Accelerator Upgrades for SLHC

- Introduction
- Summary of the general performance limitations
- Summary of the main upgrade phases
  - Phase 0: performance upgrade with out hardware modifications
  - Phase 1: performance upgrade with IR modifications
  - Phase 2: performance upgrade with major hardware modifications
- General summary

Introduction

- 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’

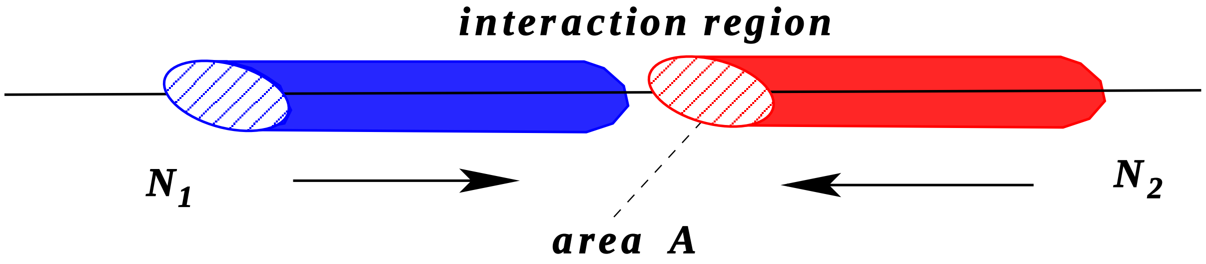
- February 2003 and 2004: LHC Performance Workshop, Chamonix

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

- 2004: CARE project for future accelerator R&D

LHC Performance: Luminosity

- luminosity:



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

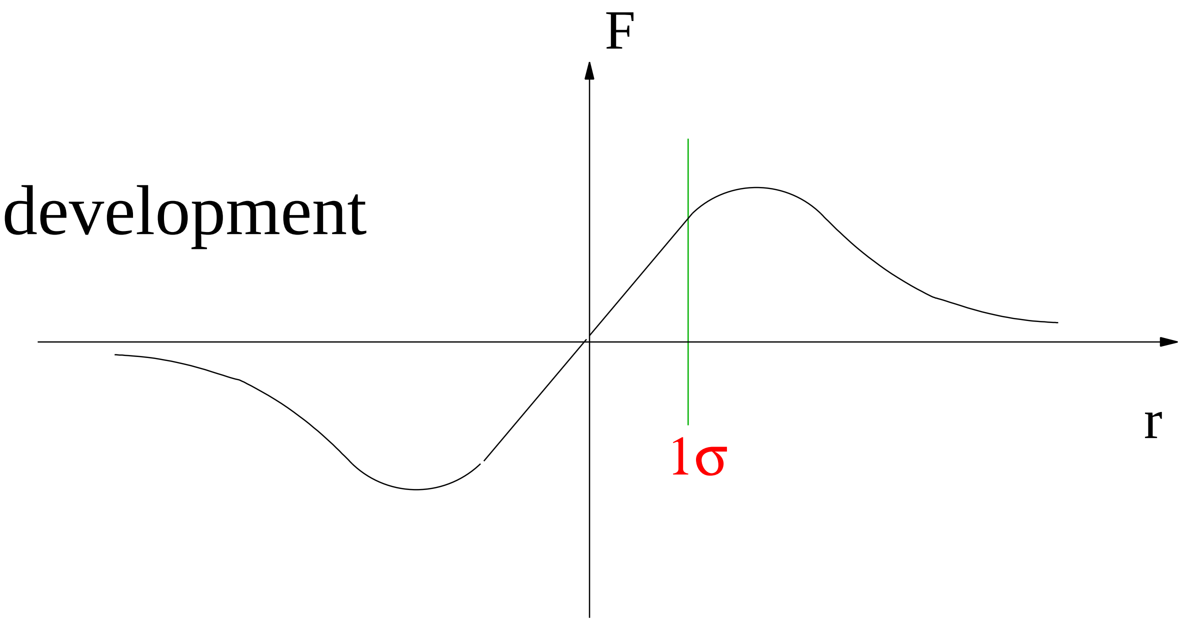
$$A = \frac{4\pi \bullet \beta \bullet \varepsilon}{(4\pi\,\sigma^2)}$$

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

→ increase bunch intensity and number of bunches,

reduce β at the IP, increase the collision energy

Limits Due to Beam Beam Interaction



- LHC studies, optics development

- small amplitudes:

$$\frac{F}{v \cdot p} \approx \frac{N_2 \cdot r_p}{\gamma} \cdot \frac{r}{\sigma^2} \longrightarrow \text{quadrupole}$$

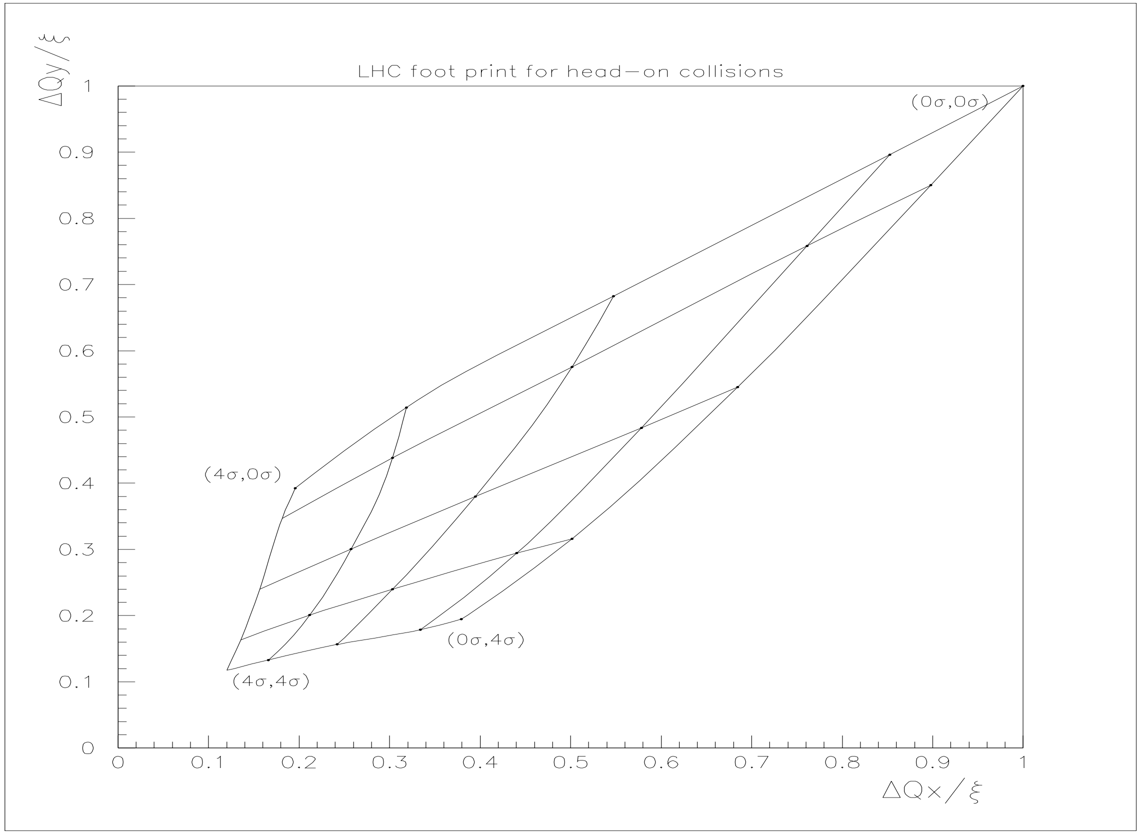
- intermediate amplitudes ($r \approx \sigma$): ⟶ strong non−linearity

- large amplitudes: $\frac{F}{v \cdot p} \propto \frac{2}{r}$ ⟶ charged wire

Head−On Beam−Beam Limit

- 🟩 particle tune varies with amplitude: $\Delta Q = \dfrac{N_2 \cdot r_p}{4\pi \cdot \gamma \cdot \varepsilon}$ → $\boxed{\xi_{\text{beam−beam}}}$

- 🟩 foot print:



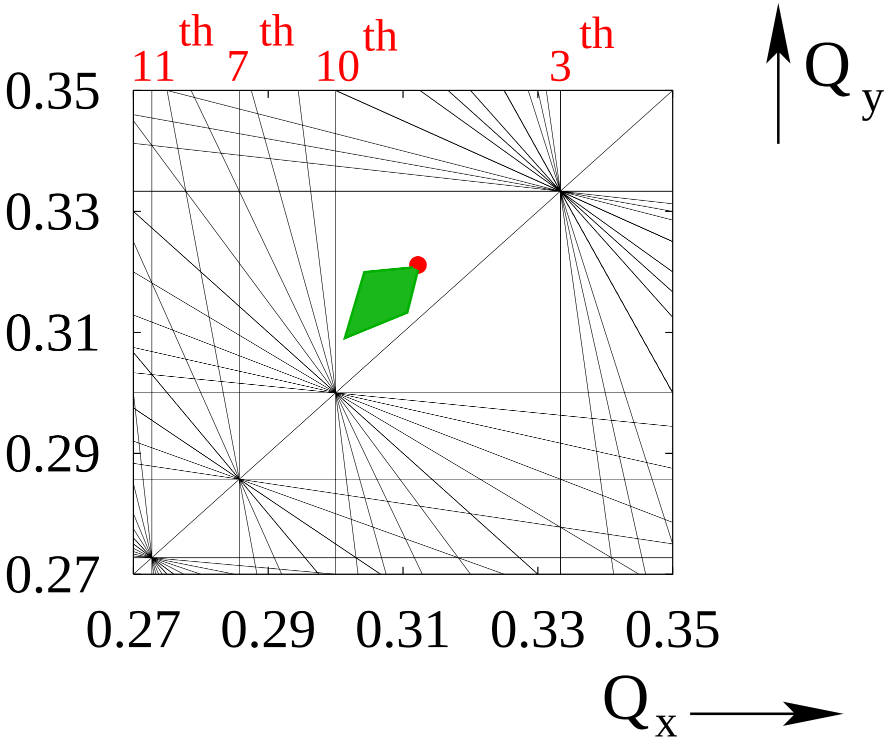
→ particle tune depends on particle amplitude

Head On Beam−Beam Limitations

- 🟩 LHC working point: $Q_x = 64.31; \quad Q_y = 59.32$

SPS experience

$n + m < 12$



total beam−beam tune shift must be smaller than 0.015!

3 head on collisions

→ $\boxed{\xi < 0.005}$

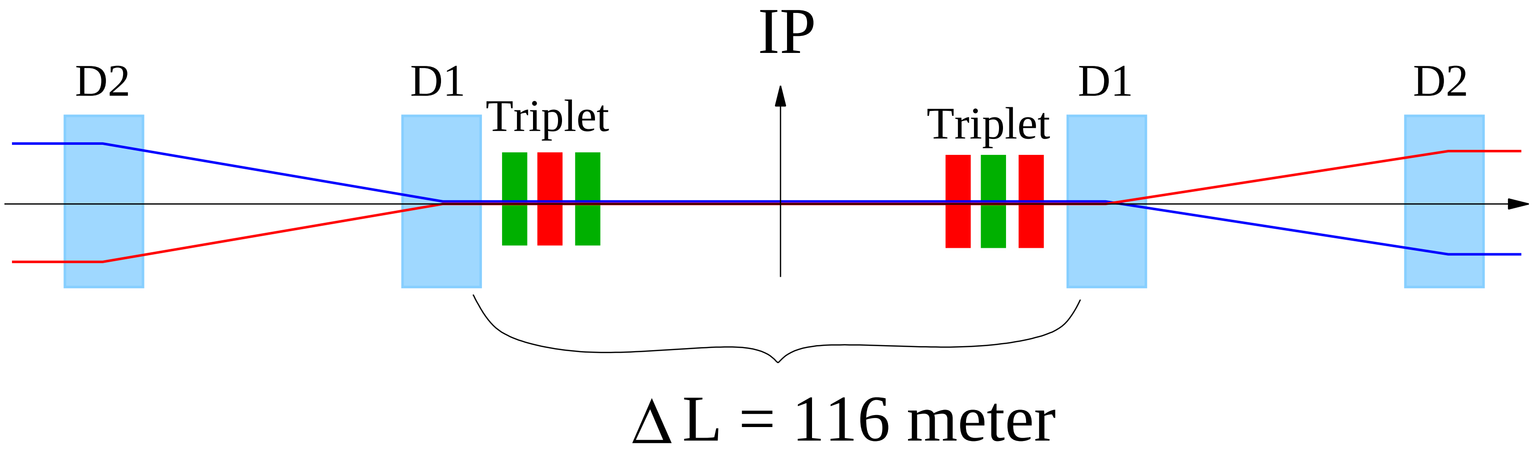
(1 per experiments)

- 🟩 LHC magnet aperture: → $\varepsilon < 5 \cdot 10^{-10}$ m

→ $\boxed{N < 1.5 \cdot 10^{11}}$ → can be increased for 2 experiments

Crossing Angle at the Interaction Point

🟩 IR layout:



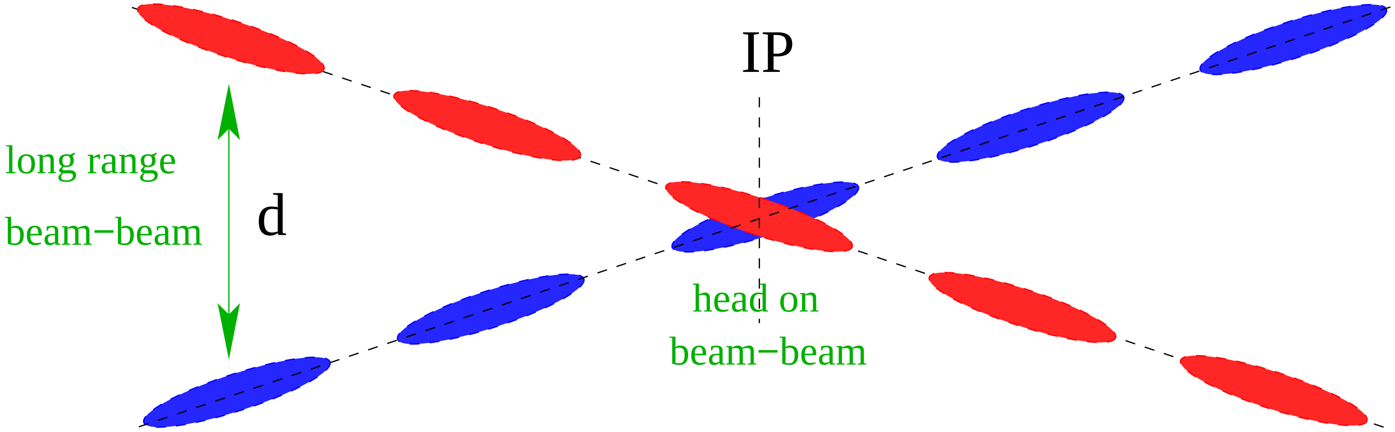
→ additional head on collisions for a bunch separation of less than 232 metre

🟩 crossing angle:

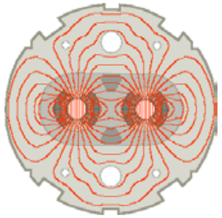
→ separate the two beams left and right from the IP with additional orbit bumps over the insertions

Accelerator Upgrades for SLHC

- crossing angle:



- disadvantage:
  - → generates additional tune shift
  - → requires larger triplet magnet aperture
  - → increases interacting cross section
  - → breaks the bunch train symmetry (kicker gaps)
  - → breaks the symmetry between x and y planes
  - → drives additional resonances



Luminosity Reduction Factor

- 🟩 geometric reduction factor:

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

$\longrightarrow$ short bunches and minimum crossing angle for maximum L

- 🟩 beam−beam tune spread:

the beam−beam parameter is reduced by the same reduction factor

- 🟩 super bunch operation mode:

operation with very long bunches and large crossing angles results in a partial compensation of the long range and head on beam−beam tune spreads

$\longrightarrow$ $\sqrt{2}$ larger luminosity for equal beam intensities

Long Range Beam−Beam Tune Shift

- the sign of the long range tune shift depends on the crossing angle plane:

  alternate crossing angle planes in the LHC experiments can partially compensate the long range beam−beam effects

→ luminosity operation requires an even number of experimental insertions with squeezed optics

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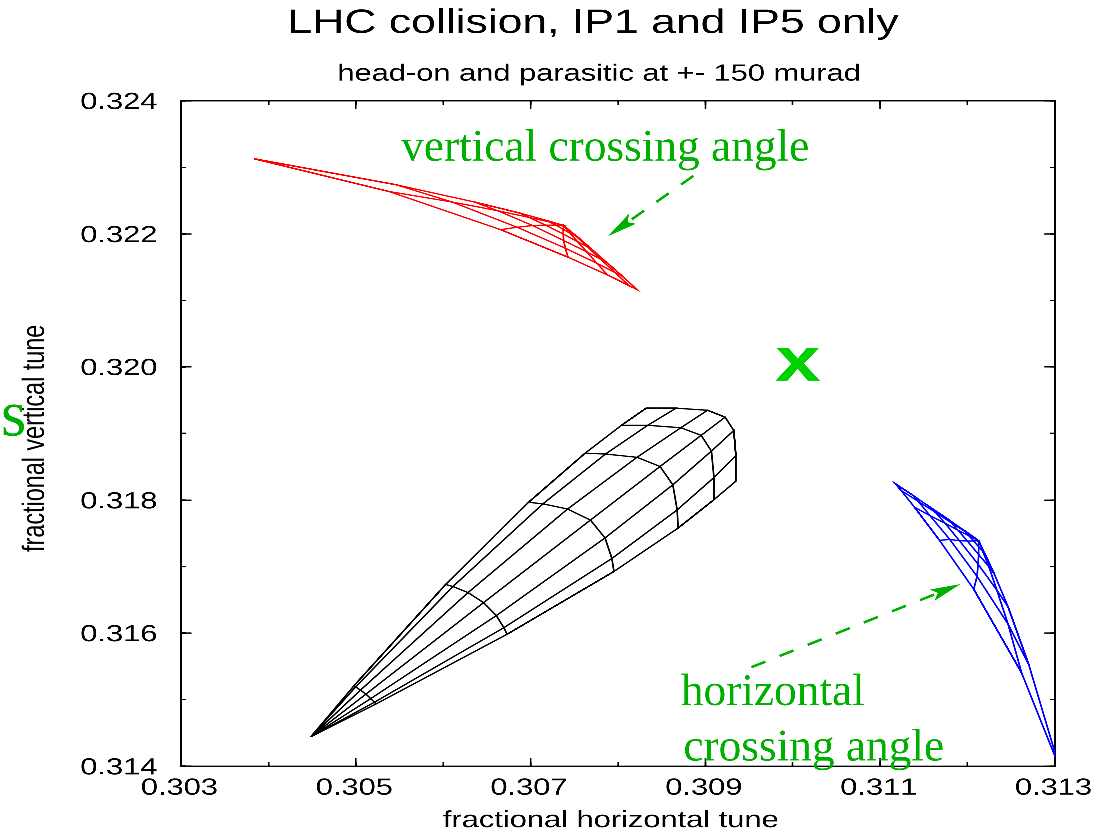
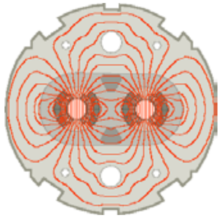




Aperture Limitations for β^*

- 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

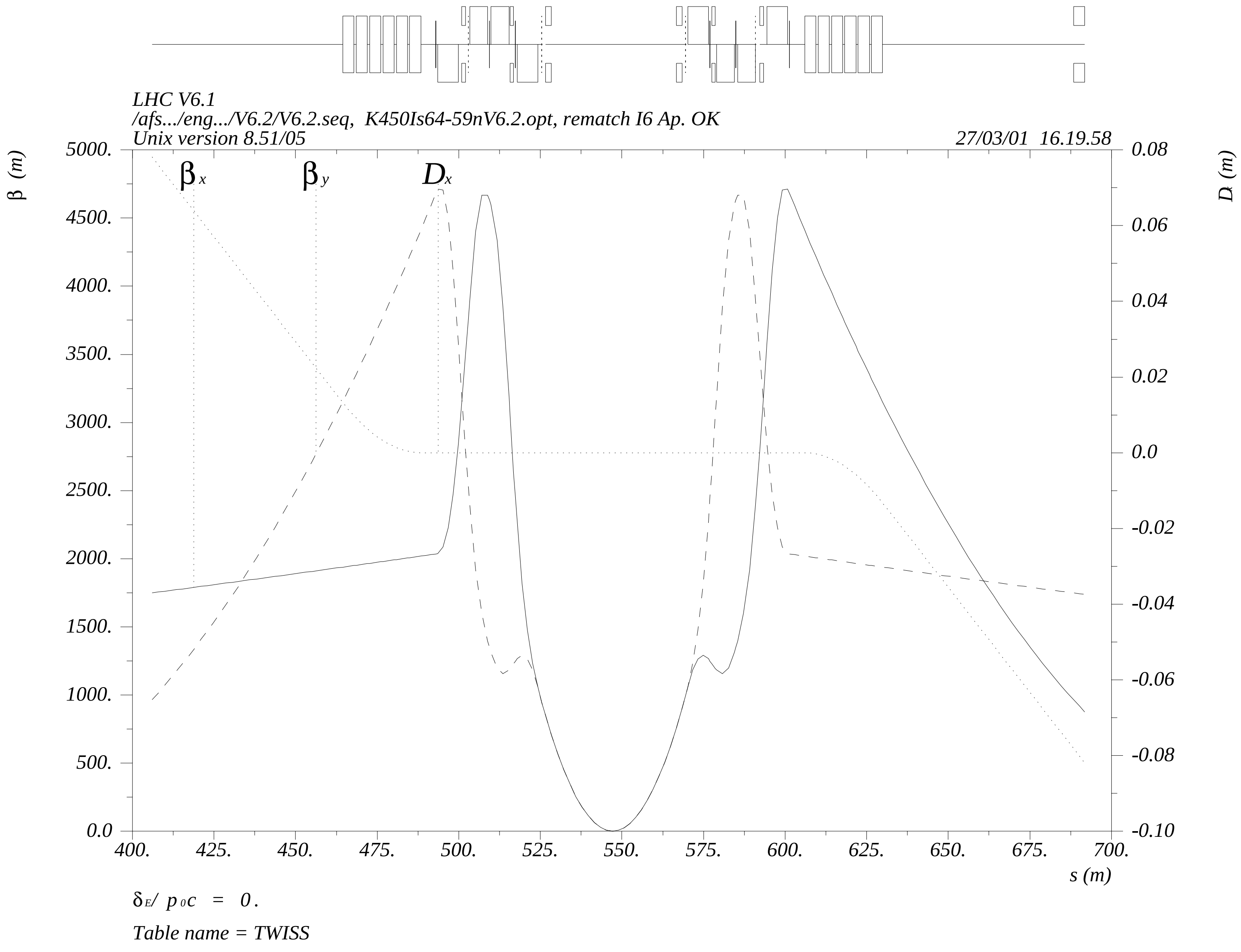
  → good orbit and optics control during operation

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

  $\varepsilon = 5 \cdot 10^{-10}$ m → $\sigma^* = 16.6\,\mu$m

(determined by injector complex and collision energy)

$\beta^* = 0.5\text{m}$ Optics



Aperture

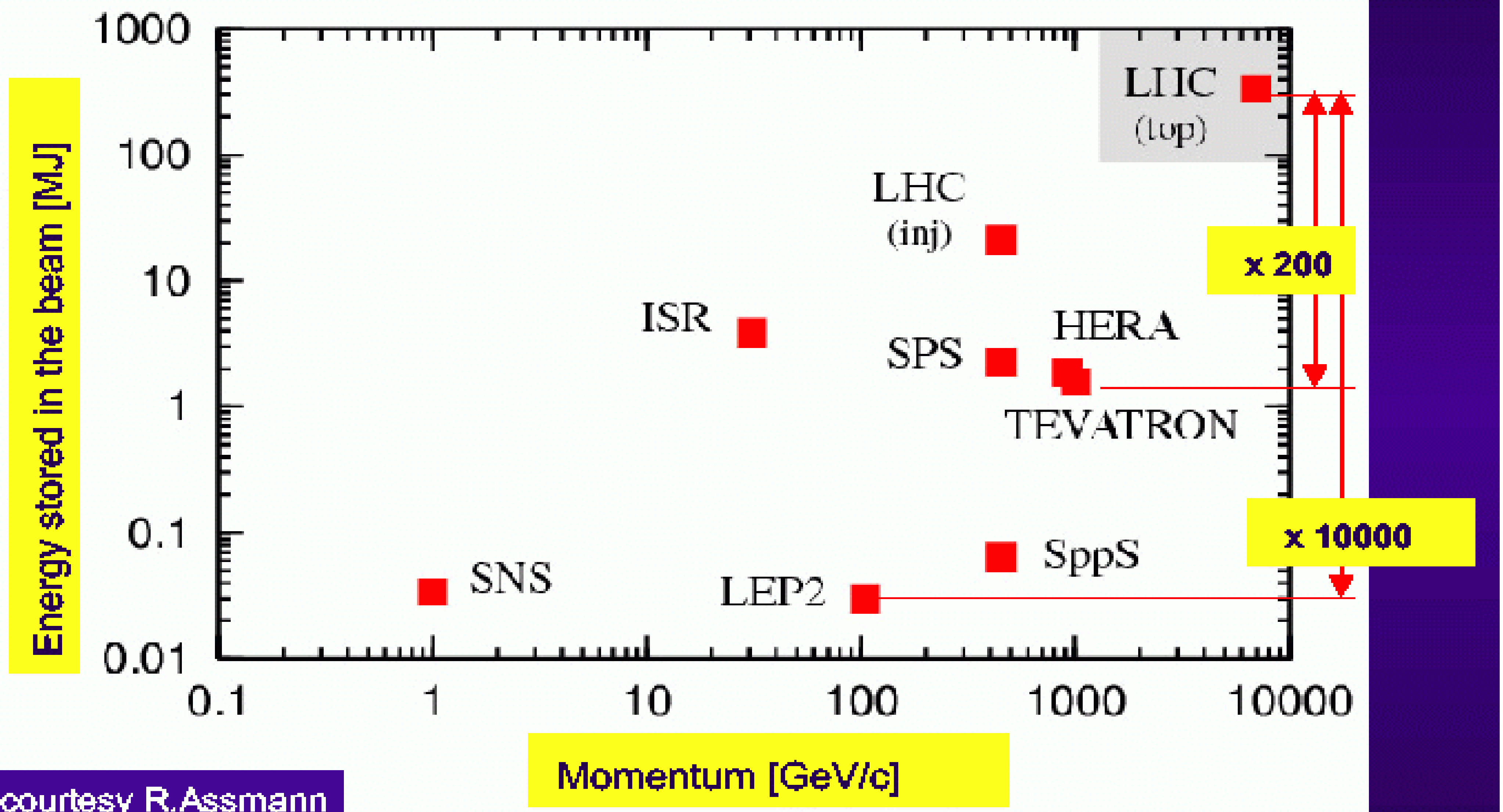
- ***common triplet elements (rough estimate, L^* = 23m):***
  - 9 σ beam envelope
  - 7.5 σ beam separation
  - 20% β −beat
  - 4mm spurious dispersion
  - 3mm orbit errors
  - 1.6mm alignment errors
  - 0.6mm beam screen

→ D(triplet) > 28σ + 2*9.2 mm D(β^* = 0.55m) > 59.8mm

Total Intensity Limitations

- beam−beam effects and dynamic aperture
- quench level and collimator efficiency
- impedance and collective instabilities
- heat load due to electron cloud bombardment on the beam screen
- LHC beam dump design
- performance limits of the injector complex (transfer efficiency)
- radiation dose in the cleaning insertions and the experiments

Challenges: Energy stored in the beam



courtesy R.Assmann

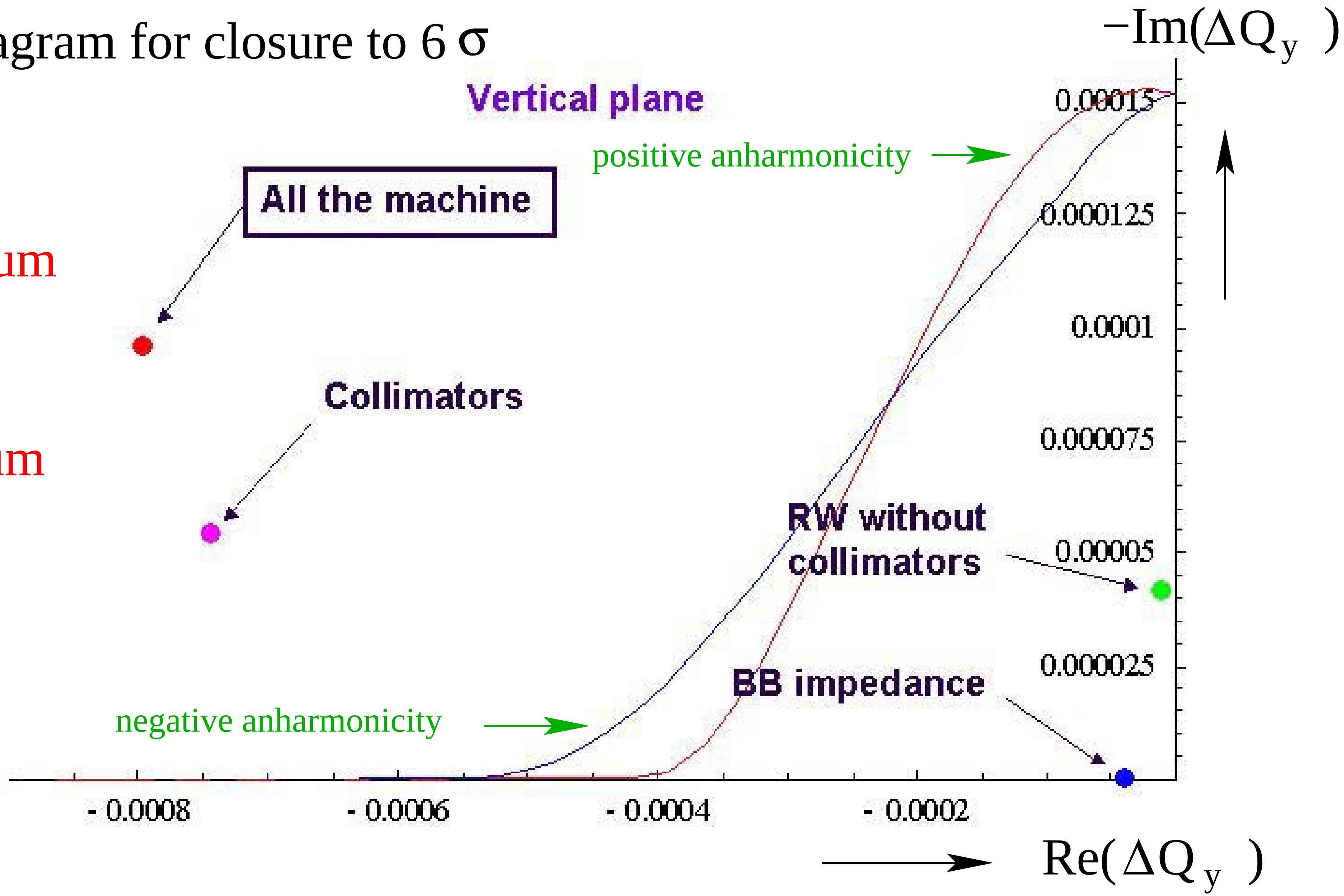
Transverse energy density: even a factor of 1000 larger

Impedance Due to Collimators

E. Metral & F. Ruggiero

🟩 stability diagram for closure to 6 σ

impedance can limit the minimum collimator aperture and thus the minimum β^*

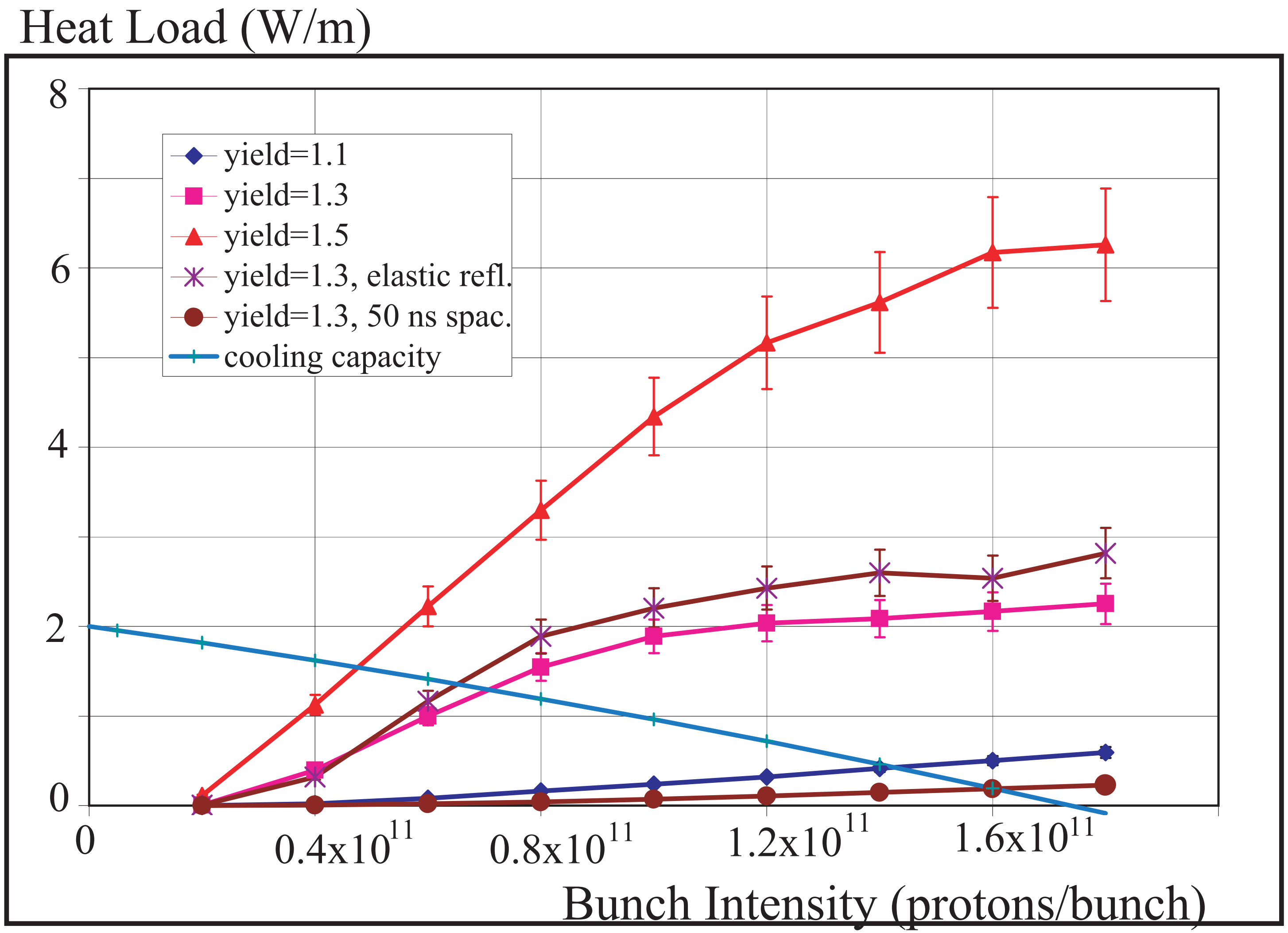


Heat Load Due to Electron Cloud

- heat load on the beam screen

→ increases for small bunch spacing!

F. Zimmermann



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	$1.0*10^{34}$ $cm^{-2}sec^{-1}$	
luminosity lifetime	15 h	
E[TeV]	7	quench margin
E [MJ]	366	quench and damage potential

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

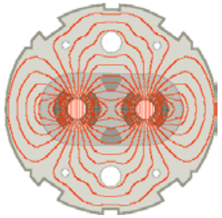
  $N_{bunch} = 1.7 * 10^{11}$ seems just possible

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

- 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	
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 $\beta^{*} = 0.25\,\mathrm{m}$

  increased beam size in triplet magnets:

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

  → larger triplet aperture

  2 design proposals

  half the bunch length with a new RF system

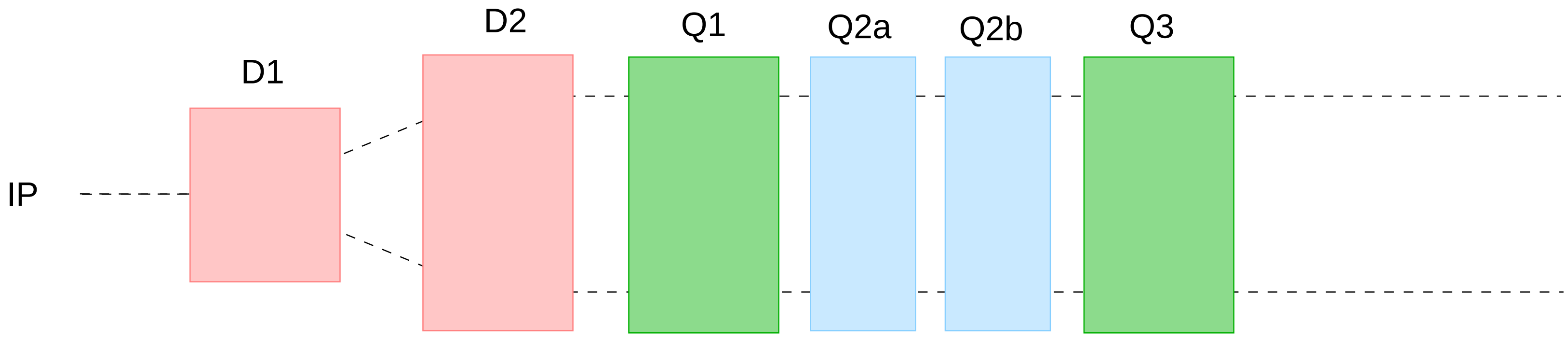
- maintain ultimate bunch intensities: $N_{\mathrm{bunch}} = 1.7 * 10^{11}$
- double the number of bunches: (incompatible with e−cloud estimates)
- install a ’wire’ compensation for the long−range beam−beam effects

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

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

Separate Triplet Magnets

- insertion layout:



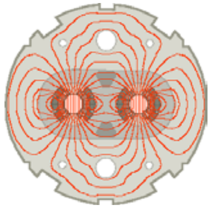
- requires radiation hard large aperture D1 dipole magnets

  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 diametere
- trade−of between radiation hard dipole and quadrupole magnets

IR Upgrade Parameters

parameter \ value	nominal	phase 0	phase 1
# bunches	2808	2808	5616
N / bunch	$1.15*10^{11}$	$1.70*10^{11}$	$1.70*10^{11}$
β^*	0.55 m	0.5 m	0.25 m
ε_n	3.75 μ m	3.75 μ m	3.75 μ m
σ^*	16.7 μ m	16 μ m	11.3 μ m
σ_L	7.55cm	7.55cm	3.8cm
full crossing angle	285 μ rad	315 μ rad	445 μ 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
E[TeV]	7	7 -> 7.45	7 -> 7.45
E [MJ]	366	541	1082

Integrated Luminosity

🟩 luminosity lifetime:

$$\frac{dN_{\mathrm{bunch}}}{dt} = \overset{2}{k_{IP}} \cdot \overset{10^{-25}\,\mathrm{cm}^2}{\sigma_{bb}} \cdot \frac{\overset{3.53 \cdot 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}}{L_{0-\mathrm{bunch}}}}{(N_{\mathrm{bunch}})^2}$$

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

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

→ large peak bunch luminosity implies short beam lifetimes

Integrated Luminosity

- 🟩 integrated luminosity:

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

$\longrightarrow$ maximum performance requires minimum turnaround times

$\longrightarrow$ minimize the number of quenches and beam aborts

$\longrightarrow$ limit for beam energy density

Integrated Luminosity

- 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 $N_{bunch} \longrightarrow 1.7 * N_{bunch}$

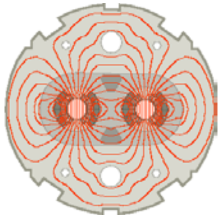
$\longrightarrow$ $L_{0,bunch} \longrightarrow 5 * L_{0,bunch}$

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

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

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

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



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

  R&D work for a new injector upgrade are already under way at CERN in collaboration with CARE and ESGARD

→ 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

Luminosity Upgrade Phase 2

- 🟩 increase the injection energy into the LHC: $\sigma = \sqrt{\beta \ \varepsilon_n / \gamma}$
  - → increased aperture
  - → increase bunch intensity with constant brightness (beam−beam)

−equip the SPS with superconducting magnets and upgrade the transfer lines

−install a compact booster ring int he LHC tunnel

→ 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

Long Range Beam−Beam Tune Shift

- tune change for long range beam−beam interaction: $\Delta Q_{lr} = \frac{N_2 \cdot r_p}{2\pi\gamma} \cdot \frac{\beta}{d^2}$

with: $d = 2 \cdot \tan(\alpha / 2) \cdot s$ ($\alpha =$ total crossing angle) and $\beta = \beta^* + \frac{s^2}{\beta^*}$

$$\Delta Q_{lr} = \frac{N_2 \cdot r_p}{2\pi \cdot \gamma} \cdot \frac{1}{\alpha^2 \cdot \beta^*}$$

tune shift
depends
on crossing
angle plane!

→

alternate
crossing
angle plane!

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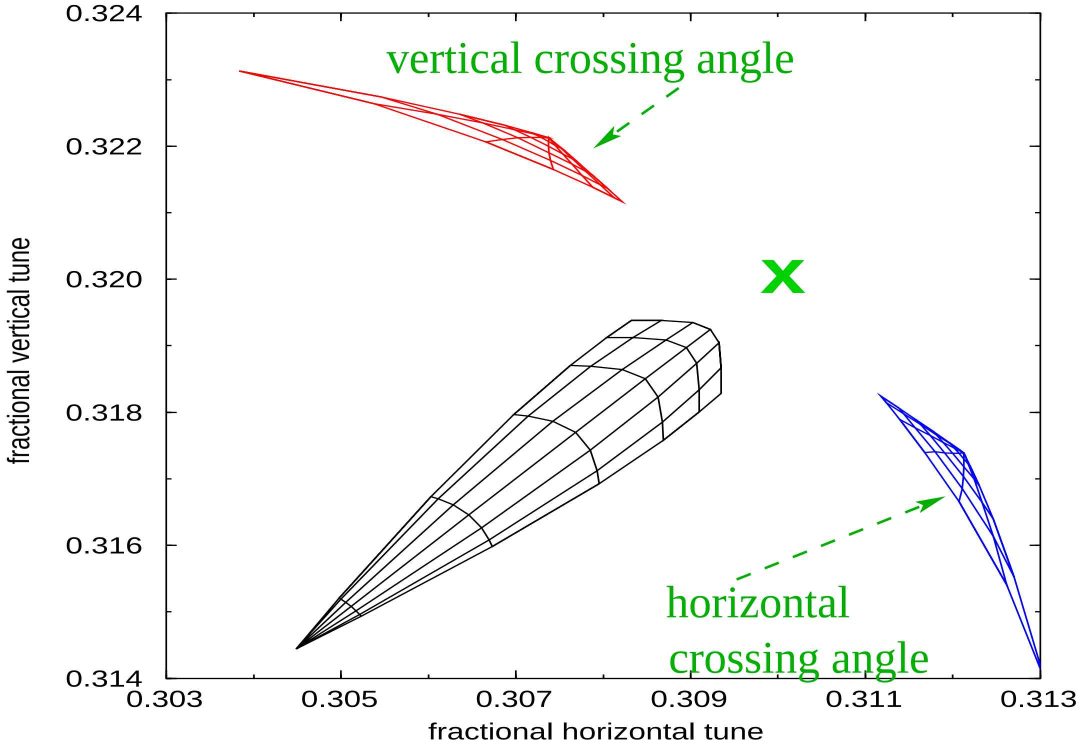
LHC collision, IP1 and IP5 only

head-on and parasitic at +- 150 murad

Compensation of Long−Range Beam−Beam

- alternate crossing angle planes in IR1 and IR5:

→ partial compensation of the long range tune shift

- foot print:

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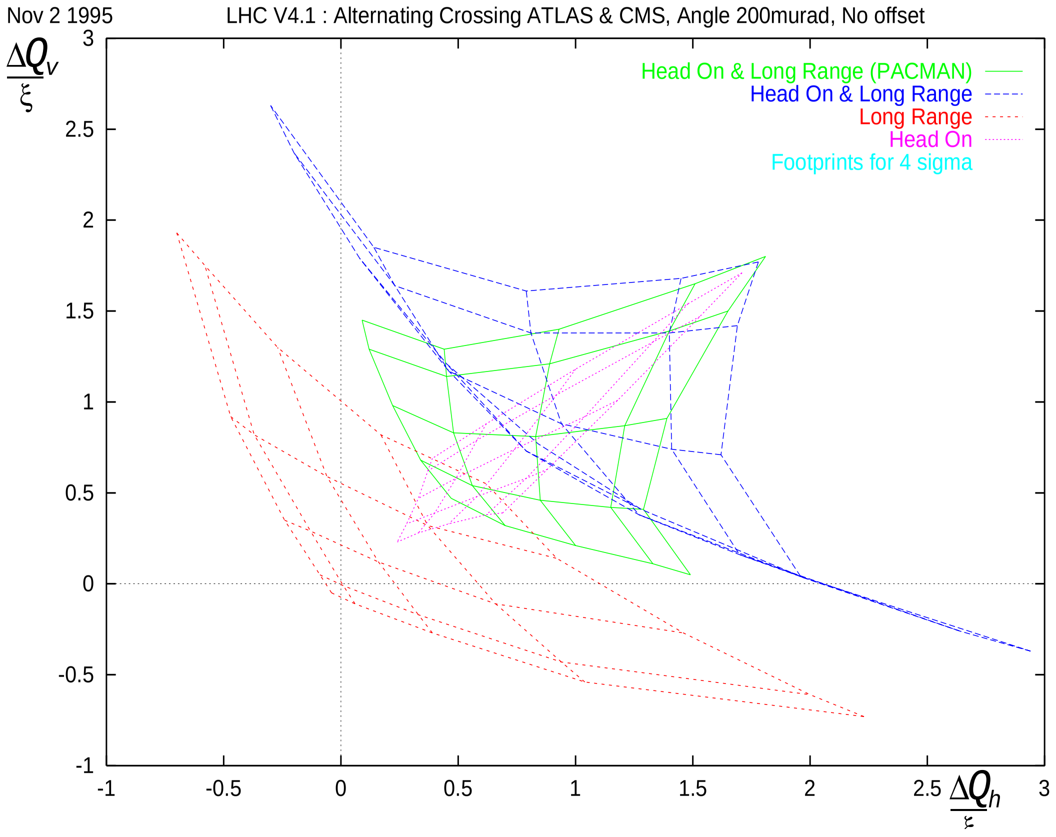

Long Range Beam−Beam Tune Shift

- LHC parameter: $n_b < 2808$ → 30 long range / insertion

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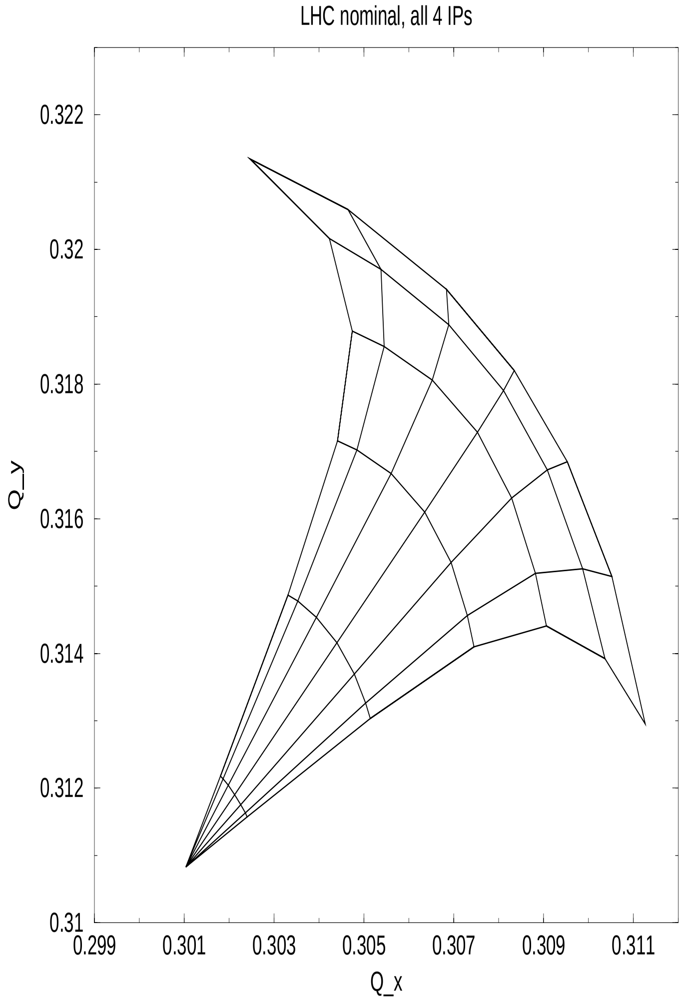


- crossing angle:

$$60 \cdot \Delta Q_{lr} < \xi_{tot}$$

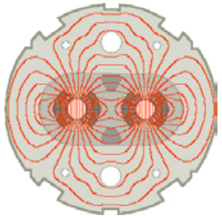
ξ_{tot} → 0.015

$$\rightarrow \quad \alpha^2 > 120 \cdot \frac{\varepsilon}{\beta^*}$$

ε → $5 \cdot 10^{-10}$ m

β^* → 0.5 m

→ $\boxed{\alpha > 340\ \mu\text{rad}}$



Separate Triplet Magnets

beam separation and crossing angle:

- horizontal crossing angle can be generated via D1 and D2
  - → no additional beam offset inside the triplet magnets
- vertical crossing angle requires additional corrector elements
  - → no amplification from triplet quadrupoles!
  - → requires strong / long corrector magnets
    - → L^* versus β inside triplet magnets
    - → beam offset inside the triplet magnets?