Limitations for heavy-ion performance in the LHC

R. Bruce, J.M. Jowett, M. Schaumann

Outline

- Introduction: Where are we now?
  - 2018 Pb run
- Encountered limitations on luminosity
  - Collisional processes: Burnoff and beam losses
- Encountered limitations on beam parameters so far
  - Collimation
  - Beam from injectors
  - Evolution in the LHC
- Future performance and plans

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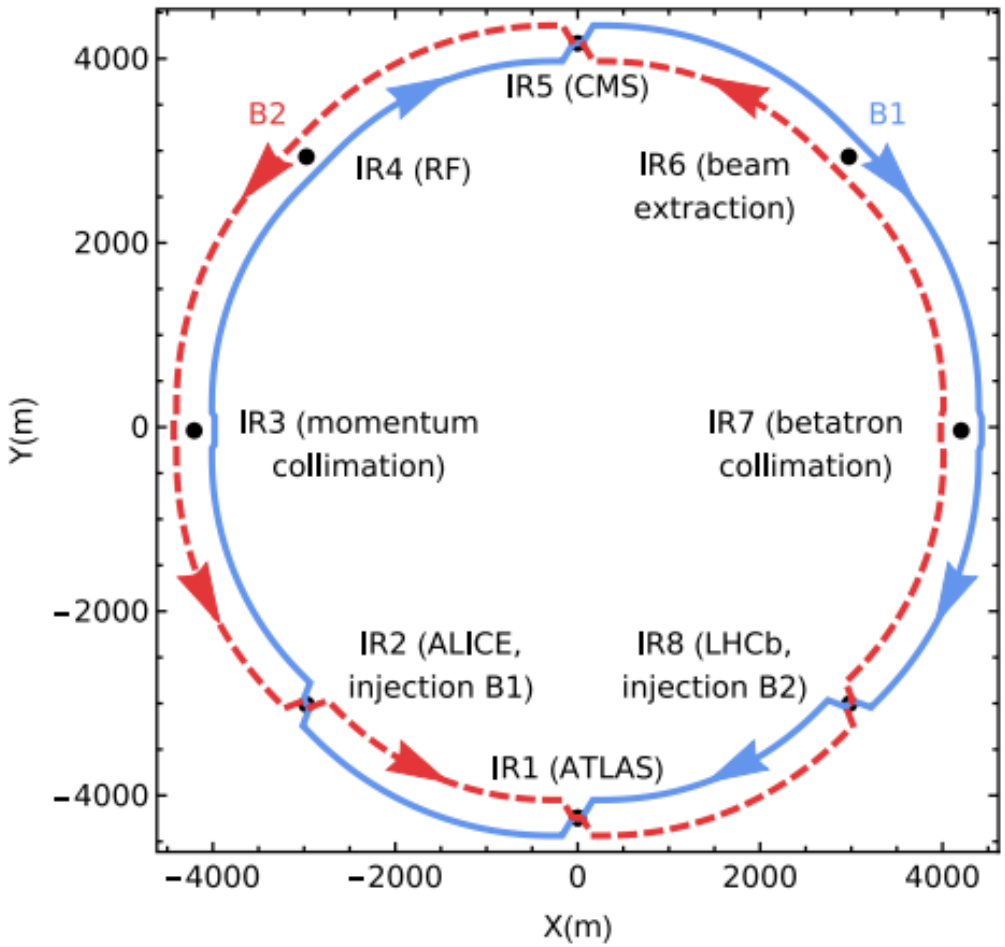
- Future performance and plans ← See next talk by Michaela

Large Hadron Collider

- LHC designed to collide both protons and nuclei
- 8 straight sections (4 with experiments) and 8 arcs



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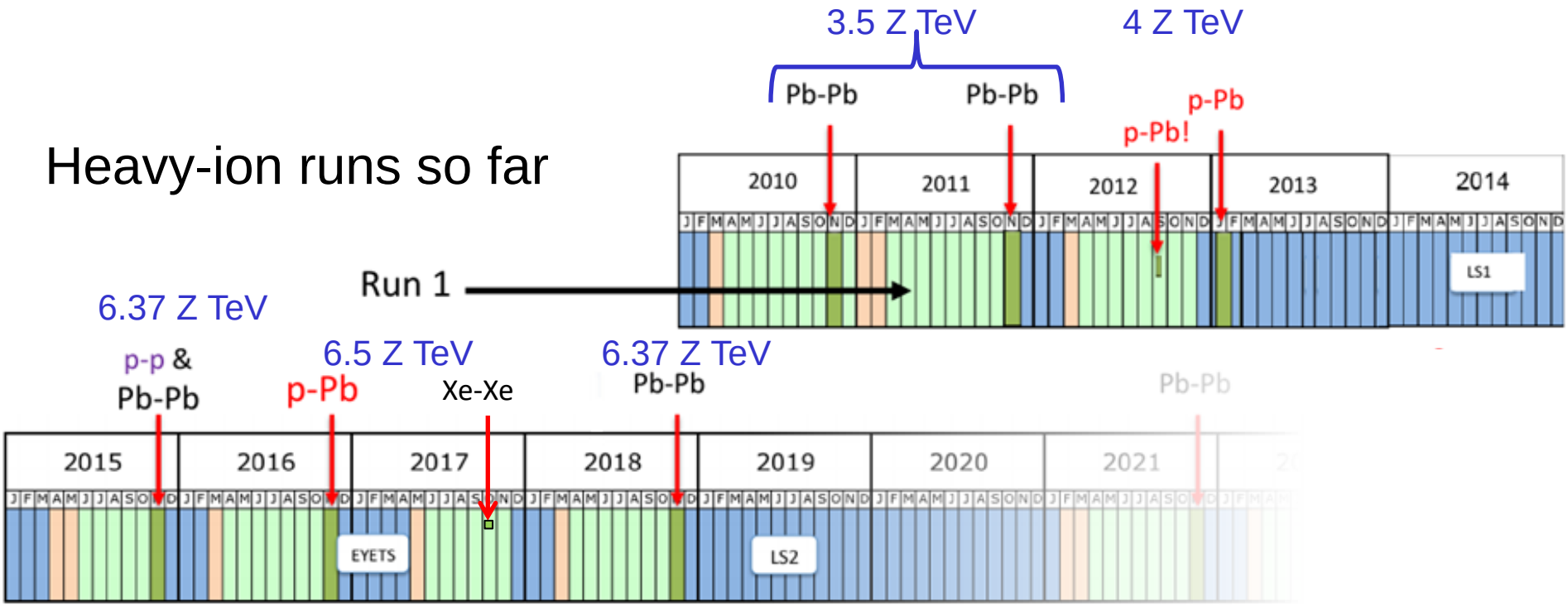
- So far: Pb-Pb runs at 3.5 Z TeV and 6.37 Z TeV, p-Pb runs at 4 Z TeV and 6.37 TeV

Heavy-ion runs so far



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Parameter for Pb beam	LHC design value	Achieved 2018
Beam energy	2.76 TeV / nucleon 7 Z TeV	2.51 TeV / nucleon 6.37 Z TeV
Bunch intensity	7E7	**2.3E8**
Number of bunches	592	733
Stored beam energy	3.8 MJ	13.9 MJ
Bunch spacing	50 ns	**75 ns**
Normalized emittance	1.5 μm	2.0 μm
β*	0.5 m	0.5 m
Number of collision points	1	4
Peak luminosity (Pb-Pb)	1E27 cm^{-2} s^{-1}	**6.4E27 cm^{-2} s^{-1}**
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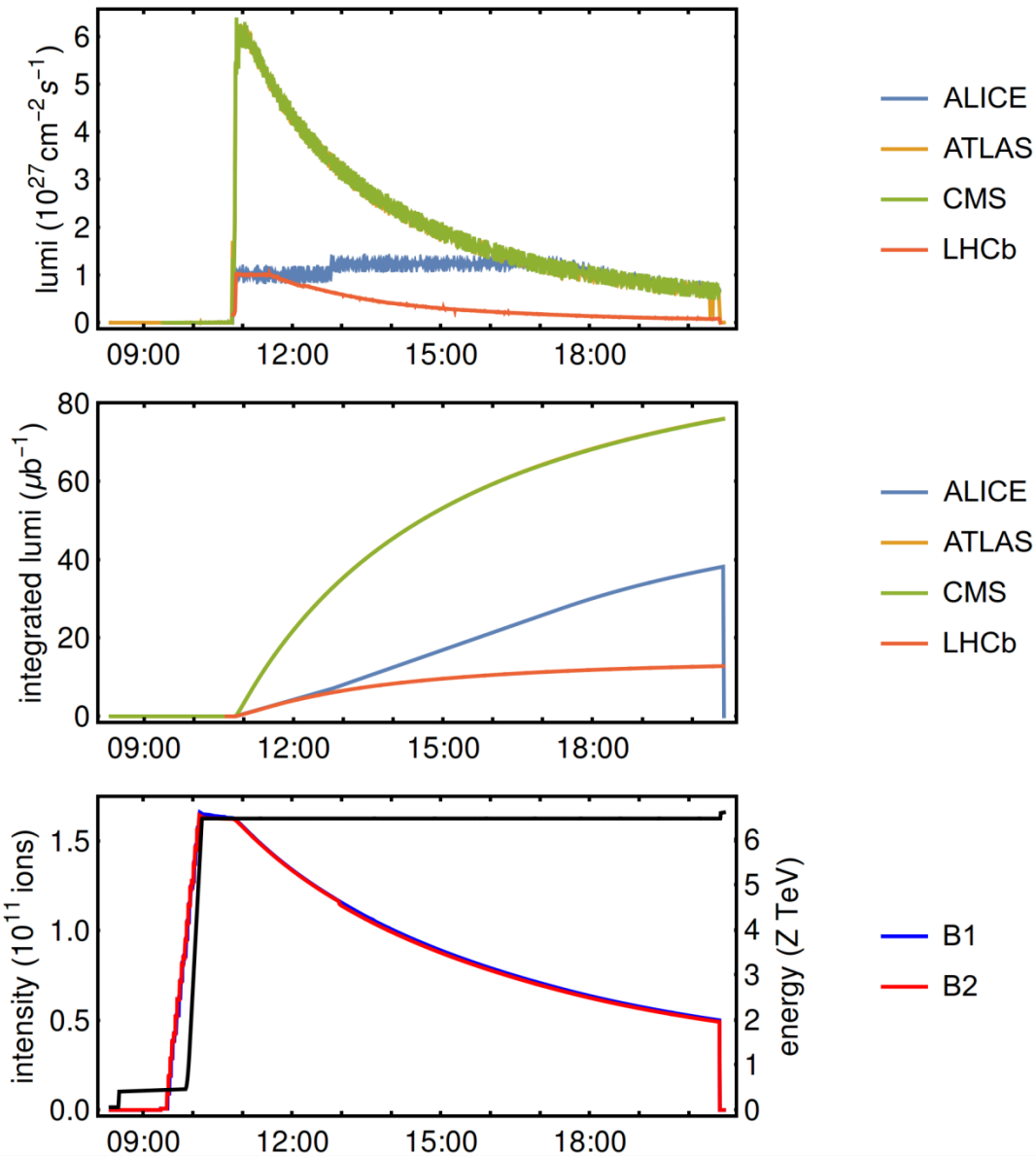
- In addition: p-Pb : new mode of operation not foreseen in LHC design

Typical LHC Pb-Pb fill in 2018

- Leveling in ATLAS and CMS gradually increased to 6E27 $cm^{-2}s^{-1}$
- ALICE leveled at design luminosity 1E27 $cm^{-2}s^{-1}$



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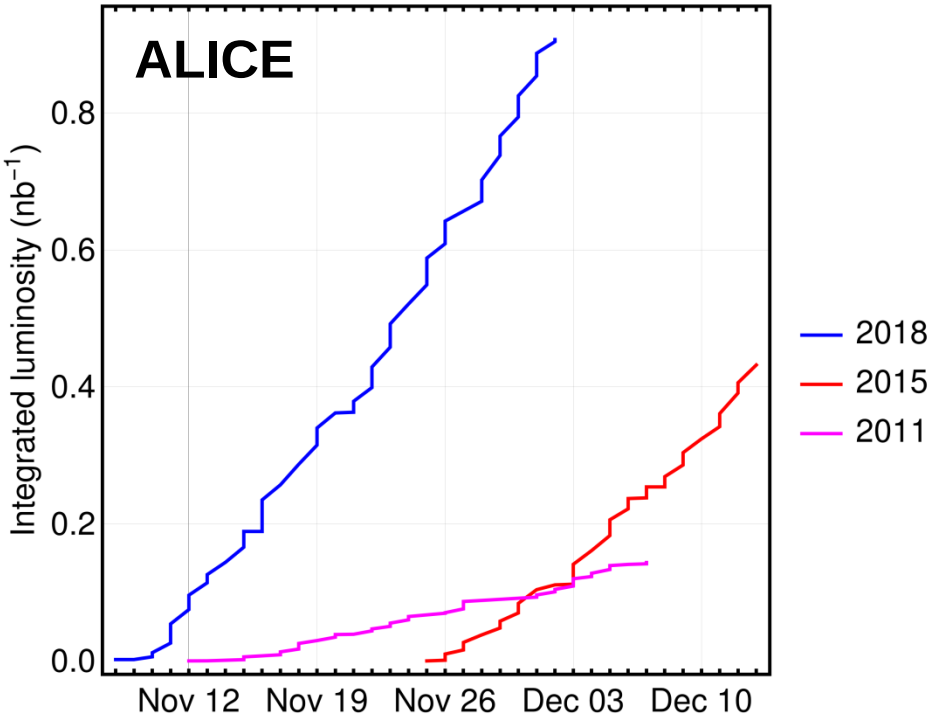

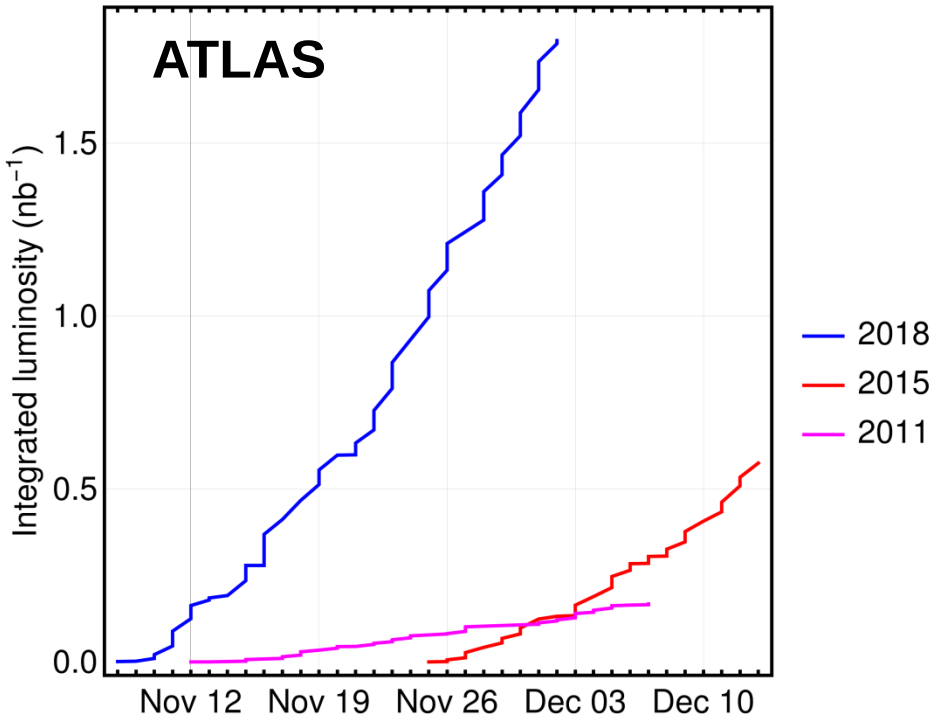

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- Achieved in total 2.5 nb^{-1} in ATLAS/CMS, in 1.5 nb^{-1} ALICE and 0.26 nb^{-1} in LHCb over all Pb-Pb runs
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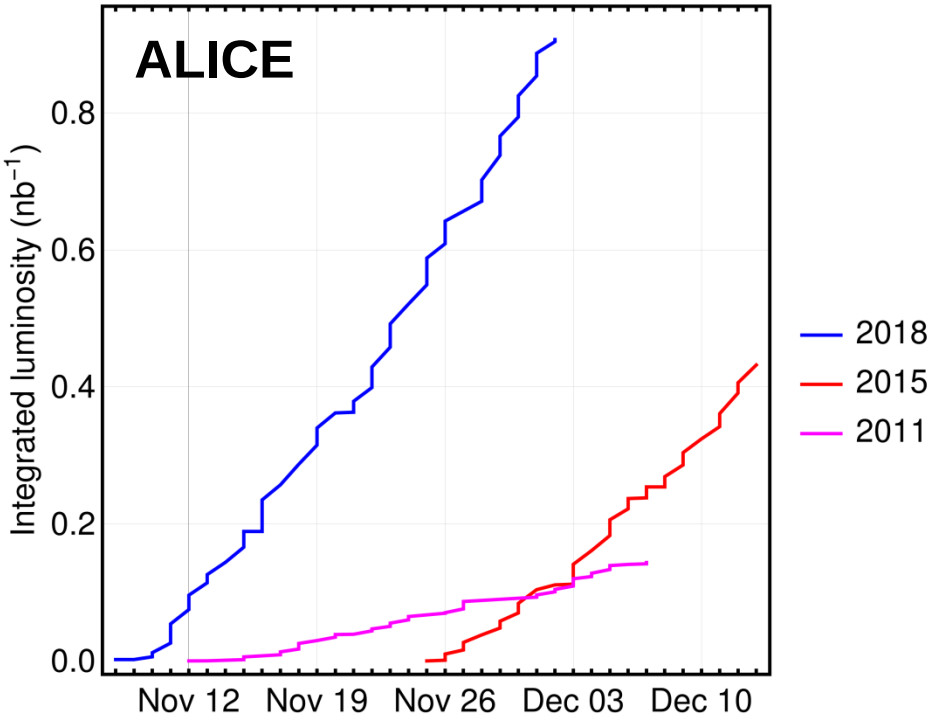

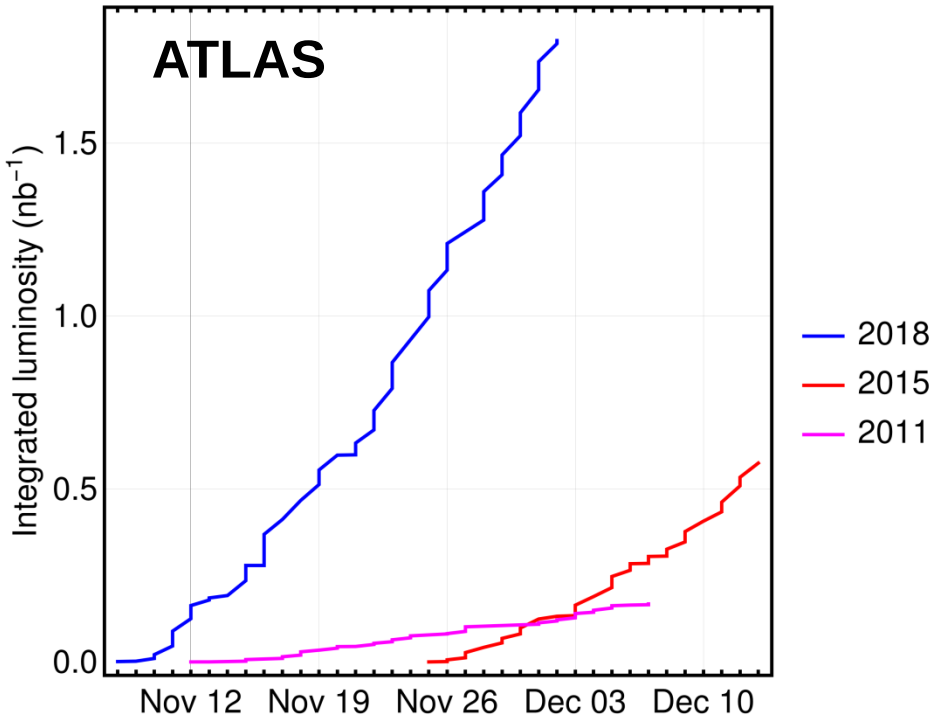

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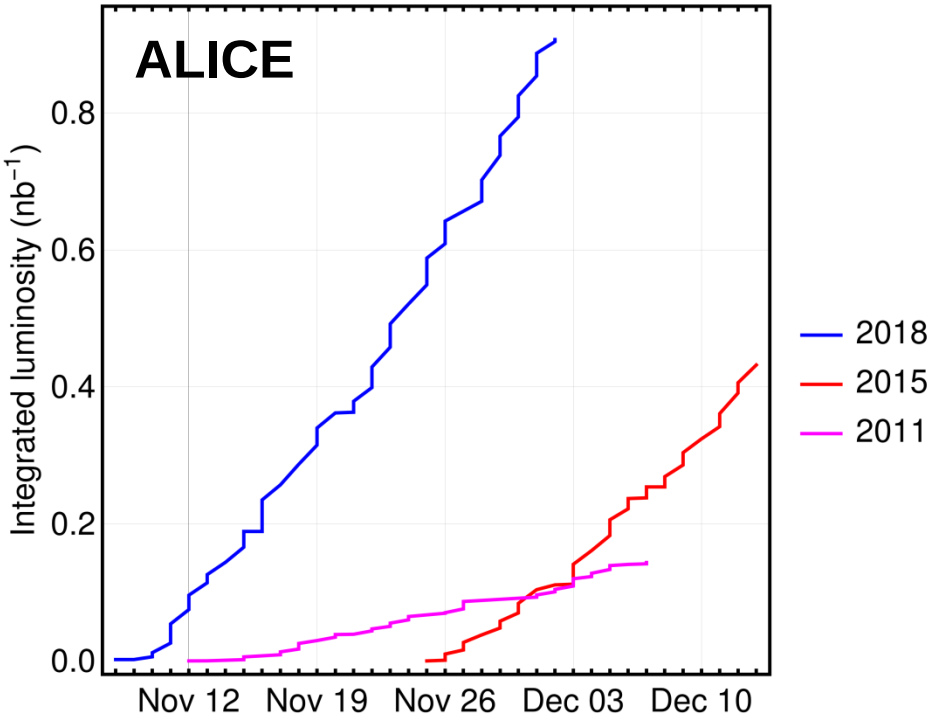
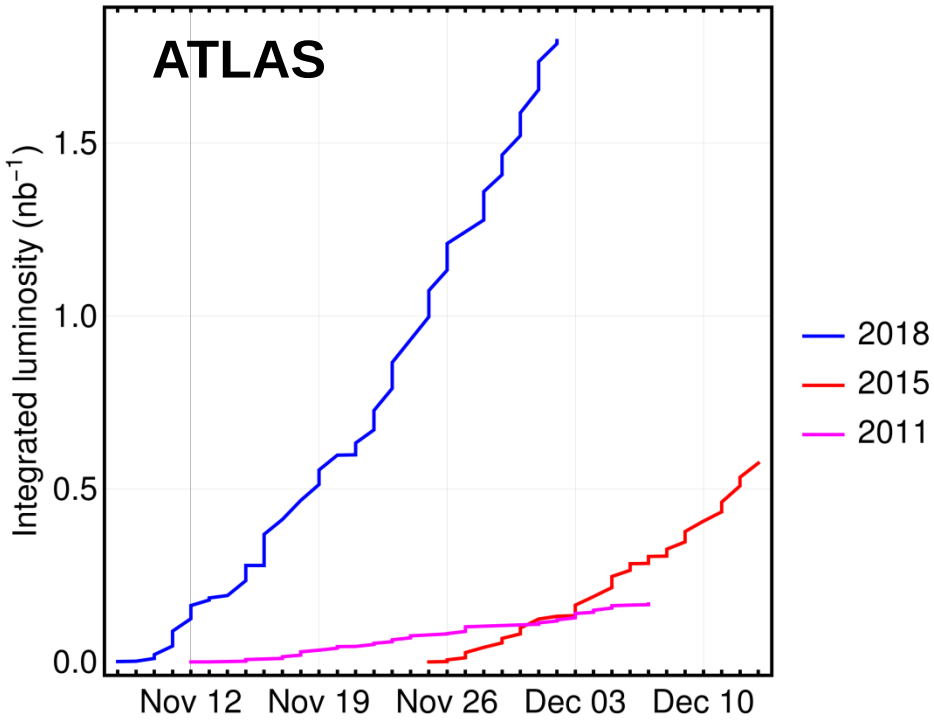
- 2018: best year so far





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Cross sections for Pb-Pb collisions at 2.76 TeV / nucleon

Process	Cross section (b)
Bound-free pair production	281
Electromagnetic dissociation	226
Hadronic nuclear inelastic	8
Total	515

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- All these processes create unwanted beam losses

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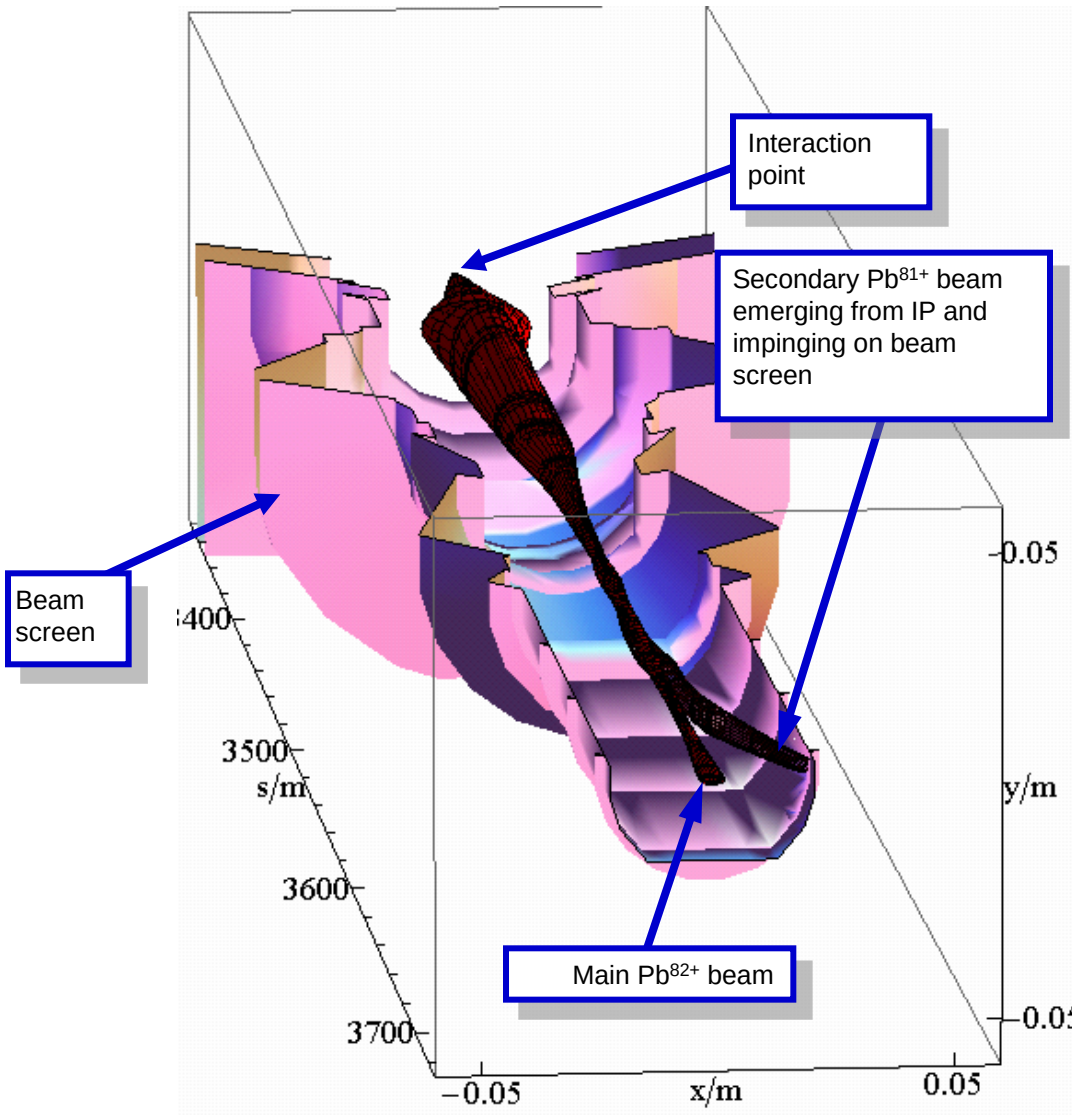

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  - 25 W beam for nominal LHC conditions
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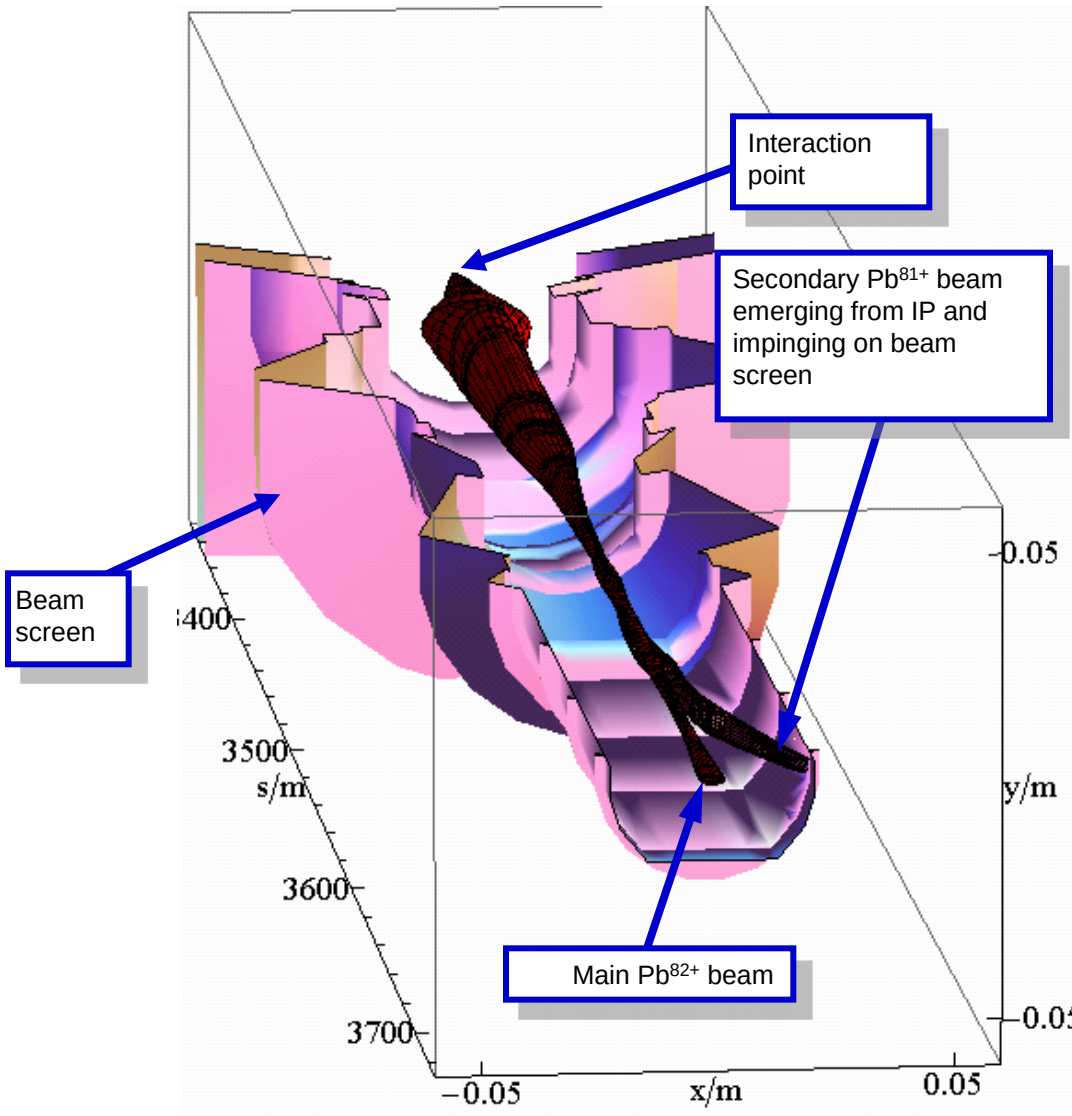
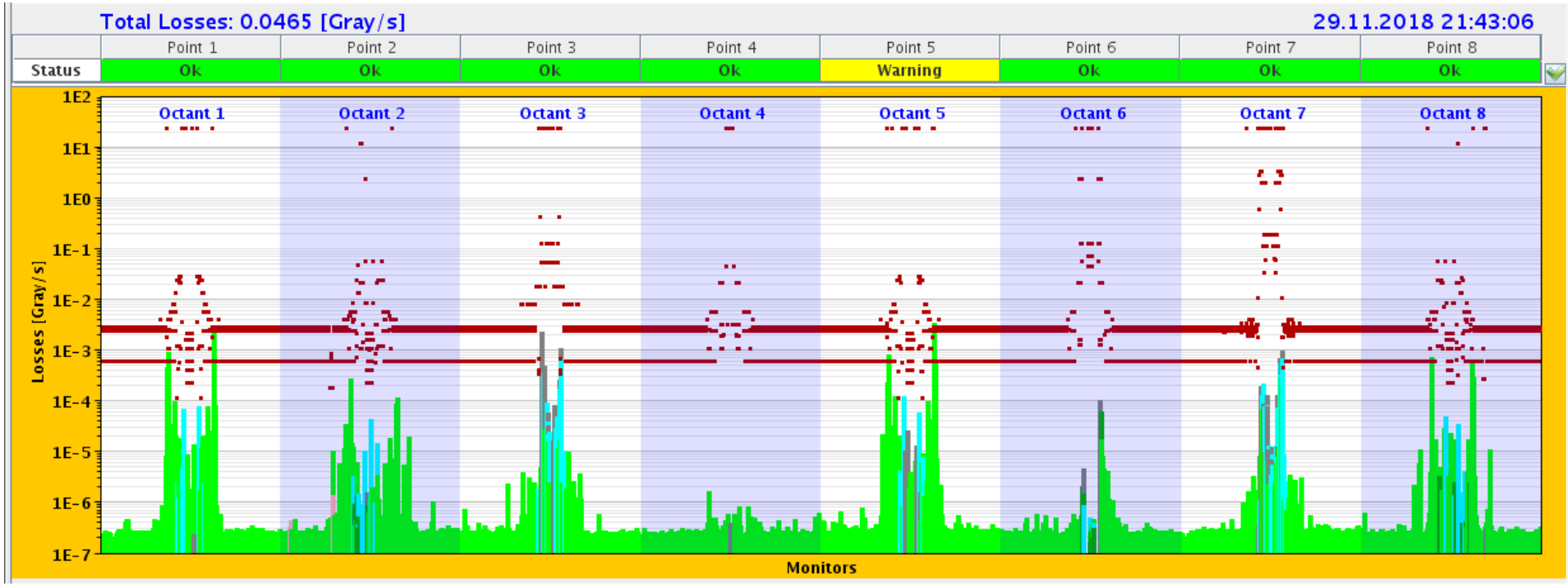
- Puts upper limit on luminosity
  - Limit found experimentally at 2.3E27 $cm^{-2}s^{-1}$ in IR5.
  - Could be different at different magnets / IRs



Observations of BFPP during operation



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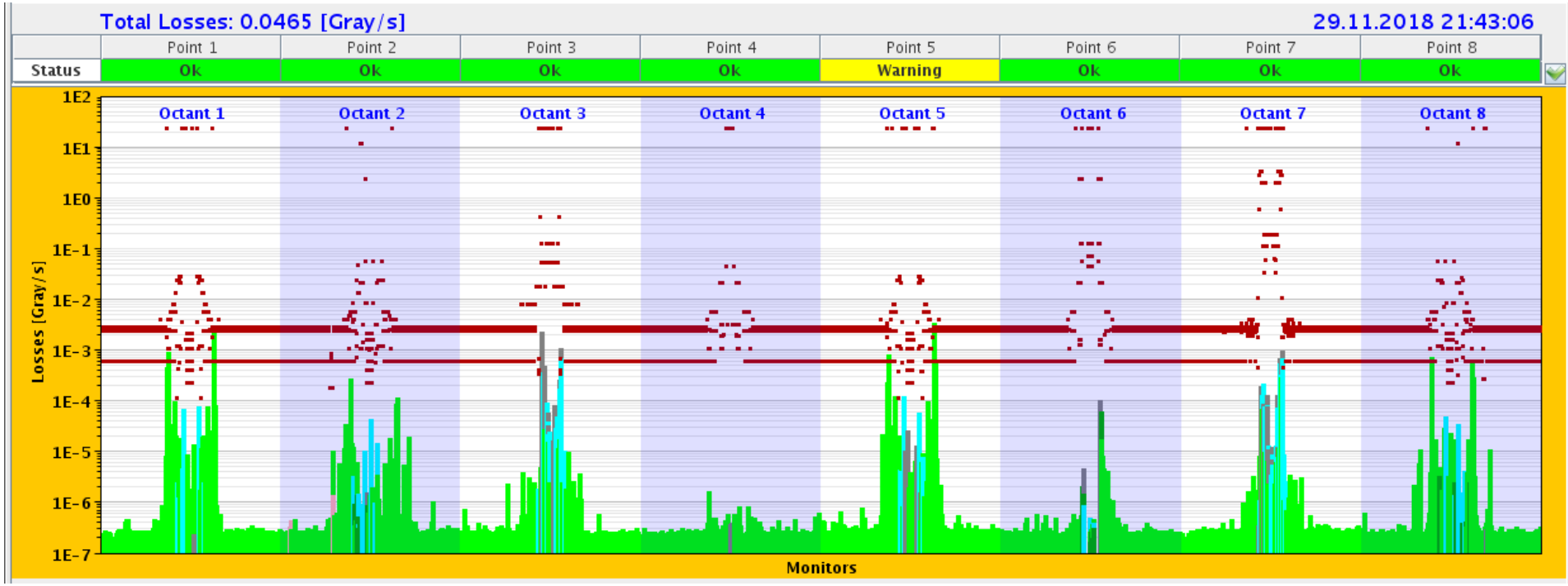

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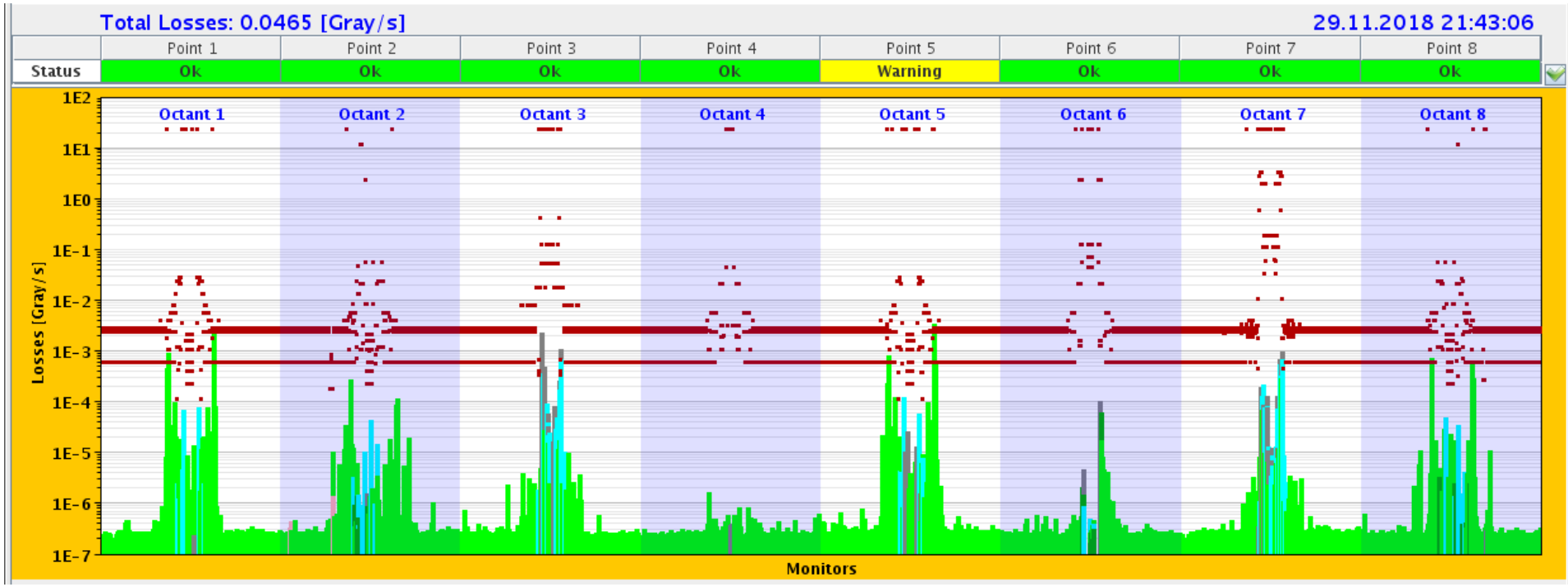

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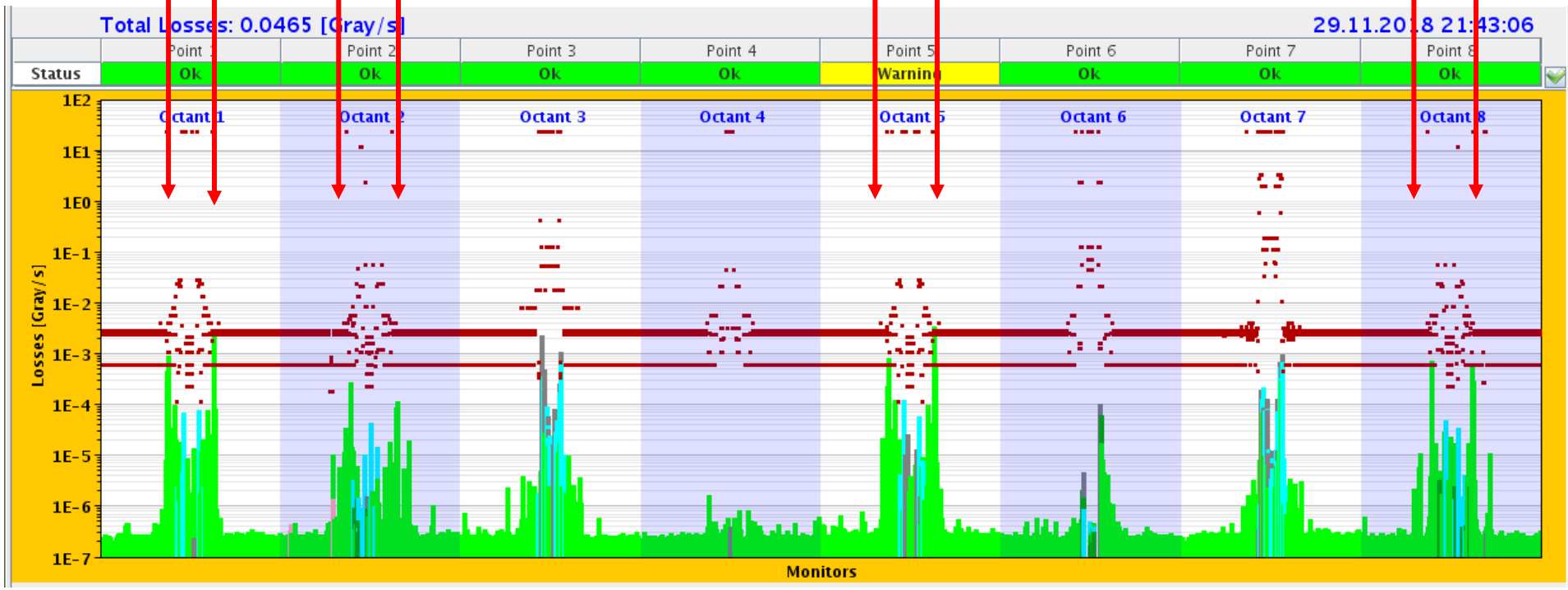

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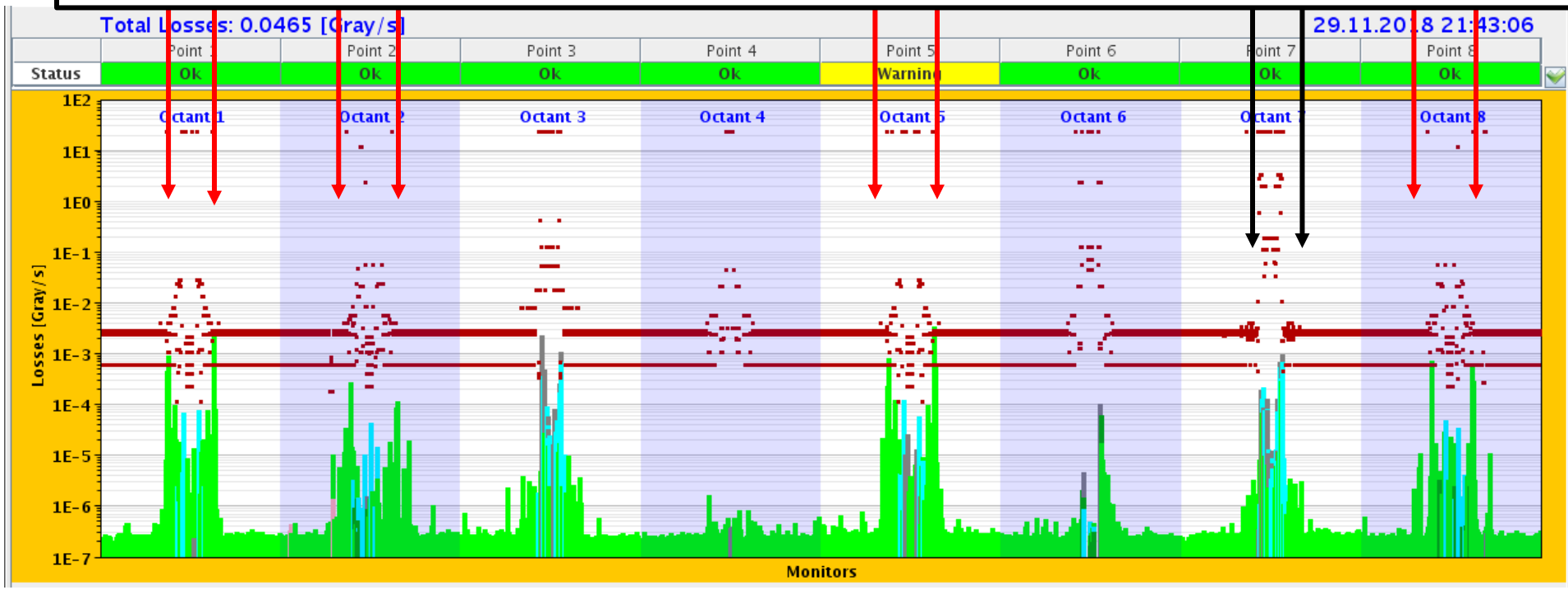

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IBS & Electromagnetic dissociation at IPs, taken up by momentum collimators

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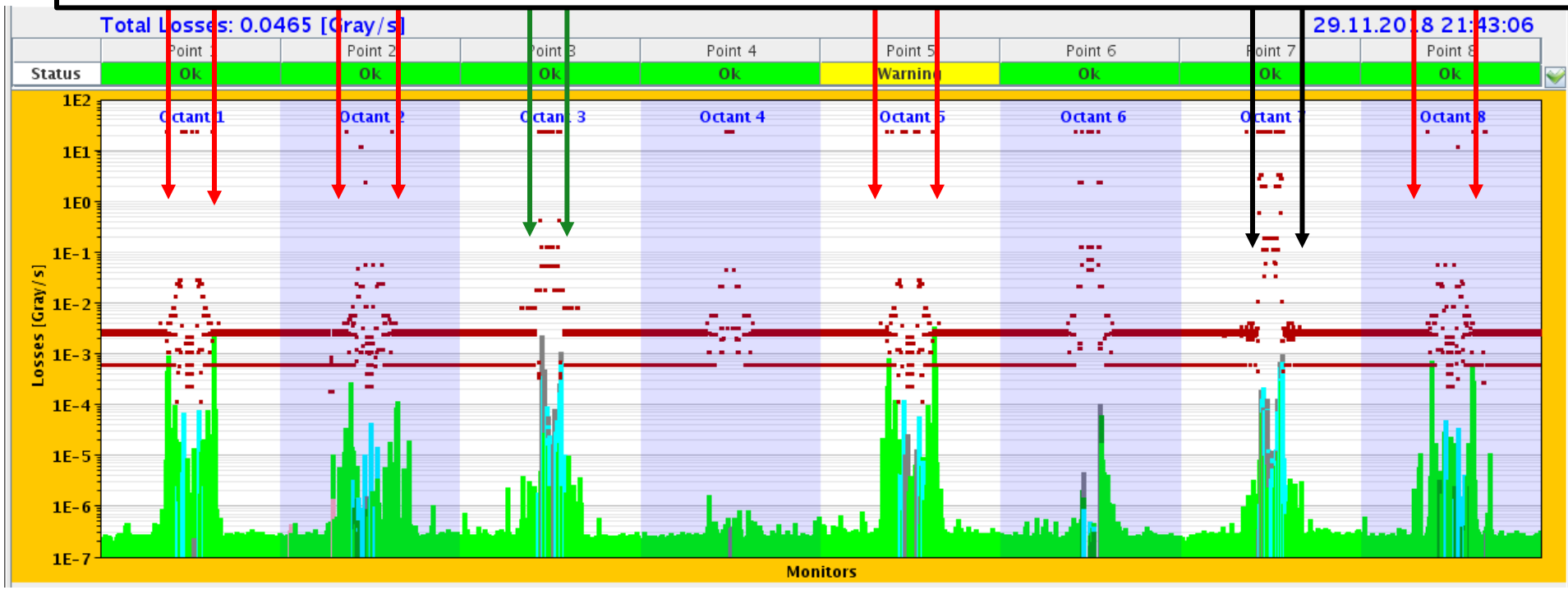

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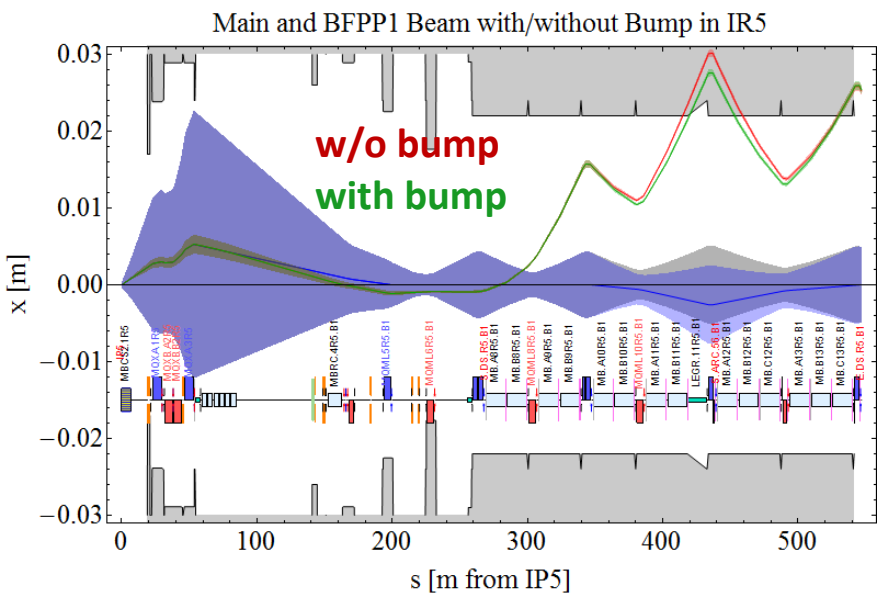

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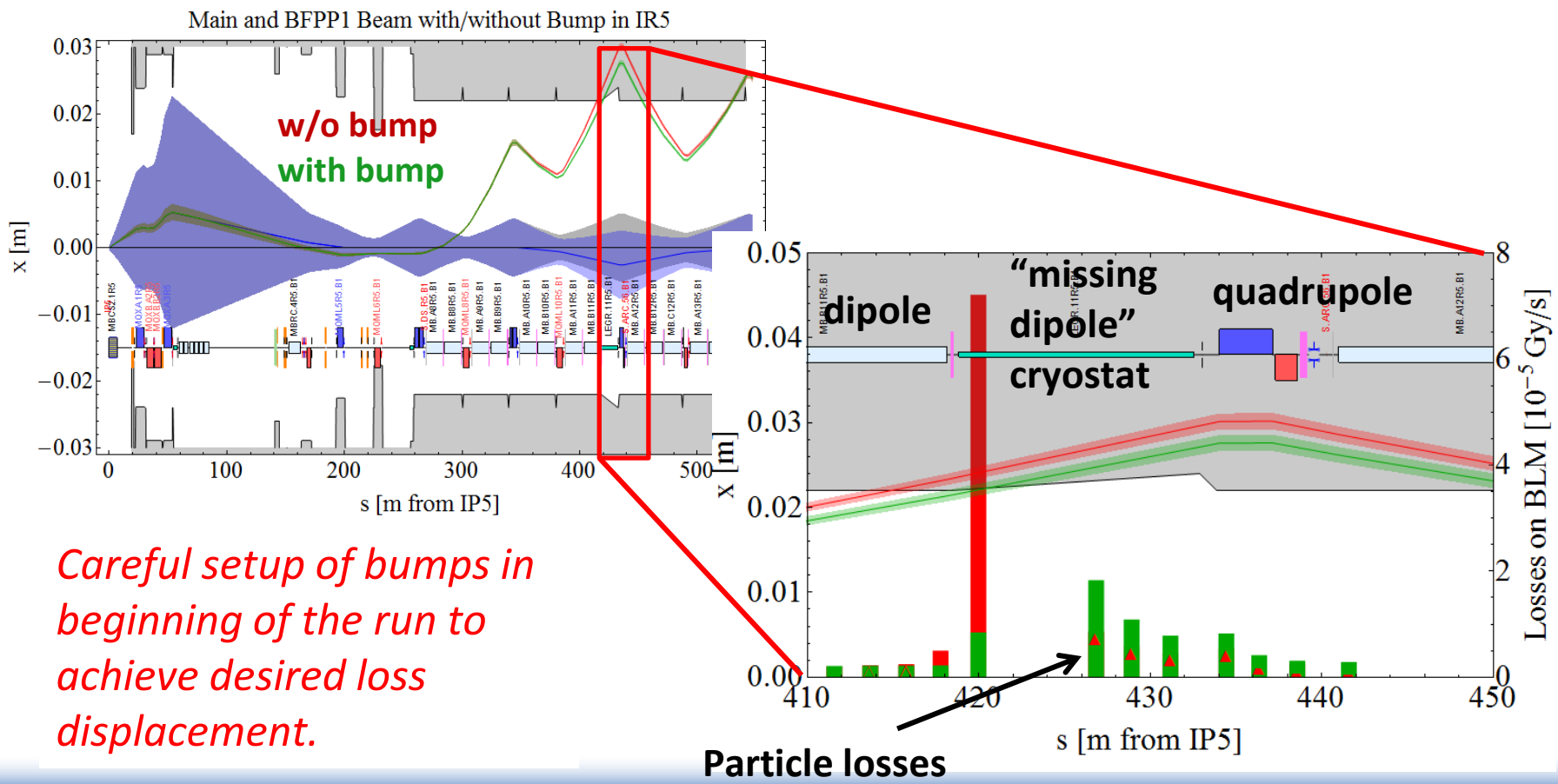

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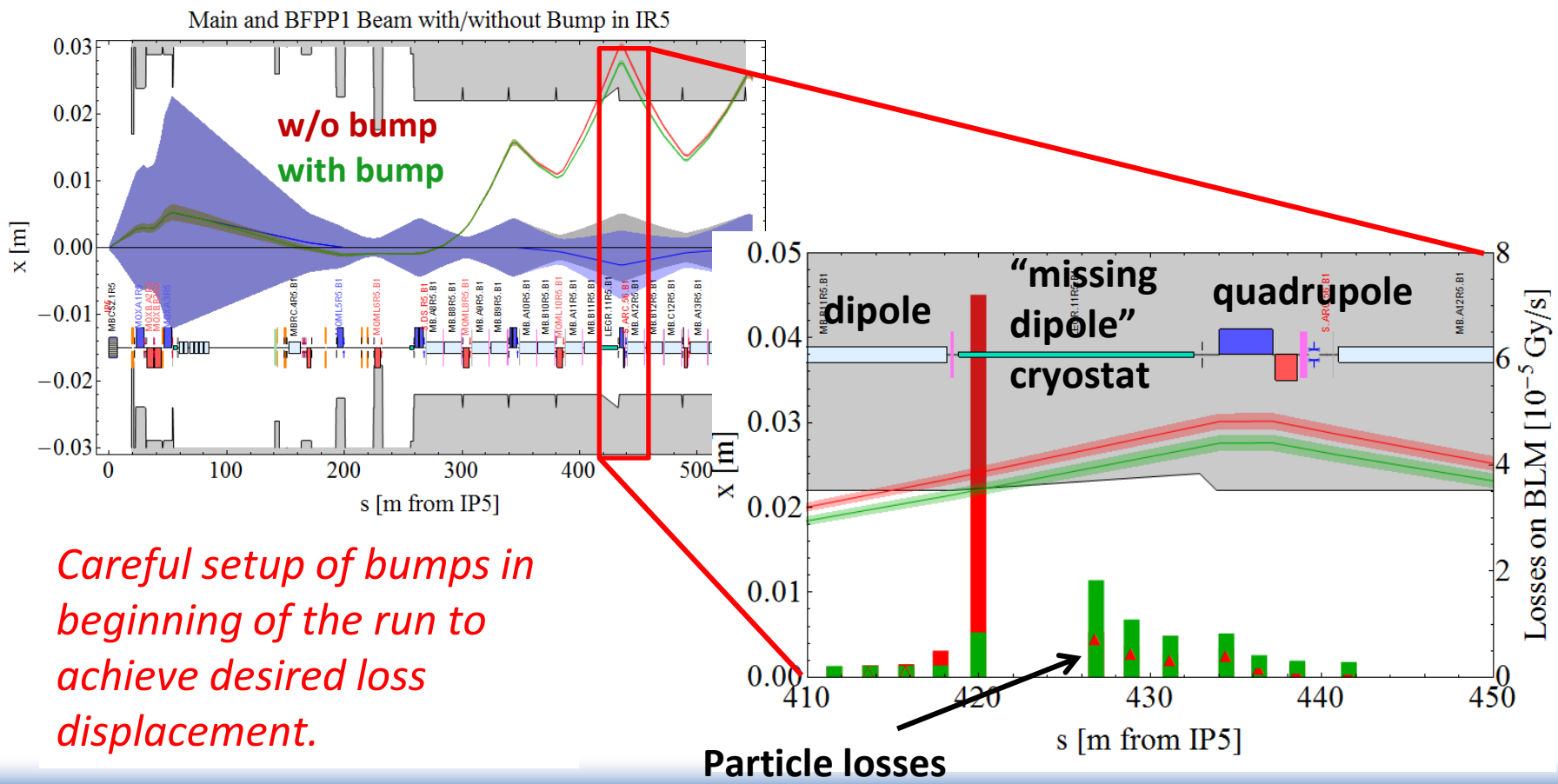
- With bumps, achieved ~6E27 $cm^{-2}s^{-1}$ in ATLAS / CMS



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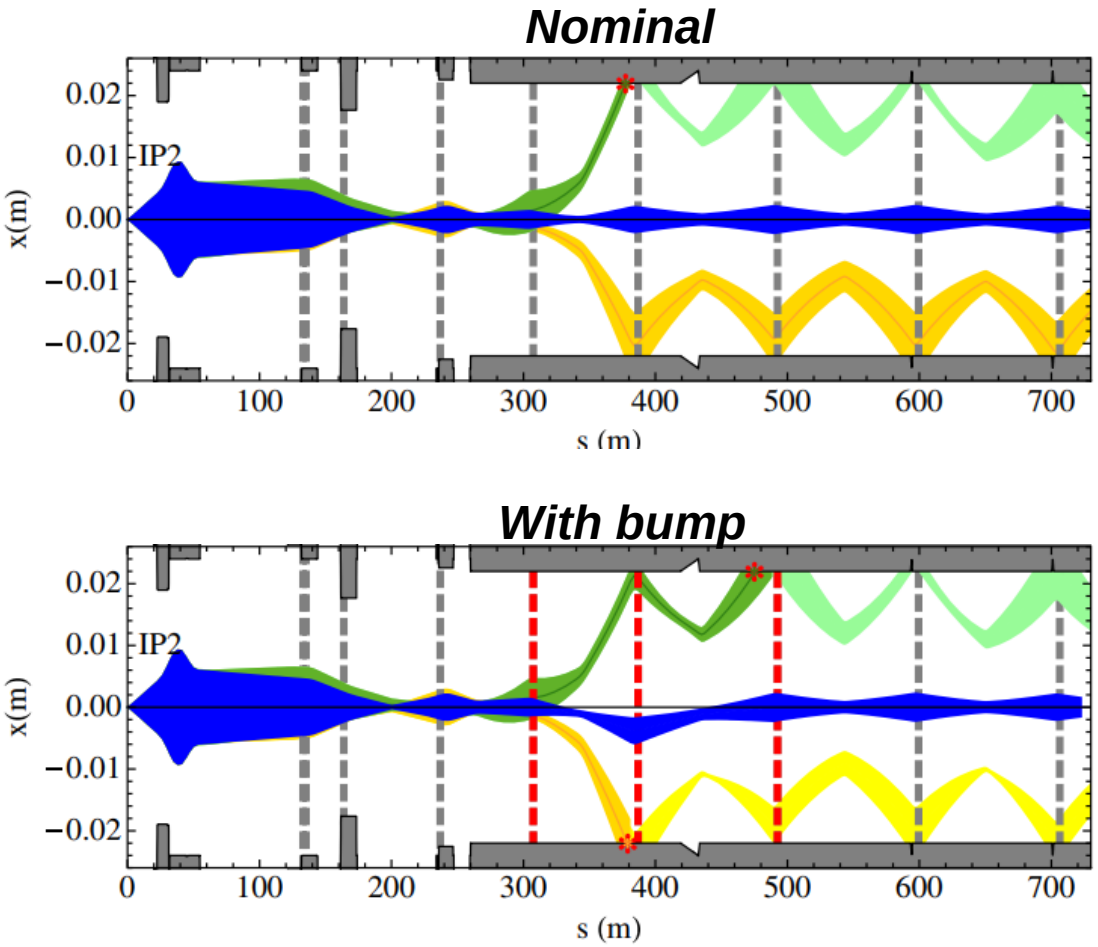

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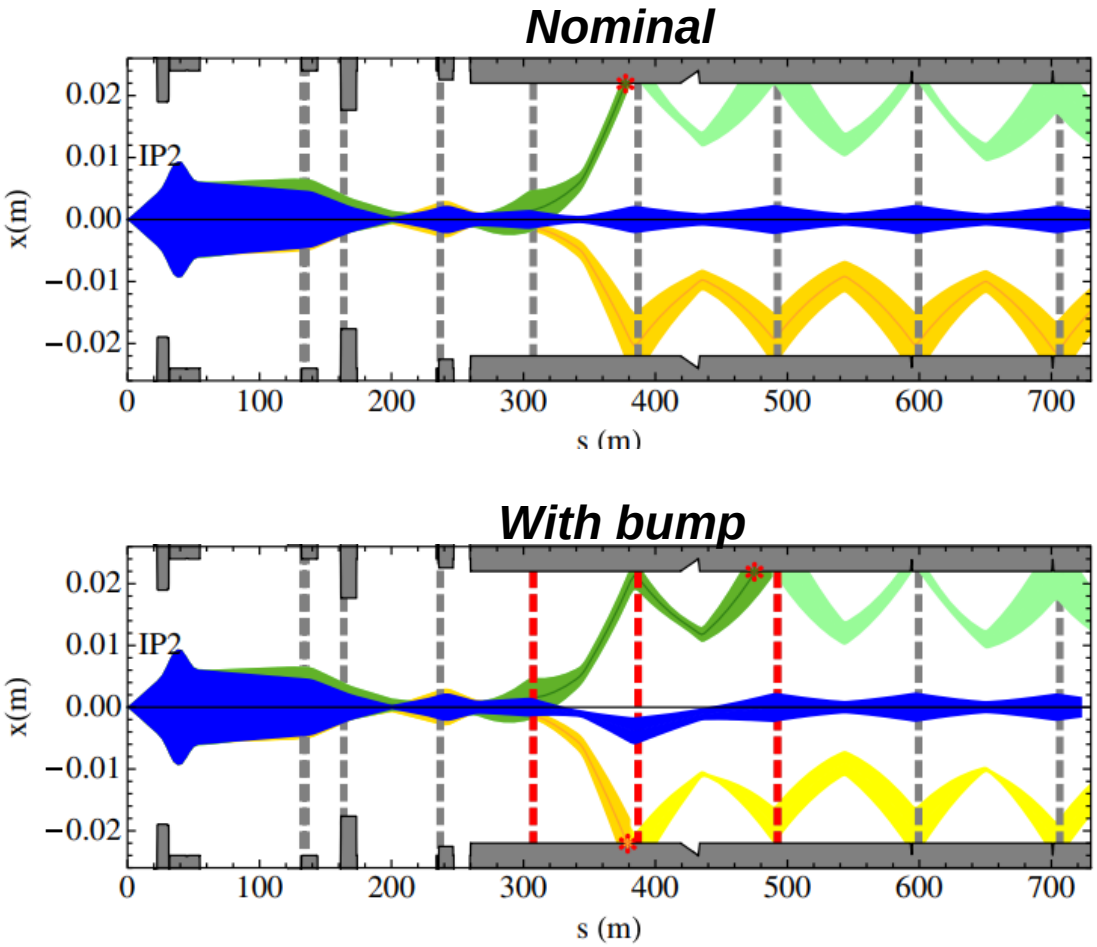
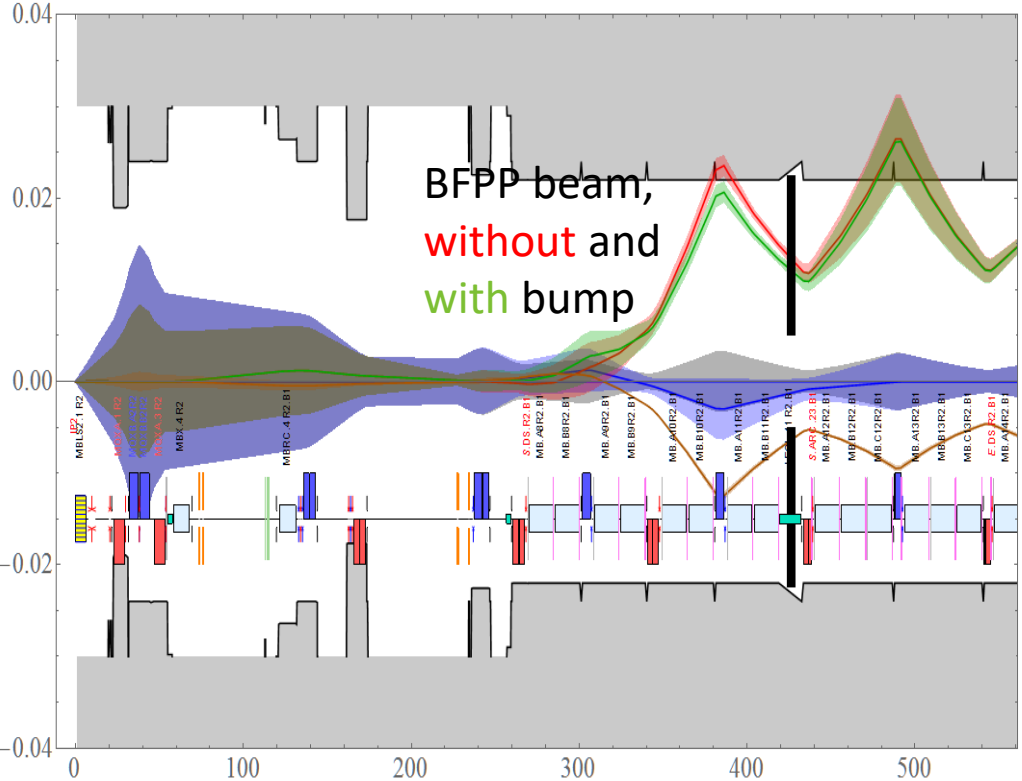
- Use orbit bump to distribute losses between different magnets
  - Upper luminosity limit not investigated experimentally
- ALICE anyway leveled at 1E27 $cm^{-2}s^{-1}$
  - Too high event rate for detector otherwise
  - ALICE upgrade foreseen in LS2



Future alleviation: extra collimators



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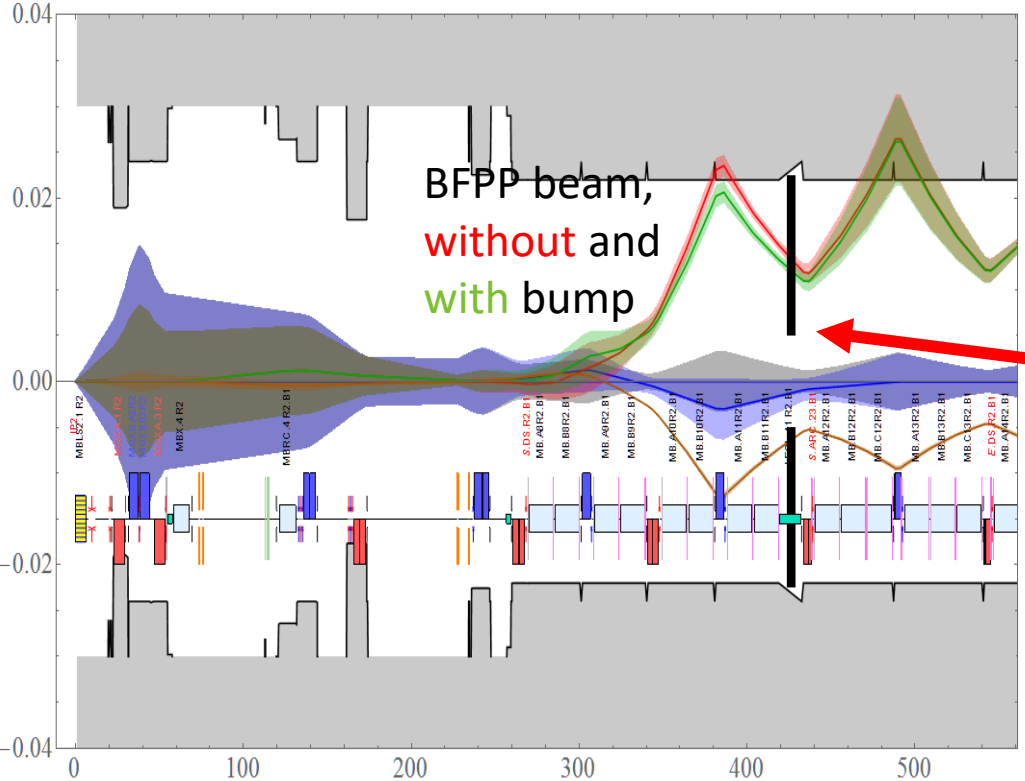

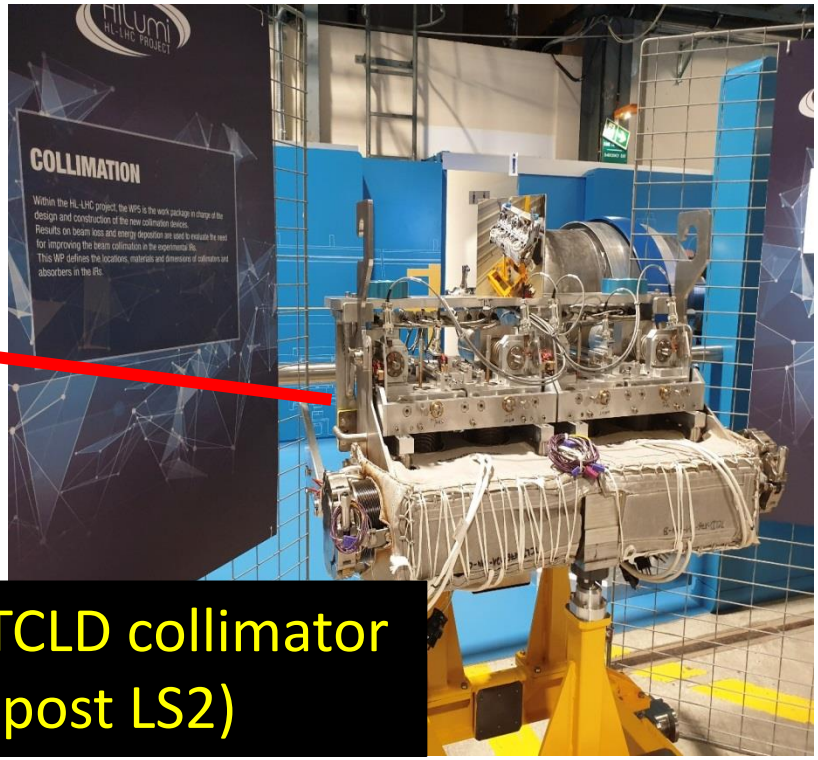

TCLD collimator (post LS2)

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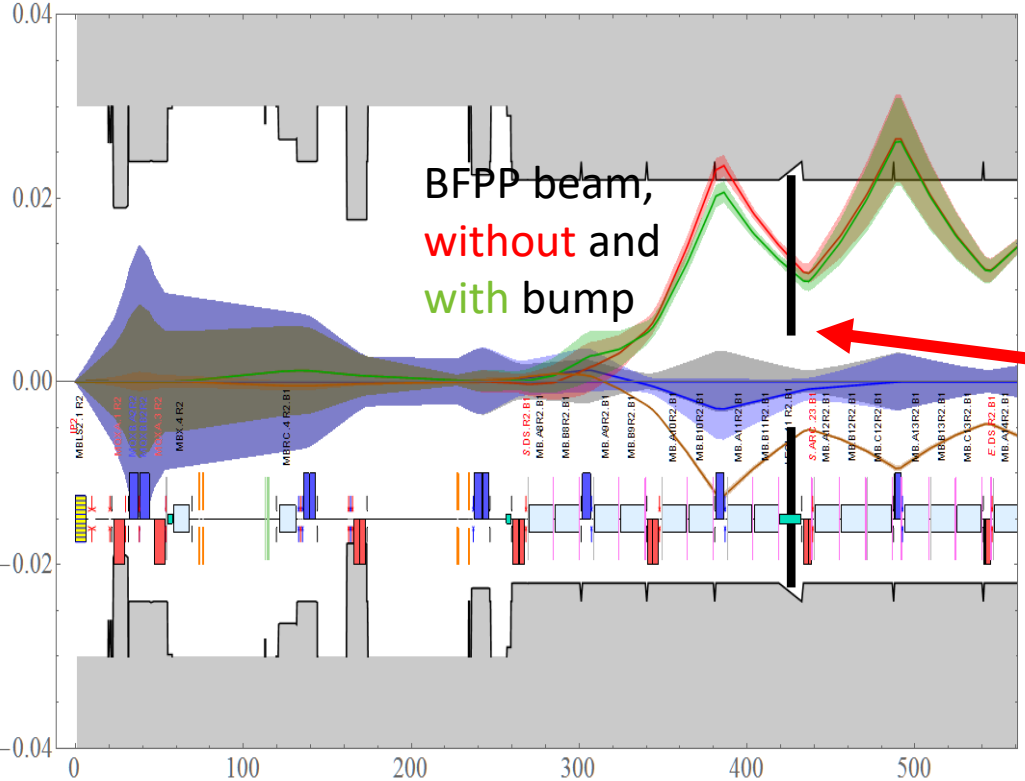

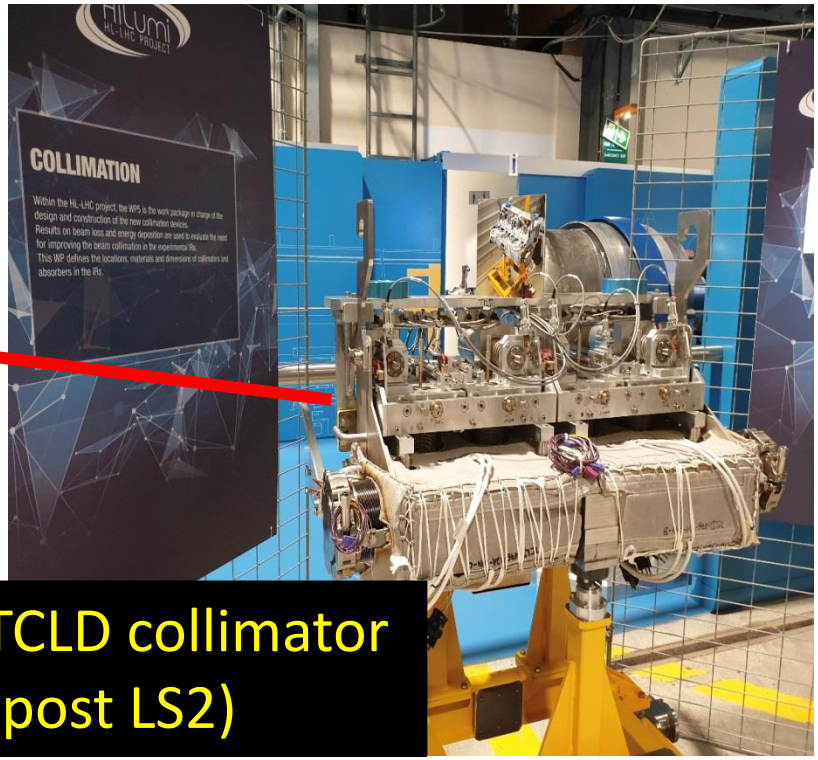

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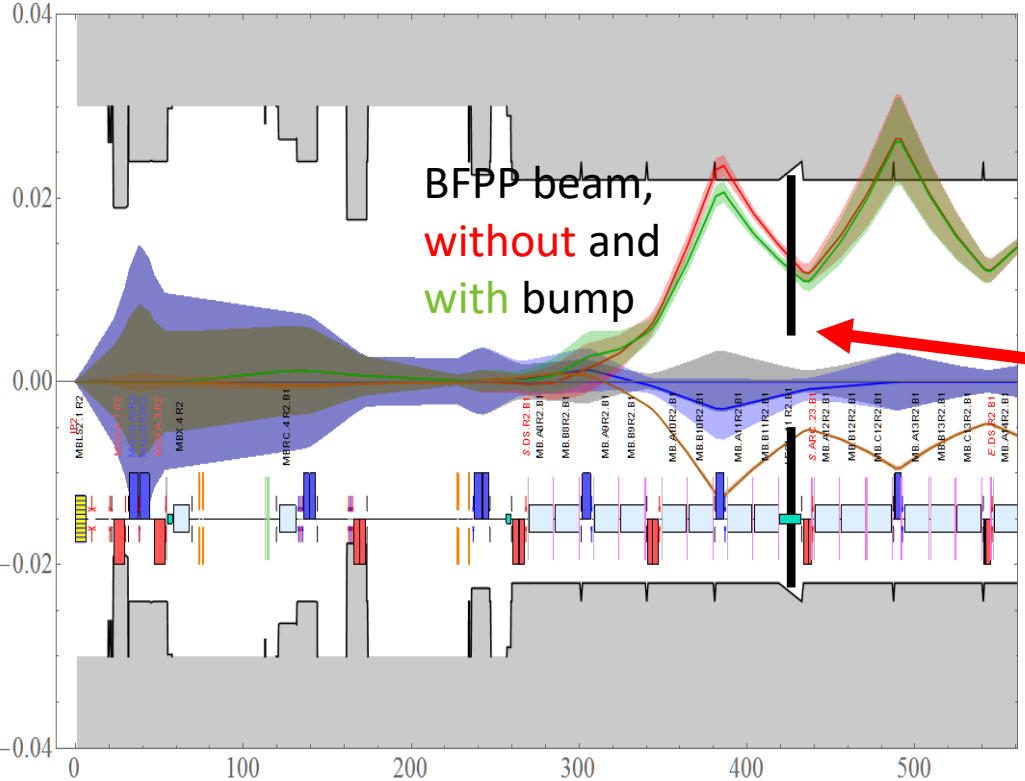

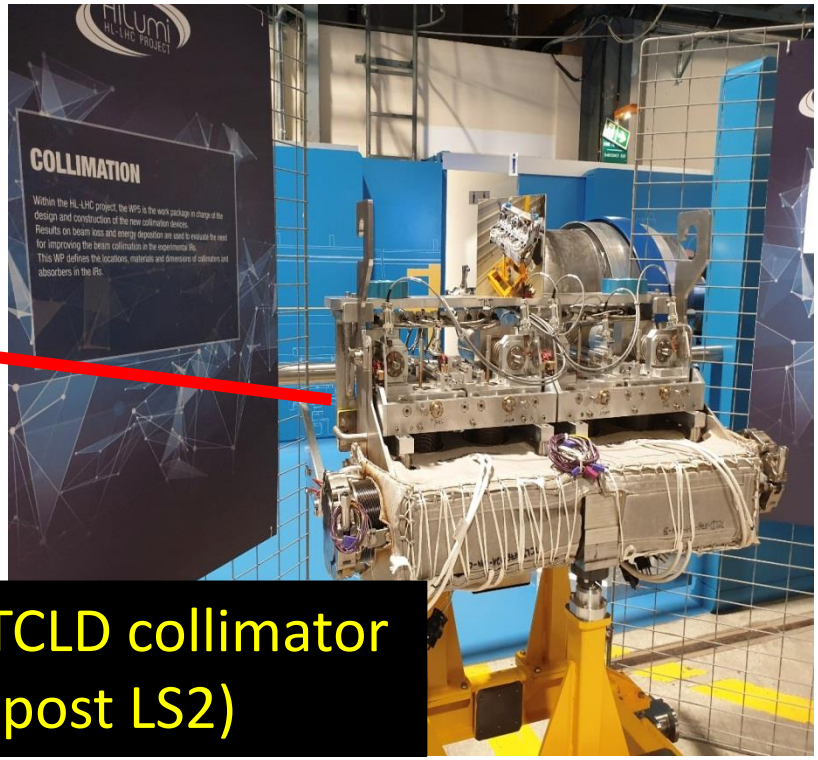

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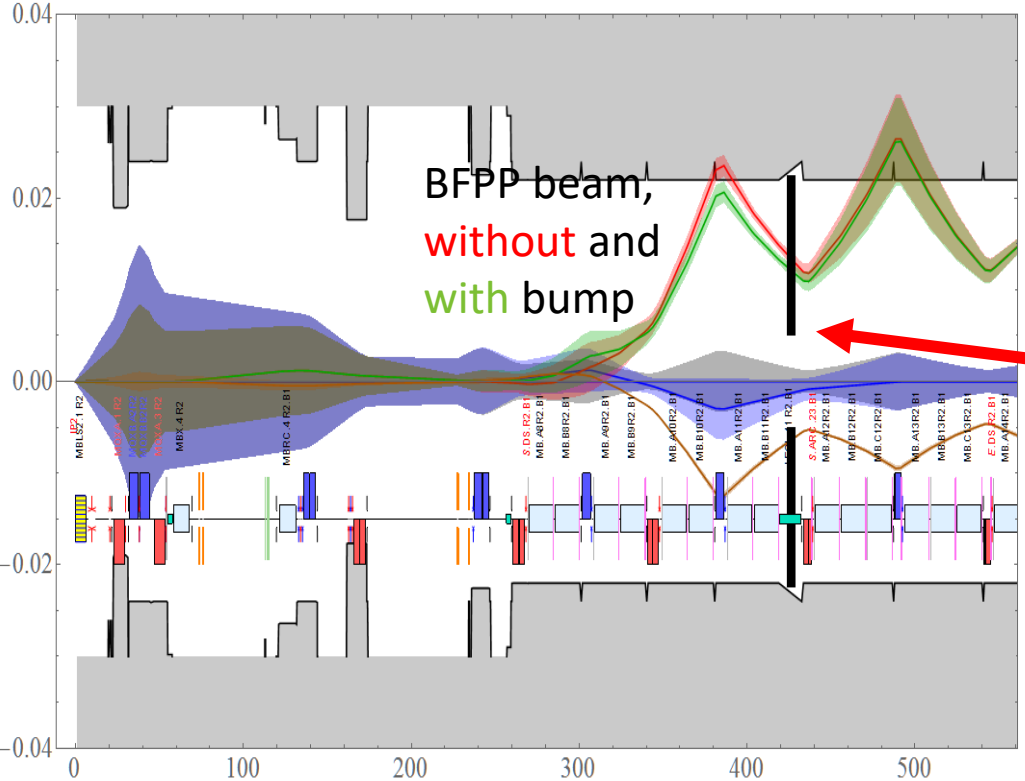

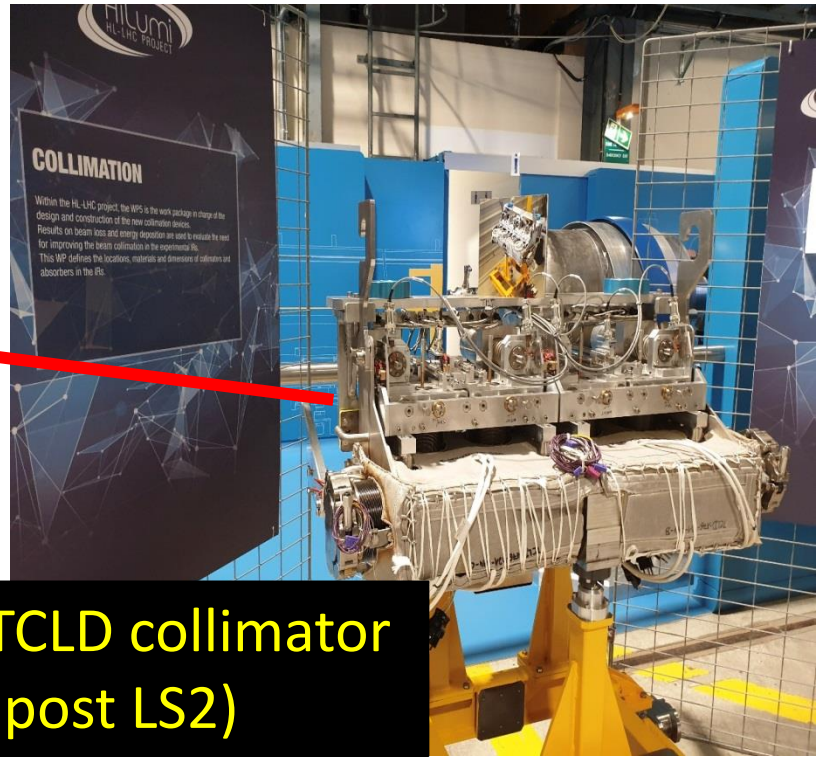

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- TCLDs should allow luminosity increase for upgraded ALICE to run at 50 kHz

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  - Even a tiny beam loss in a magnet could cause a quench or even damage
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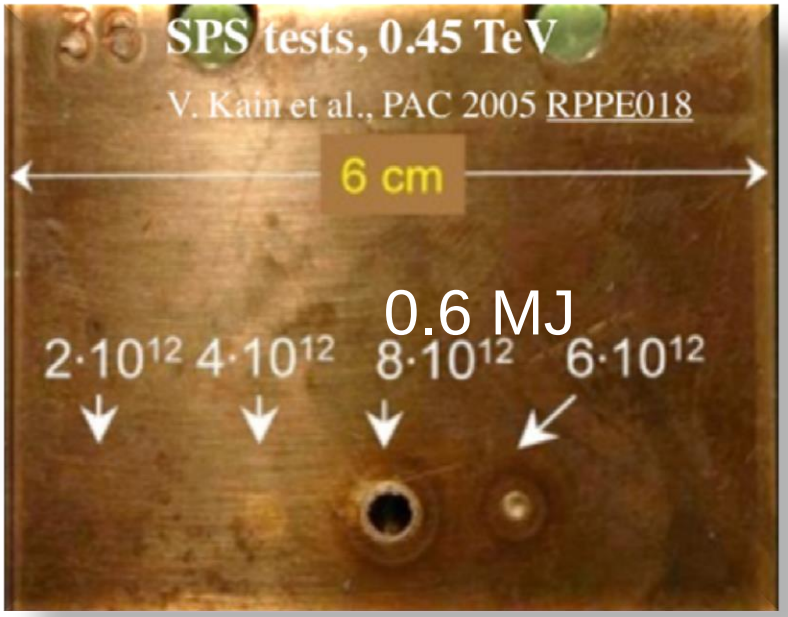

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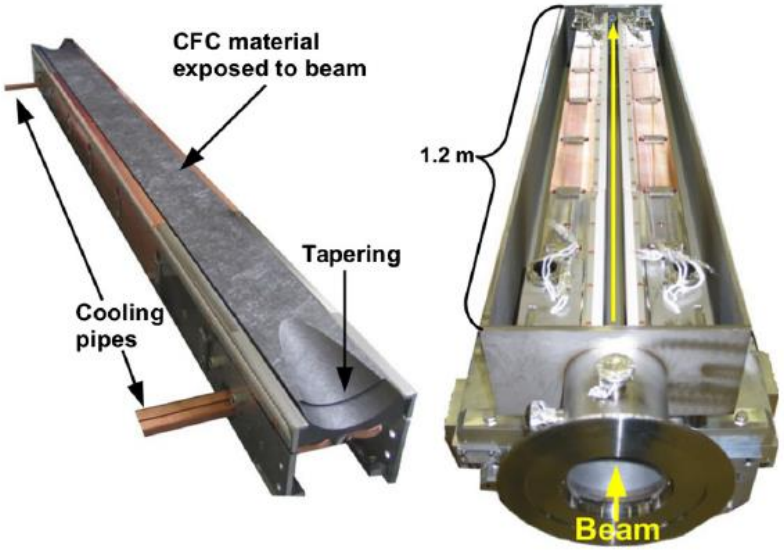

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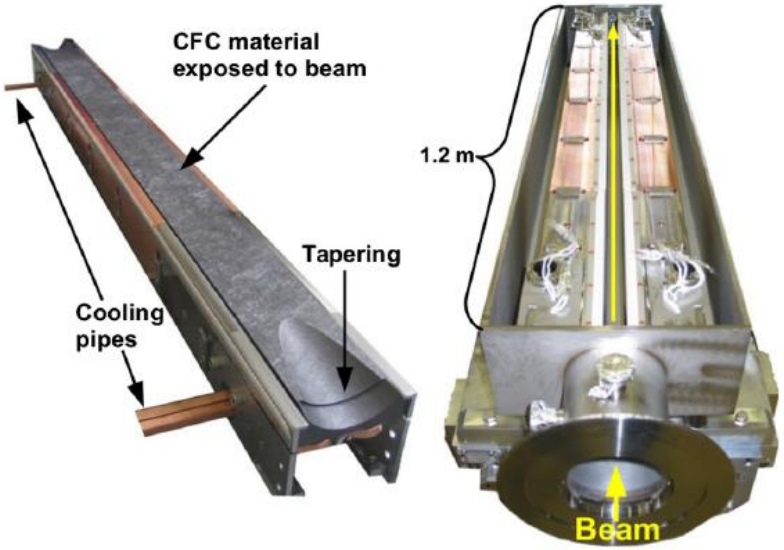

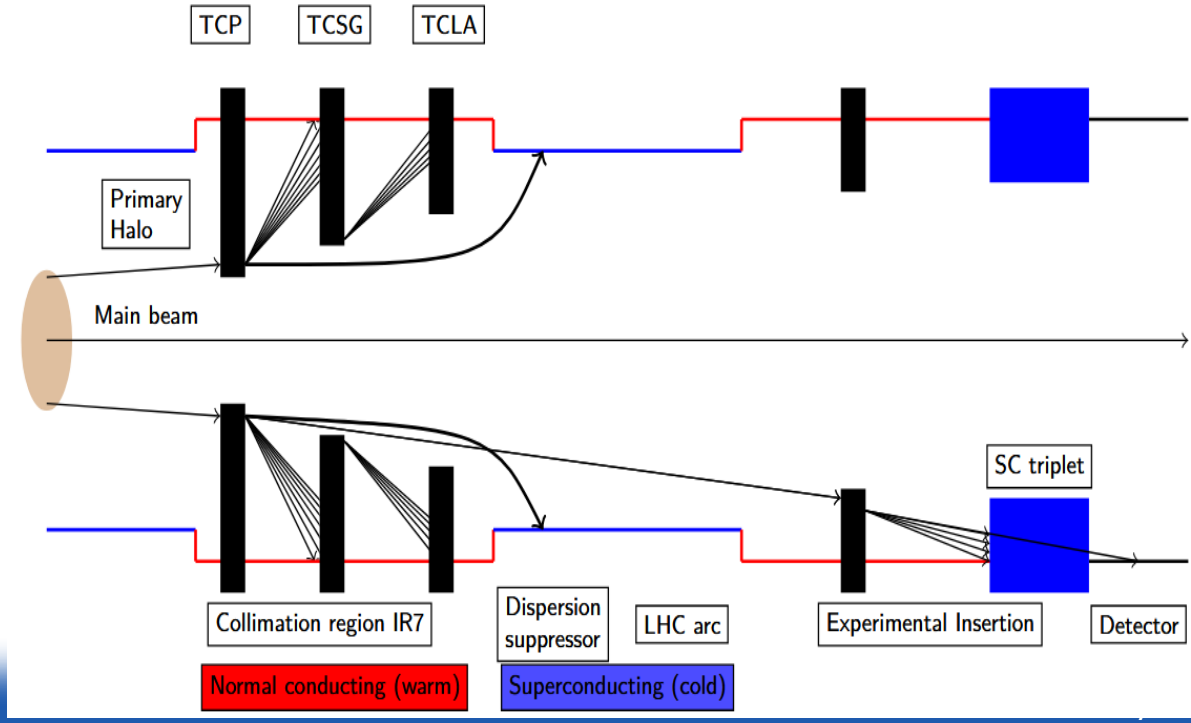

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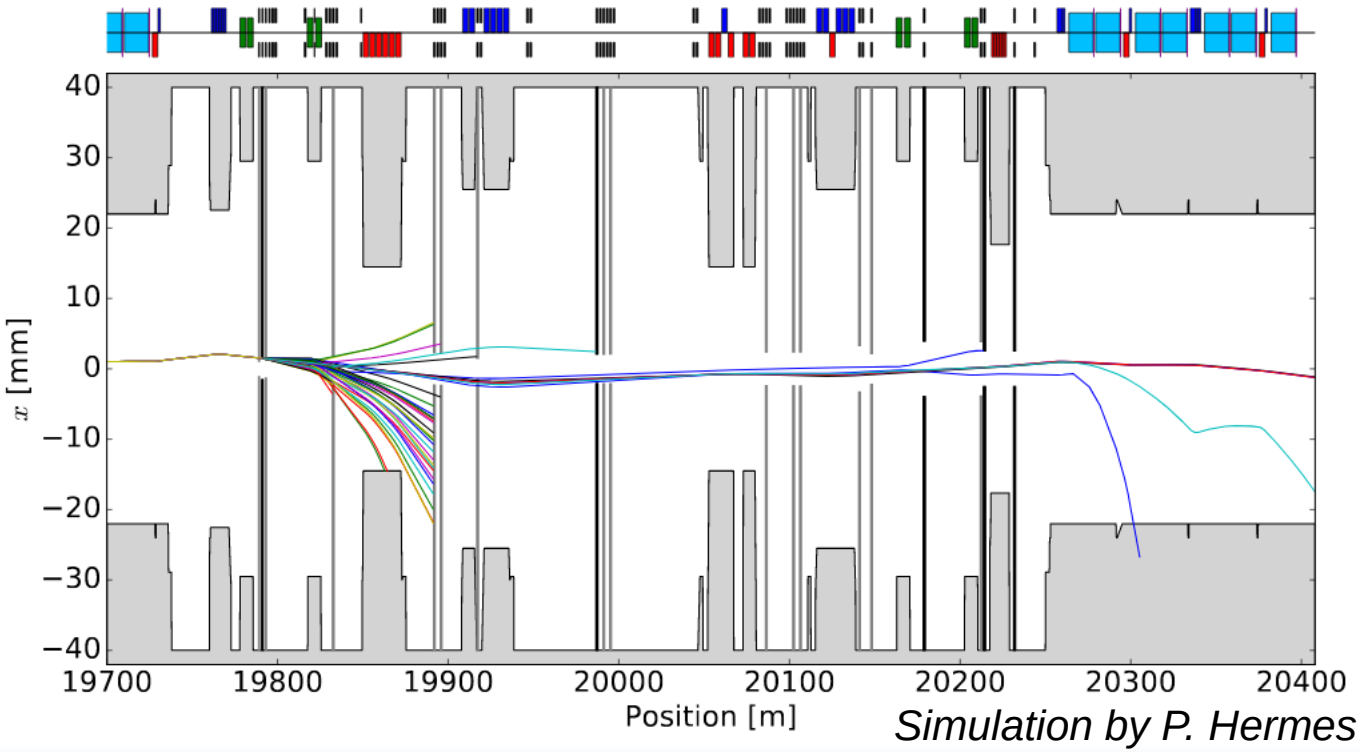

Simulation by P. Hermes

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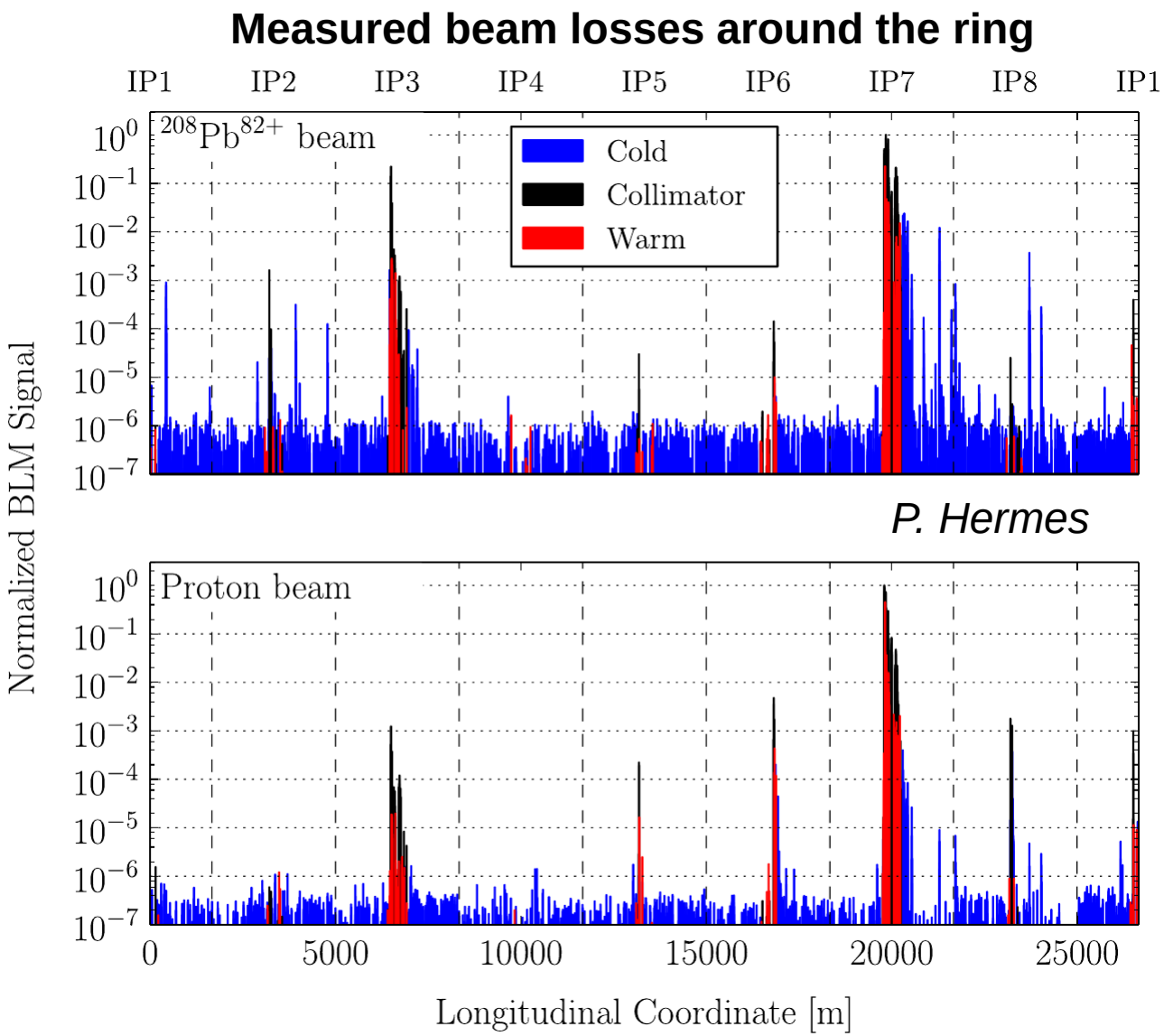

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- Gives effectively an upper limit on the total beam intensity

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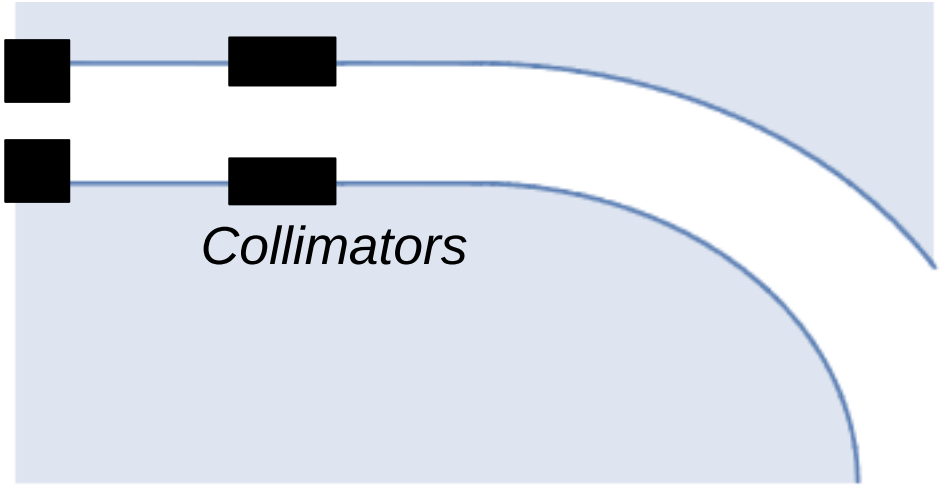

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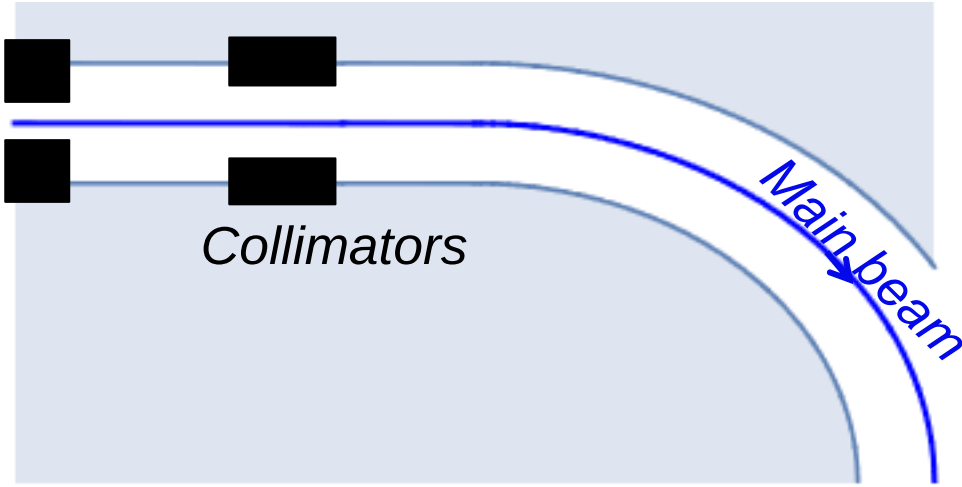

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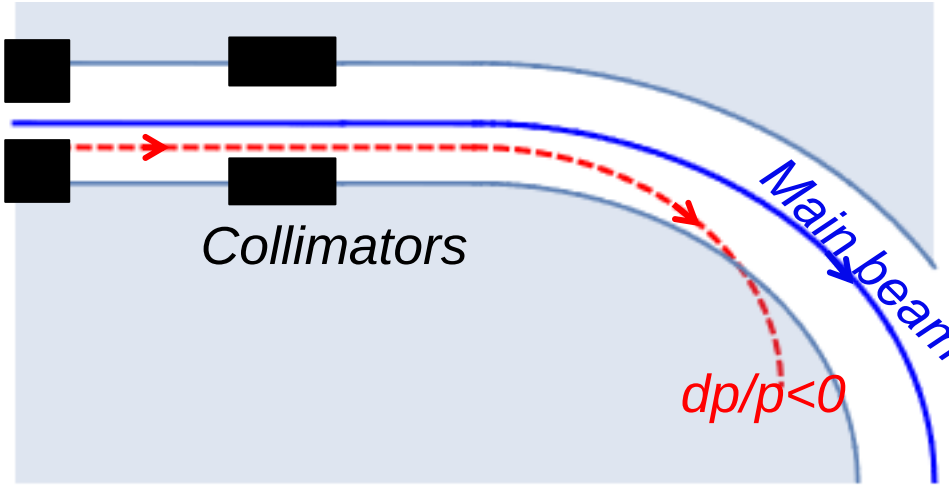

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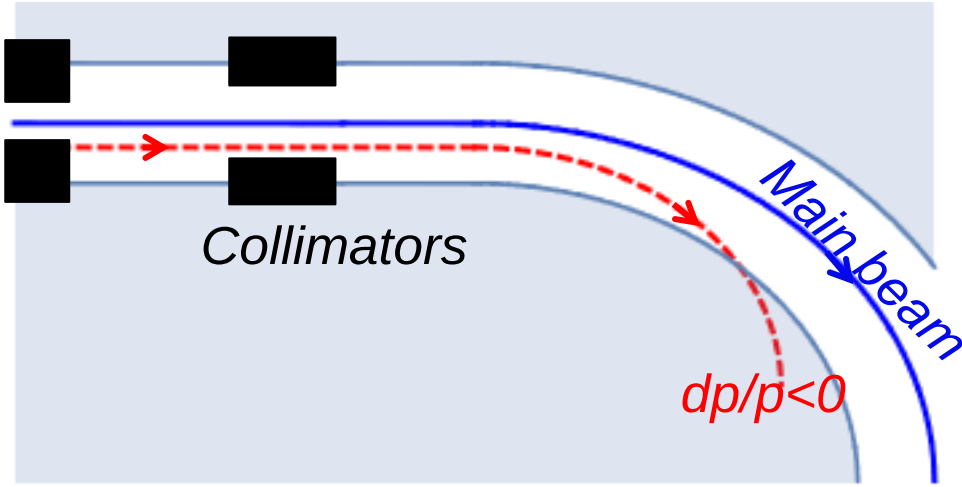

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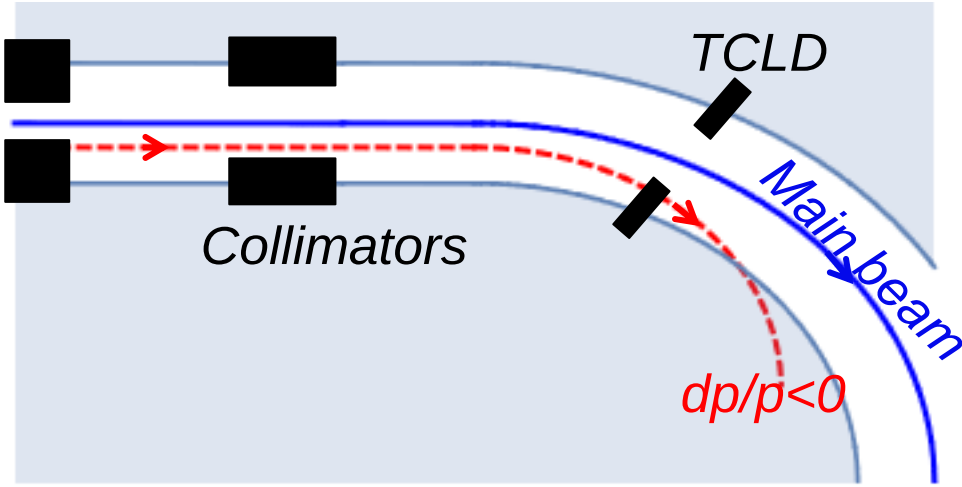

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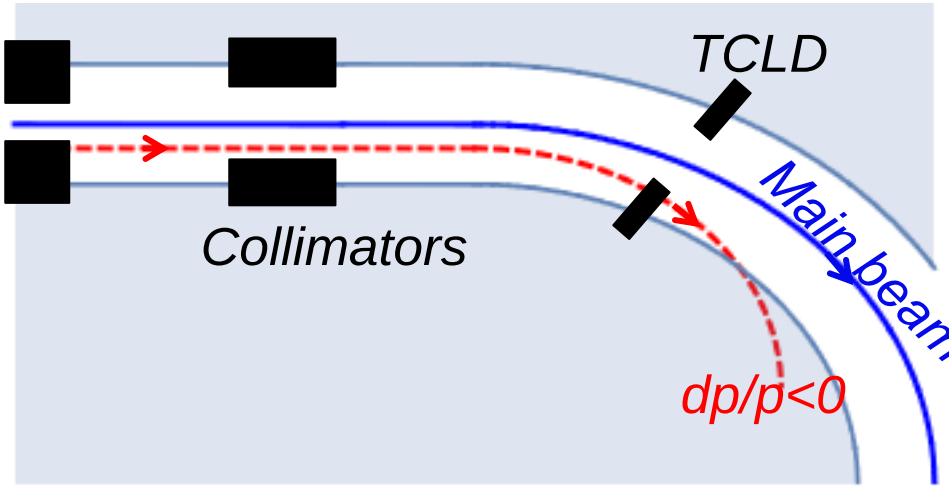
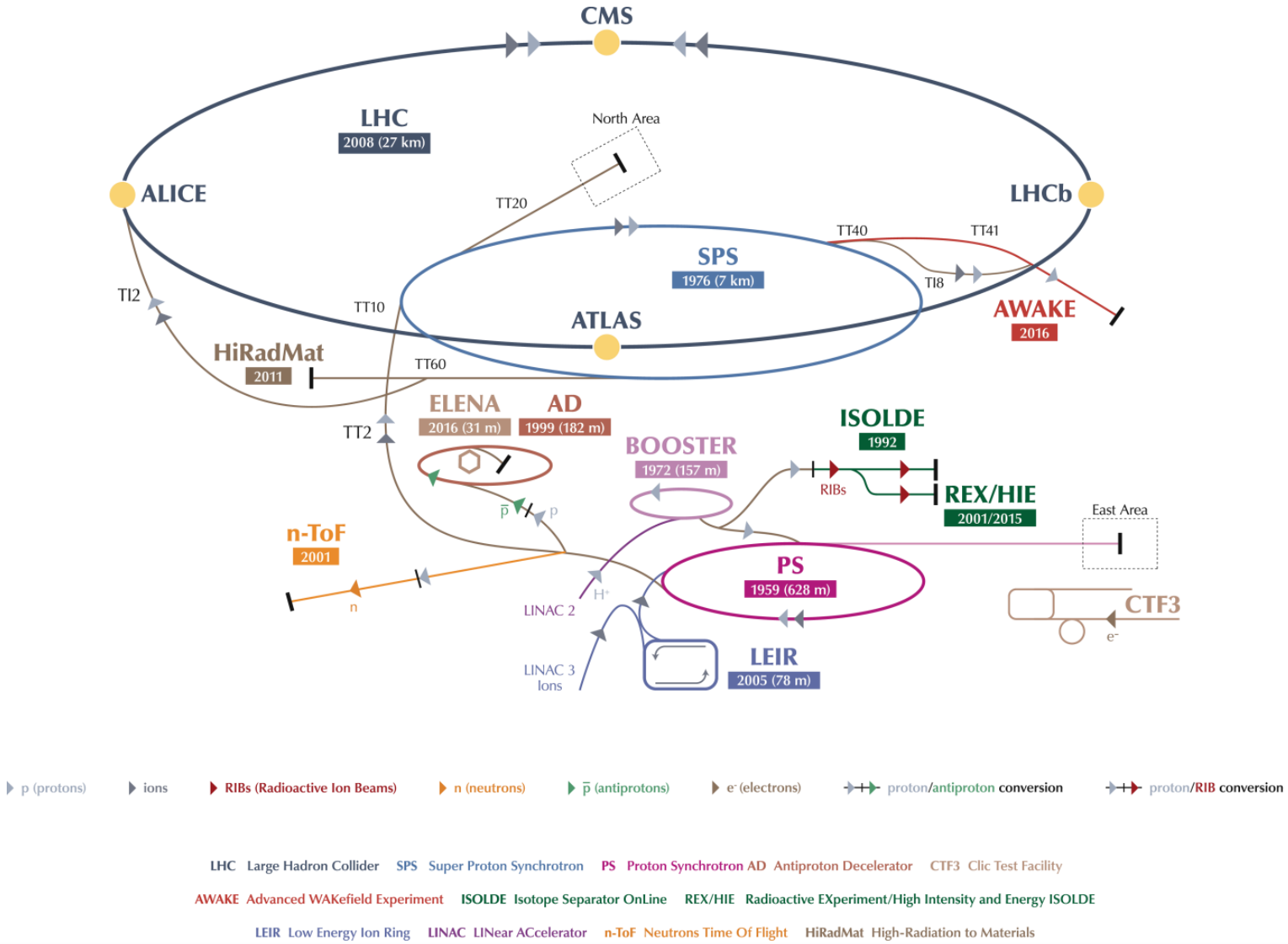


LHC injectors

- Ion beam passes through a chain of injectors before reaching the LHC



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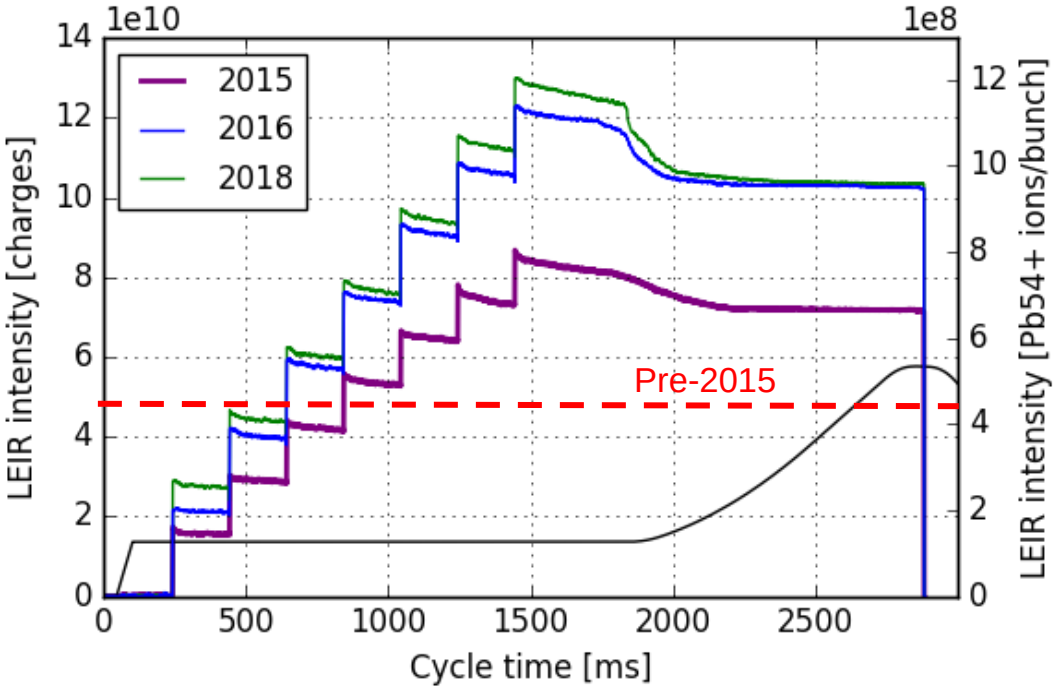

H. Bartosik, G. Rumolo et al.

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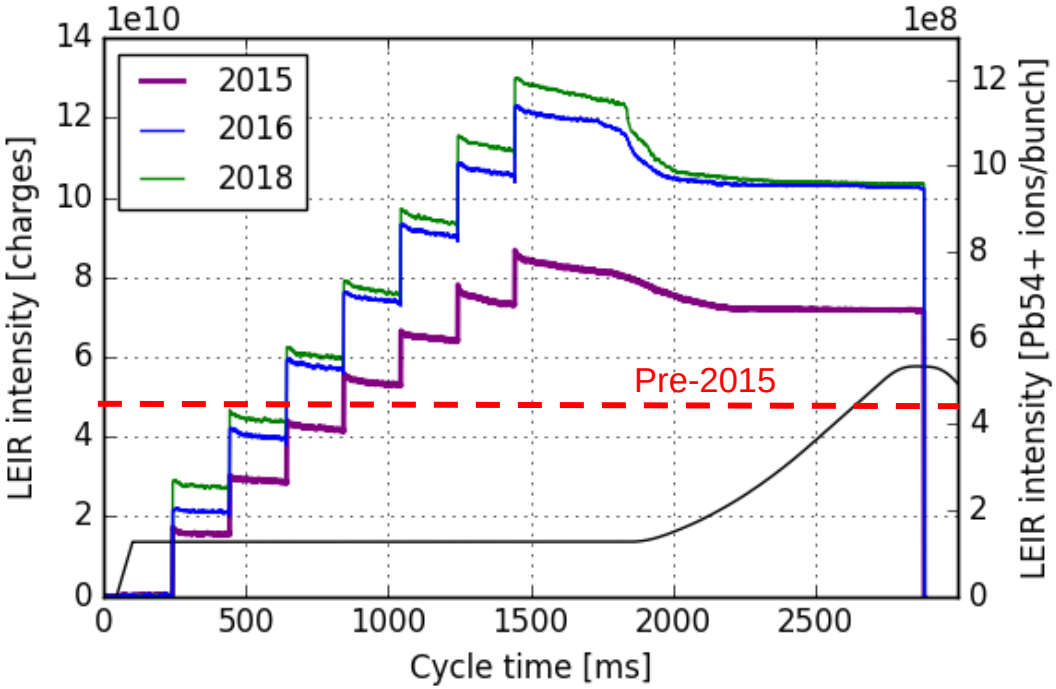

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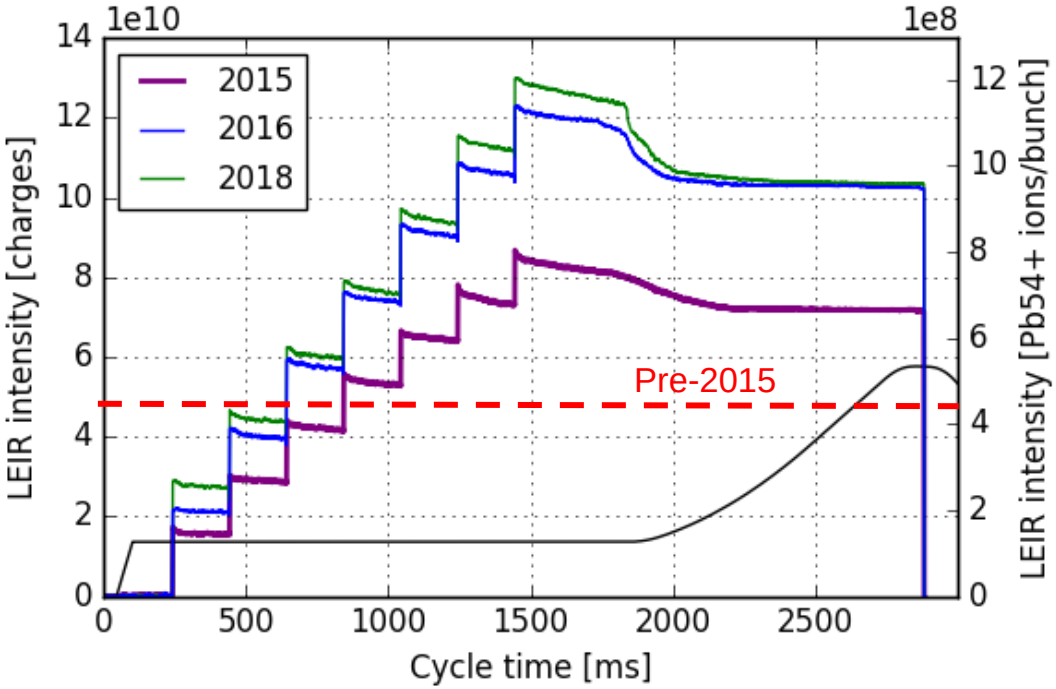
– **2018**:

  - LEIR performance confirmed, higher accumulated intensity reached
  - Better reproducibility from Linac3/LEIR thanks to improved diagnostics (e.g. BPMs in injection line, Schottky monitor for energy matching)



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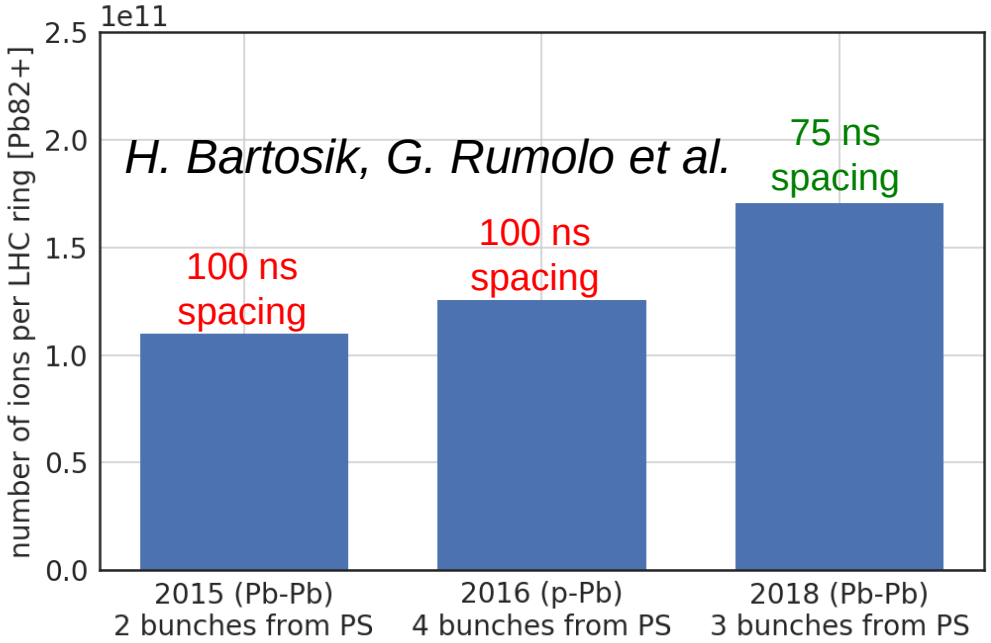

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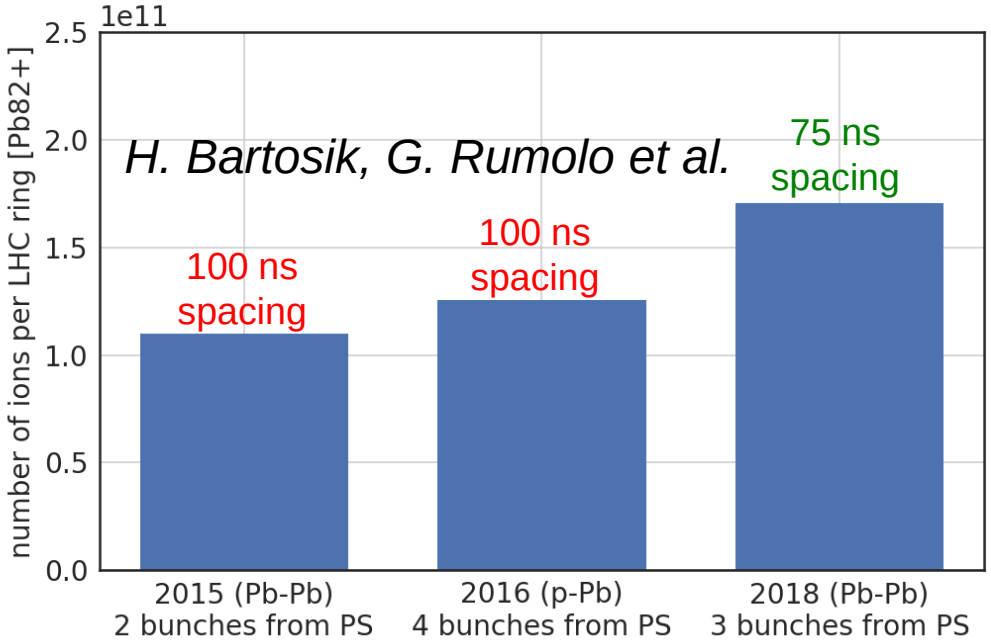

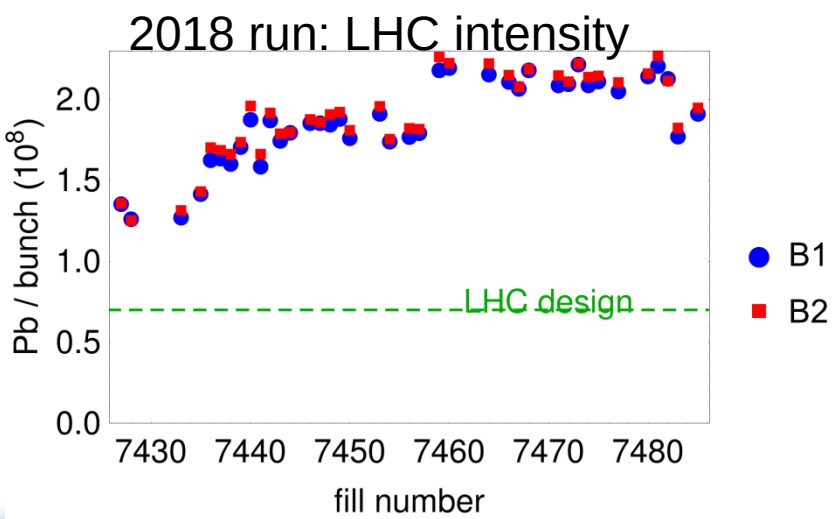

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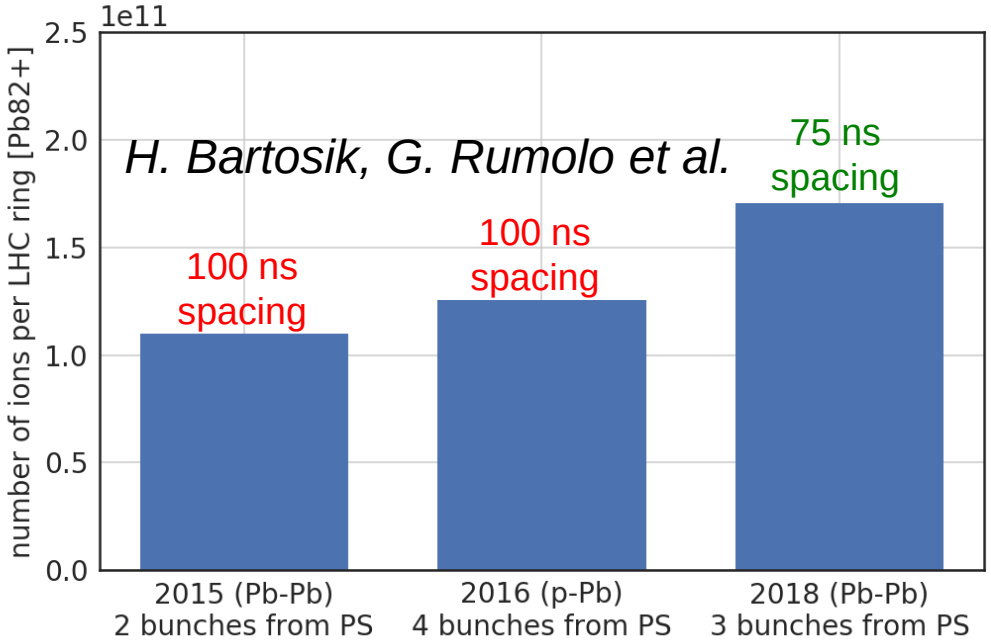

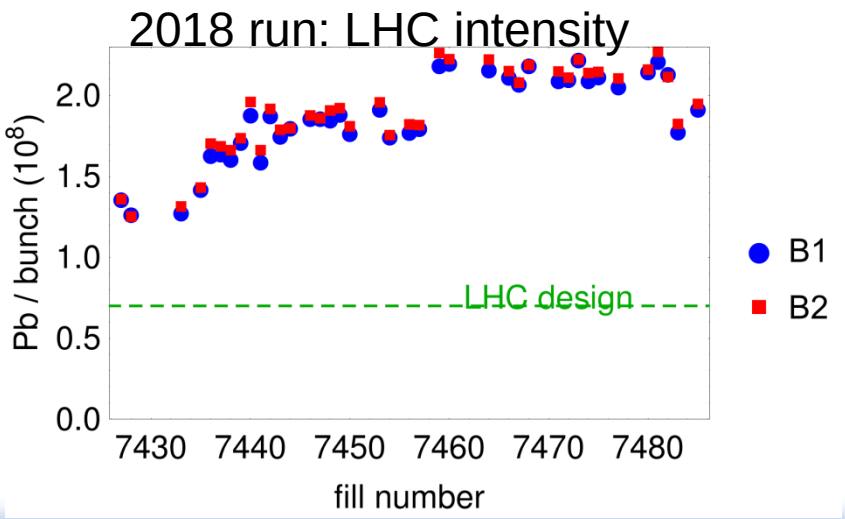

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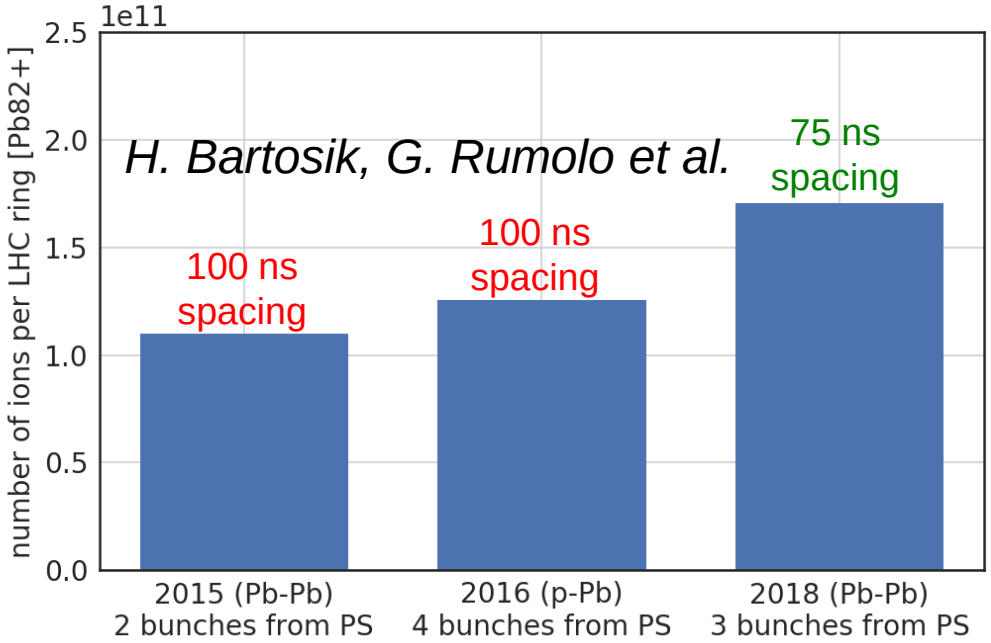

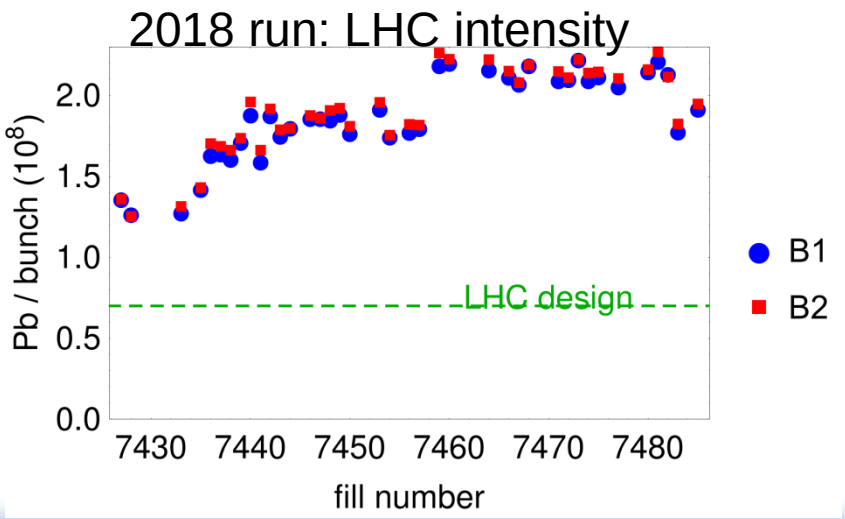

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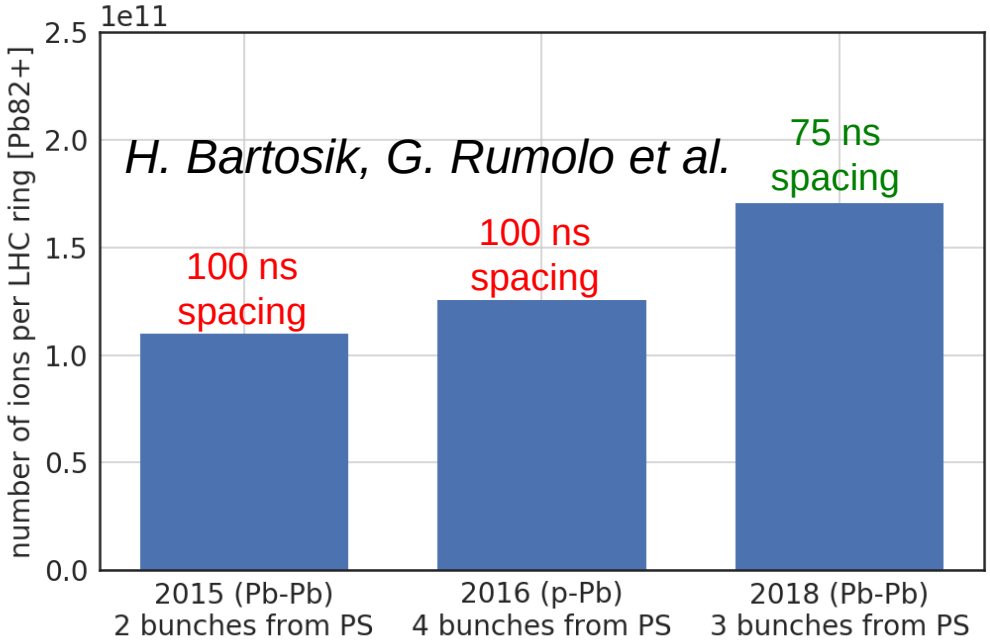

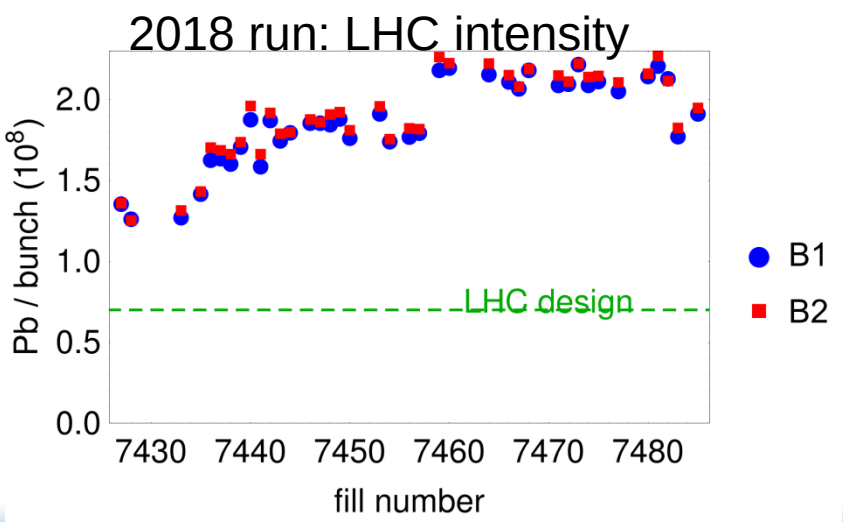

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- Not evident how to further increase injected intensity in LHC with present hardware

Beam evolution in LHC

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- Once injected in the LHC, beams suffer from further blowup and losses
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  - At top energy, radiation damping dominates over intrabeam scattering => blowup not a big issue at top energy
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- Some losses throughout the cycle, but transmission generally good
  - Usually a few percent of beam lost between start of ramp and start of collisions

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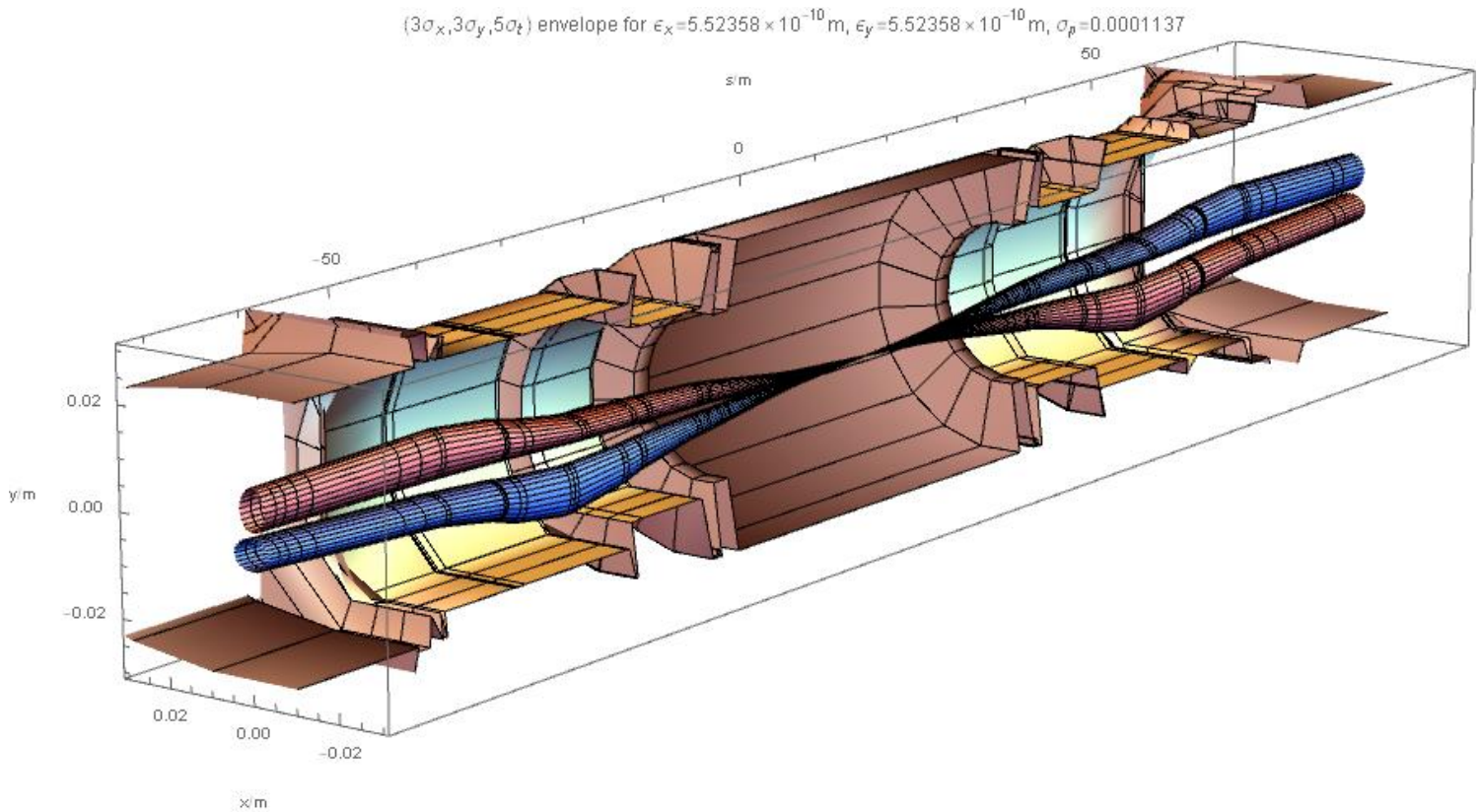

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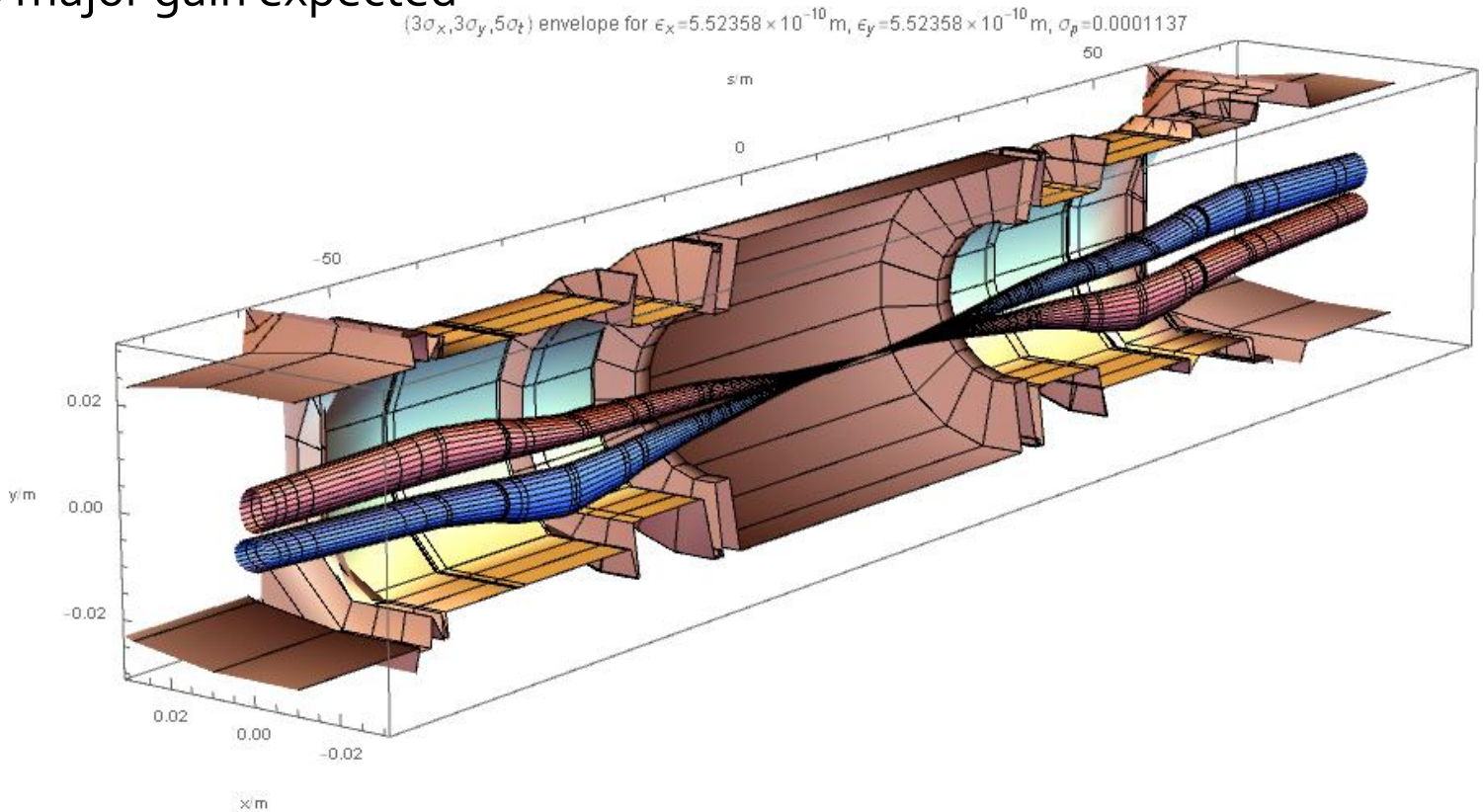
- We are not yet at a hard limit for Pb-Pb, however, as long as ALICE is leveled, no major gain expected



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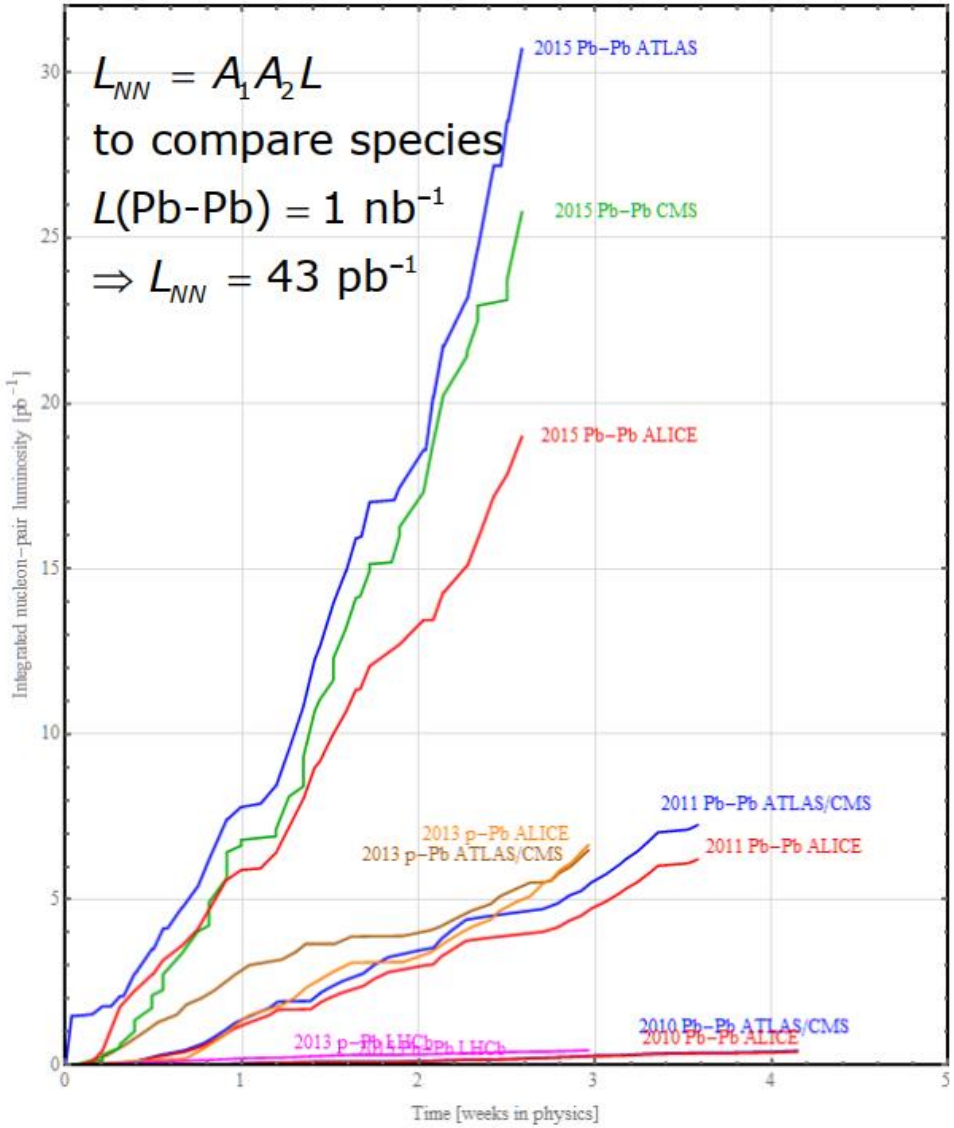
  - 4 experiments taking data instead of 1
  - New operation mode: p-Pb
- **Still several limitations for further performance increase**
  - Collisional losses
    - High burn-off cross section
    - Secondary beams, in particular bound-free pair production
  - Collimation efficiency
  - Not easy to increase injected intensity from injector chain

Backup

Luminosity production so far

- Achieved in total in ATLAS/CMS, in ALICE and in LHCb
- Include 2018



Magnetic rigidity change

- EM interactions create ions with altered magnetic rigidity:

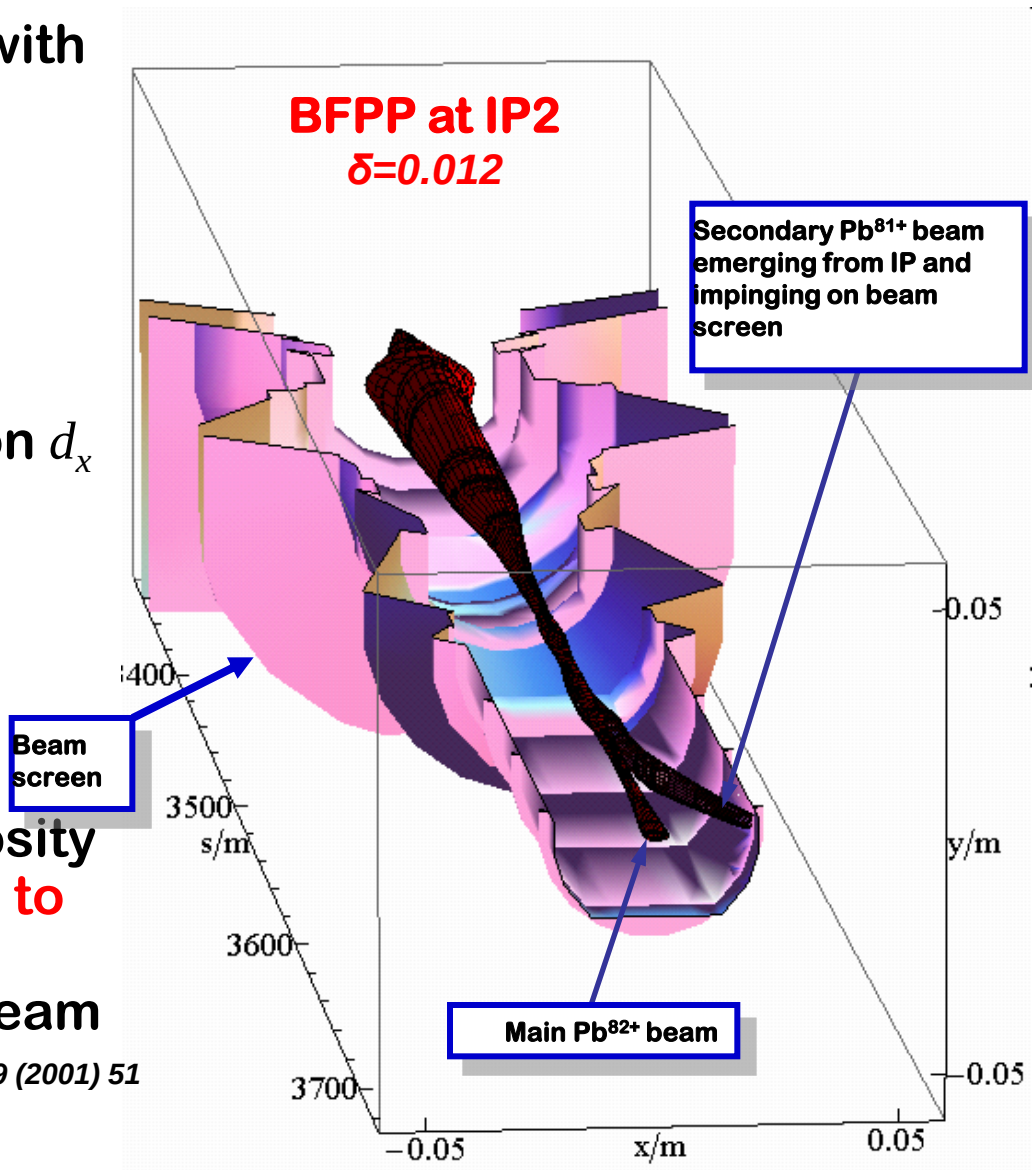
$$\delta = \frac{Z_0}{A_0}\frac{A}{Z}(1+\delta_{\mathrm{kin}}) - 1$$

- These ions follow locally generated dispersion function d_x from IP
- Lost in localized spot where aperture A_x , d_x and δ satisfy

$$\delta\, d_x = A_x$$

- Apart from significant luminosity decay, induced heating risks to quench superconducting magnets - BFPP gives 25W beam

S. Klein, NIM A 459 (2001) 51



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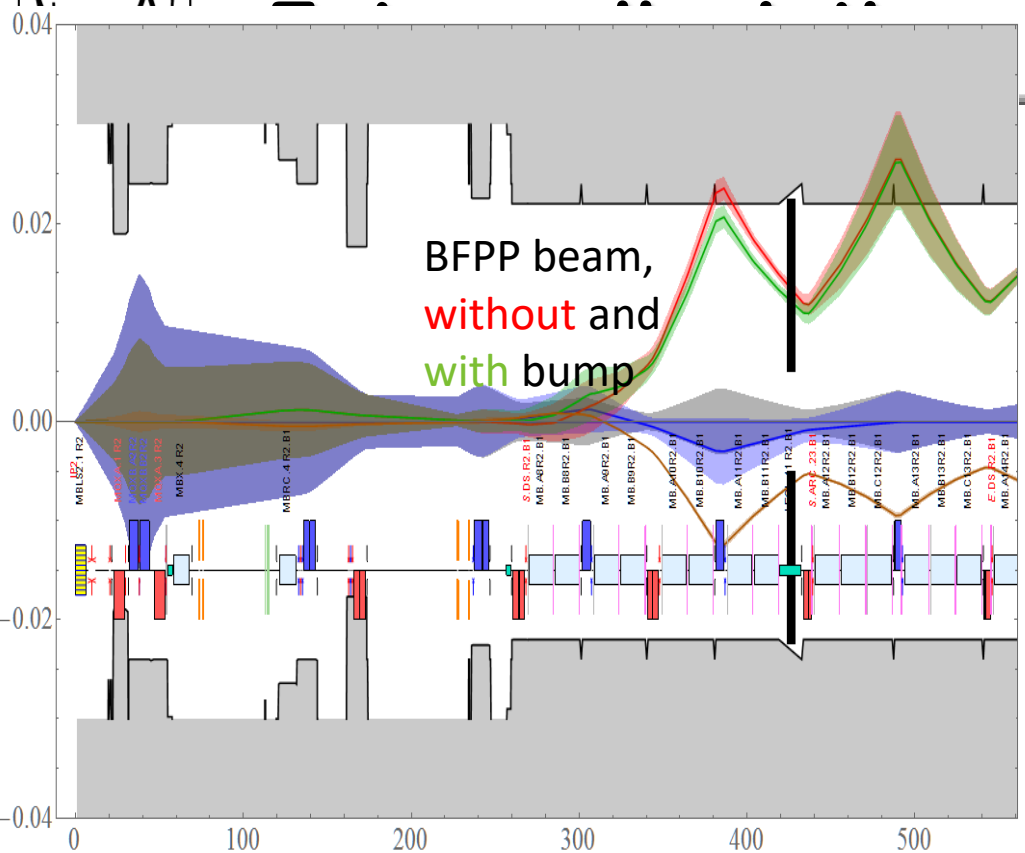
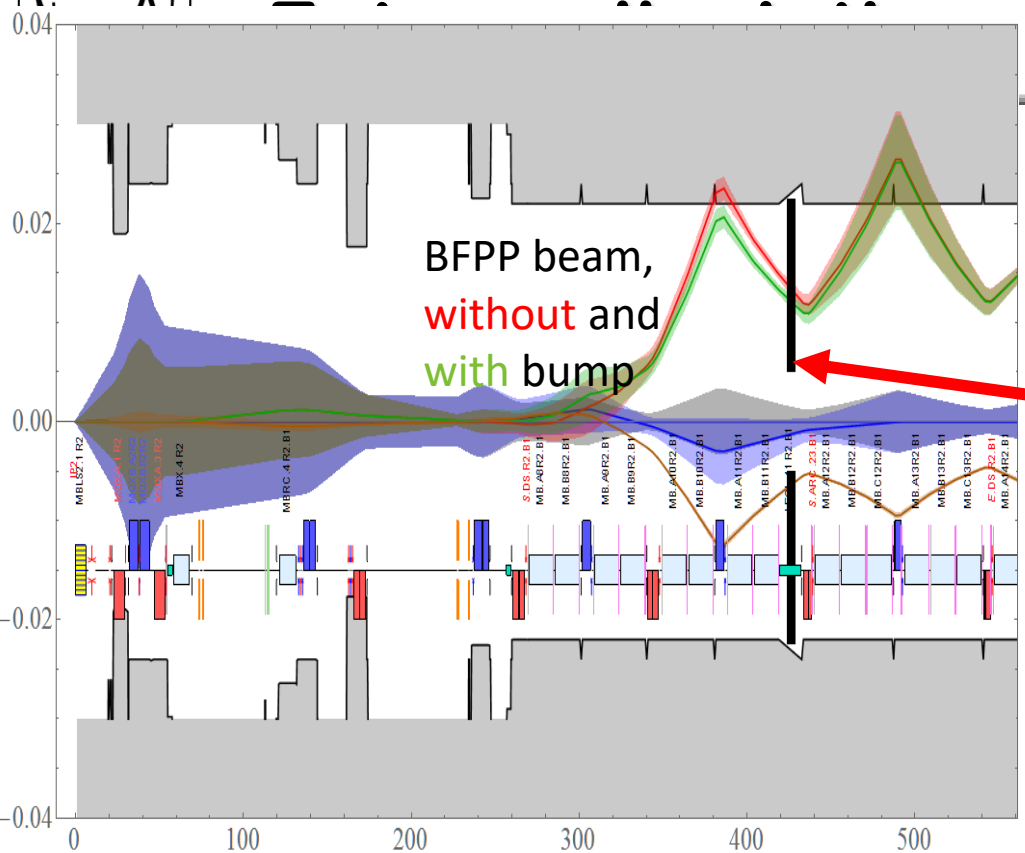
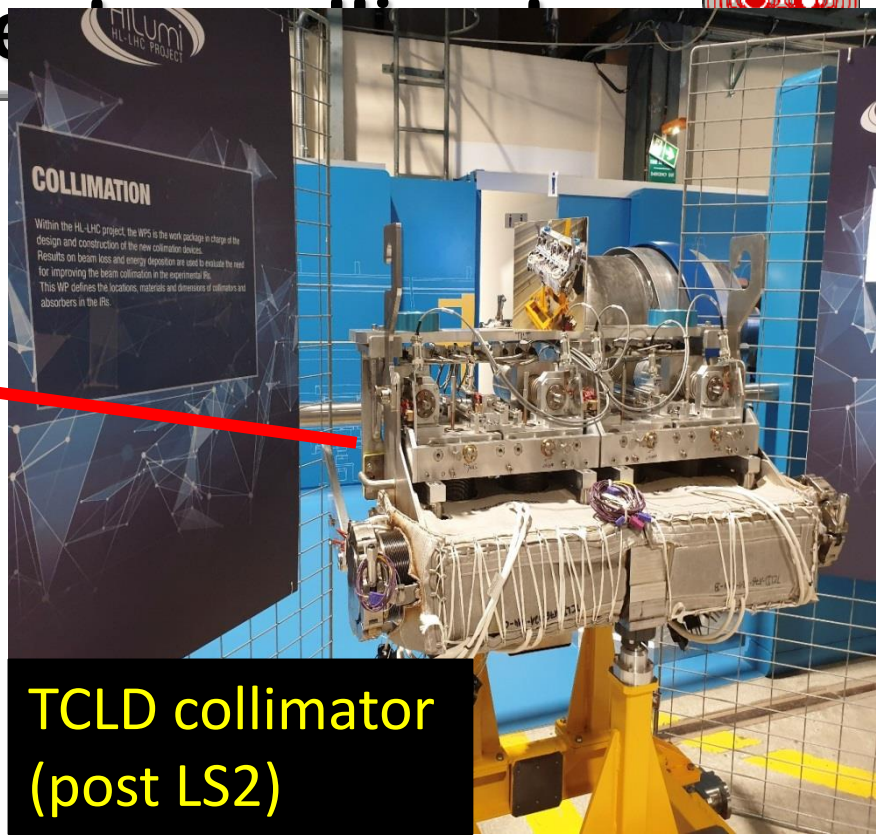


TCLD collimator (post LS2)

- IR2 has different quadrupole polarity and dispersion from IR1/IR5
- Primary BFPP loss location is further upstream from connection cryostat
- Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam – **to be ready for LS2 installation**
- With levelled luminosity in ALICE, quenches were not seen in 2015





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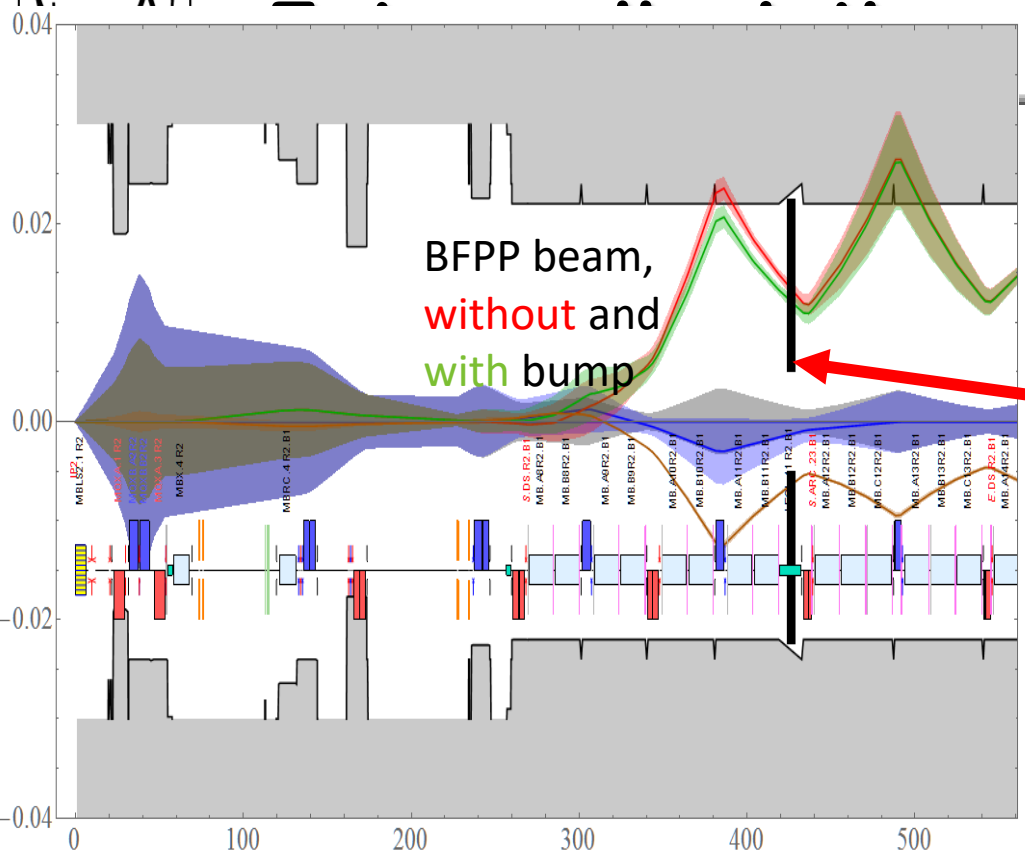

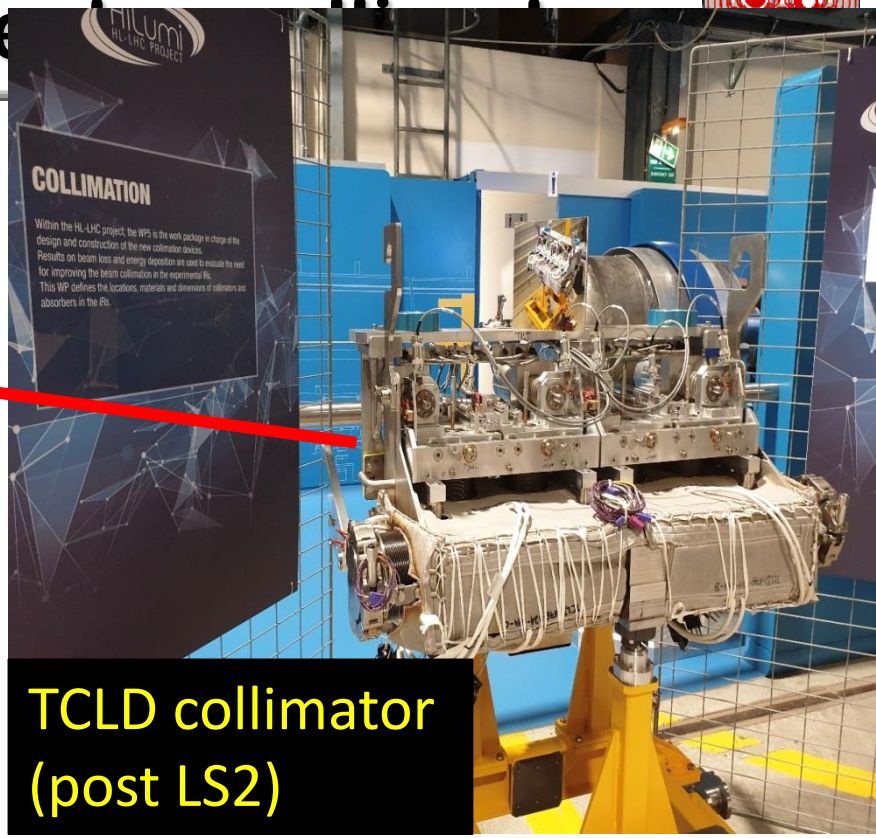

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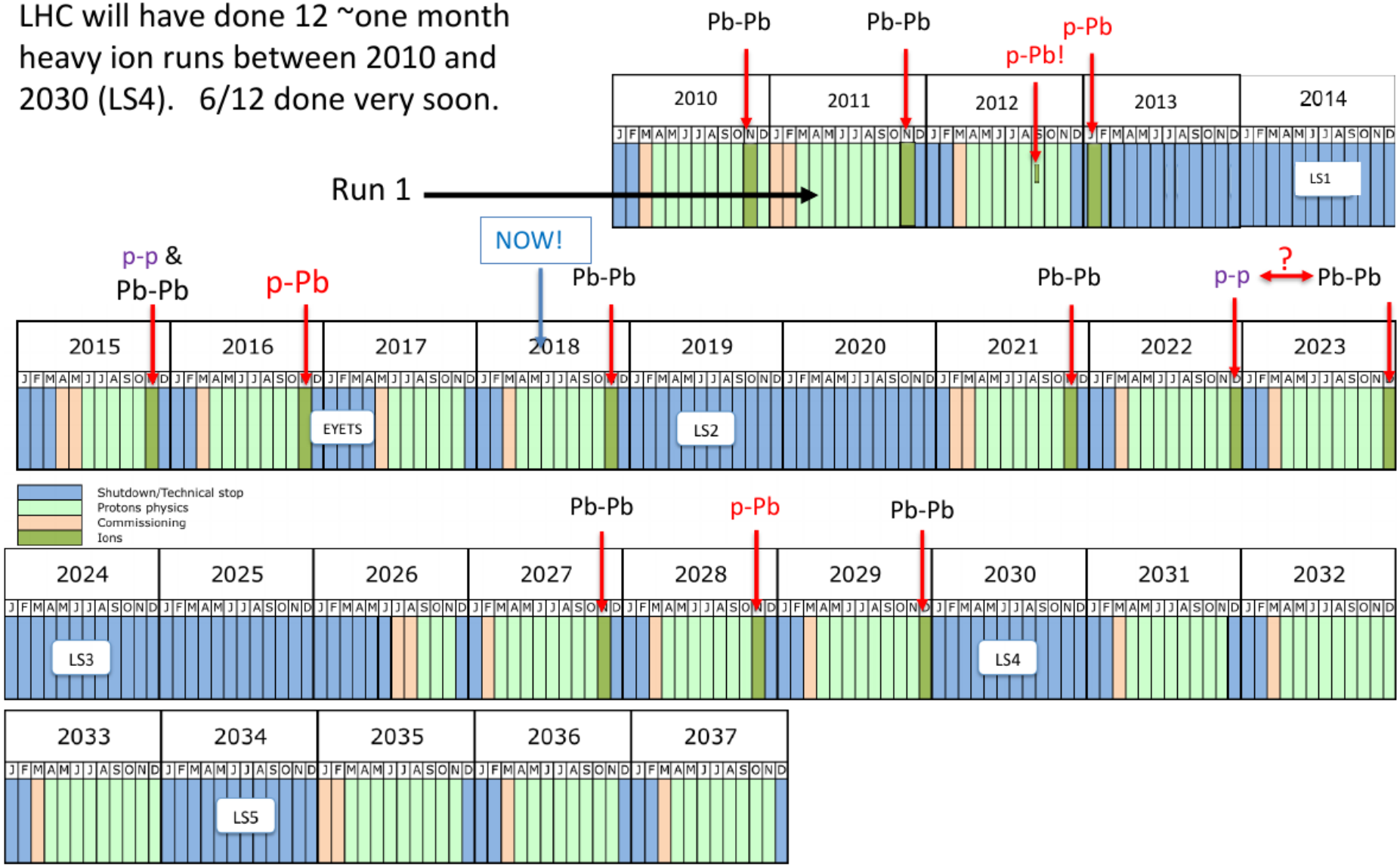
- **IR2 has different quadrupole polarity and dispersion from IR1/IR5**
- **Primary BFPP loss location is further upstream from connection cryostat**
- **Solution is to modify connection cryostat to include a collimator to absorb the BFPP beam – to be ready for LS2 installation**
- **With levelled luminosity in ALICE, quenches were not seen in 2015**

Also during LS2, further TCLD collimators will be installed between 11 T magnets in IR7 to improve Pb collimation (first application of Nb_3Sn superconductors in an operating accelerator).

Timeline of heavy-ion runs

LHC will have done 12 ~one month heavy ion runs between 2010 and 2030 (LS4). 6/12 done very soon.



Geometric reduction factor

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- Fewer collisions when bunches are not fully overlapping

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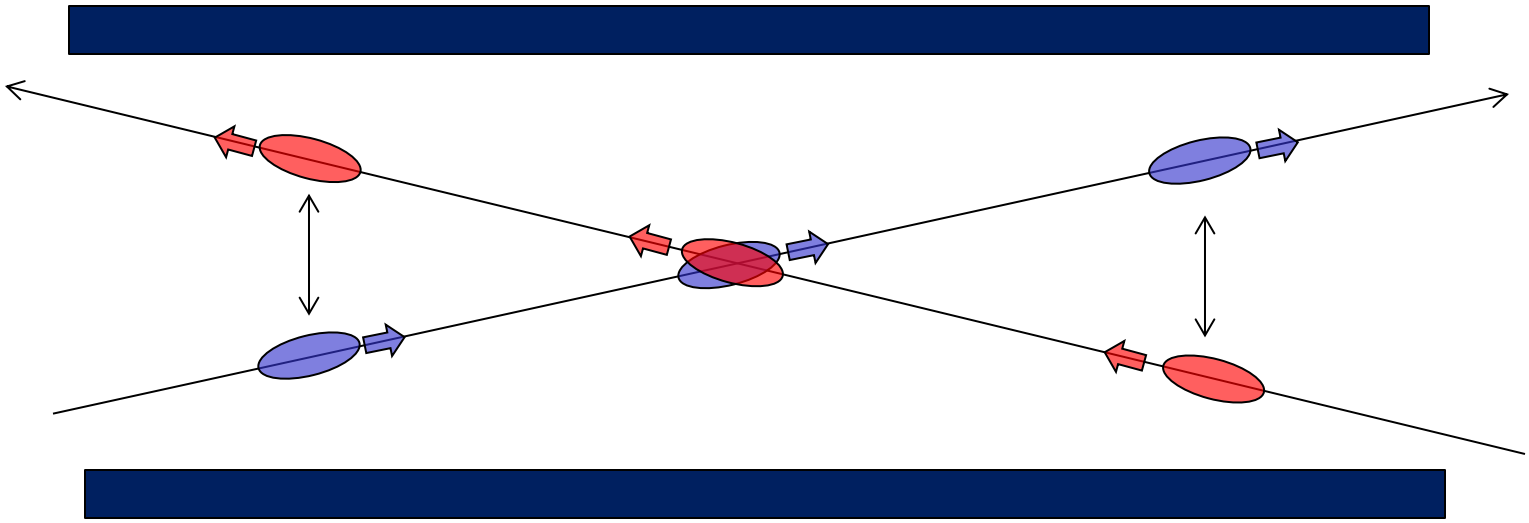

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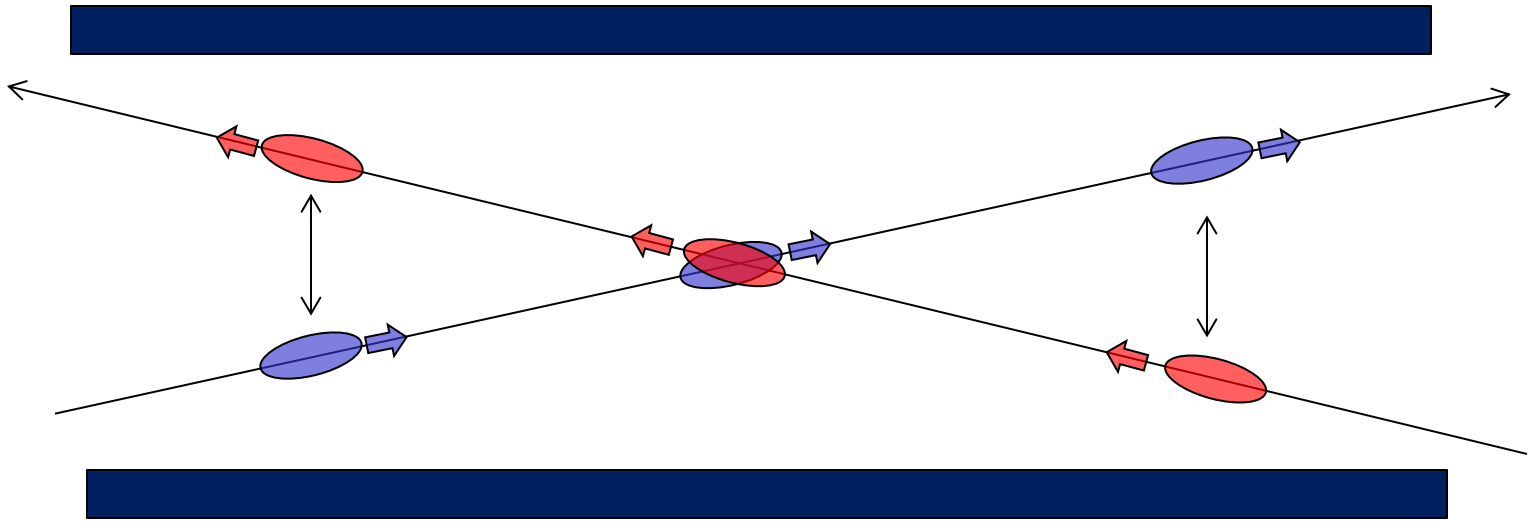

- Decrease bunch length and crossing angle to minimize effect

Geometric reduction factor

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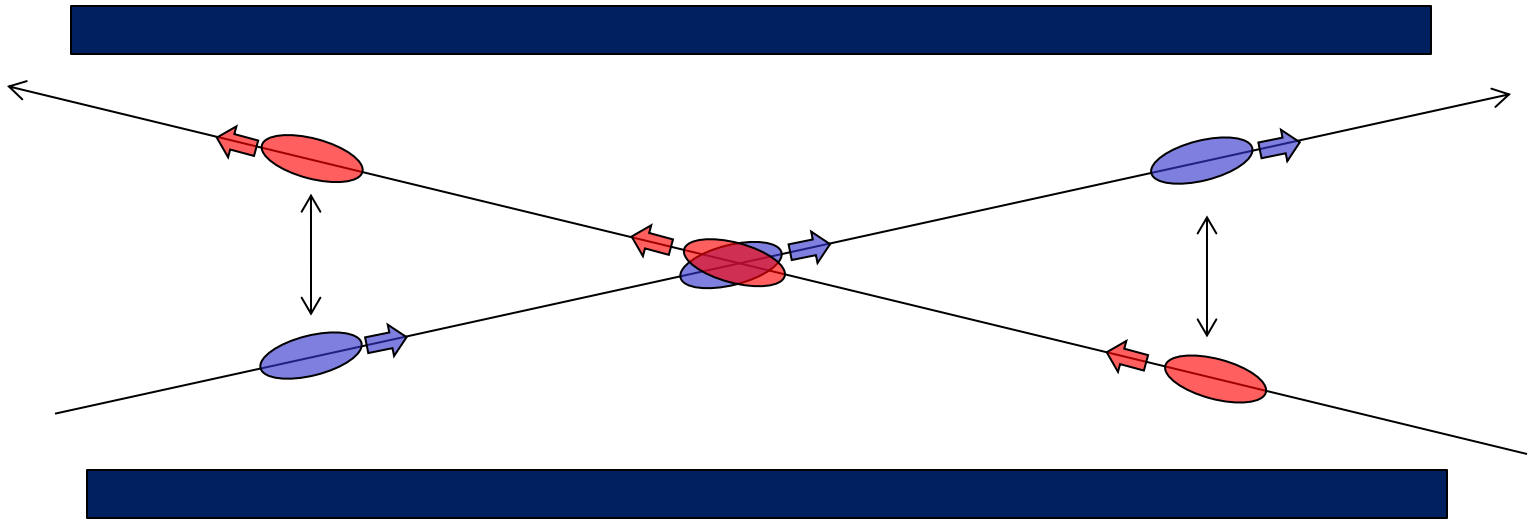
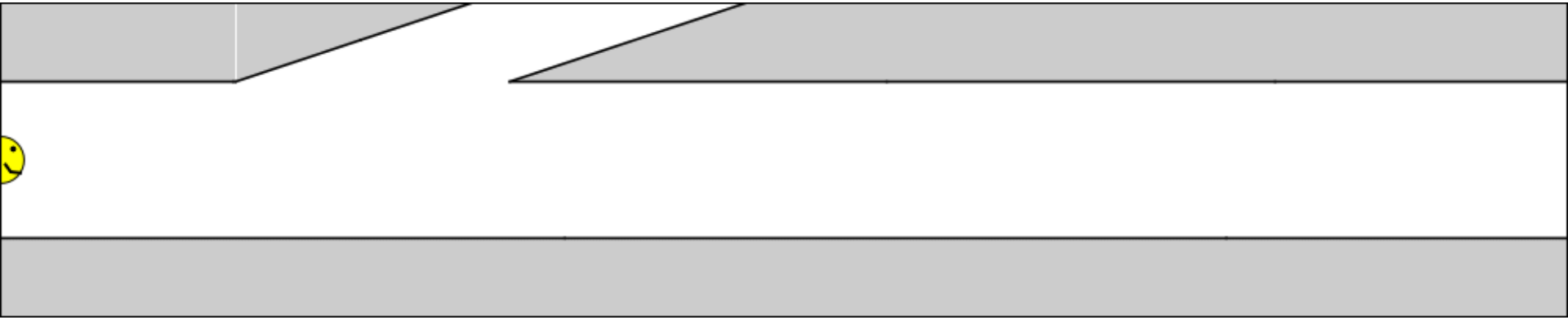


- Decrease bunch length and crossing angle to minimize effect
- Crossing angle limited by beam-beam separation and aperture

Asynchronous beam dump

- Standard dump: extraction kickers fire when no beam passes



- Asynchronous dump: kicker(s) fire when beam passes – kicked beam damage could TCTs/triplets. TCDQ should protect

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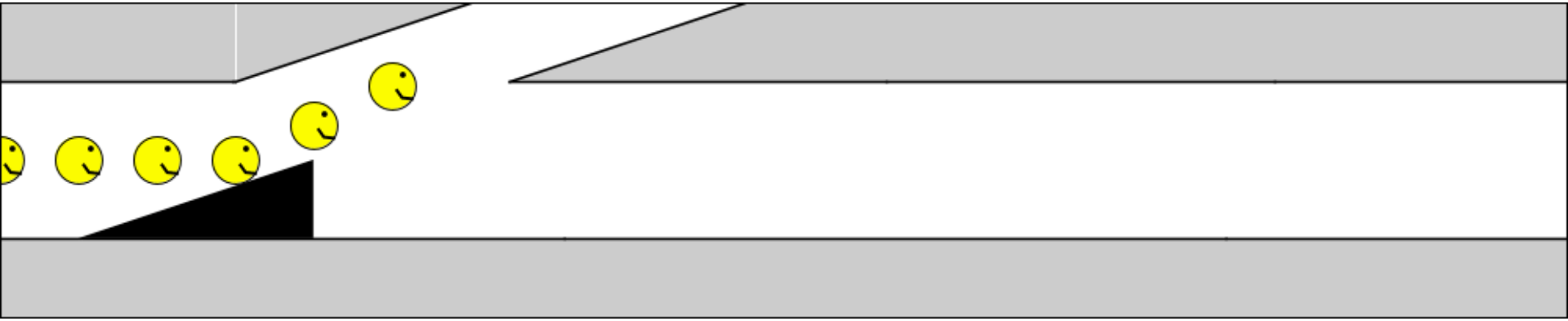

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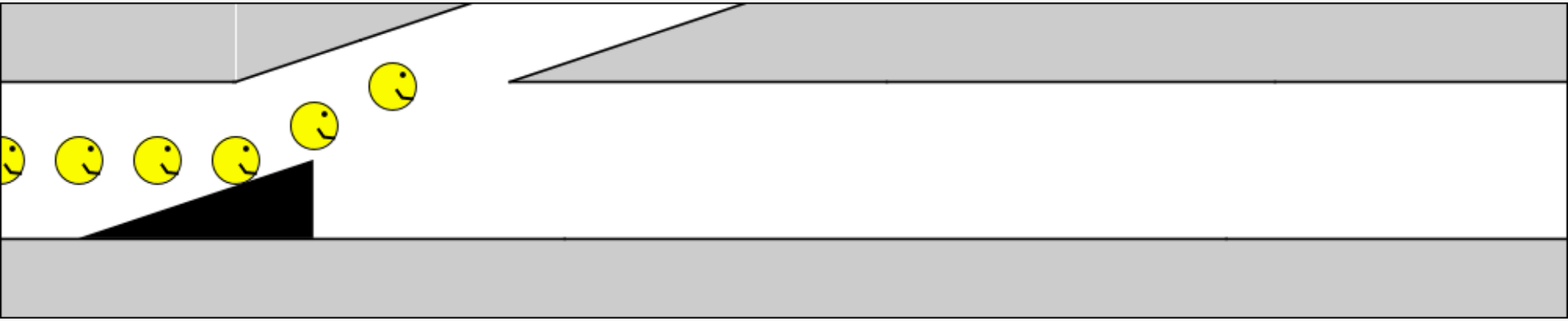

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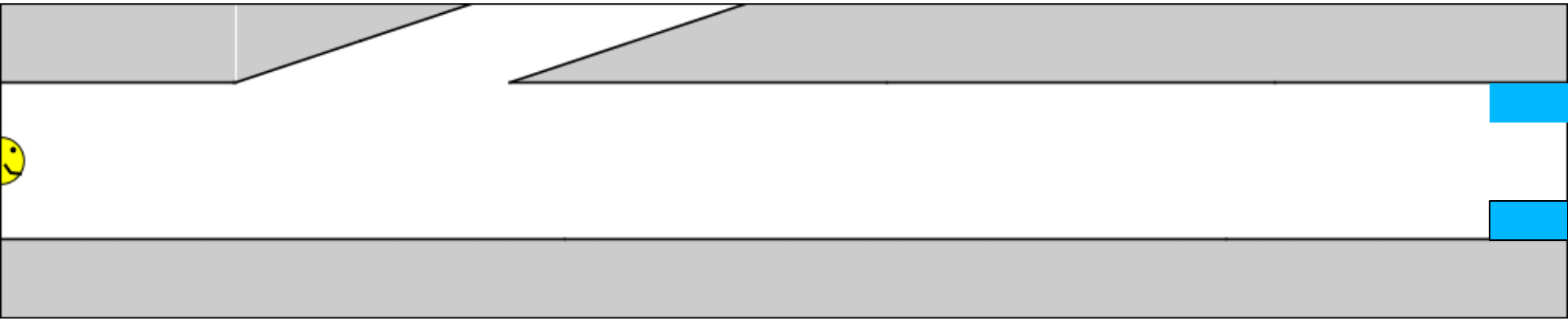

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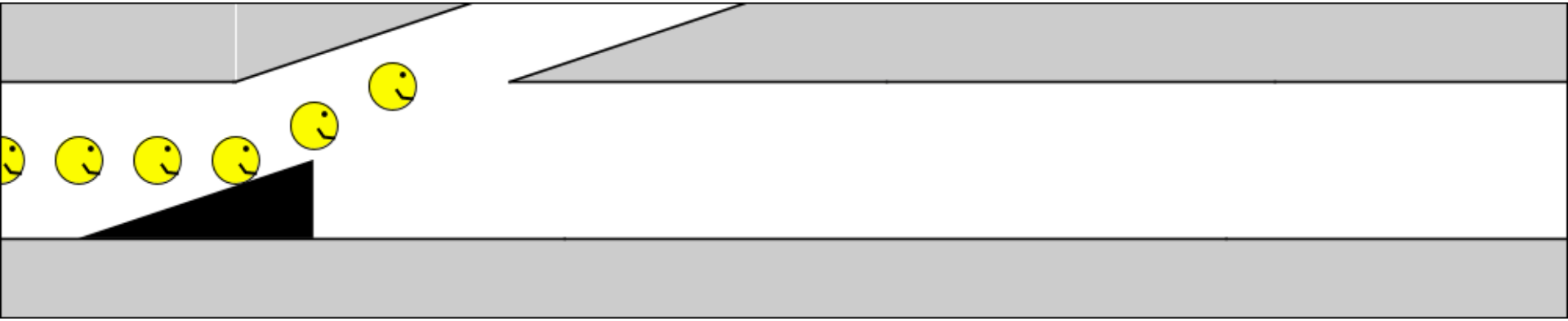

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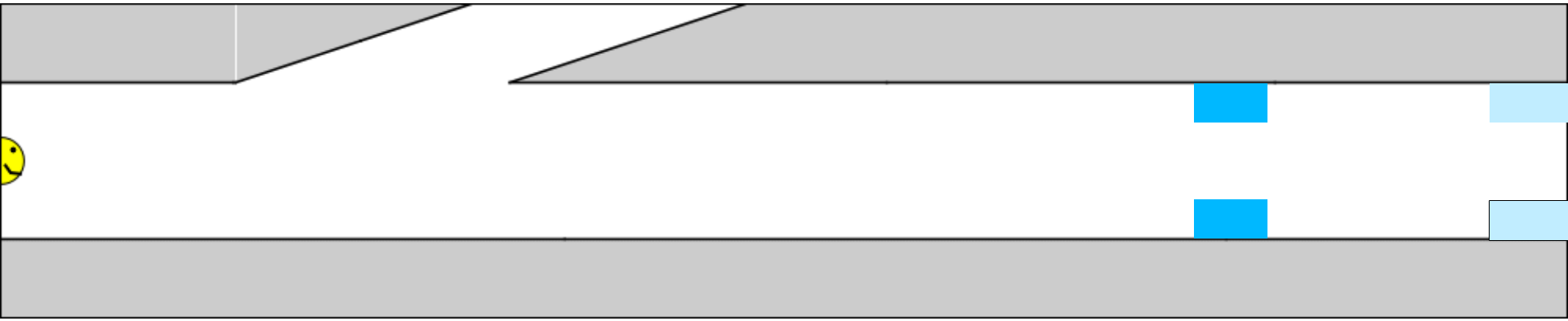
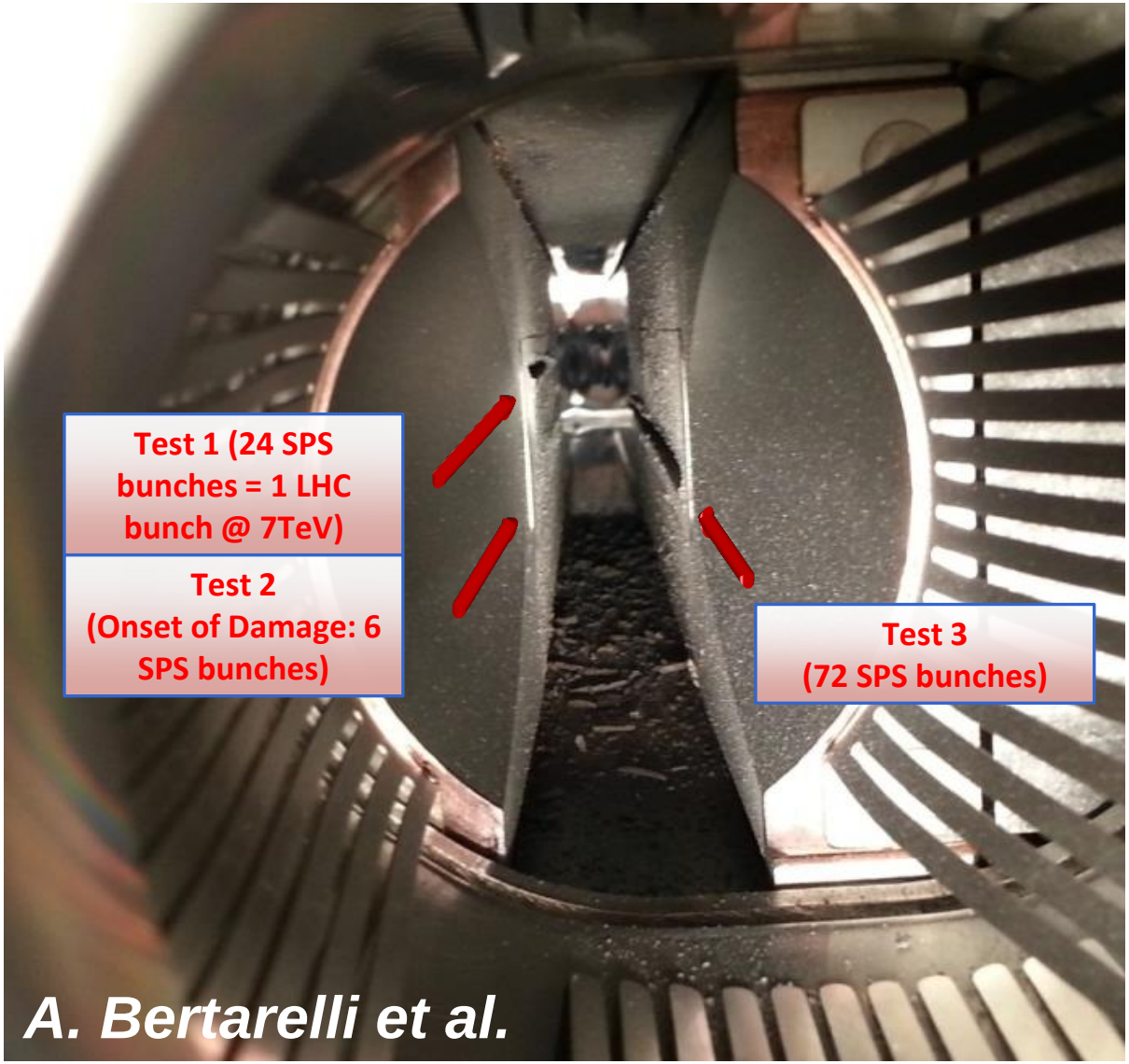
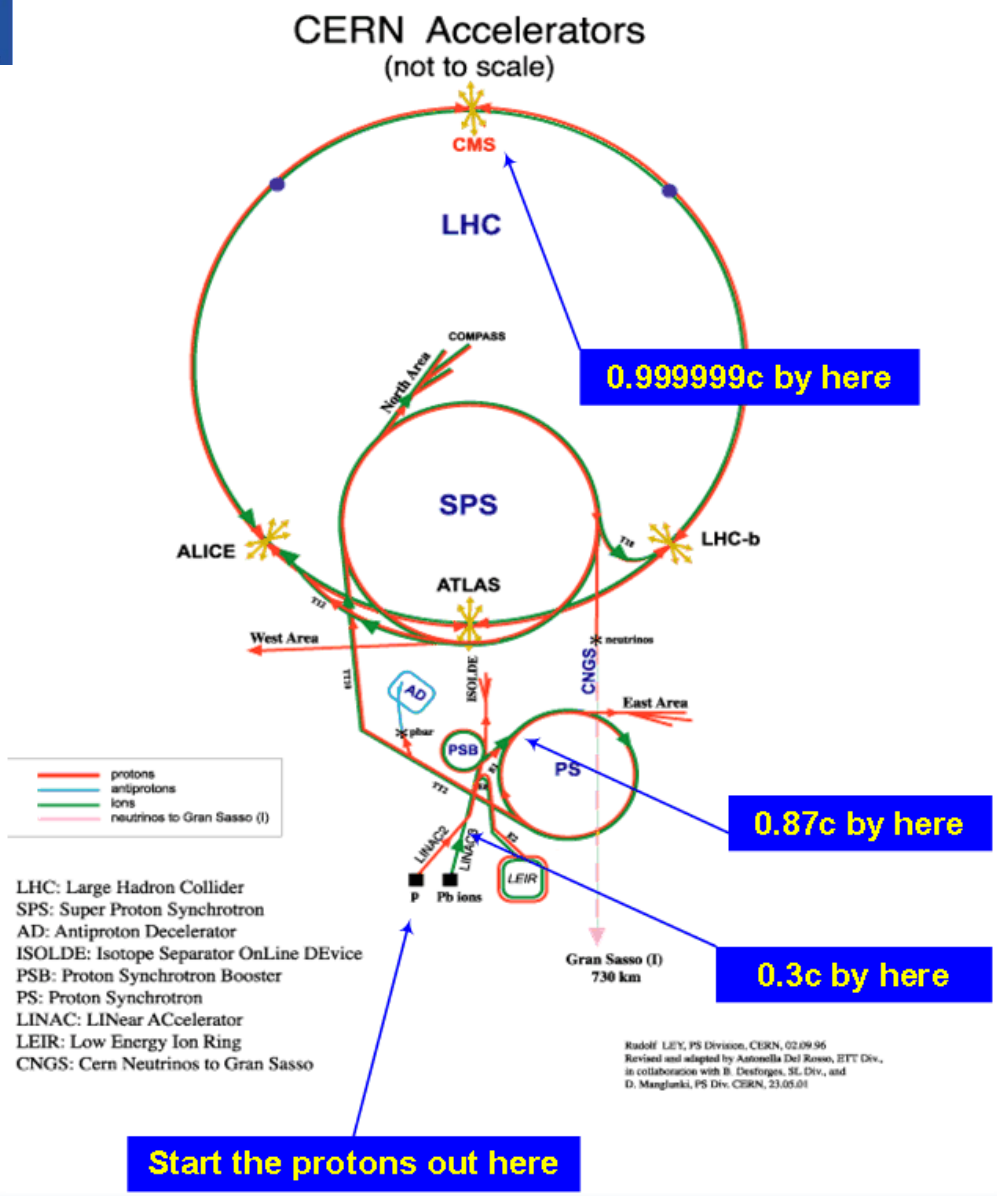


What can happen if a TCT is hit?

- Impacts studied in HiRadMat
- Significant damage observed



Proton acceleration to LHC



Energy:

Linac 50 MeV

PSB 1.4 GeV

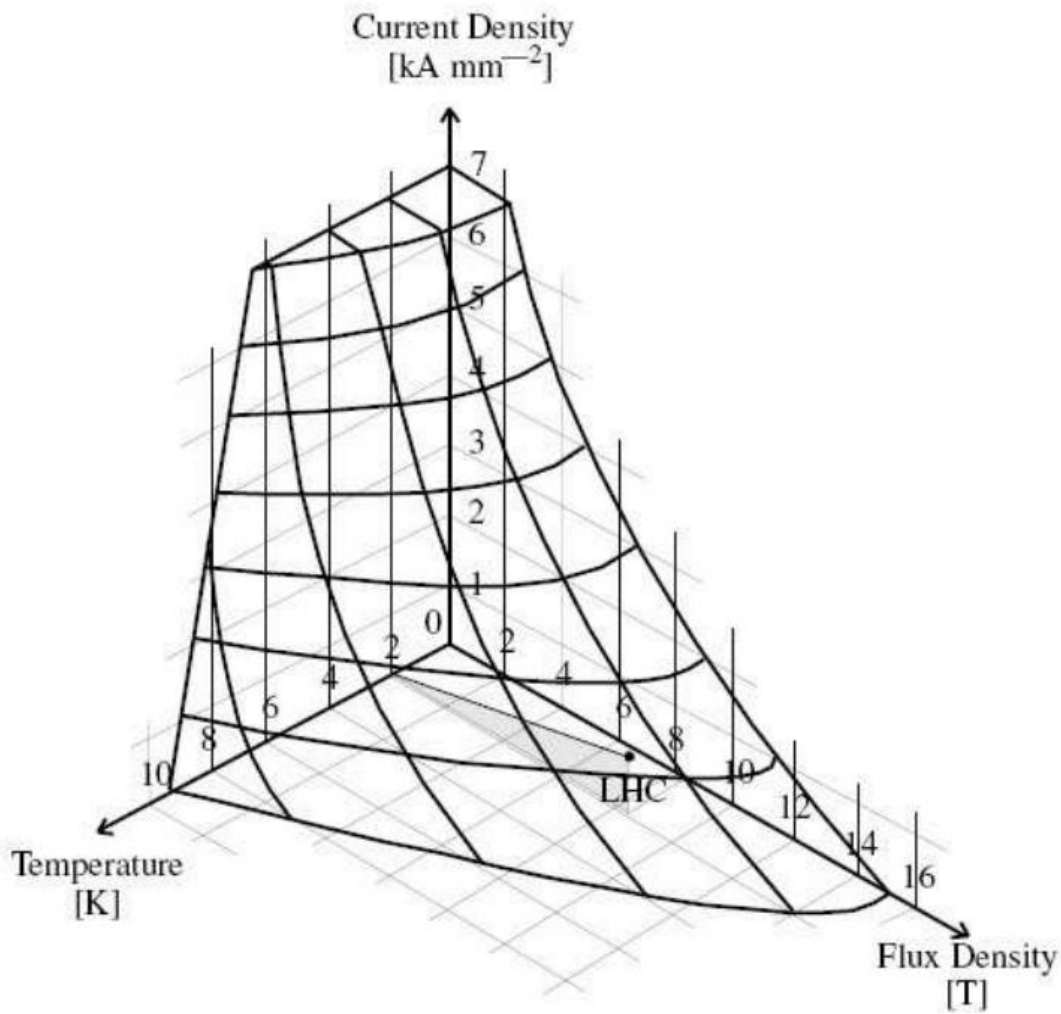
PS 28 GeV

SPS 450 GeV

LHC 7 TeV

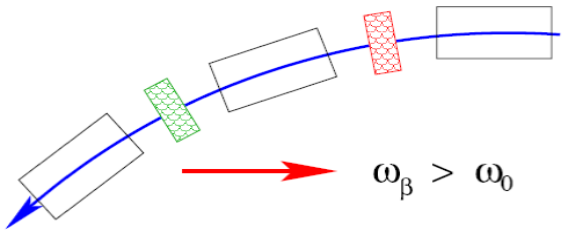
Superconducting magnets

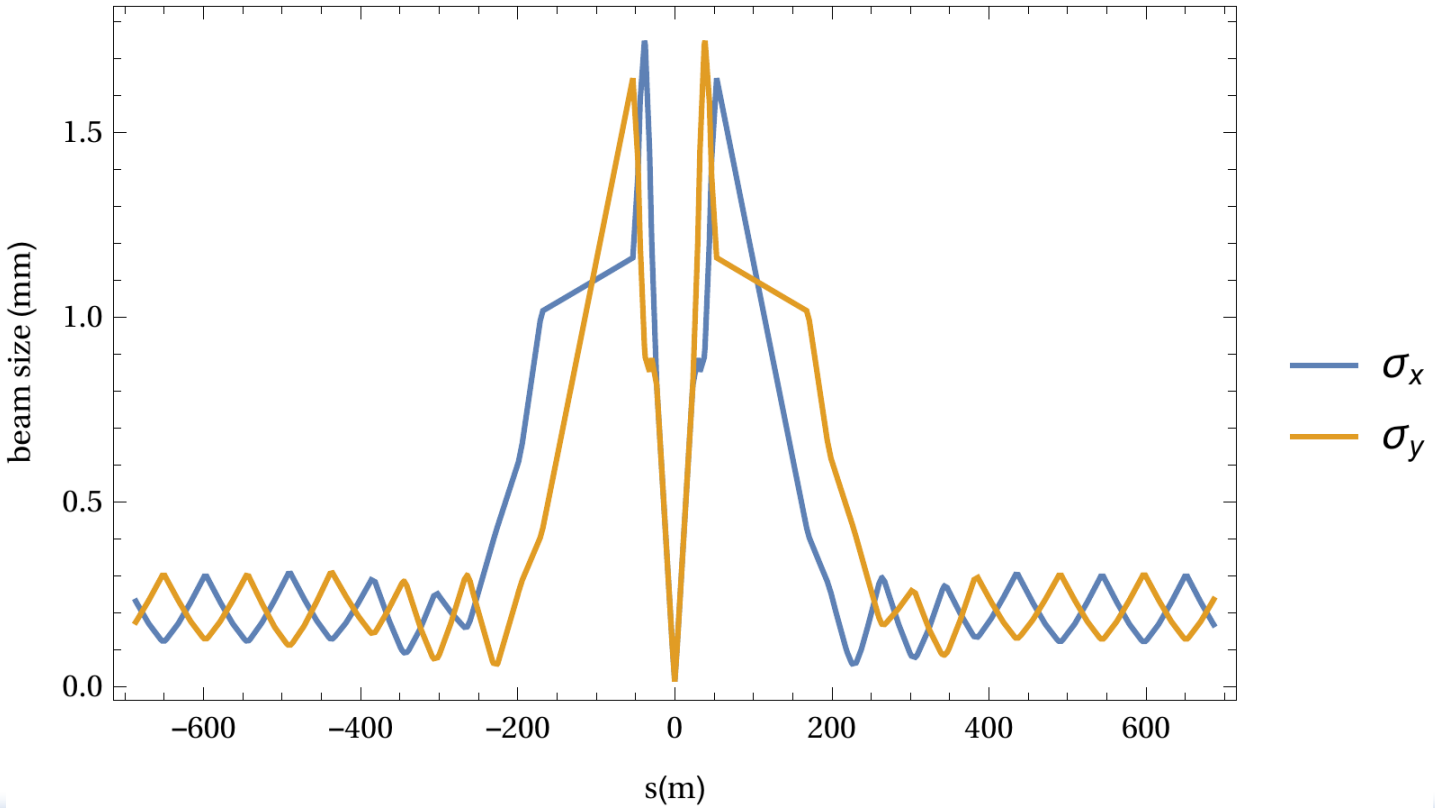
- "Quench" = loss of superconductivity
- Happens if working point is outside of surface in magnetic field (B), current (I) and temperature (T)



LHC lattice

- In the bends: periodic layout of dipoles interleaved with focusing and defocusing quadrupoles
- At collision points: beam focused down to very small transverse size (2018: ~10 µm in pp, 20 µm in PbPb)





Ion fragment distribution after collimator

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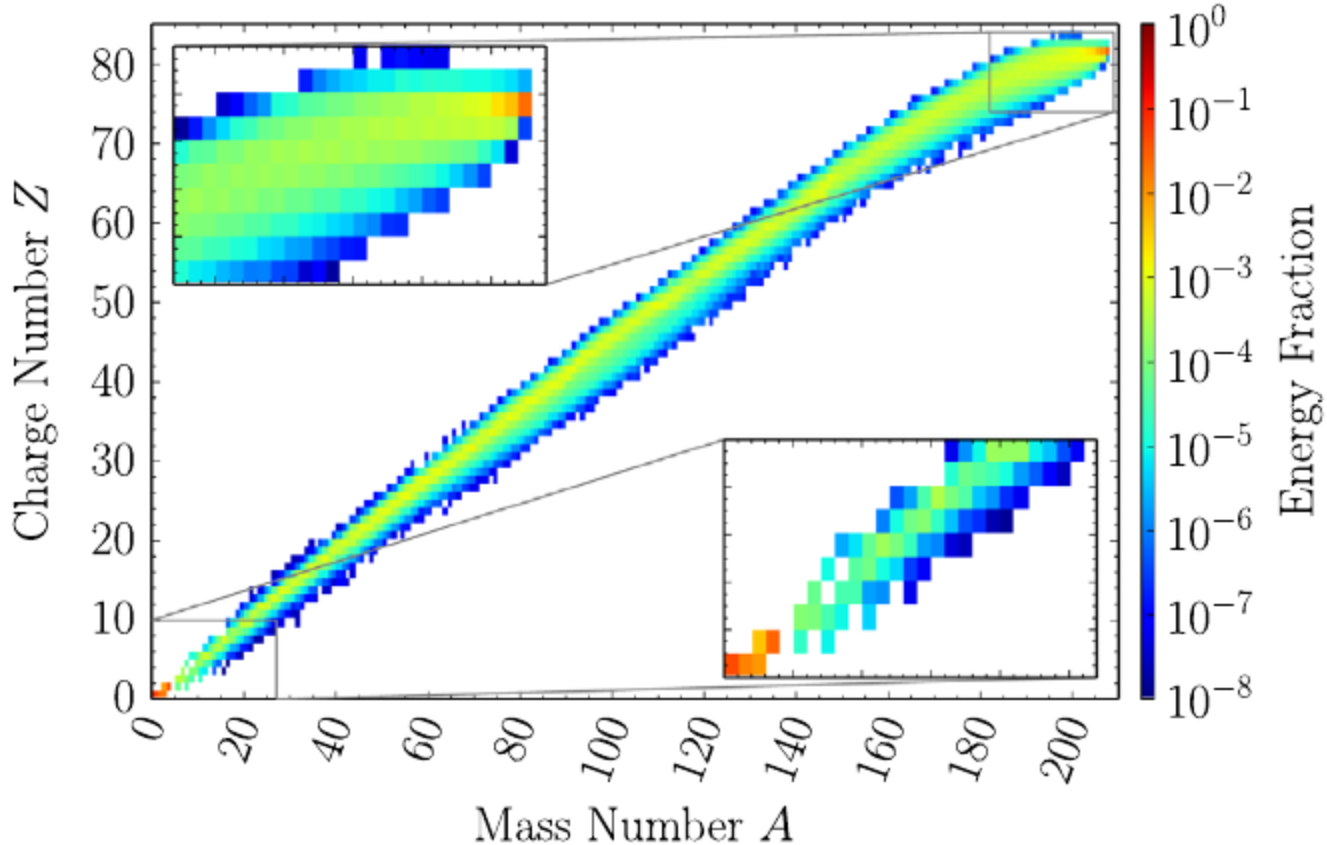

Fig. 4. Energetic fractions of the individual isotopes emerging from the IR7 horizontal TCP from an impacting $^{208}Pb^{82+}$ beam at 3.5 Z TeV, simulated with FLUKA as shown in Fig. 3 with an impact parameter of $b = 3$ μm. The energy fraction is computed by multiplying the isotope abundance $N(A,Z)$ with the nucleon number A and the momentum per nucleon $p(A,Z)$ and normalizing by the total ion energy coming out of the collimator $\sum_{A,Z} A \times N(A,Z) \times p(A,Z)$. It is assumed that the momentum per nucleon is approximately identical for all ions $p(A,Z) \approx p$.