MANCHESTER 1824
The University of Manchester

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

The Large Hadron Collider

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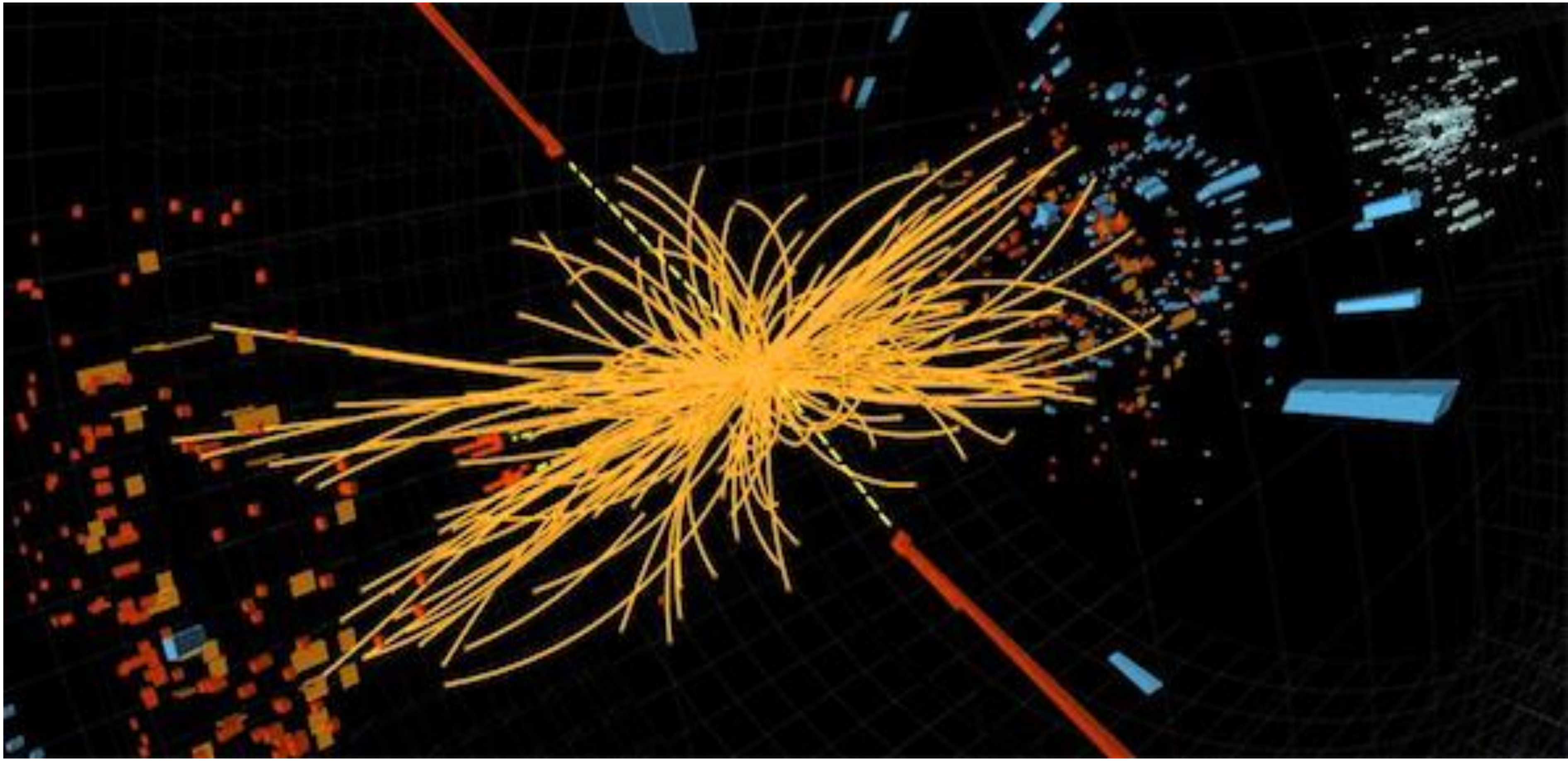
Outline

- – Devin
  - How a beam works
  - How to improve luminosity
  - Security issues
- – Cosmin
  - Upgrade of the LHC

Beam walkthrough



Guess what this is

Injection Chain

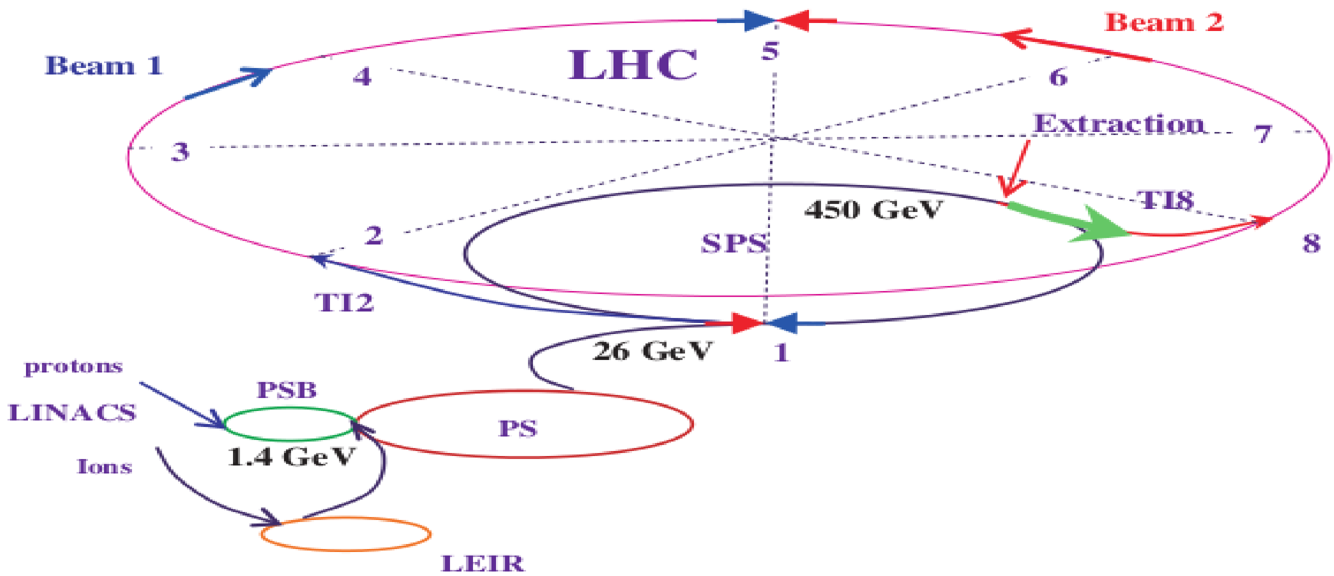
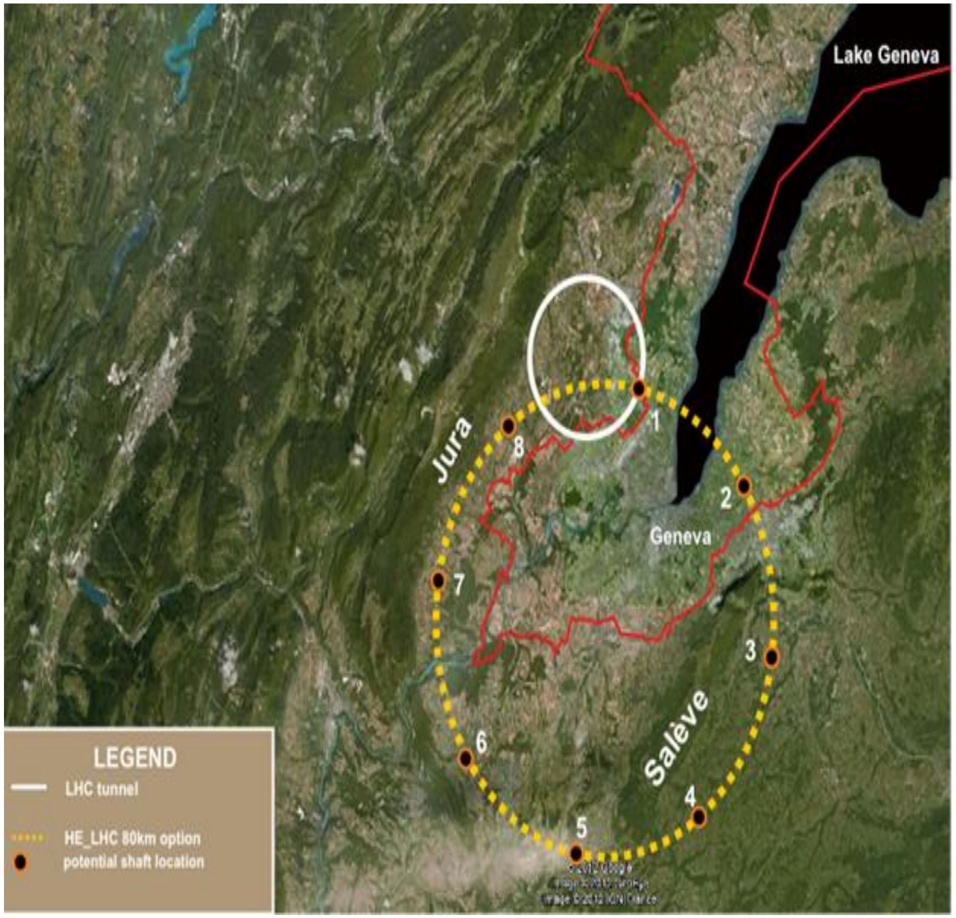
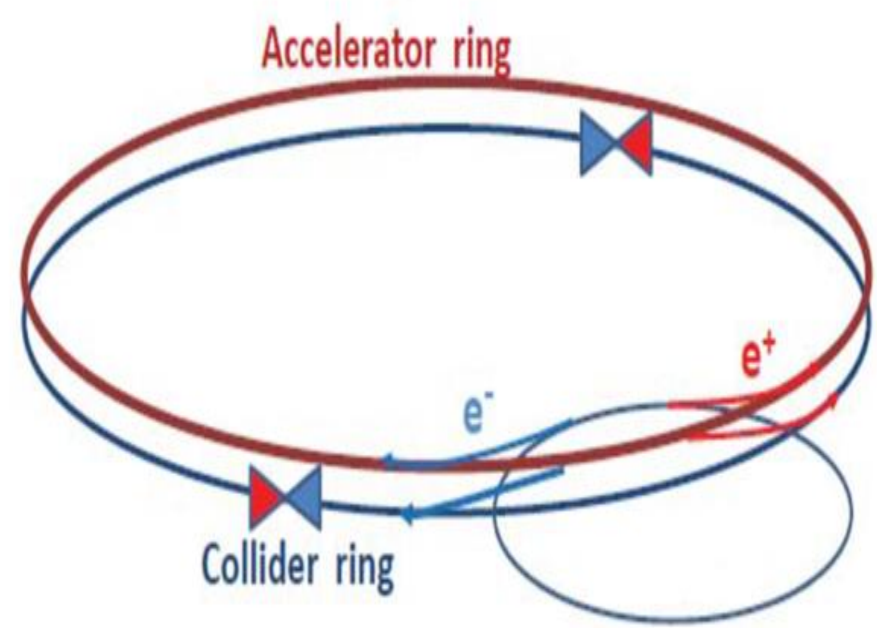


Figure 6: Schematic view of the LHC with its injectors.

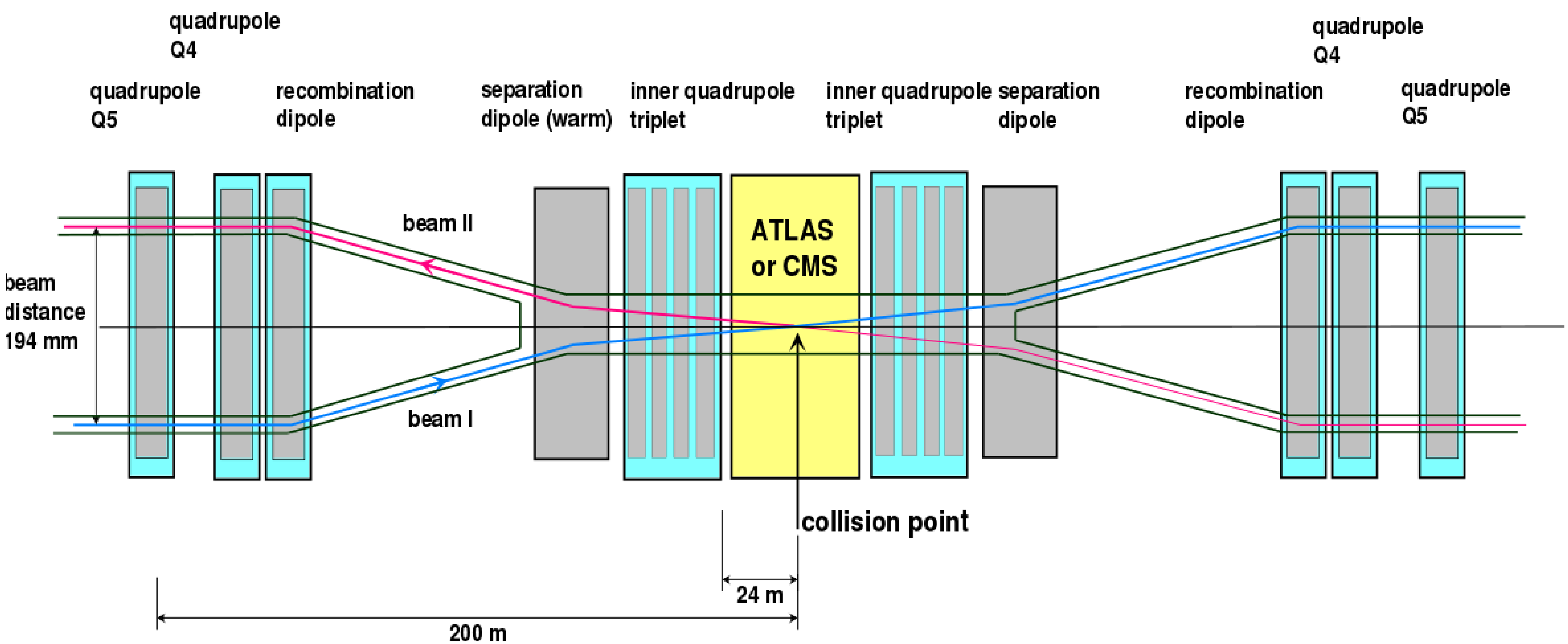
machine	L [m]	relative	ρ [m]	beam momentum [GeV/c]	bunches
LINAC	30		–	10^{-4}	4×2
PSB	157		8.3	0.05	4×2
PS	628.318	1	70.676	1.4	72
SPS	6911.56	11×PS	741.257	26	4×72
LHC	26658.883	27/7×SPS	2803.98	450	2×2808

Injection Chain: the future





Interaction region



Example for an LHC insertion with ATLAS or CMS

Luminosity

$$L\sigma = \dot{n}$$

$$L = \frac{N_1 N_2 n_b f_{rev}}{\pi\sqrt{({\sigma^2}_{x,1} + {\sigma^2}_{x,2})}\sqrt{({\sigma^2}_{y,1} + {\sigma^2}_{y,2})}} FH$$

- L, Luminosity
- N_i, number of protons per bunch
- n_b, number of bunches
- f_{rev}, frequency
- $\sigma_{j,i}$, cross section of the beams
- F, geometric reduction factor

$$F = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_t}\frac{\emptyset}{2}\right)^2}}$$

- σ_s is the longitudinal section
- σ_t is the transverse
- $\emptyset$ is the crossing angle between the two beams

How to maximise L?

- Optimise overlap
- Minimise beam size
- Maximise particle per bunch
- Maximise bunches in collider

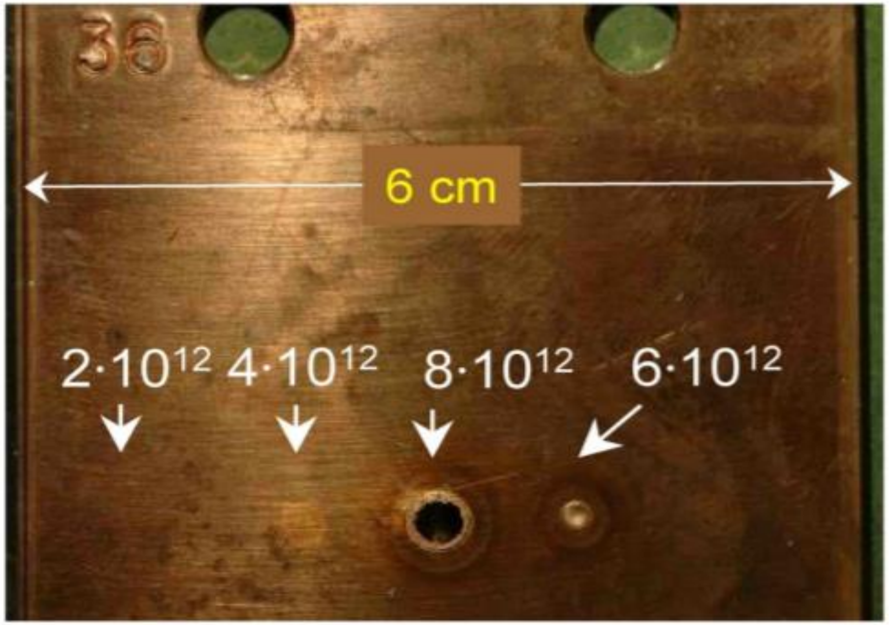
Security & protection

Quenching

A quench is an abnormal termination of magnet operation that occurs when part of the superconducting coil enters the normal (resistive) state – Wikipedia

- 12kA required to generate 8.33T
  - Joule effect
    - $P = I^2R$
  - Magnetic energy ~7.2MJ
    - $E = \frac{1}{2}I^2L$
- As soon as 100mV rise in 10ms is detected
  - Ohmic loss is distributed on larger area
  - Quenched magnet is discharged

Beam Loss protection



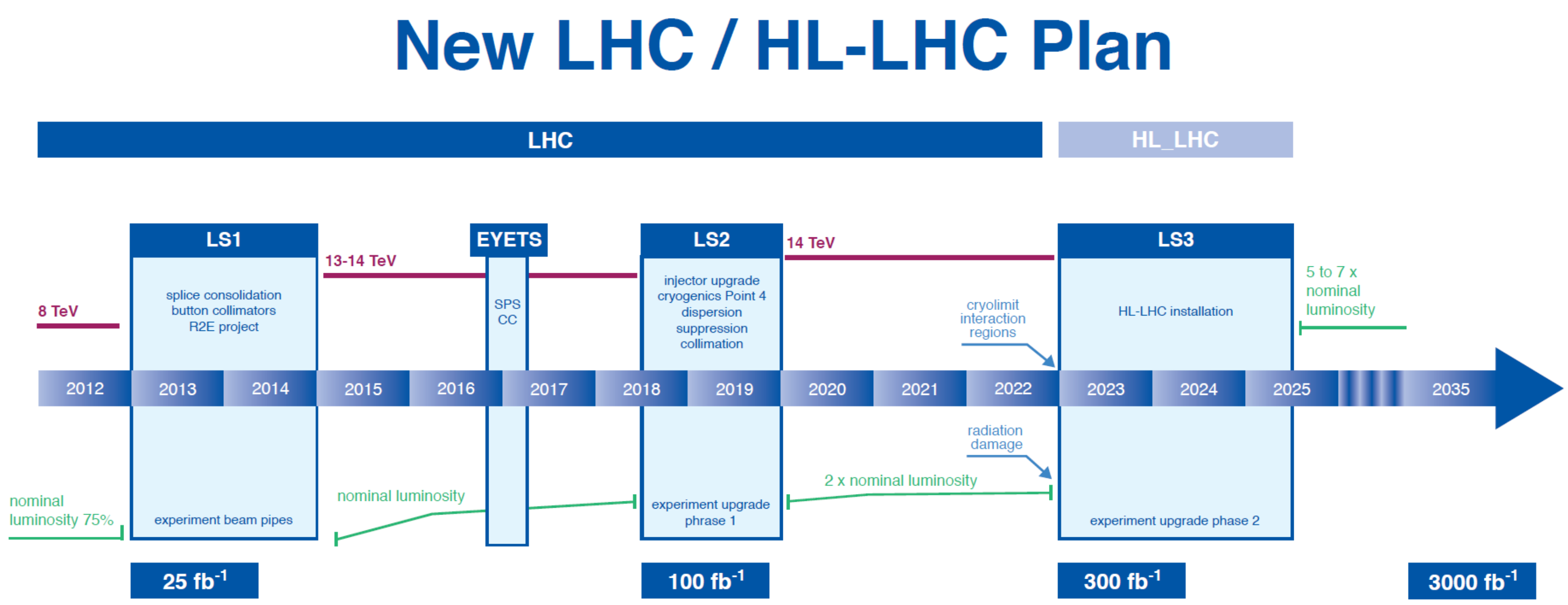
Beam energy ~362MJ
Energy required to Melt 1kg copper~ 0.7MJ

INSTANT QUENCHING!

Ways to maximise instantaneous luminosity

- Optimise overlap
- Minimise beam size
- Maximise number of particle per bunch
- Maximise the number of bunches In the collider

Upgrade plans



Upgrade planned stages

- **Long Shutdown 1 (LS1), 2013-2014**, for consolidating the LHC inter-magnet splice connections and allowing operation at nominal beam energies of 7TeV. Luminosity expected above the design value of $L = 10^{34}\ cm^{-2}\ s^{-1}$.

- **LS2, 2018**, for connecting the LINAC4 accelerator and for consolidating the LHC and its injector chain. $L = 2.5 \times 10^{34}\ cm^{-2}\ s^{-1}$.

- **LS3, 2022** for LIU and HL-LHC.
- LIU is an injector upgrade project, designed to deliver the high brightness beams required for HL-LHC.
- HL-LHC with a goal of integrated L of 200 to 300 fb^{-1} per year.

The HL-LHC upgrade goals

- Peak instantaneous luminosity and luminosity leveling
- Limits for β^* values
- Geometric reduction factor for an operation with crossing angle
- Maximizing the single bunch intensity and the beam-beam limit
- Maximizing the number of bunches

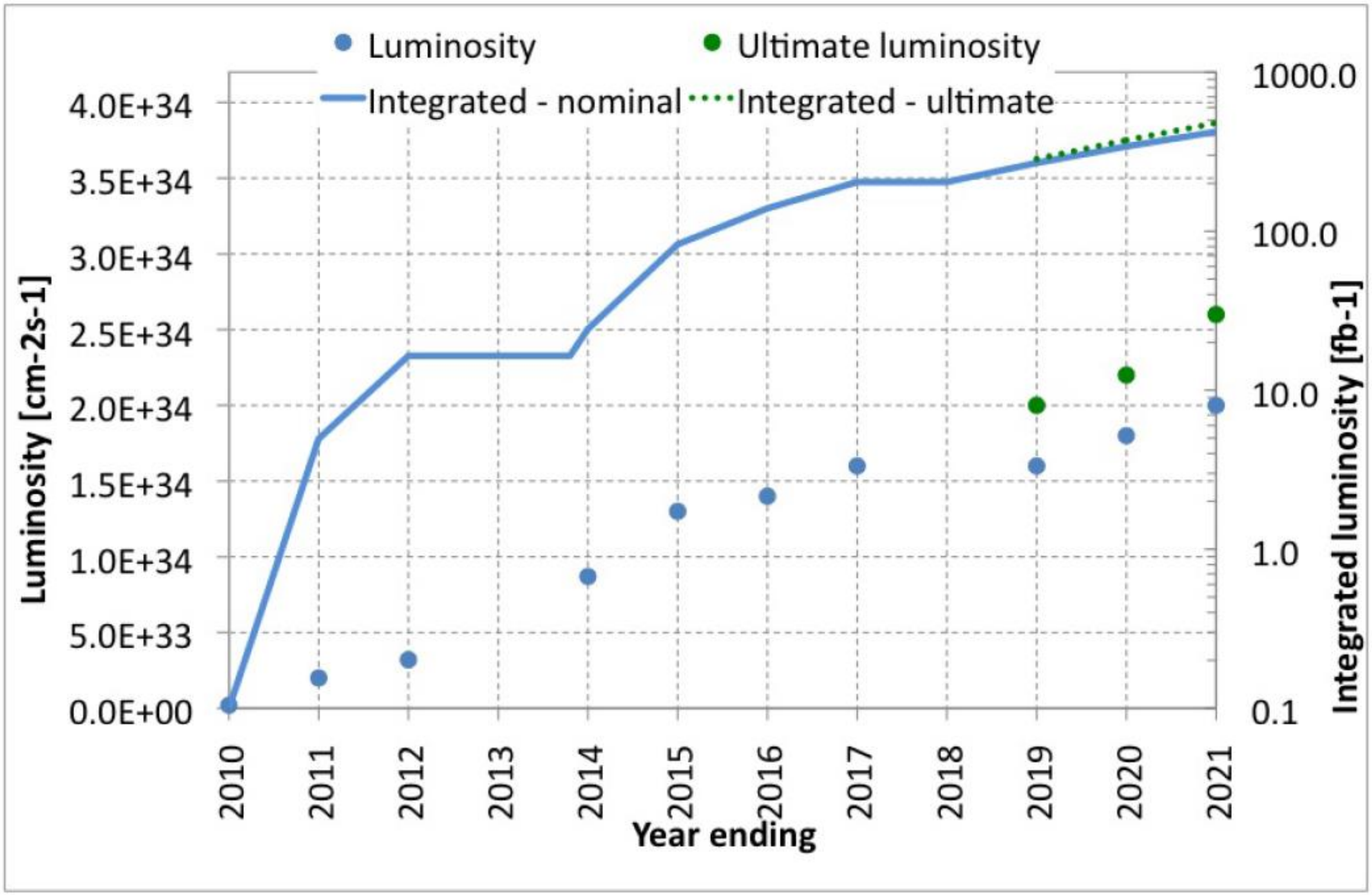
Peak instantaneous luminosity and luminosity leveling

- Currently 20 events per bunch crossing. Expected to rise to 100 events.
- L increased to 5×10^{34} cm^{-2} s^{-1} .

- Upgrade relies on luminosity leveling. – this reduces too high event pileup rates, while maximizing the integrated luminosity over a fill. The following procedures are considered:

  - Transverse offsets of the beams at the IP
  - Use of Crab cavities for manipulating beam overlap
  - Manipulation of external crossing angles
  - A dynamic change of the β-functions at the IPs
  - Bunch length variation

Peak instantaneous luminosity and luminosity leveling



Limits for β^* values

- The LHC triplet configuration is compatible with an operation with $\beta^* = 0.5$m, featuring gradients of 200T/m.
  - This corresponds to peak magnetic fields of more than 6T at the magnet coils which is at the limit of the NbTi technology.

- Reducing β^* implies either:
  - Magnet technologies that are compatible with higher peak magnetic fields at the coil (e.g. Nb_3Sn)
  - Or use of triple magnets with lower gradients

Limits for β^* values

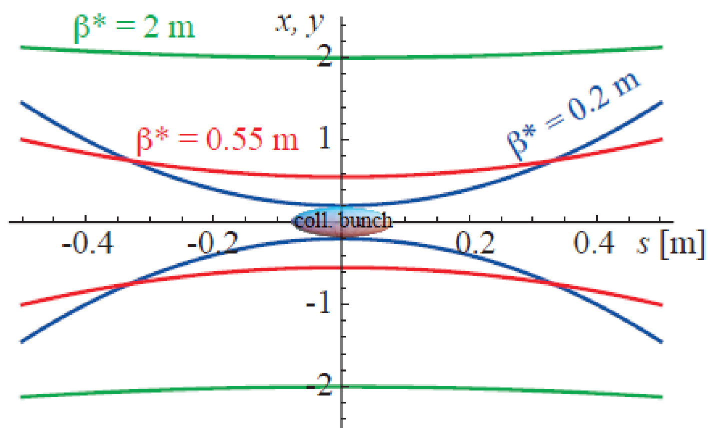


Figure 35: Illustration of the hour-glass effect for a β^* of 2 m, the nominal 0.55 m and 0.2 m as considered for the LHC upgrade. For small β^*, the variation of the β-function over the bunch length of the colliding bunches becomes non-negligible.

Geometric reduction factor for an operation with crossing angle

- The two counter-rotating beams collide in the LHC with a crossing angle in order to avoid unwanted head-on collisions in the common vacuum beam pipe away from the actual IP.

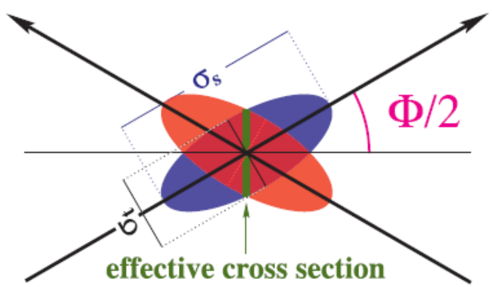


Figure 33: Two beams crossing at the angle Φ. The effective beam overlap cross-section is increased compared to the transverse beam size σ_t.

Geometric reduction factor for an operation with crossing angle

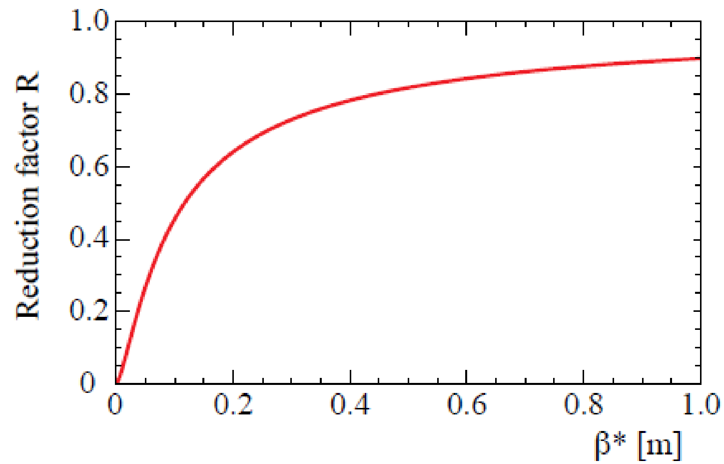
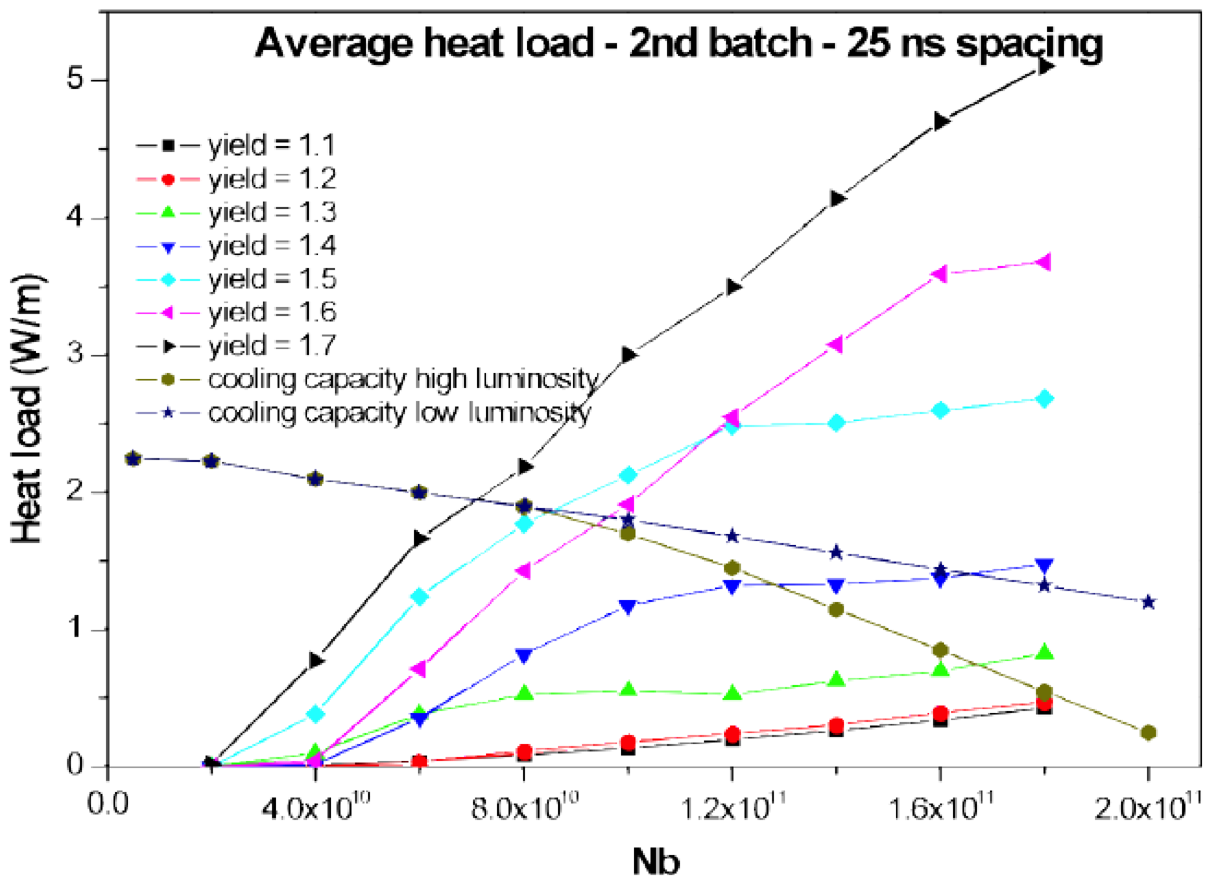


Figure 34: The geometric luminosity reduction factor as a function of β^* for a crossing angle corresponding to a beam separation of 10 σ, for the nominal bunch length of 7.55 cm and $\epsilon_n = 3.75\,\mu$m.

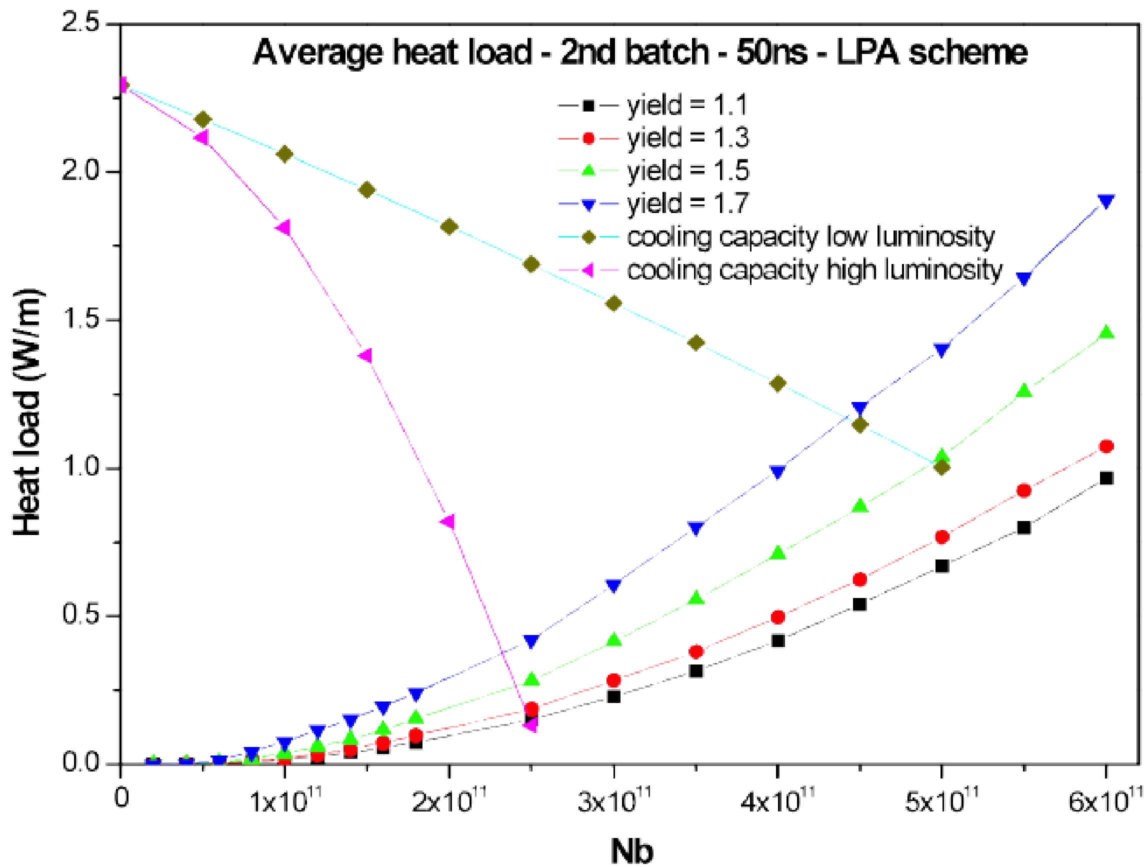
Maximizing the number of bunches

- The number of bunches in the LHC can be limited by the electron-cloud effect.
  - Electrons in the beam vacuum chamber are accelerated by the positively charged proton beams and release secondary electrons after impact on the vacuum chamber walls.
- The LHC operation with more than 300 bunches showed in 2010 the onset of electron cloud activity.
- HL-LHC will come with an improved cryogenic system that prevent the release of electrons from the vacuum chamber walls.

Maximizing the number of bunches



Maximizing the number of bunches



Thank you for the attention.

Questions?