# The LHC Collider

- Introduction
- Challenges for the LHC:
  1) beam energy and magnet technology
  2) resonances and operation margins
  3) bunch and total beam intensity
  4) beam size and magnet technology
  5) operation efficiency & integrated luminosity
- Summary of the nominal LHC parameters
- General summary and LHC upgrade options

# Introduction: LHC Goals & Performance

- Collision energy: Higgs discovery requires $E_{CM} > 1$ TeV

p−collisions ⟶ $E_{beam} > 5$ TeV ⟶ requires strong magnetic fields

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

rare events ⟶ $L > 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ ⟶ $L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

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

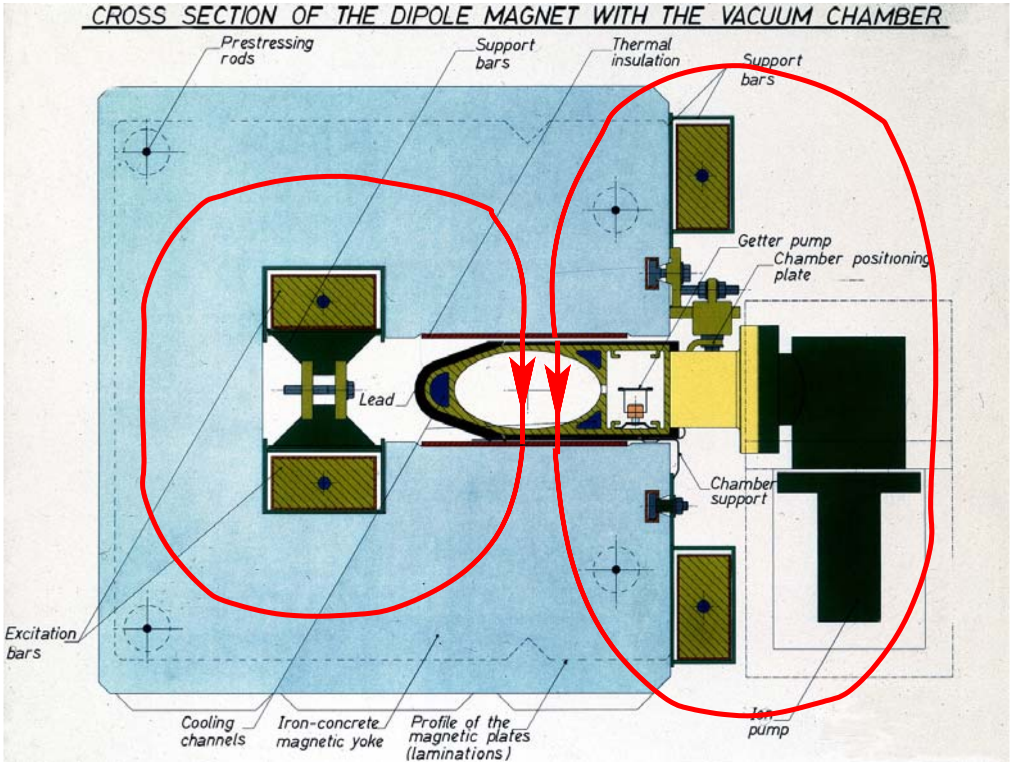
depends on the beam lifetime, the LHC cycle and

´turn around´ time and the overall accelerator efficiency

# Performance Limitations: Magnet Technology

- high beam energies require large accelerators and high magnetic fields

1) iron joke magnet design:



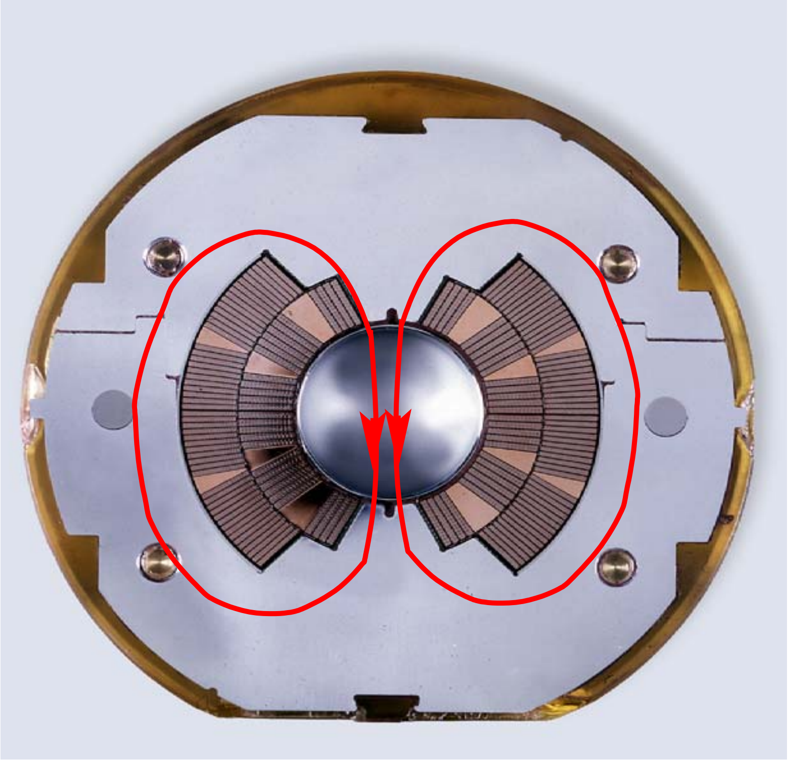
−field quality given by pole face geometry

−field amplified by Ferromagnetic material

−iron saturates at 2 T!

−Ohmic losses for high magnet currents!

2) air coil magnet design:



−field quality given by coil geometry

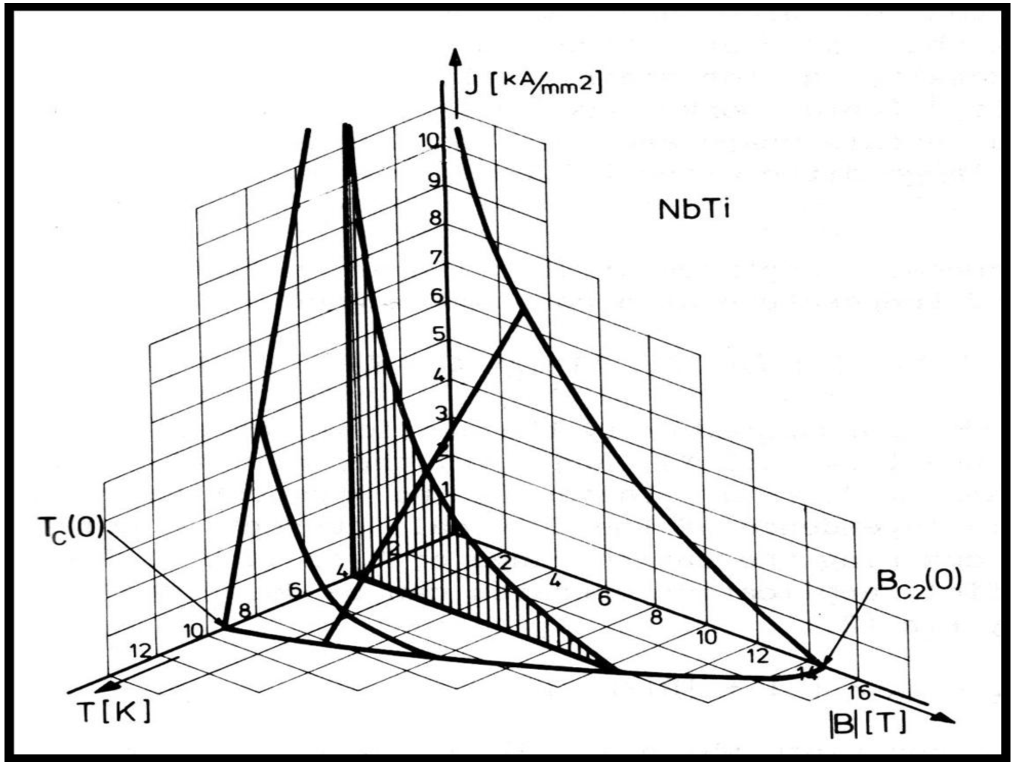
−SC technology avoids Ohmic losses

−risk of magnet quenches

−field quality changes with time!

# LHC Challenges: Magnet Technology

- critical surface of NbTi:



−high ambient magnetic field lowers the capability to sustain large current densities

−low temperatures increase the capability to sustain large current densities

−LHC parameters: B = 8.4 T
T = 1.9 K; j = 1−2 kA / mm$^2$

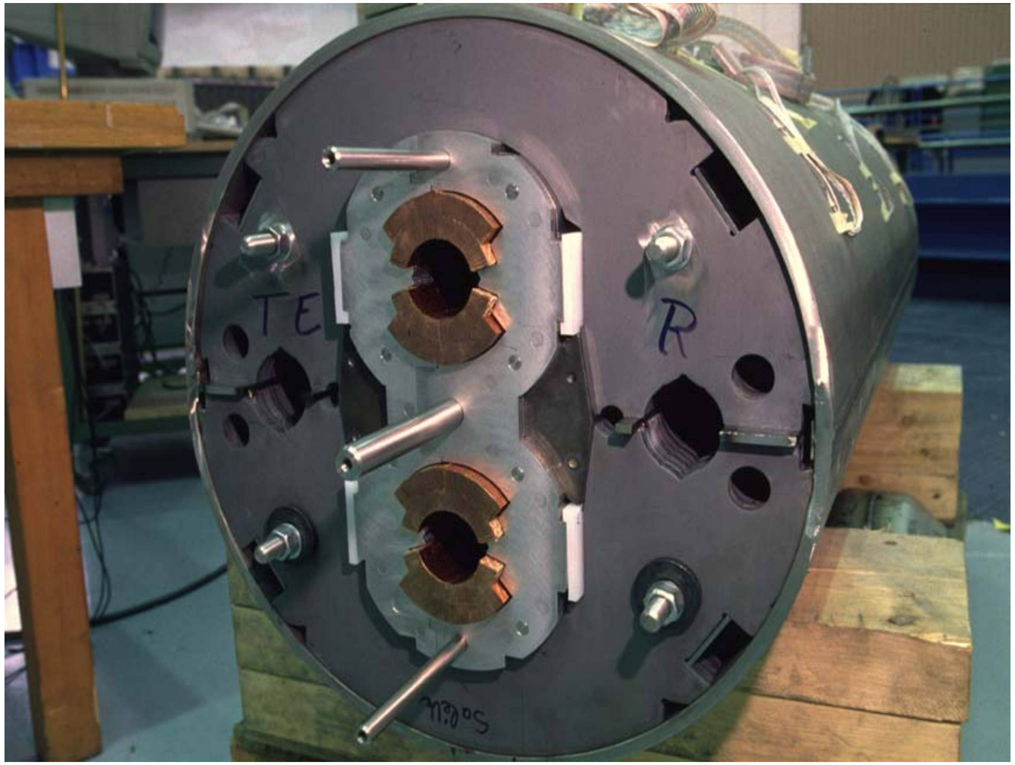
→ small margins for thermal and mechanical stress!

- existing machines: Tevatron: B = 4.5T; HERA: B = 5.5T; RHIC: B = 3.5T

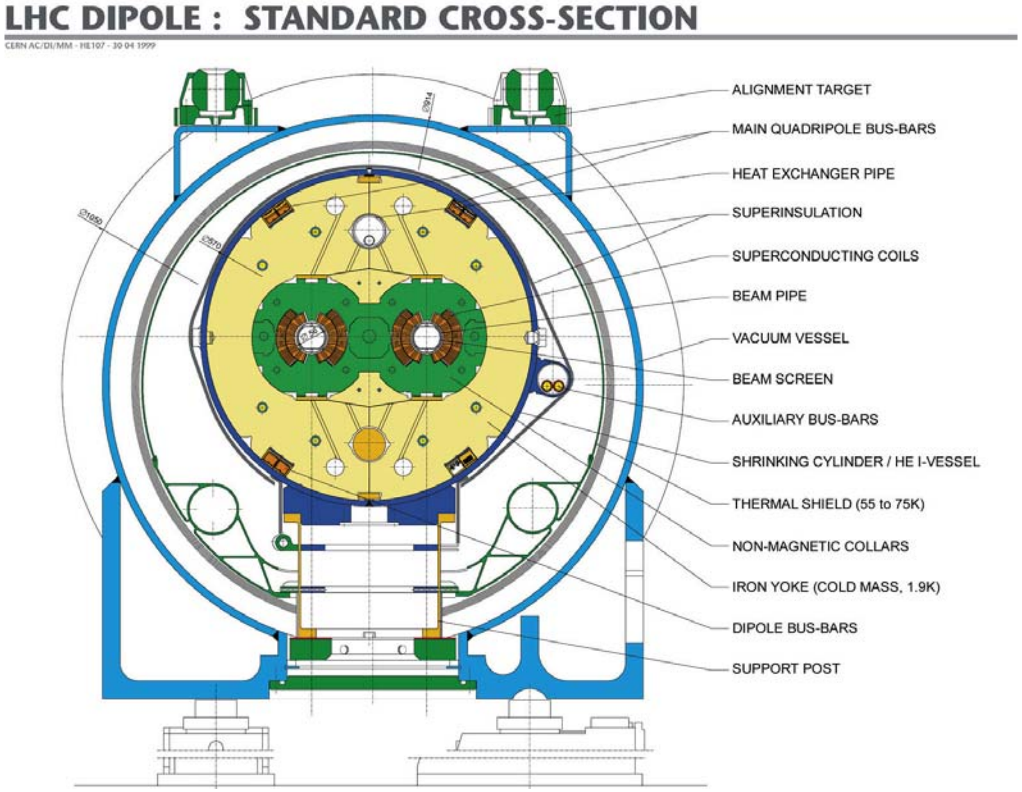
- He is super fluid below 2 K and has a large thermal conductivity!

# *LHC Challenges: Magnet Technology*

🟩 2−in−1 magnet design:



🟩 common infrastructure:



−15 m long dipole cold mass → few interconnects (high filling factor)
but difficult transport (ca. 30 tons)!

−compact 2−in−1 magnet design → allows p−p collisions in LEP tunnel

−corrector magnets at extremities → tight mechanical tolerances!

# LHC Challenges: Layout & Powering

- 2−in−1 magnet design

  ⟶ p−p and ion−ion collisions!

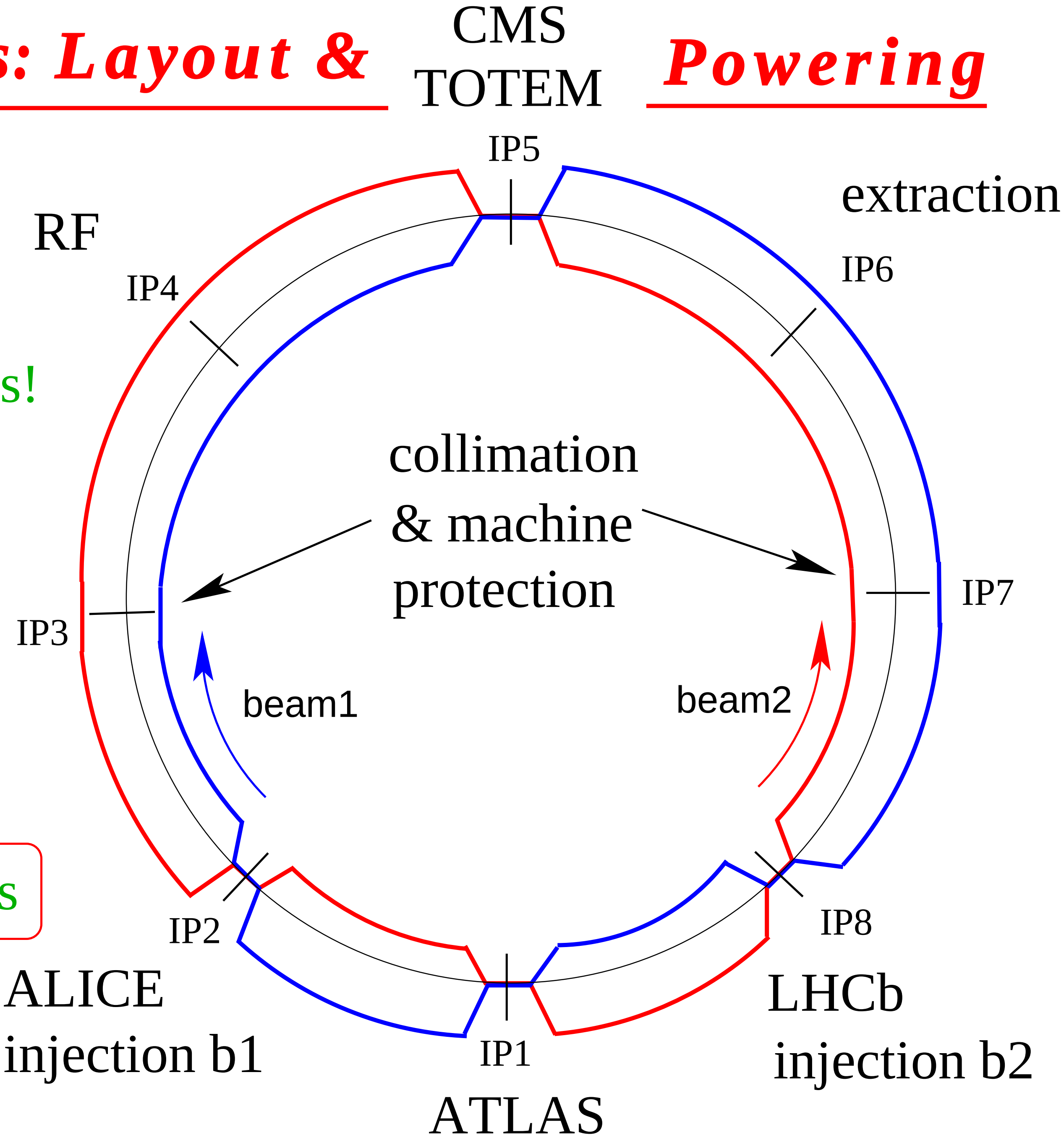
- more than 10GJ stored electromagnetic energy

  ⟶ damage potential!

  powering in 8 independent octants

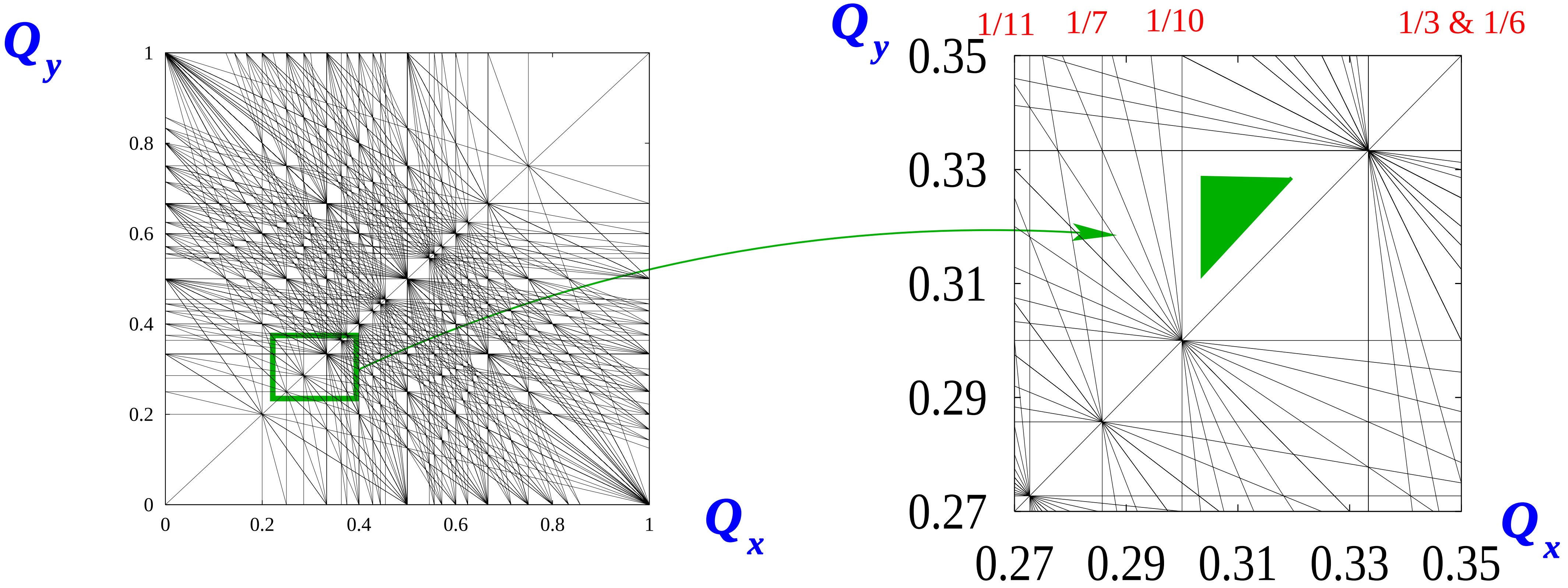
  ⟶ power converter tracking!

- injection in 2 experimental insertions



# LHC Challenges: Resonances

- tune: Q = number of transverse oscillations per revolution
- resonances: $n \cdot Q_x + m \cdot Q_y = p$ "resonance order" = n + m
- experience from SppS, HERA, Tevatron: avoid resonances with n+m <12

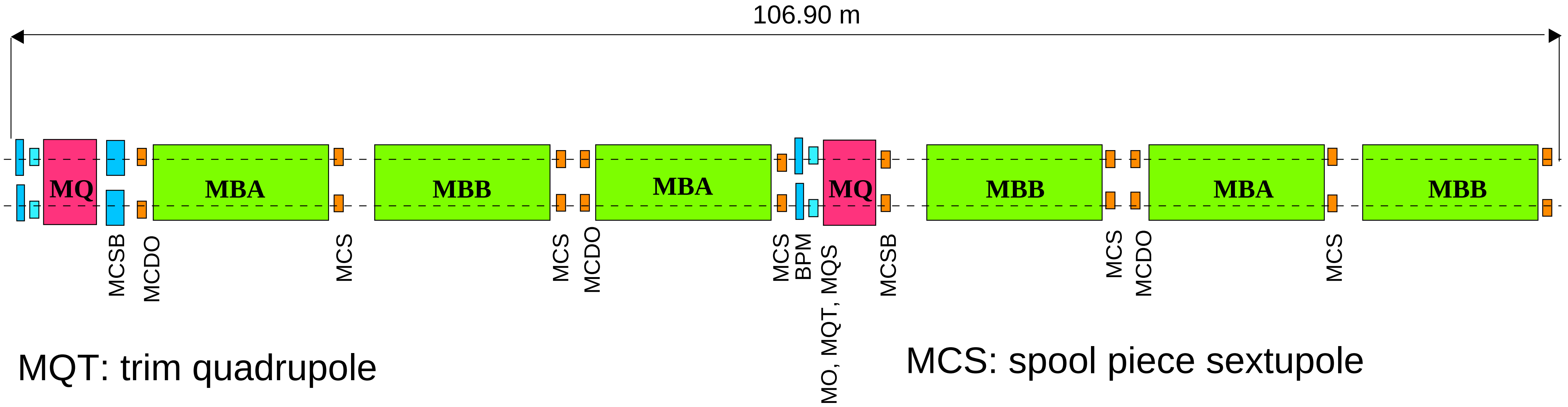


limited accessible area → limit for field quality and $\Delta Q$ tolerance

# *LHC Challenges: Errors & Operation Margins*

- a large number of circuits (2*112) need to be adjusted during operation:

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



MQT: trim quadrupole

MQS: skew trim quadrupole

MO: lattice octupole

MCSB: sextupole + orbit corrector (skew sextupole)

MCS: spool piece sextupole

MCDO: spool piece octupole + decapole

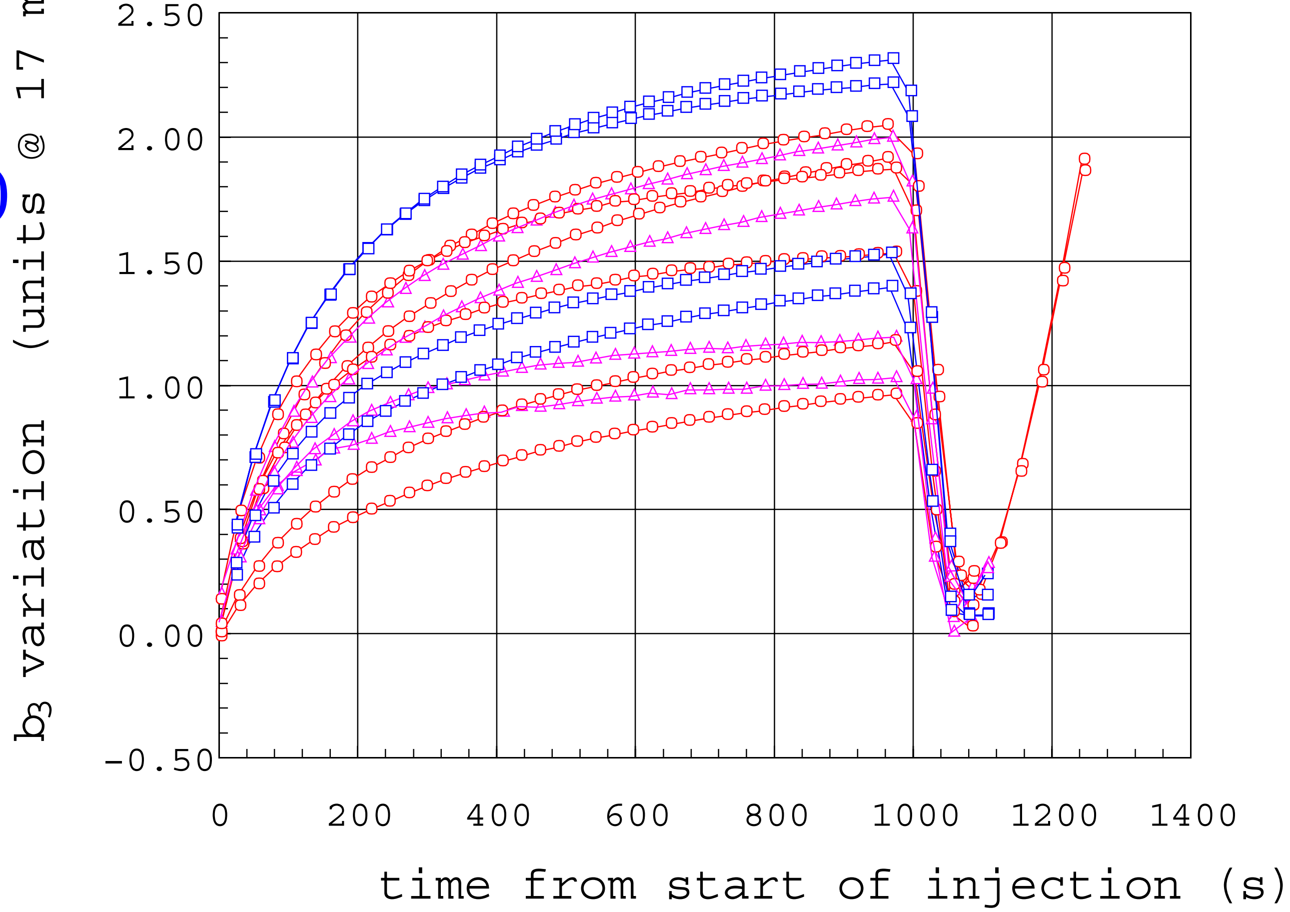
→ observables?

# *LHC Challenges: Dynamic Effects*

🟩 persistent current errors

change with time (ca. 30%)

- −decay varies from magnet to magnet
- −control spread during design and production
- −average errors depend on powering history


Courtesy of Luca Bottura

🟩 correction circuit powering must change during operation

- −operation requires correction on % level → operation procedures and Beam Instrumentation

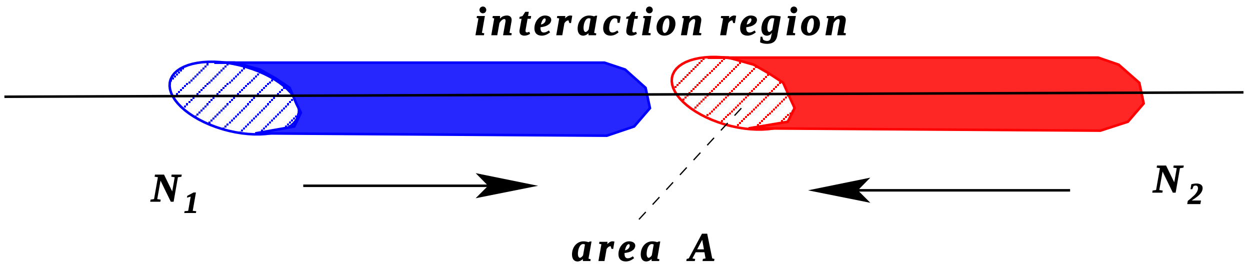
# LHC Challenges

- beam energy and magnet technology: 7 TeV at the limit of available technology (field quality!!)
- resonances and operation margins field quality, correction circuits and beam instrumentation (BI)
- bunch and total beam intensity
- beam size and magnet technology
- operation efficiency and integrated luminosity

# LHC Challenges: Instantaneous Luminosity

🟩 luminosity:

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



$A = 4\pi \bullet \sigma_x \bullet \sigma_y$ with: $\sigma = \sqrt{\beta \bullet \varepsilon}$ and:

$\beta$: is determined by the quadrupole magnet arrangement & powering

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

goal: → high bunch intensity and large number of bunches,

small $\beta$ at the IP and highest possible collision energy

$$\boxed{L = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}}$$

# LHC Challenges: Beam−Beam Interaction

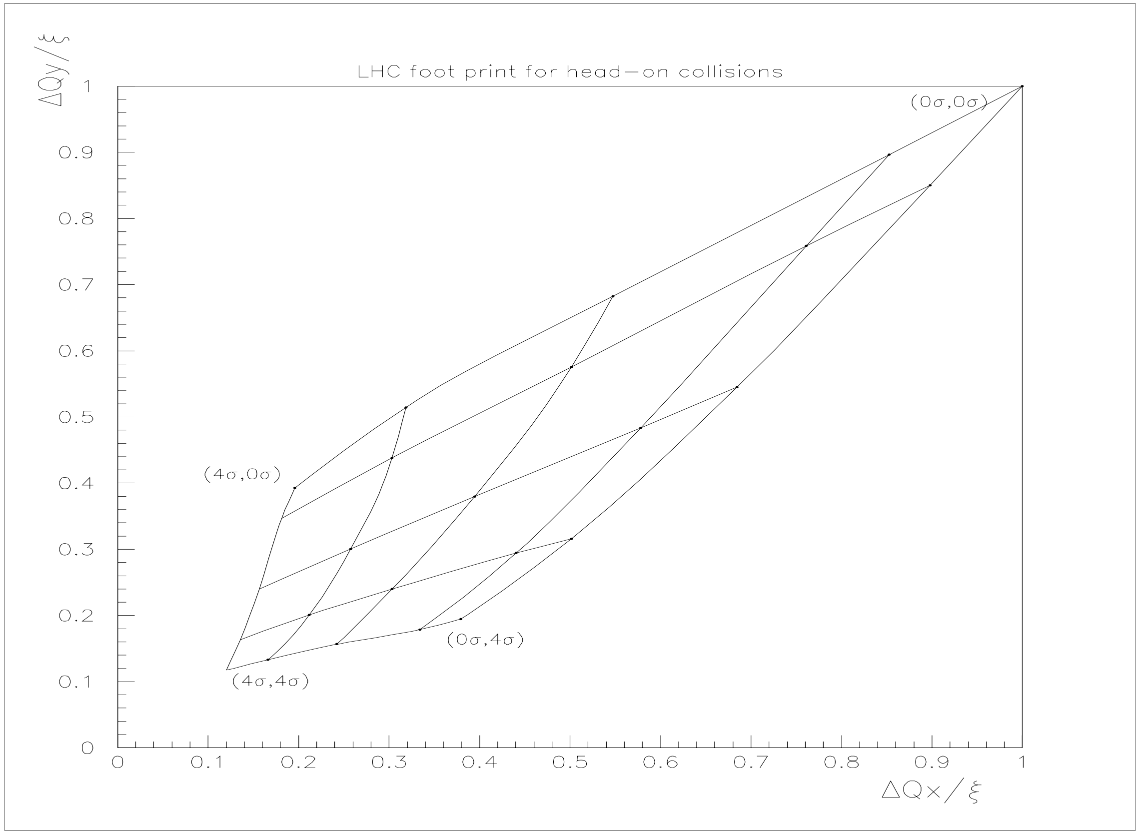
- tune spread due to beam−beam interaction:

independent from $\beta^*$ $\sigma^2 = \varepsilon \cdot \beta$

$$\Delta Q = \frac{N_2 \cdot r_p}{4\pi \cdot \gamma \cdot \varepsilon} \boxed{= \xi_{\text{beam−beam}}}$$

- foot print: →

particle tune
depends on
particle
amplitude

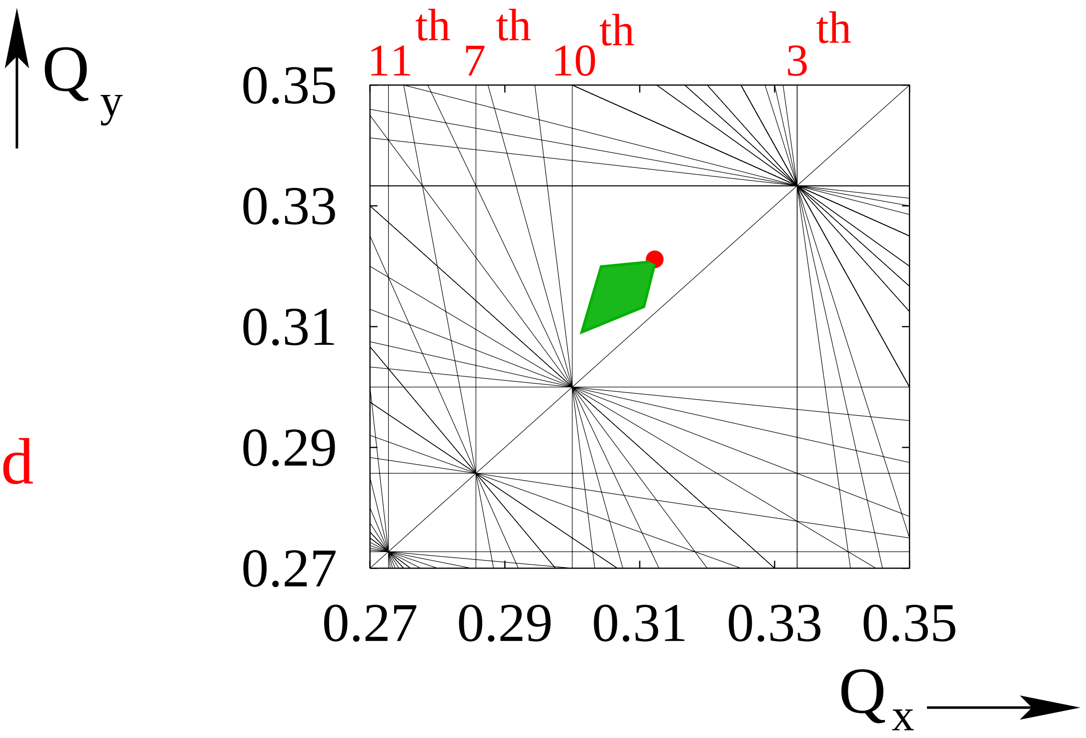


# LHC Challenges: Beam−Beam Interaction

- LHC working point: $n + m < 12$

$$Q_x = 64.31; \quad Q_y = 59.32$$

→ total beam−beam tune spread must be smaller than 0.015!



- the LHC features 3 proton experiments with:

head on collisions: → $\boxed{\xi < 0.005}$

- LHC magnet aperture and β −function in the arc: $(\sigma = \sqrt{\varepsilon\,\beta})$

→ $\varepsilon < 5 \cdot 10^{-10}$ m → $\boxed{N < 1.5 \cdot 10^{11}}$

LHC nominal: $N = 1.1 \cdot 10^{11}$

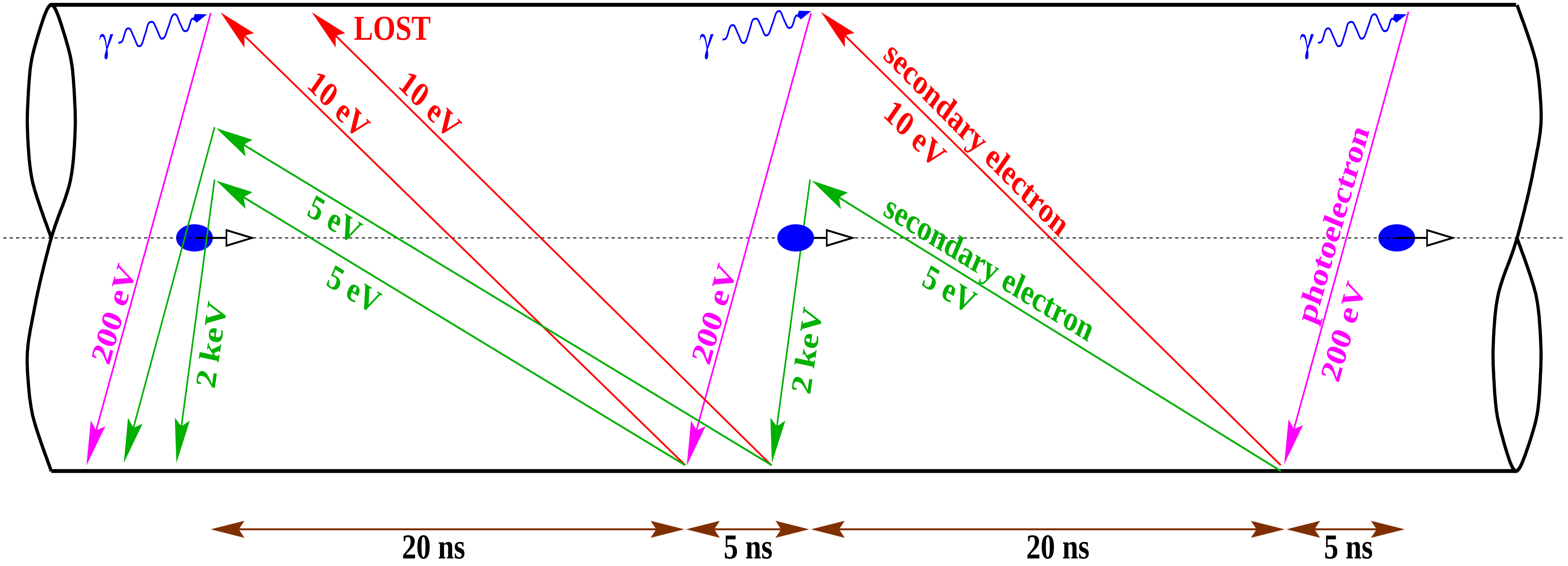
LHC ultimate: $N = 1.7 \cdot 10^{11}$

# *LHC Challenges: Beam Intensity*

- beam−beam effects and aperture: $\varepsilon_n < 3.75 \cdot 10^{-6}$ m $N < 1.5 \cdot 10^{11}$
- heat load due to electron cloud bombardment on the beam screen
- impedance and collective instabilities
- radiation issues and damage potential

# LHC Challenges: Electron Cloud

- synchrotron light removes electrons from chamber wall
- electrons are accelerated by the beam
- electrons hit vacuum chamber and generate more electrons
- electron cloud → instability and heat losses at cryogenic temperatures!



# *Heat Load Due to Electron Cloud*

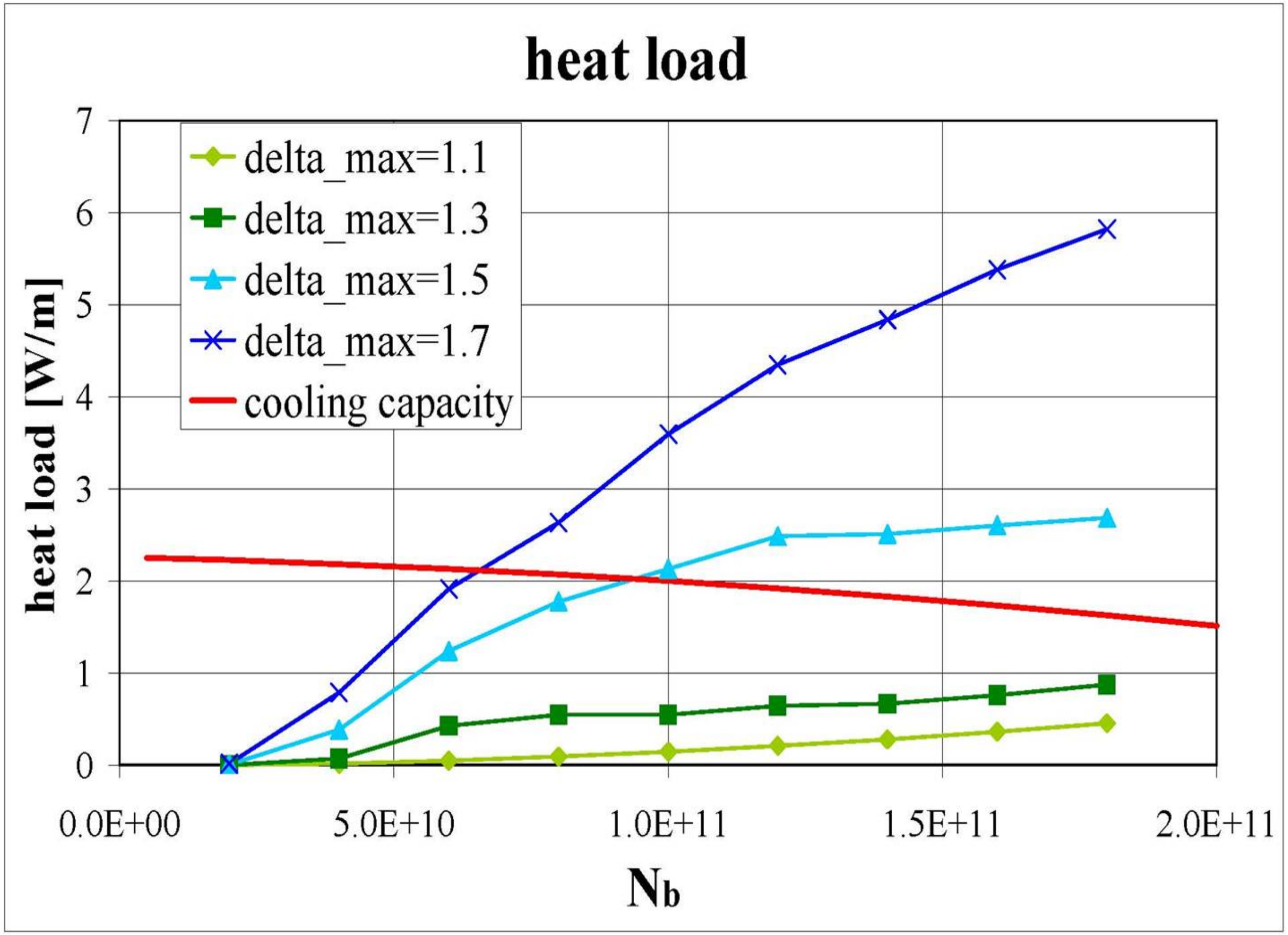
F. Zimmermann: preliminary data for 25ns bunch spacing

🟩 heat load on the beam screen

→ increases for small bunch spacing!

25 ns is OK for well conditioned surfaces!

12.5 ns bunch spacing at the limit of electron cloud induced heat load!



→ final conclusion on 12.5 ns operation is only possible after LHC startup

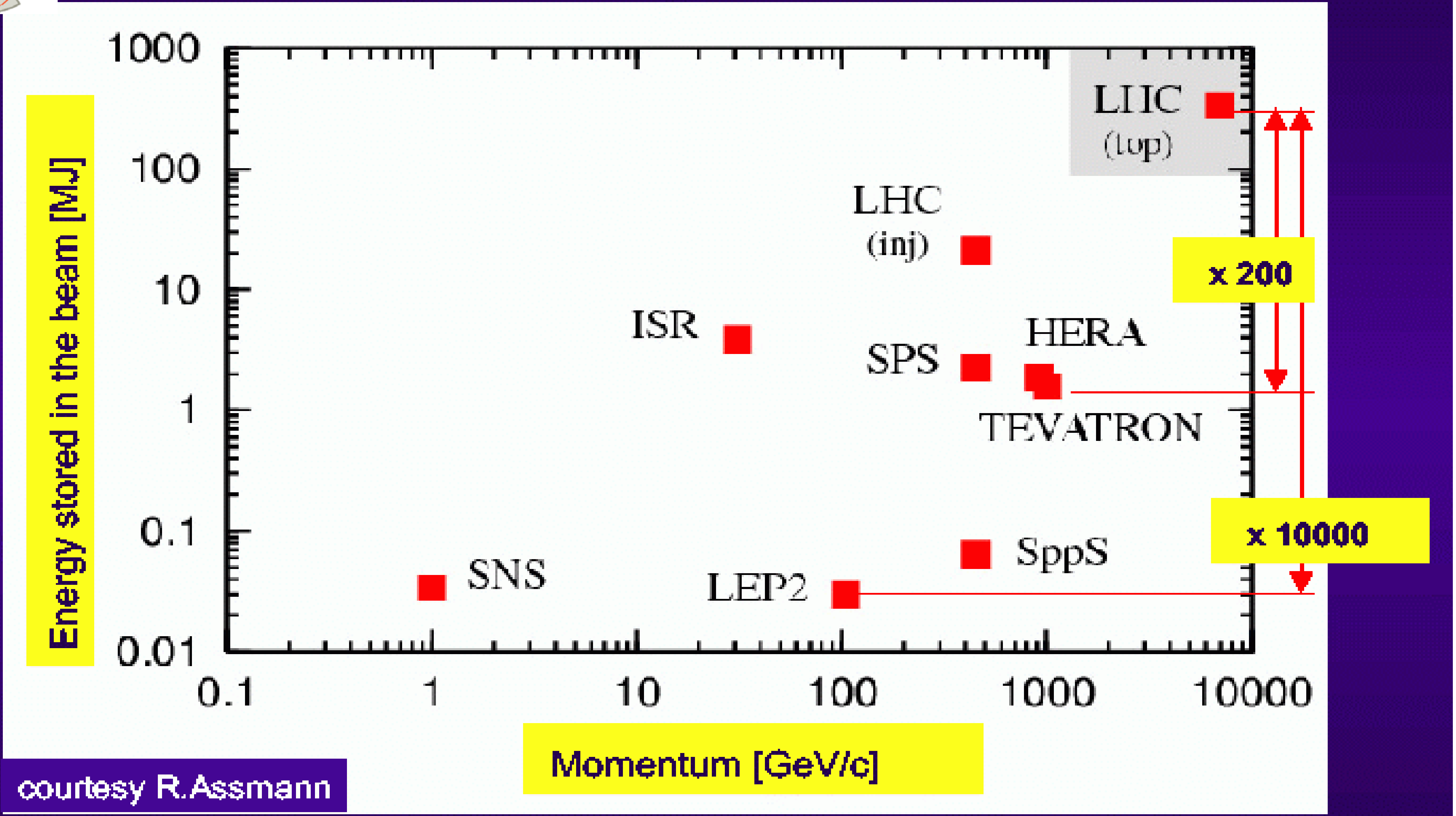
# *LHC Challenges: Beam Intensity*

- beam−beam effects and aperture: $\varepsilon_n < 3.75 \cdot 10^{-6}$ m $N < 1.5 \cdot 10^{11}$
- heat load due to electron cloud bombardment on the beam screen

  electron cloud limits the bunch spacing:

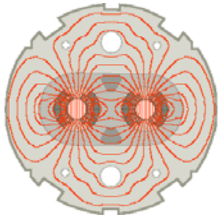
  25 ns (−> 2808 bunches) for nominal beam parameters
- radiation issues and damage potential
- impedance and collective instabilities

# Challenges: Energy stored in the beam



courtesy R.Assmann

Transverse energy density: even a factor of 1000 larger



# LHC Challenges: Total Intensity

- Magnet Quench:

  → beam abort

  → several hours of recovery

- LHC nominal beam intensity:

$$\boldsymbol{I = 0.5\ A} \longrightarrow \boldsymbol{3 \cdot 10^{14}\ p/beam} \quad (E = 370\ MJ)$$

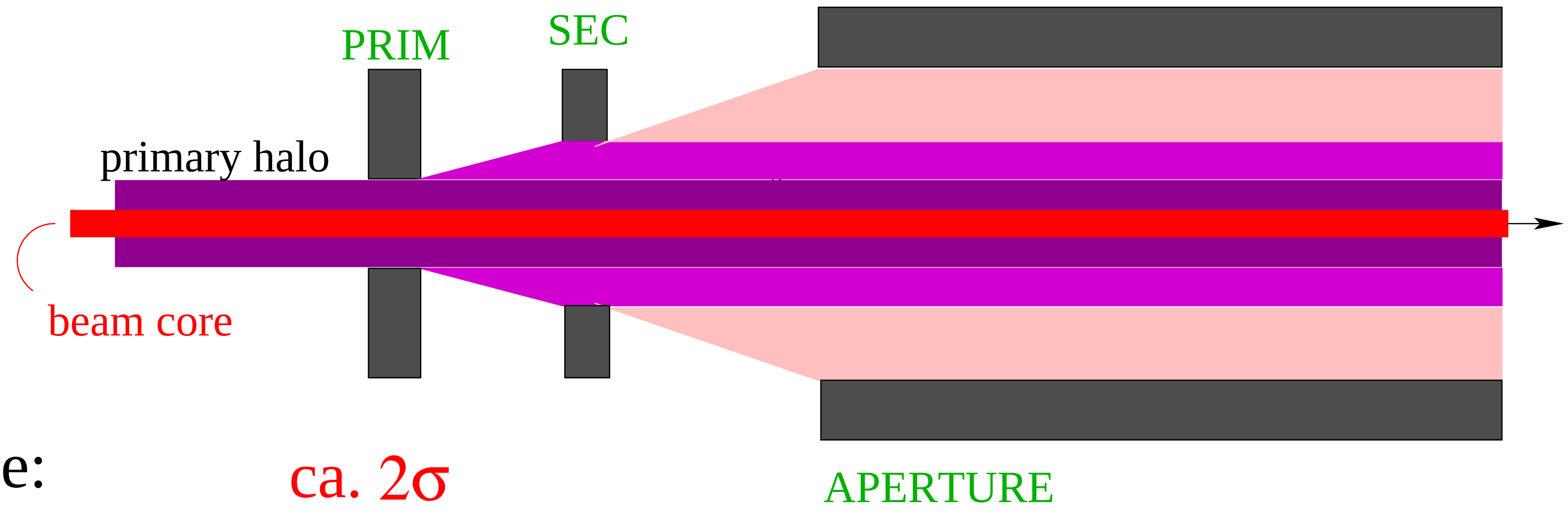
- Quench level:

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

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

→ remove stray particles and maximize aperture

# Collimation & Machine Protection



- beam core: ca. $2\sigma$
- 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
- required collimator gap opening depends on mechanical aperture margins!

# *LHC Challenges: Equipment Damage*

- quench level and collimator efficiency

  avoid beam losses! −> 370 MJ per beam (1 MJ melts 2 kg Cu)

  first storage ring with collimation during all operation stages!

  operation efficiency and beam loss induced beam aborts / damage!

several hours of operation stop for each beam induced abort!

# *LHC Challenges: Radiation & Damage*

- LHC beam dump and machine protection devices:

designed only up to ultimate beam intensity

- radiation dose in the cleaning insertions and the experiments is just compatible with nominal intensities

higher than nominal beam intensities require more studies / optimizations

# LHC Challenges: Beam Intensity

- beam−beam effects and aperture: $\varepsilon_n < 3.75 \cdot 10^{-6}$ m $N < 1.5 \cdot 10^{11}$
- heat load due to electron cloud bombardment on the beam screen

  25 ns bunch spacing −> 2808 bunches per beam
- radiation issues and damage potential

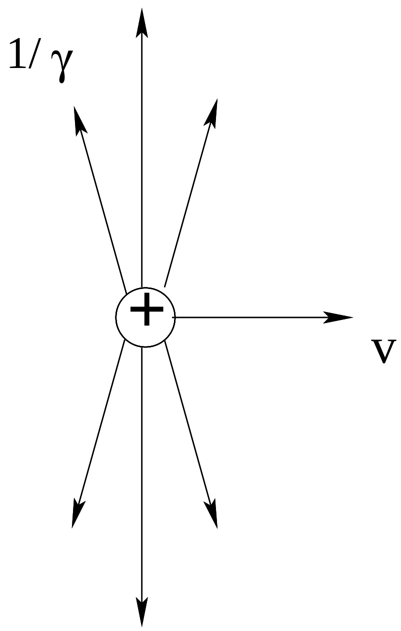
  370 MJ stored energy per beam (1 MJ melts 2 kg Cu)

  first storage ring with collimation during all operation stages!

  particle losses generate radiation in the storage ring
- impedance and collective instabilities

# Performance Limitations: Beam Instability

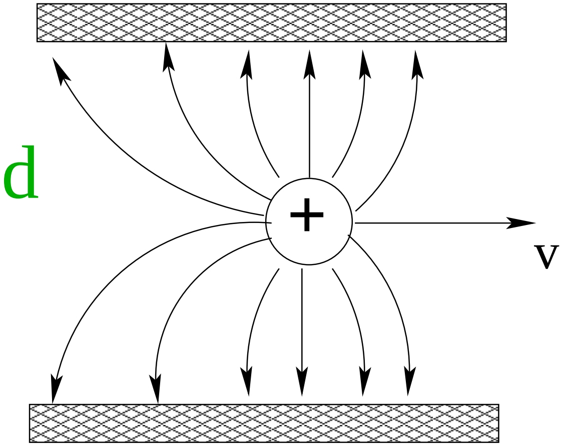
- electro−magnetic field of a moving charge:



E−Field compressed by $1/\gamma$

- image charge currents on vacuum chamber wall:

wake field
trailing
behind



field lines of image charges act back on on the bunch distribution

→ mechanism for beam instability

→ effect becomes stronger for small openings and low conductivity!

# *LHC Challenges: Beam Instabilities*

- 2 phase collimation system for the LHC:

  - Phase 1: optimized for robustness against failure scenarios

    → graphite collimator jaws –> robust against beam loss

    → bad conductivity –> large wake fields

  → beam stability imposes limits for the beam intensity and beam size

  - Phase 2: optimized for small wake fields

    → Cu collimator jaws –> can be damaged by beam impact

    → good conductivity –> small wake fields

  → procedure for operating the two systems still needs to be specified!

# *LHC Challenges: Beam Intensity*

- beam−beam effects and aperture: $\varepsilon_n < 3.75 \cdot 10^{-6}$ m $N < 1.5 \cdot 10^{11}$

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

  25 ns bunch spacing −> 2808 bunches per beam

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  370 MJ stored energy per beam (1 MJ melts 2 kg Cu)

  first storage ring with collimation during all operation stages!

  particle losses generate radiation in the storage ring

- impedance and collective instabilities

  Phase I: $I_{beam} < 0.3$ A Phase II: $I_{beam} < 0.85$ A

# *LHC Challenges*

| | | |
|---|---|---|
| 🟩 | beam energy and magnet technology: | 7 TeV at the limit of available technology (field quality!!) |
| 🟩 | resonances and operation margins | field quality, corrector circuits and beam instrumentation (BI) |
| 🟩 | bunch and total beam intensity | $N < 1.7\cdot 10^{11}$ ; $n = 2808$;<br>$\varepsilon_n < 3.75\mu\,m$; $I < 0.85$ A |
| 🟩 | beam size and magnet technology | |
| 🟩 | operation efficiency and integrated luminosity | |

# LHC Challenges: Beam Size

- beam size in the triplet magnets: $\beta(s) = \beta^{*} + \dfrac{s^{2}}{\beta^{*}}$

limit: → quadrupole aperture $(\sigma = \sqrt{\varepsilon\,\beta})$

→ 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 → $\sigma(\text{triplet}) = 1.54$ mm

- beam size in the triplet magnets: → collimator impedance

# LHC Challenges

| | |
|---|---|
| 🟩 beam energy and magnet technology: | 7 TeV at the limit of available technology (field quality!!) |
| 🟩 resonances and operation margins | field quality, corrector circuits and beam instrumentation (BI) |
| 🟩 bunch and total beam intensity | $N < 1.7 \cdot 10^{11}$ ; $n = 2808$;<br>$\varepsilon_n < 3.75 \mu m$; $I < 0.85$ A |
| 🟩 beam size and magnet technology | $0.55\,\mathrm{m} < \beta^* < 1\,\mathrm{m}$ |
| 🟩 operation efficiency and integrated luminosity | |

# LHC Challenges: Integrated Luminosity

🟩 integrated luminosity:

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

→ maximum performance requires minimum turnaround times

→ minimize the number of quenches and beam aborts

→ limit for beam energy density

(see ´total intensity limitations´)

# Initial Design Parameters

| parameter \ value | ´white book´ | DIR−TECH/84−01 & ECFA 84/85 CERN 84−10; 1984<br>maintain margins for total intensity and aperture |
|---|---|---|
| # bunches | 3564 | (slightly too large due to non realistic kicker rise times) |
| N / bunch | $0.34*10^{11}$ | margins for beam−beam effects |
| $\beta^*$ | 1.0 m | margins for aperture and impedance |
| $\varepsilon_n$ | $1.07 \mu$ m | factor 3 margin for $N_{bunch} / \varepsilon_n$ (injector chain+op) |
| $\sigma^*$ | $12 \mu$ m | |
| $\sigma_L$ | 7.55cm | |
| full crossing angle | $100 \mu$ rad | margins for triplet aperture |
| events per crossing | 1 <−> 4 | |
| peak luminosity | $0.1*10^{34}$ $cm^{-2} sec^{-1}$ | |
| luminosity lifetime | 56 h | allows long physics runs −> efficiency! |
| E[TeV] | 8.14 | 10 T magnetic field compared to 8.4 T |
| E [MJ] | 121 | factor 70 compared to existing SC machines(20 to ISR) |

# Nominal Parameters

| parameter \ value | nominal | competition with SSC |
|---|---|---|
| # bunches | 2808 | |
| N / bunch | $1.15 * 10^{11}$ | factor 3 smaller margin for beam−beam effects |
| $\beta^*$ | 0.55 m | reduced margin for aperture and impedance |
| $\epsilon_n$ | $3.75 \mu m$ | |
| $\sigma^*$ | $16 \mu m$ | |
| $\sigma_L$ | 7.55cm | |
| full crossing angle | $285 \mu rad$ | aperture margin reduced by factor 3 |
| events per crossing | 19.2 | |
| peak luminosity | $1.0 * 10^{34}$ $cm^{-2} sec^{-1}$ | |
| luminosity lifetime | 15 h | |
| E[TeV] | 7 | |
| E [MJ] | 366 | quench and damage potential (factor 200!) |

# Summary

- the nominal LHC operation is very challenging!!!
  - → LHC upgrade studies could provide means to overcome operational limitations for the nominal performance
  - → R&D results should therefore 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

# Options for Future High Luminosity Upgrades for the LHC

- CERN 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

(existing injector complex at CERN is only compatible with nominal beam parameters)

# *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

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

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

- decrease $\beta^*$ 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 operation margins left |
|---|---|---|---|
| # bunches | 2808 | 2808 | limit os cryogenic system? |
| N / bunch | $1.15*10^{11}$ | $1.70*10^{11}$ | |
| $\beta^*$ | 0.55 m | 0.5 m | |
| $\varepsilon_n$ | 3.75 $\mu$ m | 3.75 $\mu$ m | |
| $\sigma^*$ | 16.7 $\mu$ m | 16 $\mu$ m | |
| $\sigma_L$ | 7.55cm | 7.55cm | |
| full crossing angle | 285 $\mu$ rad | 315 $\mu$ rad | |
| events per crossing | 19.2 | 44.2 | detector limit? |
| peak luminosity | $1.0*10^{34}$ $cm^{-2}sec^{-1}$ | $2.4*10^{34}$ $cm^{-2}sec^{-1}$ | |
| luminosity lifetime | 15 h | 10 h | run length and efficiency? |
| E[TeV] | 7 | 7 –> 7.45 | –> L = $2.6*10^{34}$ $cm^{-2}sec^{-1}$ |
| E [MJ] | 366 | 541 | damage potential/efficiency? |

# *Luminosity Upgrade Phase 1*

- modify insertion layout for $\beta^* = 0.25\,\mathrm{m}$ (lifetime for triplet = 700 $\mathrm{fb}^{-1}$)
  - increased beam size in triplet magnets
  - requires increased beam separation

  → larger triplet aperture

  magnet technology!

  - 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: (compatibility with e−cloud heat load?)
- increase the machine energy to 'ultimate' dipole field settings $E = 7.54$ TeV

# IR Upgrade Parameters

| parameter \ value | nominal | phase 0 | phase 1 | |
|---|---|---|---|---|
| # bunches | 2808 | 2808 | 5616 | |
| N / bunch | $1.15*10^{11}$ | $1.70*10^{11}$ | $1.70*10^{11}$ | |
| $\beta^*$ | 0.55 m | 0.5 m | 0.25 m | |
| $\varepsilon_n$ | 3.75 $\mu$ m | 3.75 $\mu$ m | 3.75 $\mu$ m | |
| $\sigma^*$ | 16.7 $\mu$ m | 16 $\mu$ m | 11.3 $\mu$ m | |
| $\sigma_L$ | 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 injection energy into the LHC: $\sigma = \sqrt{\beta \, \varepsilon_n / \gamma}$

  → increased aperture and bunch intensity with constant (beam−beam)

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

  −install a compact booster ring in the LHC tunnel

- install new dipole fields with 15 T in the LHC target(energy & aperture)

  → beam energy of 12.5 TeV (synchrotron radiation!)

- 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