Collimation update plans

Stefano Redaelli, BE-ABP, on behalf of WP5

International Review of the HL-LHC Collimation System
11-12 February, 2018
CERN, Geneva (CH)

Introduction

The collimation system fulfils **several roles** in the LHC

- **Halo cleaning** versus quench limits
- Passive **machine protection**
  First line of defence against beam losses. Critical to allow small β^*.
- **Cleaning of physics debris** (collisions products)
  Avoid magnet quenches close to the experiments.
- Optimize **background** in the experiments
  Minimize the impact of halo losses on quality of detector's data.
- **Concentration of losses/activation** in controlled areas
  Ease maintenance by avoiding many distributed high-radiation areas.
- **Reduction total doses** on accelerator equipment
  Maximise lifetime of equipment exposed to radiation ware.
- Beam tail/halo **scraping, halo diagnostics**
  Control and probe the transverse or longitudinal shape of the beam.

Collimation challenges for the HL-LHC

Critical collimation upgrades needed to handle **~700 MJ !**

- ☑ **Improve the collimator impedance**

  Present carbon-based primary and secondary collimators are not compatible with stability requirements of HL beams.

- ☑ **Improve the collimation cleaning**

  Performance limited by "dispersive" losses for proton and ion beams.

- ☑ **New solutions in high-luminosity experiments**

  Collimation of incoming beam protection;
  Disposal of collision products for outgoing beams.

- ☑ **Improve operational efficiency**

  BPM collimator design, improved alignment and validation.
  More complex operational scenarios with levelling.

- ☑ **Control tail population and loss rates**

  Control primary beam losses with multi-MJ halo tails.

Crucial synergy with CONS: successful LHC upgrade relies on collimators not replaced within HL

Beam brightness

Beam intensity

Peak luminosity

Damage potential

Machine availability

(Recent) collimation upgrade reviews

General international collimation reviews

- External review 2013, mainly on dispersion suppressors
- External review on the overall upgrade for HL-LHC — TODAY

Hollow electron lenses for collimation

- Internal review in 2012
- External review on needs for halo control in 2016
- External technical review on readiness in 2017

Crystal collimation

- Crystal collimation day in 2018 (no formal review)

Three cost&schedule reviews

- 2015
- 2016 (new baseline for 11T dipole)
- 2018

LHC performance workshops “Chamonix”, combined to CMAC

- 2014, 2016 (general strategy)
- 2017 (hollow lenses)
- 2018 (essentially: present baseline)

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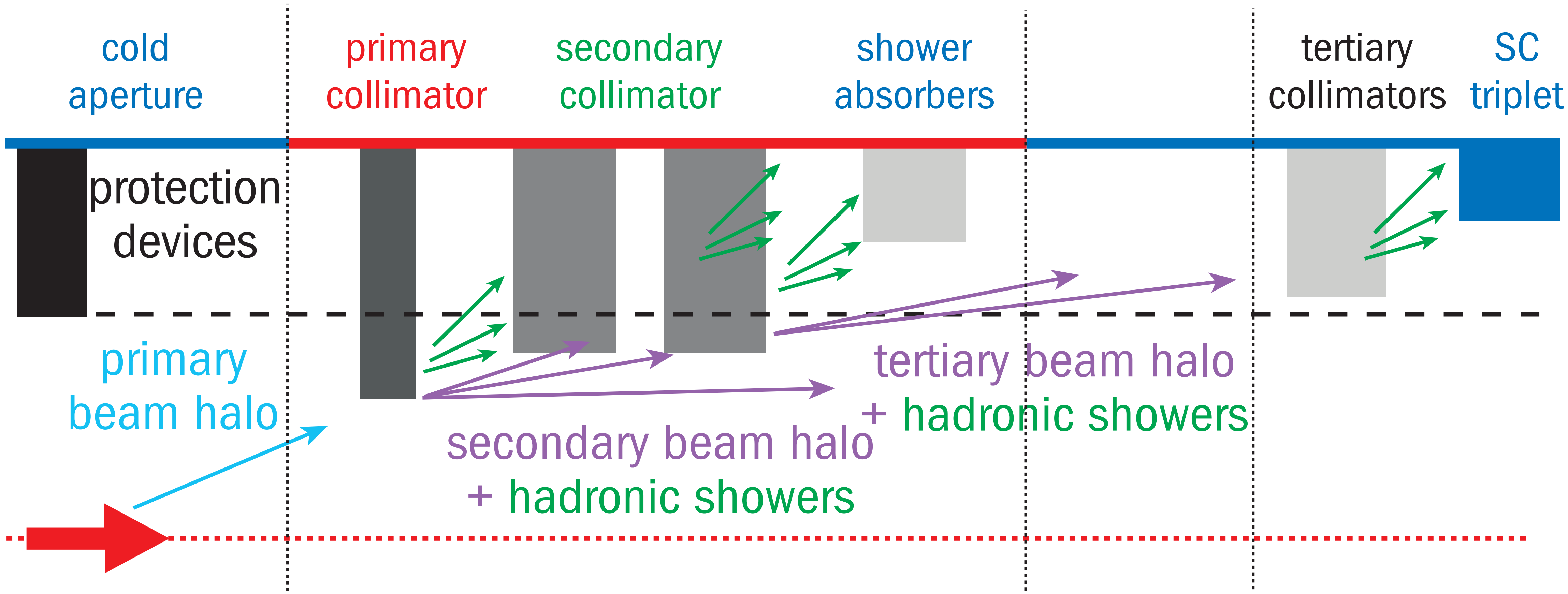
- **Crystal and hollow e-lenses**
- **Conclusions**

LHC multi-stage collimation



Three-stage cleaning in warm **cleaning insertions**: betatron (IR7) and off-momentum (IR3); local "tertiary" collimators at inner triplet.

Well-defined *collimation hierarchy* that integrates injection and dump protection collimators (as well as Roman pots). **Five stages**!

Machine aperture sets the scale for collimation hierarchy

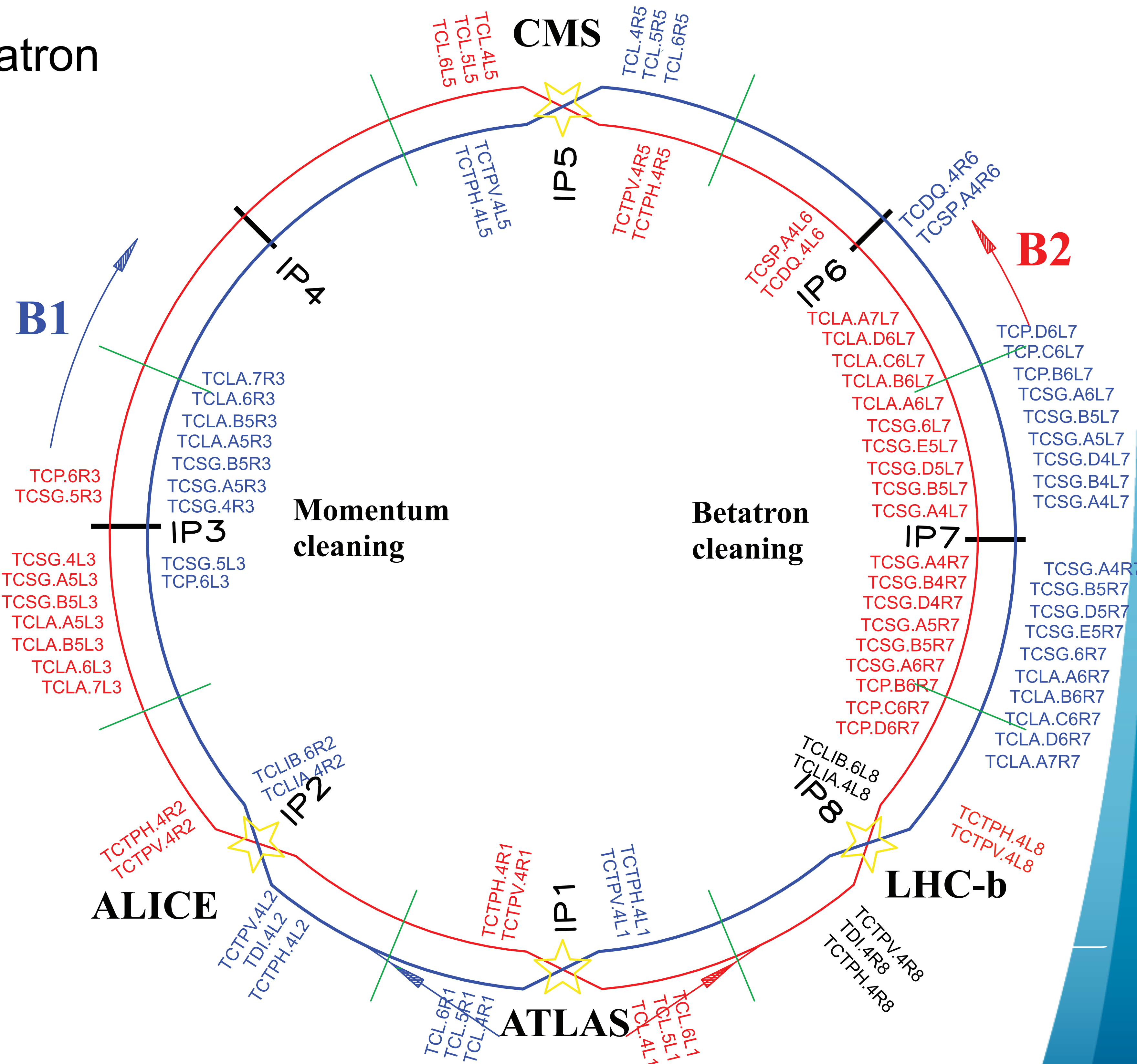
Critical beam-based alignment to determine local orbit and beam size.

LHC Collimation system in Run II

Dedicated insertions for betatron (IR7) and momentum (IR3) cleaning systems.

Cleaning of incoming beam in all experiments.

Physics debris collimation in the high-lumi IR1/5.



Total of 118 [was 108 in Run I] **collimators**
(108 [was 100] **movable).**

Nomenclature — i

<u>Betratron cleaning</u>

- Primary and secondary collimators and shower absorbers in IR7
- Tertiary collimators in IR1/2/5/8
- Passive collimators in IR7
- Dispersion suppressor collimators around IR7
- Crystal collimation (IR7) [not baseline]
- Hollow electron lenses (IR4) [not baseline]

<u>Off-momentum cleaning</u>

- Primary and secondary collimators and shower absorbers in IR3
- Passive collimators in IR3

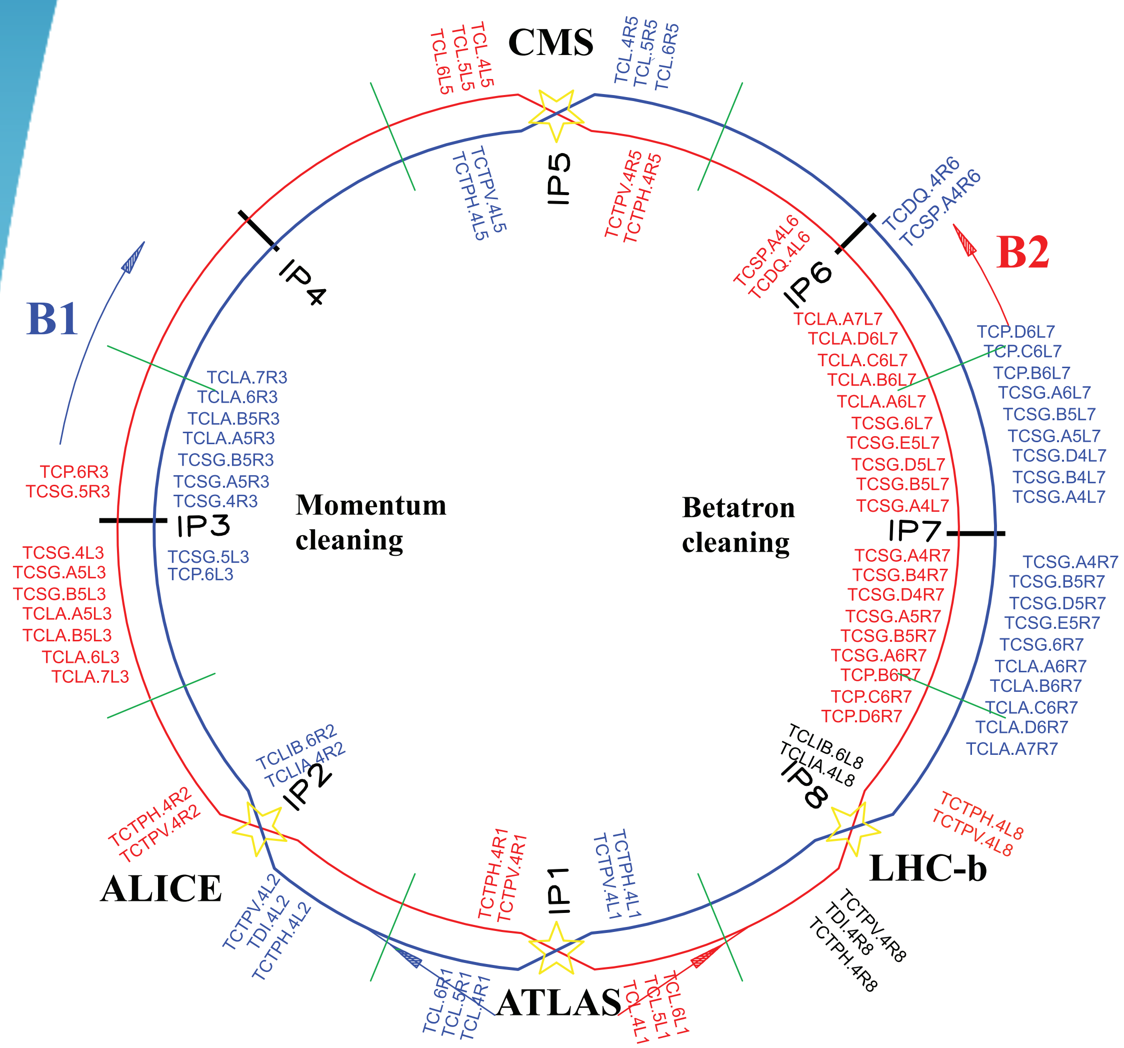
<u>Interaction region “IR” cleaning</u>

- Tertiary collimators *(though part of the betatron cleaning)*
- “Physics debris” cleaning of outgoing beams
- Fixed masks for physics debris

<u>Dispersion suppressor “DS” cleaning</u>

- Dispersion suppressor collimators around IR7
- Dispersion suppressor collimators around IR2 (ion interactions)

Nomenclature — ii



Present LHC collimators

TCP Primary (IR3/7)
TCSG Secondary (IR3/7)
TCLA Shower absorbers (IR3/7)
TCPC Crystal primary (IR7)
TCSP Secondary with BPM (IR6)
TCTP Tertiary with BPM (IR1/2/5/8)
TCL Physics debris (IR1/5)
TCAP (A, B, C, D) Fixed masks (IR3/7)

New ones beyond LS2 (HL-LHC+Cons.)

TCLD Dispersion suppressor (with BPM)
TCPPM Primary: BPM+new material
TCSPM Second.: BPM+new material
TCTPM Tertiary: BPM+new material
TCLP Physics debris + BPM
TCLPX, TCTPXH/V New TCL/TCT in the recombination regions (with BPM)
TCAPM, TCLM Fixed masks IR1/5/7

Collimator material names:

CFC (fibre-reinforced carbon); Inermet180: tungsten heavy alloy (often “W”); Glidcop: copper alloy; MoGr: Molybdenum-Graphite; CuCD: Copper-Diamond

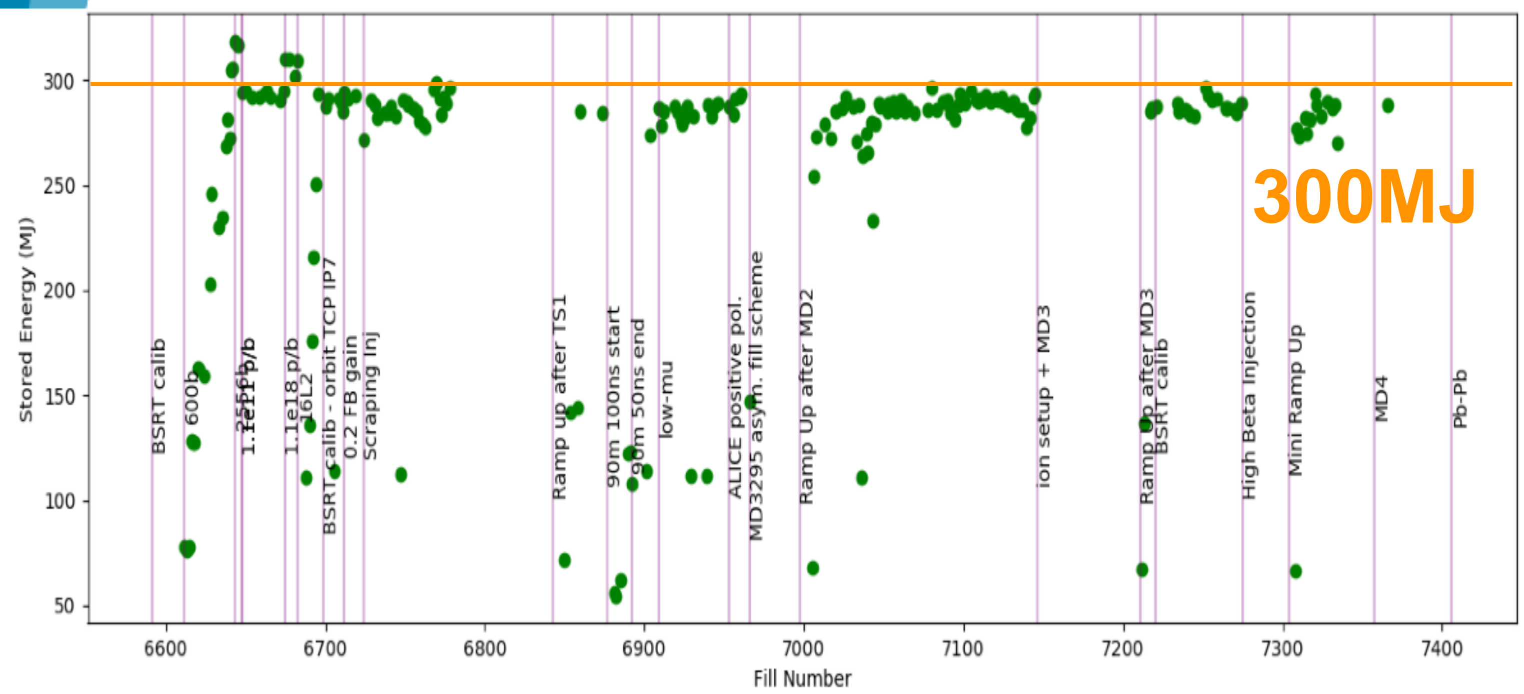
Nomenclature — iii

List of movable collimators in the LHC ring

Functional type	Name	Plane	Number	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorber IR3	TCLA	H, V	8	Inermet 180
Primary IR7	TCP	H, V, S	6	CFC
Secondary IR7	TCSG	H, V, S	22	CFC
Absorber IR7	TCLA	H, V, S	10	Inermet 180
Tertiary IR1/IR2/IR5/IR8	TCTP	H, V	16	Inermet 180
Physics debris absorbers IR1/IR5	TCL	H	12	Cu, Inermet180
Dump protection IR6	TCDQ	H	2	CFC
	TCSP	H	2	CFC
Injection protection (transfer lines)	TCDI	H, V	13	Graphite
Injection protection IR2/IR8	TDI	V	2	hBN, Al, Cu/Be[1]
	TCLI	V	4	Graphite, CFC
	TCDD	V	1	Copper

System performance in 2018

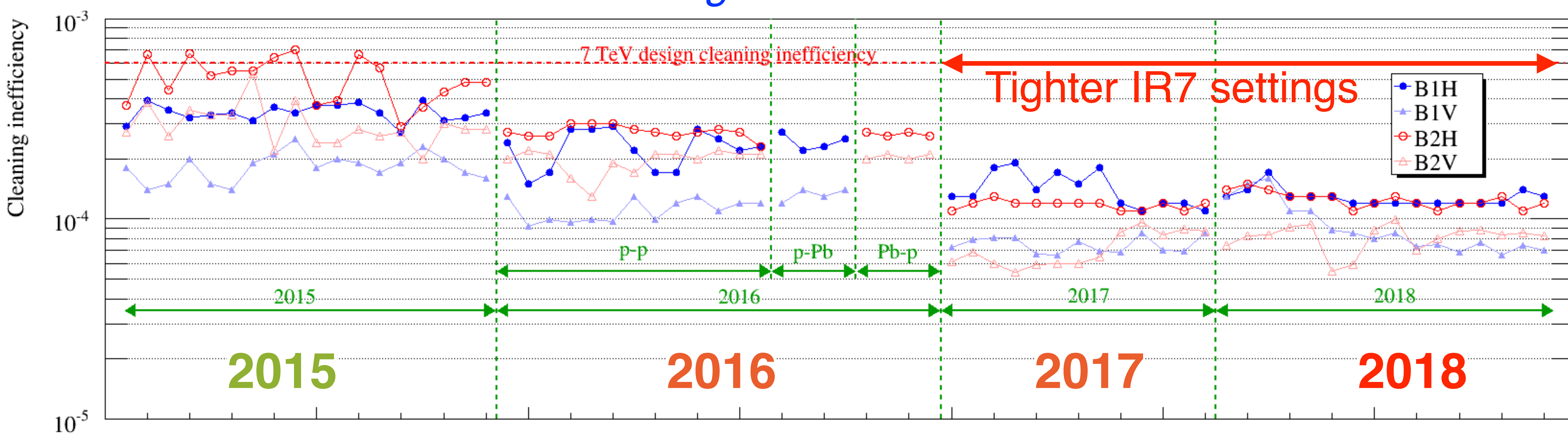
Stored beam energy in 2018 at 6.5 TeV



Handling regularly a **300MJ** stored beam energy, and still **no quenches** from collimation losses!

1. Cleaning inefficiency ~1e^{-4}
2. Experiment backgrounds **low**
3. **Excellent system availability**!
4. More than **200 loss maps** executed/analysis (+ for MDs).

Collimation cleaning in IR7 for the whole Run II



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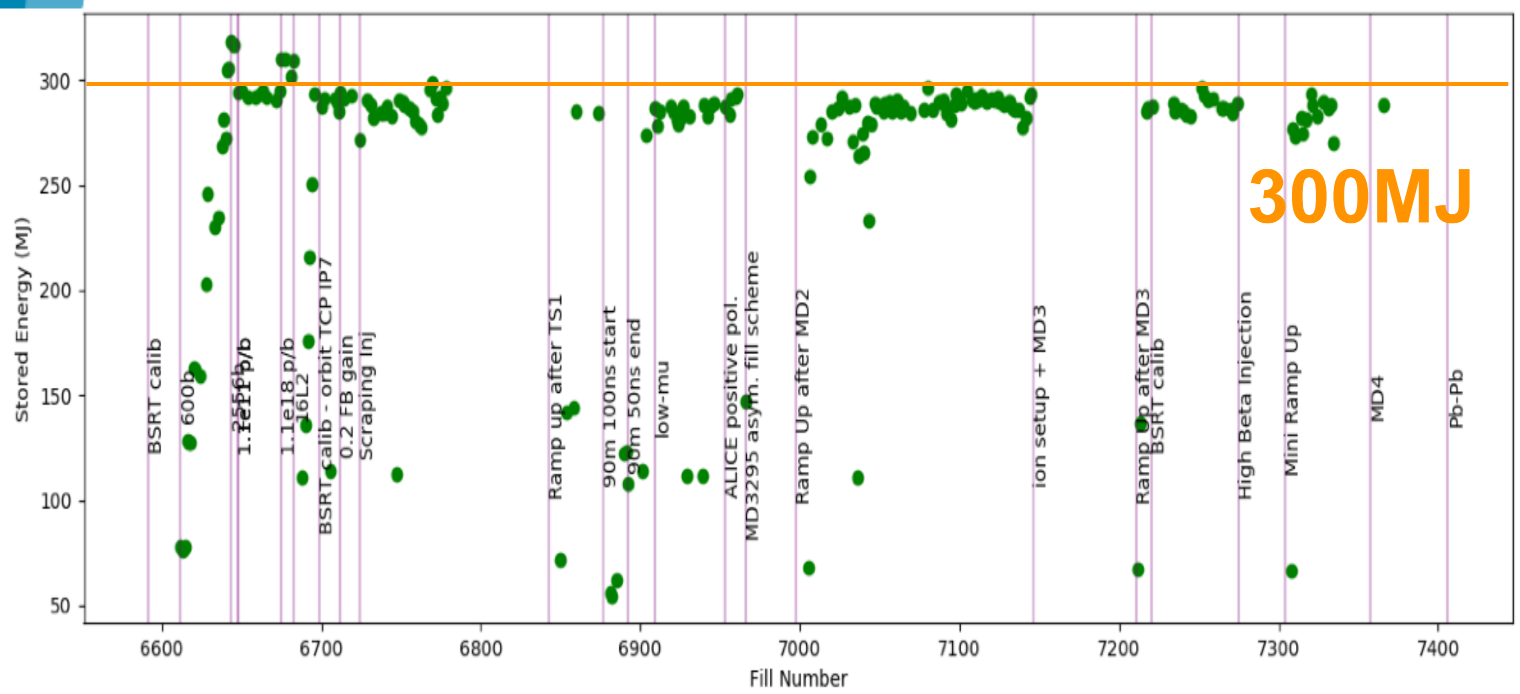

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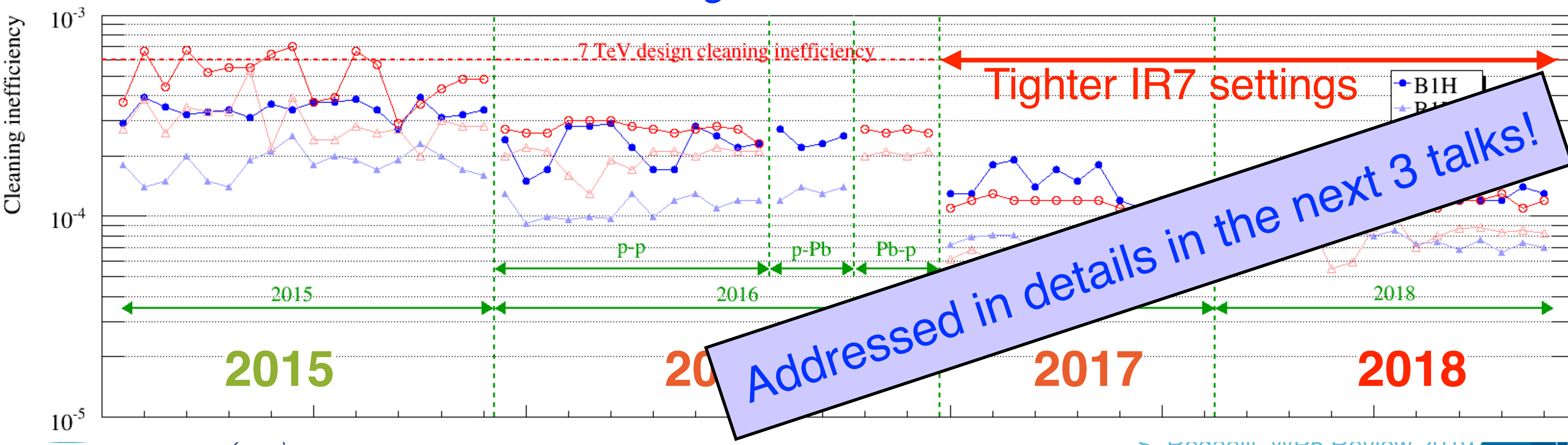
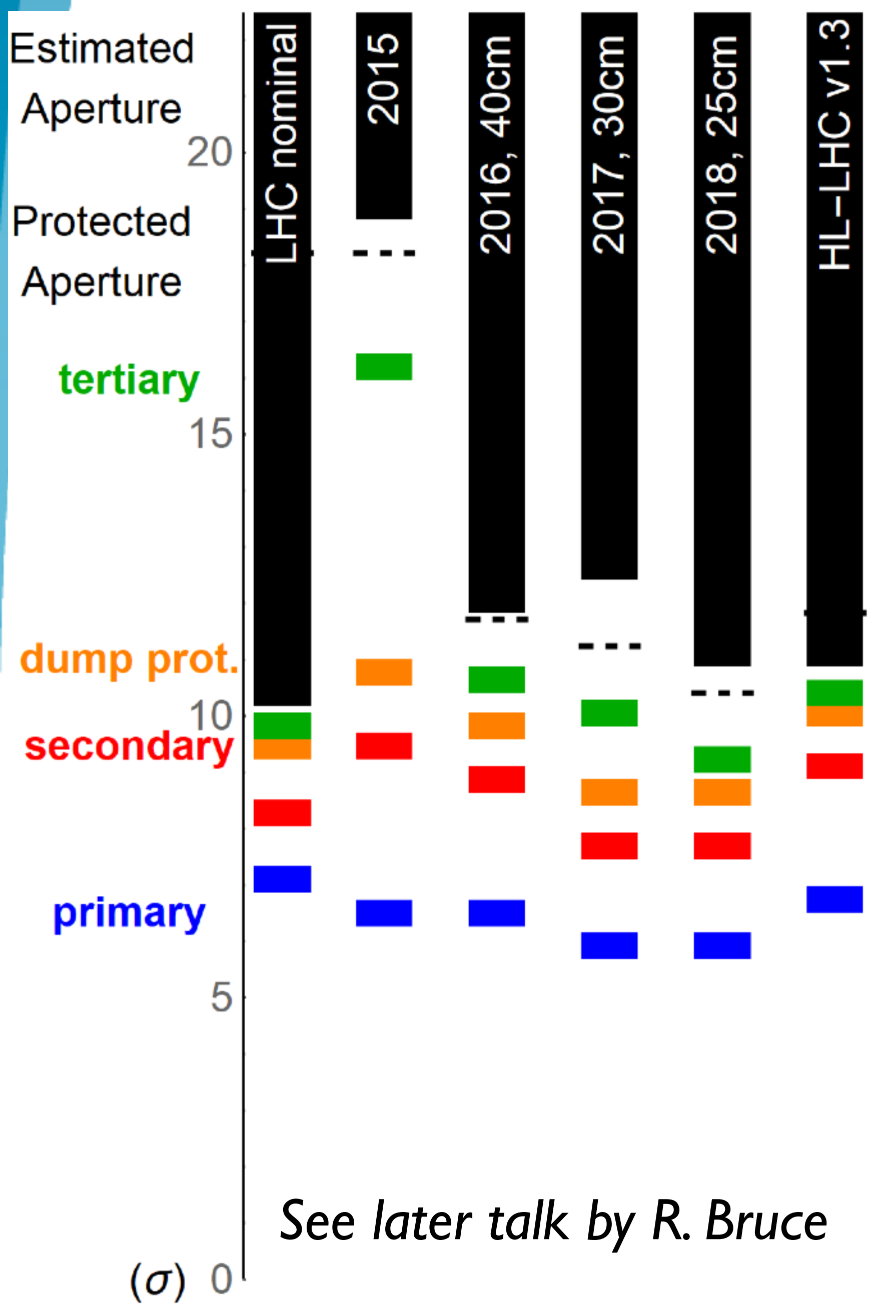


Considerations on operational feedback



See later talk by R. Bruce

- Can operate reliably with tight collimator settings.
- Very robust performance of the system with no loopholes identified for cleaning and aperture protection.
- Collimation cleaning good: close to simulations. No evident issue of backgrounds from halo losses.
- Excellent machine stability (orbit, optics): one single alignment per year sufficient!
- Excellent performance of BPM collimator design.
- With the present collimators (settings larger than design in IR7) and with a well tuned machine, nominal LHC beams with ~1.1e11p/bunch are stable: damper performance, operation with high Q' and octupoles, impedance-optimised settings for small beta*, … (but not without risks).
- Dispersion suppressors remain the critical loss locations around the ring.
- Operational experience limited at ~1/2 target bunch intensity.

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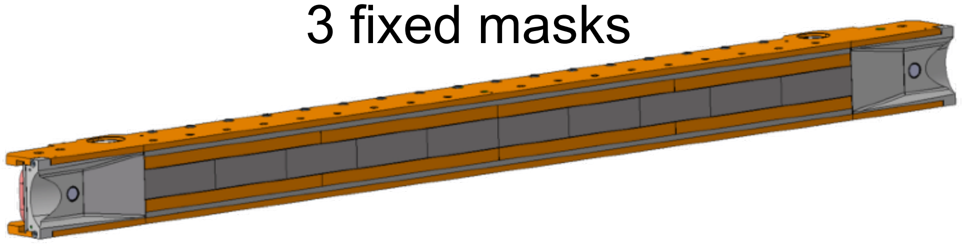
Four pillars of collimation upgrade

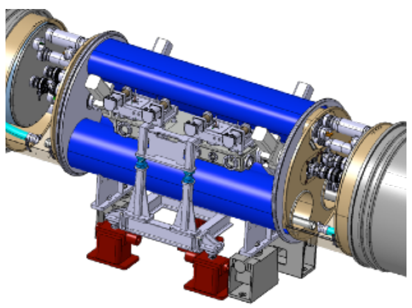
- **New interaction region (IR) collimation**
  Re-design layouts of in-coming and out-going collimation for the new high-luminosity insertions of HL-LHC
- **Low-impedance reduction in betatron cleaning**
  Reduce contribution from present primary and secondary collimators
- **Dispersion suppressor (DS) cleaning improvement**
  Improve DS collimation, with or without 11T dipoles
- **Collimation consolidation**
  Renew primary collimators for higher reliability, faster alignment;
  New collimator controls by LS3;
  Maintenance/replacement of the rest of the system (IR2/3/8, ….).

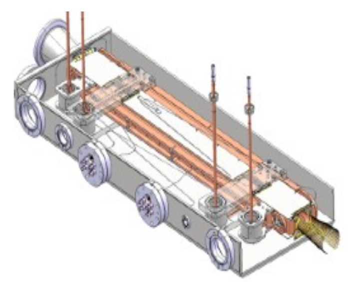
Collimation HL-LHC upgrade baseline

Completely new layouts
Novel robust material: CuCD
IR1+IR5, per beam:
- 4 tertiary collimators (TCTs)
- 3 physics debris collimators
- 3 fixed masks

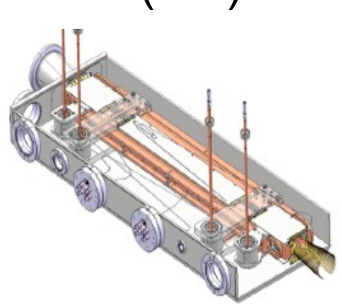


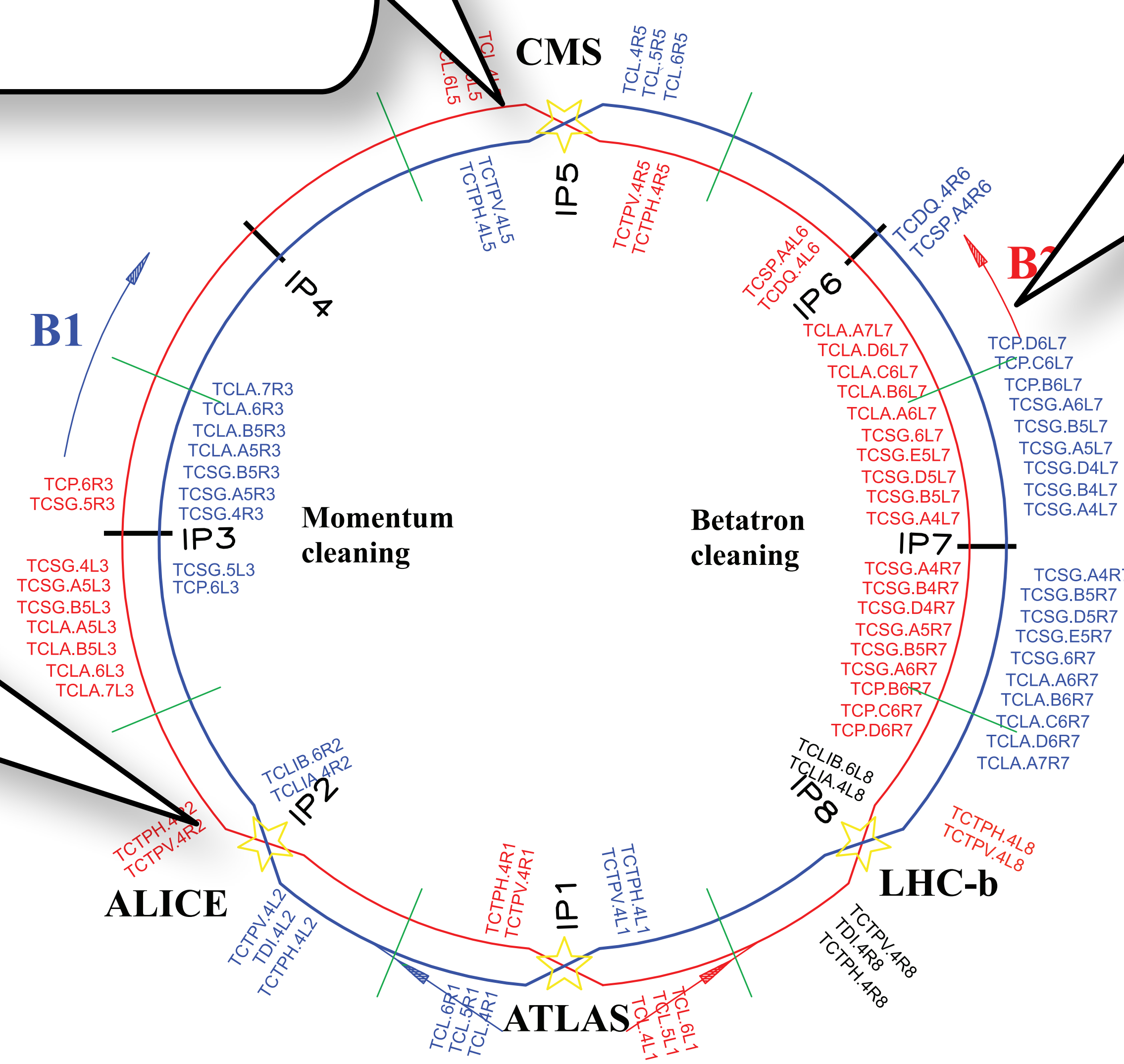
Cleaning: DS coll. + 11T dipoles, 1 unit per beam



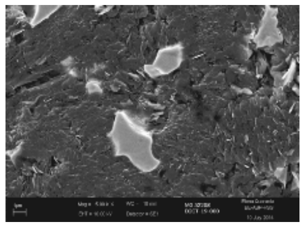


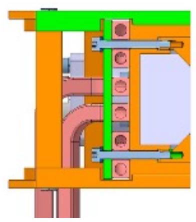
Ion physics: dispersion suppressor (DS) collimation

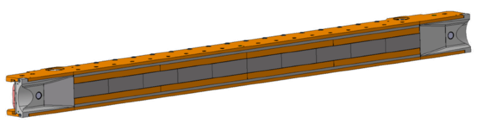




9 low-impedance, high robustness secondary collimators: coated MoGr







WP5 deliverables

- **Collimation upgrades in the second long shutdown (LS2)**
  — *4 (+1 spare) dispersion suppressor collimators (TCLD), around IR2/7*
  — *8 (+2) low-impedance collimators (TCSPM), IR7*
  — *procurement of the low-impedance material for 3 of the of 4 (+1) primary collimators built under Consolidation.*
- **Collimation upgrades in the third long shutdown (LS3)**
  — *10(+2) low-impedance collimators (TCSPM)*
  — *12(+2) tertiary collimators (TCTPM, TCTPXH/V)*
  — *8(+2) physics debris collimators (TCLP, TCLPX)*
  — *12(+3) fixed masks (TCLM)*
- **Prototypes and testing of baseline items**
  — *Prototypes for each major design changes: TCLD, TCSPM, new 'X' designs.*
  — *Validation without/with beams (HiRadMat, prototype in the LHC, irradiation…)*
- **R&D on non-baseline items: crystals and hollow lens**
  — *Crystal collimation test stand in IR7*
  — *Electron beam components (guns, cathodes, …)*
  — *4 collimators with wire for beam-beam long range studies (with WP13)*
  — *…*

WP5 deliverables

- **Collimation upgrades in the <u>second long shutdown</u> (LS2)**
  - *4 (+1 spare) dispersion suppressor collimators (TCLD), around IR2/7*
  - *8 (+2) low-impedance collimators (TCSPM), IR7*
  - *procurement of the low-impedance material for 3 of the of 4 (+1) primary collimators built under Consolidation.*
- **Collimation upgrades in the <u>third long shutdown</u> (LS3)**
  - *10(+2) low-impedance collimators (TCSPM)*
  - *12(+2) tertiary collimators (TCTPM, TCTPXH/V)*
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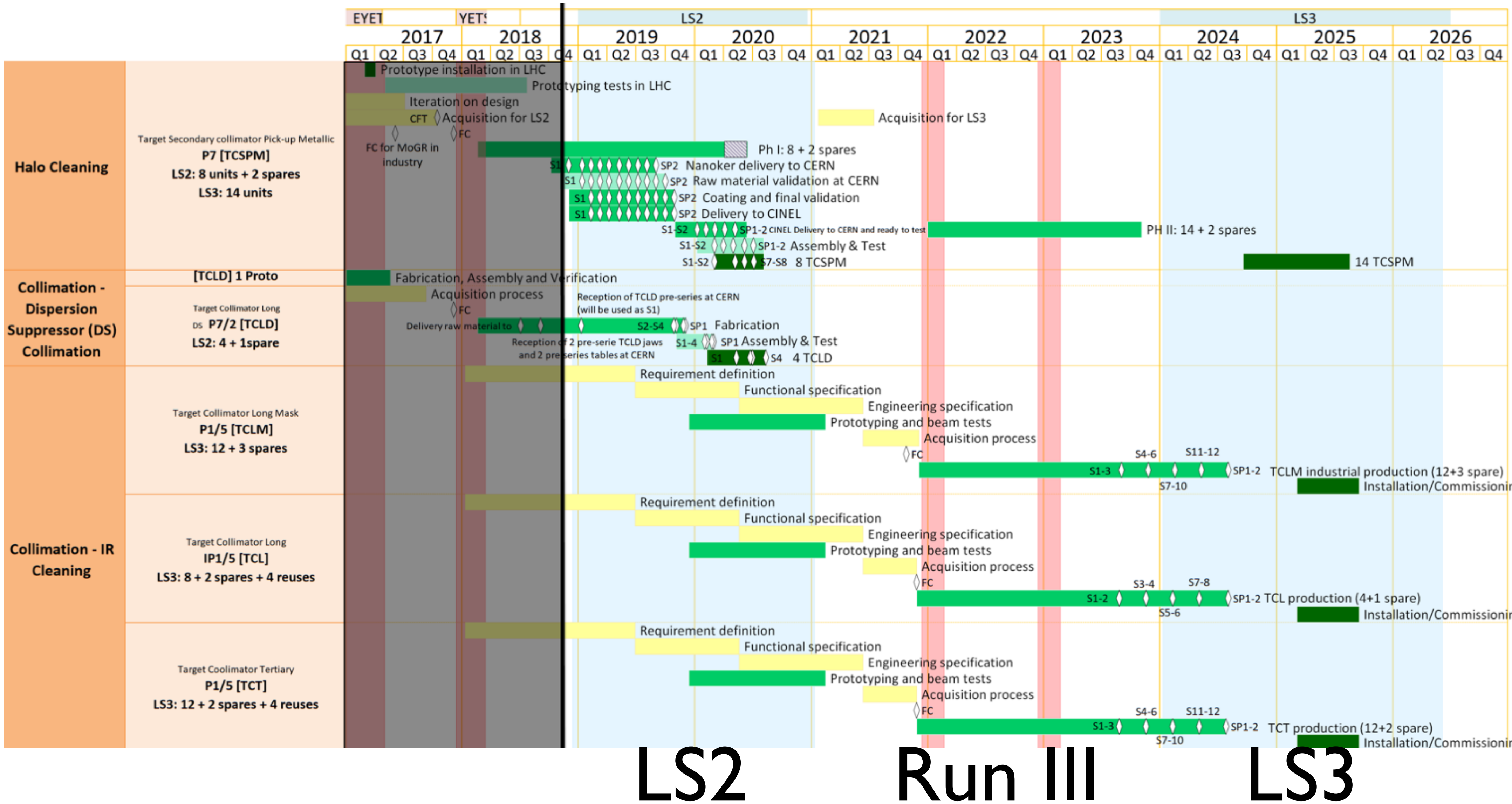
  - *…*

More details in the backup slides.

WP5 upgrade master plan

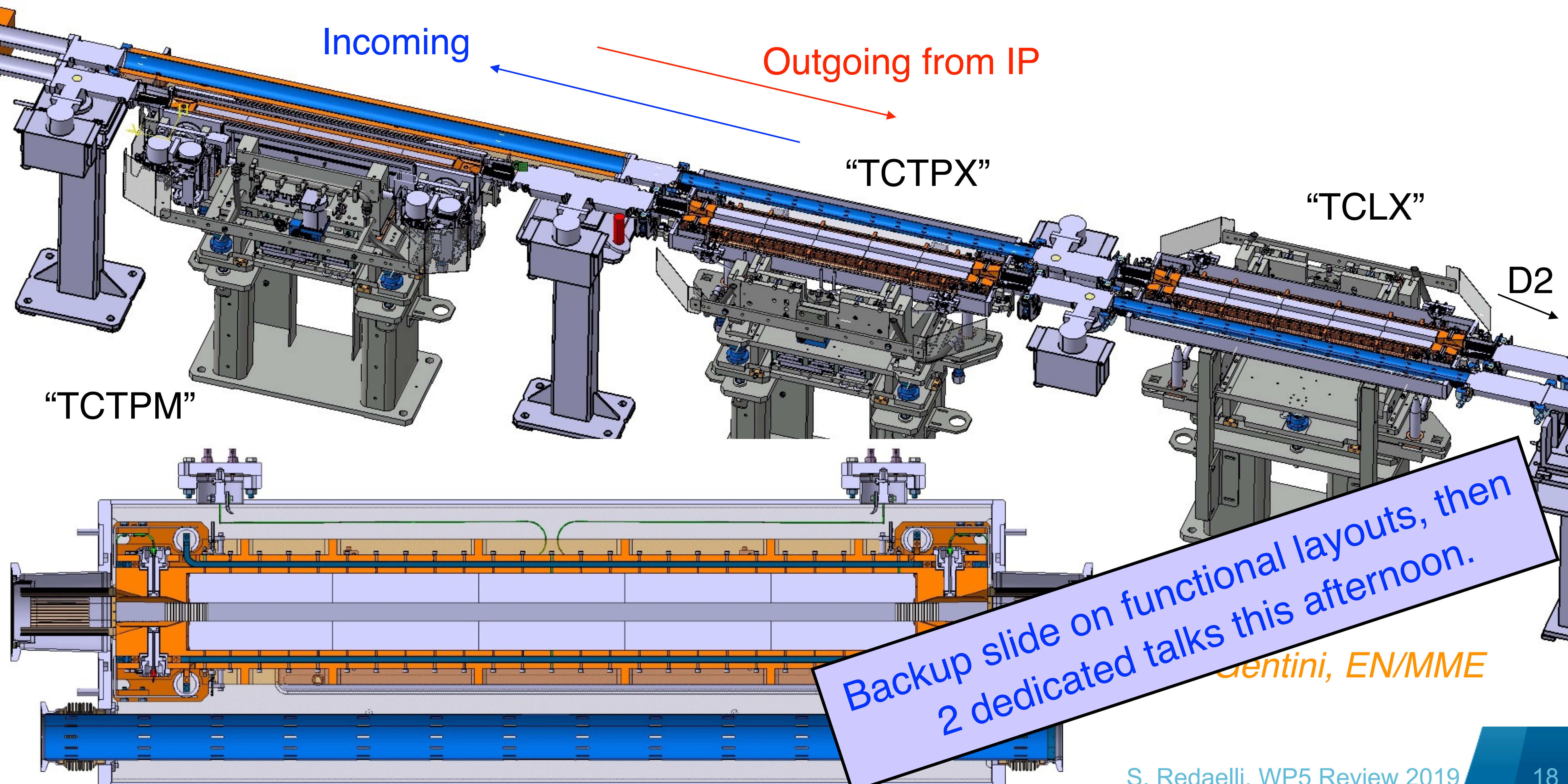


<u>Key aspects:</u>

- New interaction regions of ATLAS/CMS done in LS3
- Two “phases” of the low-impedance upgrade in IR7
  - *Largest contributors to IR7 impedance addressed in LS2*
  - *Completion of upgrade in LS3, after beam experience in Run III*
- Dispersion suppression cleaning completed in LS2 (IP2 + IP7)

Collimation in new IR1/IR5

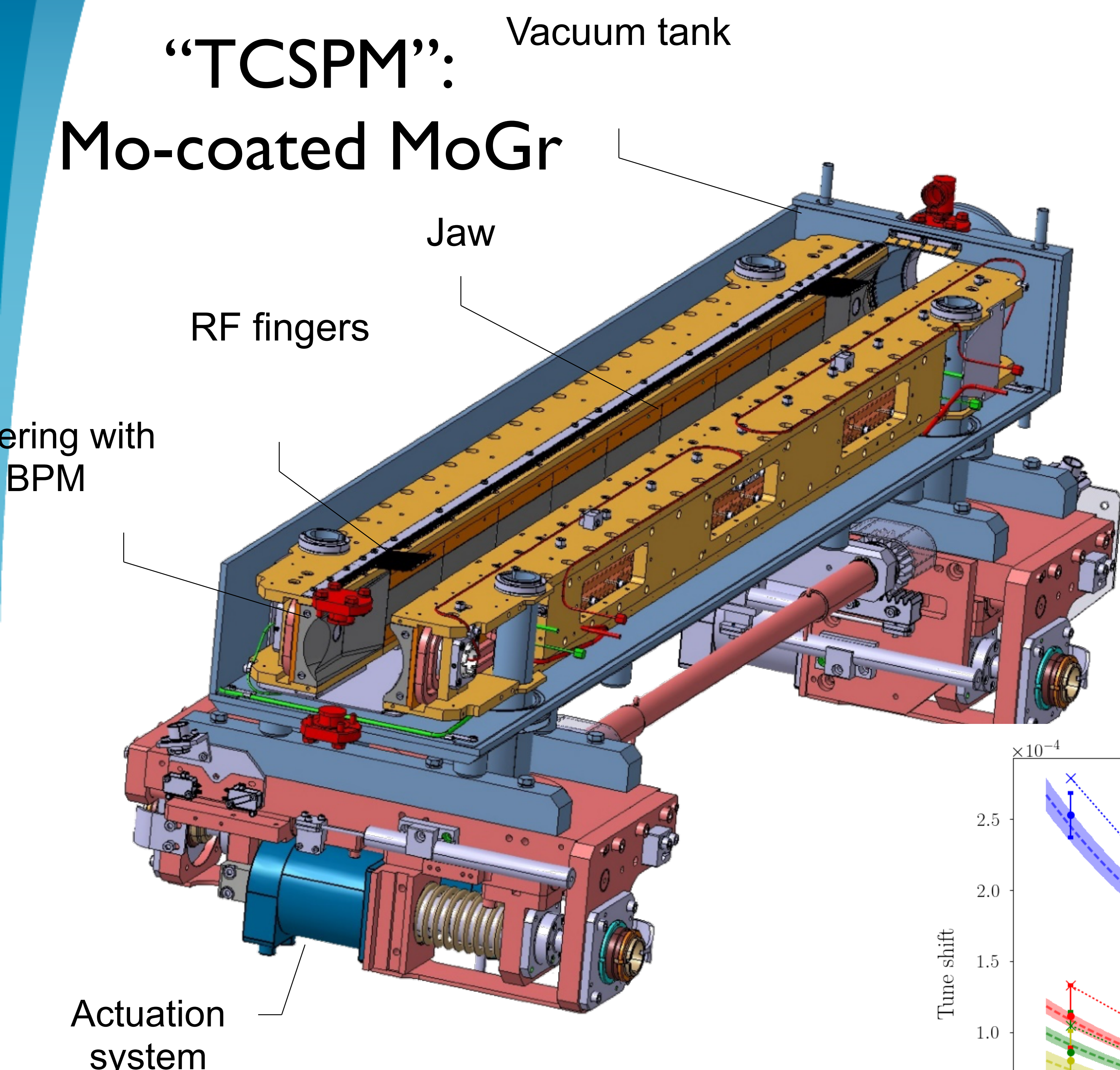
- Complex integration in recombination region: larger β* and thicker jaws
- New “2-in-1” design for horizontal collimators: common tank for both beams.
- Adequate protection of aperture for the β* = 15 cm requires an additional pair of TCT collimators in from of the Q5 (in addition to the one at the triplet)
- Detailed designs still to be finalized, in time for LS3.



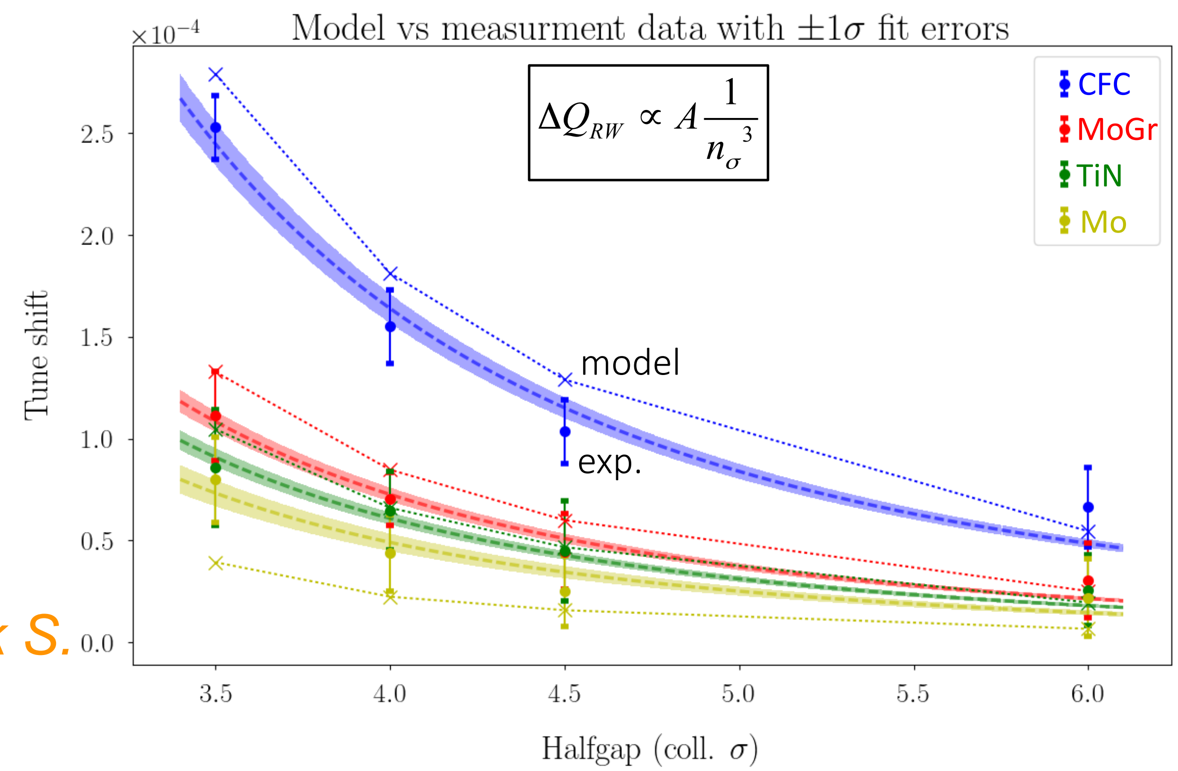
Backup slide on functional layouts, then 2 dedicated talks this afternoon.

New low-impedance secondary collimator

“TCSPM”: Mo-coated MoGr



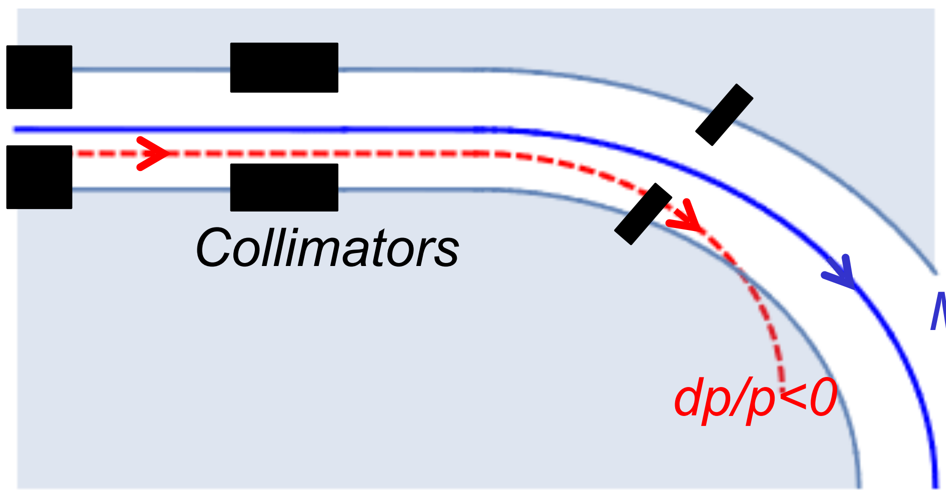
- **Various iterations** on the number of secondary collimators to be upgraded with the new design.
- Present baseline: 9/11 secondaries to be upgrade (4 in LS2) per beam, with coated MoGr.
- Same design used for primary collimators, jaw of MoGr (no coating).
- … tion

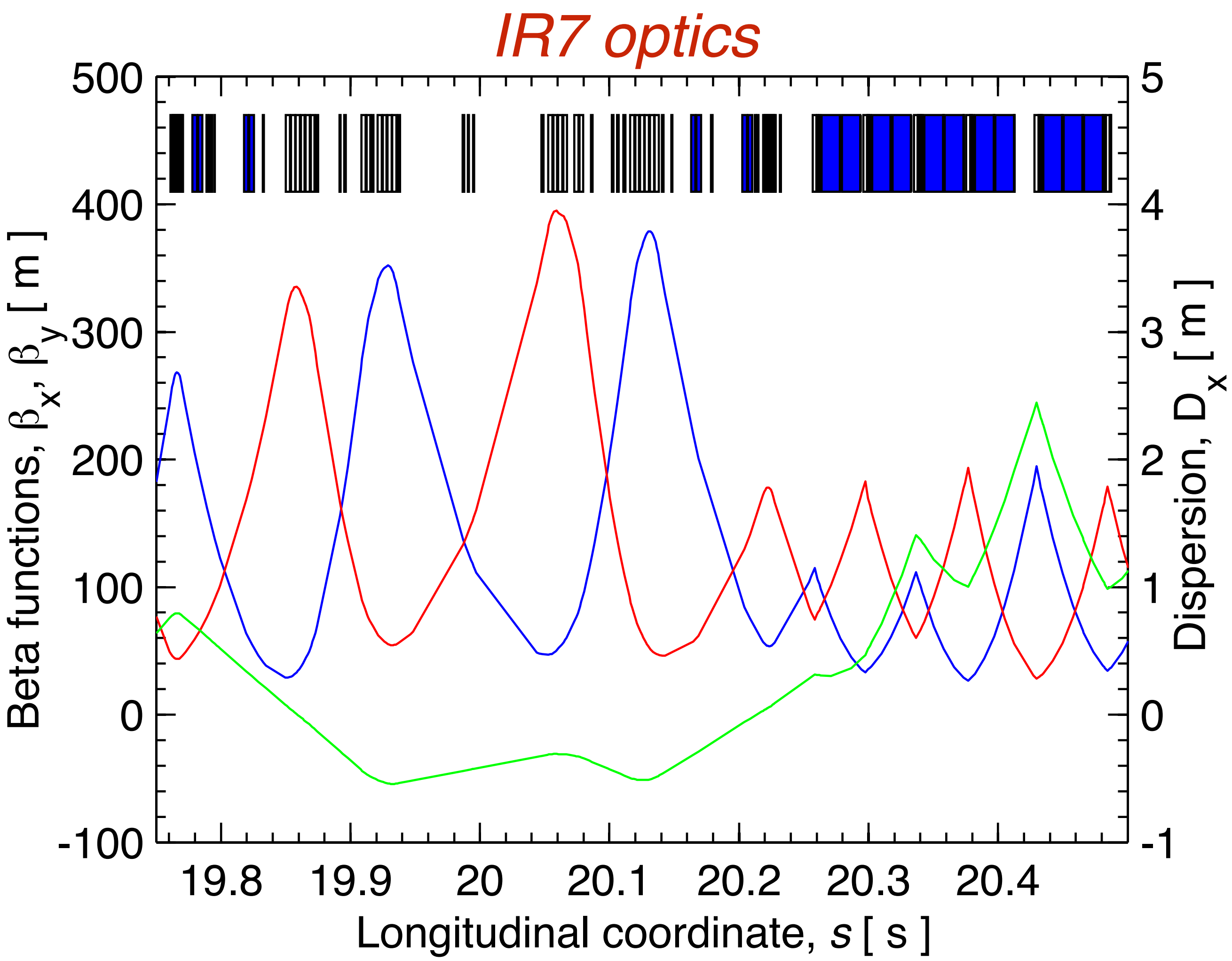


See talk S. Antipov

HiLumi HL-LHC PROJECT CERN

Dispersion suppressor collimation





Out-scattered off-energy particles have different bending radius than main beam

Qualitatively similar behaviour in collimation insertion and experiments:

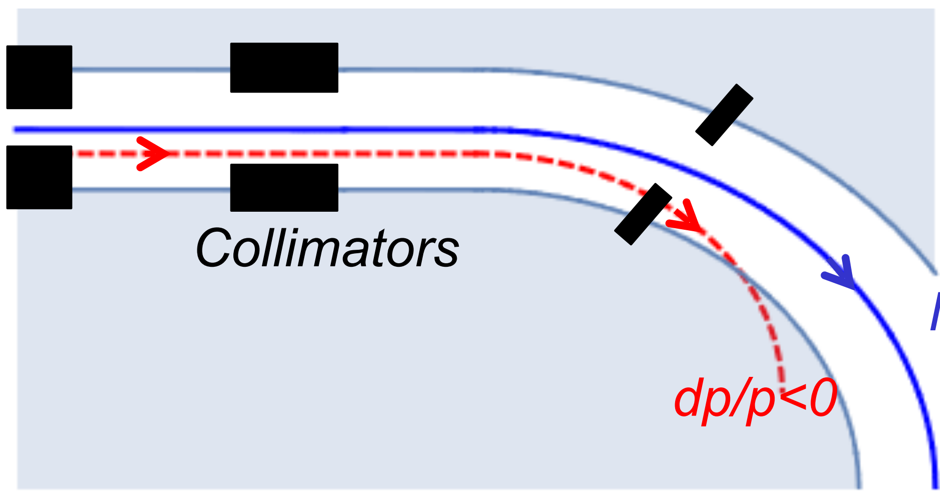
Start deviating significantly only in first bends, downstream of collimators.

Present multi-stage system is <u>not</u> optimised to catch these dispersive losses.

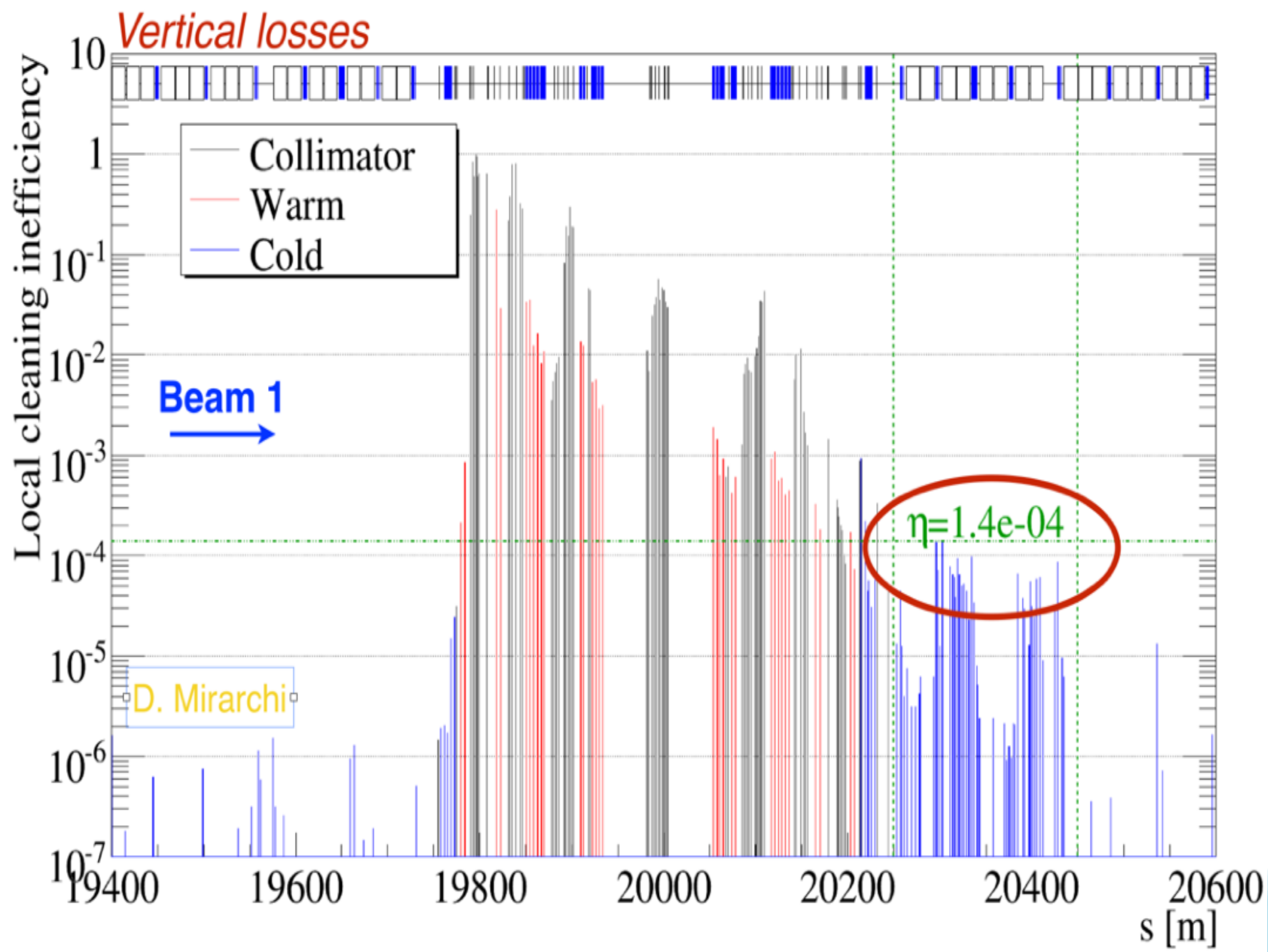
<u>Idea</u>: Install new collimators (TCLD) in front of exposed magnets, where there is already separation from main beam.

Need two jaws: ion beams; better shower absorption; more precise alignment.

Dispersion suppressor collimation



R. Bruce



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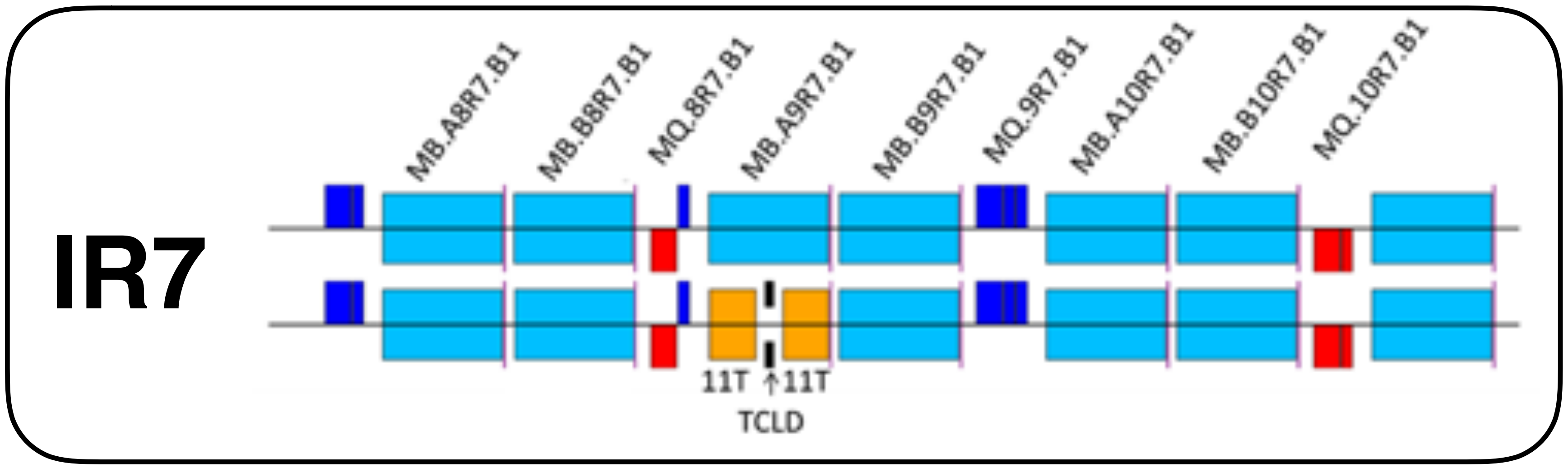
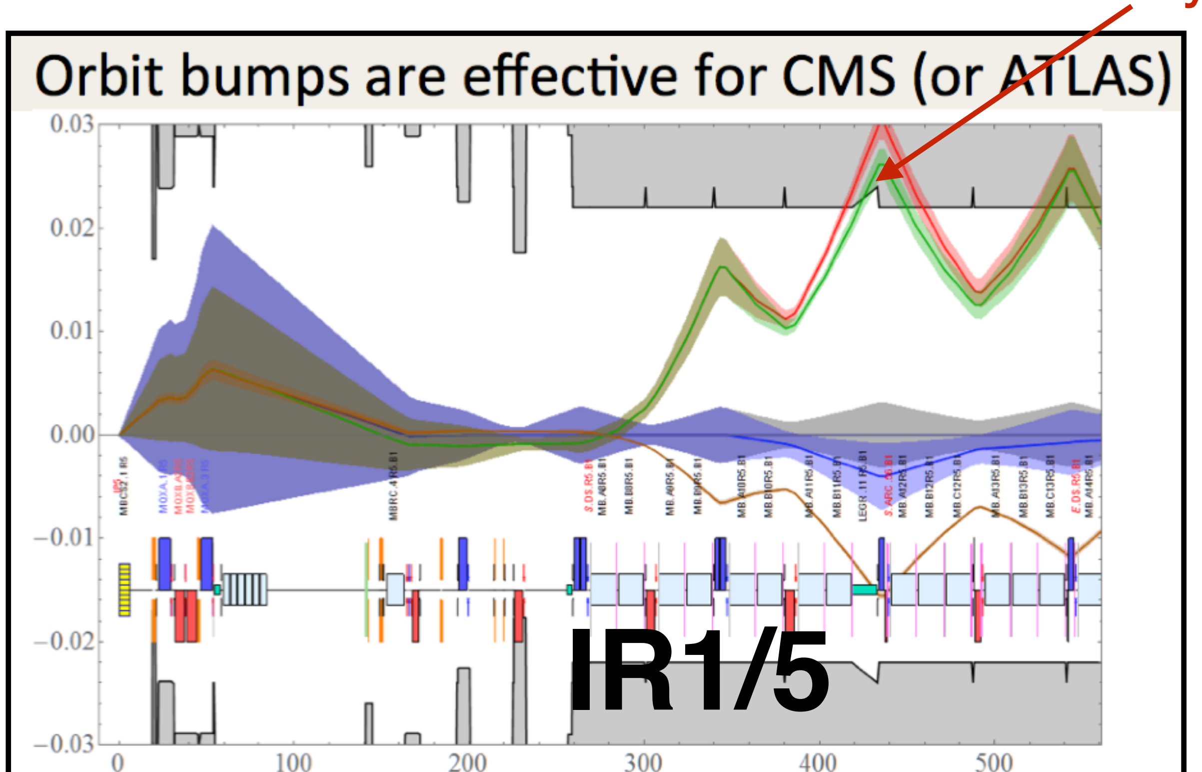
Solutions for dispersion suppressors

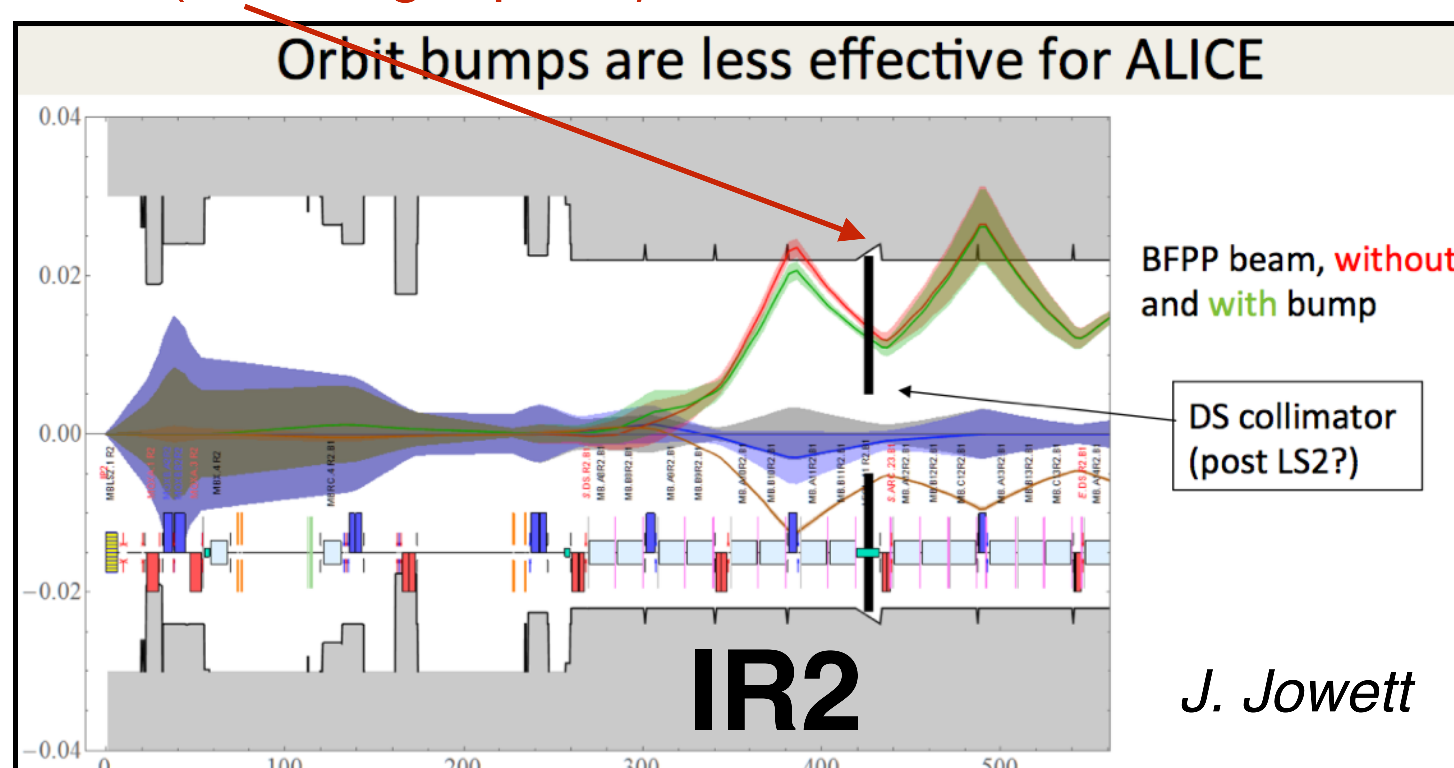
- [Protons and ions] One TCLD collimator with 11T dipoles around IR7
- [Ion operation] Bumps around IP1/5: losses moved tp connection cryostat
- [Ion operation] Bumps around IP2 and 1 TCLD collimator, no new dipole



LS2 plans: 2 TCLDs around IP2, 2 TCLDs and 4 11T dipoles around IP7, and many orbit bumps!

Connection cryostat ("missing dipole")

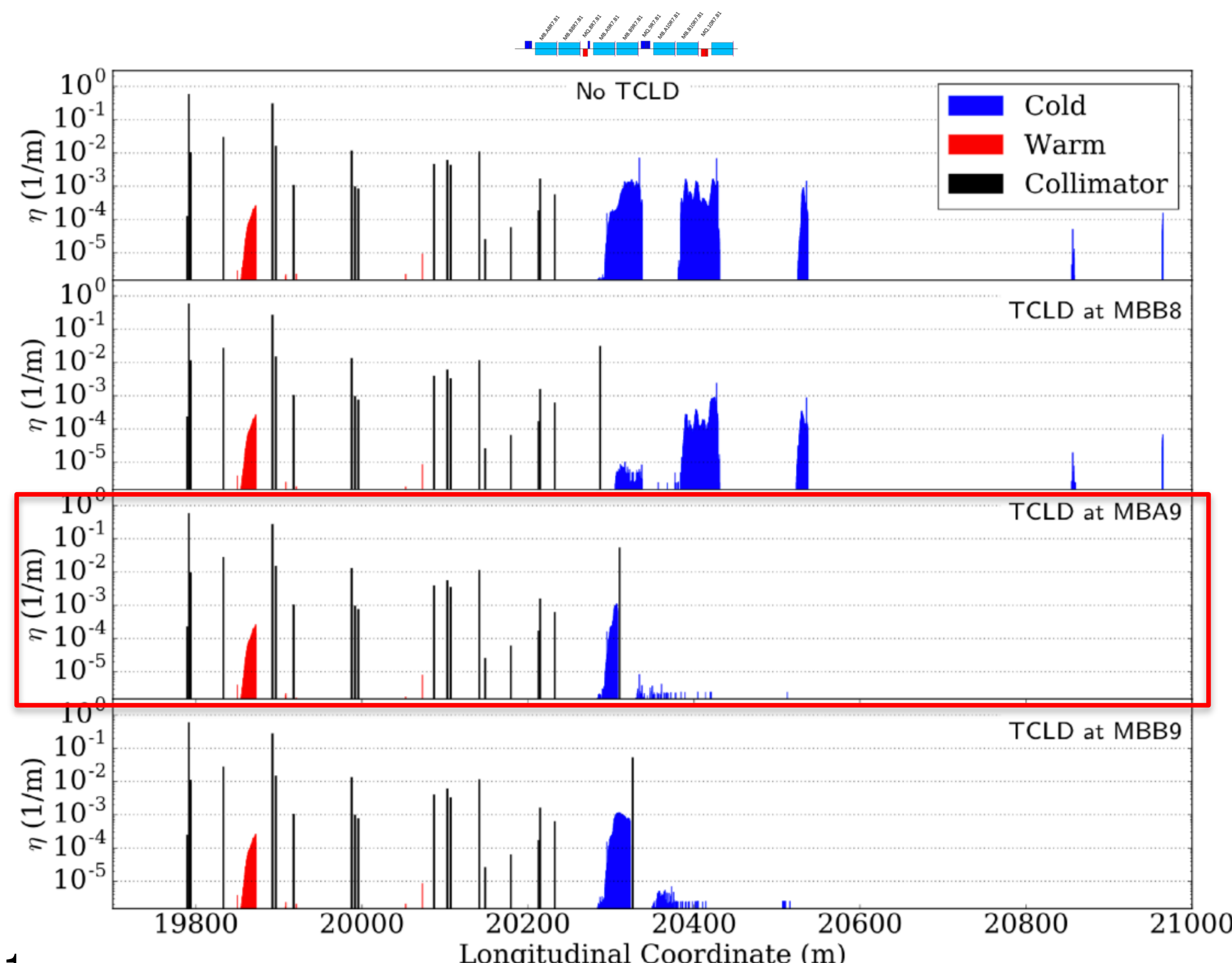




J. Jowett

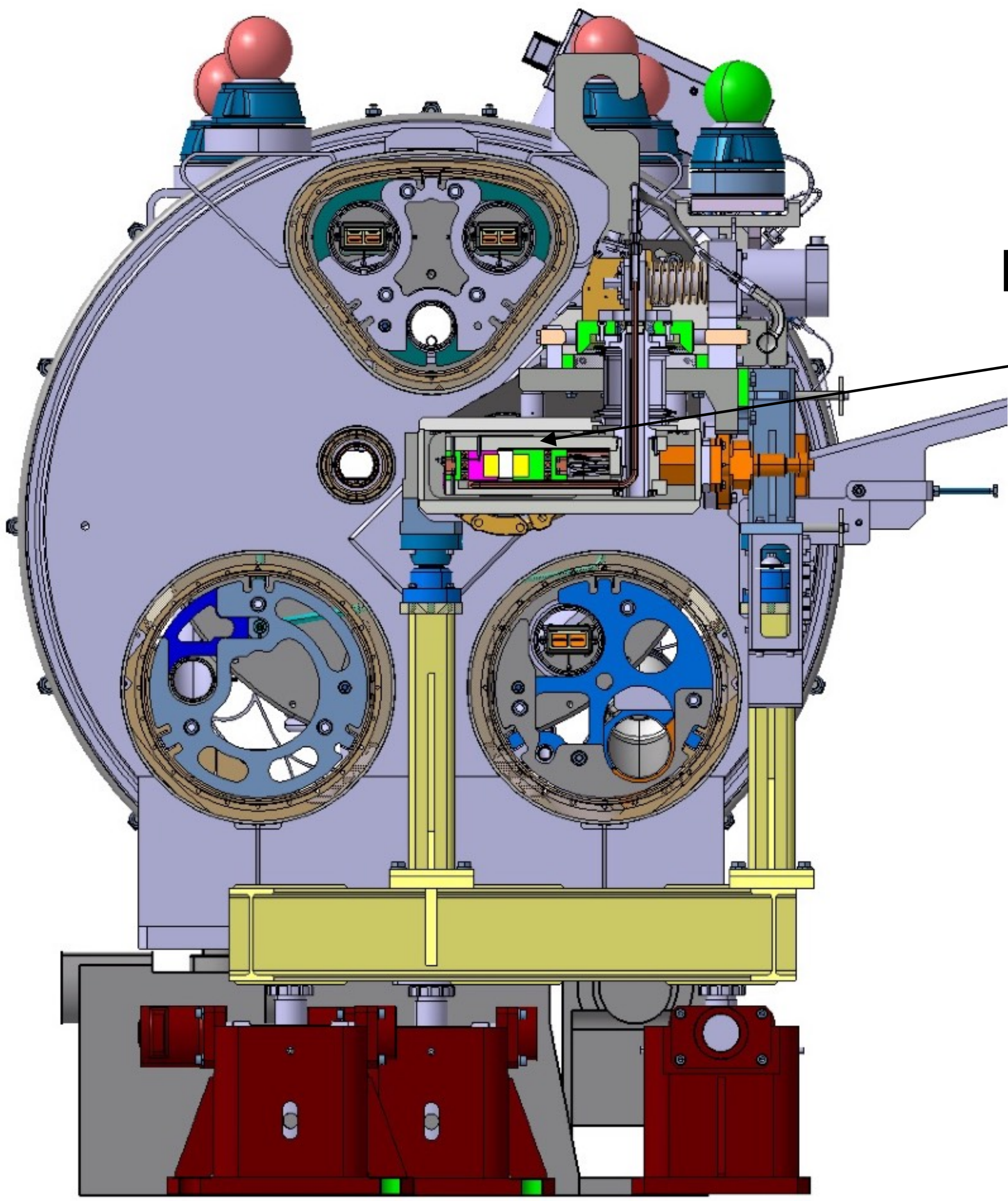
Evolutions of IR7 layouts

- Optimum performance for a layout with 2 TCLD collimators that cure both loss clusters.
- **Re-baseline in 2016** left some open concerns for ion cleaning, further emphasized by the first successful quench tests in 2016 with ion beams at 6.37 Z TeV
  - See WP5 report by R. Bruce at Chamonix 2017: serious concerns for cleaning of second DS loss cluster;
  - Pushed forward **crystal collimation** as mitigation.
- Simulation campaigns with tracking launched in early 2017 in WP5's ABP team to study a possible optimizations of the DS layouts with one TCLD only
  - Ions by P. Hermes: 89th ColUSM, June 16th, 2017
  - Protons by D. Mirarchi: 94th ColUSM, Sep. 29th, 2017

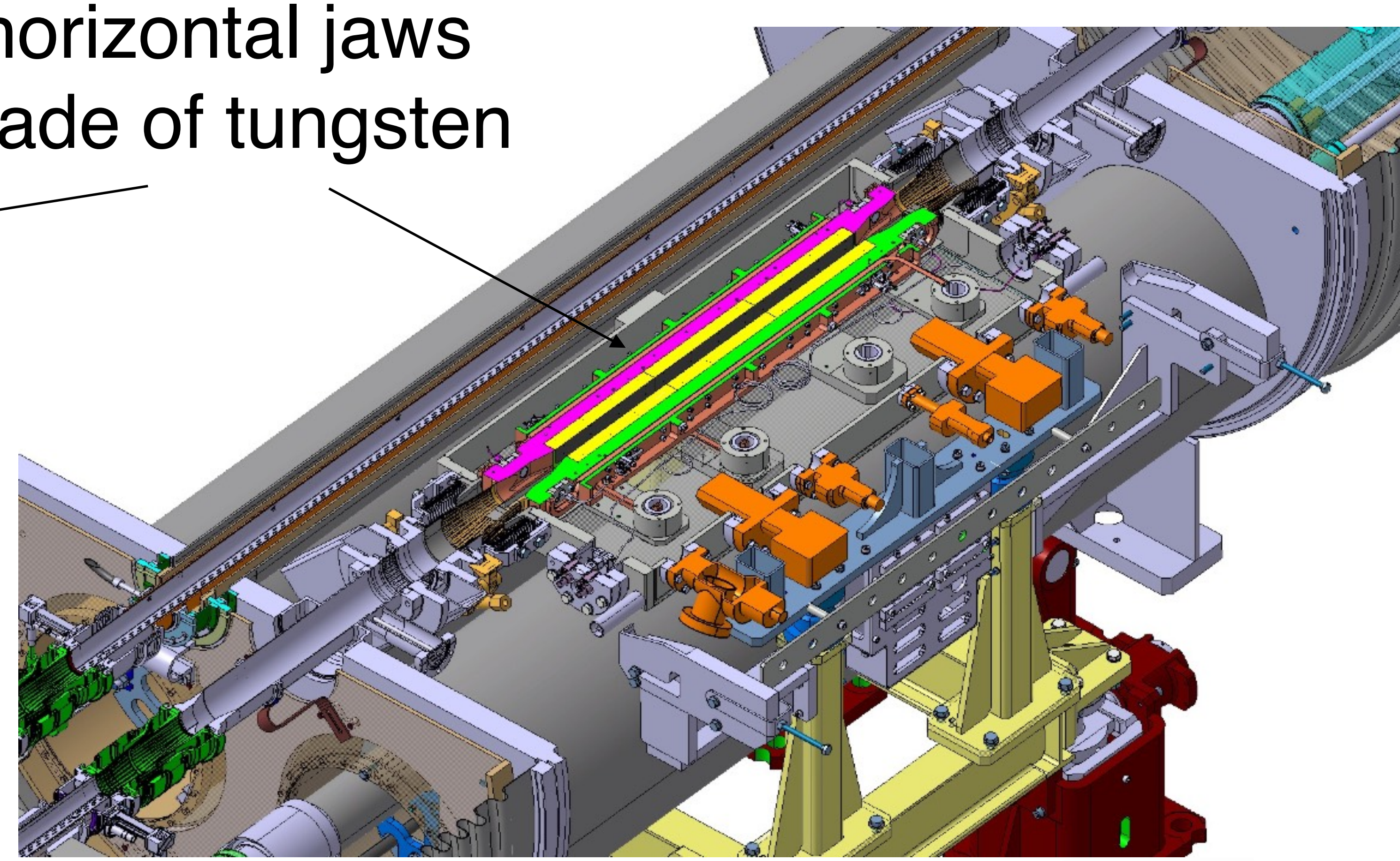


- Complete energy deposition simulations with the performance of TCLD in cell 9:
  Protons: C. Bahamonde *et al.*: 94th ColUSM meeting, Sep. 29th, 2017
  First complete assessment, ions + protons by C. Bahamonde *et al.*: 7th Annual Meeting, Madrid, 2017.
- Solution initially disregarded in absence of a solid experimental assessment of quench limits of new magnet. Measurement results available in 2018 finally lead to the decision to install **the TCLD in cell 9** (previous baseline: cell 8). Presented to HL technical committee (TCC) and LHC committee (LMC).

Dispersion suppressor collimator design

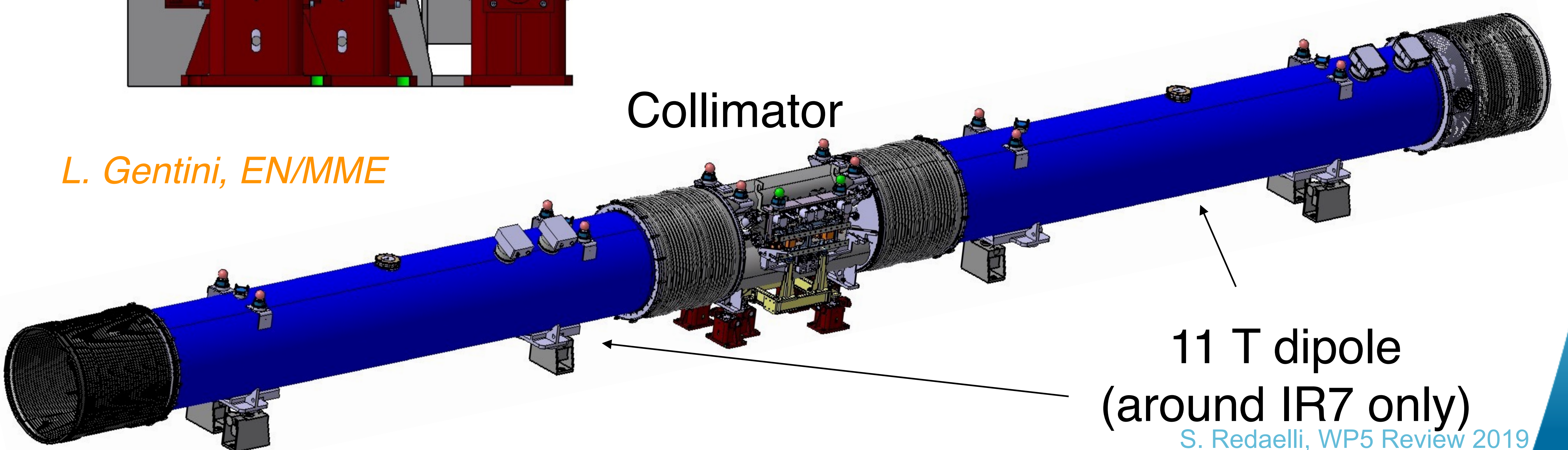


Two, 60cm long horizontal jaws made of tungsten



Collimator

L. Gentini, EN/MME



11 T dipole (around IR7 only)

gn

Pre-series off the TCLD, received less than 2 weeks ago (Courtesy EN/STI). We will see it this morning.

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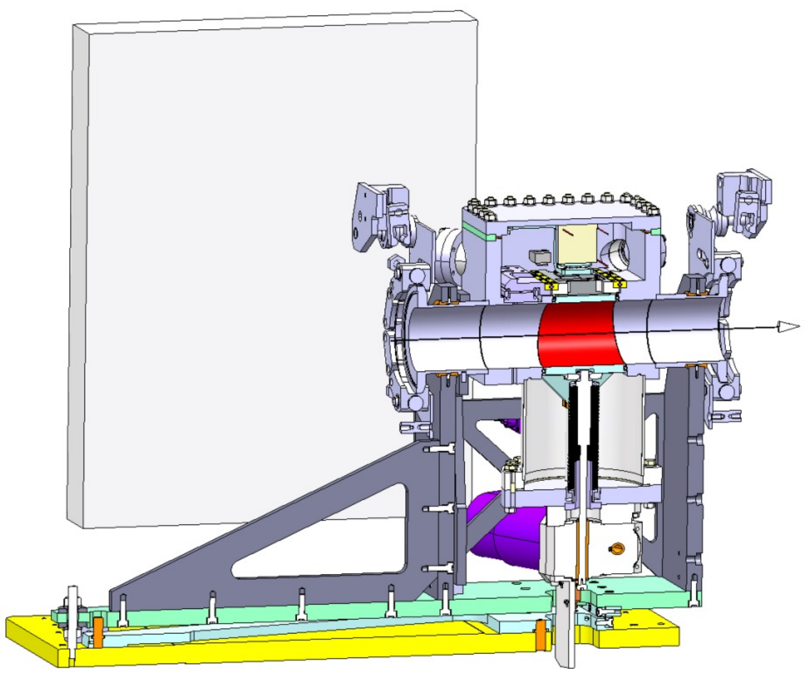
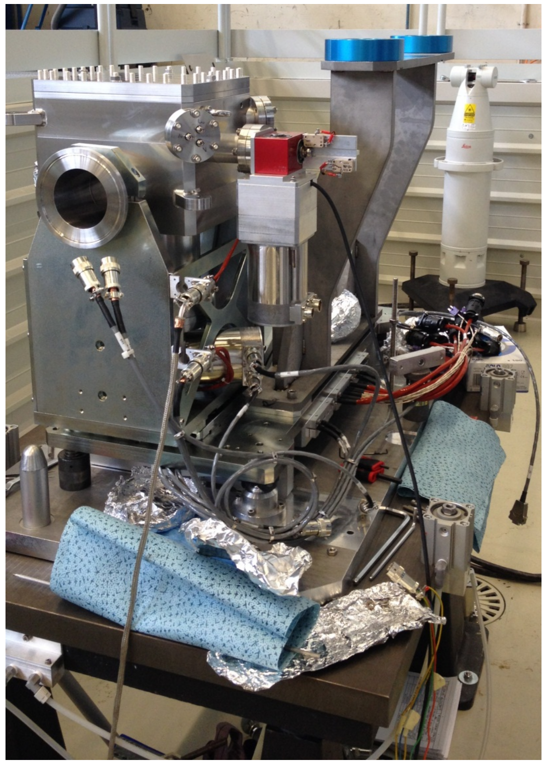
Status of crystal collimation

Scope: further improvement of ion cleaning after 2016 re-baselining.
Studying if, for ions, as it can be an "adiabatic" upgrade of the IR7 system.

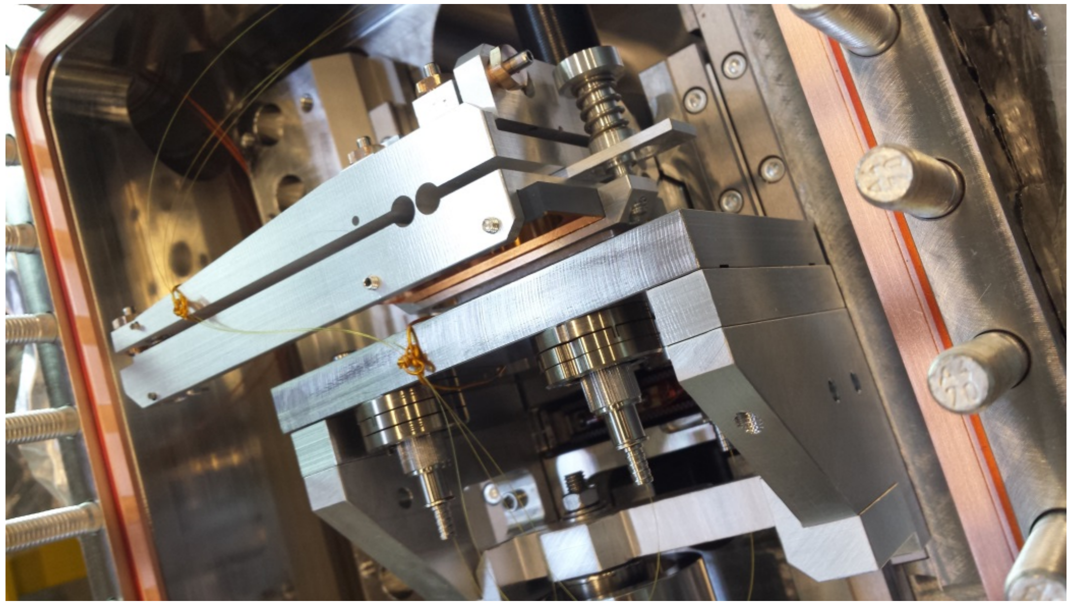




Two goniometers installed on B1 in LS2; two more on B2 in 2017.
System for complete collimation tests (1 primary crystal per beam per plane)

Developed a control technique based on **interferometer to stabilise angle**.
Pioneer technology for accelerators.

A. Masi for the EN/SMM controls team

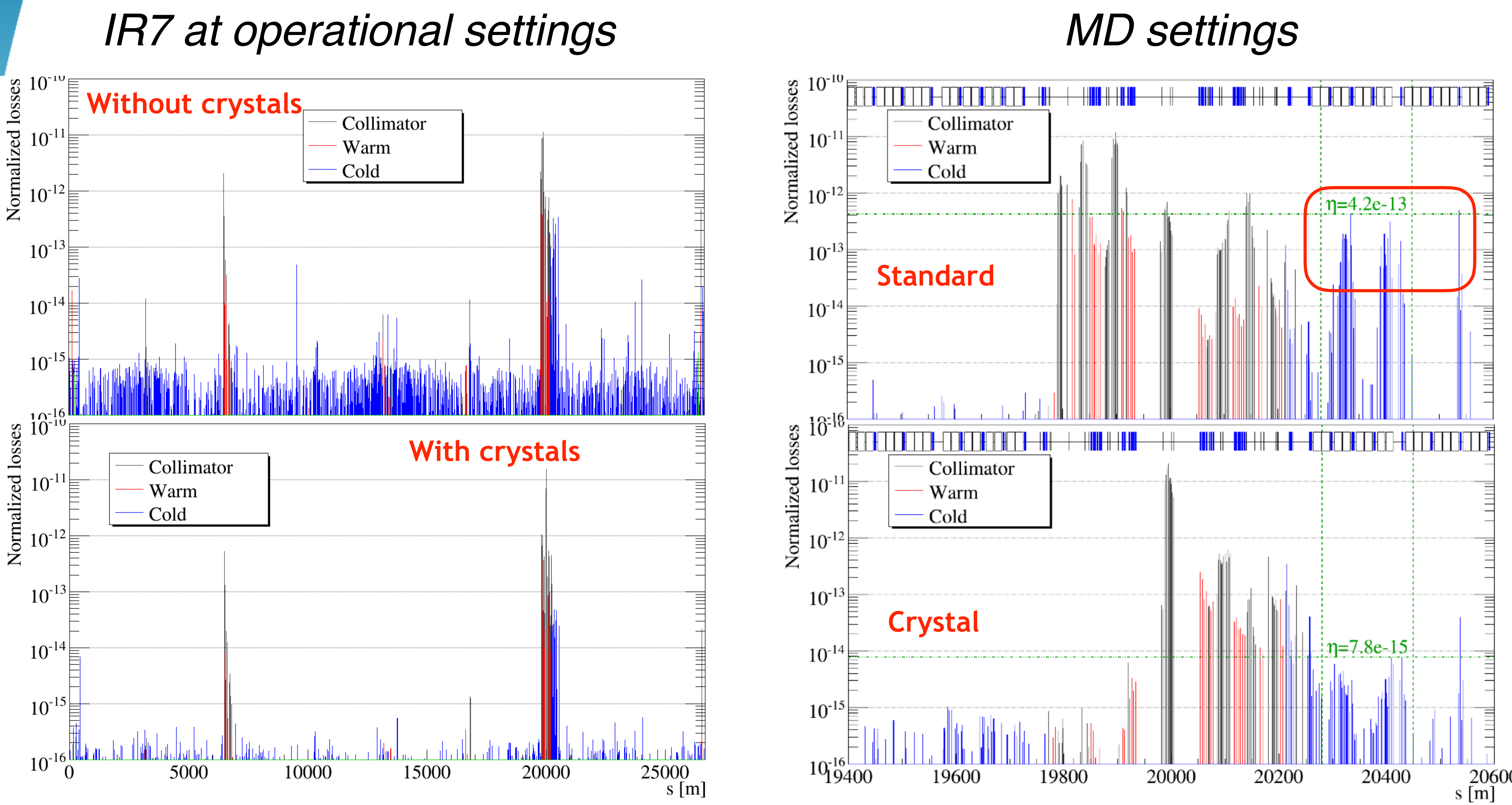


Piezo rotational stage controlled in closed loop using the Attocube FPS3010 interferometric measurement system based on 3 linear axes +/- 5 nrad

1. Reliably achieved channeling at 6.5TeV (critical angle = 2.5 μrad)
2. Continuous channeling during ramp.
3. Demonstrated improvement of ion cleaning!

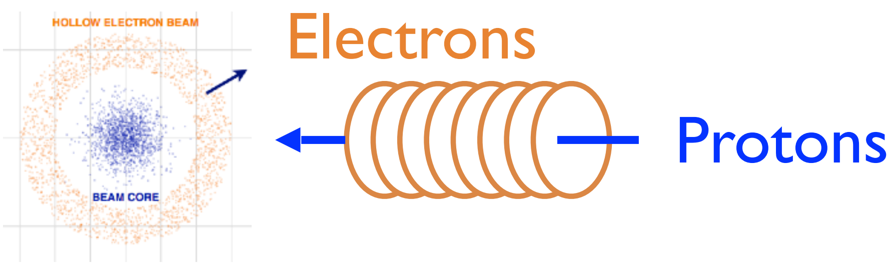
Thanks: UA9 collaboration

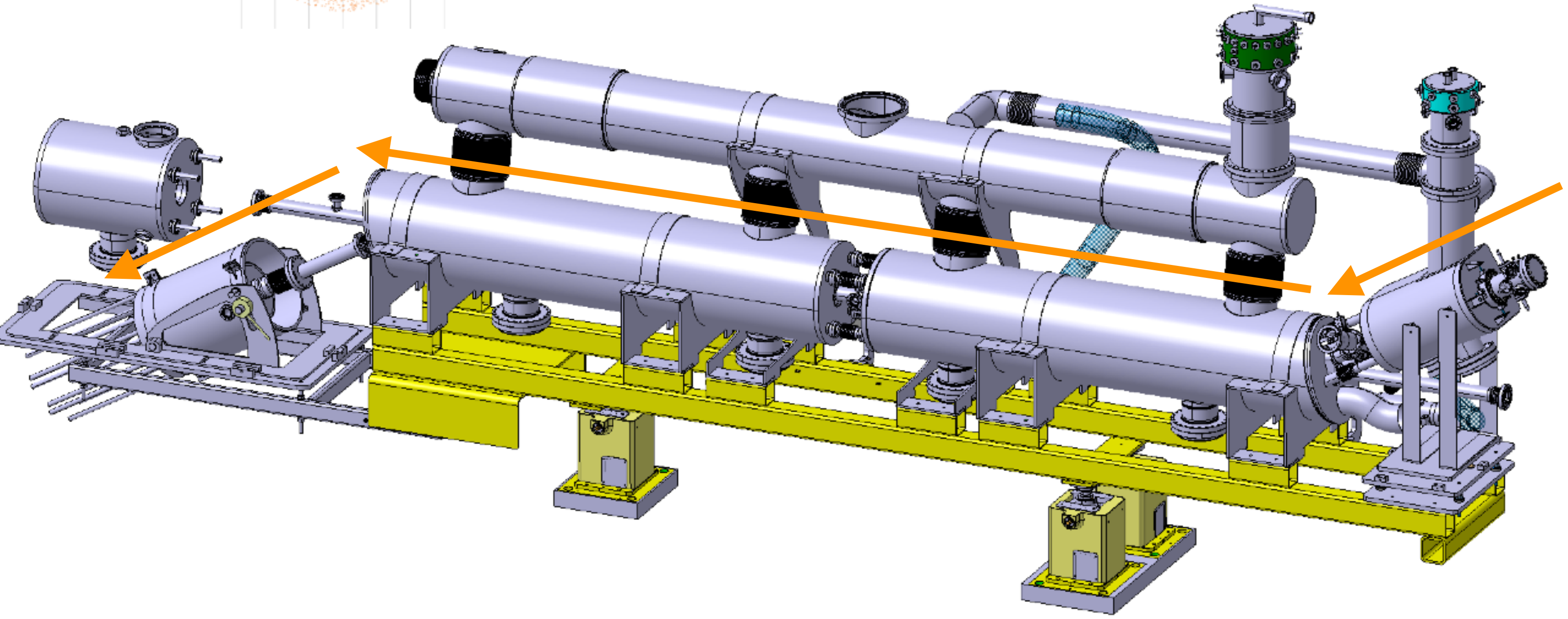
Crystal collimation cleaning of Pb beams



- Overall reduction of losses around the ring.
- Tests with high ions intensities, as part of intensity ramp up!
- Cleaning improvement up to a **factor 7** (more with MD settings)

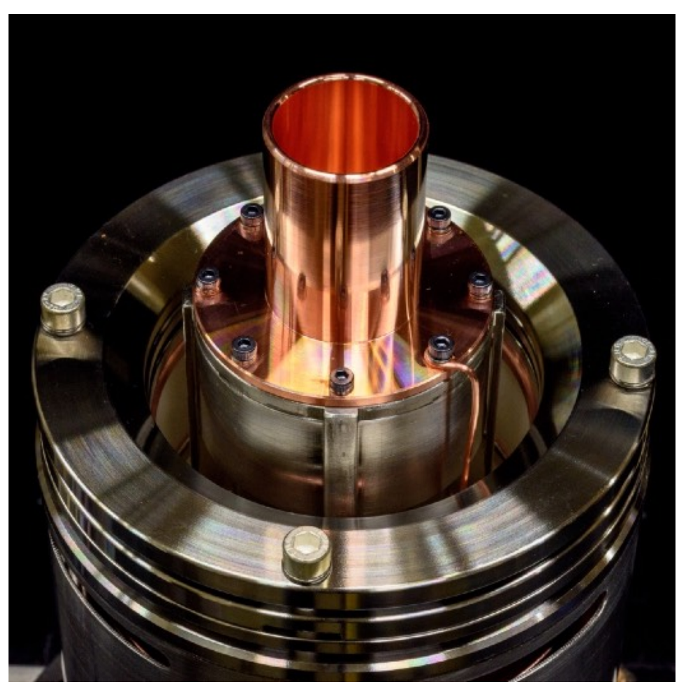
Hollow electron lenses





Hollow electron beam: *controlling actively the halo, through a **hollow electron beam** (overlapped over three meters to the proton/ion beams) that selectively excites halo particles too far from core.*

Cathode



Electron gun

Design nearly complete. Surpassed target e-beam current of 5A, now final cathode design (smaller) under test at FNAL.

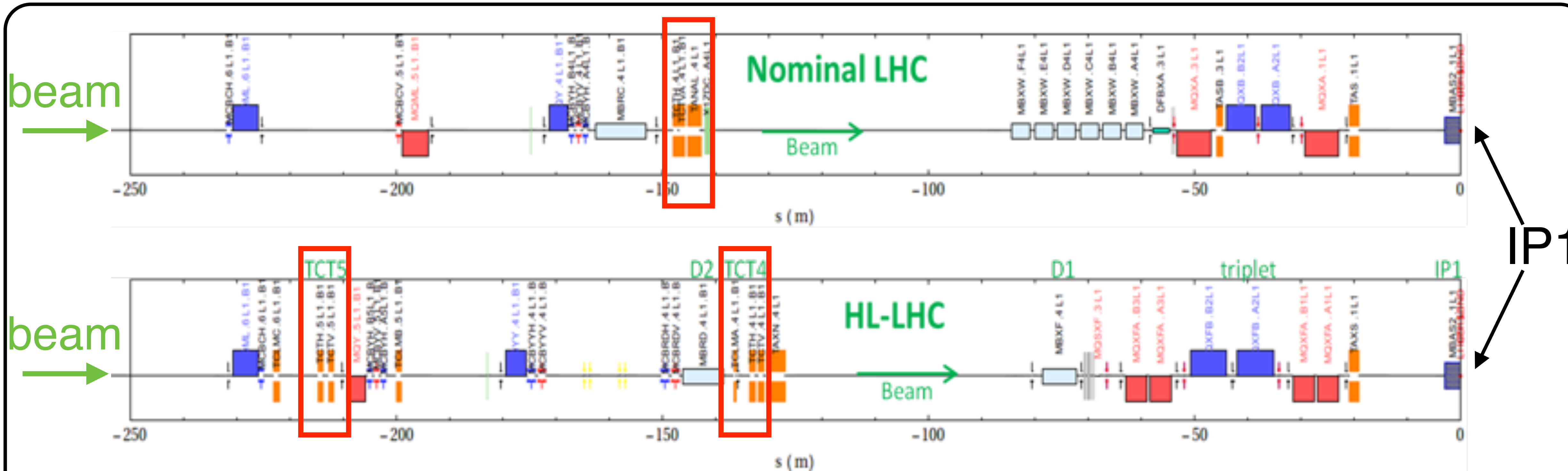
Ready to build it if integrated into the baseline: promising collaborations with Russia being explored.

Conclusions

- Introduced the challenges of beam collimation at the HL-LHC and presented our upgrade plans.
  - Many more details coming up in the next 1.5 days! Thanks to all speakers!
- The planned upgrade addresses satisfactorily the limitations identified, to achieve the HL-LHC goals.
  - Main "pillars" address cleaning, impedance limitations and challenges of experimental regions with x5 LHC design luminosity.
- Some of the key upgrade technologies secured already by LS2, as we are proceeding at full steam with the production
  - First stage of low-impedance upgrade and dispersion suppressor cleaning
  - Scope: 20 new collimators (with spares) for HL-LHC + CONS — <u>challenging</u>!
  - We will be ready to collimate the upgraded beams from the injectors progressively becoming available in the LHC Run III.
- Important to review the plans and iterate for the LS3 implementations!
  - Many thanks in advance for your help and feedback in this review.

Reserve slides

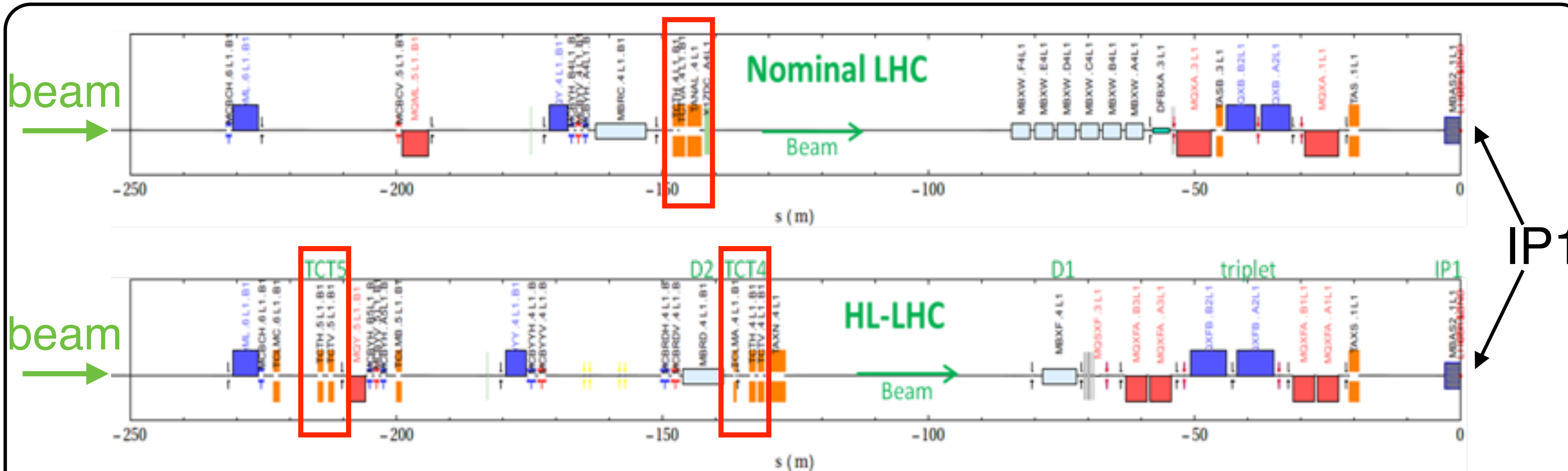
Illustrative scheme of new IR collimation



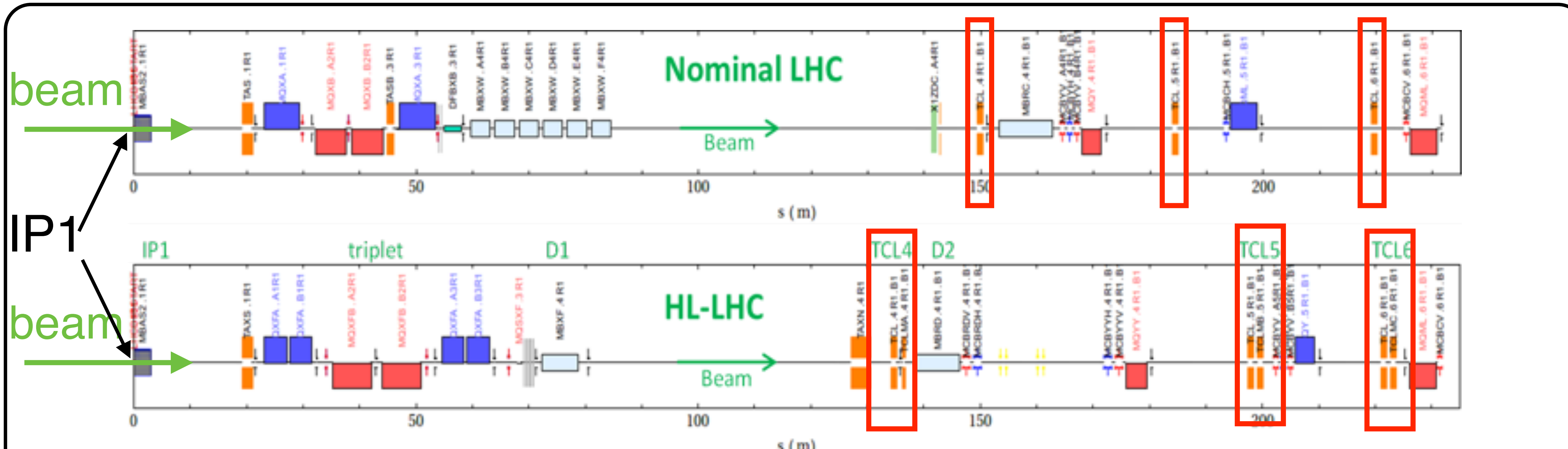
Two pairs of H/V tertiary collimators (TCTs) protect against ***incoming beam*** *losses.*

IP1

Illustrative scheme of new IR collimation



*Two pairs of H/V tertiary collimators (TCTs) protect against **incoming beam** losses.*



R. Bruce

*Cleaning of **physics debris**: 3 movable collimators (TCL) and fixed masks.*

Detailed scope: IR cleaning (5.1)

Detailed scope	• Complete operational system: 28 movable collimators + 12 fixed masks • New production: 20 movable collimators + 12 fixed masks • Re-use of 8 present TCTPs from pool of spares/operational [June 2016] • Spares: 4; prototypes: 3.
Performance target	• Avoid quenches of matching section and triplets, protect IR from incoming beam losses • Protect the triplet magnets from failures • Operate at design luminosity staying below quenches from physics debris • Efficient operation and changes of configuration for operational levelled scenarios
Timeline	Complete implementation planned for LS3
Material choices	• Inermet for all movable TCLs, vertical TCTs and masks • 8 new CuCD collimators for TCTs, horizontal plane • Fixed masks TCLM also in inermet
Comments	• **Design** still ongoing for 2-in-1 collimators in recombination chamber • Detailed **mask design** not started. • New CuCD essentially material qualified: ready to launch production if needed. • Possibility to re-use present TCTPs subject to radiation dose assessment

Detailed scope: DS cleaning (5.2)

Detailed scope	• Complete system: 4 movable TCLD collimators for DSs of IR2/IR7 • All produced in industry • Spares: 1; prototypes: 1 (operational spare).
Performance target	• Avoid quenches of DS magnets around IR7 in proton and ion operation • Avoid quenches of DS magnets around IR2 in ion operation (upgraded ALICE)
Timeline	Complete implementation planned for LS2
Material choices	• Inermet for all TCLDs
Comments	• Schedule: coupled to 11T dipole • Note that limitations in IR1/5 in ion operations solved by local bumps without need for TCLD

Detailed scope: betatron cleaning (5.3)

Detailed scope	• Complete system: 18 movable collimators • All produced in industry • Spares: 4; prototypes: 2. • Low-impedance material procurement for primary collimators in LS2 (CONS)
Performance target	• Operate the HL-LHC beams with sufficient stability margins • Ensure efficient system setup and availability for the HL-LHC lifetime • Withstand the design failure cases with sufficient margins
Timeline	Two stages: LS2 (8+2) and LS3 (10+2)
Material choices	• LS2: Mo-coated MoGr • LS3: Mo-coated MoGr (iteration possible after experience with LIU beams in Run III)
Comments	• Recent change of baseline: reduced by 4 unit the number of collimators, i.e. 2 less per beam, in light of the assessment of cost for the MoGR. • Need an iteration on the secondary collimator design to improve dynamic jaw deflection that affects a few very-exposed secondaries.

Detailed scope: “General studies” (5.4)

Detailed scope	• HiRadMat tests: material samples, individual jaws, full collimators [design validation] • Irradiation tests of material samples and support to material development. • Prototype testing • Remote handling of radioactive collimators: study + implementation
Performance target	• Perform the necessary tests, without and with beam, to validate fully the new collimator designs against design loss scenarios • Same for sub-components: active jaw materials, entire jaws, … • Assess needs, and provide solutions, for a remote handling/commissioning of radioactive collimators.
Timeline	Activities spans throughout the project timeline
Material choices	• N/A
Comments	• Timeline vs availability of HRM tests in Run III to be checked

Crystal collimation and hollow lenses

LHC Collimation Project CERN

Crystal collimation

Detailed scope	• Install and operate crystal collimators for both beams/planes at the LHC (evolved from initial plan to equip only one beam) • Procure/characterize crystals for a possible intervention in LS2
Performance target	• Successfully demonstrate the feasibility of crystal collimation of heavy ion beams • Assess relevant operational aspects for crystal collimation at the LHC • Validate required hardware for angular control of crystals at the LHC energy range • Assess relevant aspects for impedance, compatibility with high-intensities • Establish final prototyping of key components
Timeline	Various installation campaigns: LS1 + (E)YETS. Further iterations in LS2.
Material choices	• Two technologies for crystals: strip (INFN+PNPI) and quasi-mosaic (PNPI) • (Unique) interferometric system for angular control • Two different crystal hold technologies by different producers.

Hollow e-lenses

Detailed scope	• Validate key components for the HL-LHC lenses: cathodes, collectors, … • Procure/characterize optimised cathodes • E-beam characterisation at FNAL
Performance target	• Design HEL for the HL-LHC • Demonstrate e-beam current requirement with correct cathode dimensions • Support test facility at CERN
Timeline	Design by 2015-19
Material choices	• Different cathode producers