26th US-LARP Collaboration Meeting - CM26
May 18th-20th, 2016
Standford Linear Accelerator Centre, SLAC, Menlo Park, CA, USA

Collimation System — Status and Plans

Stefano Redaelli, CERN, BE-ABP

on behalf of HL-WP5

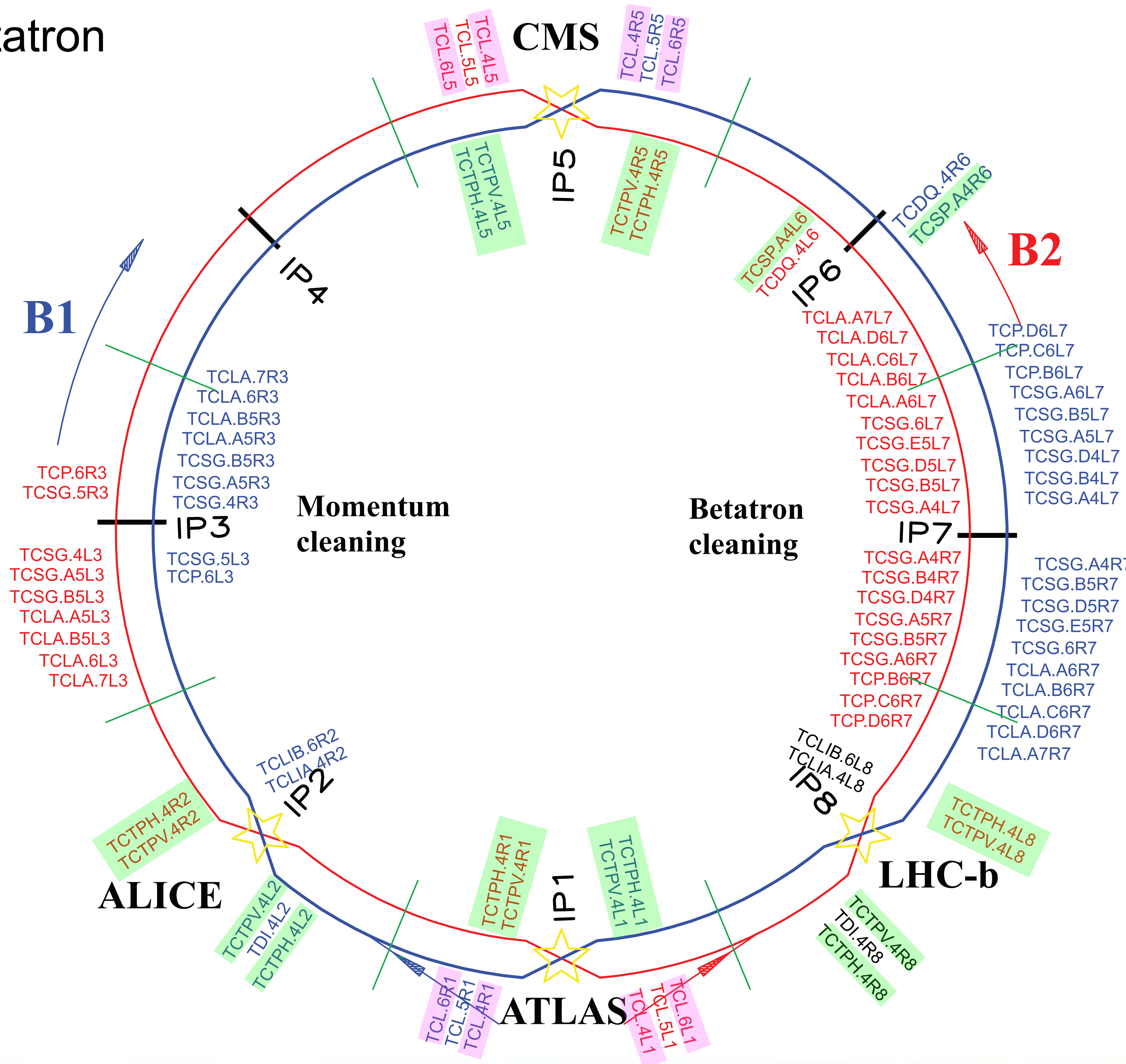
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Introduction

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.



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Total of 118 collimators (108 movable).

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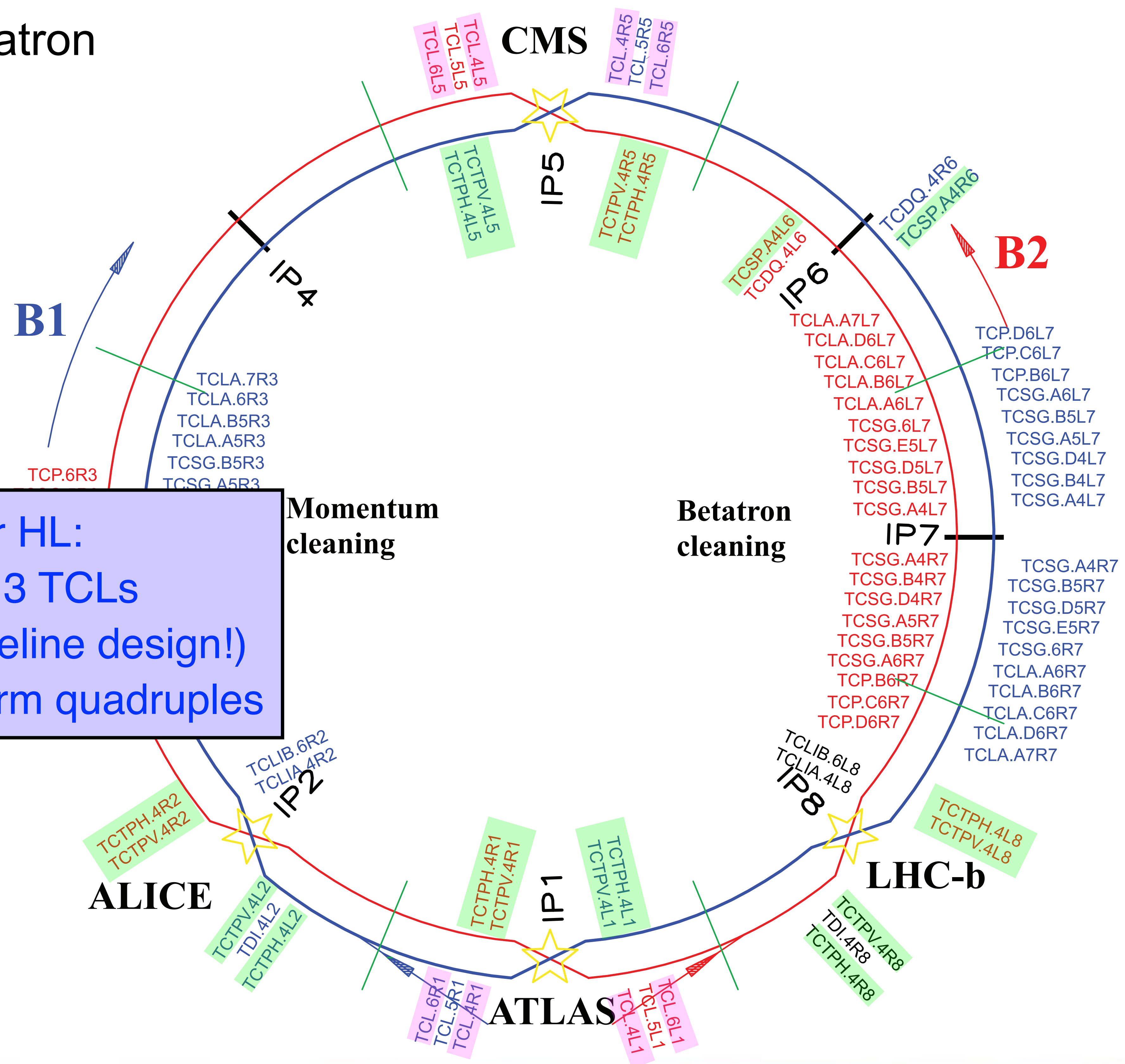
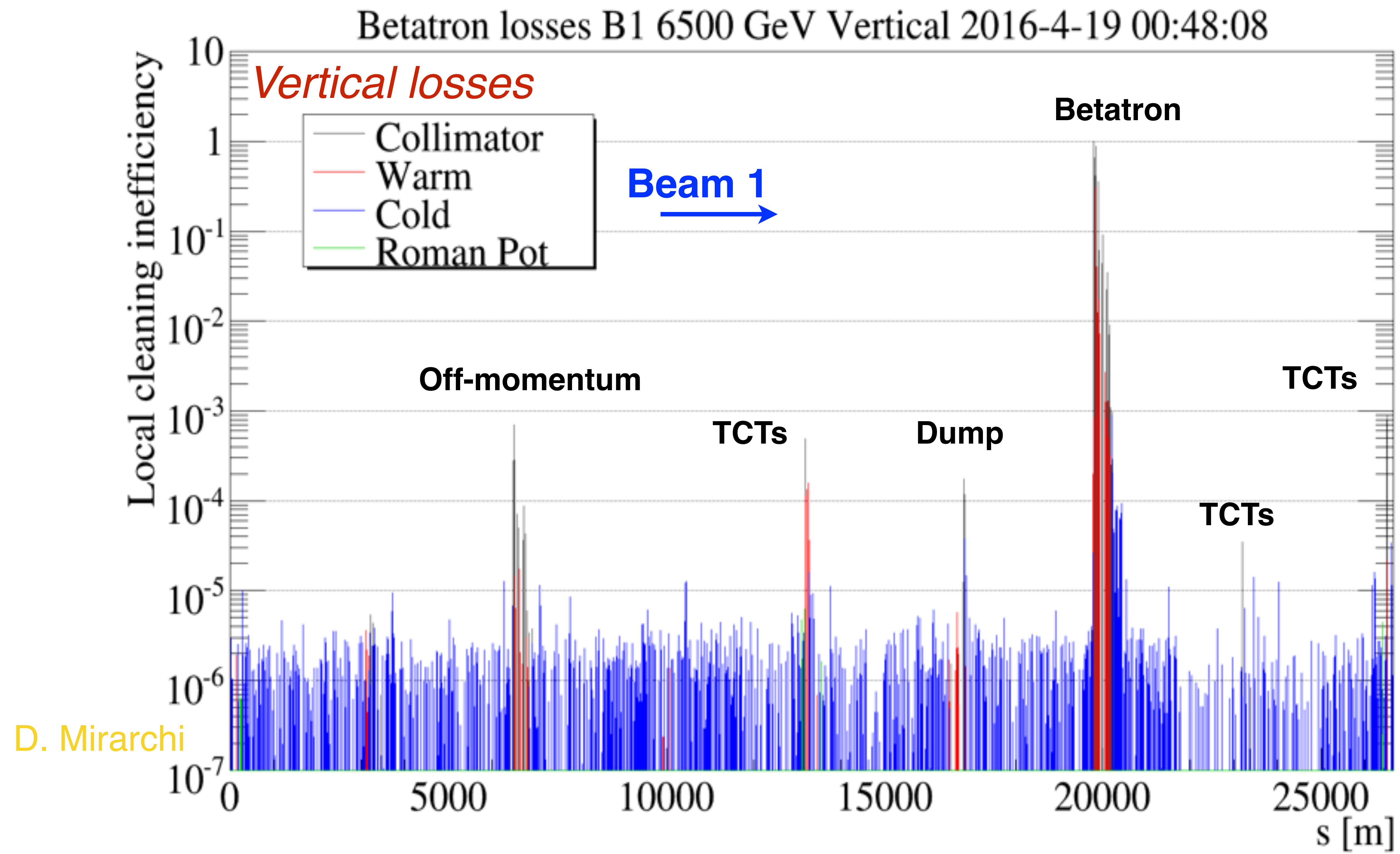


Important activities relevant for HL:

- Physics debris layout with 3 TCLs
- BPM collimators (new baseline design!)
- Improved protection of warm quadruples

LHC Run II:
Total of 118 collimators (108 movable).

Collimation cleaning 6.5TeV, β^*=40cm



Excellent performance, but need further improvements for HL-LHC

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Collimation cleaning and beam losses at higher energies;
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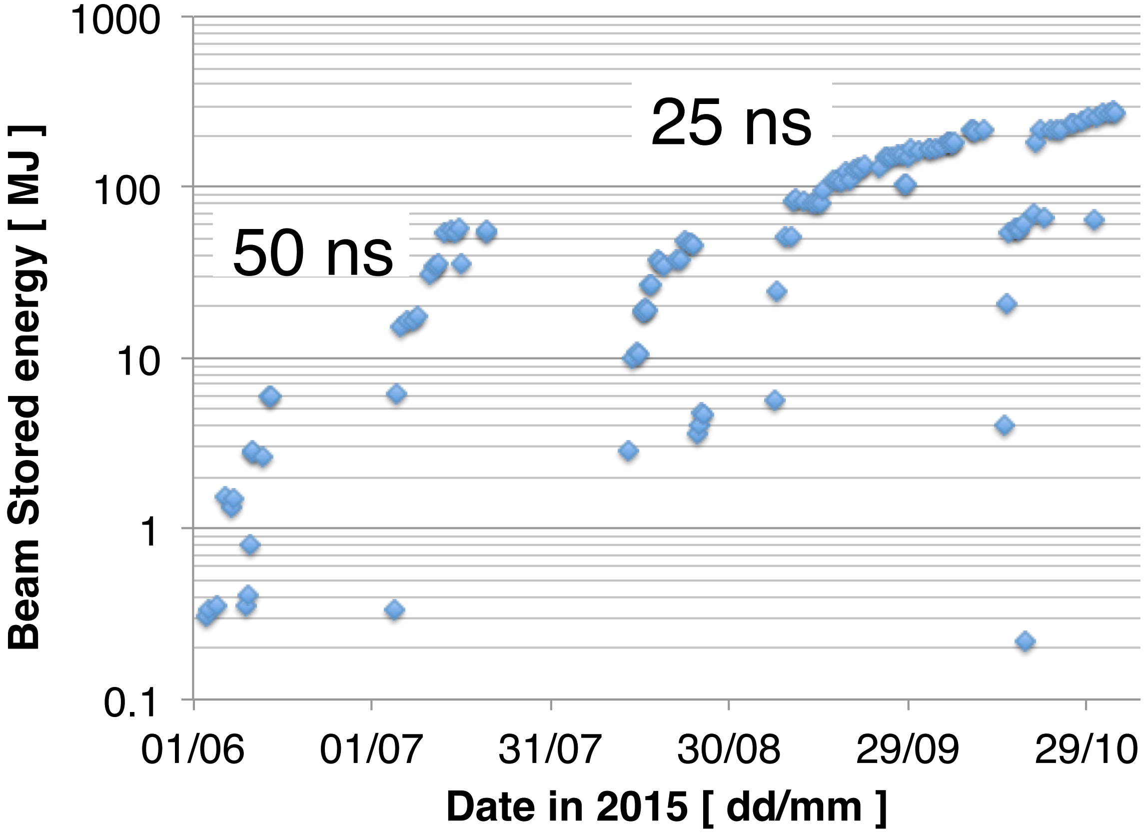
- **Continued effort in simulations to find conceptual and technical solutions.**

2015 operational experience



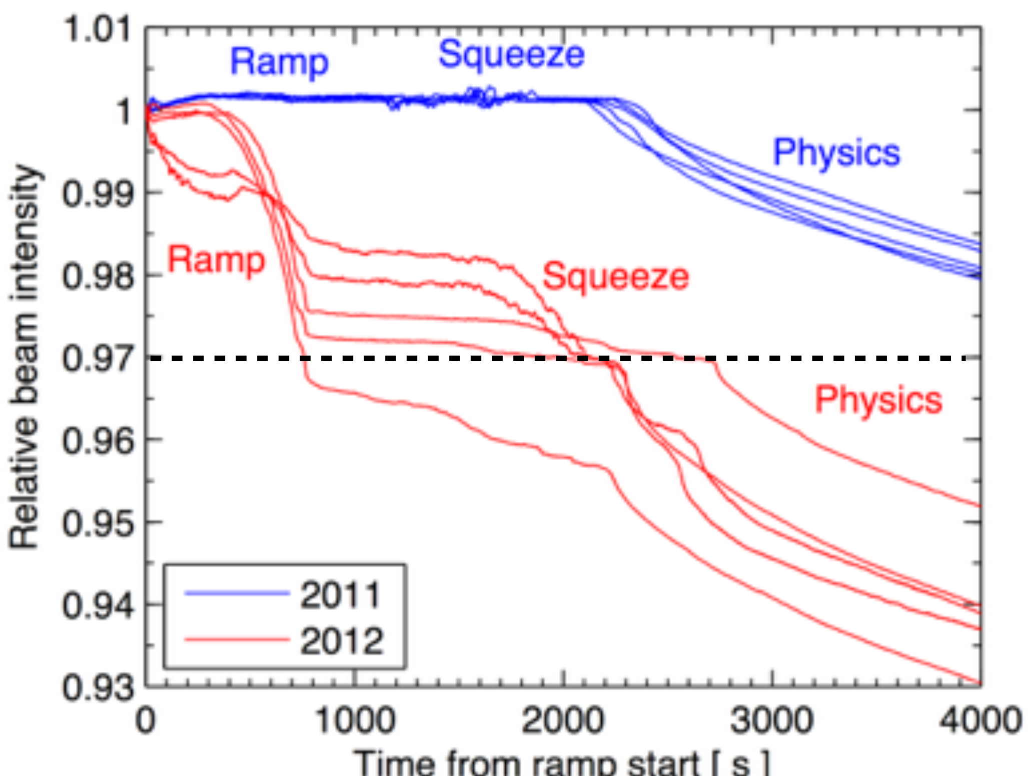
Proton stored energy up to 280 MJ.

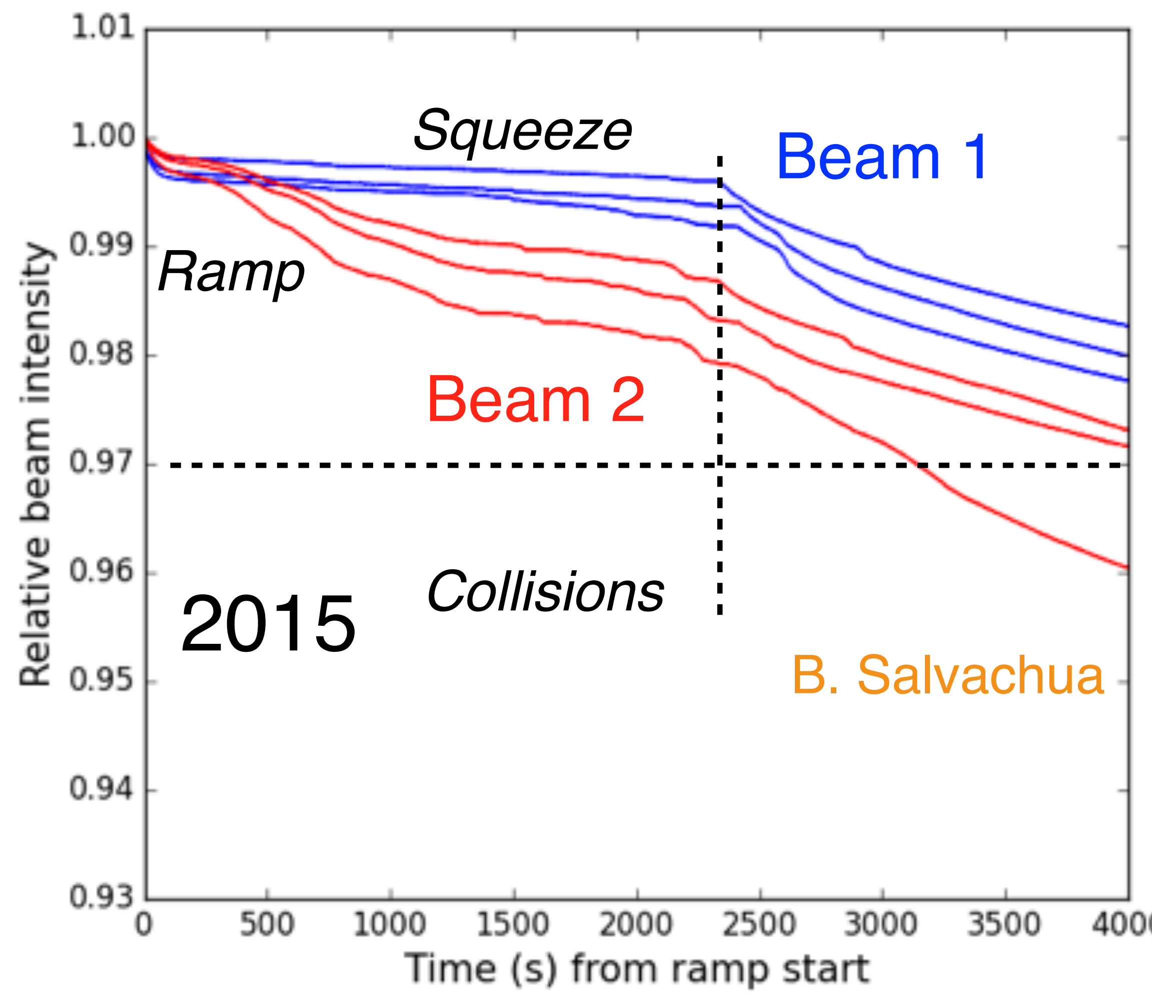
No quench from circulating beam losses!

BUT: Machine parameters and configuration were not yet pushed.

Relevant for collimation: Stored beam energy, minimum lifetime during cycle.

We cannot yet make solid extrapolations to the HL-LHC parameter set.





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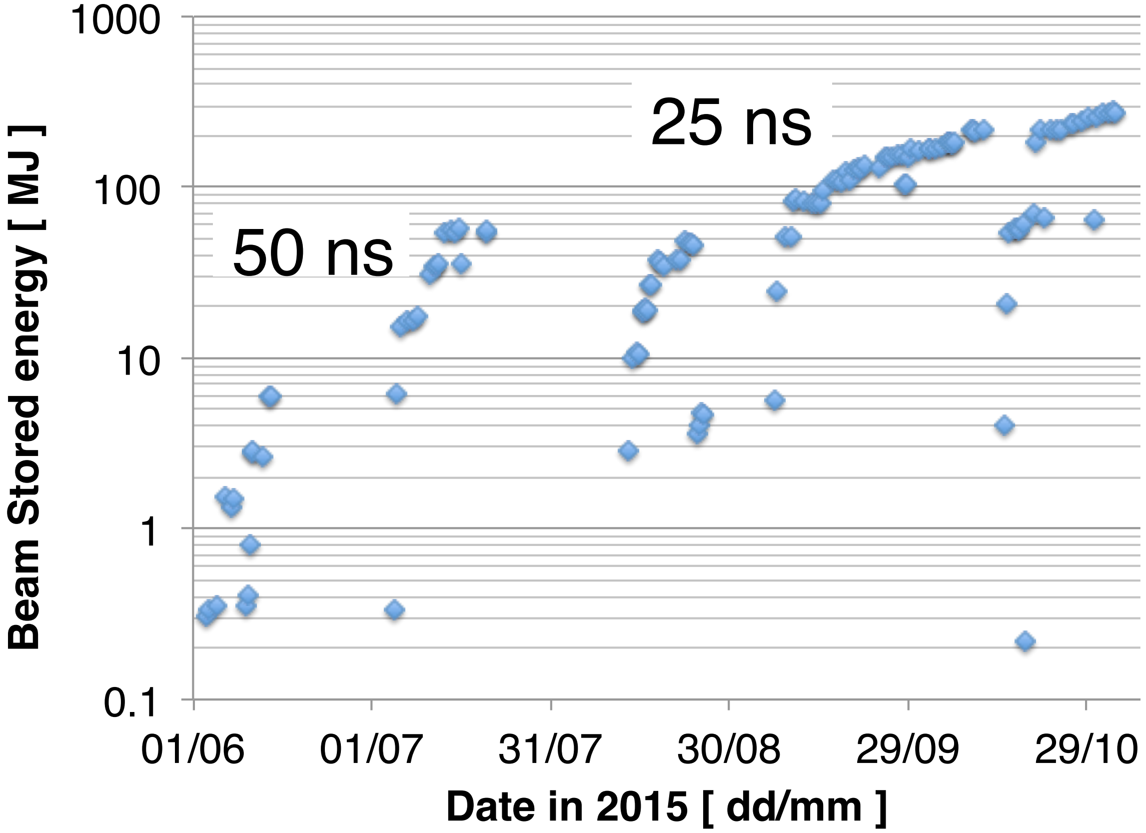

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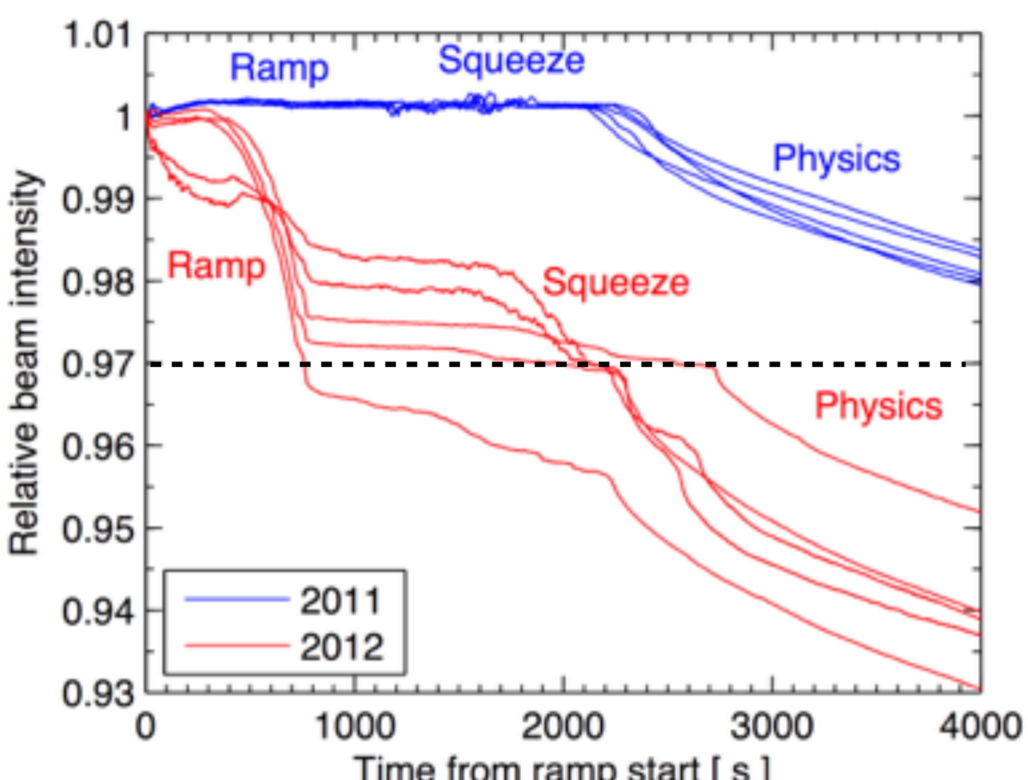
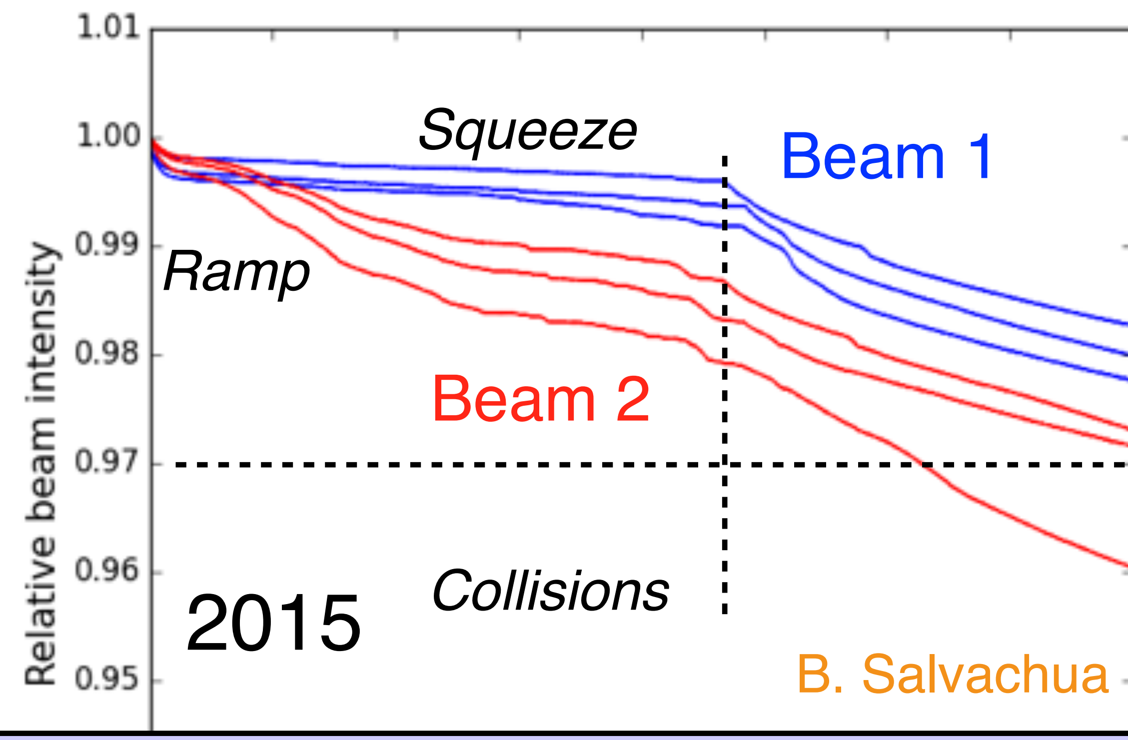
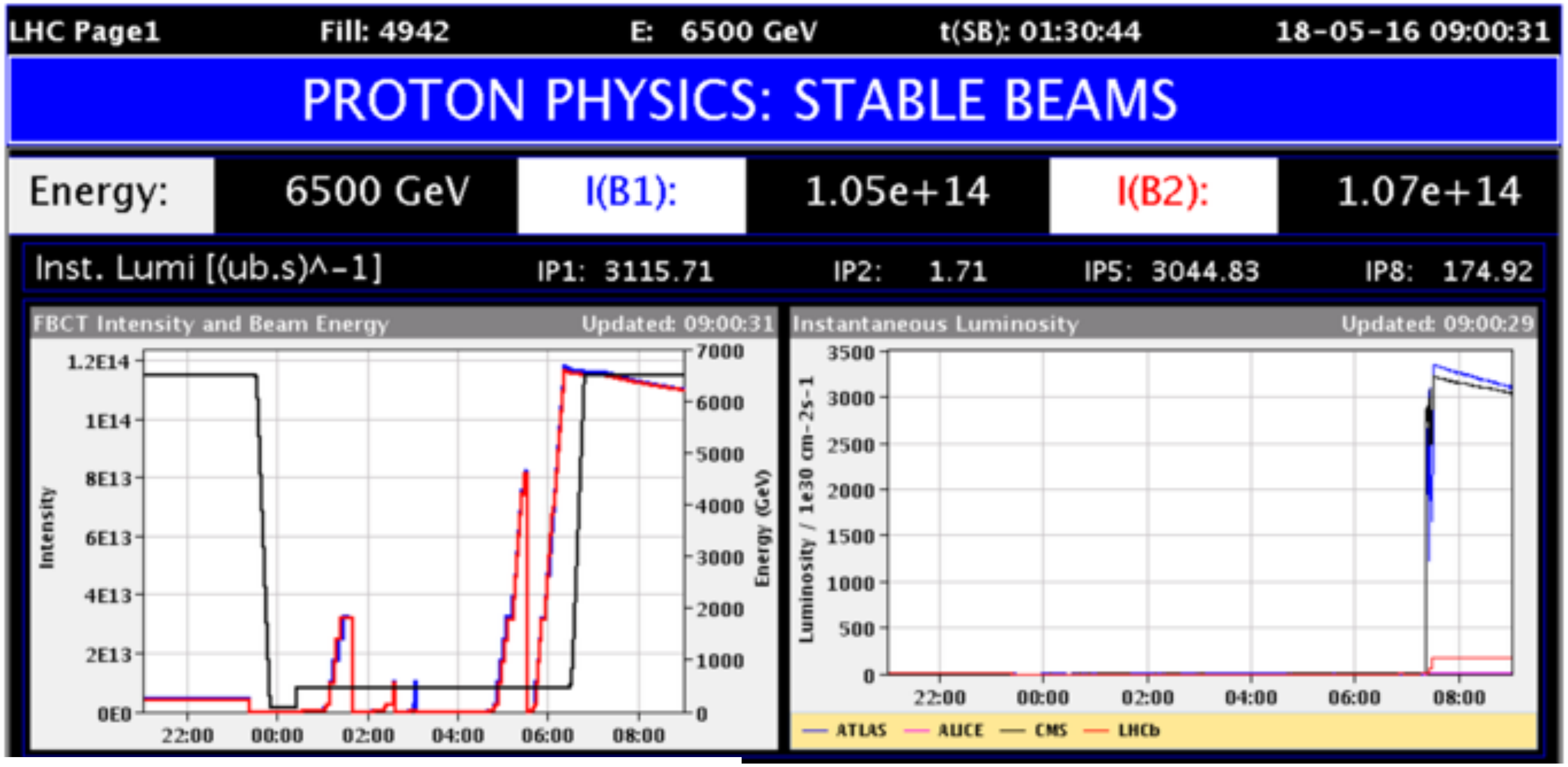
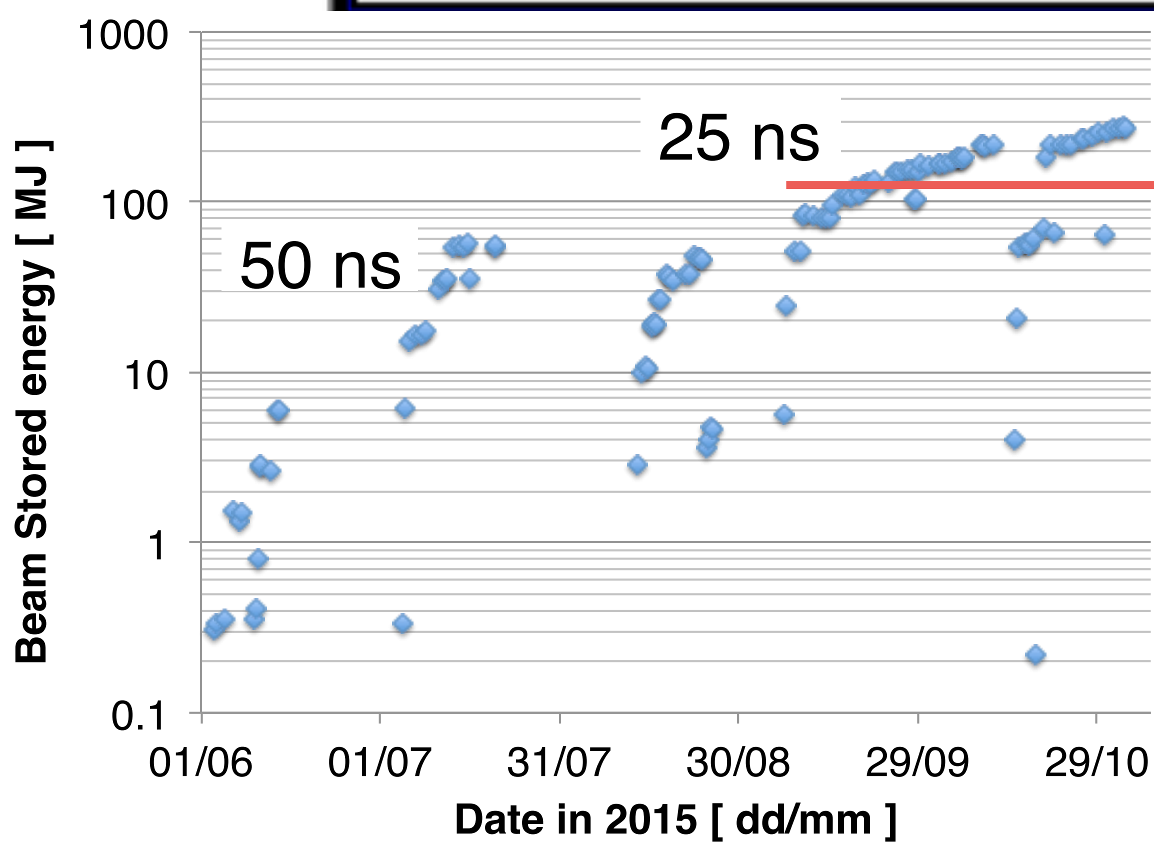




Cannot consider 2015 as fully representative.
Important to continue monitoring in 2016.

Where we are today





~120 MJ
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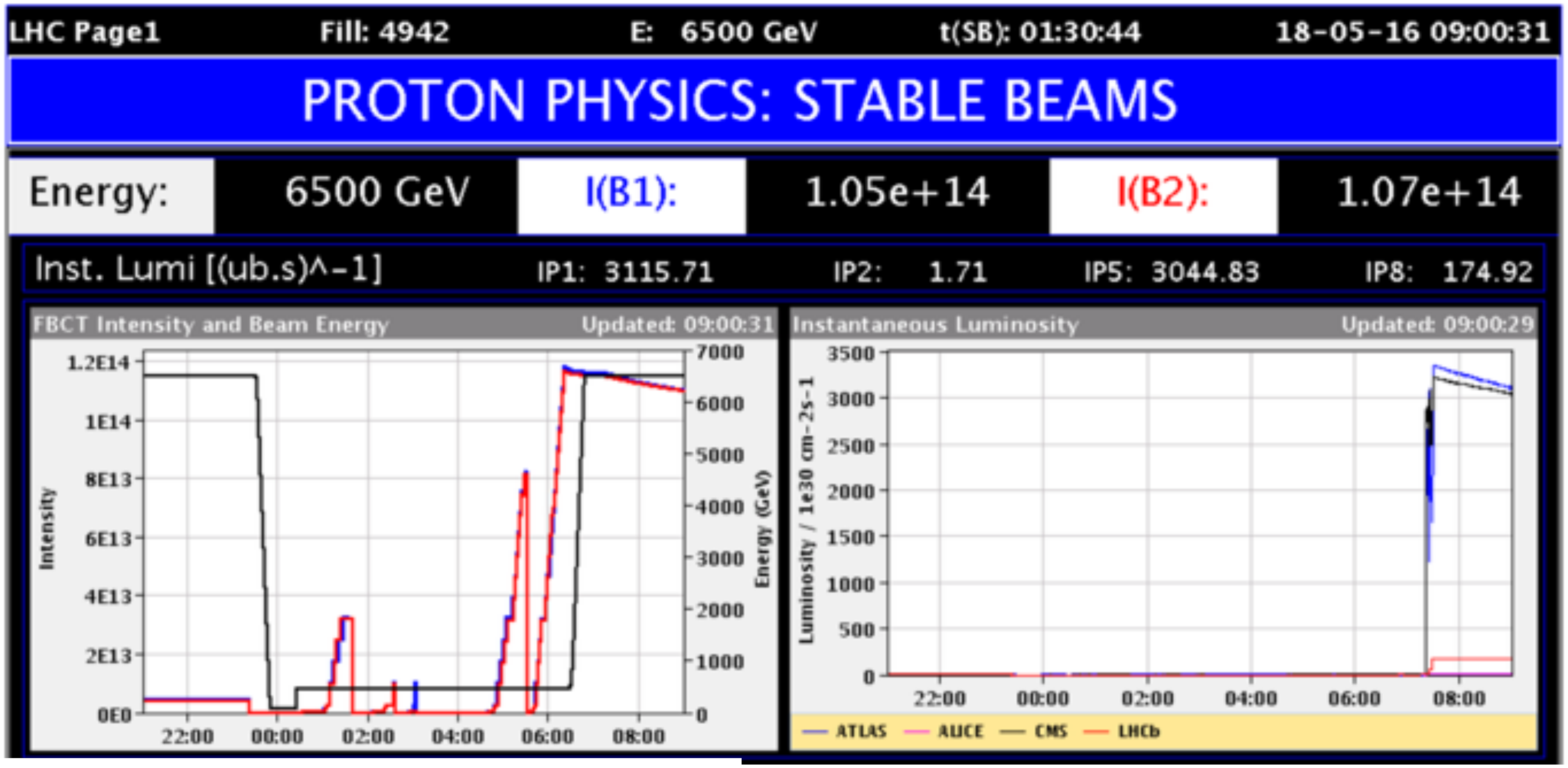

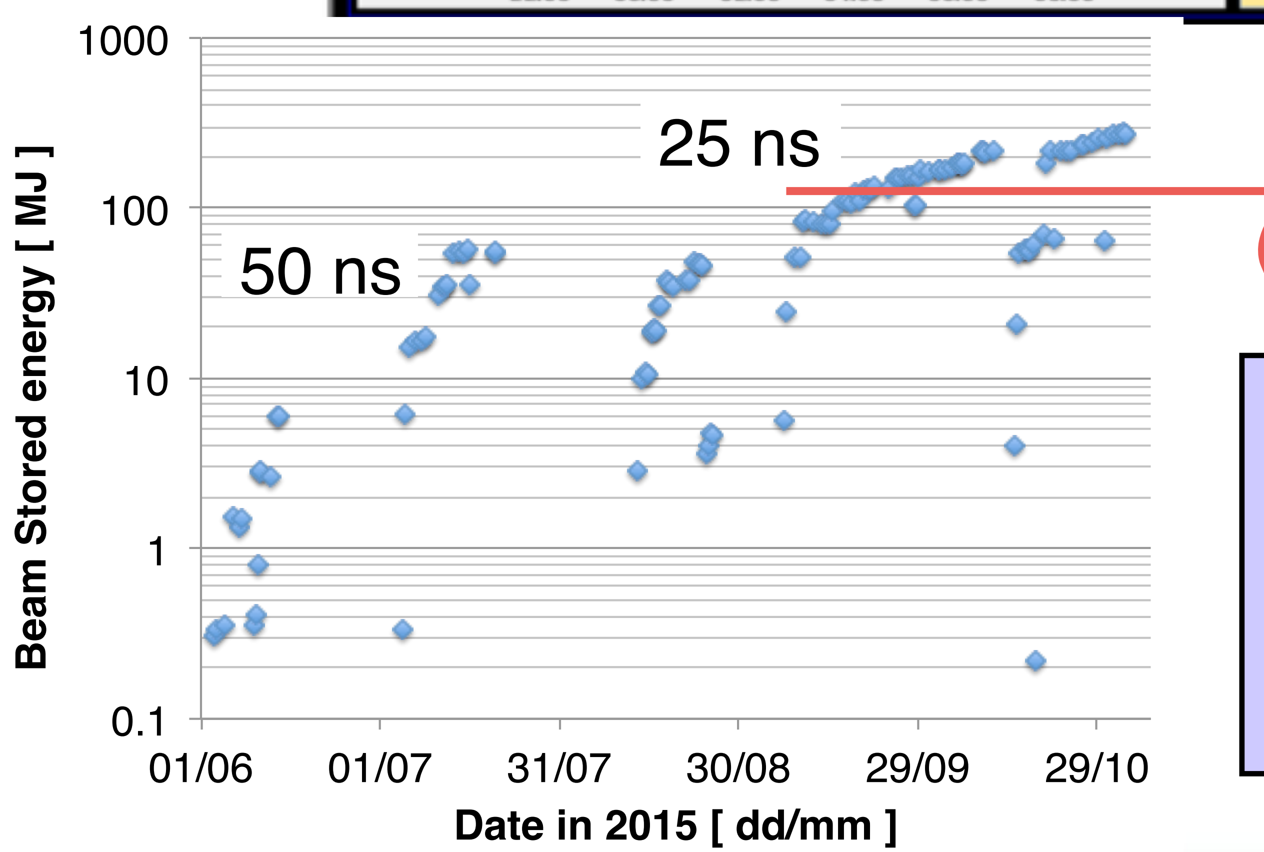

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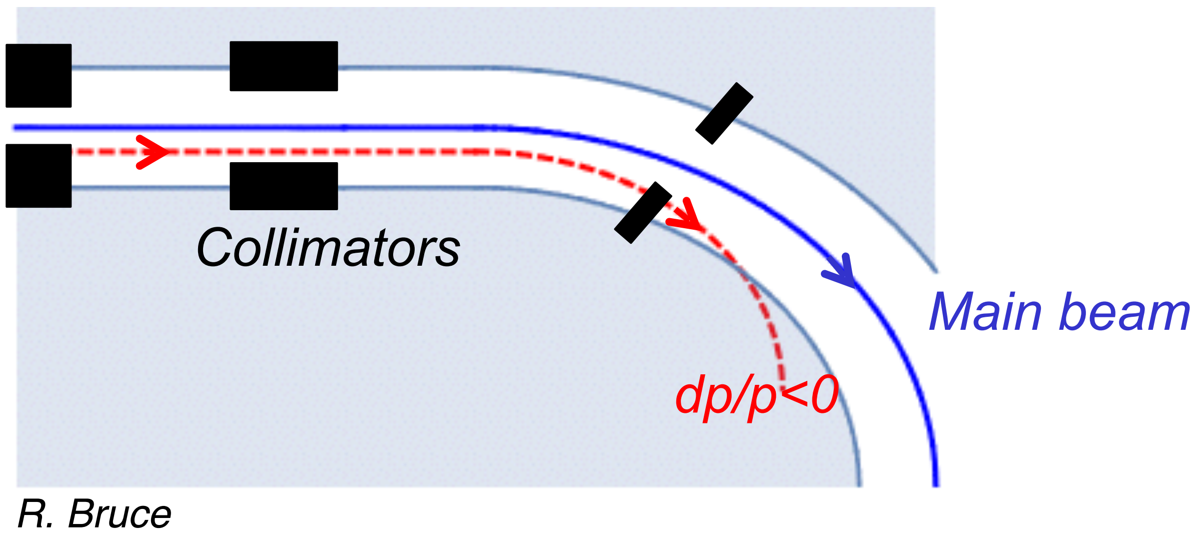
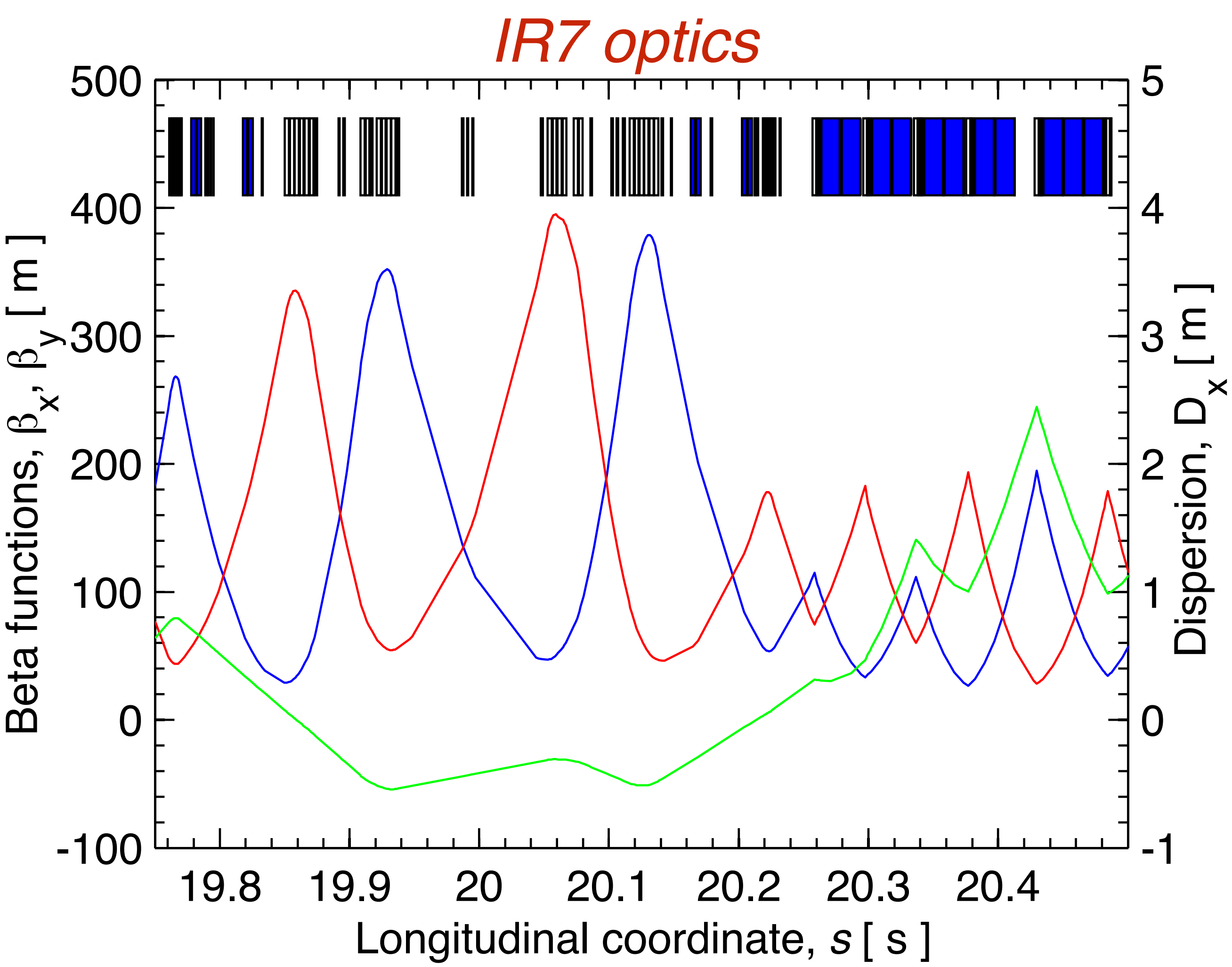
We need to monitor the performance in steady operation with maximum number of bunches and pushed bunch intensity: Review in 2-3 months seems feasible.

Dispersion suppressor (DS) losses





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

*Qualitatively same behaviour in **collimation insertions** and **experiments**.*

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.

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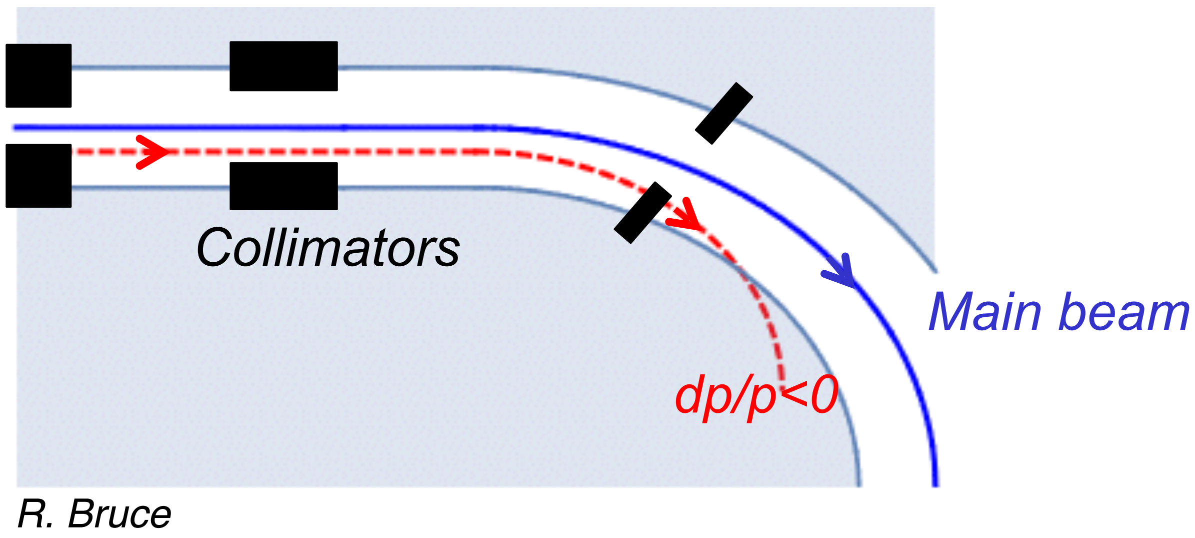

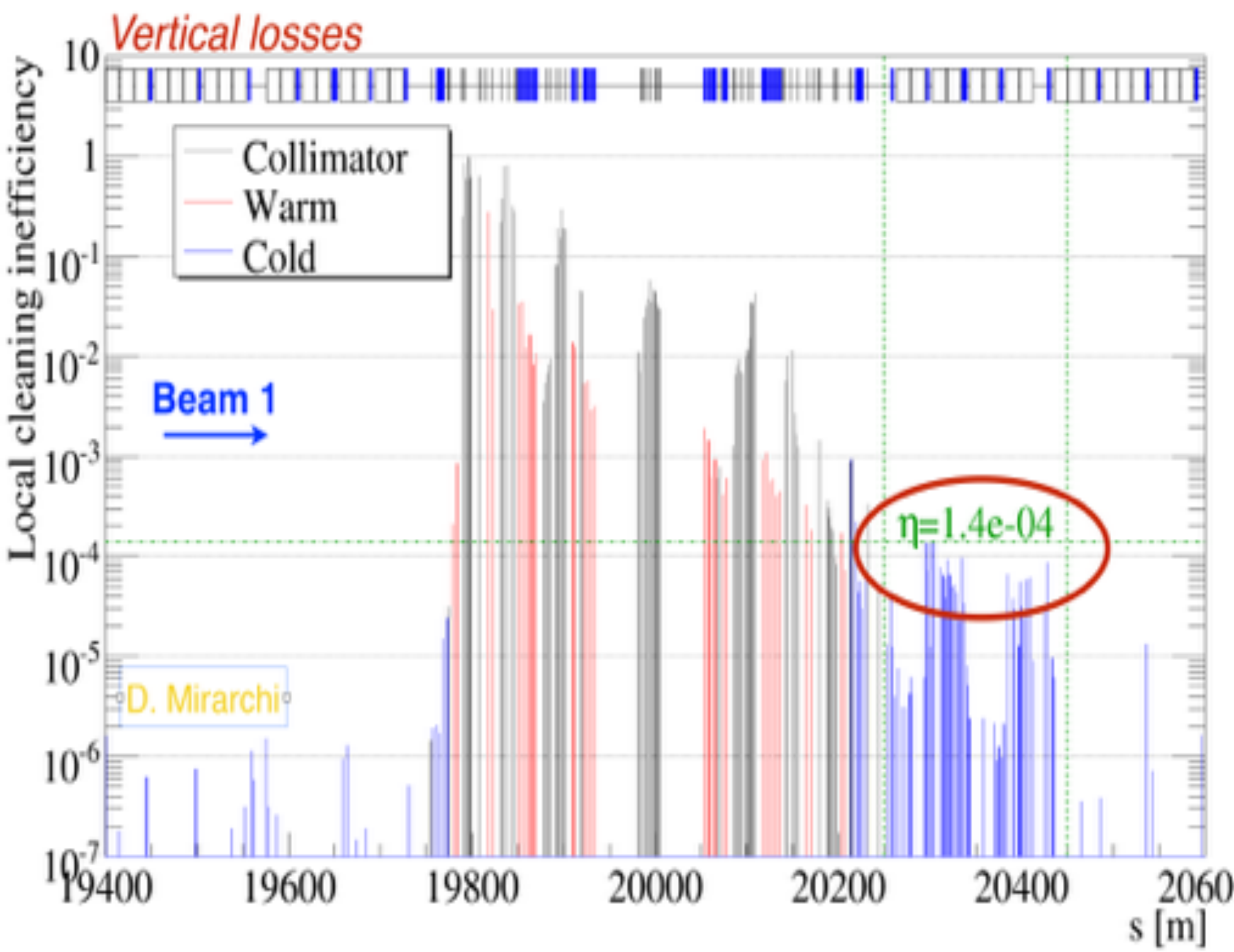

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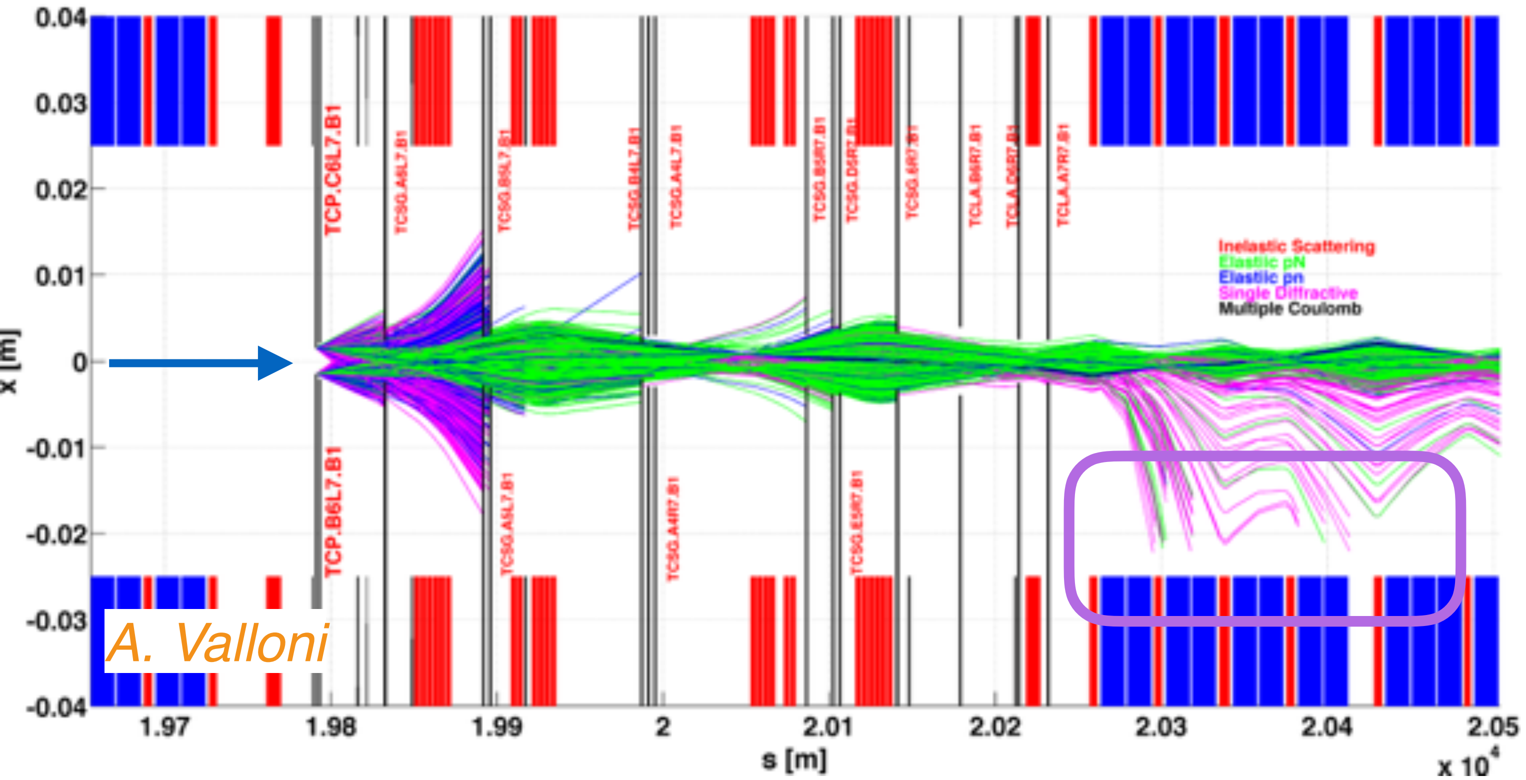
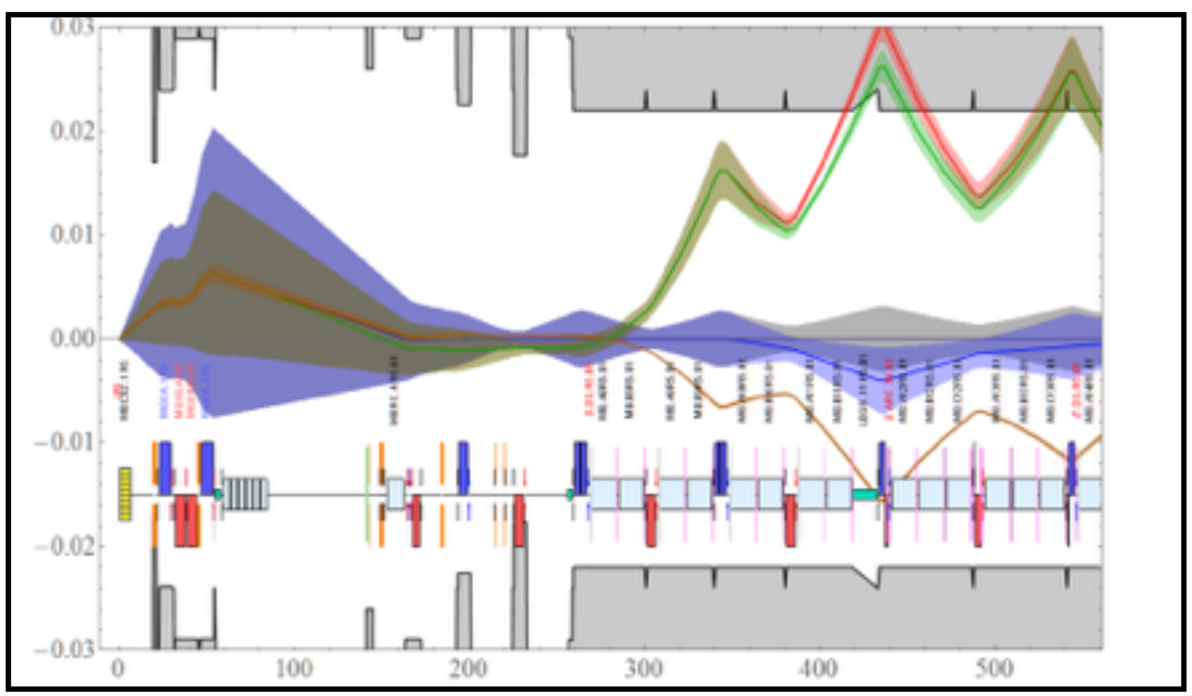
Specific requirements



Dispersion suppressors downstream of collimation insertions: limiting locations for dispersive losses of protons and ions interacting with collimator jaws



Dispersion suppressors downstream of interaction points: Bound-Free Pair Production (BFPP) with heavy-ion collisions.

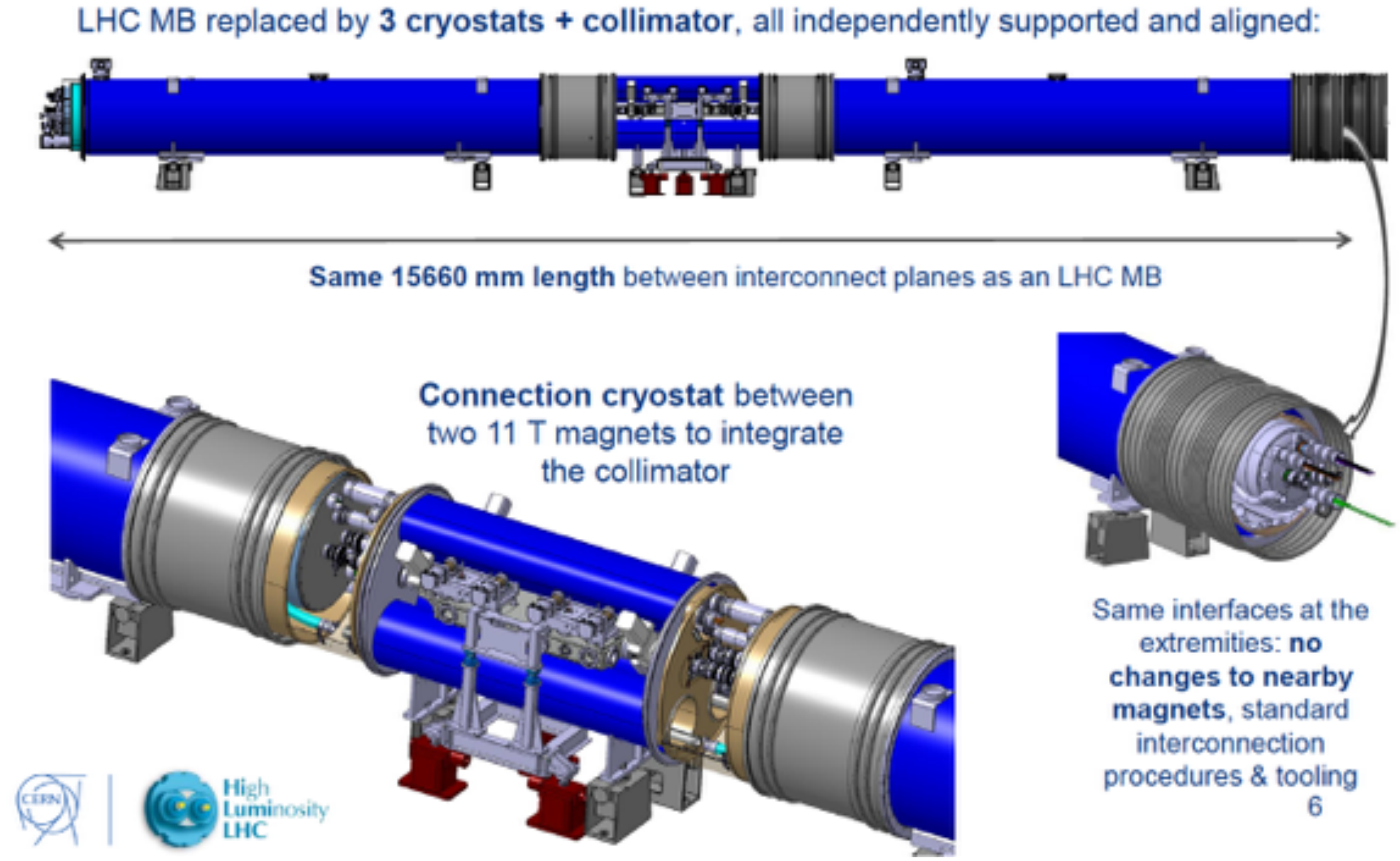
J. Jowett

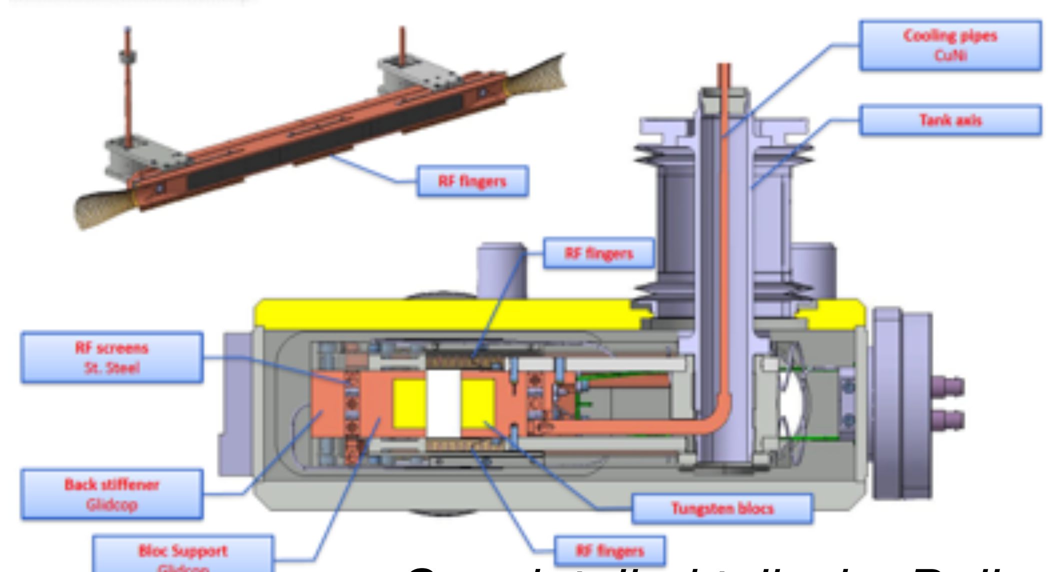
Technical solution based on 11T dipole

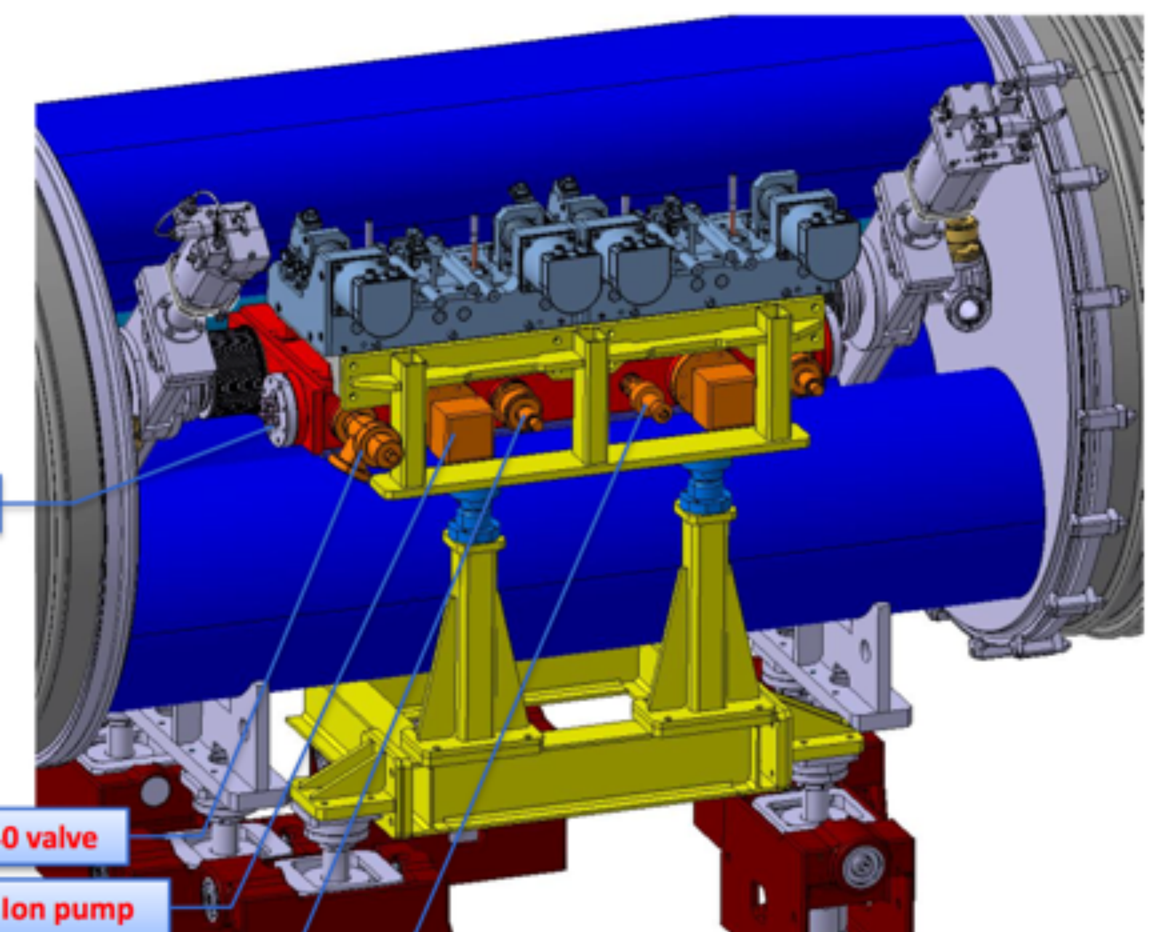
Completed final design of the TCLD collimator, 60 cm long jaw. Synergy between WP5 and WP11.

Launched in 2015 the construction of a **prototype**.

Need to work on the **integration into a connection cryostat**, without 11 T dipoles around.







See detailed talks by Delio D. and Luca G. at ColUSM, 18/09/2015

Quench from debris of 6.5TeV ion collisions

BFPP Quench MD – first luminosity quench in LHC

- BLM thresholds in BFPP loss region raised by factor 10 for one fill 8/12/2015 evening.
- Prepared as for physics fill, separated beams to achieve moderate luminosity in IP5 only.
- Changed amplitude of BFPP mitigation bump from -3 mm to +0.5 mm to bring loss point well within body of dipole magnet (it started just outside).
- Put IP5 back into collision in 5 μm steps.
- Unexpectedly quenched at luminosity value (CMS):

$L \approx 2.3 \times 10^{27}\ \mathrm{cm^{-2}s^{-1}}$

$\Rightarrow$ 0.64 MHz event rate, about 45 W of power in Pb^{81+} beam into magnet

J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016 14

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J.M. Jowett, LHC Performance Workshop, Chamonix, 28/1/2016

Consequences of the BFPP quench result

- Resolves long-standing (since mid-1990s) uncertainty on steady state quench and BFPP luminosity limit
  - Factor 2-3 lower than recent expectations
  - Main errors BFPP cross section, luminosity
- Efficacy of BFPP bumps clear – we already needed them in 2015 to avoid luminosity quenches around ATLAS and CMS!
  - FLUKA analysis confirms this is still OK for further increase in luminosity.
  - Radiation effects and heat load may still be issues.
- Closes the case for collimators in the LHC dispersion suppressors around ALICE (where the bump mitigation alone does not work), discussed since Chamonix 2003 …
- The design work for integration of TCLD collimators in the connection cryostats needs to start now so that they can be installed during LS2.

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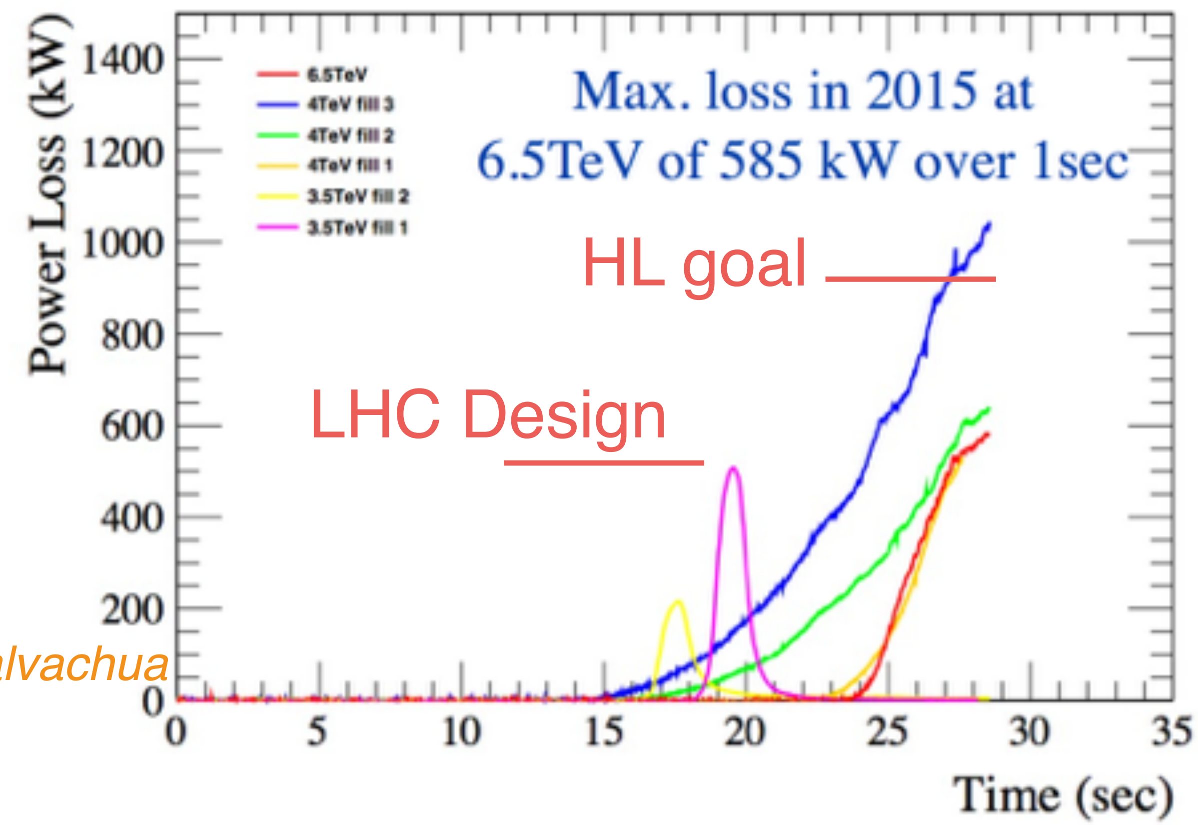
Quite unexpected result that definitely confirms the needs for IR2 collimation upgrade.

J. Jowett

2015 quench tests and intensity reach

Primary beam losses on collimators



B. Salvachua

Summary of 6.5TeV test in 2015:
p beam: no quench with **585kW** primary beam losses (design = 500kW).
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*Intensity reach obtained scaling losses to a **0.2h lifetime at full intensity**.*

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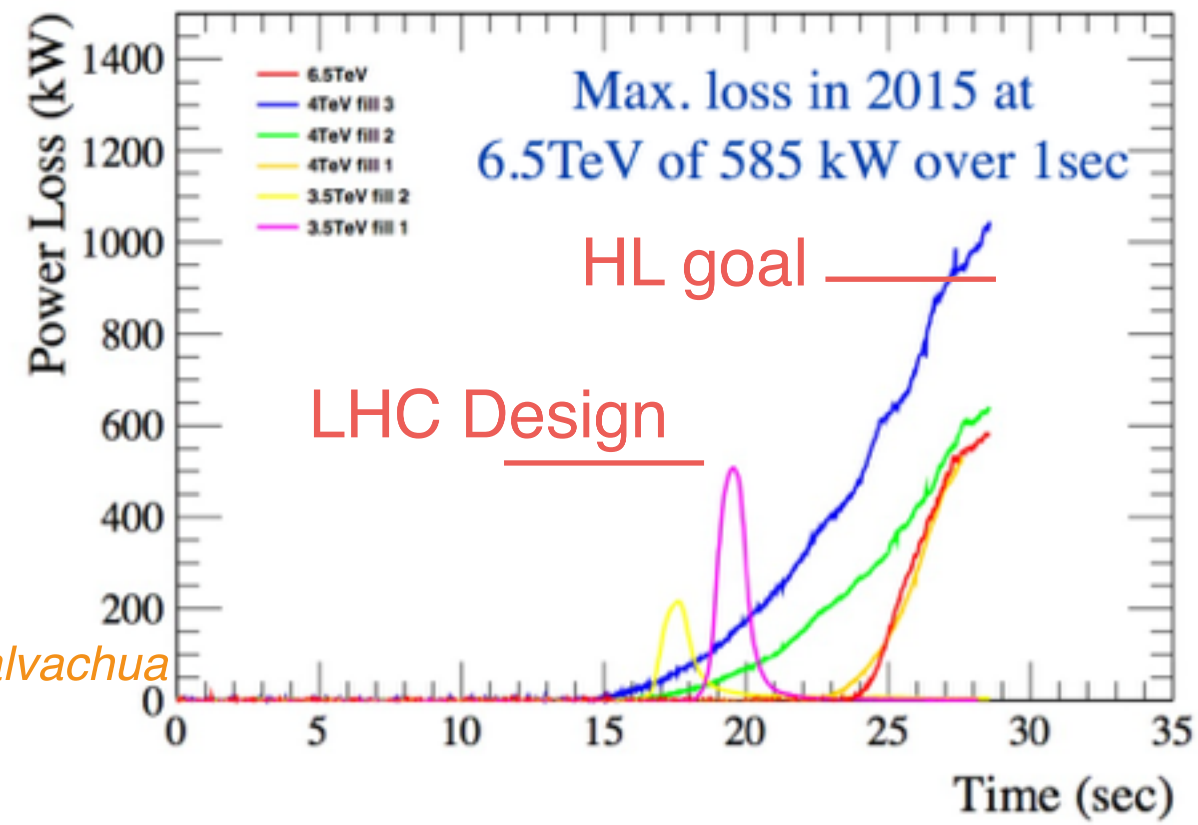

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	Imax	E_b^{max}	*Design*	*HL-LHC*
Protons (6.5 TeV) [lower limit, as no quench]	*> 4e14p*	***> 420 MJ***	335 MJ	630 MJ
PB ions (6.37 Z TeV)	<11.4e10Pb	**<10.8 MJ**	3.5 MJ	16 / 22 MJ

Extrapolations to an energy of 7 TeV need inputs on quench limits.

2015 quench tests and intensity reach

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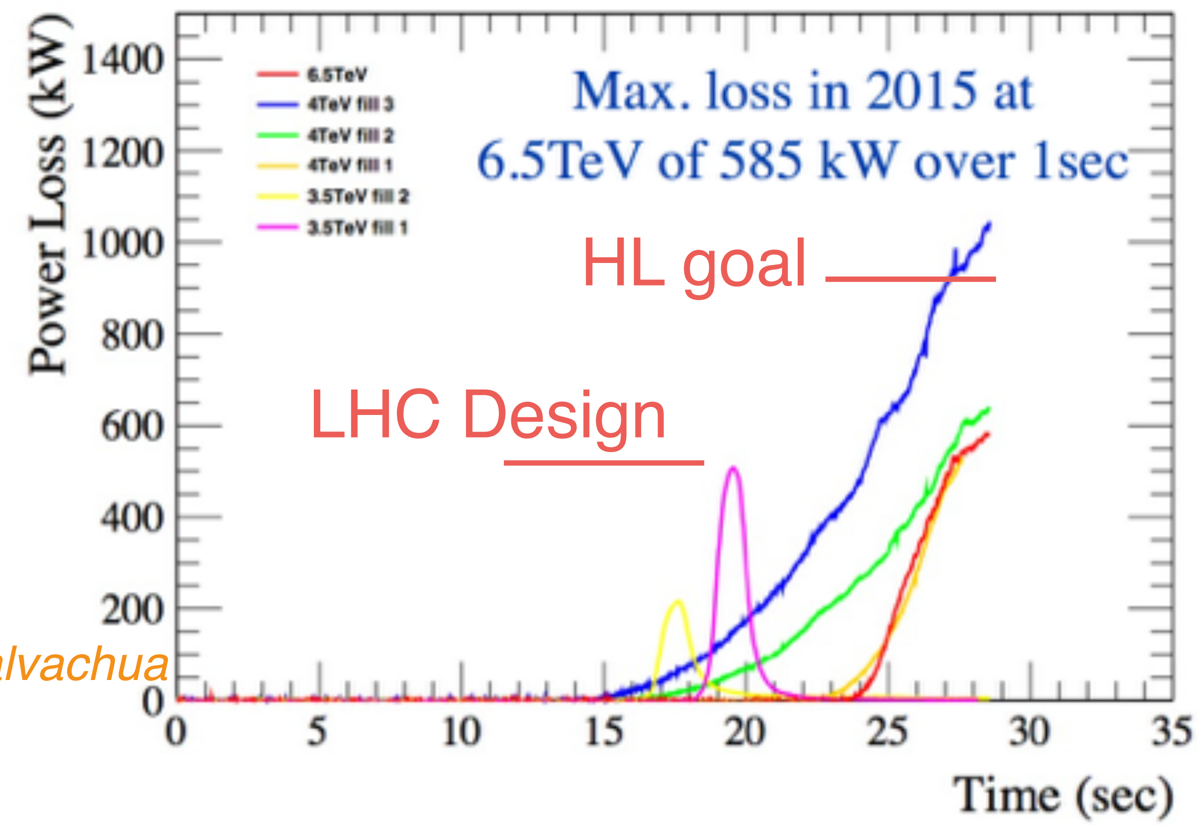

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Potentially, one significant limitation to go to 7TeV before LS2.

Extrapolations to an **energy of 7 TeV**

New DS collimation baseline

Proposed **DS collimation baseline** based on recent quench tests and operational experience with IR bumps:

- ***2 dispersion suppressor collimators (TCLDs) around IP2, no 11T dipoles***
  Bumps to steer BFPP losses in collimators located in the connection cryostat.
  Backup slide if you are interested.

- *2 {TCLD + 11T dipoles} cryo-units around IR7:*
  Staged installation with 1 unit per beam in LS2 (2 collimators, 4 dipoles).

- *Complete installation with 2 more full units in LS3, **if needed** (present baseline).*

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This proposal is approved by the HL-LHC project, also thanks to the promising results from the 11T team indicating the feasibility to have 4 dipoles by LS2.
Activities for IR2 (no 11T) and IR7 (11T) approved by the LMC.

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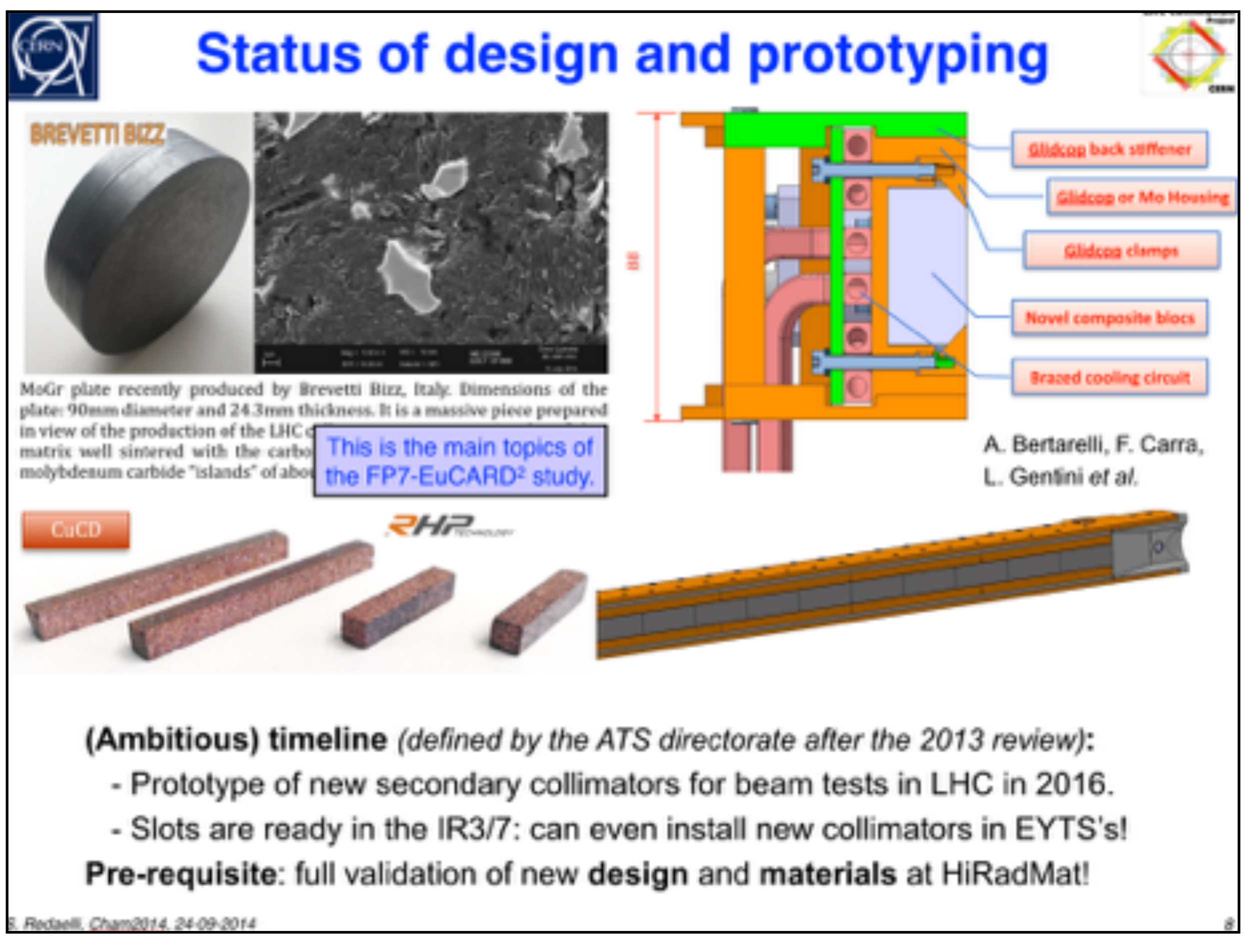
- New elements for road map
  - *Operational losses*
  - *Quench tests at 6.5 TeV*
  - ***Results of new material R&D***
- Collimation upgrade path
- Alternative scenarios
- Conclusions

Material R&D and jaw prototyping

Cannot find one single solution that addresses conflicting requirement.
Baseline material choices:

- CuCD (Copper diamond): more robust tertiaries for triplet protection
- MoGR (Molybdenum GRaphite), with Mo coated, for high robustness and reduced impedance in IR7 (secondary collimators).



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C … requirement.
B …

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… high robustness
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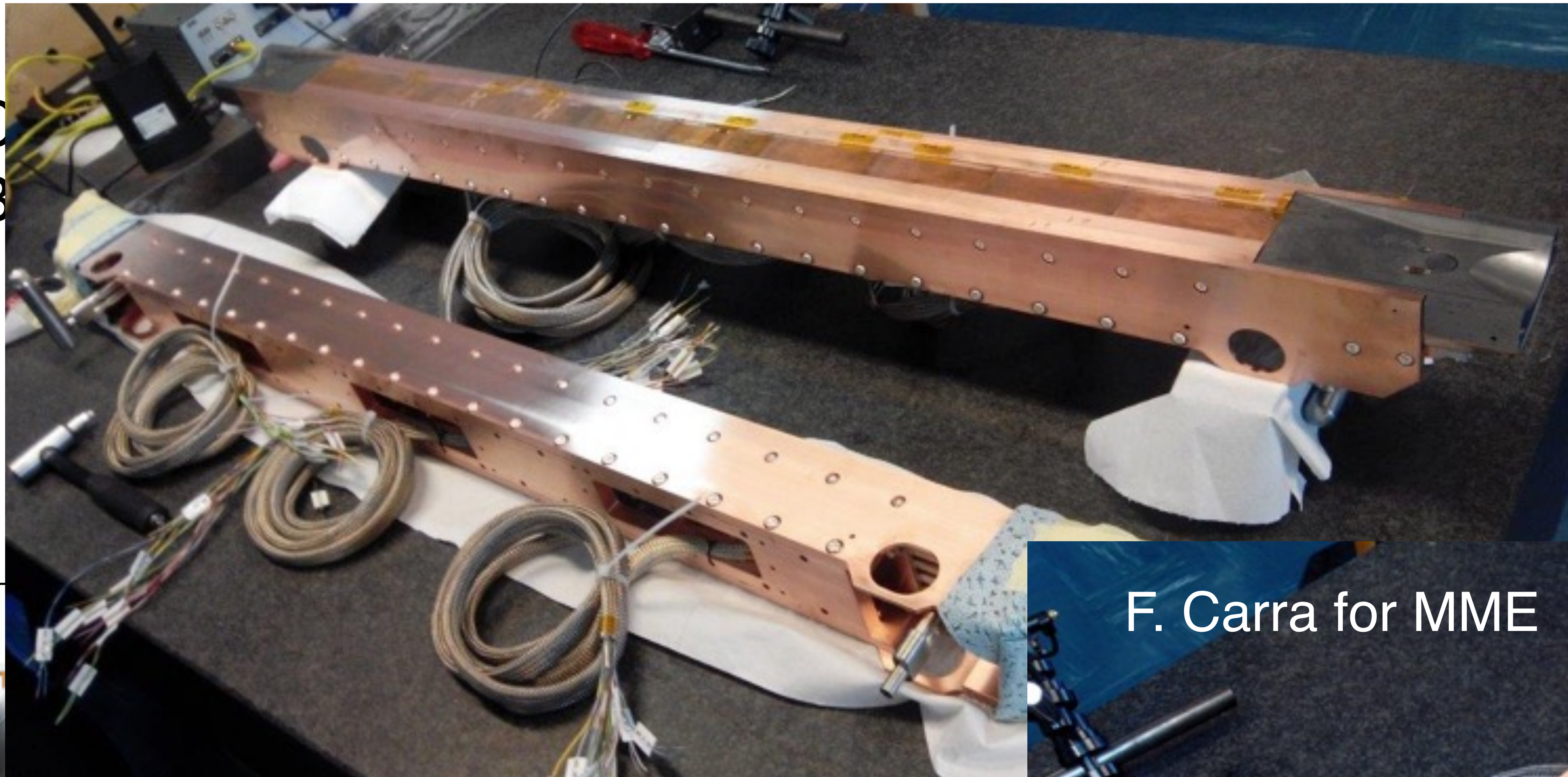

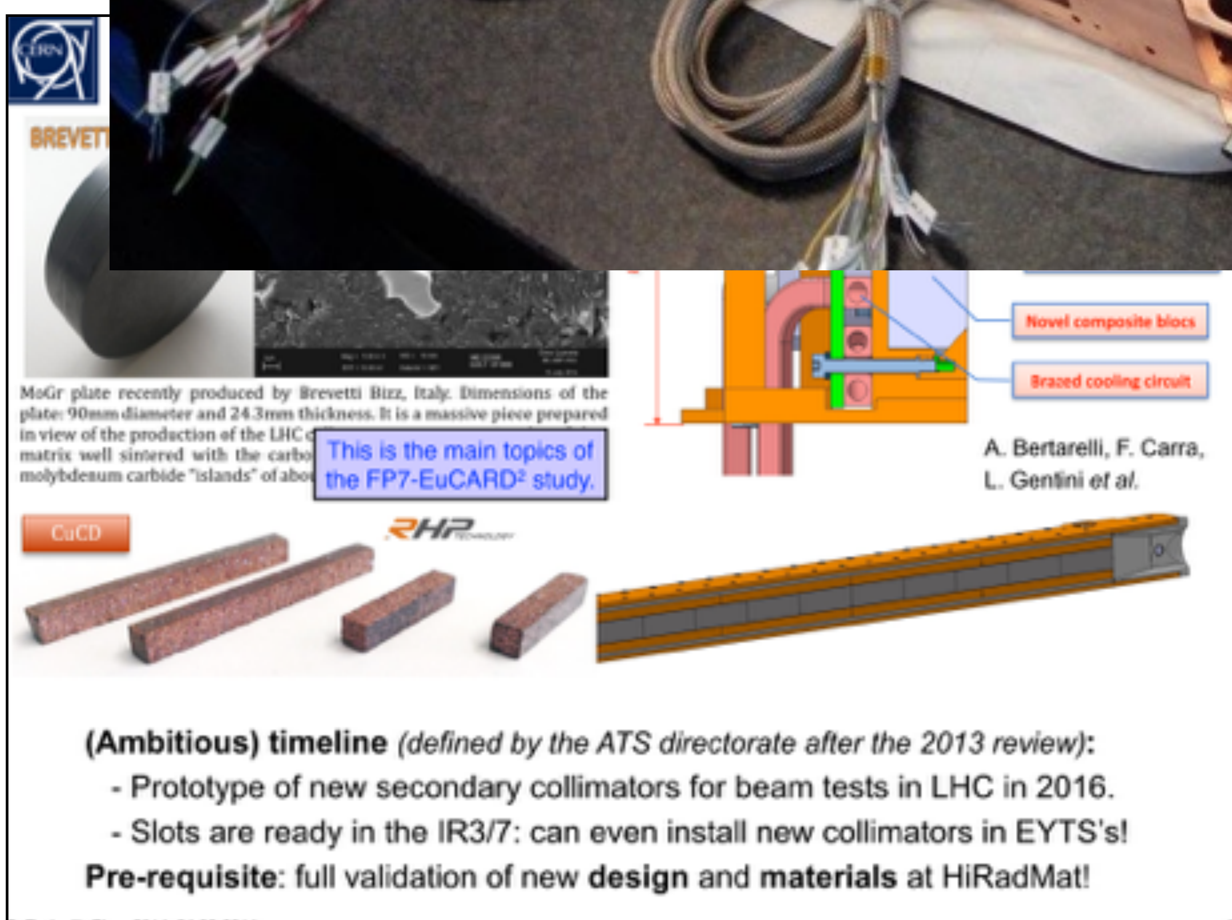

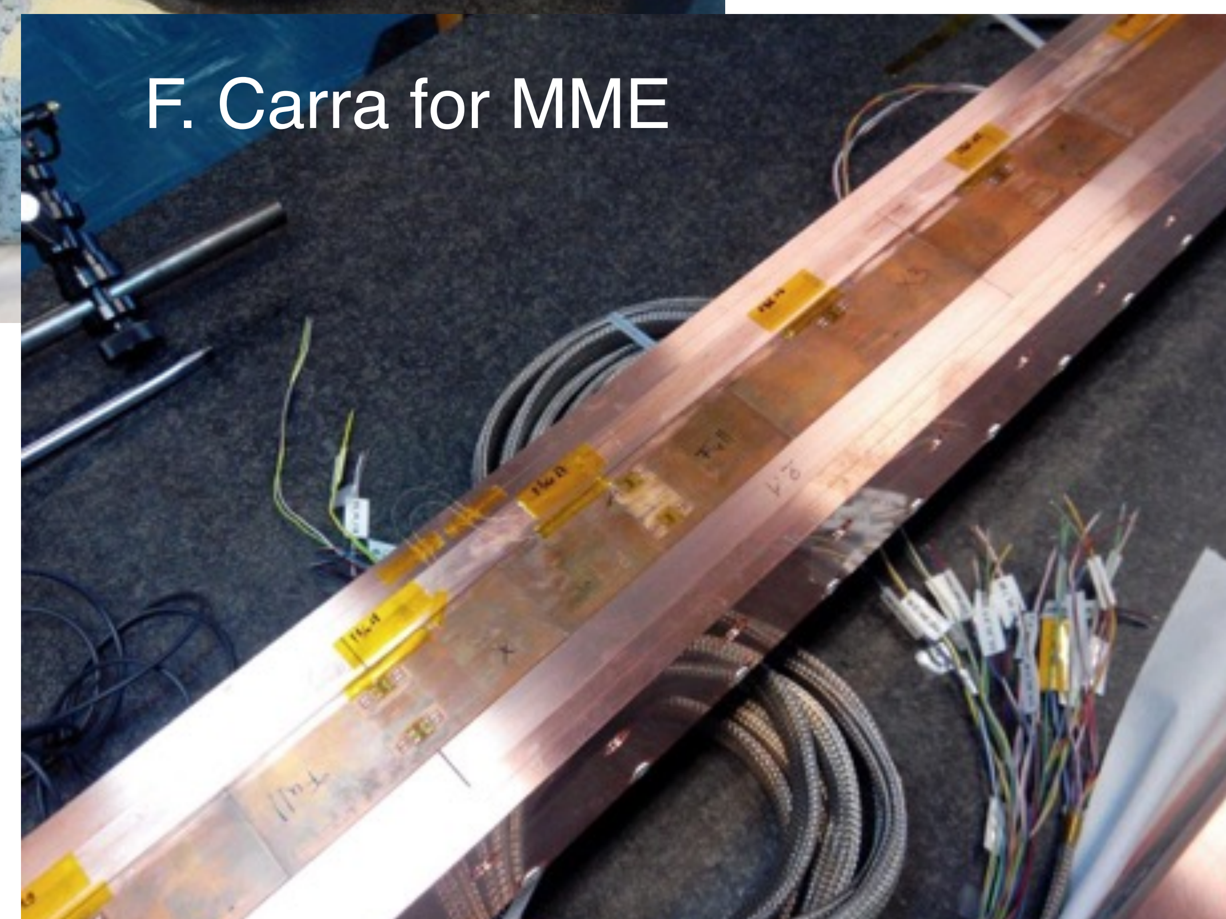

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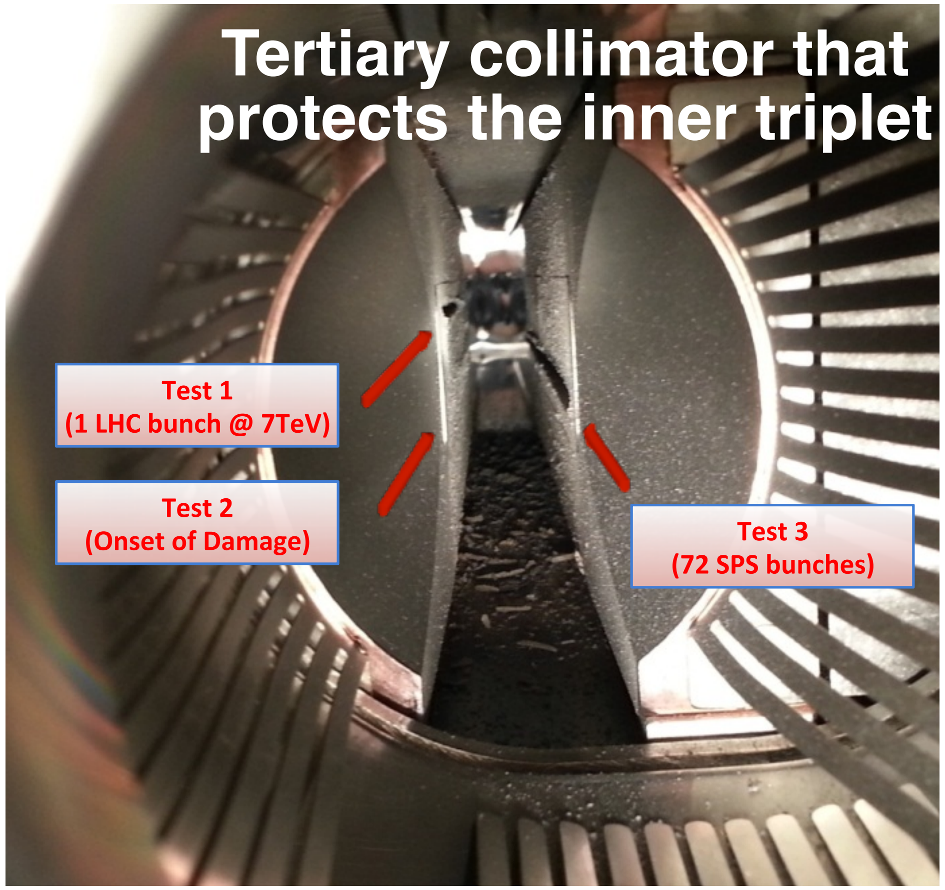

A. Bertarelli, F. Carra

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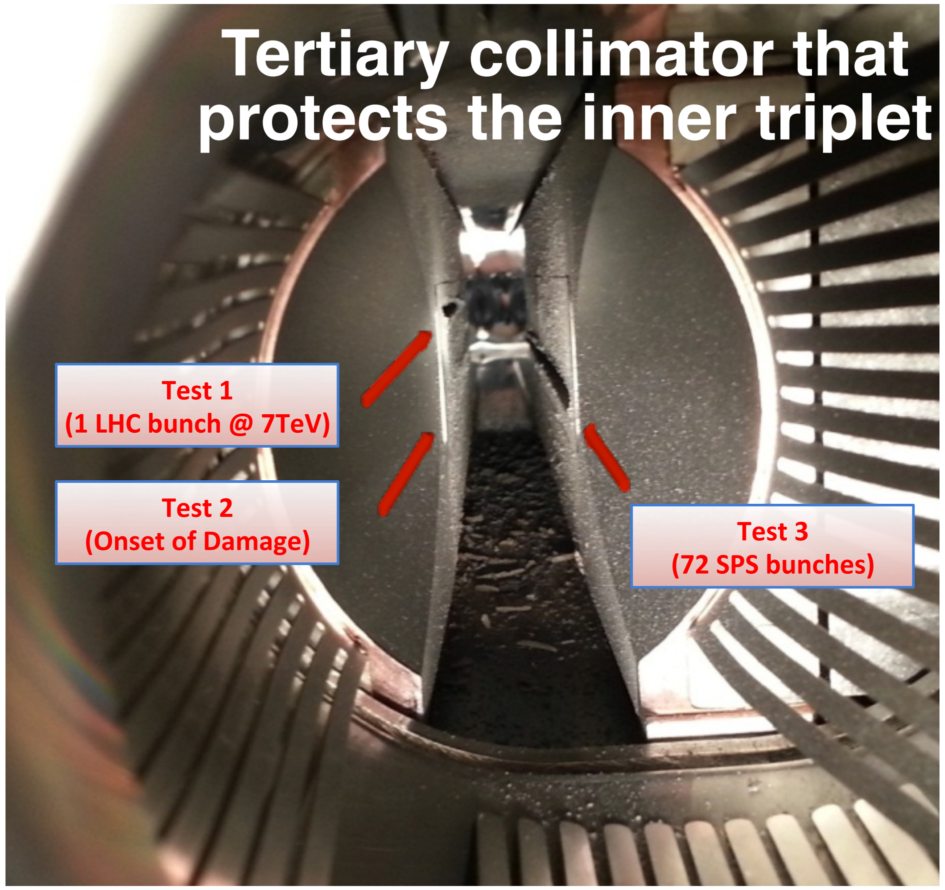

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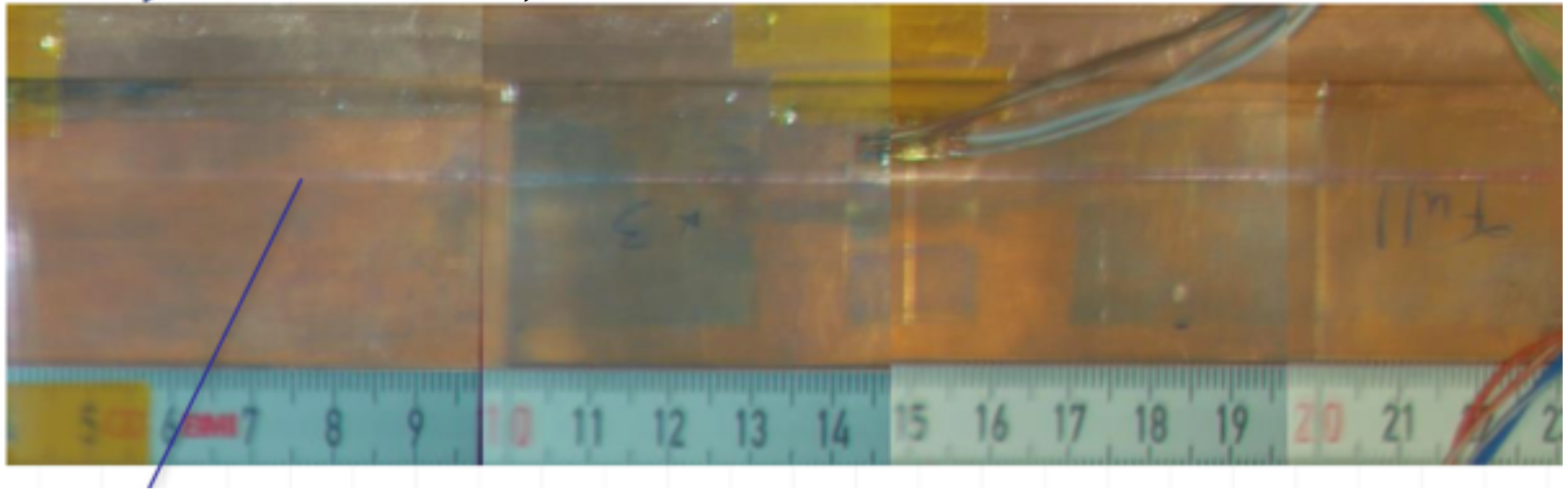
Copper Diamond: candidate tertiary collimator material, 10-15 times more robust.



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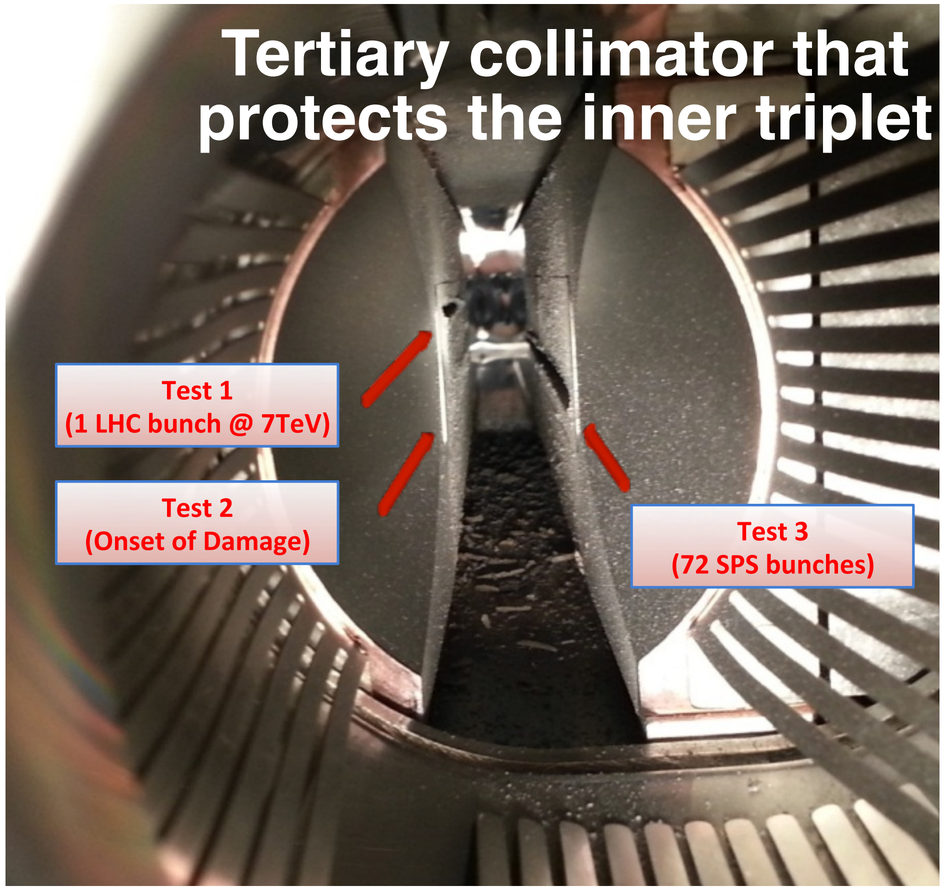

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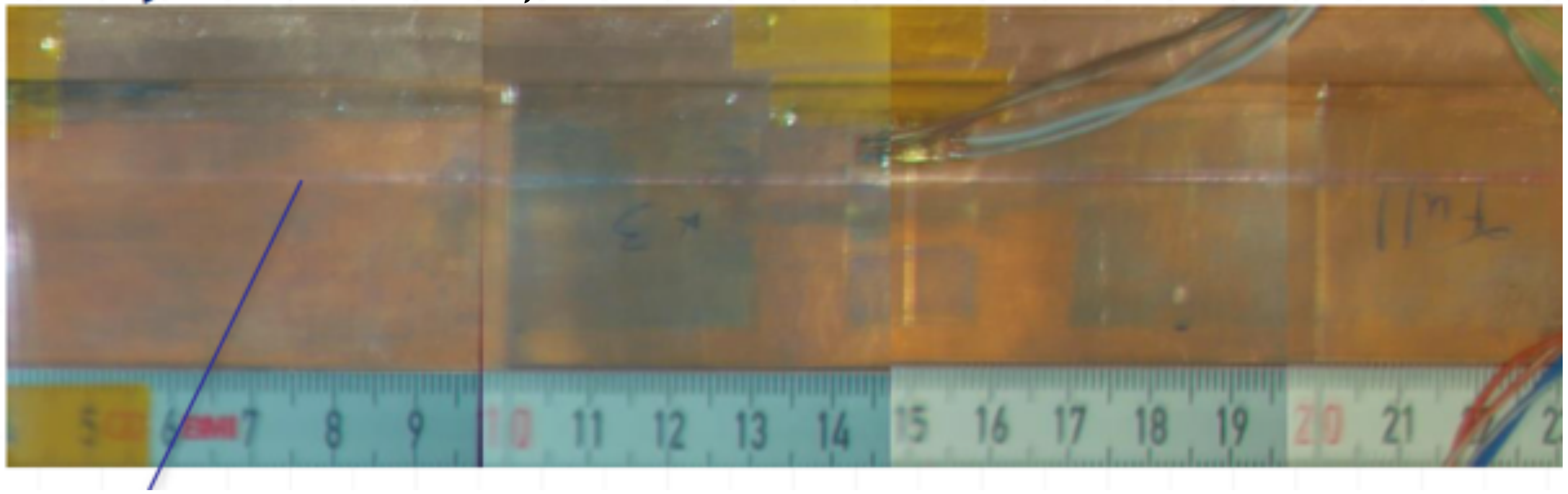

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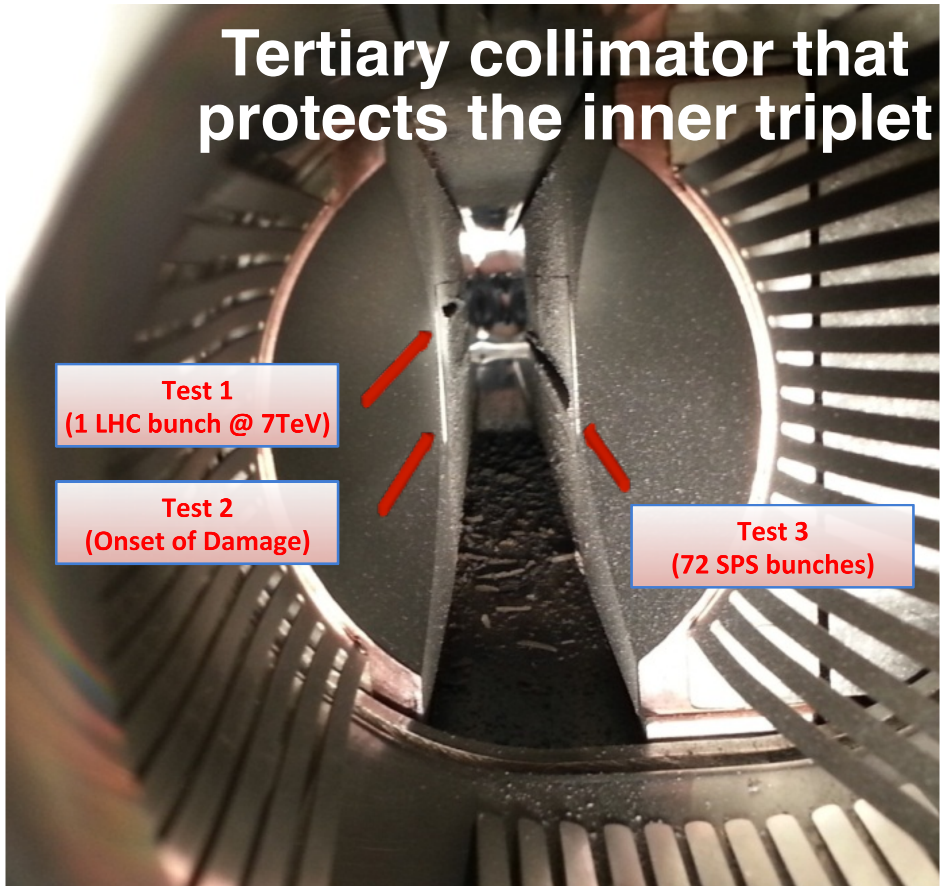

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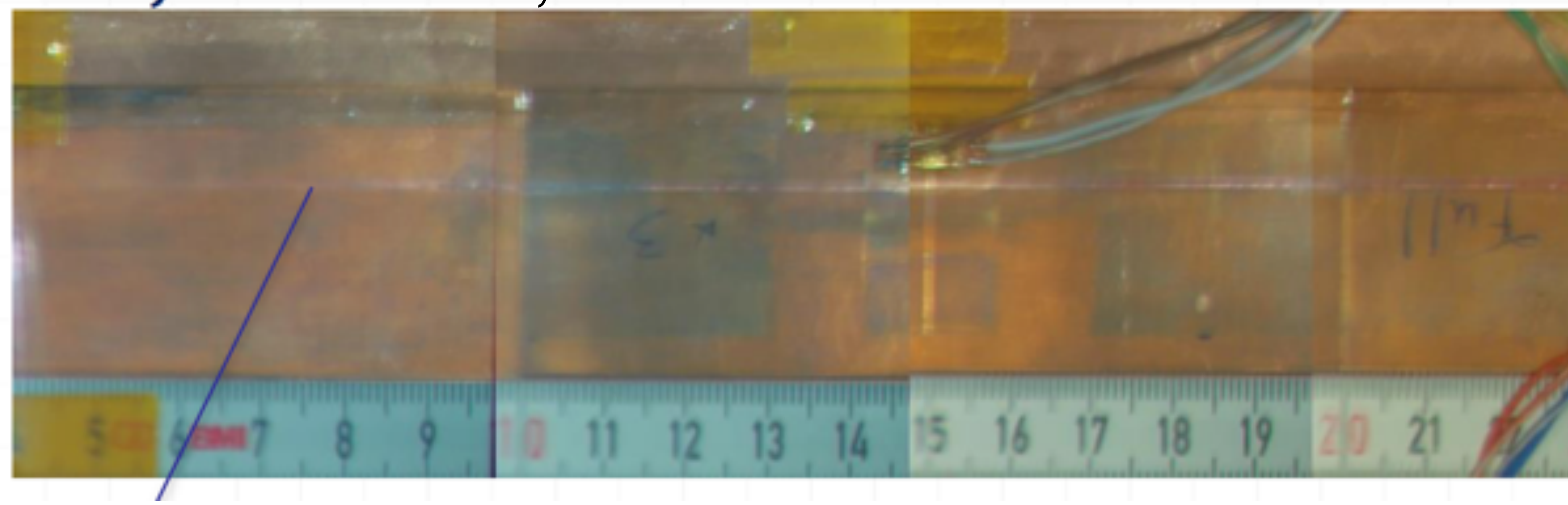
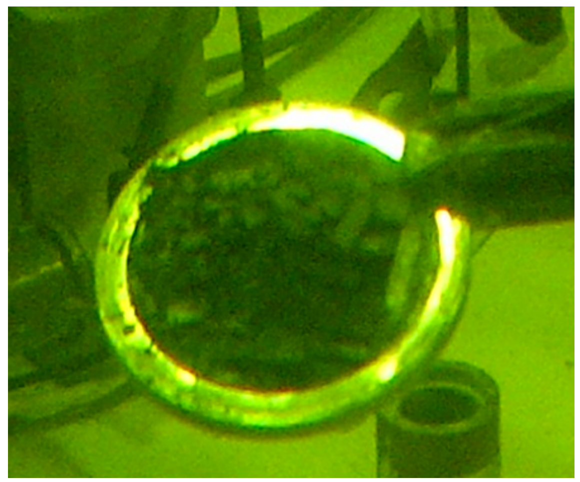


Excellent results: full MoGR jaw survived as well as CFC to impact of 288b of 1.3x1011p with σ=350μm (density beyond LIU)

Radiation tests of new materials - MoGR

(Not so good) news presented at last CM in Fermilab:



State of Mo-GR after 1.1 10^{21} p/cm^2 FLUENCE !!!!

Several samples MoGR broke!

*Launching another set of measurements with **latest MoGR grades**. Very important for us.*

BNL IRRADIATION DAMAGE STUDIES OF THE METAL MATRIX COMPOSITE Mo-GR CONSIDERED FOR HIGH LUMINOSITY LHC COLLIMATOR UPGRADE

PROGRESS REPORT

Main Contributors:

N. Simos[1]

P. Nocera[2] and E. Quaranta[3]

Added Contributions from

Stefano Redaelli[3] and A. Bertarelli[3]

[1]Brookhaven National Laboratory, Upton, NY 11973, USA

[2]University of Rome

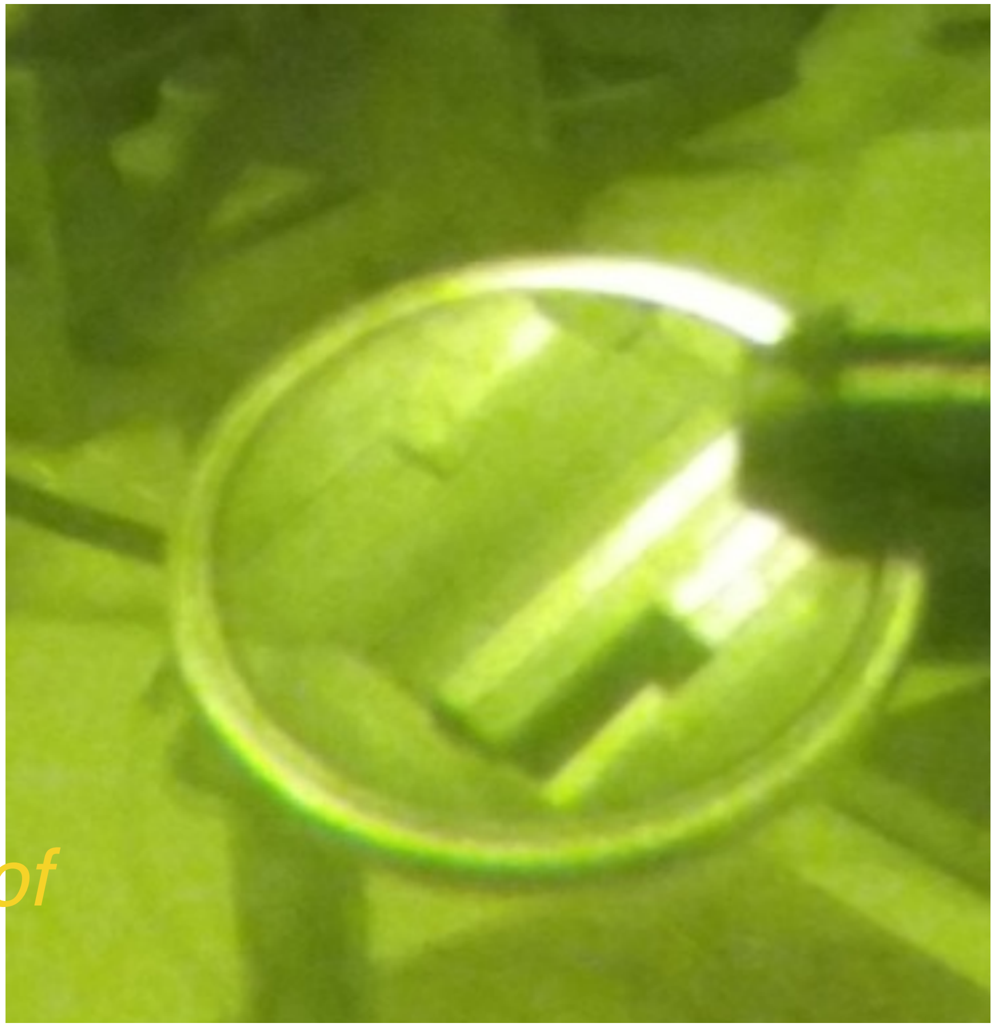
[3]CERN

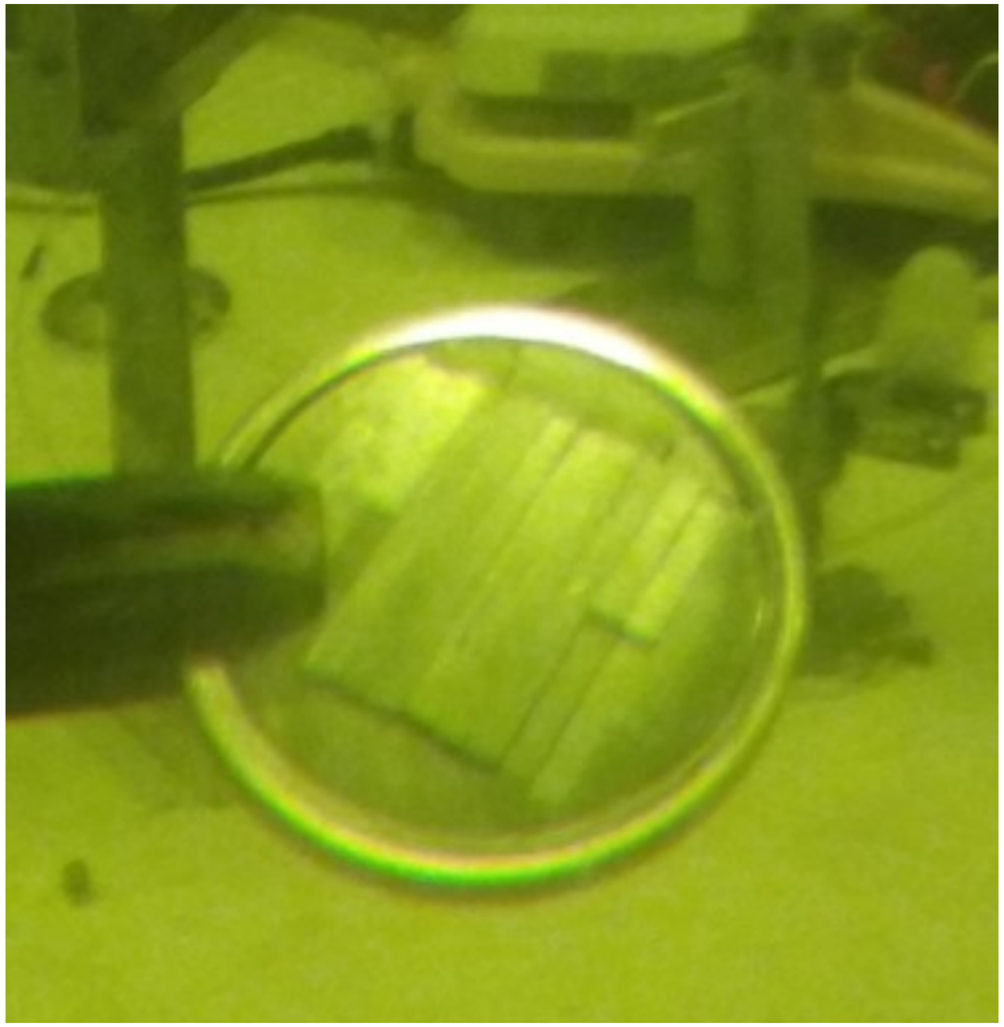
DRAFT

*Launched a new collaboration contract in 2016 to repeat these test with the **latest grades** and to determine **onset of damage** vs doses. Note: unfortunately no more funding from US-LARP.*

Preliminary results of new BNL irradiation

Two sets of samples of latest grades (improved from the 2012 ones used in the first irradiation campaign) recently inspected after doses of **7×10^{19} p/cm^2**





Courtesy of N. Simos

Very promising result!

Next: plan to put back in beam new samples to continue irradiation and build a curve of damage versus dose.

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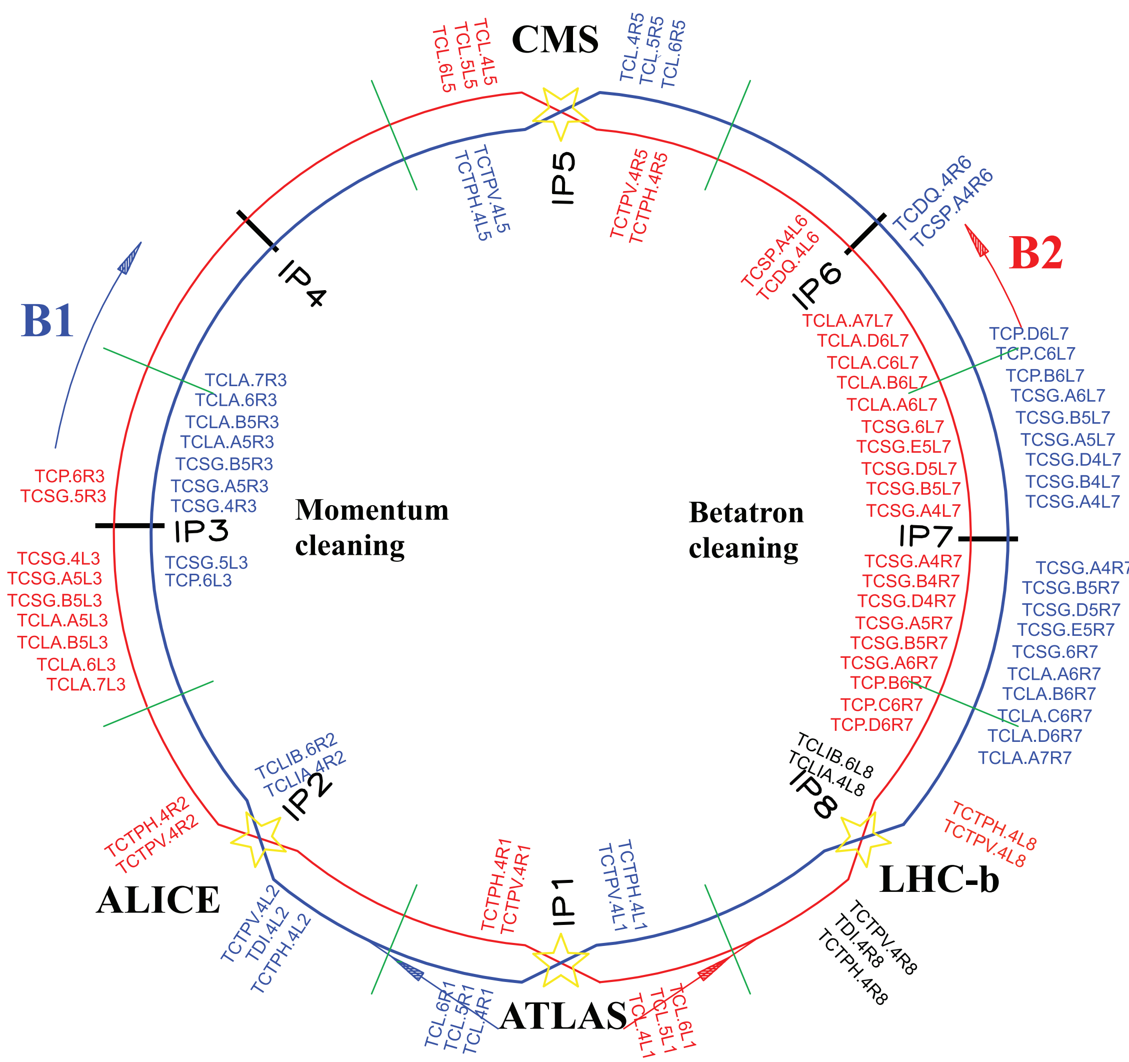
Baseline upgrades



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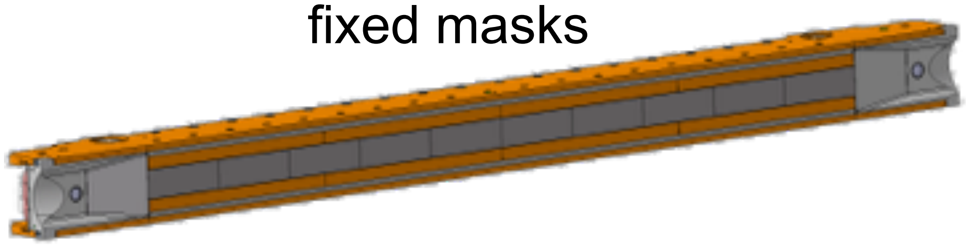
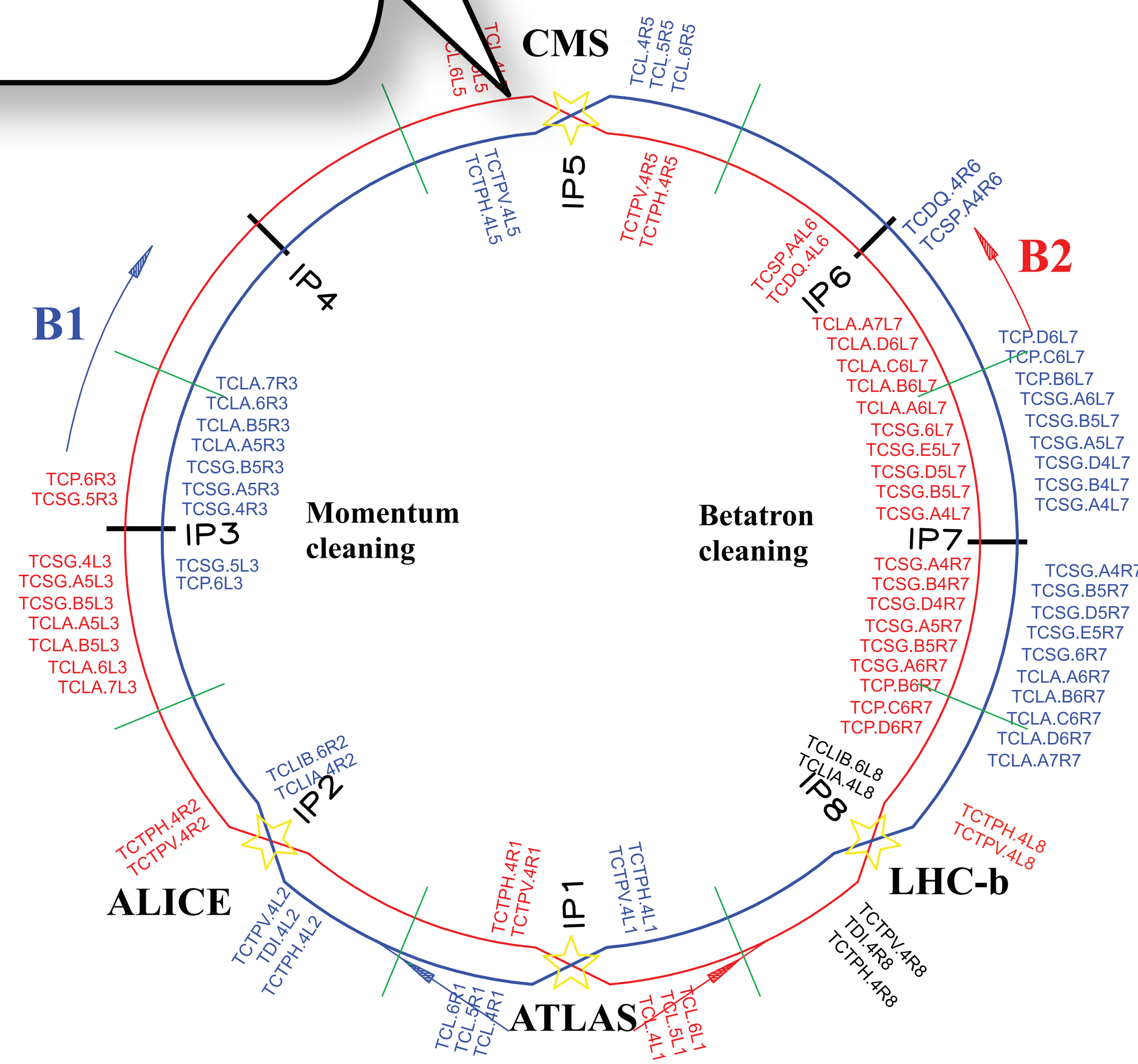
Novel materials: TCTs in CuCD
IR1+IR5, per beam:
- 4 tertiary collimators
- 3 physics debris collimators
- fixed masks





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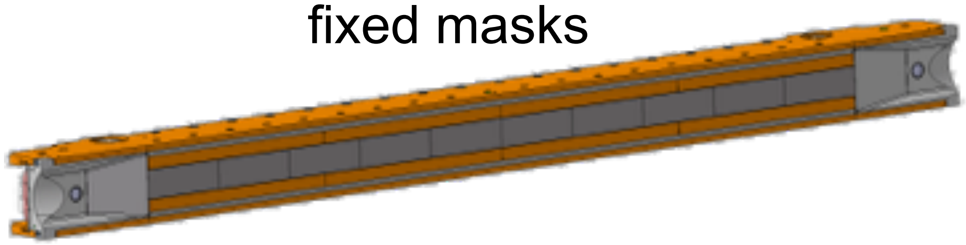
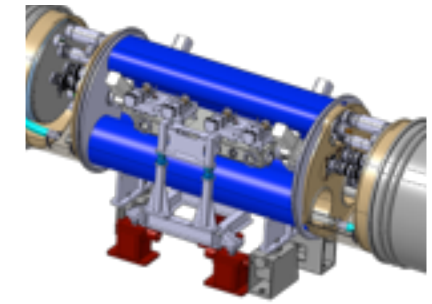
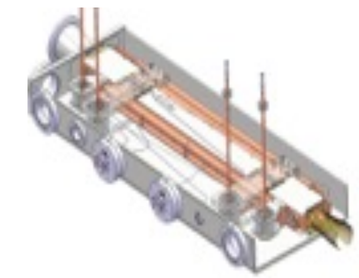
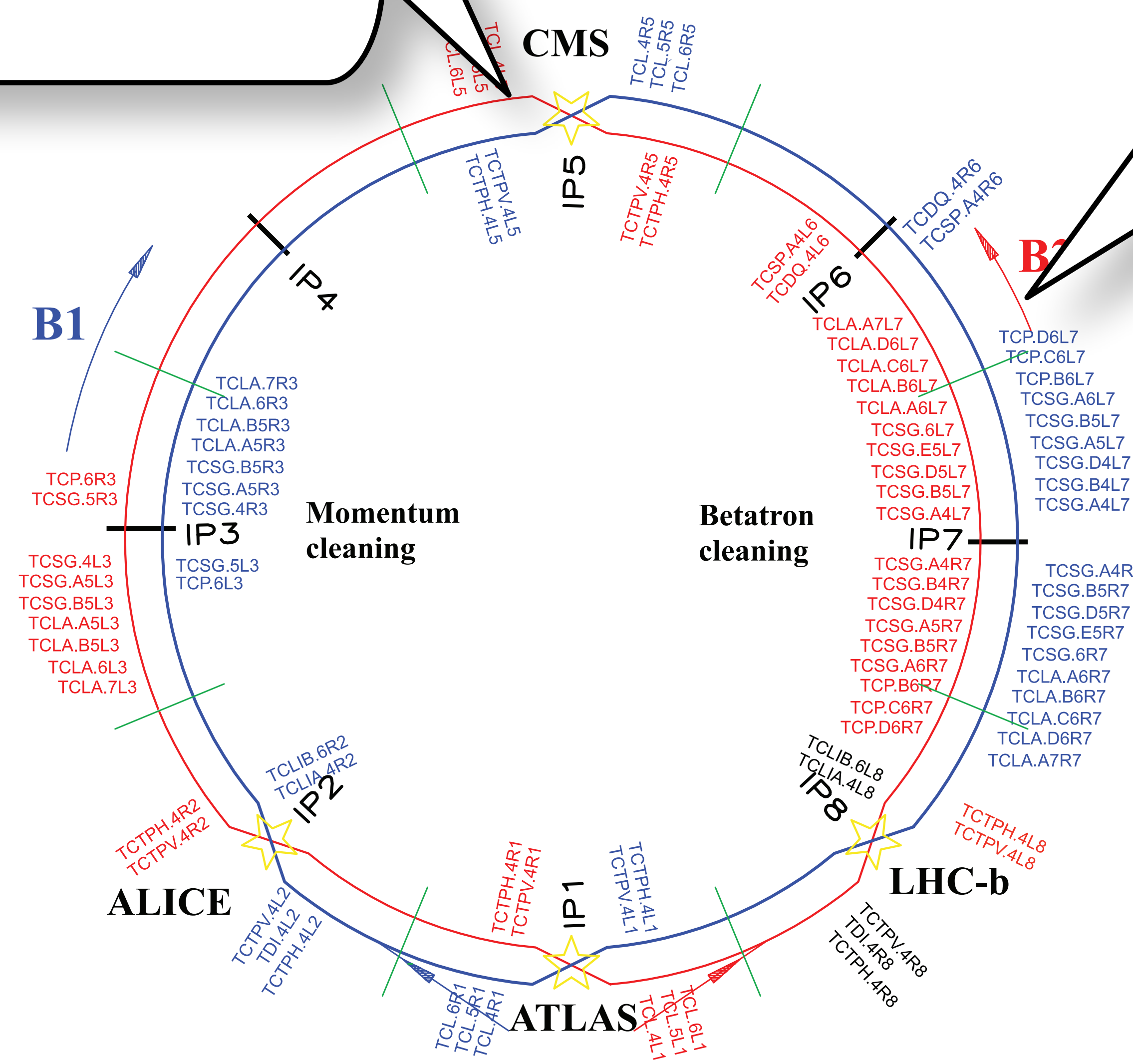


Cleaning: DS coll. + 11T dipoles, 2 units per beam







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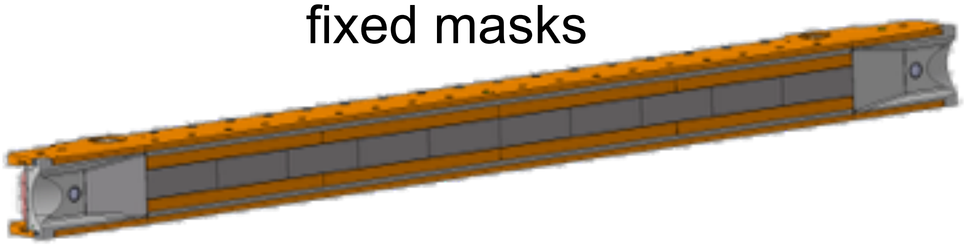

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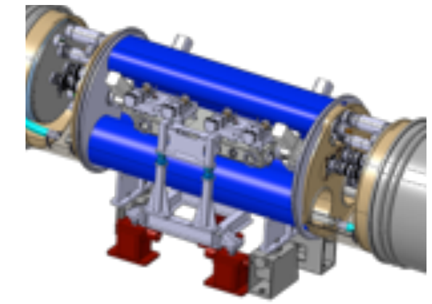

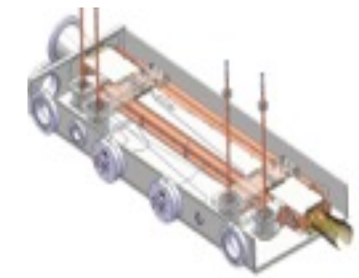

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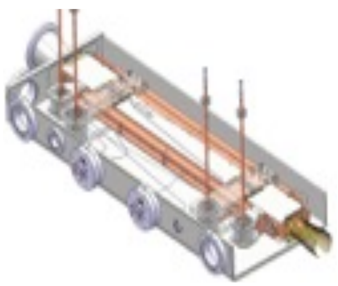
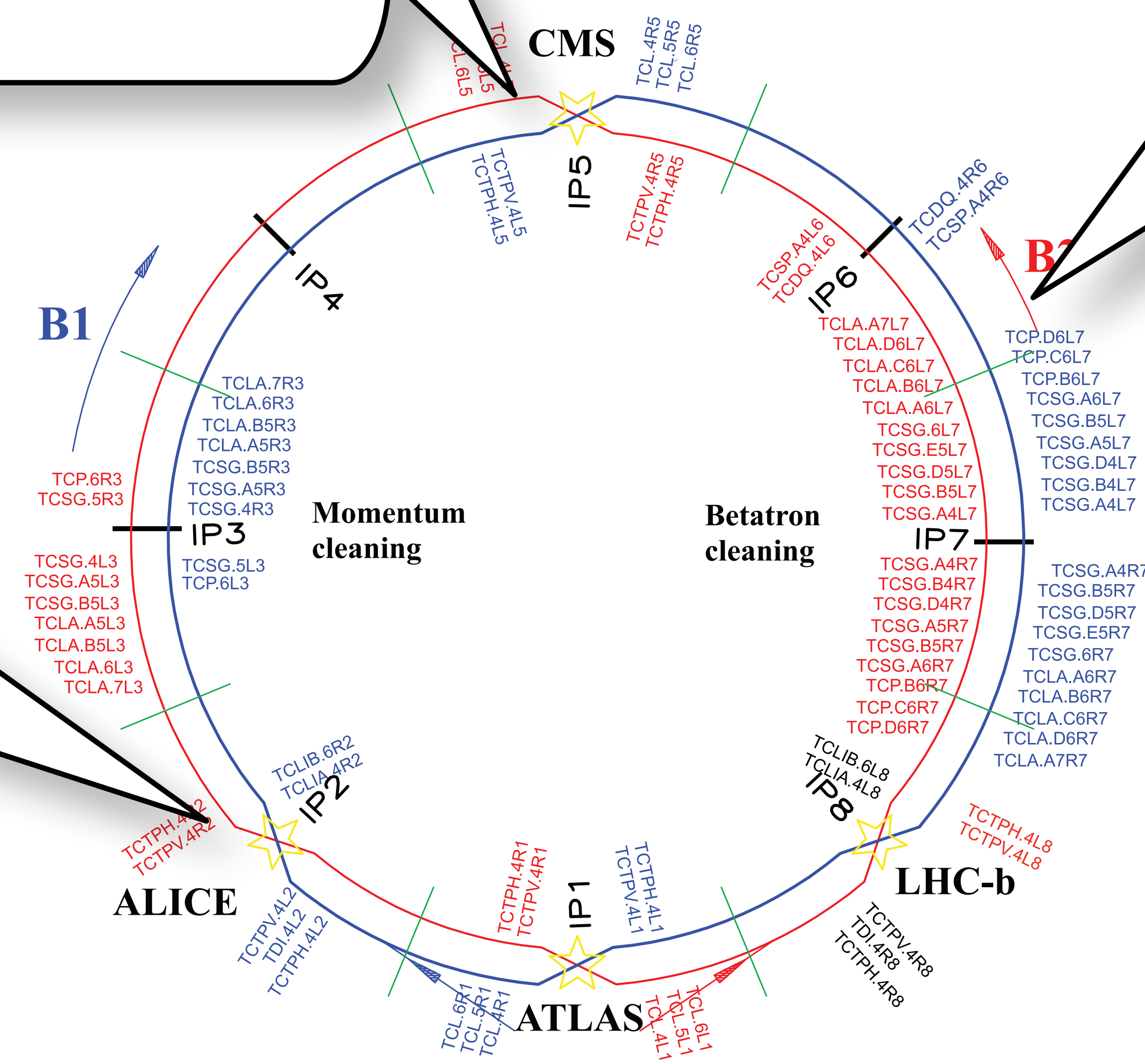
DS collimation





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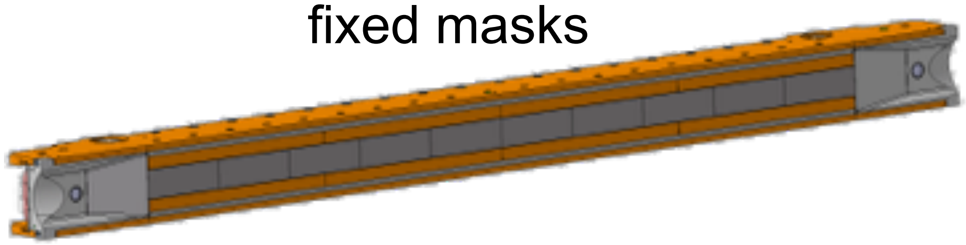

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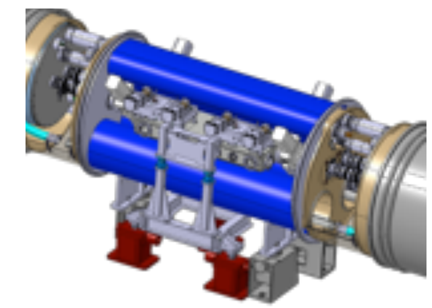

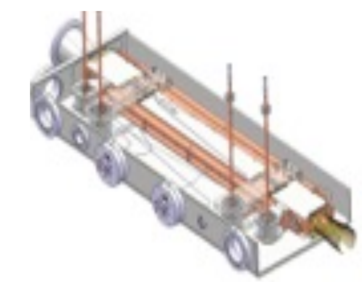

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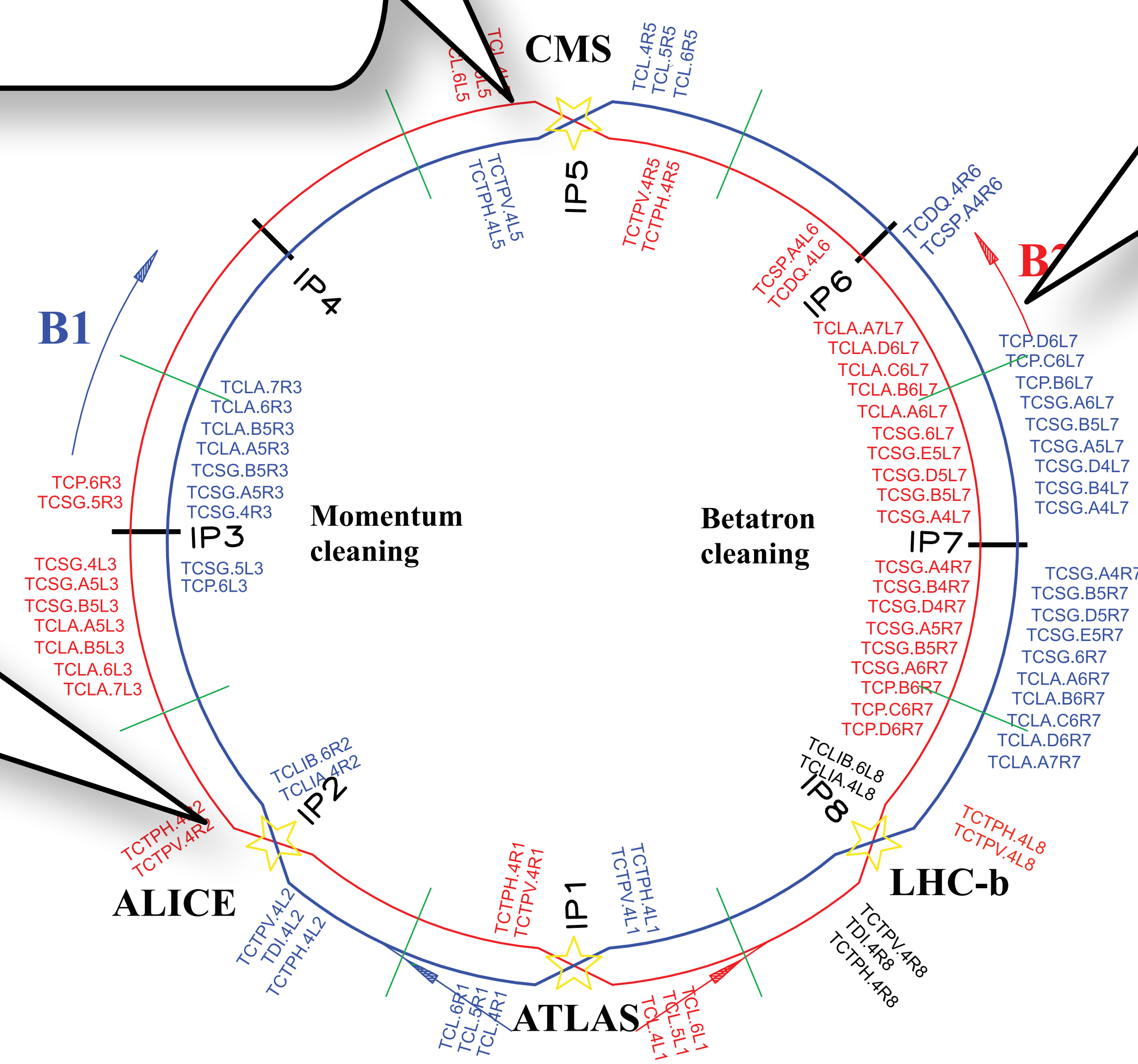

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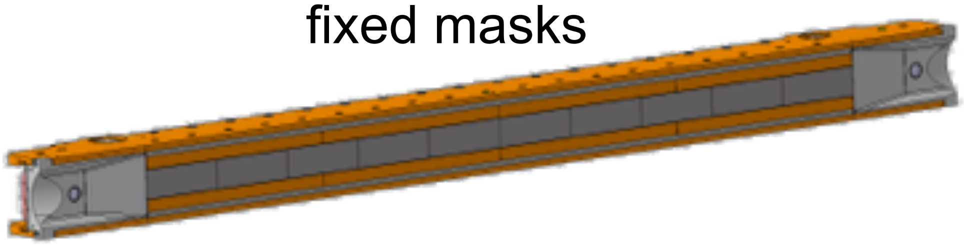

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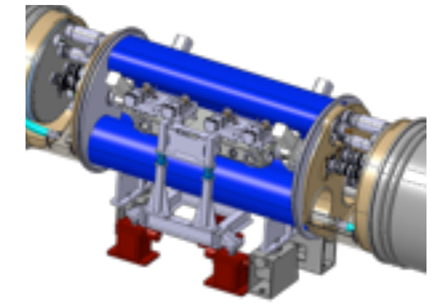

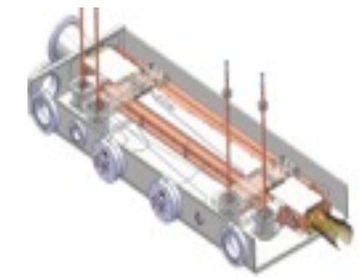

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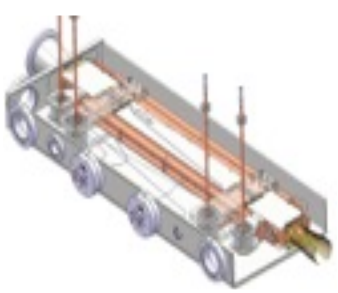
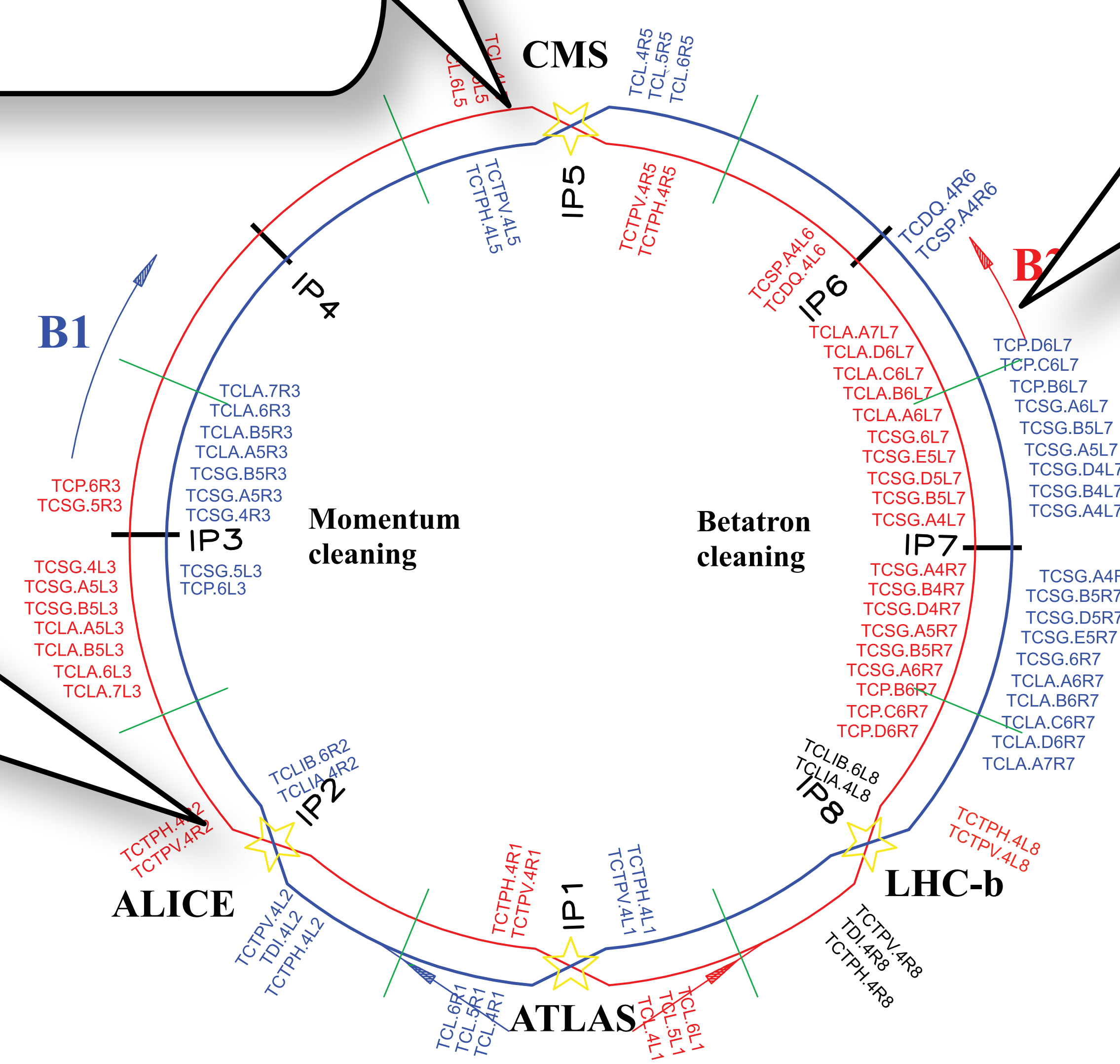
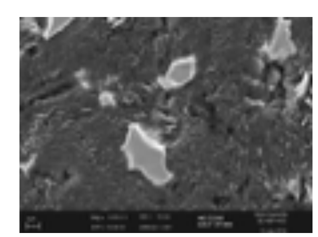
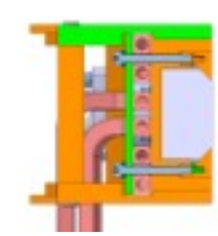
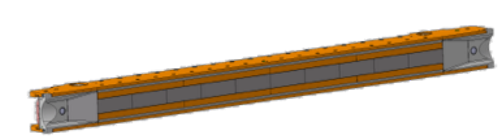




Low-impedance, high robustness secondary collimators: Mo coated MoGr







Main production lines for HL

LS2 (ALICE upgrade, LIU beams available)

2 dispersion suppressor collimators (TCLD) + spare for IR2
2 additional TCLDs for IR7, with 11T dipoles
8 units of low-impedance secondary collimators (TCSPW) for IR7

LS3 (Final HL)

Complete low-impedance solution in IR7 (14 TCSPW units)
New tertiary collimators in IR1/5: (16 TCTPW units)
New physics debris absorbers and masks (12 TCL units + 12 masks)
Up to 4 TCLD units in IR7 - complete with 2 missing units.

Until LS2 (prototyping and beam tests)

Prototype low-impedance collimator for LHC beam tests in 2017.
Four collimators with wires for beam-beam long range compensation.
Interventions on crystal collimation test stand - new goniometers.
Heavy involvements with beam tests outside LHC (SPS, HiRadMat, etc.)

Production numbers

		Mar. 2015		Feb. 2016	
Type	IR	LS2	LS3	LS2	LS3
TCLD	IP2	2		2	
	IP7		4	2	2
	IP1				
	IP5				
TCSPM	IP3				
	IP7	8	14	8	14
TCTPM	IP1		8		8
	IP5		8		8
TCL	IP1/5		8		8
TCLX	IP1/5		4		4
TCLM	IP1/5		8		8
TOTAL - HL		10	54	12	52
TCPP	IP3	2			2
	IP7	6		4	2
TCSP	IP3		8		8
	IP7				
TCTPM	IP1/5	4		4	
	IP2		4		4
	IP8		4		4
TCAP	IP7	2		2	
TOTAL - CONS		14	16	10	20

DS cleaning

Low-impedance

IR collimation

Consolidated primary and secondaries

Consolidated IR collimation

Because of expected radiation doses, must assume that all new collimators must be produced as new.

Production lines followed up by EN/STI.

Ongoing prototype preparation (EN/MME):
TCSPM -> EYETS2016
TCLD -> 2017

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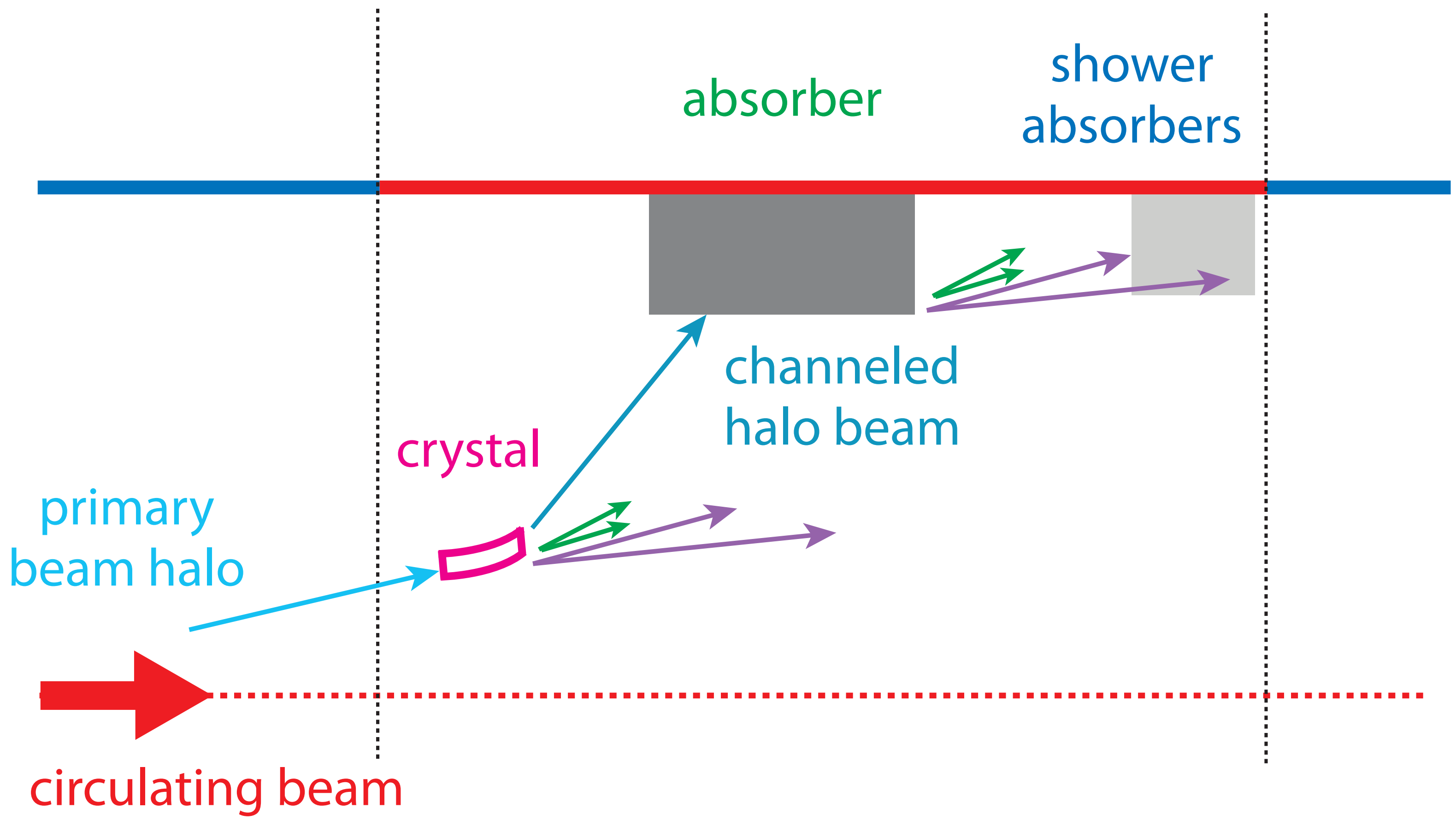
Crystal collimation concept



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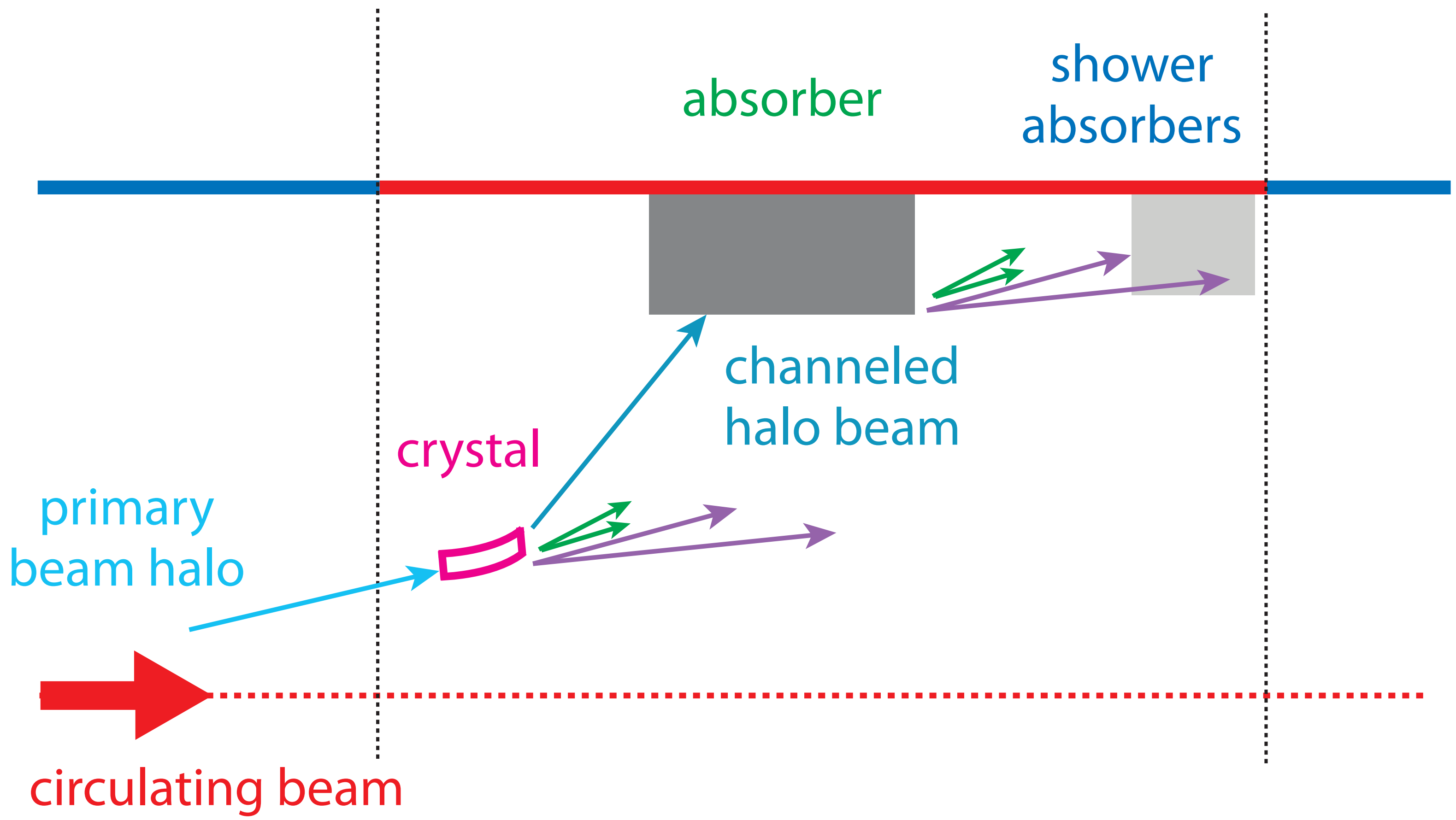
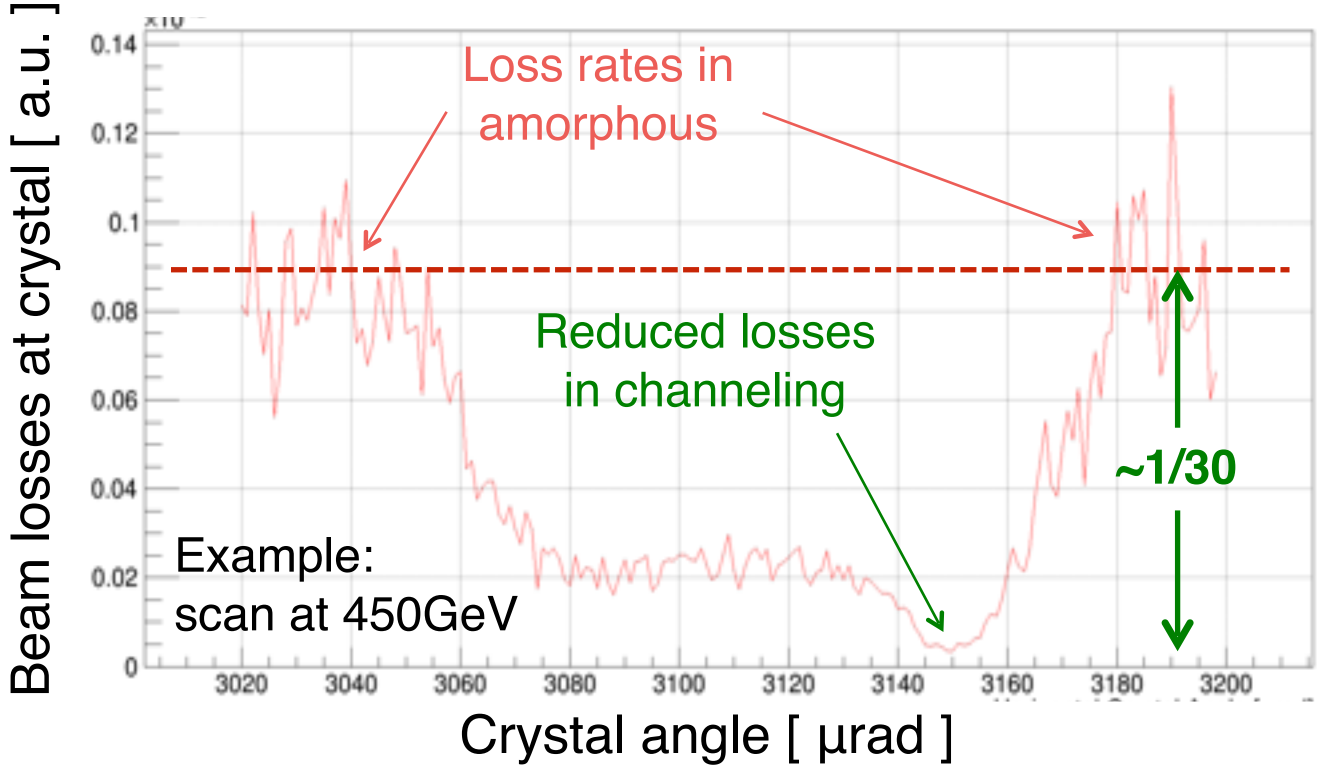


MDs in 2015 carried out with low intensities demonstrated: proton channeling at 6.5TeV; Pb channeling at 450GeV.

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

Preliminary results

Angular scan: reduction of local losses in channeling compared to amorphous.



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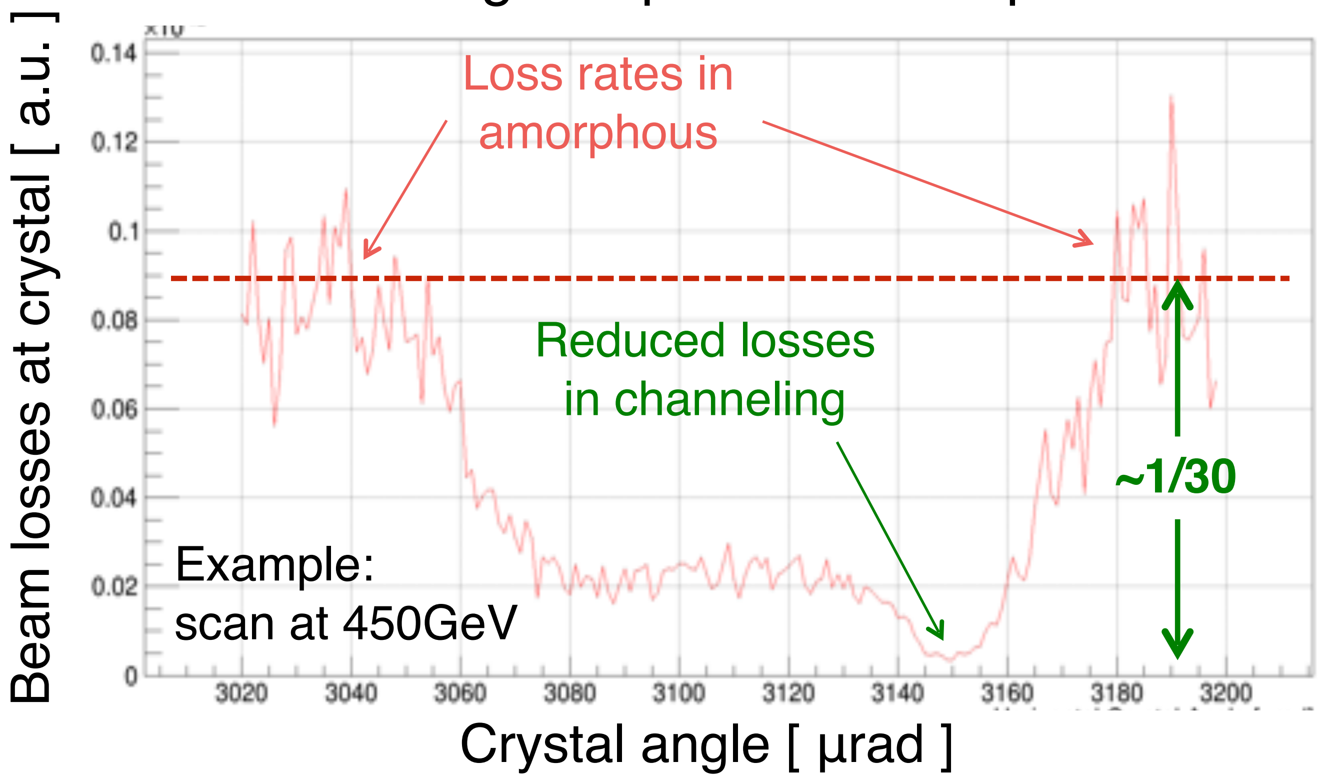

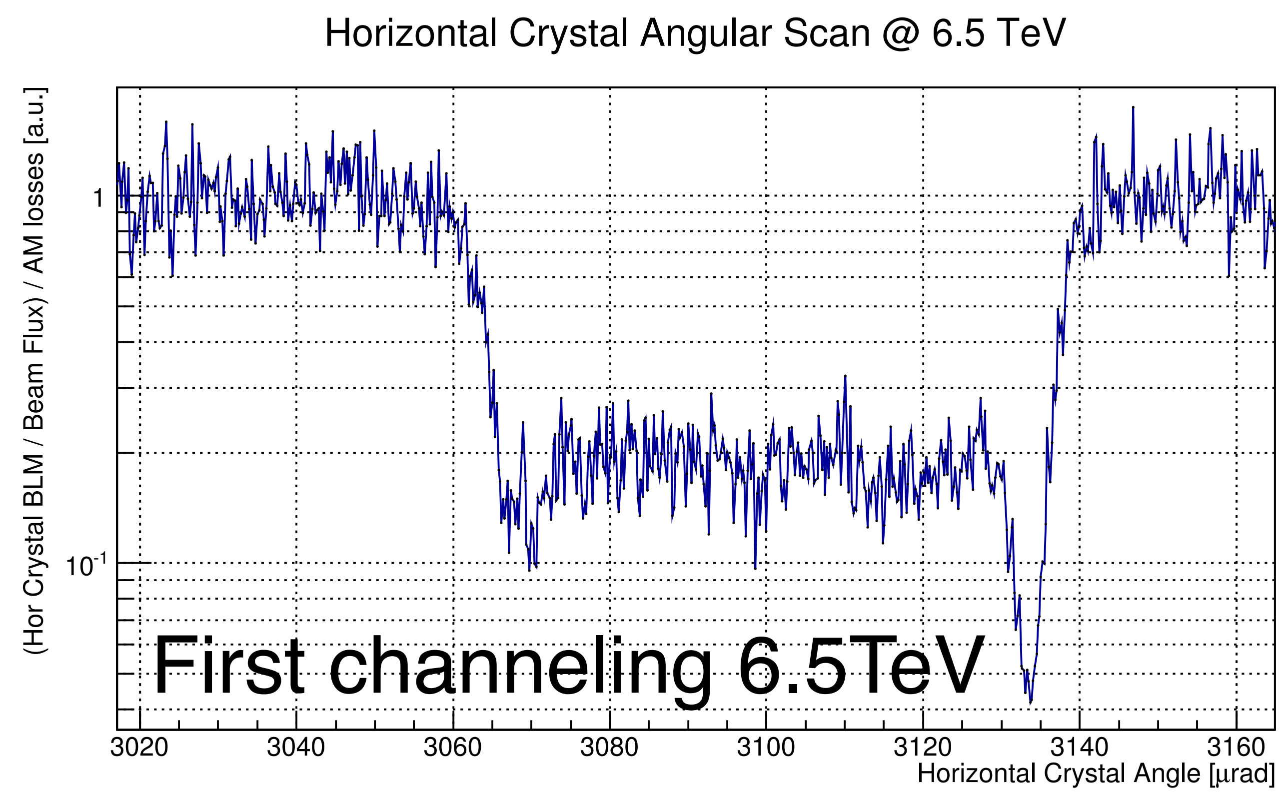

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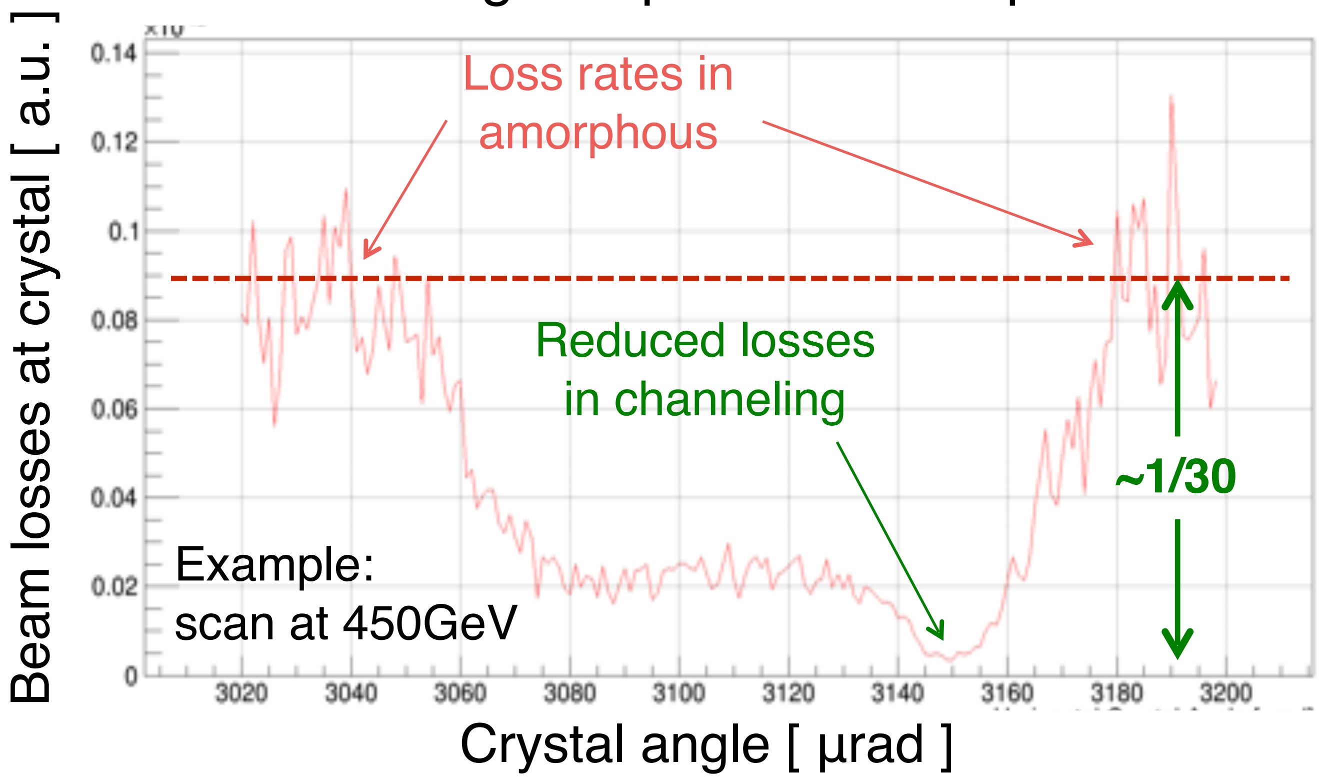
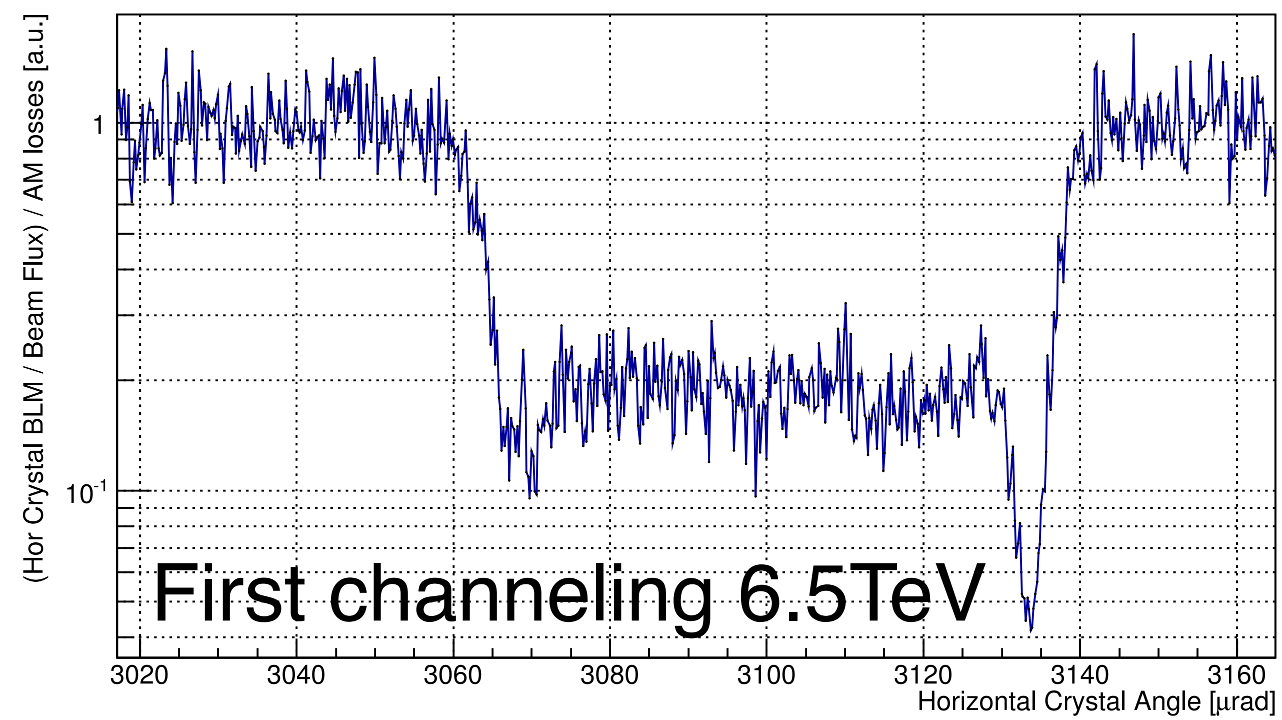
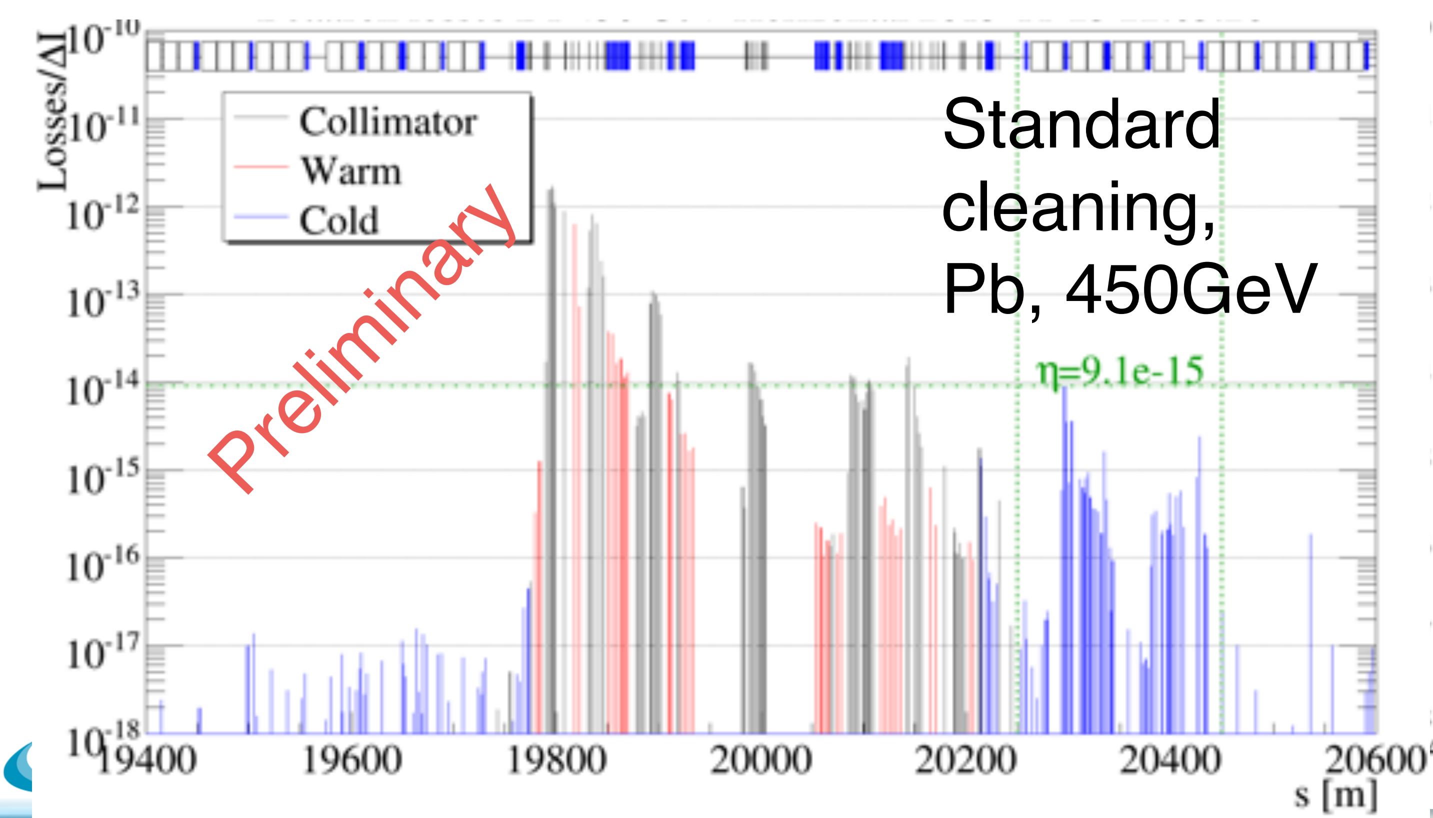
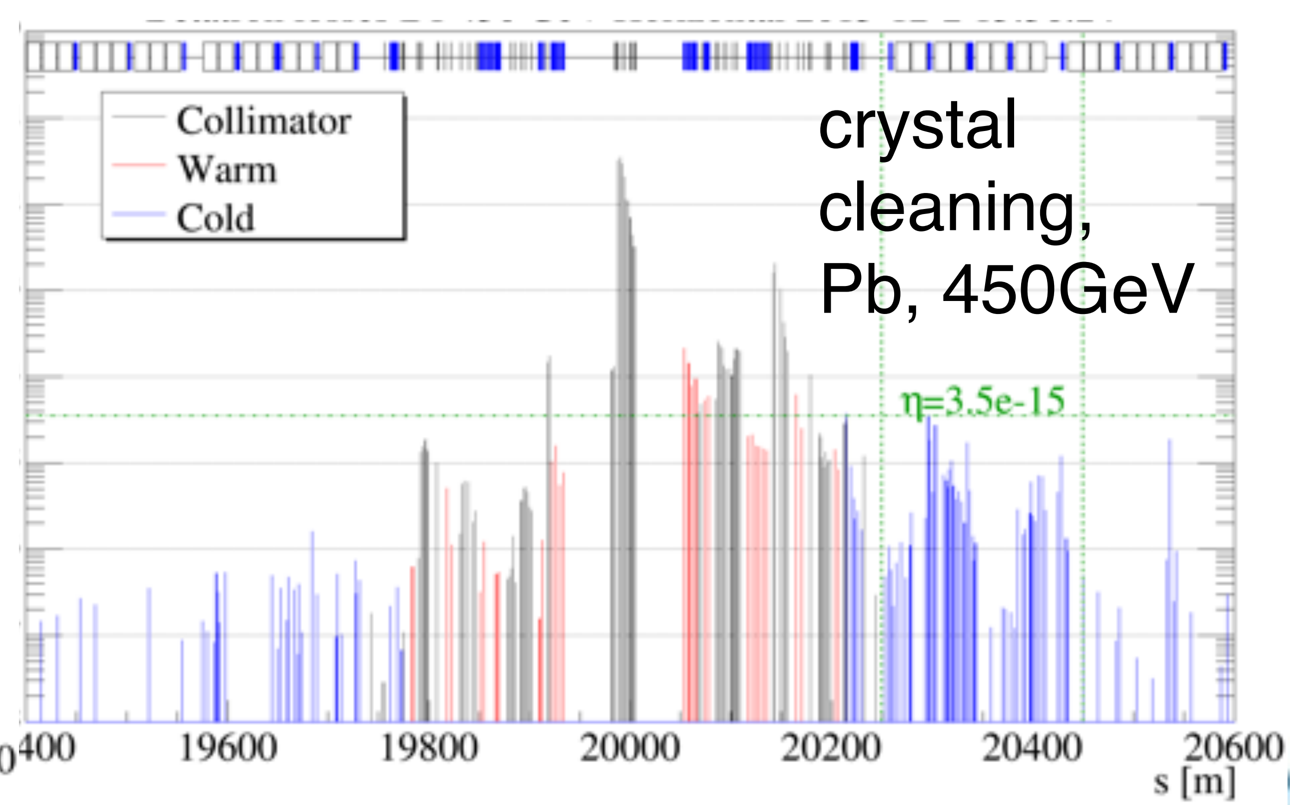








Prospect for crystal collimation

Handling the proton stored energies will be very challenging:

Deploying a crystal-based system requires dismounting the present IR7 system. We do not have yet a solution.

Smaller total intensities of Pb beams are easier to handle by the present system (up to 1 kW intercepted by the secondary collimators).

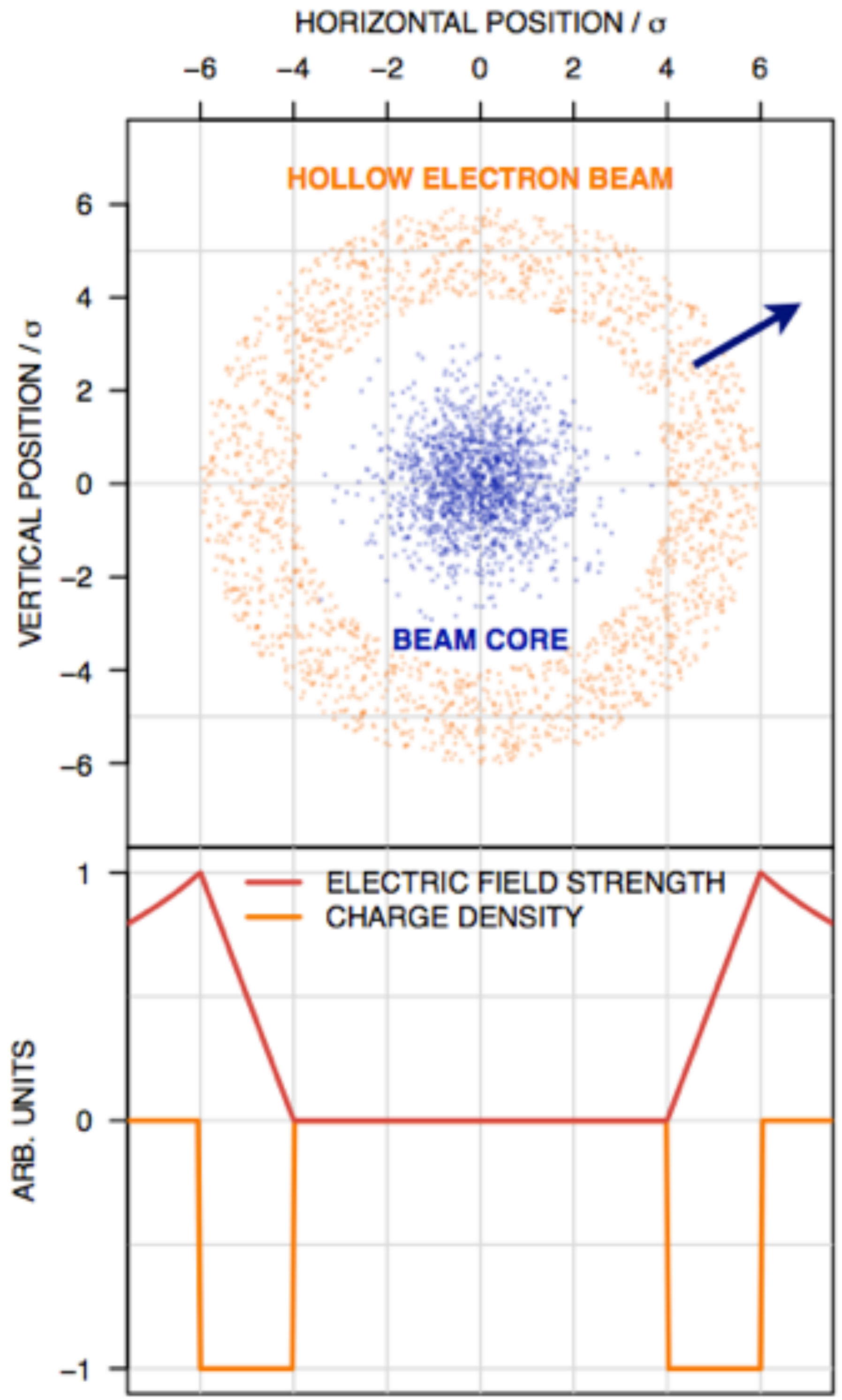
Supplementary measure to the baseline 11T collimator modules for mitigating Pb beam losses in the dispersion suppressor (LS2).

Still several outstanding questions to address with beam:

- Pb ions: channeling and cleaning at 6.5TeV;
- Protons: cleaning at 6.5TeV;
- Performance in **dynamic machine phases** (ramp, squeeze).

(1) and (2) planned for 2015 but not complete — lack of time.

Hollow e-lens beam (HEB)



G. Stancari

Provides selective and controllable excitation of halo particles above amplitude of the r_{in}.

Complementary to present system and other upgrades, like crystals.

Outstanding for LHC: need modulated currents to excite halos fast enough. Effect on core?

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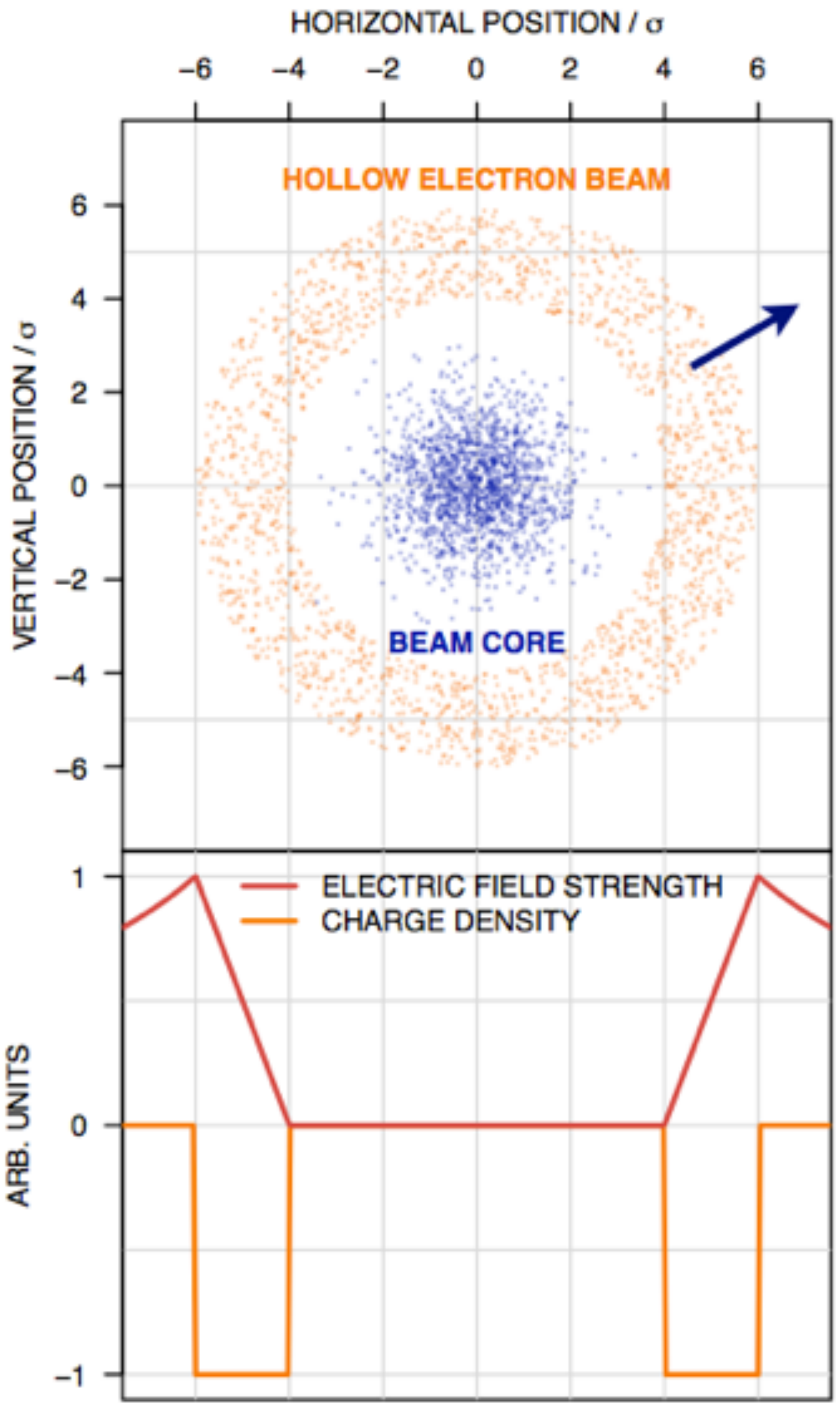

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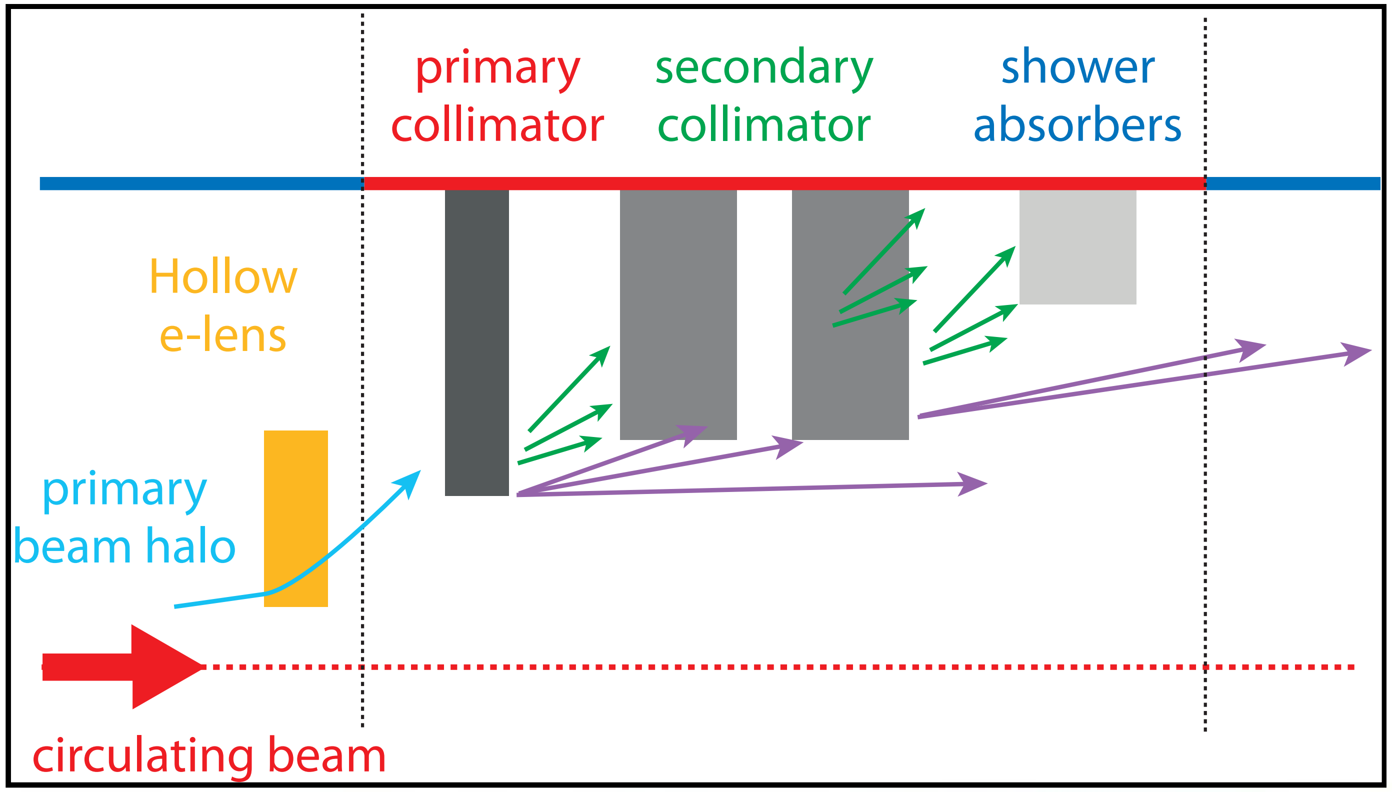
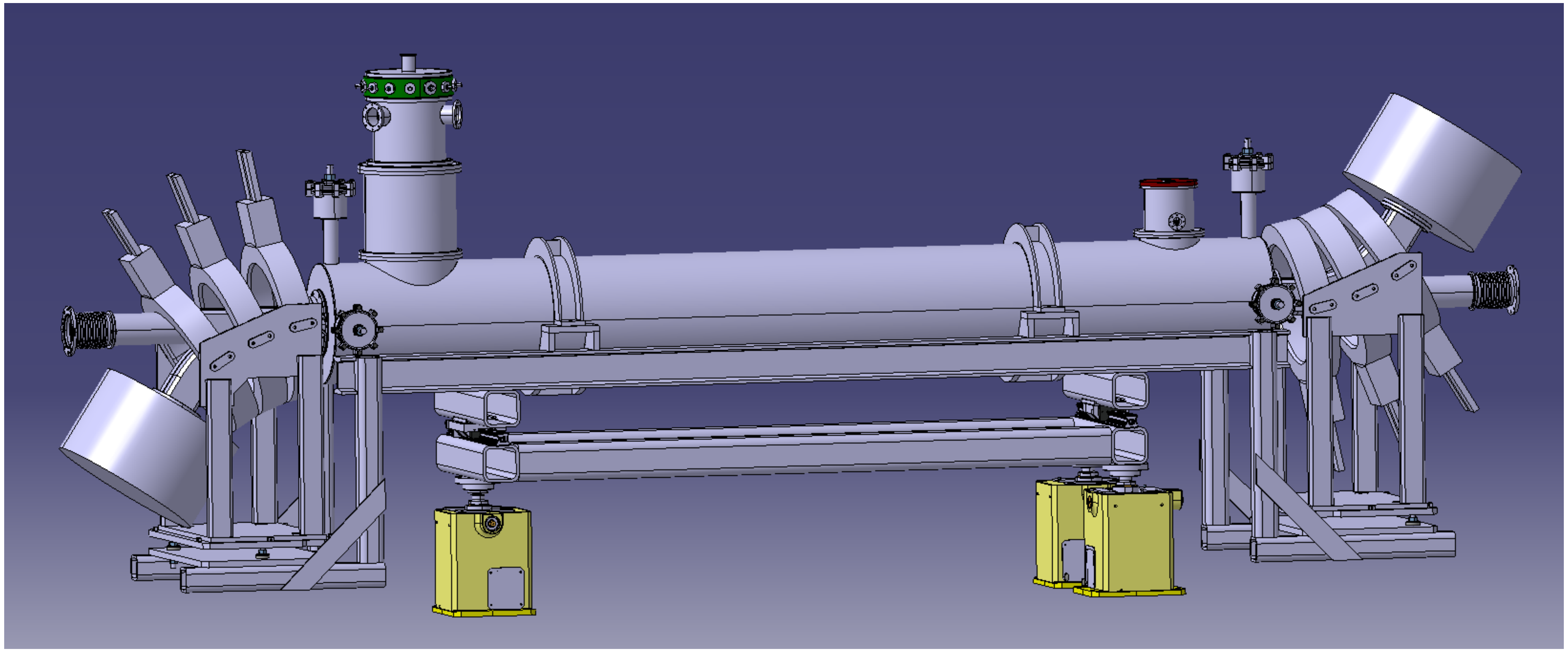


Active halo control

The operation in 2012 indicated strongly the need of an active mechanisms to mitigate loss spikes at the LHC. This conclusion must be confirmed at 6.5TeV.

Goal: Control actively transverse halo above 3-4 σ. Essential in order to
- mitigate loss spikes on primary collimators with HL intensities;
- control static halo population → **fast failures of crab-cavities.**
- New: dynamic losses during vibrations/earthquakes.

Recap.: Synergy with BE/BI effort to measure halos at the LHC and develop e-beams. Key role by the US-LARP collaboration (Fermilab)



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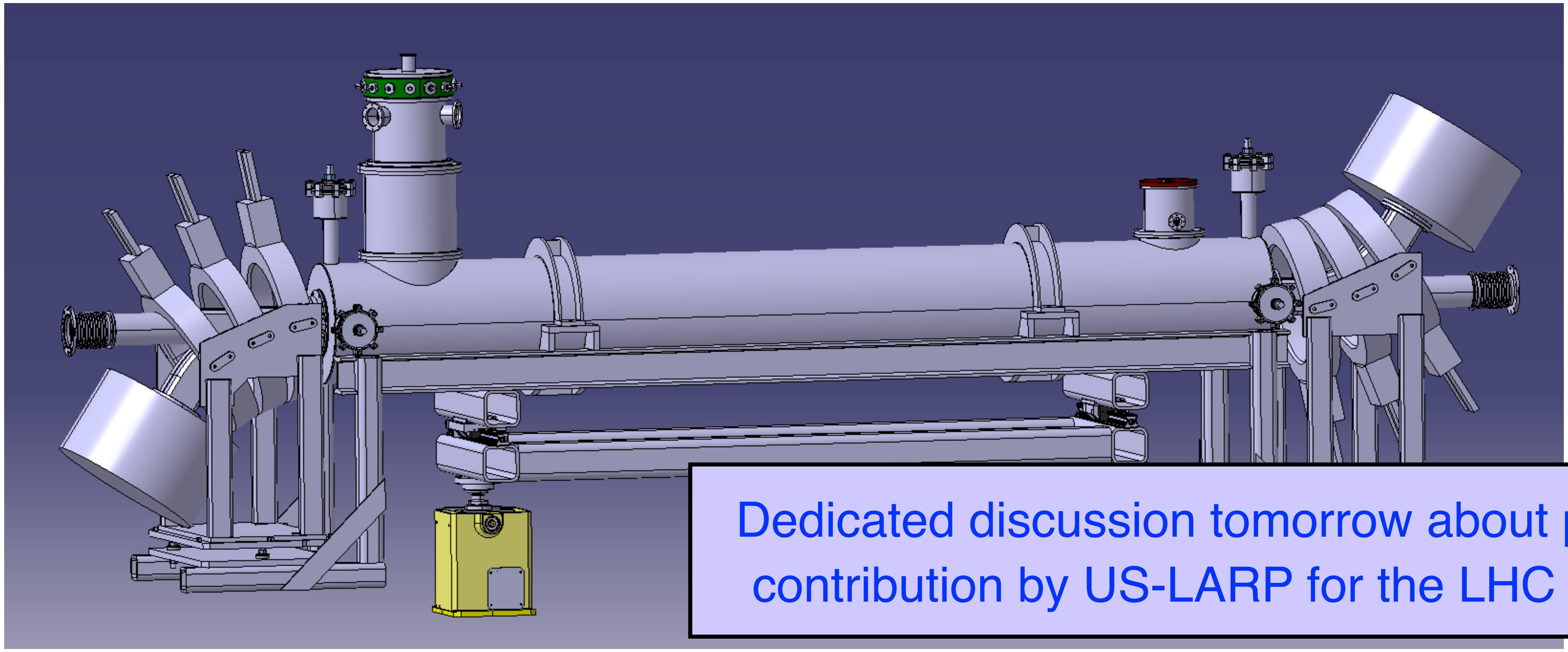


Dedicated discussion tomorrow about possible contribution by US-LARP for the LHC lenses.

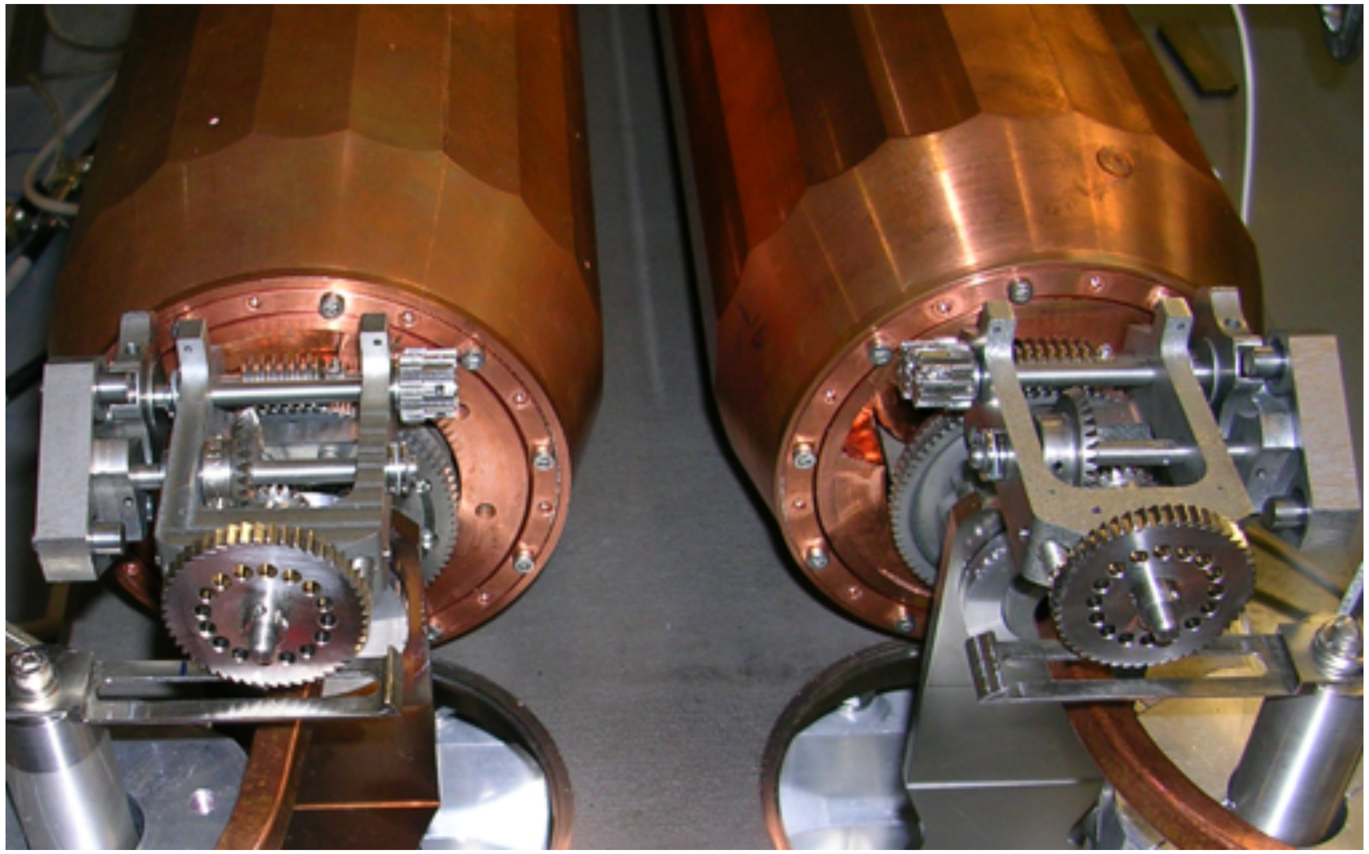
Production of CERN gun

Design report: 5A at 10 kV.
FNAL "1-inch" design developed for LHC.

Planned to ship the CERN gun to FNAL for e-beam test before this meeting.
Problems with cathode delivery by USA producer.
Details in D. Perini's talk tomorrow.

D. Perini et al., EN/MME

SLAC Rotatable collimator



Complete prototype delivered to CERN in Dec. 2013

Validation tests (2014) showed **excellent quality**: decided to test it with circulating at the **SPS** in 2015 (alignment, BPM, impedance: OK)

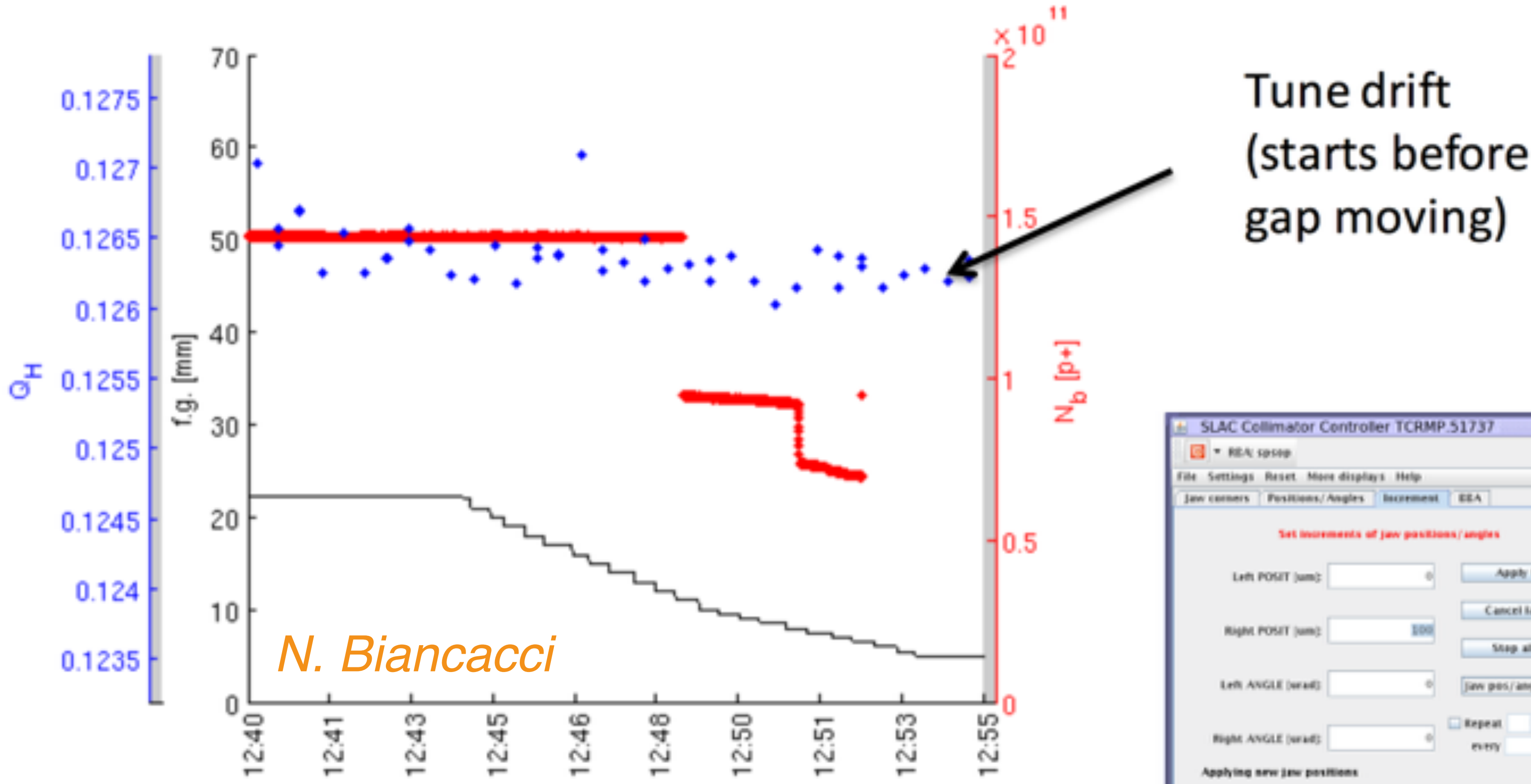
Now, being prepared for HiRadMat “destruction tests”

Rotation mechanism status after design beam impact (and beyond)

Planned **this June**, might be delayed because of a problem with SPS.

Will prepare a detailed report on possible usage in the future.

SPS results with the SLAC-RC



Fill #7

G. Valentino

Achieved positioning accuracy comparable to a standard collimator.
Reliable operation with 270GeV stored beams.

Controls integrated into standard LHC system (used at the SPS for prototype tests).

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  - *First results of quench tests at 6.5TeV indicate lower limits than expected.*
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  - *Good experience up to 280MJ, but loss rates might be worst in 2016.*

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- Deployment of new IR collimation solutions will happen in LS3
  - *Still open questions on integration, requiring a new 2-in-1 collimator (TCLX)*
- Promising first results from crystal collimation
  - *Interesting alternative to ion collimation in IR7 for Run III. Not obvious for protons.*

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  Confirmed that ion upgrade in LS2 can be handled without 11T dipoles, but:
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  Need 4 TCLD collimators and 4 11T dipoles, plus cryo-bypasses.
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- Deployment of new IR collimation solutions will happen in LS3

  Still open questions on integration, requiring a new 2-in-1 collimator (TCLX)
- Promising first results from crystal collimation

  Interesting alternative to ion collimation in IR7 for Run III. Not obvious for protons.
- In the process of including hollow e-lens as baseline.

  Technical work advanced very well, justification will be based on LHC performance.

Conclusions

- ☑ **Presented the updated collimation baseline for HL-LHC**
- ☑ **Several important results achieved in the last year**
  - *First results of quench tests at 6.5TeV indicate lower limits than expected.*
  - *Excellent results on novel collimation material, with still some open questions.*
  - *Good experience up to 280MJ, but loss rates might be worst in 2016.*
- ☑ **Important change on collimation requirement for 11T dipoles**
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- ☑ **On very good track for low-impedance and high-robustness collimators — plan a staged installation working on LS2**
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  - *Interesting alternative to ion collin*
- ☑ **In the process of including**
  - *Technical work advanced very well, justification will be based on LHC performance.*

Many thanks to the US-LARP team, as it contributed to several key collimation topics!

Reserve slides

Key stepping stones in ~2016

Analysis of operational performance at 6.5TeV

- Losses with pushed machine configuration.

Further understanding of beam-based quench limits.

Crucial prototyping of new collimator designs

Full prototype of the dispersion suppressor collimator:

new design to be tested before launching production.

LHC-ready prototype of low impedance collimator.

Expect important results on coating and radiation hardness.

Results from HL MDs: crystal collimation, halo measurements and control

Test of CERN gun for high-current hollow e-beams.

Follow with interest the development of 11 T dipoles.

Pillars of the collimation upgrade

Collimation upgrades are needed to handle **~700 MJ** at the HL

- ☑ **Improve the collimator impedance**
  Present carbon-based primary and secondary collimators are not compatible with stability requirements of HL beams.
- ☑ **Improve the collimation cleaning**
  Present system not optimised to intercept "dispersive" losses for proton and ion beams (IR's + cleaning insertions).
- ☑ **New solutions in high-luminosity experiments**
  Incoming beam protection: new tertiary collimators;
  Physics debris collimation.
- ☑ **Improve operational efficiency**
  BPM collimator design, improved alignment and validation.
- ☑ **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

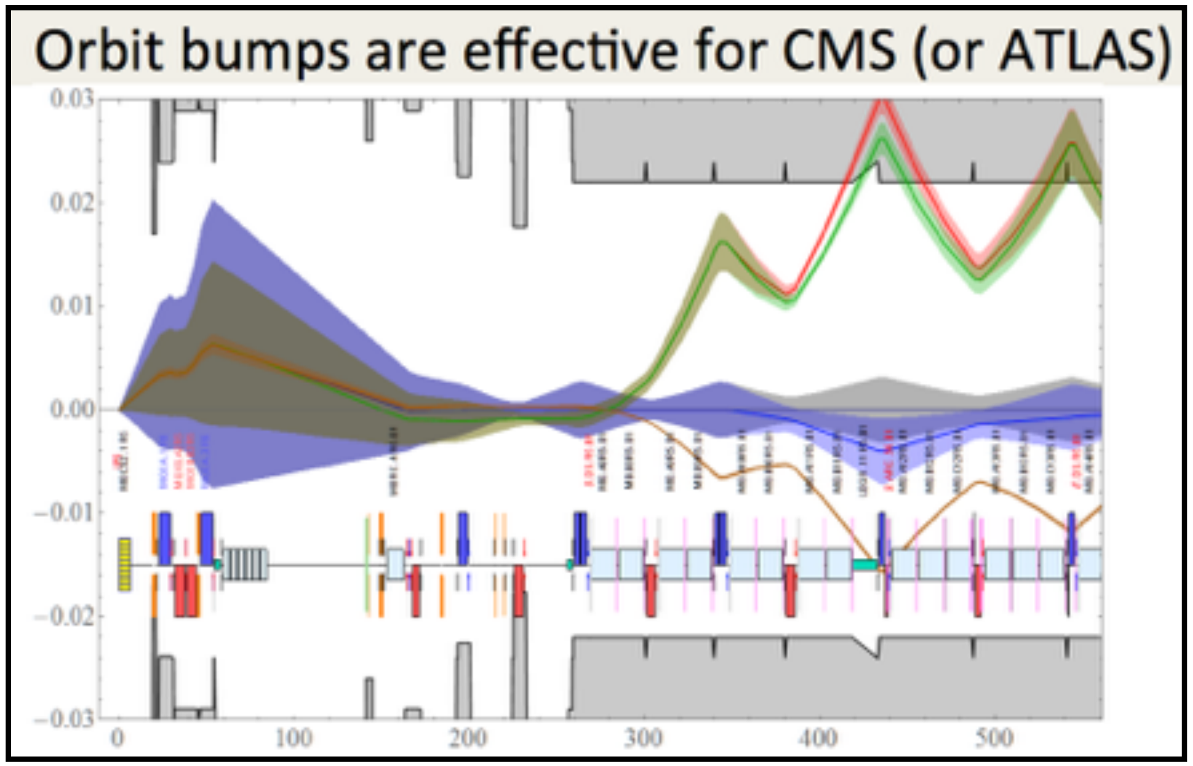
Beam intensity

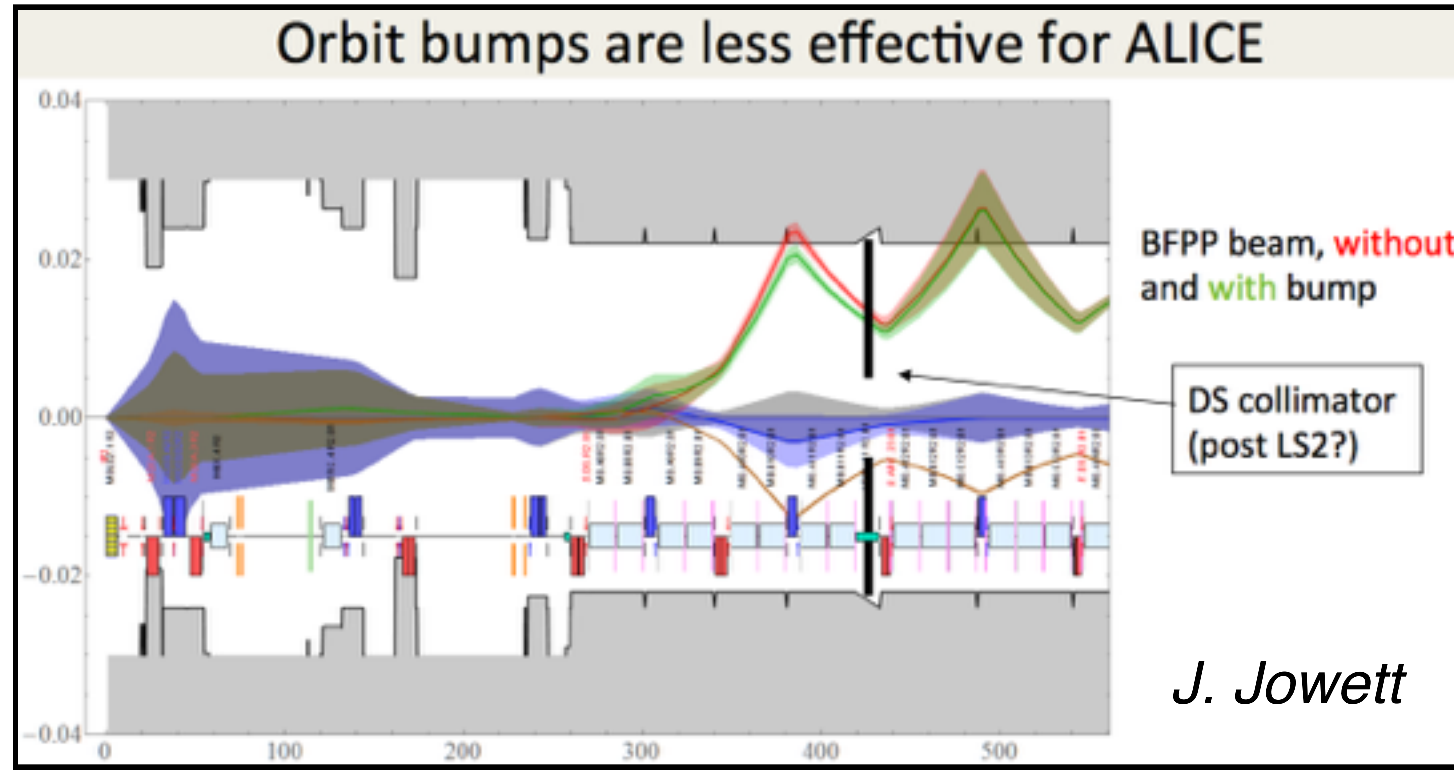
Damage potential

Peak luminosity

Machine availability

Bumps in IR2 and IR1/5 for ions



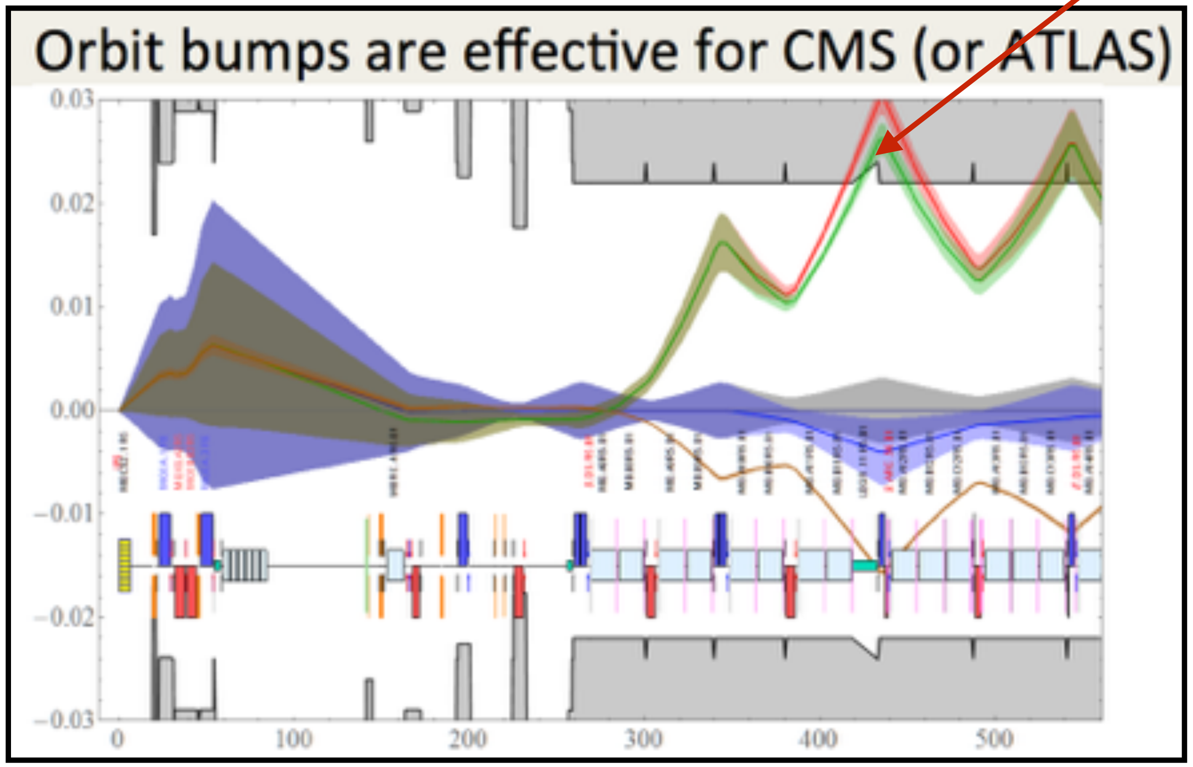


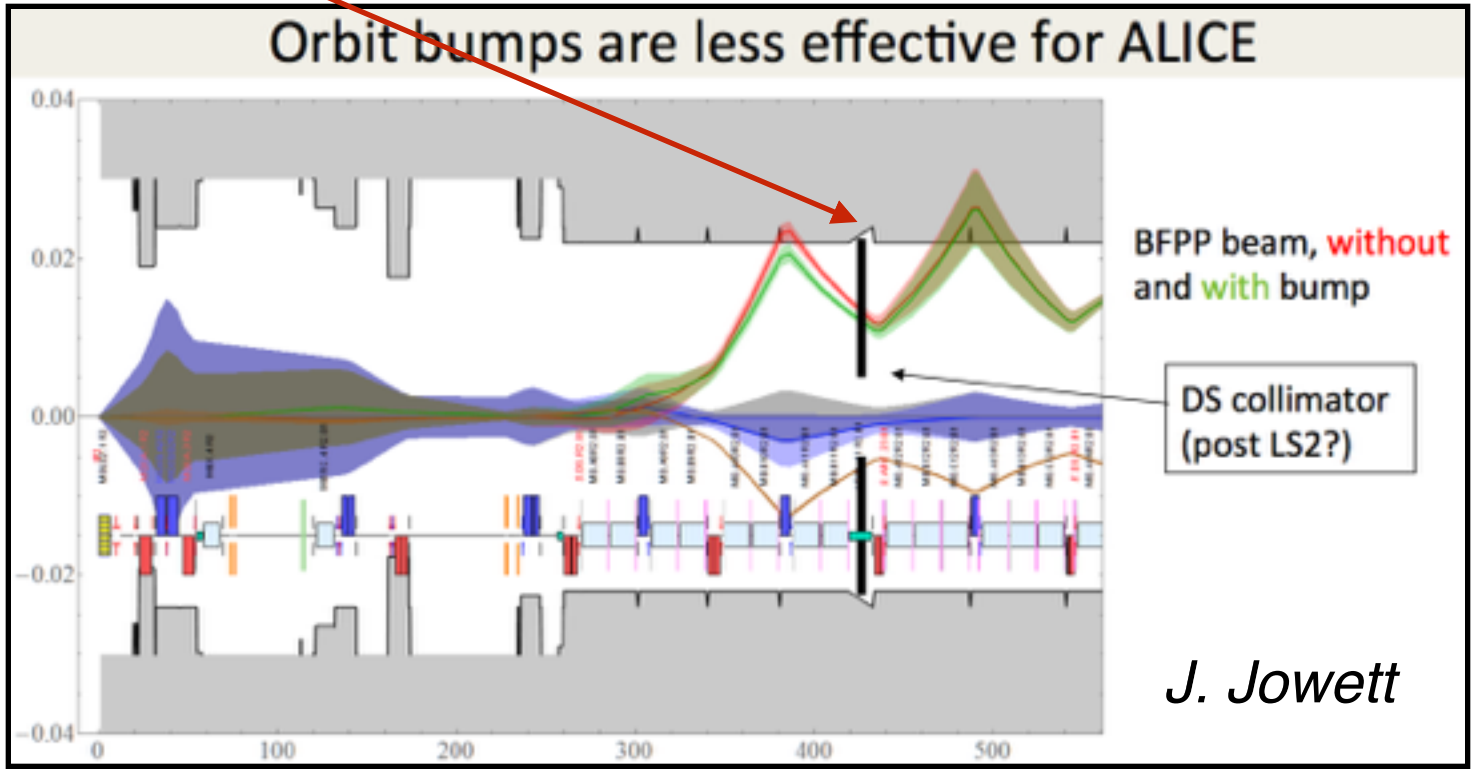
Fundamental layout/optics differences between IR1/5 and IR2:

- Bumps in IR1/5 can move ion losses to connection cryostat with no risk of quenches → no need for collimator nor for 11T dipoles
- Protons: Losses under control with new TCL layout (*TBC for V1.2*)
- Bumps in IR2 can move the losses such that the first magnet is missed → we still need a collimator, but likely not the 11T dipoles

Bumps in IR2 and IR1/5 for ions

Connection cryostat ("missing dipole")





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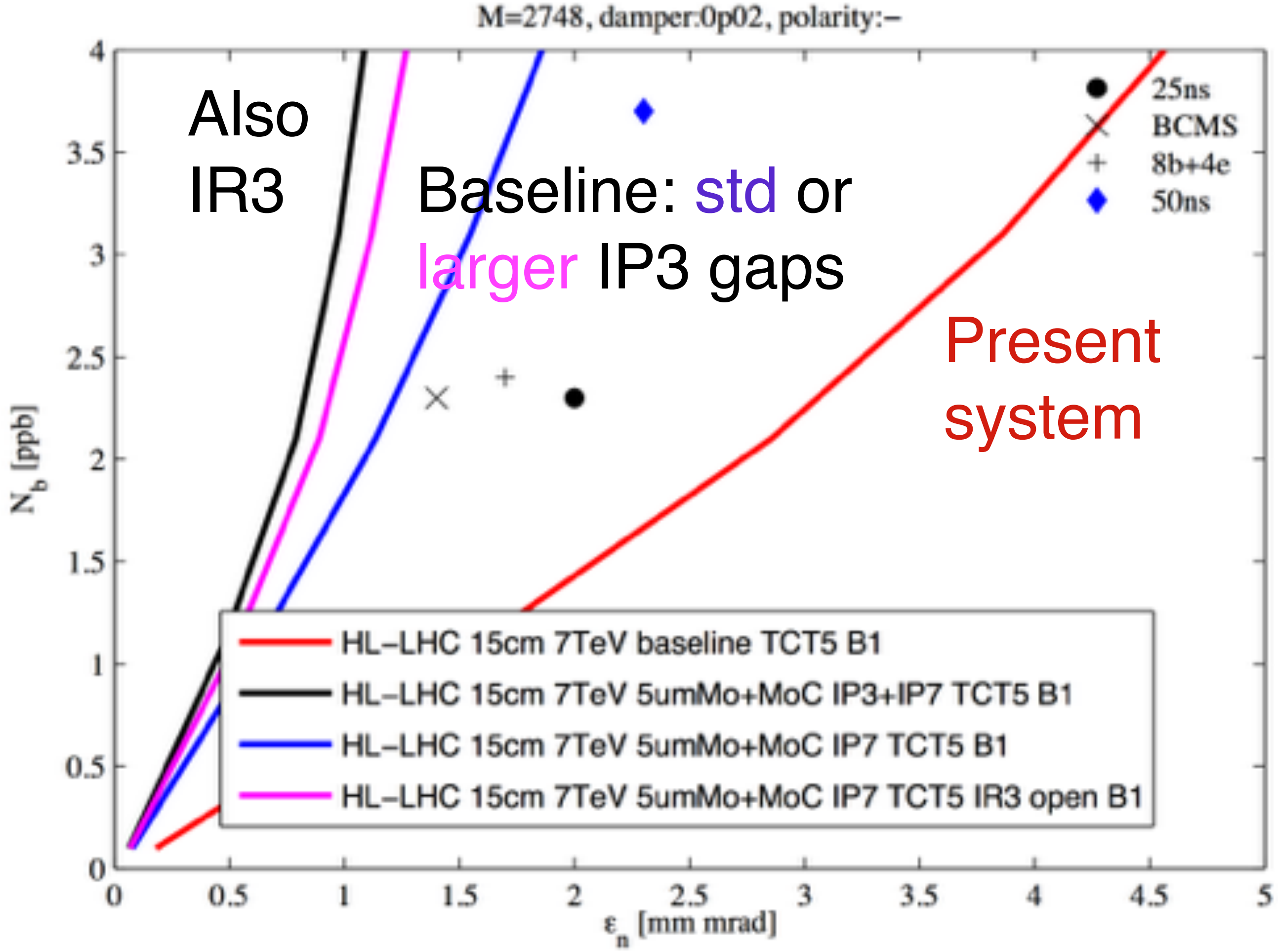
Collimation impedance reduction



No HL-LHC beam stable with the present carbon-based secondary collimators (TCS). "Historical" limitation of the system addressed by changing materials of TCSs.

N. Biancacci, impedance team
Latest info in talk by E. Métral tomorrow

BASELINE: New secondary collimators in the betatron cleaning (22 collimators). MoGR jaw coated with pure Mo. (Alternative coatings being studied.) Staged installation: 8 collimators in LS2, remaining 22 in LS3.

OPTION: New TCS also for momentum cleaning (8) if need more margin.

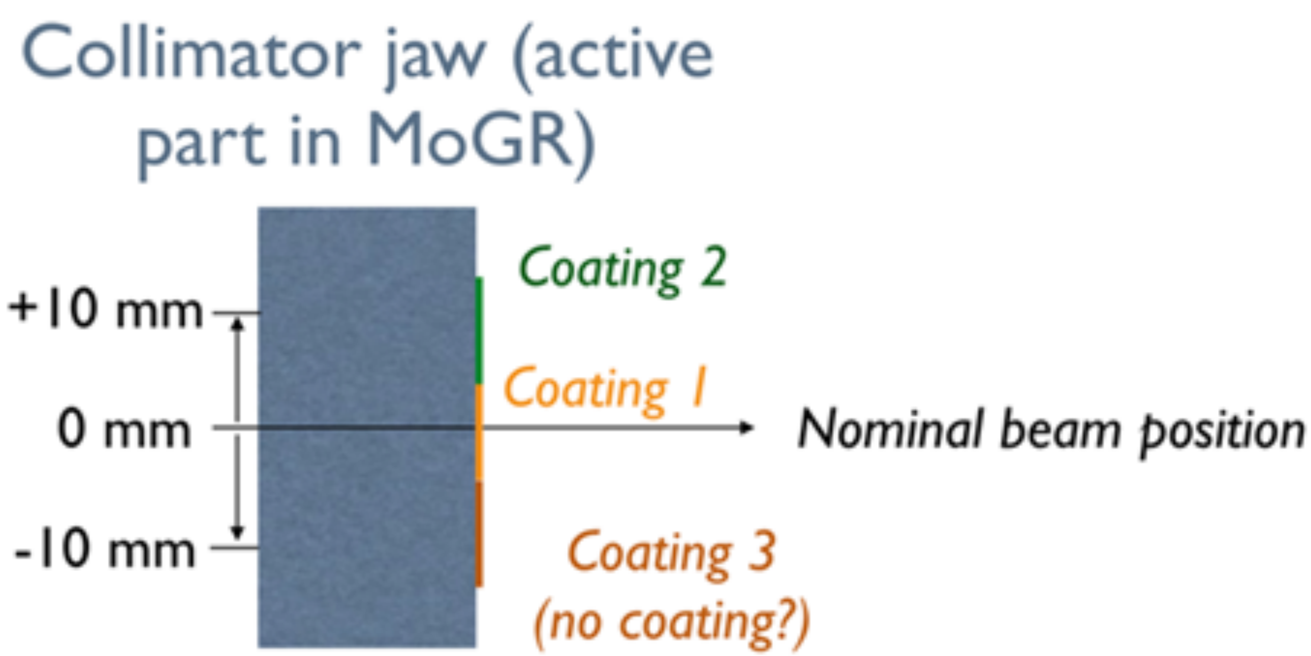
Remark: present primary collimators changed within consolidation until LS3. Also propose to change material to lower impedance.

Coating for reduced impedance

Different possible implementations for coating are being explored.

- Ideally, combine good robustness with high electrical conductivity.
- Best impedance performance from pure Mo or Cu.
- Studying also ceramic coating: more robust but higher impedance.

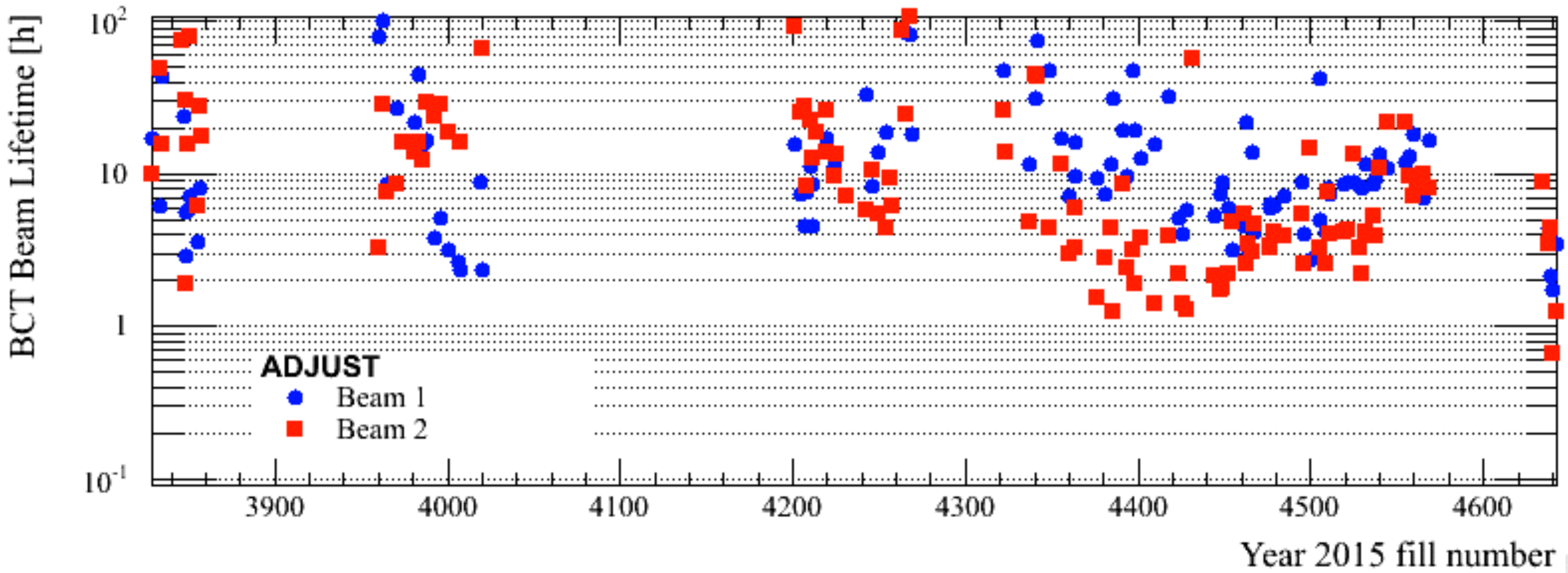
Building a prototype ready for installation in the LHC at the end of 2016!



Considering having 2/3 layers on prototype jaws, for impedance measurements.

A. Bertarelli for MME

Beam lifetime 2015



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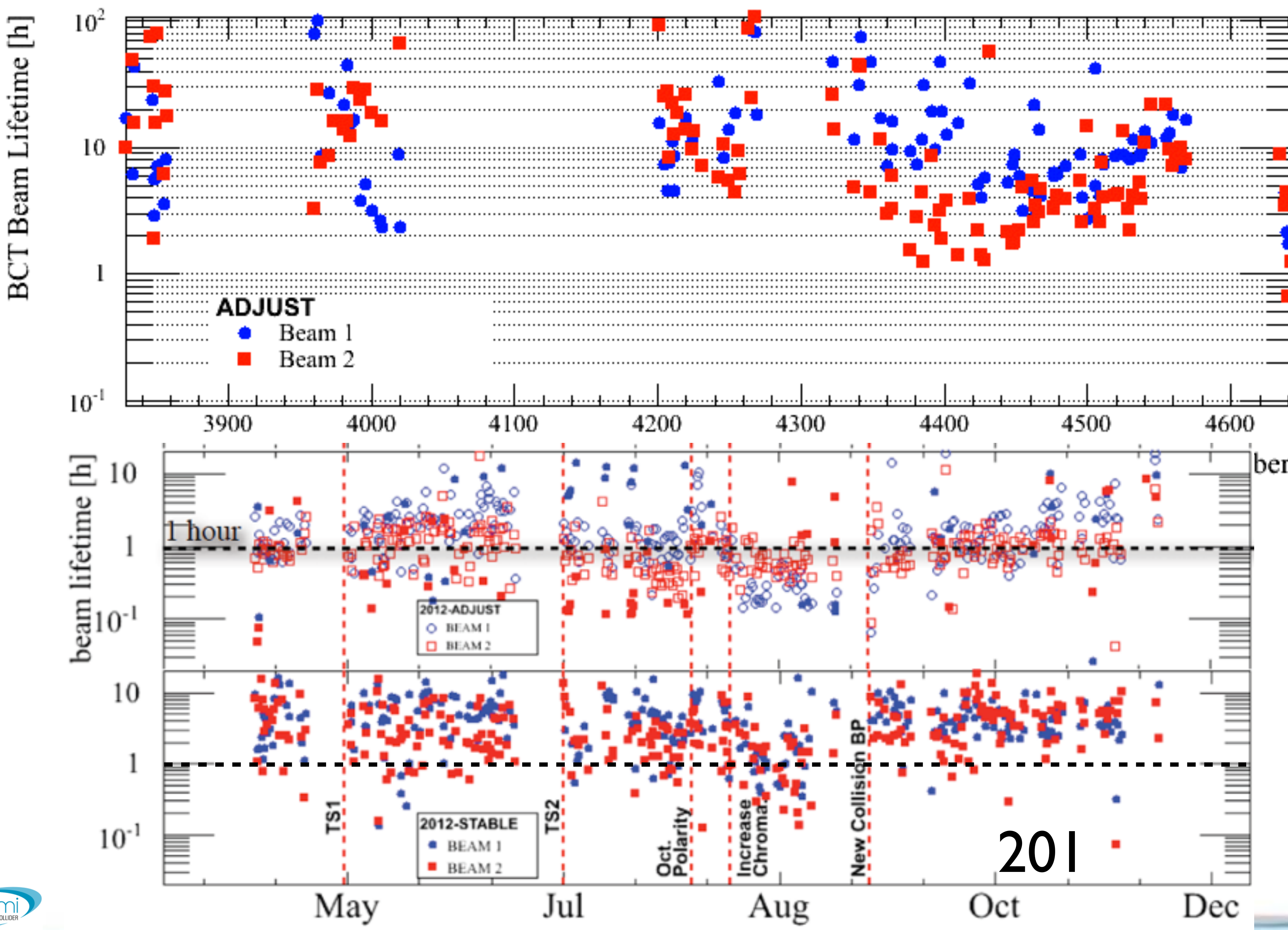
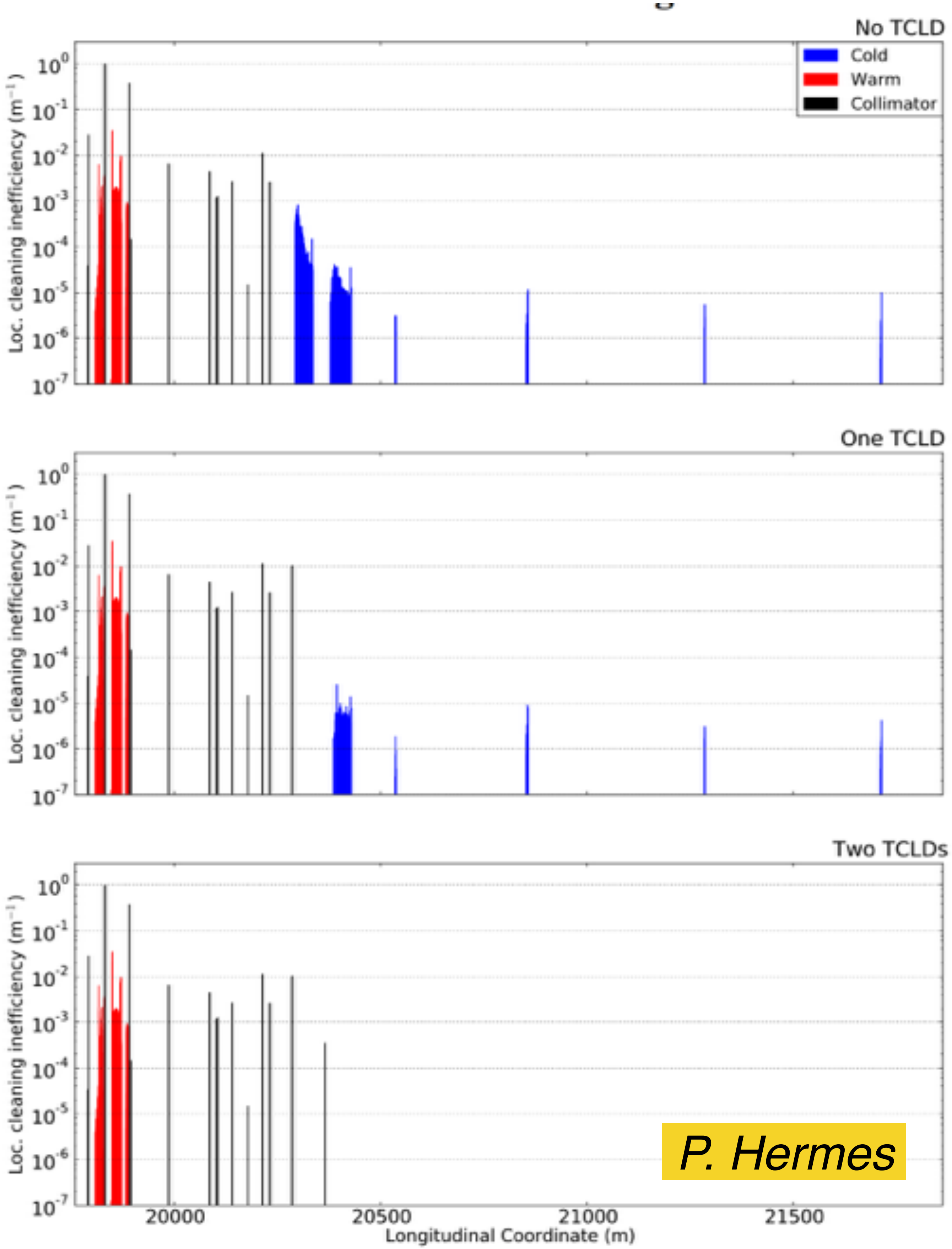


Backup — locations for 11T dipoles

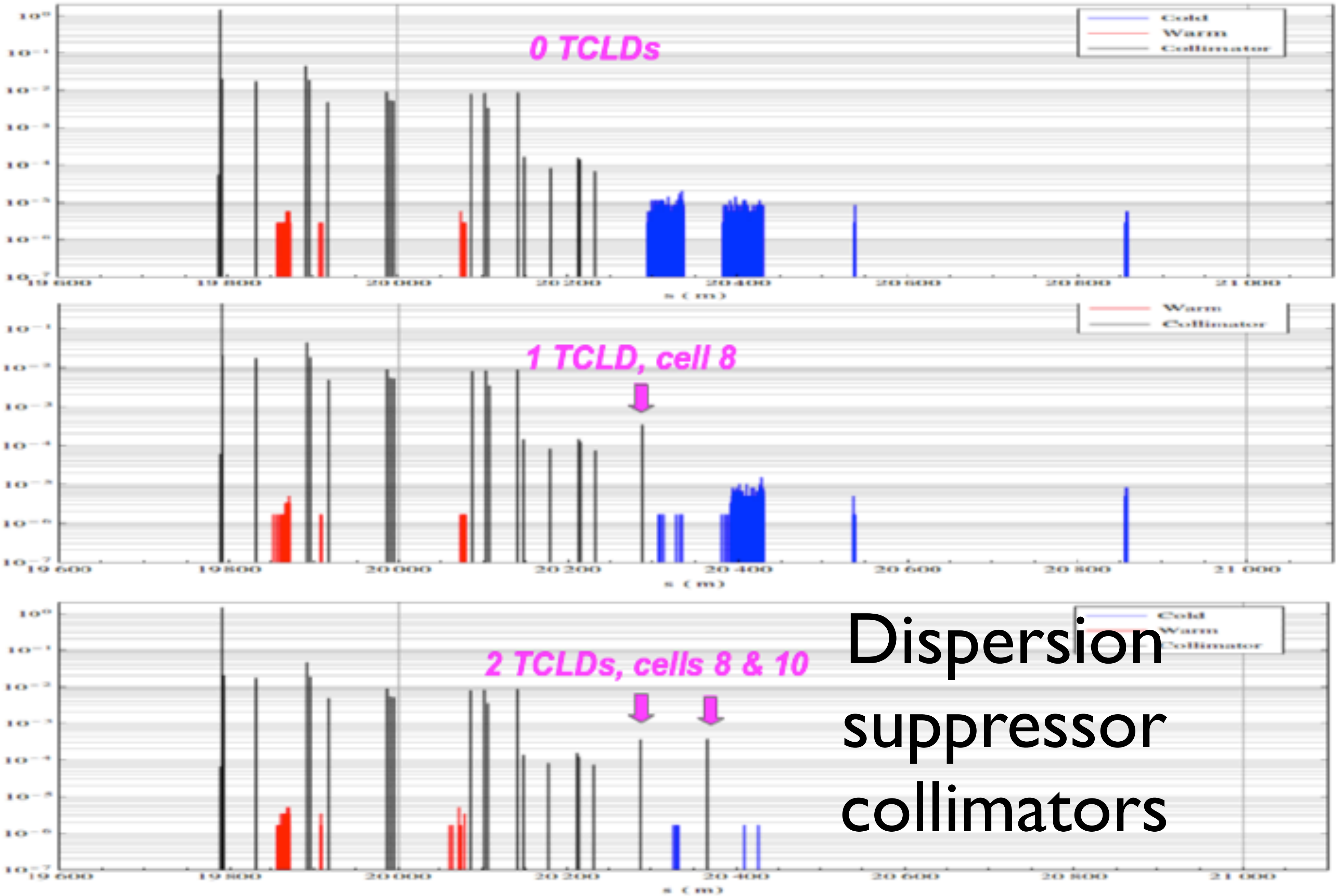


For the case without TCLD collimators, two clusters of losses in the cold cells 8-9 and 11-12, located in the IR7 DS, are clearly visible. Further losses appear throughout the entire LHC ring. With the sole inclusion of the TCLD8, the losses in the aperture of the cells 8-9 are completely removed. The losses in the cells and 11-12 are slightly reduced. Given that the highest losses were observed in the cells 8-9, the performance of the collimation system is improved already by the usage of one TCLD.

IPAC2015.

Protons: 1 TCLD units with 2 dipoles reduced the peak energy deposition by a factor ~3.

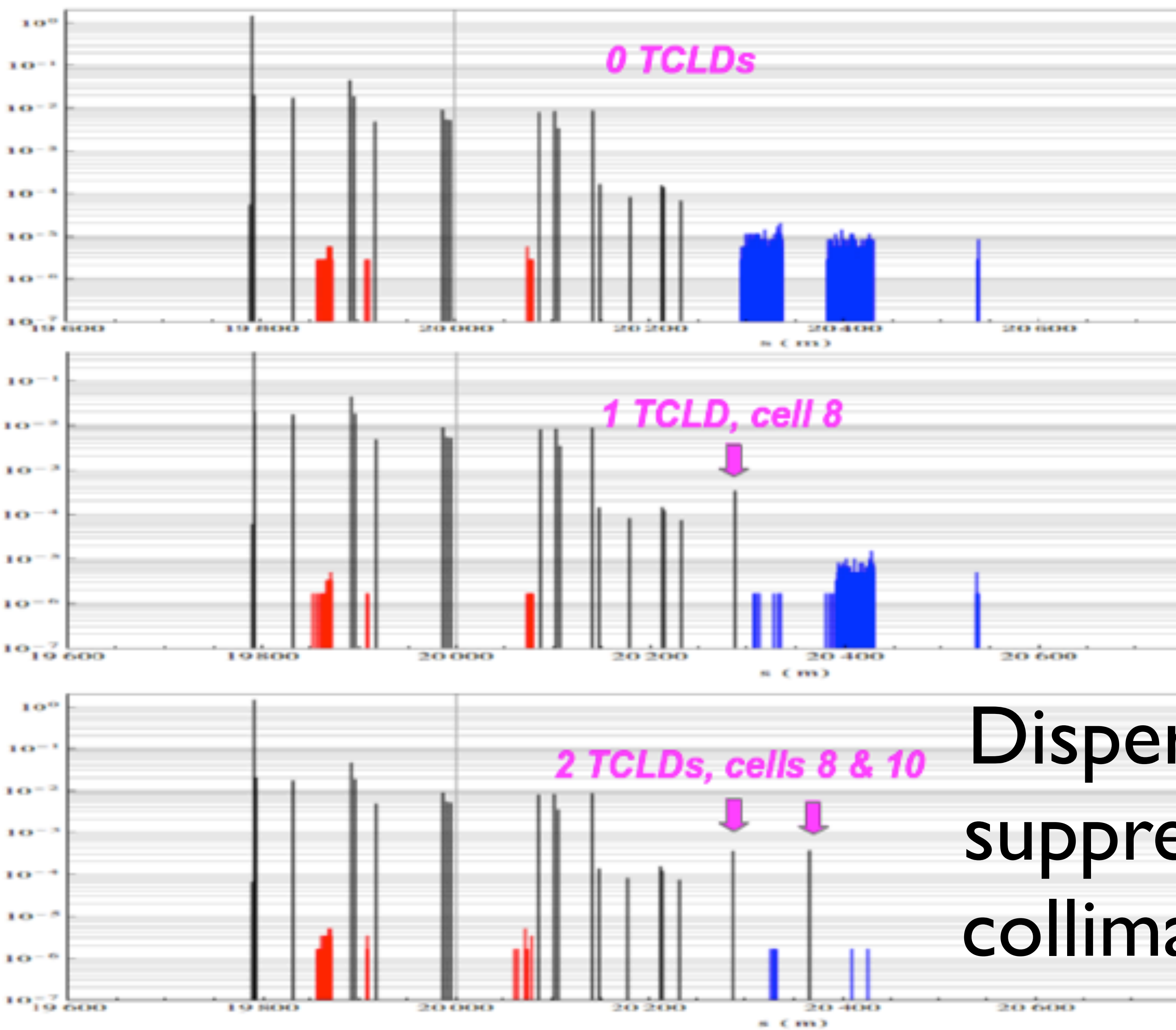
Crystal collimation concept

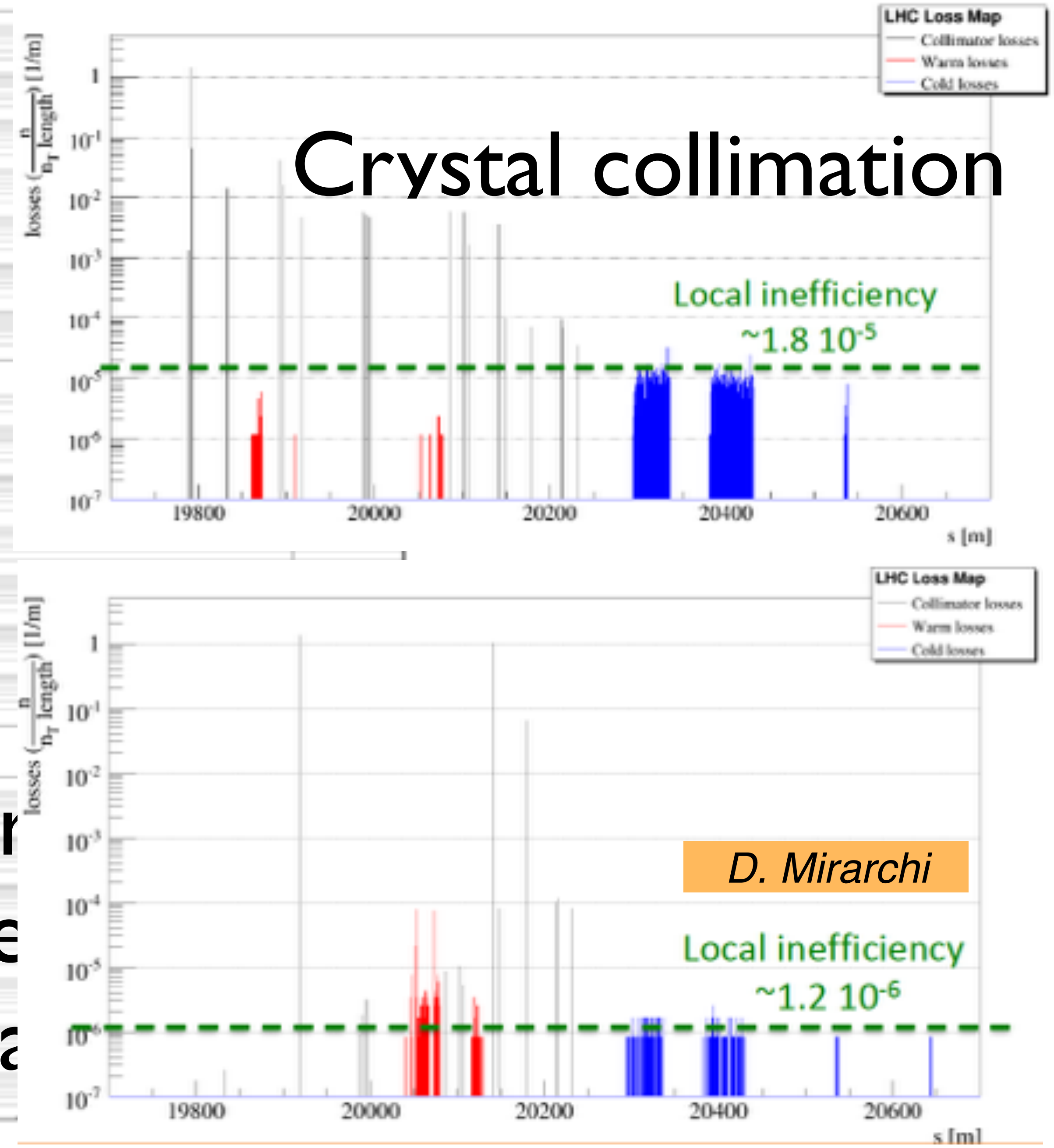


Dispersion suppressor collimators

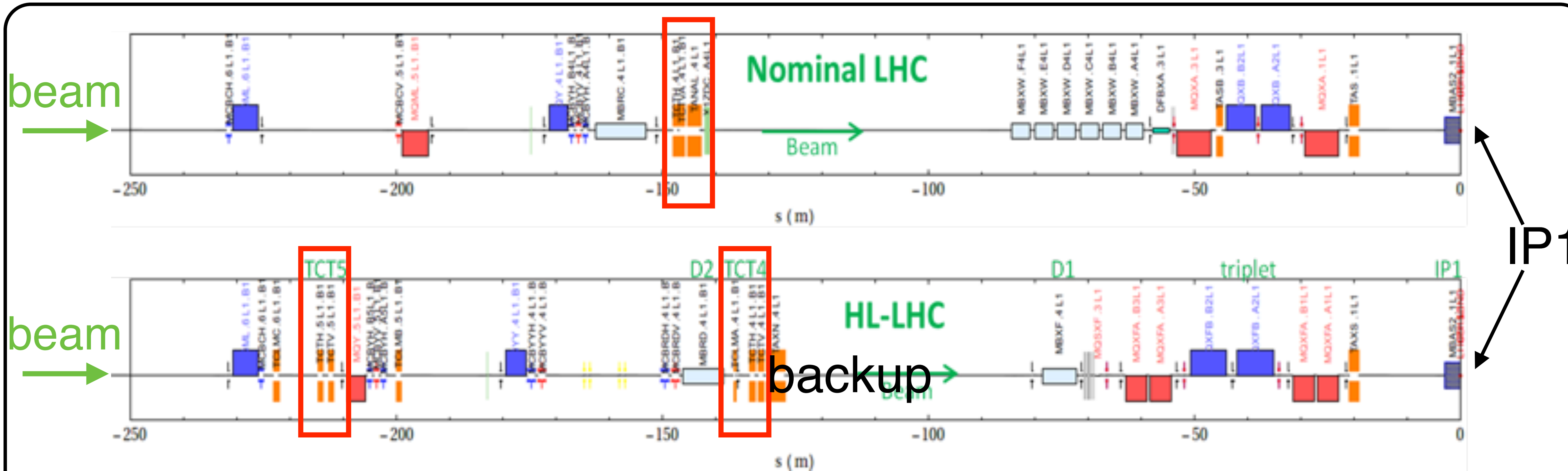
D. Mirarchi

Crystal collimation concept





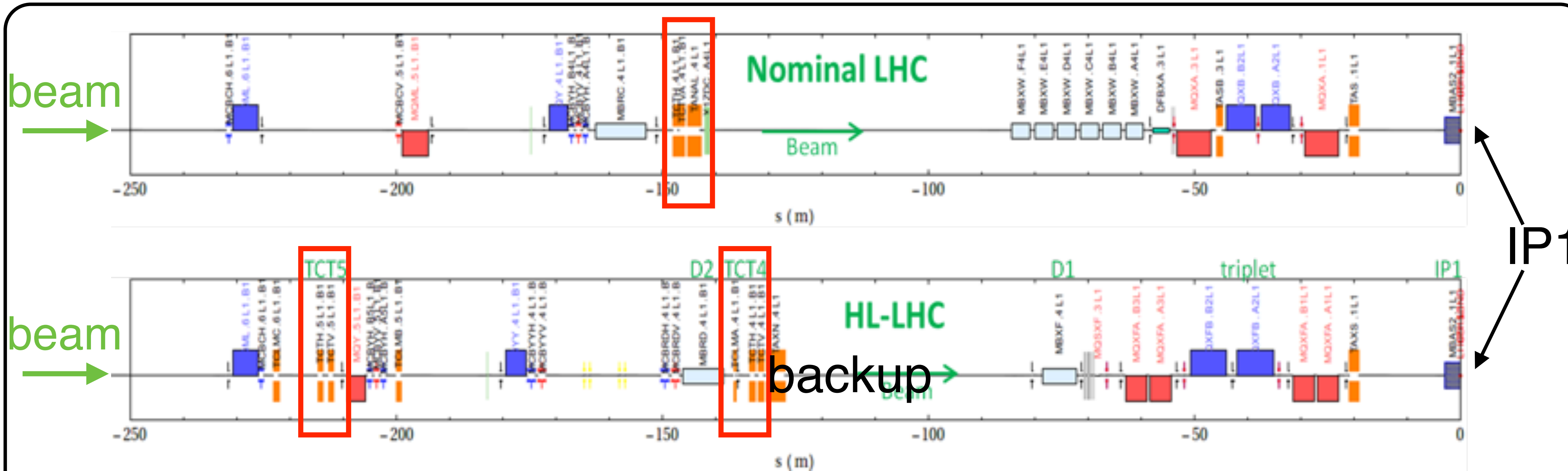
Upgraded IR collimation



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

IP1

Upgraded IR collimation



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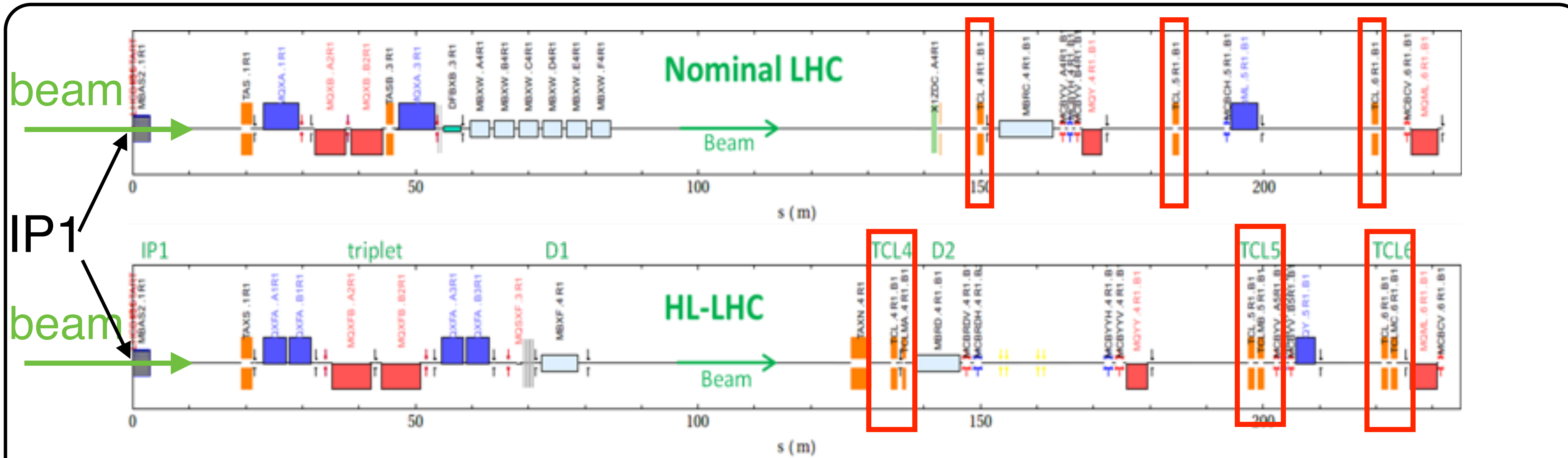
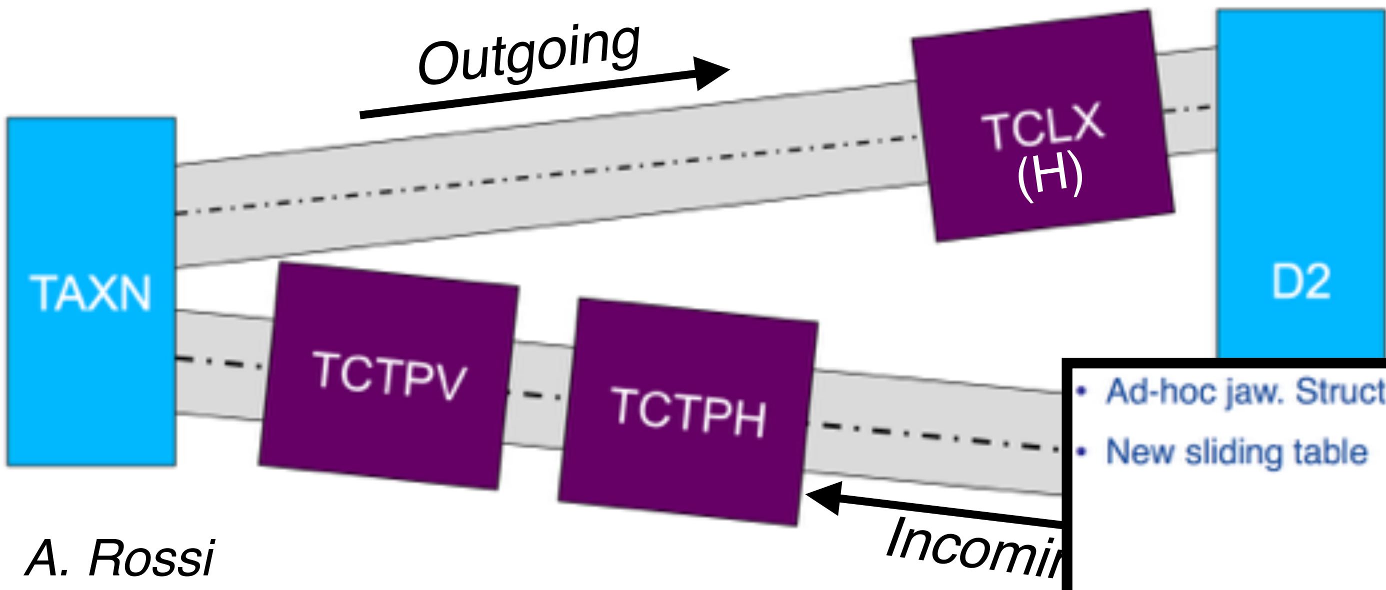


R. Bruce

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

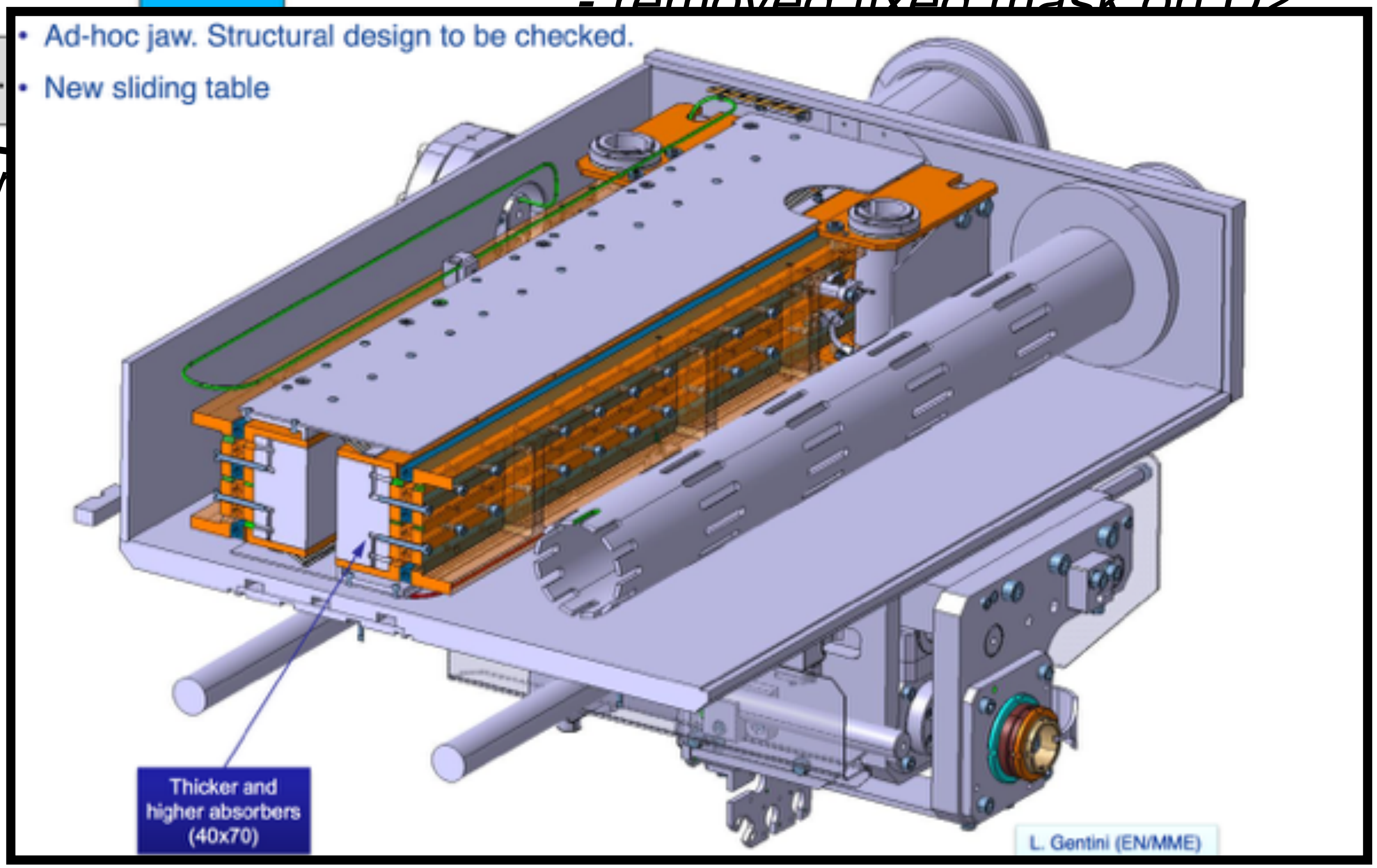
Status of new design and integration



A. Rossi

☑ Key features:

- *Improved performance for round and flat beams;*
- *removed fixed mask on D2;*



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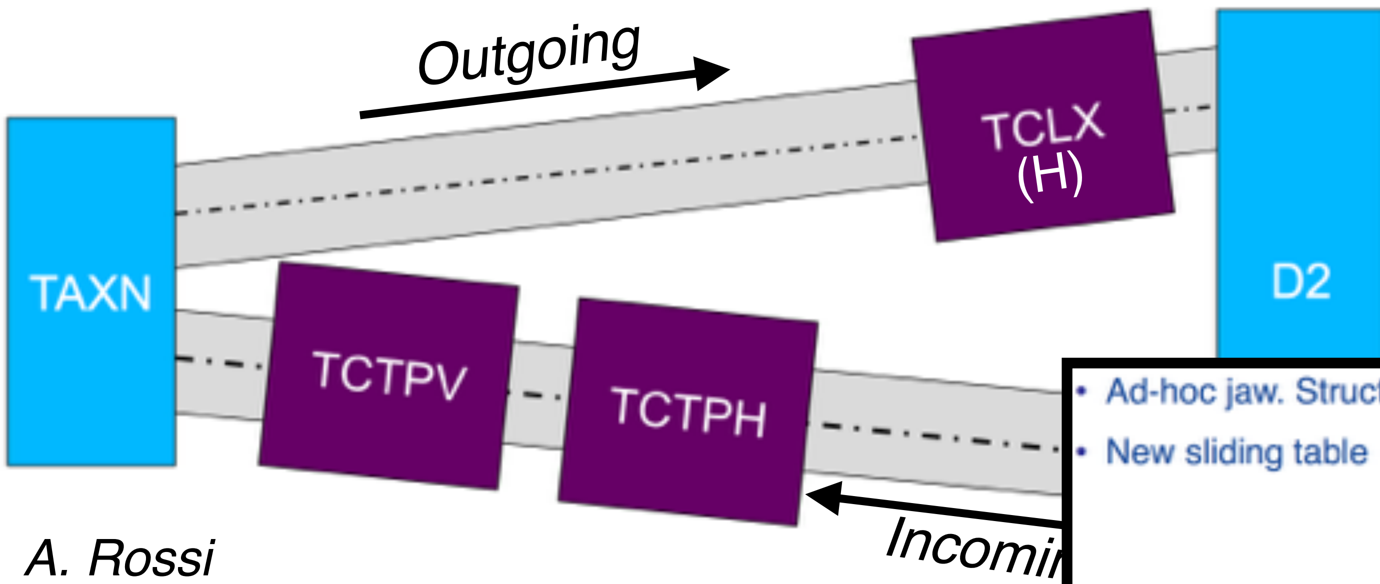

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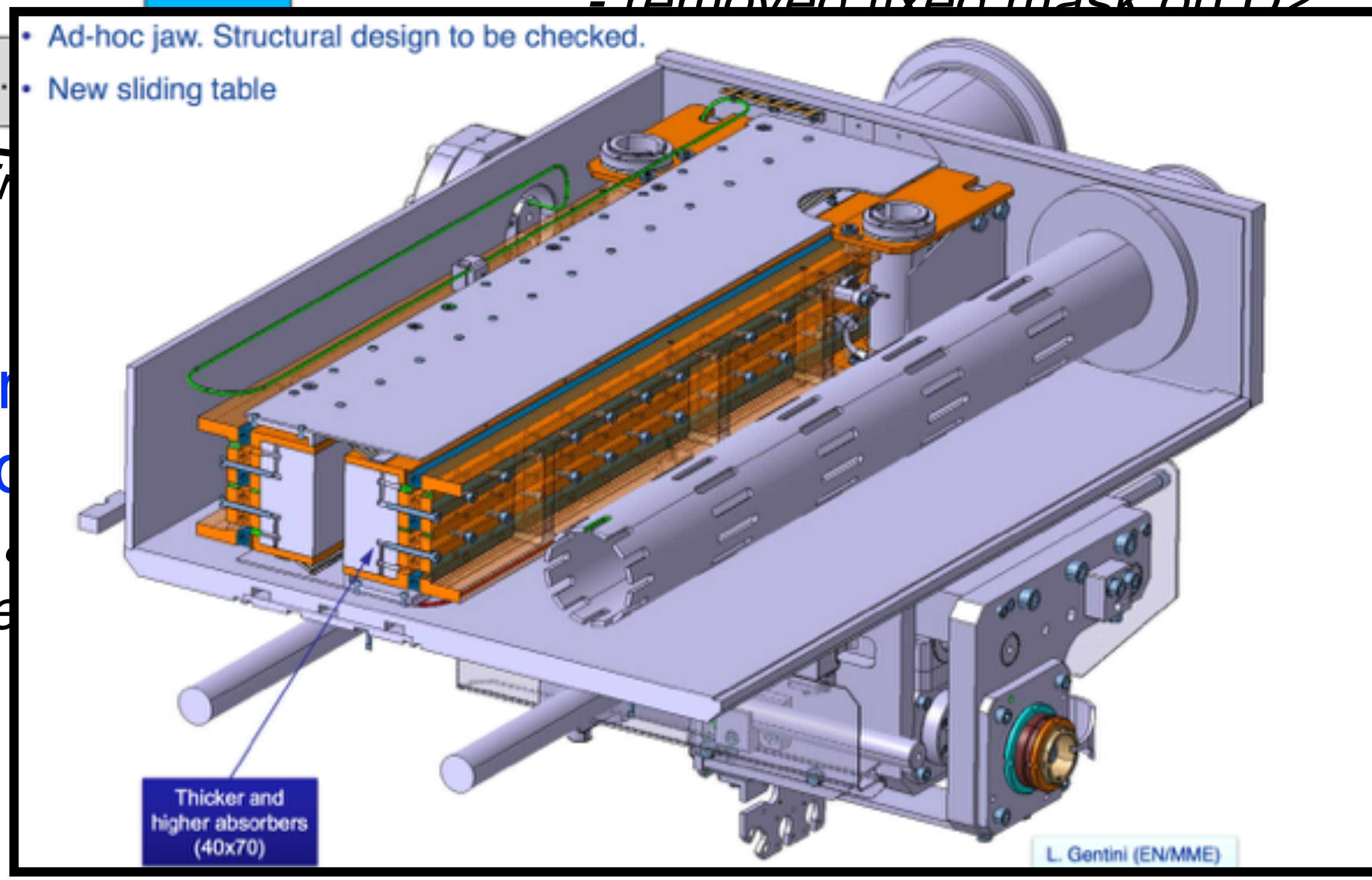

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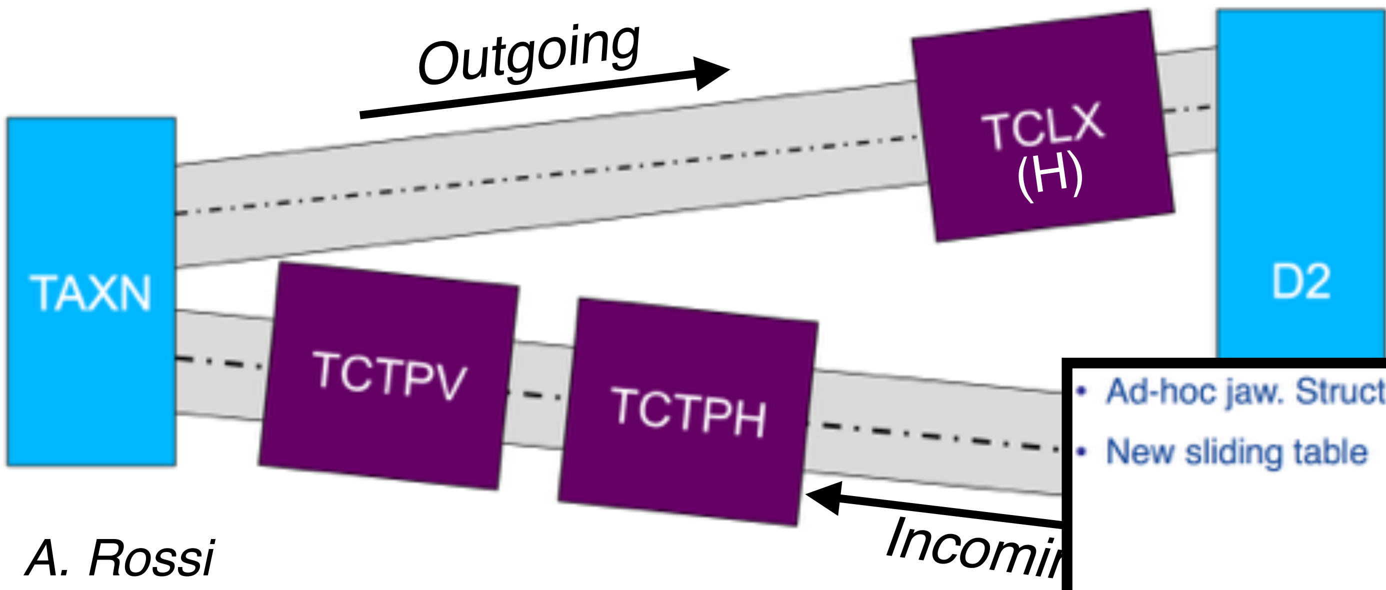

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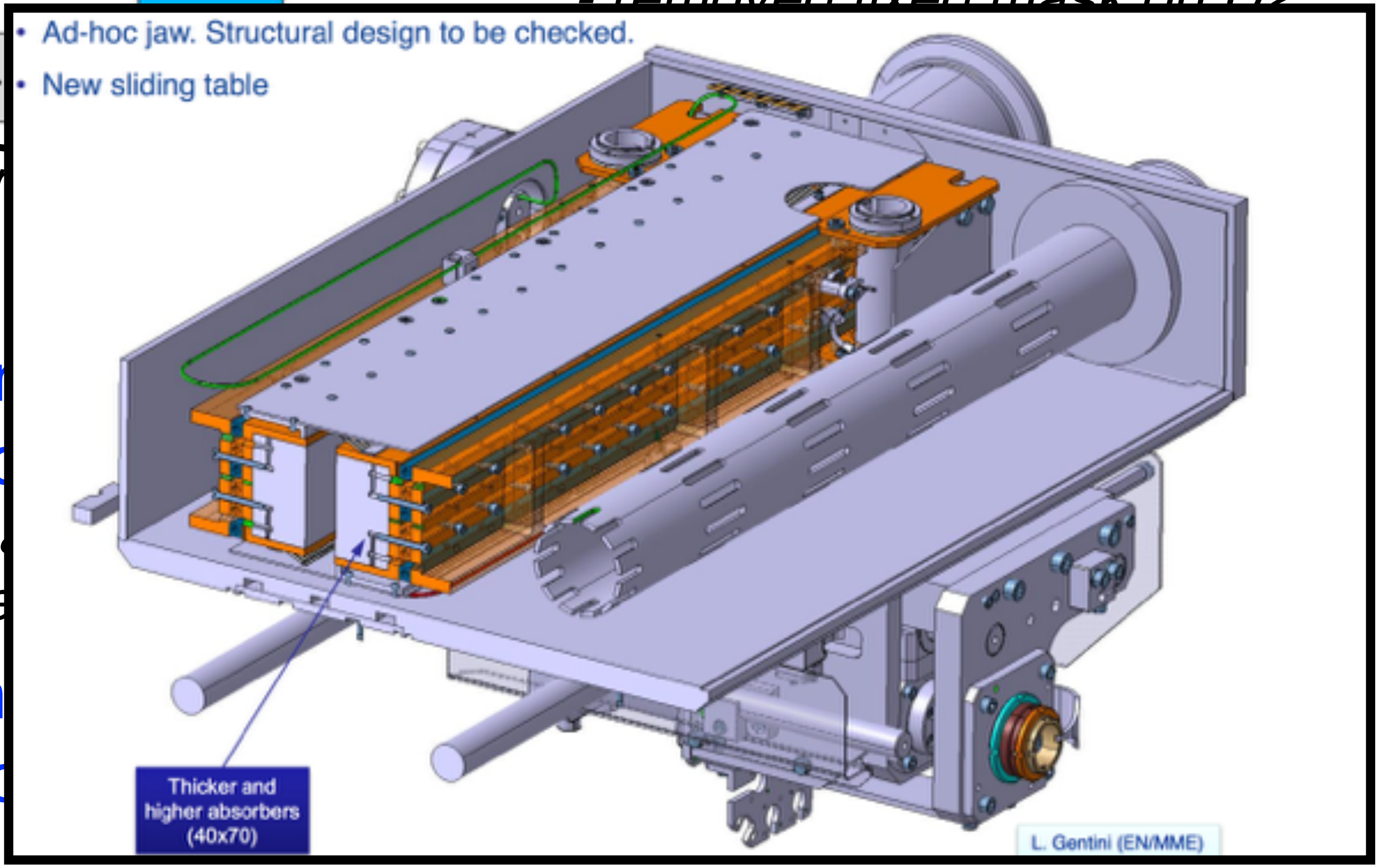

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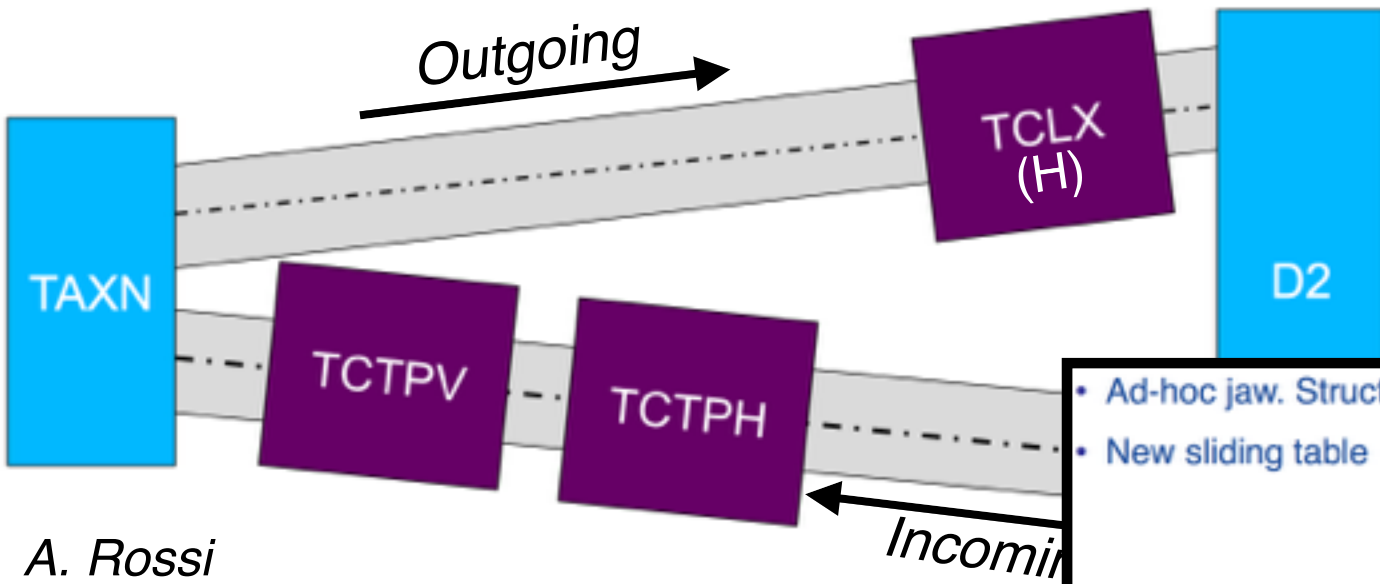

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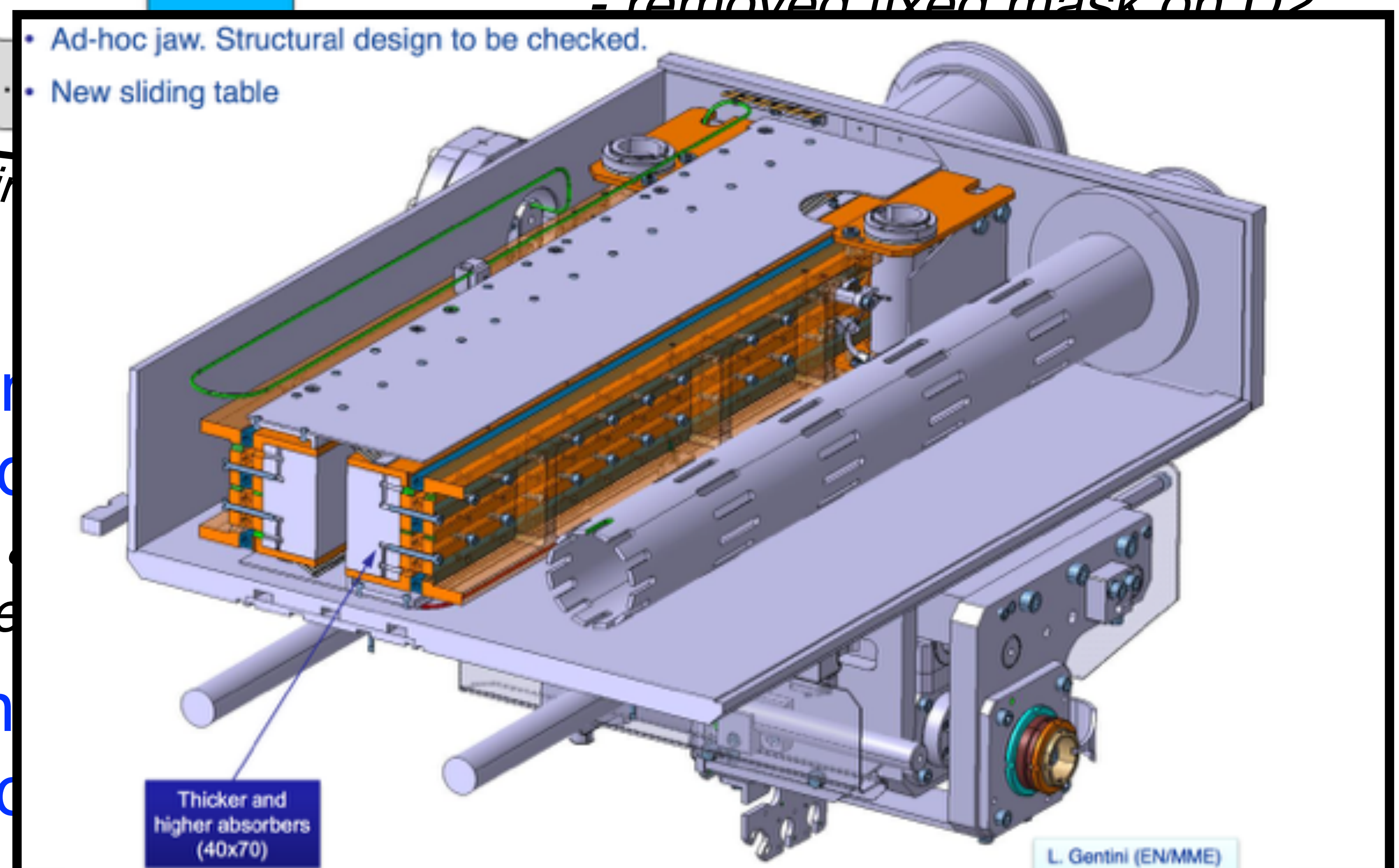

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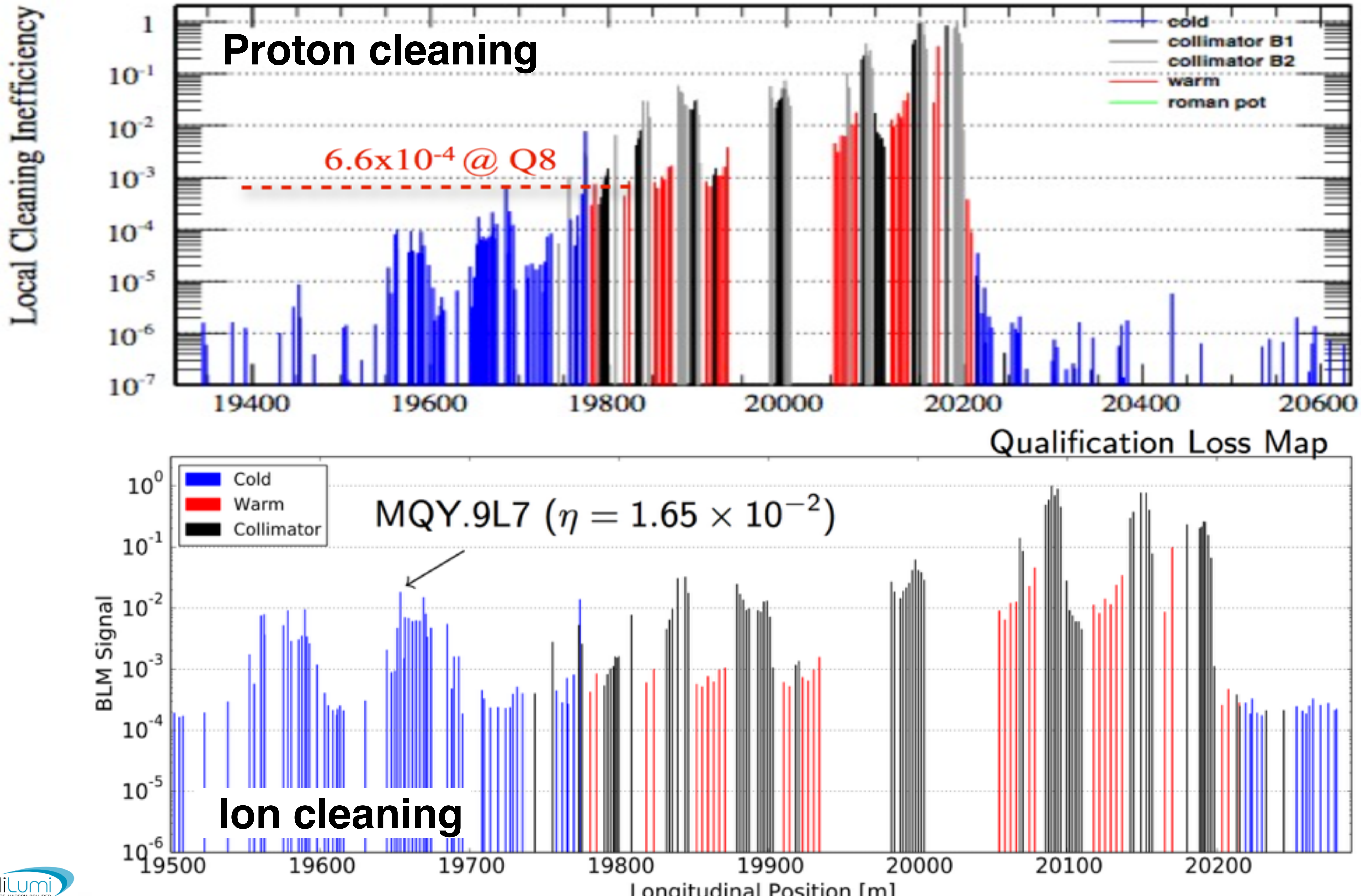
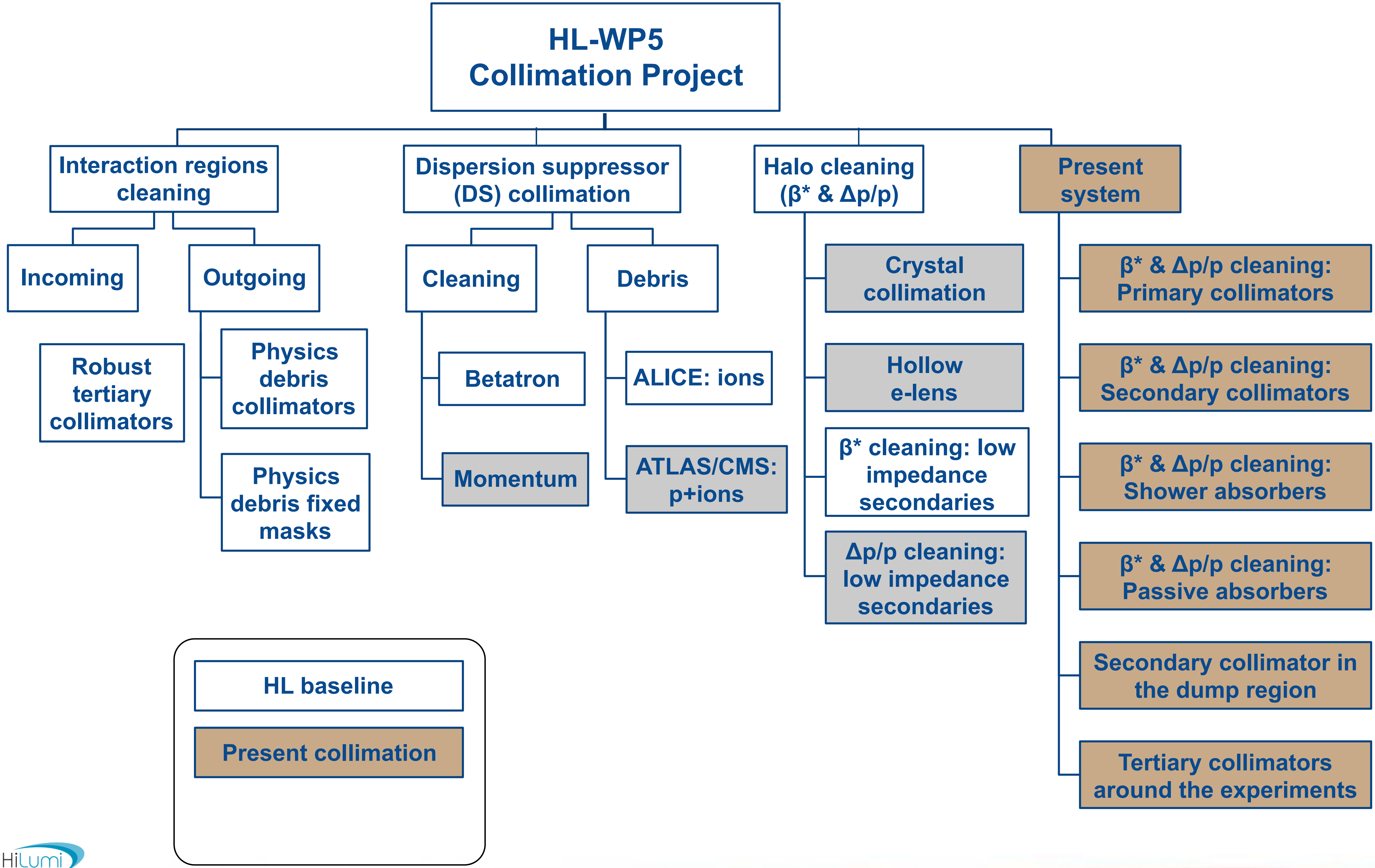
- New tertiary will be x15-x100 times more robust than present ones!

Collimation cleaning: protons and ions



Project upgrade structure



Changes of baseline - March 2015

Presented at the Cost&Schedule review and at the HiLumi/US-LARP spring meeting

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Keep in the baseline all secondary collimators in IR7

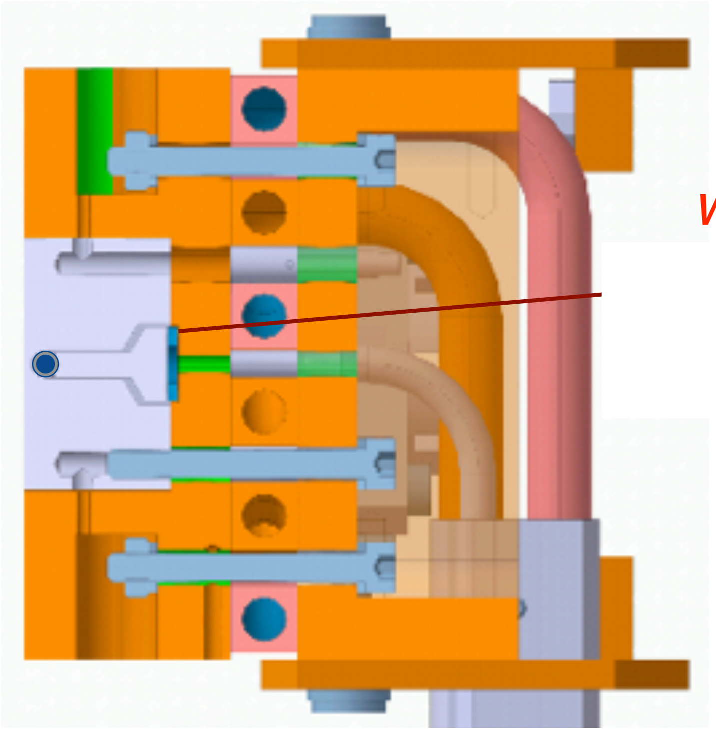
3) New, more robust tertiary collimators in IR2/8

Keep in the baseline the devices for the new IR1/5 layouts

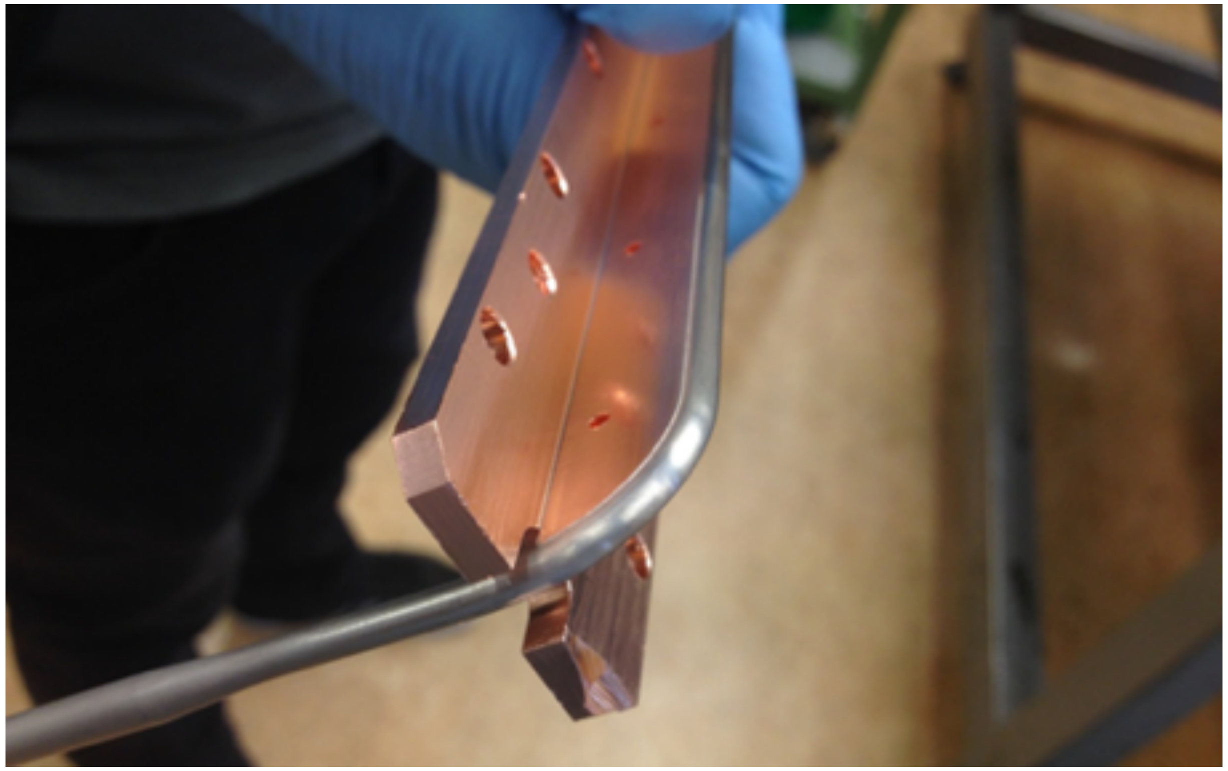
Presented at the Cost&Schedule review and at the HiLumi/US-LARP spring meeting

Recent progress on new designs

Jaws with embedded wires for LRBB compensation



Tertiary collimator with embedded wire for LRBB MDs



4 units being produced - ready for installation in EYETS 2016

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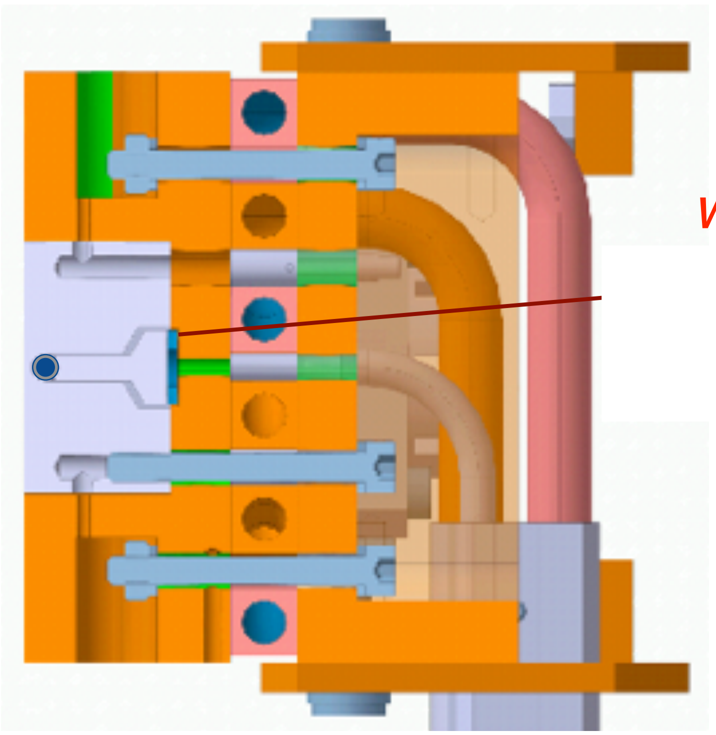

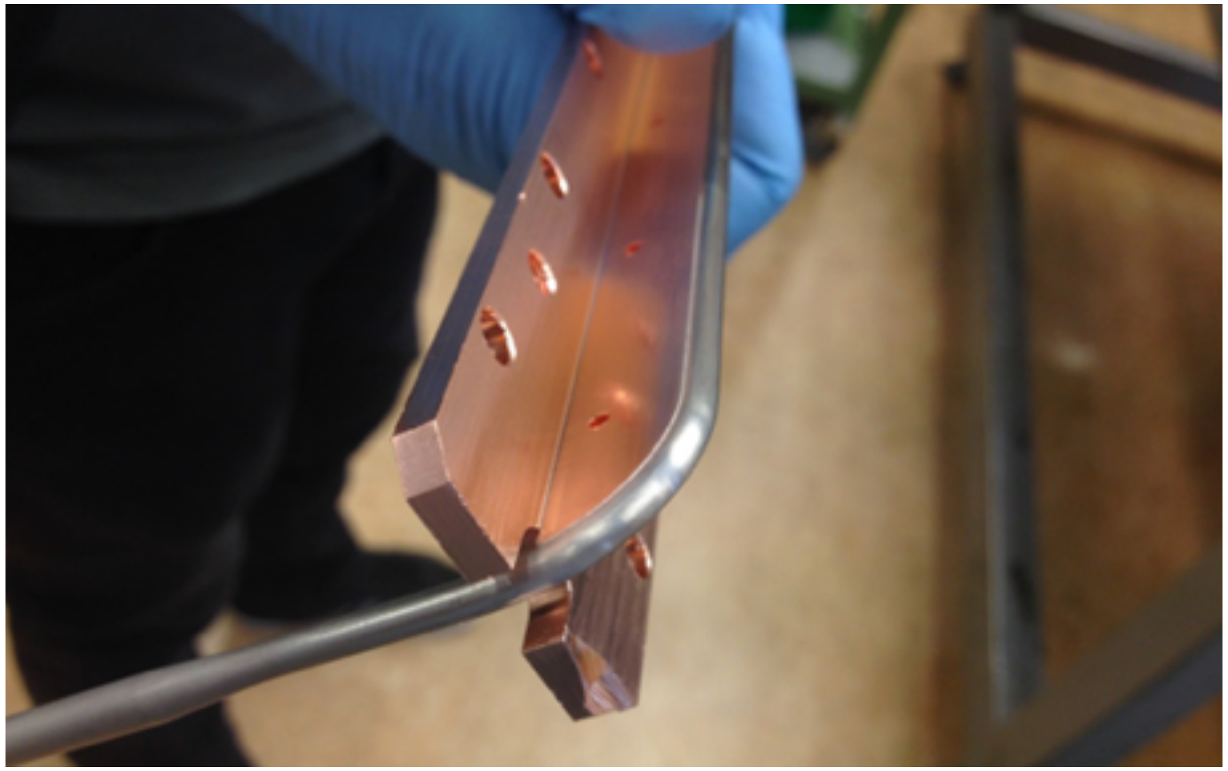

4 units being produced - ready for installation in EYETS 2016

Very positive beam tests with the SLAC rotatable collimator at the SPS.

Proved basic alignment features, measured impedance.
Next year: final validation at HiRadMat.

HL challenges for collimation

- Increased beam stored energy: 362MJ → 680MJ at 7 TeV
  Collimation cleaning, quench limits, tail population issues.
- Larger bunch intensity (I_b=2.3x10^{11}p) in smaller emittance (2.5 μm)
  Collimation impedance and robustness.
- Larger p-p luminosity (1.0 x 10^{34}cm^{-2}s^{-1} → 7.5 x 10^{34}cm^{-2}s^{-1})
  New IR layouts and collimation of collision products.
- Much smaller β^* in the collision points (55 cm → 15 cm)
  Cleaning and protection of new triplets, physics background, new designs.
- Operational efficiency is a must for HL-LHC!
  High precision and reliability in harsh radiation environments.
- Upgraded ion performance (6 x 10^{27}cm^{-2}s^{-1}, i.e. 6 x nominal; total stored beam energy up to 6 times higher)