Collimation system study overview and plans

M. Fiascaris and S. Redaelli

Ackowledgments to J. Molson, B. Dalena, P. Bambade, A. Lachaize, G. Holzer, A. Langner, A. Faus-Golfe, D. Schulte, R. Bruce, R. Martin

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Outline

- Introduction
- Goals of the FCC collimation studies
- FCC collimation: our initial approach
- Roadmap to first baseline
- 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 100-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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- **O**

Our first goal:
conceptual design that addresses the main **cleaning challenge**, taking into account impedance and machine protection aspects. Allow first iterations on collimator design and materials.

Collimation challenges for FCC

	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

Required cleaning efficiency at the LHC:

99.998% (10^{-5})

Stringent cleaning requirements at the FCC!

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2 orders of magnitude above the LHC:
outstanding challenges for collimator materials

Goals of FCC collimation studies (I)

- First baseline for a collimation system design
    - based on a scaled-up version of the present LHC system
      → results should tell us how far we can go with current state-of the art
        - very good performance of the present system so far (validated up to 6.5 TeV)
        - feasible in short timescale and given available man-power
- List of alternative options and layouts for further studies

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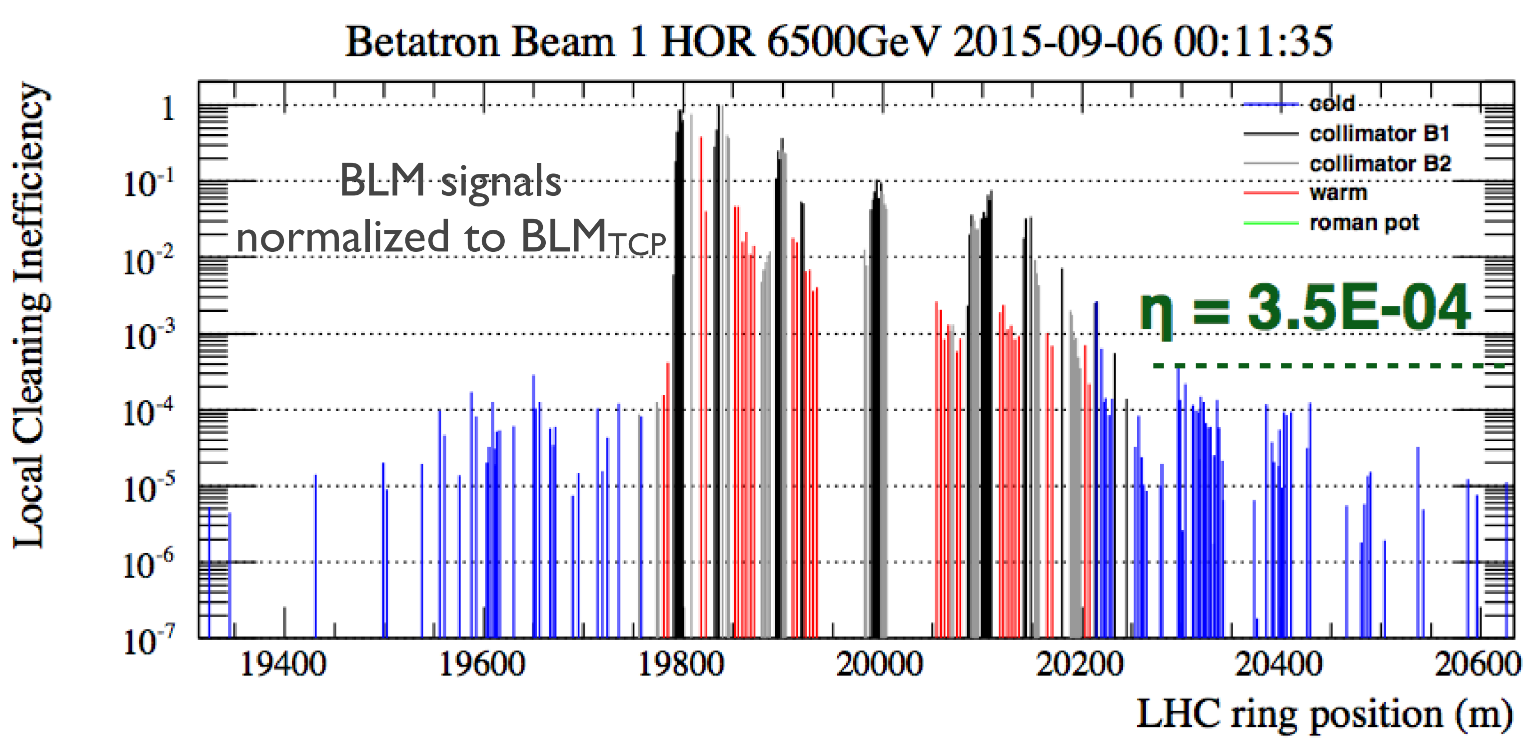
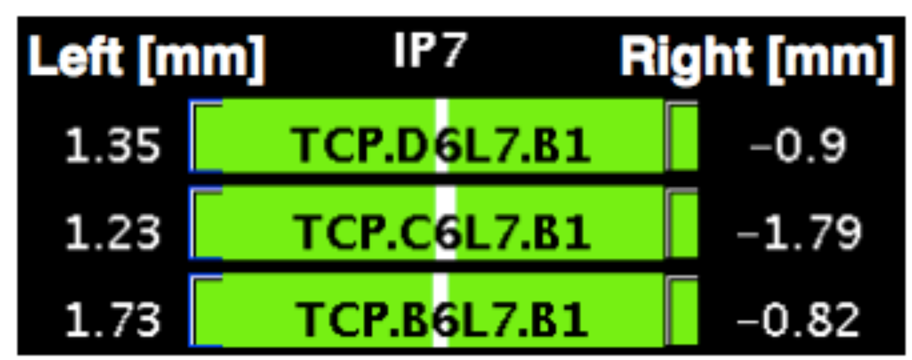


LHC collimation cleaning at 6.5 TeV in IR7 (betatron cleaning)
Performance limitation: losses in the dispersion suppressor after IR7



LHC collimator gaps @ 6.5 TeV down to **2.2 mm in IR7 !**

Goals of FCC collimation studies (II)

Detailed scope for first baseline:

- dedicated insertions for betatron and momentum cleaning
- IR collimation: incoming beam ("tertiary collimators")
- IR collimation: physics debris cleaning
- define interfaces to other relevant systems (injection/dump)

Requirements to achieve first baseline:

- Define ring layout (FCC collimation WG + FCC dump WG)
- Calculation of FCC aperture and definition of baseline for collimator settings
- Validation of the cleaning performance with tracking simulations (complete loss maps)
- First evaluation on contribution to impedance

➡ All this will serve as input for the collimation hardware design

Organization:

• FCC collimation working group meetings once per month- interface between different teams to cover several aspects (optics, performance, energy deposition studies, hardware design, etc.)

FCC Collimation: our initial approach

Betatron cleaning

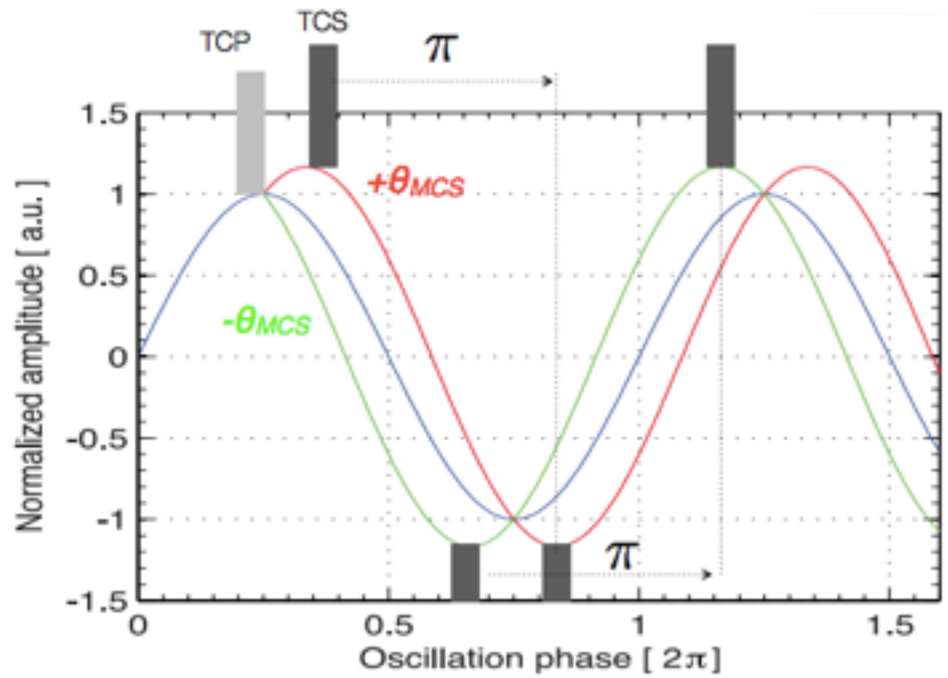
- Present LHC collimation solution fully validated: **natural and solid solution** to start with!
- First conceptual solution for the betatron collimation at the FCC: **scaled-up system** derived from the present one

Betatron cleaning

- Present LHC collimation solution fully validated: **natural and 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*



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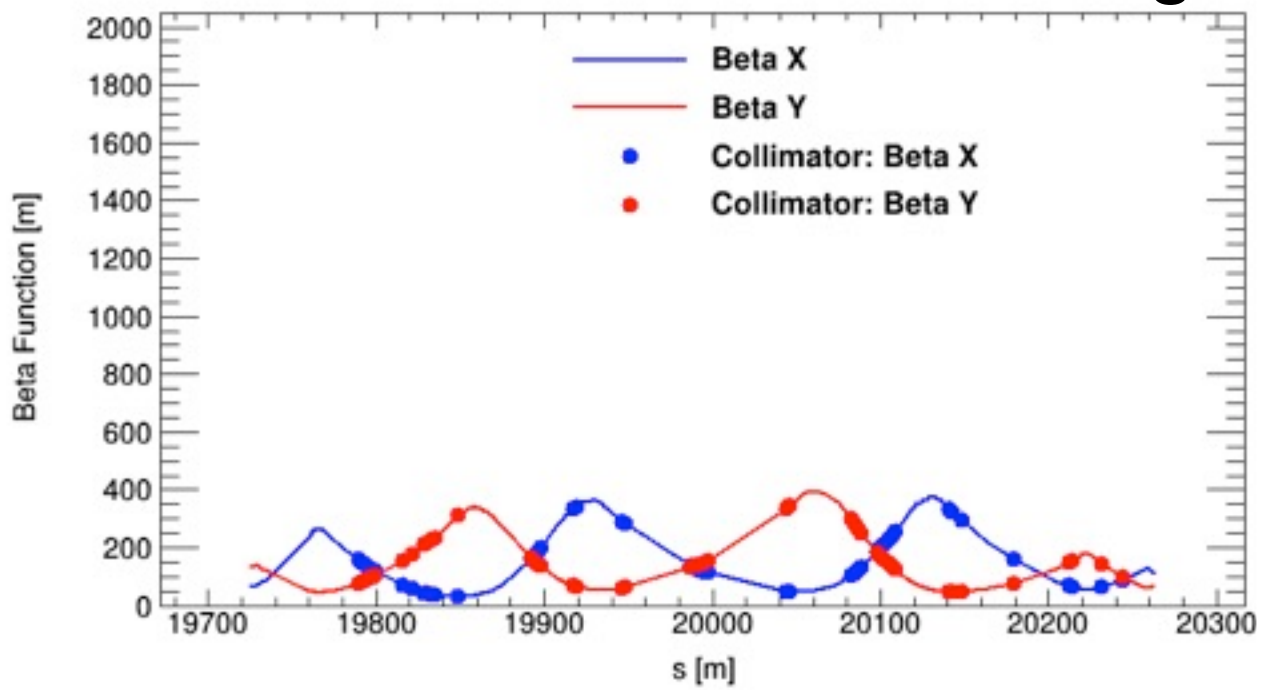
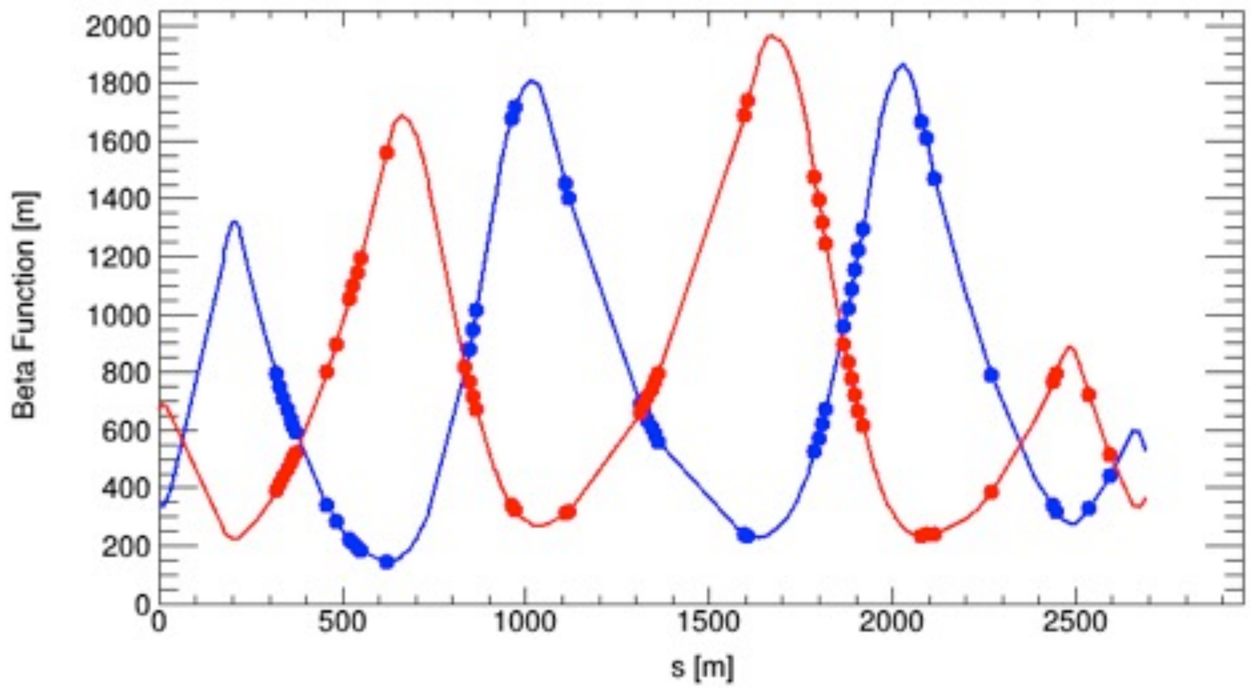
LHC IR7 - betatron cleaning



FCC IRD - 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

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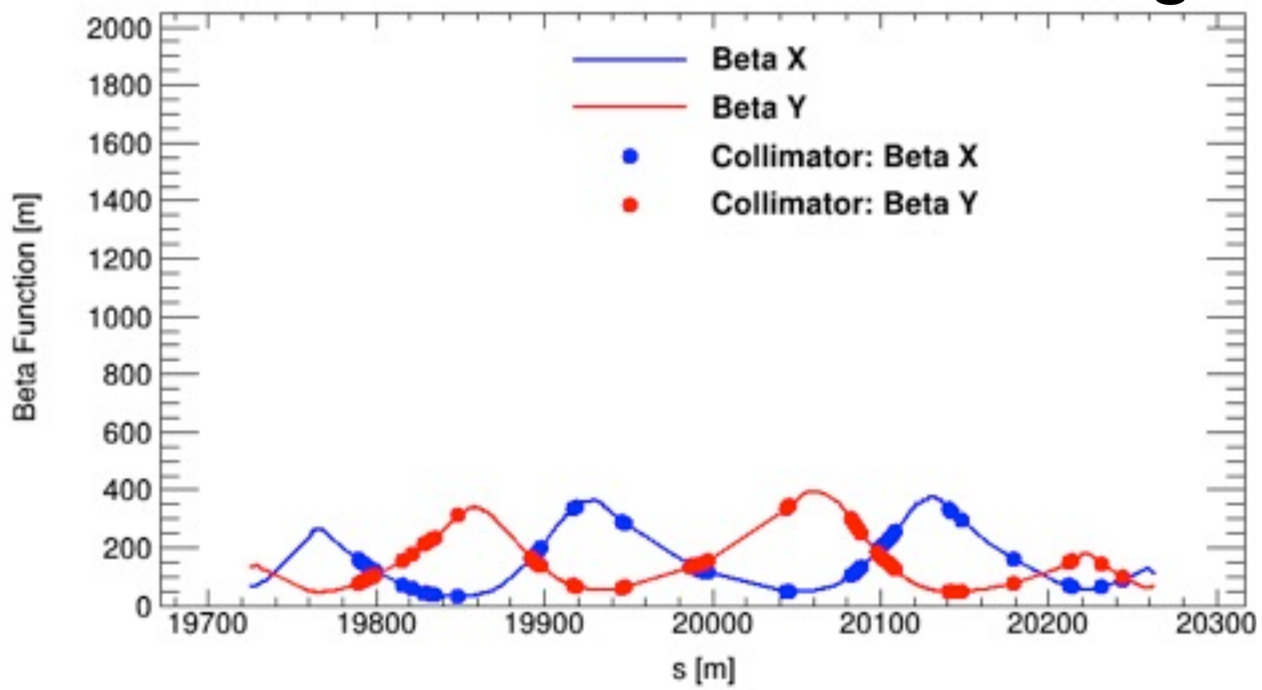

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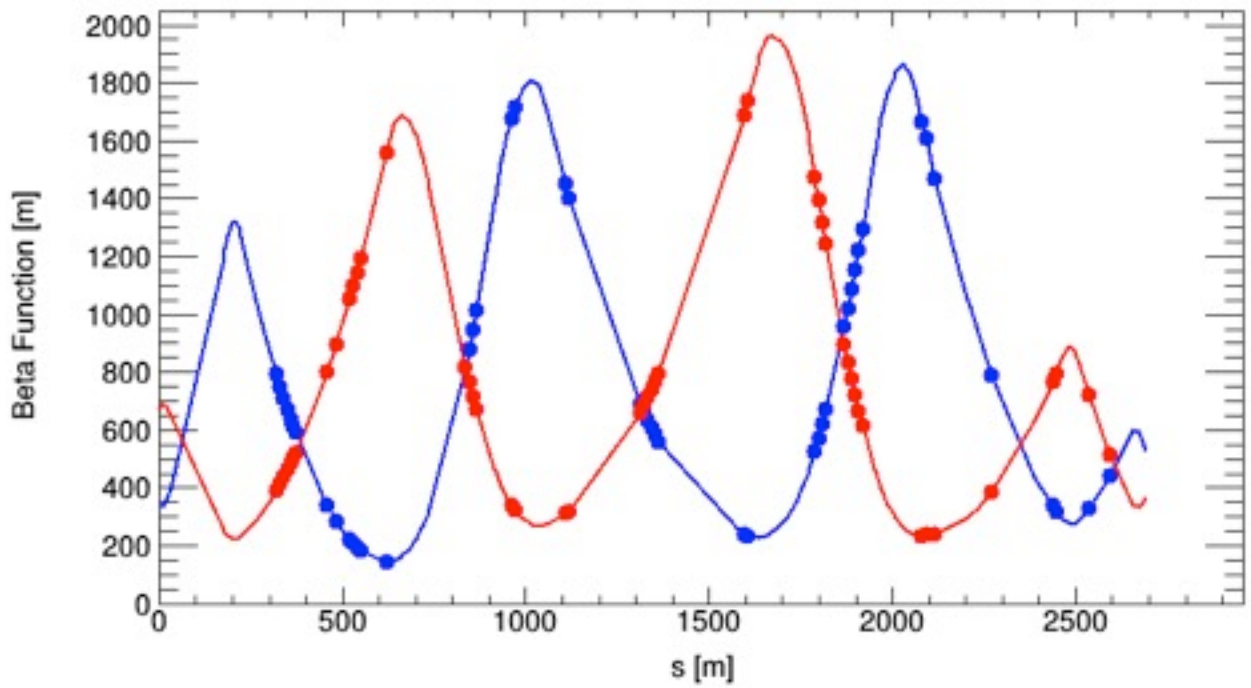

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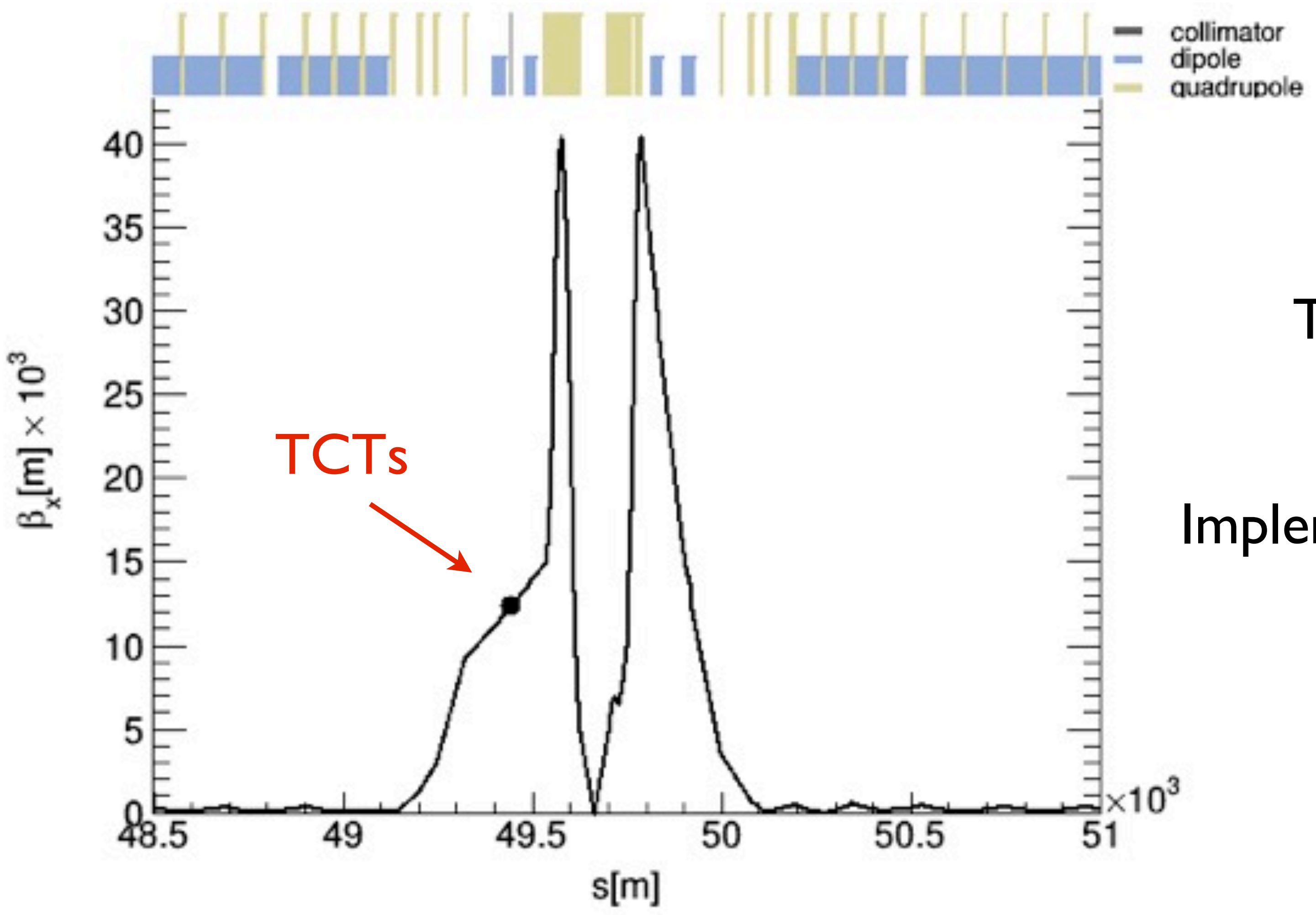
Collimation in the IR



Tertiary collimators (TCTs) provide local protection of the inner triplet

Implemented 2 TCTs (one horizontal, one vertical) in experimental insertions

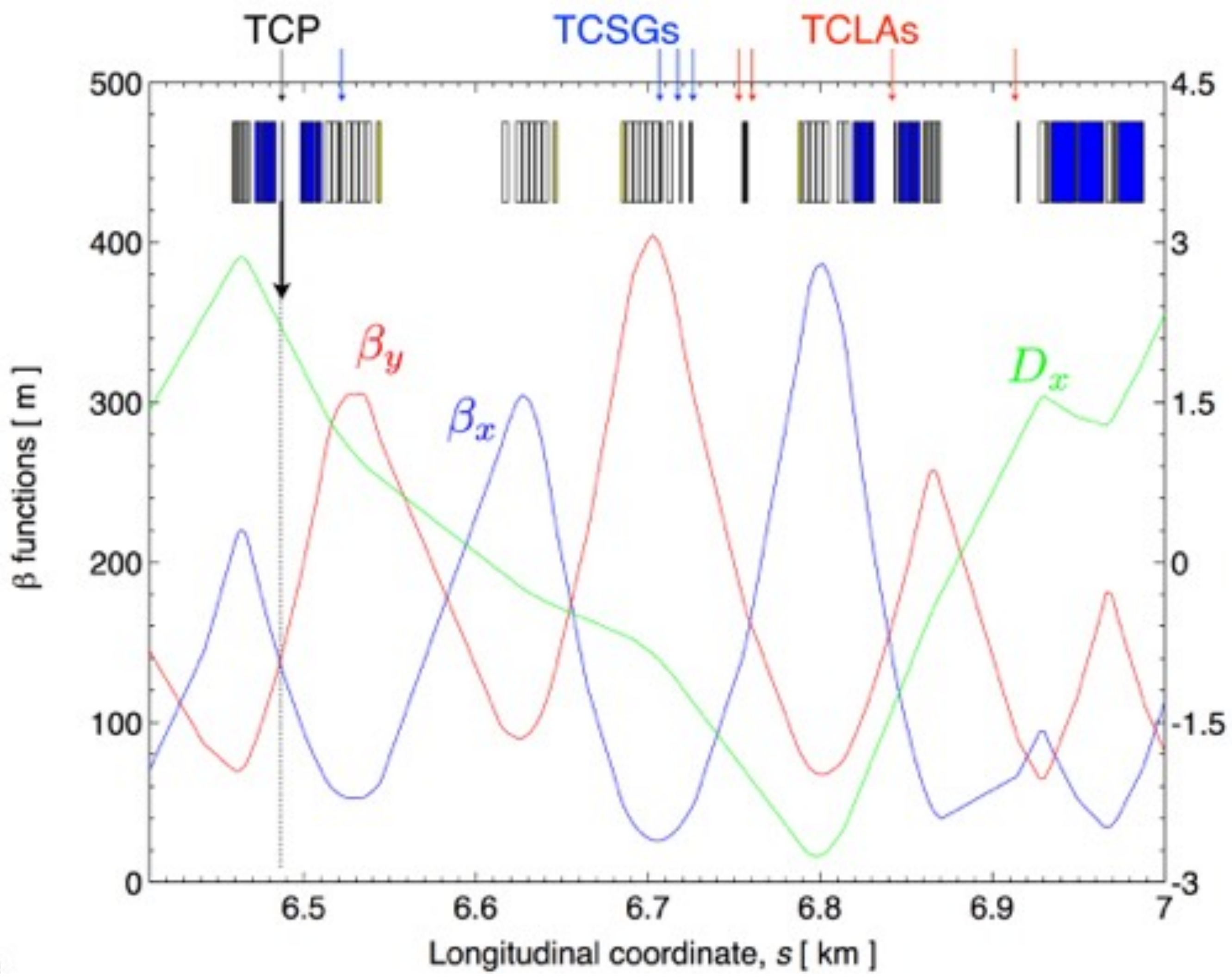
Off-momentum cleaning (I)

Main purpose

- Intercept primary off momentum losses
  - *Capture losses, synchrotron radiation losses, …*
  - *Important for failures: RF off, wrong frequency settings*
- Provide adequate cleaning for design loss scenarios

LHC solution

- Dedicated cleaning insertion
- Three stage cleaning (TCP/TCS/TCLA)
- Maximised normalized D_x



Off-momentum cleaning (II)

Specifications for FCC:

• Momentum cut at the TCP tighter than the arc acceptance:

➡ FCC arc acceptance ~ 0.71% → cut at the TCP ~0.12%

• Beta functions such that collimation hierarchy in betatron cleaning insertions is not violated (ie. beyond TCP^{β} /$TCSG^{\beta}$ at 7.6/8.8 σ)

Start with LHC-scaled solution:

• Beta functions scaled by √(50/7)

• Dispersion like at the LHC

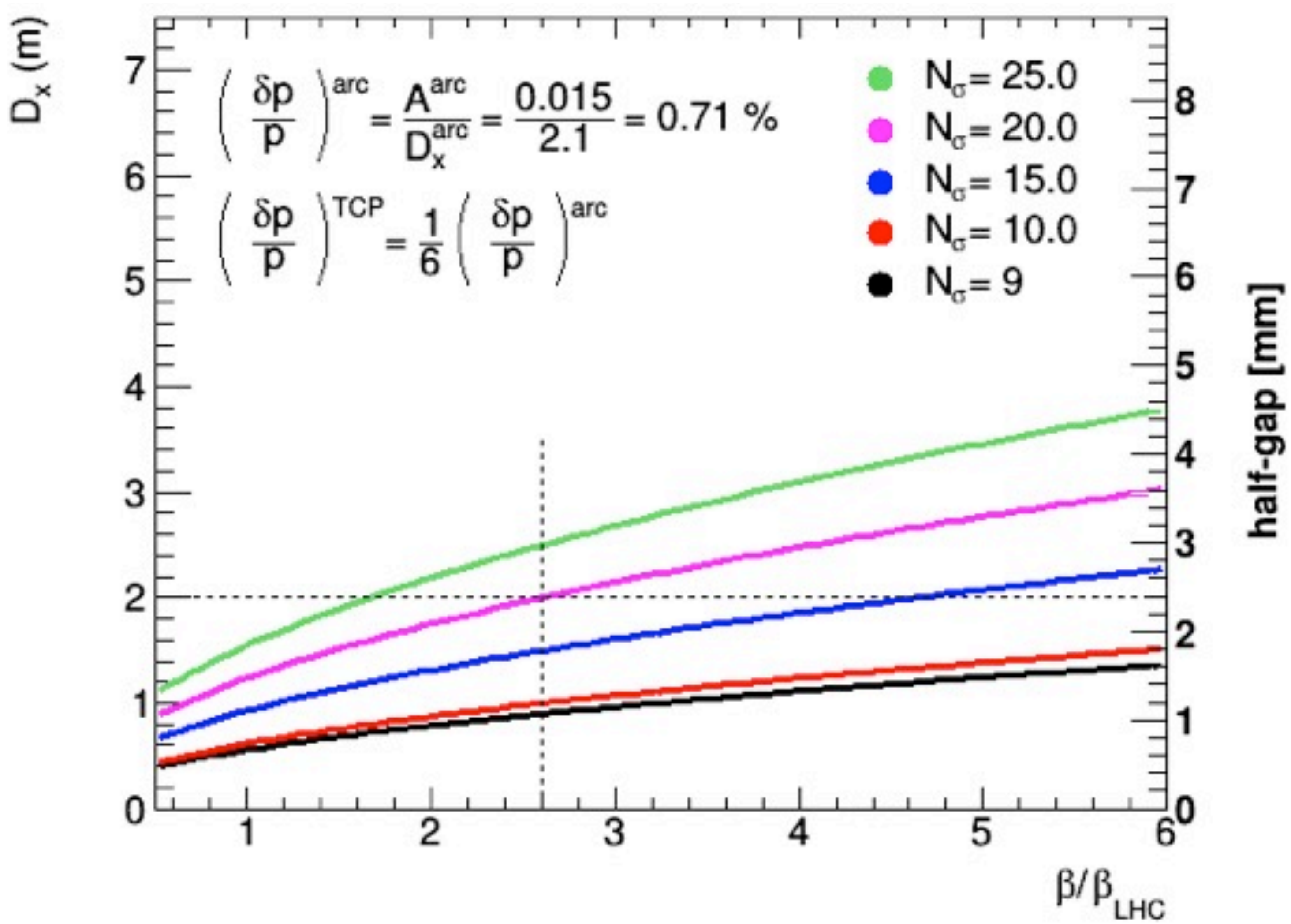
Can achieve a momentum cut of 0.12% with

➡ half-gap ~ 2 mm

➡ Nσ (TCP) = 20

Ok for cleaning hierarchy!

Alternative optics also being investigated



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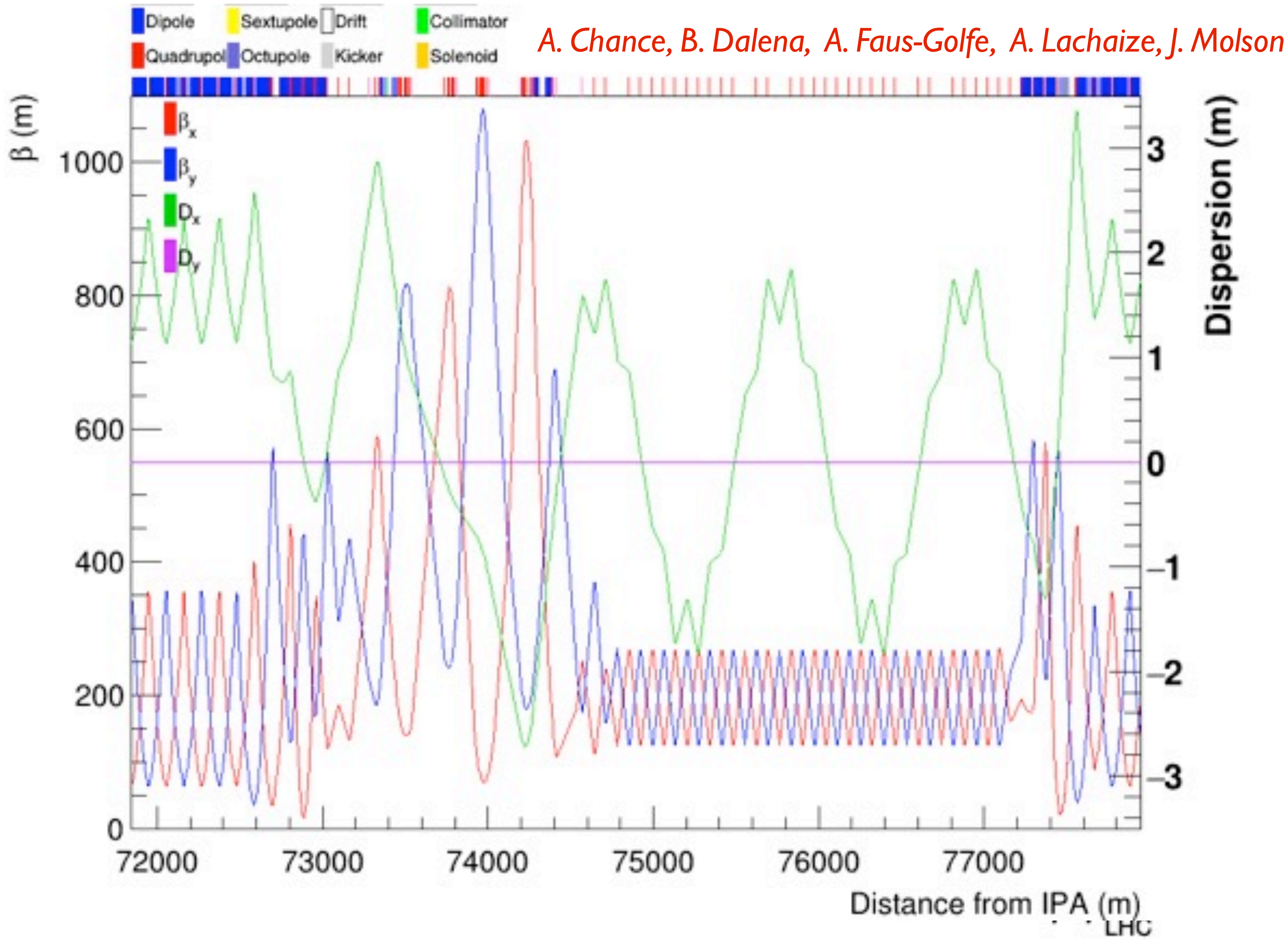
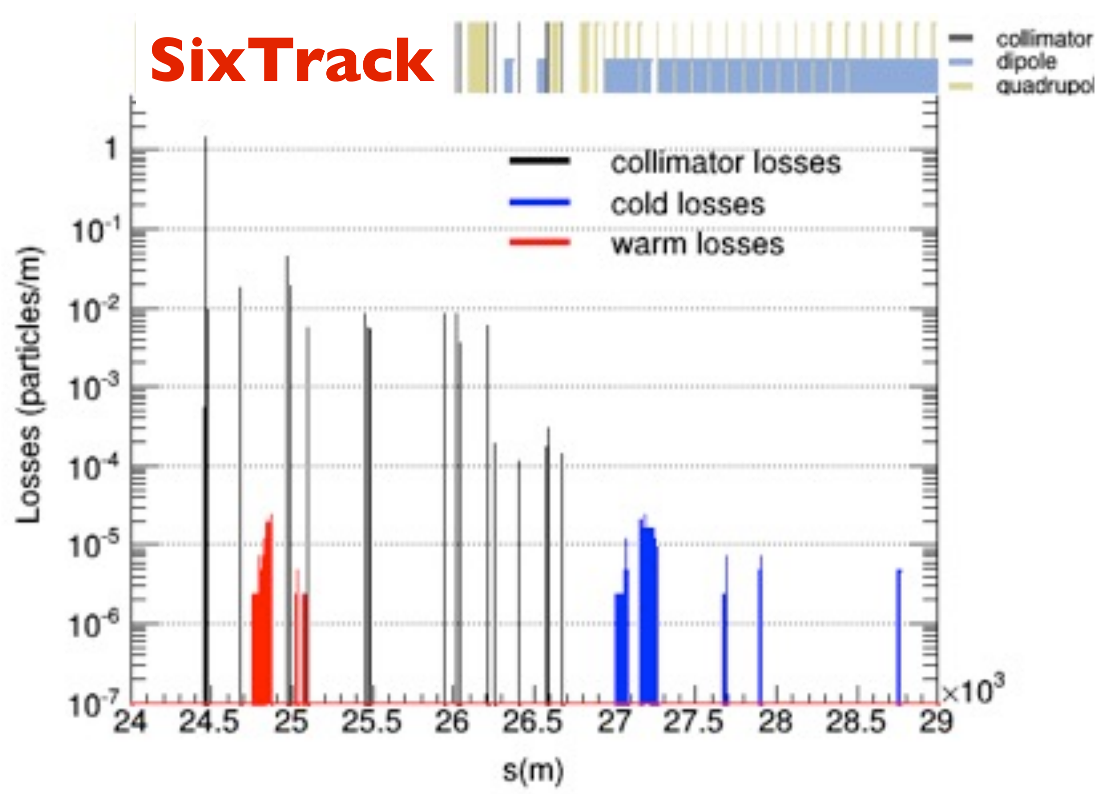


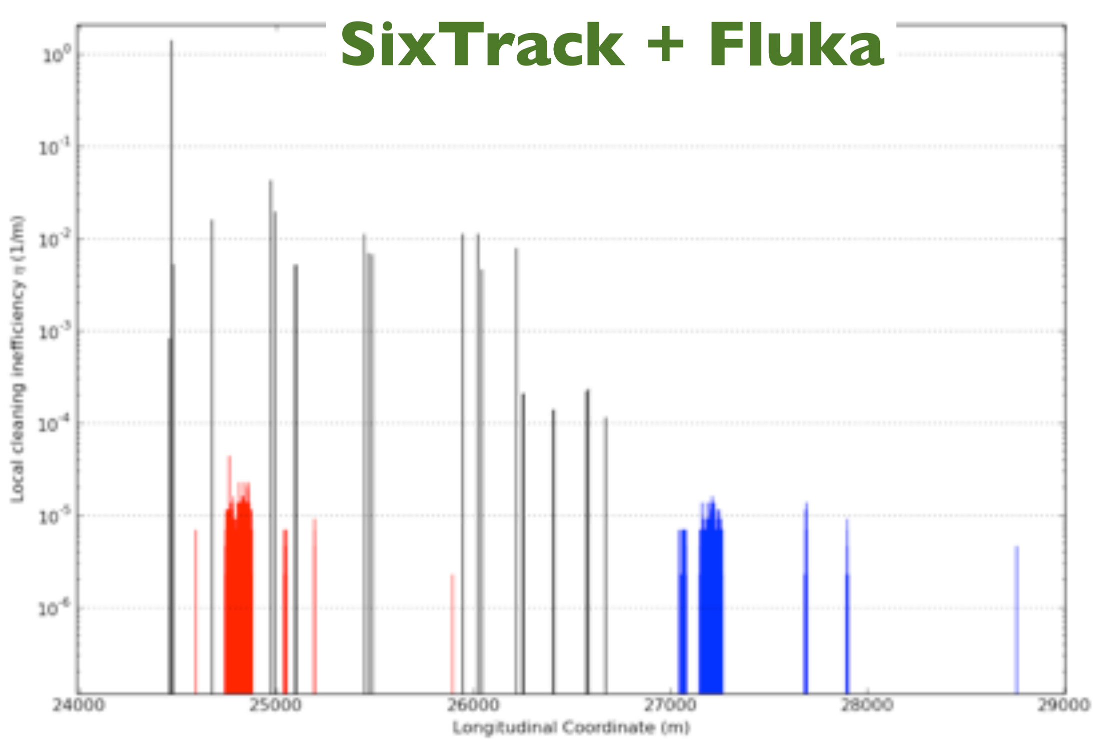
Tools for performance studies

Take advantage of the developments and experience built up for other projects (LHC, HiLumiLHC, EuCard). Several tools available for precise tracking simulations:

- Merlin: 6D tracking in thick lens + beam particle scattering — used at LAL (see talk by J. Molson)
- SixTrack: 6D tracking in thin lens + beam particle scattering — used at CERN (see talk by M. Fiascaris)
- SixTrack + Fluka: tracking engine of SixTrack + full MC functionalities of Fluka for beam machine interactions — ongoing effort at CERN

We have defined a set of baseline inputs to be used across different groups: optics, layout, collimator settings, aperture model → benchmarking of codes and comparison between different tools to validate the results





Where we are

Roadmap to first baseline

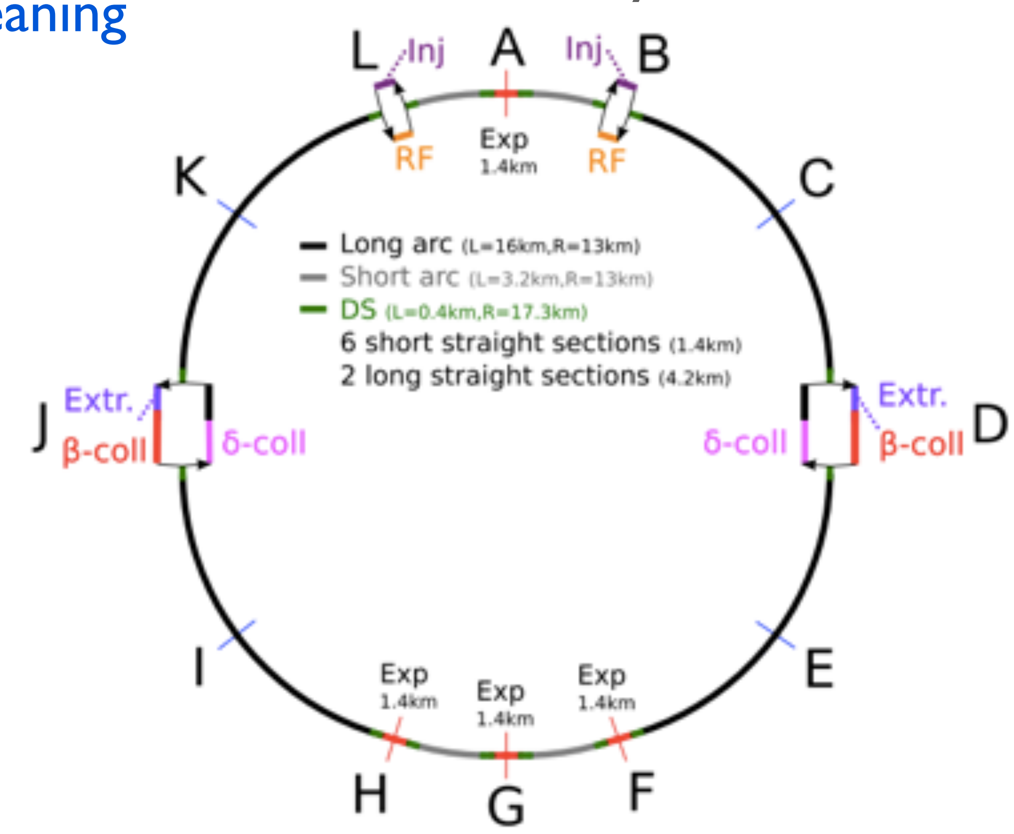
Roadmap to first baseline - *work is progressing on several aspects:*

- Lattice for collimation studies (with betatron and momentum cleaning insertions)

  → *integrated lattice for baseline layout available*

  → alternative layouts to be explored

FCC baseline layout



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- Lattice for collimation studies (with betatron and momentum cleaning insertions)

  → *integrated lattice for baseline layout available*

  → alternative layouts to be explored

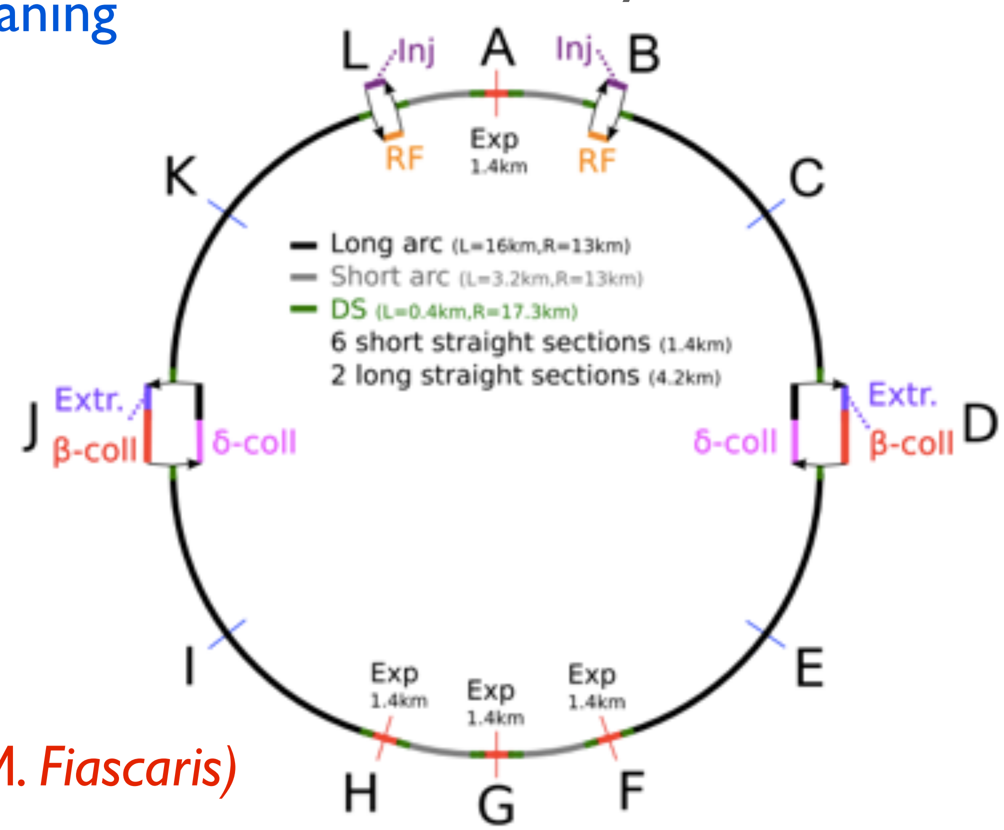
- Development of an aperture model for the full FCC ring

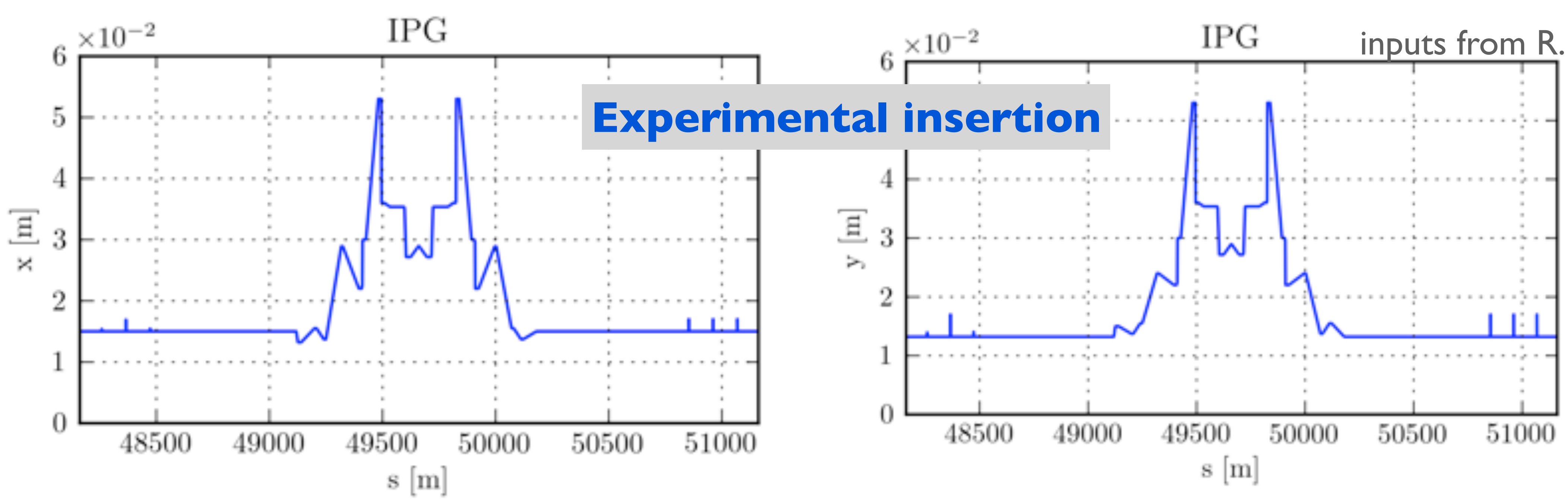
  → *preliminary aperture model defined (see details in talk by J. Molson)*

- Aperture calculations and definition of baseline collimator settings

  → *first evaluation performed at injection and top energy (see talk by M. Fiascaris)*

FCC baseline layout





Roadmap to first baseline (II)

- Optics for momentum cleaning

  → *first version available (see talk by J. Molson)*

  Alternatives to be investigated (see talk by A. Lachaize)

- Design of dispersion suppressor regions including TCLD collimators

  → *first studies on performance with TCLD collimators (see talk by M. Fiascaris)*

  Design of DS to be optimized - detailed energy deposition studies required

- Performance evaluation with full set of loss maps and optimization of collimation settings

  → *First loss maps (see talks by J. Molson and M. Fiascaris)*

  Systematic studies for performance evaluation and optimization planned

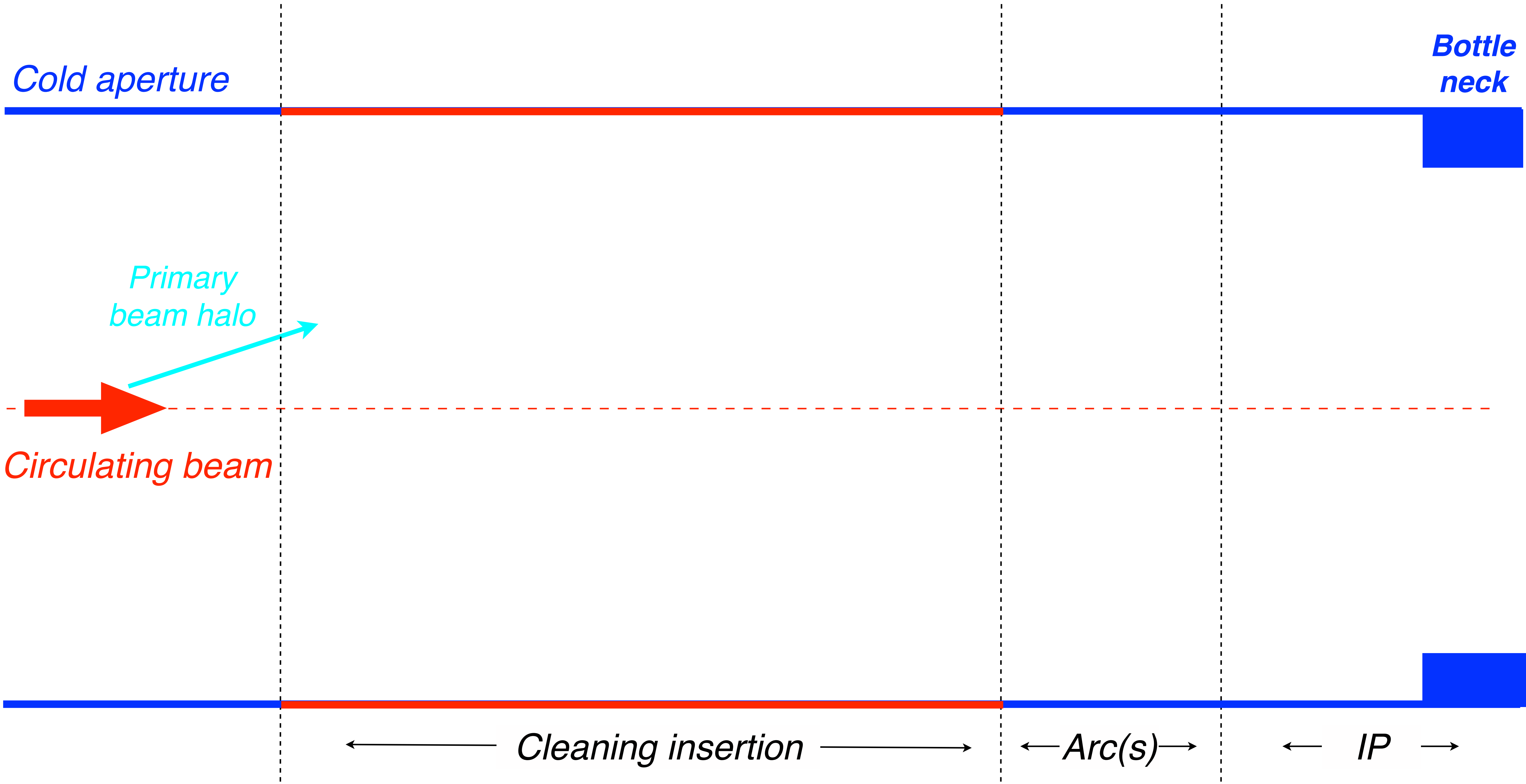
  Need to converge soon on input for impedance evaluation and HW design

Conclusions and Outlook

- Good progress was made in the last months to converge towards a first baseline:
  - dedicated insertions for betatron and momentum cleaning *done*
  - IR collimation: incoming beam ("tertiary collimators") *done*
  - IR collimation: physics debris cleaning
  - define interfaces to other relevant systems (injection/dump)
- We have the tools in hand to evaluate and optimize the system performance
  - We have completed a first iteration to define baseline collimator settings
  - Systematic studies of betatron and momentum cleaning, and benchmarking of codes are ongoing
- Interactions with other teams will be crucial for the next steps:
  - **Collimator settings:** trade-off between impedance and efficiency of the system → iterations with impedance team, study of new materials
  - **Collimator design specifications:** to be defined once we have more detailed studies on energy deposition
  - **Performance optimization:** need iterations with optics team to add collimators in critical locations (like in the dispersion suppressor) and maximize their performance.
- Beyond the first baseline: advanced collimation concepts (crystal collimation, hollow e-lens)
  - Profit of experience from LHC: MDs on crystal collimation in 2015 carried out with low intensity demonstrated proton channeling at 6.5 TeV and ion channeling at 450 GeV!

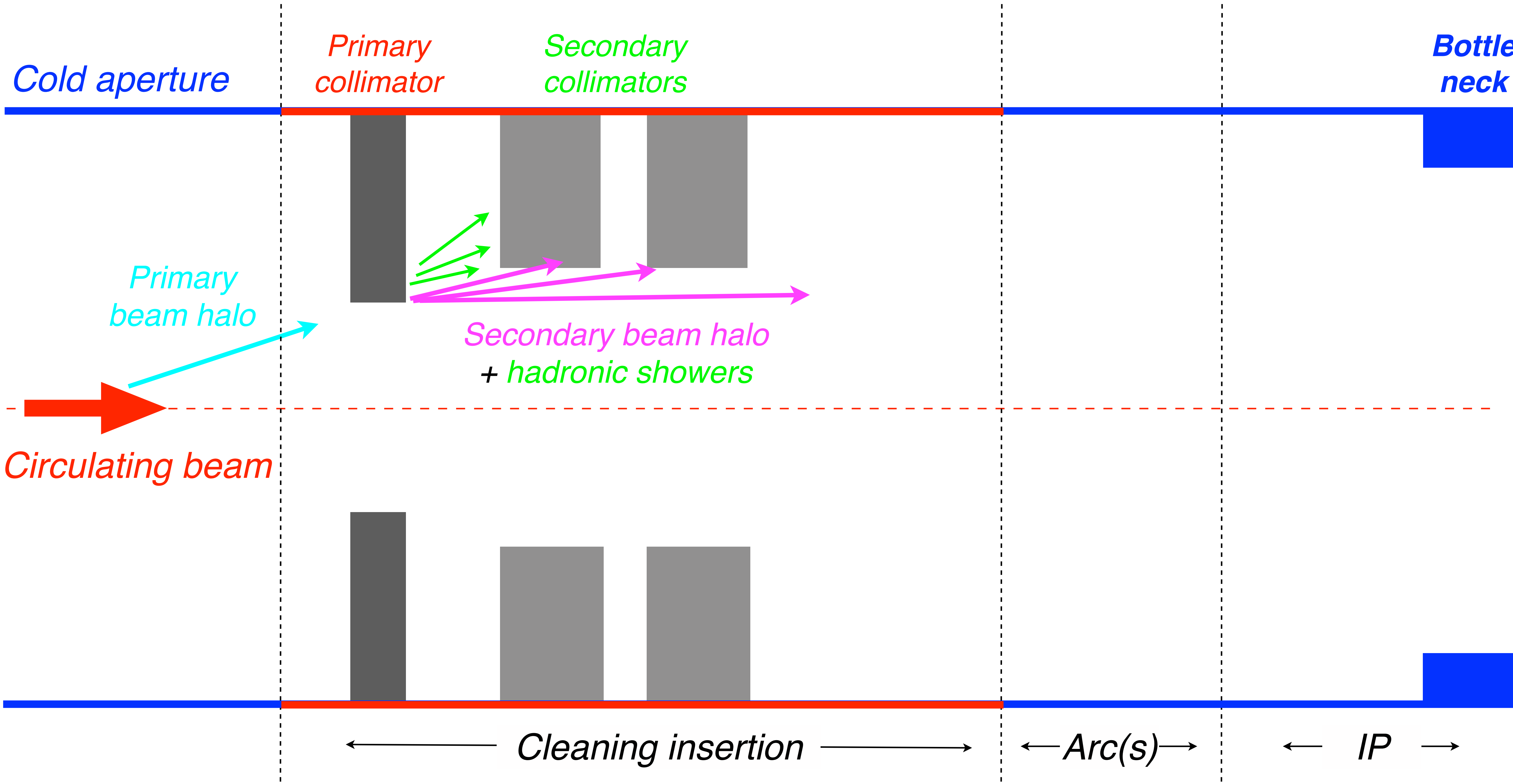
EXTRAS

Multistage betatron cleaning



Betatron cleaning: intercept primary losses with cleaning efficiency that ensures losses below quench limits in all operational loss scenarios.
The available transverse aperture sets the scale.

Multistage betatron cleaning



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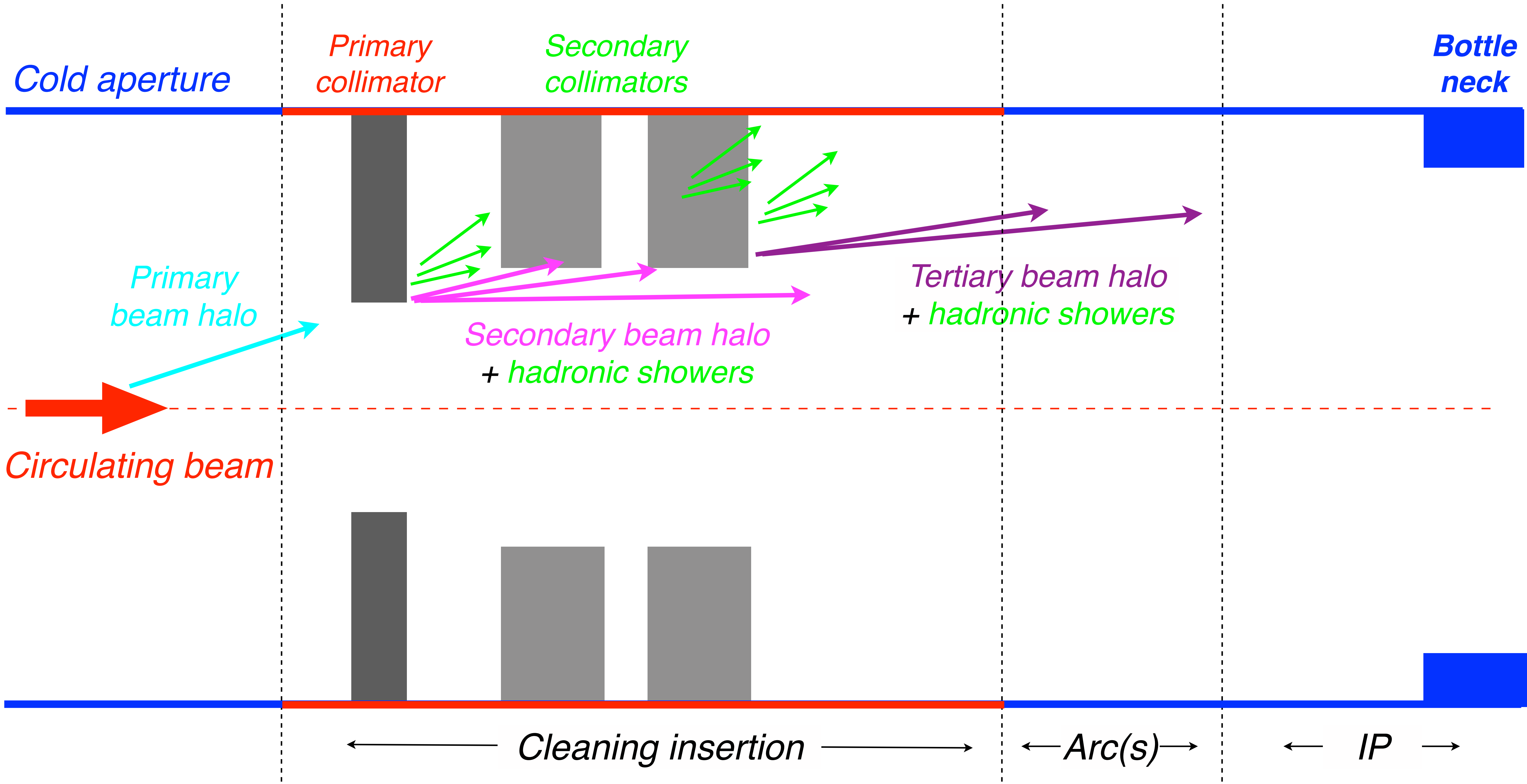

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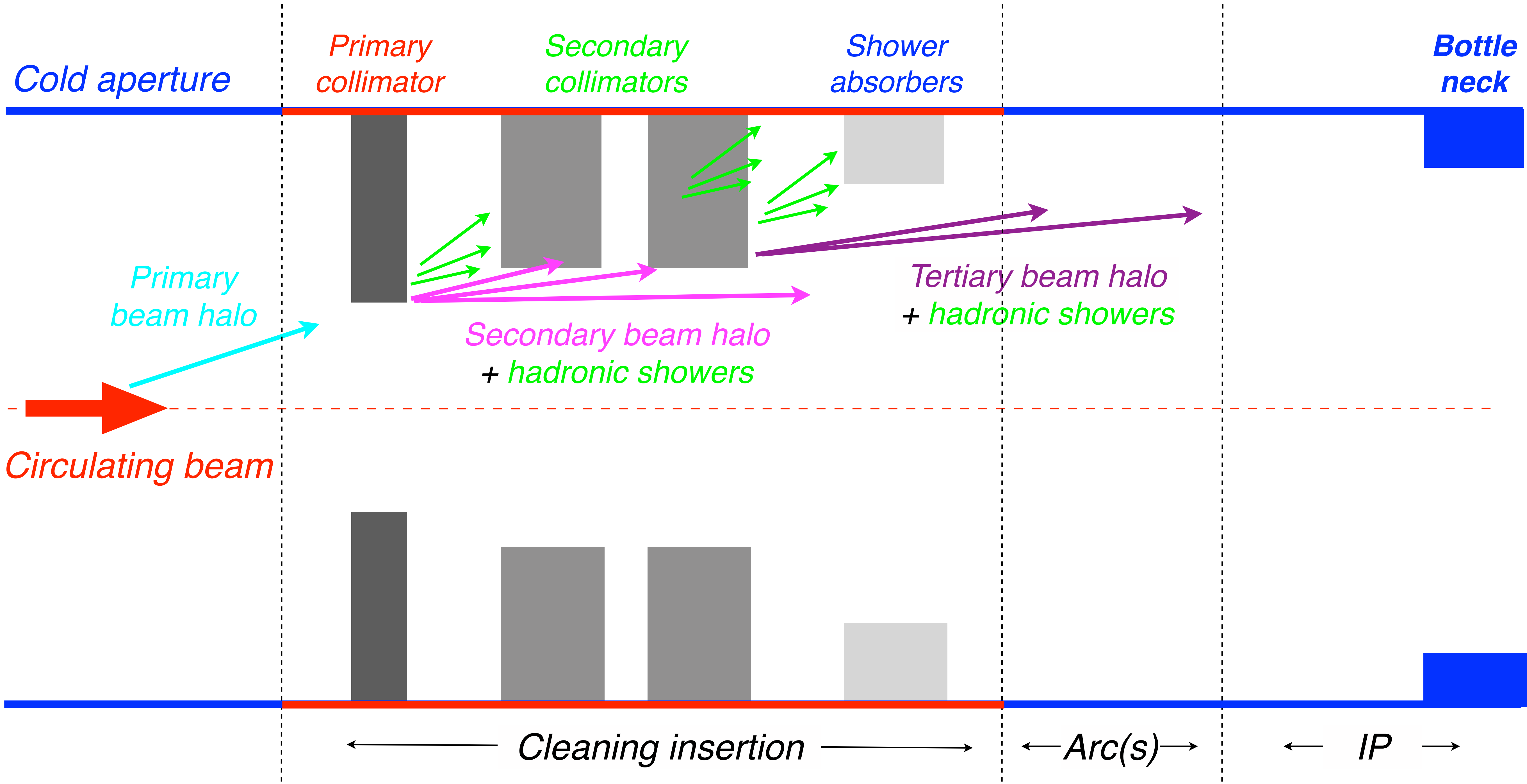

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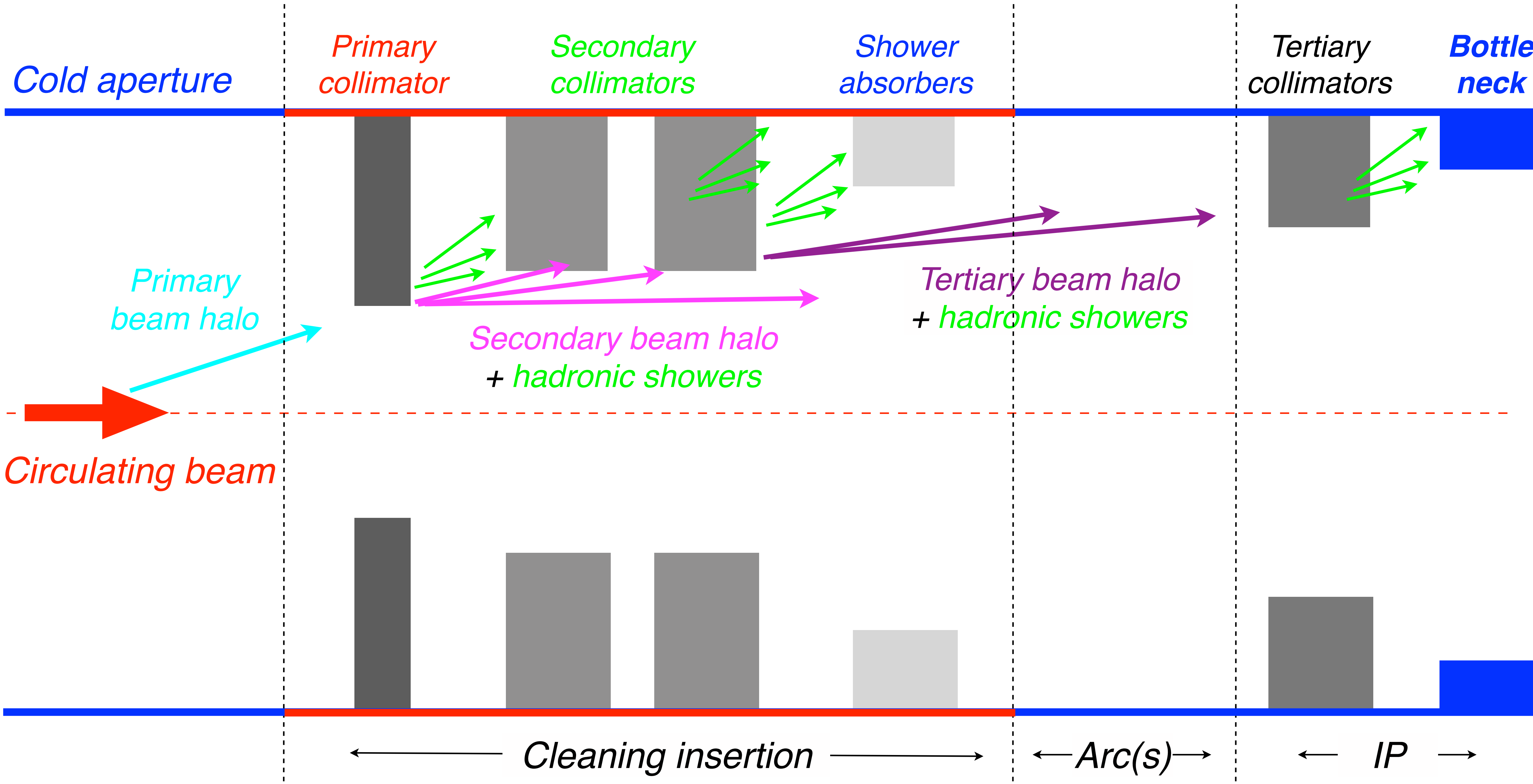

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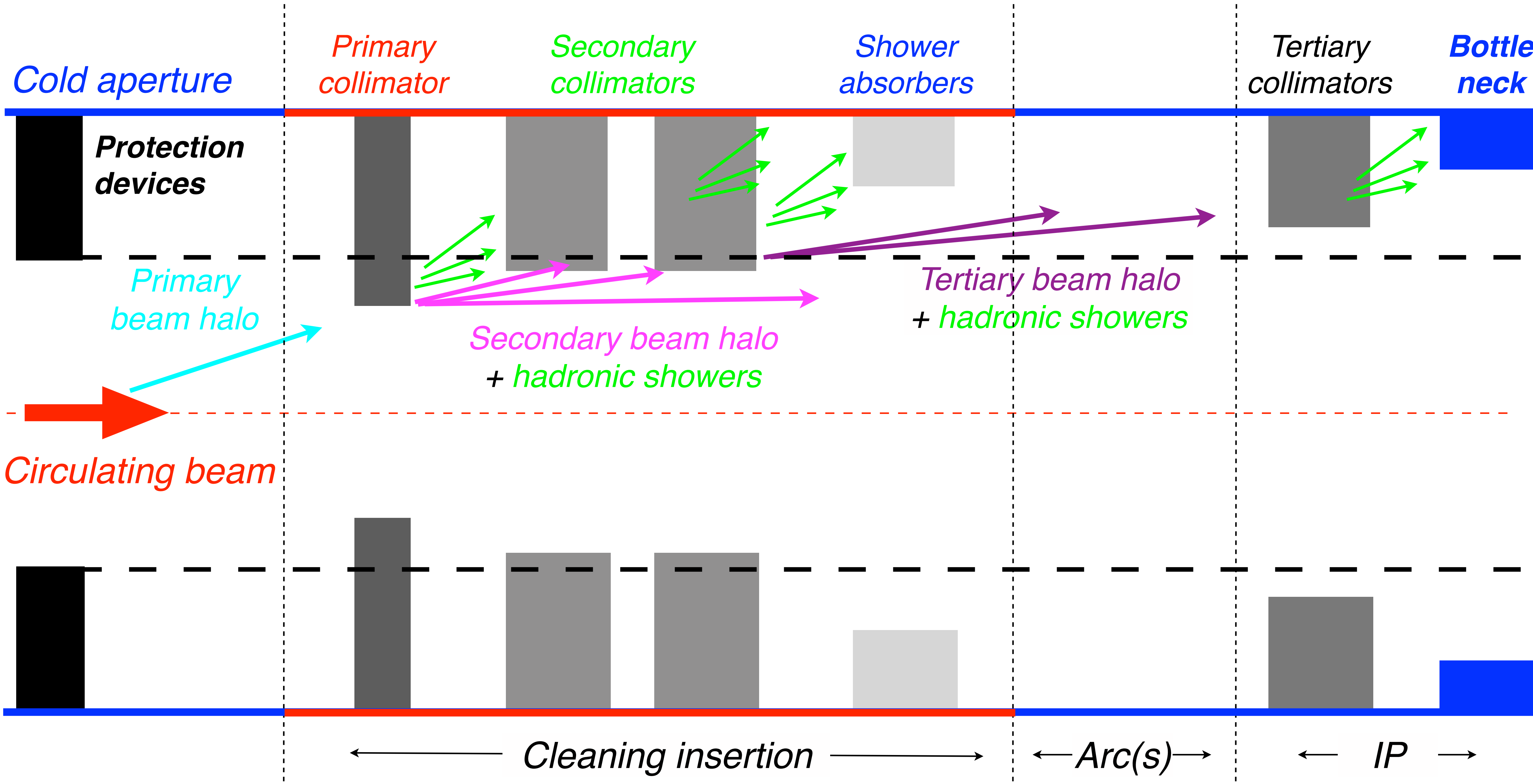

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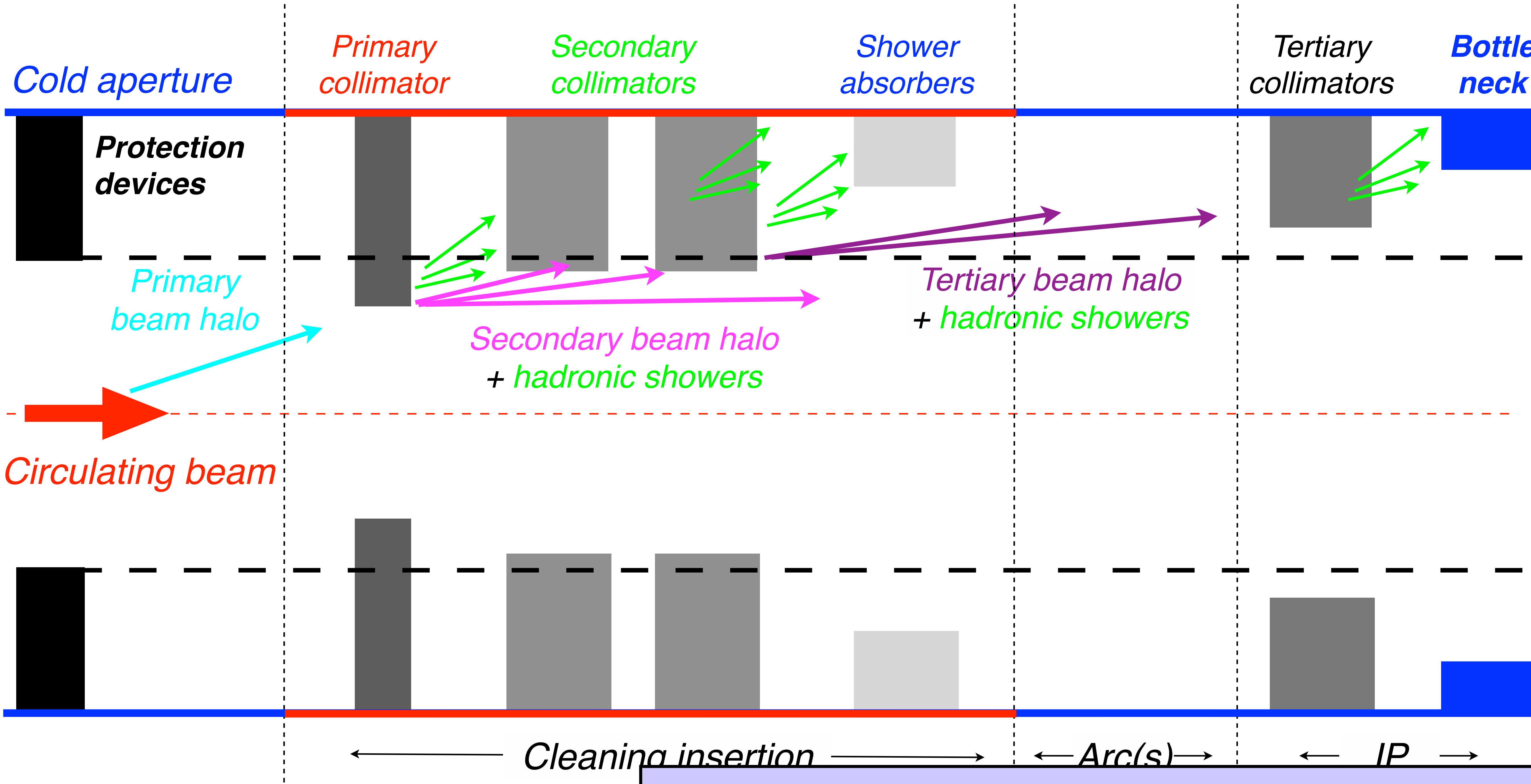


Betatron cleaning: intercep
ensures losses below quenc
The available tra

By design, aperture constraints usually are:
injection ↦ arcs
collisions ↦ inner triplet

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

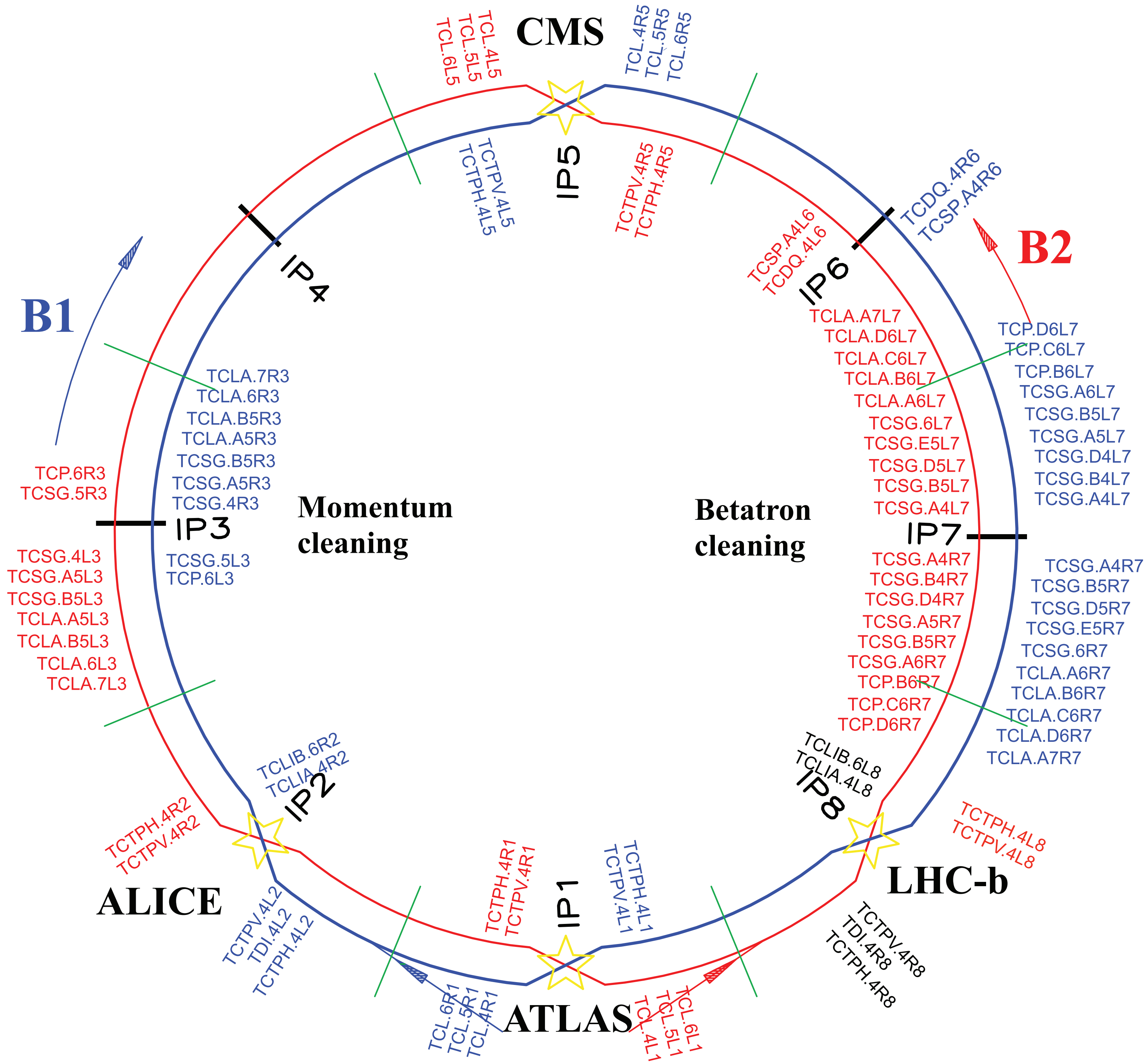
Physics debris absorbers

Transfer lines

Injection and dump protection

> 100 movable collimators

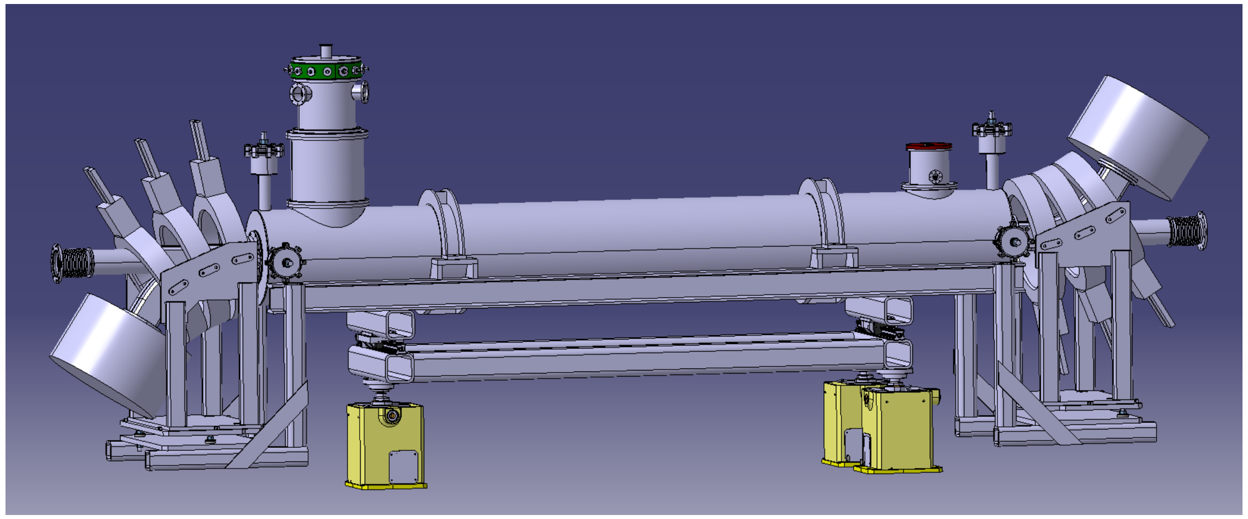
Two jaws (4 motors) per collimator



Advanced collimation concepts

Hollow e-lens

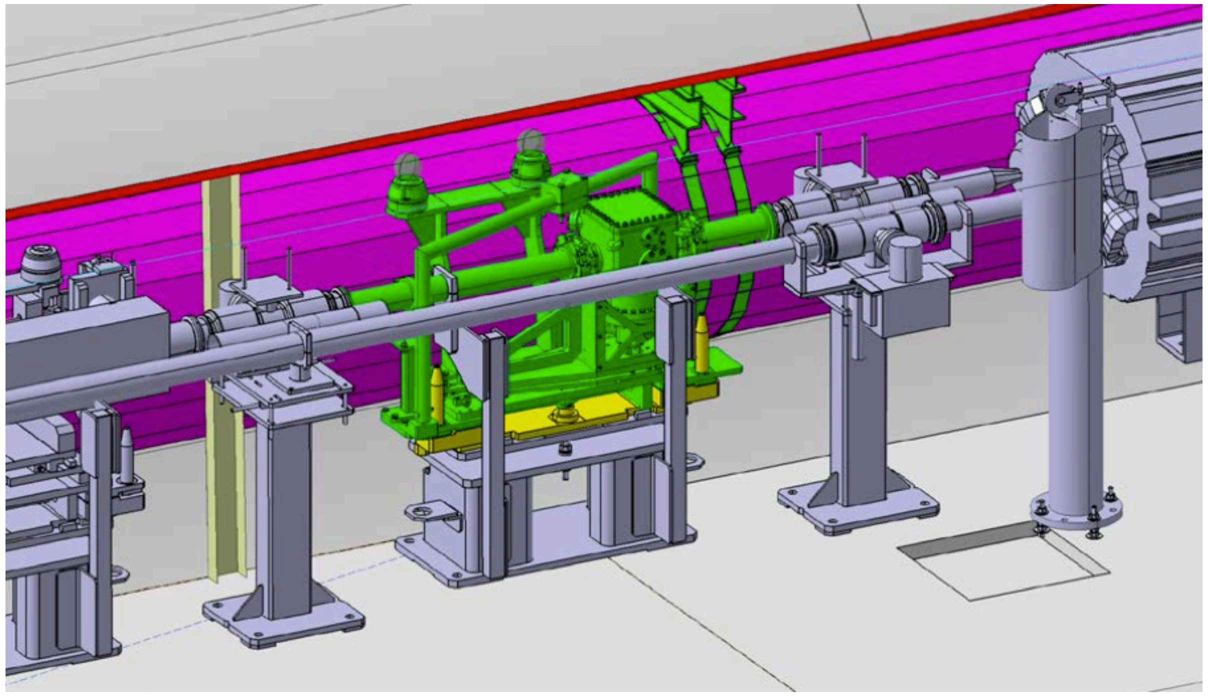
- Hollow electron beam parallel to the p-beam:
  - halo particles see field dependent on (Ax, Ay) plane, while core is unaffected
  - adjusting e-beam parameters can be used as halo scraper



- Expect to be a key asset to control loss rates on collimators
- Working on a design for implementation in LHC in LS2. Decided to build test bench at CERN → 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.

Inputs to cleaning studies

Minimum beam lifetime

Quench limit of SC magnets

LHC total intensity reach from collimation

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

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**!*

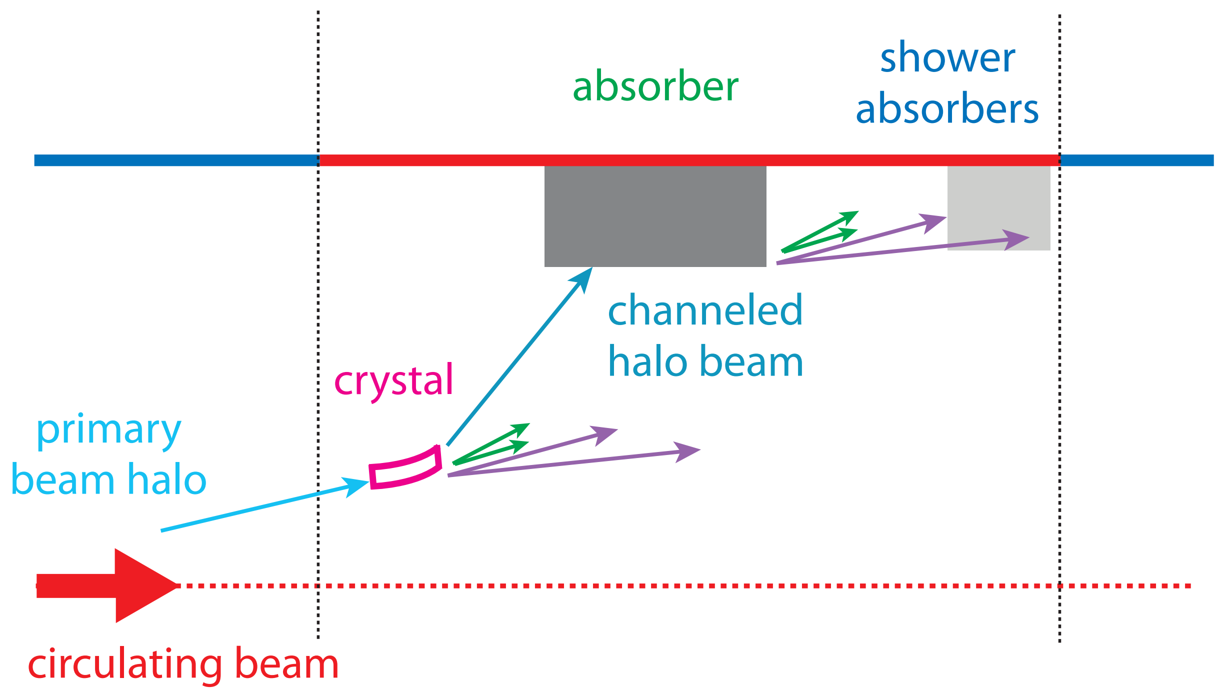
- **Quench limits of superconducting magnets**

  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.

Crystal collimation at the LHC



MDs in 2015 carried out with low intensities demonstrated:
proton channeling at 6.5TeV;
Pb channeling at 450GeV.

Collimation tests at LHC: collaboration with UA9 team (W. Scandale) and EN-STI.