Status and Results of HL-LHC Collimation MDs

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On behalf of the Collimation Team

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Acknowledgments

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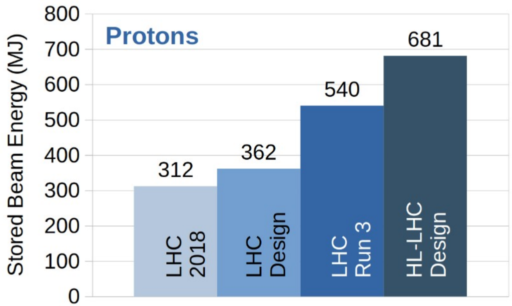
LHC Machine Operators

LHC Machine Protection Team

Collimation in HL-LHC



Collimation system specification

Machine	Duration (s)	Min. beam lifetime (s)	Stored beam energy (MJ)	Beam loss power (kW)
LHC	10	720	362	503
HL-LHC	10	720	681	946

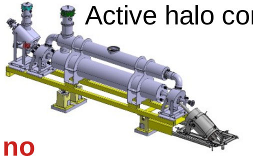
- **HL-LHC collimation system upgrade**: cope with brighter and more intense beams
- First upgrade items installed in LS2, more upcoming, some de-scoped/postponed
- **Crucial role of collimation MDs in Run 3:**
  - **Probe performance** of upgrades already installed
  - **Re-evaluate assumptions and estimates** for pending upgrades using post-LS2 beams
  - Use Run 3 to **consolidate needs** and **upgrade plans**
- MD1 block postponed due to machine availability issues
- **This presentation: overview of planned collimation MDs and first results**

Potential performance limitations in HL-LHC

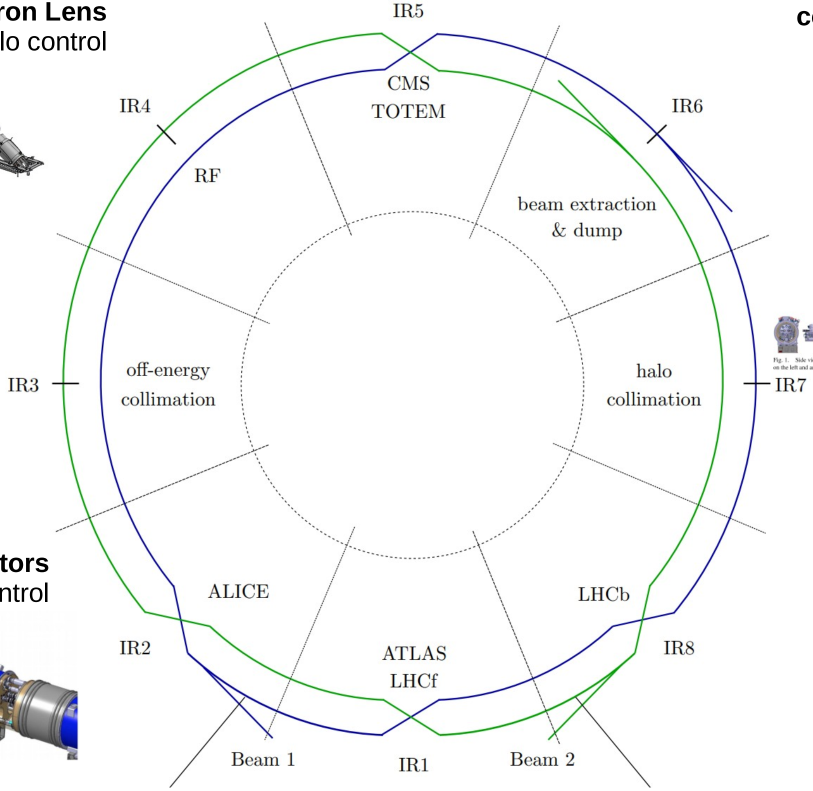
- **Collimation cleaning performance and quench limit**
  - Increased beam intensity: potential magnet quench from collimation debris
  - Issue in particular for protons but also heavy ions
  - Loss spikes and lifetime w.r.t. 12 min specification
- **Transverse beam halo**
  - Overpopulated halo endangers collimation system in case of sudden orbit shifts
- **Impedance**
  - Beam stability with higher intensities requires upgrade of collimator material

Collimation system upgrades (selection)

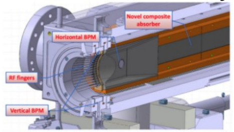
Hollow Electron Lens
Active halo control



Uncertain and no longer compatible with present LS3 schedule: In-kind from Russia



Low impedance collimators : beam stability



Phase I completed in LS2

IR7 DS collimators
Quench mitigation

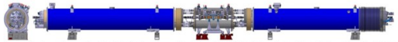
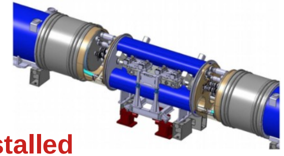


Fig. 1. Side view on the connection side with the diode container, and front view of the MBHFA with the collimator integrated in the middle, with an LMBHA on the left and an LMBHB on the right.

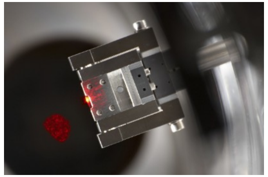
Deferred after 11T dipole testing

IR2 DS Collimators
Ion debris control



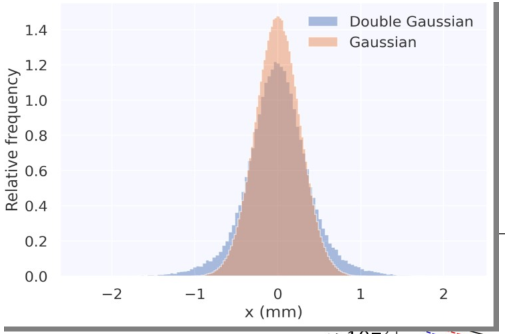
Installed

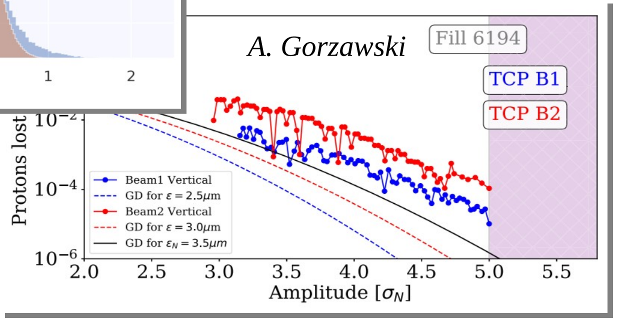
Crystal collimators
Heavy-ion collimation



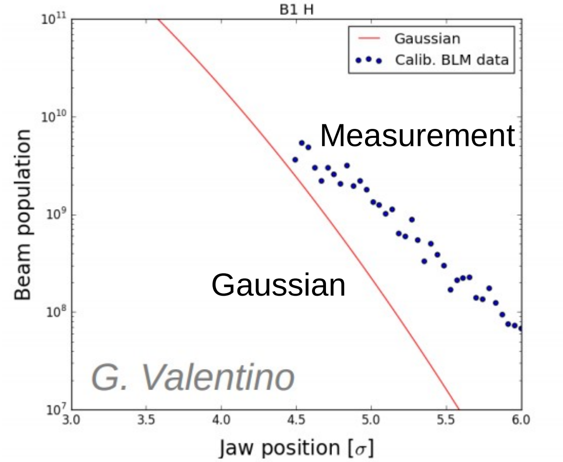
Two/four units upgraded YETS22/23 remaining upgrade

Halo characterization and control



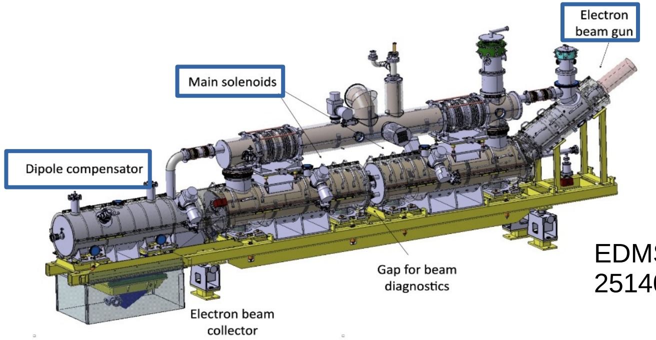


Transverse beam halo in LHC and HL-LHC



- LHC measurements: **Five percent of beam energy stored in halo** above 3.5σ
- Scaling to **HL-LHC: 35MJ in halo** (uncertain but best available estimate)
- Fast failure scenarios: could induce high losses → **potential collimator damage**

- Initial HL-LHC baseline: actively **remove halo particles with Hollow Electron Lens** (HEL)
- Russian in-kind: **HEL descoped**
- **Important Run 3 MDs to**
  - **Assess halo population** and diffusion towards large amplitudes with LIU beams
  - **Re-evaluate assumptions / limitations** for/from halo and control in HL-LHC



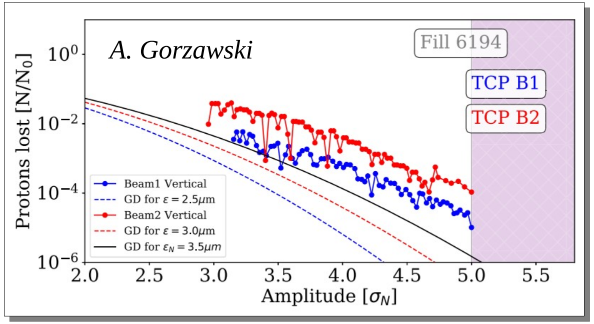
EDMS 2514085

Transverse halo characterization MDs

Purpose

- Estimate impact of missing HELs for Run 4 operation
- Input for halo depletion studies preparing post Run 4

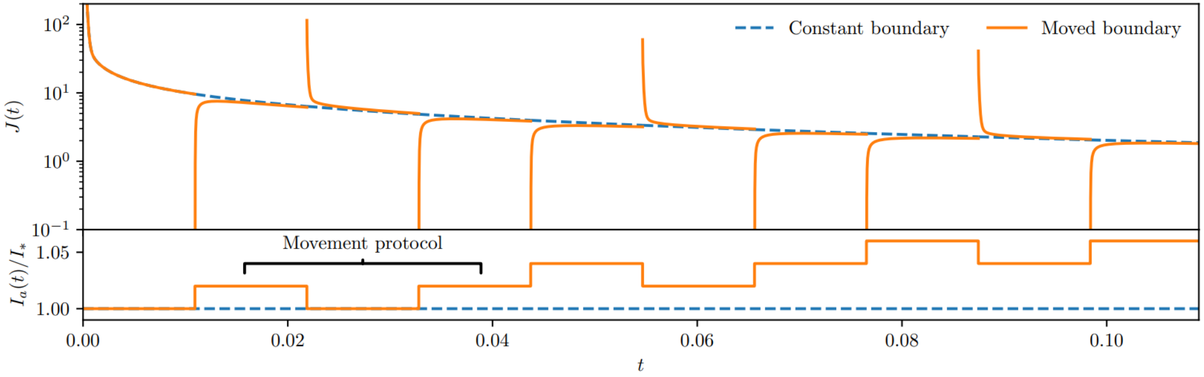
Halo Measurement in Run 2



- **Starting point: BLM calibration** – gauge BLM signal in Gy/s w.r.t. protons lost
  - MD 6950: Scrape beam to calibrate BLM signal for all primary collimators
- **Characterize halo population** with post-LS2 beams
  - Scrape beam with collimator - deduce halo population from BLM signal
  - **Start with EoF measurement** (MD 8183) then probe other configurations
  - **Repeat at 1.8e11 bunch intensity if reached**
  - Preparation of Run 4 without HELs and wider TCPs: **measurement at larger amplitudes** (up to 8.5σ)

Transverse Diffusion MD

C.E. Montanari



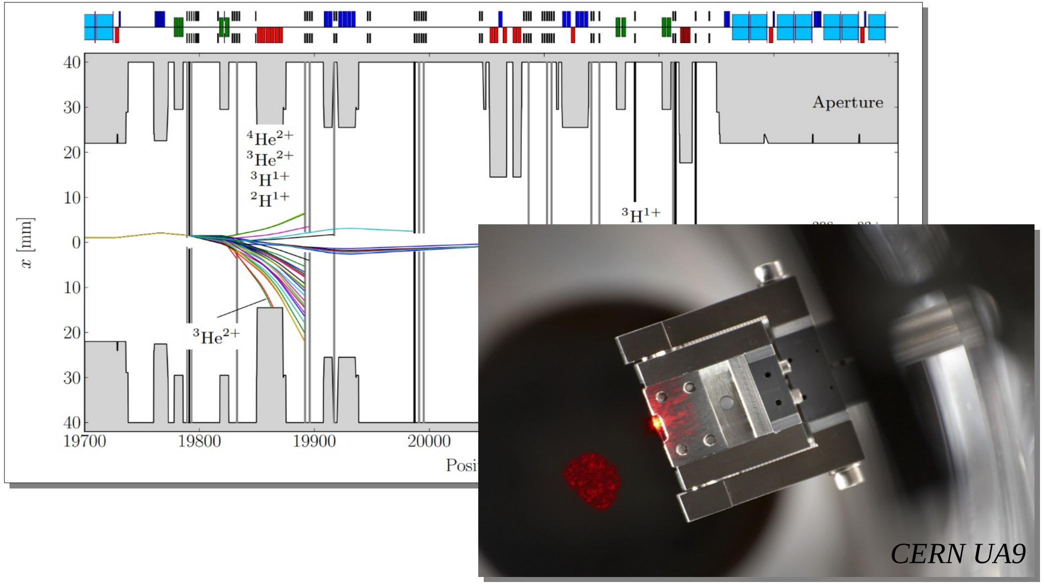
$$D(I) = c\exp\left[-2\left(\frac{I_*}{I}\right)^{\frac{1}{2\kappa}}\right]$$

Fit parameters from measurement

- Diffusion drives halo formation: **understanding diffusion allows predicting halo population**
- MD 8003: **Measure non-linear diffusion coefficients** in different configurations
- Apply optimized collimator movement protocol and observe proton flux at collimator
- Relies on previous calibration of BLM signal

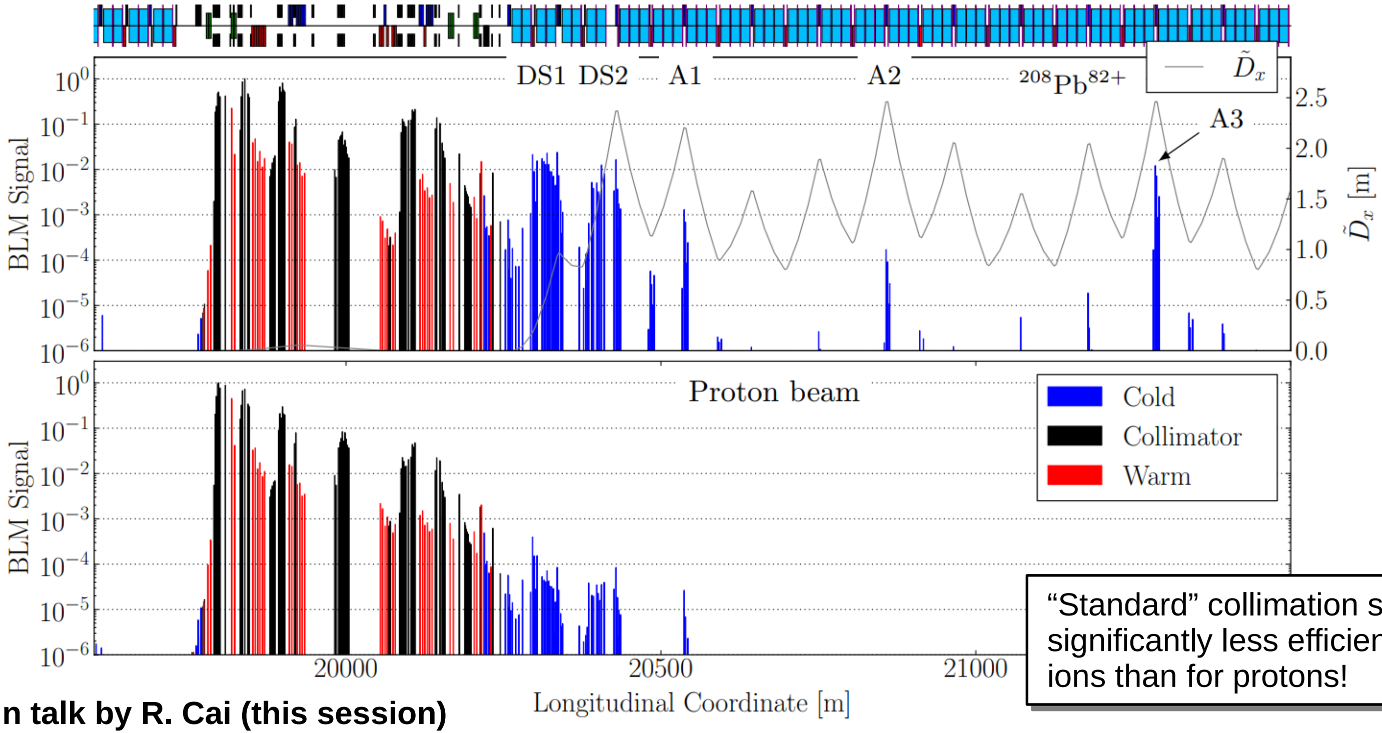
Significant synergies: MD 8003, 6950 and 8183 could be combined

Heavy-ion collimation



Heavy-ion collimation

2011 qualification loss map B1H: ions and protons

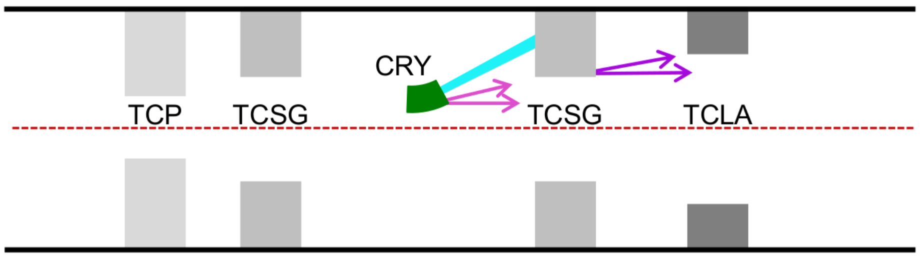


“Standard” collimation system significantly less efficient for heavy ions than for protons!

More details in talk by R. Cai (this session)

Crystal collimators for heavy-ions

Schematics of crystal based collimation



M. D'ANDREA

- **Standard system** relies on random scattering in primary collimator: **inefficient due to fragmentation**
- HL-LHC design intensities already reached in Run 3: **quench risk!**
- **Solution from Run 3 onwards: crystals** deterministic steering of particles into absorber ("channelling")
- Make sure that all key elements are operational and behave as expected

More details in talk by R. Cai (this session)

Studies for heavy-ion collimation

Done in commissioning

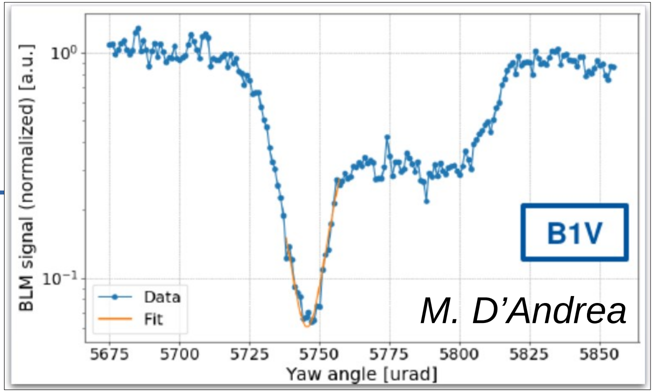
- Characterized crystal units: good performance: ready for next heavy-ion run
- Tbd: repeat for new units once installed

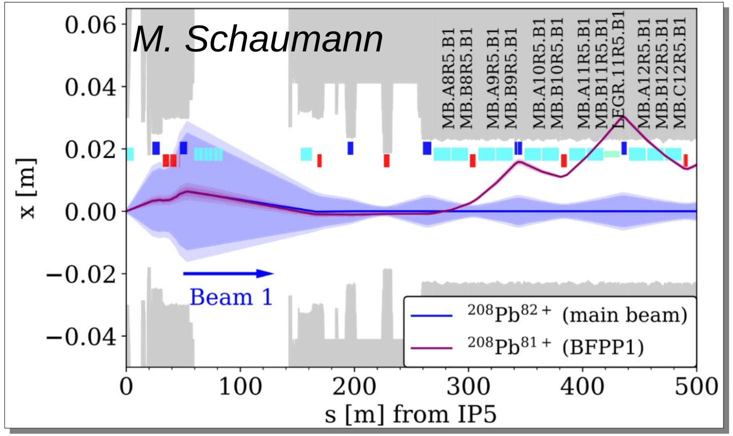
Foreseen for MD1 with protons

- **MD 7007**: Probe crystal ramp functions to confirm channelling condition is consistently met

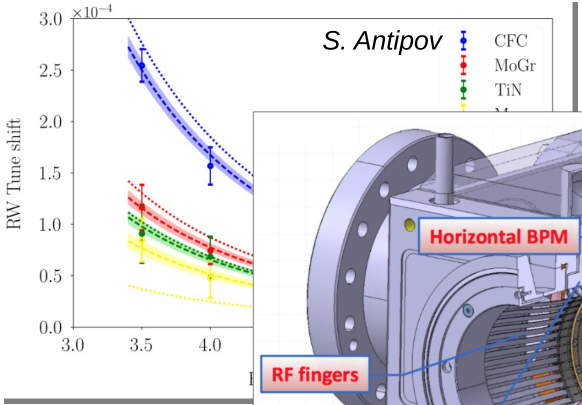
Next Pb heavy-ion run

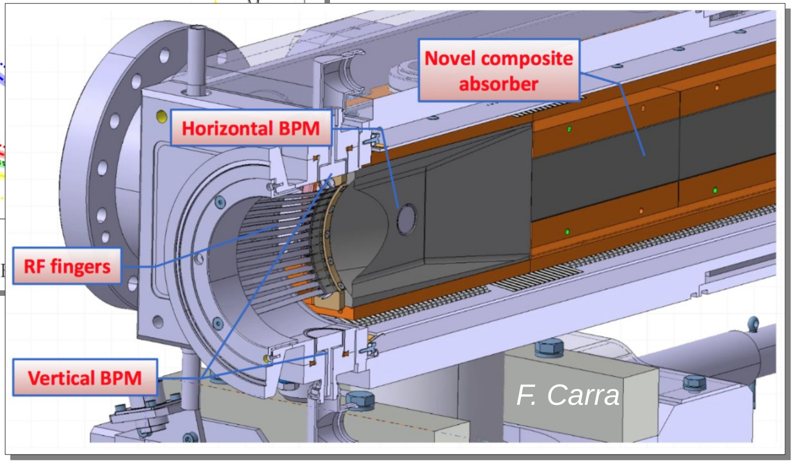
- Crystal long term stability evaluation (parasitic)
- Heavy-ion **crystal collimation quench test**
- Collision product **(BFPP) quench test in IR1/IR5**
- Test different settings while crystals are primary





Impedance


S. Antipov
CFC
MoGr
TiN
RW Tune shift
$\times 10^{-4}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3.0
3.5
4.0


Novel composite absorber
Horizontal BPM
RF fingers
Vertical BPM
F. Carra

HL-LHC low impedance collimator MDs

Phase 1 completed as planned

- Installed 4 MoGr primary (TCPPM) collimators
- Installed 8 secondary collimator (TCSPM) in IR7

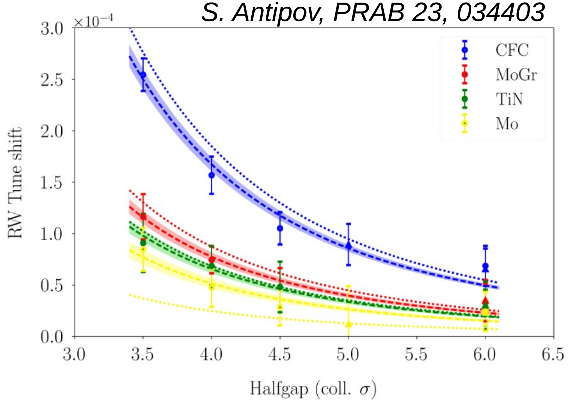
Phase 2 scheduled for LS3

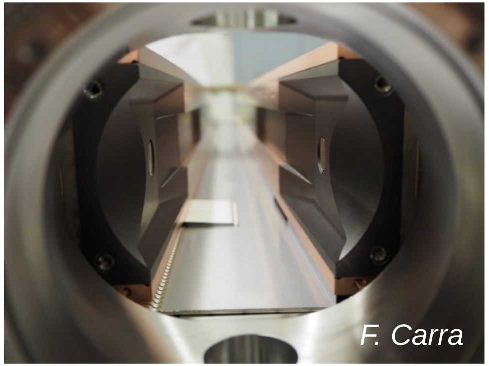
- Ten additional TCSPM collimators for IR7

Planned Run 3 experiments

- **Demonstrate gains in impedance** (tune shift measurements, partly completed)
- **Identify possible radiation induced degradation** (tune shift measurements throughout Run 3)
- **Measure total impedance** (dedicated MDs)
- **Validation of beam stability models** (impact of noise), dedicated MDs (general effort of WP2)

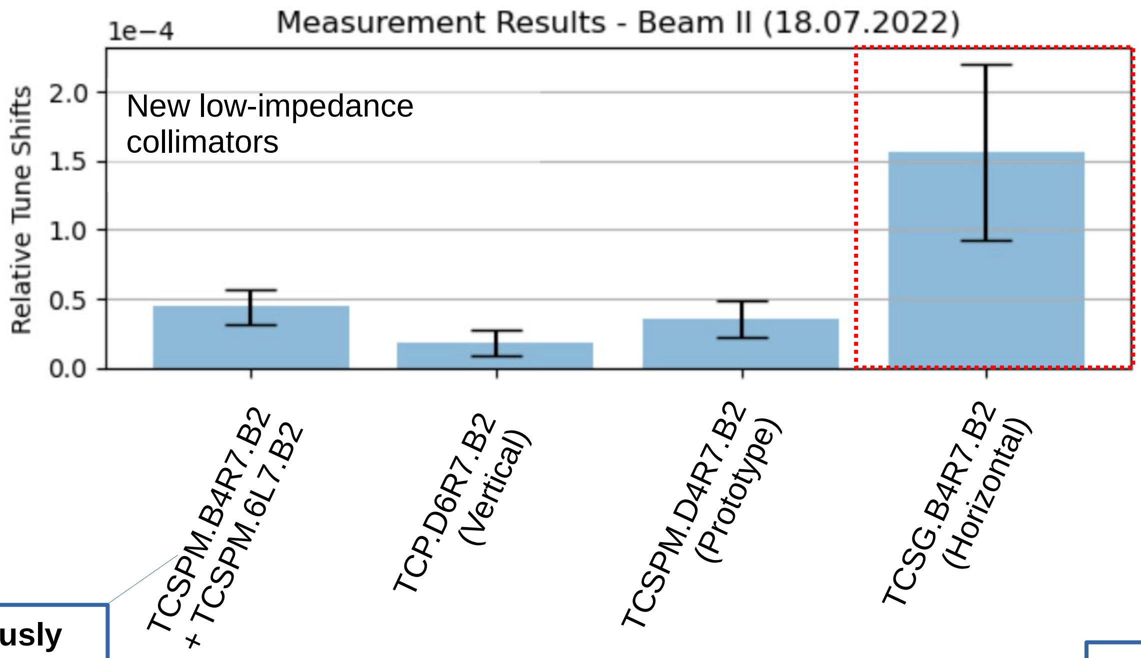
S. Antipov, PRAB 23, 034403





F. Carra

First tune shift measurement results

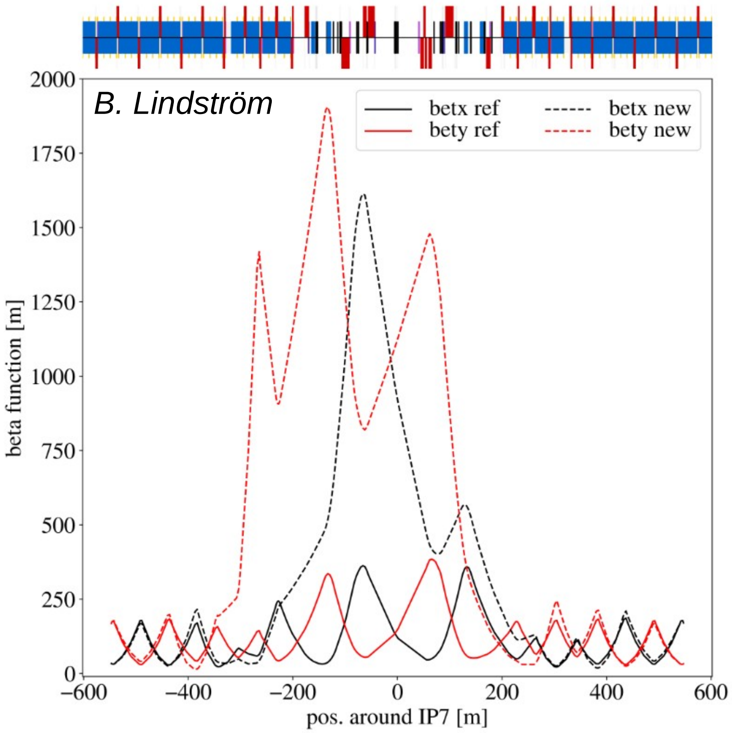


Pre-LS2 carbon collimator

Moved **simultaneously and closer to the beam** because signal of one alone was too low

More information in talk by Lorenzo Giacomel on Thursday

Optimized optics for impedance improvement

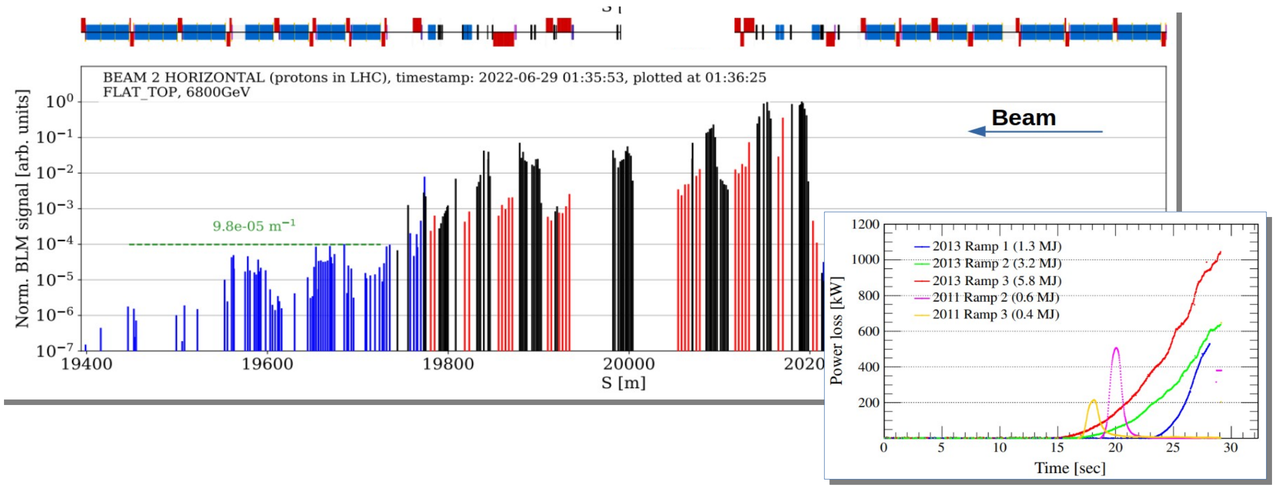


More details in talk by B. Lindström (this session)

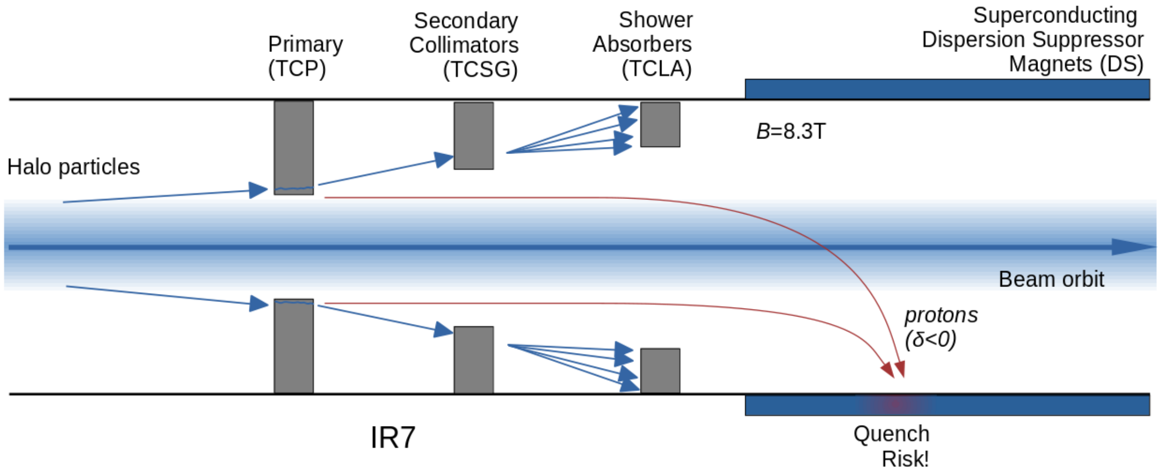
MD 7203

- Collimators in IR7 contribute to significant part of impedance budget
- Different new optics proposals with larger β-functions allowing for bigger collimator gaps
- Expect **improvement** in **impedance and cleaning** performance (could help with missing 11T issue)
- Study of cleaning performance and impedance proposed for MD1

DS Magnet quench mitigation



Collimation inefficiency



- Upgrade with local DS collimators (TCLD) deferred
- Must rely on standard collimation system
- Crystals can not be used with protons (too high intensity)
- **Can we reach HL-LHC design intensity and losses without quenching?**

Collimation inefficiency without 11T upgrade

Simulated MB coil
peak power deposition (PPD)

Year	Machine	PPD (mW/cm³)
2019	HL-LHC	**21**
2021 (updated TCP material)	HL-LHC	**15**

Click for references

MB quench limit

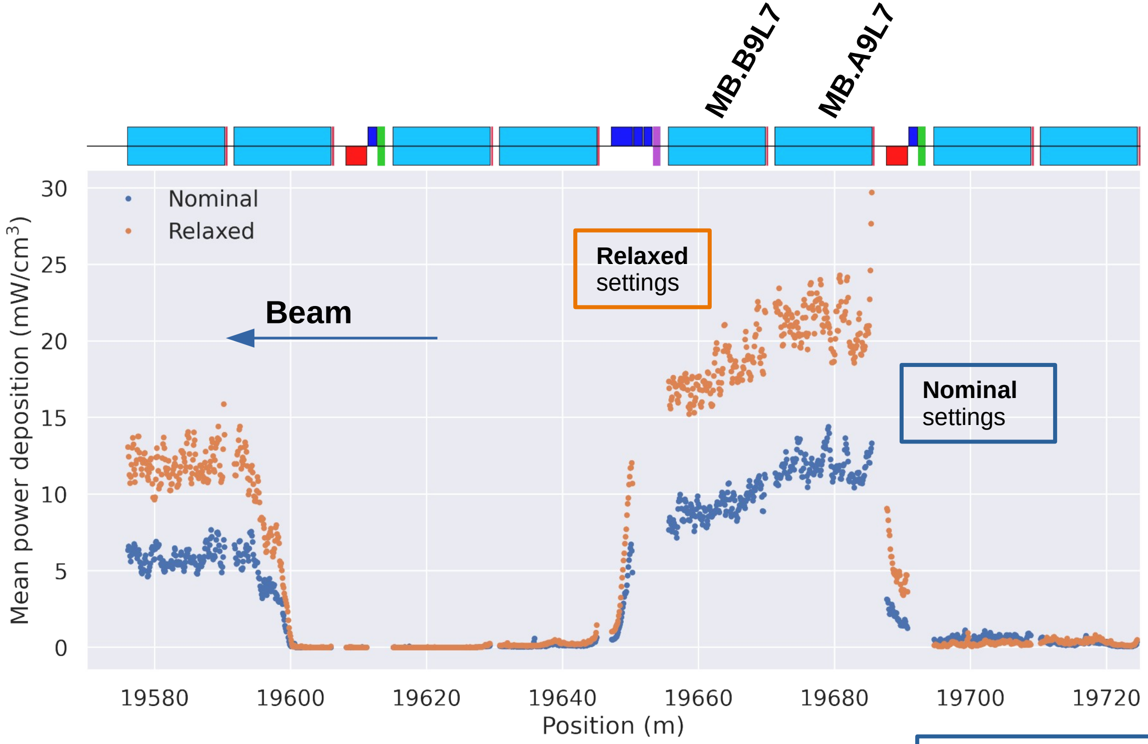
- Latest estimate (L. Bottura et al., 2019): for 7 TeV with losses of ~1s duration: **20-30mW/cm³**

Expected HL-LHC MB peak power deposition

- Complex simulation chain (SixTrack → FLUKA)
- Latest estimate (A. Waets et al., 2021)**: 15 mW/cm3**

- With uncertainties: **very tight margin**!
- Without 11T upgrade: can't exclude that intensity limitations due to quench risk may arise
- Quench from collimation debris in proton operation never observed
- **Test under operational conditions needed**
- Strategy (dedicated MD): Induce high losses at collimators to quench IR7 DS MB magnet on purpose

Expected power deposition in quench test



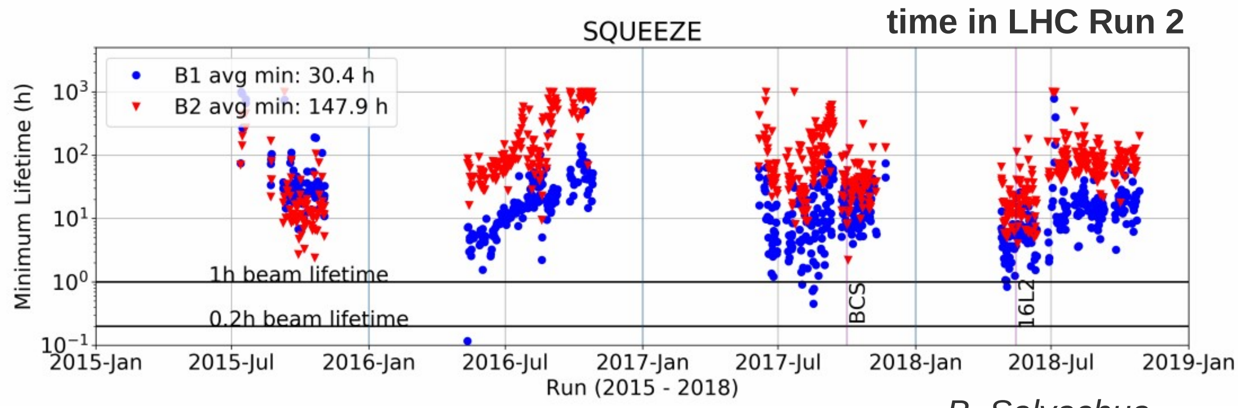
FLUKA power deposition studies: ***V. Rodin, A. Lechner, L. Esposito***

Knob - variation of collimator settings: increase peak power load on MB magnets

Expect to quench **MB.A9L7** (also quenched in heavy-ion collimation quench test 2015)

Beam lifetime

Observed beam life time in LHC Run 2



B. Salvachua

- **Quench risk defined by collimation inefficiency, quench limit and min. beam lifetime**
- In Run 2: beam lifetime rarely came close to specification of 0.2h and was mostly better
- Run 3: monitor lifetime (parasitically) → can evaluate quench risk if combined with quench test results

Further studies

- Study on impedance induced beam instabilities with **changing collimator settings** between flat top and collision (dedicated MD)
- Current one-sided crystal collimators cover diffusing losses and orbit drifts in one direction – **study necessity for two-sided crystals** in Pb operation (parasitic, potentially MD)
- Physics beyond colliders: study crystal setup in **IR3 for fixed target experiments** (dedicated test stand to be installed at end of Run 3)

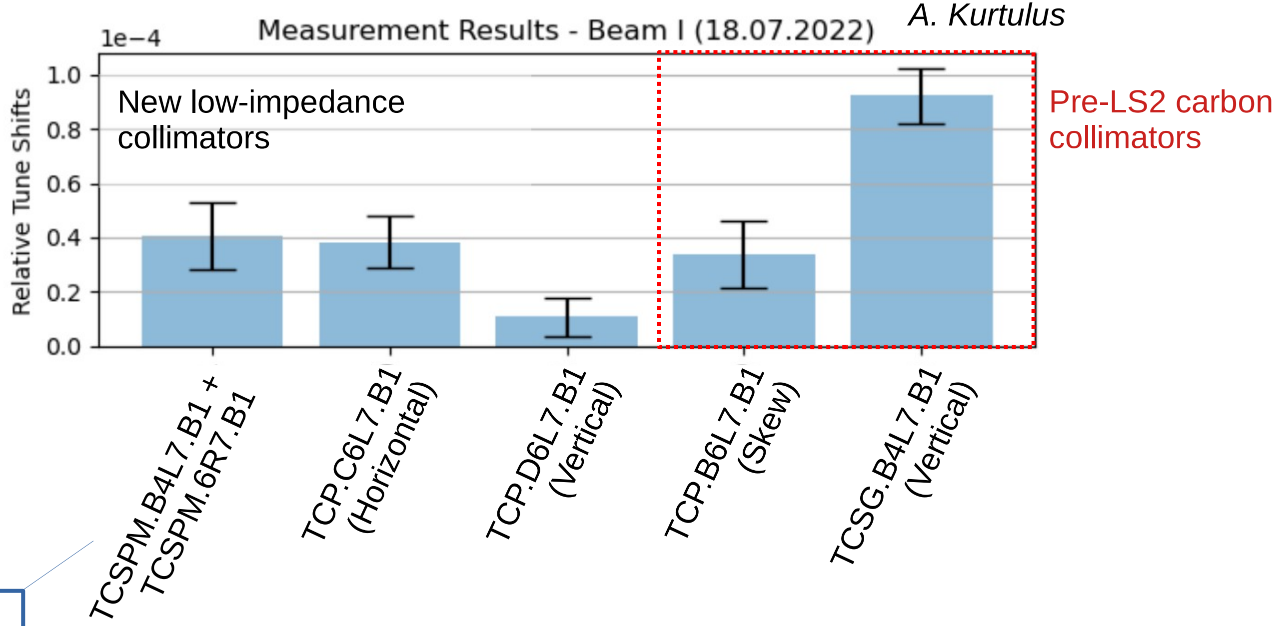
Summary

- Broad variety of HL-LHC collimation MDs foreseen for LHC Run 3
- **Halo dynamics** and characterization studies
- **Heavy-ion collimation**: crystals and quench limits
- **Impedance reduction**: collimator material upgrade characterization, optics upgrades
- **Quench risk mitigation**: quench test, beam life time analysis
- MD1 block postponed, most studies still pending – first promising results for low impedance collimators
- Remaining studies proposed to be done starting 2022 – depends on machine availability

Backup

First tune shift measurement results

A. Kurtulus



Moved **simultaneously and closer to the beam** because signal of one alone was too low

More information in talk by L. Giacomel on Thursday