Betatron collimation efficiency

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with R. Bruce and S. Redaelli

Acknowledgements to A. Chance, B. Dalena, R. De Maria, R. Martin, J. Molson, D. Schulte

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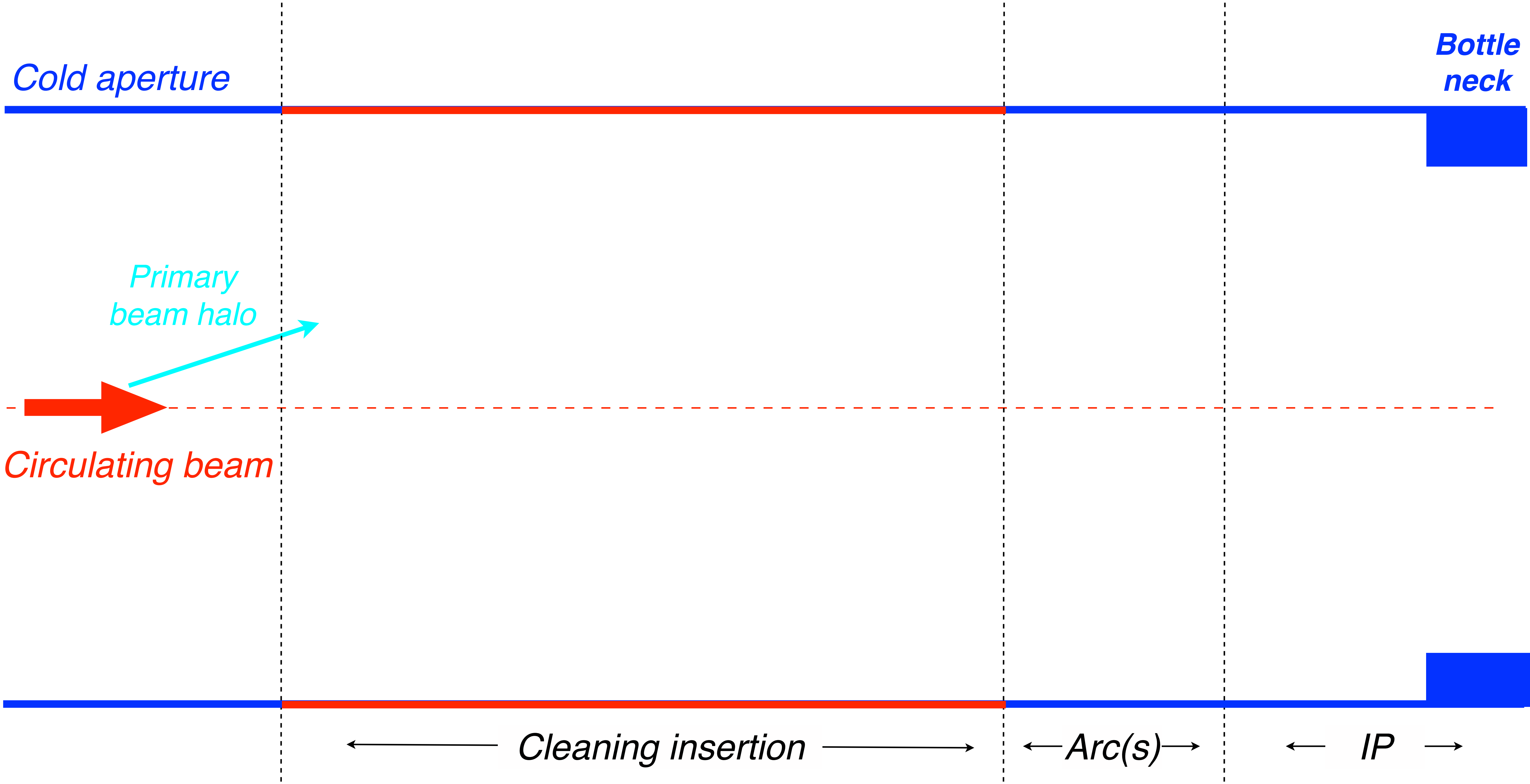
Outline

- Introduction
- Geometrical acceptance:
  - method
  - inputs
  - results
  - conclusions
- Simulations
  - global cleaning inefficiencies
  - loss maps
  - DS suppressor collimators
- Outlook

Introduction



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.

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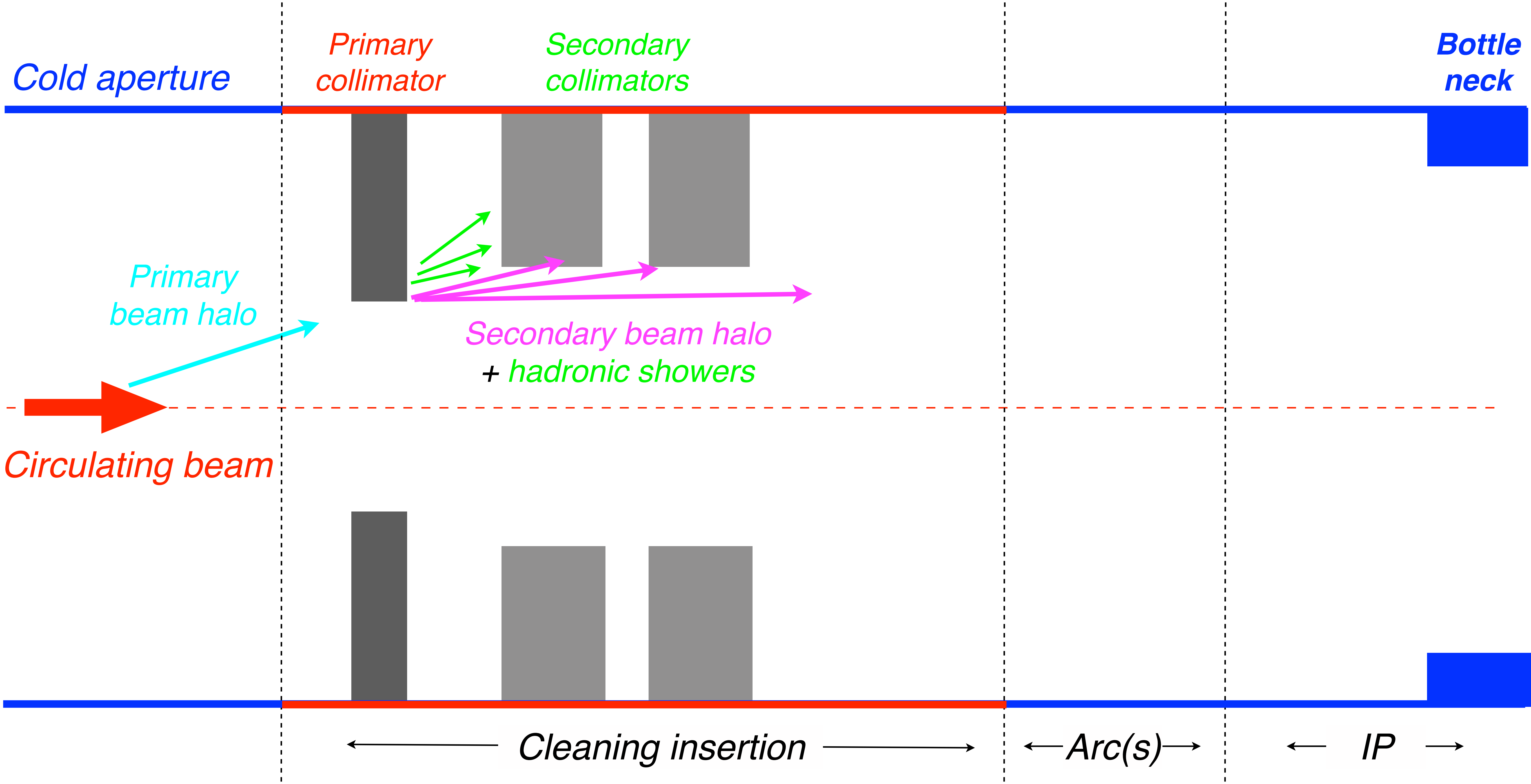

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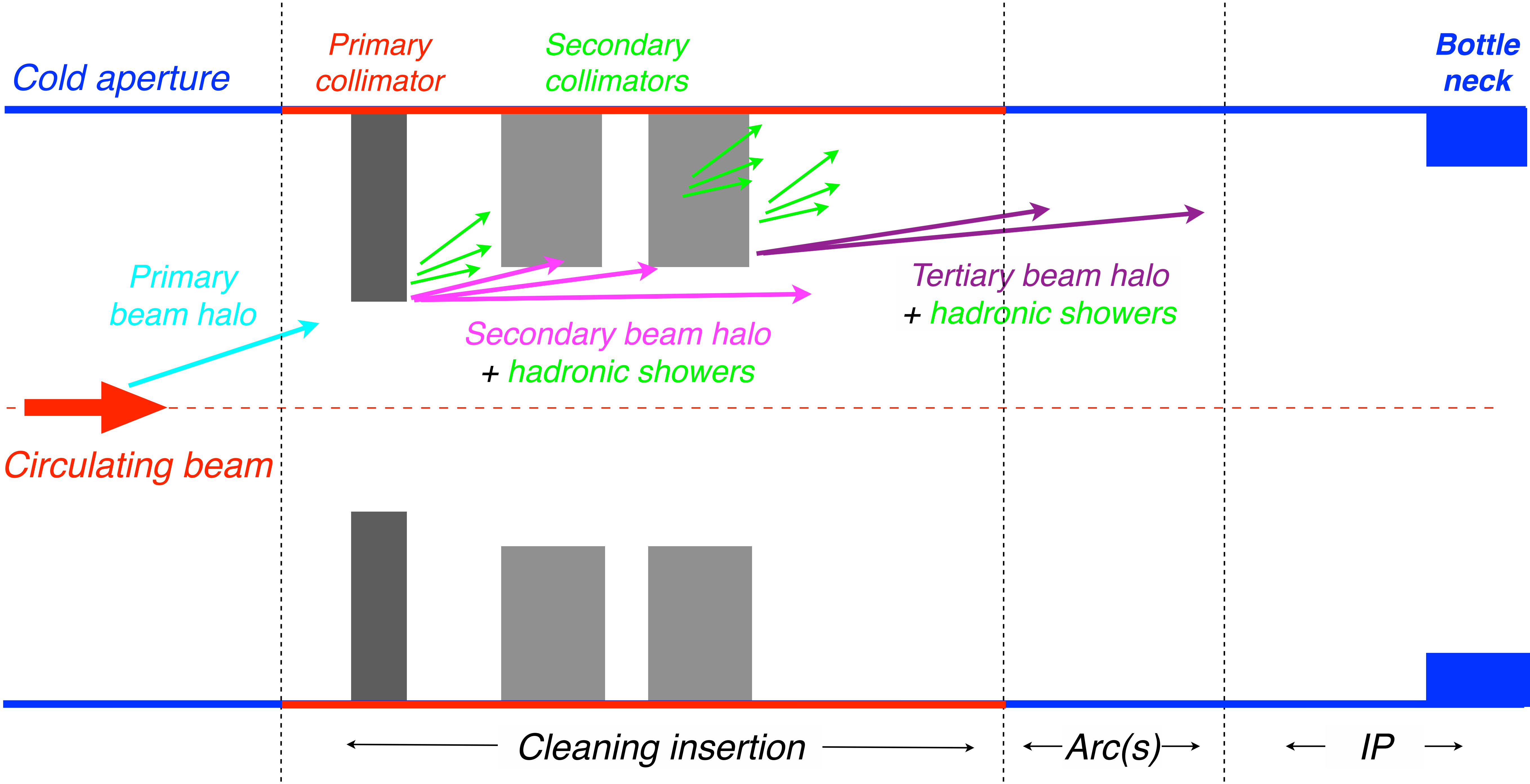

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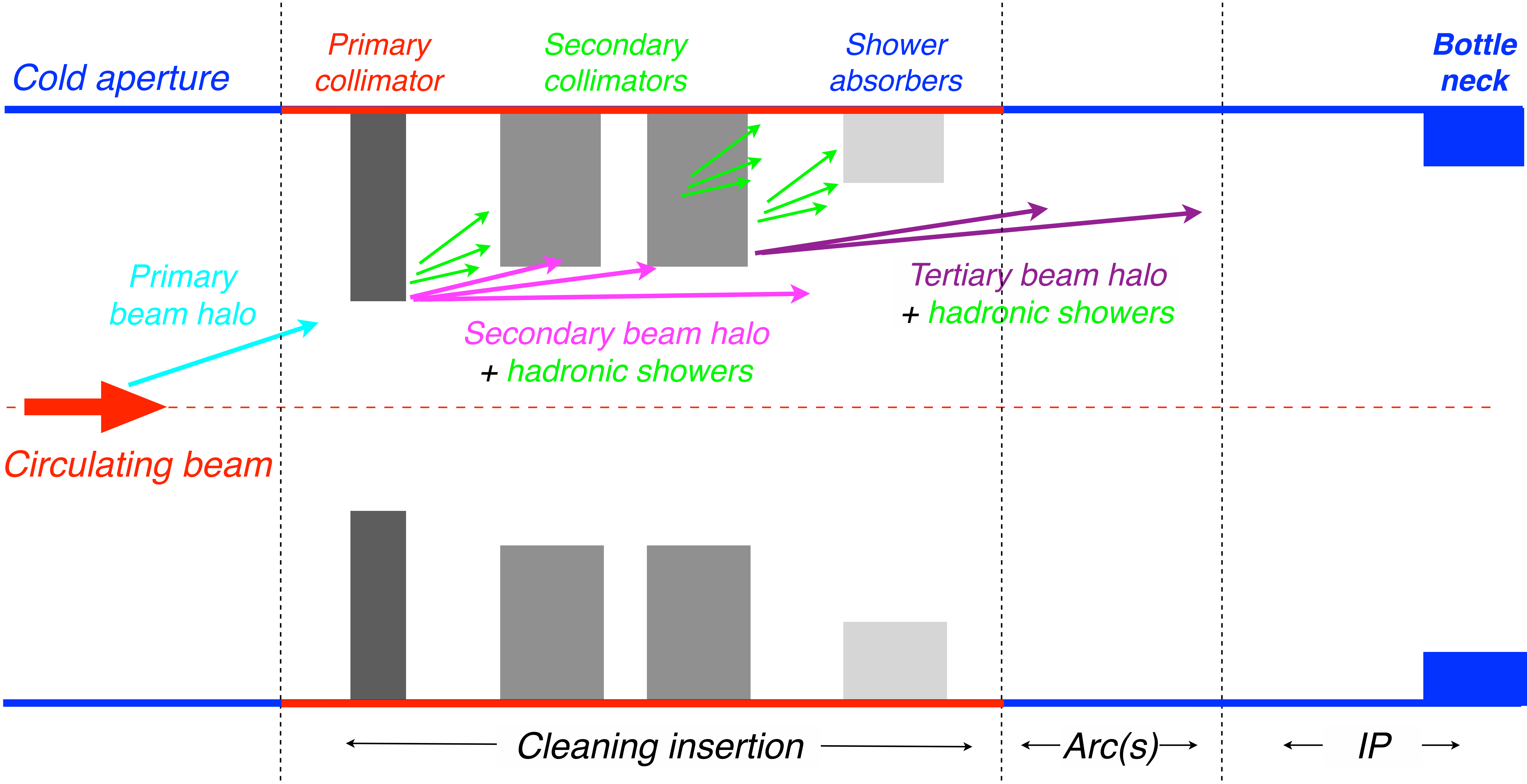

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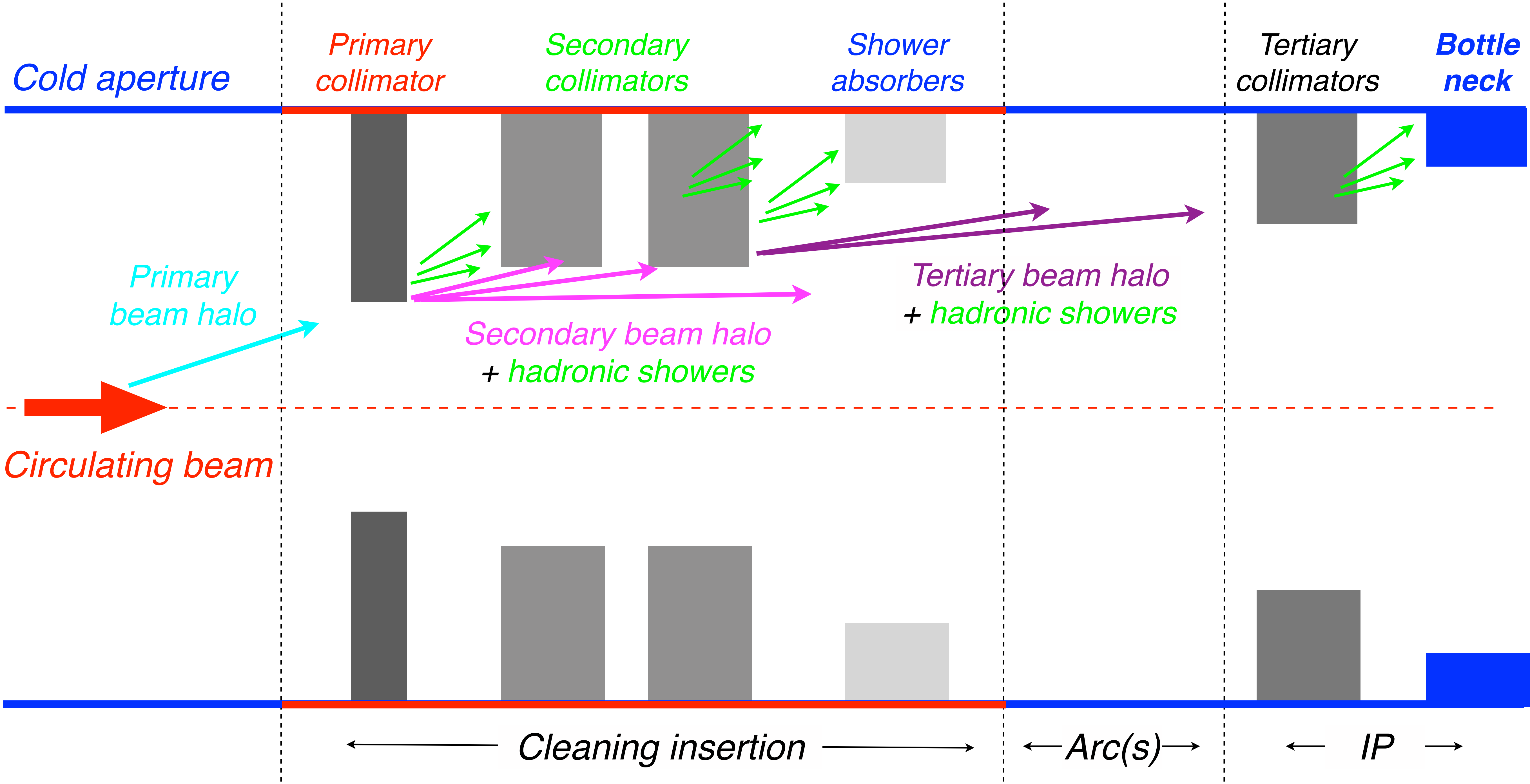

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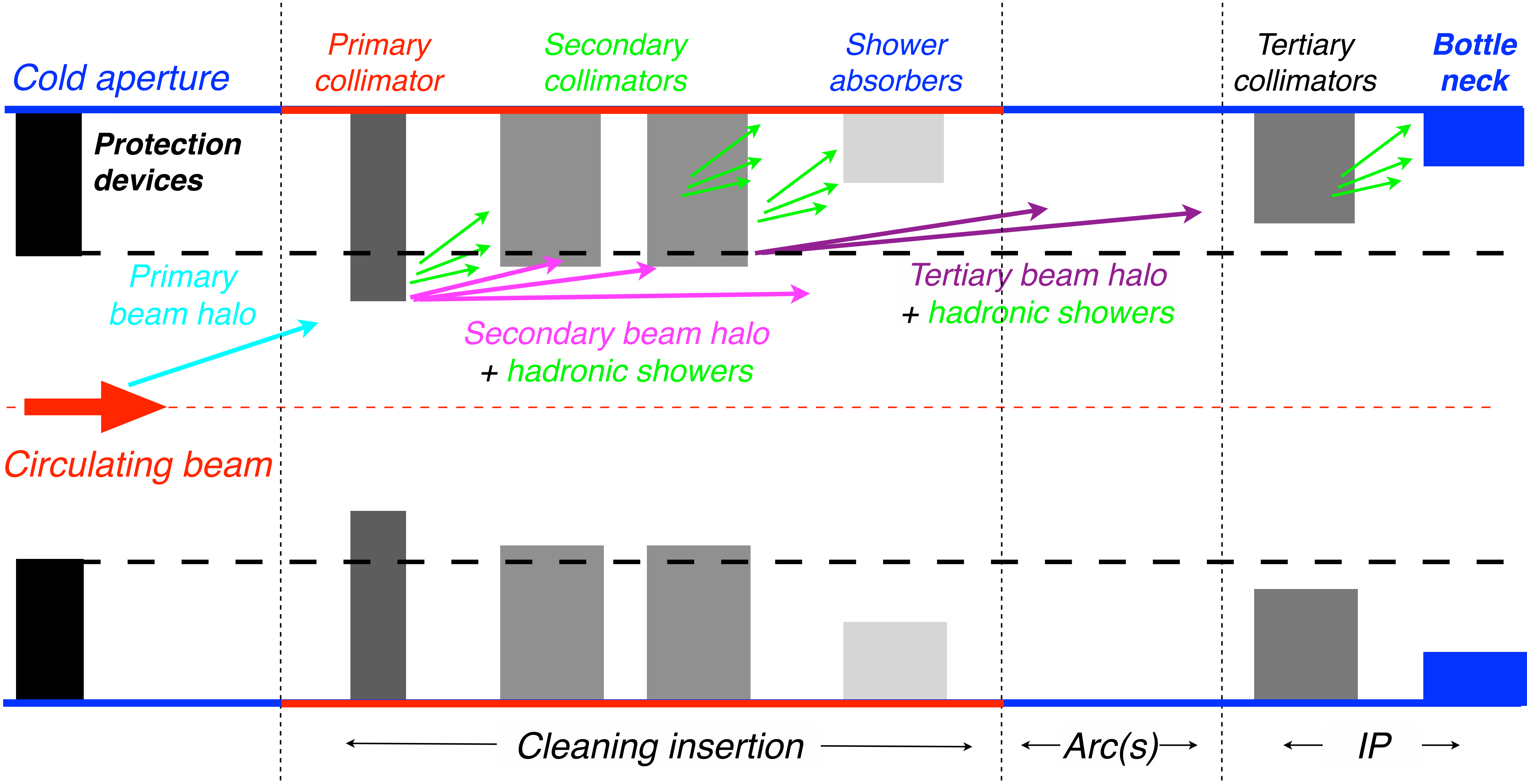

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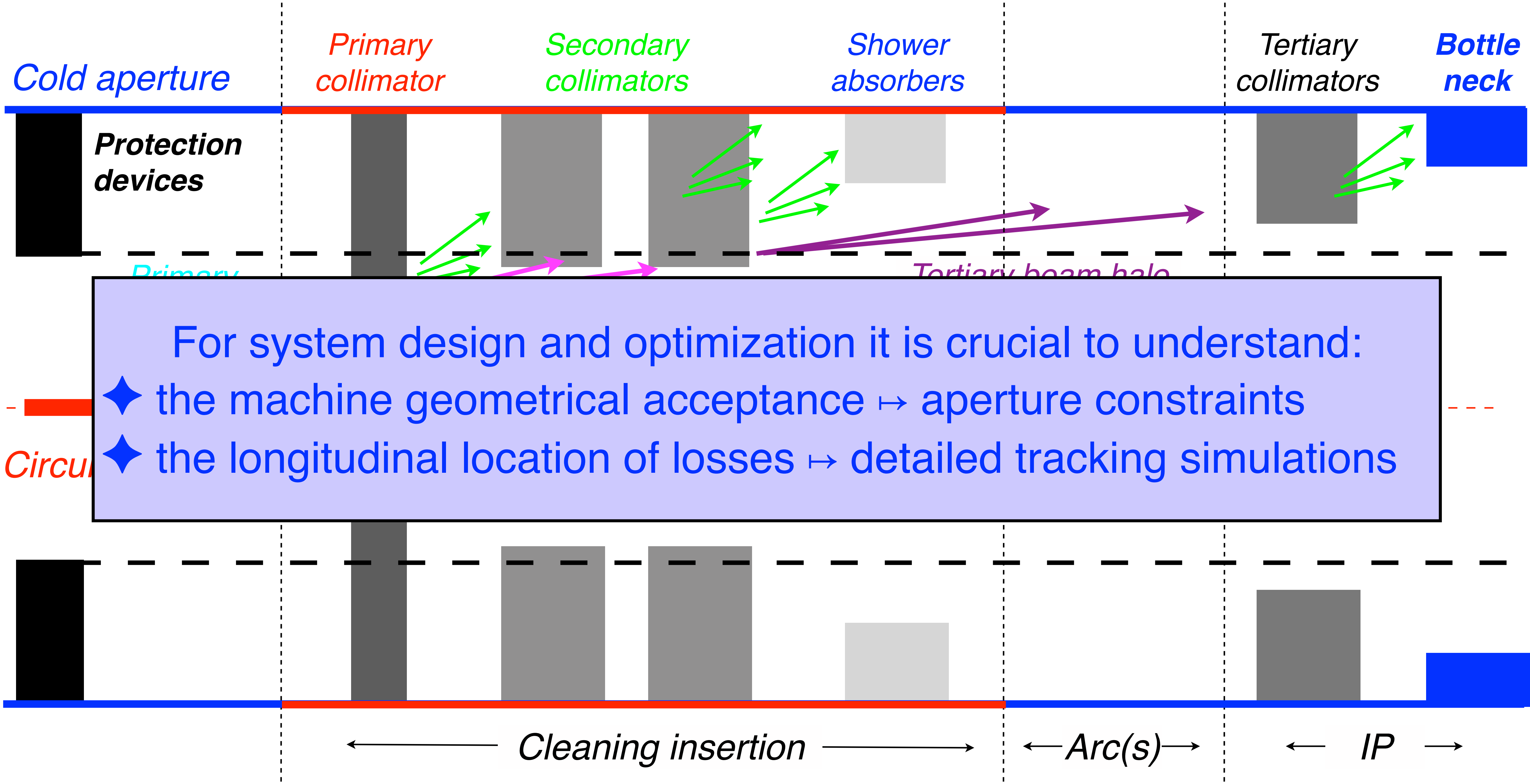


For system design and optimization it is crucial to understand:

- ✦ the machine geometrical acceptance ↦ aperture constraints
- ✦ the longitudinal location of losses ↦ detailed tracking simulations

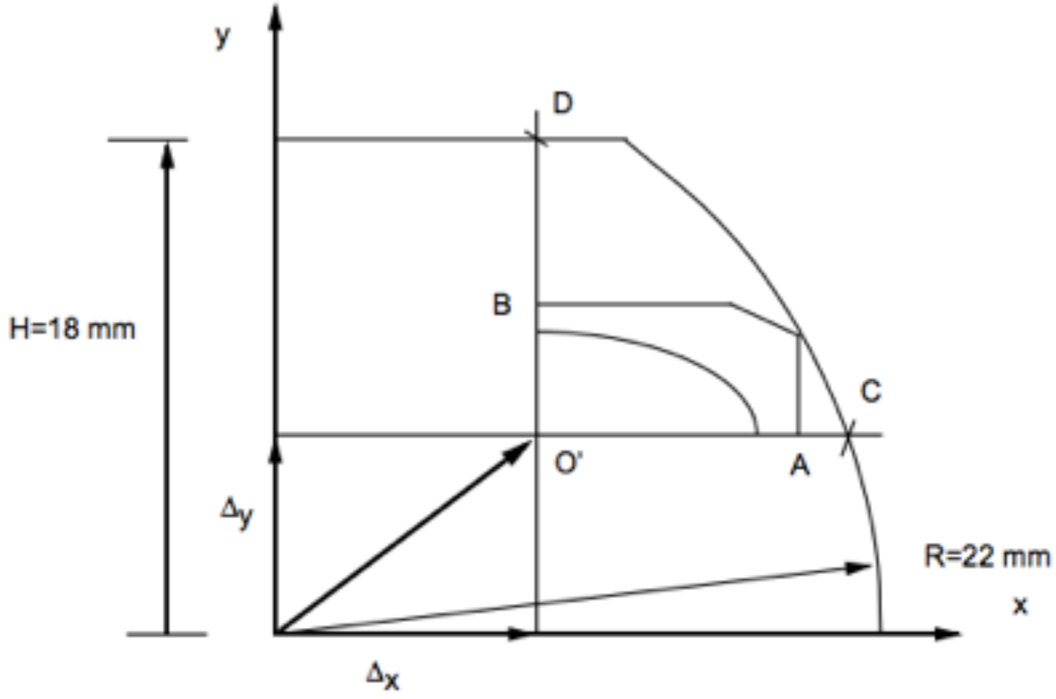
Betatron cleaning: intercept primary losses with cleaning efficiency that ensures losses below quench limits in all operational loss scenarios.

The available transverse aperture sets the scale.

FCC-hh geometrical acceptance

Geometrical acceptance

- Compute the **effective aperture** of the machine element by element, taking into account mechanical and optical tolerances
- Important for collimation studies to identify potential **aperture bottlenecks** in the machine:
  - definition of the **collimator settings** needed to protect machine aperture
    - by design, aperture constraints usually are: injection → arc, collision → inner triplet
  - feedback for improvements on the aperture and tolerances
- Profit from the LHC experience:
  - the method was developed in the LHC design phase.
  - tolerances have been reviewed based on LHC operational experience.



The algorithm

- compute the largest possible secondary halo that can be inscribed in the vacuum chamber
- beam is displaced from the ideal position by the **linear** sum of different errors (pessimistic → worst case scenario)

Inputs to aperture calculations

- **Optics files** including crossing and separation schemes
  - **Injection energy (3.3 TeV),** β* = 4.6m and L* = 36m
  - **Collision energy (50 TeV),** β* = 0.3 m, L* = 36 m
- **Aperture model** (see details in talk by J. Molson)
- **Global parameters** (tolerances, primary and secondary halo):

Lattice with no momentum cleaning insertion

Note: new baseline is L*=45m

Parameters	Injection	Collision
Primary halo extension	6 σ	6 σ
Secondary halo, hor./ver.	6 σ	6 σ
Secondary halo, radial	6 σ	6 σ
Radial closed orbit excursion	4 mm	2 mm
β-beating fractional beam size change	1.05	1.1
Momentum offset	6×10^{-4}	2×10^{-4}
Relative parasitic dispersion	0.14	0.1

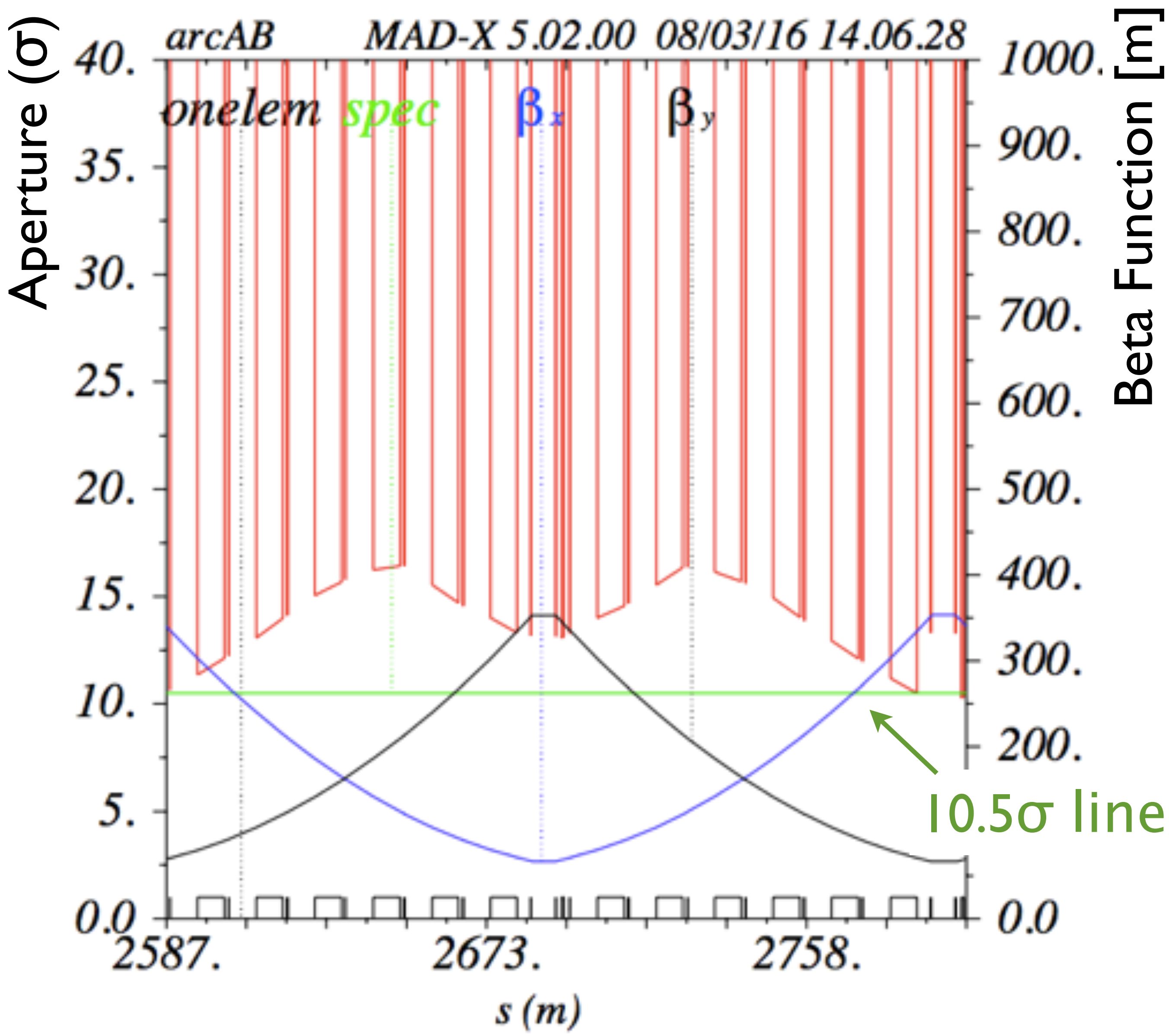
Secondary and primary halo extensions set to the same value → apertures in units of beam σ

Same parameters used for HL-LHC. Refined from LHC design after LHC operational experience.

- **Mechanical and alignment tolerances:** same tolerances used at the LHC design stage (see *LHC Project Note 111*)

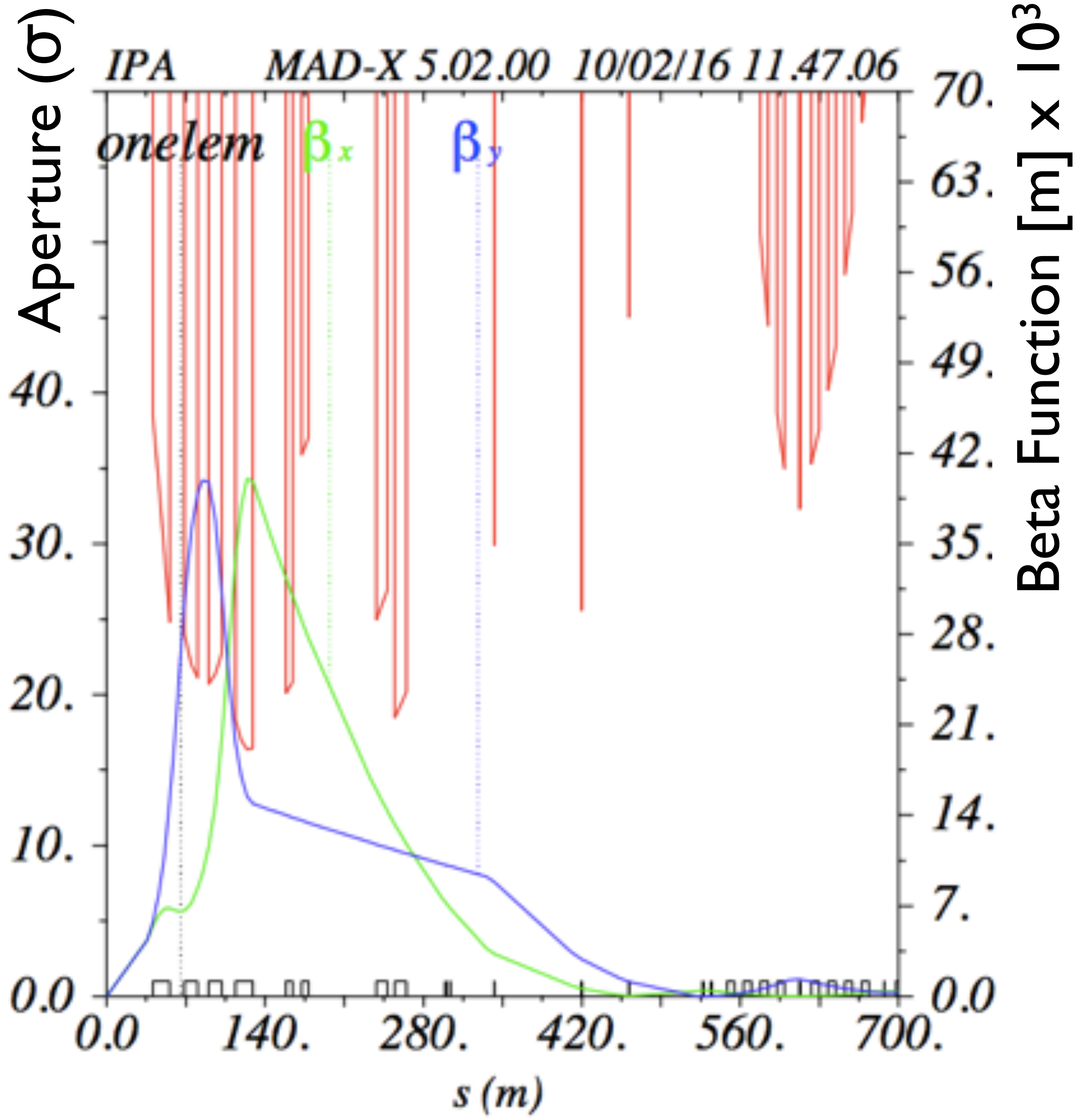
Results

Injection: ARC



10.5σ line

Collision: IPA



Injection

Tightest aperture in the arc: 10.4 σ
Other limiting locations (down to 8.7 σ) identified
in the cleaning insertion matching section

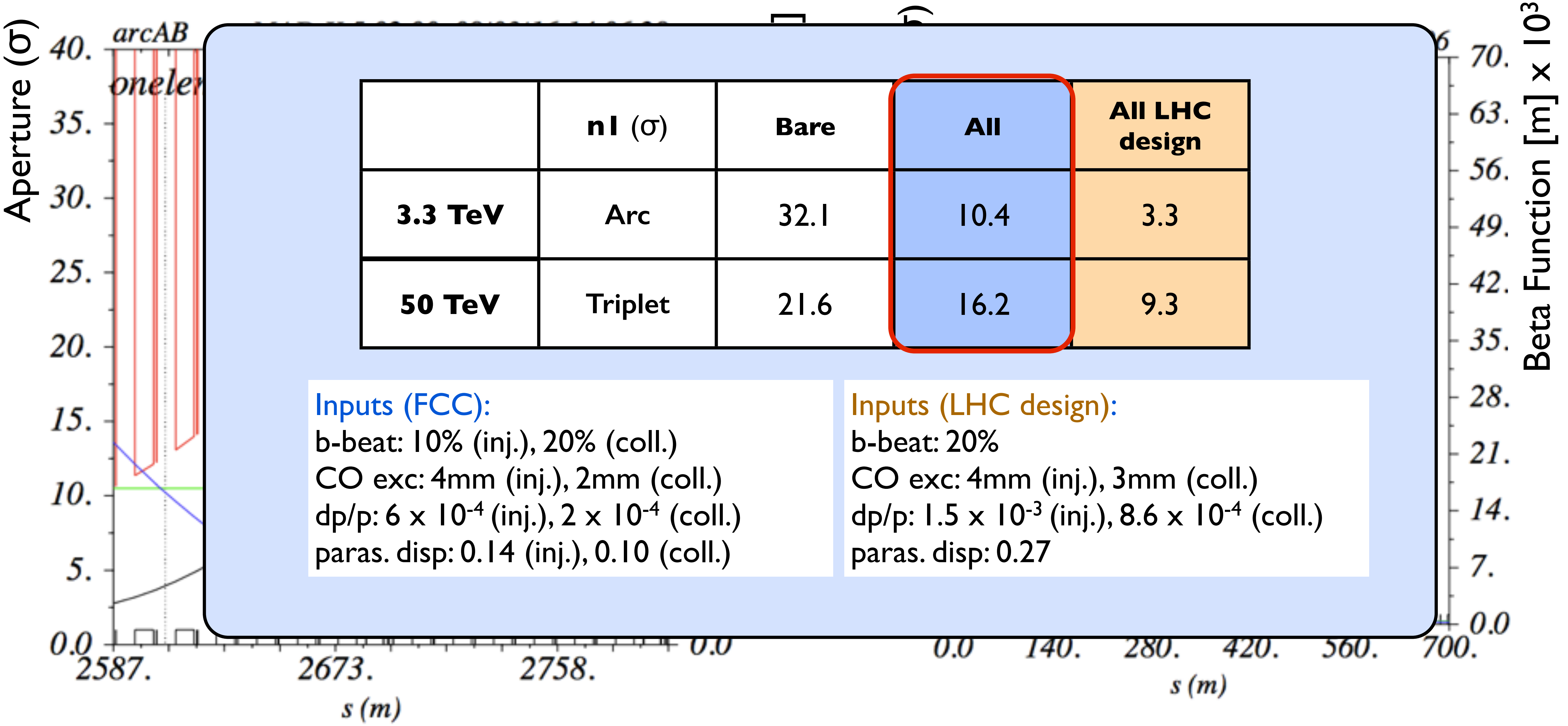
Collision

Tightest aperture: 16.2 σ
in the triplet

Results

Injection: ARC

Collision: IPA



	n1 (σ)	**Bare**	**All**	**All LHC design**
3.3 TeV	Arc	32.1	10.4	3.3
50 TeV	Triplet	21.6	16.2	9.3

Inputs (FCC):
b-beat: 10% (inj.), 20% (coll.)
CO exc: 4mm (inj.), 2mm (coll.)
dp/p: 6 x 10^{-4} (inj.), 2 x 10^{-4} (coll.)
paras. disp: 0.14 (inj.), 0.10 (coll.)

Inputs (LHC design):
b-beat: 20%
CO exc: 4mm (inj.), 3mm (coll.)
dp/p: 1.5 x 10^{-3} (inj.), 8.6 x 10^{-4} (coll.)
paras. disp: 0.27

Injection
Tightest aperture in the arc: 10.4 σ
Other limiting locations (down to 8.7 σ) identified
in the cleaning insertion matching section

Collision
Tightest aperture: 16.2 σ
in the triplet

Conclusions on aperture calculations

- At **injection** found tight aperture in several locations:
    - minimum aperture in the arc is 10.4 σ
    - betatron cleaning insertion with 8.7 σ
- At **top energy** the bottleneck is the triplet, with an aperture of 16.2 σ (for L* = 36m, β* = 0.3 m)
- What can we conclude on the collimator settings? If we scale the settings from the HL-LHC baseline (see CERN-ACC-2014-0044) we obtain the following:

HL-LHC (top energy)

TCP	5.7
TCS	7.7
TCDQ	9.0
TCT	10.9
min. aperture	12.3

scaled for $\varepsilon=2.2$ →

FCC-hh

TCP	7.2
TCS	9.7
TCDQ	11.4
TCT	13.7
min. aperture	15.5

FCC collimator gaps (in mm) ~ 0.84 x LHC gaps

Ok for top energy!
Note: with L*=45 m triplet aperture is expected to increase by about a factor of 2!

At **injection** ideally keep same settings (with TCTs retracted) for optimum phase advances

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→ need improvements on aperture and tolerances

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→ need to revise tolerances
(eg. closed orbit excursion, alignment)

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- At **injection** found tight aperture in several locations:
  - minimum aperture in the arc is 10.4 σ
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→ need to revise tolerances
(eg. closed orbit excursion, alignment)

→ can optimize the mechanical aperture

- At **top energy** the bottleneck is the triplet, with an aperture of 16.2 σ (for L^* = 36m, β^* = 0.3 m)
- What can we conclude on the collimator settings? If we scale the settings from the HL-LHC baseline (see CERN-ACC-2014-0044) we obtain the following:

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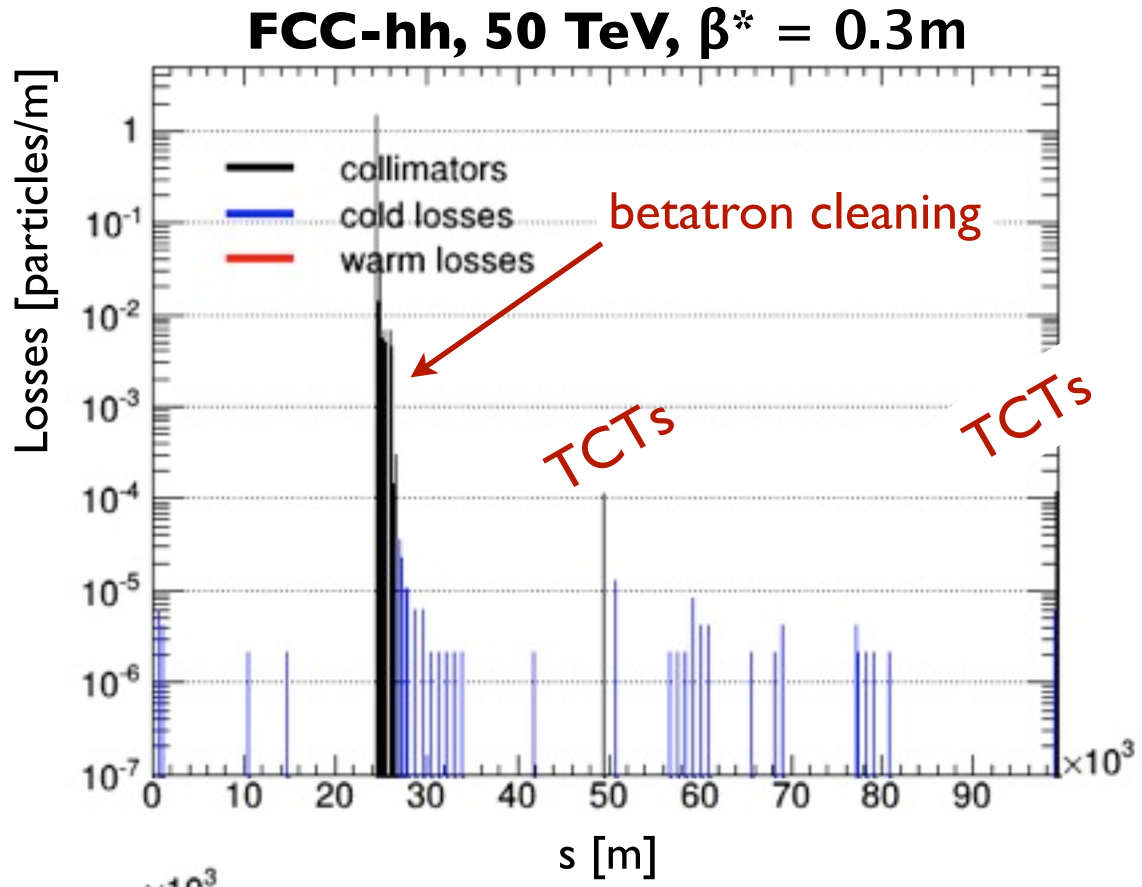
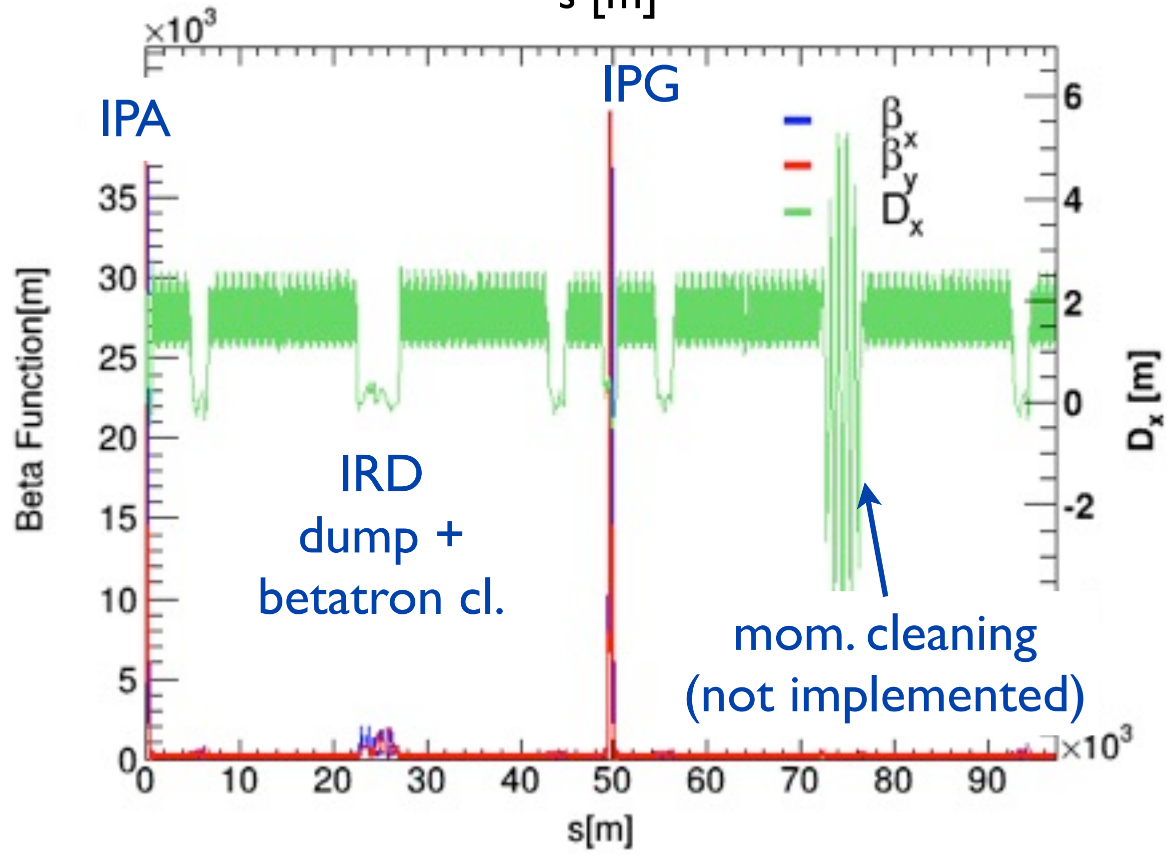
→ need improvements on aperture and tolerances

Tracking simulations

Loss maps





Tracking simulations using **SixTrack**

6.4 M particles tracked for 200 turns.

Horizontal annular halo

- Top energy (50 TeV), β* = 0.3 m, L* = 36 m
- Lattice - Baseline layout:
  - betatron cleaning insertion (LHC scaled)
  - momentum cleaning insertion (not LHC scaled) - collimation not implemented
  - tertiary collimators to protect inner triplet

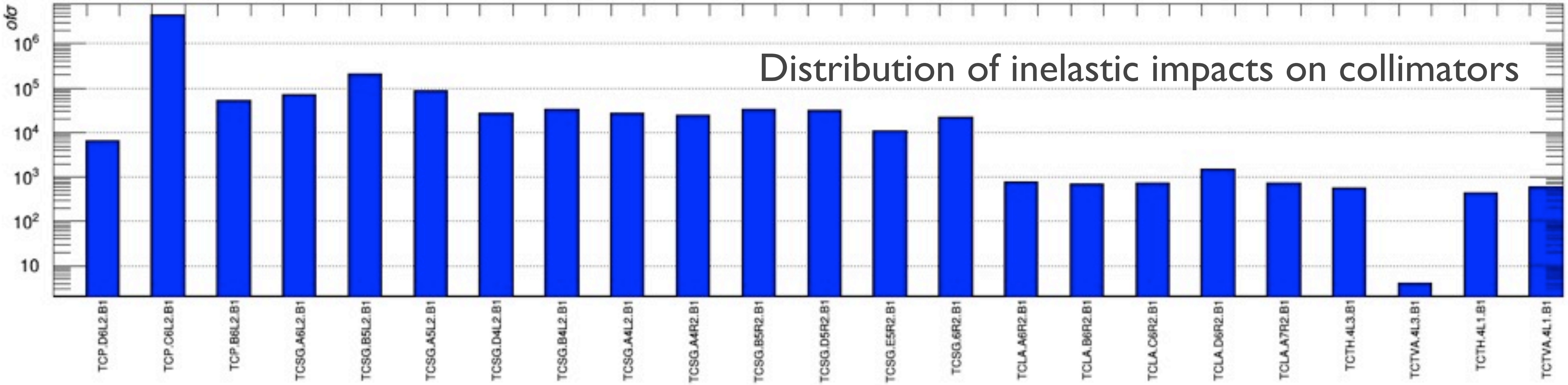
➡ Implemented a **three-stage betatron cleaning** plus **tertiary collimators** in the experimental IRs

➡ No momentum cleaning, nor collimation in dump

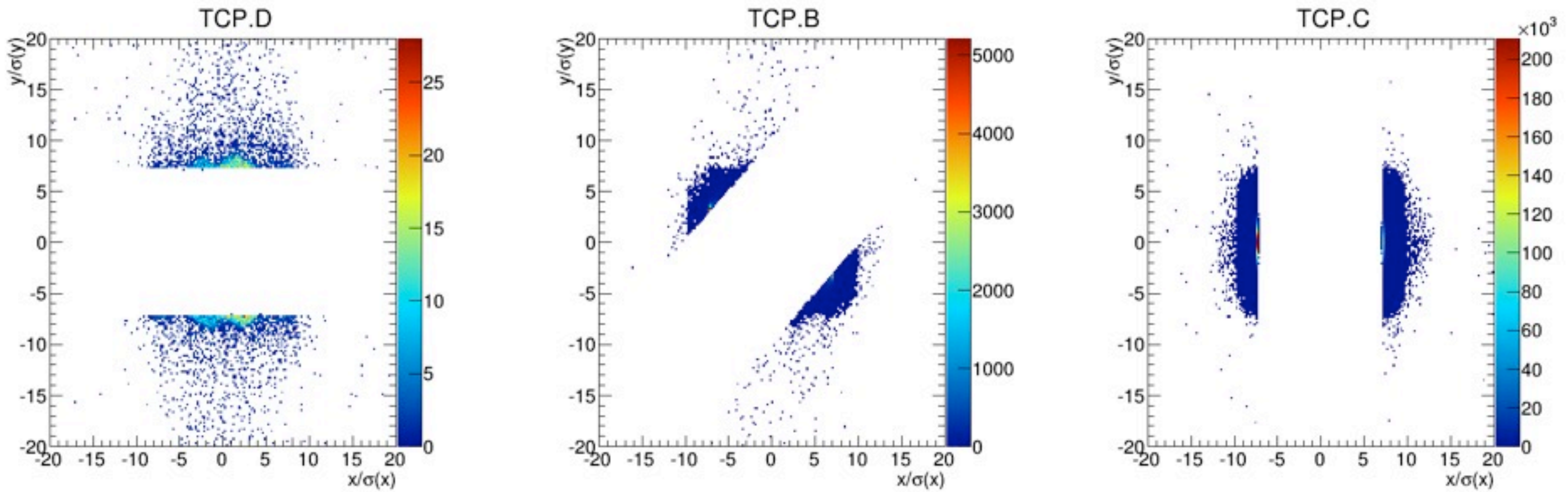
➡ Collimator settings HL-LHC scaled (see slide 8)

Inelastic impacts on collimators

Inputs to FLUKA for energy deposition studies

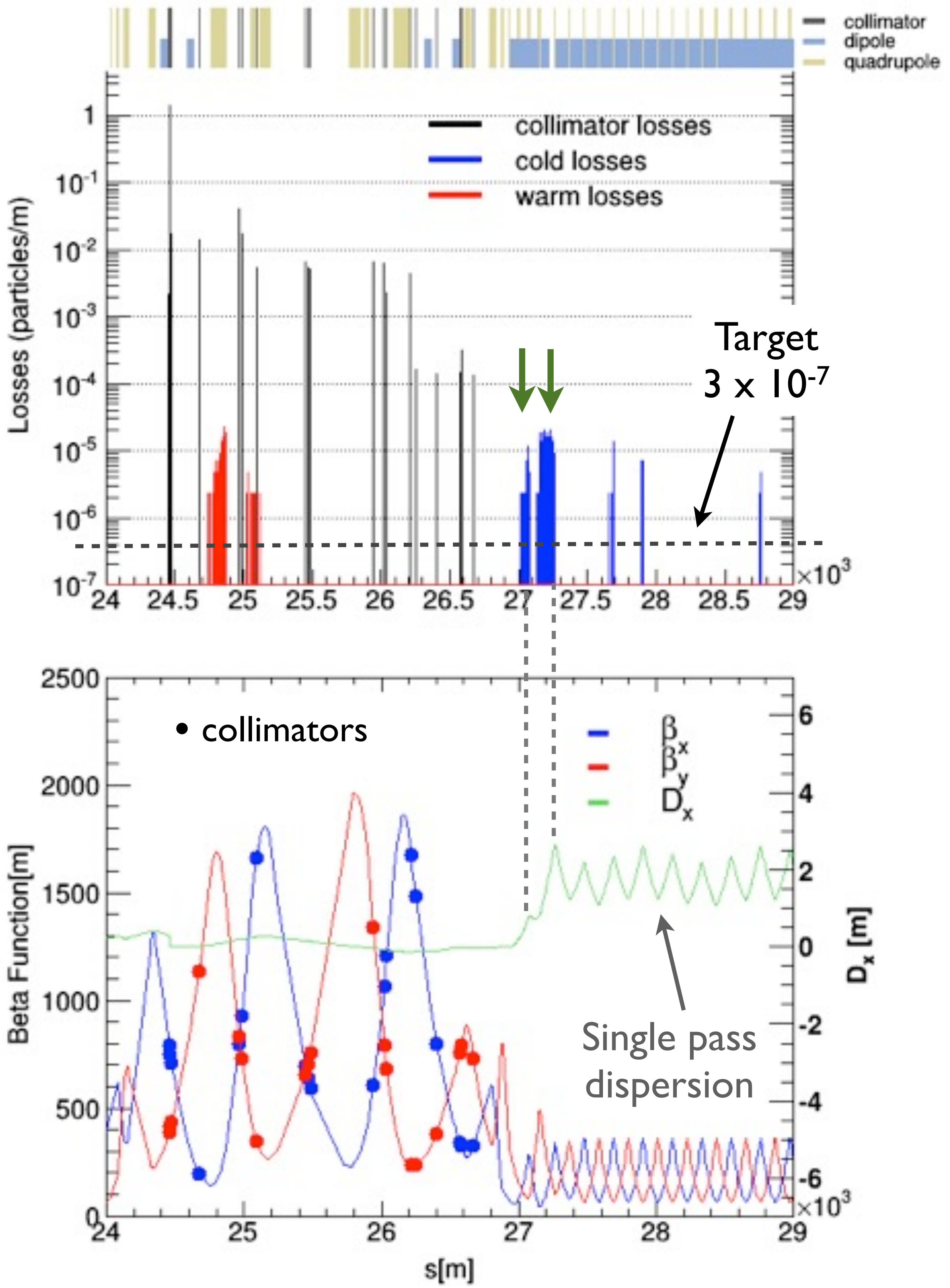


Distribution of inelastic impacts on collimators



Distribution of inelastic impacts on primary collimators in the x-y plane

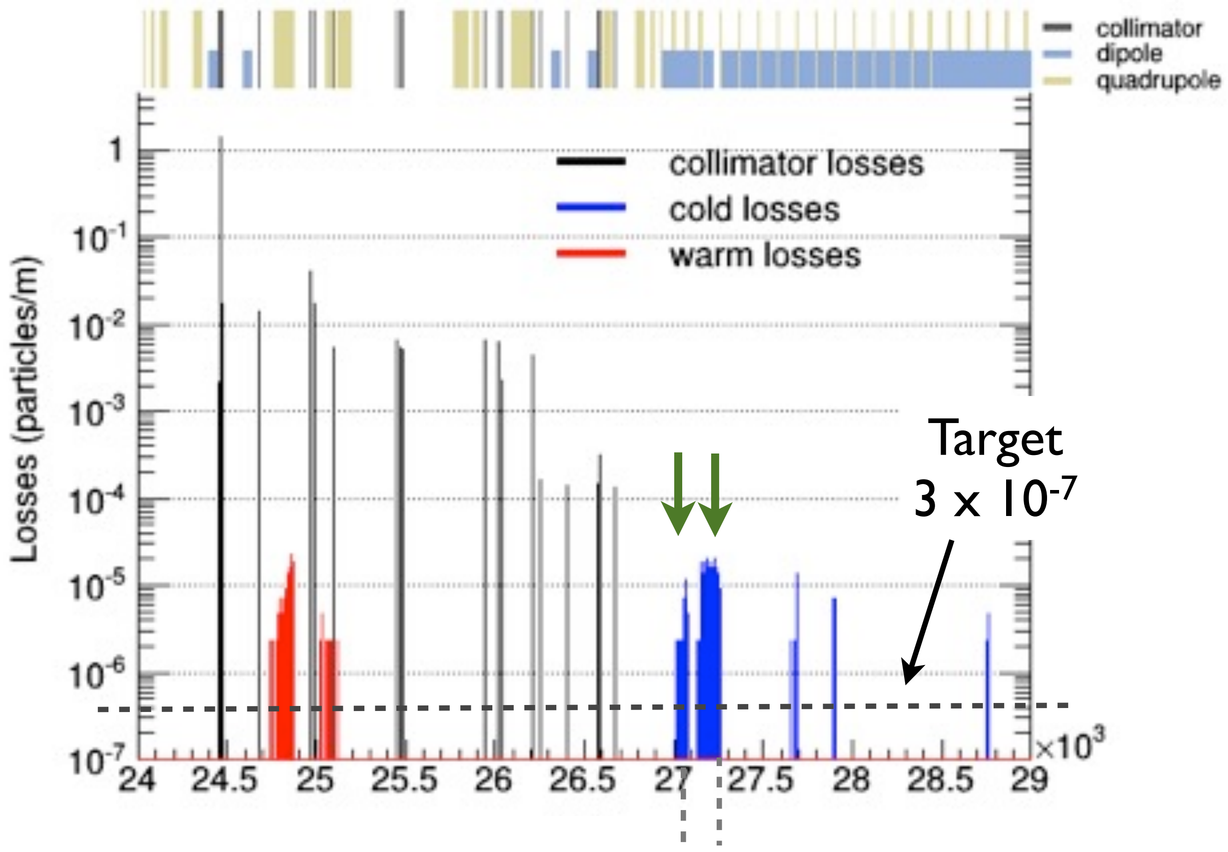
Loss maps - Zoom in IRD



Cold losses in the dispersion suppressor where the dispersion starts to rise.

Due to single diffractive events from interactions with primary collimators

Loss maps - Zoom in IRD

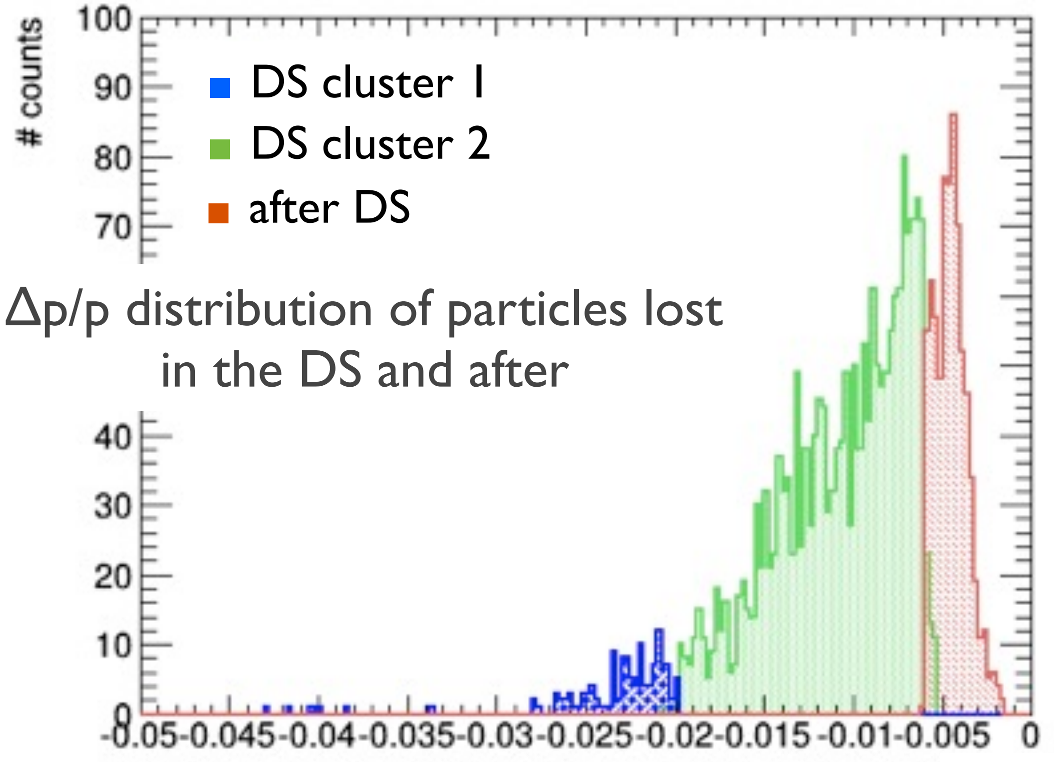


Cold losses in the dispersion suppressor where the dispersion starts to rise.

Due to single diffractive events from interactions with primary collimators

Losses concentrated in 2 clusters from particles with characteristic Δp/p distribution:

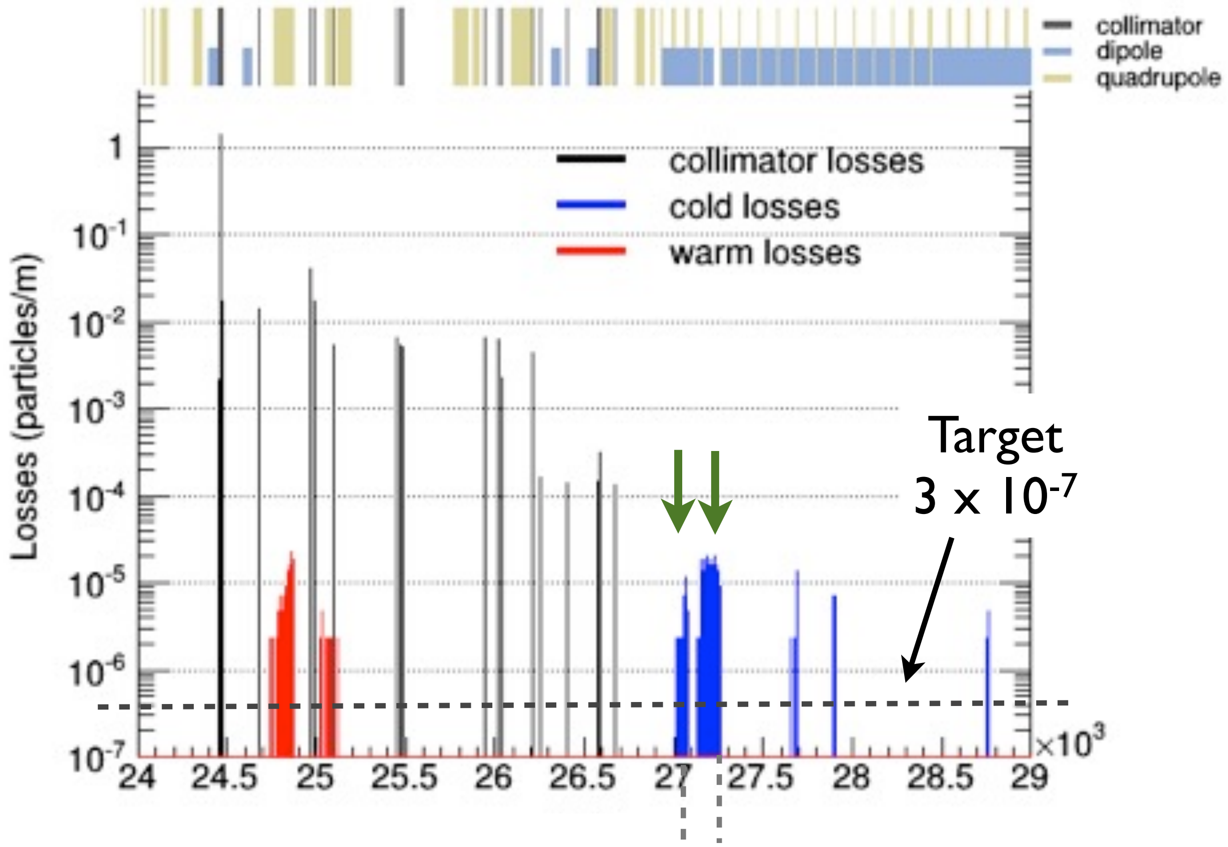
- **1st cluster:**
  - peak loss (± stat.)= $(1.2 \pm 0.2) \times 10^{-5}$
  - $\Delta p/p < -0.02$
- **2nd cluster**:
  - peak loss (± stat.)= $(2.2 \pm 0.2) \times 10^{-5}$
  - $-0.02 < \Delta p/p < -0.005$



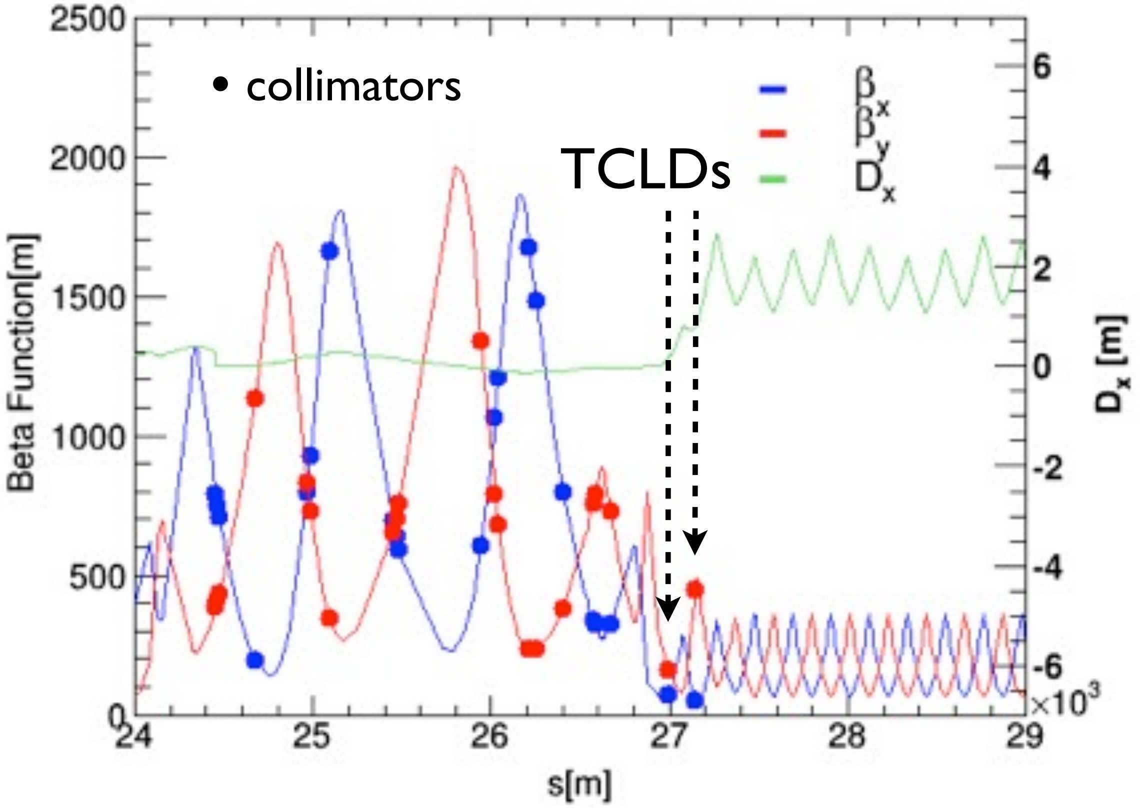
Δp/p distribution of particles lost in the DS and after

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

Loss maps - Zoom in IRD



Target
3×10^{-7}



- collimators

TCLDs

Cold losses in the dispersion suppressor where the dispersion starts to rise.

Due to single diffractive events from interactions with primary collimators

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  - peak loss (± stat.)= $(1.2 \pm 0.2) \times 10^{-5}$
  - $\Delta p/p < -0.02$
- **2nd cluster**:
  - peak loss (± stat.)= $(2.2 \pm 0.2) \times 10^{-5}$
  - $-0.02 < \Delta p/p < -0.005$

Fundamental limitation of the current system: need to catch losses close to the first dipoles where the dispersion starts to grow
→ **add two TCLD collimators**

Performance with TCLDs

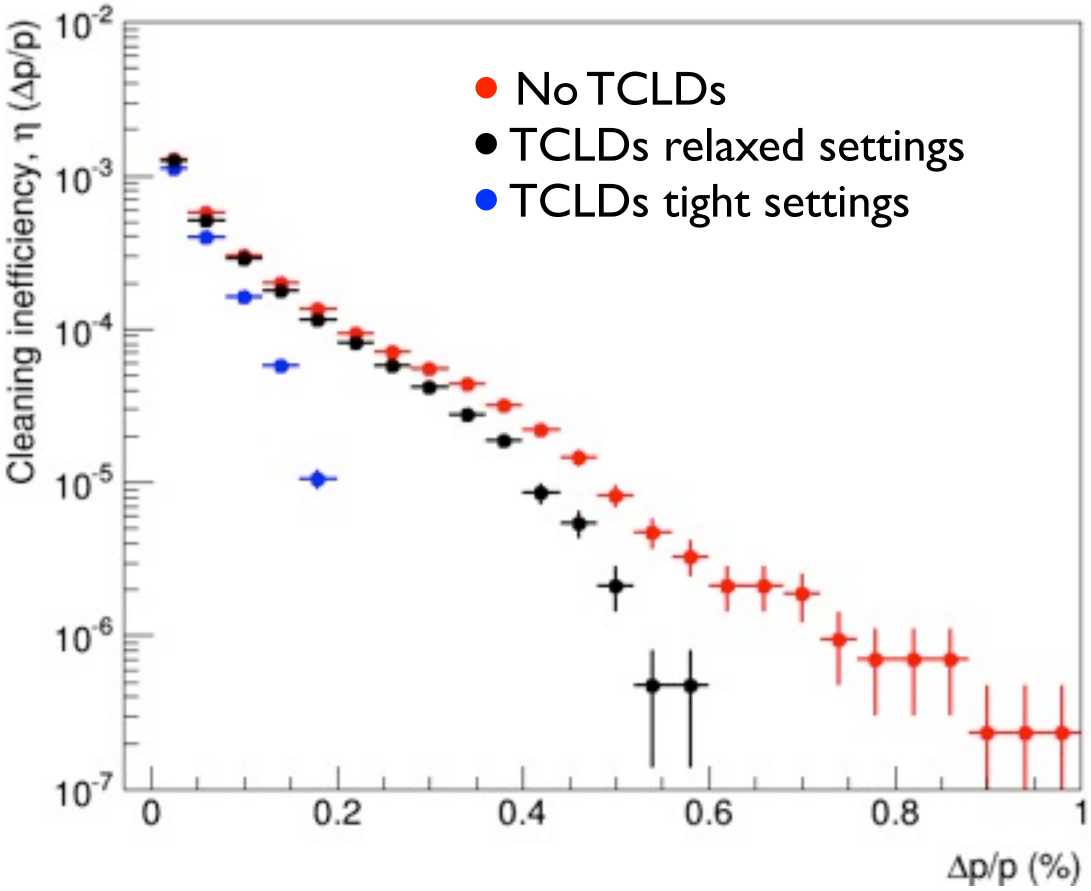
Global cleaning inefficiency vs. Δp/p

$$\eta_c(\delta p_i) = \frac{N_p(\delta p > \delta p_i)}{N_{abs}}$$

$N_p(\delta p > \delta p_i)$ → number of particles above δp_i

N_{abs} → number of particles absorbed in coll. system

where $\delta p = \Delta p/p$



Performance with TCLDs

Global cleaning inefficiency vs. $\Delta p/p$

$$\eta_c(\delta p_i) = \frac{N_p(\delta p > \delta p_i)}{N_{abs}}$$

number of particles above δp_i

number of particles absorbed in coll. system

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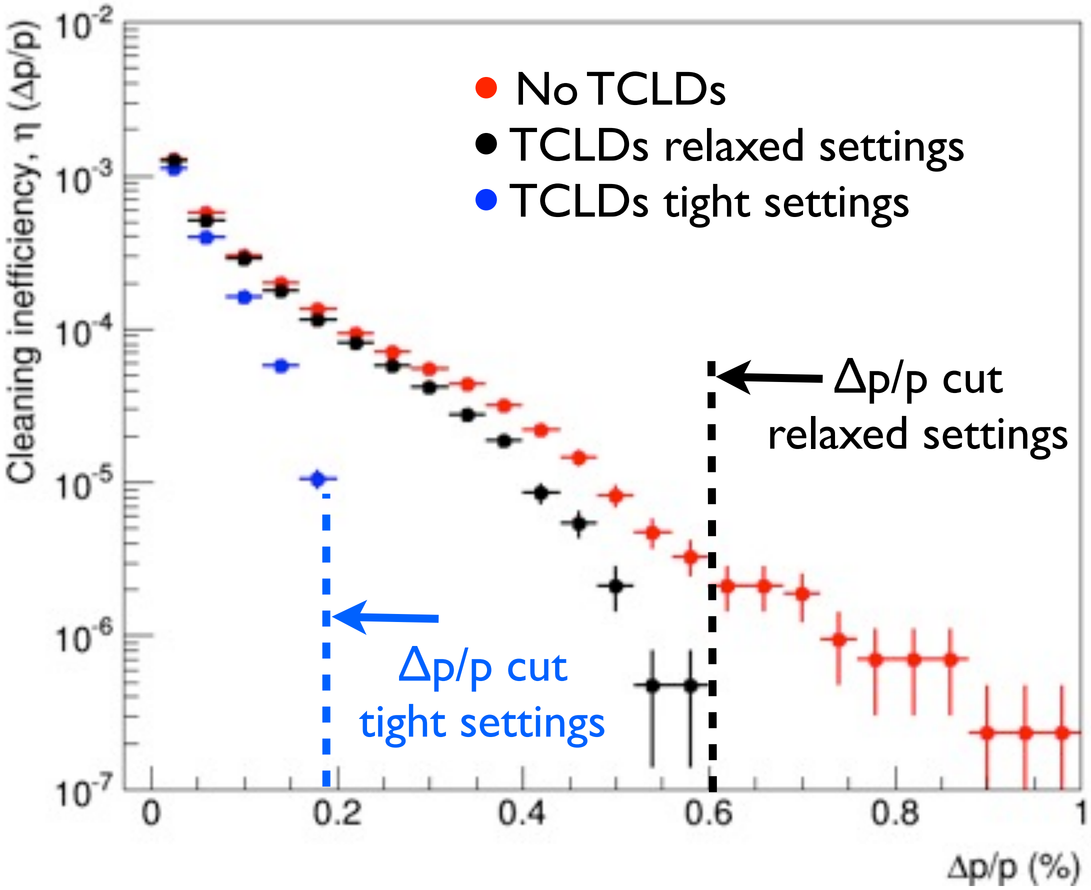

Tried two choices of TCLD settings:

- relaxed: 86 σ → $(\Delta p/p)^{TCLD2} = 6 \times 10^{-3}$
- tight: 24 σ → $(\Delta p/p)^{TCLD2} = 1.7 \times 10^{-3}$

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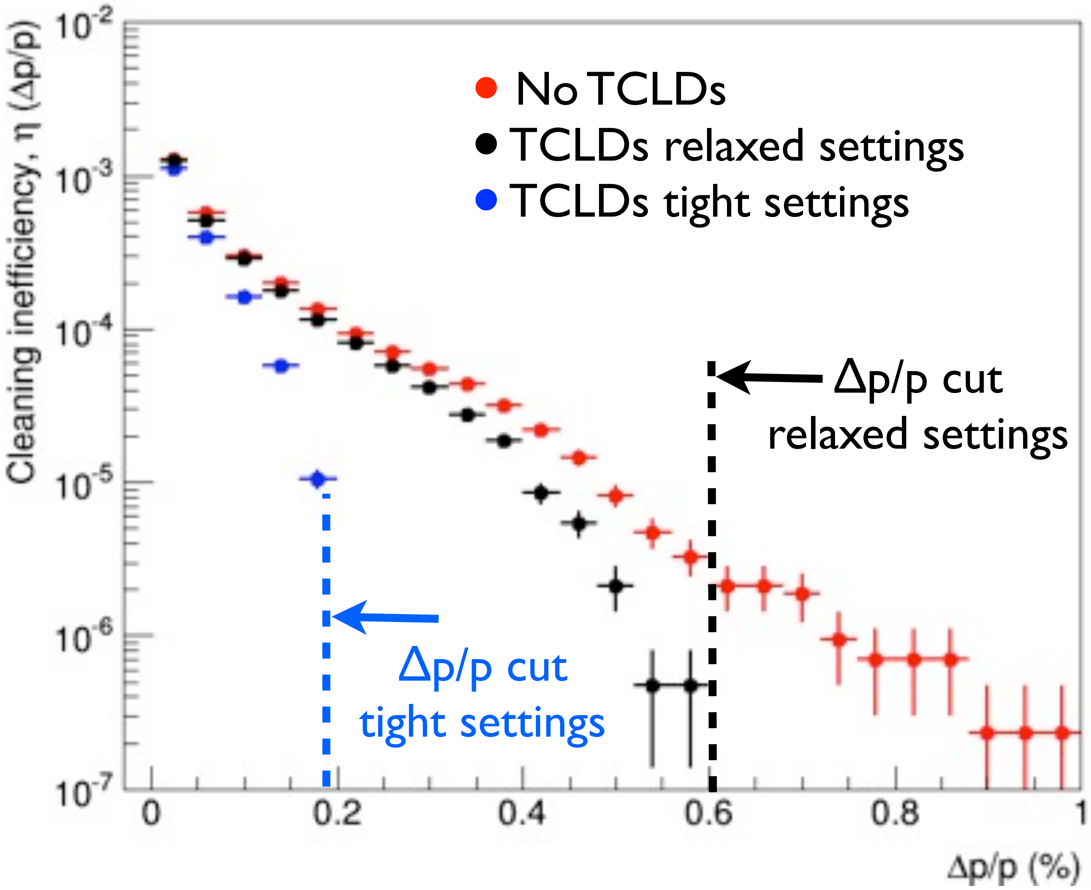

Δp/p cut relaxed settings

Δp/p cut tight settings

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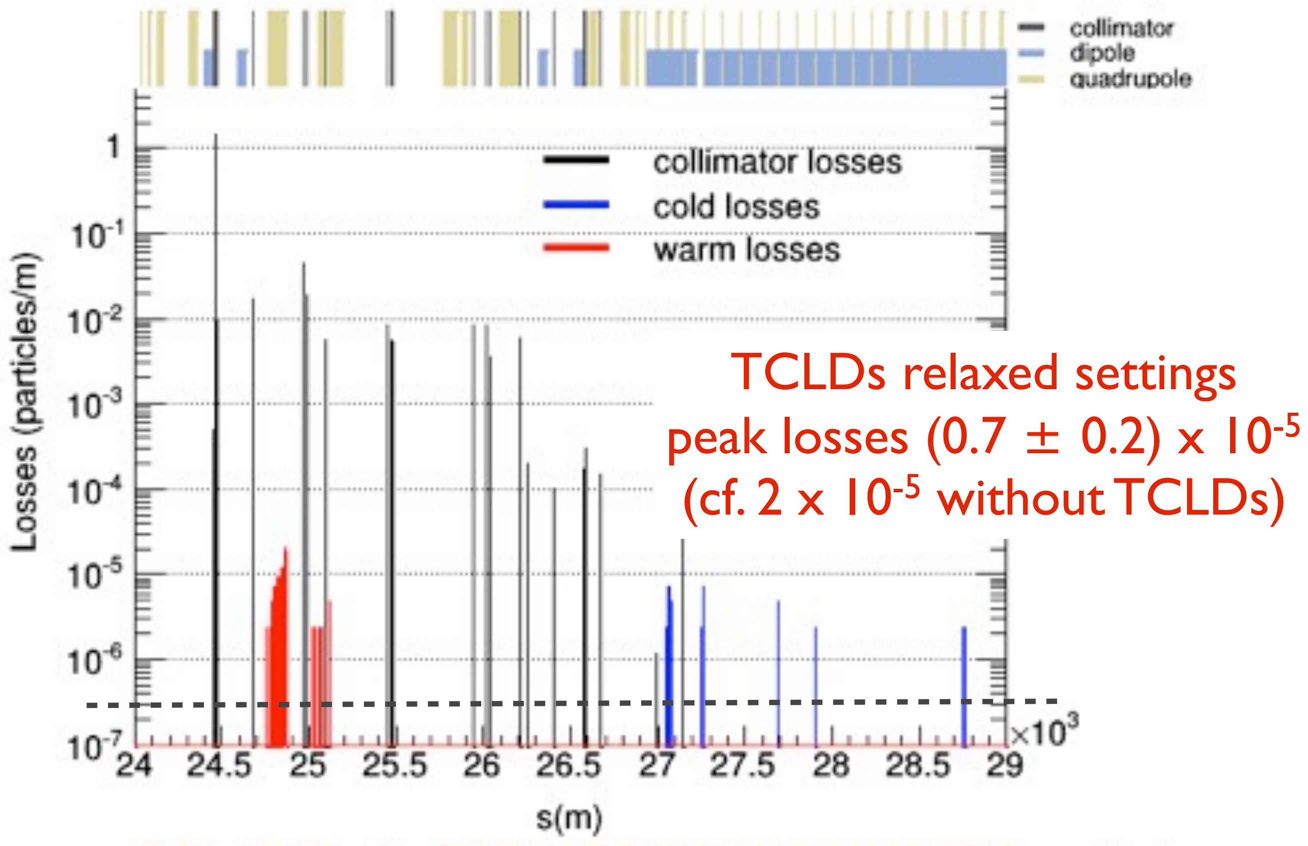
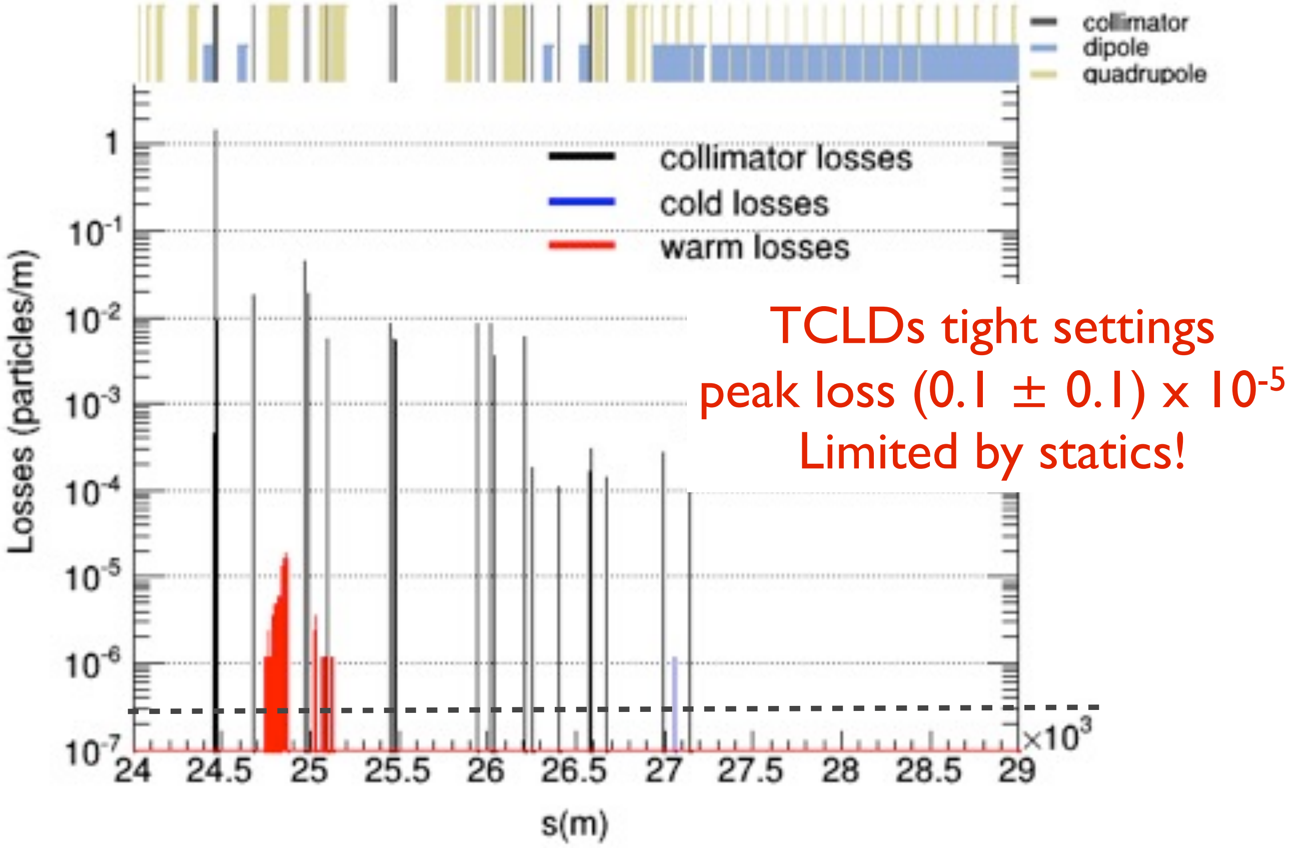


TCLDs relaxed settings
peak losses $(0.7 \pm 0.2) \times 10^{-5}$
(cf. 2×10^{-5} without TCLDs)



TCLDs tight settings
peak loss $(0.1 \pm 0.1) \times 10^{-5}$
Limited by statics!

Performance with TCLDs

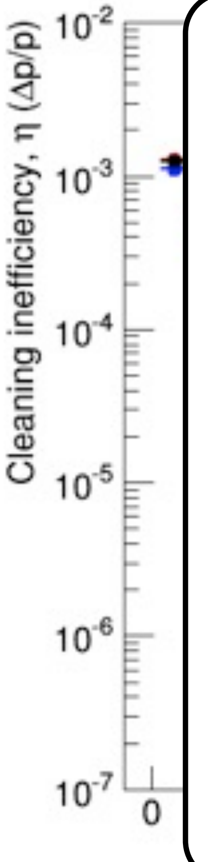
Global cleaning inefficiency vs. Δp/p

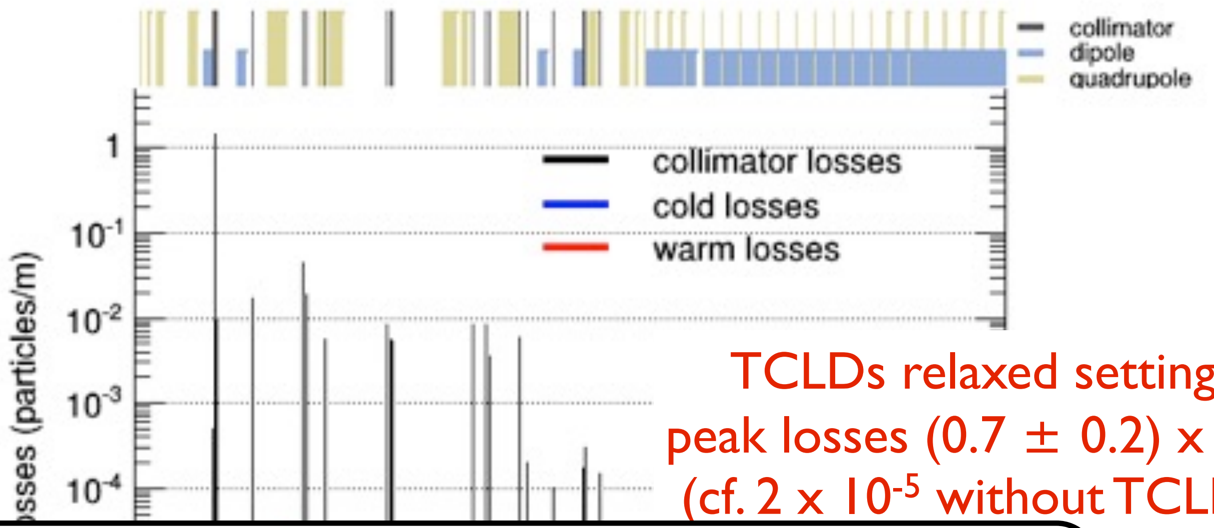
$$\eta_c(\delta p_i) = \frac{N_p(\delta p > \delta p_i)}{N_{abs}}$$

number of particles above δp_i

number of particles absorbed in coll. system

where $\delta p = \Delta p/p$





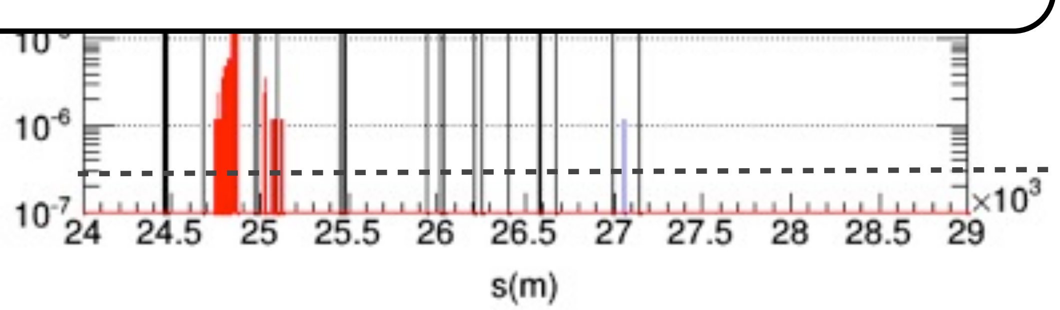
TCLDs relaxed settings
peak losses (0.7 ± 0.2) x 10^{-5}
(cf. 2 x 10^{-5} without TCLDs)

Installation of TCLDs effective in reducing losses in the DS downstream of betatron cleaning.
Is it enough? Aim at cleaning inefficiency of 3 x 10^{-7} (see talk by D. Schulte).
Should increase the statistics to draw conclusions.

Need more studies for optimization:

- TCLD collimator settings: improve cleaning performance while respecting momentum collimation hierarchy
- dispersion suppressor design: showers downstream of TCLDs are a concern

→ Need detailed energy deposition studies



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tics!

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Conclusions

- We performed a first iteration to define a baseline for the betatron cleaning insertion:
  - Aperture evaluation → definition of baseline settings → simulations
  - More iterations will follow as optics and aperture models are improved
- From aperture calculations we identified aperture restrictions at injection energy: need improvements on aperture model and tolerances
- Triplet aperture at collision energy compatible with HL-LHC scaled settings.
- From tracking simulations: identified performance limitation in the dispersion suppressor downstream of the betatron cleaning insertion
- Installation of TCLD collimators improves the cleaning performance. More studies to assess it this is enough to achieve the target cleaning inefficiency of 3×10^{-7}
- What's next:
  - Complete the studies at injection
  - Further optimization of the system (eg. dispersion suppressor design, phase advances, aperture model)
- Tracking simulation results will serve as input for collimator design:
  - energy deposition studies, impedance, materials

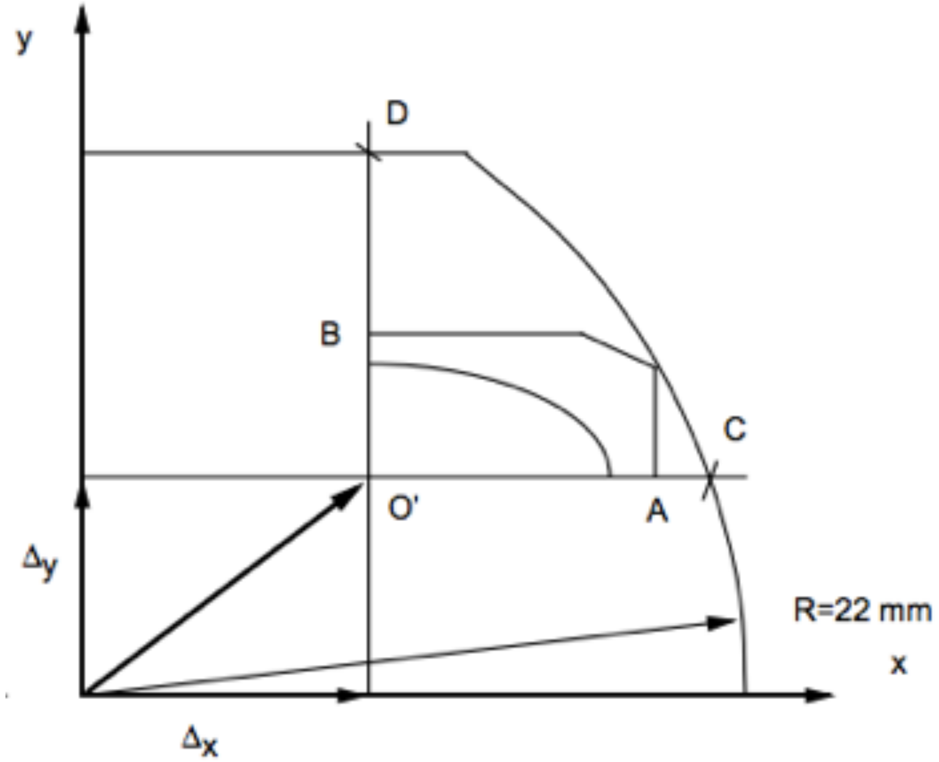
EXTRAS

The algorithm

- How it works:
  - compute the largest possible secondary halo (ie. particles that escape from the primary collimators) from the collimation system that can be inscribed in the vacuum chamber
  - beam is displaced from the ideal position by the **linear** sum of different errors:

$$\Delta_{x,y}(s) = CO_{x,y} + \delta^{mech}{}_{x,y}(s) + k_\beta \cdot D_{x,y}(s) \cdot \delta_p + d_{x,y}(s)$$

$CO_{x,y}$: peak closed orbit excursion
δ^{mech} : mechanical and alignment tolerances
k_β : β-beating
$D_{x,y}(s)$: dispersion term (includes linear $D_{x,y}$ and parasitic coupling)
δ_p : momentum offset
$d_{x,y}$: beam offset (due to separation and crossing angle schemes)

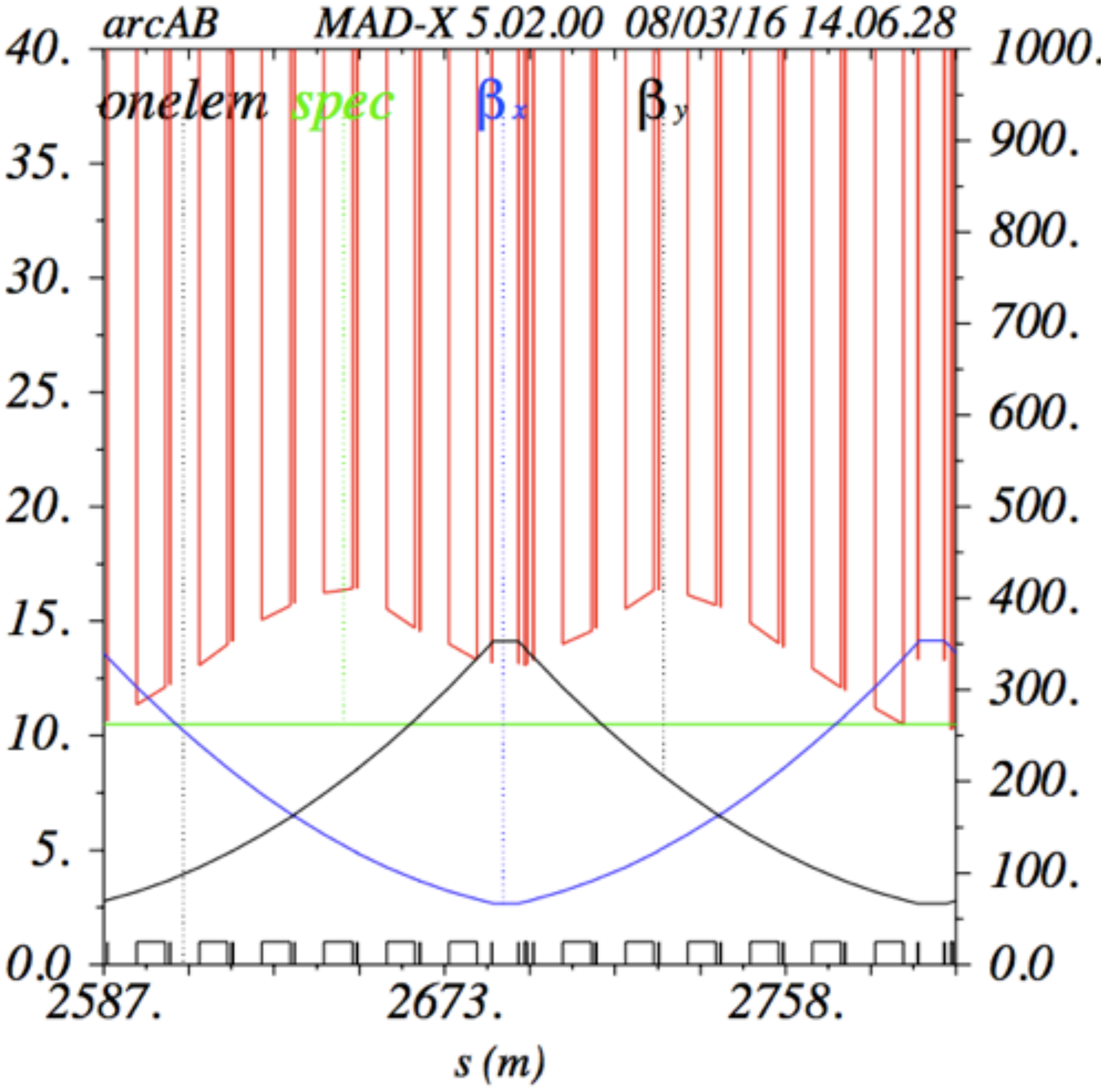


Note:

- Relies on assumption of secondary halo shape → can be avoided by appropriate choice of settings
- Does not account for tertiary halo or single turn dispersive effects → need detailed tracking

Results: Injection energy

ARC



All tolerances included

focusing quadrupole

defocusing quadrupole

Tolerances considered one by one

n1 (σ)	**MQ.26**	**MQ.27**	**MS.27**
Bare	28.1	31.9	32.1
b-beat	26.7	30.4	30.6
COexc	19.6	23.4	23.5
Off-momentum	27.9	28.3	28.5
All except mech. tol.	18.3	18.7	18.9
All	12.9	13.4	10.4
All LHC design	10.2	6.3	3.3

Inputs:
b-beat: 10%
CO exc: 4mm
dp/p: 6 x 10^{-4}
paras. disp: 0.14

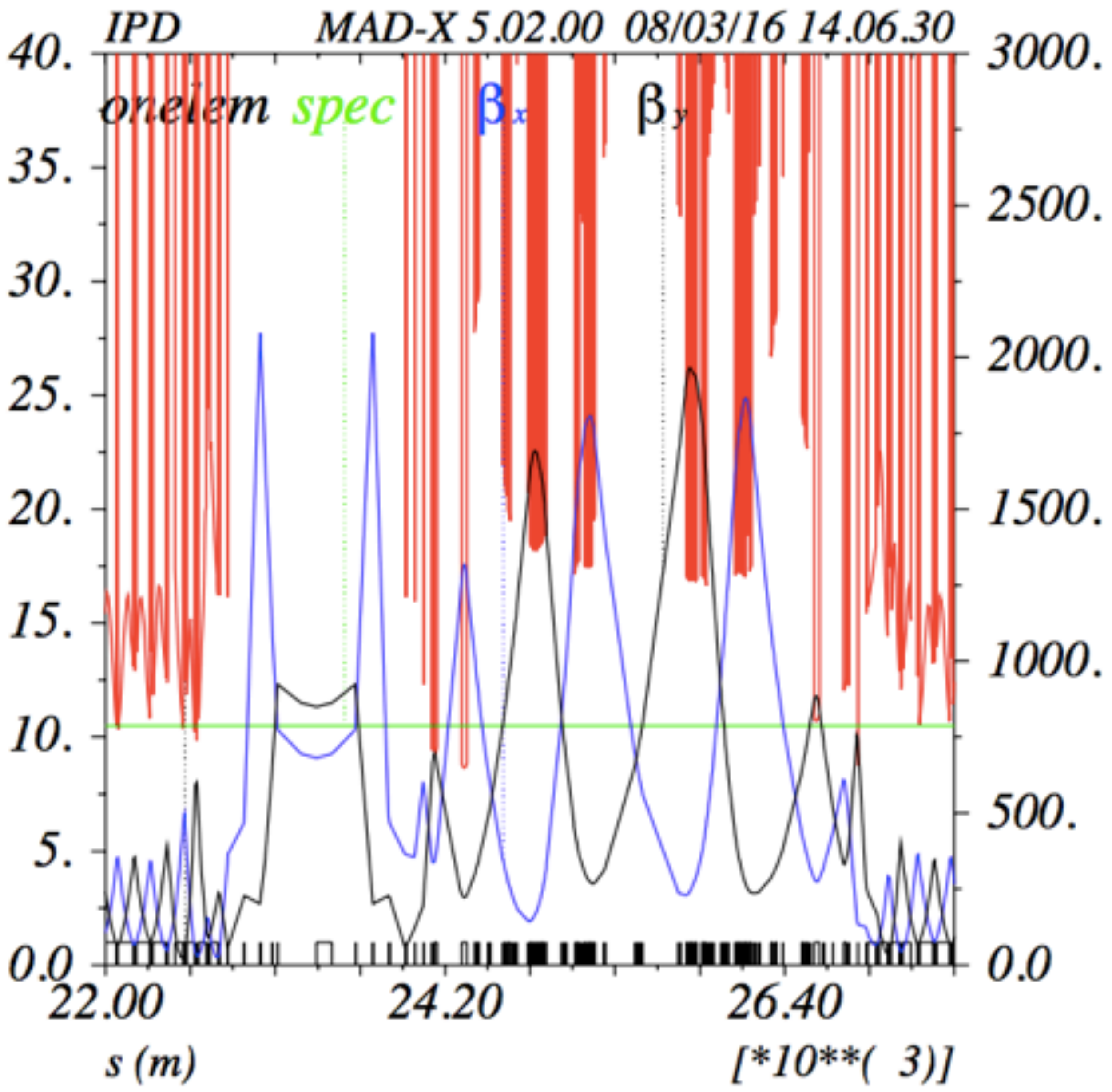
Inputs (LHC design):
b-beat: 20%
CO exc: 4mm
dp/p: 1.5 x 10^{-3}
paras. disp: 0.27

Results: Injection energy

Minimum n1 (limiting location in the whole ring):
8.7 at element MQTLH.C6

List of elements in collimation insertion with n1 < 10.5:

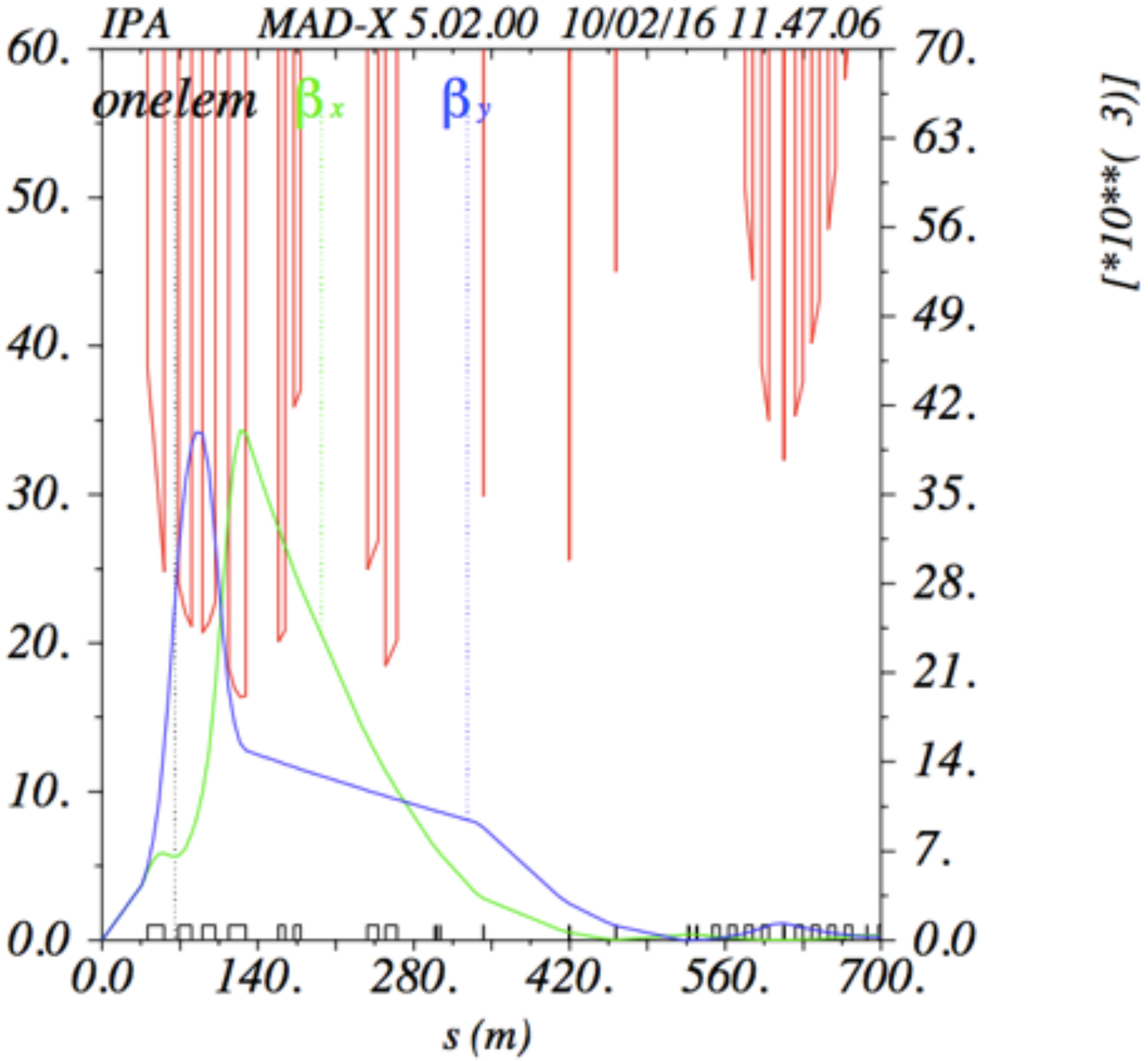
Element	s (m)	n1	aperture
MQ.4LD1	24113	9.4	like arc
MQ.7L2	24126	9.2	like arc
MQTL1.7L2	24143	9.4	like arc
MQTLH.F6L2	24300	8.8	arc+0.5mm
MQTLH.E6L2	24306	8.7	arc+0.5mm
MQTLH.D6L2	24314	8.7	arc+0.5mm
MQTLH.C6L2	24320	8.7	arc+0.5mm
MQTLH.B6L2	24328	8.7	arc+0.5mm
MQTLH.A6L2	24335	8.7	arc+0.5mm
MQ.6RD	26866	8.7	like arc



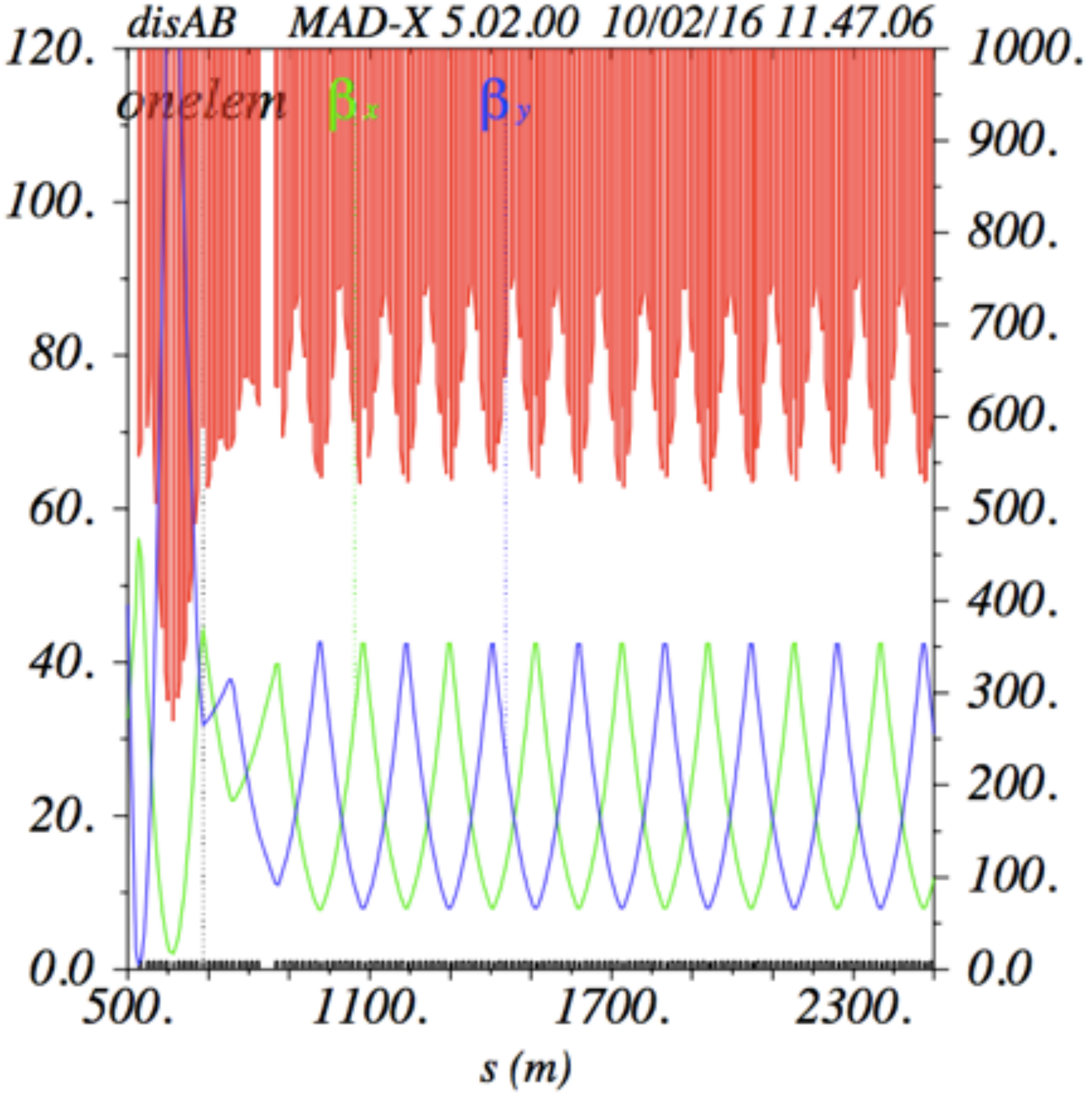
Arc aperture: 13.2 x 15 mm

Results: top energy

IPA



DS and arc



Results: top energy

Triplet quadrupoles in the experimental IR → **Limiting location: Q2 with 16.2 σ**

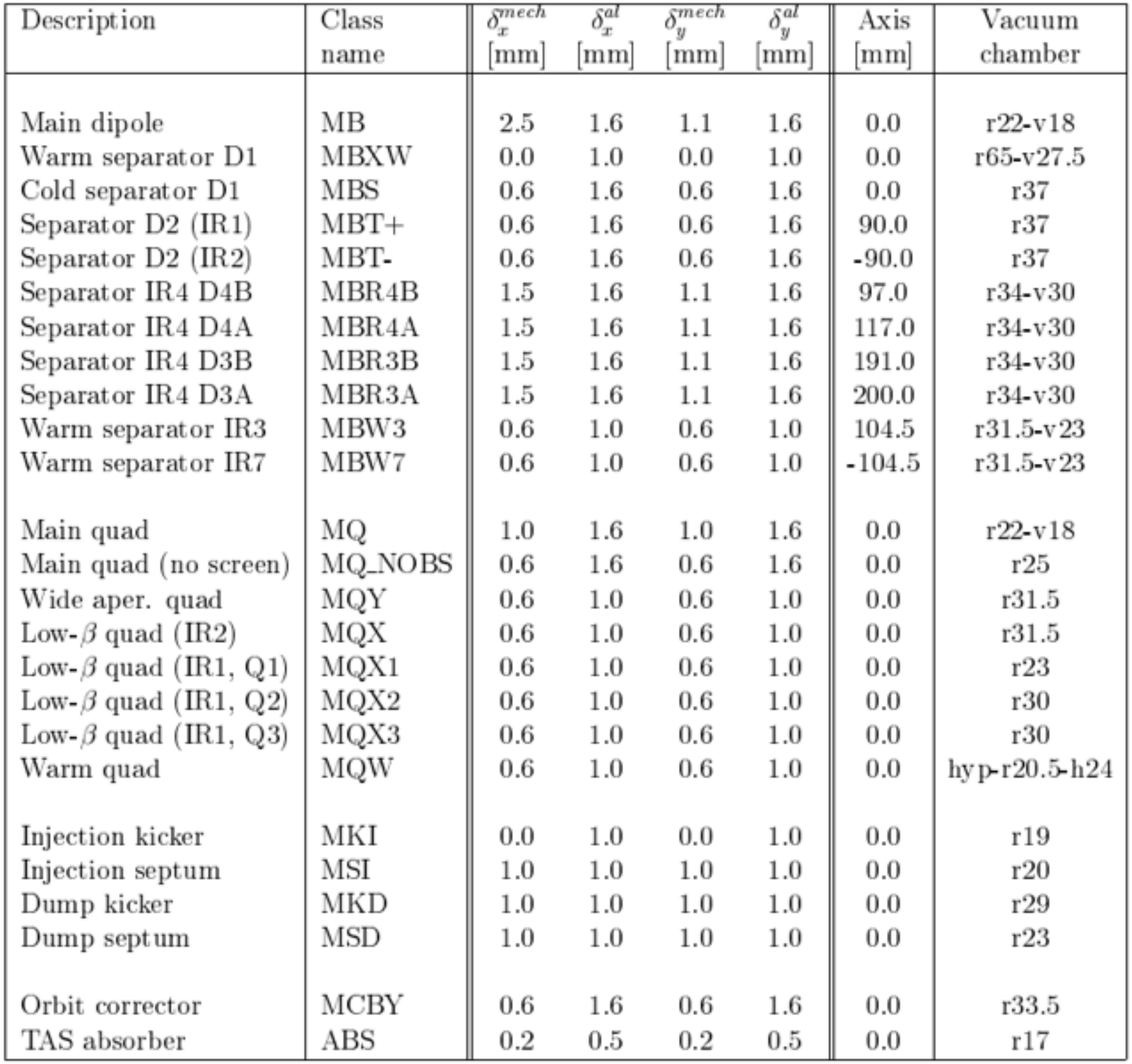
Tolerances considered one by one

	Element	Bare	b-beat	CO_{ex}	Off-momentum	All except mech. tol.	All	All (LHC design)
Q3	MQXC.3LA	27.0	24.5	25.4	25.6	21.7	20.5	10.9
Q2	MQXD.B2LA	21.6	19.7	20.1	20.7	17.3	**16.2**	9.3
	MQXD.A2LA	22.0	20.0	20.4	21.0	17.6	16.5	9.7
Q1	MQXC.1LA	28.2	25.6	25.7	27.2	22.4	20.6	16.7
Q1	MQXC.1RA	33.5	30.4	30.9	32.1	26.7	24.8	12.9
Q2	MQXD.A2RA	27.5	25.1	25.9	26.2	22.3	21.1	10.5
	MQXD.B2RA	27.1	24.6	25.6	25.8	21.9	20.7	10.1
Q3	MQXC.3RA	21.9	19.9	20.3	20.9	17.5	16.4	8.9

Inputs:
b-beat: 20%
CO exc: 2mm
dp/p: 2×10^{-4}
paras. disp: 0.1

Inputs (LHC design):
b-beat: 20%
CO exc: 3mm
dp/p: 8.6×10^{-4}
paras. disp: 0.27

Inputs: mechanical tolerances (II)



Description	Class name	δ_x^{mech} [mm]	δ_x^{al} [mm]	δ_y^{mech} [mm]	δ_y^{al} [mm]	Axis [mm]	Vacuum chamber
Main dipole	MB	2.5	1.6	1.1	1.6	0.0	r22-v18
Warm separator D1	MBXW	0.0	1.0	0.0	1.0	0.0	r65-v27.5
Cold separator D1	MBS	0.6	1.6	0.6	1.6	0.0	r37
Separator D2 (IR1)	MBT+	0.6	1.6	0.6	1.6	90.0	r37
Separator D2 (IR2)	MBT-	0.6	1.6	0.6	1.6	-90.0	r37
Separator IR4 D4B	MBR4B	1.5	1.6	1.1	1.6	97.0	r34-v30
Separator IR4 D4A	MBR4A	1.5	1.6	1.1	1.6	117.0	r34-v30
Separator IR4 D3B	MBR3B	1.5	1.6	1.1	1.6	191.0	r34-v30
Separator IR4 D3A	MBR3A	1.5	1.6	1.1	1.6	200.0	r34-v30
Warm separator IR3	MBW3	0.6	1.0	0.6	1.0	104.5	r31.5-v23
Warm separator IR7	MBW7	0.6	1.0	0.6	1.0	-104.5	r31.5-v23
Main quad	MQ	1.0	1.6	1.0	1.6	0.0	r22-v18
Main quad (no screen)	MQ_NOBS	0.6	1.6	0.6	1.6	0.0	r25
Wide aper. quad	MQY	0.6	1.0	0.6	1.0	0.0	r31.5
Low-β quad (IR2)	MQX	0.6	1.0	0.6	1.0	0.0	r31.5
Low-β quad (IR1, Q1)	MQX1	0.6	1.0	0.6	1.0	0.0	r23
Low-β quad (IR1, Q2)	MQX2	0.6	1.0	0.6	1.0	0.0	r30
Low-β quad (IR1, Q3)	MQX3	0.6	1.0	0.6	1.0	0.0	r30
Warm quad	MQW	0.6	1.0	0.6	1.0	0.0	hyp-r20.5-h24
Injection kicker	MKI	0.0	1.0	0.0	1.0	0.0	r19
Injection septum	MSI	1.0	1.0	1.0	1.0	0.0	r20
Dump kicker	MKD	1.0	1.0	1.0	1.0	0.0	r29
Dump septum	MSD	1.0	1.0	1.0	1.0	0.0	r23
Orbit corrector	MCBY	0.6	1.6	0.6	1.6	0.0	r33.5
TAS absorber	ABS	0.2	0.5	0.2	0.5	0.0	r17

Mechanical and alignment tolerances used at the LHC design stage (from *LHC Project Note 111*)

Simulations setup

Tracking simulations using **SixTrack** on lattice v5:

- ✦ Top energy (50 TeV), β* = 0.3 m, L* = 36 m
- ✦ Baseline layout:
  - ✦ betatron cleaning insertion (LHC scaled)
  - ✦ momentum cleaning insertion (not LHC scaled) - collimation not implemented
  - ✦ tertiary collimators to protect inner triplet

➡ Implemented a **three-stage betatron cleaning** plus **tertiary collimators** in the experimental IRs

Collimator Settings

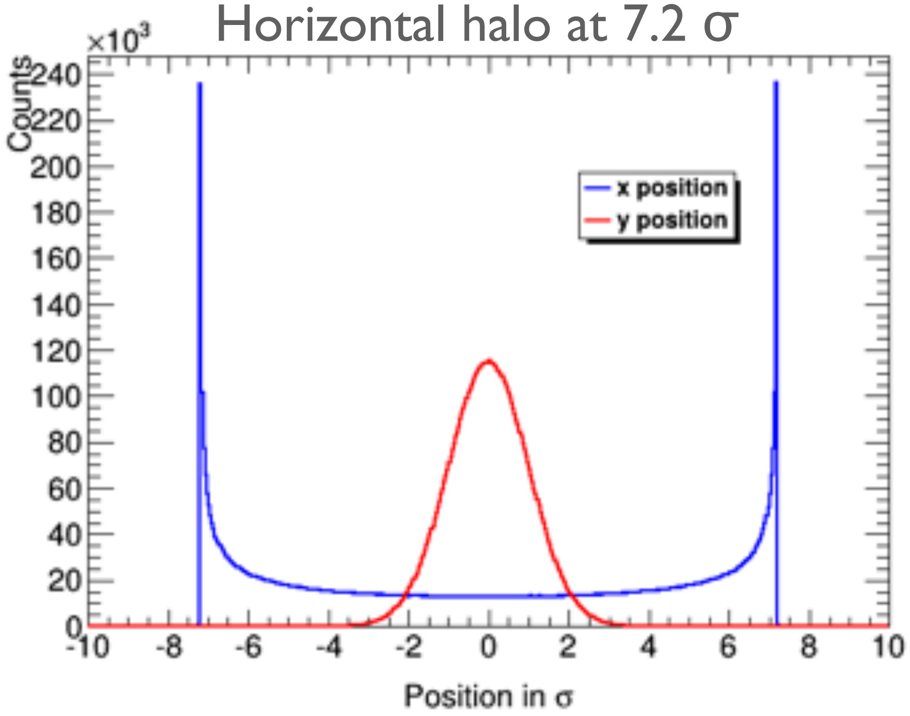
3 primaries	TCP	7.2 σ
11 secondaries	TCSG	9.7 σ
5 absorbers	TCLA	12.6 σ
4 tertiaries	TCT	13.7 σ

* same settings as for HL-LHC nominal expressed in σ units for the FCC-hh emittance of 2.2 μm

➡No momentum cleaning, nor collimation in dump

Initial distribution: annular halo with predefined impact parameter on primary collimator

Horizontal halo at 7.2 σ



Impact parameter on TCP