HL-LHC project

Accelerator outlook and challenges

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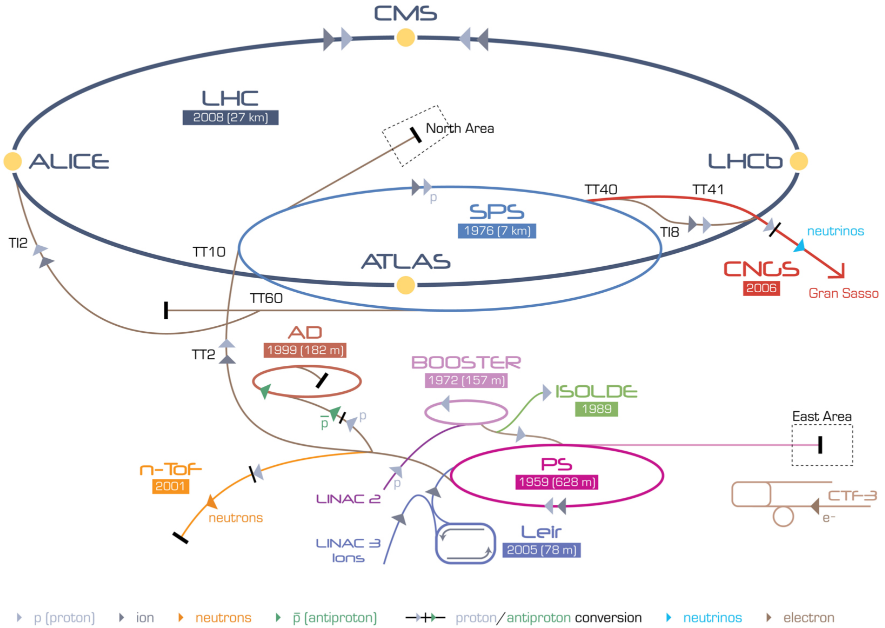
Content and motivation

- LHC status and HL-LHC upgrade goals
- Machine parameters outlook
- Possible hardware changes
- Ongoing and future studies
- Project structure and planning

LHC: the scene

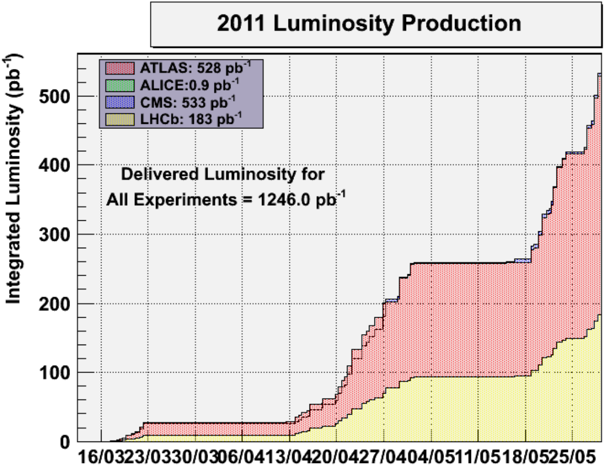
LHC: the scene



Present LHC: the status

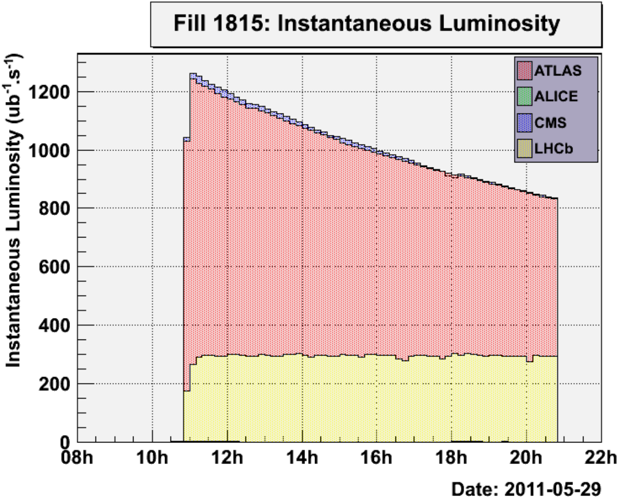
Integrated luminosity target for ATLAS and CMS of the 2011 [1]:

$$\int L dt = 1\,\mathrm{fb}^{-1}$$



[1] from Chamonix Perfomance Workshop 2011

Present LHC: a good fill

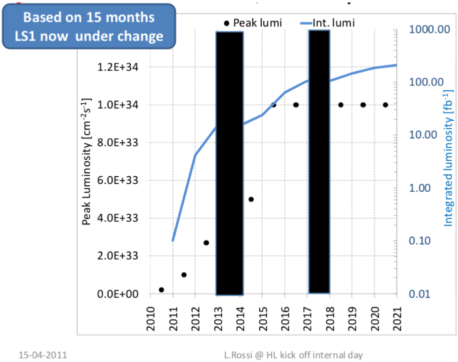


$L_{\text{peak}} = 1.2 \cdot 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ $\int L dt = 38\,\text{pb}^{-1}$

The nominal LHC peak luminosity is $L_{\text{peak}} = 1 \cdot 10^{34}$

LHC: integrated luminosity projection

How the luminosity might evolve up to 2020 and beyond



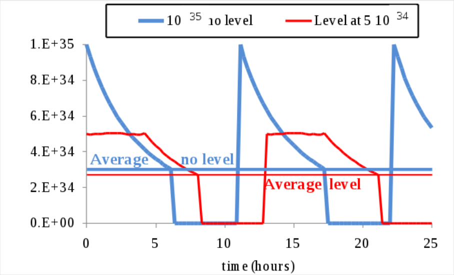
L. Rossi 15-04-2011 HL-LHC kickoff meeting

Upgrade necessary for

- saturation of statistical improvements or
- radiation accumulated damage in the triplet quadrupoles

HL-LHC: upgrade goals

"The HL-LHC study combines all work related to the provision of a peak luminosity of five times the design luminosity of the LHC (i.e. $5 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and with an enhanced luminosity lifetime by luminosity leveling".

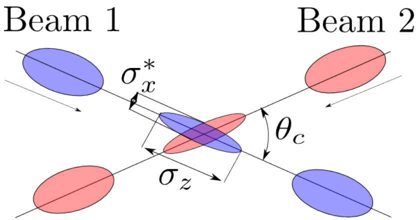


Luminosity leveling: change dynamically one beam parameter to compensate the natural luminosity decay starting the fill with a lower but, virtually possible, peak luminosity.

Illustration by E. Todesco

An integrated luminosity of $200 - 300\,\mathrm{fb}^{-1}$ per year and $3000\,\mathrm{fb}^{-1}$ by 2030 would be in reach.

Luminosity: Present parameters

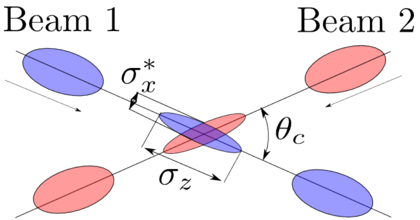


$$L = \frac{f_{\text{rev}} n_b N^2}{4\pi\sigma_x^*\sigma_y^*} F_{\text{geo}} F_{\text{hr}}$$

$$F_{\text{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x^*}\right)^2}},$$

Energy	E	$3.5\,\mathrm{TeV}$
Luminosity	L	$1.2\cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Protons per bunch	N_b	$1.2\cdot 10^{11}$
Number of bunches	n_b	1092
Bunch spacing	d_b	$25\,\mathrm{ns}$
Beam Current	I	$0.24\,\mathrm{A}$
Longitudinal RMS beam size	σ_z	$7.5\,\mathrm{cm}$
Transverse RMS beam size in the arcs	σ_{arc}	$300\,\mu\mathrm{m}$
Transverse RMS beam size in the IP	$\sigma_{x\|y}^*$	$23\,\mu\mathrm{m}$
Crossing angle	θ_c	$296\,\mu\mathrm{rad}$

Luminosity: Nominal parameters

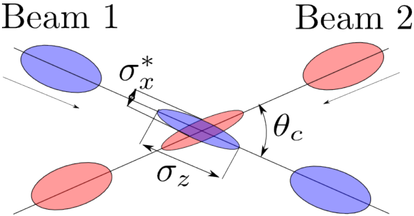


$$L = \frac{f_{\mathrm{rev}} n_b N^2}{4\pi\sigma_x^*\sigma_y^*} F_{\mathrm{geo}} F_{\mathrm{hr}}$$

$$F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x^*}\right)^2}},$$

Energy	E	$7\,\mathrm{TeV}$
Luminosity	L	$1\cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Protons per bunch	N_b	$1.15\cdot 10^{11}$
Number of bunches	n_b	2808
Bunch spacing	d_b	$25\,\mathrm{ns}$
Beam Current	I	$0.58\,\mathrm{A}$
Longitudinal RMS beam size	σ_z	$7.5\,\mathrm{cm}$
Transverse RMS beam size in the arcs	σ_{arc}	$300\,\mu\mathrm{m}$
Transverse RMS beam size in the IP	$\sigma_{x\|y}^*$	$16\,\mu\mathrm{m}$
Crossing angle	θ_c	$296\,\mu\mathrm{rad}$

Luminosity: Upgrade challenges



$$L = \frac{f_{\mathrm{rev}} n_b N^2}{4\pi\sigma_x^*\sigma_y^*} F_{\mathrm{geo}} F_{\mathrm{hr}}$$

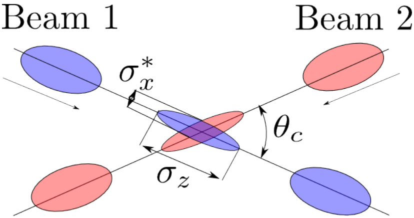
$$F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x^*}\right)^2}},$$

Name	Symbol	Values
Luminosity	L	$5\cdot10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

At $5\cdot10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, obviously, detectors has to cope with more interactions, debris, data but also in the machine will suffer from:

- higher debris power to be intercepted (e.g. neutral $100\,\mathrm{W}\rightarrow500\,\mathrm{W}$)
- more frequent electronics reliability issues
- faster accumulated radiation damage

Luminosity: Upgrade challenges on beam current



$$L = \frac{f_{\mathrm{rev}} n_b N^2}{4\pi\sigma_x^*\sigma_y^*} F_{\mathrm{geo}} F_{\mathrm{hr}}$$
$$F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z\theta_c}{2\sigma_x^*}\right)^2}},$$

Beam Current	I	$\to 1\,\mathrm{A}$

$\dot{N}(t) = L\sigma_{\mathrm{total}} + \mathrm{losses}$

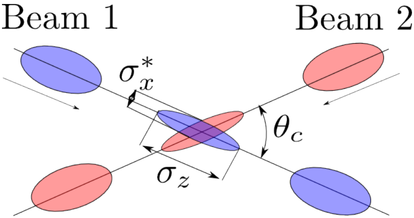
Challenges:

- Stored energy and machine protection
- Cryogenic limit
- collimation efficiency: magnet quenches

Beam current limit[2] : $\sim 1\,\mathrm{A}$

[2] R. Assman, Chamonix 2010

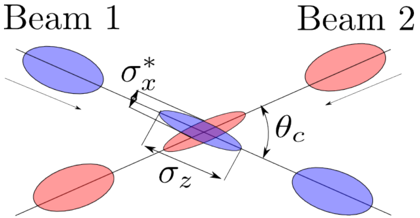
Luminosity and β functions



$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$
$$\theta_\mathrm{c} = d_\mathrm{s}\sqrt{\epsilon/\beta_x^*},$$
$$L = \frac{f_\mathrm{rev} n_b N^2}{4\pi\epsilon\sqrt{\beta_x^*\beta_y^*}} F_\mathrm{geo} F_\mathrm{hr}$$
$$F_\mathrm{geo} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_\mathrm{s}}{2\beta_x^*}\right)^2}},$$

Protons per bunch	N_b	$1.15 \cdot 10^{11}$
Number of bunches	n_b	2808
Longitudinal RMS beam size	σ_z	7.5 cm
Emittance	ϵ	3.75γ mm mrad
Transverse β in the arcs	β_arc	180 m
Transverse β in the IP	$\beta^*_{x\|y}$	55 cm
Crossing angle	θ_c	296 μrad

Luminosity: Upgrade challenges for emittance



$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$
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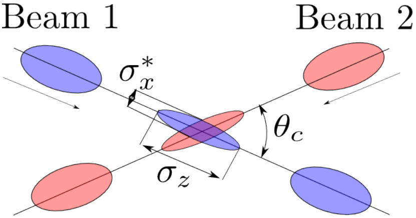
$$F_{geo} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_s}{2\beta_x^*}\right)^2}},$$

Emittance	ϵ	$\rightarrow 2.5\gamma\,\mathrm{mm\,mrad}$

- $\dot{\epsilon}(t) > 0$ for IBS, instabilities, noise, non linear resonances and diffusion, but some synchrotron radiation damping...
- Once produced can be only preserved in injector chain and the LHC.
- LHC already running with $2.5\gamma\,\mathrm{mm\,mrad}$, with painting in LINAC4, $1.5\gamma\,\mathrm{mm\,mrad}$ is in reach.

But at which bunch current? ....

Luminosity: Upgrade challenges for brilliance



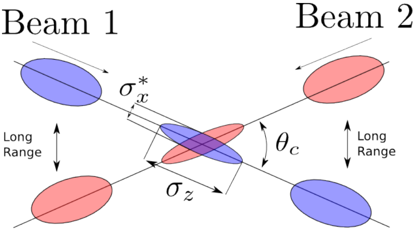
$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$
$$\theta_{\mathrm{c}} = d_{\mathrm{s}}\sqrt{\epsilon/\beta_x^*},$$
$$L = \frac{f_{\mathrm{rev}} n_b N^2}{4\pi\epsilon\sqrt{\beta_x^*\beta_y^*}} F_{\mathrm{geo}} F_{\mathrm{hr}}$$
$$F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_{\mathrm{s}}}{2\beta_x^*}\right)^2}},$$

Emittance	ϵ	$3.75 \to 2.5\gamma\,\mathrm{mm\,mrad}$
Protons per bunch	N_b	$1.1 \to 1.3 \to 3.3 \cdot 10^{11}$
Brilliance	N/ϵ	$2.9 \to 5.2 \to 8.8 \cdot 10^{16}\,\mathrm{ppb}/(\gamma\mu\mathrm{rad})$

High brilliance makes bunches more unstable due to wake field, e-cloud, beam beam collision, increases the luminosity and event pile-up (and space charge in the injectors).
Preserving high brilliant beams is a challenge also for the injector chain.
Possible option for the upgrade:

- 25 ns 2808 bunches beyond ultimate intensity at reduced emittance
- 50 ns 1404 bunches with 50% higher intensity at nominal emittance

Luminosity: Upgrade challenges for crossing angle

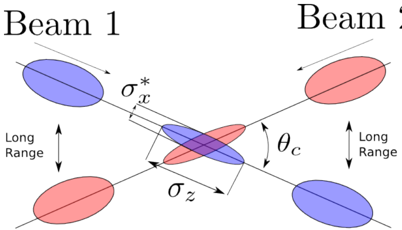


$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$
$$\theta_{\mathrm{c}} = d_{\mathrm{s}}\sqrt{\epsilon/\beta_x^*},$$
$$L = \frac{f_{\mathrm{rev}} n_b N^2}{4\pi\epsilon\sqrt{\beta_x^*\beta_y^*}} F_{\mathrm{geo}} F_{\mathrm{hr}}$$
$$F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_{\mathrm{s}}}{2\beta_x^*}\right)^2}},$$

Beam beam separation	d_s	10σ

Long range beam beam effects are intensity dependent and induce coherent instabilities, tune spread and non linear resonances.
The effects are cured by the crossing angle at a cost of luminosity and may induce synchro-betatron resonances.
A beam separation of 9.8σ is the nominal value, 13σ is safe.

Luminosity: Upgrade challenges for β^*



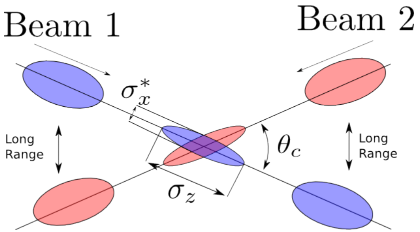
$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$
$$\theta_c = d_s\sqrt{\epsilon/\beta_x^*},$$
$$L = \frac{f_{\mathrm{rev}} n_b N^2}{4\pi\epsilon\sqrt{\beta_x^*\beta_y^*}} F_{\mathrm{geo}} F_{\mathrm{hr}}$$
$$F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_s}{2\beta_x^*}\right)^2}},$$

Transverse β in the IP	$\beta^*_{x\|y}$	15 or 7.5|30 cm
Transverse β in the 4 arcs	β_{arc}	$\to$ 1440 m
Crossing angle	θ_c	580 or 1060 $\to$ 530 μrad

β^* can be reduced by replacing the triplet quadrupole with larger aperture, longer, with possibly higher peak field, as well as other magnets closer to the IP. Challenges:

- beam optics flexibility and chromatic aberrations $\to$ new optics scheme proposed (ATS)
- exceptional field quality for the new magnets.
- tight collimation settings for an efficient use of the triplet aperture

Luminosity and β functions



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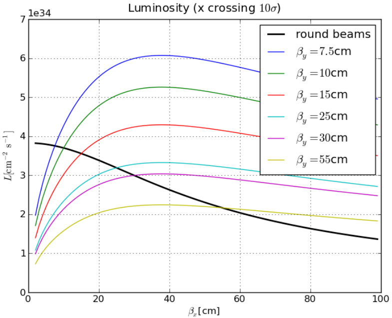
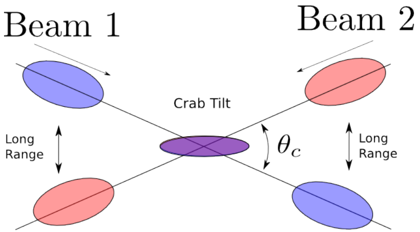
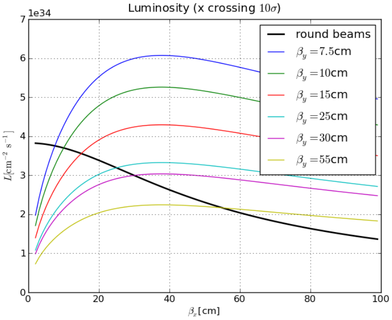


Crossing angle depends on beta star $\rightarrow$ luminosity saturate...
Optimal values can be found for $\beta_x^* \neq \beta_y^*$, unless crab cavities are used which restore the geometric overlap.
Geometric overlap through crossing angle or crab cavities is the baseline method for leveling. Parallel separation or dynamic β^* are possible too.

Luminosity and β functions



$$\sigma(s) = \sqrt{\epsilon\beta(s)}$$
$$\theta_\mathrm{c} = d_\mathrm{s}\sqrt{\epsilon/\beta^*_x},$$
$$L = \frac{f_\mathrm{rev} n_b N^2}{4\pi\epsilon\sqrt{\beta^*_x\beta^*_y}} F_\mathrm{geo} F_\mathrm{hr}$$
$$F_\mathrm{geo} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_\mathrm{s}}{2\beta^*_x}\right)^2}},$$



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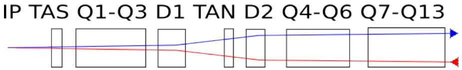
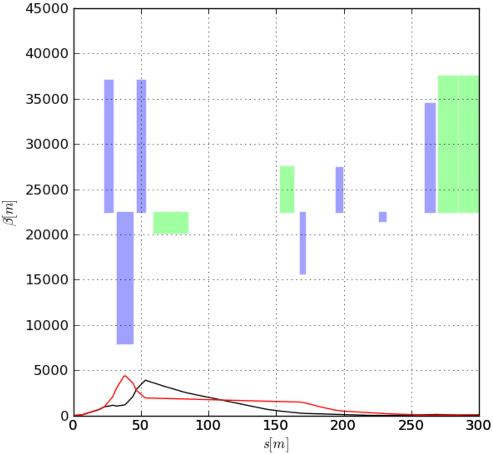
Geometric overlap through crossing angle or crab cavities is the baseline method for leveling. Parallel separation or dynamic β^* are possible too.

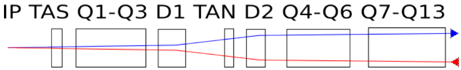
New interaction region for beta* reduction

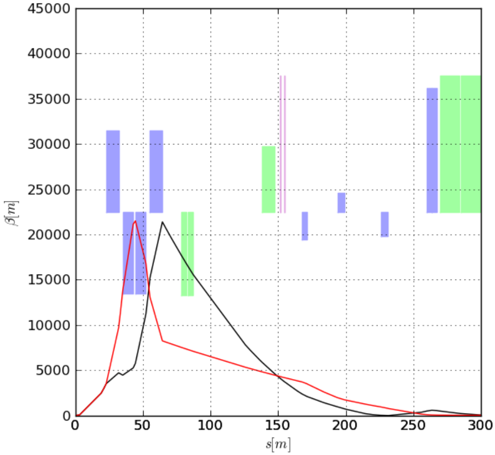




Nominal collision optics

New interaction region for beta* reduction

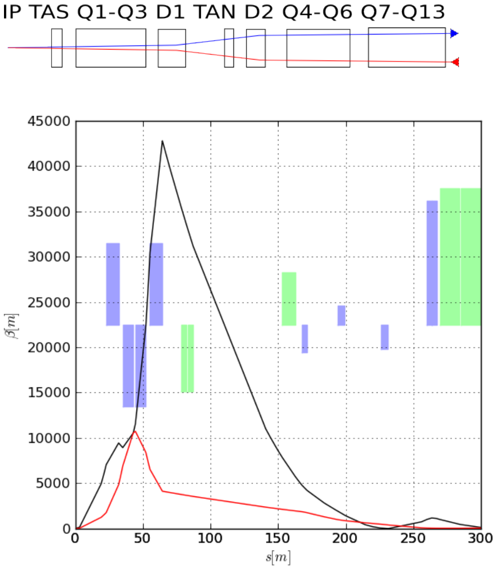




Round beam upgrade optics with crab cavities

Layout and optics not final, they depends on the available technology for common bore and 2-in-1 quadrupoles and dipoles.

New interaction region for beta* reduction

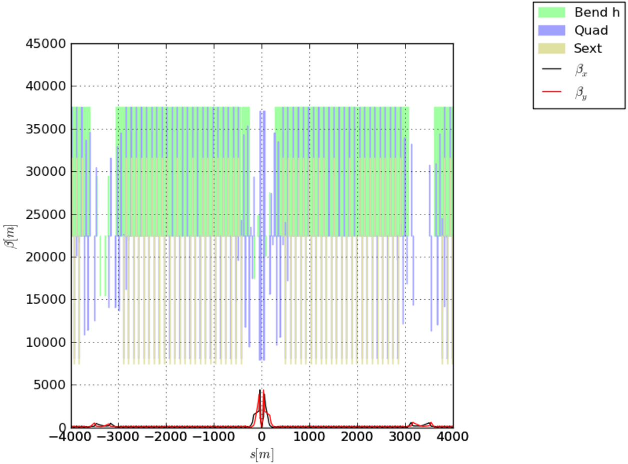


Flat beam upgrade optics

Layout and optics not final, they depends on the available technology for common bore and 2-in-1 quadrupoles and dipoles.

ATS optics for low β^*

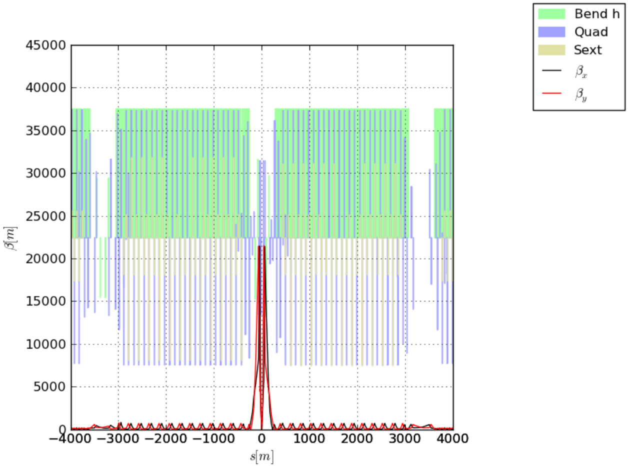
$\beta^* = 55\,\mathrm{cm}$



Achromatic telescopic squeezing scheme (ATS) solves optics flexibility and chromatic aberration issues. Being tested in the LHC.

ATS optics for low β^*

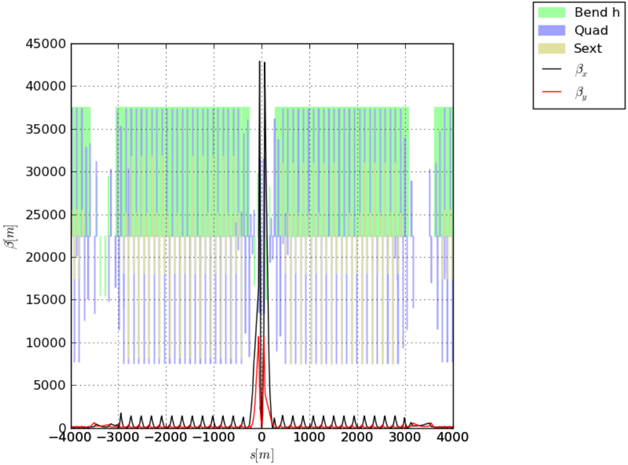
$\beta^* = 15\,\mathrm{cm}$



Achromatic telescopic squeezing scheme (ATS) solves optics flexibility and chromatic aberration issues. Being tested in the LHC.

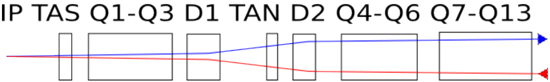
ATS optics for low β^*

$\beta^* = 7.5/30\,\mathrm{cm}$

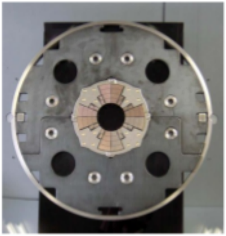


Achromatic telescopic squeezing scheme (ATS) solves optics flexibility and chromatic aberration issues. Being tested in the LHC.

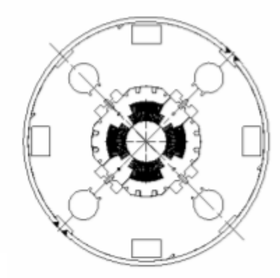
New magnets: triplets



MQXA



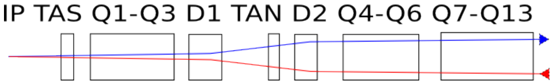
MQXA cross-section

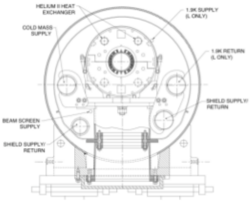


MQXB

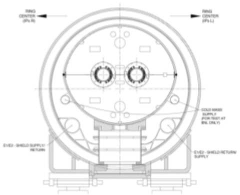
New designs: Q1-Q3
Longer $\rightarrow 8\,\mathrm{m}$ and larger aperture up $80\,\mathrm{mm} \rightarrow 150\,\mathrm{mm}$ with higher peak field (Nb3Sn technology) to fully exploit β^* potential.
NbTi technology can be used at the price of even longer magnets $\rightarrow 11\,\mathrm{m}$ and higher β^*.

New magnets: matching section

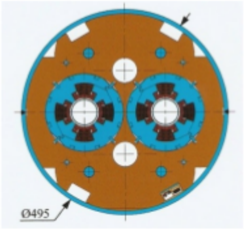




D1



D2



Q4

New larger aperture design are needed for D1, D2, Q4, orbit correctors and non linear correctors.
New magnets (standard design) are also needed for Q5 in IR1-5-6.
Displacement of Q4, Q5 maybe be needed as well.
Commissioning: MS to 600A in 4 sectors.
New elements: MSCB in Q10 in IR1 and IR5.

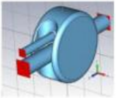
Crab cavities integration

Parallel bar elliptical TEM cavity (JLAB)

Half wave spoke resonator (SLAC)

Four rod compact crab cavity (Cockcroft)

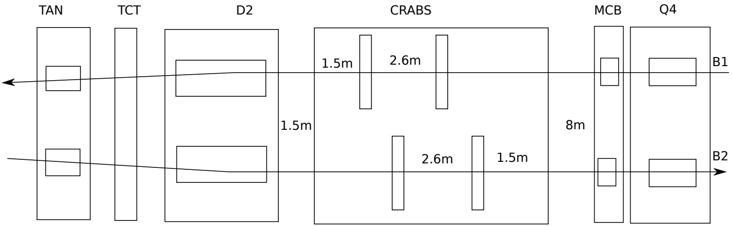
Rotated pill-box cavity (KEK)



Quarter-wave resonator (BNL)

Baseline $V = 10\,\mathrm{MV}$, $\theta_c = 580\,\mu\mathrm{rad}$, $\omega = 2\pi \cdot 400\,\mathrm{MHz}$

$$V = \frac{cp}{e\omega}\frac{\theta_c}{2}\frac{1}{\sqrt{\beta^*\beta_{\mathrm{crab}}}}$$



Other new elements

- Larger aperture beam pipes and beam screen.
- Protection and shielding: TAN TAS TCT
- Power converters and superconducting links for the surface
- Cryogenics and RF power for crab cavities

Additional enhanchent:

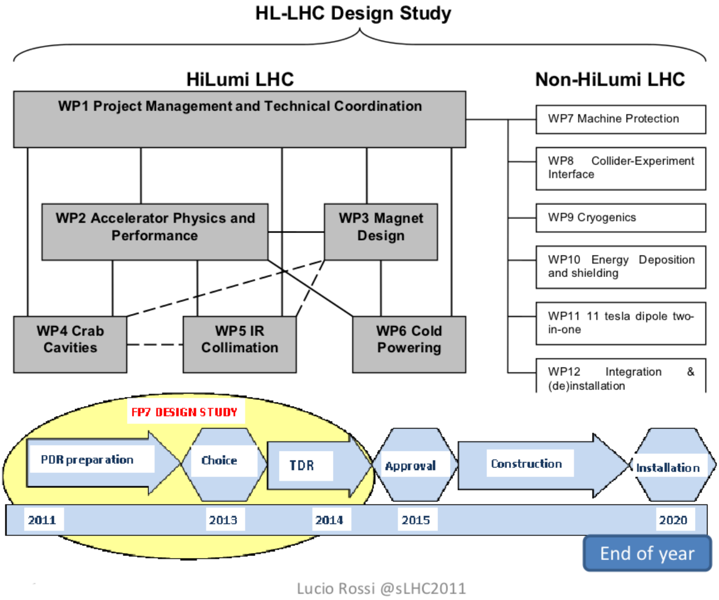
- Long range compensation wires: gain in the crossing angle
- Laundau cavities to control longitudinal instabilities (may reduce bunch length provided IBS is acceptable)

Studies

On going studies:

- ATS optics design and test with beam
- IR layout design
- parameter optimizations
- energy deposition and collimation studies
- new large aperture magnets
- crab cavities
- cold powering

Structure and planning



Final remarks

LHC upgrade first ideas started around 2000.

In 2010 the LHC is on track towards nominal performance

Around 2020 ideal time for an upgrade to assure a steady growth of LHC performance up to 2030 and beyond...

References

- 15-4-2011 HL-LHC Kick off Internal Meeting:
http://indico.cern.ch/conferenceDisplay.py?confId=132315
- Chamonix 2011 workshop, LHC upgrade session
http://indico.cern.ch/conferenceOtherViews.py?confId=103957
- LHC-CC10 Crab cavity workshops
http://indico.cern.ch/conferenceOtherViews.py?confId=100672
- sLHC project reports 49, 50, 53
http://cdsweb.cern.ch/record/1341874
http://cdsweb.cern.ch/record/1307558
http://cdsweb.cern.ch/record/1301180

Backup