FCC-hh: Collimation system design

M. Fiascaris
with R. Bruce and S. Redaelli

Acknowledgements to X. Buffat, R. De Maria,
D. Mirarchi, D. Schulte, R. Tomas

Outline

- Introduction
- FCC challenges for collimation
- The LHC collimation system
- First FCC collimation system design: status of simulations
- Outlook and Conclusions

Introduction: roles of collimation systems

- **Halo cleaning** versus quench limits (for SC machines)
- Passive **machine protection**

  First line of defense in case of accidental failures
- **Reduction of total doses** on accelerator equipment

  Provide local protection to equipment exposed to high doses
- **Cleaning of physics debris** (collision products)

  Avoid SC magnet quenches close to the high-luminosity experiments
- **Concentration of losses/activation** in controlled areas

  Avoid many loss locations around the 27-km tunnel
- **Optimize background** in the experiments

  Minimize impact of halo losses on quality of experimental data

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Main role of collimation
in hadron colliders
before the LHC

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Driving constraint for LHC and FCC-hh!

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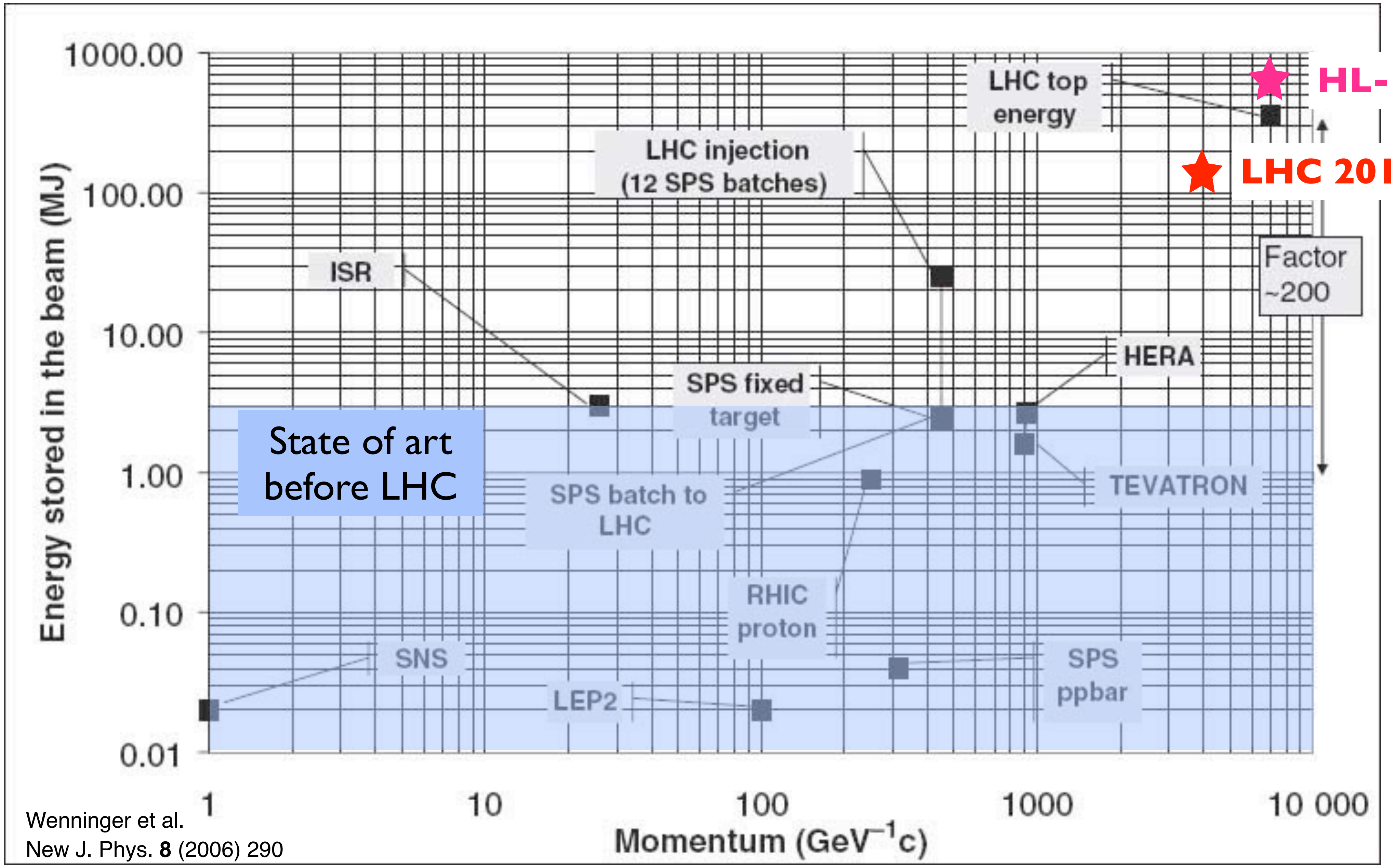
Collimation at the LHC

The LHC collimation system is the **current state-of-the-art** for particle accelerators



Wenninger et al.
New J. Phys. **8** (2006) 290

Required cleaning efficiency:
99.998% (10^{-5})

LHC beam highly destructive

Beam cleaning requirements exceed previous machines by order of magnitudes!

FCC vs LHC

	LHC (Design)	**HL-LHC**	**FCC-hh (Baseline)**
Beam energy	7 TeV	7 TeV	50 TeV
Beam intensity	3×10^{14}	6×10^{14}	10×10^{14}
Stored energy	360 MJ	690 MJ	8500 MJ
Power load (τ=0.2h)	~500 kW	~960 kW	~11800 kW
Energy density	~1 GJ/mm^2	~1.5 GJ/mm^2	~200 GJ/mm^2

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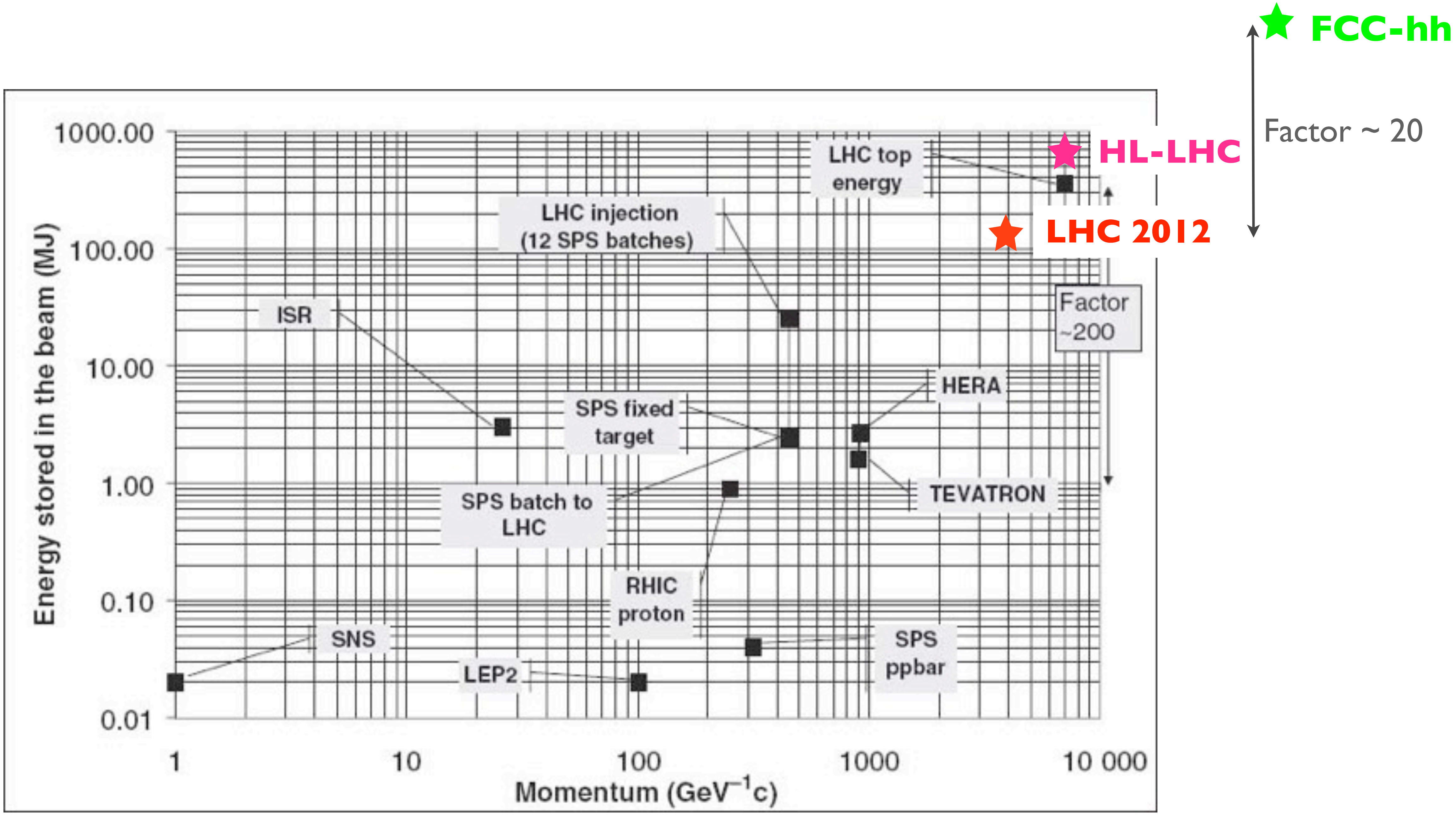
Factor 20 x LHC:

stringent requirements on **cleaning inefficiency** to avoid quenches

➡ optimization of collimation cleaning
➡ addition of collimators in most critical loss location

FCC vs LHC



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2 order of magnitudes above the LHC:

↓

outstanding challenges for collimator materials and mechanical position with 50 TeV beam

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LHC collimation layout

IR3: Momentum cleaning

1 primary (H)
4 secondary (H)
4 shower absorber (H,V)

IR7: Betatron cleaning

3 primary (H,V,S)
11 secondary (H,V,S)
5 shower absorber (H,V)

Local cleaning at triplets

8 tertiary (2 per IP)

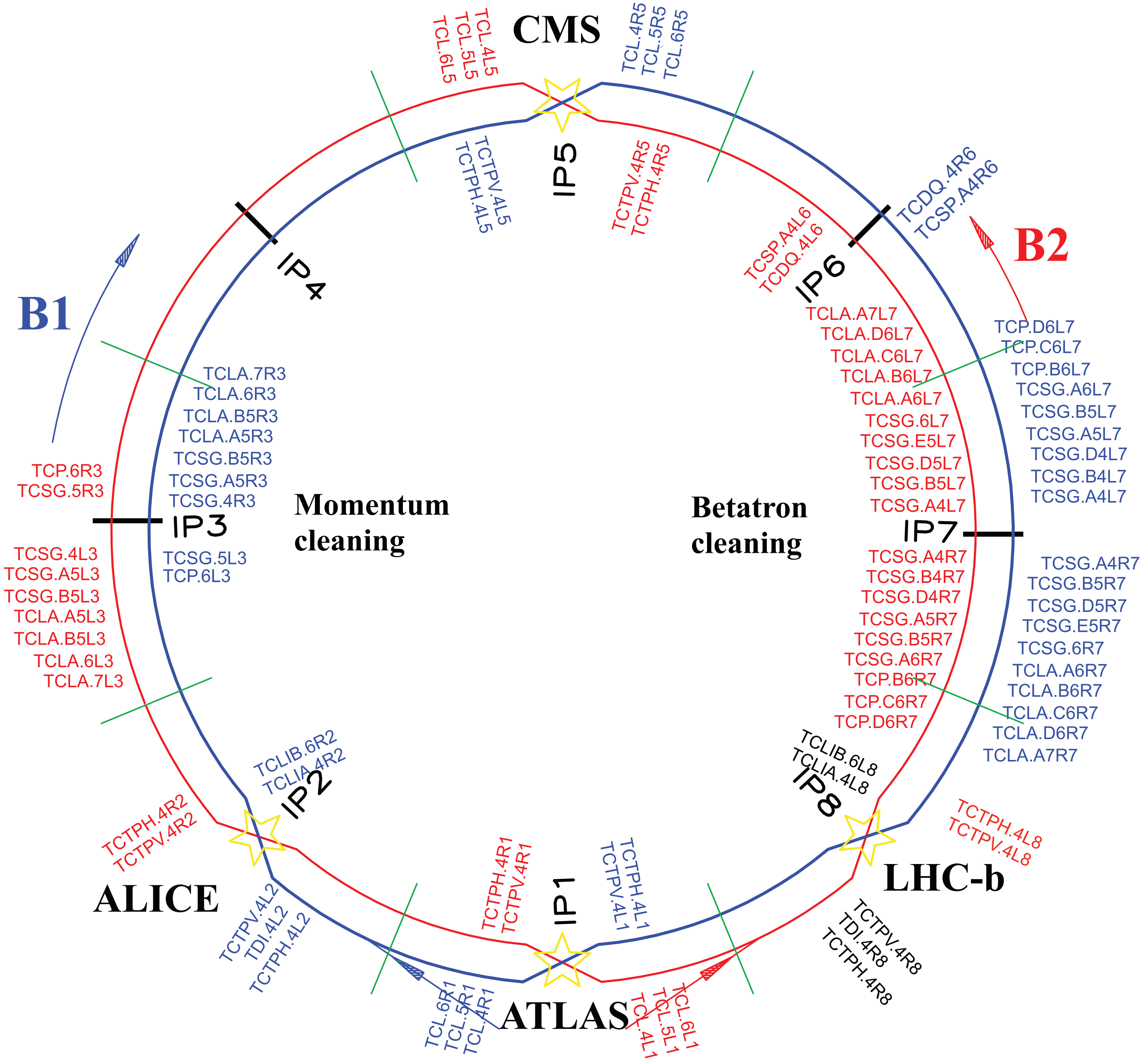
Passive absorbers for warm magnets

Physics debris absorbers

Transfer lines
Injection and dump protection

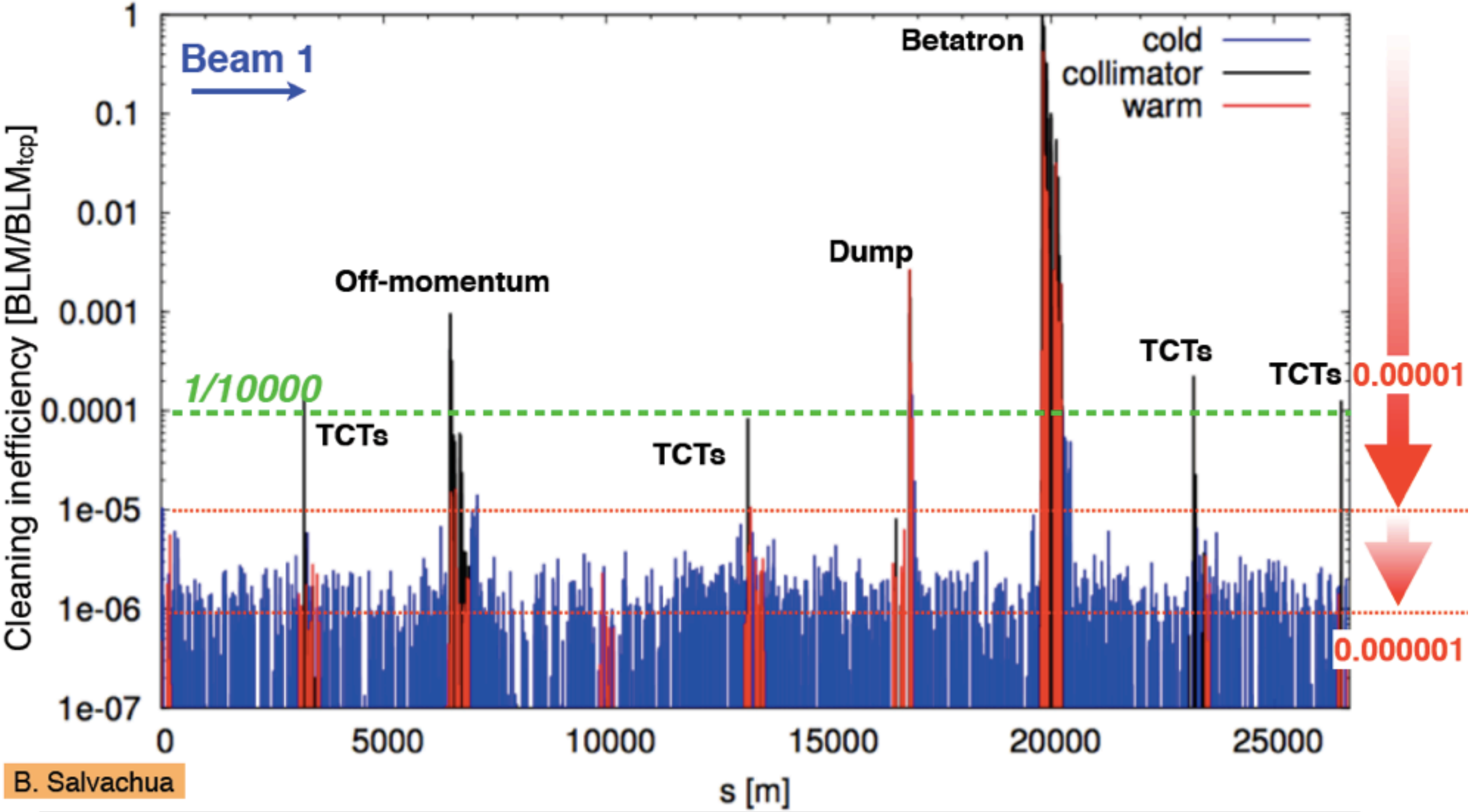
> 100 movable collimators

Two jaws (4 motors) per collimator



LHC collimation cleaning at 4 TeV

- No quenches up to 150 MJ of stored energy!
- Validation of simulations tools over 7 orders of magnitude



B. Salvachua

LHC operational experience

✓ **Very good performance** of the collimation system so far

- Compatible with HL-LHC parameters at 7 TeV - pending verification with operational experience in 2015

✓ **Validation of simulation** tools over 7 orders of magnitude

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✓ **Validation of simulation** tools over 7 orders of magnitude

➡ **Main cleaning limitation:** critical losses in the dispersion suppressor after the betatron cleaning

➡ The **β* reach** is determined by collimation constraints: respect collimator hierarchy - retraction between the dump and horizontal tertiary collimators which are not robust

➡ Collimators determine the **LHC impedance**: research of new materials

➡ Collimator handling in **radiation environment** is challenging

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FCC collimation: our initial approach

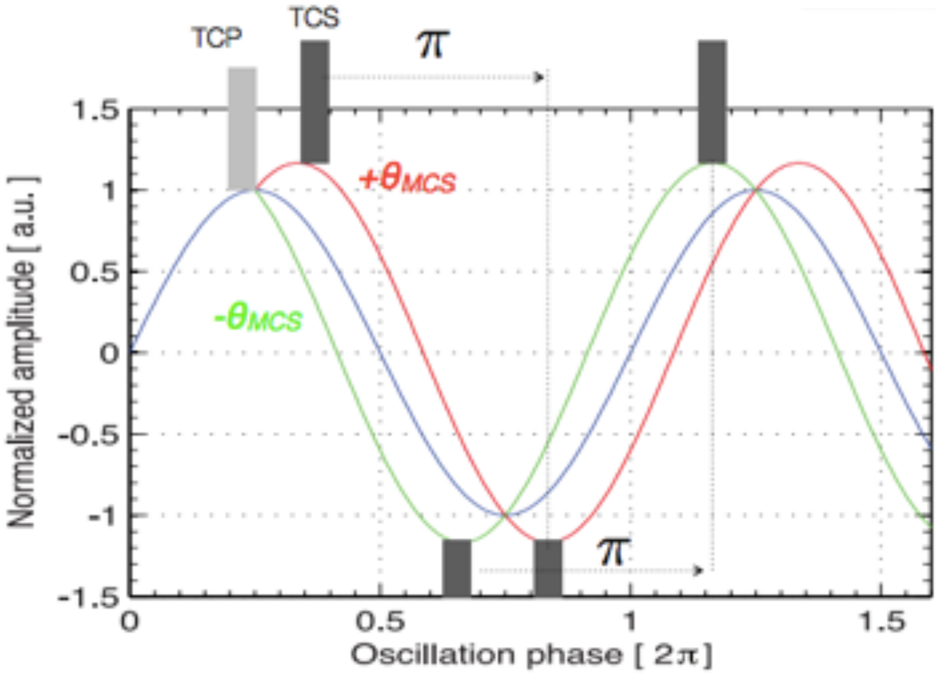
- Very good performance of the collimation system so far: **solid solution** to start with!
- First conceptual solution for the betatron collimation at the FCC: **scaled-up system** derived from the present one

FCC collimation: our initial approach

- Very good performance of the collimation system so far: **solid solution** to start with!
- First conceptual solution for the betatron collimation at the FCC:
  scaled-up system derived from the present one
  - Standard optics for multi-stage cleaning
  - Beta functions scaled to have similar collimator gaps as in the LHC
    → push until later technological developments beyond present state-of-the-art
  - Initially, keep current collimation system layout (same number of collimators, positioned at same phase advance, based on C-reinforced-C material for primary and secondary stages)
    → to be optimized later (more collimators for secondary and tertiary stages, new materials...)

Secondary collimators must be
placed at optimum phase locations
to catch secondary halo

see *Phys. Rev. Spec. Top. Accel. Beams 1 (1998) 081001*



- Dedicated insertion for off-momentum cleaning

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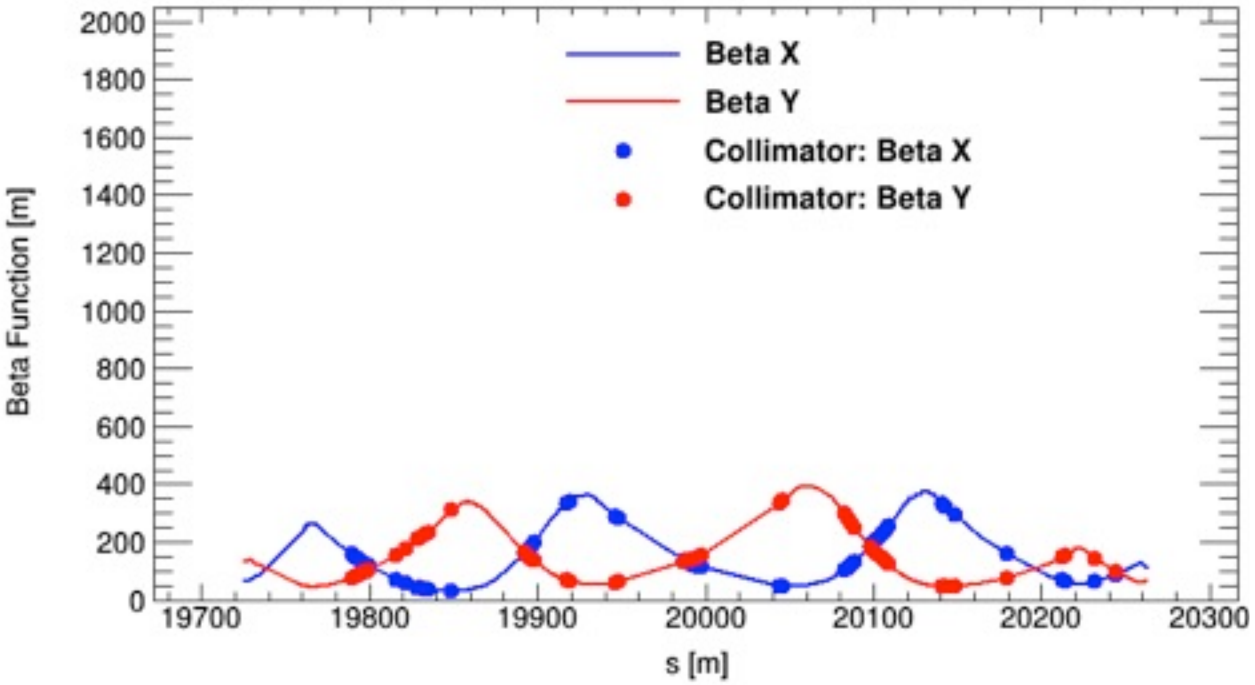
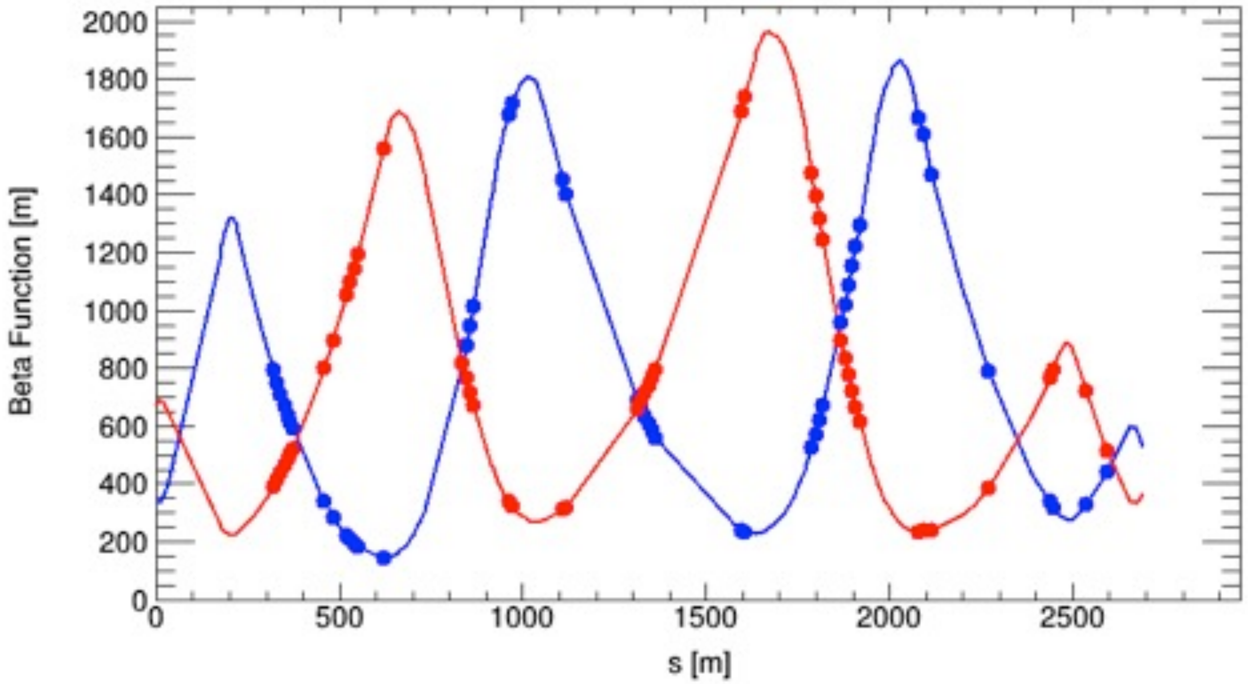
LHC IR7 - betatron cleaning



FCC IR2 - betatron cleaning



Optics and insertion lengths scaled up by a factor 5

- insertion length ~ 2.7 km
- collimator gaps (in mm): 0.84 x LHC gaps

Tracking simulation setup

Tracking simulations using a lattice with:

- 2 low-beta insertions
- 2 cleaning insertions

➡ Implemented a **three-stage betatron cleaning** with 19 collimators

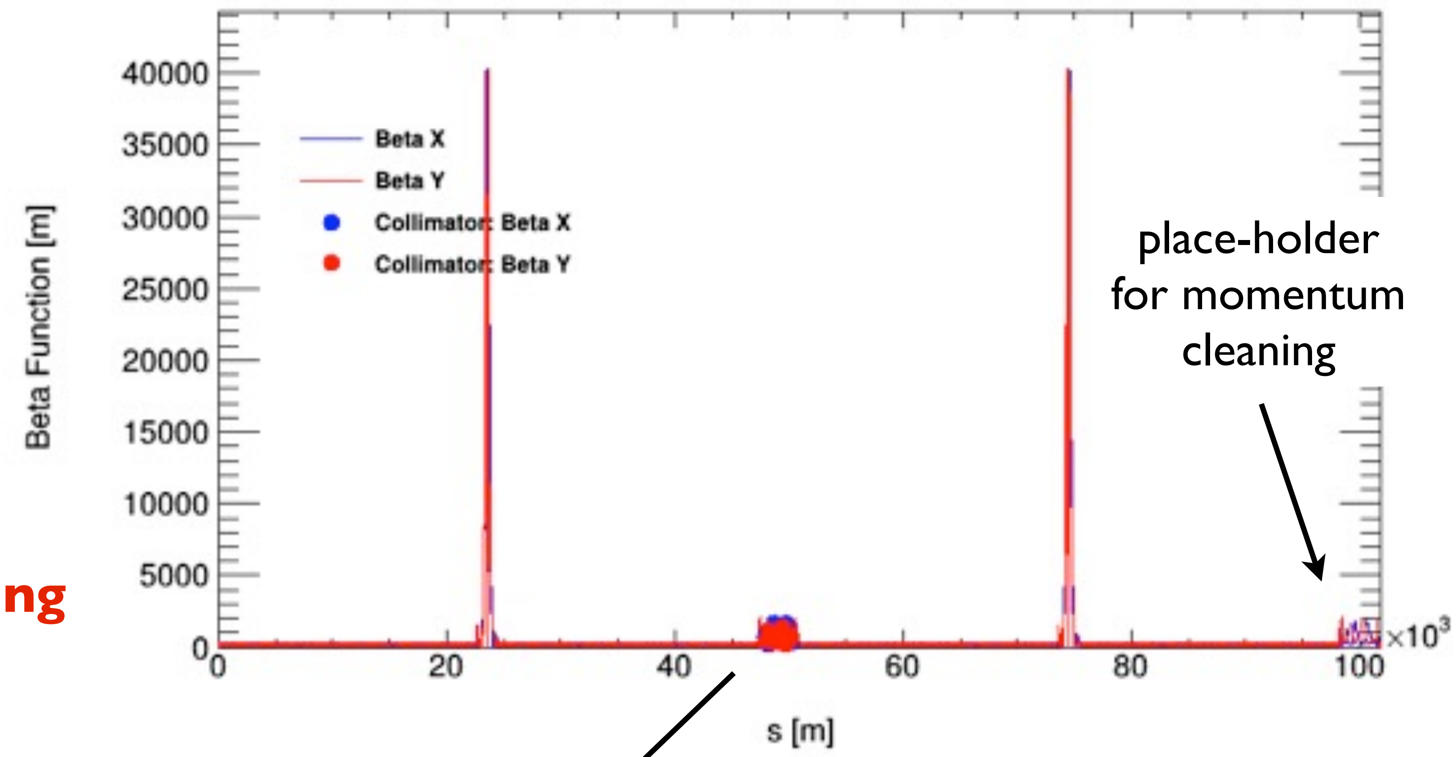
Collimator Settings

3 primaries	TCP	7.6 σ
11 secondaries	TCSG	8.8 σ
5 absorbers	TCLA	12.6 σ

* same settings as for LHC nominal (6/7/10 σ) expressed in σ units for the FCC-hh emittance of 2.2 µm

➡ No momentum cleaning, nor collimation in experimental IRs or dump

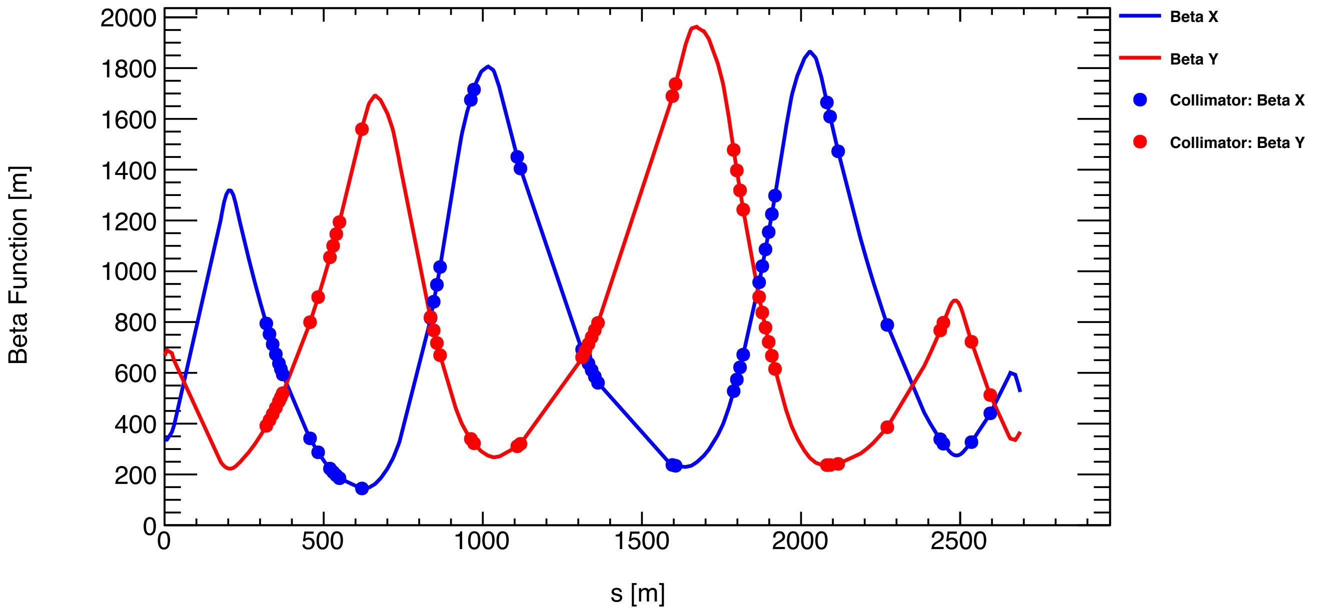
➡ No aperture model available yet



place-holder for momentum cleaning

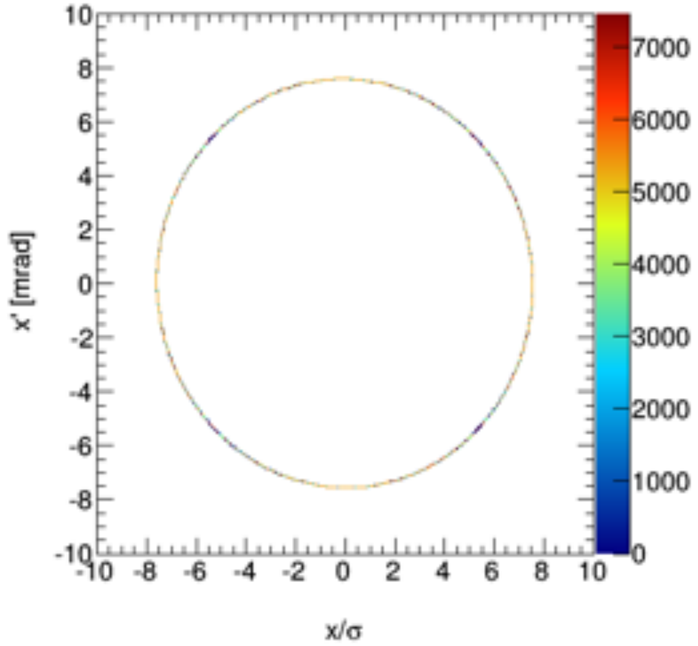
Zoom

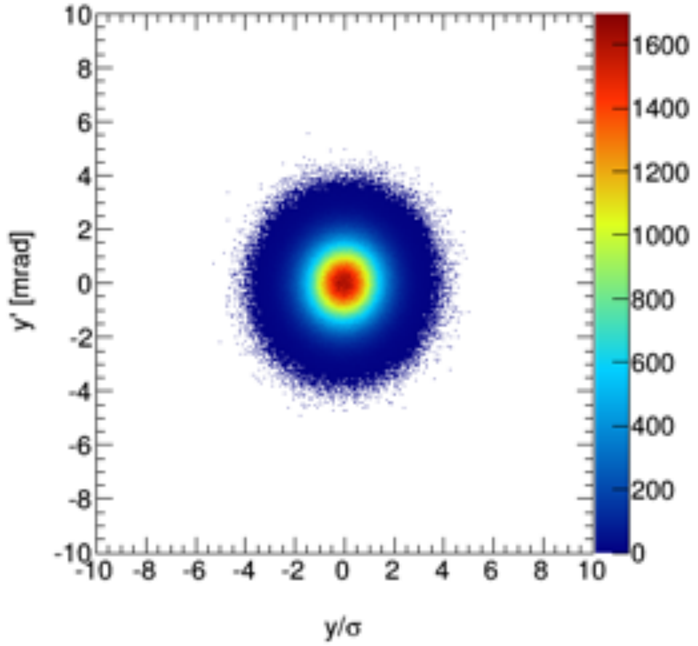
IR2: betatron cleaning

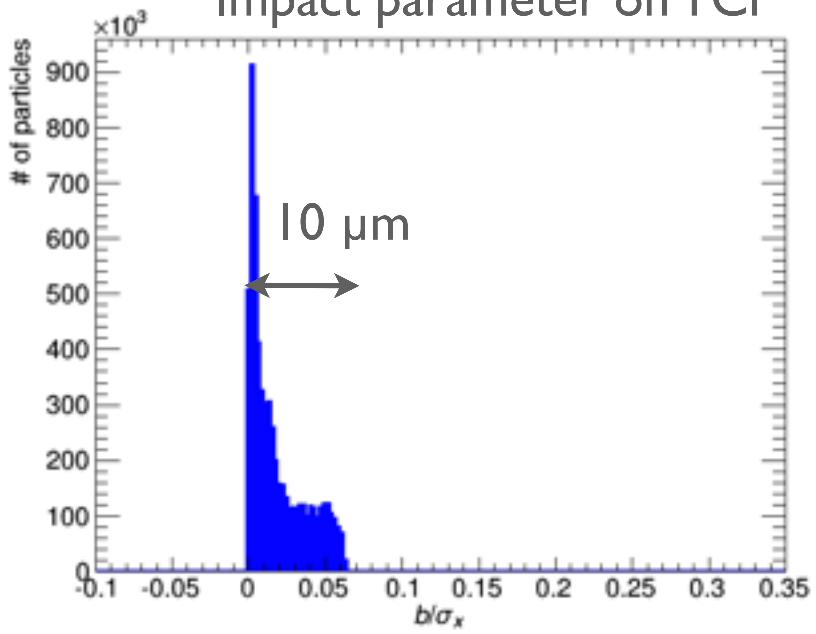


Tracking simulation results

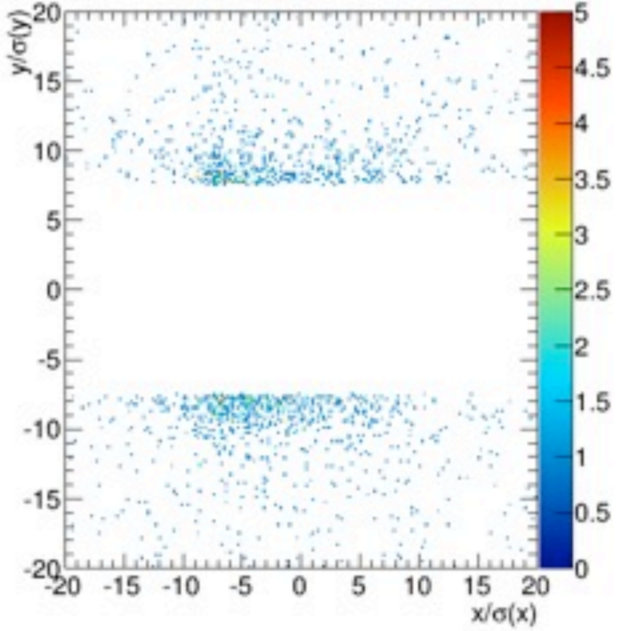
Annular halo setup with predefined impact on primary collimators

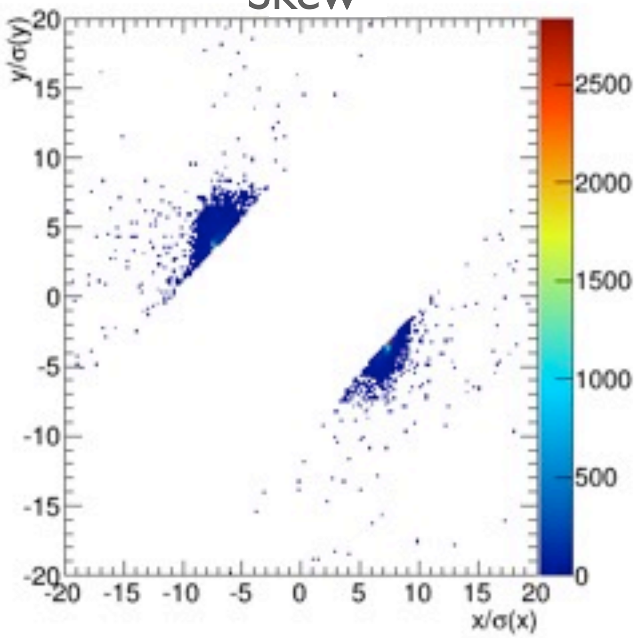

Horizontal halo at 7.6 σ

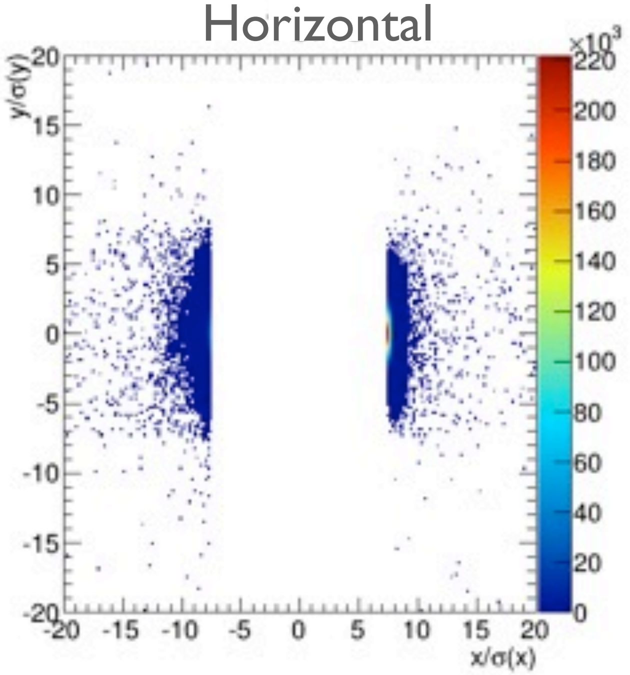

Gaussian distribution in y-plane


Impact parameter on TCP

Distribution of inelastic impacts on the primary collimators


Vertical


Skew


Horizontal

Cleaning inefficiency

Performance of the system characterized by a global cleaning inefficiency

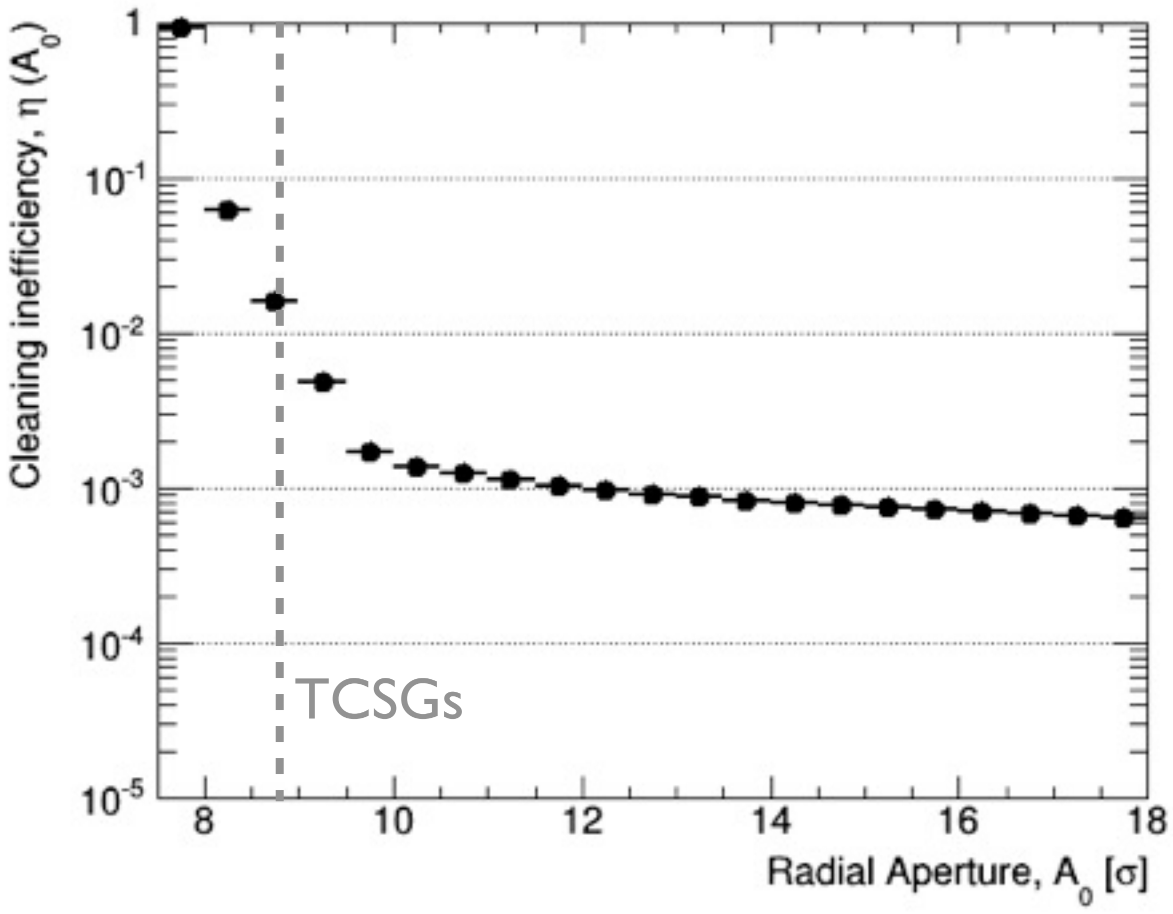
- depends on collimator settings
- no need for machine aperture model

Cleaning inefficiency vs. radial amplitude

$$\eta_c(A_i) = \frac{N_p(A > A_i)}{N_{abs}}$$

→ number of particles above amplitude A_i

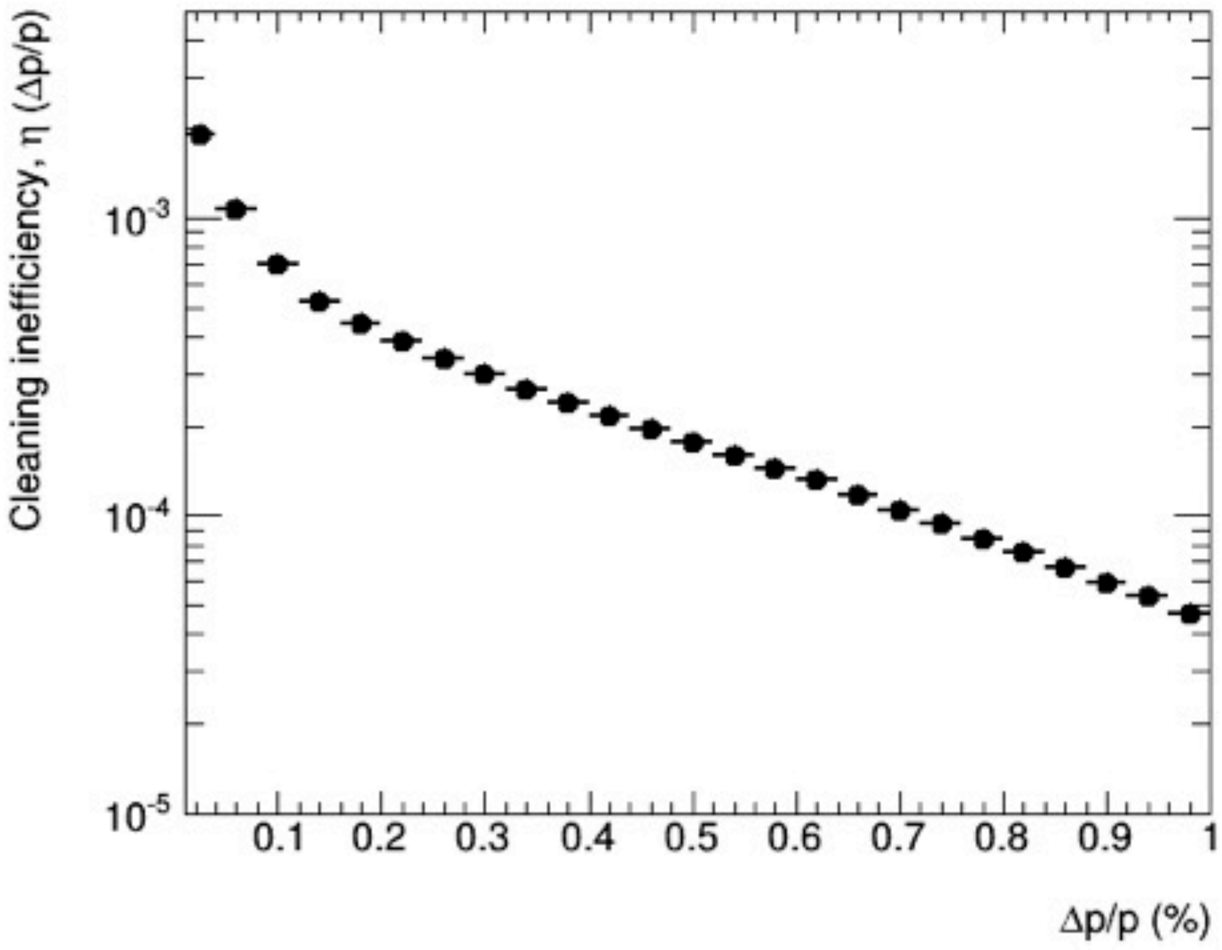
→ number of particles absorbed in coll. system



Cleaning inefficiency vs. Δp / p

(off-momentum halo population)

Δp/p: relative momentum loss of protons after interaction in the collimators



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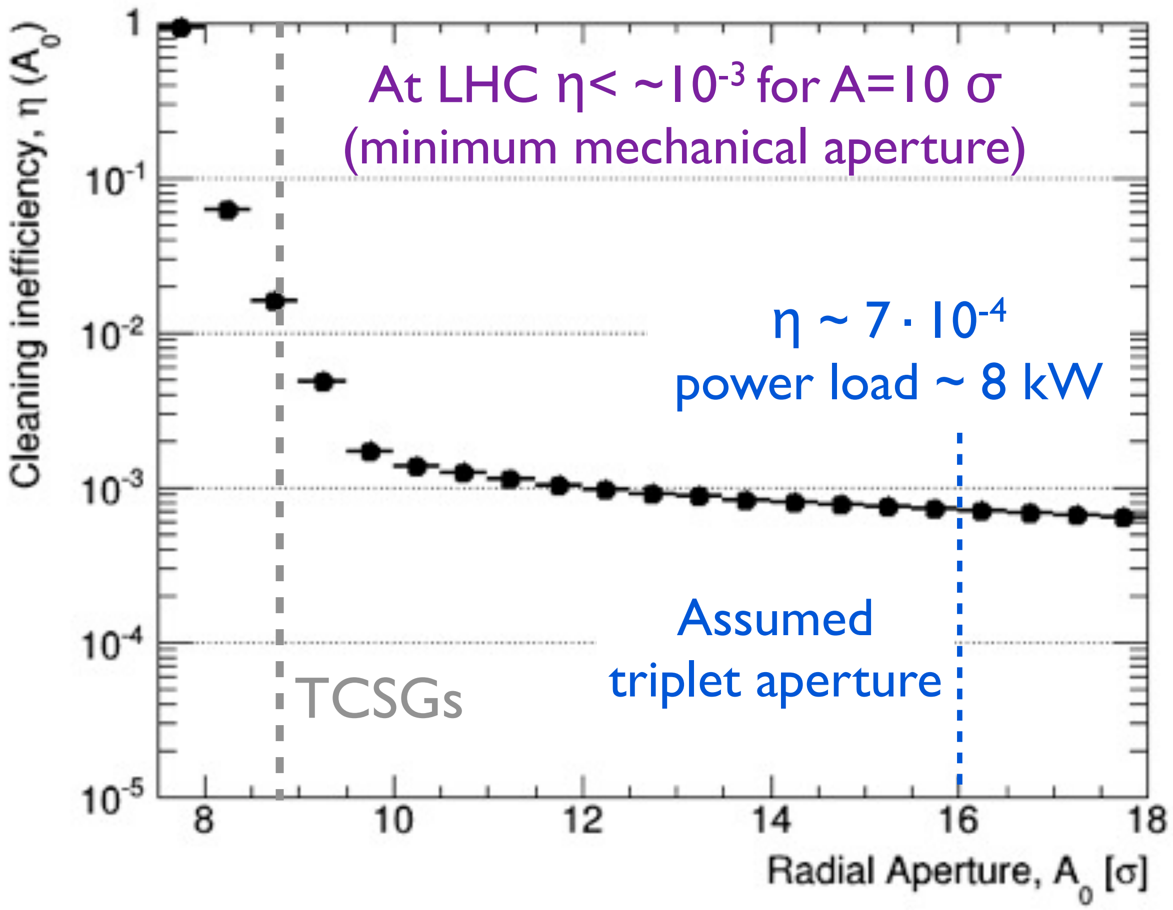


At LHC η< ~10^{-3} for A=10 σ (minimum mechanical aperture)

η ~ 7 · 10^{-4} power load ~ 8 kW

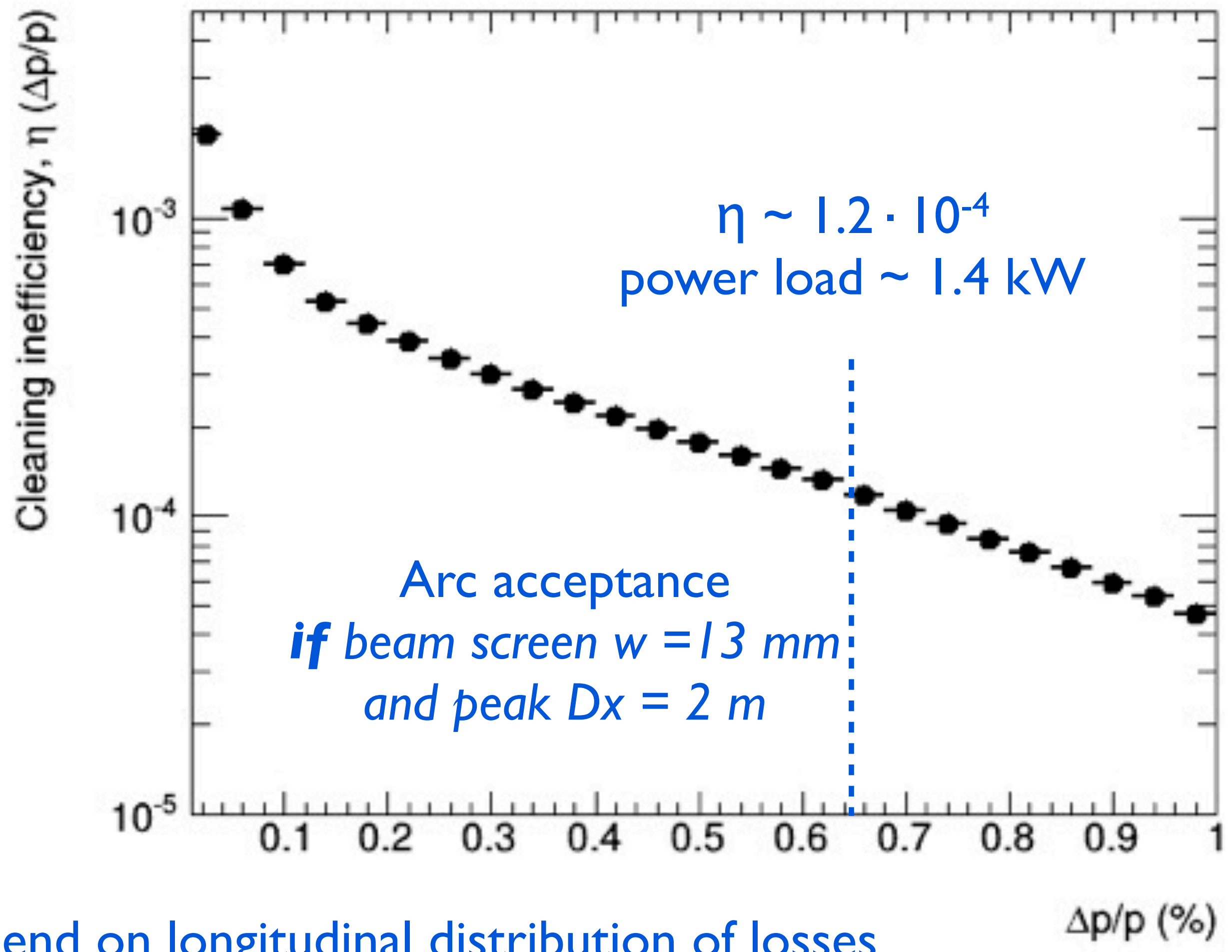
Assumed triplet aperture

TCSGs

Cleaning inefficiency vs. Δp / p

(off-momentum halo population)

Δp/p: relative momentum loss of protons after interaction in the collimators



η ~ 1.2 · 10^{-4} power load ~ 1.4 kW

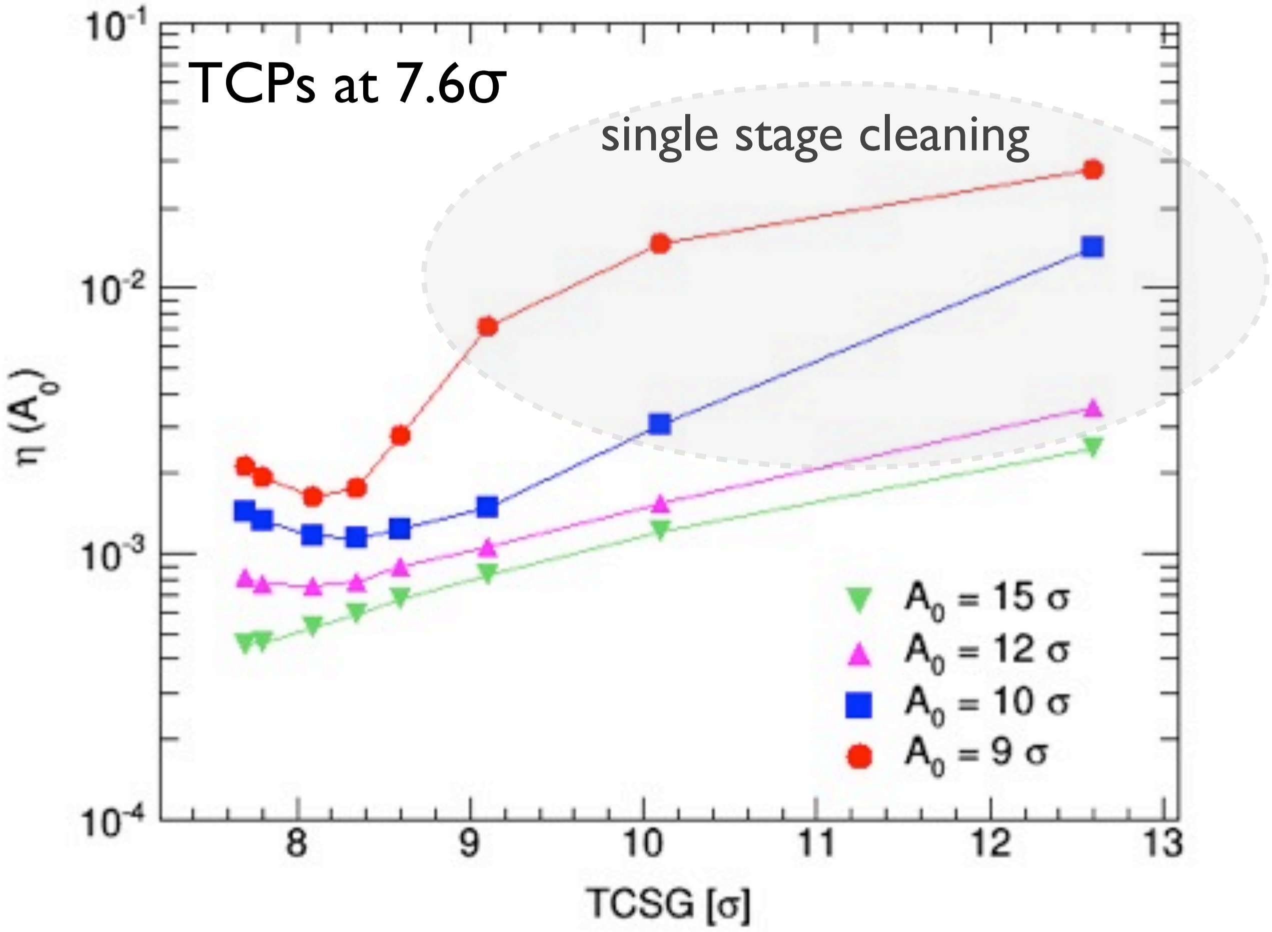
Arc acceptance ***if** beam screen w =13 mm and peak Dx = 2 m*

Power loads on cold elements will depend on longitudinal distribution of losses

Cleaning inefficiency vs. settings

Performed a scan of simulation varying the retraction between primary and secondary collimators

Cleaning inefficiency vs. setting of secondaries



→ will re-optimize phases and optics if needed, once aperture well defined

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Outlook: where we are

- Tools we have in hand already allow us to improve the system performance by optimizing the cleaning inefficiency curves η (A), η ($\Delta p/p$).
- More inputs required to assess if the performance of the collimation system is sufficient to run at the design parameters (maximum intensity, β^* reach):

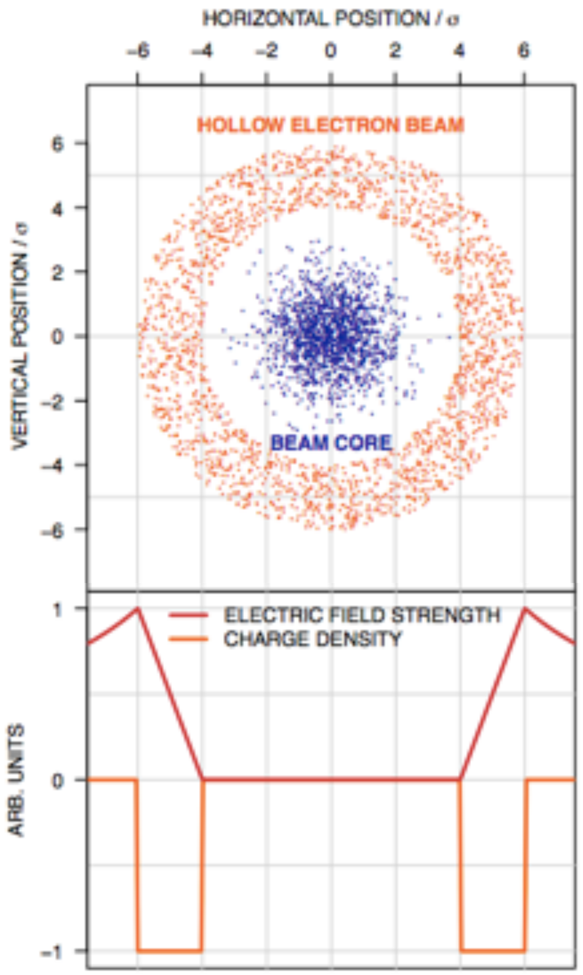
  eg. knowledge of the mechanical aperture, quench limits for superconducting magnets.

- Interactions with other teams:
  - **Collimator settings:** trade-off between impedance and efficiency of the system → iterations with impedance team, study of new materials (talk by A. Bertarelli on Thursday)
  - **Collimator design specifications:** to be defined once we have more detailed studies on energy deposition (talk by A. Lechner on Thursday)
  - **Performance optimization:** need iterations with optics team to add collimators in critical locations (like in the dispersion suppressor) and maximize their performance.

Advanced collimation concepts

Hollow e-lens

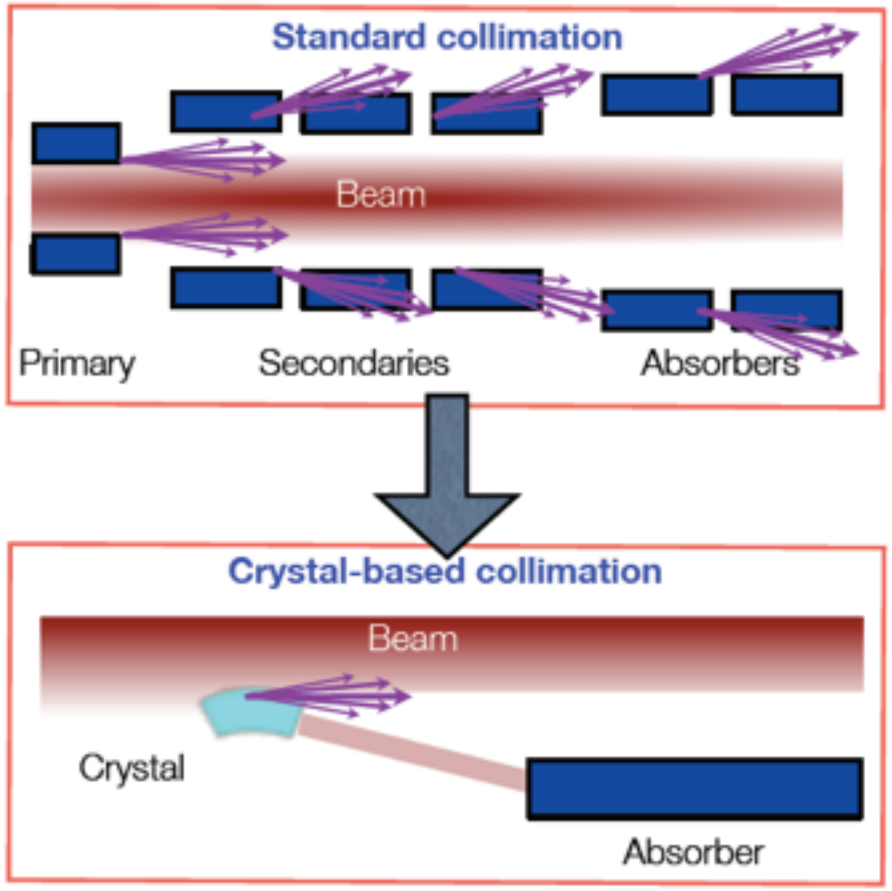
- Hollow electron beam parallel to the p-beam:



  - halo particles see field dependent on (Ax, Ay) plane, while core is unaffected
  - adjusting e-beam parameters can be used as halo scraper
- Expect to be a key asset to control loss rates on collimators
- Working on a design for implementation in LHC in LS2, if needed → also crucial for FCC

Crystal collimation

- Bent crystal can be used for channeling and extracting the beam halo in a controlled way
  - can improve cleaning efficiency
  - reduce impedance: less secondary collimators, larger gaps



- Low intensity beam tests at the LHC in 2015
- Promising for the FCC, but large uncertainties on extrapolations to high energies and several operational challenges.

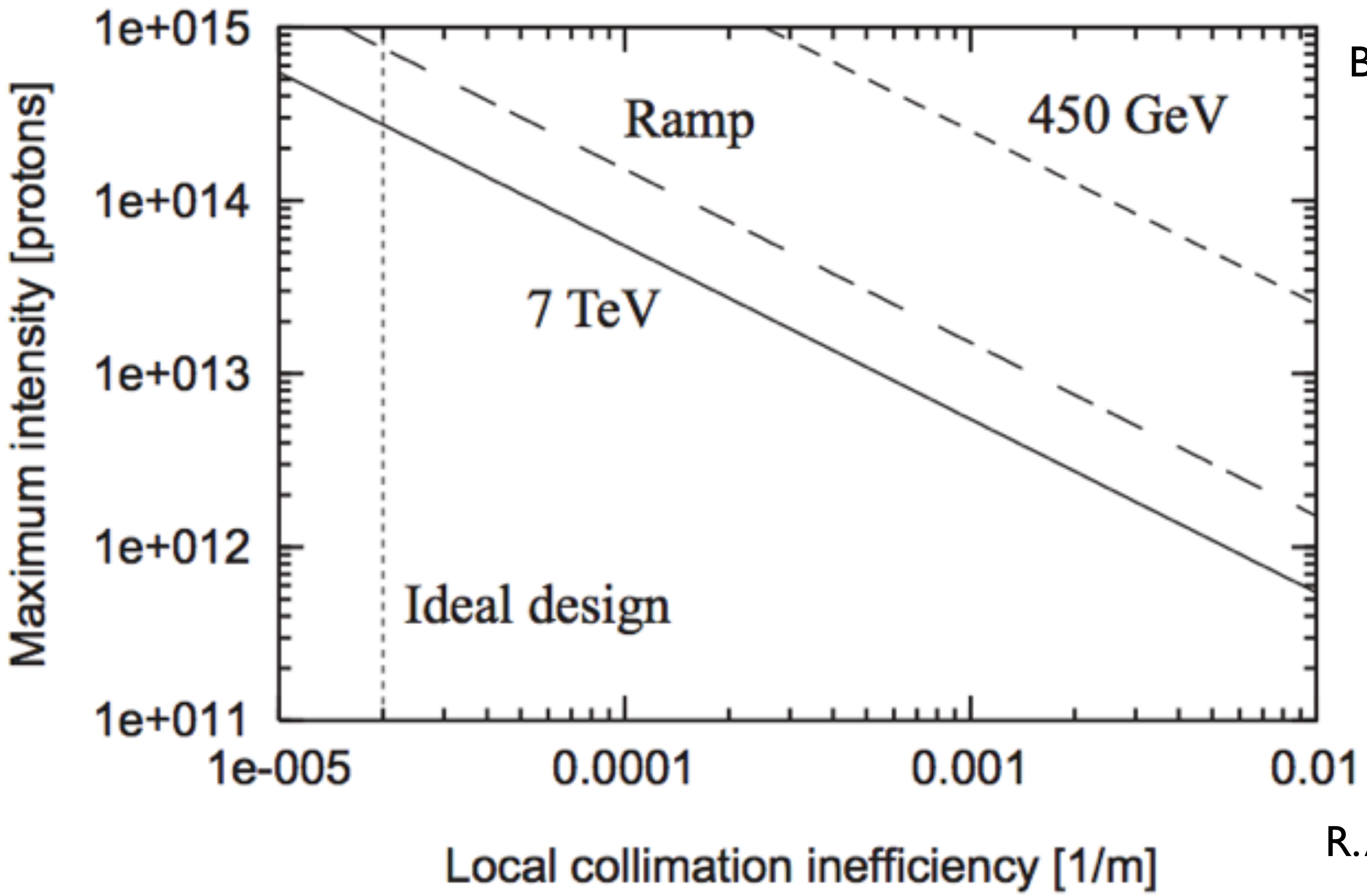
Conclusions

- Large stored energy of the FCC implies new challenges for the collimation system!
- Baseline available for a 0th order FCC betatron collimation layout:
  - “conservative approach”: first conceptual design based on a scaled-up version of the present system
  - results should tell us how far we can go with current state-of the art
- Simulation tools are well set-up and we performed first systematic studies of betatron cleaning
  - however to assess if the performance is sufficiently good we need more inputs (quench limits, aperture model, etc.)
- Collimation layout to be extended soon to include momentum cleaning and collimation in the experimental insertions and dump
- Further optimization of the system and studies of advanced collimation concepts are foreseen.

EXTRAS

The LHC collimation system

Collimation cleaning requirement: one of the key parameters that determine the intensity reach in a collider

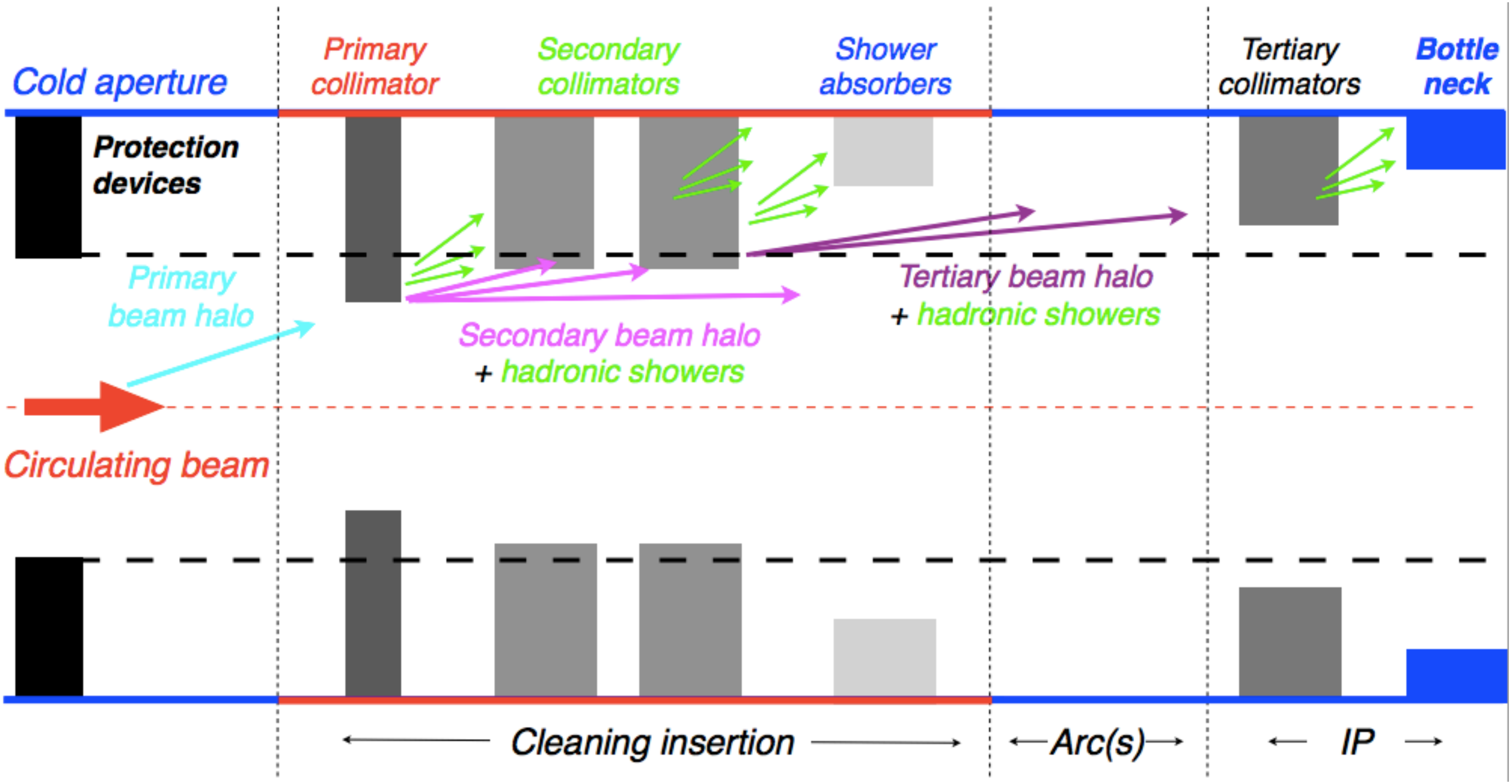


Beam lifetime 0.2h

R. Assmann

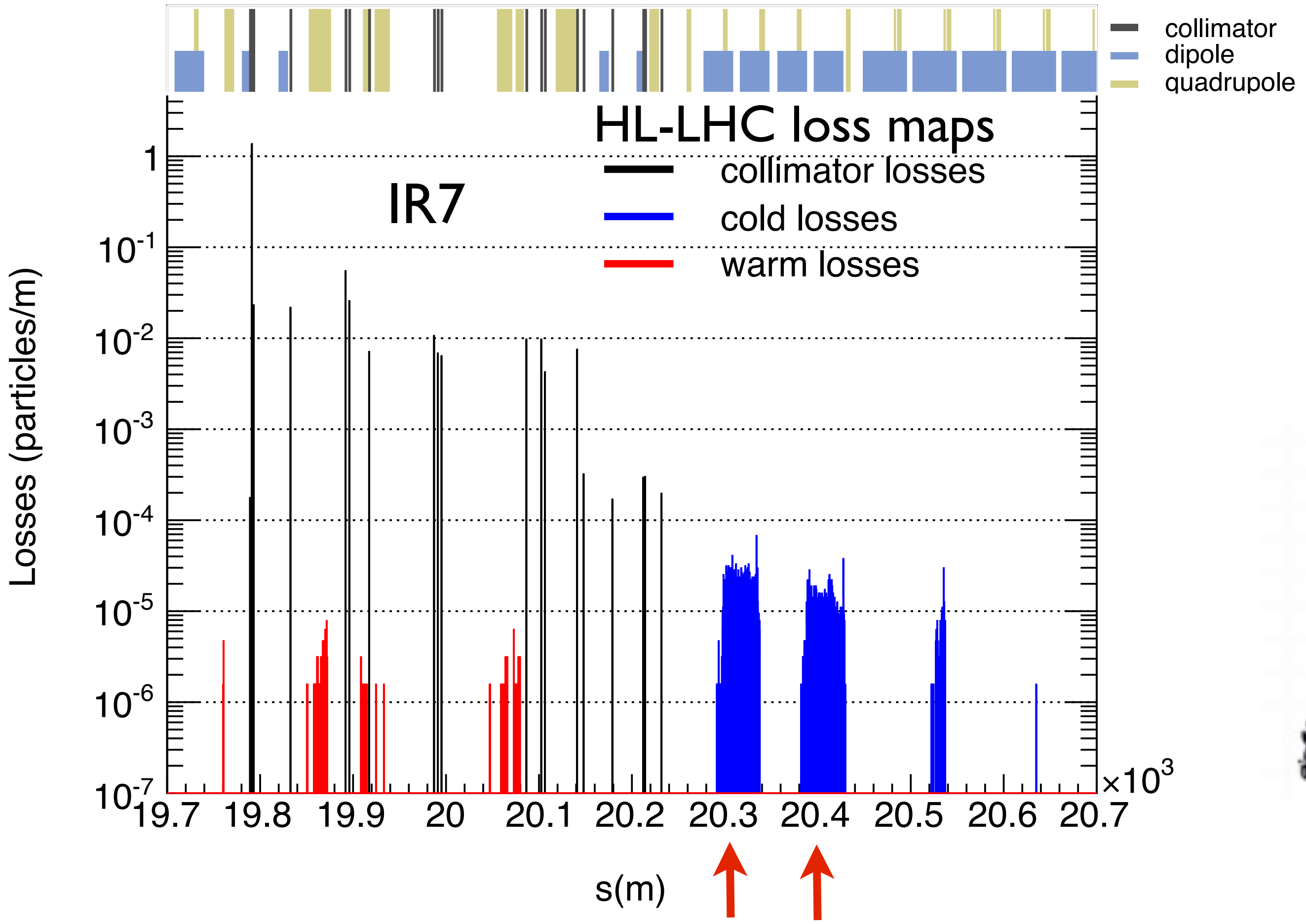
For given quench limit, trade-off between:
inefficiency - maximum intensity - minimum allowable lifetime

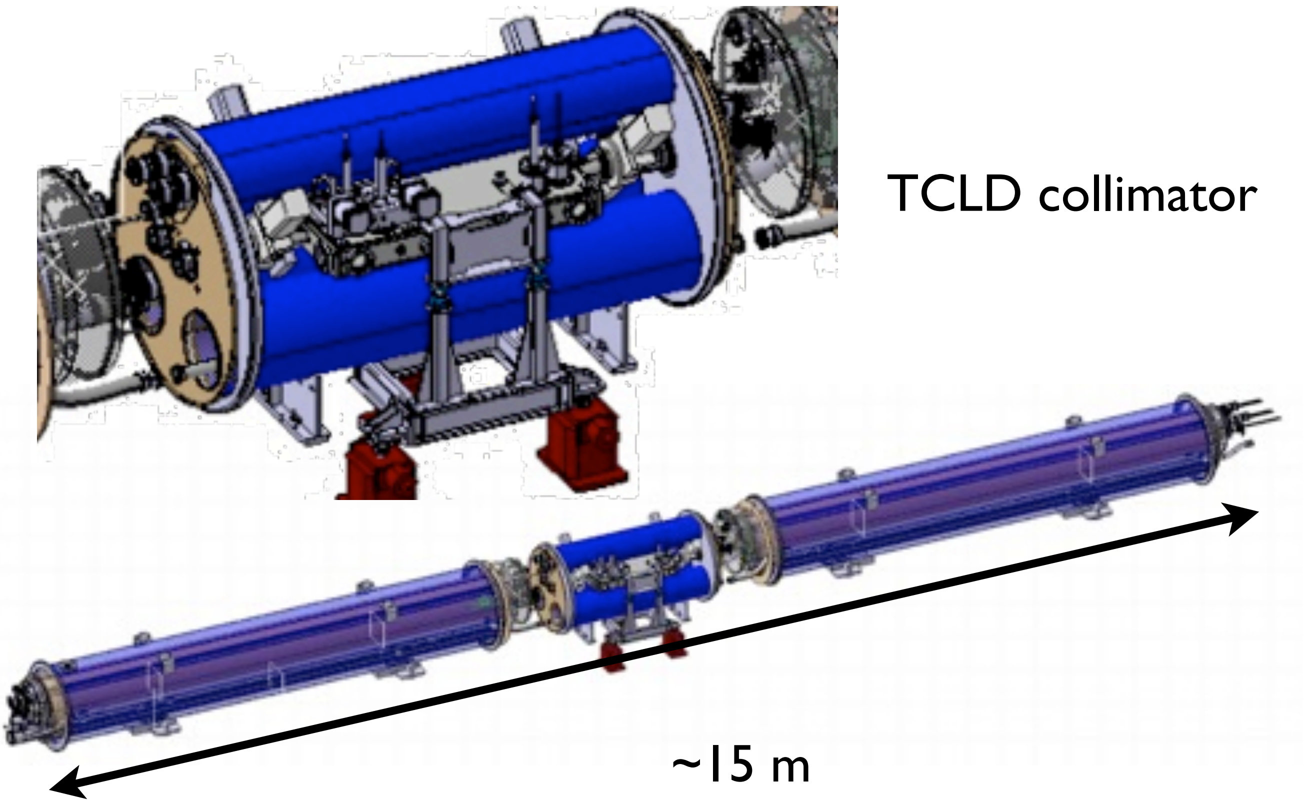
Multi-stage collimation at the LHC



Losses in the dispersion suppressor

Critical location: fundamental limitation of the current system are losses in the cold dispersion suppressor from single diffractive interactions with the primary collimators



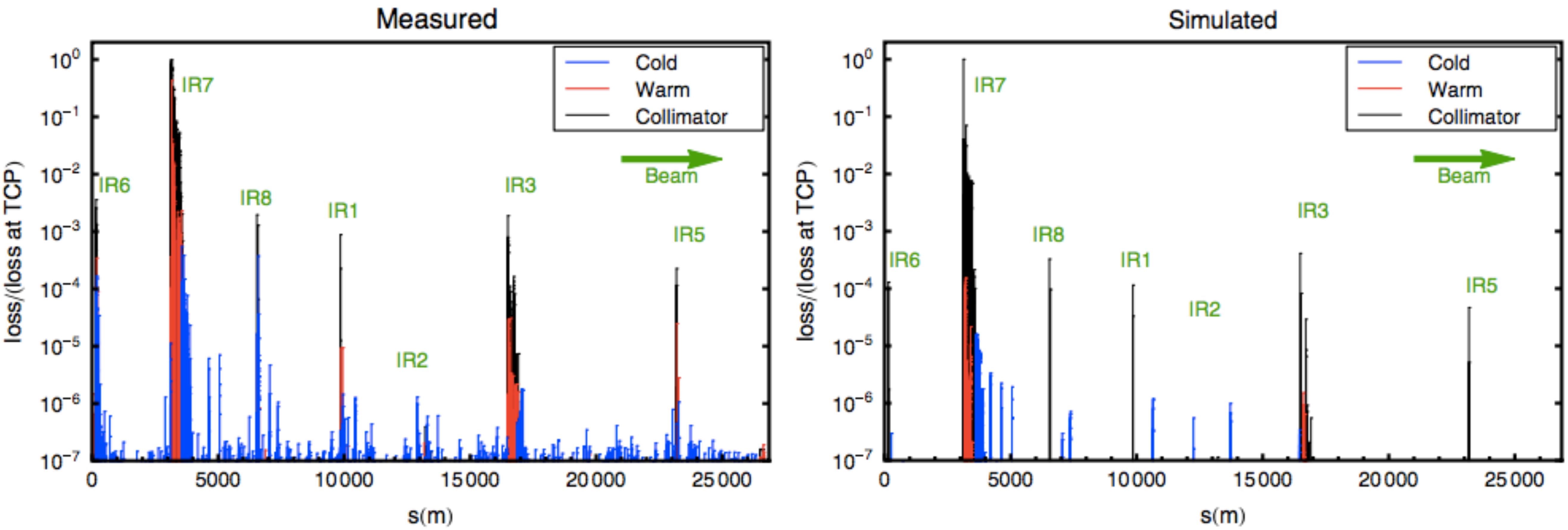


Need to catch losses close to the first dipoles where dispersion starts growing.
Present system: make space for a room temperature collimator replacing one 15m long dipole with two 5.5m long 11T dipoles.

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

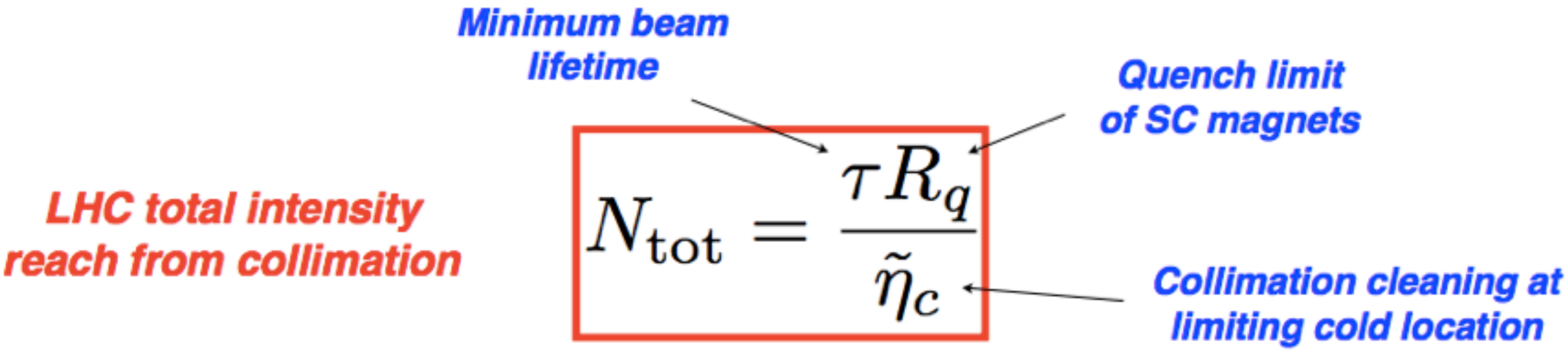
Validation of simulations for the LHC

Phys. Rev. ST Accel. Beams 17, 081004 (2014)



SixTrack used for detailed studies to predict the beam loss distribution around the LHC ring. Comparison between **measurement and simulation** show **very good agreement**: confidence in the reliability of simulation tools

Inputs to cleaning studies



Minimum beam lifetime

Quench limit of SC magnets

LHC total intensity reach from collimation

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

Collimation cleaning at limiting cold location

Key parameters that determine the intensity reach in a collider:

- **Collimation cleaning**

  *Determined by **collimation system**: optics, collimation layouts, materials, settings,...*
  *Requires an understanding of the **machine aperture**!*

- **Quench limits of superconducting magnets**

  Parameter that "evolved" in last years. Now relying on beam induced quench tests.
  What about magnets for 50 TeV machine?

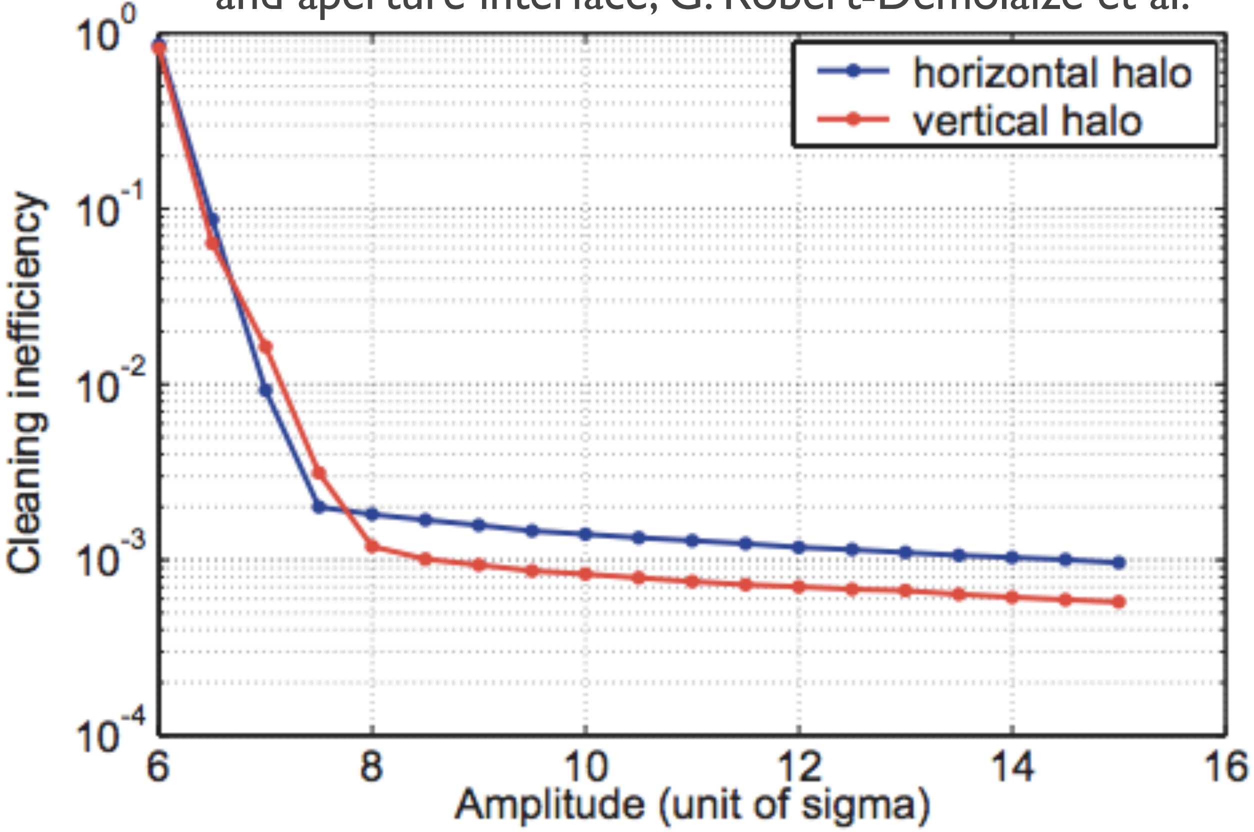
- **Beam lifetime assumptions**

  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.

from S. Redaelli

Simplified cleaning analysis

- High level of accuracy in LHC loss maps is the result of years of experience and operations.
- In view of FCC studies we need to go one step backward, reviving the performance studies done at the time of the LHC system design



PAC 2005, A new version of SixTrack with collimation and aperture interface, G. Robert-Demolaize et al.

Cleaning inefficiency

$$\eta_c(A_i) = \frac{N_p(A > A_i)}{N_{abs}}$$

→ number of particles above amplitude A_i

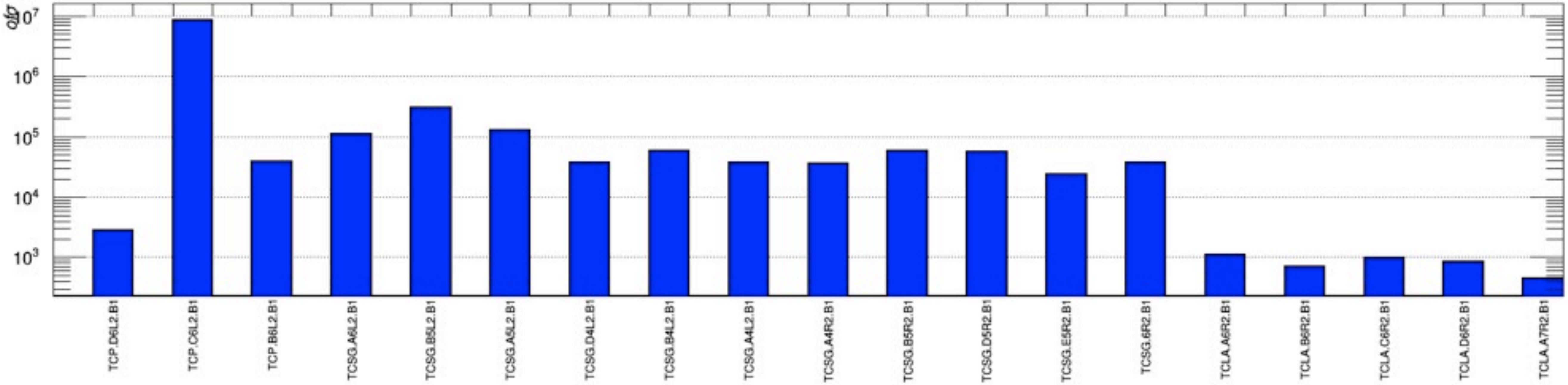
→ number of particles absorbed in coll. system

- depends on collimator settings
- no need for machine aperture model

→ Included new performance plots for momentum cleaning performance studies

FCC simulations

Distribution of inelastic interactions at collimators



Distribution of absorbed particles at collimators