





LHC Injectors Upgrade



Beam Dynamics Challenges for the LHC and Injector Upgrades

Giovanni Rumolo, CERN, Genève, Switzerland

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LHC Injectors Upgrade



- Why upgrades and what are the upgrades for LHC and its injector chain?
- Performance of the LHC injectors
 - Present performance limitations → beam dynamics challenges
 - How far we can go with the upgrades
- Beam dynamics challenges for HL-LHC





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Goals of upgrades in a nutshell (HL-LHC)

Beam properties @LHC injection

	N_b ($\times 10^{11}$ p/b)	$\epsilon_{x,y}$ (μm)	Bunch spacing	Bunches
HL-LHC beam	2.3	2.1	25 ns	4x72 per injection

Goals of upgrades in a nutshell (HL-LHC)

The **High Luminosity LHC (HL-LHC)** upgrade

➤ Performance:

- Aims at **3000 (4000) fb^{-1}** total integrated luminosity over the HL-LHC run (2026 – 2037)
- Based on operation at levelled luminosity of **5 (7.5) $\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$** by lowering β^*

Beam properties @LHC injection

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➤ Sustainability/availability:

- Change/upgrade systems vulnerable to breakdown/ageing and improve infrastructure, especially in view of future operation in a higher radiation environment

➤ Challenge: Employ cutting edge accelerator technology to push innovation!

Goals of upgrades in a nutshell (LIU)

Beam properties @LHC injection

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HL-LHC target	2.3	2.1	25 ns	4x72 per injection
Present	1.3	2.7	25 ns	4x72 per injection



Goals of upgrades in a nutshell (LIU)

The LHC Injectors Upgrade (LIU)

➤ Performance:

- Aims at **matching the beam parameters** at LHC injection with HL-LHC target
- Needs to deploy **means** to overcome **performance limitations** in all injectors!

Beam properties @LHC injection

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➤ Sustainability/availability:

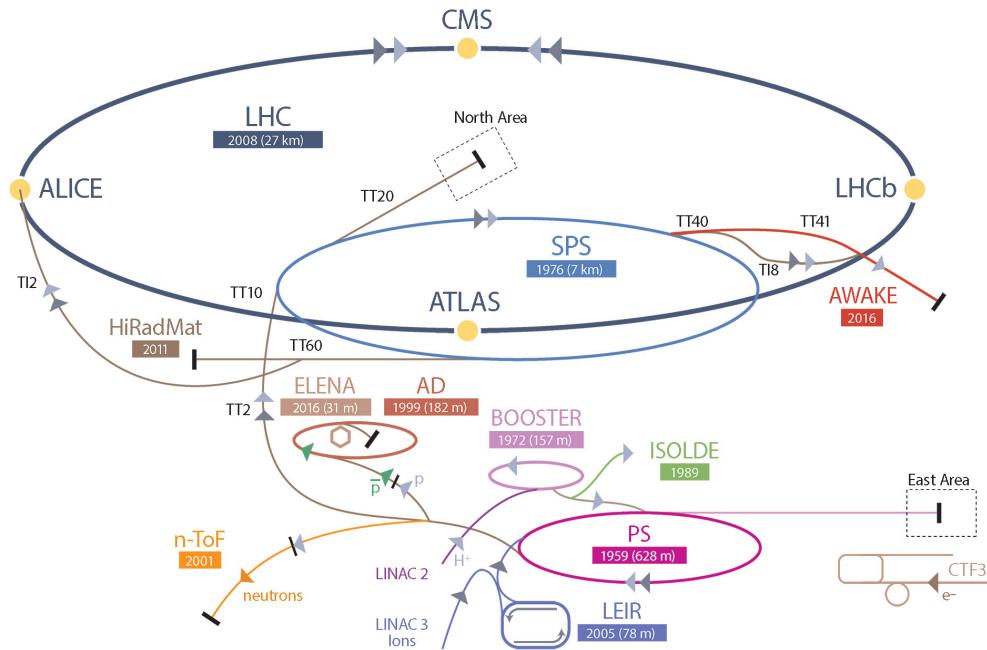
- Ensure and improve injectors' availability/reliability well into the HL-LHC era by upgrading sensitive/ageing equipment, improve radioprotection and services



LHC Injectors Upgrade



A view on LHC Injectors and LIU

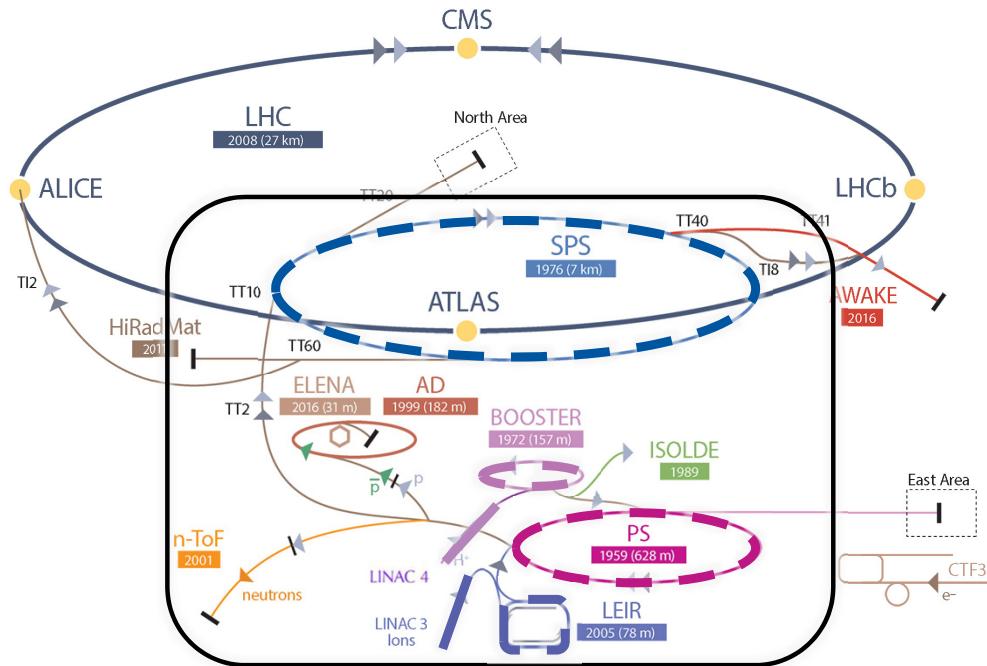




LHC Injectors Upgrade



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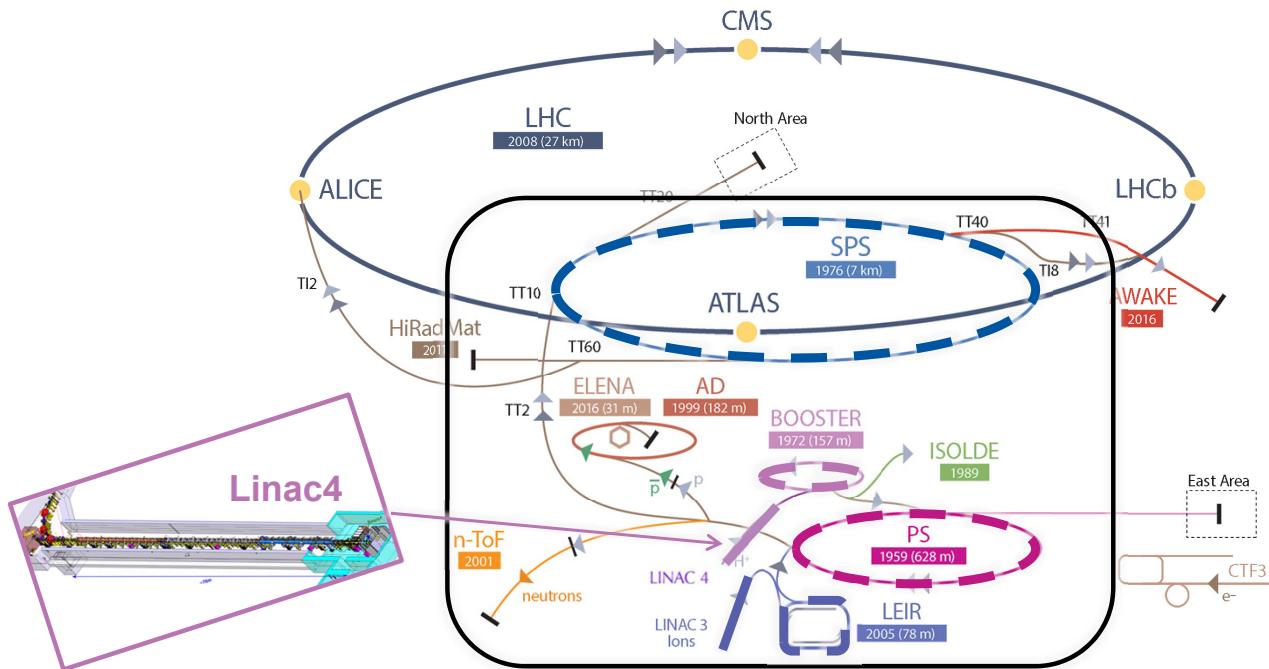




LHC Injectors Upgrade



A view on LHC Injectors and LIU



HB2018, Daejeon, Korea, 17 June, 2018

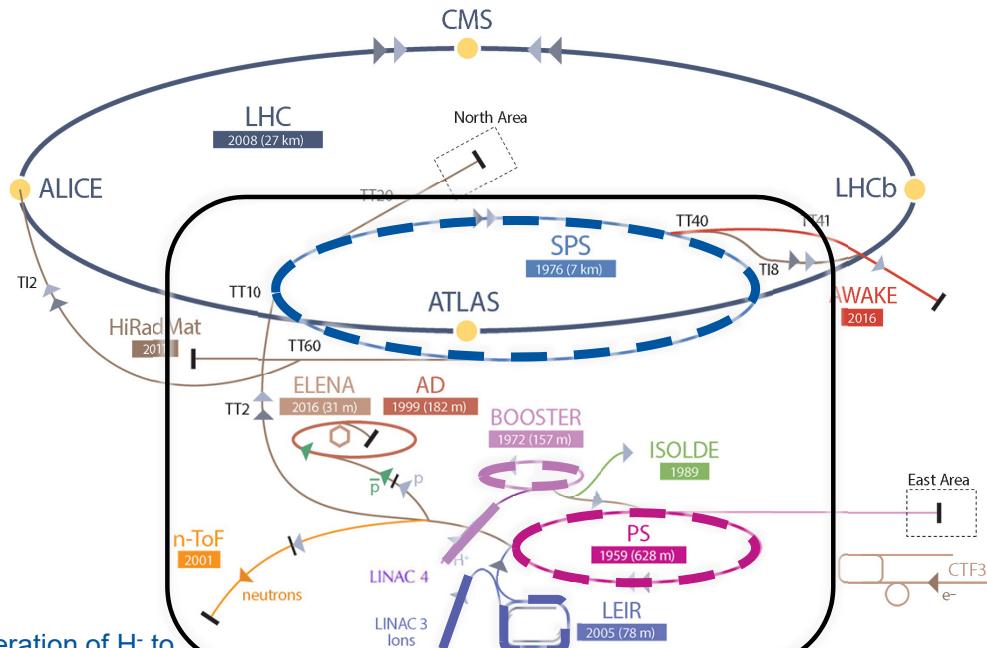
Giovanni Rumolo, Beam Dynamics Challenges for the LHC and Injector Upgrades



LHC Injectors Upgrade



A view on LHC Injectors and LIU



- Acceleration of H^- to 160 MeV (target 40 mA)
- Details of commissioning in next talk by G. Belloddi

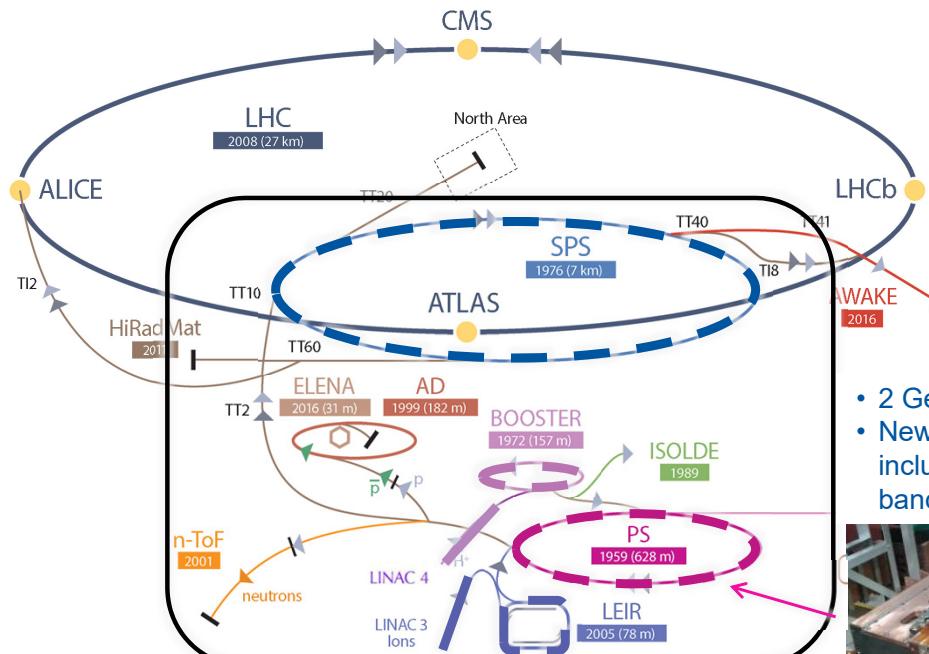




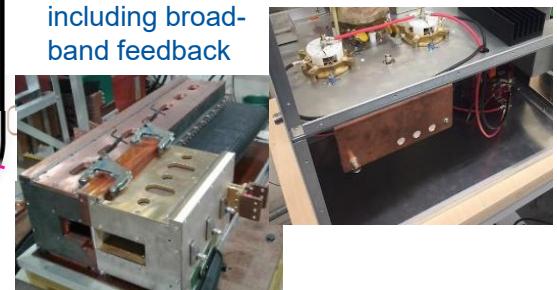
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A view on LHC Injectors and LIU



- 2 GeV injection
- New RF equipment including broad-band feedback

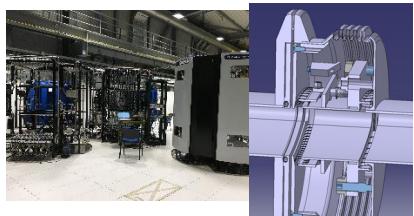




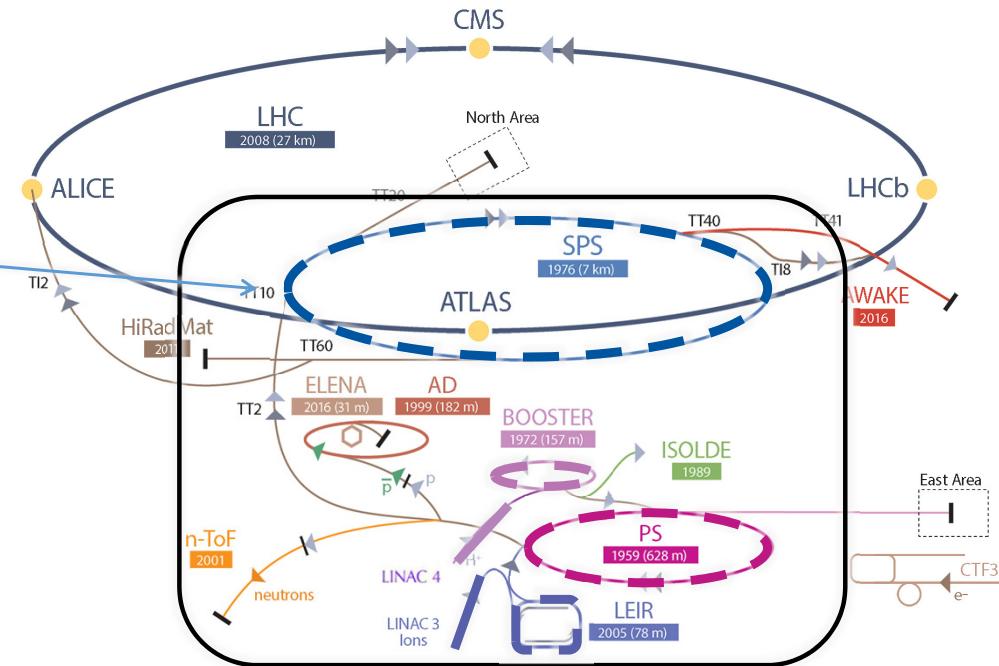
LHC Injectors Upgrade



A view on LHC Injectors and LIU



- Main RF system (200 MHz) upgrade
- Longitudinal impedance reduction & anti-ecloud coating
- New beam dump and protection devices

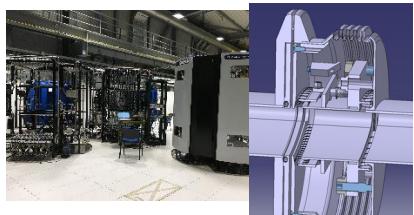




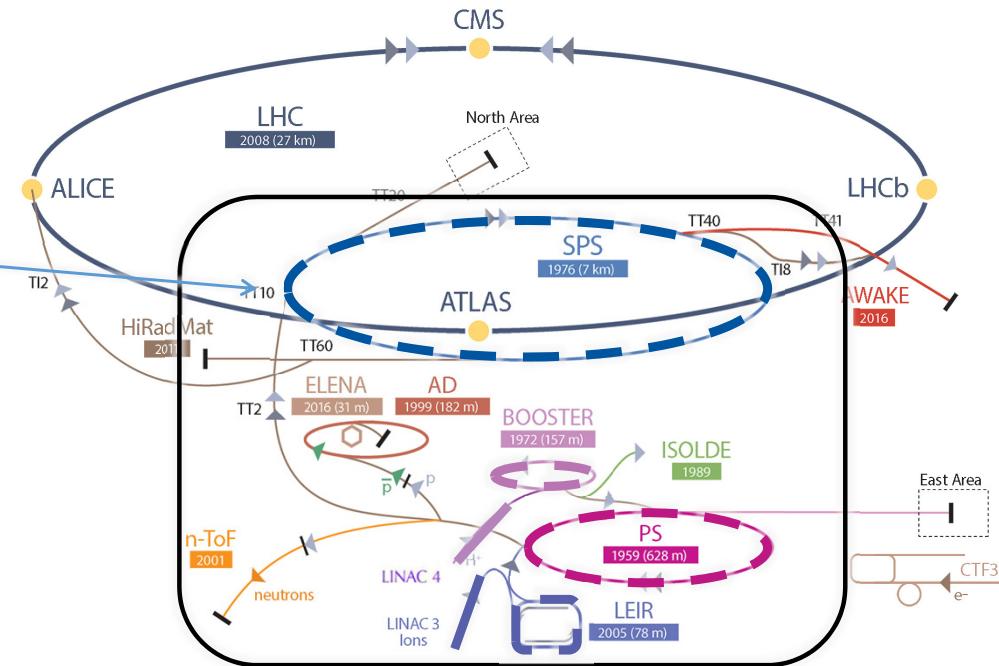
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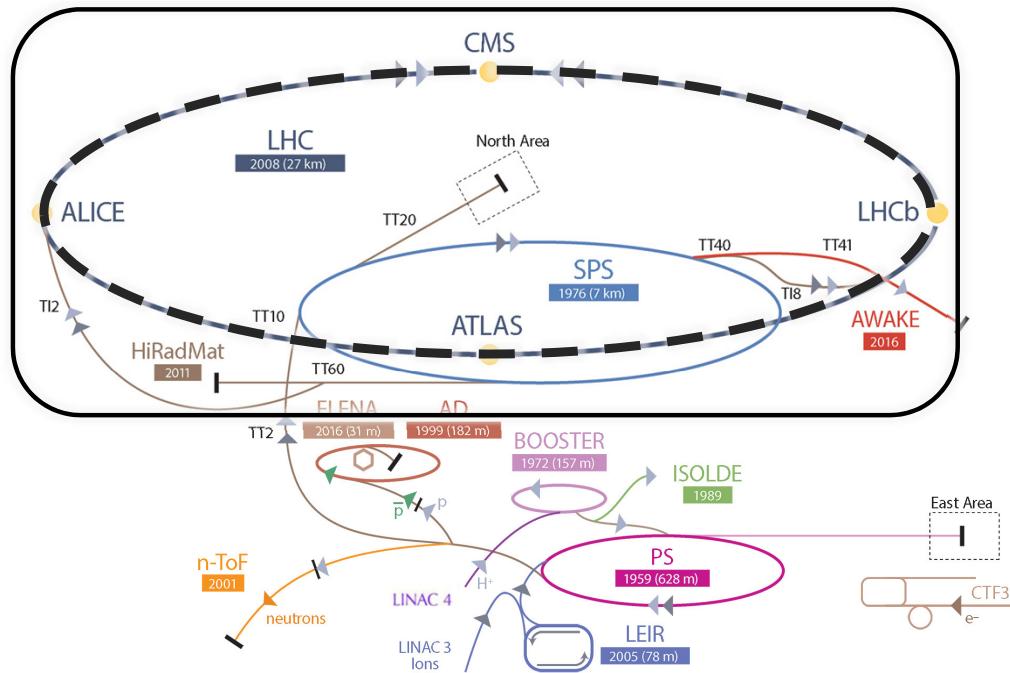




LHC Injectors Upgrade



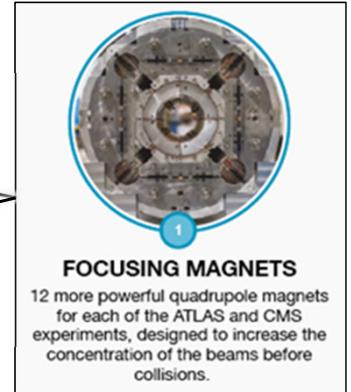
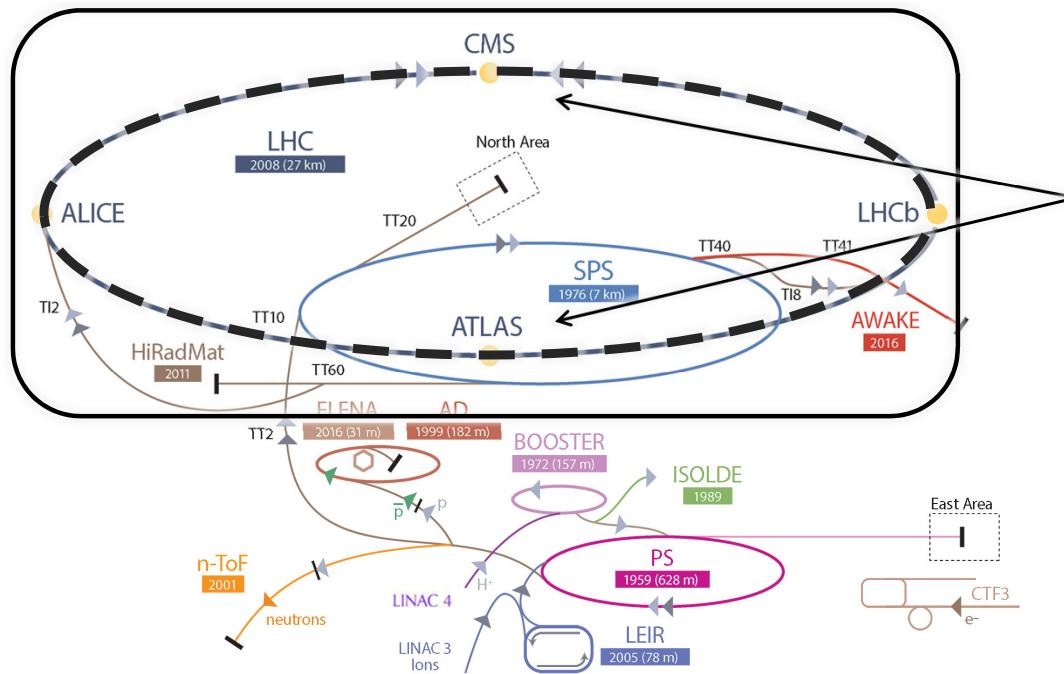
A view on LHC and HL-LHC





LHC Injectors Upgrade

A view on LHC and HL-LHC





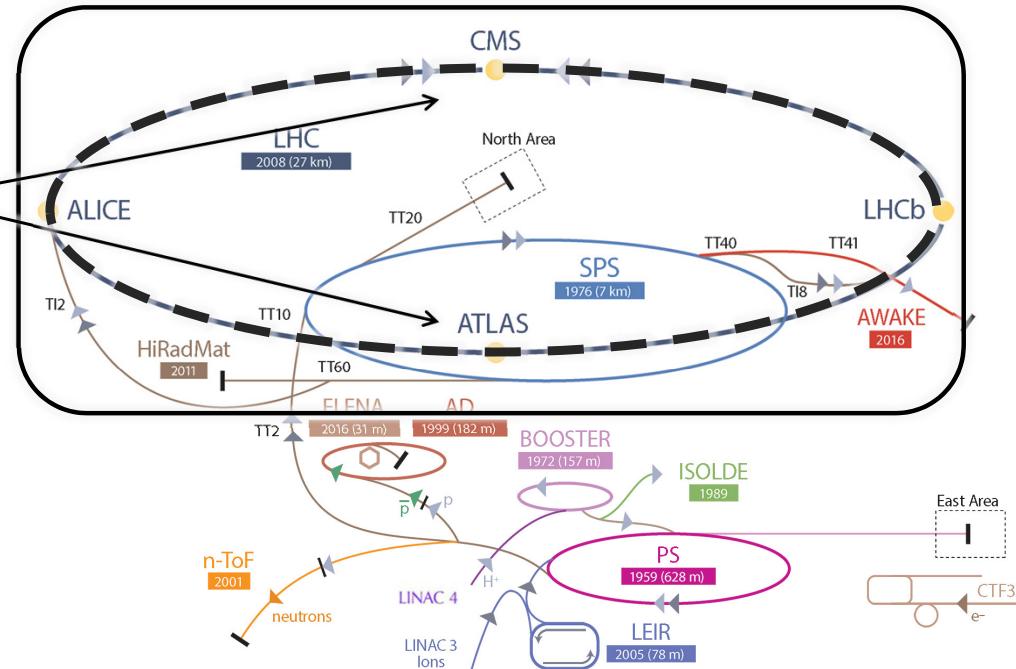
LHC Injectors Upgrade



A view on LHC and HL-LHC



"CRAB" CAVITIES
8 superconducting "crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

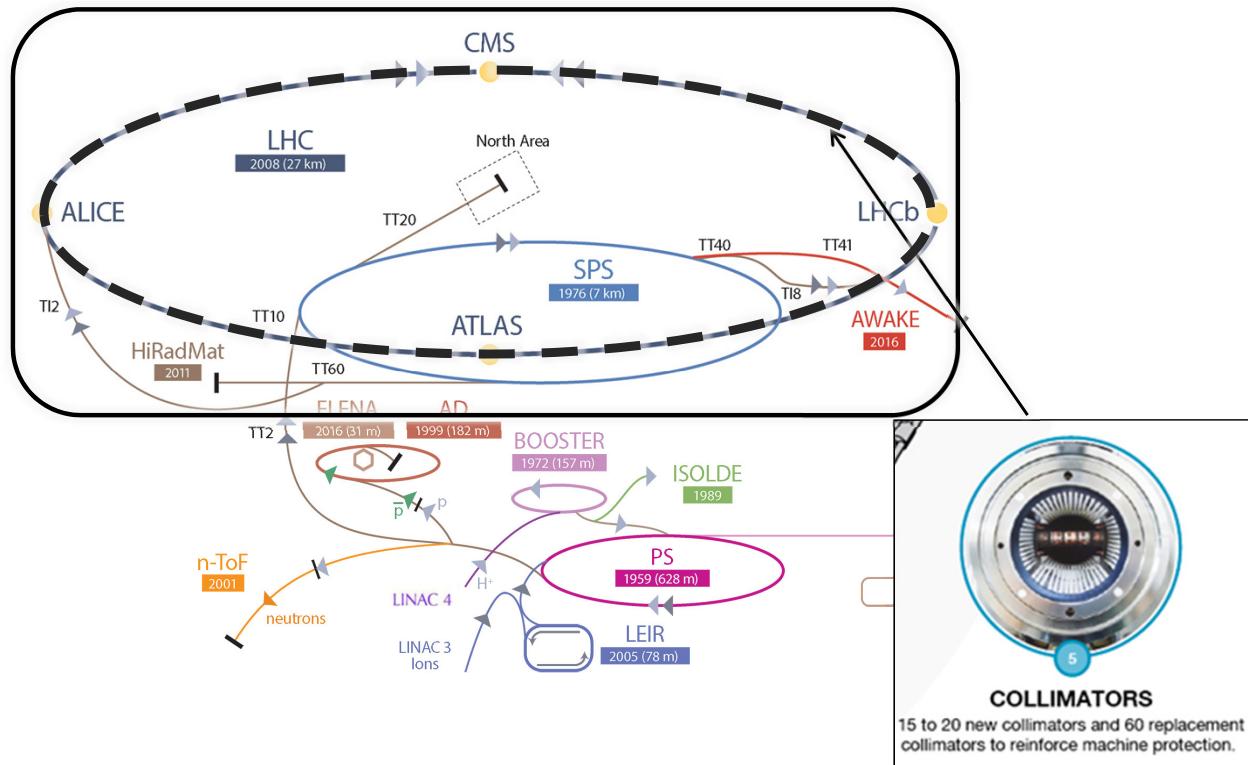




LHC Injectors Upgrade



A view on LHC and HL-LHC

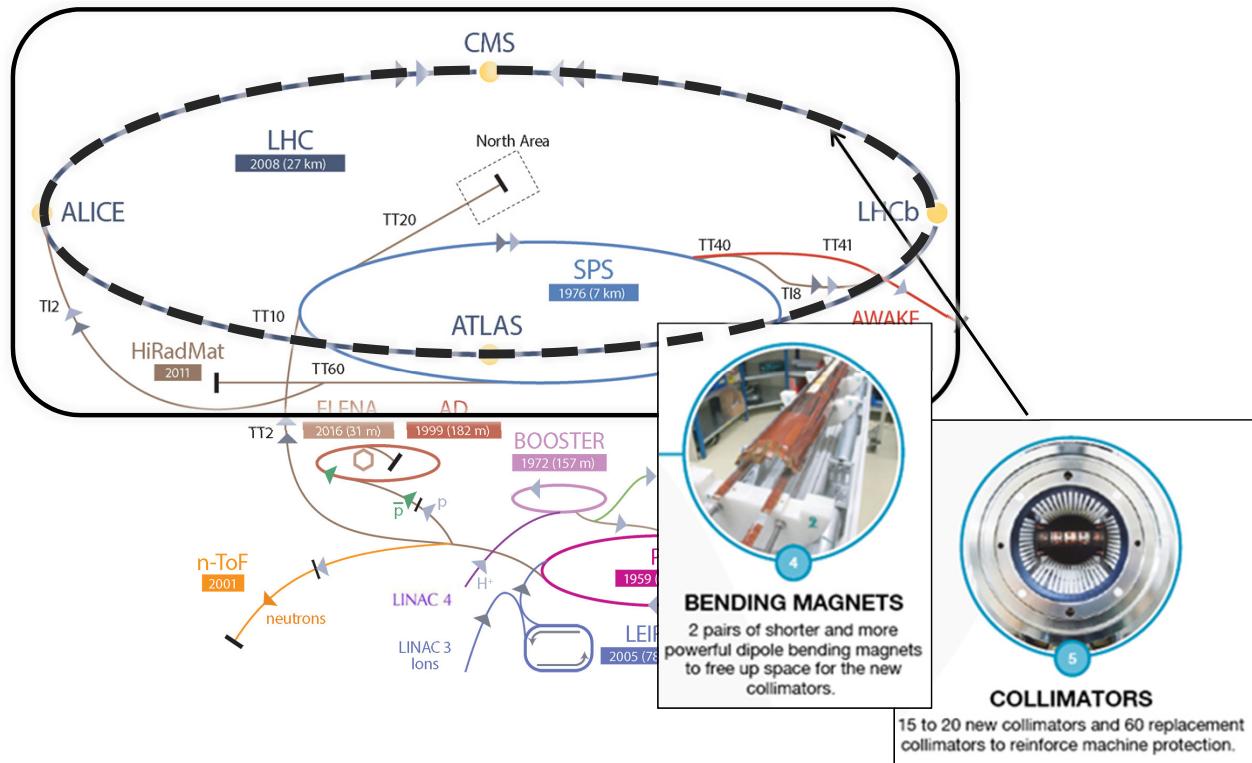




LHC Injectors Upgrade



A view on LHC and HL-LHC

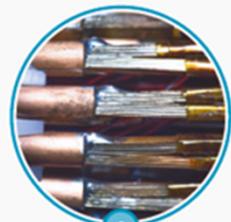
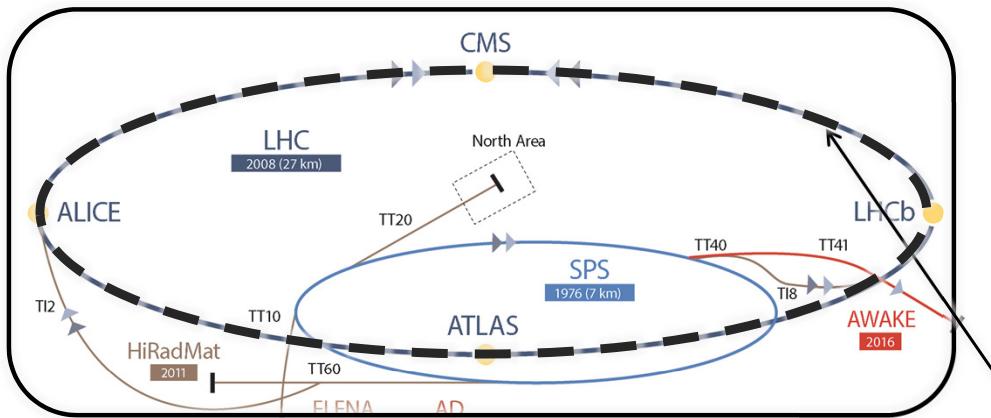




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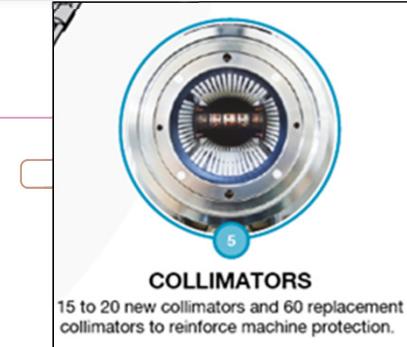


A view on LHC and HL-LHC



SUPERCONDUCTING LINKS

Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.



COLLIMATORS

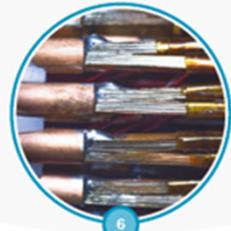
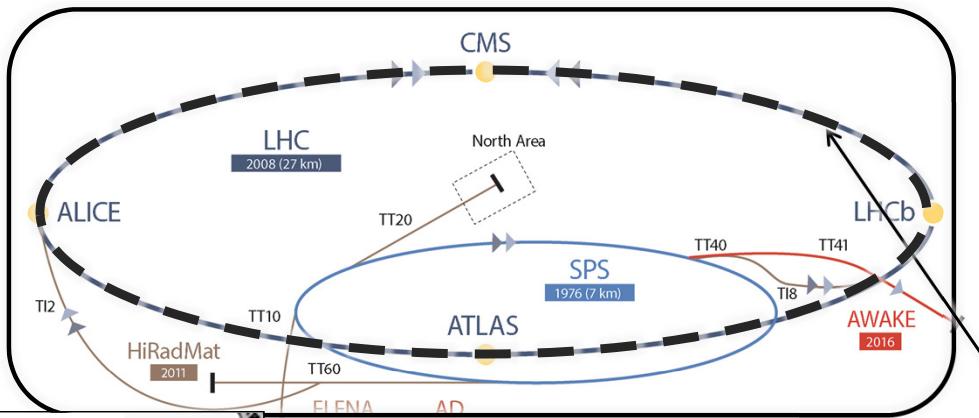
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.



LHC Injectors Upgrade



A view on LHC and HL-LHC



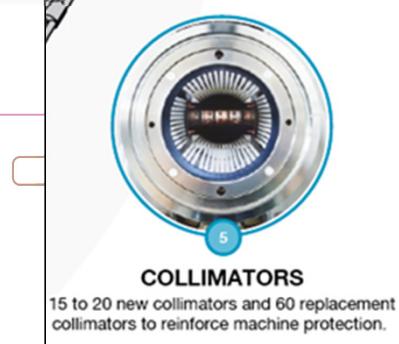
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CRYOGENICS

2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS



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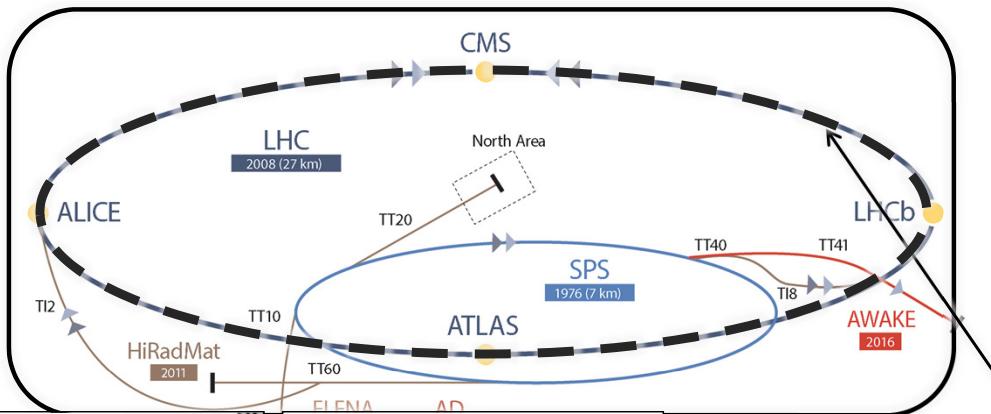




LHC Injectors Upgrade



A view on LHC and HL-LHC



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Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.



CRYOGENICS

2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS



CIVIL ENGINEERING

2 new caverns and two new 300-metre service galleries; two new large shafts; new technical buildings on surface in P1 and P5 (ATLAS and CMS)



COLLIMATORS

15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.





LHC Injectors Upgrade



Timeline of the projects

Proton Runs



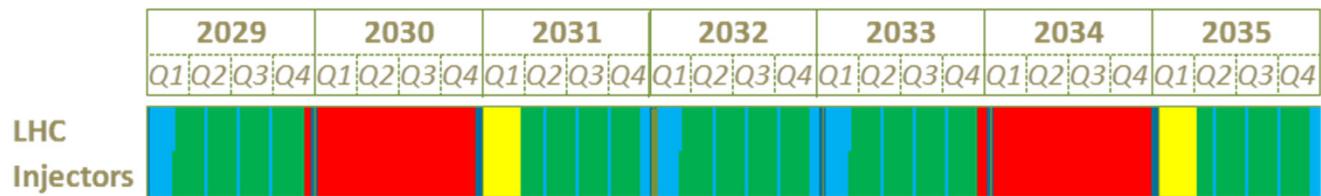
Technical Stops



Long Shutdowns



Beam Commissioning





LHC Injectors Upgrade



Timeline of the projects

Proton Runs

	2015	2016	2017	2018	2019	2020	2021
	Q1 Q2 Q3 Q4						

Technical Stops



Long Shutdowns

Beam Commissioning





LHC Injectors Upgrade



Timeline of the projects

Proton Runs



Technical Stops



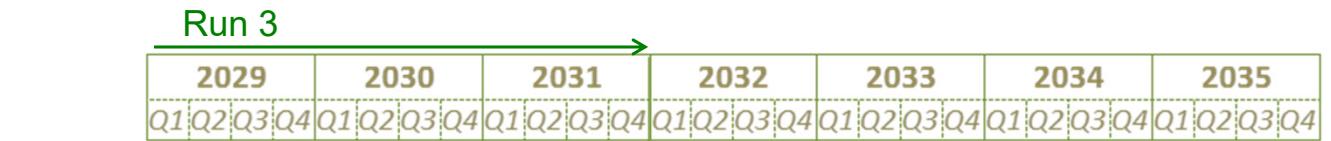
Long Shutdowns



Beam Commissioning



Run 3





LHC Injectors Upgrade



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Proton Runs

2015	2016	2017	2018	2019	2020	2021
Q1	Q2	Q3	Q4	Q1	Q2	Q3

Technical Stops



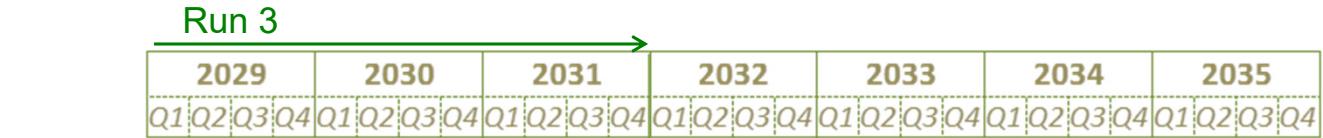
Long Shutdowns

2022	2023	2024	2025	2026	2027	2028
Q1	Q2	Q3	Q4	Q1	Q2	Q3

Beam Commissioning



Run 3: LIU beam commissioning through the injector chain





LHC Injectors Upgrade



Timeline of the projects

Proton Runs



Technical Stops

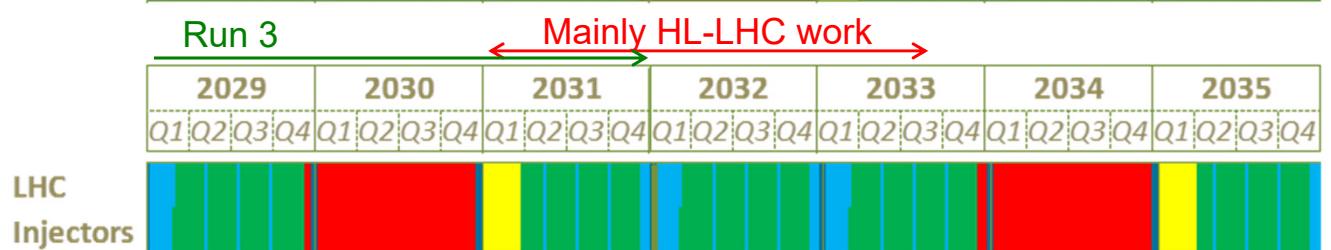


Long Shutdowns



Beam Commissioning

Run 3: LIU beam commissioning through the injector chain





LHC Injectors Upgrade



Timeline of the projects

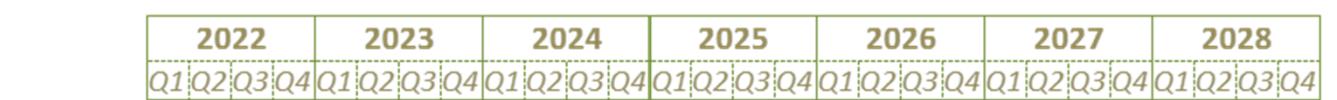
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Technical Stops



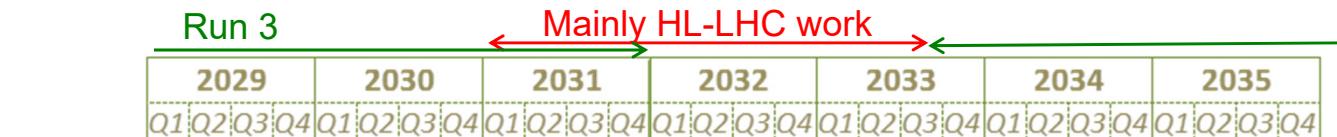
Long Shutdowns



Beam Commissioning



Run 3: LIU beam commissioning through the injector chain



Run 4
----->





LHC Injectors Upgrade



Timeline of the projects

Proton Runs



Technical Stops

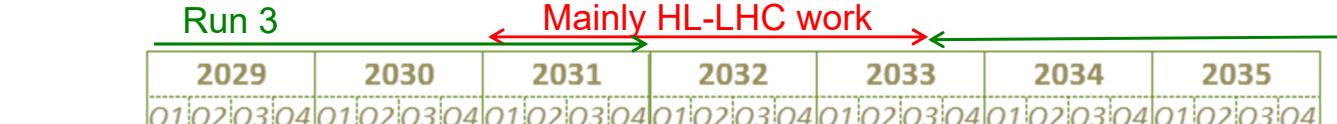


Long Shutdowns

Beam Commissioning



Run 3: LIU beam commissioning through the injector chain



Run 4: HL-LHC run with a period of 'luminosity learning'

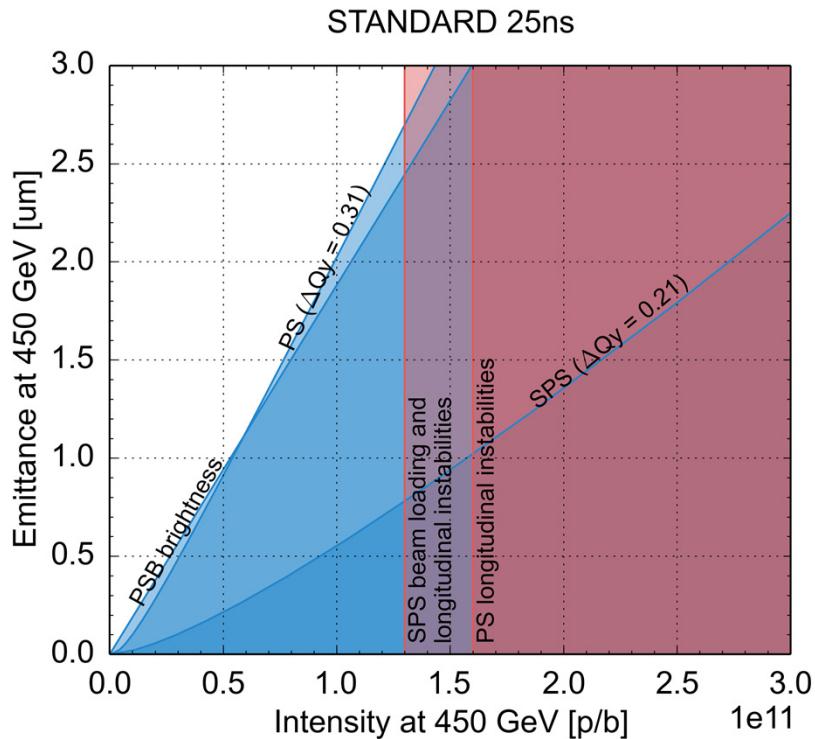




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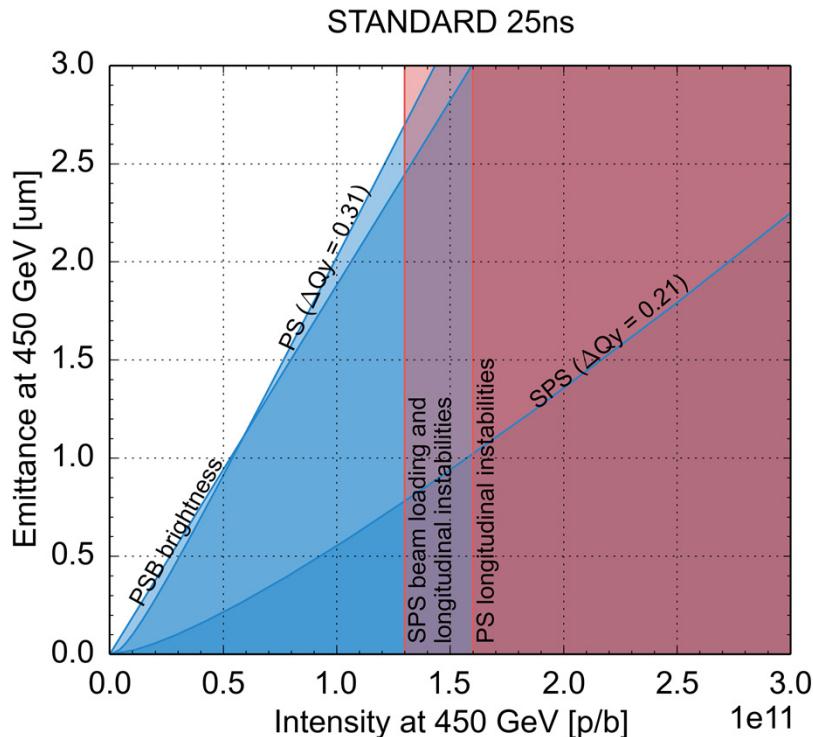


Present performance limitations



	$N_b \times 10^{11} p/b$	$\epsilon_{x,y} (\mu m)$
HL-LHC target	2.3	2.1
Present	1.3	2.7

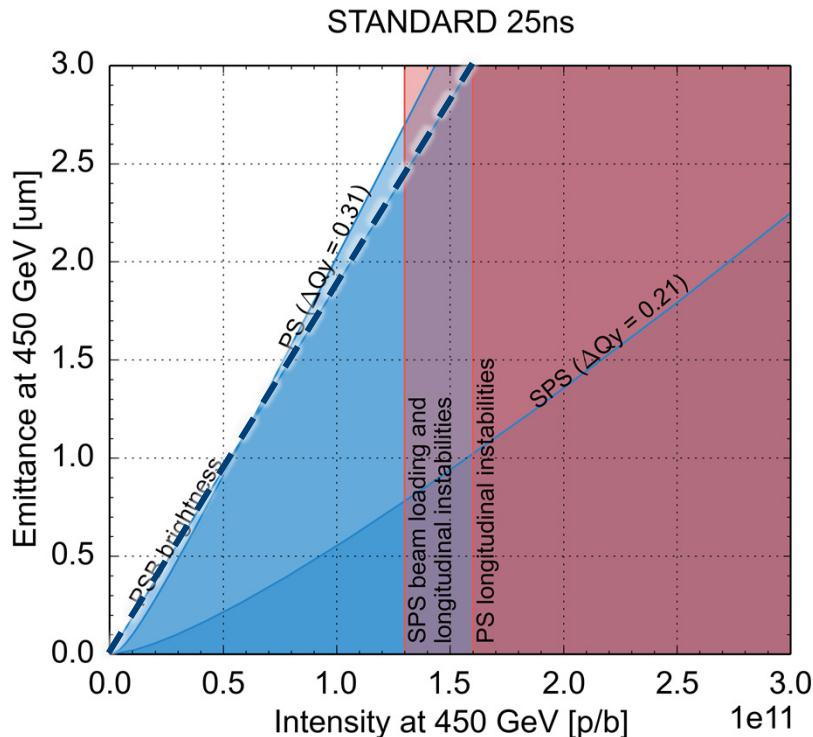
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- **PS and SPS injection:** Brightness limited by space charge – $\Delta Q < 0.31$ (PS) and 0.21 (SPS), to limit beam degradation (**H. Bartosik's talk**)
- **PS cycle:** Bunch intensity limited by longitudinal coupled bunch dipolar instability
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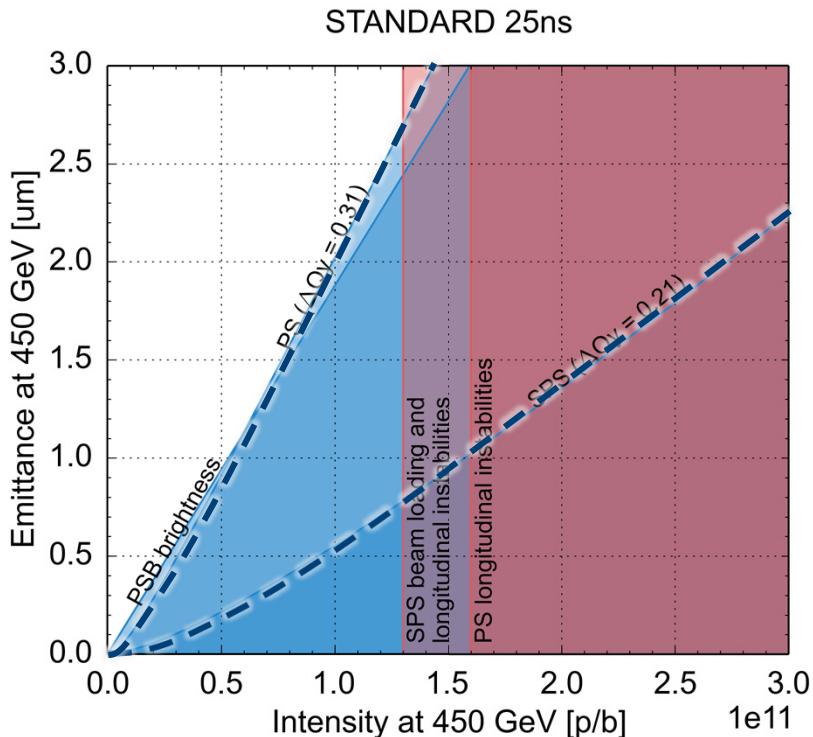
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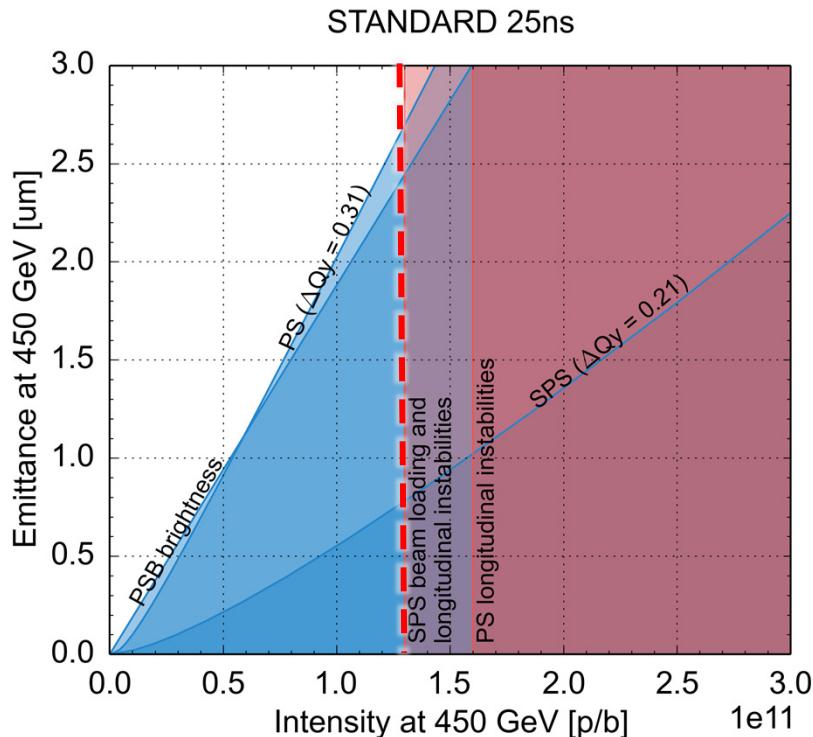
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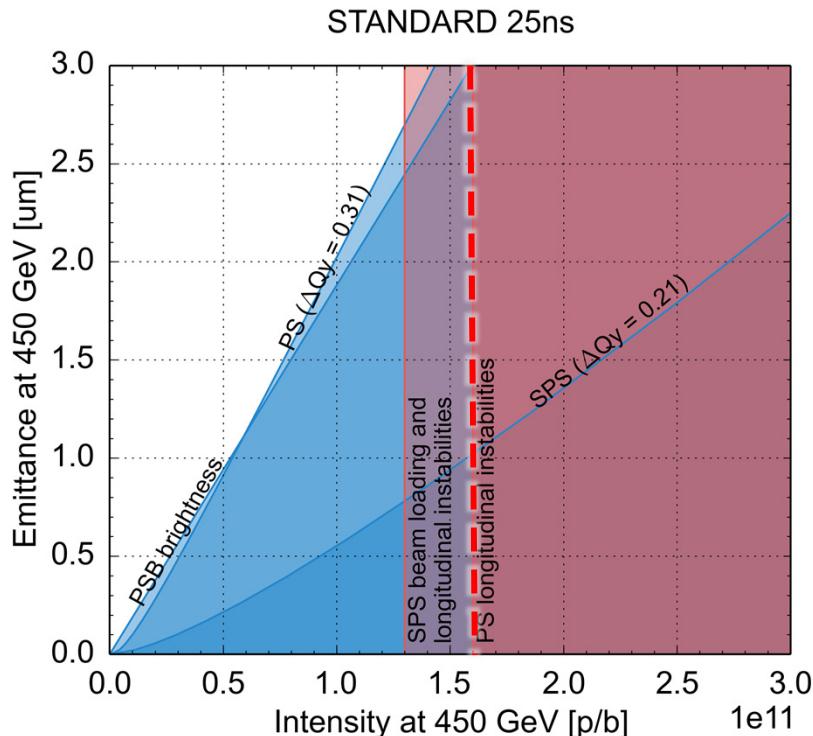
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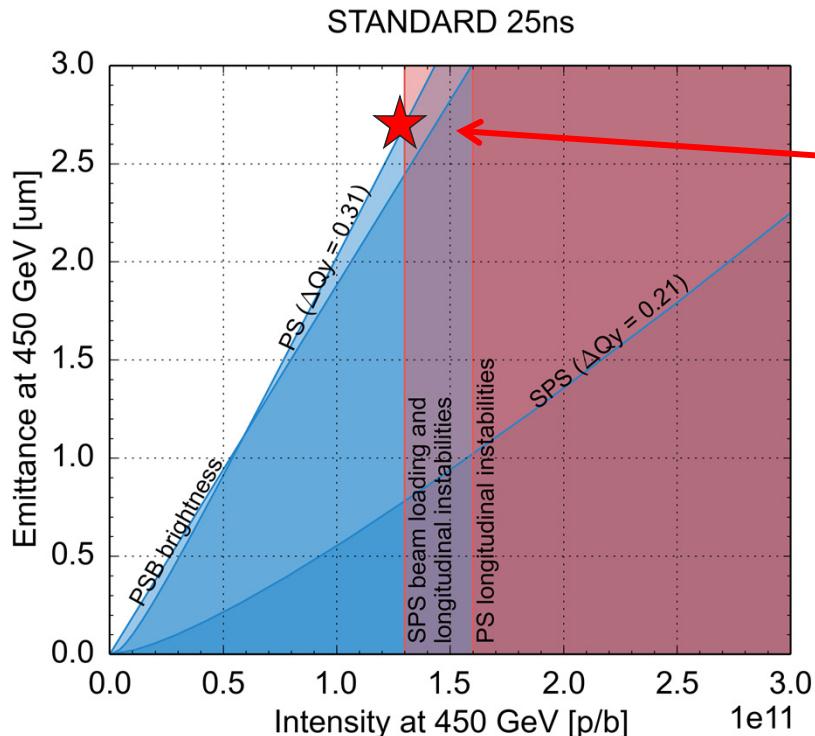
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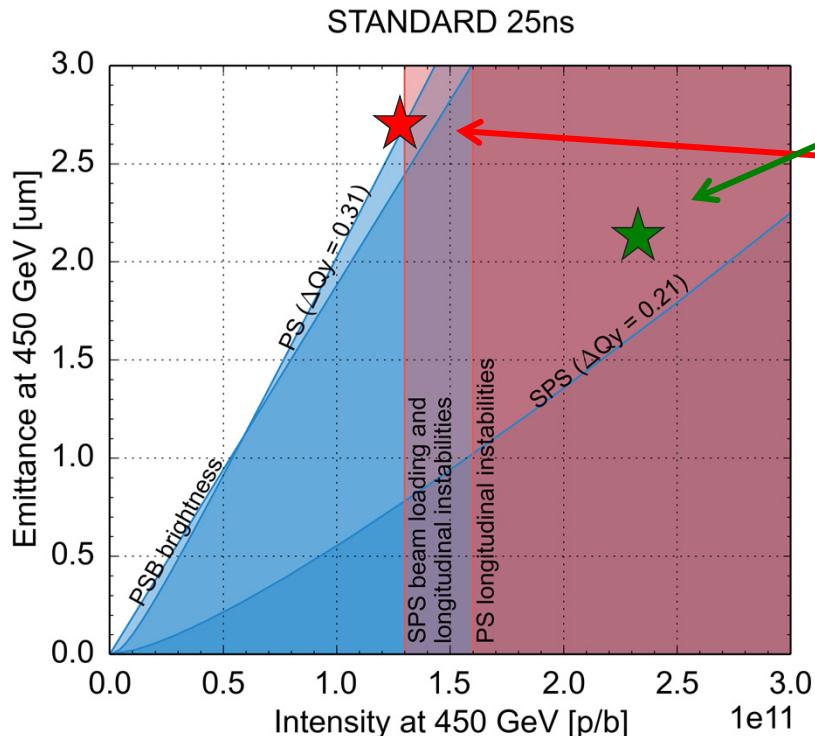
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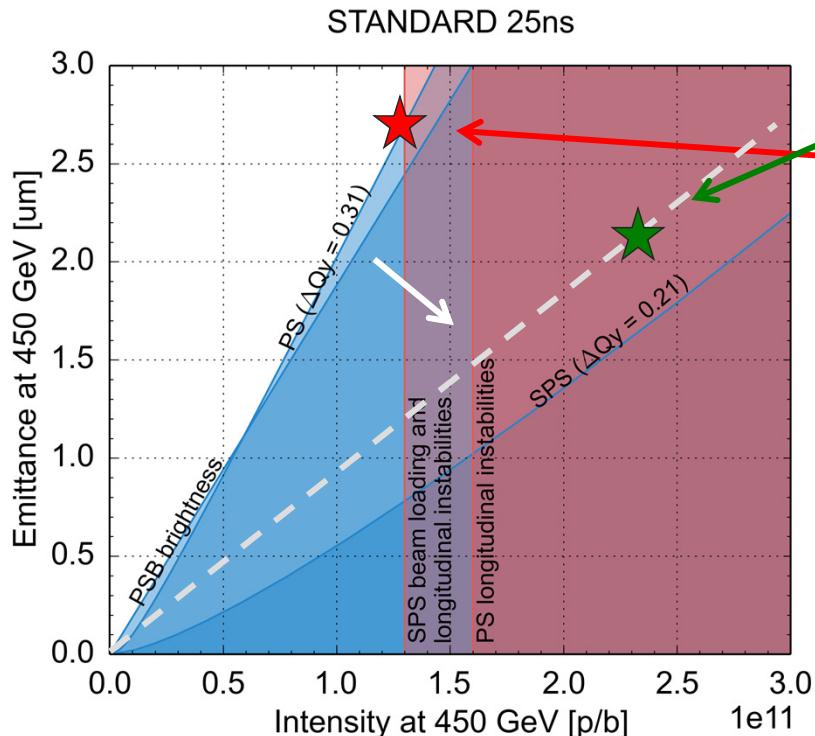
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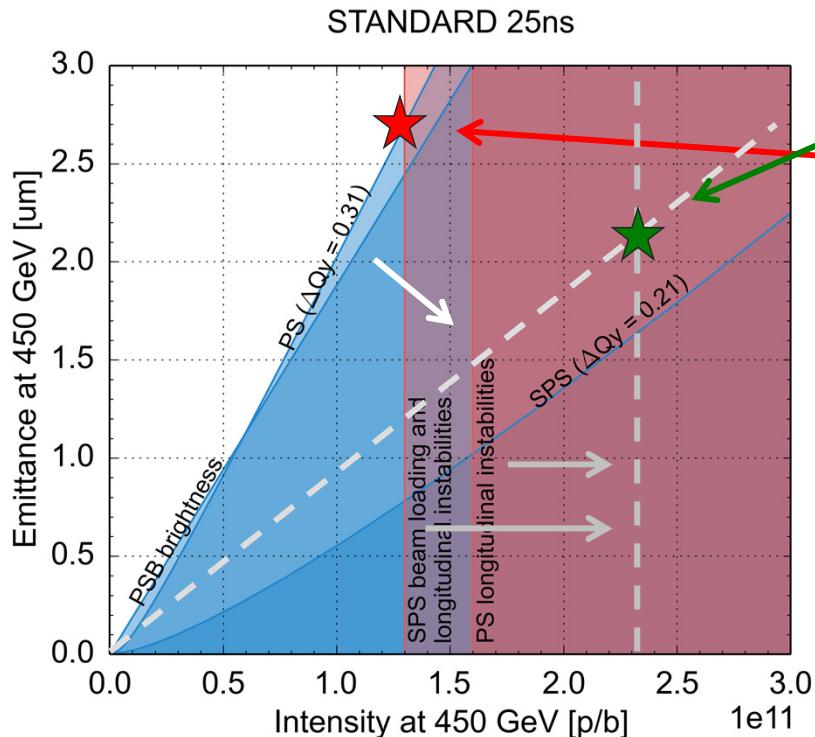
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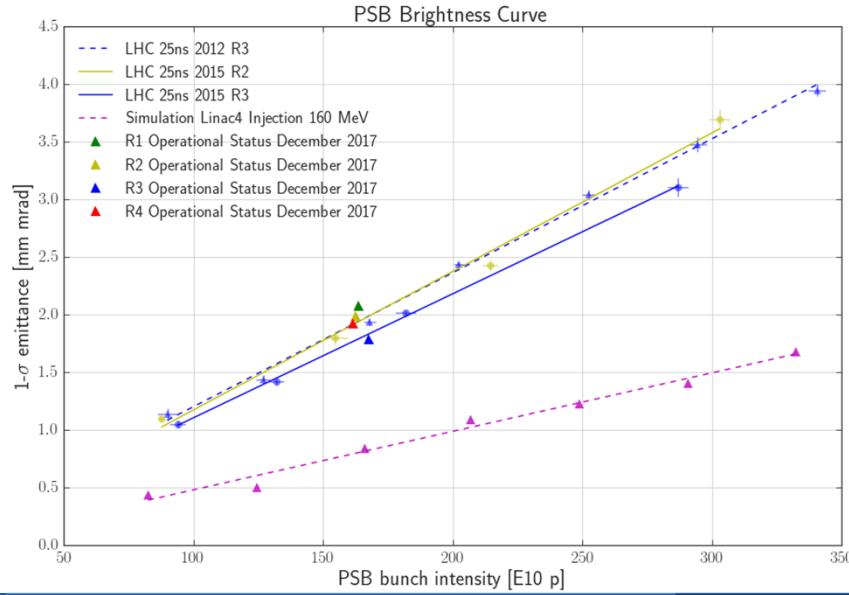


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Lifting the brightness limitations

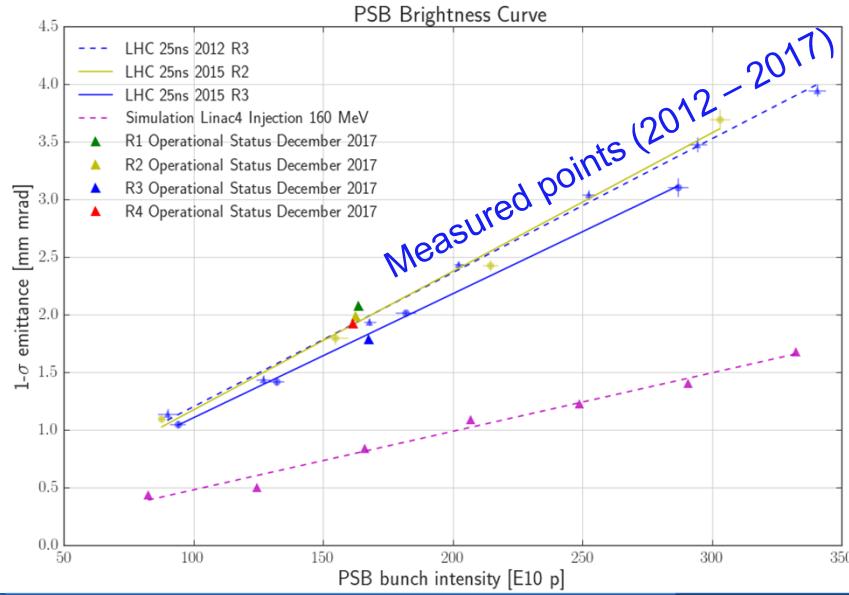
- Halve the slope of the **PSB brightness line**
 - 160 MeV H⁻ charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2



$$\left[\frac{(\beta\gamma^2)_{160 \text{ MeV}}}{(\beta\gamma^2)_{50 \text{ MeV}}} \right] = 2$$

Lifting the brightness limitations

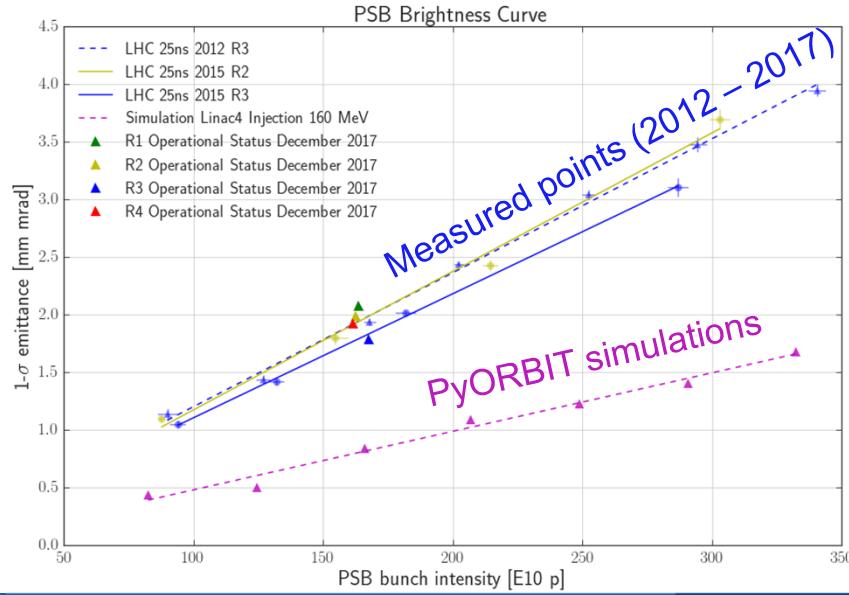
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Lifting the brightness limitations

- Halve the slope of the **PSB brightness line**
 - 160 MeV H⁻ charge exchange injection from Linac4 replacing 50 MeV multiturn injection from Linac2
- Reduce **space charge at PS injection** to accommodate same tune spread as current LHC beam ($\Delta Q_y = -0.31$)
 - Increase of PS injection energy from 1.4 GeV to 2 GeV
 - Increase of longitudinal emittance (compatibly with other constraints) at transfer in order to gain from decreasing λ_{\max} and increasing $\delta = (\delta p/p_0)$

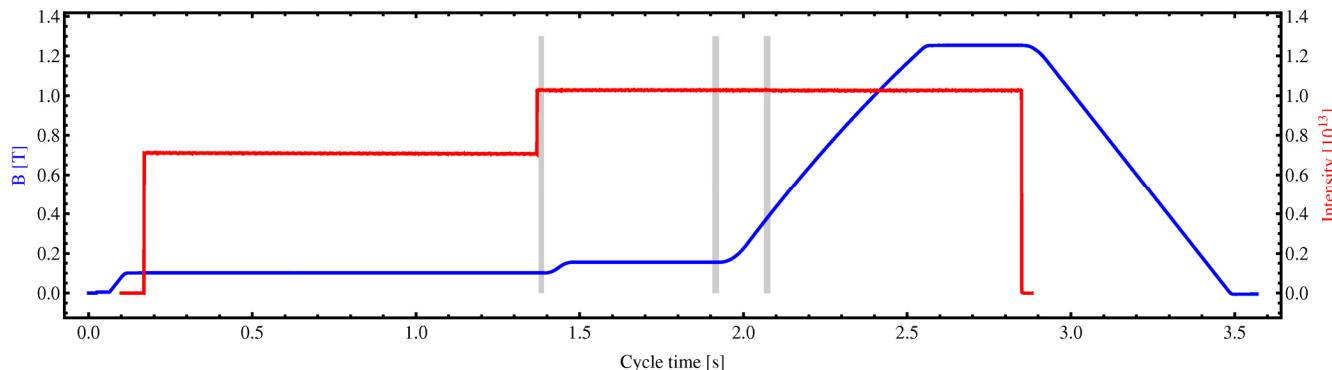
$$\Delta Q_{x,y} = \frac{\lambda_{\max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_{x,y}(s) ds}{\sqrt{\epsilon_{x,y}\beta_{x,y}(s) + D_{x,y}^2(s)\delta^2} \left(\sqrt{\epsilon_x\beta_x(s) + D_x^2(s)\delta^2} + \sqrt{\epsilon_y\beta_y(s) + D_y^2(s)\delta^2} \right)}$$



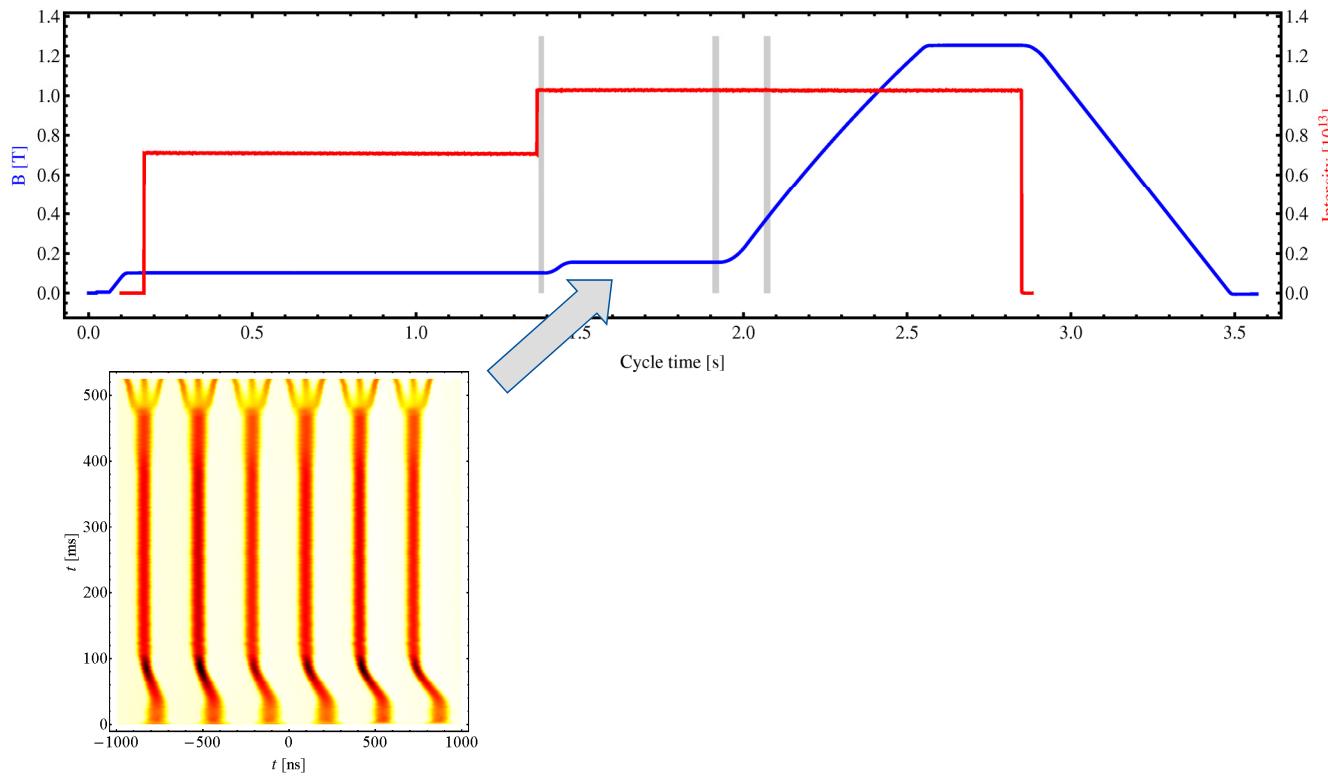
LHC Injectors Upgrade



Lifting the PS intensity limitation



Lifting the PS intensity limitation

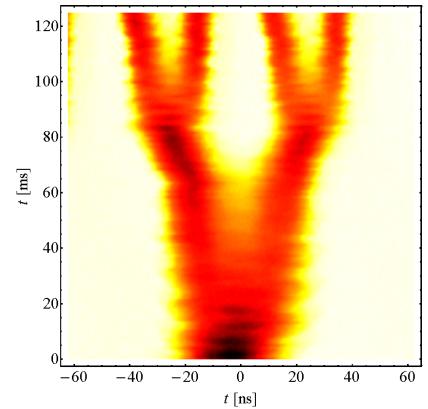
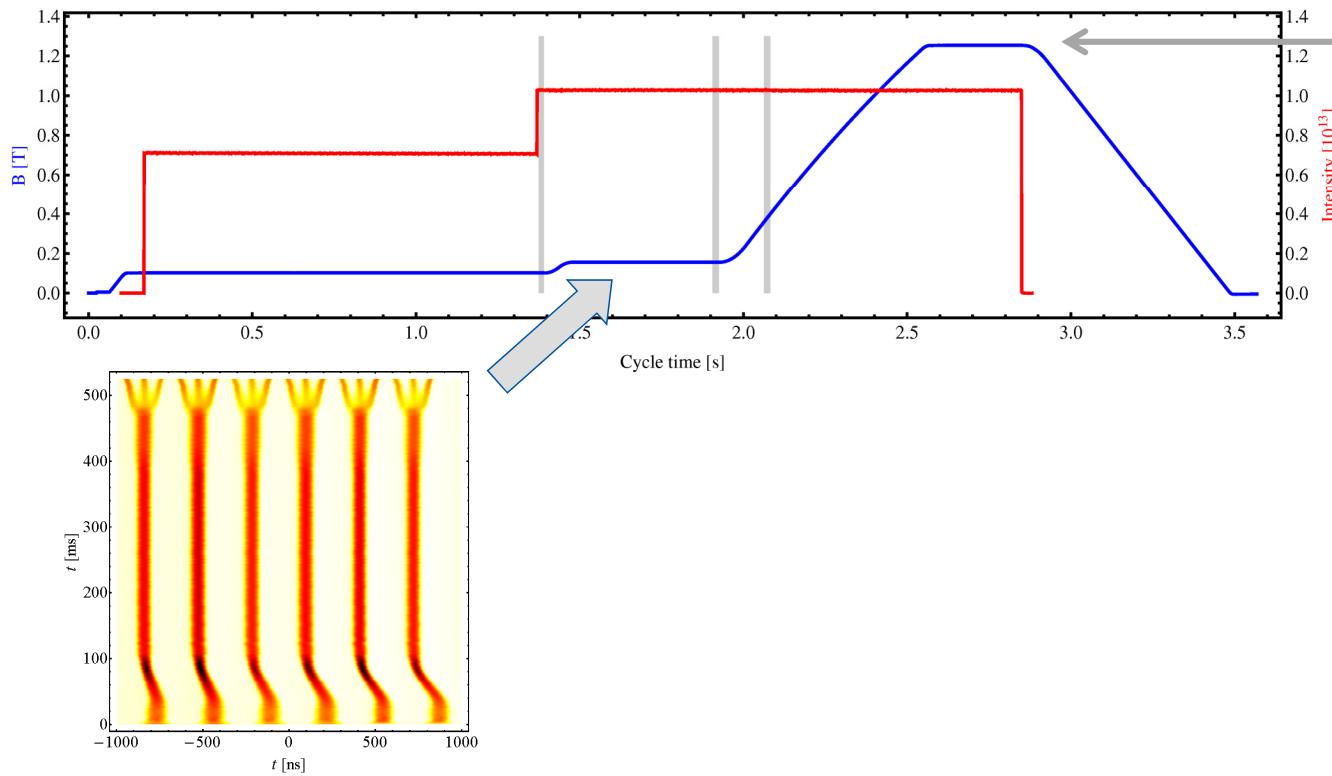




LHC Injectors Upgrade

HiLumi
HL-LHC PROJECT

Lifting the PS intensity limitation



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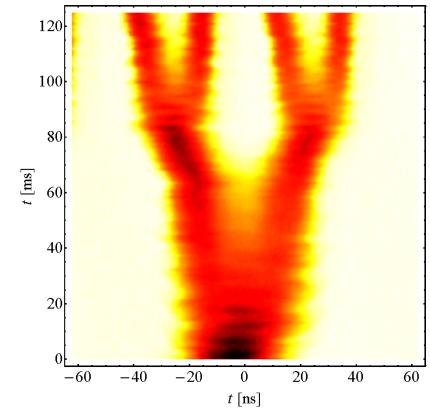
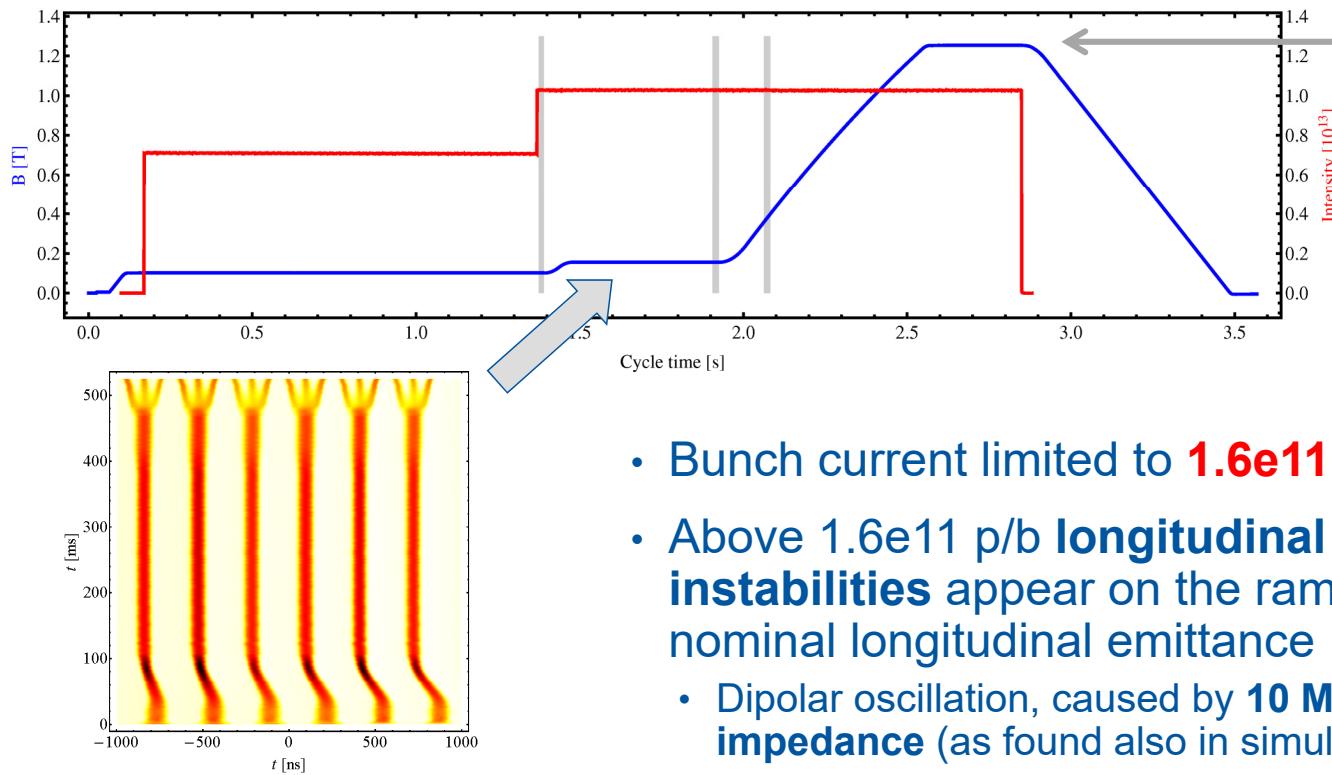
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LHC Injectors Upgrade

HiLumi
HL-LHC PROJECT

Lifting the PS intensity limitation



- Bunch current limited to **1.6e11 p/b at extraction**
- Above 1.6e11 p/b **longitudinal coupled bunch instabilities** appear on the ramp and at flat top for nominal longitudinal emittance
 - Dipolar oscillation, caused by **10 MHz RF system impedance** (as found also in simulations)

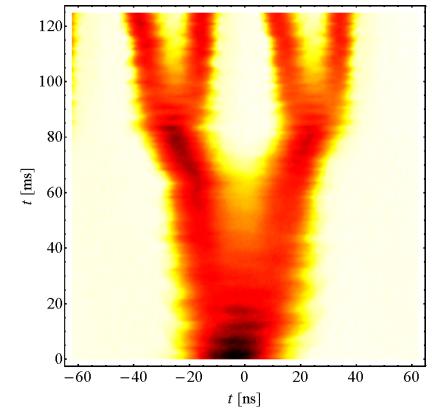
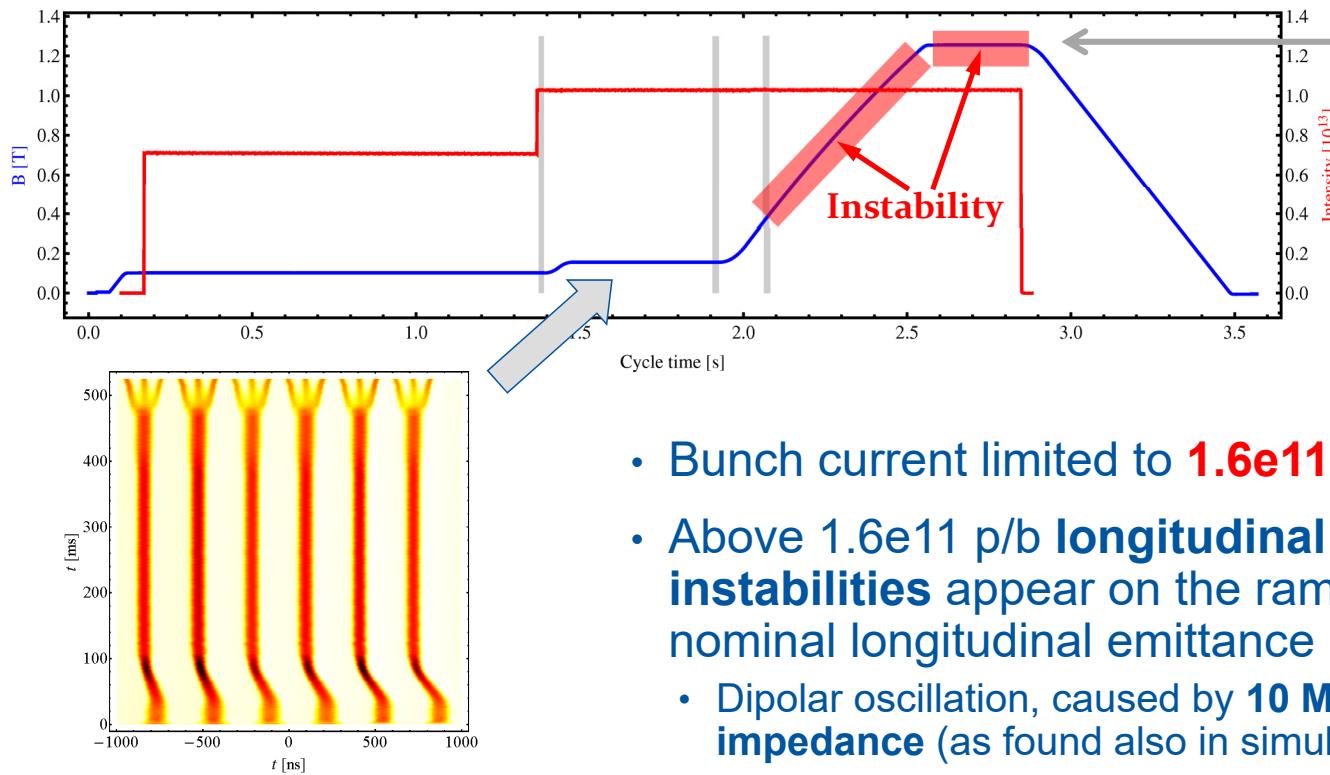




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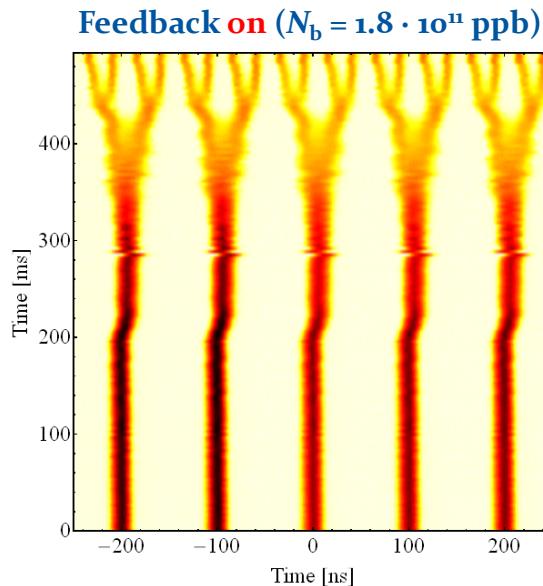
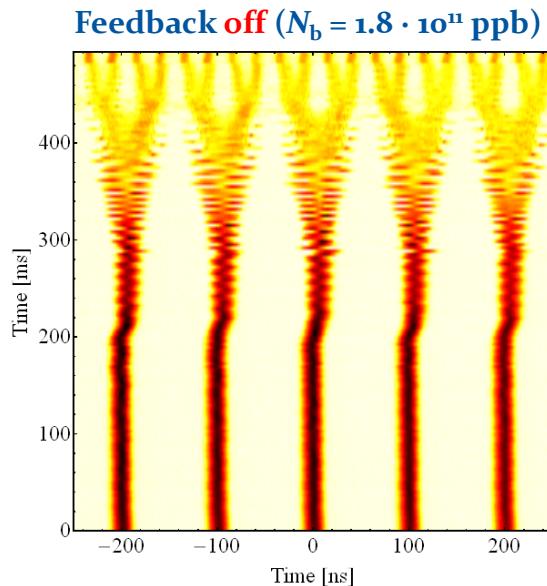


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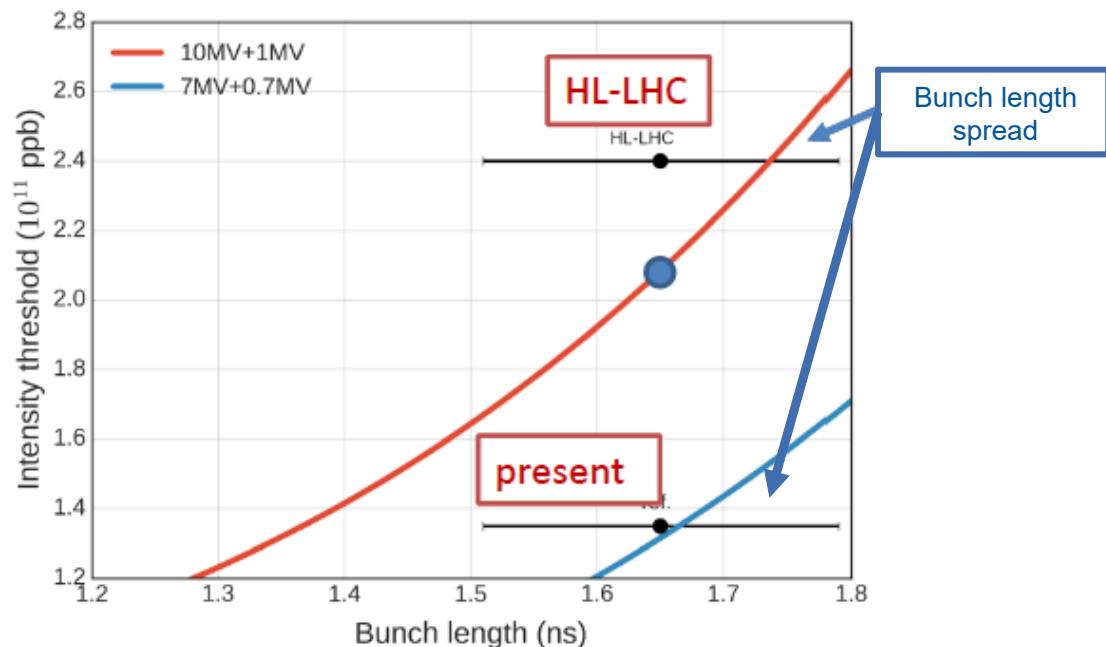


Lifting the PS intensity limitation

- **Longitudinal feedback** based on broad-band Finemet cavity as kicker installed and deployed over the last three years → stabilizes above $2e11$ p/b
- **Impedance reduction** of the 10 MHz cavities with upgrade of power amplifier → currently tested on one cavity, to be deployed on all cavities in LS2
- Ongoing study on the option of a **higher harmonic ('Landau') cavity** to have another weapon against longitudinal instabilities and reach the target LIU/HL-LHC intensity

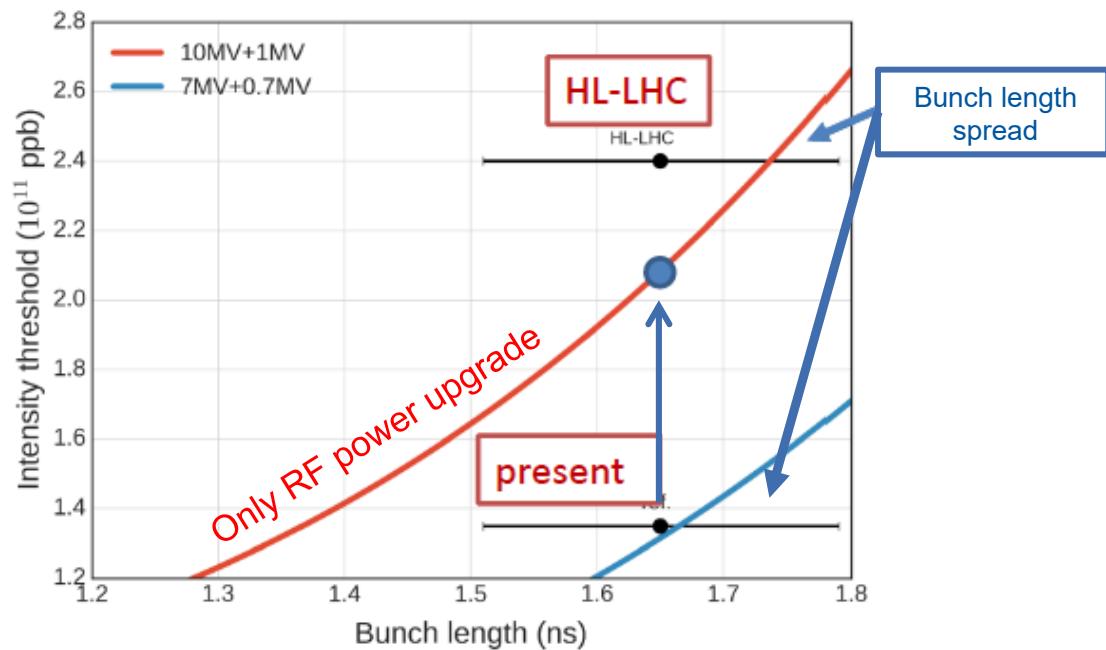
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 - Controlled emittance blow-up (with constraint of 1.7 ns bunch length at extraction)



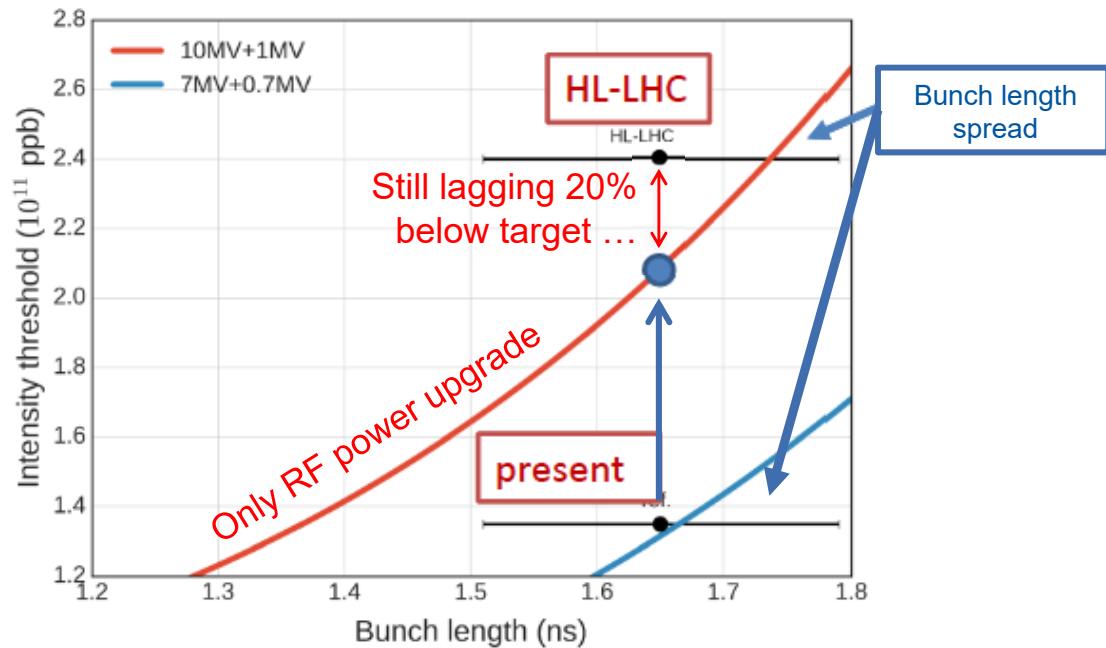
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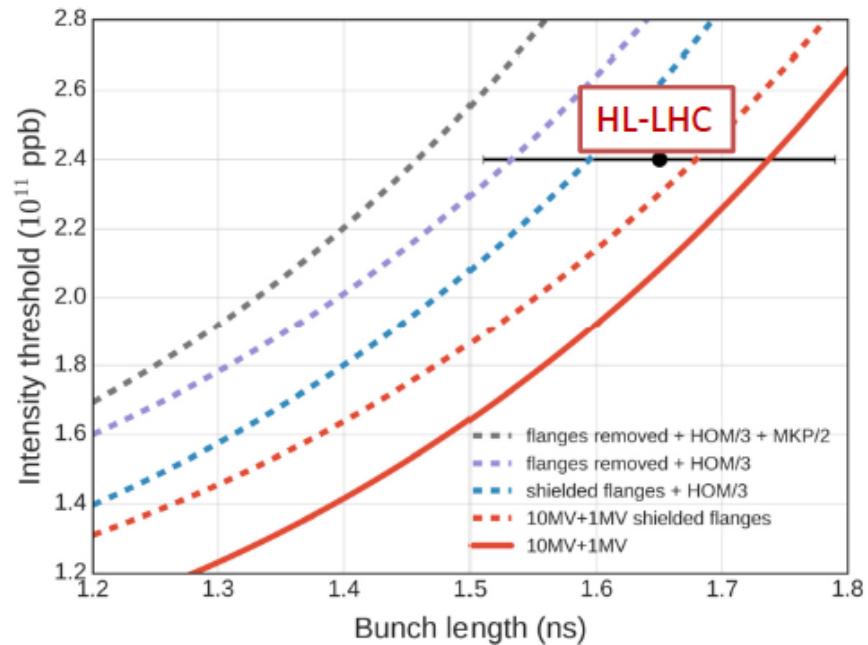


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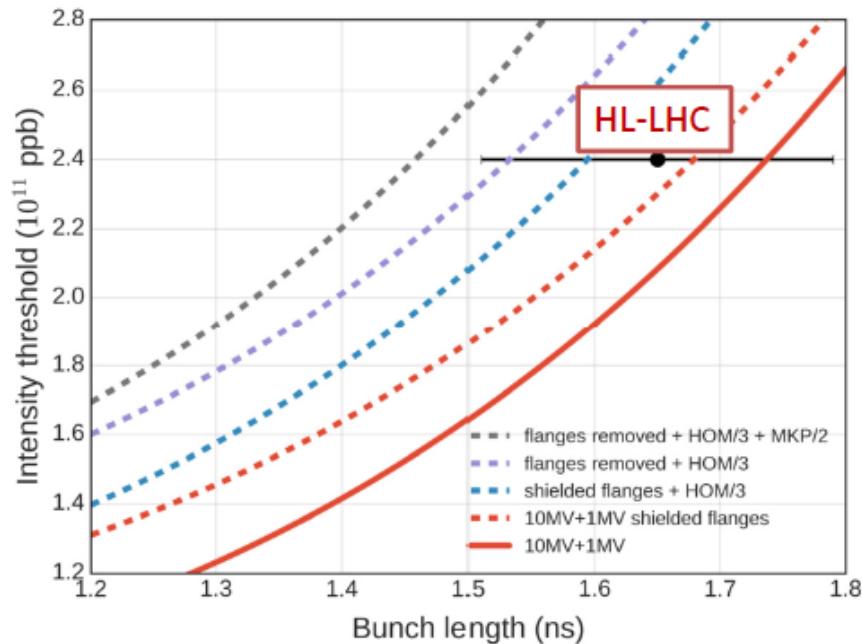


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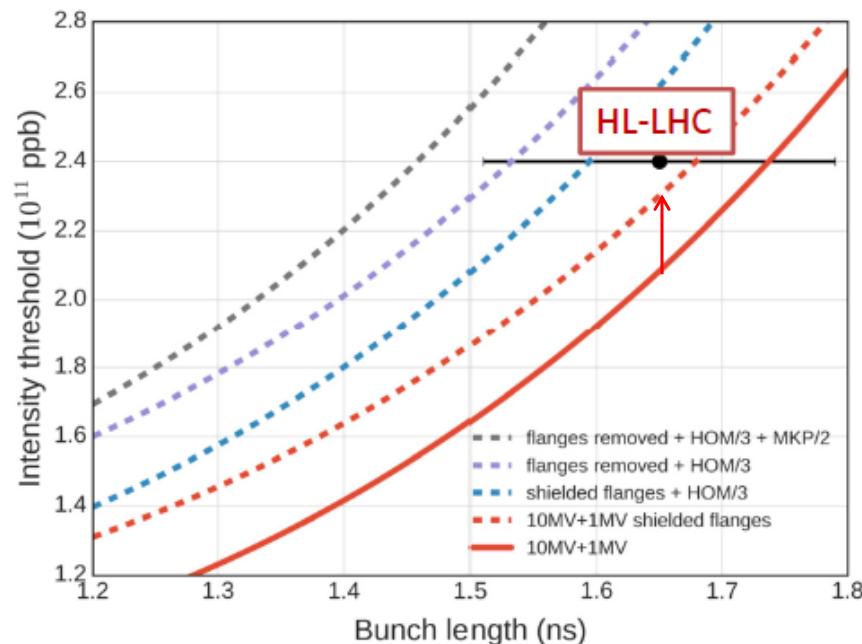
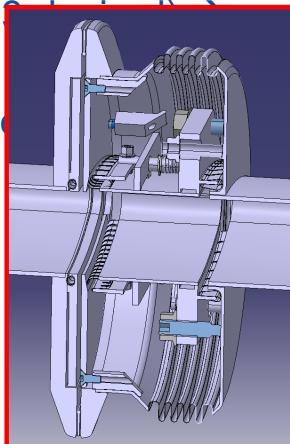
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 - Enhanced damping of HOMs of 200 MHz (factor 3 desired) → baseline for LIU
 - Serigraphy on the injection kickers MKP



Lifting the SPS intensity limitation

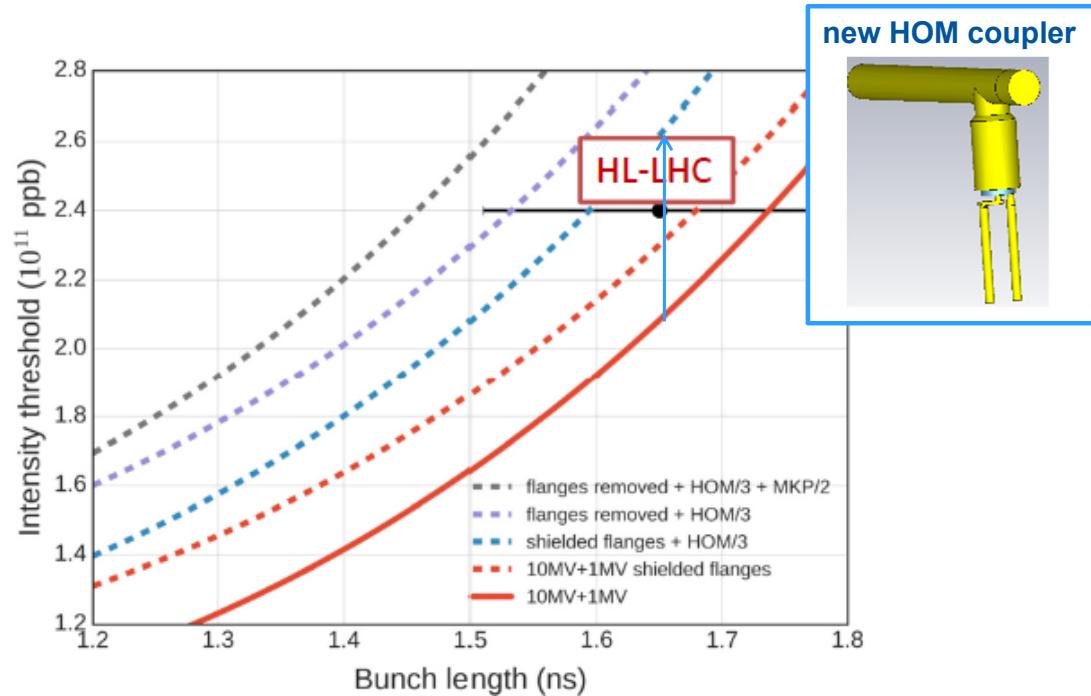
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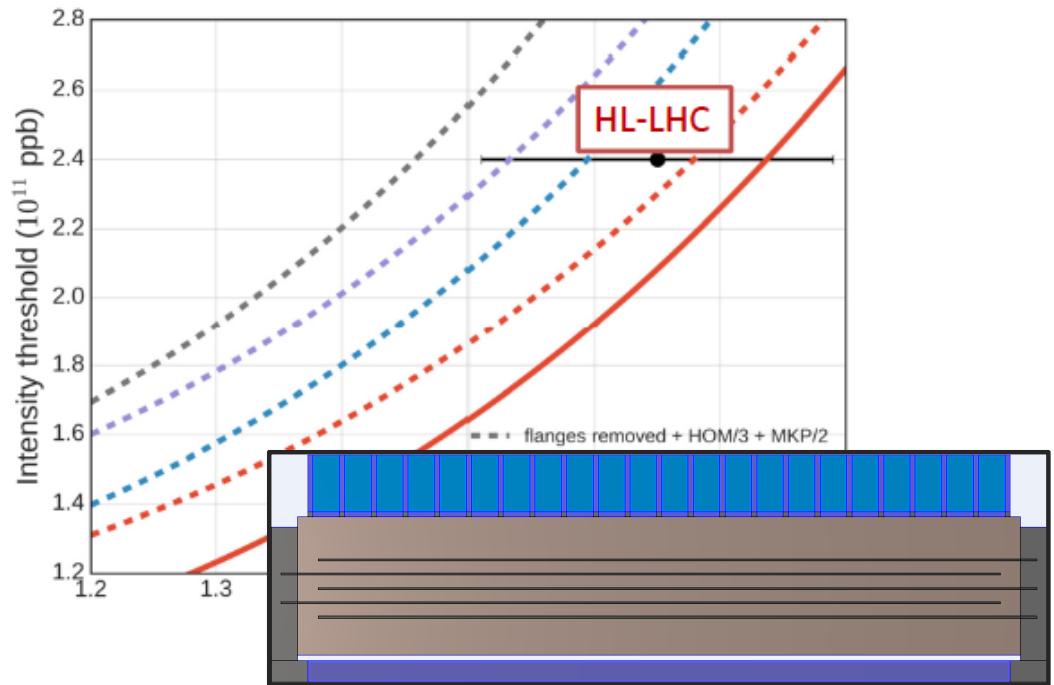
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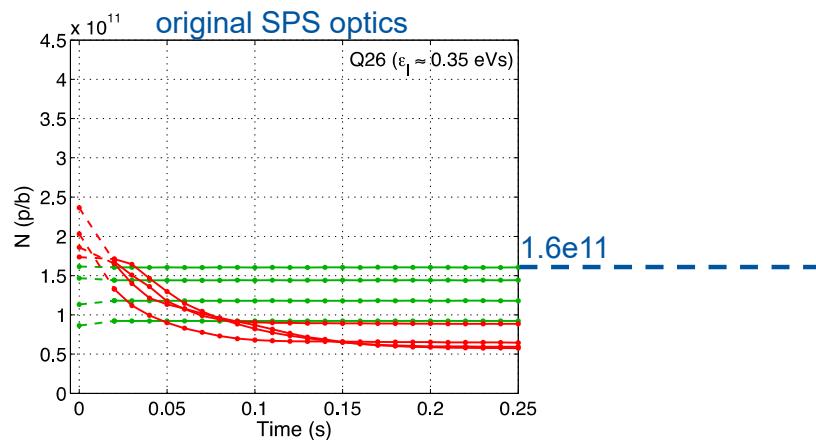
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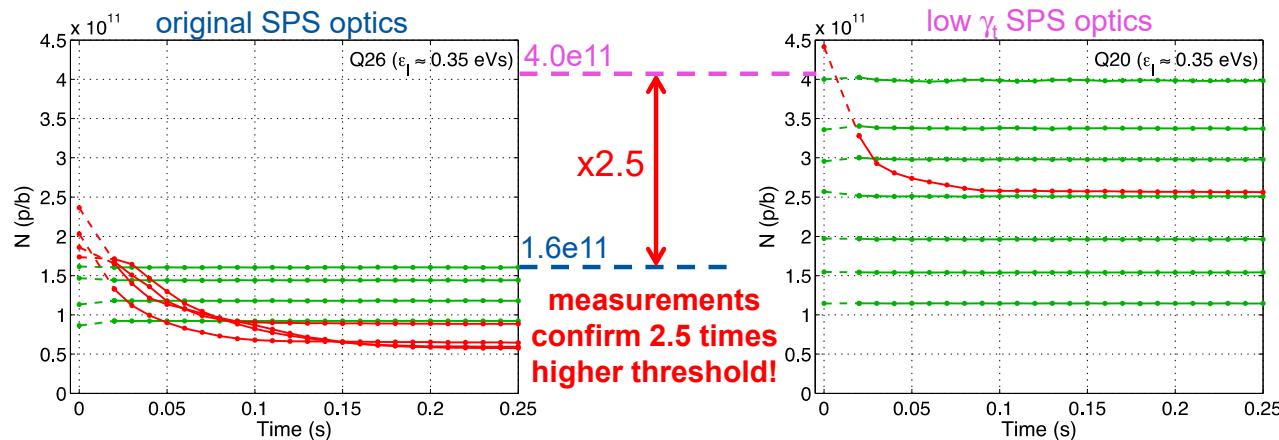
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LHC Injectors Upgrade

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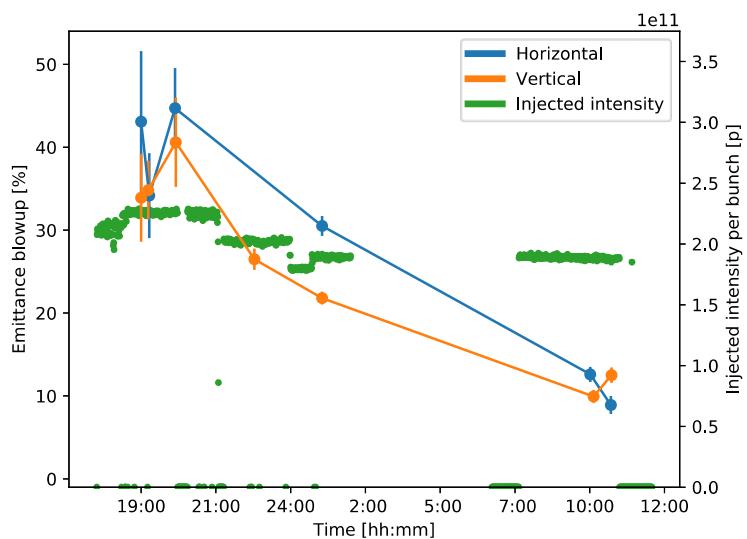


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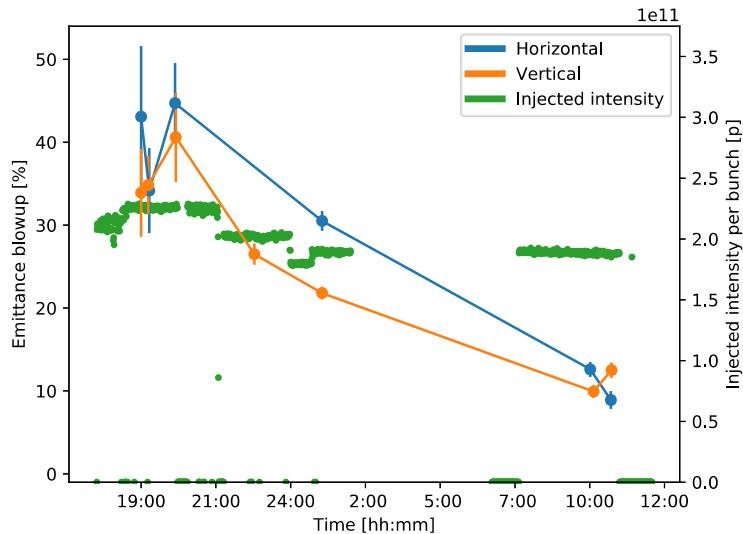
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Other SPS intensity limitations?



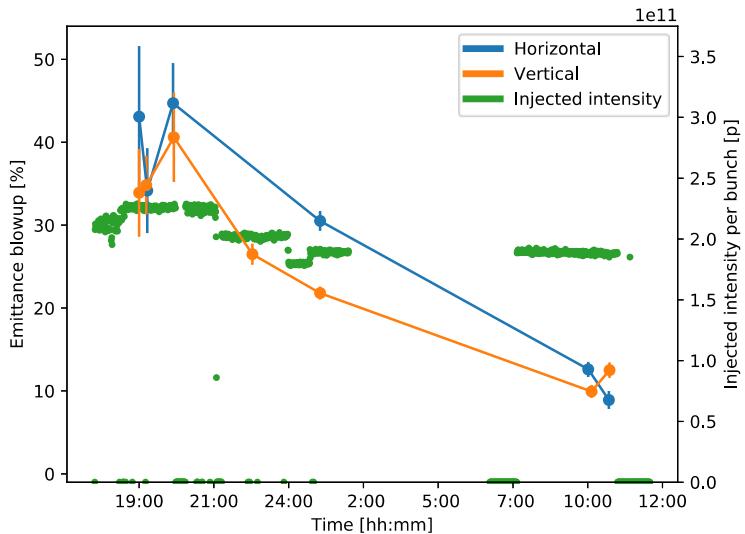
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 - Coating with a-C the chambers of the focusing quadrupoles and adjacent drift chambers



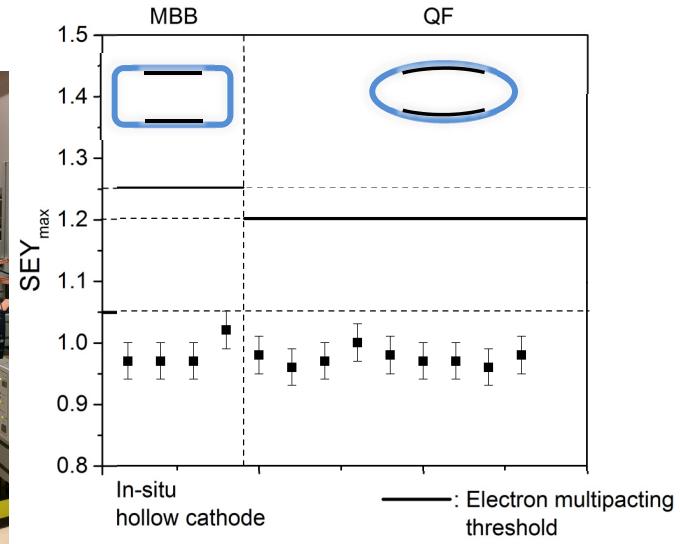
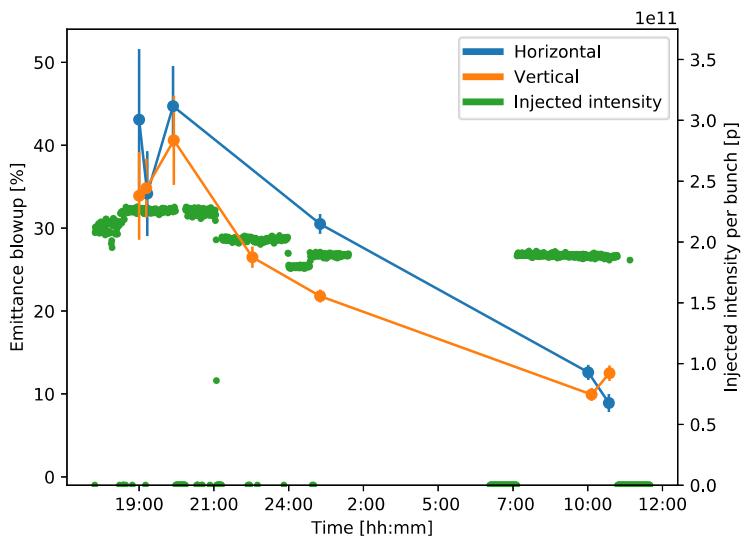
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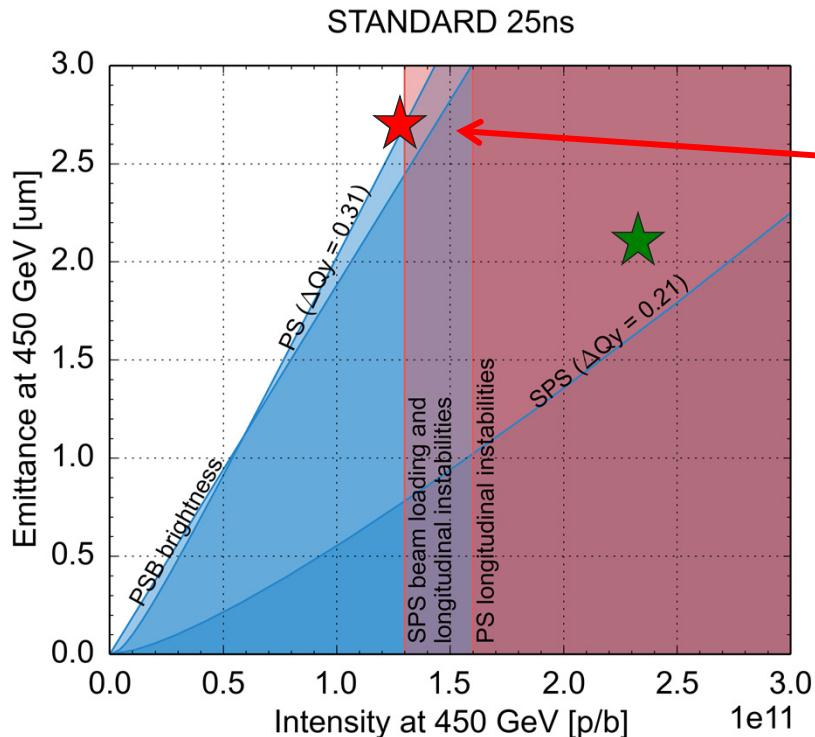


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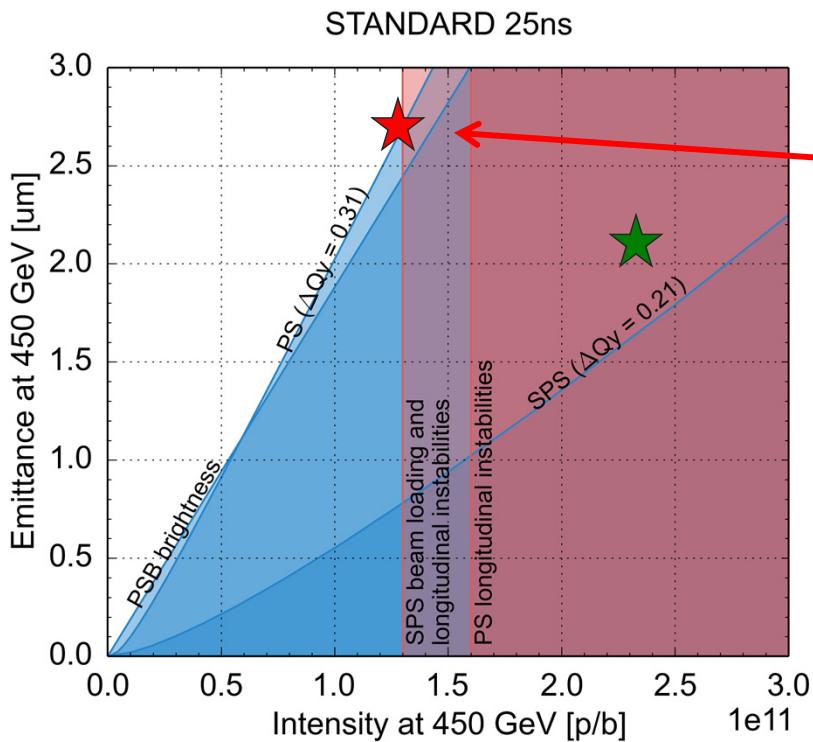


Summary: Future LIU performance



	$N_b (\times 10^{11} \text{ p/b})$	$\epsilon_{x,y} (\mu\text{m})$
HL-LHC target	2.3	2.1
Present	1.3	2.7

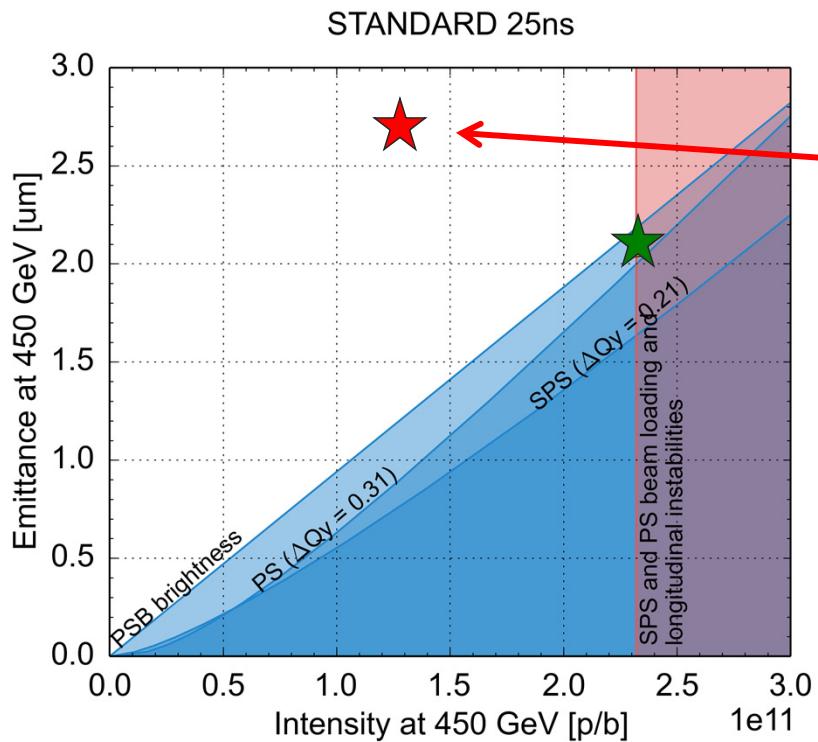
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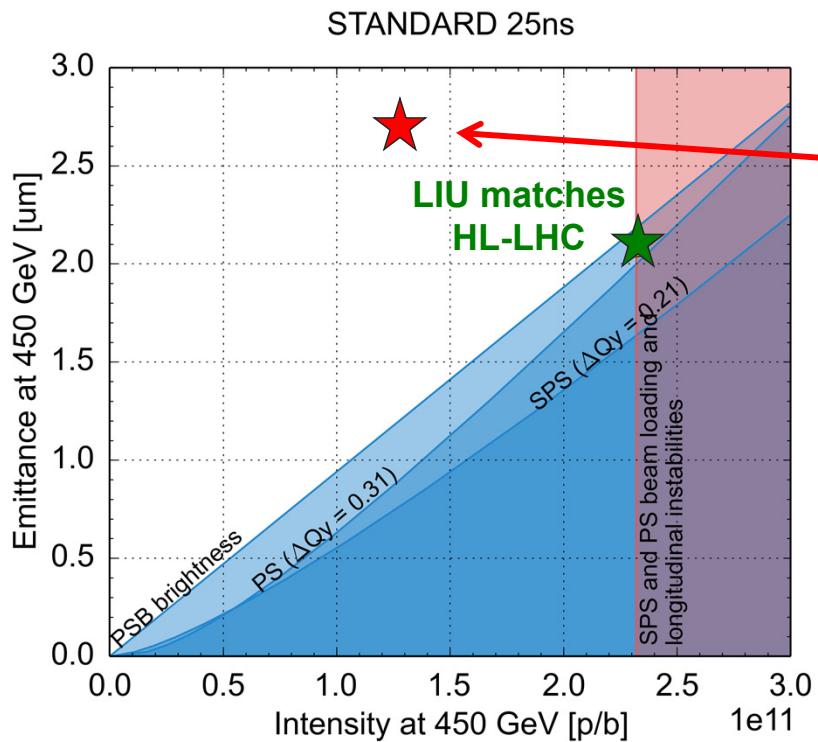
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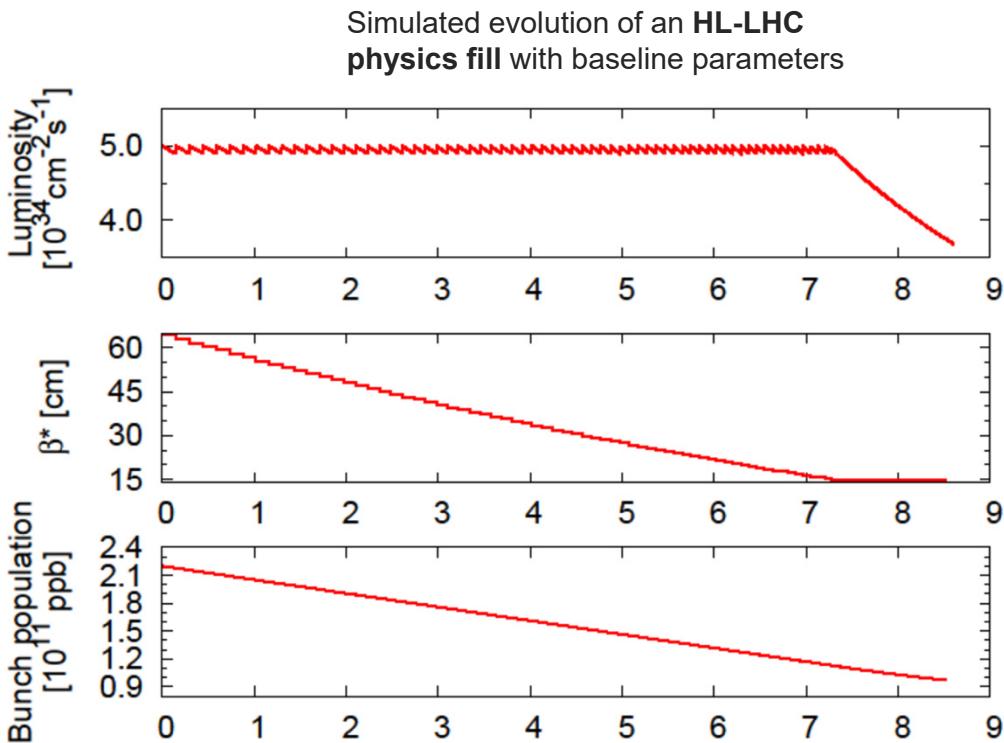
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- Why upgrades and what are the upgrades for LHC and its injector chain?
- Performance of the LHC injectors
 - Present performance limitations → beam dynamics challenges
 - How far we can go with the upgrades
- Beam dynamics challenges for HL-LHC



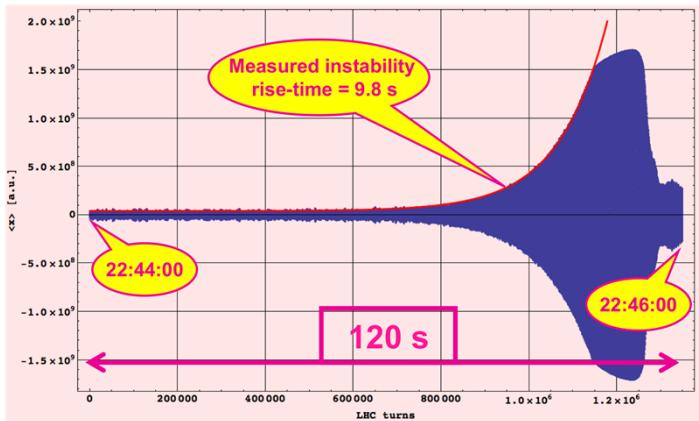
HL-LHC single particle dynamics



- Strong effect of **linear and nonlinear errors** in IRs due to **large β** → **Low Dynamic Aperture** in absence of correction
- **Pre-computed corrections** from magnetic measurements needed even for basic optics measurements
- β^* levelling will require commissioning of a **large number of optical configurations** → Challenge for efficiency of the optics measurement and correction tools

LHC beam stability

- LHC transverse beam instabilities observed with different types of beams and at different stages of the LHC cycle

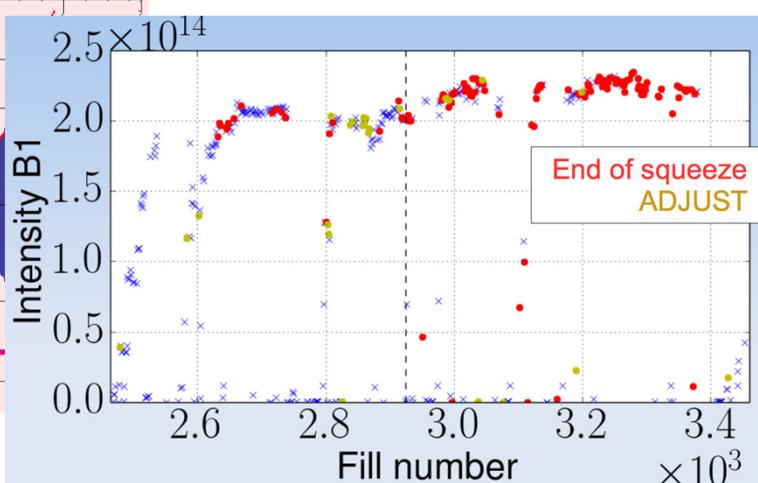
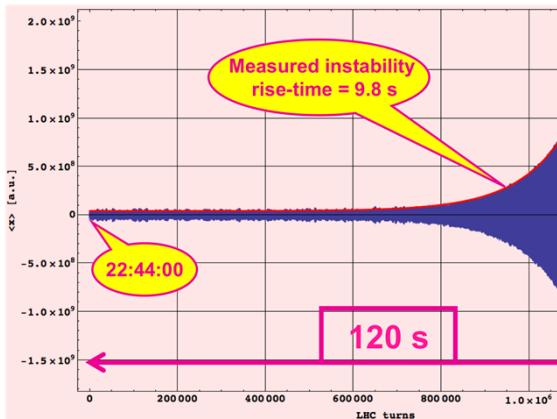


2010, single bunch
during the ramp



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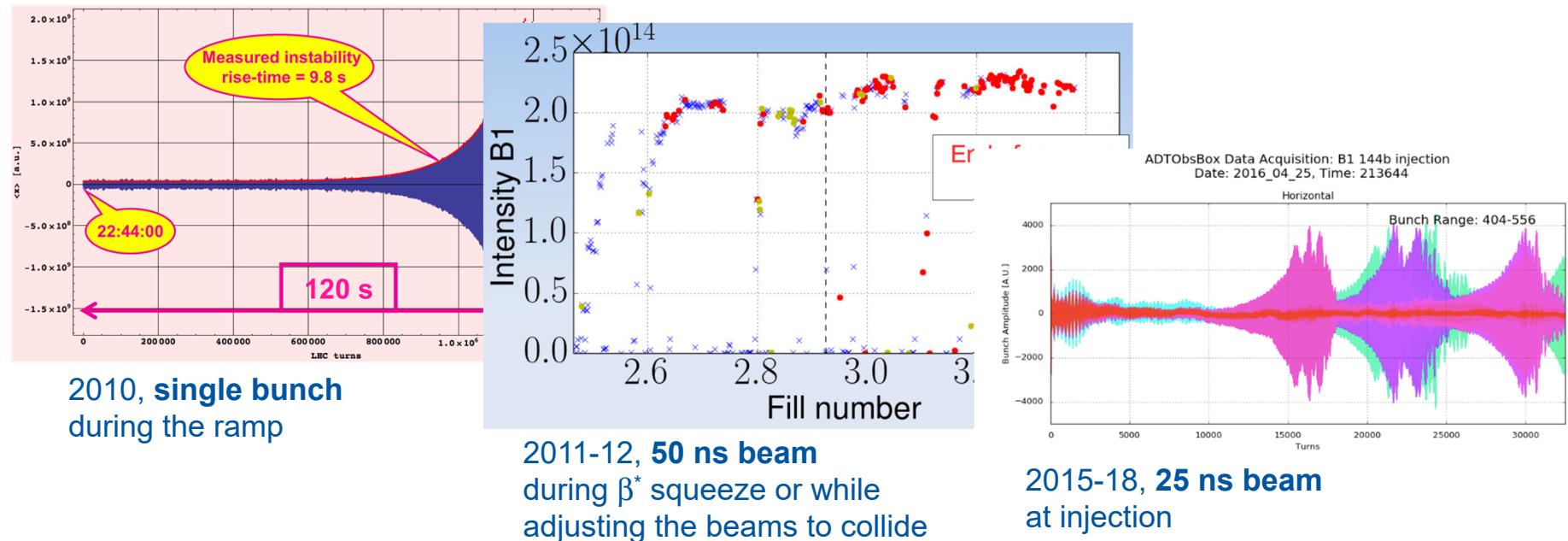


2011-12, 50 ns beam
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2011-12, 50 ns beam
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2015-18, 25 ns beam
at injection



LHC Injectors Upgrade

LHC beam stability



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LHC Injectors Upgrade

LHC beam stability



- **LHC transverse beam instabilities** observed with different types of beams and at different stages of the LHC cycle
- Sources are mainly **transverse impedance** (loss of Landau damping) and, at least with 25 ns beams, **electron cloud**
- Controlled through “**extreme**” **machine settings**, e.g. at 6.5 TeV $Q' = +15$, octupole strength close to maximum, maximum damper gain and bandwidth
 - Need to gain some margin with stabilisation knobs **for operation with HL-HLC beam parameters** (double intensity) → Impedance reduction





LHC Injectors Upgrade

LHC beam stability



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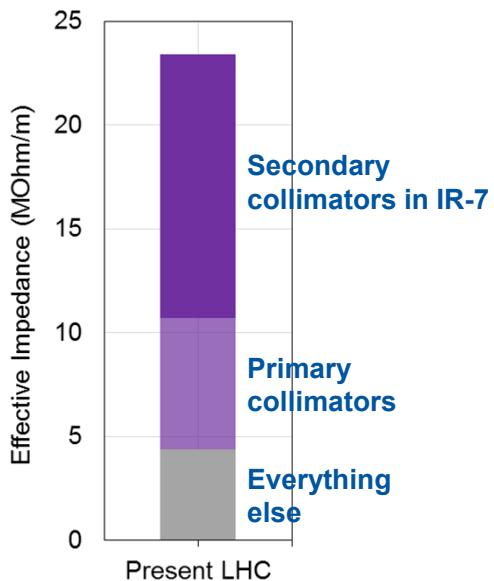
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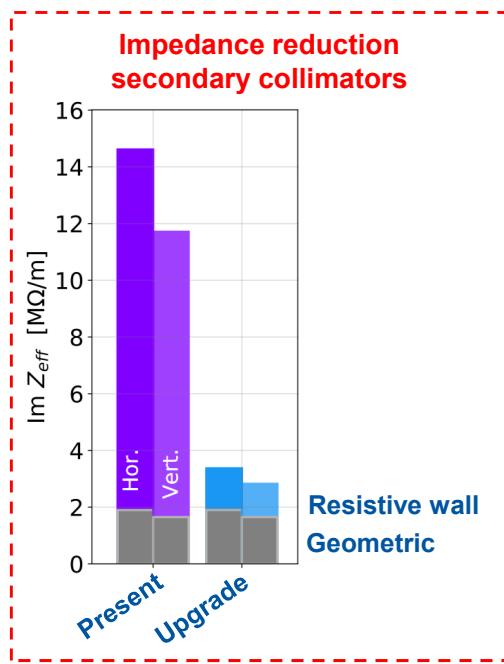
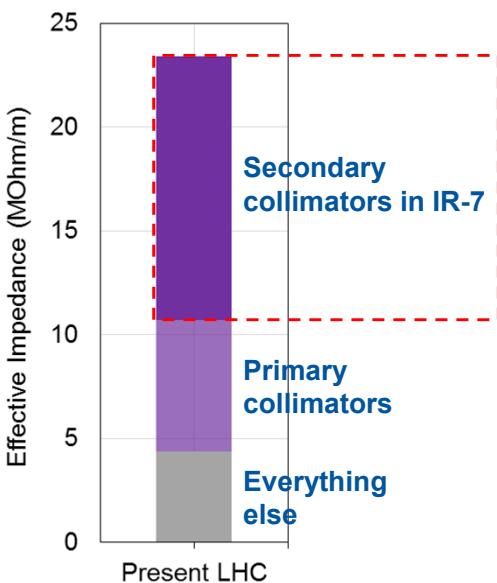
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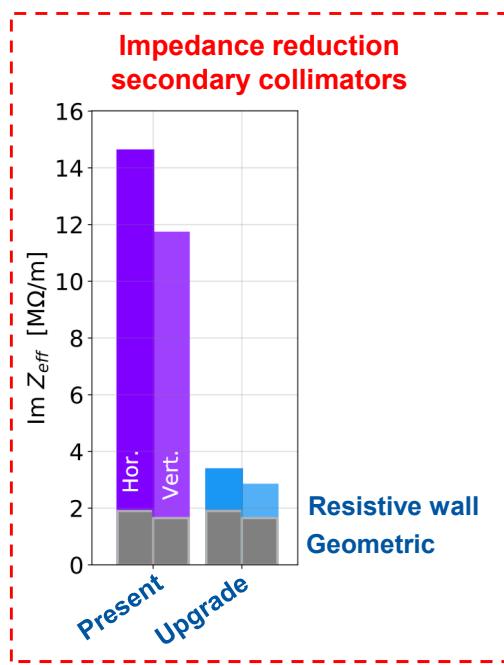
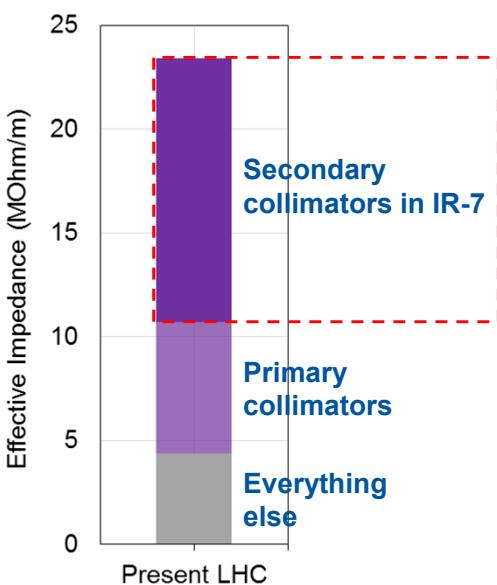
LHC beam stability



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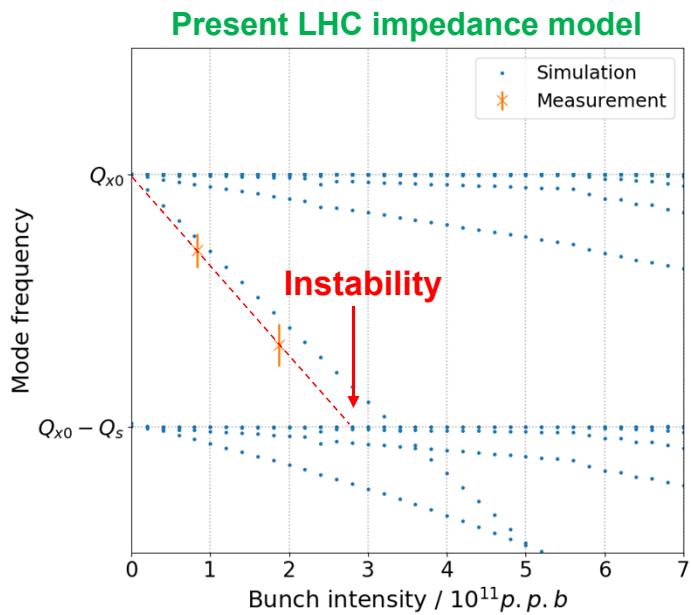
LHC beam stability



- Due to the small gaps, at 6.5 TeV the most critical impedance contributor (80%) is **collimators**
- Within HL-LHC secondary collimators replaced by new ones **with Mo-Gr jaws** having same robustness and higher conductivity → One order of magnitude lower RW impedance

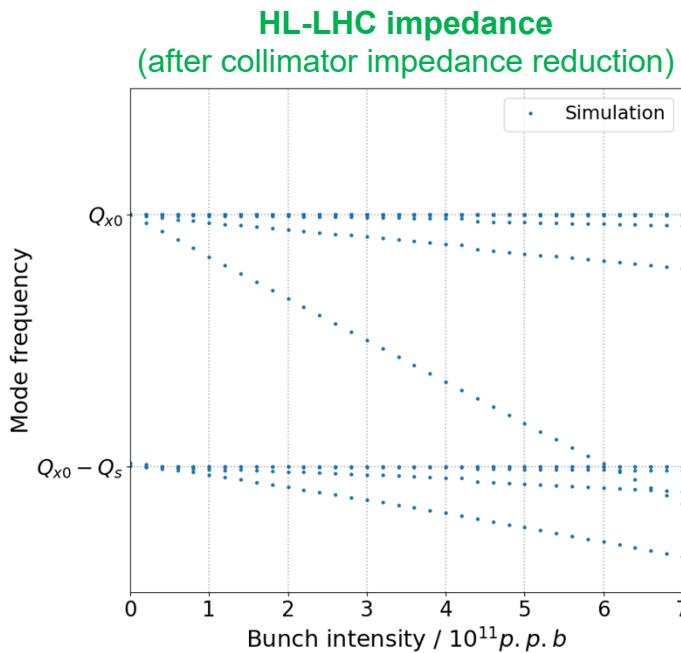
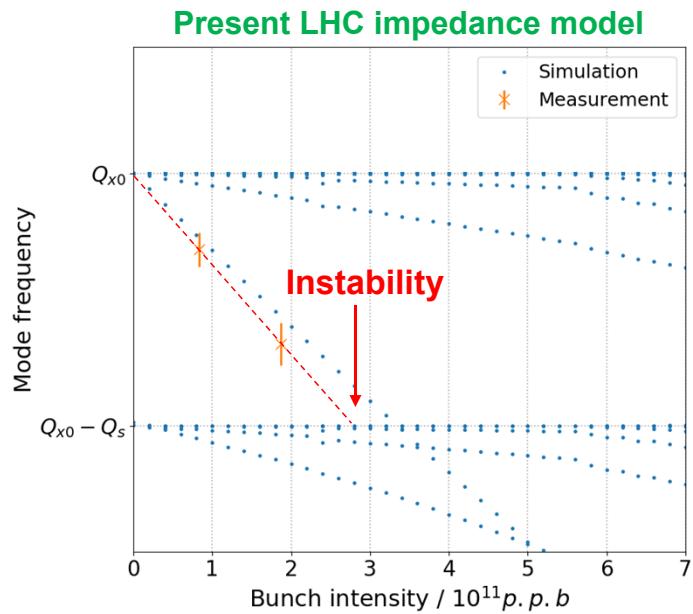
LHC beam stability

- Example: Effect of impedance reduction on TMCI threshold



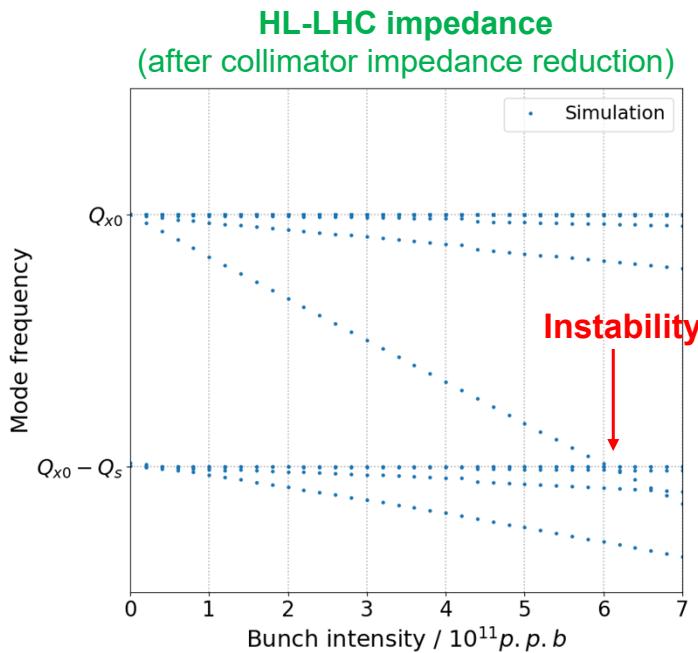
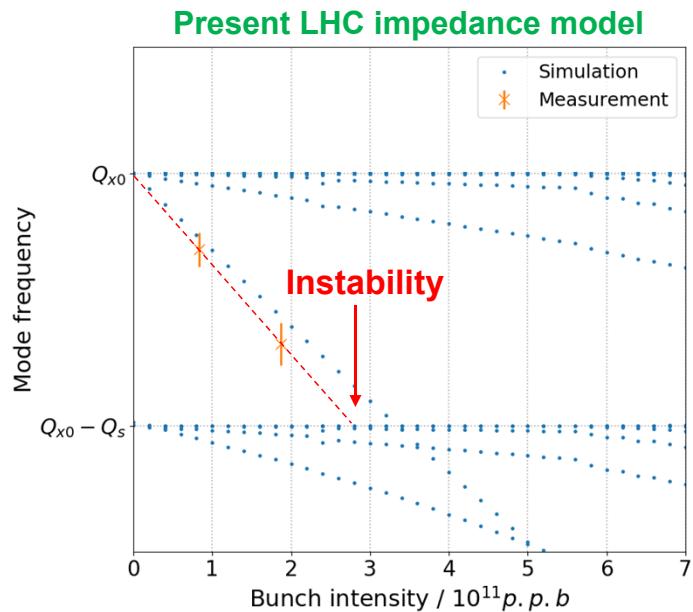
LHC beam stability

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LHC beam stability

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LHC Injectors Upgrade

LHC beam stability



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LHC Injectors Upgrade

LHC beam stability

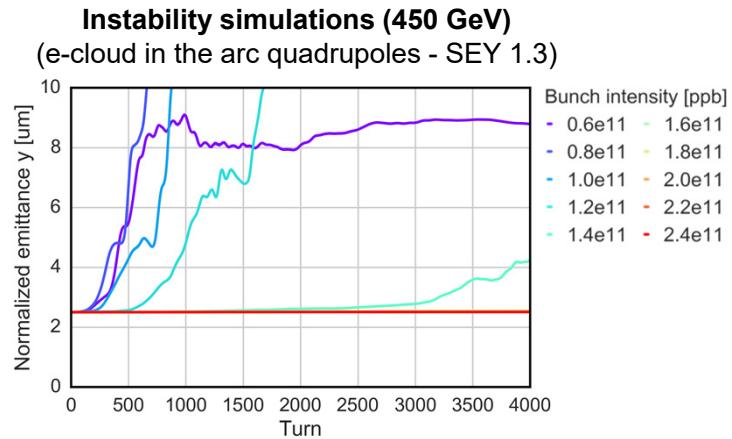


- Strong instabilities observed at 450 GeV with 25 ns beams, in both x and y
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 - Caused mainly by electron cloud in quadrupoles
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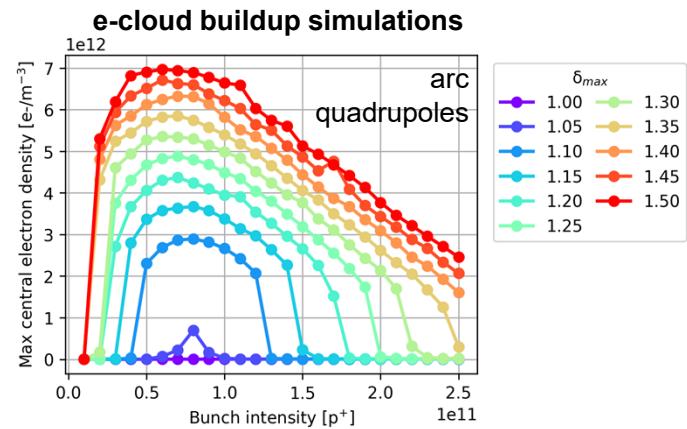
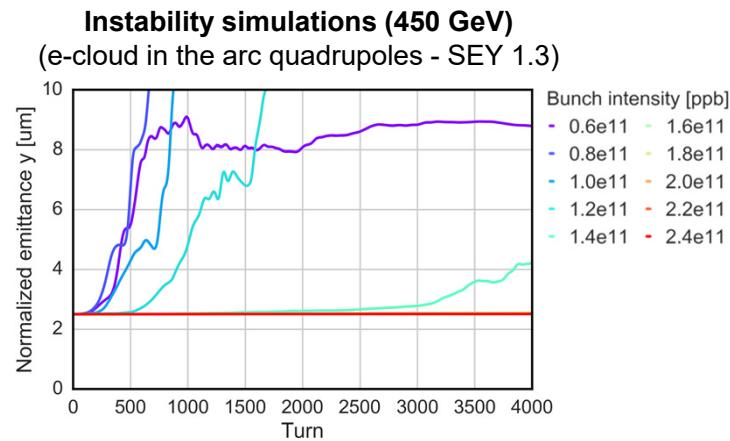
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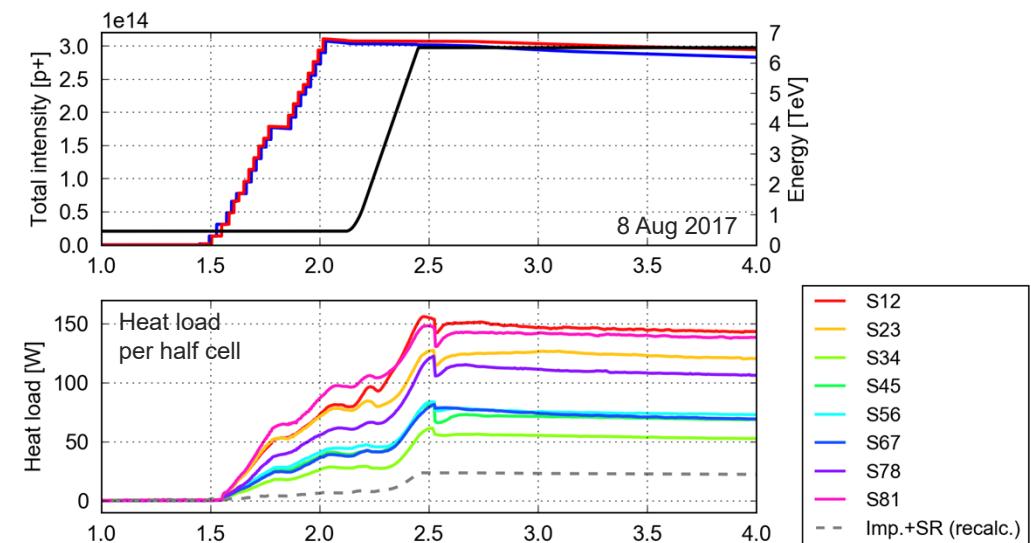




LHC Injectors Upgrade



Beam induced heat load in LHC

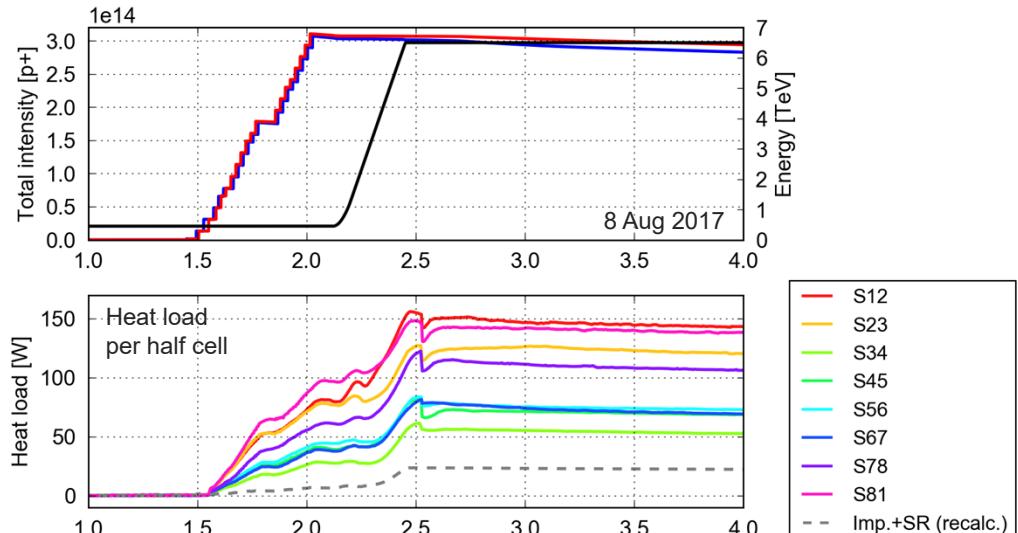


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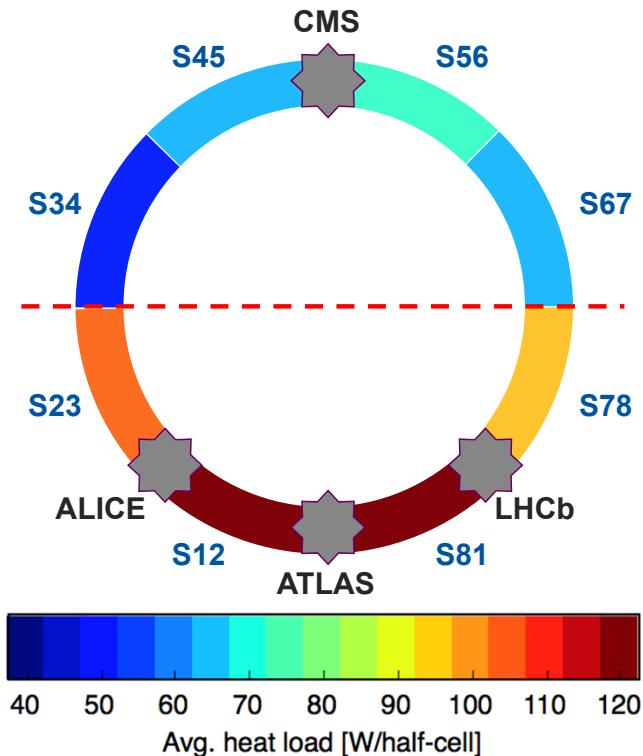
90

Beam induced heat load in LHC



- High heat load on beam screen in cold regions (cryo limit 160 W/hc in the arcs)
 - With 25 ns beams
 - Much higher than calculation from impedance + synchrotron radiation
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Beam induced heat load in LHC



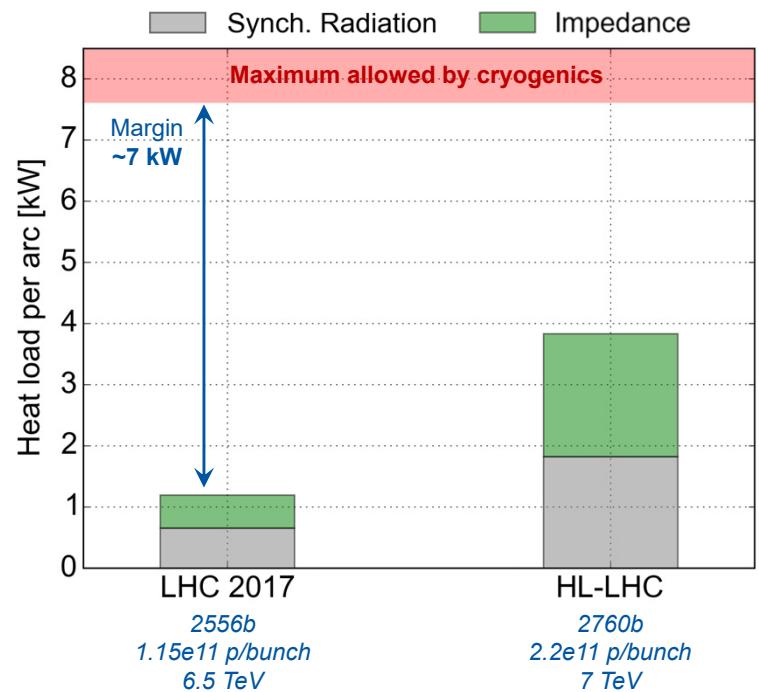
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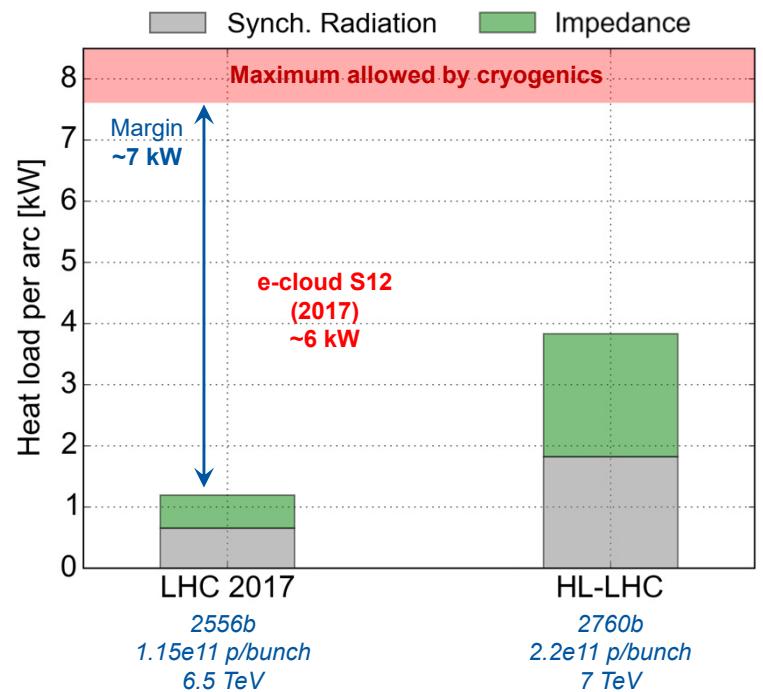




LHC Injectors Upgrade



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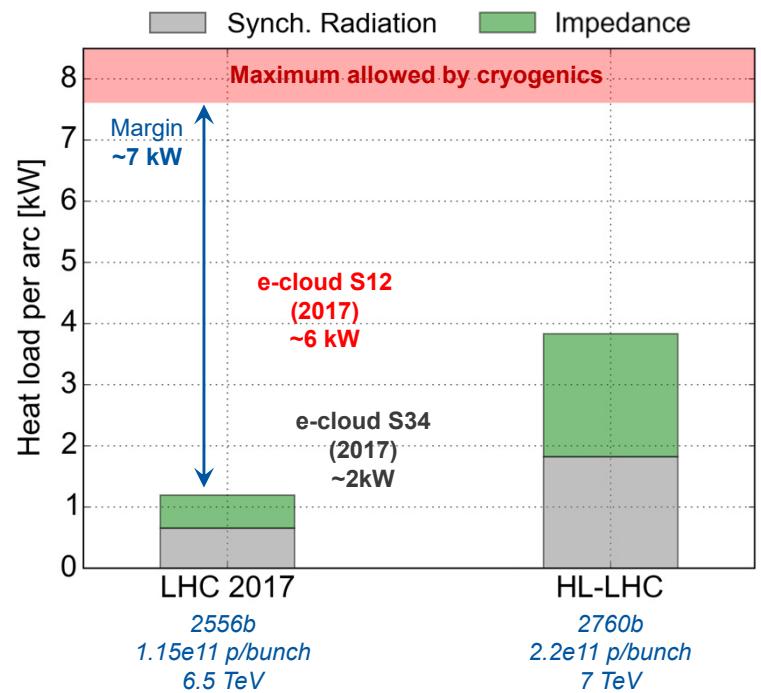




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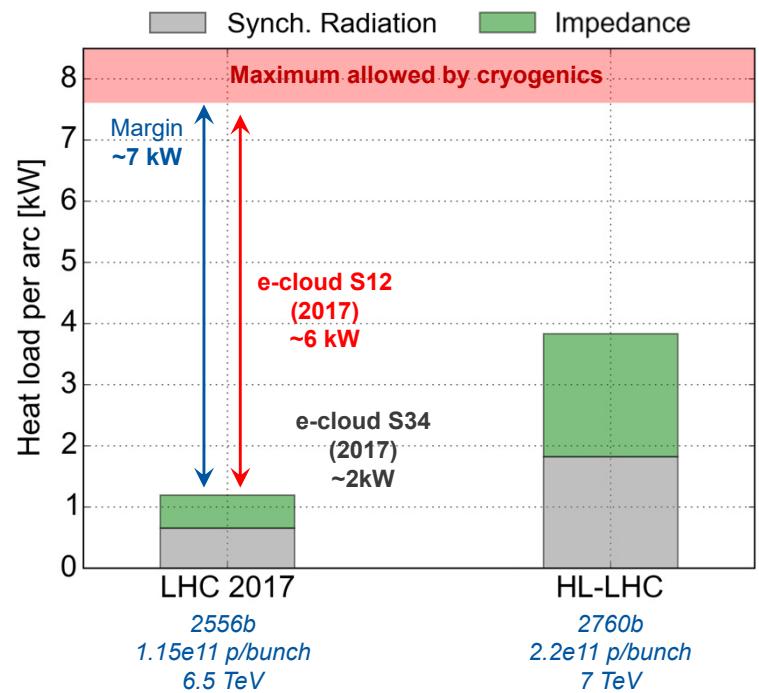




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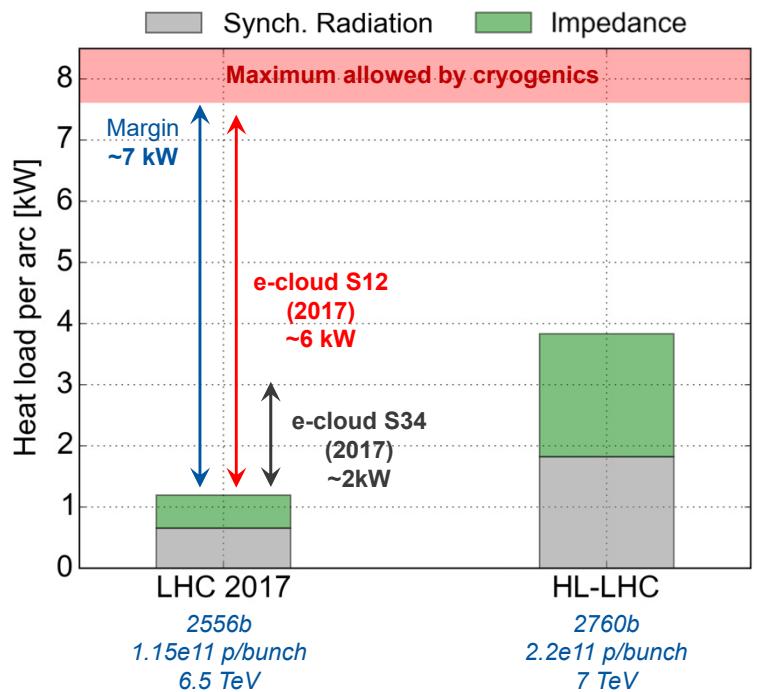




LHC Injectors Upgrade



Beam induced heat load in LHC

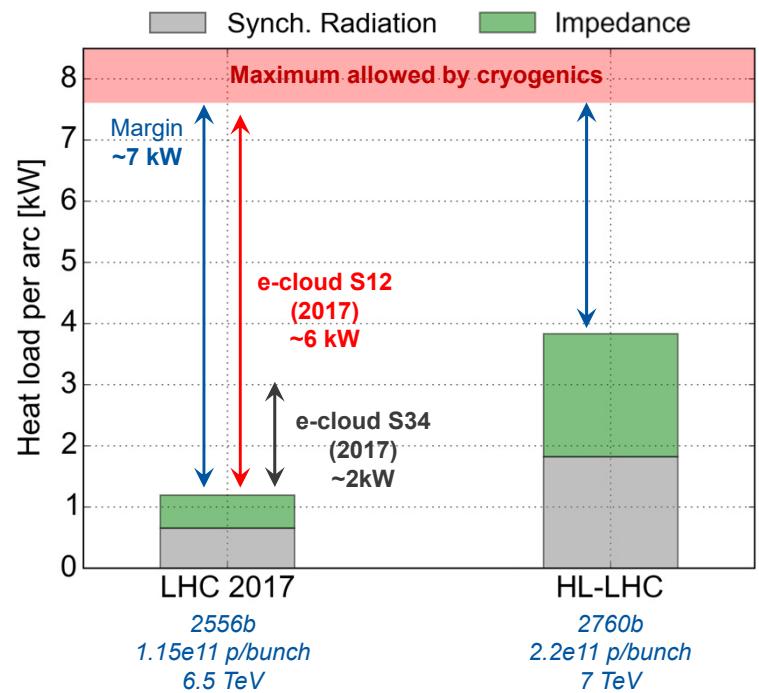




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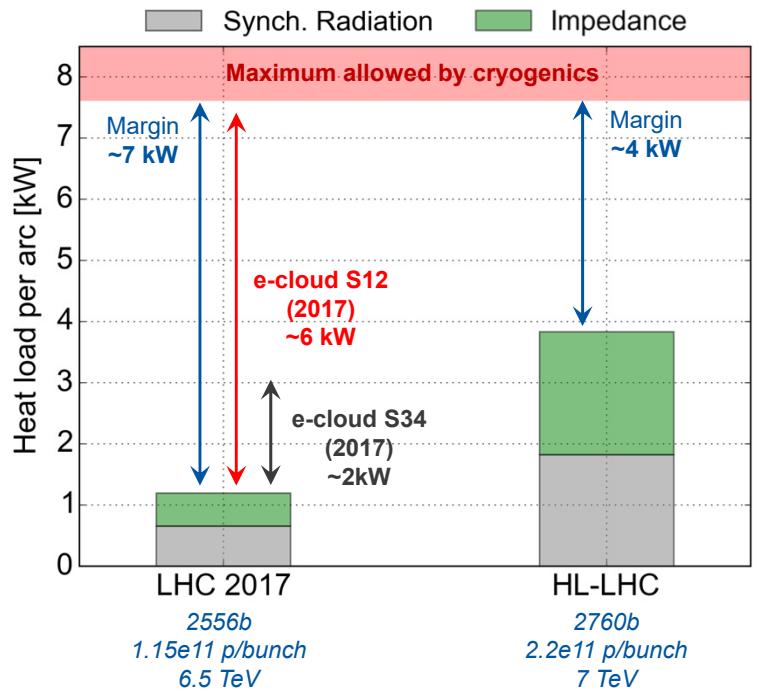




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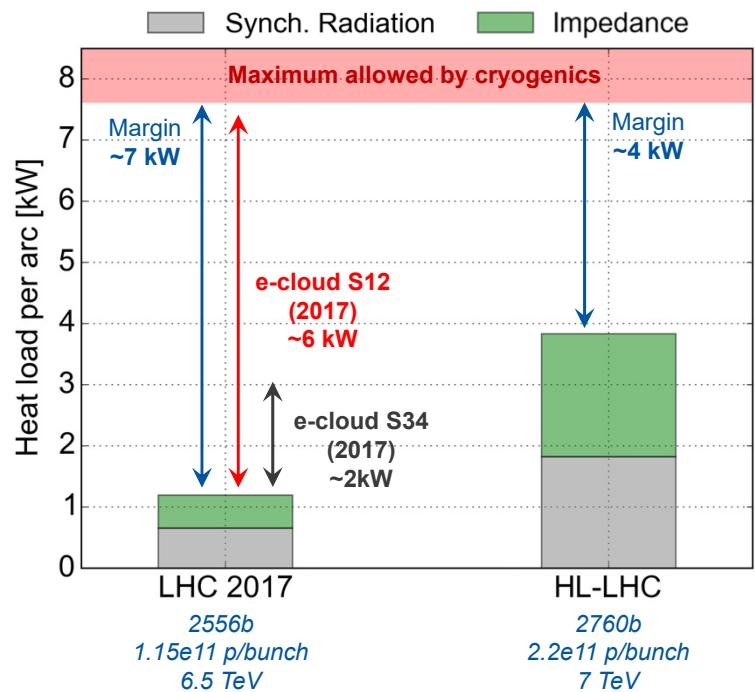


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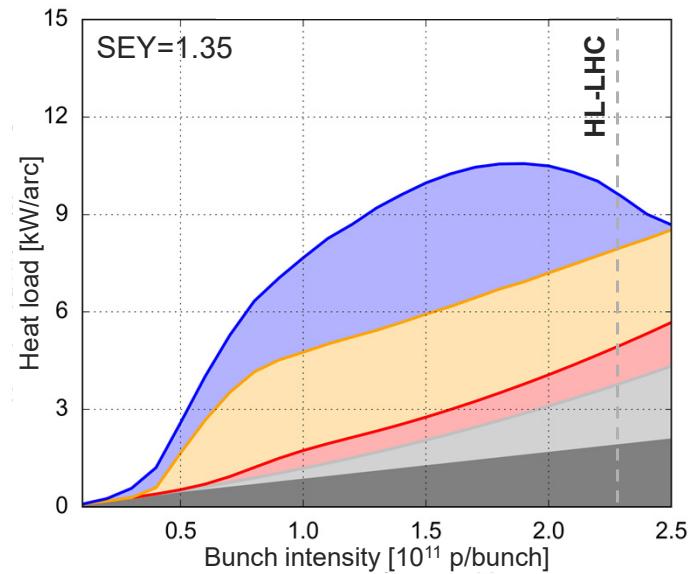
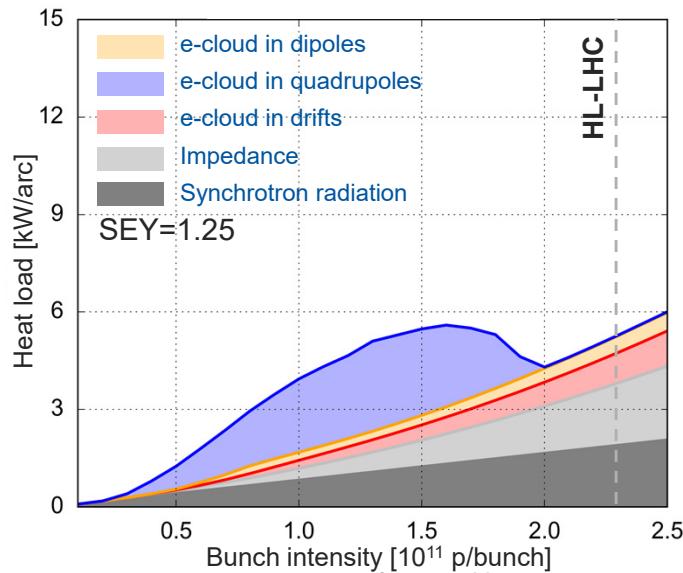
Beam induced heat load in LHC

- Two fold issue for HL-LHC
 - Less margin for cryostat with HL-LHC parameters (three-fold contribution from impedance and synchrotron radiation)
 - How does the additional load scale with bunch intensity? → We can make a prediction only if we assume it is caused by electron cloud



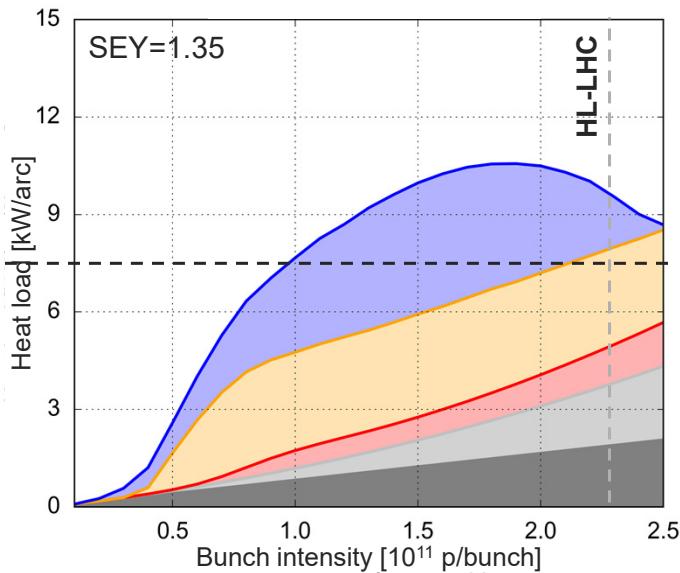
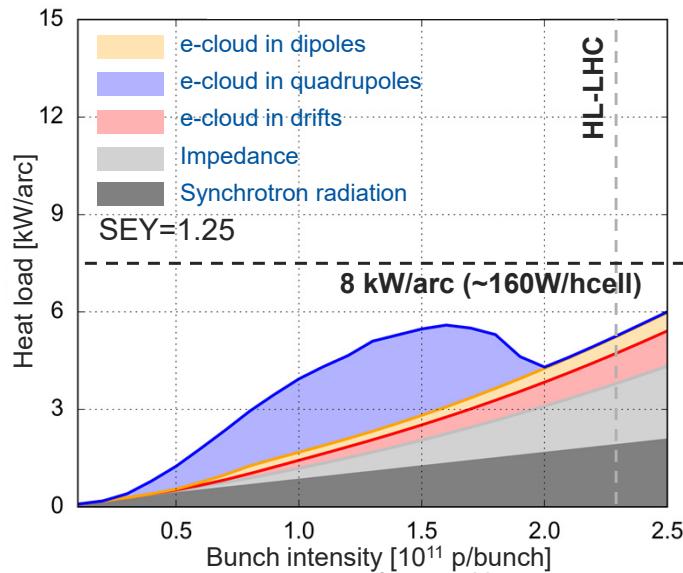
Beam induced heat load in LHC

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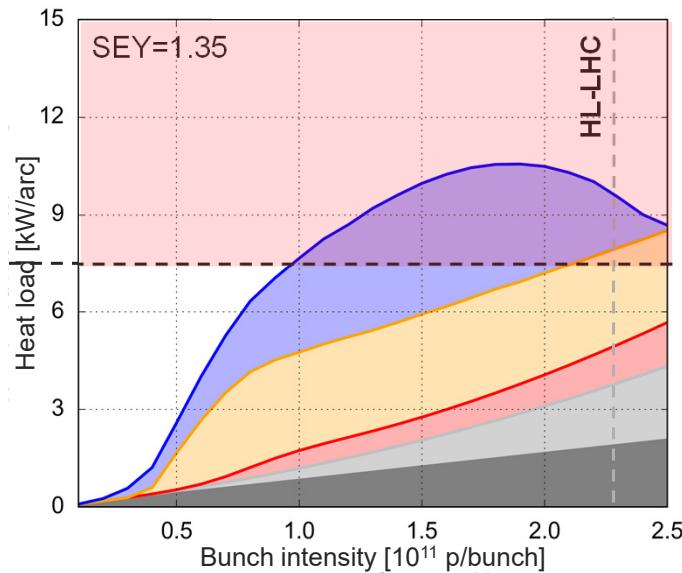
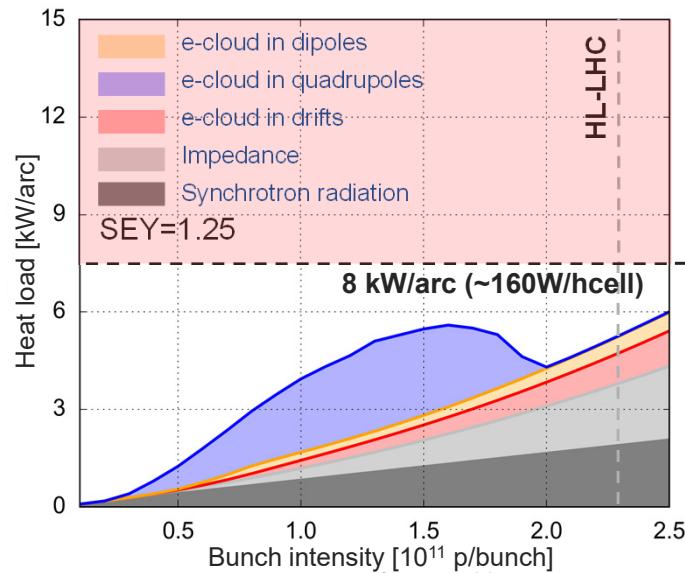
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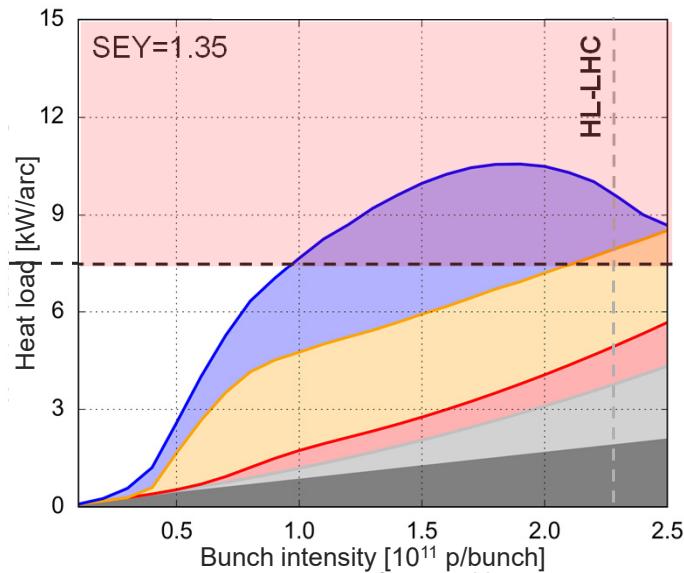
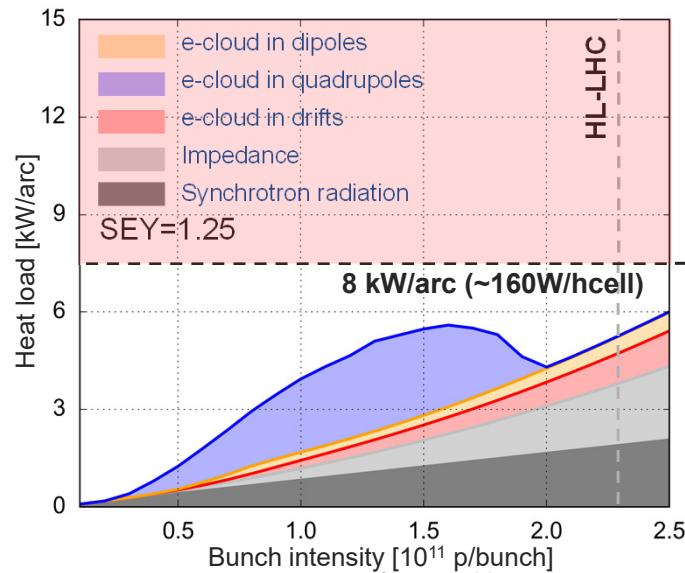
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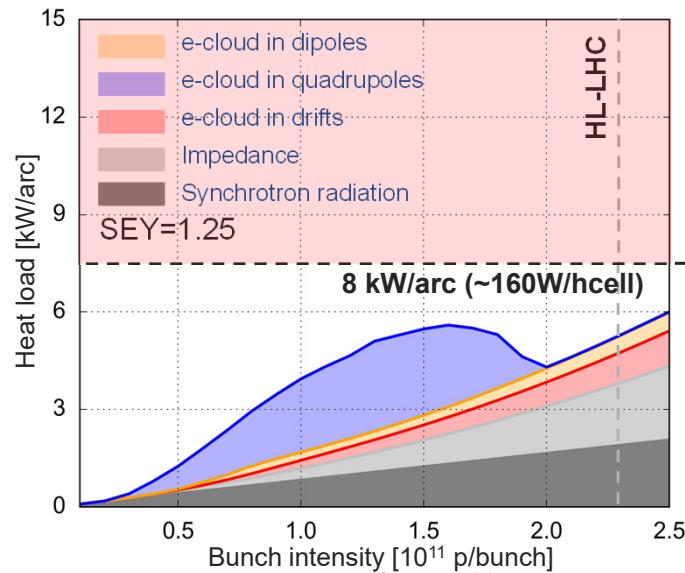
**Low-load
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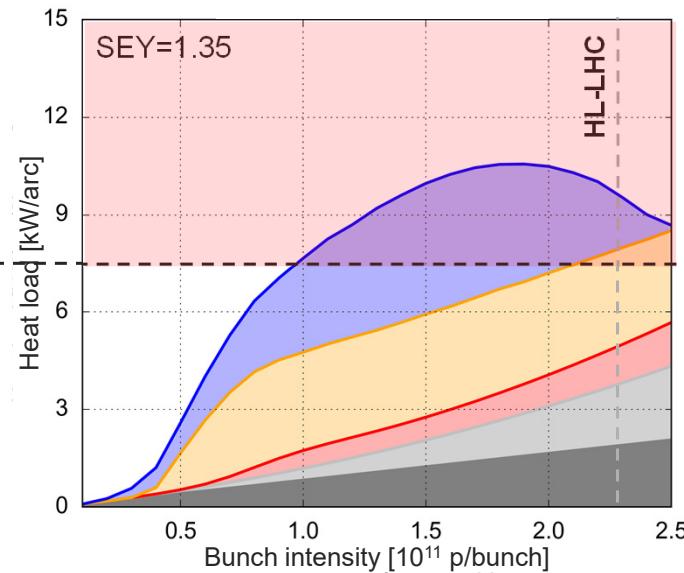
Beam induced heat load in LHC

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Low-load sectors ok with HL-LHC



High-load sectors above capacity for HL-LHC



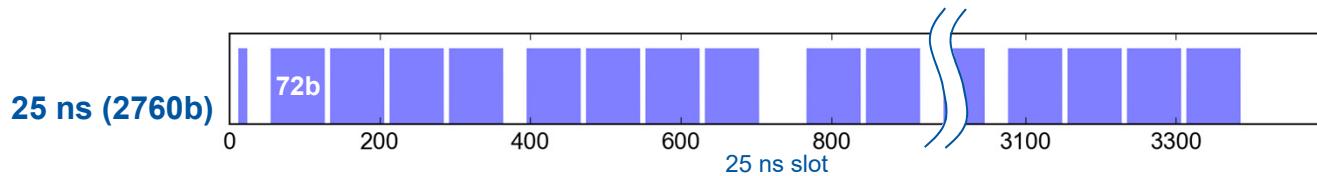
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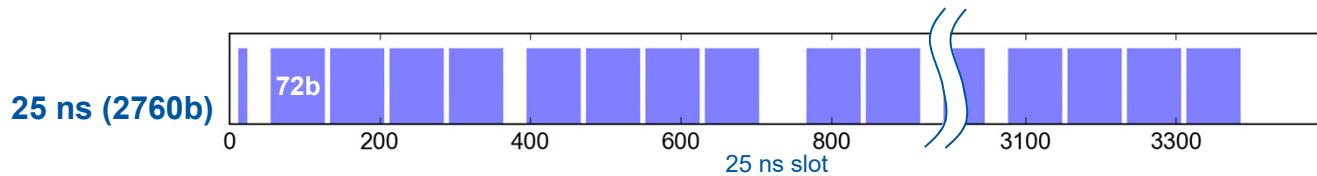
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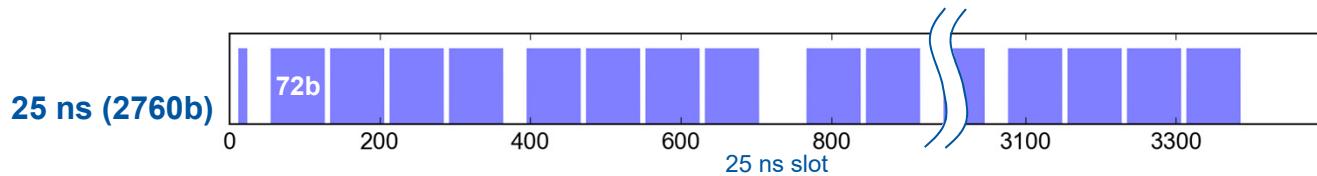
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8b+4e (1972b)

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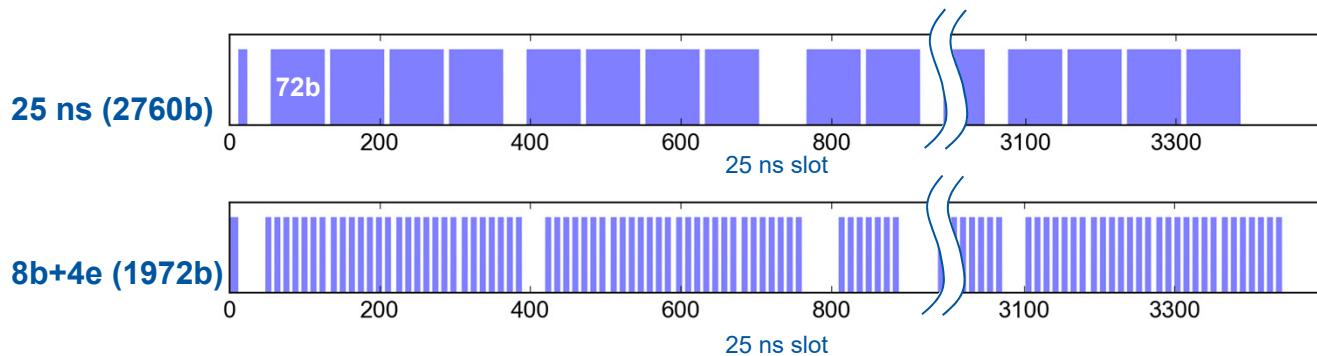
8b+4e (1972b)

25 ns slot



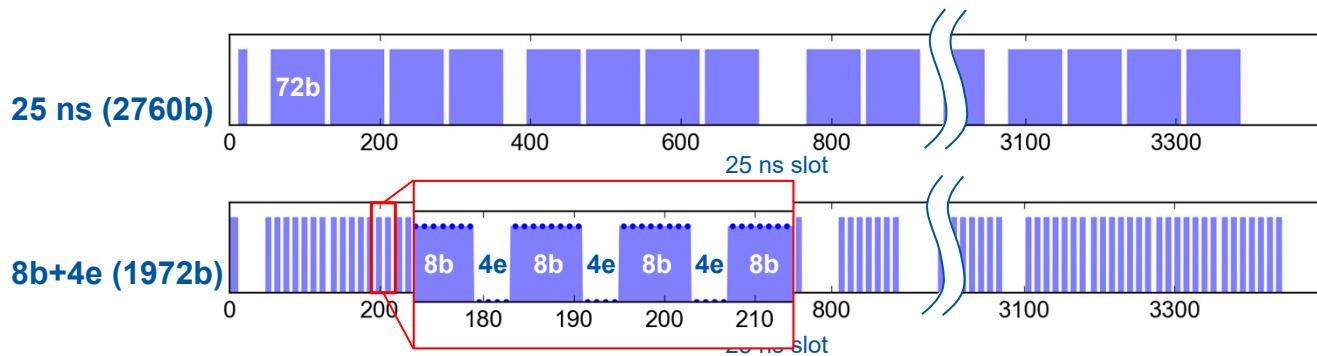
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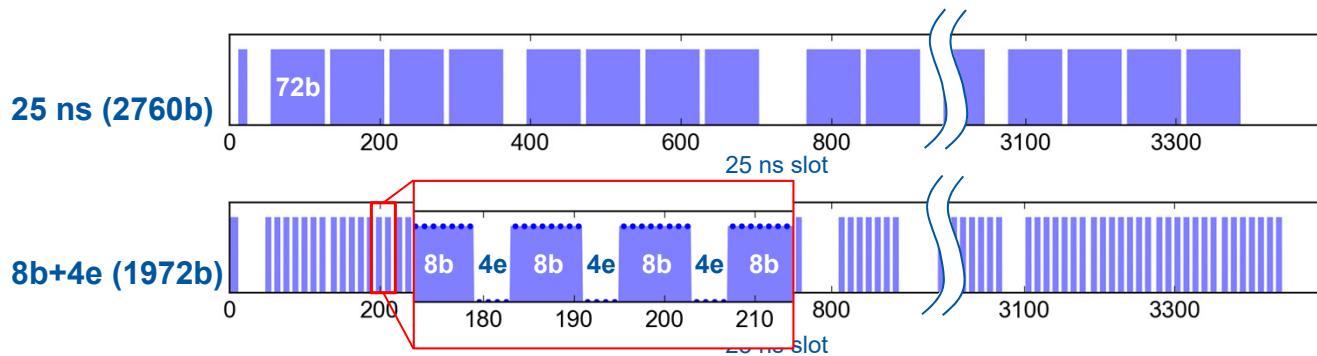
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Beam induced heat load in LHC

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→ Pure 25 ns and 8b+4e can be combined to reach the maximum heat load



LHC Injectors Upgrade



Some other challenges in LHC



HB2018, Daejeon, Korea, 17 June, 2018

Giovanni Rumolo, Beam Dynamics Challenges for the LHC and Injector Upgrades

113

Some other challenges in LHC

- Beam-beam interaction
 - Head-on beam-beam tune shift limit (based on past experience) currently surpassed
 - Effect of the long-range → 6σ DA comfortably achieved during the whole levelling process, even including the chromaticity and octupole settings necessary for beam stability
- Incoherent emittance growth along the cycle
 - Larger than expected from Intra Beam Scattering (with margin), but impact de-facto mitigated by β^* levelling
 - Influence of noise → minimise sources by careful design of power converters, crab cavity controls, transverse damper upgrade (it might also benefit coherent instabilities)
- Beam halo active control for machine protection
 - Potentially large halo generation with HL-LHC beams, especially during commissioning
 - Cleaning techniques under study, option for Hollow Electron Lens



LHC Injectors Upgrade



To wrap up and conclude



To wrap up and conclude

- LHC and its injectors set to major upgrades: **LIU, HL-LHC**
 - Injectors upgraded in 2019-2020, LIU beam commissioning in 2021-2024
 - LHC upgraded in 2024-2025 and HL-LHC era >2026
- Beam dynamics challenges for upgrade of the injectors
 - Produce/preserve **higher brightness** → Linac4, mitigation of space charge, optimised transfers
 - Produce **more intense beams** → Cure coherent instabilities and/or incoherent degradation with impedance reduction, electron cloud mitigation, active feedback, longitudinal emittance blow up, enhanced Landau damping, optics change, resonance compensation...
- Beam dynamics challenges for upgrade of LHC
 - Preservation of **beam stability** → Landau damping & impedance reduction, electron cloud build up & instability scaling
 - Beam induced **heat load** → Understanding of present situation
 - Optics corrections, operational scenarios with beam-beam, reduction of emittance growth sources, beam halo cleaning



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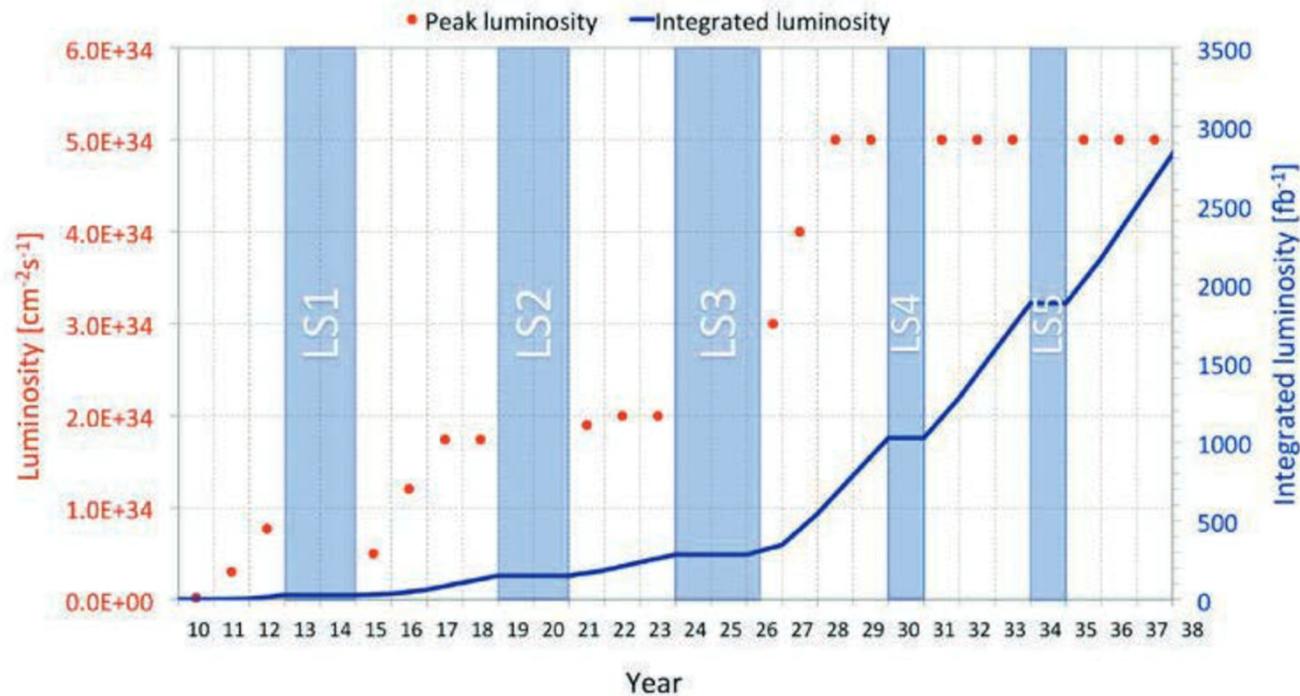
*THANK YOU
FOR YOUR
ATTENTION*



LHC Injectors Upgrade

HiLumi
HL-LHC PROJECT

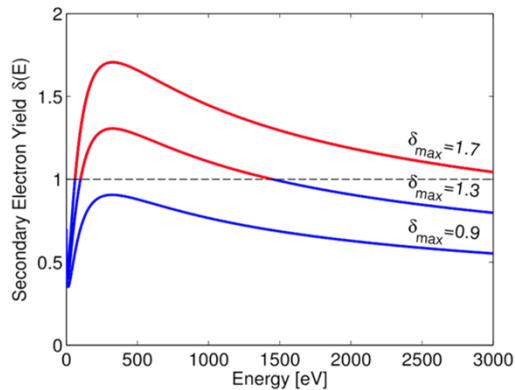
Luminosity projection



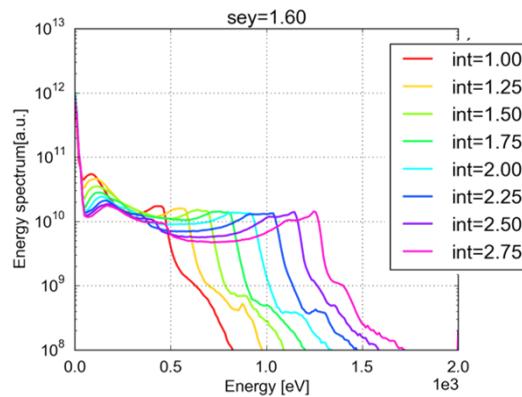
E-cloud build up with intensity

Underlying mechanism:

When the SEY decreases the **energy window for multipacting** becomes narrower



For high bunch intensity the e- spectrum drifts to higher energies and can move outside the most efficient region

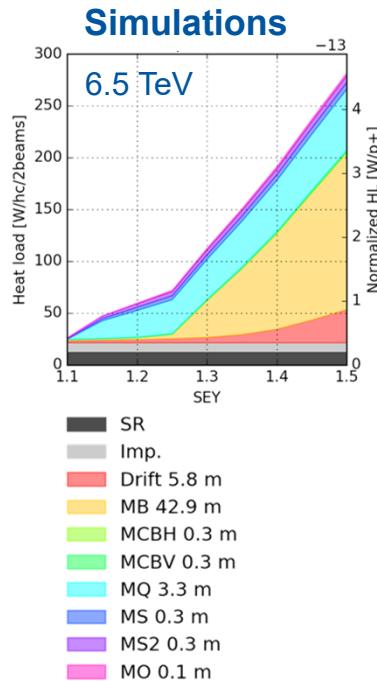




LHC Injectors Upgrade



Inferring the average SEY

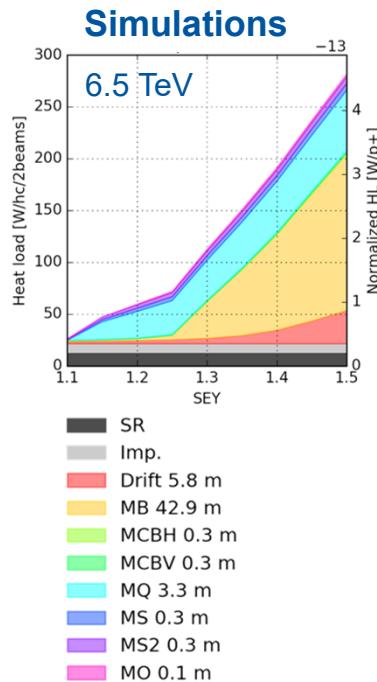




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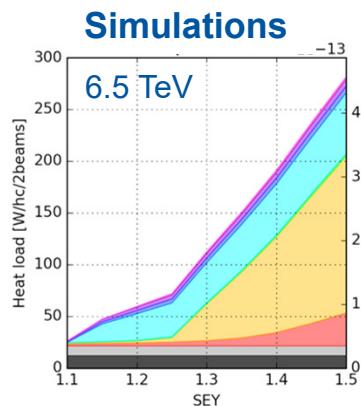


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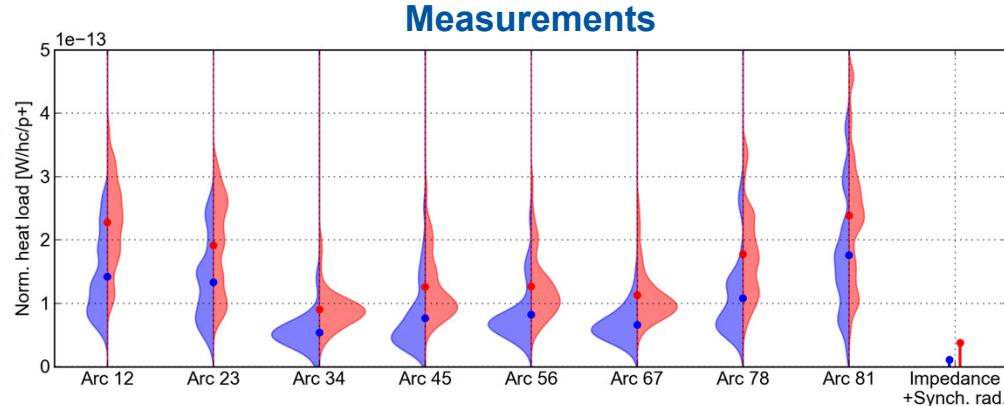


Measurements

Inferring the average SEY



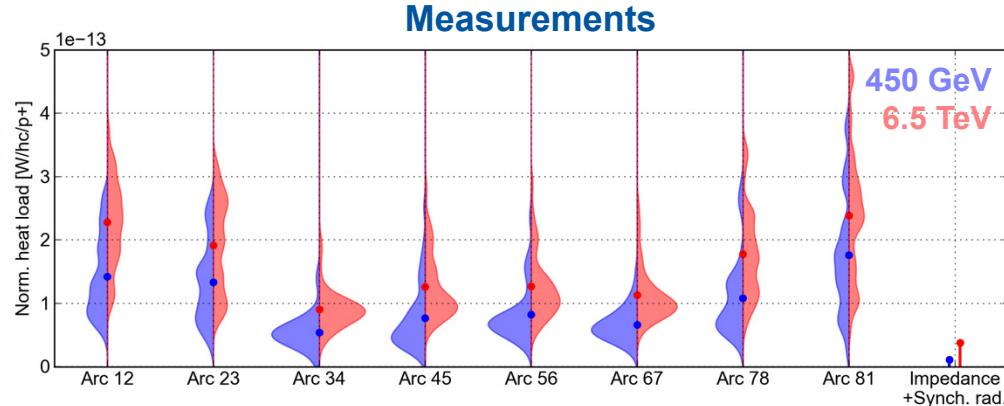
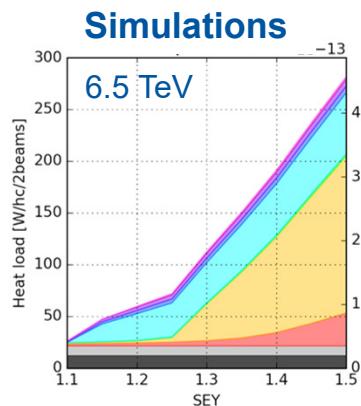
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- MB 42.9 m
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- MQ 3.3 m
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- MO 0.1 m



Fill	6674	6674
Started on	12 May 2018 02:35	12 May 2018 02:35
T_sample [h]	1.70	2.40
Energy [GeV]	450	6499
N_bunches (B1/B2)	2556/2556	2556/2556
Intensity (B1/B2) [p]	$2.84\text{e}14/2.86\text{e}14$	$2.79\text{e}14/2.83\text{e}14$
Bun.len. (B1/B2) [ns]	1.17/1.34	1.09/1.08
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H.L. exp. imp.+SR [$\text{W}/(\text{p}^+)$]	$1.08\text{e}-14$	$3.72\text{e}-14$
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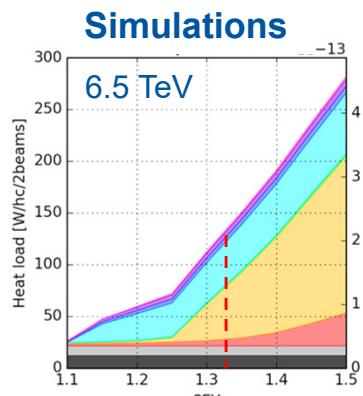


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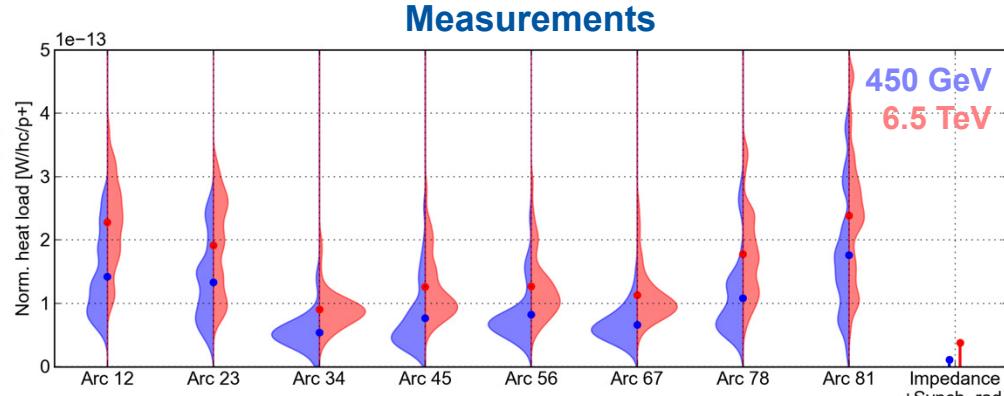
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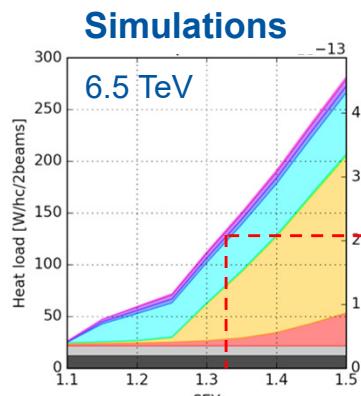
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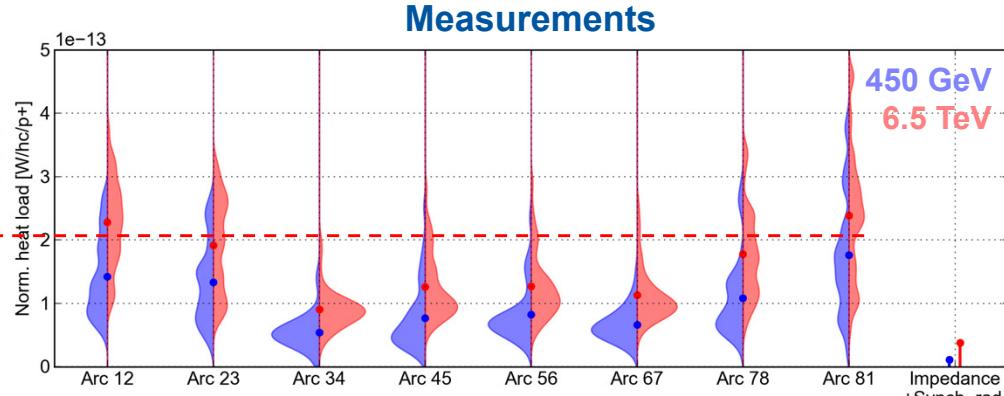
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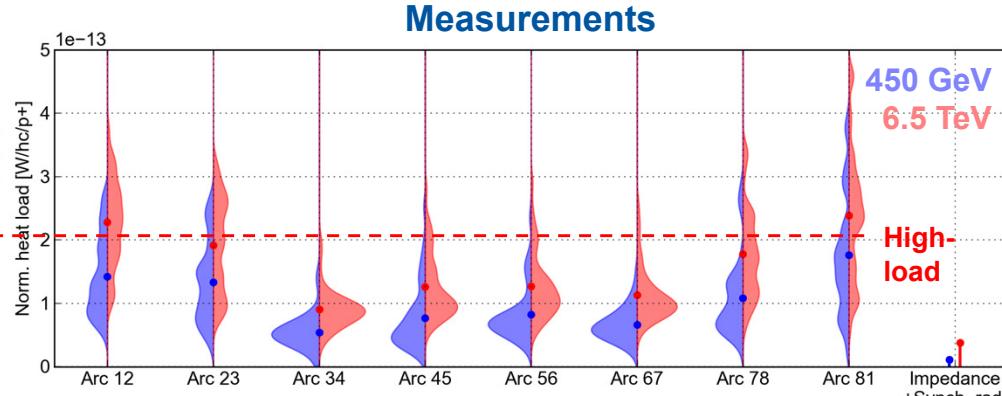
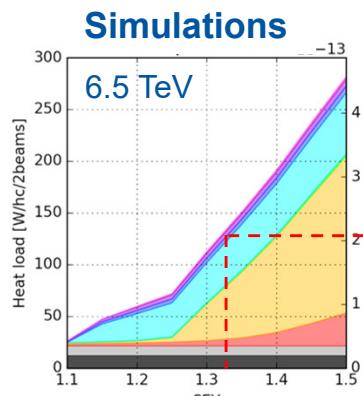


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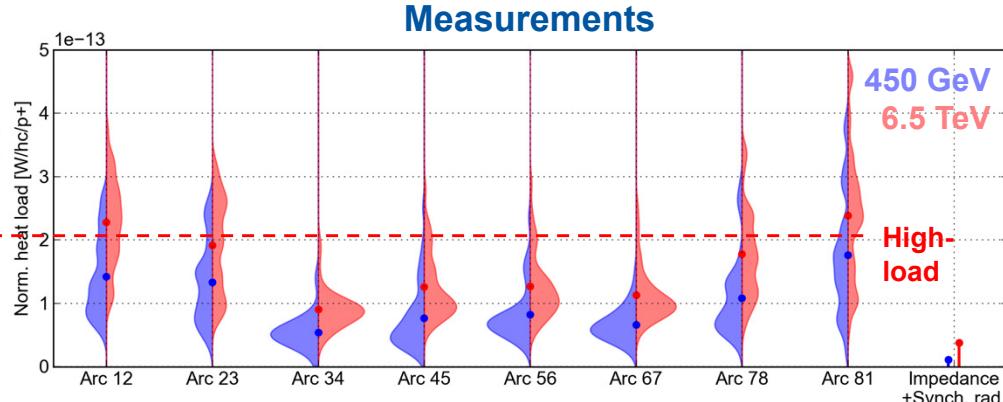
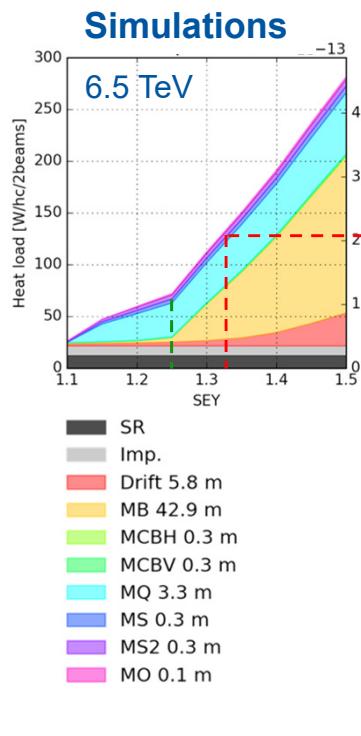
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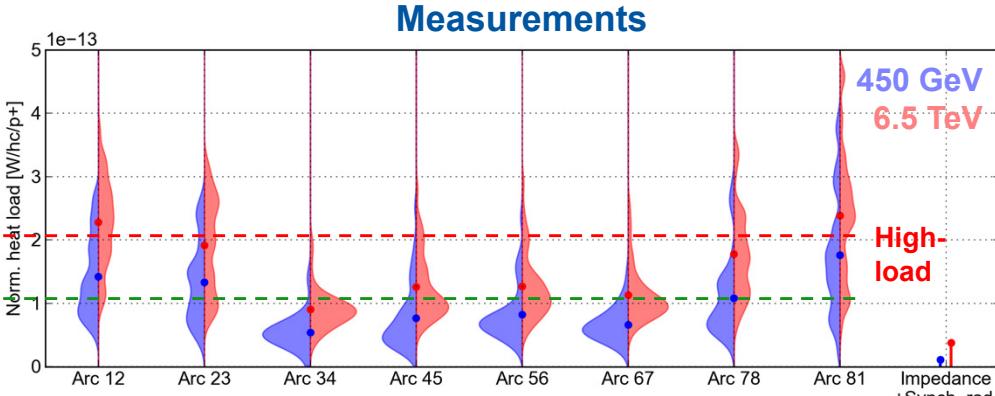
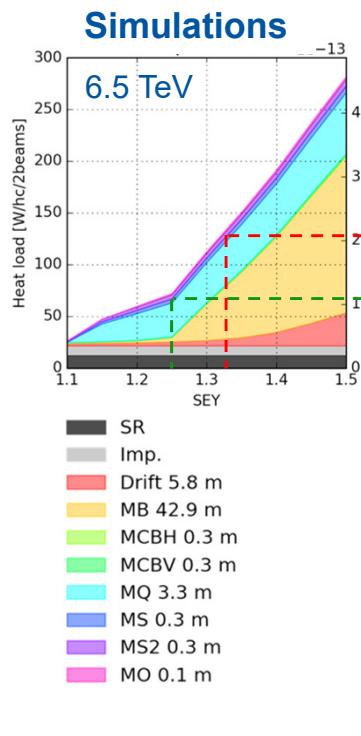
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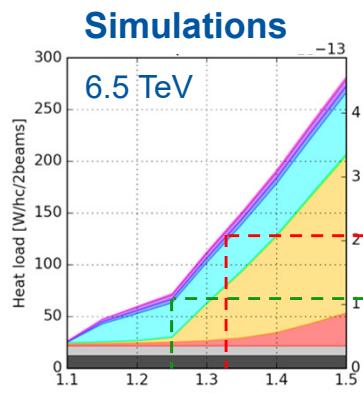
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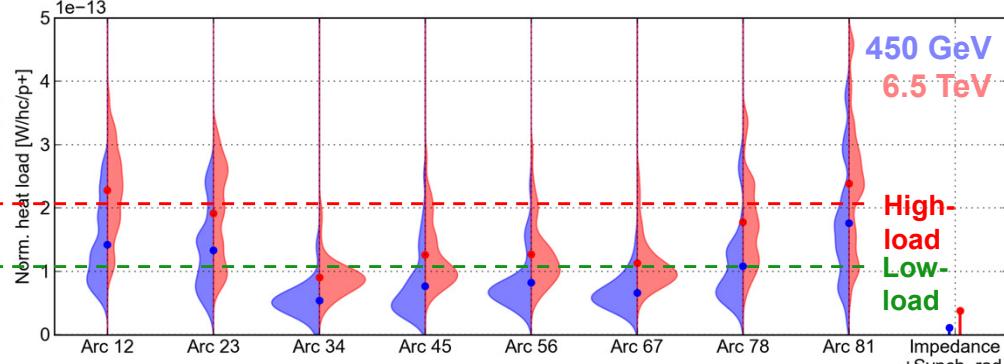
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