Options for Future
High Luminosity Upgrades for the LHC

- Introduction
- Performance limitations for the LHC
- Summary of the nominal LHC parameters
- Main upgrade options and phases
  - Phase 0: performance upgrade without hardware modifications
  - Phase 1: performance upgrade with IR modifications
  - Phase 2: performance upgrade with major hardware modifications
- General summary

Introduction: I

- LHC performance: luminosity and E_{CM}

- Instantaneous luminosity ´L´: # events in detector / sec = $L \cdot \sigma_{event}$

- Integrated luminosity ***L*:** $\boldsymbol{L} = \int L(t)\, dt$

depends on the beam lifetime, the LHC cycle and ´turn around´ time and the overall accelerator efficiency

Introduction: II

🟩 collision energy: $E_{CM} = 2 \cdot E_{\text{beam}}$

uniform B−field:

$$\boldsymbol{r} = \frac{\boldsymbol{m_0}}{\boldsymbol{Q}} \bullet \frac{\gamma}{\boldsymbol{B}} \bullet \boldsymbol{v} \qquad R = \text{const.} \qquad \boldsymbol{p} = \mathbf{Q} \bullet \frac{\boldsymbol{B} \bullet \boldsymbol{L}}{2\pi} \approx \boldsymbol{E} / \boldsymbol{c}$$

realistic synchrotron:

magnetic field is not constant

$$\boldsymbol{E} = \frac{\mathbf{Q} \bullet \mathbf{c}}{2\pi} \bullet \oint \vec{\boldsymbol{B}} \bullet \boldsymbol{d}\,\vec{\boldsymbol{l}}$$

→ high beam energy requires:

−high peak magnetic field

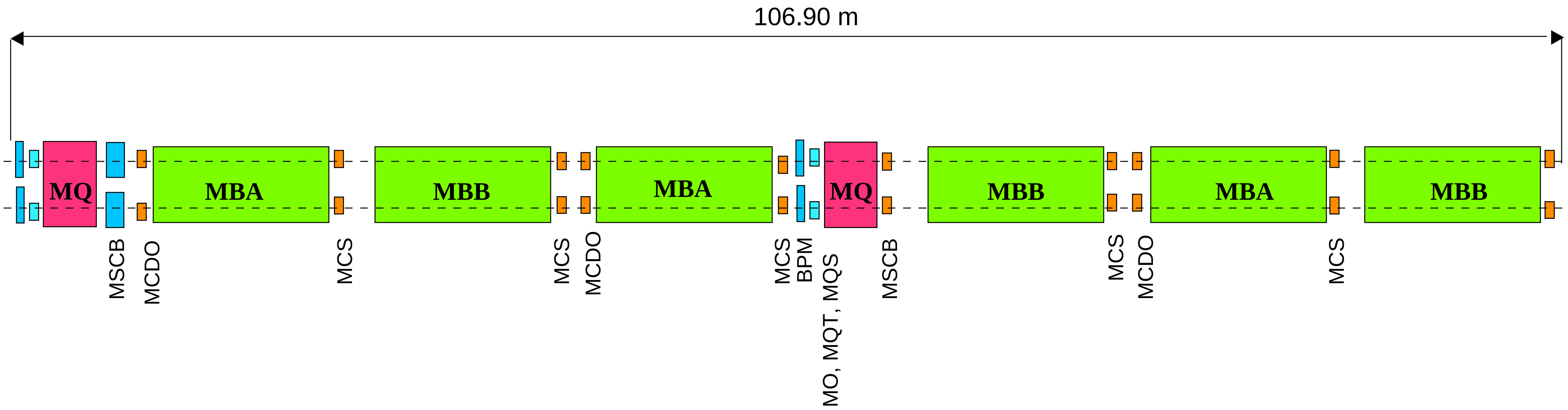
−large packing factor

Introduction: III

- maximum dipole length in order to minimize number of interconnects:

  15 m long dipole magnets are at the limit of mechanical stability

Schematic layout of one LHC cell (23 periods per arc)

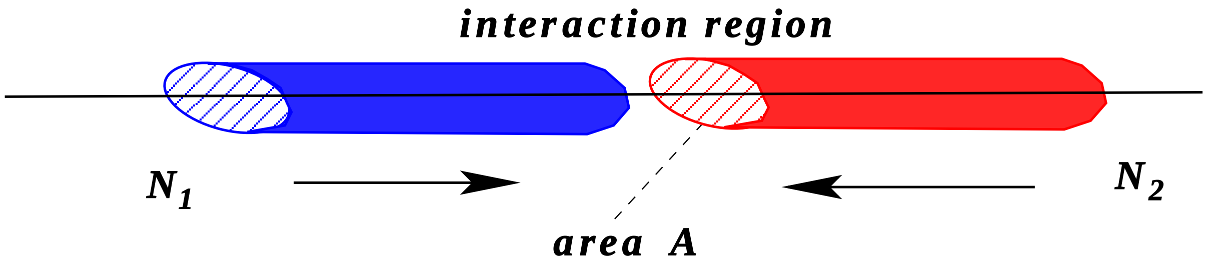


- maximum dipole field:

  8.4 T for nominal operation with peak field at cold tests of 9 T (−>7.54 TeV)
  (50% higher compared to existing super conducting storage rings)

Introduction: IV

- luminosity:



$$L = \frac{n_b \bullet N_1 \bullet N_2 \bullet f_{rev}}{A}$$

$$\underline{A = 4\pi \bullet \beta \bullet \varepsilon}$$

$(4\pi\,\sigma^2)$

$\varepsilon = \varepsilon_n / \gamma$ ε_n is determined by the injector chain

→ increase bunch intensity and number of bunches,

reduce β at the IP, increase the collision energy

Performance Limitations

- number of particles per bunch
- total intensity and number of bunches
- beam size at the interaction point (IP)
- integrated luminosity

Performance Limitations: Bunch Intensity

- number of events per bunch crossing: → that is your problem!

- non−linearities from interactions at the IP: → limit for: $\frac{N_{\text{bunch}}}{\varepsilon_n}$

  −depends on the number of interaction points

  −leaves the option of increasing N with constant $\frac{N_{\text{bunch}}}{\varepsilon_n}$

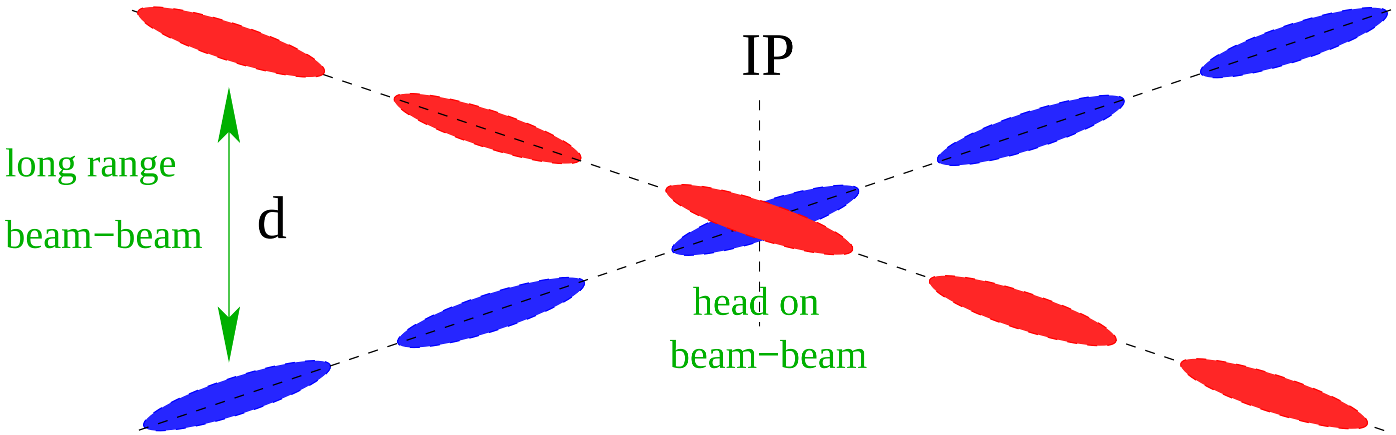
- magnet aperture: → limit for: ε_n $\sigma = \sqrt{\beta\,\varepsilon_n / \gamma}$

  −imposes a bunch intensity limit for constant $\frac{N_{\text{bunch}}}{\varepsilon_n}$

Performance Limitations: Total Intensity I

🟩 number of bunches: avoid additional beam collisions via crossing angle!

→ crossing angle:



→ disadvantage:

→ requires larger triplet magnet aperture

→ generates additional non linearities (−> large angle)

→ increases interacting cross section

−reduces luminosity

−reduces beam−beam non−linearities

Performance Limitations: Total Intensity II

- geometric reduction factor:

$$L_{\mathrm{eff}} = L_0 \cdot \frac{1}{\sqrt{1 + \left(\frac{\theta \cdot \sigma_z}{2\,\sigma^*}\right)^2}}$$

conventional optimization: minimize the geometric reduction factor

→ short bunches and minimum crossing angle

→ bunch length limited by RF frequency

→ short bunches result in emittance growth (IBS)

→ minimum crossing angle dictated by beam−beam

Performance Limitations: Total Intensity III

- geometric reduction factor:

$$L_{eff} = L_0 \cdot \frac{1}{\sqrt{1 + \left(\frac{\theta \cdot \sigma_z}{2\,\sigma^*}\right)^2}}$$

optimization with large geometry factor: Piwinski option

the beam−beam non−linearities are reduced by the same reduction factor

→ keep the bunch length fixed and increase $\frac{N_{bunch}}{\varepsilon_n}$ proportionally to the geometric reduction factor

→ constant beam−beam parameter

→ the luminosity increases linearly with N_{bunch}

BUT: crossing angle limited by triplet aperture

Performance Limitations: Total Intensity IV

🟩 geometric reduction factor:

$$L_{eff} = L_0 \cdot \frac{1}{\sqrt{1+\left(\frac{\theta\cdot\sigma_z}{2\,\sigma^*}\right)^2}}$$

optimization via flat bunches (50cm) arranged in one continues sequence:

super bunch mode

super bunch operation results in a partial compensation of the head−on and long range beam−beam interactions:

⟶ $\sqrt{2}$ larger luminosity for equal beam intensities(flat bunches)

⟶ helps for electron cloud effect(arrangement into one super bunch)

BUT: loss in timing from bunch crossing (vertex detection) and very large number of event per bunch crossing!

Performance Limitation: Total Intensity V

- beam−beam effects and aperture ✓

- heat load due to electron cloud bombardment on the beam screen

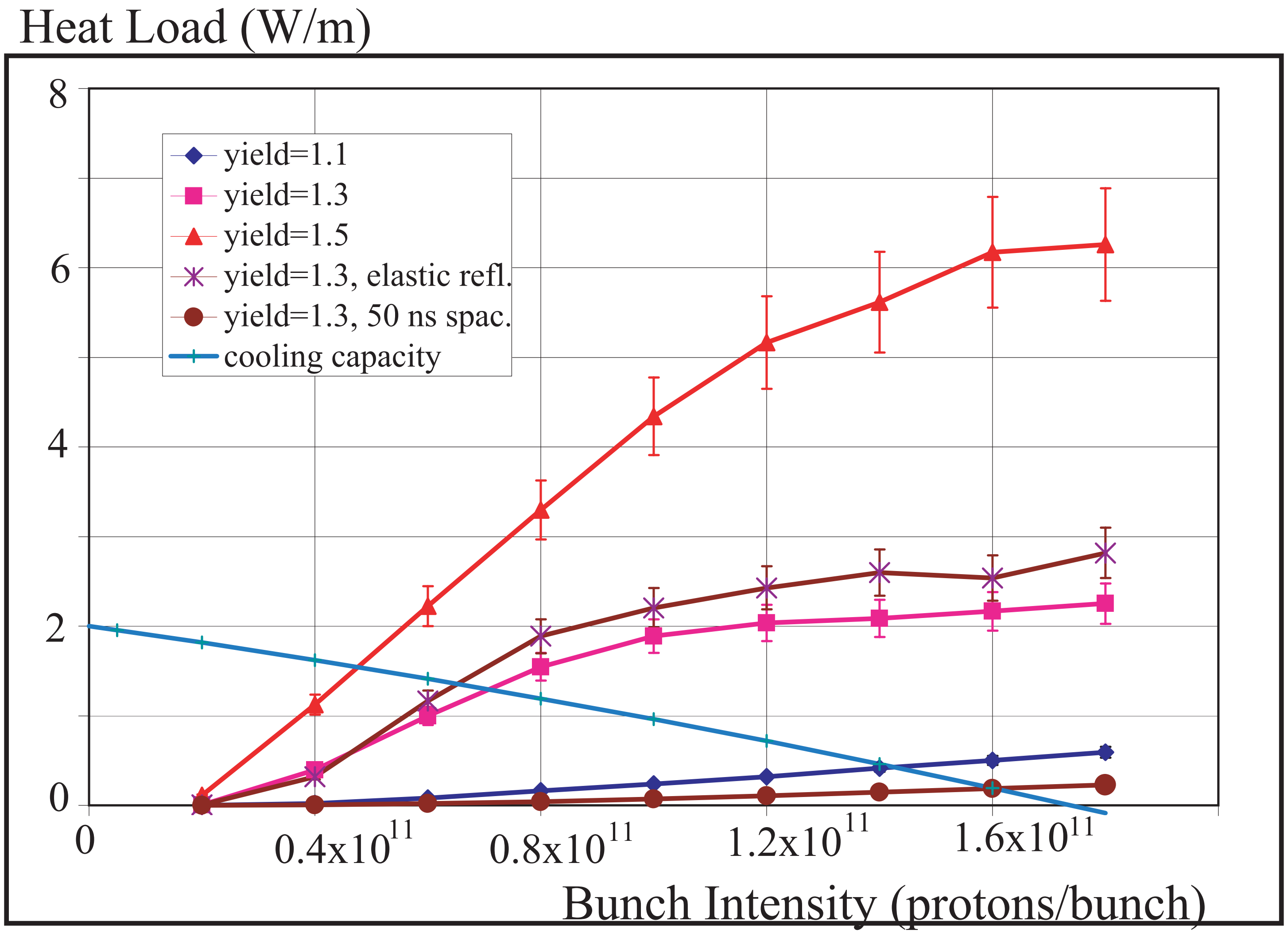
  the electron cloud effect limits minimum bunch spacing and number of bunches for a given bunch intensity

- quench level and collimator efficiency

- impedance and collective instabilities

Heat Load Due to Electron Cloud

F. Zimmermann



🟩 heat load on the beam screen

→ increases for small bunch spacing!

nominal bunch intensities limit bunch spacing to > 25 ns

(25 ns is OK for well conditioned surfaces)

12.5 ns bunch spacing is incompatible with electron cloud induced heat load!

Performance Limitation: Total Intensity VI

- beam−beam effects and dynamic aperture √
- heat load due to electron cloud bombardment on the beam screen √

  the electron cloud effect limits minimum bunch spacing and number of bunches for a given bunch intensity

- quench level and collimator efficiency
- impedance and collective instabilities

Challenge of a Cold Machine

- Magnet Quench:

→ beam abort

→ several hours of recovery

- LHC nominal beam intensity:

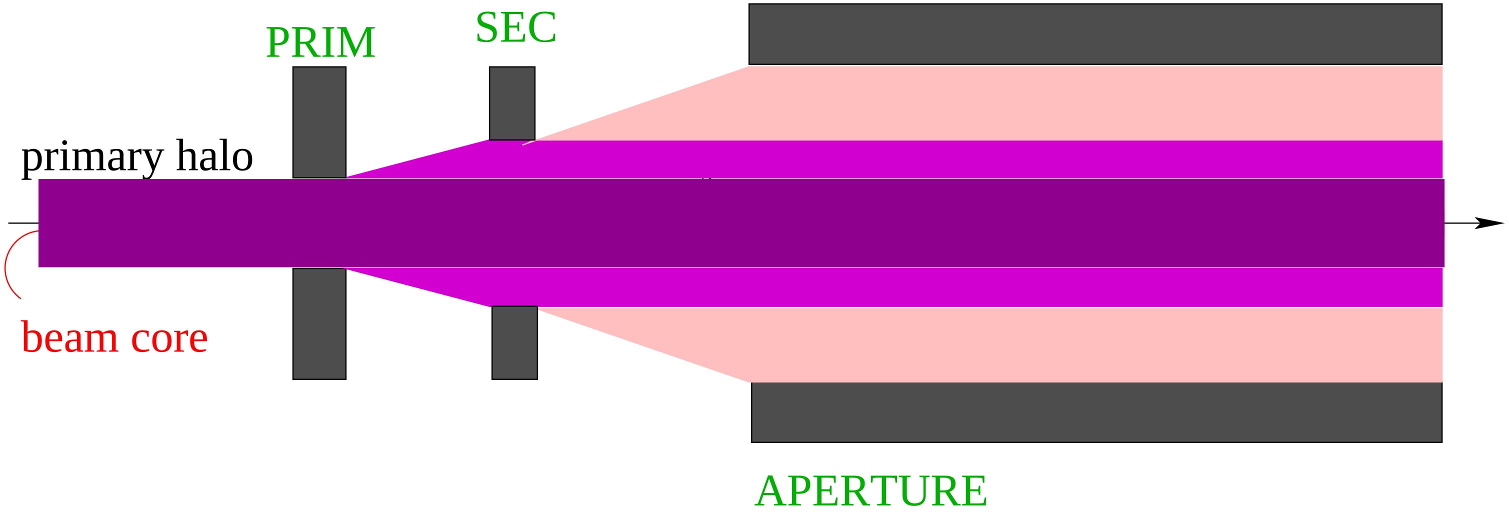
$$I = 0.5\ A \longrightarrow 3 \cdot 10^{14}\ p/beam$$

- Quench level: $N_{lost} < 7.0 \cdot 10^{8}\ m^{-1} \longleftrightarrow \boxed{2.2 \cdot 10^{-6} \cdot N_{beam}}$

(compared to 20% to 30% in other super−conducting proton storage rings)

→ remove stray particles and maximize aperture

Collimation & Machine Protection

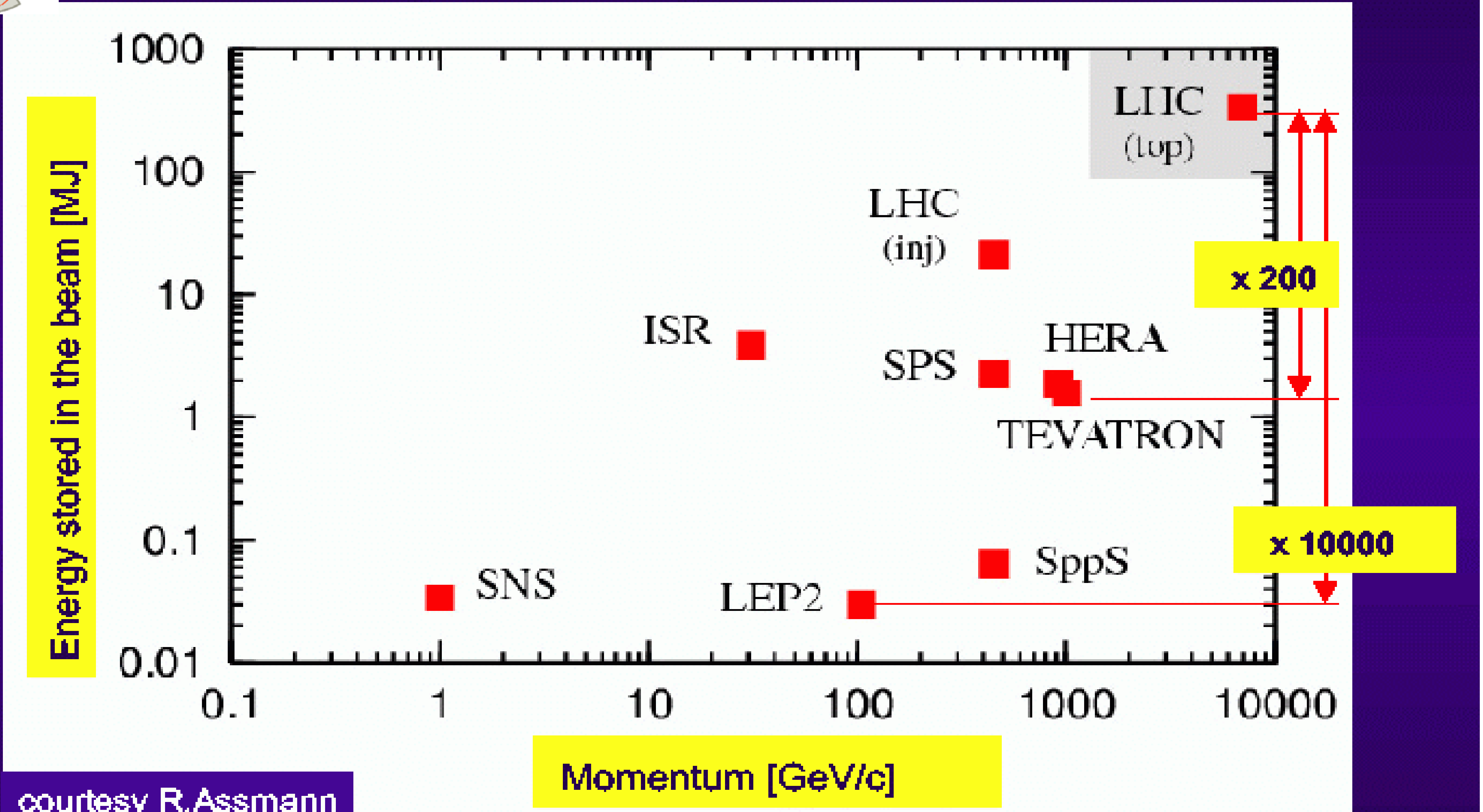


- beam core: ca. 2σ

- primary beam halo: generated by: non−linearities (beam−beam)
  noise
  IBS
  ca. $2\sigma - 6\sigma$
  → can damage equipment

- secondary beam halo: generated by: primary collimator
  ca. $6\sigma - 8\sigma$ → can quench cold equipment

Challenges: Energy stored in the beam



courtesy R.Assmann

Transverse energy density: even a factor of 1000 larger

Performance Limitation: Total Intensity VII

- beam−beam effects and dynamic aperture ✓
- heat load due to electron cloud bombardment on the beam screen ✓

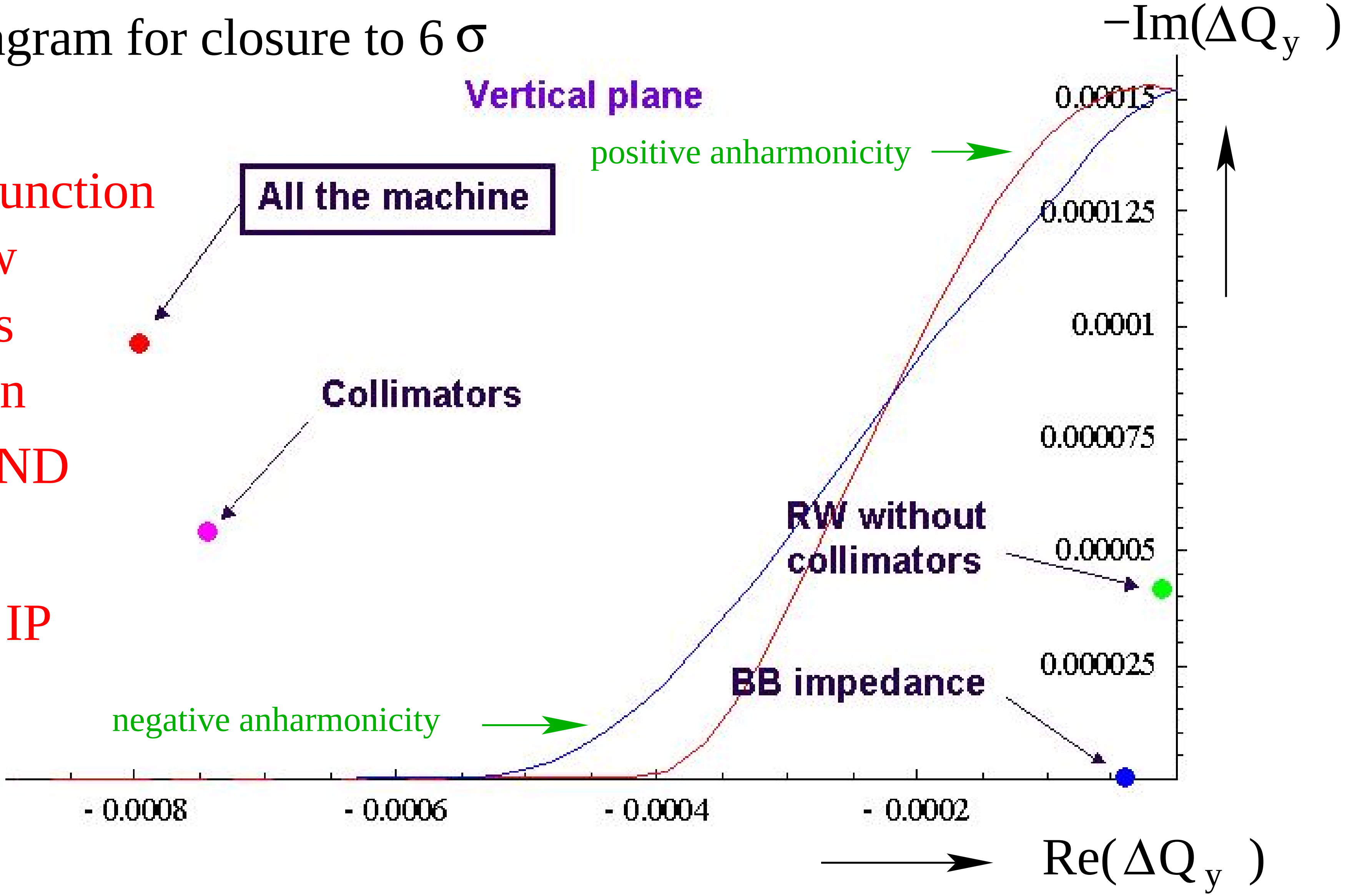
  the electron cloud effect limits minimum bunch spacing and number of bunches for a given bunch intensity
- quench level and collimator efficiency ✓
- impedance and collective instabilities

Impedance Due to Collimators

E. Metral & F. Ruggiero

🟩 stability diagram for closure to 6 σ

impedance is a function of collimator jaw opening and thus imposes limits on total intensity AND the minimum beam size at the IP (β^*)



Performance Limitations: Total Intensity VIII

- LHC beam dump and machine protection devices:

  designed only up to ultimate beam intensity

- performance limits of the injector complex (transfer efficiency)

  only compatible with nominal LHC beam intensities

  higher than nominal beam intensities require special filling schemes

- radiation dose in the cleaning insertions and the experiments

  more studies are required for this limitation!

Performance Limitations: Beam Size

- beam size in the triplet magnets:

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

limit: → quadrupole aperture

→ large aperture triplet quadrupoles and small distance from the IP

→ good orbit and optics control during operation

LHC parameters: → $L^* = 23\ \mathrm{m};\ \beta^* = 0.55\ \mathrm{m}$ → $\beta_{max} = 4.7\mathrm{km}$

$\varepsilon = 5 \cdot 10^{-10}\ \mathrm{m}$ → $\sigma^* = 16.6\ \mu\mathrm{m}$ → $\sigma(\mathrm{triplet}) = 1.54\ \mathrm{mm}$

- beam size in the triplet magnets: → collimator impedance

Performance Limitations: Integrated Luminosity I

🟩 luminosity lifetime:

2 <–> 3 $\quad 10^{-25}\,\mathrm{cm}^{2} \quad 3.53\cdot 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$

$$\frac{dN_{bunch}}{dt} = k_{IP}\cdot\sigma_{bb}\cdot\frac{L_{0-bunch}}{(N_{bunch})^{2}}$$

→ $N_{bunch}(t) = \dfrac{N_0}{1 + t/\tau_{bb}}$ $\qquad L_{bunch}(t) = \dfrac{L_0}{(1 + t/\tau_{bb})^{2}}$

→ $\tau_{bb}^{-1} = k_{IP}\cdot\sigma_{bb}\cdot\dfrac{L_{0-bunch}}{N_{bunch}}$ $\qquad \tau_{bb-1/2-lum,\ nom} = 16\ \mathrm{hours}$

→ large peak bunch luminosity implies short beam lifetimes

Performance Limitations: Integrated Luminosity II

- integrated luminosity:

$$L_{tot} = L_0 \cdot \tau_{lumi} \cdot [1 - e^{-T_{run}/\tau_{lumi}}] \cdot \frac{200 \cdot 24}{T_{run}[\mathrm{hours}] + T_{turnaround}[\mathrm{hours}]}$$

→ maximum performance requires minimum turnaround times

→ minimize the number of quenches and beam aborts

→ limit for beam energy density

(see ´total intensity limitations´)

Performance Limitations: Integrated Luminosity III

- maximum integrated luminosity:

$$L_{tot} = L_0 \cdot \tau_{lumi} \cdot [1 - e^{-T/\tau}] \cdot \frac{200 \cdot 24}{T_{run}[\text{hours}] + T_{turnaround}[\text{hours}]}$$

assume: $\beta^* \longrightarrow \beta^* / 2$ and $N_{bunch} \longrightarrow 1.7 * N_{bunch}$

$\longrightarrow$ $L_{0,bunch} \longrightarrow 5 * L_{0,bunch}$

$$L_{0,bunch} = 1.78 \cdot 10^{31}\ \text{cm}^{-2}\text{sec}^{-1}$$

$$L_{0,bunch} = 0.35 \cdot 10^{31}\ \text{cm}^{-2}\text{sec}^{-1}$$

τ_{lumi} \ T_{turn}	1	6	10	20	[hours]
5	482	249	190	123	L_{tot}
15	122	78	65	47	[fbarn^{-1}]

$\longrightarrow$ L increase by factor 4 to 2.5 depending on turn around time!

Nominal Parameters

parameter \ value	nominal	maintain margins for total intensity and aperture
# bunches	2808	
N / bunch	$1.15*10^{11}$	margin for beam−beam effects
β^*	0.55 m	aperture and impedance margin
ε_n	3.75 μ m	
σ^*	16 μ m	
σ_L	7.55cm	
full crossing angle	285 μ rad	aperture margin
events per crossing	19.2	
peak luminosity	$1.0*10^{34}$ $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$	
luminosity lifetime	15 h	
E[TeV]	7	quench margin
E [MJ]	366	quench and damage potential

Early Design Parameters

parameter \ value	´white book´	DIR−TECH/84−01 & ECFA 84/85 CERN 84−10; 1984
# bunches	3564	slightly larger due to non realistic kicker rise times
N / bunch	$0.34*10^{11}$	factor 3 smaller beam−beam effects
β^*	1.0 m	more margins for aperture and impedance
ε_n	1.07 µ m	factor 3 smaller value for $N_{bunch} / \varepsilon_n$ (injector chain)
σ^*	12 µ m	
σ_L	7.55cm	
full crossing angle	100 µ rad	factor 3 larger aperture margin (assuming same triplet)
events per crossing	1 <−> 4	order of magnitude smaller than ´nominal´
peak luminosity	$0.1*10^{34}$ $cm^{-2} sec^{-1}$	
luminosity lifetime	56 h	factor 4 larger lifetime −> efficiency!
E[TeV]	8.14	10 T magnetic field compared to 8.4 T
E [MJ]	121	factor 3 smaller quench and damage potential

Nominal Parameters

´nominal´ LHC is allready VERY challenging!

→ ´upgrade´ = ´backup´ and ´more´

parameter \ value	nominal	
# bunches	2808	
N / bunch	$1.15*10^{11}$	margin for beam−beam effects
β^*	0.55 m	aperture and impedance margin
ε_n	$3.75\,\mu$ m	
σ^*	$16\,\mu$ m	
σ_L	7.55cm	
full crossing angle	$285\,\mu$ rad	aperture margin
events per crossing	19.2	
peak luminosity	$1.0*10^{34}$ $cm^{-2}sec^{-1}$	
luminosity lifetime	15 h	
E[TeV]	7	quench margin
E [MJ]	366	quench and damage potential

margins?

LHC Upgrade Studies

- Summer 2001:

  CERN task force investigates a possible staged upgrade of the LHC

  LHC Project Report 626

- March 2002: LHC IR upgrade collaboration meeting:

  "http://cern.ch/lhc−proj−IR−upgrade"

- October 2002:

  ICFA Seminar on ’Future Perspectives in High Energy Physics’

- February 2003 and 2004: LHC Performance Workshop, Chamonix

  "http://ab−div.web.cern.ch/ab−div/Conferences/Chamonix/2003/default.html"

- 2004: CARE project for future accelerator R&D

  "http://care−hhh.web.cern.ch/care−hhh/" with F. Ruggiero from CERN as coordinator

Options for Future
High Luminosity Upgrades for the LHC

- The CERN task force identified 3 main options for the LHC upgrade and grouped them according to their impact on the LHC infrastructure into three phases

Phase 0: performance upgrade without hardware modifications

Phase 1: performance upgrade with IR modifications

Phase 2: performance upgrade with major hardware modifications

Luminosity Upgrade Phase 0

- increase the bunch intensity to the beam−beam limit:

  collision only in 2 experiments: $N_{bunch} = 1.15 * 10^{11} \longrightarrow N_{bunch} = 1.7 * 10^{11}$

  just compatible with the LHC beam dump and injector complex (see later)

- increase the total beam current to the electron cloud limit (cryogenic system)

  $N_{bunch} = 1.7 * 10^{11}$ seems just possible

- decrease β^* to triplet aperture limit: $\beta^* = 0.5\mathrm{m}$

- increase the machine energy to ’ultimate’ dipole field settings $E = 7.54$ T

Ultimate Parameters

parameter \ value	nominal	phase 0	no margins left
# bunches	2808	2808	limit by cryogenic system?
N / bunch	$1.15*10^{11}$	$1.70*10^{11}$	
β^*	0.55 m	0.5 m	
ε_n	3.75 μ m	3.75 μ m	
σ^*	16.7 μ m	16 μ m	
σ_L	7.55cm	7.55cm	
full crossing angle	285 μ rad	315 μ rad	
events per crossing	19.2	44.2	
peak luminosity	$1.0*10^{34}$ $cm^{-2} sec^{-1}$	$2.4*10^{34}$ $cm^{-2} sec^{-1}$	
luminosity lifetime	15 h	10 h	
E[TeV]	7	7 -> 7.45	-> $L = 2.6*10^{34}$ $cm^{-2} sec^{-1}$
E [MJ]	366	541	

Luminosity Upgrade Phase 1

- modify insertion layout for $\beta^* = 0.25\mathrm{m}$ (lifetime for base line triplet = 700 fb^{-1}

  increased beam size in triplet magnets:

  increased crossing angle: $\theta = 445\ \mu\mathrm{rad}$

  $\xrightarrow{\quad}$ larger triplet aperture

  2 design proposals

  half the bunch length with a new RF system

- reduce L* if possible

- maintain ultimate bunch intensities: $N_{\mathrm{bunch}} = 1.7 * 10^{11}$

- double the number of bunches: (incompatible with e−cloud estimates)

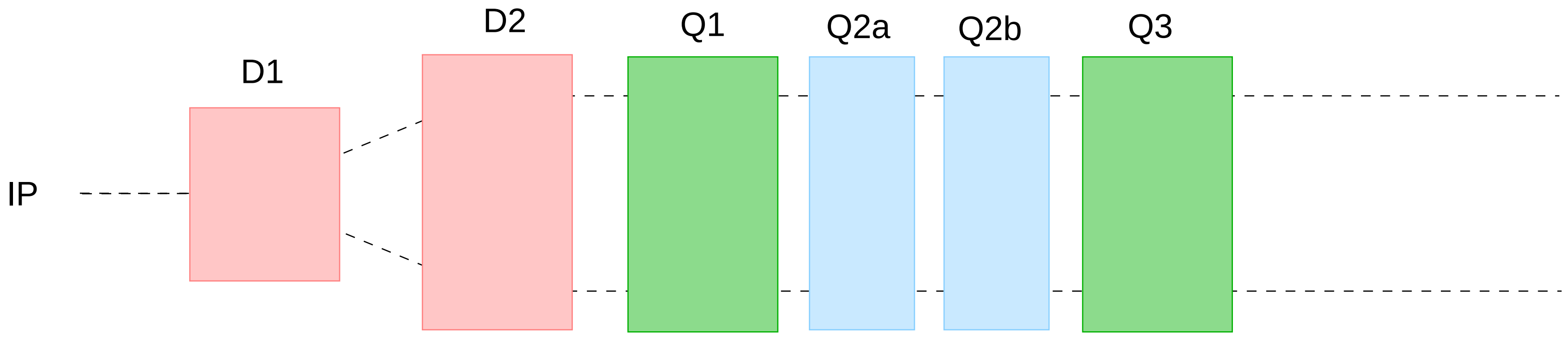
- install a 'wire' compensation for the long−range beam−beam effects

  (J−P Koutchouk: proposed at CERN and currently studied at TEVATRON)

- increase the machine energy to 'ultimate' dipole field settings E = 7.54 TeV

Separate Triplet Magnets

- insertion layout:



- requires radiation hard large aperture D1 dipole magnets

  nominal layout requires radiation hard large aperture quadrupole magnets

  both layouts require comparable quadrupole apertures (L^*)

- D1 dipole functions as spectrometer for TAS absorber

  TAS and TAN designs need to be revised for increased luminosities

IR Layouts for Luminosity Upgrade

- separate triplet layout reduced the number of long range beam−beam
- separation dipole improves the efficiency of the TAS absorber
- relevance of magnet field quality increases with β and crossing angle bump amplitude inside the triplet
- separate triplet magnets offer:
  - → decoupled correction left and right from the IP
  - → decoupled correction for beam1 and beam2
  - → fully decoupled optics for beam1 and beam2
- both IR designs require triplet magnets with 90mm cold bore diameter
- trade−off between radiation hard dipole and quadrupole magnets

IR Upgrade Parameters

parameter \ value	nominal	phase 0	phase 1
# bunches	2808	2808	5616 → 2808
N / bunch	$1.15*10^{11}$	$1.70*10^{11}$	$1.70*10^{11}$
β^*	0.55 m	0.5 m	0.25 m → < 0.25 m?
ε_n	3.75μ m	3.75μ m	3.75μ m
σ^*	16.7μ m	$16\ \mu$ m	$11.3\ \mu$ m
σ_L	7.55cm	7.55cm	3.8cm
full crossing angle	$285\ \mu$ rad	$315\ \mu$ rad	$445\ \mu$ rad
events per crossing	19.2	44.2	88.4
peak luminosity	$1.0*10^{34}$ $cm^{-2}sec^{-1}$	$2.4*10^{34}$ $cm^{-2}sec^{-1}$	$9.6*10^{34}$ $cm^{-2}sec^{-1}$
luminosity lifetime	15 h	10 h	5 h → integrated
E[TeV]	7	7 -> 7.45	7 -> 7.45 luminosity and
E [MJ]	366	541	1082 → efficiency?

Luminosity Upgrade Phase 2

- increase the beam brilliance in the injector complex:
  - the ultimate injector performance is just compatible with the Phase 0 upgrade
  - assuming beam losses during the transfer processes the current injector complex is just compatible with the nominal LHC parameter

various options are currently discussed at CERN in collaboration with CARE and ESGARD

→ SPL project

→ upgrade of existing injection Linac4:

→ super PSB, PS and SPS:

Luminosity Upgrade Phase 2

- increase the beam brilliance in the injector complex:

additional studies are required for the handling of larger beam intensities:

→ launch R&D work for an upgraded LHC beam dump system

→ R&D for an upgraded collimation system (protection & radiation)

→ study machine protection issues for increased beam intensities

→ launch R&D work for vacuum and electron cloud aspects

→ launch R&D work for an LHC cryogenic upgrade

all studies are done in collaboration with CARE and ESGARD

Luminosity Upgrade Phase 2

- increase the injection energy into the LHC: $\sigma = \sqrt{\beta \, \epsilon_n / \gamma}$

  → increased aperture

  → increase bunch intensity with constant brightness (beam−beam)

  −equip the SPS with super−conducting magnets and upgrade the transfer lines

  −install a compact booster ring in the LHC tunnel(aperture limit in TL)

  → R&D work for both options has been initiated under ESGARD

- install new dipole fields with 15 T in the LHC target

  → R&D work has been initiated under ESGARD with 2015 as time table

  → beam energy of 12.5 TeV (synchrotron radiation!)

Luminosity Upgrade Phase 2

- R&D for vacuum and cryogenics for high intensity beams at 12.5 TeV
  - ➞ synchrotron radiation and e−cloud

- machine and radiation protection for high intensity beams at 12.5 TeV
  - ➞ more R&D work required

- super bunch operation mode
  - ➞ very attractive for beam operation (e−cloud and beam−beam)
  - ➞ requires demanding RF upgrade that requires more R&D
  - ➞ is this mode acceptable for the experiments (loss of timing)?

Summary

- the nominal LHC operation is already very challenging
  - → the upgrade studies could also provide means to overcome operational limitations for the nominal performance
  - → R&D results should be available shortly after commissioning
- radiation limit for the IR magnets (700 fb^{-1}) might be reached by 2013
  - → we need to prepare a replacement now
  - → large triplet apertures will also help for impedance and protection issues
- radiation and machine protection issues are very demanding
- official collaborations for R&D work and machine studies are launched within US−LARP and the European ESGARD initiatives