39th ICFA Advance Beam dynamics Workshop

High Intensity High Brightness Hadron Beams - HB 2006

Tsukuba, May 29th - June 2nd, 2006

The LHC beam collimation

Stefano Redaelli, AB department

on behalf of the CERN LHC Collimation Project

CERN, CH-1211 Geneva

LHC proton collimation people

Project leader: **R. Assmann (AB department)**

Synergy among many CERN departments: AB - TS - AT - SC

People involved:

O. Aberle, R. Assmann, I. Baishev, A. Bertarelli, C. Bracco, H. Braun, M. Brugger, S. Calatroni, E. Chiaveri, A. Dallocchio, F. Decorvet, B. Dehning, A. Ferrari, D. Forkel-Wirth, A. Grudiev, E.B. Holzer, J.B. Jeanneret, M. Jimenez, M. Jonker, Y. Kadi, V. Kain, M. Lamont, R. Losito, M. Magistris, A. Masi, M. Mayer, E. Métral, R. Perret, L. Ponce, C. Rathjen, S. Redaelli, G. Robert-Demolaize, S. Roesler, F. Ruggiero, M. Santana Leitner, L. Sarchiapone, R. Schmidt, D. Schulte, G. Spiezia, P. Sievers, M. Sobczak, K. Tsoulou, V. Vlachoudis, T. Weiler, J. Wenninger, ...

Inputs from many CERN working groups:

Injection, protection, dump, . . .

Additional support for beam tests:

G. Arduini, T. Bohl, H. Burkhardt, F. Caspers, M. Gasior, B. Goddard, L. Jensen, R. Jones, T. Kroyer, R. Steinhagen, J. Uythoven, H. Vincke, F. Zimmermann

Outside collaborations with

TRIUMF (optics design - completed)

IHEP (IR3 energy deposition studies)

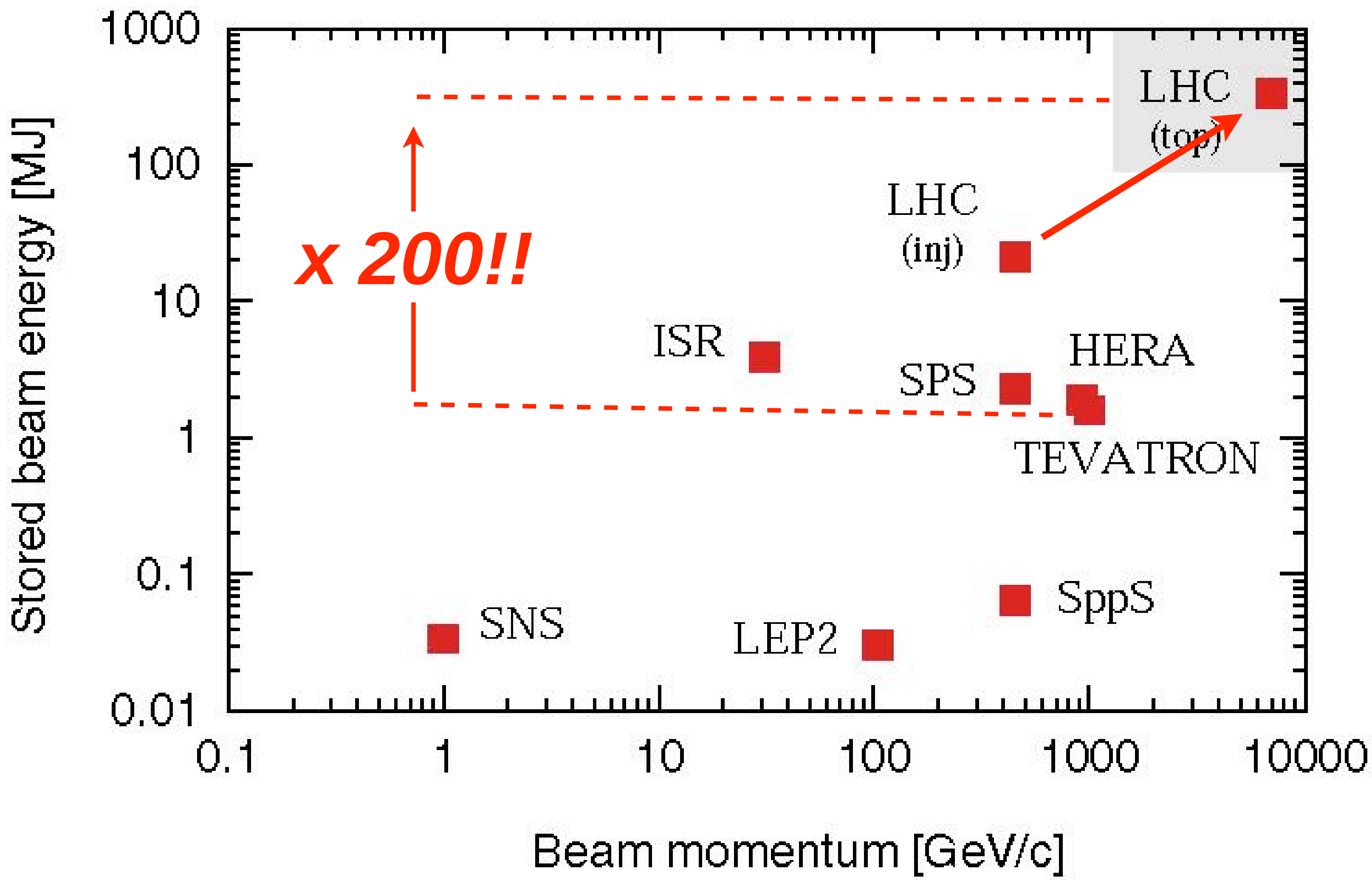
Kurchatov Institute (radiation effects on C-C jaws)

SLAC, BNL, FNAL (phase 2 R&D, tertiary collimators and material studies)

Outline

- Introduction
- LHC collimation system layout
- Mechanical design of the collimator
- Achieved cleaning performance
- System limitations and upgrades
- 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 in machine protection (no details here)*

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

Some numbers

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/mm²**
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?*

Phased approach: path towards nominal performance

	N_{coll}	I_{max}	
Phase I	**13**	**100%**	**Transfer lines** (Carbon)
Phase I	**88**	**≤ 40%**	**Robustness** (mostly Carbon-based)
Phase II	**30**	**> 40%**	**Low-impedance** (metal)
Phase III	4	- - -	> 50% of nominal luminosity
Phase IV	16	100 %	Ultimate cleaning performance

This talk ➙ Focused on Phase I system:

- *Final configuration at startup!*
- *Ensures required performance for commissioning and first years*
- *Already very challenging: 100 collimators = 500 deg. of freedom*

But we don't forget the upgrades:

- *Required ring locations are reserved*
- *R&D for the Phase II collimators has started*
- *When needed, we will be ready for nominal intensity!*

Outline

- Introduction
- **Collimation system layout**
  - ➡ Phase I collimation layout
  - ➡ Multi-stage collimation
  - ➡ LHC aperture and collimator settings
- Mechanical design of the collimator
- Achieved cleaning performance
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- Conclusions

Layout of the LHC collimation system

Multi-stage halo cleaning

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)**

Local cleaning at triplets

- **8 tertiary (2 per IP)→ TCT [W]**

Passive absorbers for warm magnets

Physics debris absorbers [Cu]

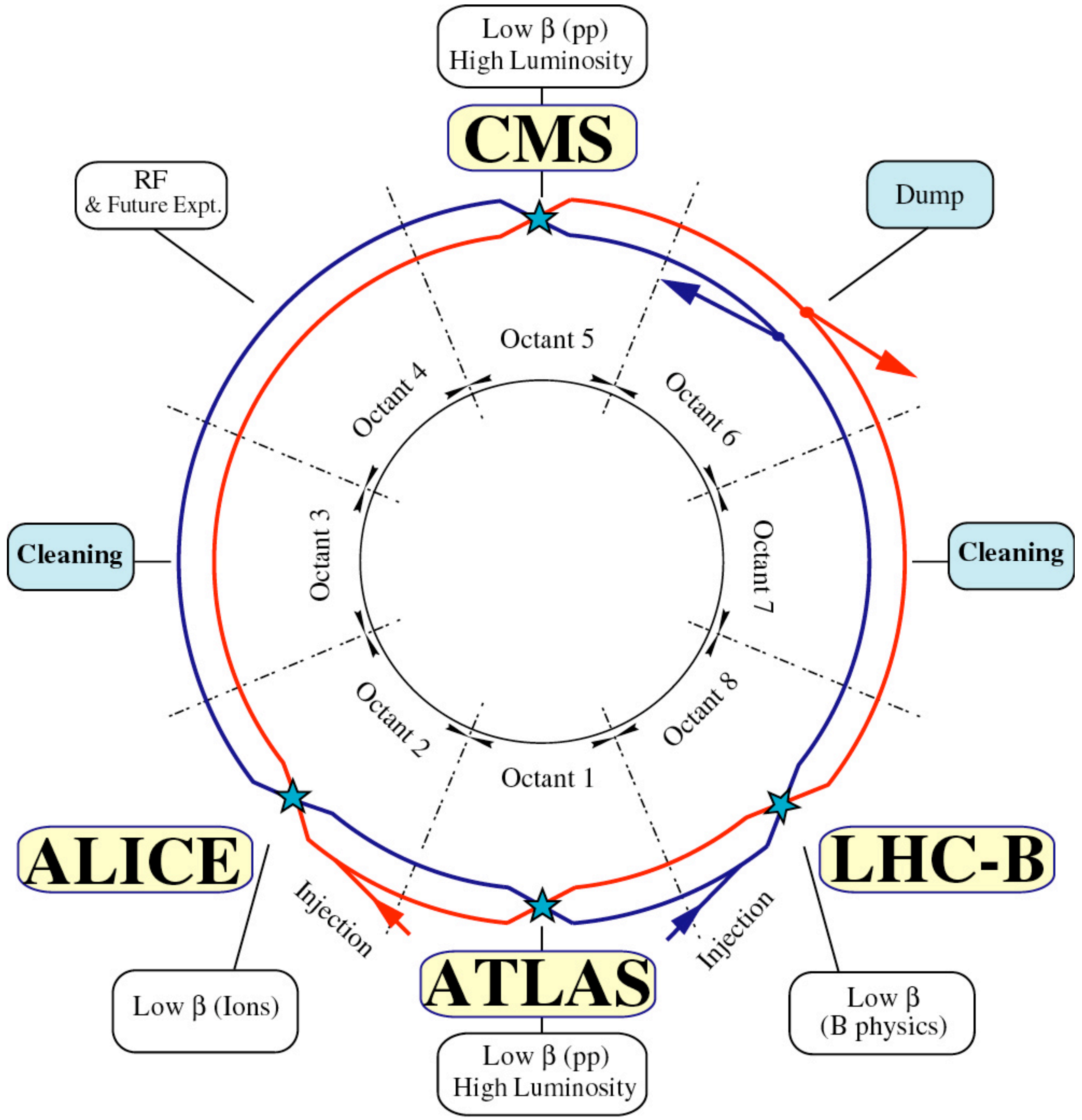
- 2 TCLP's (IP1/IP5)

Transfer lines

- 13 collimators → TCDI [C]

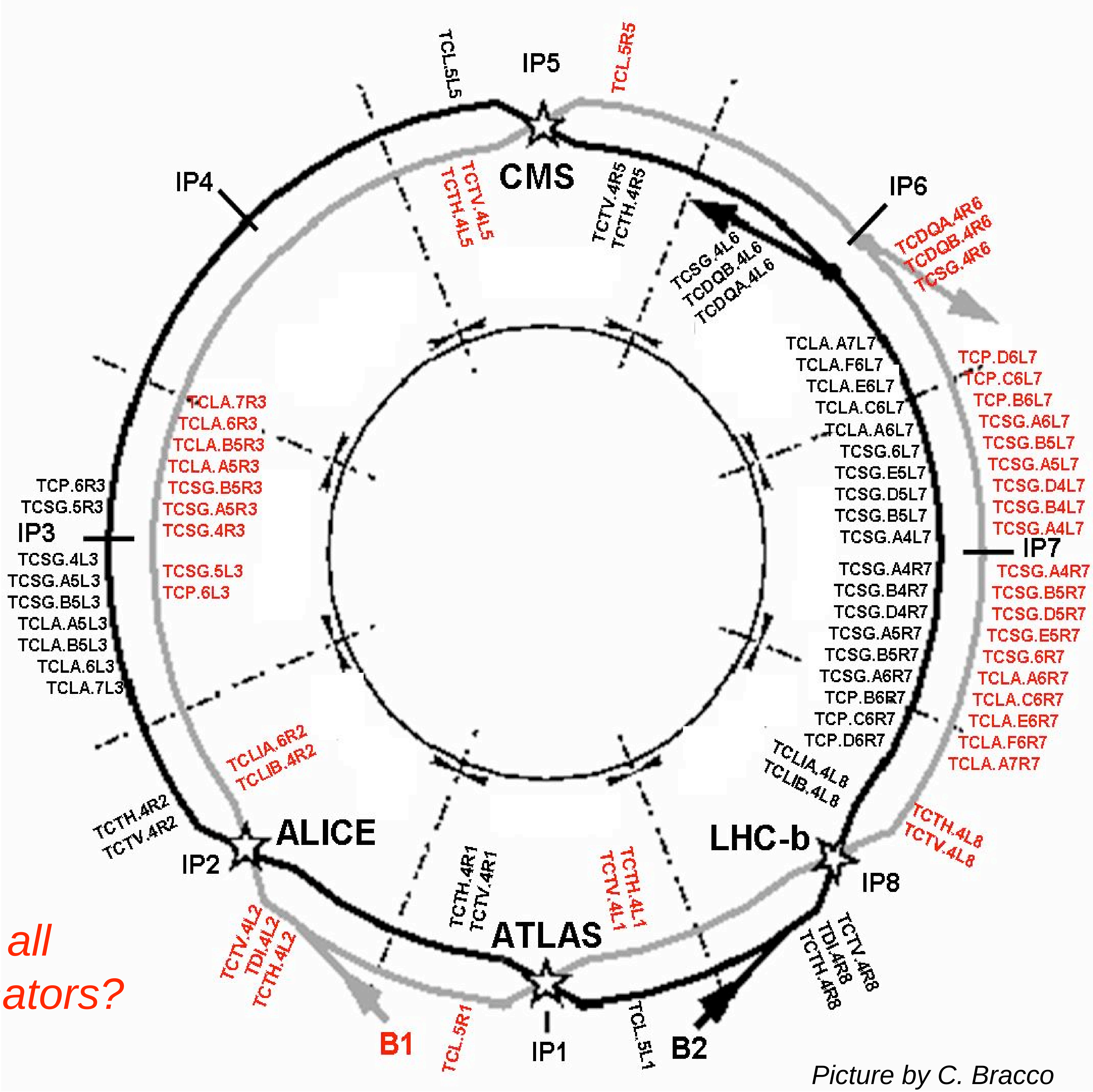
Protection (injection/dump)

- 10 elements →TCLI/TCDQ [C]



>100 collimators for the Phase I system!

Layout of the LHC collimation system



How do we want to use all these collimators?

Picture by C. Bracco

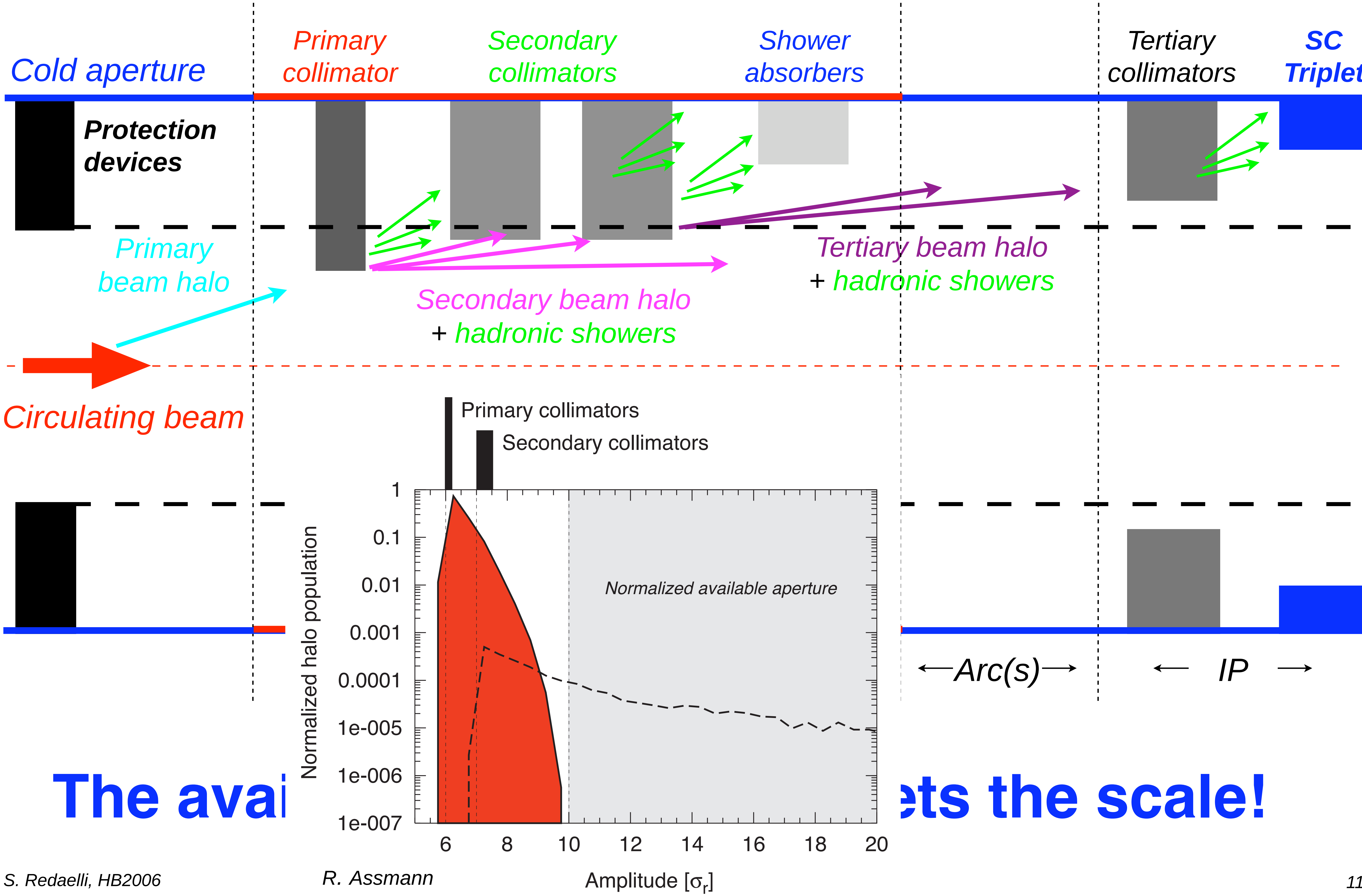
Detailed tables for the records

Phase	Acronym	Material	Length [m]	Number	Locations	INJ	TOP	Purpose
	Scrapers							
1	**TCHS**	tbd	tbd	6	**IR3, IR7**			Beam scraping
2	***TCHS***	tbd	tbd	2	**IR3, IR7**			*Skew beam scraping*
	Collimators							
1	**TCP**	C-C	0.2	8	**IR3, IR7**	**Y**	**Y**	Primary collimators
1	**TCSG**	C-C	1.0	30	**IR3, IR7**	**Y**	**Y**	Secondary collimators
1	**TCSG**	C-C	1.0	2	**IR6**	**Y**	**Y**	Help for TCDQ set-up
2	***TCSM***	tbd	tbd	30	**IR3, IR7**			*Hybrid secondary collimators*
4	***TCS4***	tbd	tbd	10	**IR7**			*Phase 4 collimators*
	Diluters							
1	**TDI**	Sandwich	4.2	2	**IR2, IR8**	**Y**		Injection protection
1	**TCLI**	C	1.0	4	**IR2, IR8**	**Y**		Injection protection
1	**TCDI**	C	1.2	14	**TI2, TI8**	**Y**		Injection collimation
1	**TCDQ**	C-C	6.0	2	**IR6**	**Y**	**Y**	Dump protection
	Movable Absorbers							
1	**TCT**	Cu/W	1.0	16	**IR1, IR2, IR5, IR8**		**Y**	Tertiary collimators
1	**TCLA**	Cu	1.0	16	**IR3, IR7**	**Y**	**Y**	Showers from collimators
1	**TCL/TCLP**	Cu	1.0	4	**IR1, IR5**		**Y**	Secondaries from IP
3	***TCL/TCLP***	Cu	1.0	4	**IR1, IR5**		**Y**	*Secondaries from IP*

How do we want to use all these collimators?

Principle of multi-stage cleaning

(illustrative scheme)

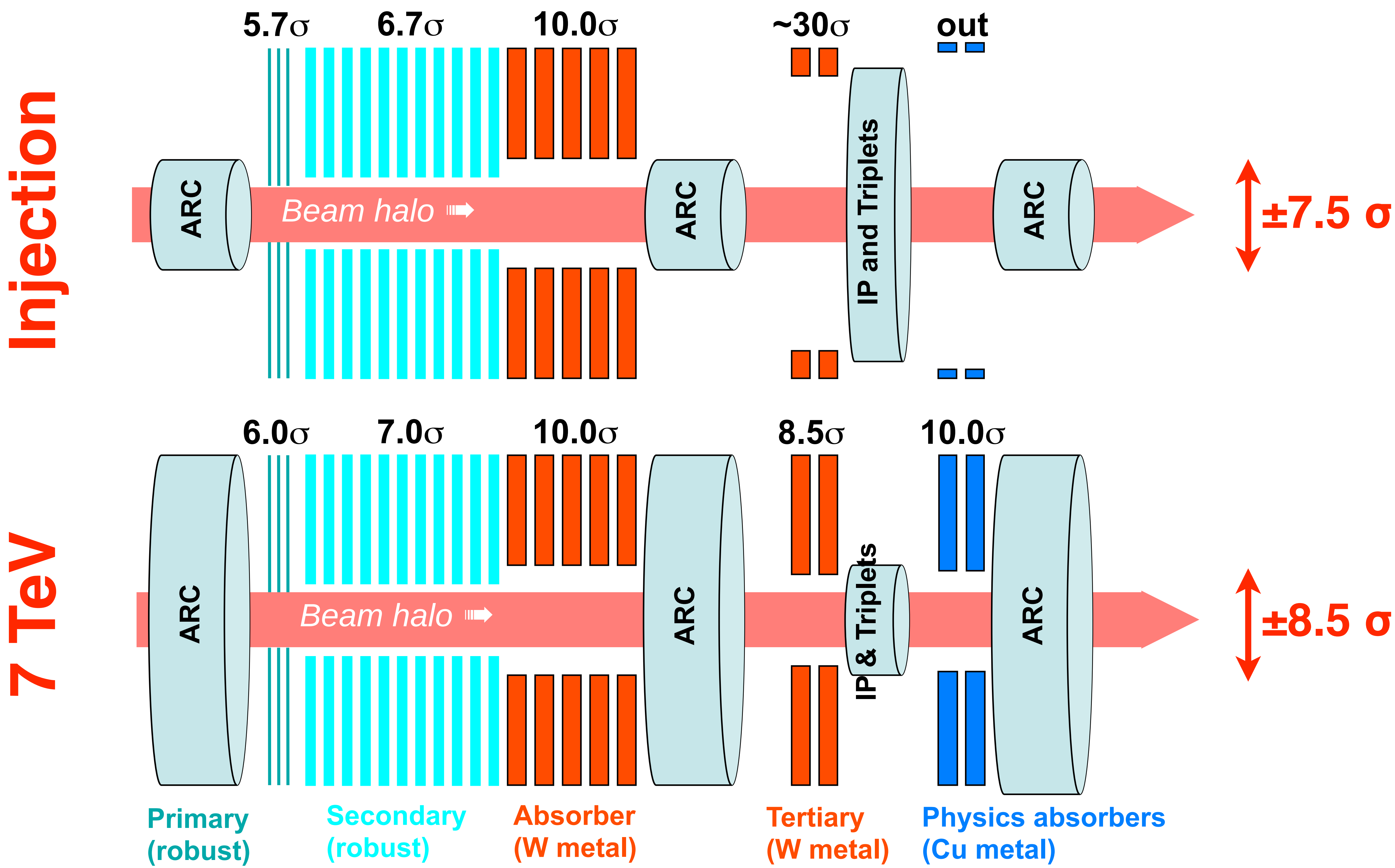


R. Assmann

The avai ... ets the scale!

LHC aperture and collimator settings

(Detailed worked out in Chamonix2005)

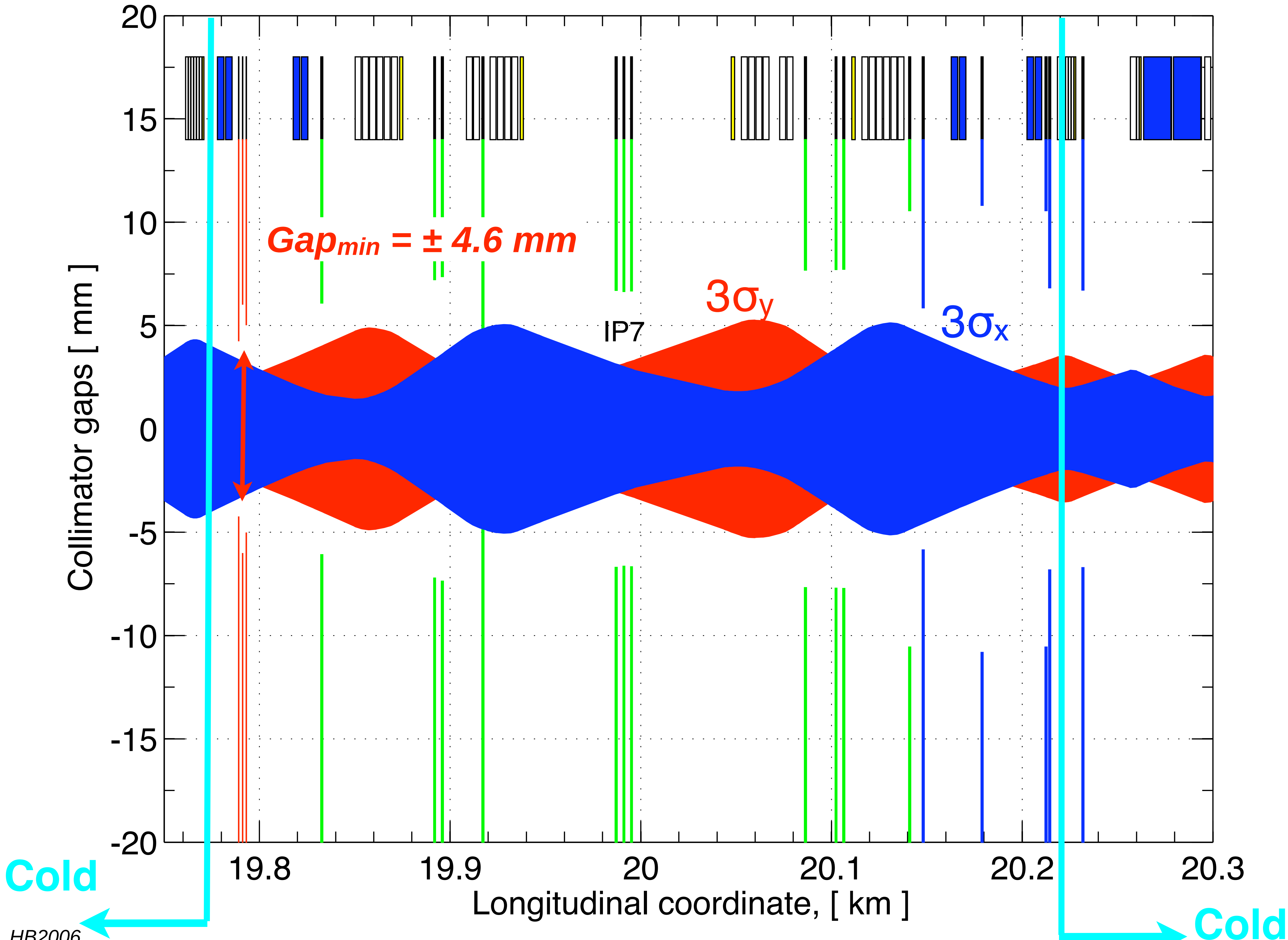


Similar normalized settings at injection (arc) and at 7 TeV (triplet).

Canonical settings: ***$A_{TCP} = 6\sigma$ / $A_{TCS} = 7\sigma$*** *($\sigma=\sqrt{\beta_i \varepsilon}$).*

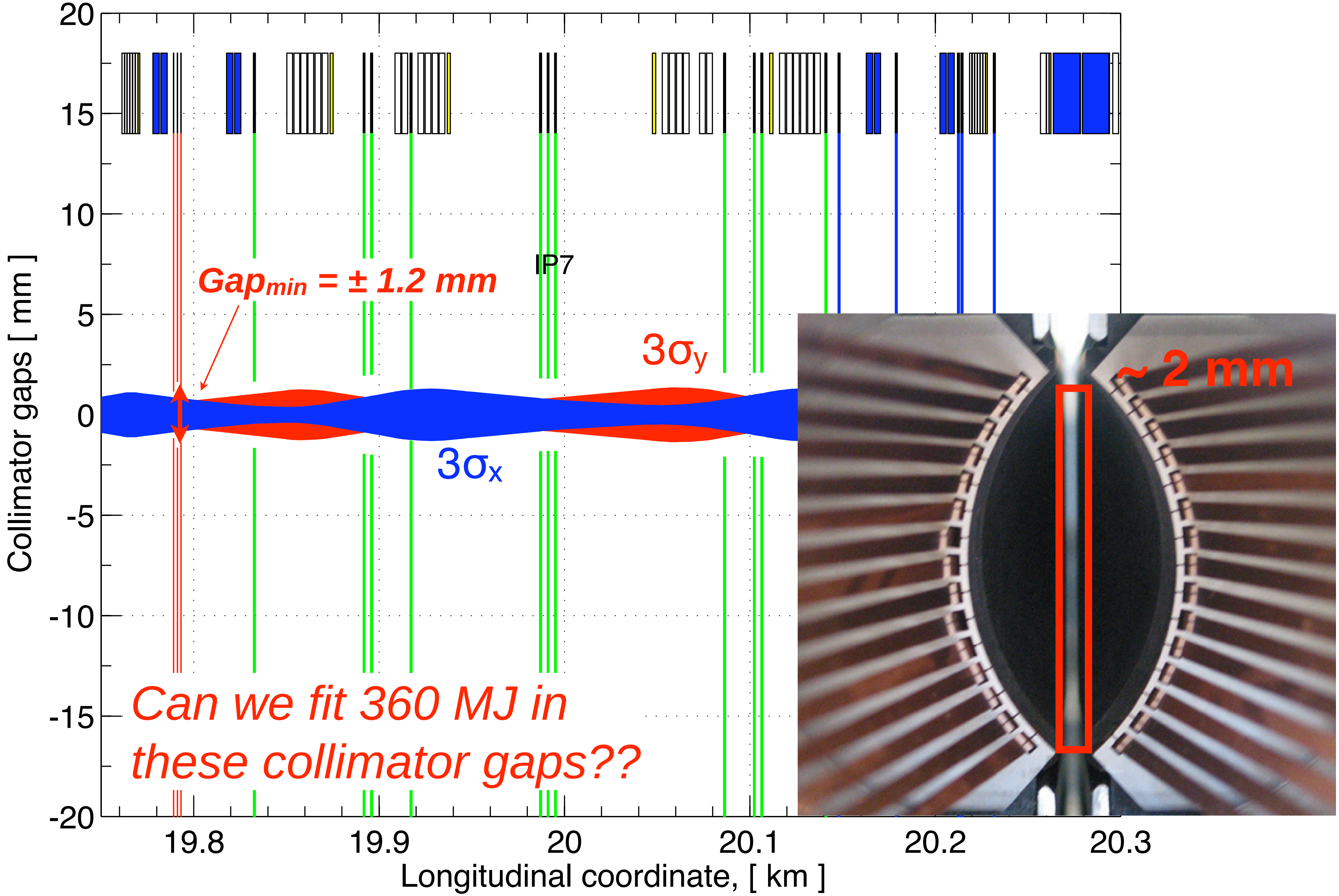
Collimator gaps at injection - IR7

A_{TCP} = 5.7 σ A_{TCS} = 6.7 σ A_{TCLA} = 10 σ



Collimator gaps at 7 TeV - IR7

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



Outline

- Introduction
- Collimation system layout
- **Mechanical design of the collimator**
  - ➡ Design criteria and challenges
  - ➡ Mechanical design
  - ➡ Beam test results
- Achieved cleaning performance
- System limitations and upgrades
- Conclusions

Challenges of the design requirements

Mechanical tolerance
σ_b = 200 μm at 7 TeV/c

40 μm surface flatness over L=1m
10 μm positioning accuracy

Heat load (7 TeV)
Minimum lifetime: τ_{min}≈0.2h

Up to **30 kW** at top energy
Keep T < 50 ^oC

Failure scenarios [Robustness!]
Full **injection** batch
8 nominal bunches at **7 TeV/c**

→ 288 bunches ≈ **2 MJ (7.2 μsec)**
→ 8 bunches ≈ **1 MJ (0.2 μsec)**

High radiation environment
~10^{16} protons per years!

Radiation hardness of components
E.g.: stepping motors: **10 MGy/year**

Robustness

Cooling

Maintainability

Precision

High absorption

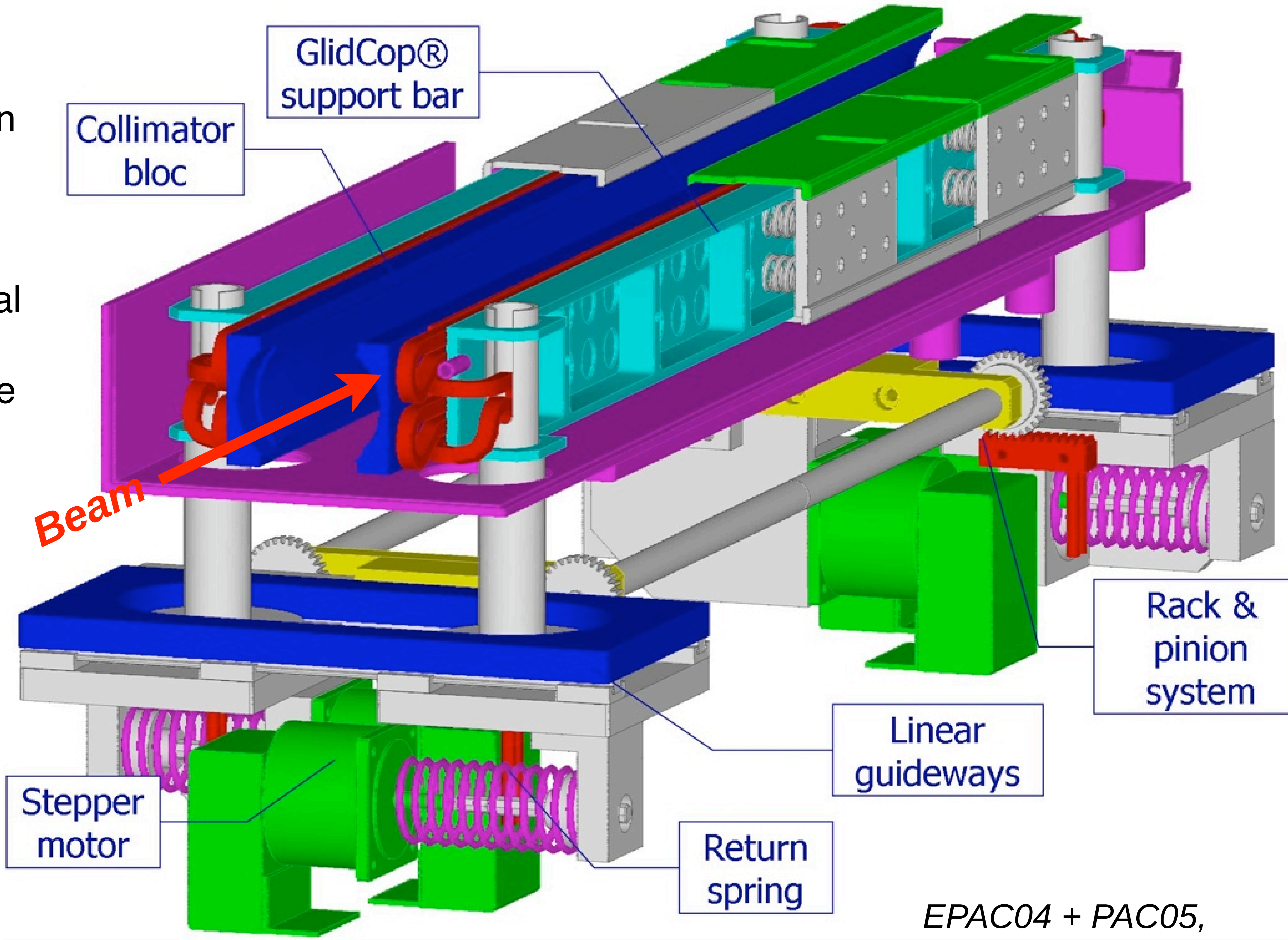
Radiation hardness

Phase I addresses successfully most of these challenges!
Here: review main design features

The collimator assembly

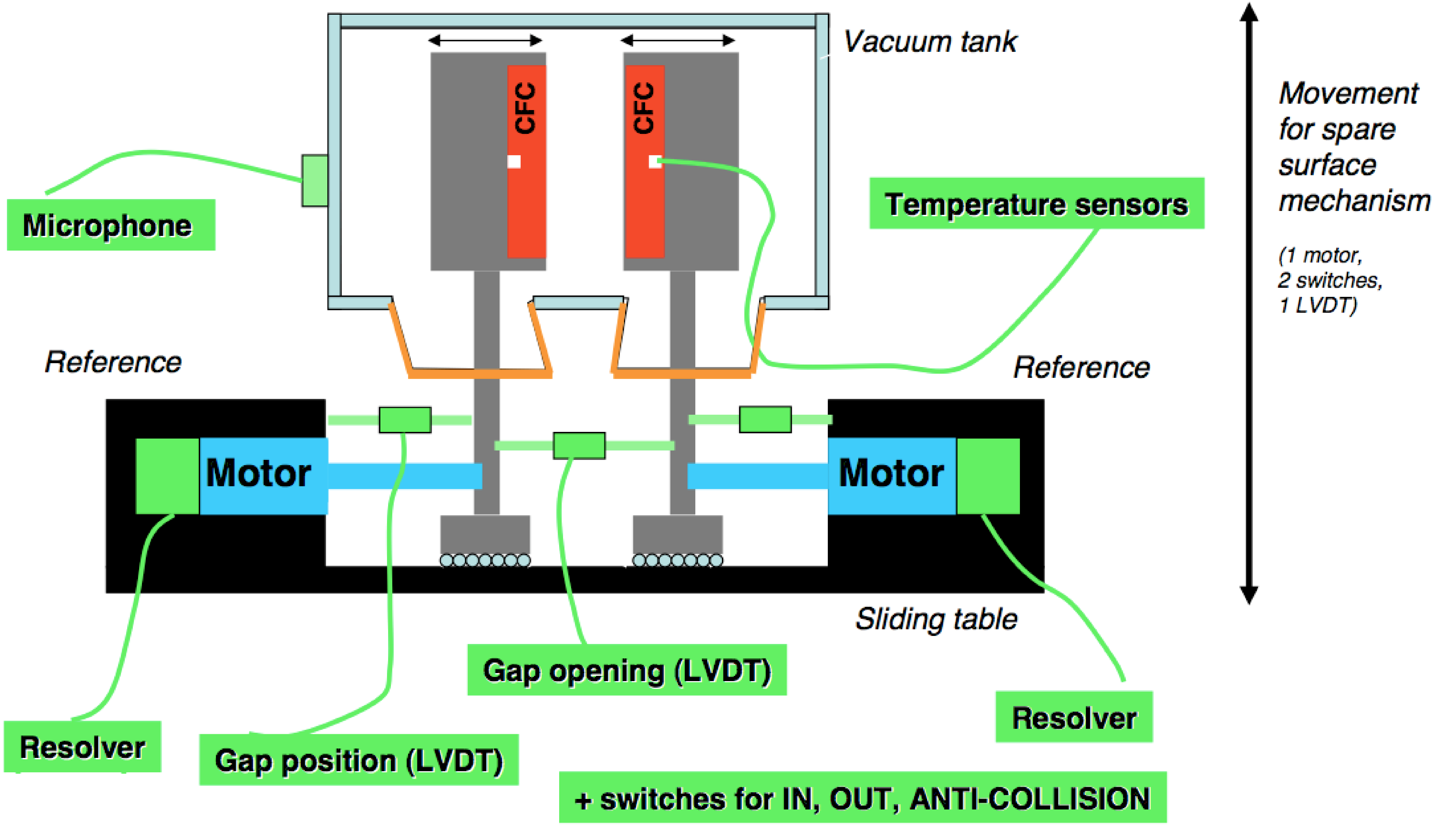
Main design features:

- Two jaws (position and angle)
- Concept of spare surface
- Different azimuthal angles (H,V,S)
- External reference of jaw position
- Auto-retraction
- RF fingers
- Jaw cooling

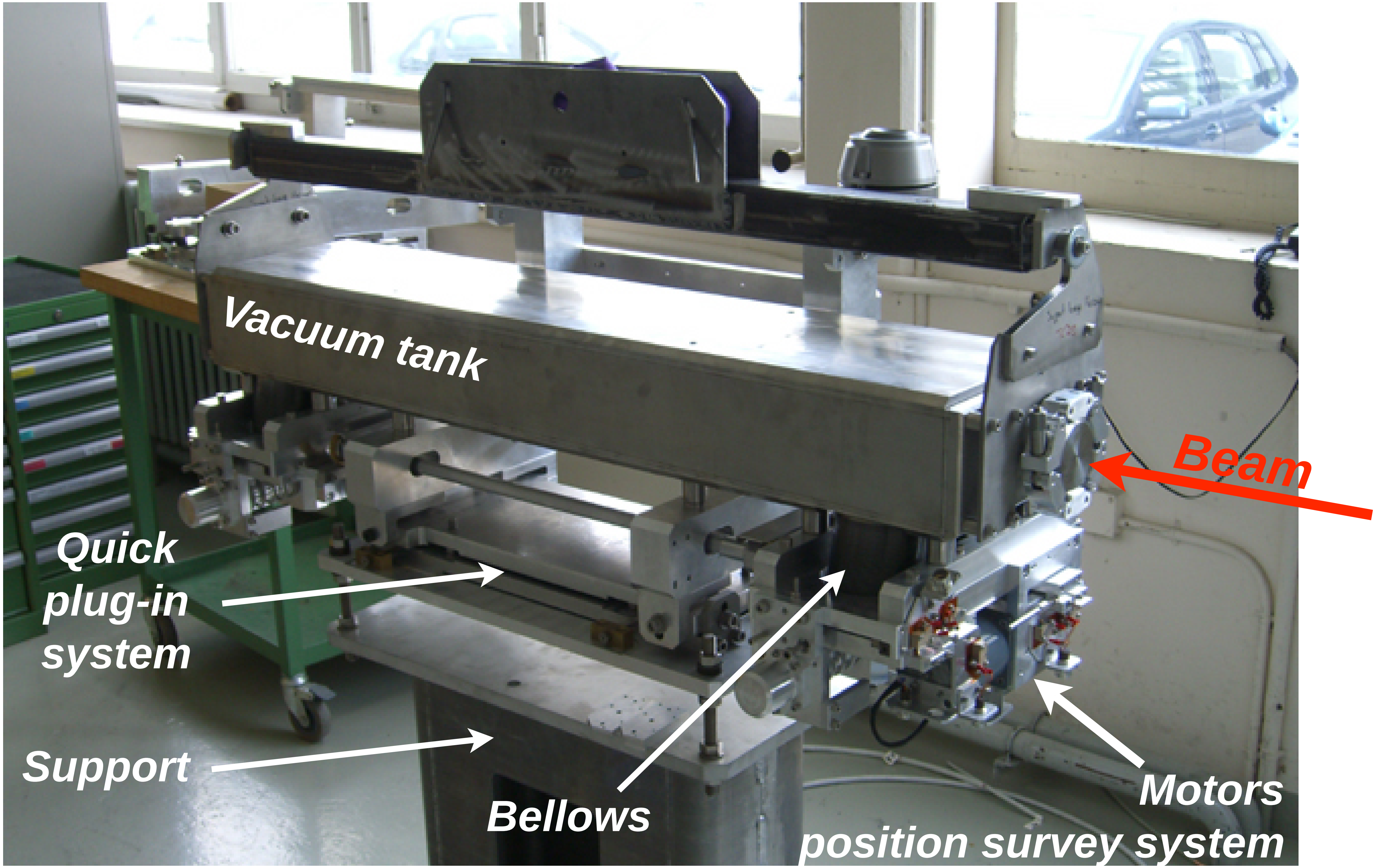


EPAC04 + PAC05, A. Bertarelli et al.

External measurements of jaw position

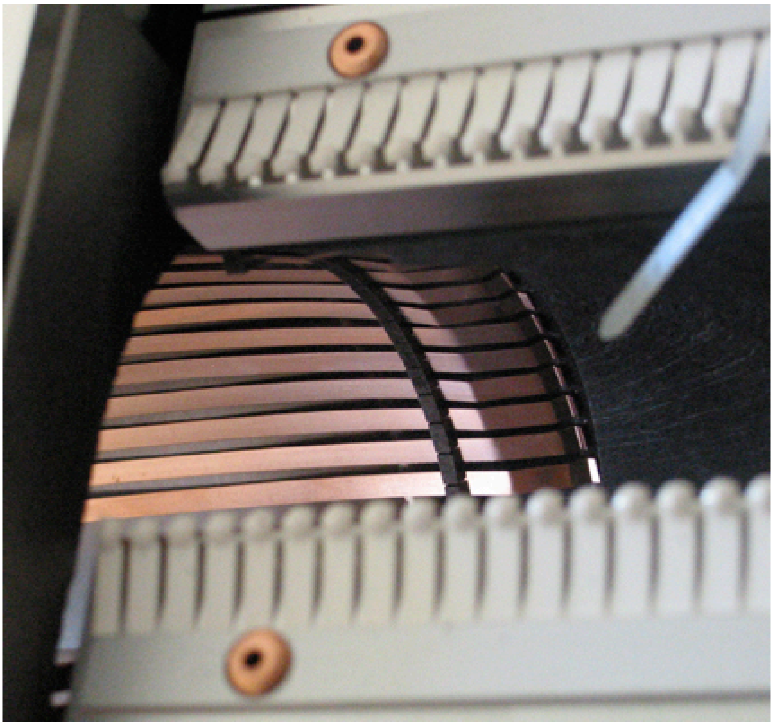


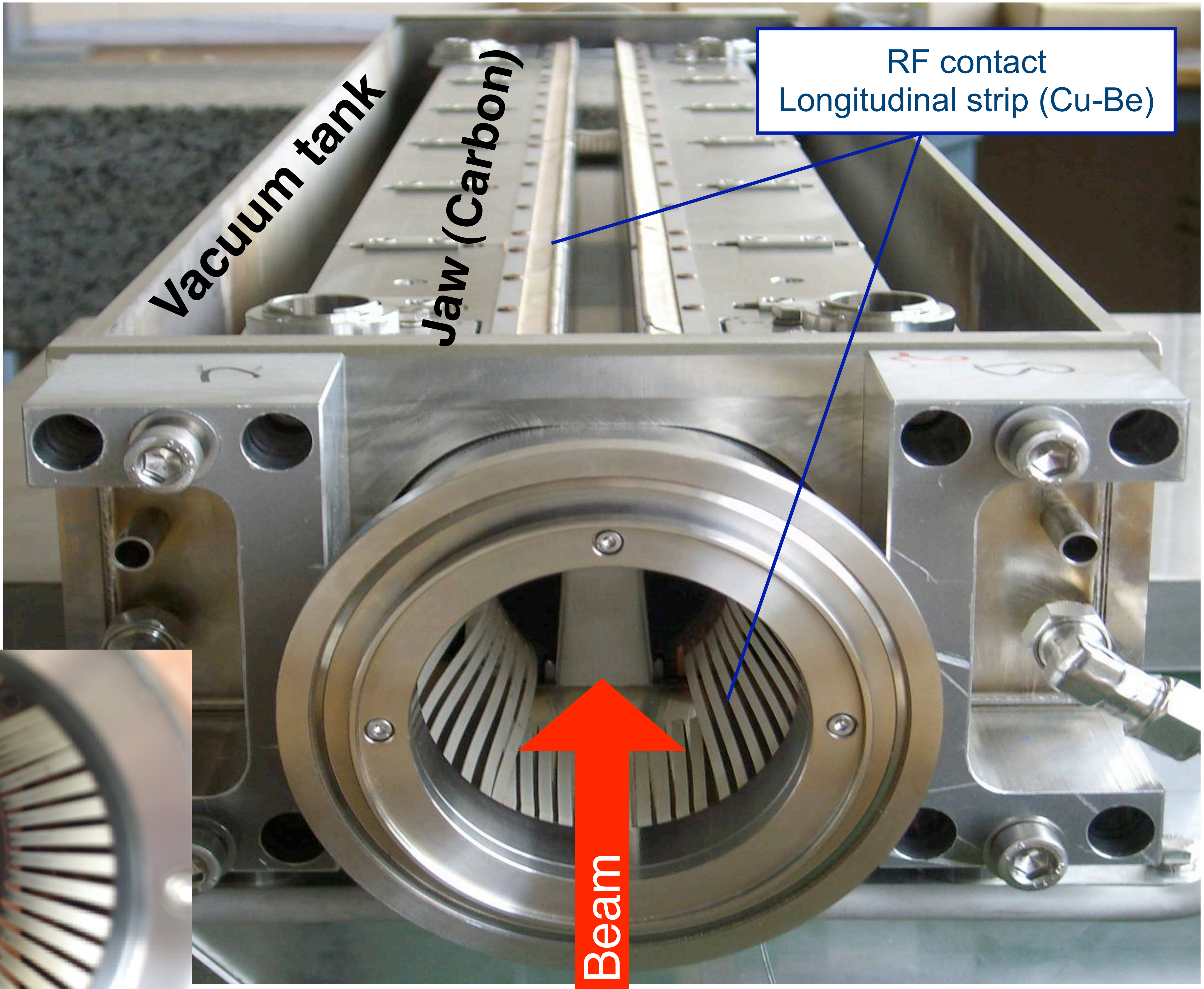
A real collimator



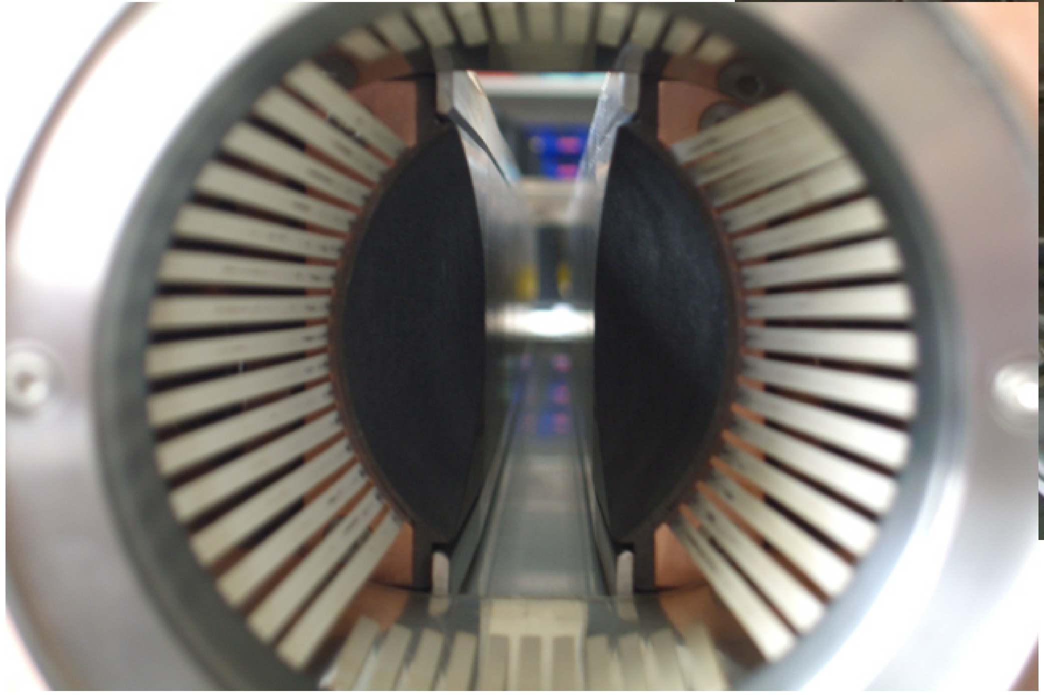
A. Bertarelli, A. Dallocchio

A look inside the vacuum tank



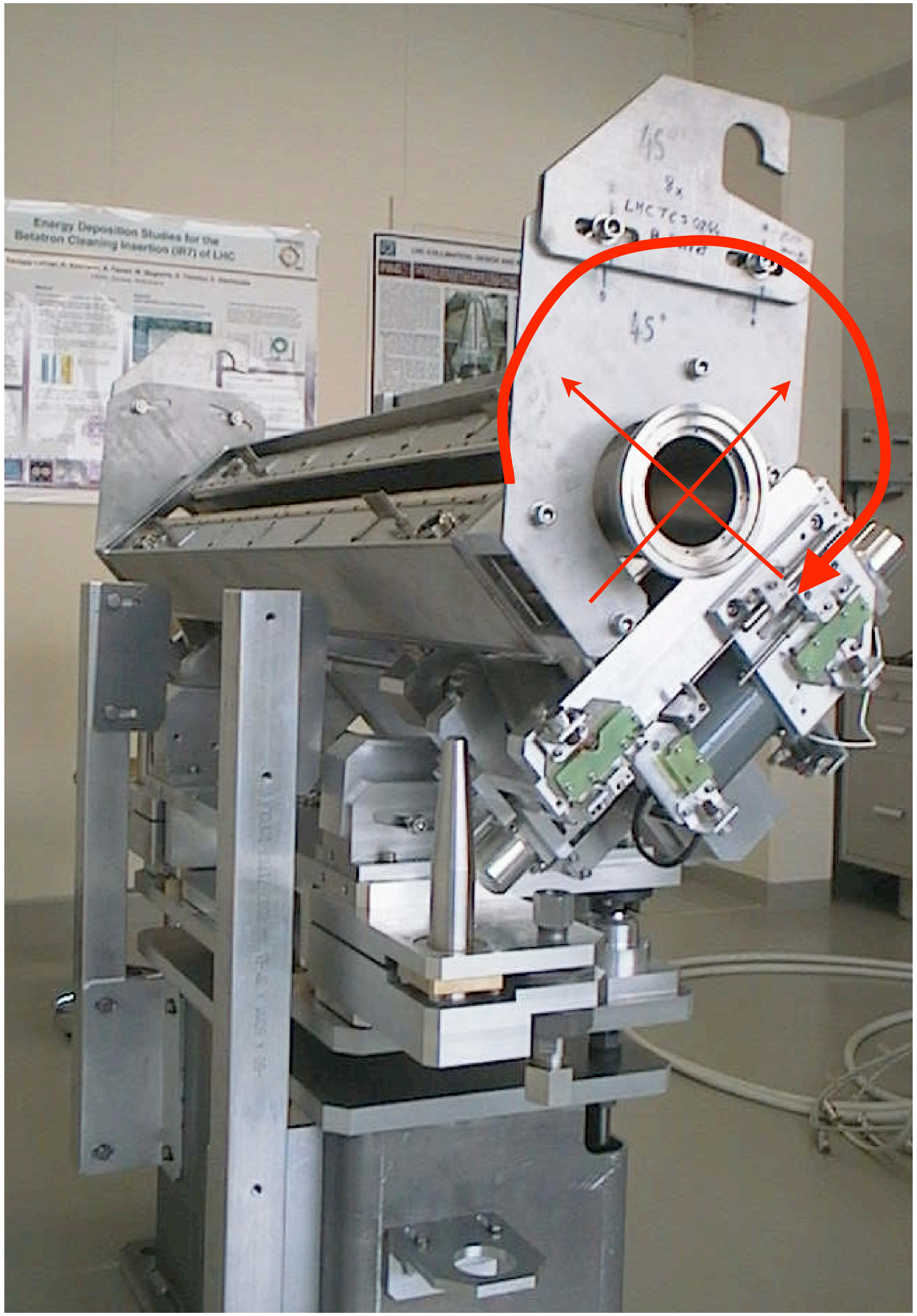


What the beam sees!

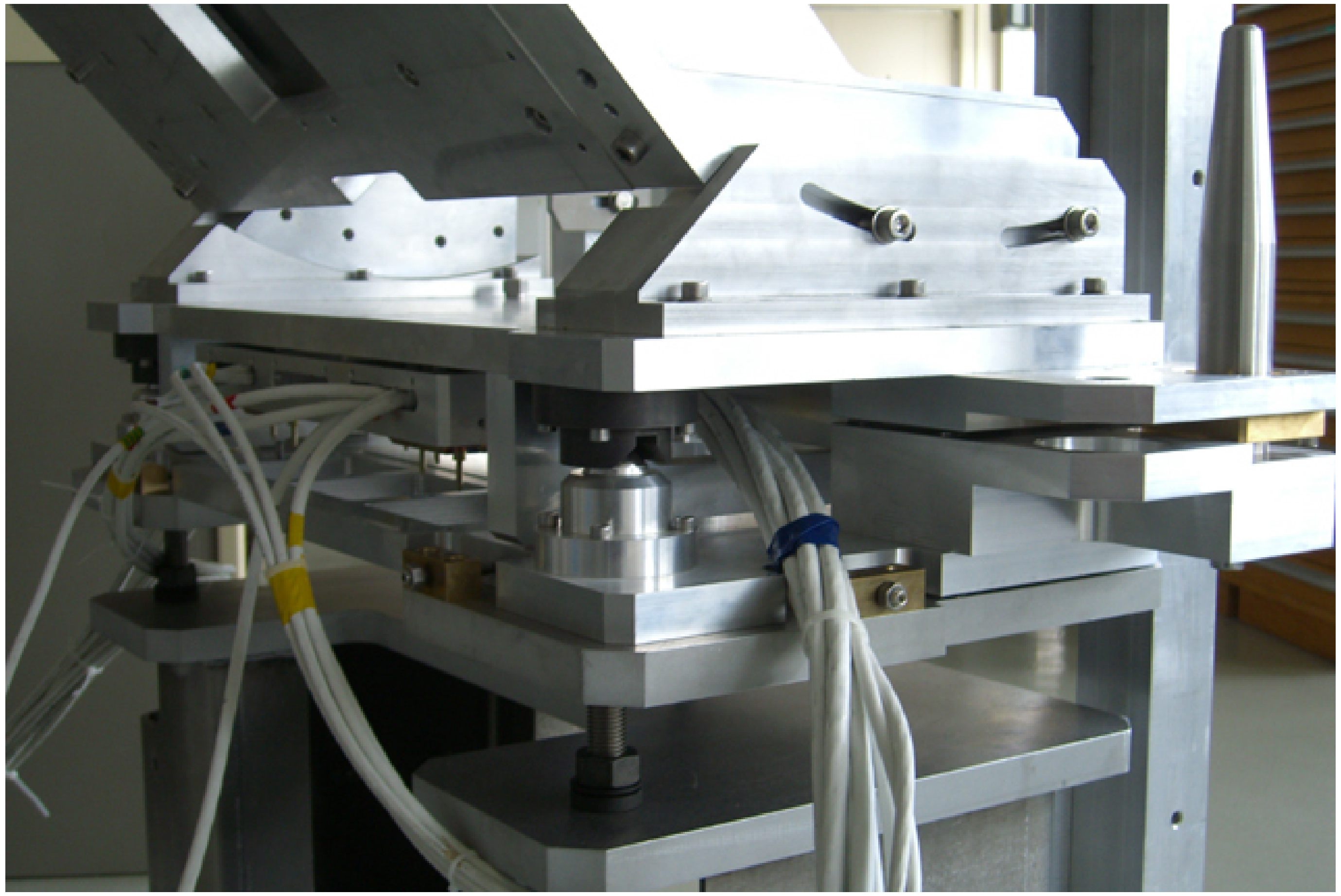


A. Bertarelli, A. Dallocchio

Dealing with different azimuthal angles

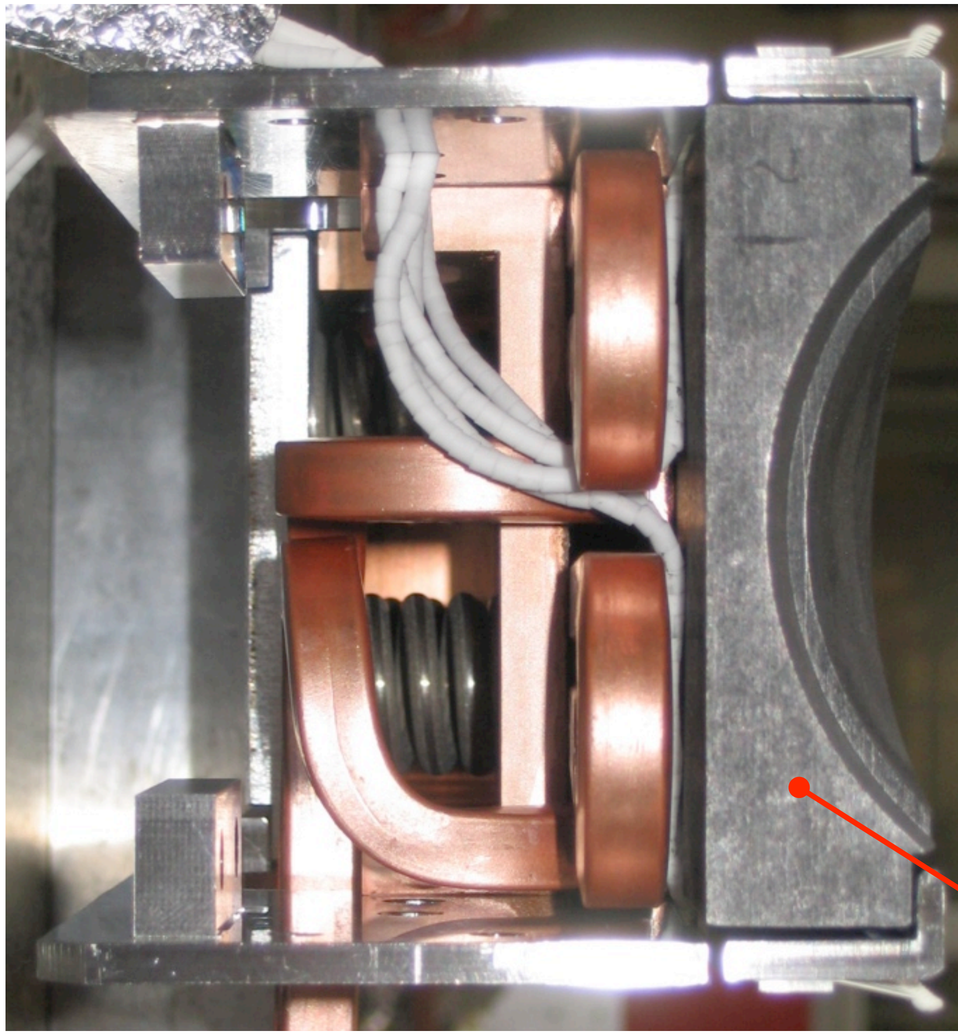


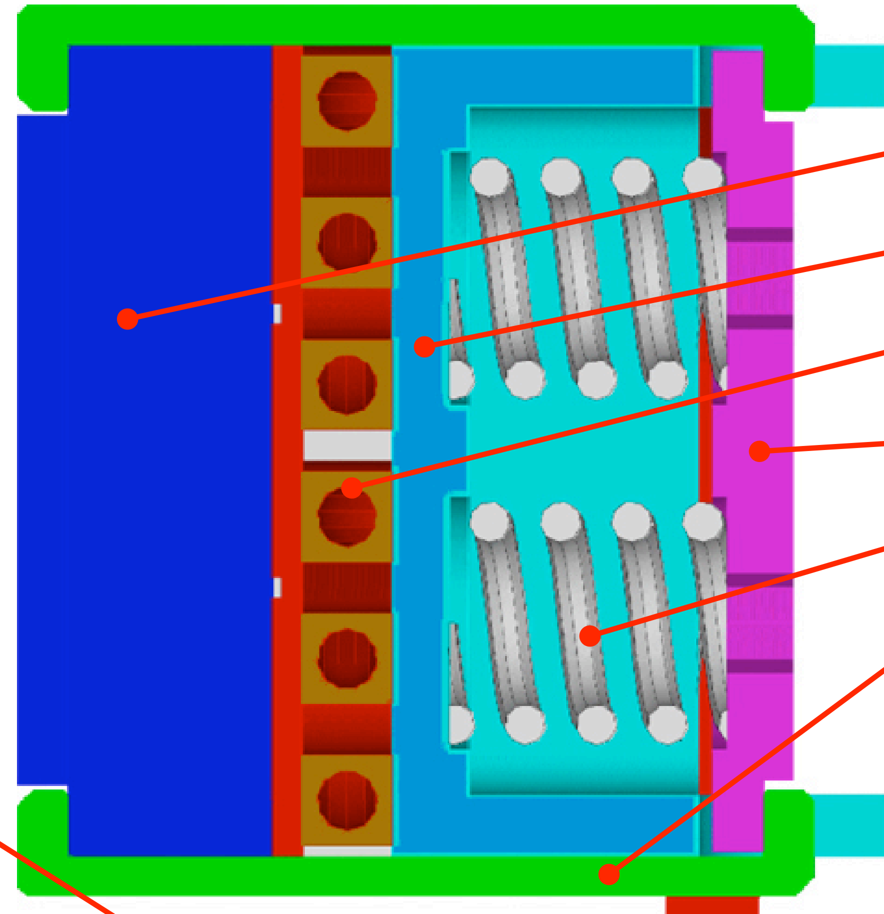
Same support and quick plug-in system for different orientations
Whole vacuum tank can be rotated to match the beam requirements (horizontal, vertical or skew)



A. Bertarelli, A. Dallocchio

The LHC collimator jaw

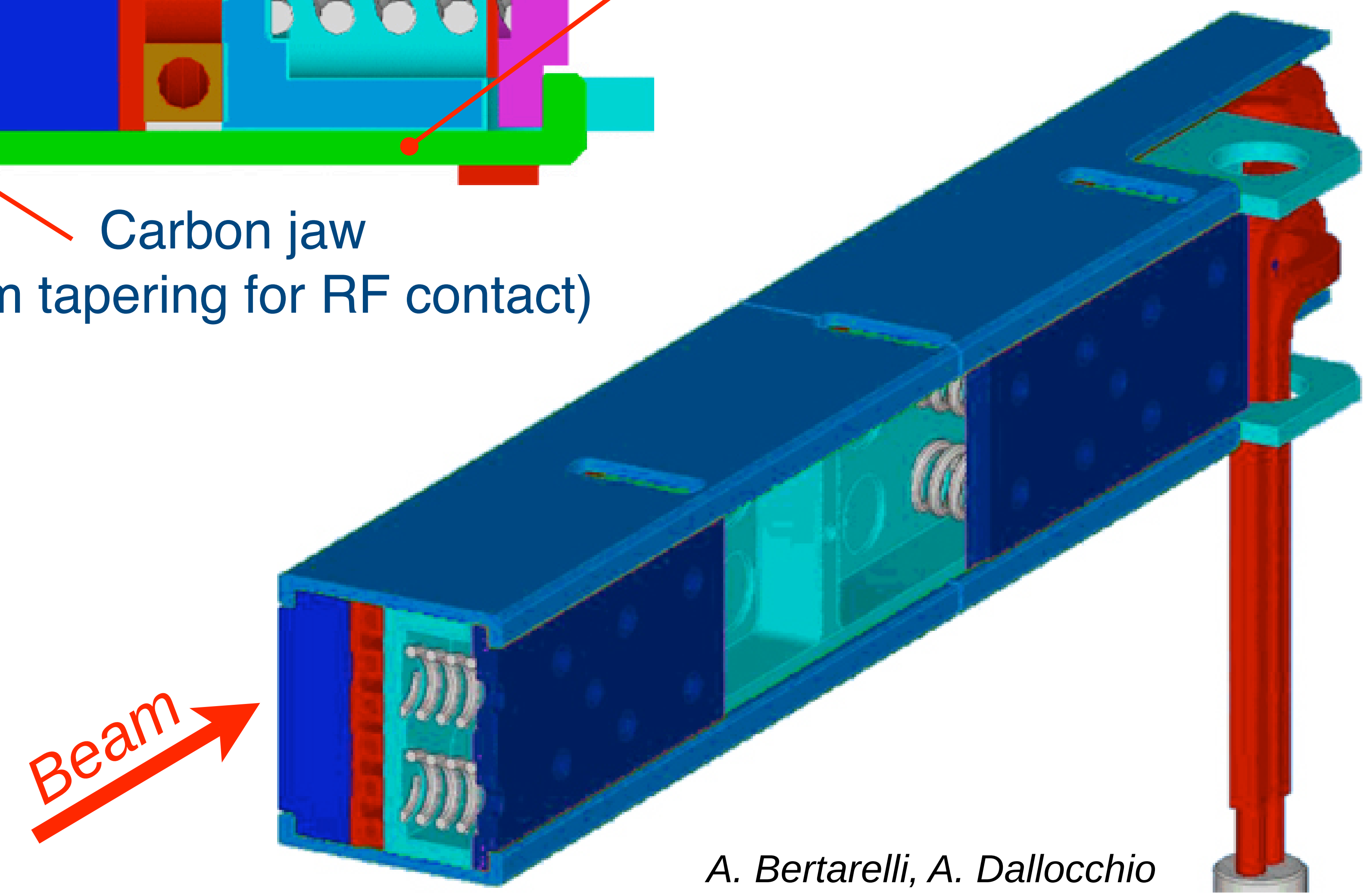




Special "sandwich" design with different layers designed to minimize the thermal deformations:

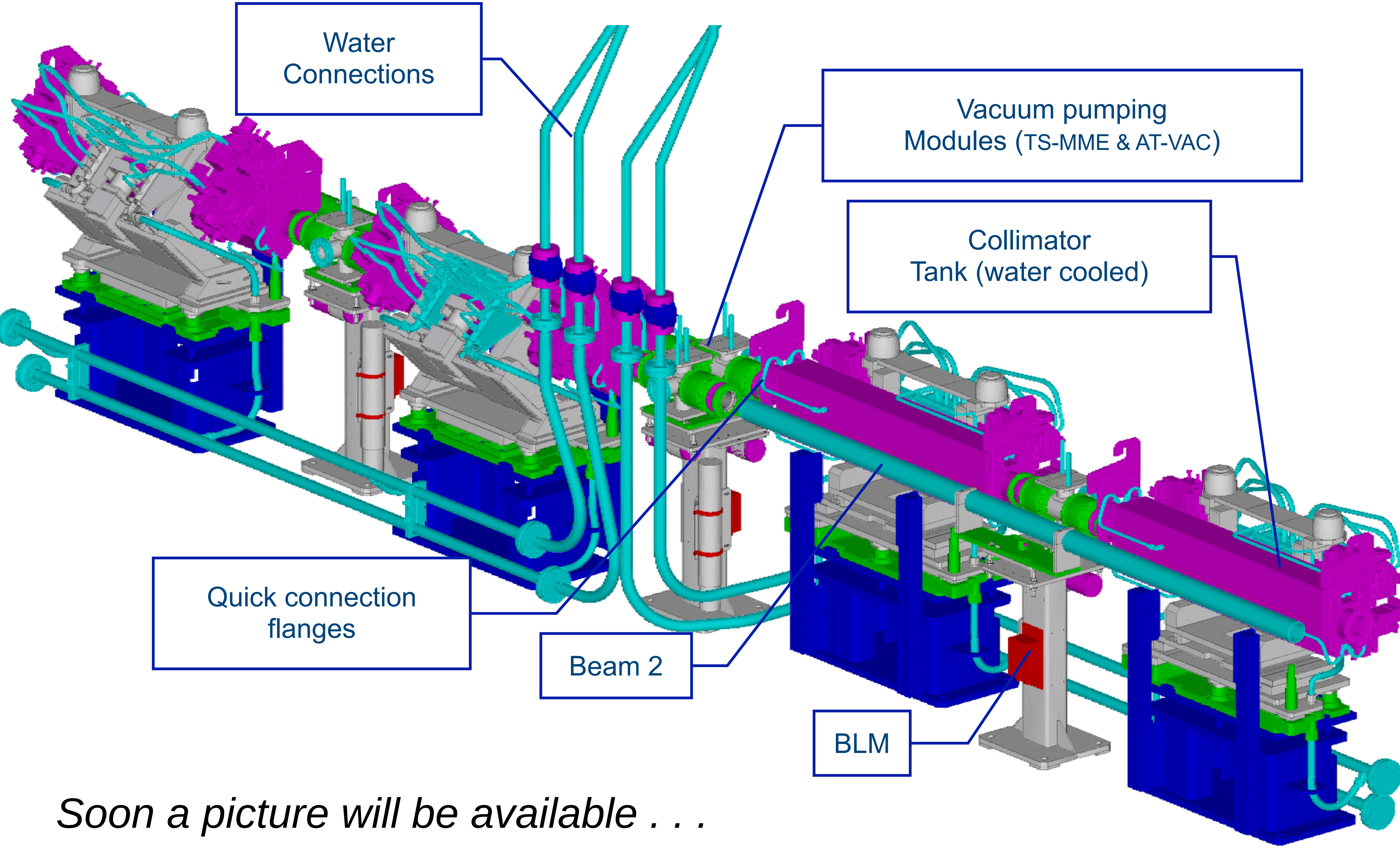
Steady (~5 kW) ➞ < 30 μm

Transient (~30 kW) ➞ ~ 110 μm



A. Bertarelli, A. Dallocchio

3D integration in the LHC tunnel



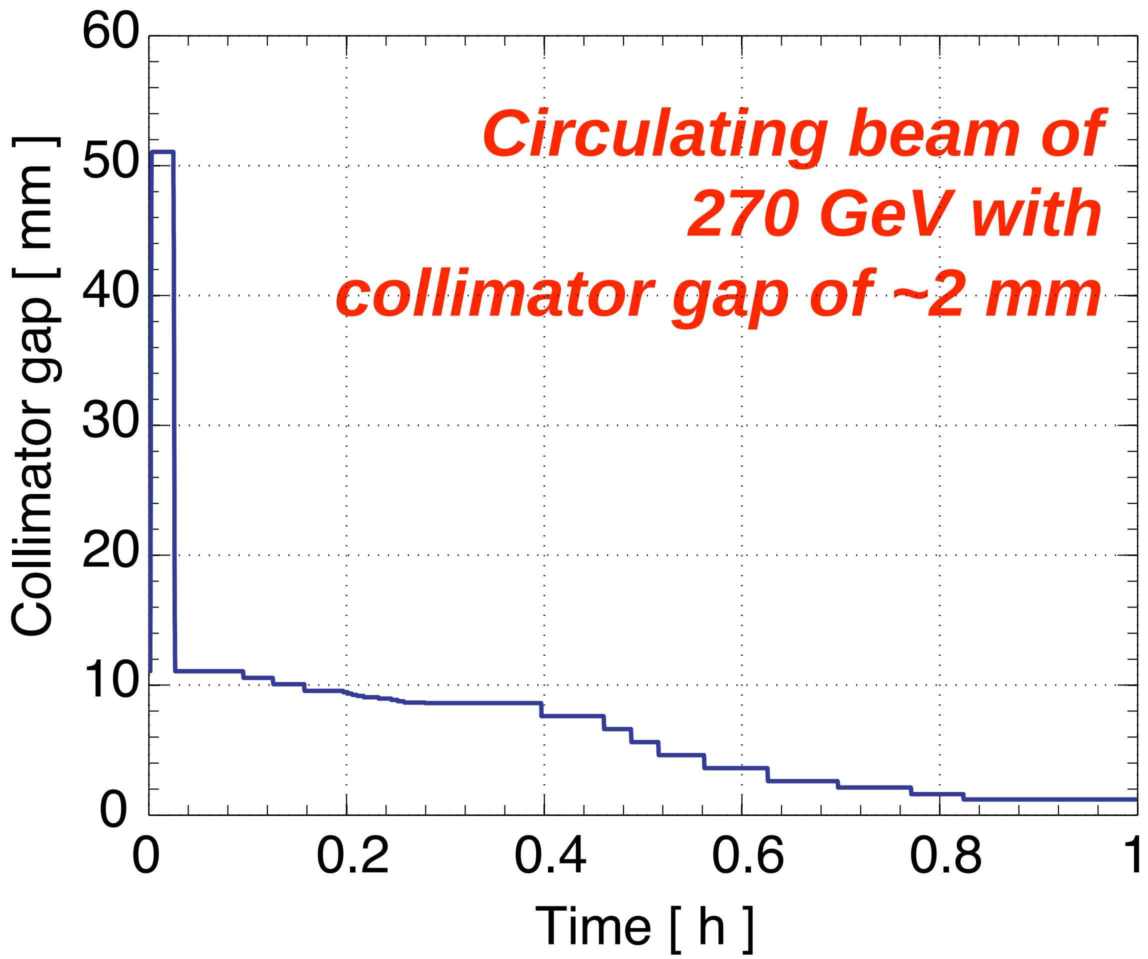
Soon a picture will be available . . .

A. Bertarelli, A Dallocchio

Highlights of lab and beam tests

Many crucial laboratory tests:

- ☑ Temperature transmission for cooling
- ☑ Contact resistance of RF fingers
- ☑ Material property measurements
- ☑ Positioning accuracy (~10 µm)
- ☑ Flatness measurements (≤ 40-60µm)
- ☑ Vacuum, bake-out, outgassing
- ☑ . . .

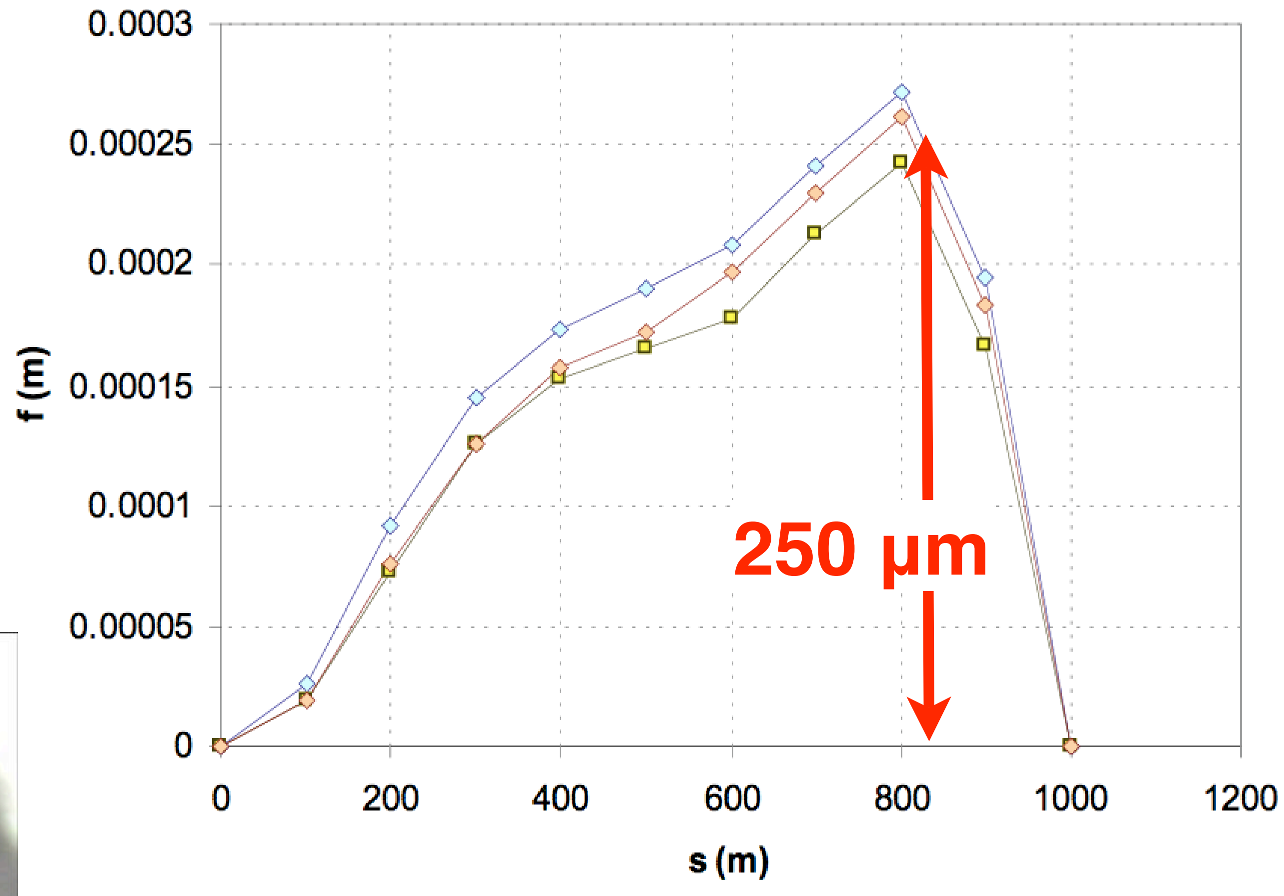


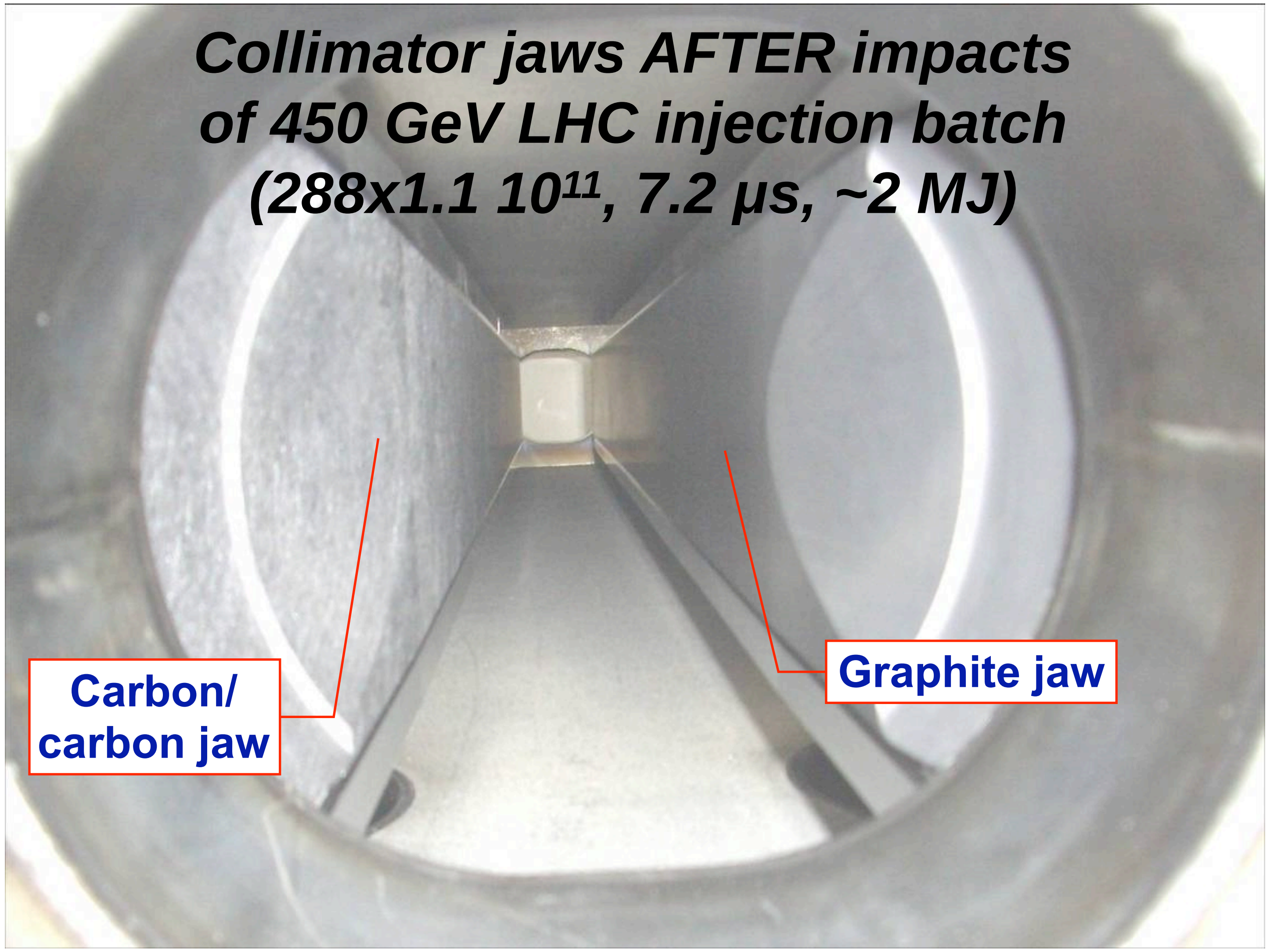
Major milestones: Beam tests in 2004 (SPS)

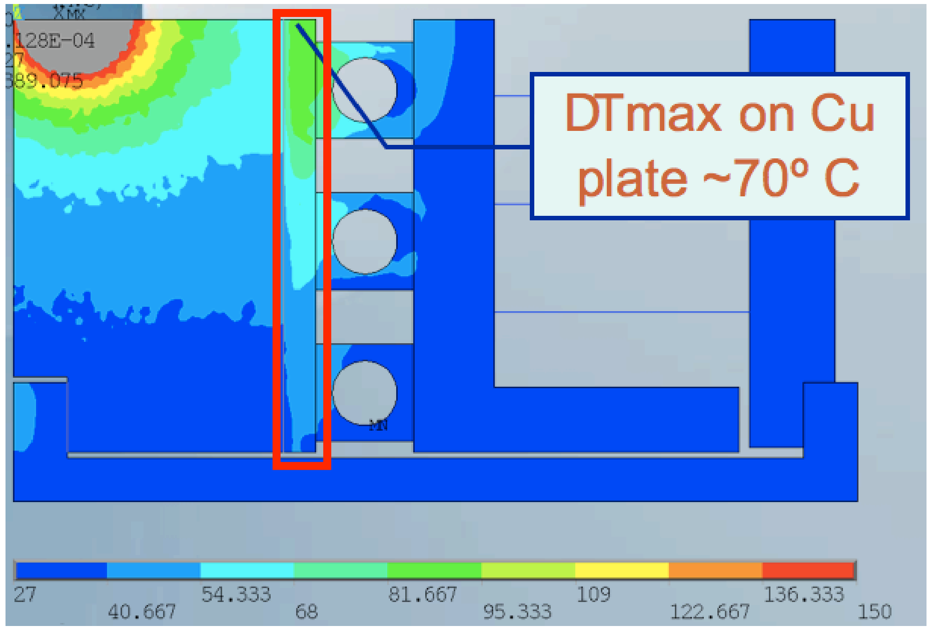
- ☑ Mechanical functionality with circulating beam
  - → Centering around beam with 50 µm accuracy (see talk on Thr.)
- ☑ Robustness test with extracted beam at 450 GeV
  - → Collimator survived at worst injection failure case!

Robustness test with 450 GeV p beams

No damage of the Carbon and Graphite blocks
Permanent deformation of the Copper plate behind the jaw
*➞ Inconel plate **solved the problem**!*







A. Bertarelli, A Dallocchio

Sound: http://lhc-collimation-project.web.cern.ch/

Outline

- Introduction
- Collimation system layout
- Mechanical design of the collimator
- **Achieved cleaning performance**
  - ➨ Simulation tools
  - ➨ Beam loss patterns
  - ➨ Energy deposition studies
- System limitations and upgrades
- Conclusions

LHC loss map simulations

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

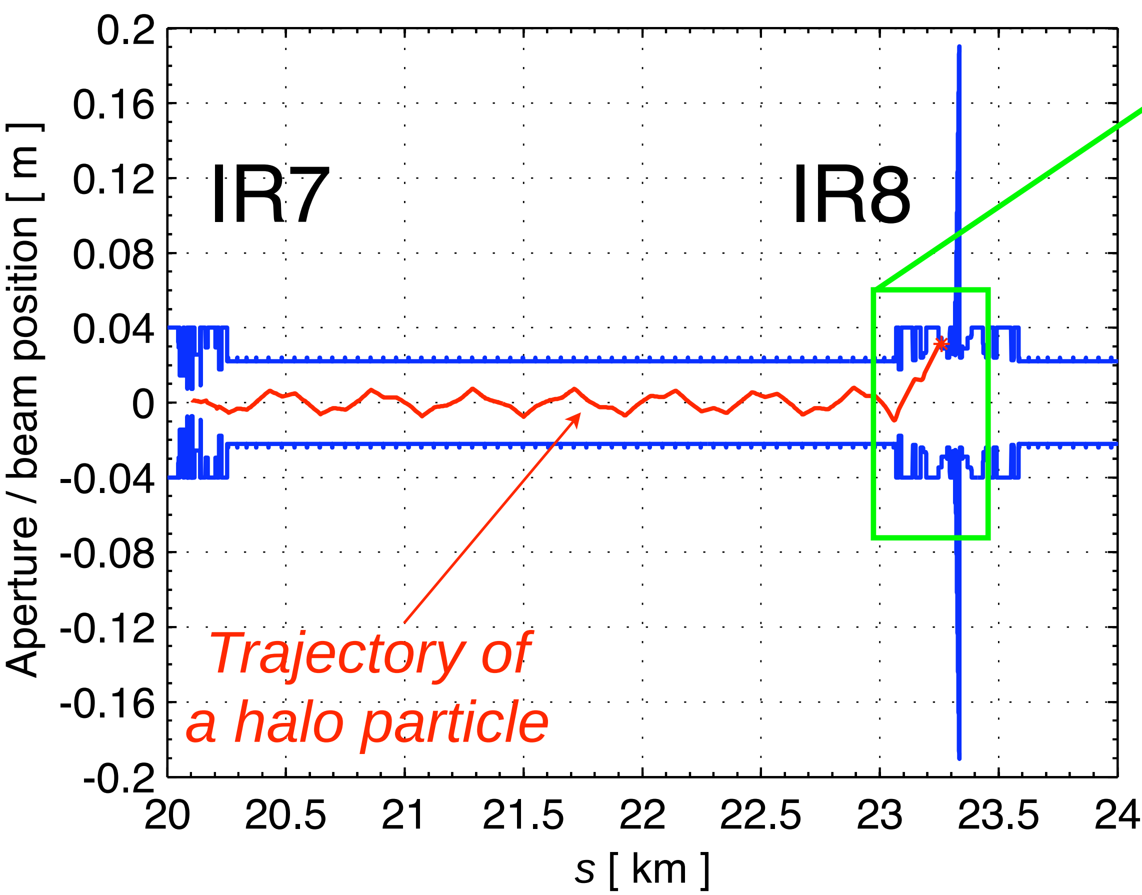
Scattering routine
Track protons inside collimator materials

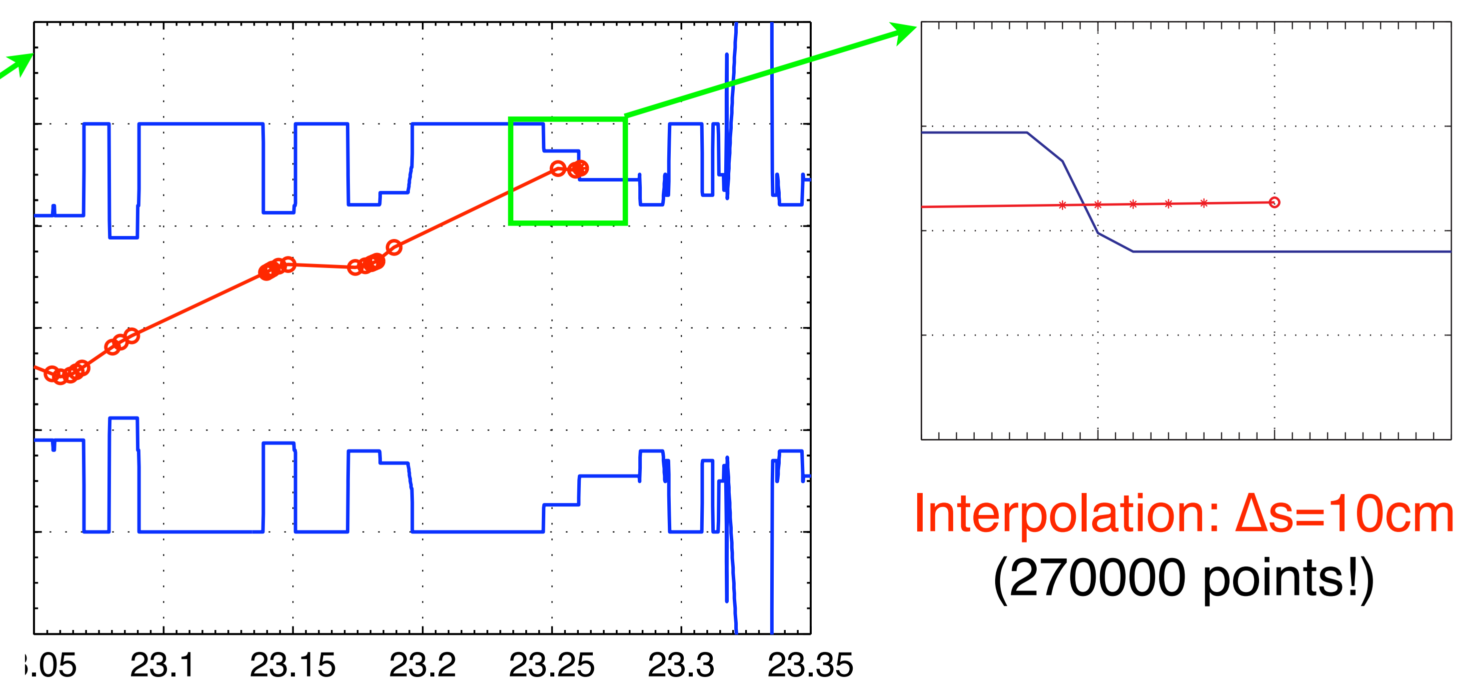
Detailed collimator geometry
Implement all collimators and protection devices, treat any azimuthal angle, tilt/flatness errors

→ **SixTrack** / **K2**

Detailed aperture model
Precisely find the locations of losses

→ **BeamLossPattern**



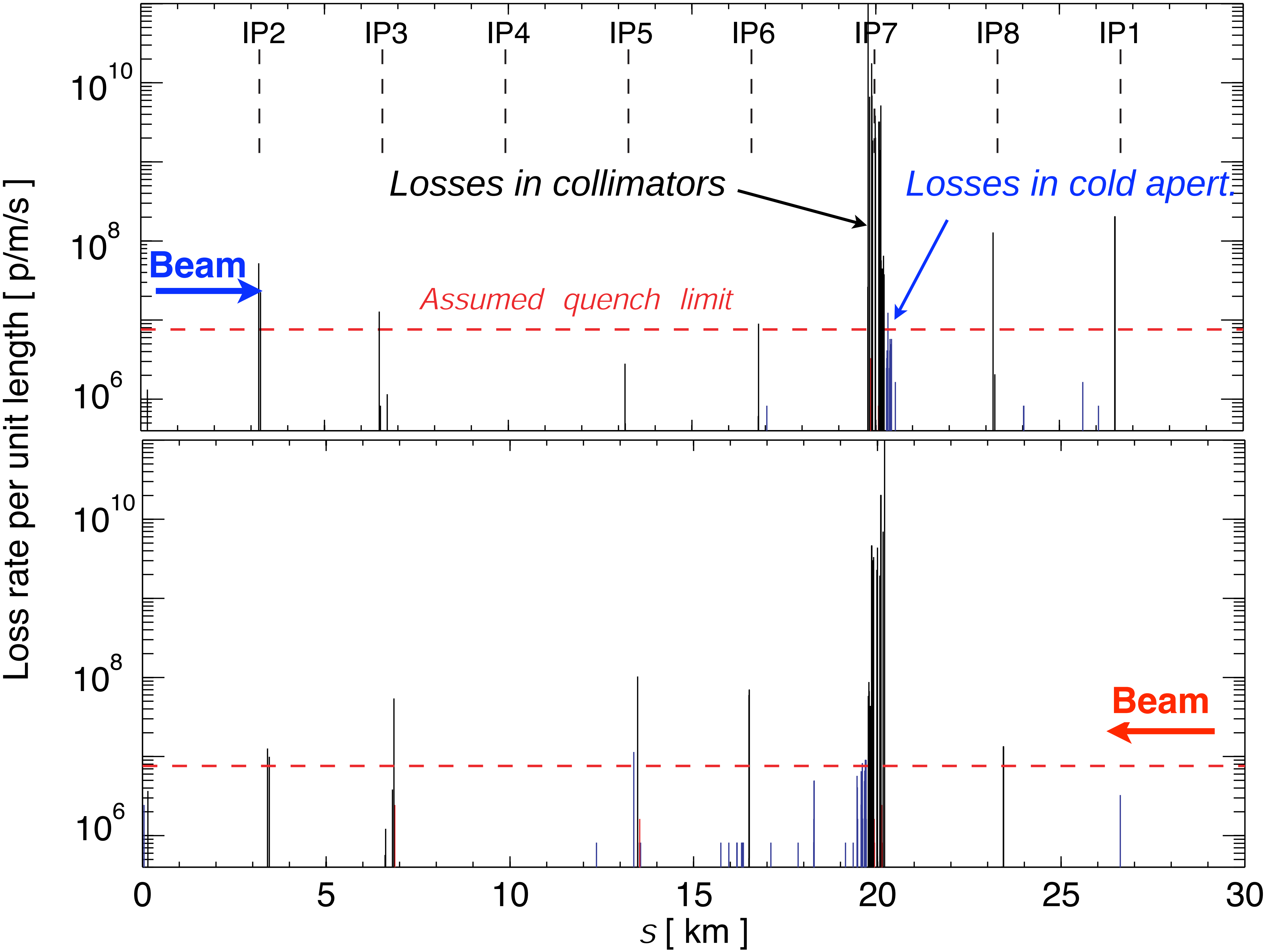


Magnet locations : Δs ≤ 100m

Interpolation: Δs=10cm
(270000 points!)

See G. Robert-Demolaize *et al.*, "A new version of SixTrack for collimation studies", PAC05

Cleaning performance at 7 TeV

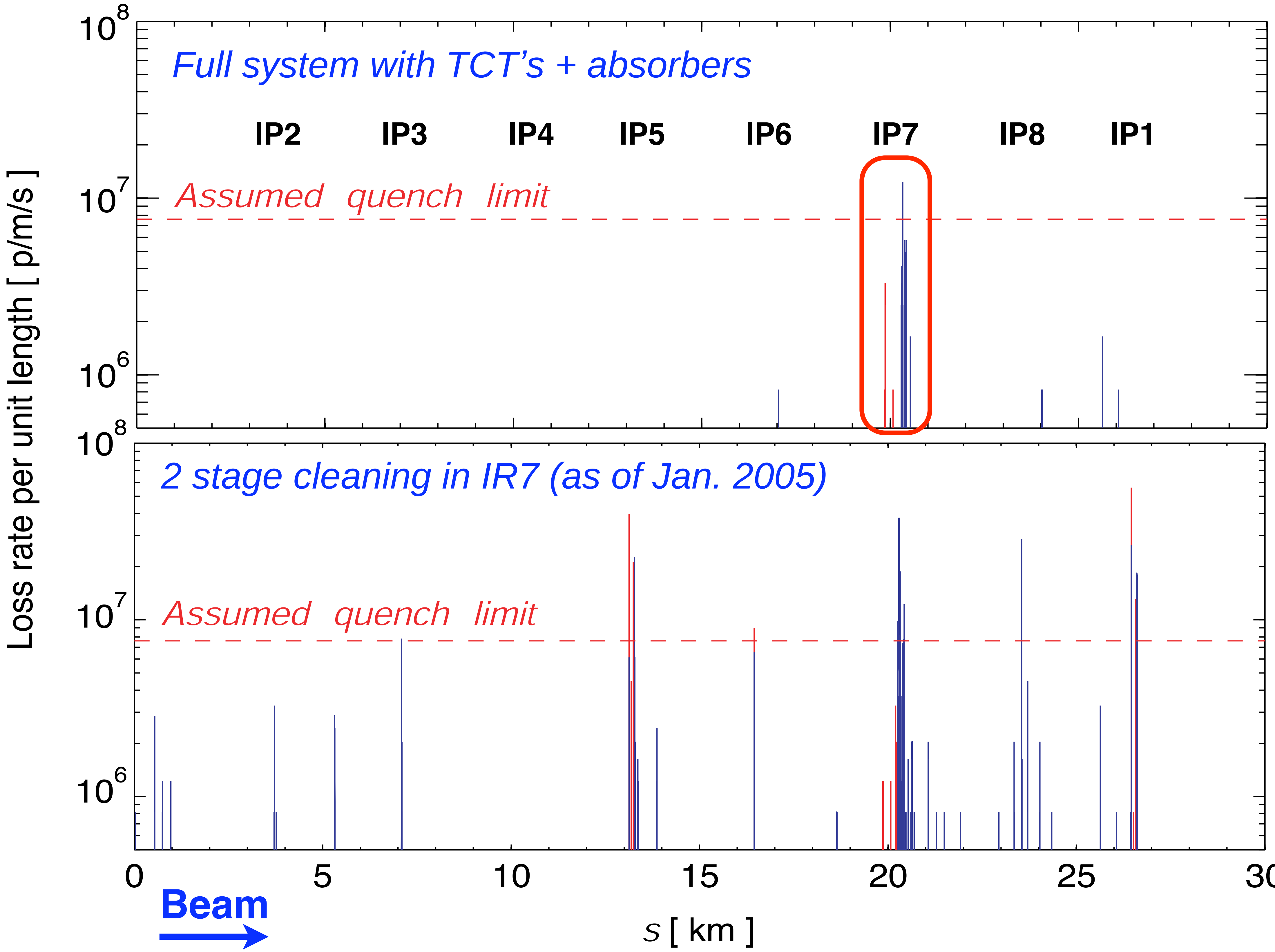


Black = okay
Controlled losses at the collimators

Blue = BAD!
Losses in cold aperture →quench

Only a few loss locations outside the collimators
(perfect machine)

Comparison with the previous system without shower absorbers and tertiary collimators (two-stage cleaning)

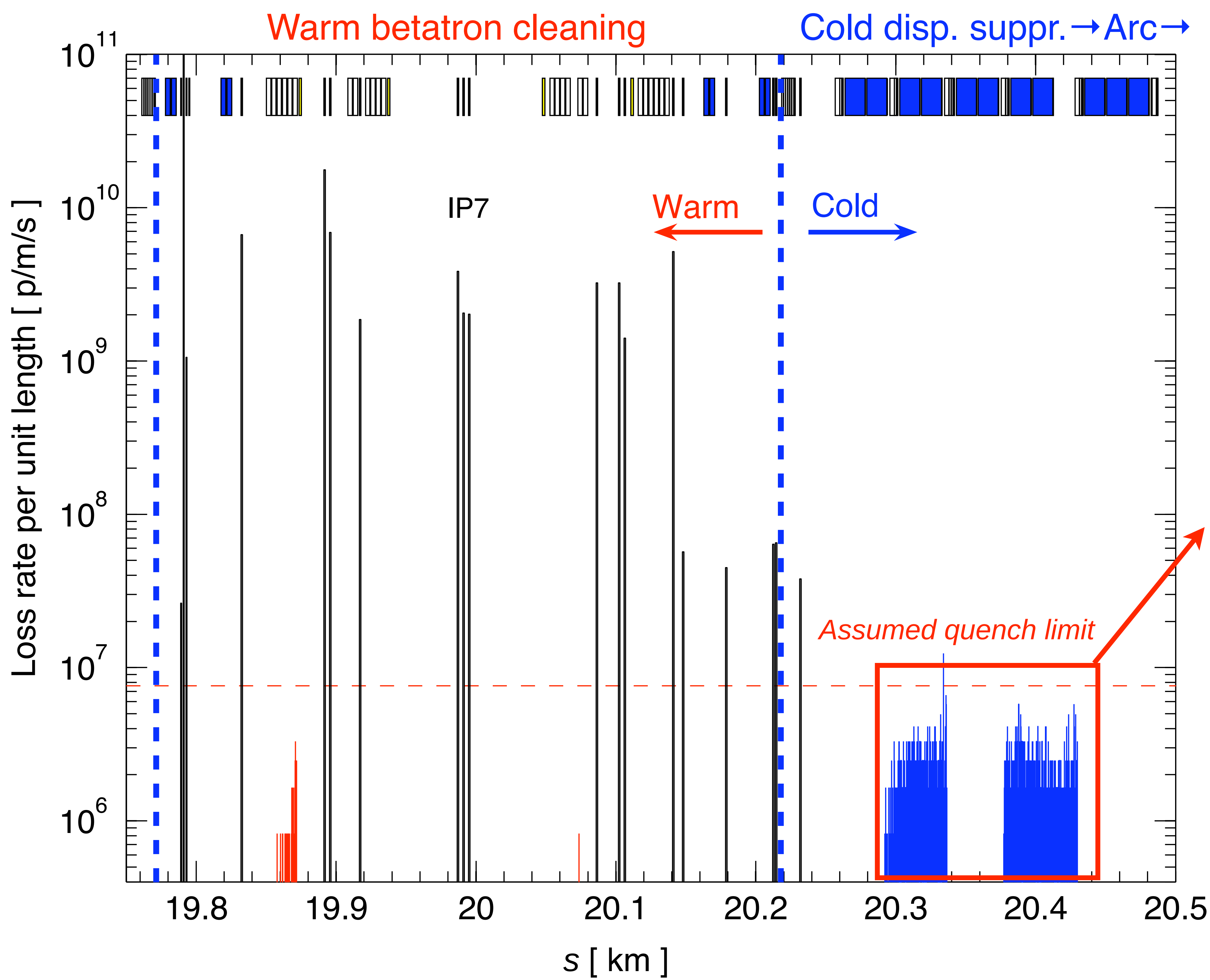


TCLA + TCT
→ Significant improvement in the IR's

Before
→ many losses outside collimators!

There are still losses above the quench limit!

Losses downstream of the betatron cleaning

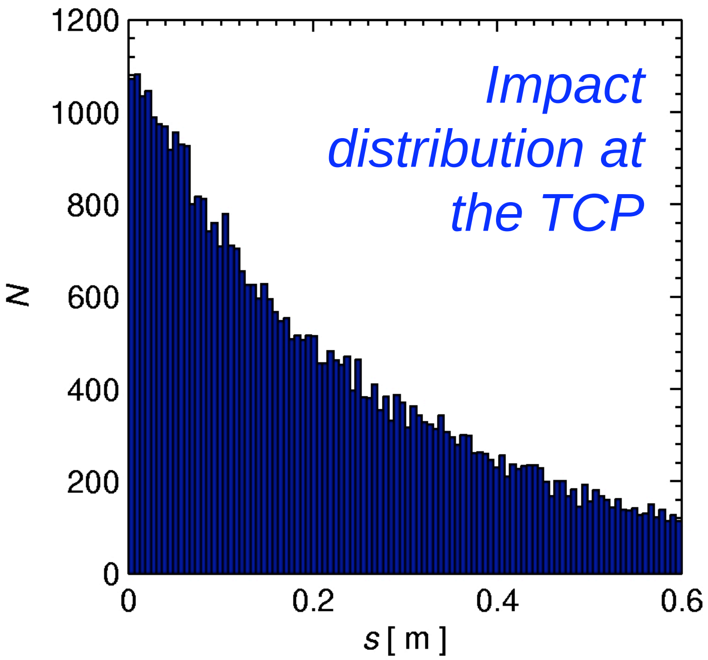


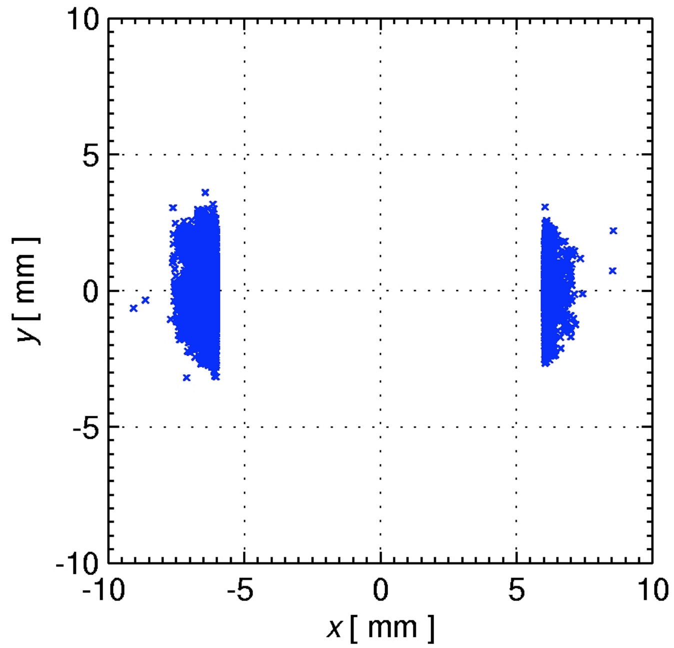
Particles with large δp/p and small β kick escape from the collimators!

With nominal intensity, the quench limit is reached.
Intrinsic limitation of the Carbon based system (low absorption)!

Energy deposition studies

Inelastic impacts inside collimators
➞input for energy deposition studies





QuickTime™ and a
3ivx D4 4.5.1 decompressor
are needed to see this picture.

Courtesy of V. Vlachoudis

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

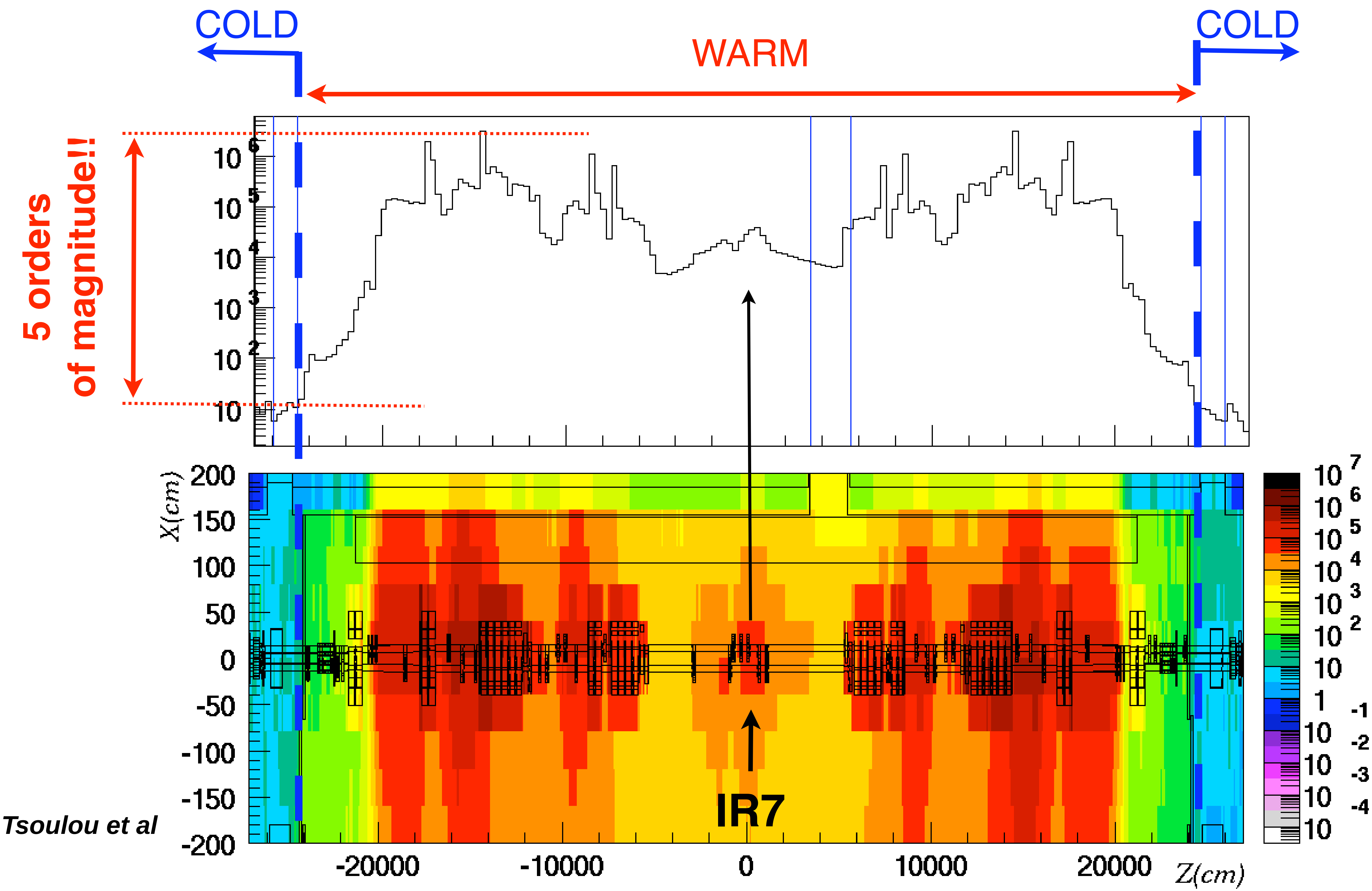
➞ Energy in the super-conducting magnets versus quench limit

➞ Estimate life time of warm magnets/electronics (passive absorbers)

➞ Optimize layout of insertion (e.g. *chicane* design)

➞ Quantify does to personnel (implications on the collimator design) and impact on the environment

Dose along the betatron cleaning



K. Tsoulou et al

Radiation is basically confined within the warm insertions!

Outline

- Introduction
- Collimation system layout
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- **System limitations and upgrades**
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Limitations of the Phase I collimation

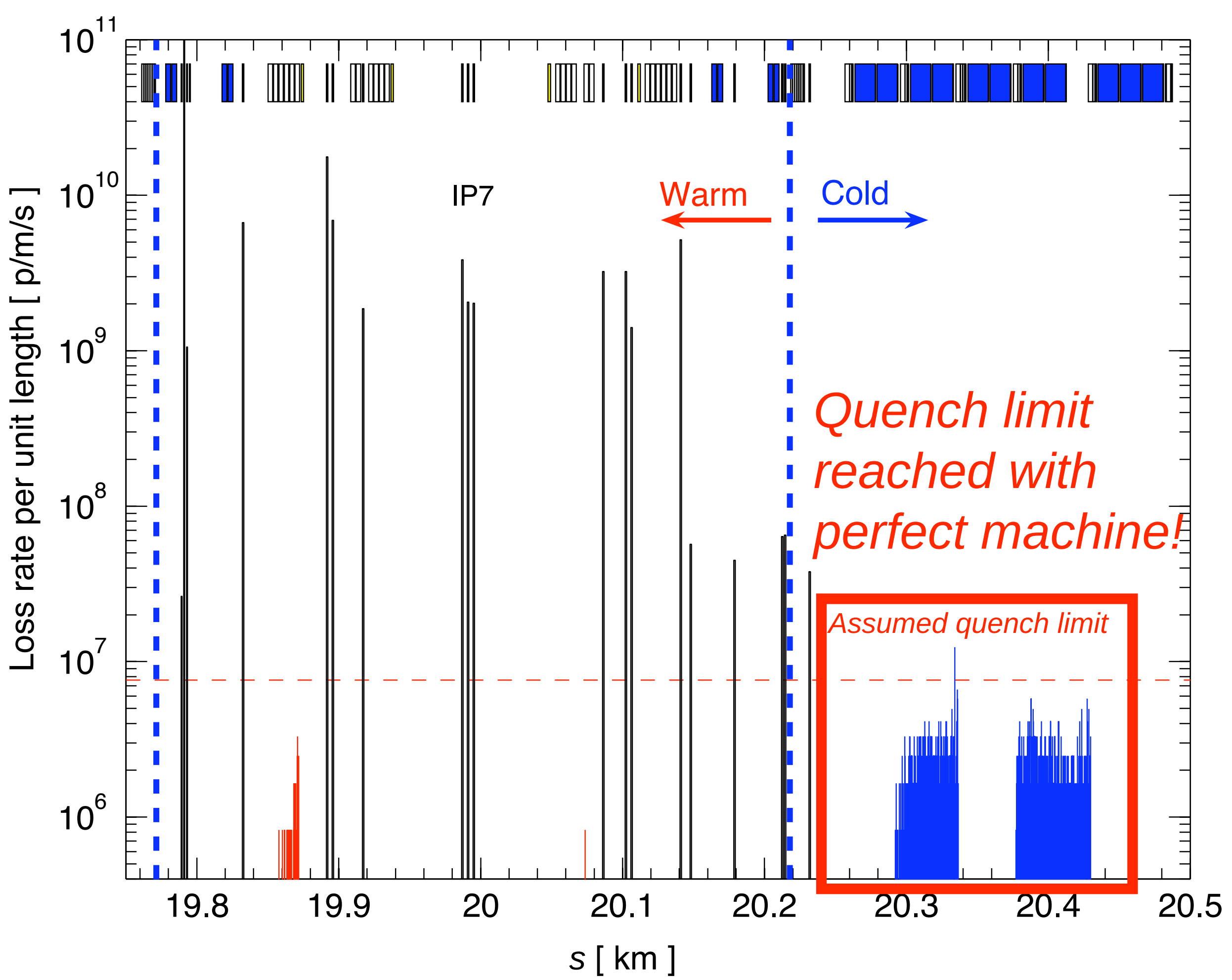
The proposed robust system (low Z) cannot achieve the I_{nom}:

⇨ Reduced efficiency (poor absorption of Carbon)

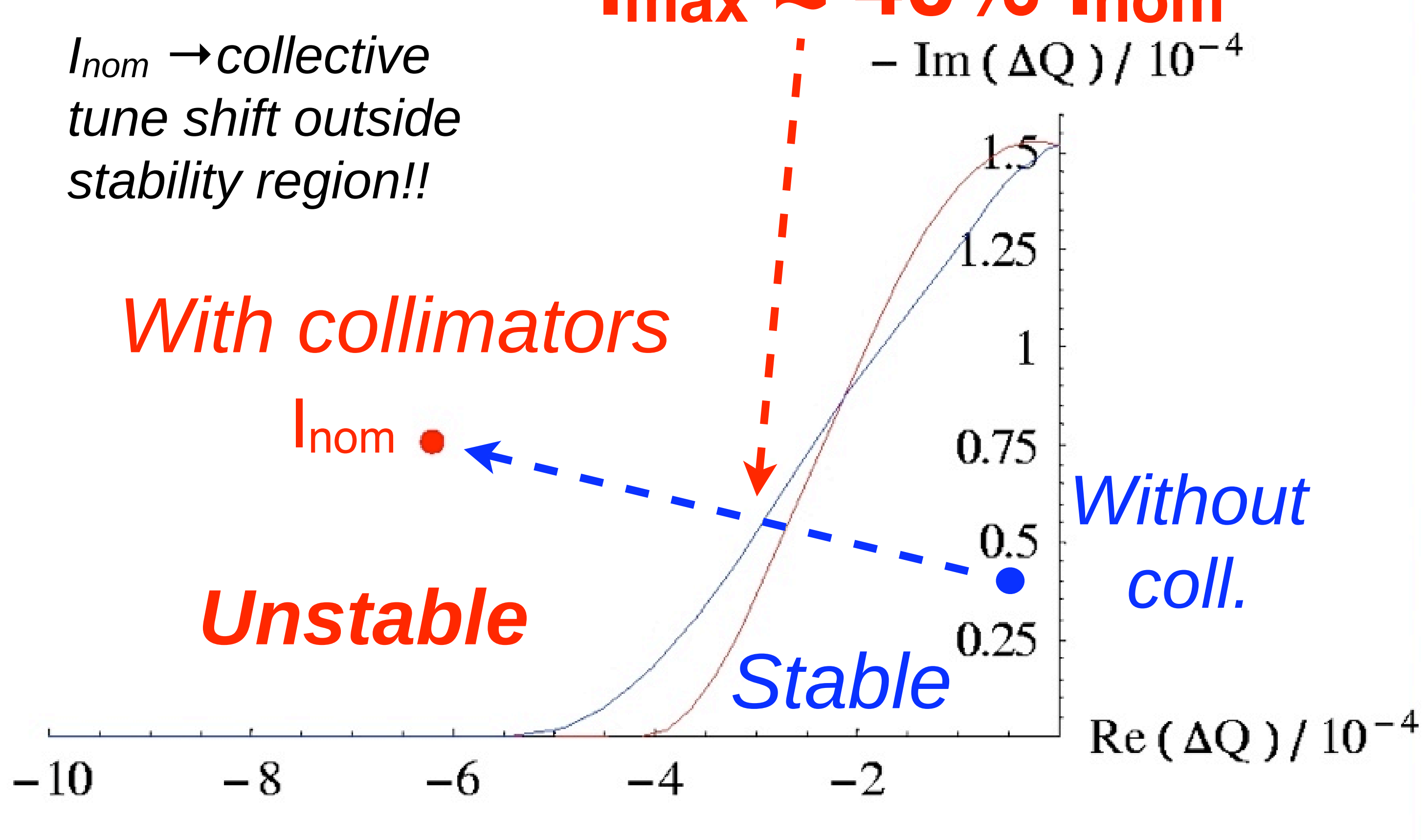
Losses downstream of IR7 close to quench limit for perfect machine

⇨ Large impedance (small gaps + large resistivity)

Severe beam instabilities at nominal intensity



$I_{max} \approx 40\%\ I_{nom}$



Courtesy of E. Métral, CERN-AB-ABP

Solution: use *high-Z* collimator material (metals) !!

Studies for system upgrades

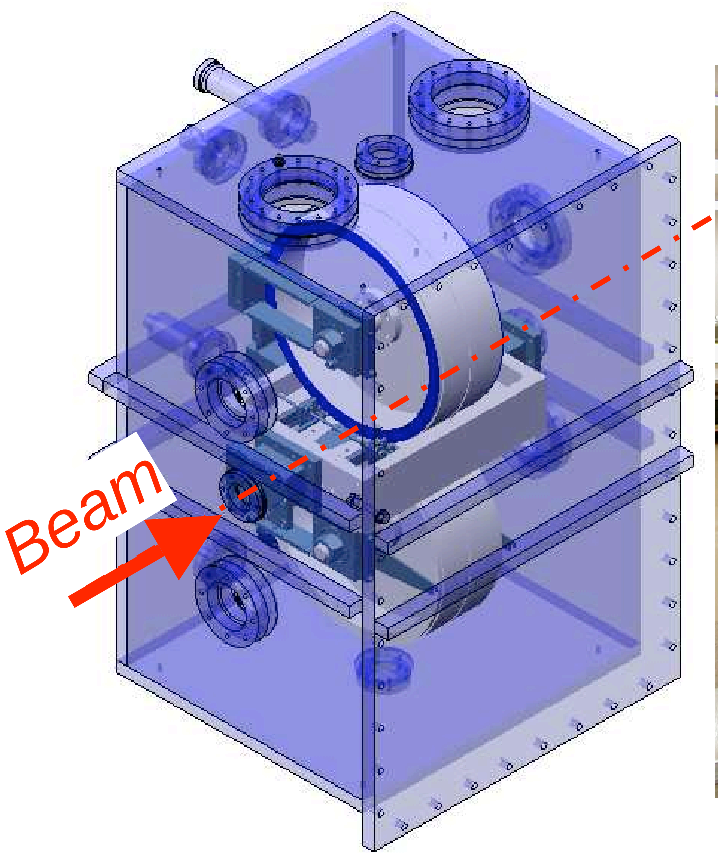
- ~50 space reservations in the LHC for additional collimators
- R&D for the ***Phase II Hybrid collimators*** has started!
- US-LARP program to build metallic consumable collimators!
- European program recently started to fund new studies

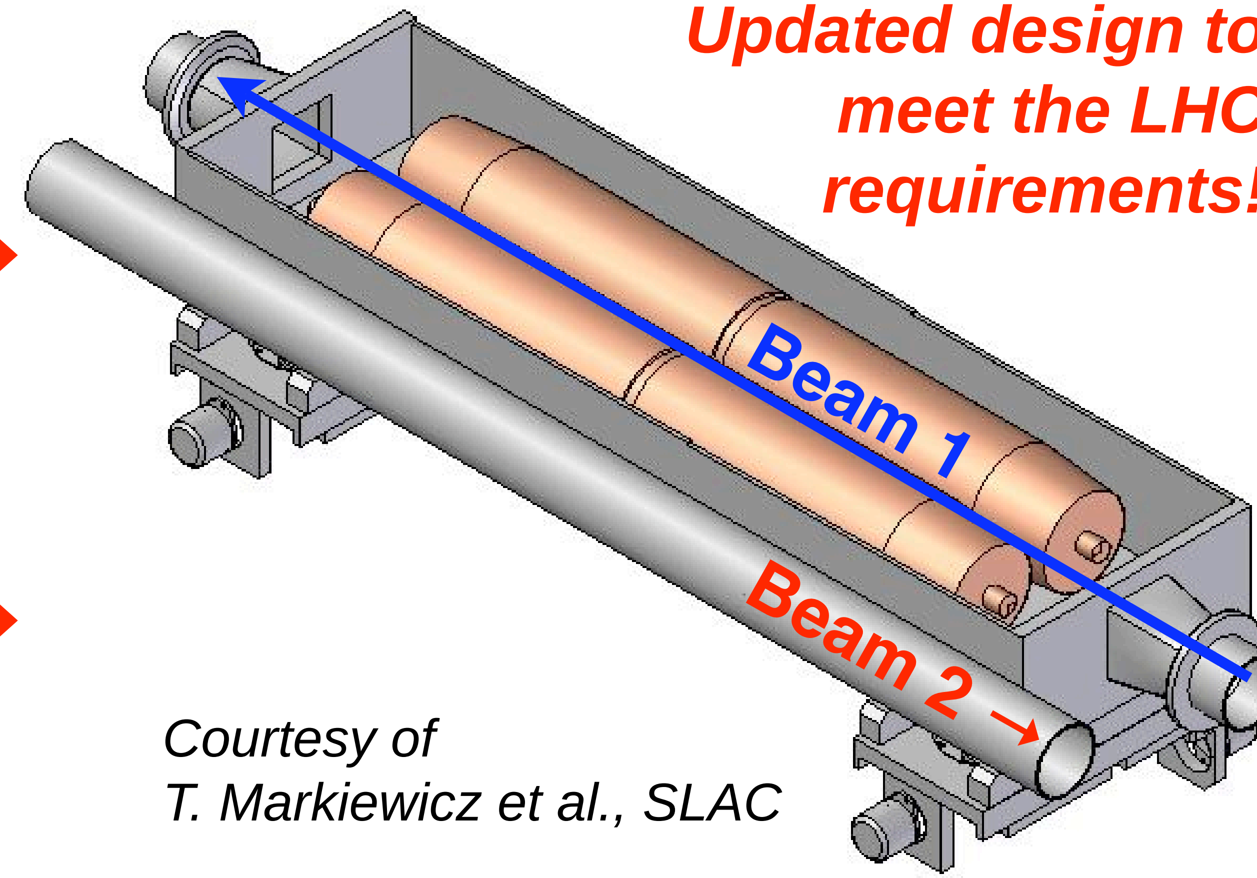
→ "The proposal aims at **significantly extending the present state-of-the-art** in high power and high efficiency collimators.
... extending the state of the art by another factor 5-10 beyond LHC phase 1 collimation, reaching the **1 GJ/mm^2 regime** with ultra-high efficiency collimation. The proposal includes phase 2 of LHC collimation but extends beyond by including novel concepts like crystals and R&D for overcoming specific limitations for ion operation."

Who wants to work with us on this challenging research topics?

US-LARP: LHC consumable collimator

Consumable rotary collimator for the NLC





Updated design to meet the LHC requirements!

Courtesy of
T. Markiewicz et al., SLAC

Time line:
(approved by DOE)

FY 2004: Introduction to project
FY 2005: Phase II CDR and set up of a collimator lab at SLAC
FY 2006: Design, construction & testing of **a mechanical prototype**
FY 2007: Design, construction & no-beam testing of **a beam test prototype**
FY 2008: Ship, Install, Beam Tests of beam test prototype in the LHC
FY 2009: Final drawing package for CERN
FY 2010: Await production & installation by CERN
FY 2011: Commissioning support

Conclusions

- LHC enters a **new territory** of hadron beam collimation!
- *Phased approach* = path towards ultimate LHC performance
- "Robustness" is the keyword for the Phase I system
  - → Multi-stage cleaning based on (mostly) Carbon collimators
  - → Mechanical design thoroughly assessed (beam + lab. tests)
  - → Expected cleaning inefficiency performance: **10^{-4}** !
  - → Impedance and cleaning limit the Phase I to **$< 1/2\ I_{nom}$**
- We are confident that we will handle the **~100 MJ regime**!
- Another step forward is needed to successfully tackle the **GJ/mm^2 regime** of nominal and ultimate LHC performance!