LHC Accelerator R&D and Upgrade Scenarios

Summer 2001: CERN task force investigated a possible staged upgrade of the LHC and of its injectors $\Longrightarrow$ increase luminosity from the nominal $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in each of the two high-luminosity experiments, possible scenarios for an energy upgrade to $\sqrt{s} \simeq 25\,\mathrm{TeV}$. See LHC Project Report 626.

March 2002: LHC IR Upgrade collaboration meeting, see web site at `http://cern.ch/lhc-proj-IR-upgrade`

October 2002: ICFA Seminar on 'Future Perspectives in High Energy Physics', CERN

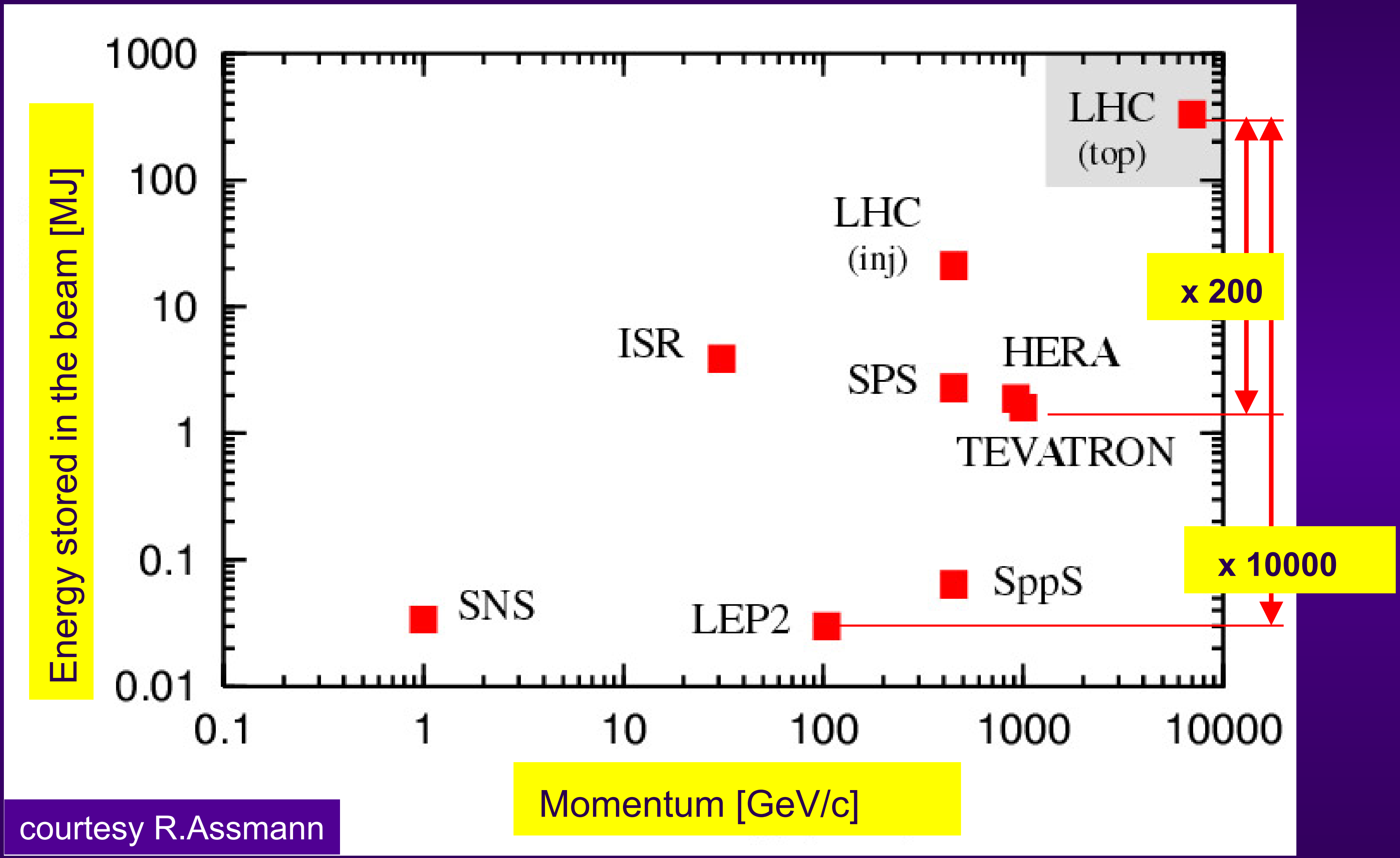
March 2003: LHC Performance Workshop, Chamonix

- LHC commissioning beams
- e-cloud, beam-beam, luminosity optimisation, and IR upgrade
- scenarios for a staged LHC upgrade and accelerator R&D

Constraints for LHC commissioning parameters

- Only 8 of the 20 LHC dump dilution kickers will be available during the first two years of operation. This limits the total beam intensity in each LHC ring to 1/2 of its nominal value.
- According to SPS experience and to electron cloud simulations, the initial LHC bunch intensity can reach and possibly exceed its nominal value for 75 ns bunch spacing, while it is limited to about 1/3 of its nominal value for 25 ns spacing.
- Machine protection and collimation favours initial operation with lower beam power and lower transverse beam density.
  Simple graphite collimators may limit maximum transverse energy density to about 1/2 of its nominal value.
- Emittance preservation from injection to physics conditions will require a learning curve $\Longrightarrow$ do not assume transverse emittance lower than nominal, even for reduced bunch intensity.
- Initial operation with relaxed parameters is strongly favoured $\Longrightarrow$ higher β^*, reduced crossing angle, and fewer parasitic collisions.

Challenges: Energy stored in the beam



Transverse energy density: even a factor of 1000 larger

Parameter	Units	75 ns spacing	25 ns spacing	nominal
number of bunches	n_{b}	936	2808	2808
protons per bunch	N_{b} $[10^{11}]$	0.9	0.4	1.15
norm. tr. emittance	ε_{n} $[\mu\mathrm{m}]$	3.75	3.75	3.75
r.m.s. bunch length	σ_{s} [cm]	7.55	7.55	7.55
r.m.s. energy spread	σ_{E} $[10^{-4}]$	1.13	1.13	1.13
IBS growth time	τ_x^{IBS} [h]	135	304	106
beta at IP	β^* [m]	1.0	0.55	0.55
full crossing angle	θ_{c} $[\mu\mathrm{rad}]$	250	285	285
luminosity lifetime	τ_{L} [h]	22	26	15
peak luminosity	L $[10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	0.12	0.12	1.0
events/crossing		7.1	2.3	19.2
lumi over 200 fills	L_{int} $[\mathrm{fb}^{-1}]$	9.3	9.5	66.2

Possible scenarios with 75 ns and 25 ns bunch spacing for an early LHC luminosity run with integrated luminosity of $\sim 10\,\mathrm{fb}^{-1}$ in about 200 fills, assuming an average physics run time $T_{\mathrm{run}} = 14$ h and $T_{\mathrm{turnaround}} = 10$ h.

LHC Upgrade

- In their present configuration, the CMS and ATLAS detectors can accept a maximum luminosity of $3 \div 5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
- An increase in luminosity may require positioning the low-β quadrupoles closer to the IP.
- An ultimate bunch intensity of 1.7×10^{11} p/bunch is compatible with the present beam dumping system. Further increases, e.g. to 2×10^{11} p/bunch or slightly higher, could still be tolerated accepting somewhat reduced safety margins or implementing moderate upgrades. Machine protection and collimation will be challenging.
- A possibility being considered also for CNGS beams is to upgrade the proton linac from 50 to $120 \div 160$ MeV, to overcome space charge limitations at injection in the booster. Then the ultimate LHC intensity would become easy to achieve and a further 30% increase would be possible with same emittance and same LHC filling time.
- If nominal (ultimate) luminosity is reached by 2011, the radiation damage limit for IR quads ($\sim 700\,\mathrm{fb}^{-1}$) is reached by 2017 (2013).

Luminosity optimization

peak luminosity for round beams colliding with full crossing angle θ_c

$$L = \frac{N_b^2 f_{rep}}{4\pi\sigma^{*2}} F \quad \text{reduced by a factor} \quad F \simeq 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

$f_{rep} = n_b f_o$: average bunch repetition frequency,
$\sigma^* = \sqrt{\varepsilon\beta^*}$: r.m.s. transverse beam size at the IP (16 μm for LHC)

maximum luminosity below beam-beam limit $\Longrightarrow$ short bunches and minimum crossing angle (baseline scheme)

H-V crossings in two IPs $\Longrightarrow$ no linear tune shift due to long range

total linear beam-beam tune shift also reduced by a factor $F_{bb} \simeq F$

$$\Delta Q_{bb} = \xi_x + \xi_y = \frac{N_b r_p}{2\pi\varepsilon_n} F$$

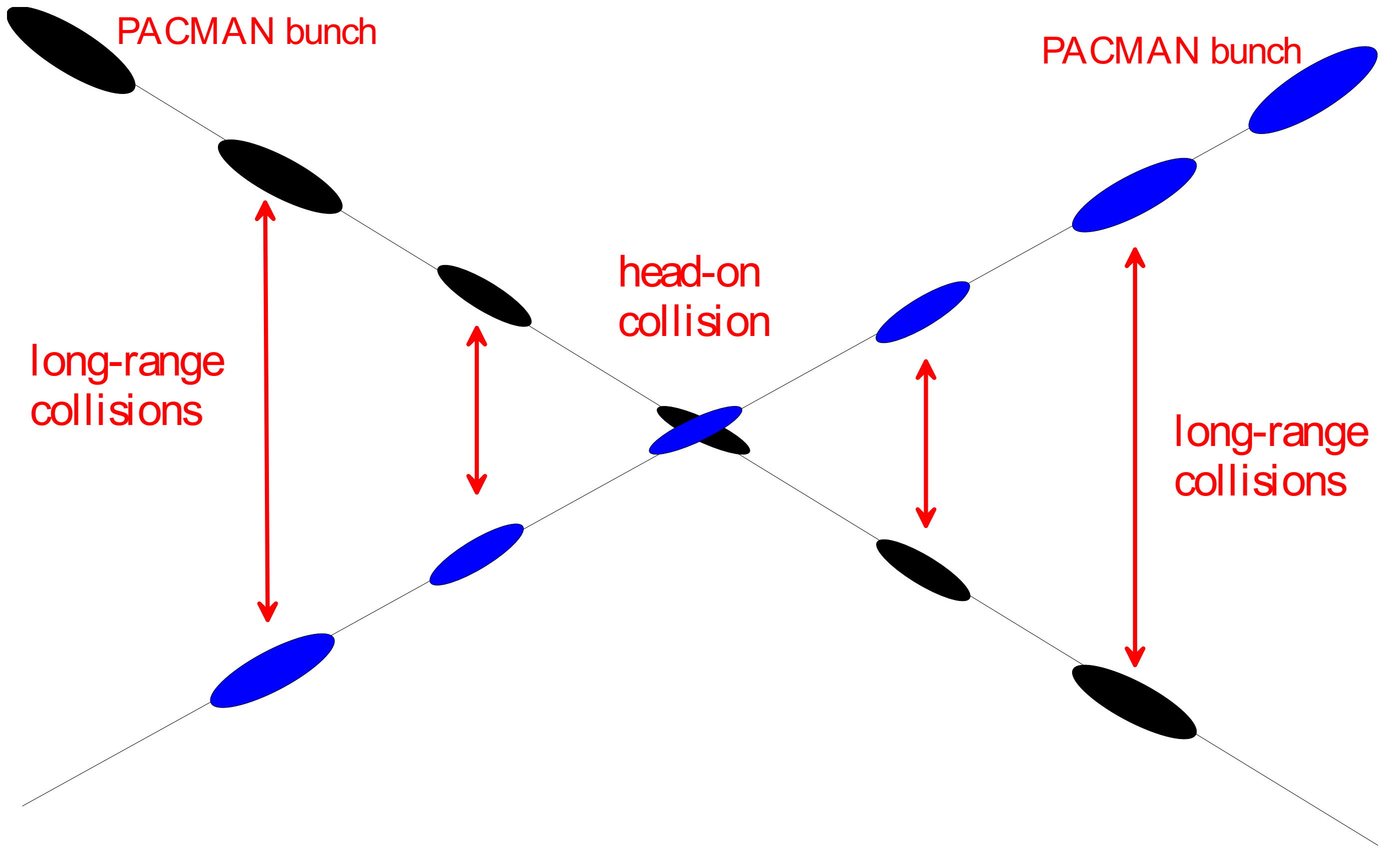
if bunch intensity and brilliance are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) $\Longrightarrow$ luminosity can be increased without exceeding the beam-beam limit $\Delta Q_{\rm bb} \sim 0.01$ by increasing the crossing angle and/or the bunch length

express beam-beam limited brilliance $N_{\rm b}/\varepsilon_{\rm n}$ in terms of maximum total beam-beam tune shift $\Delta Q_{\rm bb}$, then

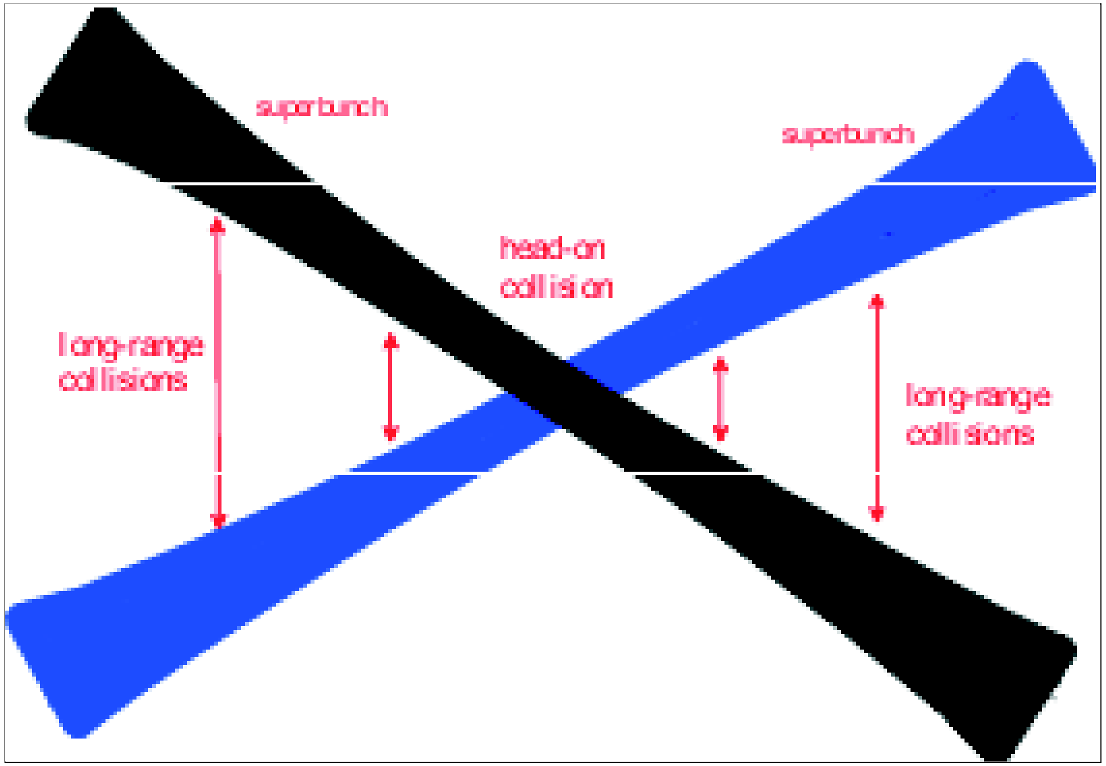
$$L \simeq \gamma \Delta Q_{\rm bb}^2 \frac{\pi \varepsilon_{\rm n} f_{\rm rep}}{r_{\rm p}^2 \beta^*} \sqrt{1 + \left(\frac{\theta_{\rm c} \sigma_z}{2\sigma^*}\right)^2}$$

luminosity is proportional to collision energy and normalized transverse emittance $\varepsilon_{\rm n} = \gamma\varepsilon \Longrightarrow$ an increased injection energy (Super-SPS) allows a larger normalized emittance and thus more intensity and more luminosity at the beam-beam limit

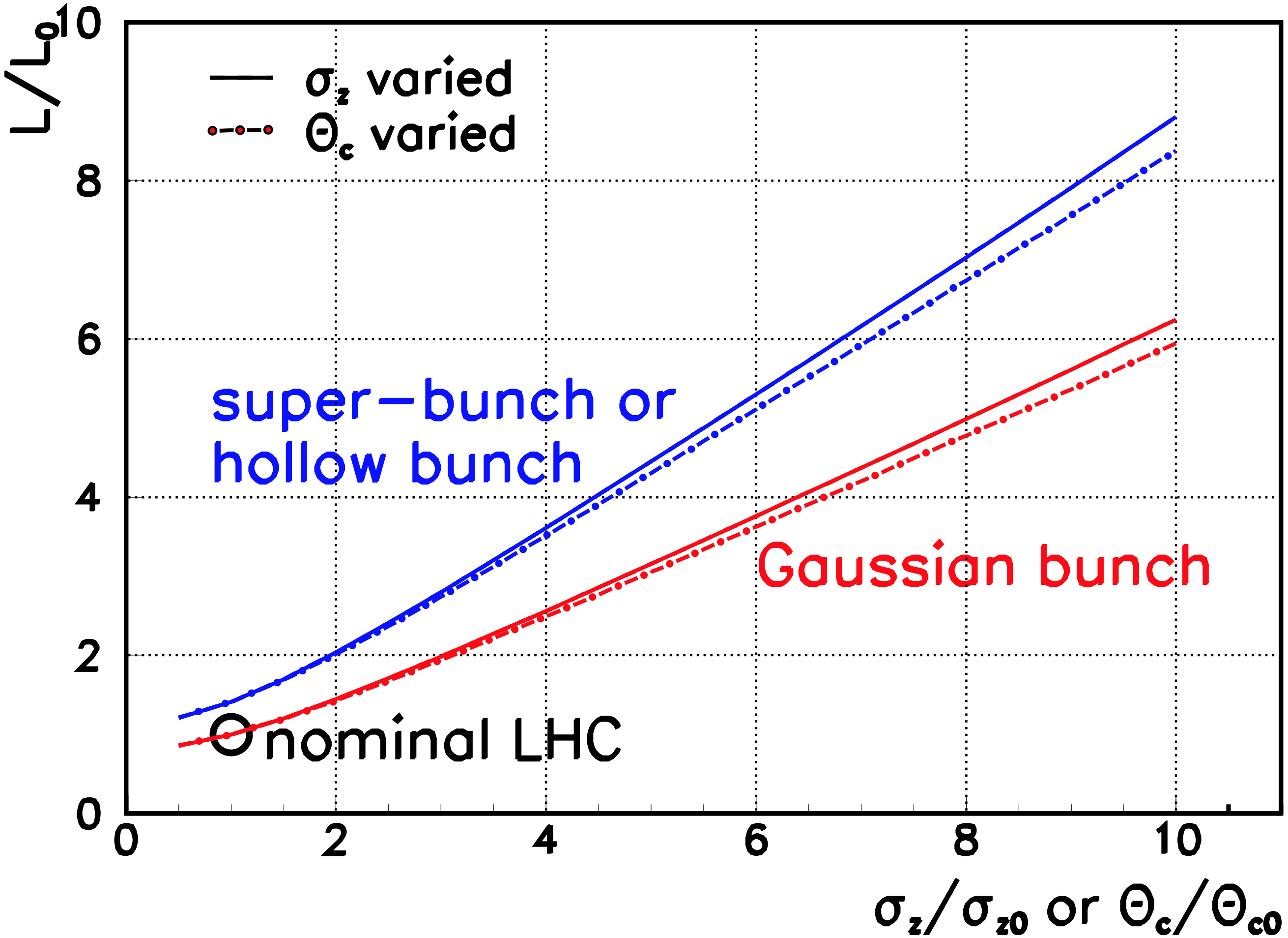
Another possibility to achieve significant luminosities with large crossing angles consists in colliding very long 'super-bunches'.



Schematic of long-range collisions on either side of the main interaction point. (Courtesy F. Zimmermann)

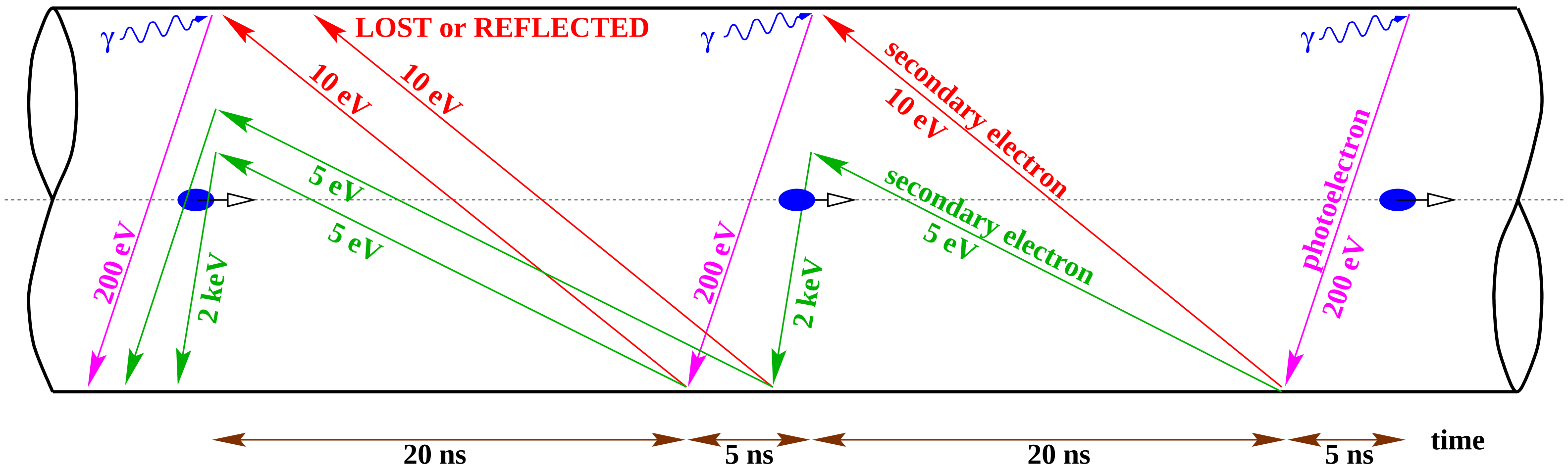


Schematic of a super-bunch collision, consisting of ‘head-on’ and ‘long-range’ components. The luminosity for super-bunches having flat longitudinal distribution is $\sqrt{2}$ times higher than for conventional Gaussian bunches with the same beam-beam tune shift and identical bunch population (see LHC Project Report 627).

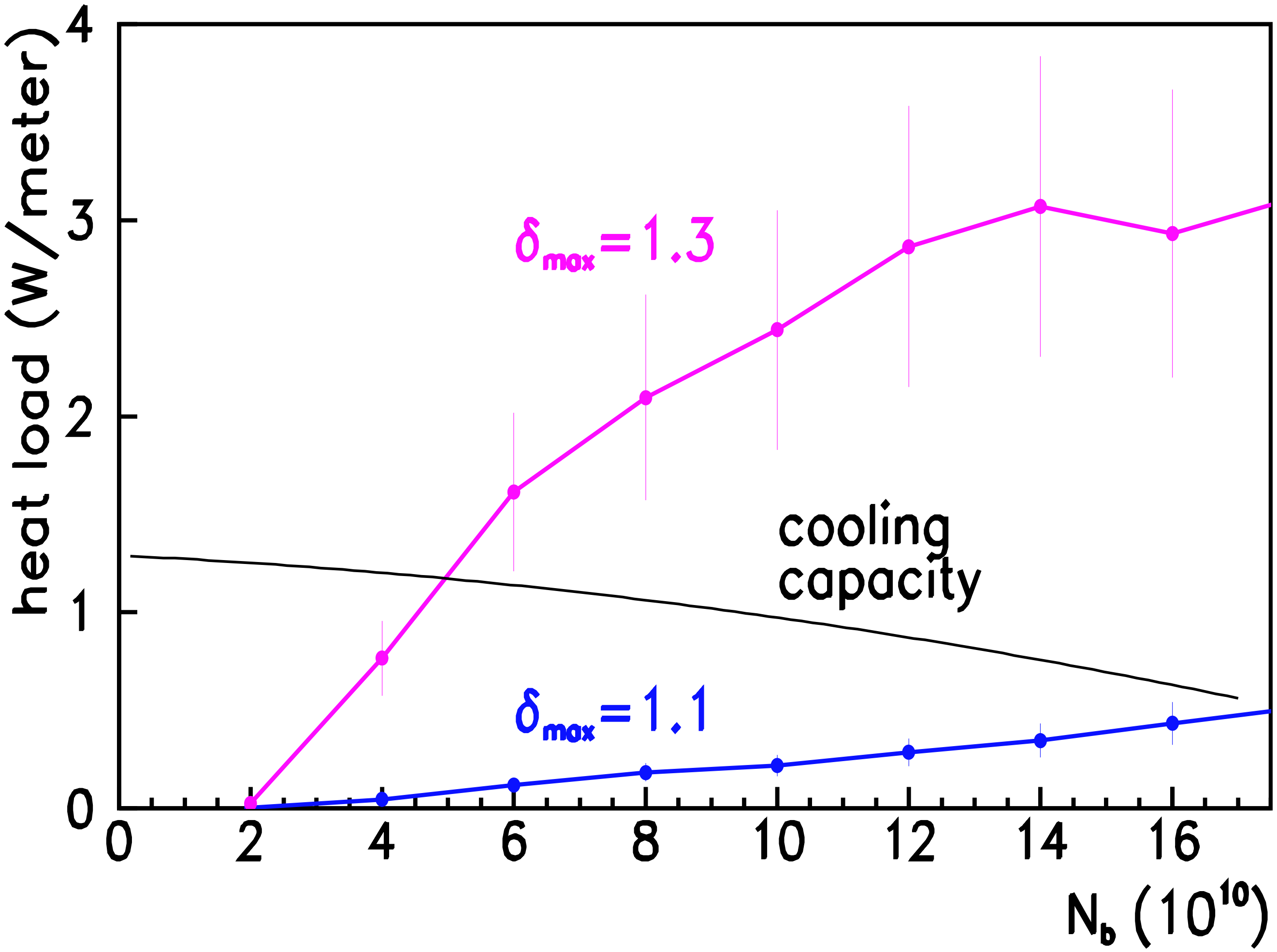


Relative increase in LHC luminosity versus bunch length (or crossing angle) for Gaussian and flat (super-)bunches at constant beam-beam tune shift with alternating crossings in IP1 and IP5.

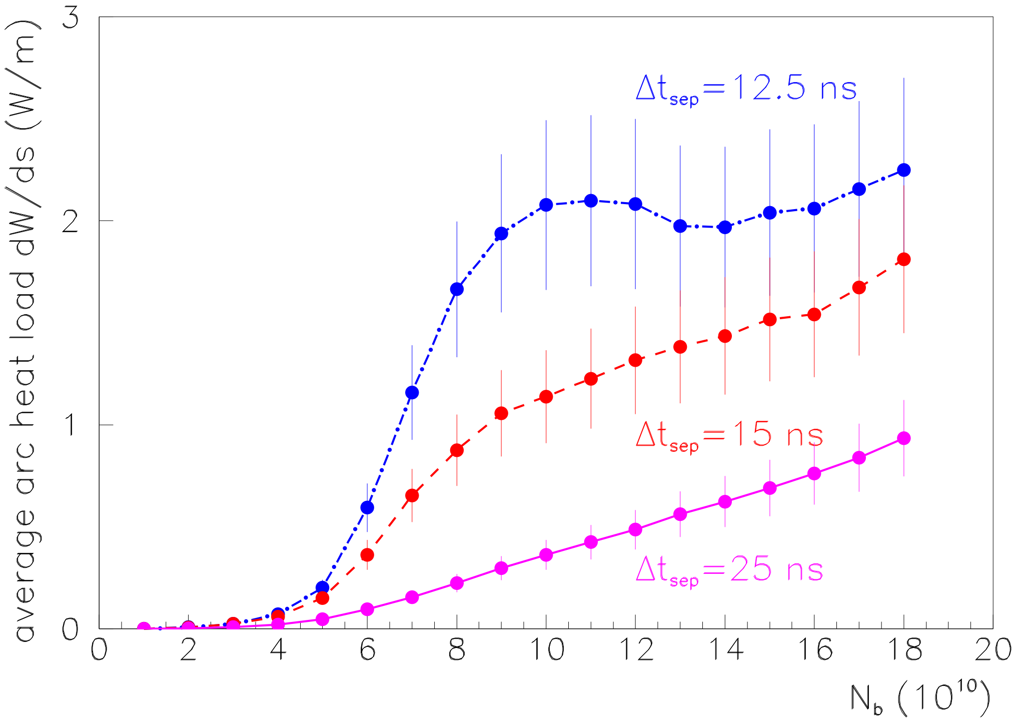
Electron Cloud Effects



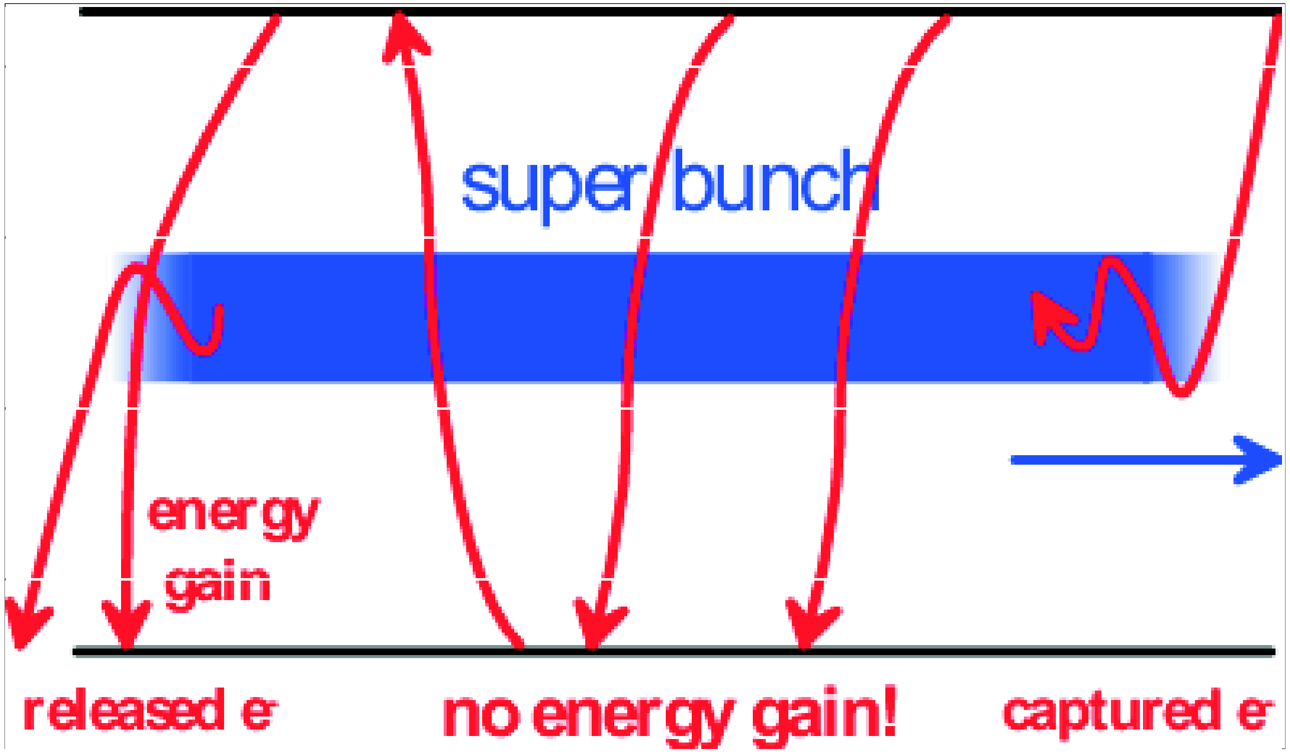
In the LHC, photoelectrons created at the vacuum pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. Slow or reflected secondary electrons survive until the next bunch. Depending on vacuum pipe surface conditions (SEY) and bunch spacing, this may lead to an electron cloud build-up with implications for beam stability, emittance growth, and heat load on the cold LHC beam screen.



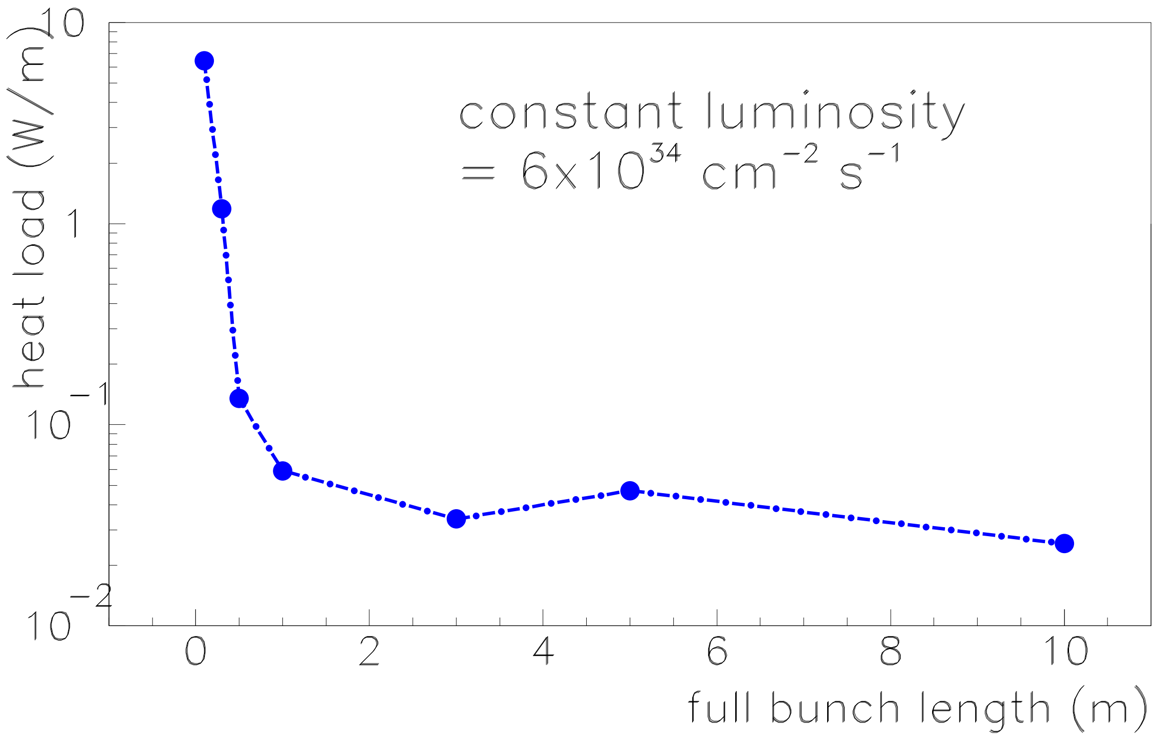
Average arc heat load due to electron cloud and LHC cooling capacity as a function of bunch population N_b, for 25 ns bunch spacing and two different values of the maximum secondary emission yield $\delta_{\max}$. Elastically reflected electrons are included. (Courtesy F. Zimmermann, PAC03)



Average arc heat load as a function of bunch population for bunch spacings of 12.5 ns, 15 ns, and 25 ns, and a maximum secondary emission yield $\delta_{\max} = 1.1$. Elastically reflected electrons are included. (Courtesy F. Zimmermann, 2002)



Schematic of reduced electron cloud build-up for a super-bunch.
(Courtesy F. Zimmermann)



Simulated heat load in an LHC arc dipole due to the electron cloud as a function of super-bunch length for $\delta_{\max} = 1.4$, considering a constant flat top proton line density of $8 \times 10^{11}\ \mathrm{m}^{-1}$ with 10% linearly rising and falling edges. The number of bunches is varied so as to keep the luminosity constant and equal to $6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Minimum crossing angle

$d_{\rm sep}/\sigma \simeq \theta_{\rm c}/\sigma_\theta$: relative beam separation

$\sigma_\theta = \sqrt{\varepsilon/\beta^*}$: r.m.s. angular beam divergence at the IP

scaling law for 'diffusive aperture' $d_{\rm da}$ with long range collisions

$$(d_{\rm sep} - d_{\rm da})/\sigma \propto \sqrt{k_{\rm par}\, N_{\rm b}/\varepsilon_{\rm n}}$$

the ratio $(d_{\rm sep} - d_{\rm da})/\sigma$ is independent of β and beam energy; it is again a function of the brilliance $N_{\rm b}/\varepsilon_{\rm n}$. From particle tracking

$$d_{\rm da}/\sigma \simeq \theta_{\rm c}\sqrt{\beta^*/\varepsilon} - 3\sqrt{\frac{k_{\rm par}}{2\times 32}\,\frac{N_{\rm b}}{10^{11}}\,\frac{3.75\,\mu{\rm m}}{\varepsilon_{\rm n}}}$$

nominal LHC parameters $\theta_{\rm c} = 300\,\mu$rad and $\sigma_\theta = 31.7\,\mu$rad $\Longrightarrow$ $d_{\rm sep} \simeq 9.5\,\sigma$ and $d_{\rm da} \simeq 6 \div 6.5\,\sigma$. Preserving a comparable dynamic aperture with higher bunch intensities, shorter bunch spacings, and/or smaller β^* requires larger crossing angles

LHC Upgrade Scenarios

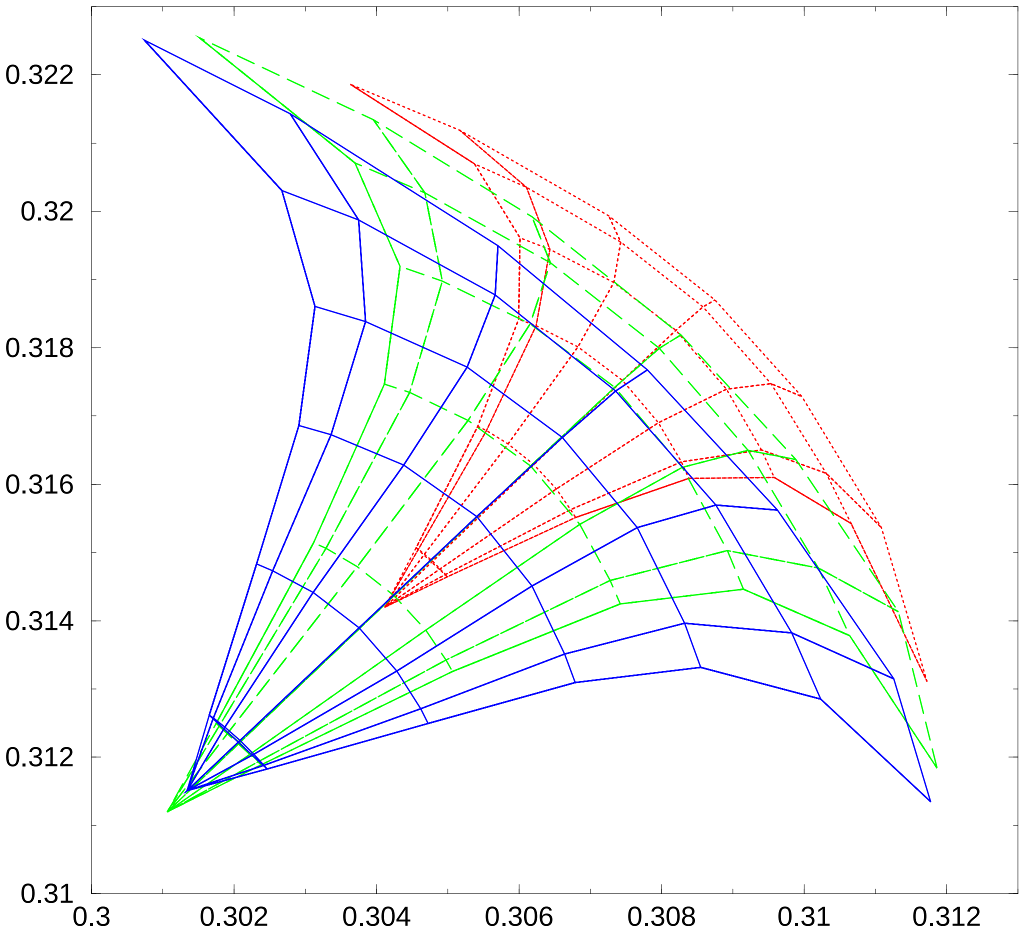
- LHC Phase 0: maximum performance without hardware changes
- LHC Phase 1: maximum performance with the LHC arcs unchanged
- LHC Phase 2: maximum performance with 'major' hardware changes

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach ultimate performance without hardware changes (LHC Phase 0) are:

1. collide beams only in IP1 and IP5 with alternating H-V crossing
2. increase N_b up to the beam-beam limit $\rightarrow L = 2.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
3. increase the dipole field to 9 T (ultimate field) $\rightarrow E_\mathrm{max} = 7.54\,\mathrm{TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.

parameter	symbol	units	nominal	ultimate	Piwinski
number of bunches	n_{b}		2808	2808	2808
bunch spacing	Δt_{sep}	ns	25	25	25
protons per bunch	N_{b}	10^{11}	1.1	1.7	2.6
aver. beam current	I_{av}	A	0.56	0.86	1.32
norm. tr. emittance	ε_{n}	μm	3.75	3.75	3.75
long. emittance	ε_{L}	eV s	2.5	2.5	4.0
peak RF voltage	V_{RF}	MV	16	16	3/1
RF frequency	f_{RF}	MHz	400.8	400.8	200.4/400.8
r.m.s. bunch length	σ_z	cm	7.55	7.55	15.2
r.m.s. energy spread	σ_{E}	10^{-4}	1.13	1.13	0.9
IBS growth time	$\tau_{x,\mathrm{IBS}}$	h	111	72	87
beta at IP1-IP5	β^*	m	0.5	0.5	0.5
full crossing angle	θ_{c}	μrad	300	315	345
lumi at IP1-IP5	L	$10^{34}/\mathrm{cm}^2\,\mathrm{s}$	1.0	2.3	3.6



Comparison of tune footprints, corresponding to betatron amplitudes extending from 0 to 6 σ, for LHC nominal (red-dotted), ultimate (green-dashed), and large Piwinski parameter configuration (blue-solid) with alternating H-V crossing only in IP1 and IP5. (Courtesy H. Grote)

LHC Phase 1: Luminosity Upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following baseline scheme:

1. modify insertion quadrupoles and/or layout $\rightarrow \beta^* = 0.25\,\mathrm{m}$
2. increase crossing angle by $\sqrt{2} \rightarrow \theta_c = 445\,\mu\mathrm{rad}$
3. increase N_b up to ultimate intensity $\rightarrow L = 3.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
4. halve σ_z with high harmonic RF system $\rightarrow L = 4.6 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
5. double number of bunches (and increase θ_c!) $\rightarrow L = 9.2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ excluded by electron cloud?

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$.

parameter	symbol	units	baseline	Piwinski	super-bunch
number of bunches	$n_{\rm b}$		2808	2808	1
bunch spacing	$\Delta t_{\rm sep}$	ns	25	25	
protons per bunch	$N_{\rm b}$	10^{11}	1.7	2.6	5600
aver. beam current	$I_{\rm av}$	A	0.86	1.32	1.0
norm. tr. emittance	$\varepsilon_{\rm n}$	μm	3.75	3.75	3.75
long. emittance	$\varepsilon_{\rm L}$	eV s	1.78	2.5	15000
peak RF voltage	$V_{\rm RF}$	MV	43	16	3.4
RF frequency	$f_{\rm RF}$	MHz	1202.4	400.8	10
r.m.s. bunch length	σ_z	cm	3.78	7.55	7500
r.m.s. energy spread	$\sigma_{\rm E}$	10^{-4}	1.60	1.13	5.8
IBS growth time	$\tau_{x,\rm IBS}$	h	42	46	63
beta at IP1-IP5	β^*	m	0.25	0.25	0.25
full crossing angle	$\theta_{\rm c}$	μrad	445	485	1000
lumi at IP1-IP5	L	$10^{34}/\rm cm^2\,s$	4.6	7.2	9.0

Triplet aperture requirements: baseline scheme

rough estimate of triplet quadrupole aperture $D_{\rm trip}$ for $\ell^* = 23\,{\rm m}$:

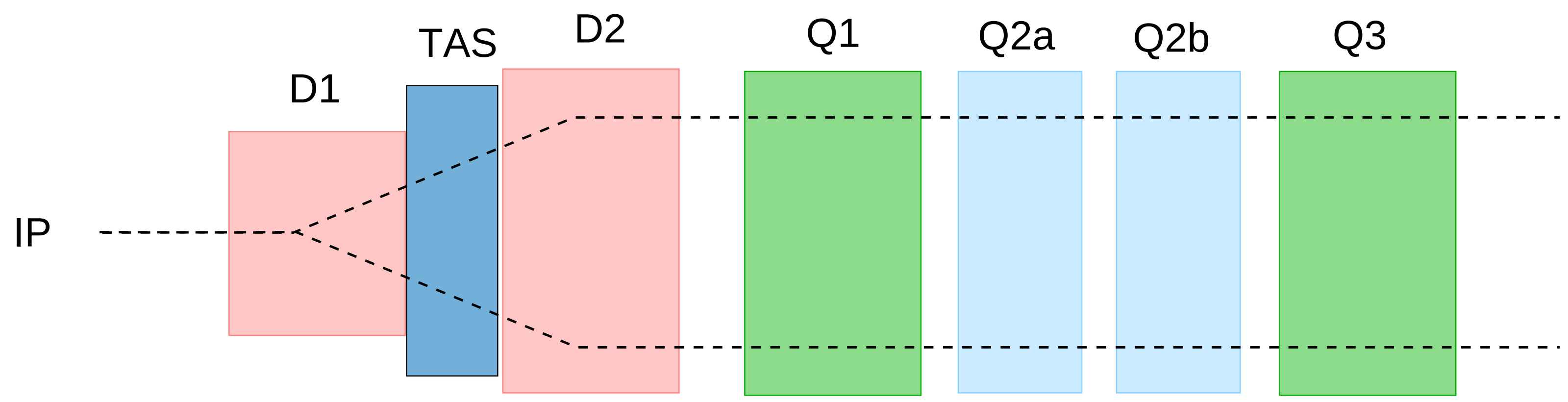
- $9\,\sigma$ beam envelope
- $7.5\,\sigma$ beam separation
- 20% β-beating
- 4 mm spurious dispersion
- 3 mm peak orbit excursion
- 1.6 mm mechanical tolerances
- beam screen and cold bore

$D_{\rm trip} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times 8.6\,{\rm mm}$

$\beta^* = 0.5\,{\rm m} \to \sigma_{\rm max} \simeq 1.5\,{\rm mm} \Longrightarrow D_{\rm trip} > 60\,{\rm mm} \to$ <u>70 mm ID coil</u>

$\beta^* = 0.25\,{\rm m} \to \sigma_{\rm max} \simeq 2.2\,{\rm mm} \Longrightarrow D_{\rm trip} > 80\,{\rm mm} \to$ <u>90 mm ID coil</u>

Alternative IR layout for LHC Phase 1



Sketch of a possible IR layout for an LHC luminosity upgrade with separation dipoles close to the IP and separated magnet bores inside the triplet magnets. (Courtesy O. Brüning)

Main advantages:

- reduce number of long range beam-beam interactions
- no crossing-angle bump inside the triplet magnets $\Longrightarrow$ no feed-down errors

Magnet requirements for alternative IR layout with $\beta^* = 0.25\,\mathrm{m}$

magnet	type	length	diameter range	beam separation	strength
D1	1 aperture	11.4 m	34 mm ↔ 131 mm	0 ↔ 84 mm	15 T
D2	2-in-1	11.4 m	50 mm ↔ 60 mm	110 mm ↔ 194 mm	15 T
Q1	2-in-1	4.5 m	60 mm ↔ 70 mm	194 mm	230 T/m
Q2	2-in-1	2 × 4.5 m	70 mm ↔ 78 mm	194 mm	257 T/m
Q3	2-in-1	5.0 m	70 mm ↔ 78 mm	194 mm	280 T/m

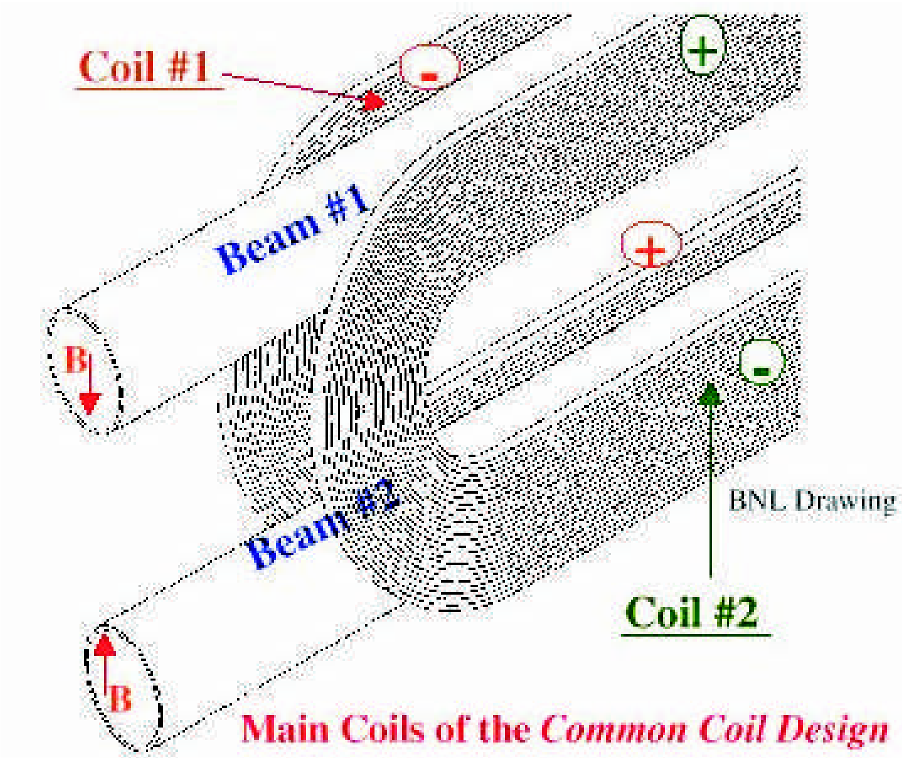
Tentative magnet parameters for a triplet layout with separated beams inside the triplet magnets. The beam separation does not include the additional separation from the crossing angle bump. We assume that the beam separation can be done via two 11.4 m long 15 T dipole magnets (possibly with high temperature superconducting coils).

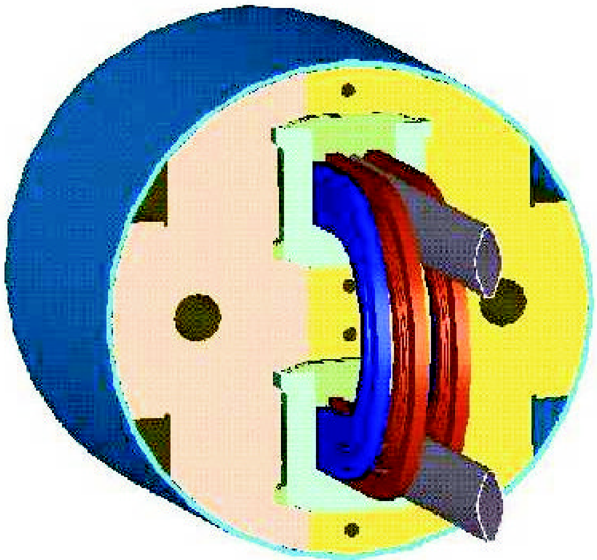
LHC Phase 2: Luminosity and Energy Upgrade

- Modify the injectors to significantly increase the beam intensity and brilliance beyond its ultimate value (possibly in conjunction with beam-beam compensation schemes).

- Equip the SPS with superconducting magnets, upgrade transfer lines, and inject into the LHC at 1 TeV. For given mechanic and dynamic apertures at injection, this option can increase the LHC luminosity by nearly a factor two, at constant beam-beam parameter $N_\mathrm{b}/\varepsilon_\mathrm{n}$, in conjunction with long range b-b compensation schemes. This would also be the natural first step in view of an LHC energy upgrade $\Longrightarrow$ energy swing reduced by a factor 2. Interesting alternative $\Longrightarrow$ cheap, compact low-field booster rings in the LHC tunnel.

- Install new dipoles with a field of 15 T and a safety margin of about 2 T, which are considered a reasonable target for 2015 and could be operated by 2020 $\Longrightarrow$ beam energy around 12.5 TeV.





Sketch of the Common Coil design for a double aperture dipole magnet.
The coils couple the two apertures and can be flat (no difficult ends).
One of the most difficult challenges will be to make it at reasonable cost, less than 5 kEuro/(double)T.m say, including cryogenics, to be compared with about 4.5 kEuro/(double)T.m for the present LHC.

Recommendations for future studies and R&D

nominal LHC performance is challenging (not to mention ultimate) $\Longrightarrow$ learn how to overcome electron cloud effects, inject, ramp, and collide almost 3000 high intensity bunches, protect superconducting magnets, safely dump the beams, etc. Upgrades in beam intensity are a viable option, require R&D for cryogenics, vacuum, RF, beam dump, and injectors, and operation with large crossing angles

radiation damage limit for IR quads ($\sim 700\,\mathrm{fb}^{-1}$) reached by 2013? $\Longrightarrow$ new triplet quadrupoles with high gradient and larger aperture (or alternative IR layouts) are needed for a luminosity upgrade. Opening the quads has the advantage of letting radiation through

further studies are needed to specify field quality of IR magnets, required upgrades of beam instrumentation, collimation and machine protection. To reduce collimator impedance during β-squeeze and physics conditions, triplet aperture should be i) LARGE and ii) possibly protected by local tertiary collimators experimental studies on electron cloud (e.g. beam scrubbing in cold conditions), long range, and strong-strong beam-beam effects are important, as well as MDs in existing hadron colliders with large Piwinski parameter and many (flat) bunches $\Longrightarrow$ international collaboration (e.g. US-LHC, ESGARD) is welcome/needed for LHC machine studies/commissioning

beam-beam compensation schemes with pulsed wires would reduce tune footprints and loss of dynamic aperture due to long range collisions $\Longrightarrow$ need experimental validation

Interesting possibilities currently under study to pass each beam through separate final quadrupoles include: alternative beam separation schemes with separation dipoles in front of the triplet quadrupoles and collision of long super-bunches with very large θ_c. With a crossing angle of a few mrad, a 300 m long super-bunch with intensity $I_{beam} = 1$ A in each LHC ring would be compatible with the beam-beam limit. The corresponding luminosity in ATLAS and CMS (with alternating H-V crossings) would be 9×10^{34} cm^{-2} s^{-1}.

The super-bunch option is interesting for large crossing angles, can potentially avoid electron cloud effects and minimize the cryogenic heat load. One could inject a bunched beam, accelerate it to 7 TeV, and then use barrier buckets to form about 100 long super-bunches to reduce pile-up noise in the experiments.

A major and sustained R&D effort on new SC materials and magnet design is needed for any LHC performance upgrade $\Longrightarrow$ foster and extend collaboration with other labs: new low-β quadrupoles with high gradient and larger aperture based on Nb_3Sn superconductor require 9-10 years for short model R&D and component development, prototyping, and final production.

An increased 1 TeV injection energy into the LHC in conjunction with beam-beam compensation schemes would yield a luminosity gain $\Longrightarrow$ a pulsed Super-SPS (and new SC transfer lines) or cheap low-field booster rings in the LHC tunnel could be the first step for an LHC energy upgrade.