The LHC Machine: prospects

Massimo Giovannozzi
CERN – Beams Department

- Introduction and a bit of history
- Upgrade options
- LHC upgrade
- MD studies
- Injectors’ upgrade
- The far future

Introduction - I

- **ATLAS**: High luminosity experiment. Search for the Higgs boson(s).
- **A Large Ion Collider Experiment (ALICE)**: Ions. New phase of matter expected (Quark-Gluon Plasma).
- **Compact Muon Solenoid (CMS)**: High luminosity experiment. Search for the Higgs boson(s). In this insertion is also located TOTEM for the measurement of the total proton-proton cross-section and study elastic scattering and diffractive physics.
- **LHCb**: Beauty quark physics for precise measurements of CP violation and rare decays.
LHC layout: the other insertions
Introduction - II

Separation/rcombination dipole
Absorber (neutral particles)

Towards dispersion suppressor and arc

Interaction point

Separation/rcombination dipole
Low-beta quadrupoles (23 m away from IP)

High luminosity insertions
High luminosity insertions: collision optics. Beta at interaction point equals 0.55 m.
Few facts from optics

\[ \beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*} \]

\( \beta_{\text{max}} \) in the triplets depends on:
- \( L^* \)
- \( \beta^* \)
- Strength of the triplets

Hence reducing \( \beta^* \) implies:
- Larger aperture triplets
- Larger strength
- Chromatic effects scale with \( \beta_{\text{max}}^n \) -> potential issue for collimation performance

In a drift space
Nominal performance and beyond

- The nominal LHC parameters allow to reach $10^{34}$ cm$^{-2}$ s$^{-1}$
- Some margin in bunch intensity was assumed originally: $1.15 \times 10^{11}$ to $1.7 \times 10^{11}$. This is the so-called ultimate intensity.
- The corresponding ultimate luminosity is $\sim 2.18 \times 10^{34}$ cm$^{-2}$ s$^{-1}$.
- Anything beyond this value requires a deep review of the LHC machine (and injectors!)
Figure-of-merit for an upgrade - I

The luminosity formula is the key ingredient:

\[
L = \frac{N_b^2 M f_{\text{rev}} \gamma_r}{4 \pi \varepsilon_n \beta^*} F
\]

\[
F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}
\]

But:
- Many hidden constraints between parameters
- Not all the parameters are determined by the LHC machine
- The formula gives the peak luminosity, the average is different
Figure-of-merit for an upgrade - II

- Constraints between parameters: crossing angle

\[ L = \frac{N_b^2 M f_{\text{rev}} \gamma_r}{4 \pi \varepsilon_n \sqrt{\beta_x^* \beta_y^*}} F \quad \theta_c = d_s \sqrt{\varepsilon / \beta_x^*} \quad F = \frac{1}{\sqrt{1 + \left( \frac{\sigma_z d_s}{2 \beta_x^*} \right)^2}} \]

- Luminosity saturates for round beams.
- Flat beams can optimise the situation.
Luminosity evolution

- The luminosity decays because of proton burn-off.
- Luminosity decay is proportional to peak luminosity!
- Luminosity leveling is an important ingredient in LHC upgrade

\[ L_{\text{peak}} = 1.2 \cdot 10^{33} \text{ cm}^{-2}s^{-1} \quad \int L dt = 38 \text{ pb}^{-1} \]
Upgrade ideas (until 2010)

- Assumptions (or common belief)
  - Lifetime of triplets under nominal conditions is few years (radiation due to debris) -> they should be replaced
  - Nominal parameters are probably tight and nominal luminosity might be difficult to achieve (triplets aperture)

- Hence, two-stage approach:
  - Phase 1: “Consolidate” the machine with new triplets aiming at reaching ~ $2-3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - Phase 2: “Real” luminosity upgrade aiming at $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. This includes a major upgrade of the detectors.
Phase 1 in short

- Rough summary of Phase 1 approach
  - Replace “only” triplets with larger aperture magnets to enable reaching smaller $\beta^*$.

- Intense studies performed:
  - Minimum $\beta^*$ achievable: $\sim 30$ cm
  - Limits have been highlighted in other parts of the machine -> much more elements than the triplets should be changed!
  - Very complex optical gymnastics in order to fulfill the correction of chromatic aberrations -> not much operational flexibility left.
How many upgrades?

Each upgrade will require a non-negligible time to recover from the stop and gain in INTEGRATED luminosity.

 Courtesy V. Shiltsev
Upgrade ideas (after 2010)

- One single upgrade.
- The time horizon is based on the projection of actual performance of the running LHC.
- For the injectors see later.

Data not approved by Mgt

Courtesy L. Rossi, M. Lamont

Upgrade ideas (after 2010)

- One single upgrade.
- The time horizon is based on the projection of actual performance of the running LHC.
- For the injectors see later.
### Latest unofficial 10 year plan

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Legend:
- **Blue**: Technical stop or shutdown
- **Pink**: Proton physics
- **Red**: Ion Physics

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Les Houches - Ecole d’été de Physique Théorique

Massimo Giovannozzi - CERN
Scope of High-Luminosity upgrade of LHC

- Targets:
  - A peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with leveling
  - An integrated luminosity of 250 fb$^{-1}$ per year, enabling the goal of 3000 fb$^{-1}$ in twelve years (nominal LHC is around 300 fb$^{-1}$ in ten years).
Injection optics: $\beta^* = 14$ m in IR1 and IR5

Nominal $\beta_{\text{arc}}$ (180m) in s45/56/81/12

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
Pre-squeezed optics: $\beta^* = 60 \text{ cm in IR1 and IR5: “1111”}$

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
Intermediate squeezed optics: $\beta^* = 30$ cm in IR1 and IR5: “2222”

Similar to Phase I
(but with much more flexibility)

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
Squeezed optics (round): $\beta^* = 15$ cm in IR1 and IR5: "4444"

HL-LHC with round optics (preferable with crabs)

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
Squeezed optics (flat): $\beta^*_{x/y} = 7.5/30$ cm alternated in IR1 and IR5: “8228”

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
Injection optics: zoom from IP4 to IP5 (beam1)

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
The line IP4-IP5 can be made achromatic (SD2 family close to 550 A, but still big margin on the SF1 circuit)
→ $\beta^*$ is further squeezed at IP5 by a factor of 2 by rematching IR4 only.
→ The line IP4-IP5 is kept achromatic at ~ cst sextupole strength.
Flat squeezed optics “8228”: zoom from IP4 to IP5 (beam1)

Equipping Q10 (MQML) with an MS becomes highly desirable for high $\beta\_arc$

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh
Luminosity levelling

Three options at hand:

- Vary crossing angle (crab cavities help here!)
  - It can be performed with dipoles
  - Easy, but requires aperture in triplets

- Vary separation
  - It can be performed with dipoles
  - Easy (already tried with Alice), but requires aperture

- Vary $\beta^*$
  - Never tried in existing machines
  - Requires an excellent control of optics and crossing scheme
KEKB B-Factory

♦ World-highest Peak Luminosity
  • $2.11 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  • Twice as high as design value

♦ World-highest Integrated Luminosity
  • Total: $1040\text{fb}^{-1}$ as of June 30th 2010

♦ Crab crossing ($\phi = 11$ mrad)

♦ Skew-sextupole magnets

The KEKB operation was terminated at the end of June 2010 for the upgrade toward SuperKEKB.
Impact on luminosity

constant beam-beam parameter: $\xi_y (\text{HER}) = 0.09 \ (I_{\text{LER}}/I_{\text{HER}} = 8/5)$

Luminosity improvement by crab cavities is about 20%.

Geometrical loss due to the crossing angle is about 11%.

with skew sextupoles

Luminosity improvement by crab cavities is about 20%.

Courtesy Y. Funakoshi

Les Hc
collisions with 280 μrad crossing angle

simulated luminosity lifetime with crab crossing is 10 times better than without crab crossing
Potential issues of crab cavities - I

- RF Noise
  - It could induce emittance growth. So far never used in any proton machine!

- Design
  - Very limited transverse space in the LHC
  - Imposes creative designs
  - Two types are needed: H and V crossing

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Potential issues of crab cavities - II

- **Machine protection**
  - The crab cavity kicks head and tail.
  - In the local scheme two crab cavities are used to cancel the transverse kick outside the insertion.

- **What happens in case of a cavity failure?**
  - Head and tail would start to oscillate all around the circumference.
  - The “effective” transverse size of the beam is increased.
  - The tails could scrape some parts of the machine (few % of beam is in the tails – around $5\sigma$ – corresponding to 3-10 MJ!)
Potential issues of crab cavities - III

- The point is the speed of the failure.
- The voltage could drop significantly in 1 turn!
- The machine protection is not capable of handling these ultra-fast failures.
- The only solution is to ensure that “by design” the probability of such an event is extremely rare.
- No clear solution at hand…
Most of the key ingredients/assumptions for the LHC upgrade can be tested in the nominal machine!

Starting from this year a series of blocks of five days are dedicated to Machine Developments (MD) studies: the actual machine is used to probe special situations.

Two topics of particular interest for upgrade:
- Beam-beam limits
- ATS optics
Reminder

- Resonances have a negative impact on beam dynamics (emittance growth).
- The nominal tunes have been chosen far away from low order resonances.
- This is the minimum optimisation: also the tune spread should be included in the optimisation!

\[ mQ_x + nQ_y = p \quad \text{m+n=resonance order} \]

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Beam-beam limit - I

- A matter of tune shift, i.e., interaction with resonances
- Increasing crossing angle is beneficial for tune spread.

Crossing angle configurations:
Top Left: only head-on
Top right: $= 200 \mu$rad
Bottom left: $= 285 \mu$rad
Bottom right: $= 400 \mu$rad

Courtesy W. Herr
Beneficial effect of alternating crossing on tune spread (nominal and PACMAN bunches)

For LHC design, maximum tune shift tolerable assumed to be 0.01.

Other machines:
- SppbarS: 0.018
- Tevatron: 0.02

Courtesy W. Herr
LHC experience and MDs

- Beam-beam can be lethal for bunches!

- MD results:
  - Head On: factor of five margin!
  - Long Range: as expected, no margin

PRELIMINARY!!!

Smaller emittance would be an advantage for upgrade
ATS: 30 cm $\beta^*$ in IP1: Measured $\beta_x$

First time ever test of this novel optics principle

Courtesy S. Fartoukh
ATS: 30 cm $\beta^*$ in IP1: Measured $\beta_y$

First time ever test of this novel optics principle

Courtesy S. Fartoukh
ATS: Meas. Beta Beat Err (here B2; B1 better)

LHCB2 ATS 4.4m-0.30m

Δβ/βₓ

Δβ/βᵧ

Longitudinal location [m]

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Massimo Giovannozzi

Courtesy S. Fartoukh
Optics:
- ATS is the most promising candidate.
- $\beta^*$ is in the range of 15 cm, with the possibility of decreasing to 7.5 in one plane (flat beams).
- Magnet R&D on-going to provide the required performance.
- Leveling is mandatory and many options at hand.

Beam:
- Both 25 ns and 50 ns spacing should be available.
- Bunch intensities around $2-3 \times 10^{11}$ depending on bunch spacing (25 ns or 50 ns).
- Emittance around 2 $\mu$m or 3.75 $\mu$m depending on bunch spacing (25 ns or 50 ns).
Three bottlenecks identified for higher intensity and/or brightness from the LHC injectors:

1. Space charge tune shift at PSB injection (50 MeV).
2. Space charge tune shift at PS injection (1.4 GeV).
3. Electron cloud and other

Low injection energy into the PSB is the first and most important bottleneck →

Decision (2007) to build a new linac (Linac4) to increase from 50 to 160 MeV (no space for energy upgrade of Linac2).

After Linac4, new program (2010):
- Upgrade of PSB final energy to 2 GeV. (or Rapid Cycling Synchrotron)
- Upgrade (coating, new RF) of SPS. Instabilities control.
Linac4 description

- Conventional (normal-conducting) layout:
  1. Pre-injector (source, magnetic LEBT, 3 MeV RFQ, chopper line)
  2. Three types of accelerating structures, all at 352 MHz.
  3. Beam dump at linac end, switching magnet towards transfer line – PSB.

From 50 MeV to 160 MeV: a gain of a factor two in space charge tune shift

Linac length ~ 80 m

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<td>PIMS</td>
<td>102 – 160</td>
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**PSB upgrade**

- **Injection:** to be adapted to the new Linac4 energy and new particle type (from protons to H-).

- **To overcome the space charge limit at PS injection:** to increase the extraction energy from 1.4 GeV to 2 GeV. This could open the possibility of generating LHC bunches of $\sim 2.7 \times 10^{11}$ (nom. $1.15 \times 10^{11}$).

- **Good news:** there is margin in the PSB magnets to allow for such an upgrade!

- **An RCS option is also under consideration.**
MD studies in the injectors

- The hot topic is the assessment of the actual performance limits in the PSB, PS, and SPS.
- Specifically, the space charge limits (e.g., maximum tune shift tolerable for a given emittance blow up) should be measured in detail.
- The starting point is probing the strength and harmfulness of resonances in a regime not dominated by space charge.
  - The excited resonances could then interact with space charge to spoil the beam quality.
  - This might require to implement schemes to compensate some resonances.
Technique and results - I

Beam
- Low intensity -> similar to a single-particle case, no space charge
- Large transverse emittance -> it almost fills the vacuum chamber, very sensitive to any emittance growth
- The tune space is scanned (one tune is kept constant and the other varied)
  - Energy is kept constant.
  - The losses occur when a resonance is crossed.
  - The derivative of the losses is proportional to the resonance strength.

![PS example graph](image)

Energy is kept constant.
The losses occur when a resonance is crossed.
The derivative of the losses is proportional to the resonance strength.
Technique and results - II

PS at 2 GeV (new injection energy)

Courtesy E. Benedetto

SPS at injection

Nominal Optics

Low \gamma_t optics
High Energy-LHC

BE-EN-TE working group since April 2010
EuCARD AccNet workshop HE-LHC’10,
14-16 October 2010

key topics
beam energy 16.5 TeV; 20-T magnets
cryogenics: synchrotron-radiation heat load
radiation damping & emittance control
vacuum system: synchrotron radiation
new injector: energy > 1 TeV

parameters

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Linac-Ring LHeC

**Overall Layout**
- Tune-up dump
- 10-GeV linac
- Comp. RF
- Injector
- Total circumference ~ 8.9 km = 1/3 LHC

**Features**
- 1.0 km comp. RF
- 0.12 km 10-GeV linac
- 0.17 km 2.0 km
- 0.26 km dump
- 0.03 km 10-GeV linac
- IP
- 3-beam IR layout

**Energy and Luminosity**
- e- energy ≥ 60 GeV
- Luminosity ~ $10^{33}$ cm$^{-2}$s$^{-1}$

**Electrical Power**
- Total electrical power for e-: ≤ 100 MW

**Beams and Collisions**
- e$^+$p collisions with similar luminosity?
- Simultaneous with LHC pp physics

**Polarization**
- e$^-$/e$^+$ polarization

**Detector Acceptance**
- Acceptance down to 1°