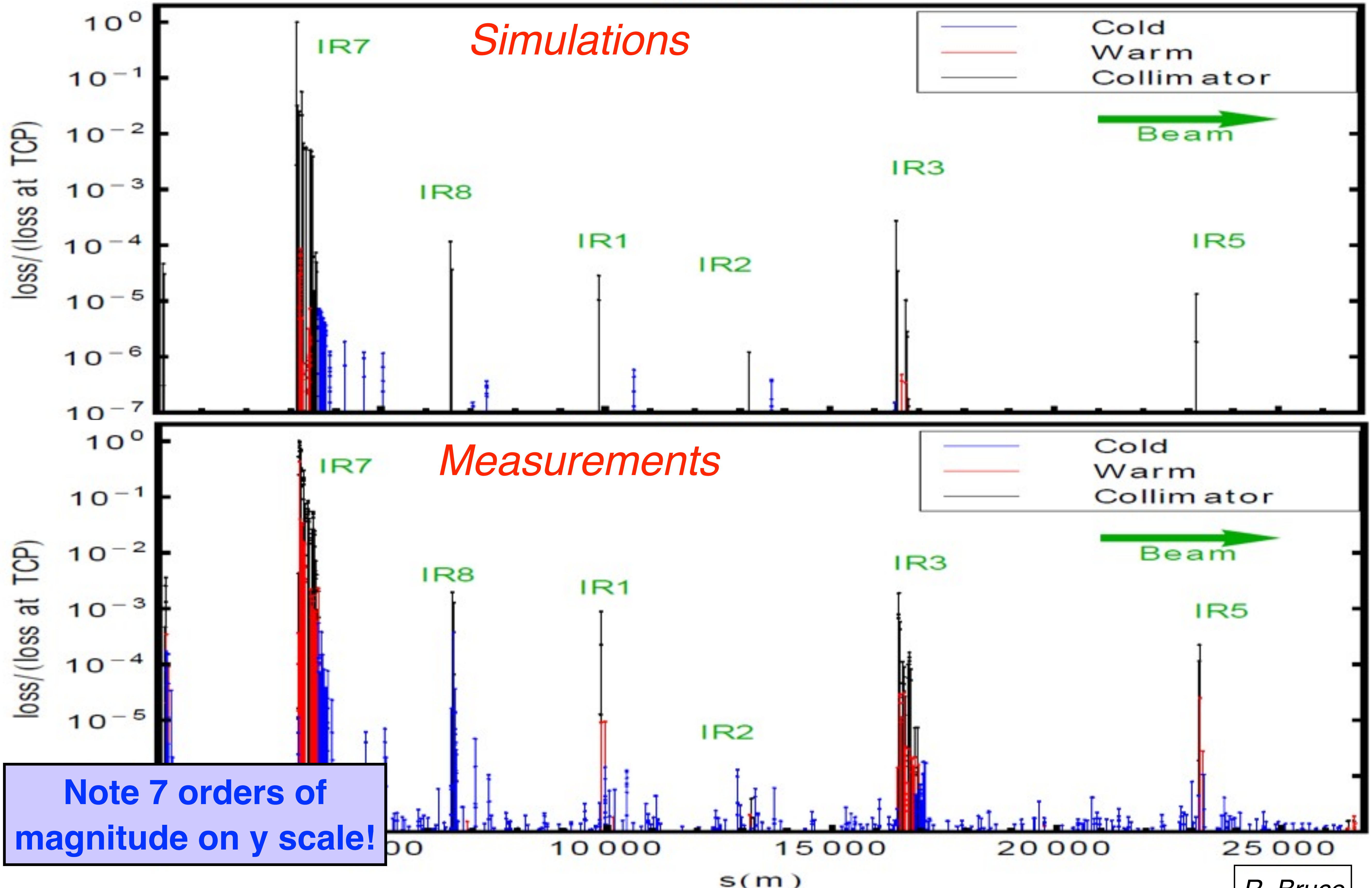

Note 7 orders of magnitude on y scale!

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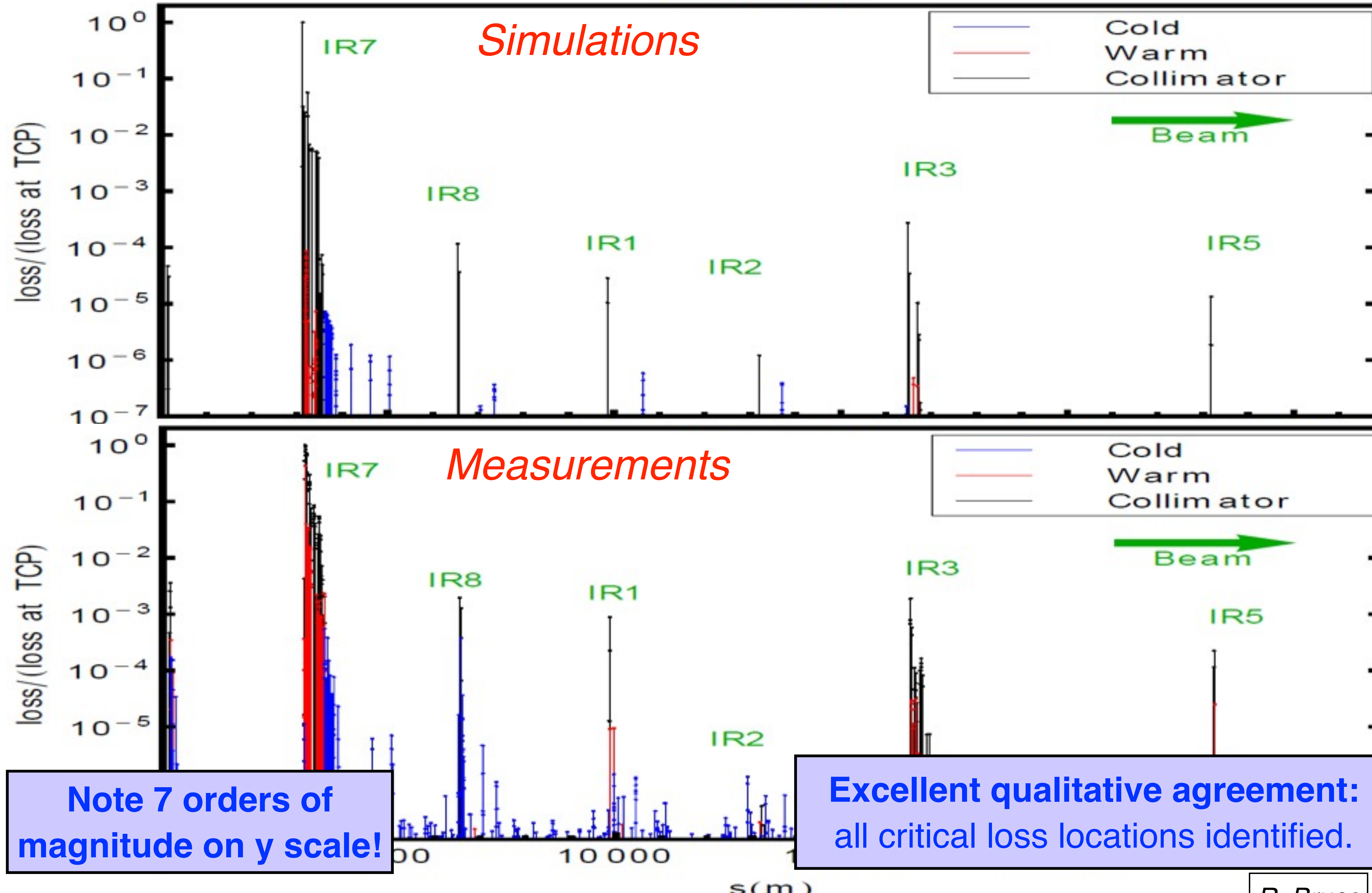

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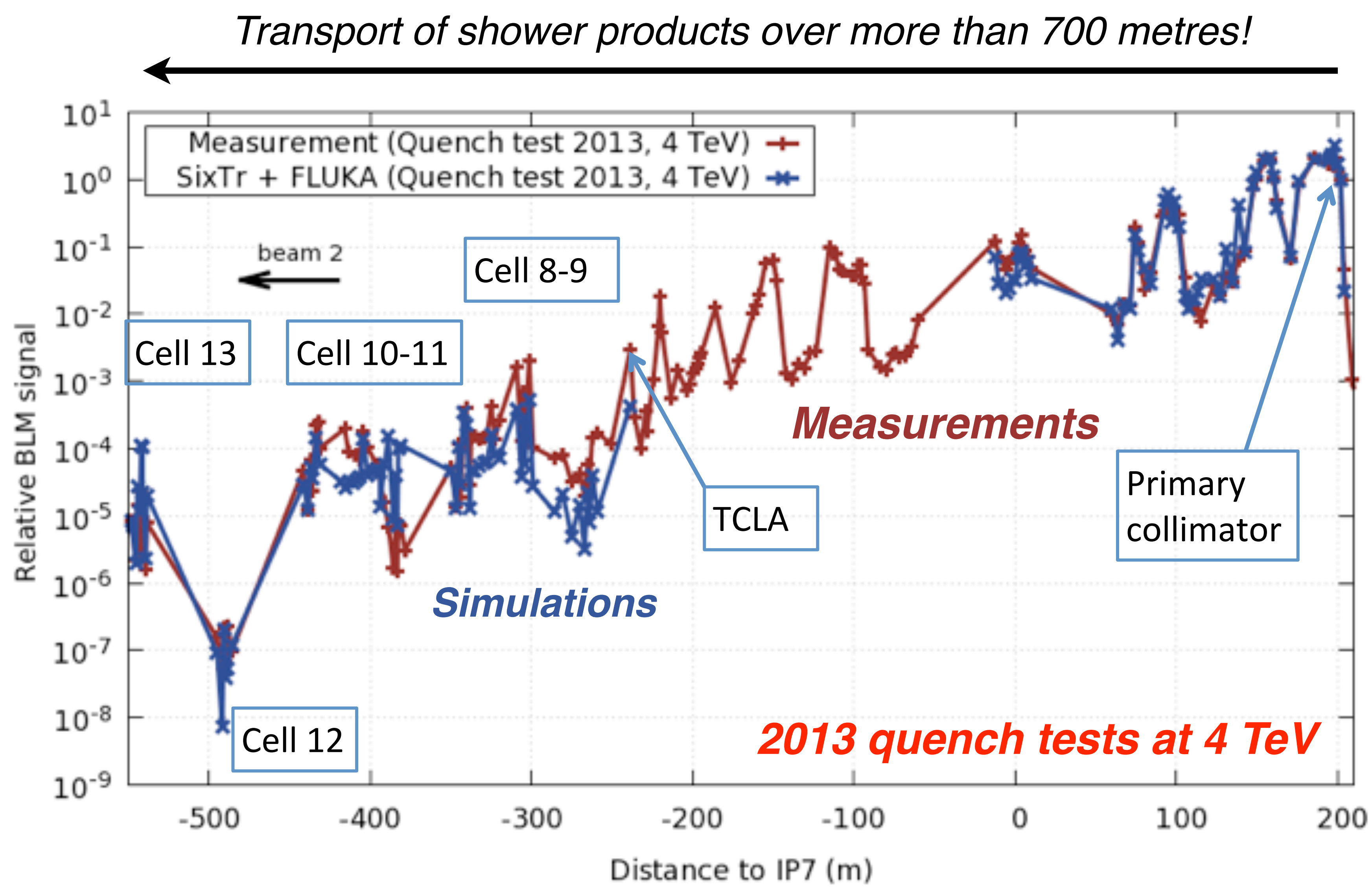
Excellent qualitative agreement:
all critical loss locations identified.

R. Bruce

Accuracy of simulation predictions (ii)



E. Skordis et al.

- Compared measured data from BLM's in IR7 against doses from shower cascades.
- **Impressive agreement** considering the complexity of the simulation behind!
- Working on improving further the agreement - some "factors" missing at specific locations (like TCLA collimators).
- Note however that this level of understanding came after years of operation - not need to have full integrated simulations to design a performing system...

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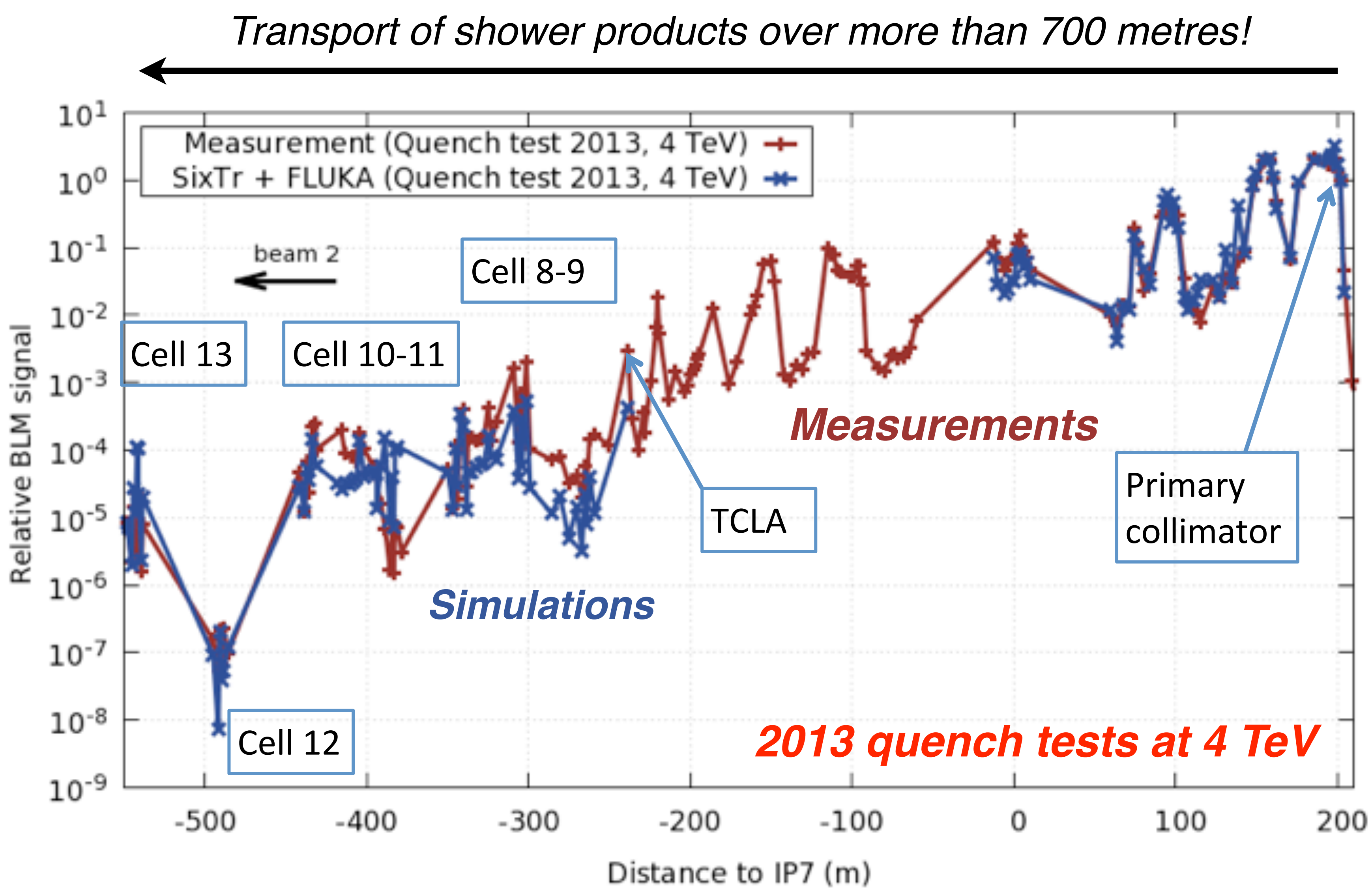

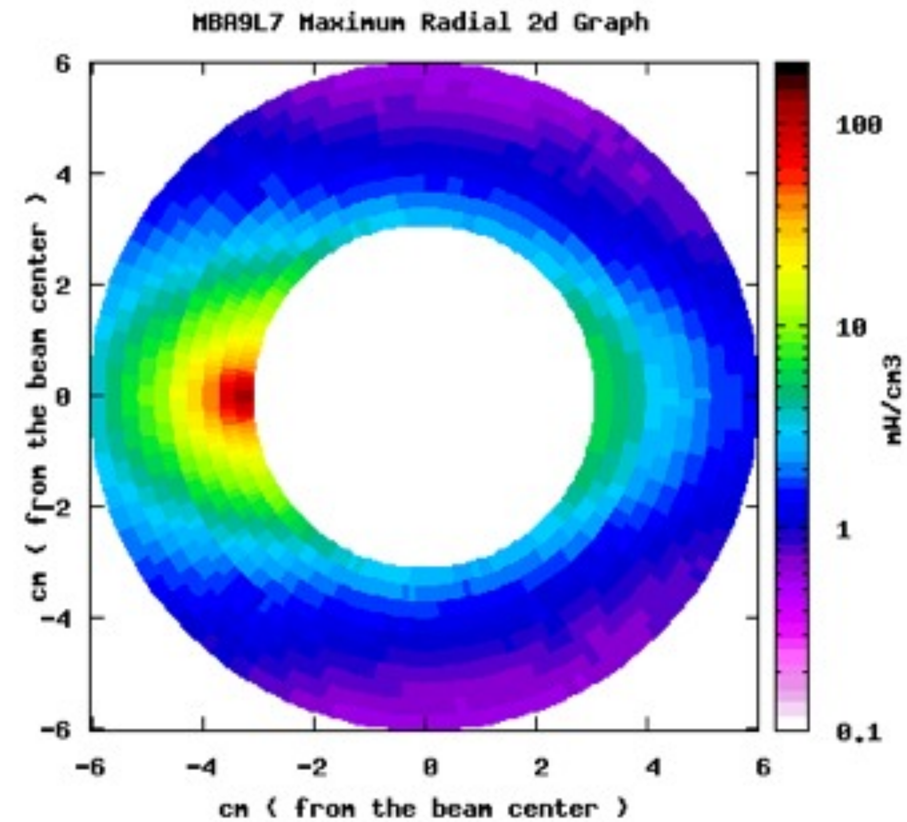

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- Collimator handling in **radiation environment** will be challenging.

Run1 operational experience

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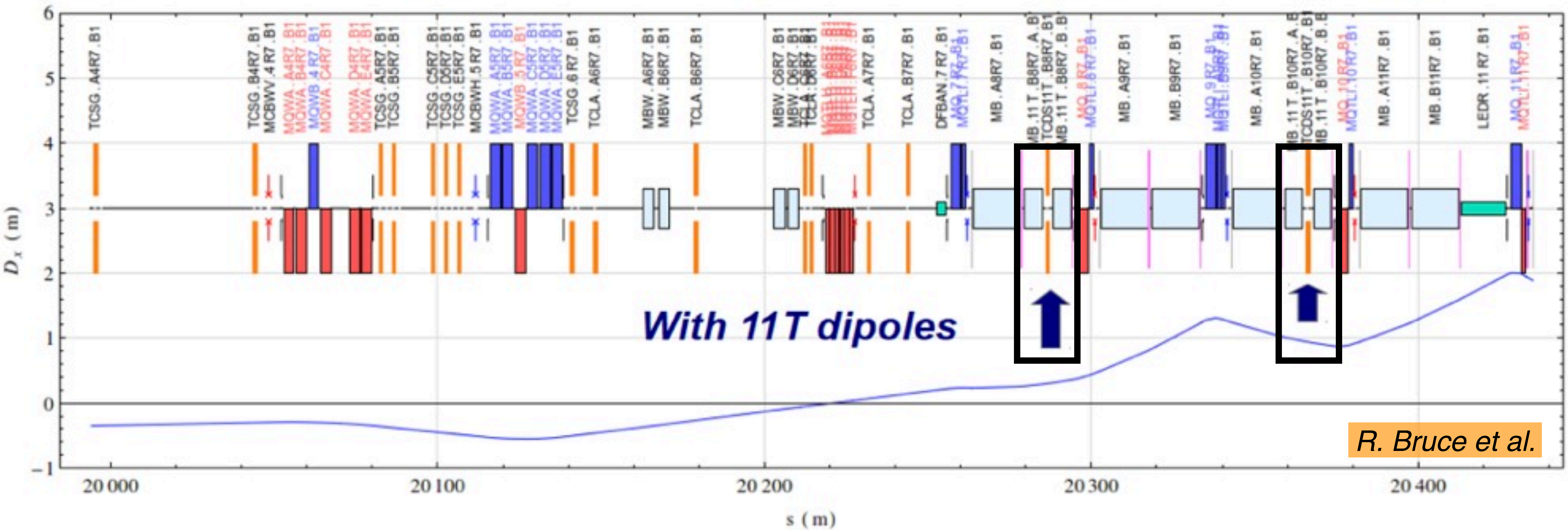
  - *Validated all critial design choices (HW, SW, interlocking, ...);*
  - *Cleaning close to simulations and ok for 1.5 nominal intensity at 7 TeV;*

  Solid solution to start with!
- ...ollimation **cannot protect** the **cold dispersion suppressors**.
  - *...itation for quench, magnet lifetime is being addressed.*
  - *...ent studies is moved to the experimental regions.*

Build this into the FCC design!!

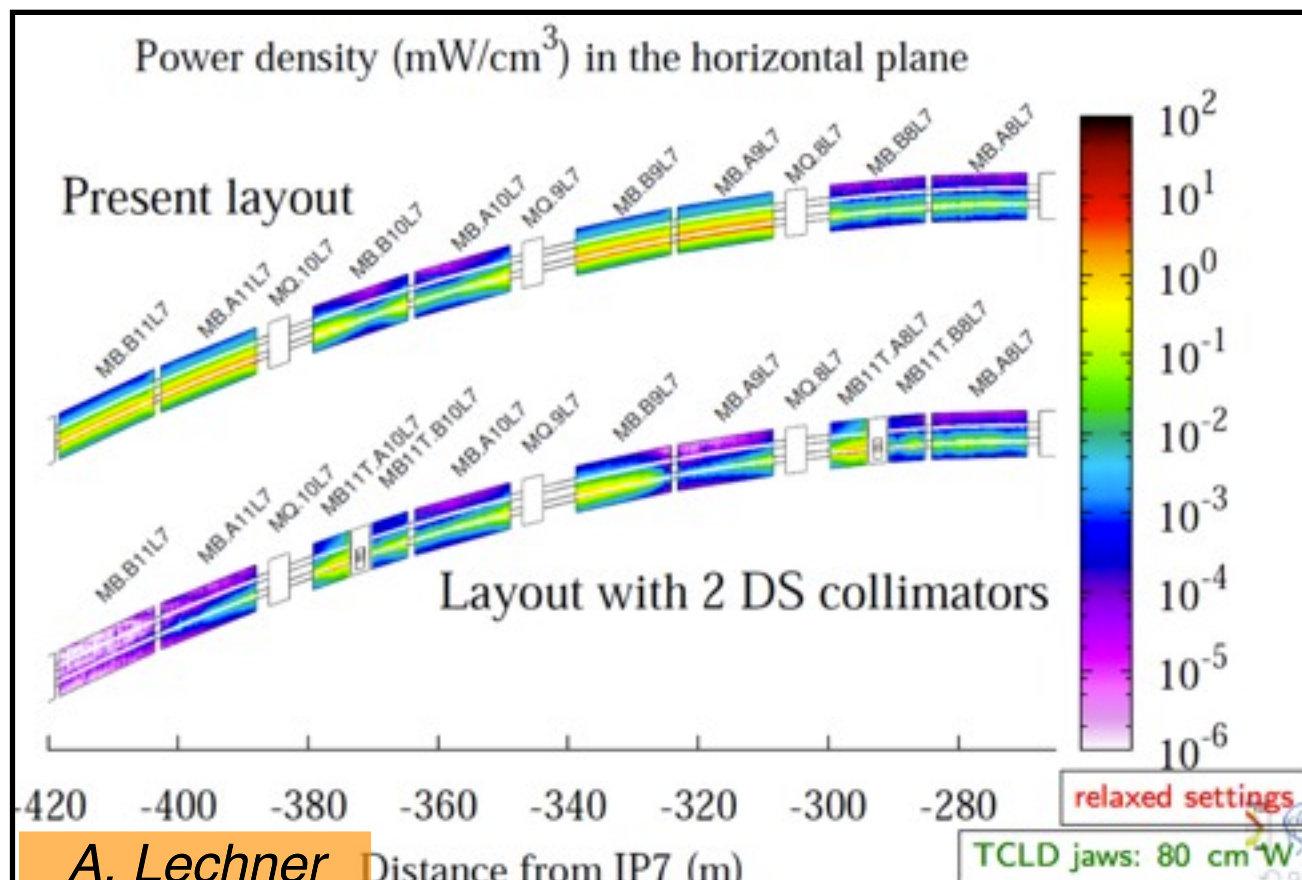
- The collimators determine the **LHC impedance**
  - *Rich program on "dream" materials and new collimator concepts.*
- Collimation alignments and validation of new setting are **time-consuming**.
- The **operation flexibility** in the experimental regions (VdM scans, spectrometer polarity, β* leveling, ...) is affected by collimation constraints.
- The ***β**** **reach** is determined by collimation constraints: retraction between beam dump and horizontal TCTs which are not robust.
- Collimator handling in **radiation environment** will be challenging.

Dispersion suppressor collimation

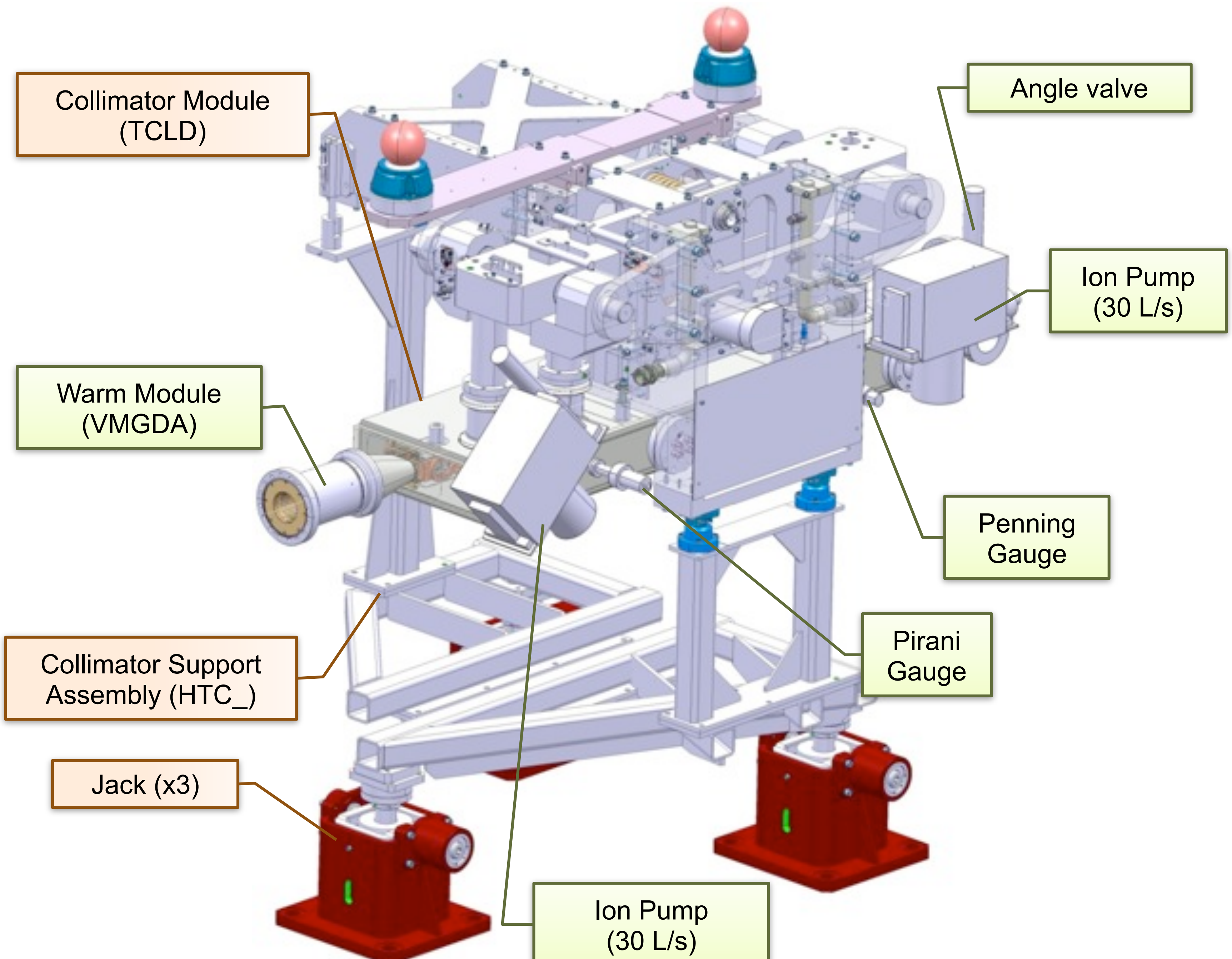


Fundamental system limitations: dispersive losses in the cold dispersion suppressor.

Appropriate solutions must be foreseen early on into the FCC lattice design!



Warm design for "cold" collimation



L. Gentini et al.

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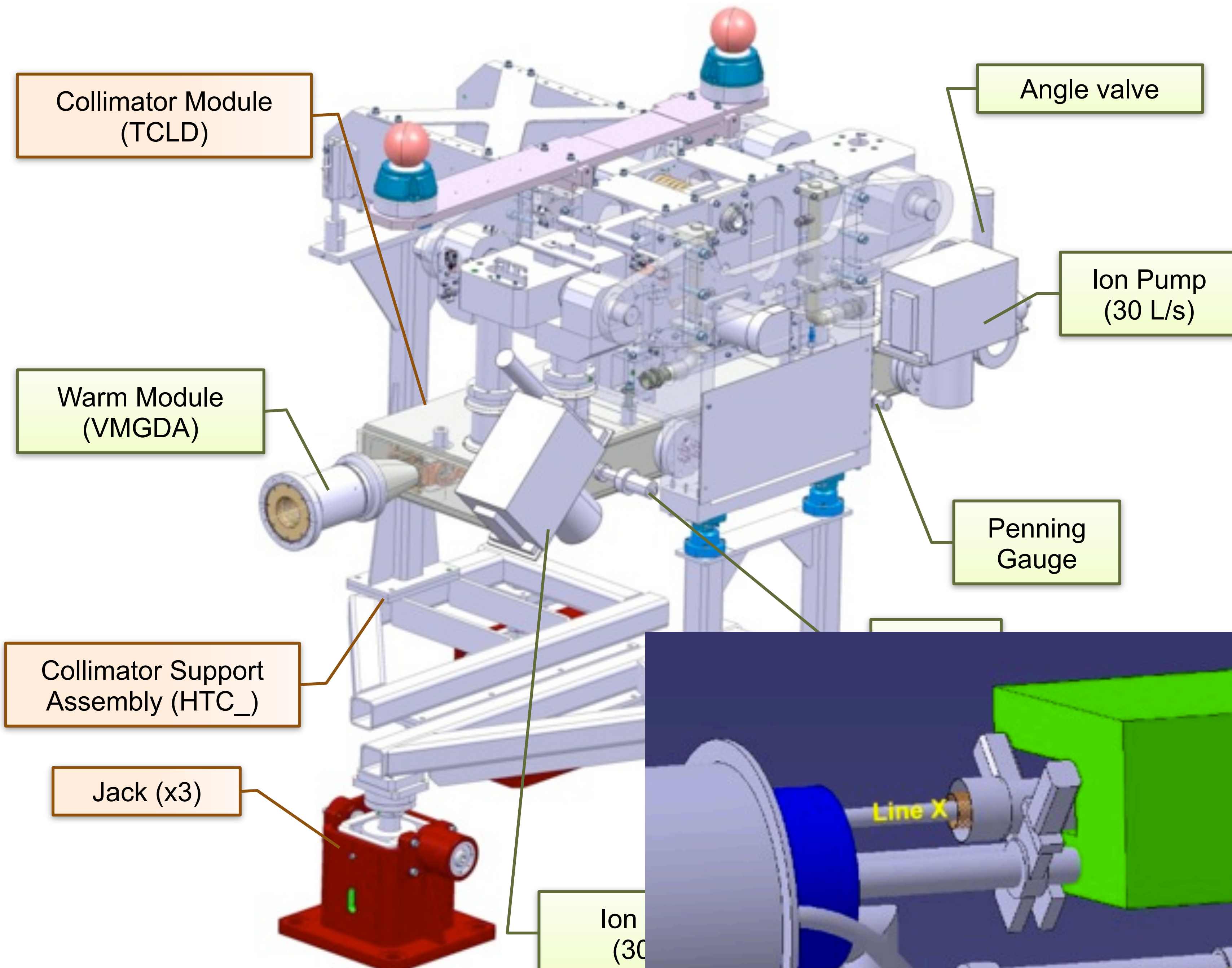

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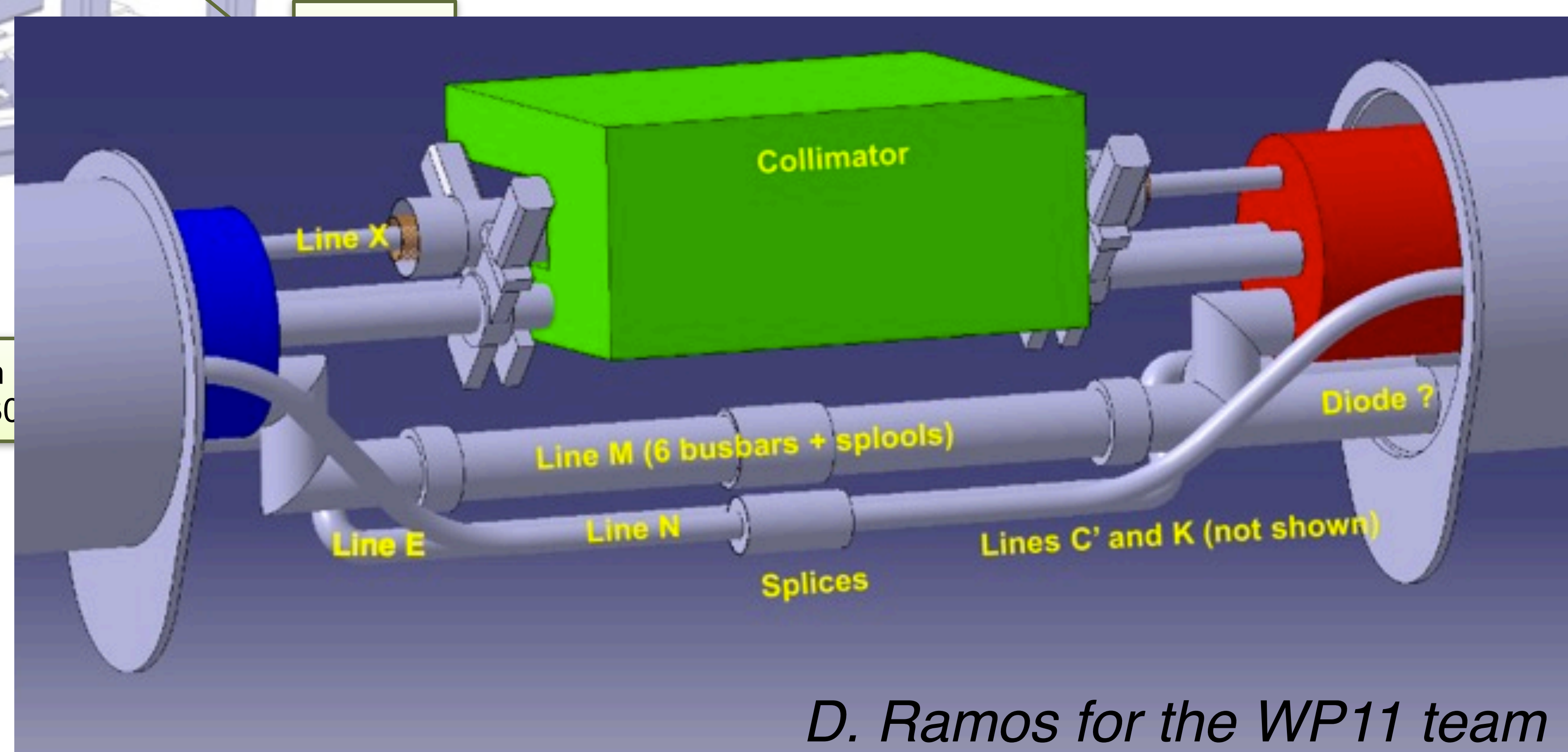

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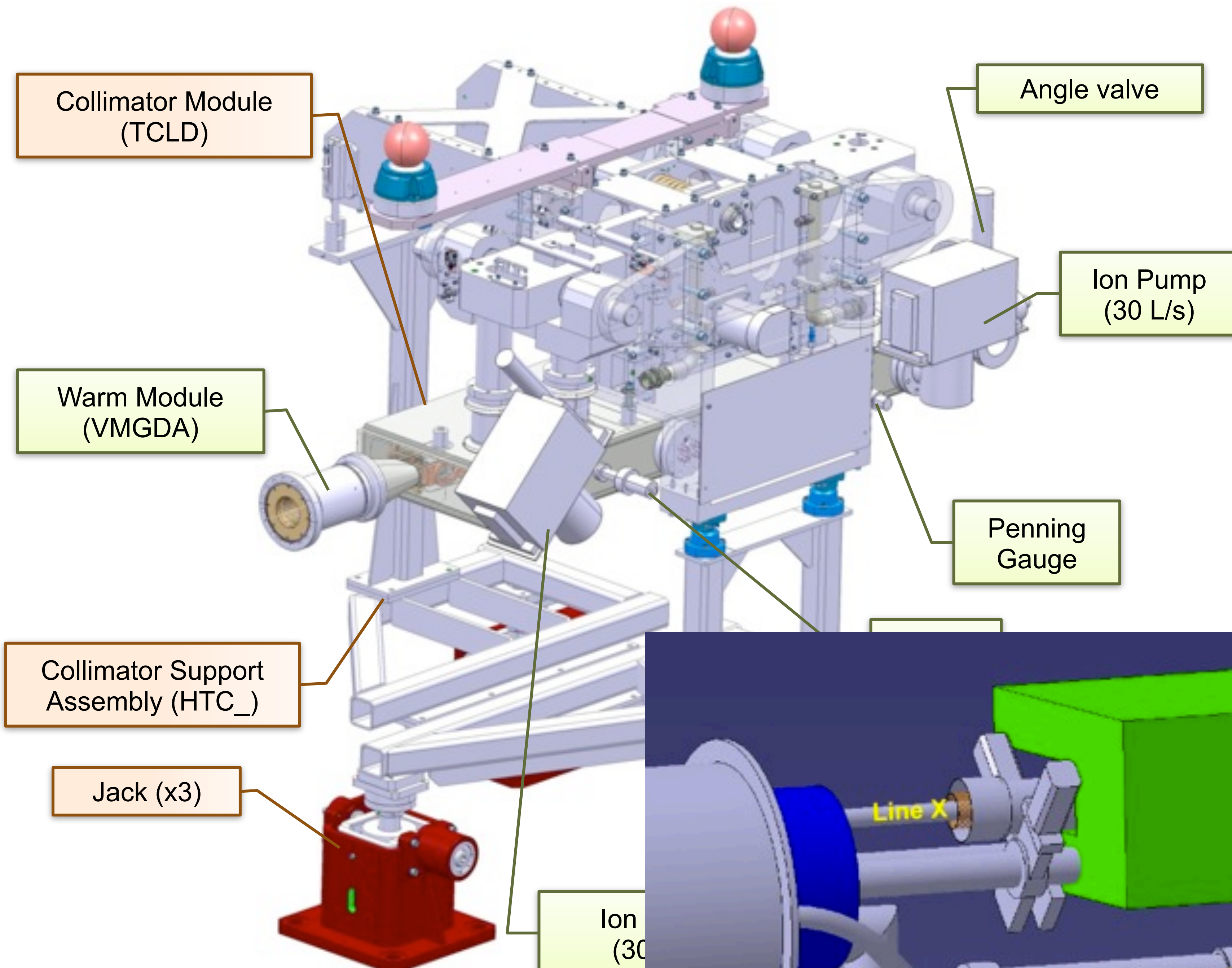
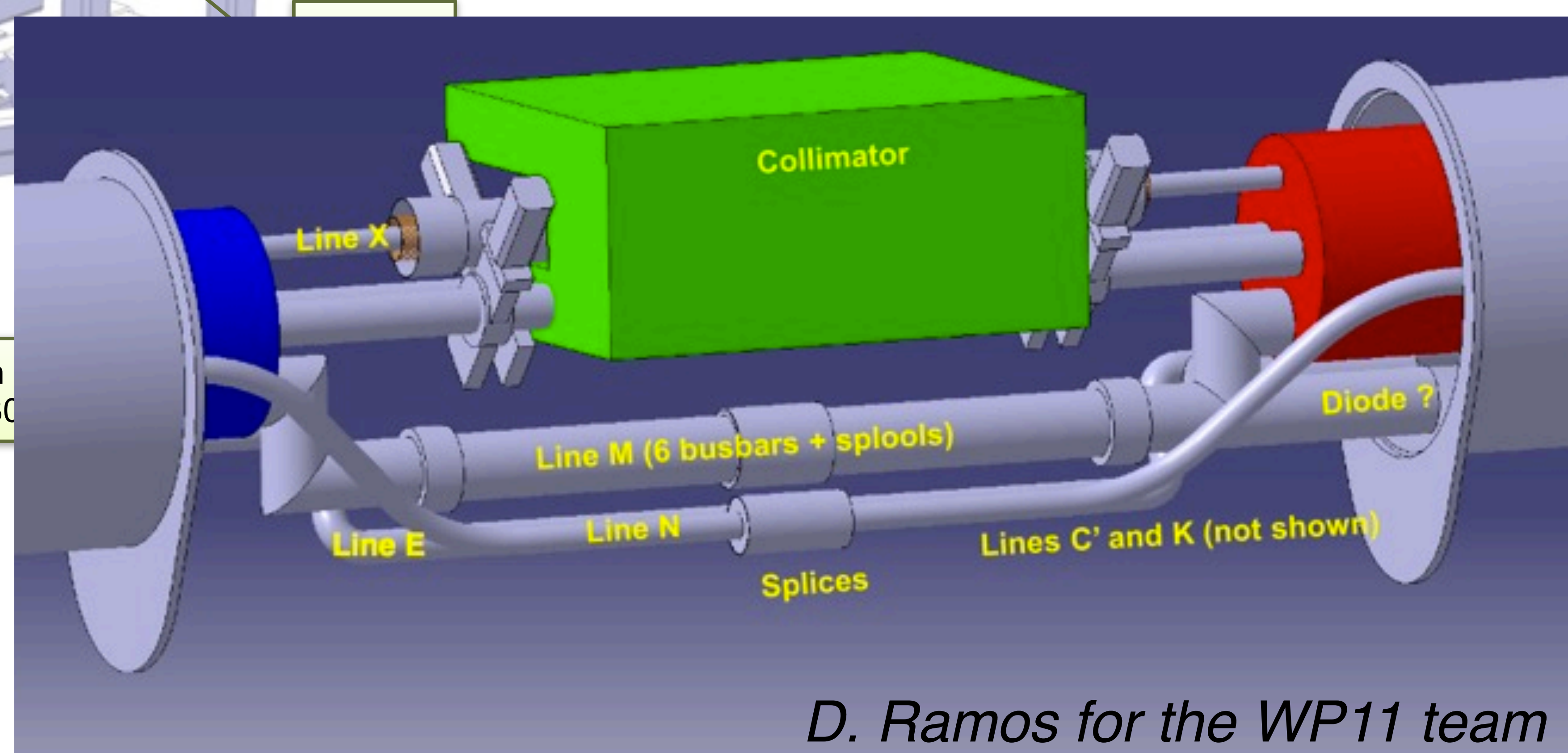


... but we will have time to think of more optimized solutions for FCC!

L. Gentini et al.



Research on new collimator materials

*A very **rich scientific program** on **future collimator materials** is part of the LHC collimation project studies!*

Our dream:

> ***Find a material with low impedance and high robustness that can clean efficiently the beam halo, withstand the worst failure scenarios and have minimum perturbation of beam stability at small gaps!***
> ***...and that does not deteriorate in a high-dose environment.***

*Important synergy with other domains, **crucial role of industry**!*

Strong collaborations world-wide:

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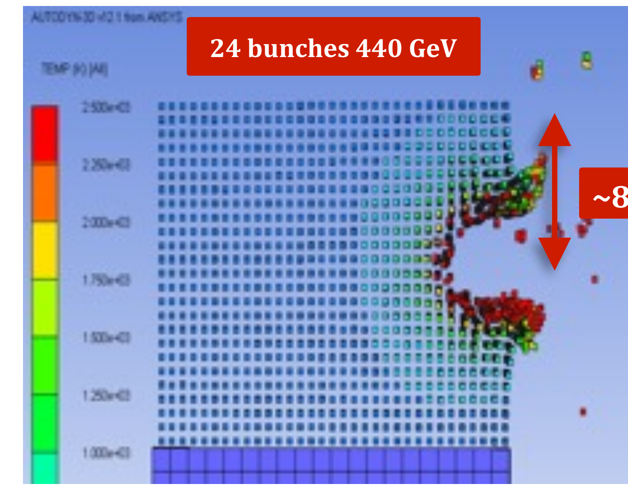
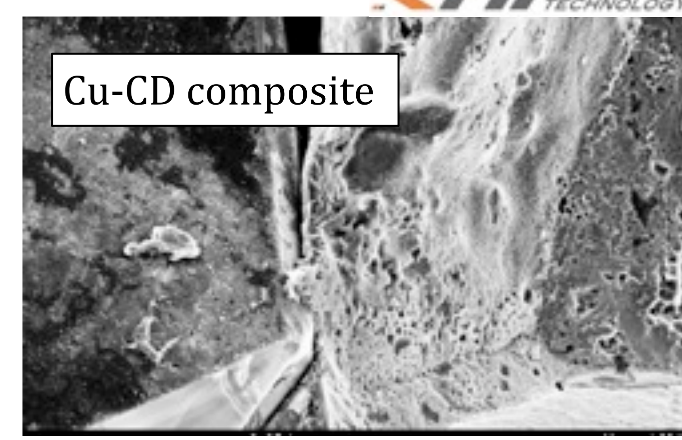
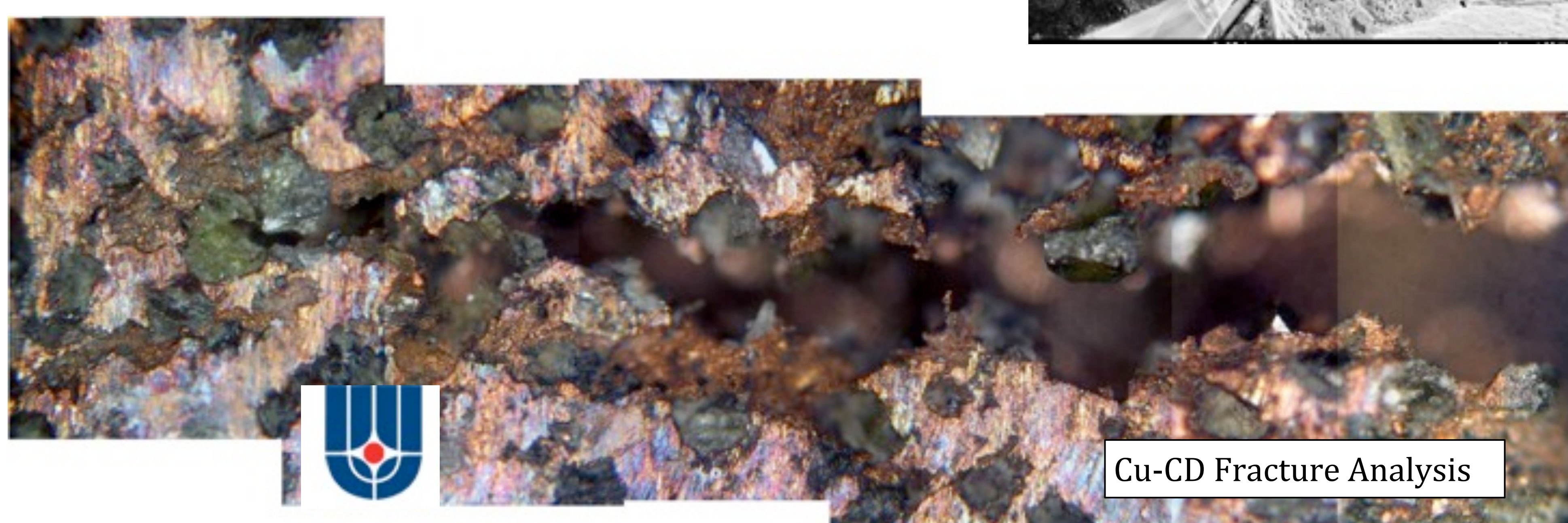
***Inter-disciplinary activity** involving beam tests, state-of-the-art simulations and material development.*




Cu-CD composite

Mo-Gr composite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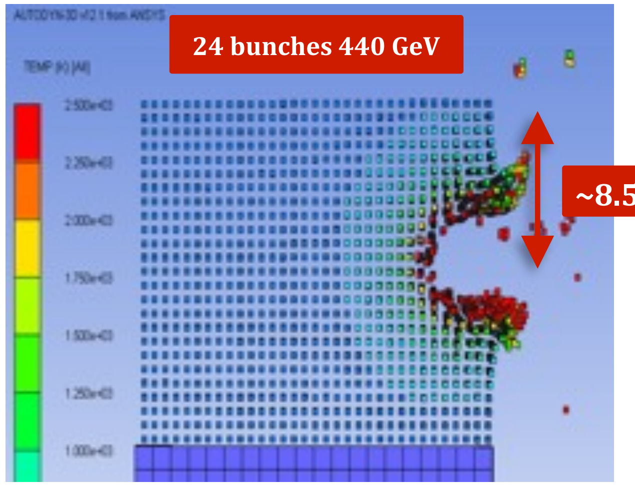

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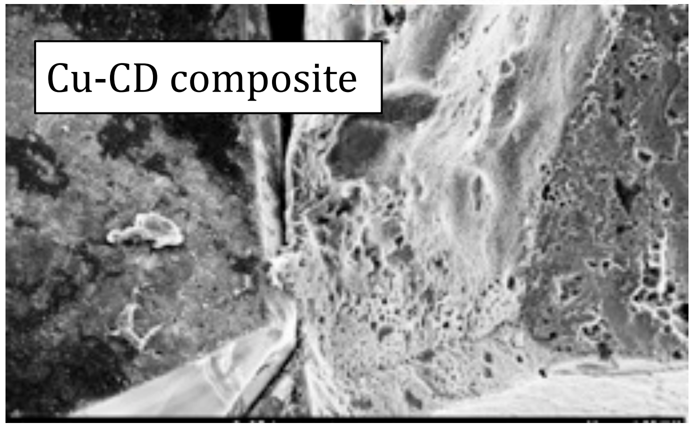

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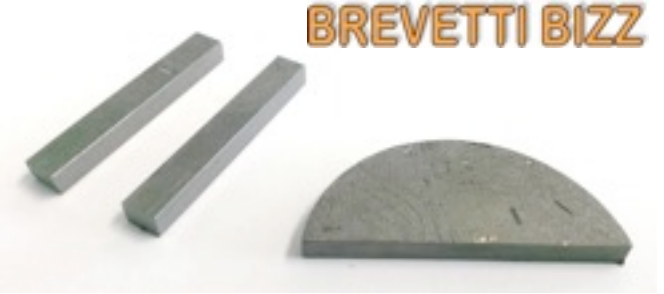

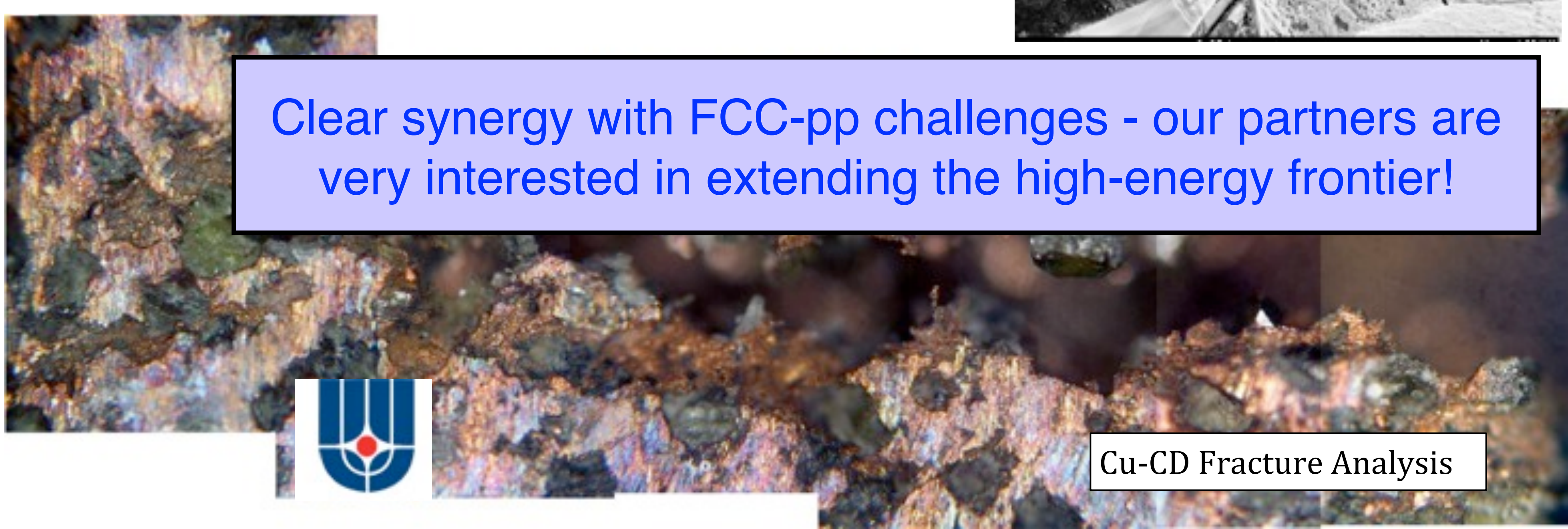

Clear synergy with FCC-pp challenges - our partners are very interested in extending the high-energy frontier!

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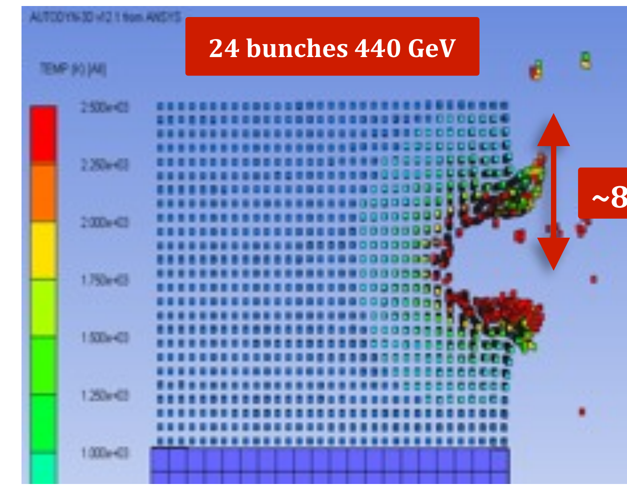

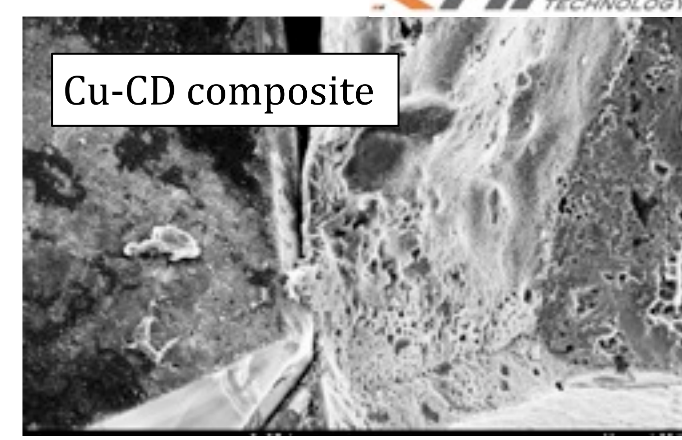
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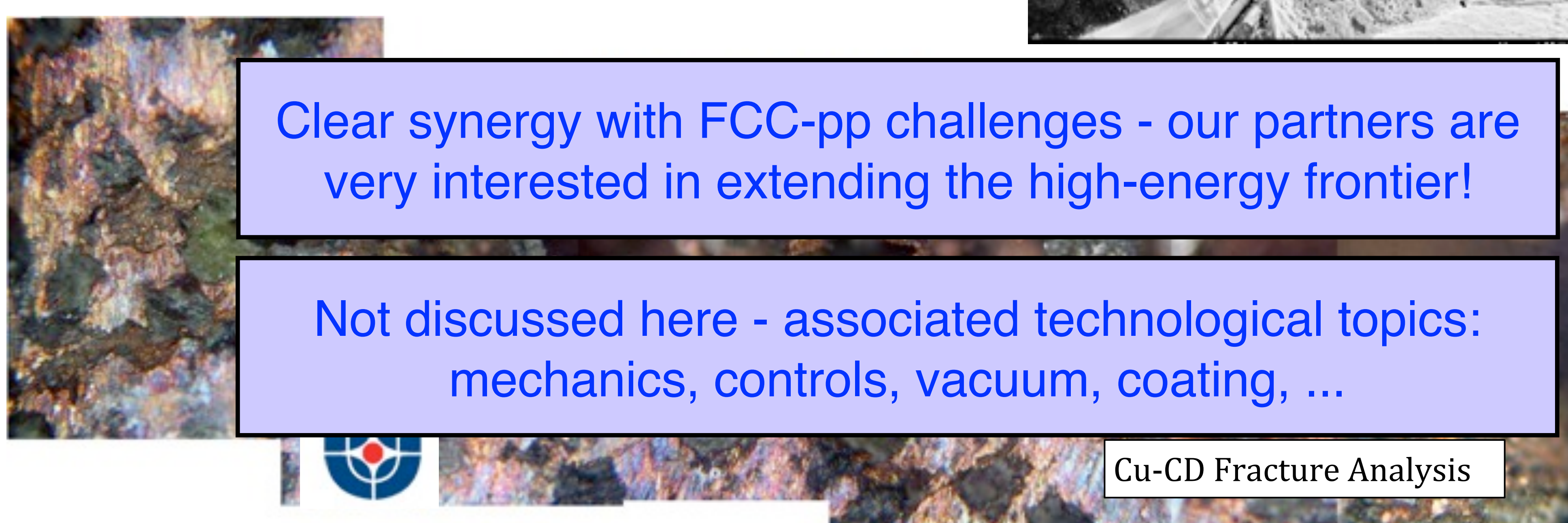
Not discussed here - associated technological topics: mechanics, controls, vacuum, coating, ...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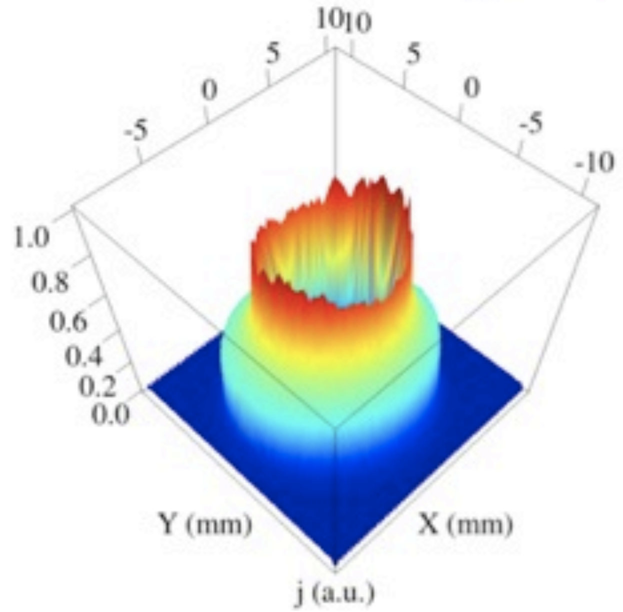
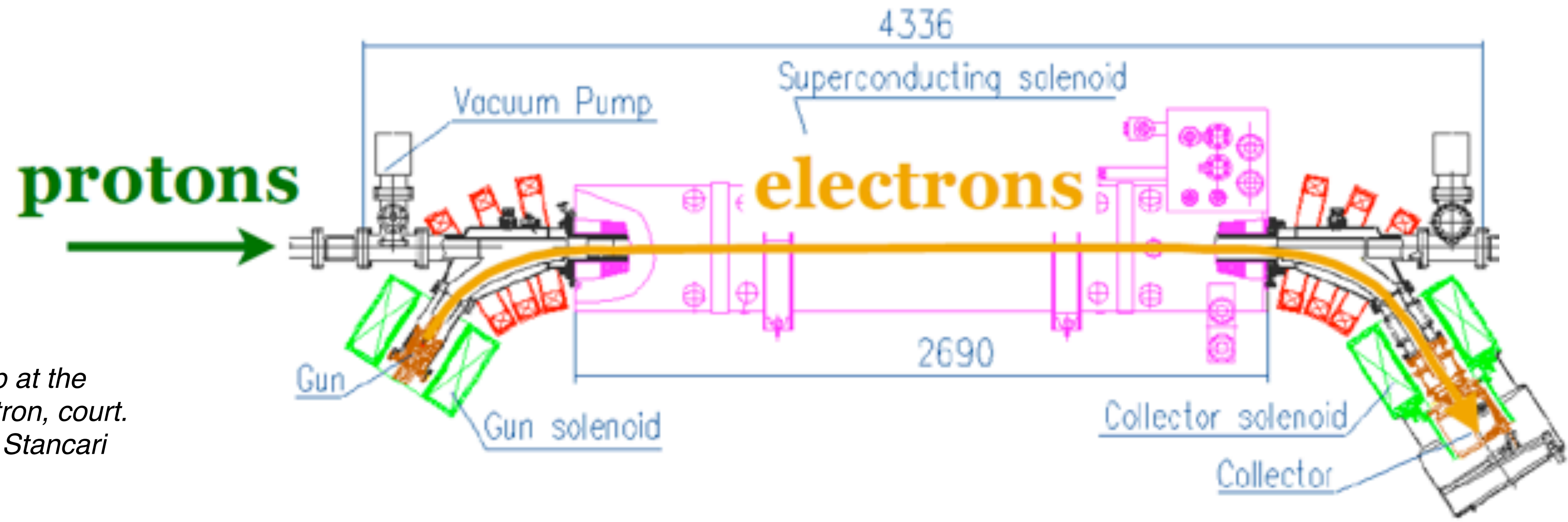
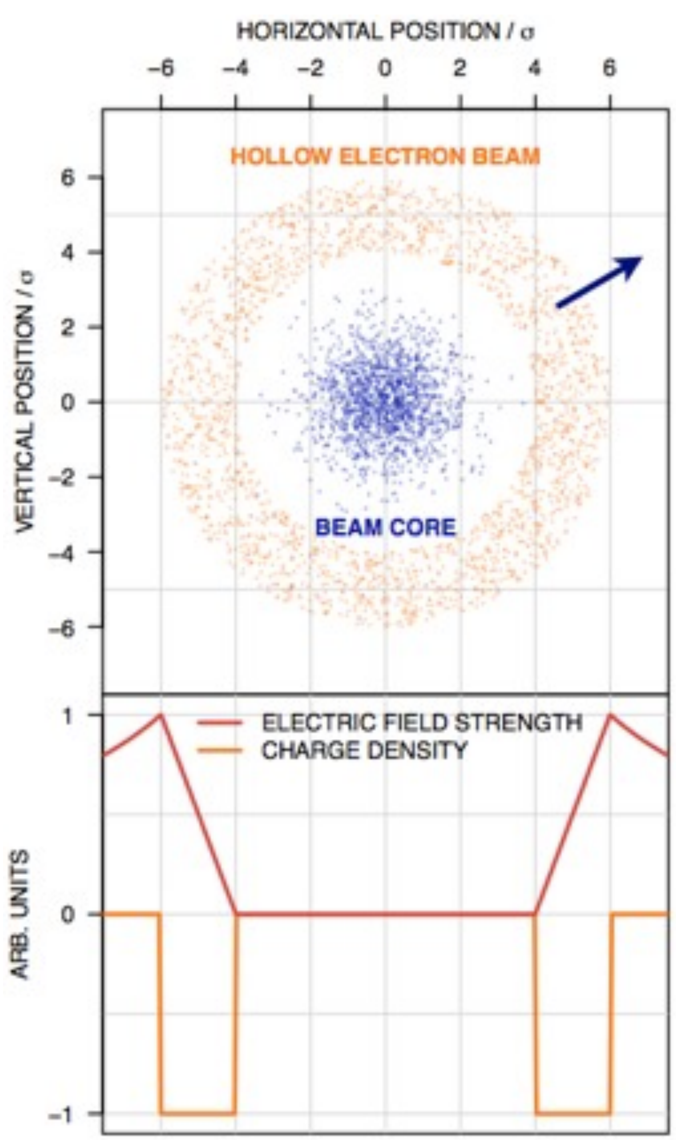
Advanced collimation: hollow e-lens





Setup at the Tevatron, court. of G. Stancari



- **A hollow electron beam** runs parallel to the proton beam
  - *- Halo particles see a field that depends on (A_x,A_y) plane*
  - *- Beam core not affected!*
- Adjusting the e-beam parameter, one can **control diffusion speed** of particles in the area that overlaps to e-beam.
  - *- Drives halo particles unstable by enhancing (even small) non-linearities of the machine.*
- This is an ideal scraper that is **robust** by definition.
- **Can be used to control the loss rates on the collimators!**
- Complex beam dynamics required beam data validation.
- Working on a design for implementation in LS2, if needed.

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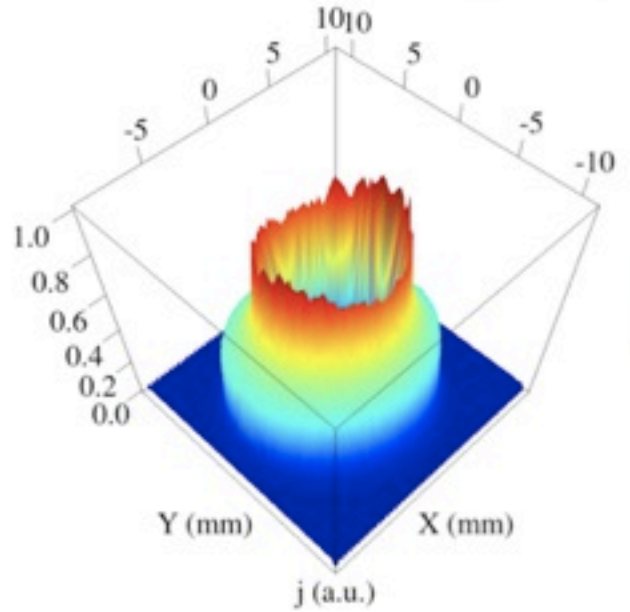

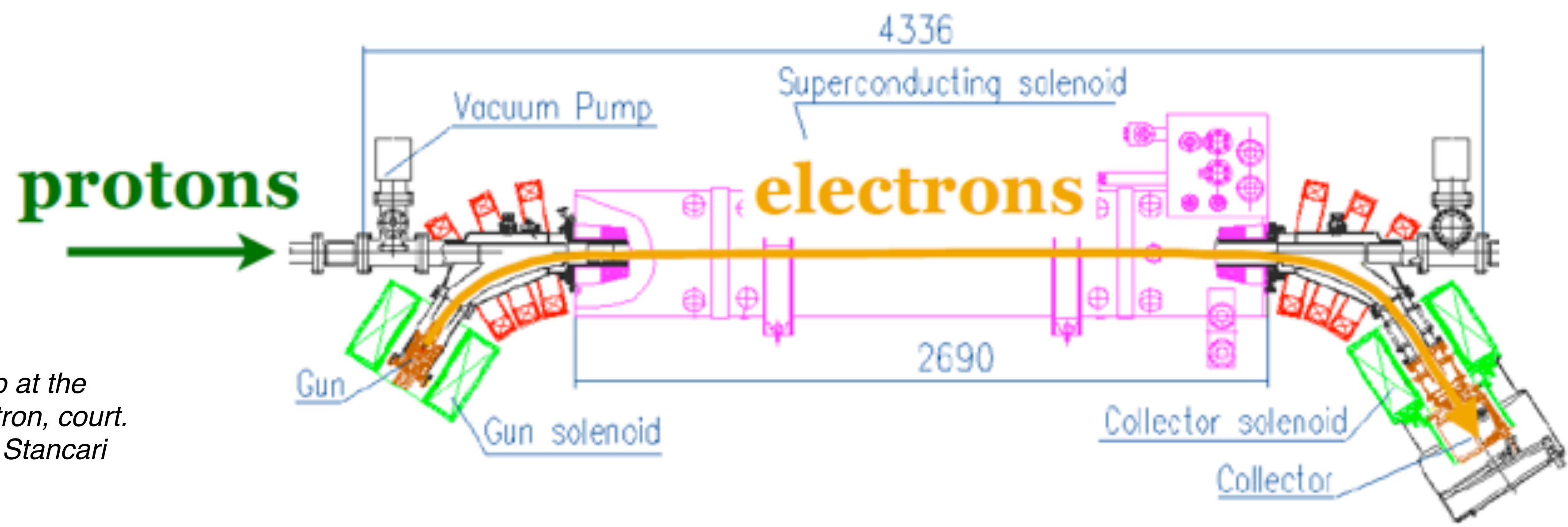

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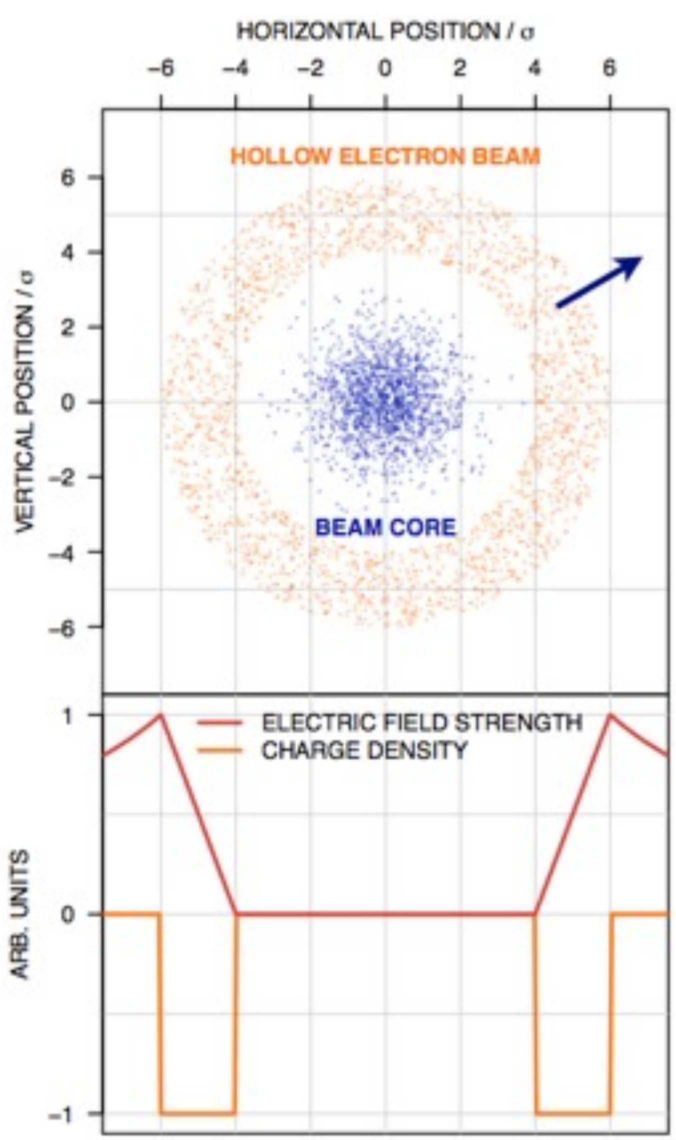

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Expected to be a key asset for the control of loss rates on the collimation system. Crucial for FCC as well!

Advanced collimation: consumable collimator

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LHC Collimation Project

Home of the Project for the LHC Collimation System

Home	Project Team	Notes	Collimator List	Sounds/Movies	Meetings
Links	Papers	Talks (WG)	Layout IR3/7	Collimator DB	Pictures
MP Tests	Sounds 2011	Lossmaps	Tracking Code	LS1 activities	ColUMM
SLAC collimation					

SLAC Rotatable Collimator

Description

The principle function of the LHC collimation system is to protect the superconducting magnets from quenching due to particle losses. The collimation system must absorb upwards of 90 kW in the steady state operating condition (1 hr beam lifetime) and withstand transient periods when more than 500 kW are deposited during up to 10 seconds. These figures might be increased by up to a factor 2 in the HL-LHC era. The system must also be robust against an accident scenario where up to 8 full intensity bunches impact on one collimator jaw due to an asynchronous firing of the beam abort system imparting 1 MJ over 200 ns. Higher Z materials can provide better collimation efficiency compared to the low Z graphite collimators of the present system, but will not withstand beam impacts in case of worst failure scenarios. A rotatable jaw concept has been designed which offers up to 20 collimator "facets" and a rotation mechanism that allows offering to the beam a fresh collimating surface in case of beam damage. This advance collimation concepts was developed at SLAC within the US-LARP collaboration of collimation studies. The SLAC effort aimed at producing a machine-ready rotatory collimator prototype ready for beam test at the CERN HiRadMat facility or at the SPS or LHC machines.

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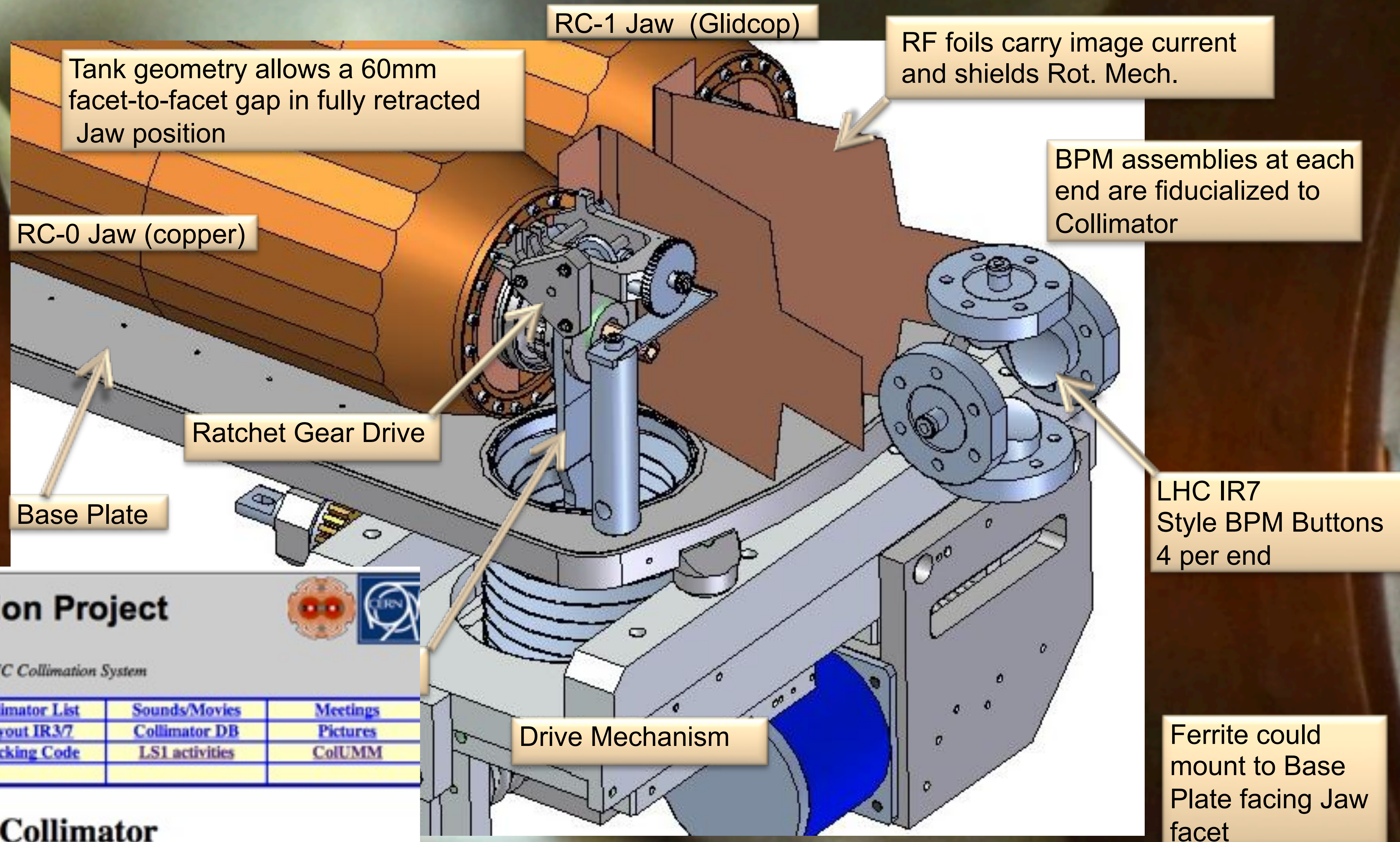

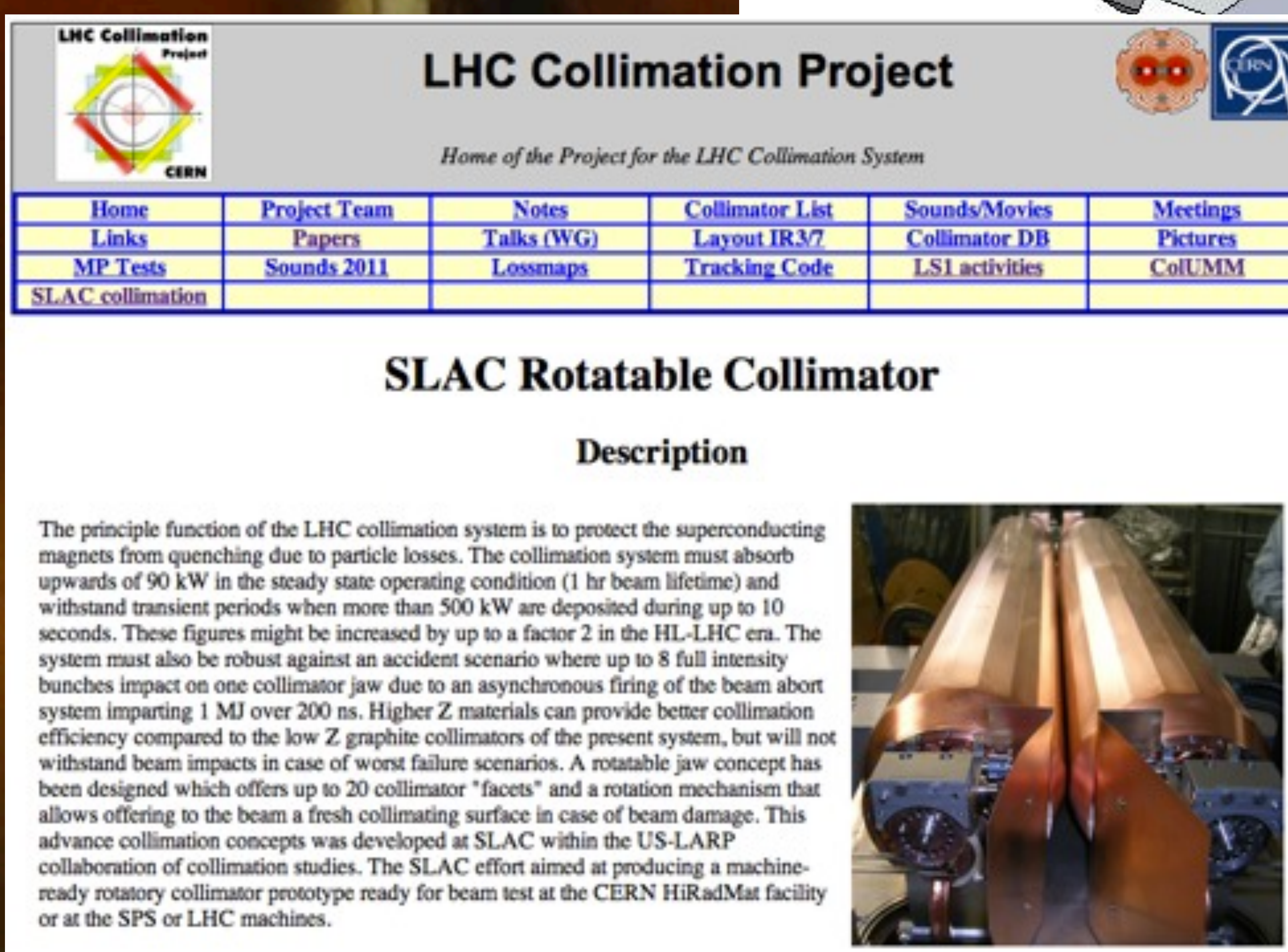

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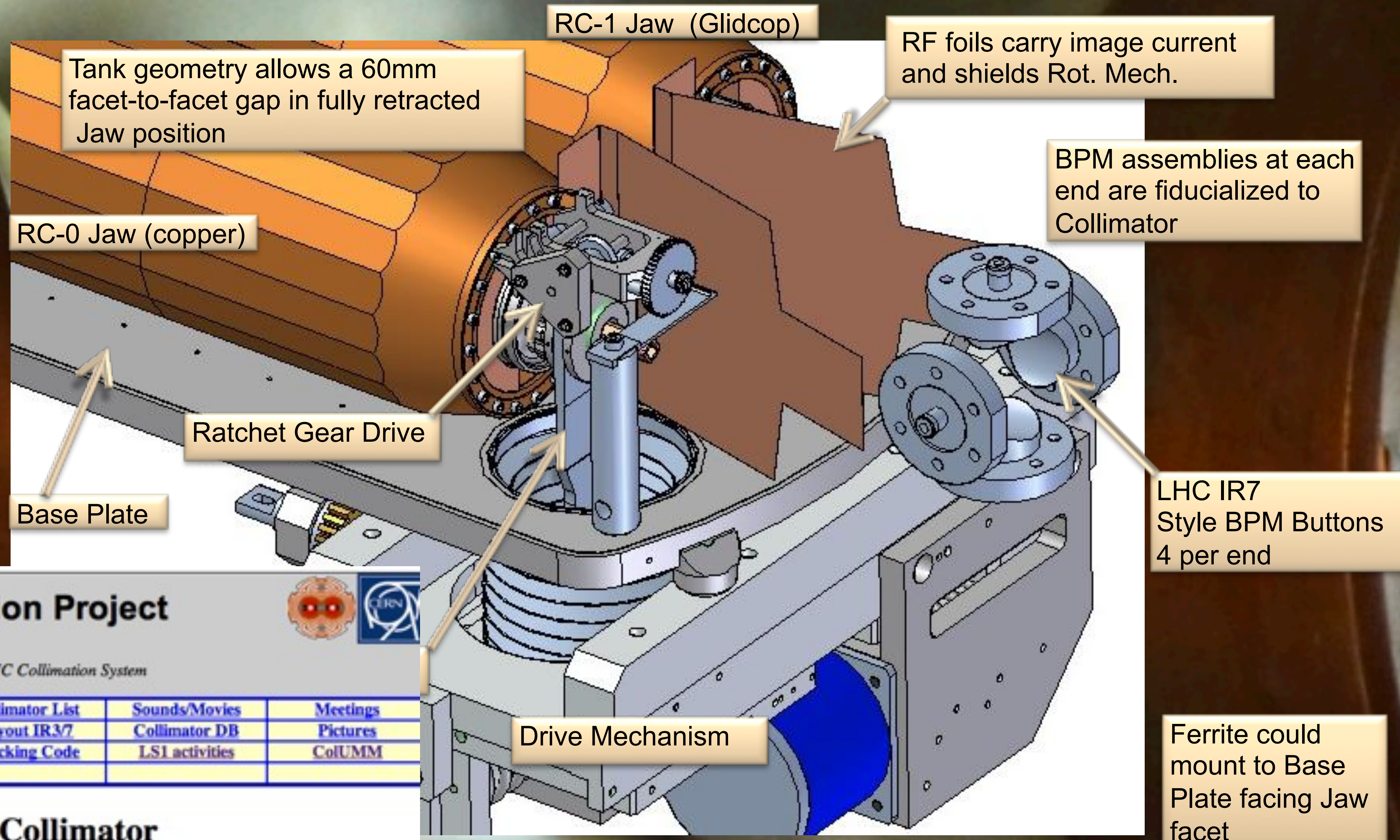

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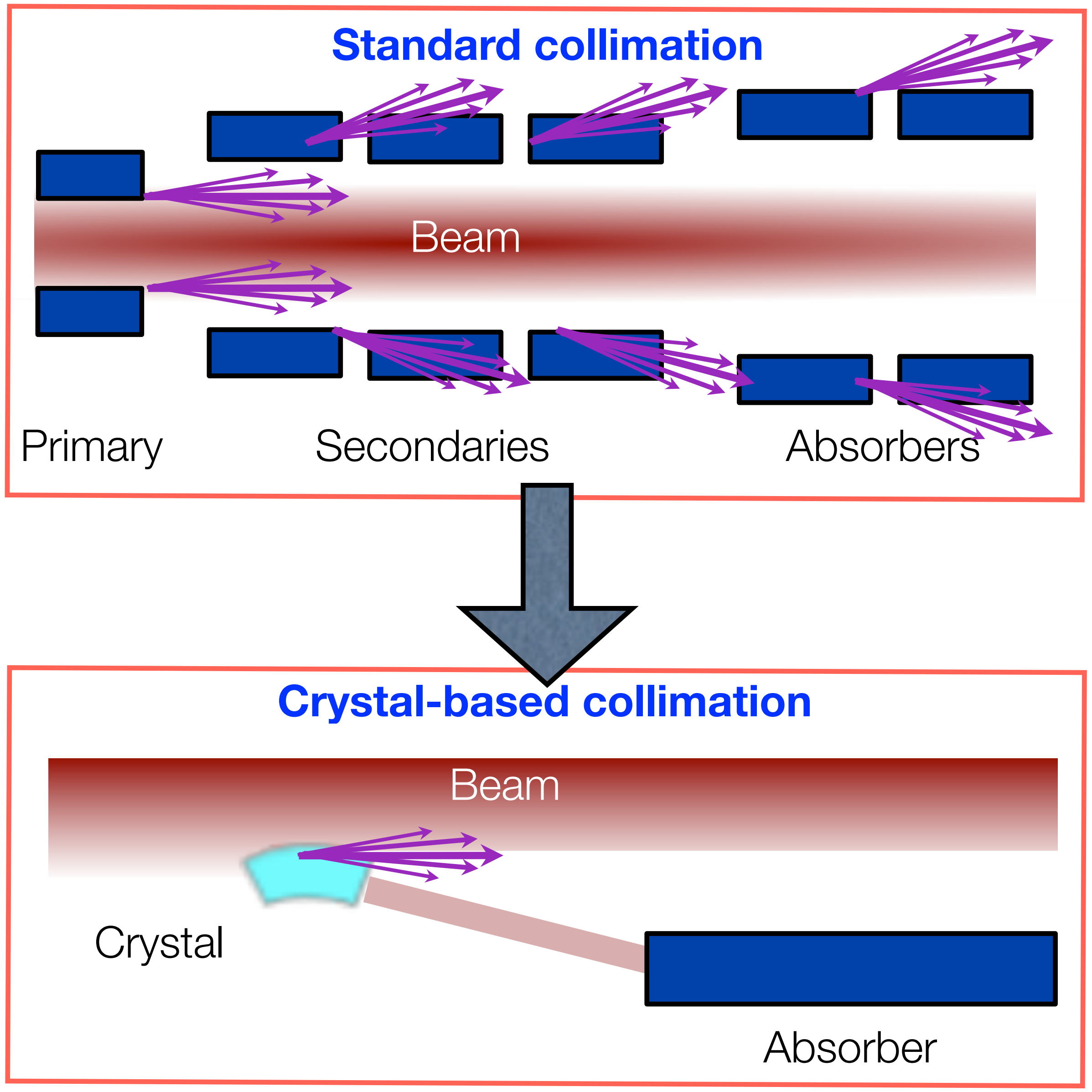
Solid base to start from, in case we cannot find suitable materials for the FCC failure scenarios.

Advanced collimation: crystals



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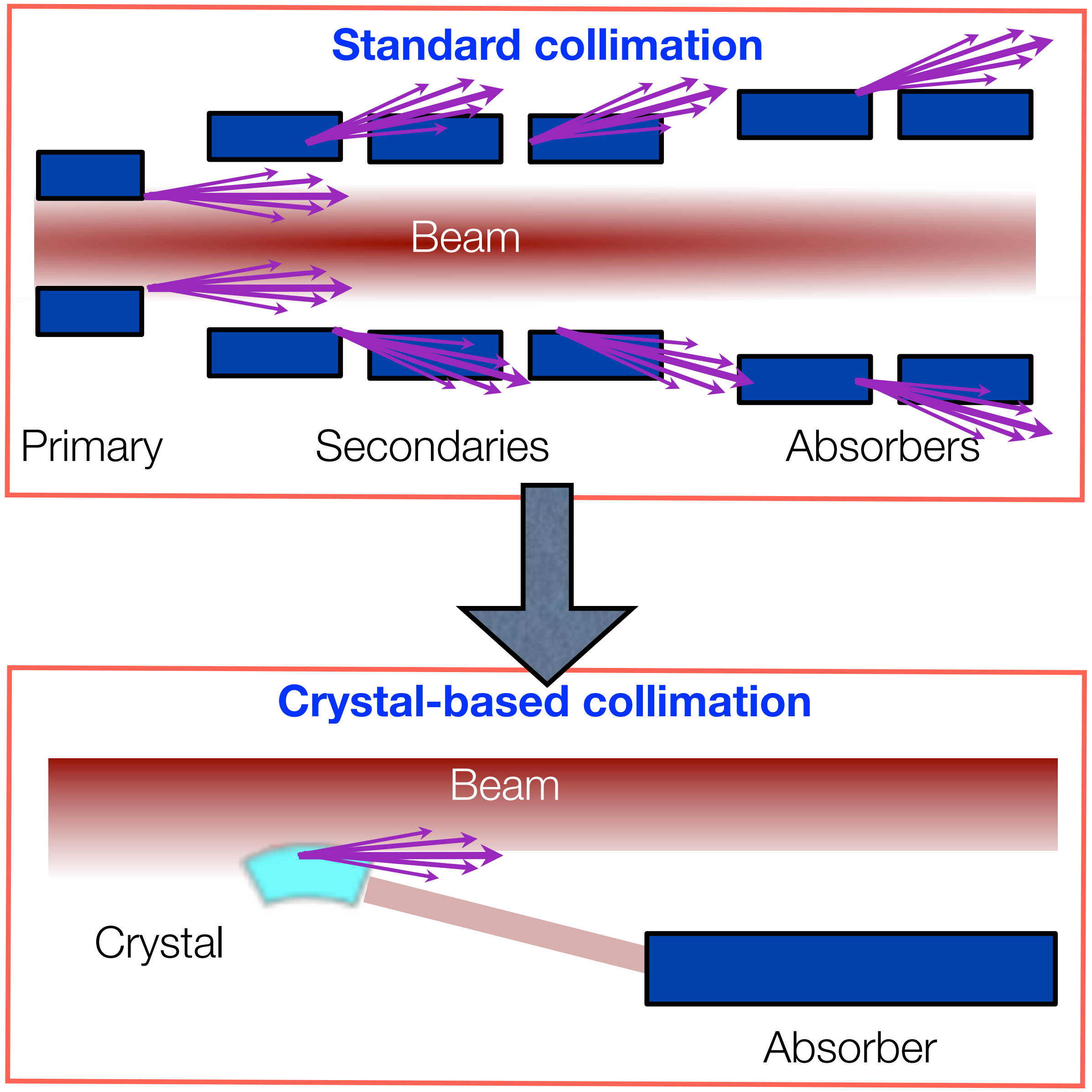

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1. Improved DS cleaning in channeling;
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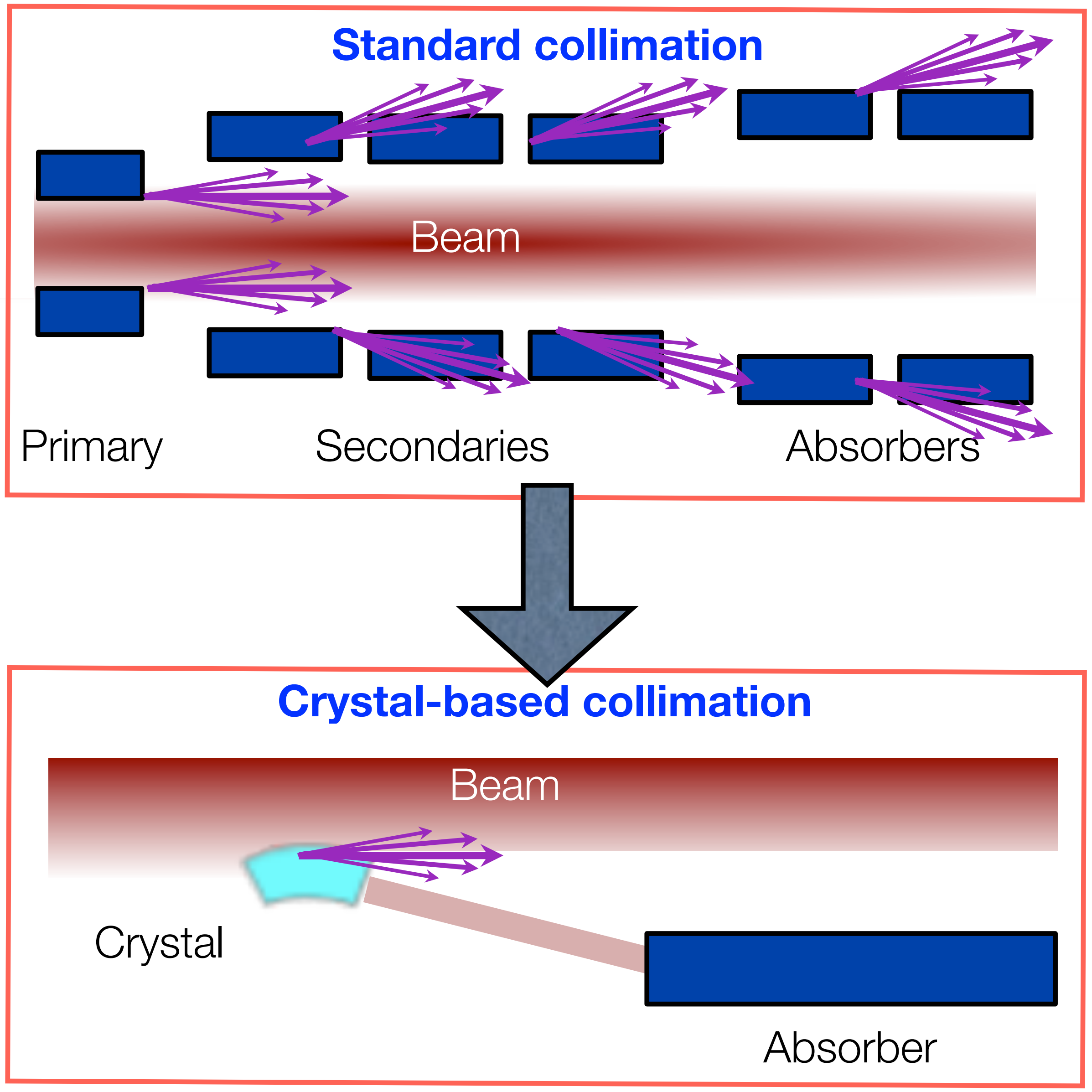

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Low-intensity beam tests at the LHC will start in 2015!

- *Horizontal and vertical crystals installed for one beam.*

Only rely on this technique after satisfactory beam results at the LHC.

Clearly, this is a promising solution for FCC. But the total stored energy poses severe challenges for the absorption of the extracted beam.

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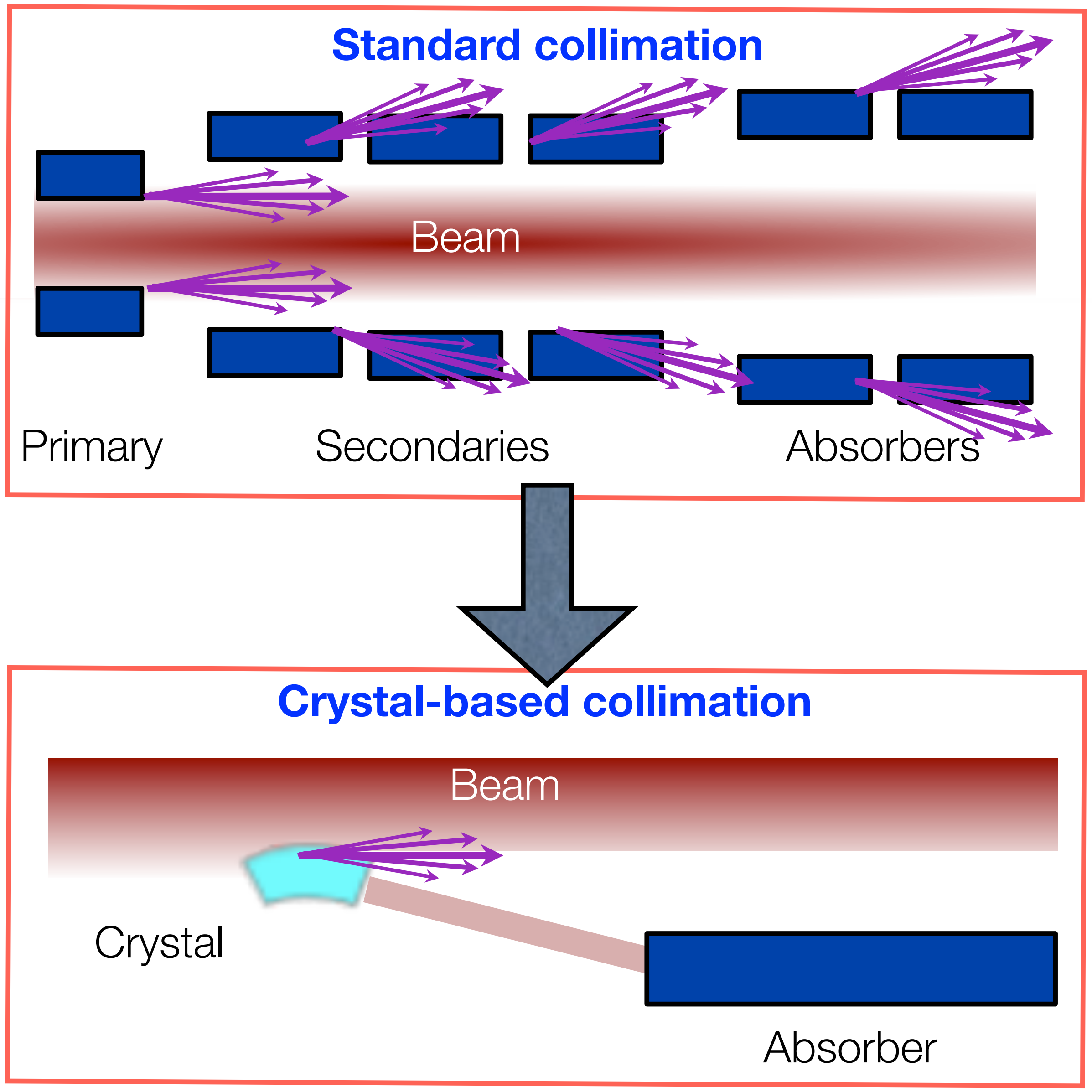

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Uncertainties on the **extrapolation** to unknown energy territories and **operational challenges** call for solid experimental validation before this technology can be relied upon for future designs.

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Outline

- Introduction
- LHC design challenges
- Present system performance
- Limitations and upgrade plans
- **FCC challenges and workplan**
- Conclusions

Kickoff FCC collimation design

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- To achieve a **first conceptual solution** in the give time constraints, we propose to startup from a scaled-up system derived from the present one:
  - *Scale the optics and insertion length.*
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  - *Optimize collimator locations an number starting from present system*

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  Clearly interaction models for 50 TeV beams must be reviewed, but present tools are expected to be good to go.

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- Tools:
  - *Clearly interaction models for 50 TeV beams must be reviewed, but present tools are expected to be good to go.*
- Important inputs/prerequisites:
  - *Optics support for collimation insertion design*
  - *Lattice for tracking and reasonably complete aperture models*
  - *First-order estimate of quench limits*
  - *First expectations for machine aperture*
  - *Reasonable assumptions for the beam lifetime.*

Proposed activities

The first conceptual design studies proposed in this document are aimed at identifying a parameter set and goals for a collimation system and at finding optics solutions that could fulfill the requirement at all levels (halo cleaning efficiency for realistic collimator settings, impedance, robustness of collimator materials against basic failure cases, ...). A first conceptual design report based on analytical or semi-analytical design of collimation insertions will be followed by a systematic performance assessment achieved with improved or newly developed simulation tools to model the behaviour of ultra-high energy protons through the optics elements (particle tracking) and with different collimator materials.

The work milestones should be structured as it follows:

- Definition of basic collimation system requirements to enable the design parameters of the machine (design cleaning to be specified for given beam parameters, machine aperture and assumed loss scenarios).
- Conceptual definition of collimation section layouts: number and roles of collimation insertions (betatron and momentum cleaning requirements at different energies and optics).
- First optics design of collimator insertions and conceptual layout of collimation system. Definition of collimator settings and modelling of transverse halo population, for example as done for the LHC in Phys.Rev.ST Accel.Beams 1:081001,1998 ("optics of a two stage collimation system").
- Development/update of simulation tools for collimation performance assessment.
- Feedback for collimator mechanical design (e.g. specification of loss rates and energy distributions on individual collimators) and assessment of performance against quench limits of superconducting magnets.
- Iteration on the layouts to improve performance.
- Outlook of remaining issues and potential improvements.

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Trade off / potential improvements:

Can we reduce the insertion length?

Need 3 cleaning insertions? Separate H and V betatron cleaning?

Can we achieve the same cleaning with different optics?

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- Clearly, this provides a solid base for the design of collimation systems in future multi-TeV machine!

  We try to put together resources to help with this design phase (supervision of a working on the first conceptual design of collimation insertions).

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- ☑ The present LHC collimation was reviewed, recalling design challenges, deployed solutions, achieved performance and limitations
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- ☑ In particular, the ongoing upgrade studies provide already useful information and feedback on design/optics

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- We try to put together resources to help with this design phase, but this is clearly challenging with the LHC startup...

  We have found a promising fellow candidate who could start after summer.