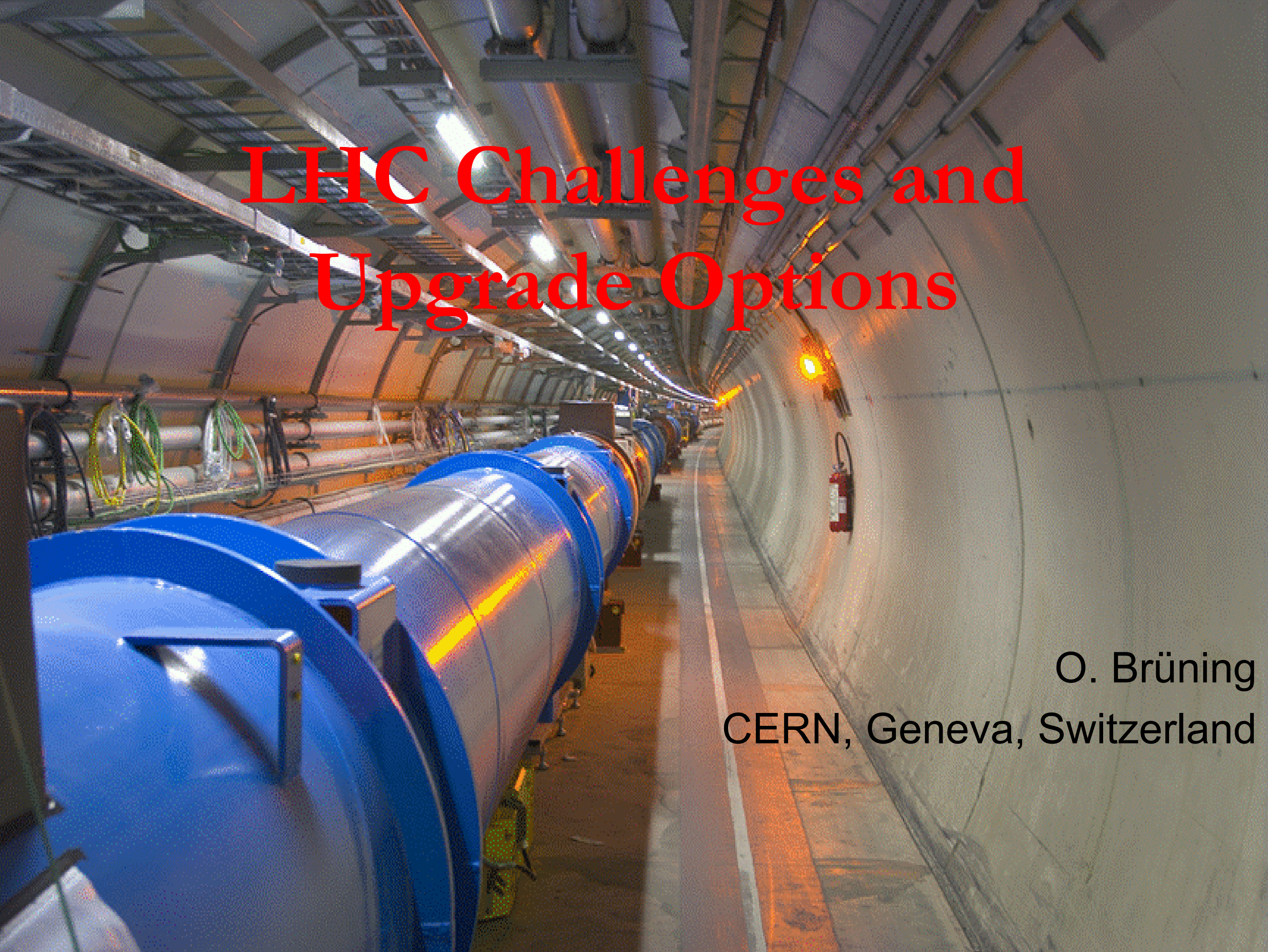

LHC Challenges and Upgrade Options

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Contents

Introduction: LHC Goals & Performance

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

  p collisions → $E_{beam} > 5$ TeV → LHC: E = 7 TeV

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

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

- Integrated luminosity: $\mathrm{L} = \int L(t)dt$

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

Introduction: the LHC is a Synchrotron

- uniform B field: R = constant

$$p = q \cdot \frac{B \cdot circ}{2\pi} \approx E / c$$

for E >> E_0

- realistic synchrotron: B-field is not uniform

-drift space for installation
-different types of magnets
-space for experiments etc

$$E = \frac{q \cdot c}{2\pi} \cdot \oint B \cdot ds$$

→ high beam energies require: -high magnetic bending field
-large circumference
-large packing factor

Introduction: the LHC is a Synchrotron

- physics goal: E = 7 TeV

- existing infrastructure: LEP tunnel: circ = 27 km
  with 22 km arcs

- assume 80% of arcs can be filled with dipole magnets: F = 0.8

- required dipole field for the LHC:

$$\frac{2\pi}{q} \cdot \frac{E / c}{circ \cdot F} = B$$

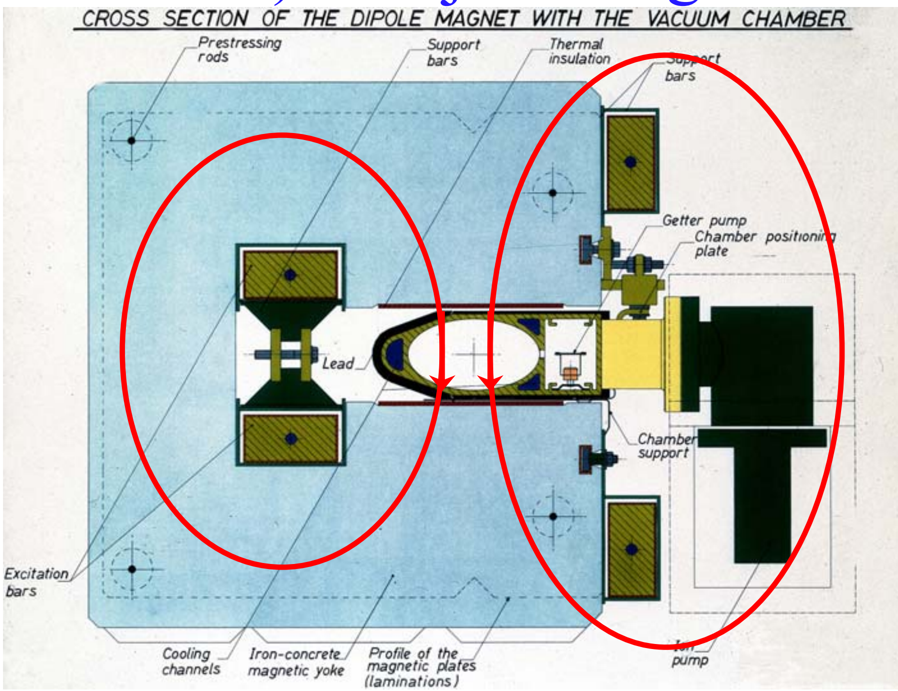
➔ B = 8.38 T

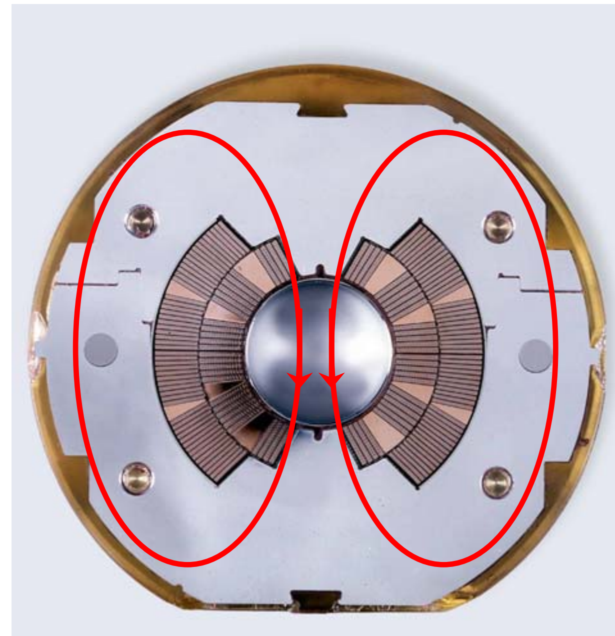
(earth: 0.3 10^{-4} T)

Magnet Technology

- high beam energies require large rings and high fields

1) Iron joke magnet design   2) air coil magnetdesign



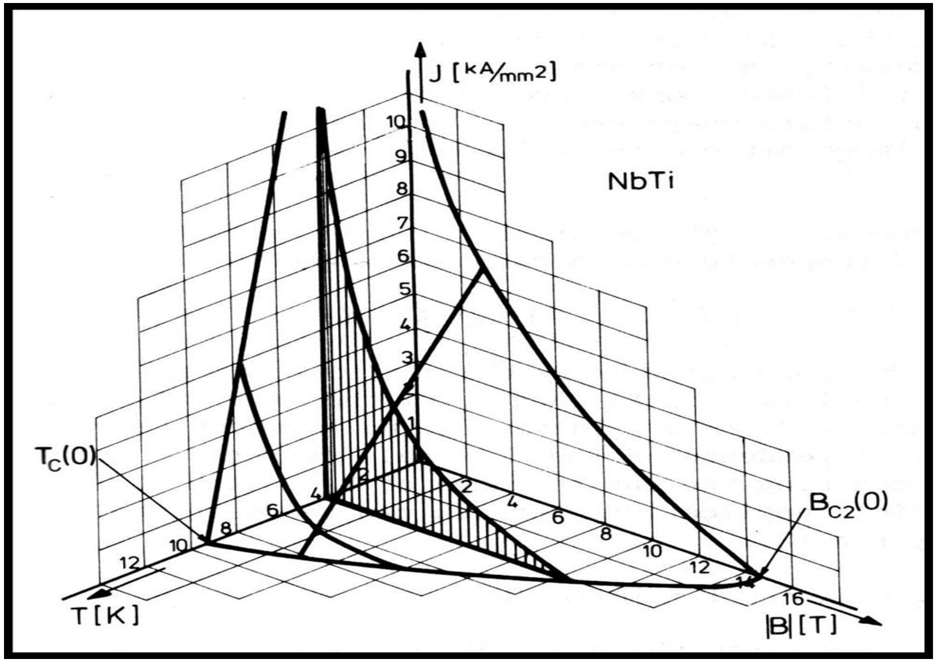


-field quality given by pole face geometry
-field amplified by Ferromagnetic material
-iron saturates at 2 T
-Ohmic losses for high magnet currents

-field quality given by coil geometry
-SC technology avoids Ohmic losses
-risk of magnet quenches
-field quality changes with time

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

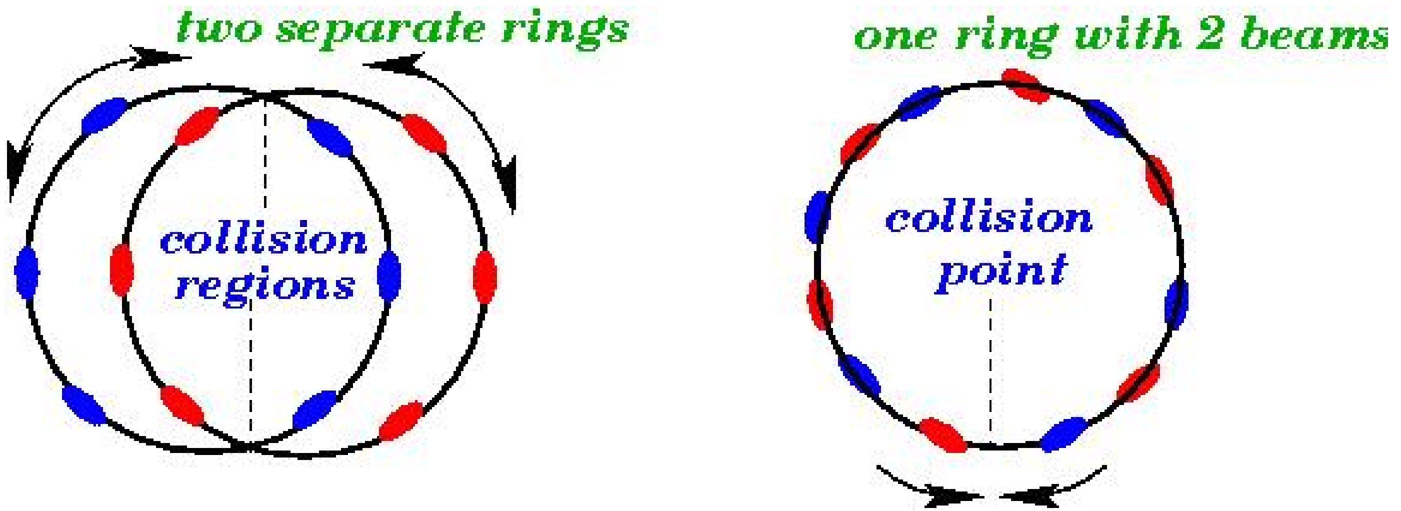
-LHC: B = 8.4 T; T = 1.9 K
j = 1 - 2 kA / mm^2

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

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

Magnet Technology

- collider ring design requires 2 beams:



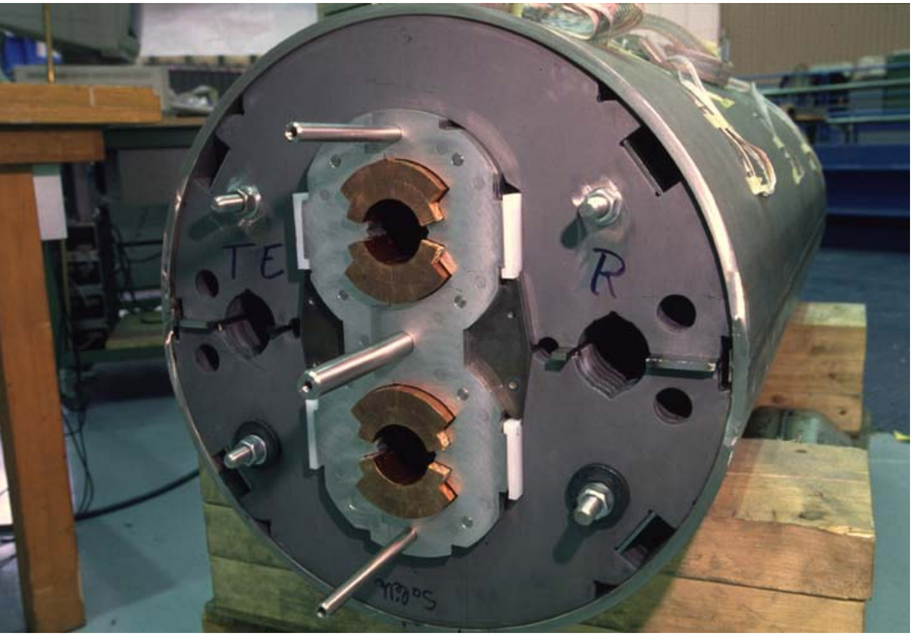
- design with one aperture requires particles & anti-particles
  Not efficient for a hadron collider! (Tevatron, Chicago USA)

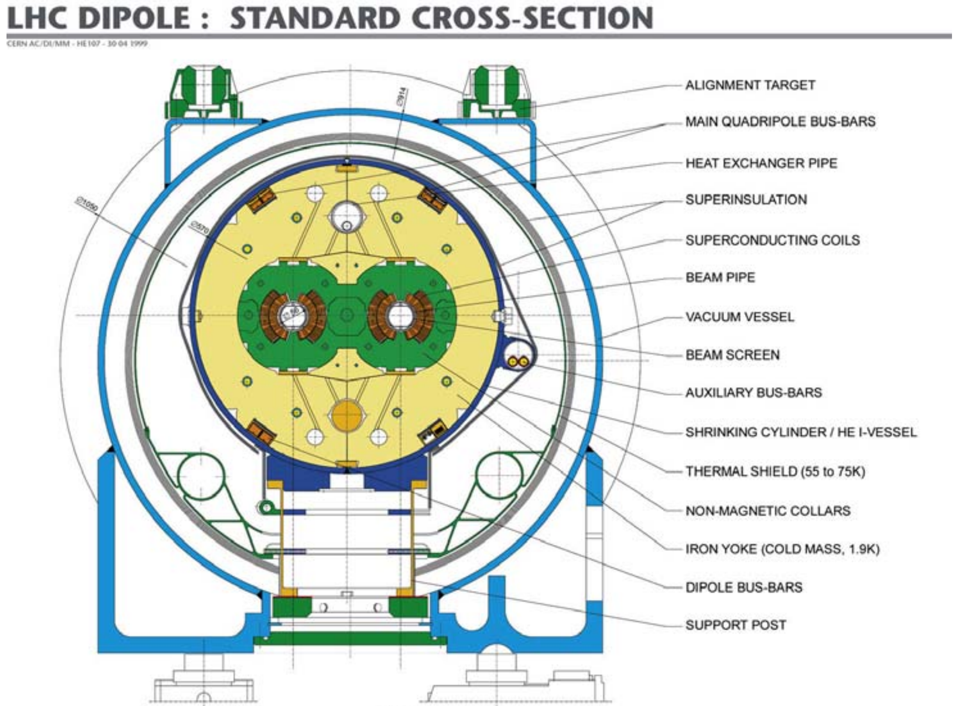
- 2-ring design implies twice the hardware

  → LHC features novel 2-in-1 magnet design

Magnet Technology

- 2-in-1 dipole magnet design with common infrastructure:





-15 m long → few interconnects (high filling factor)
but difficult transport (ca. 30 tons)

-compact 2-in-1 design → allows p-p collisions in LEP tunnel

-corrector magnets at ends → tight mechanical tolerances

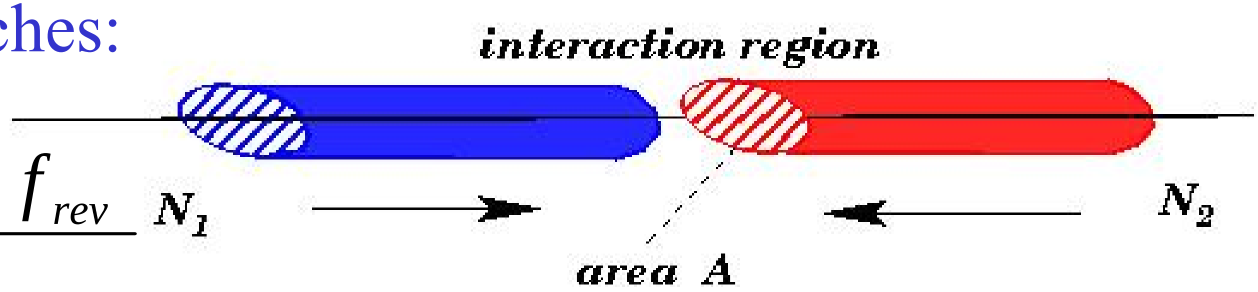
Magnet Technology

- 15 m long, 30 Ton
  difficult transport &
  tight tolerances

Luminosity

colliding bunches:

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



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

β is determined by the magnet arrangement & powering

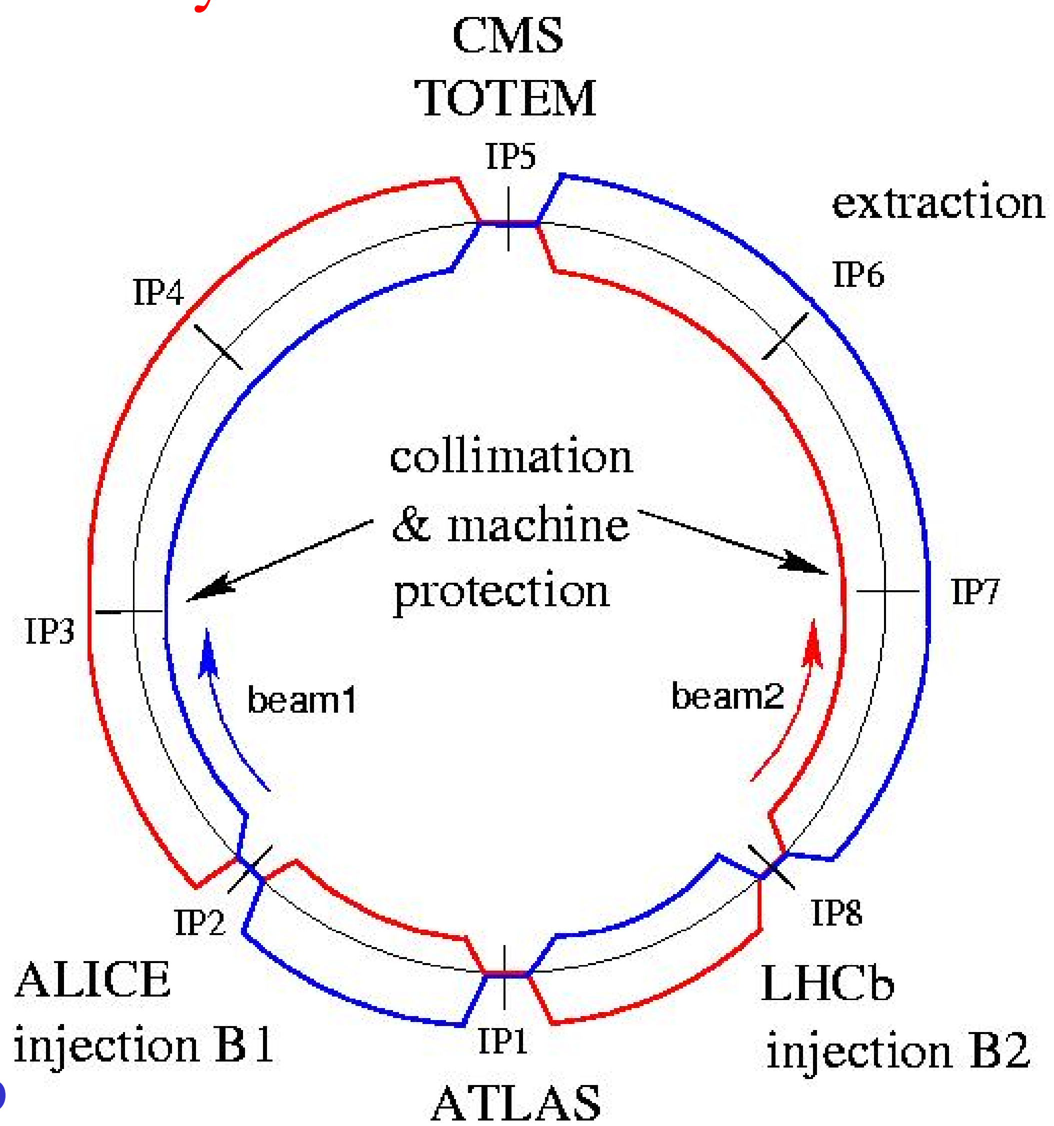
$\varepsilon = \varepsilon_n / \gamma$ ε_n is determined by the injector chain

goal: → high bunch intensity and many bunches

$L = 10^{34}$ cm^{-2}sec^{-1} small β at IP and high collision energy

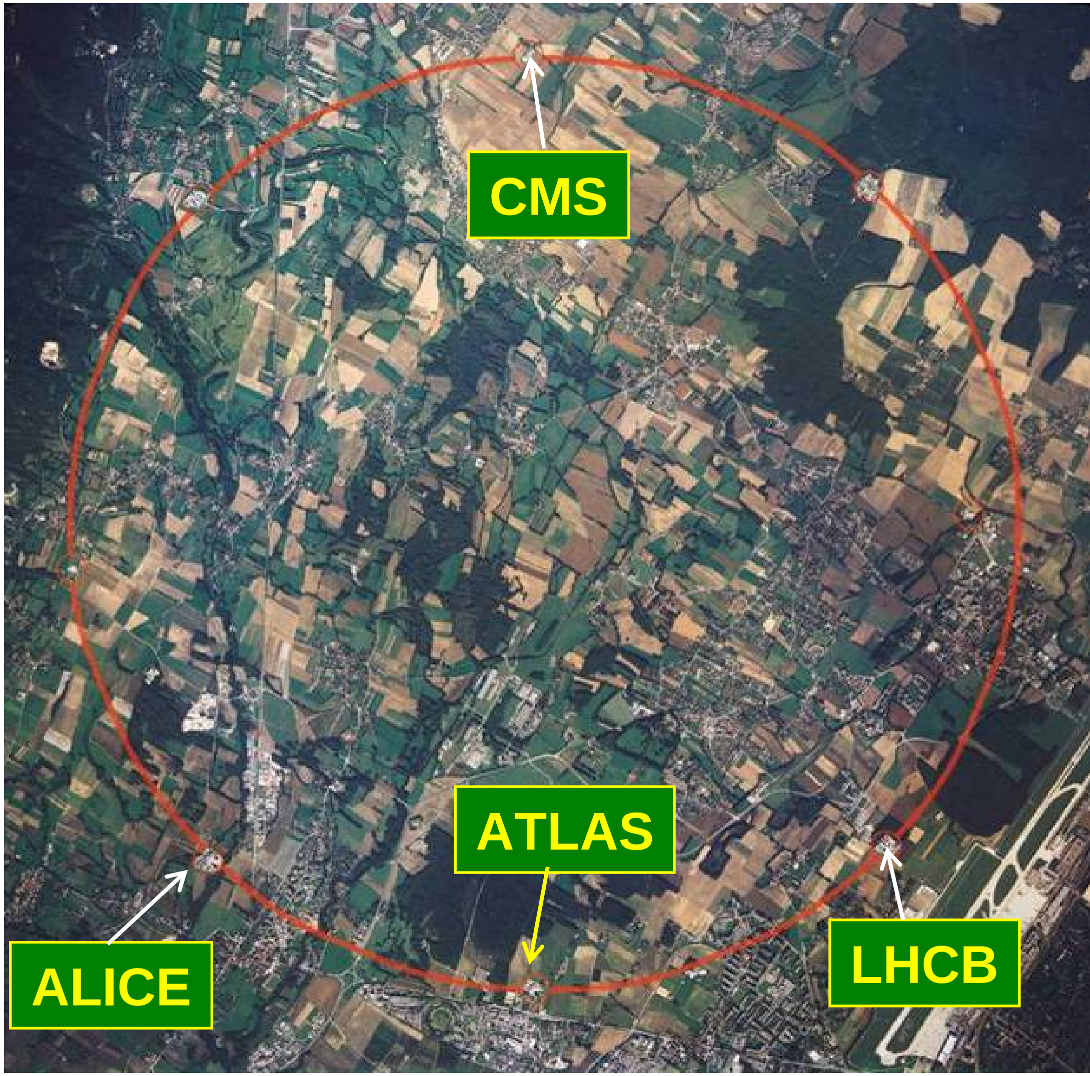
LHC Layout

- 2-in-1 magnet design
  p-p & Pb-Pb collisions
- 7 TeV p-beam energy
  ➔ > 1 TeV CM energy
  ➔ Higgs discovery
- 2 high L experiments with
  $L = 10^{34}$ cm^{-2} sec^{-1}
  ➔ 2808 bunches / beam
  with 1.15 10^{11} ppb
- 2 low L experiments:
  ALICE (Pb-Pb) & LHCb



LHC Layout

- built in old LEP tunnel
  - ➔ 8.4 T dipole magnets
  - ➔ 10 GJ EM energy
  - ➔ powering in 8 sectors
- 2808 bunches per beam with 1.15 10^{11} ppb
  - ➔ 360 MJ / beam
  - ➔ crossing angle & long range beam-beam
- Combined experiment/ injection regions

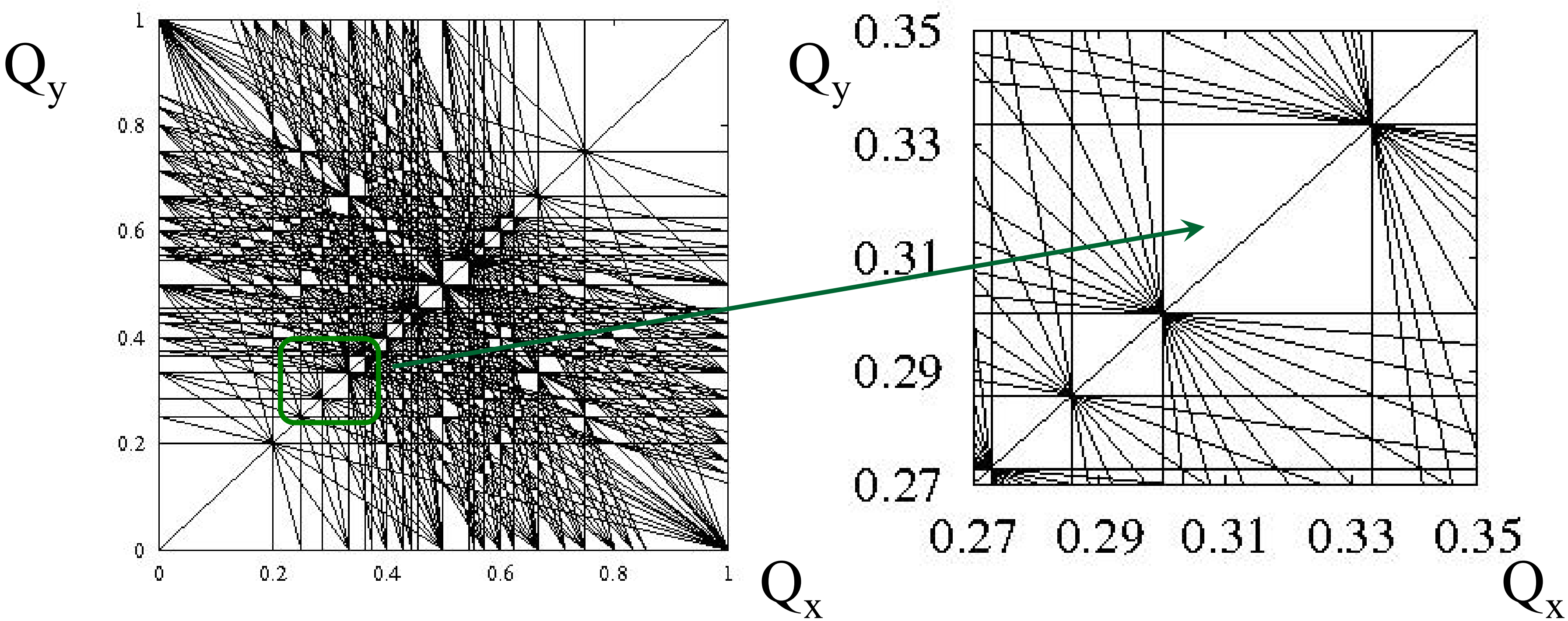


Main Challenges for the Operation

- Magnetic field perturbations & resonances
- Collimation efficiency
- Beam power and machine protection
- Collective effects and impedance
- Beam-beam interaction
- Triplet aperture and beam-beam
- Electron cloud effect

LHC Challenges: Field Quality & Resonances

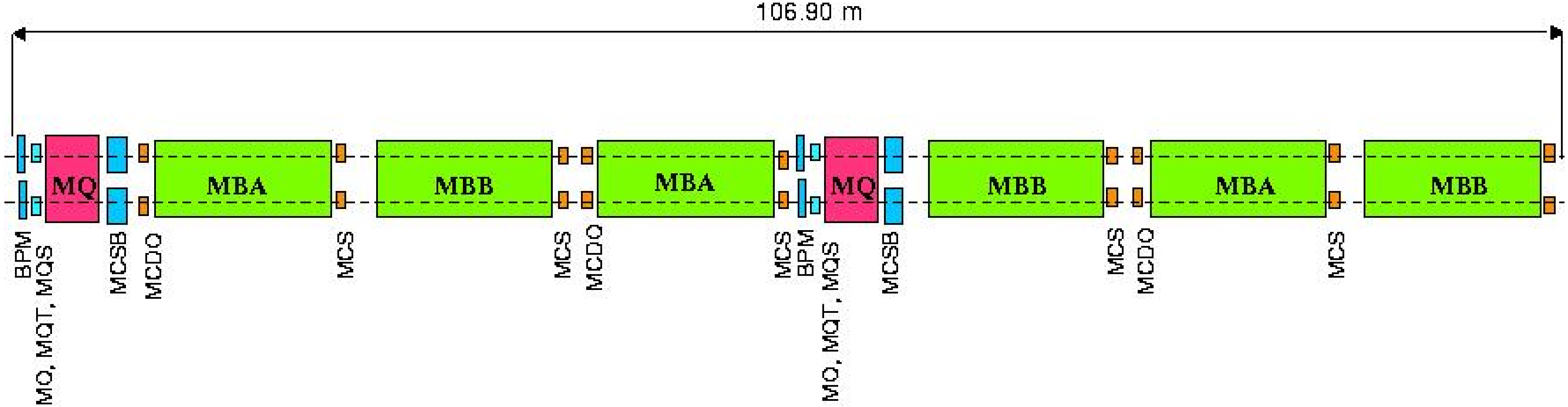
- tune: Q = number of oscillations per revolution
- resonances: $n\,Q_x + m\,Q_y + r\,Q_s = p$; "order" = n+m+r



limited accessible area; limit for field quality and ΔQ tolerance

LHC Challenges: Magnet Field Errors

- the LHC features 112 circuits / beam (+ orbit correctors)



- all magnet circuits are tested before and during installation

- field errors in SC magnets vary with time & operation history
  ➔ adjustments during operation

➔ non-destructive beam instrumentation

LHC Challenges: Collimation Efficiency

- Magnet Quench:

  → beam abort → several hours of recovery

- LHC nominal beam intensity: $I = 0.5A \Rightarrow 3\ 10^{14}$ p /beam

- Quench level: $N_{lost} < 7\ 10^{8}\ m^{-1}$ → $2.2\ 10^{-6}\ N_{beam}$!

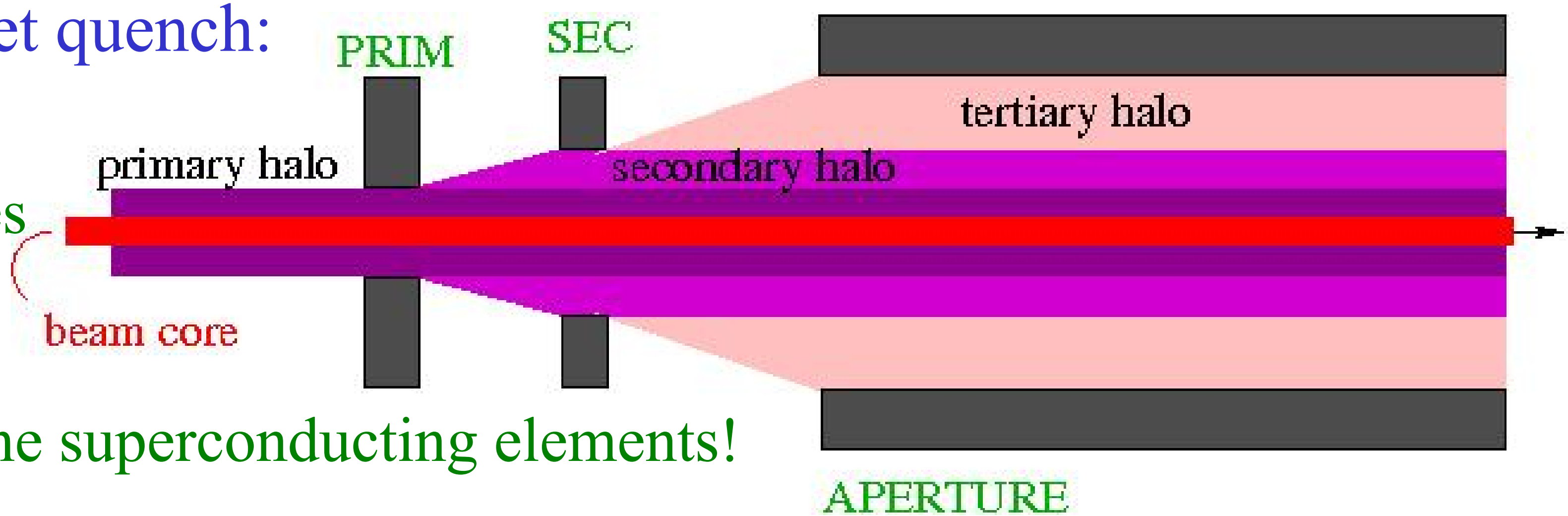
(compared to 20% to 30% in other superconducting rings)

→ requires collimation during all operation stages!

→ requires good optic and orbit control! → feedback loops

LHC Challenges: Beam Power

- Magnet quench:
  - ➔ stray particles must not reach the superconducting elements!



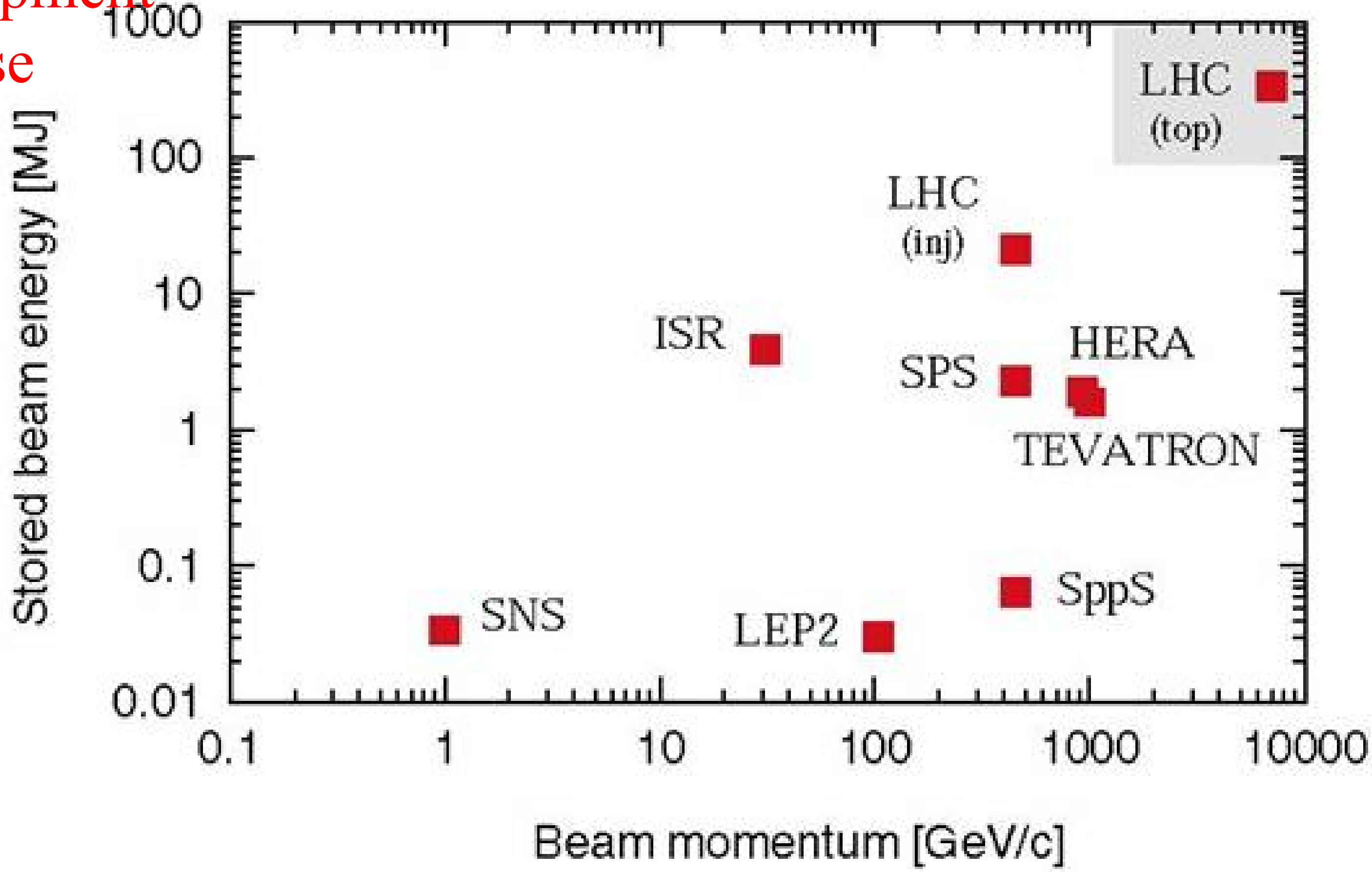
- beam core: 0 to 2 σ
- primary beam halo: 2 to 6 s; generated by: non-linearities; noise; IBS etc (can damage equipment)
- secondary halo: 6 to 8 σ; generated by collimators (quench)
- tertiary halo: > 8 σ; generated by collimators (save)

LHC Challenges: Beam Power

- Unprecedented beam power:

➔ potential equipment damage in case of failures during operation

➔ in case of failure the beam must never reach sensitive equipment!



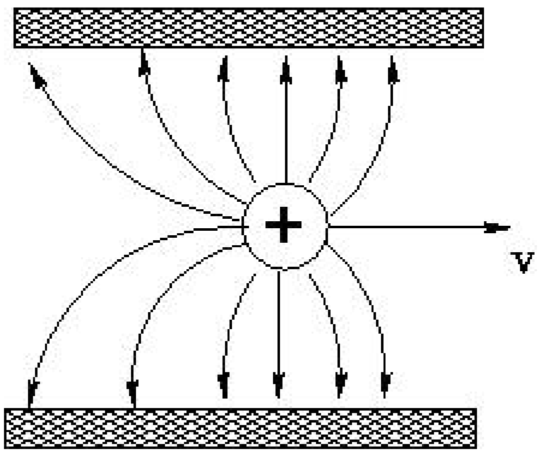
Beam Power and Machine Protection

- Unprecedented beam power:
  - ➔ all absorbers and the collimation system must be designed to survive an asynchronous beam dump!
    (total of up to 136 collimators & absorbers)
  - ➔ Machine protection System!

- Robust collimator jaw design
  - ➔ fiber reinforced graphite jaws are more robust than Cu jaws
  - ➔ fiber reinforced graphite has a higher impedance and electrical resistivity

LHC Challenges: Collective Effects

- resistive wall impedance:
  - ➔ image charges trail behind due to resistivity of surrounding materials
  - ➔ Wake fields drive beam instabilities
  - ➔ effect increases with decreasing gap opening of the collimator jaws

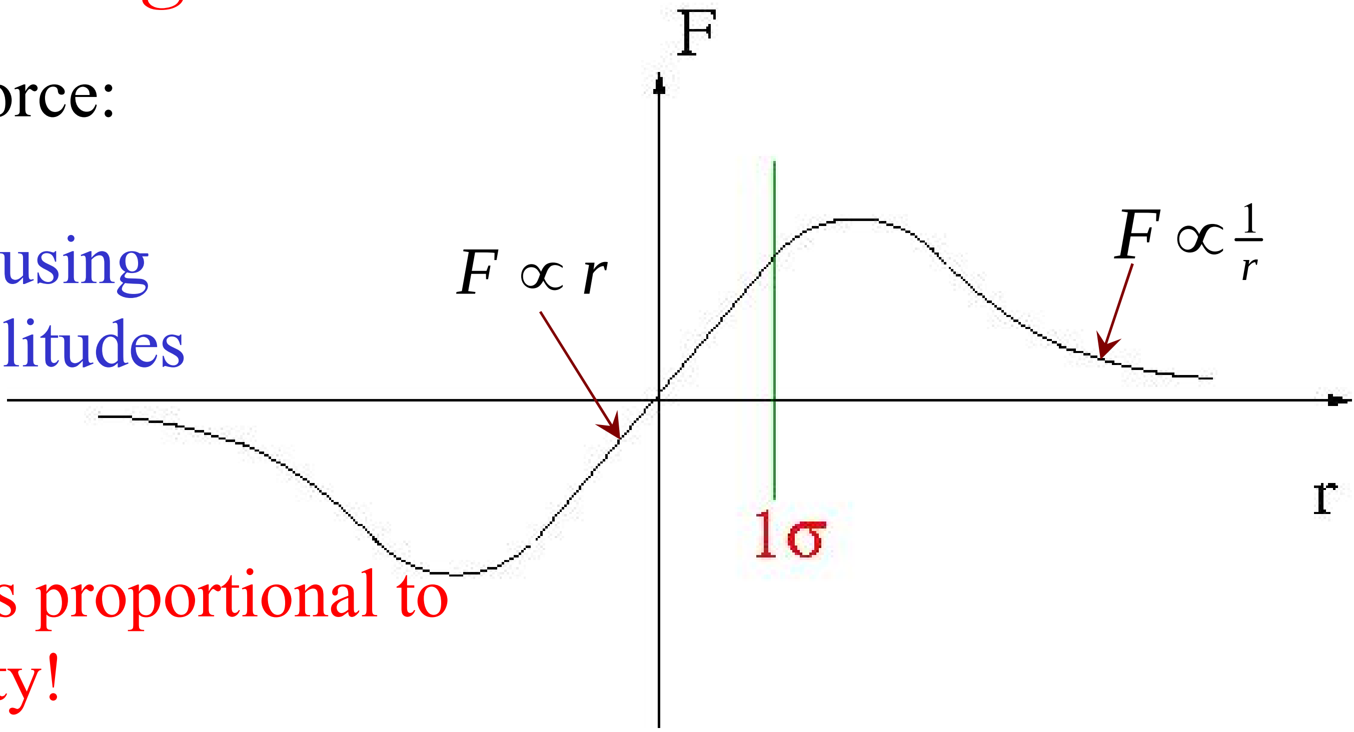


➔ impedance of Graphite jaws either limits the minimum collimator opening ➔ limit for β* or the maximum beam current

- phased collimation system for the LHC:
  - ➔ Phase 1: graphite jaws for robustness during commissioning
  - ➔ Phase 2: nominal performance (low impedance, non-linear or feedback)

LHC Challenges: Beam-Beam Interaction

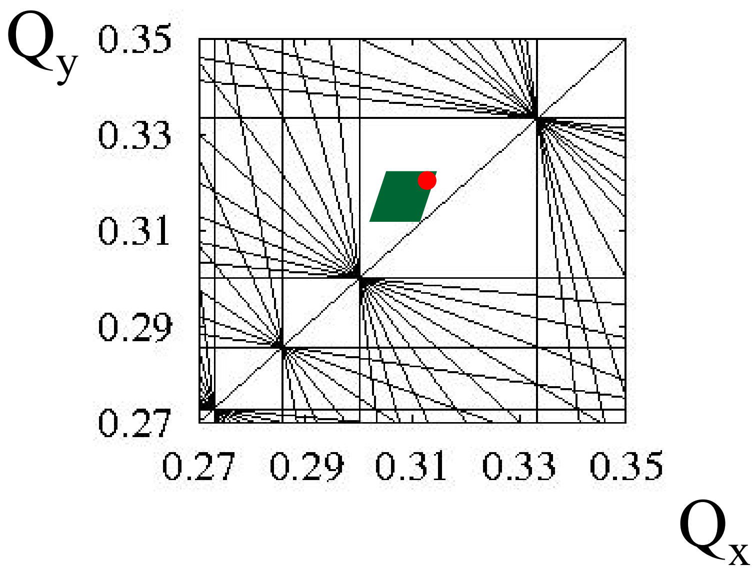
- beam-beam force:
  - ➔ additional focusing for small amplitudes
  - ➔ perturbation is proportional to bunch intensity!



- strong non-linear field:
  - ➔ tune & perturbation depends on oscillation amplitude
    - ➔ bunch intensity limited by non-linear resonances

LHC Challenges: Beam-Beam Interaction

- LHC working point: n+m < 12



→ $Q_x = 64.31$; $Q_y = 59.32$

total tune spread must be smaller than 0.015!

- the LHC features 3 proton experiments with

- bunch intensity limited by beam-beam force:

→ $N < 1.5\ 10^{11}$

→ nominal: $N < 1.15\ 10^{11}$

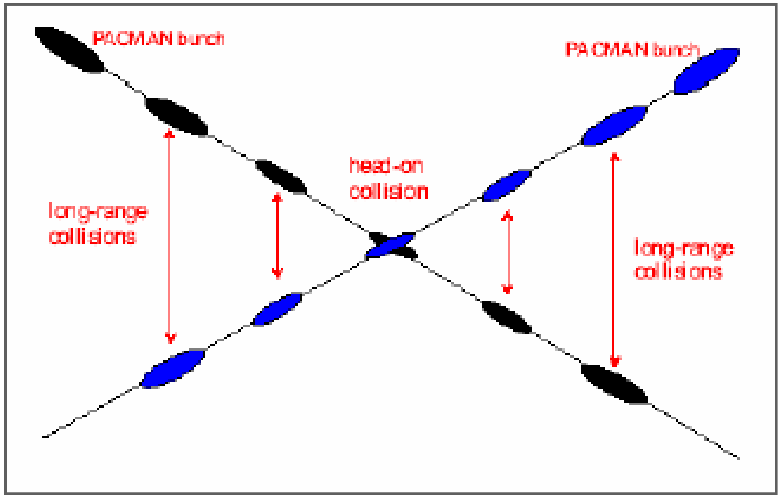
→ ultimate: $N < 1.7\ 10^{11}$

LHC Challenges: Triplet Aperture

- long range beam-beam:

Operation with 2808 bunches features approximately 30 unwanted collision points per Interaction Region (IR).

➔Operation requires crossing angle ➔ aperture reduction!



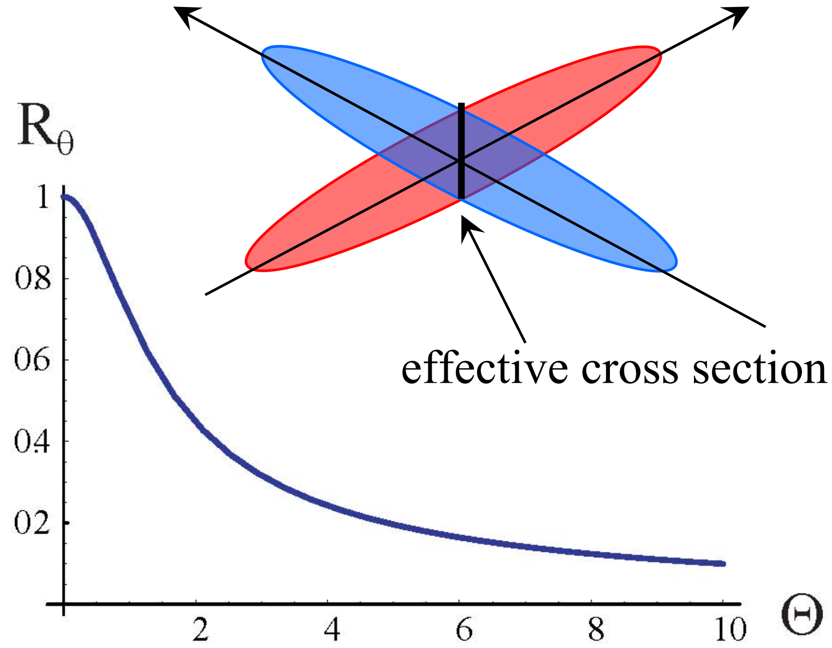
- non-linear fields and additional focusing due to beam-beam

efficient operation requires large beam separation at unwanted collision points ➔ separation of 9 σ is at the limit of the triplet aperture for nominal β* values! ➔ margins can be introduced by operating with fewer bunches, lower bunch intensities, larger β* values (or larger triplet apertures ➔ upgrade studies)

LHC Challenges: Crossing Angle

geometric luminosity reduction factor:

$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$



large crossing angle:

➔ reduction of long range beam-beam interactions

➔ reduction of the mechanical aperture

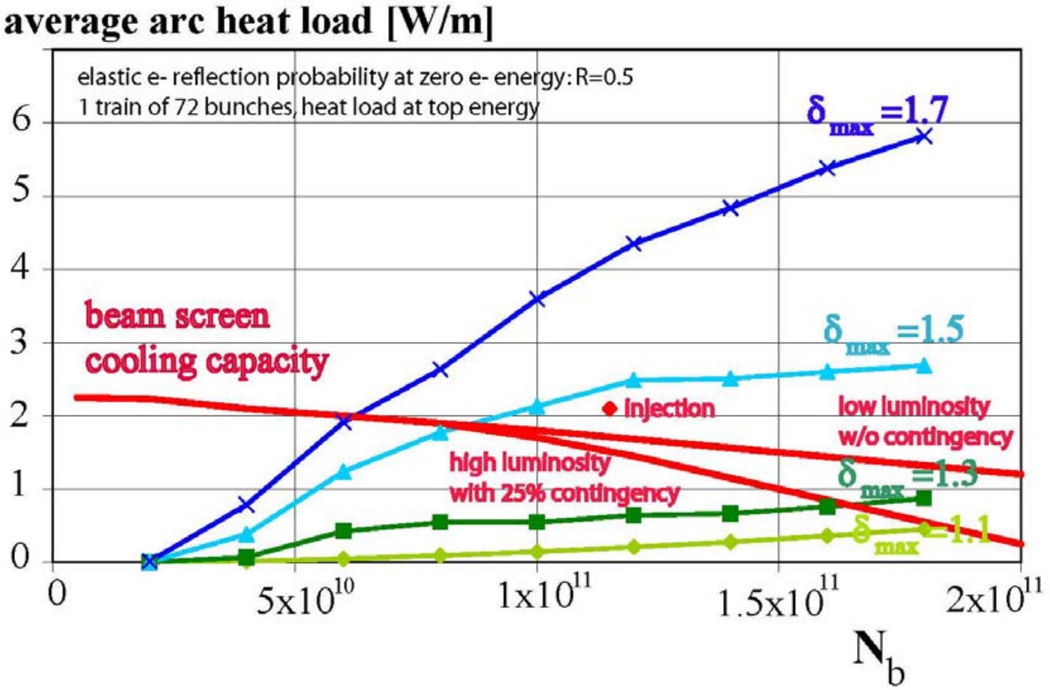
➔ reduction of instantaneous luminosity

➔ inefficient use of beam current (machine protection!)

LHC Challenges: Electron Cloud Effect

- Synchrotron light releases electrons from beam screen:

➔ electrons get accelerated by p-beam ➔ impact on beam screen
➔ generation of secondary electrons ➔ δ_{max} multiplication; e-cloud
➔ heating, instabilities and emittance growth



➔ effect disappears for low bunch currents or large bunch spacing
➔ secondary emission yield decreases during operation (beam scrubbing)

[F. Zimmermann / CERN]

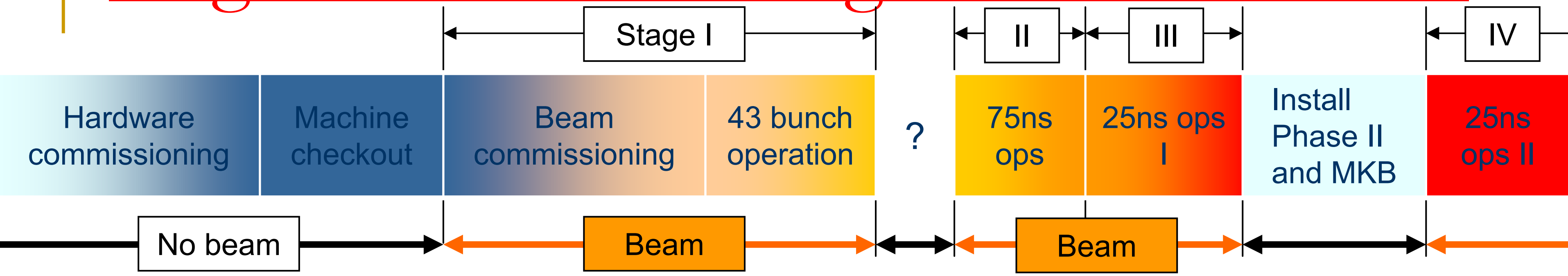
Initial Design Parameters

Parameters	‘white book’	DIR−TECH/84−01 & ECFA 84/85 CERN 84−10
# bunches	3564	slightly too large (kicker rise time)
N / bunch	$0.34 * 10^{11}$	margins for beam-beam effects
β^*	1m	margins for aperture and impedance
ε_n	1.07µm	factor 3 margin for N_b/ε_n for injector chain
σ^*	12µm	
σ_L	7.55cm	
full crossing angle	100µrad	margins for triplet aperture
events / crossing	1 ←→ 4	detector efficiency
peak luminosity	$0.1*10^{34}cm^{-2}sec^{-1}$	
luminosity lifetime	56h	long physic runs ==> efficiency
E[TeV]	8.14	10 T dipole field
E[MJ]	121	70 x energy in existing SC stortage rings

Nominal Parameters

Parameters	'white book'	Competition with SSC
# bunches	2808	
N / bunch	$1.15 * 10^{11}$	factor 3 smaller margin for beam-beam
β^*	0.55m	reduced margins for aperture and impedance
ε_n	1.75μm	
σ^*	16.7μm	
σ_L	7.55cm	
full crossing angle	285μrad	factor 3 smaller margin for triplet aperture
events / crossing	19.2	
peak luminosity	$1.0*10^{34}cm^{-2}sec^{-1}$	
luminosity lifetime	15h	1 physics run per day
E[TeV]	7	
E[MJ]	366	quench & damage potential (200 x)!

Staged Commissioning Plan for Protons



Pilot physics run

- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity

75ns operation

- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle

25ns operation I

- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal

25ns operation II

- Push towards nominal performance

Summary

Mechanical aperture	careful analysis and definition of procedures during installation → optimization in Stage I
Polarity errors	(same as above)
Global magnet field quality & corrector circuit powering	(same as above)
Collimation efficiency	optimization during Stage I
Beam power and machine protection	from Stage I to Stage II
Collective effects and impedance	only at Stage III
Triplet aperture and beam-beam	only > Stage III
Electron cloud effect	only at Stage IV

Summary

- already the nominal LHC operation is very challenging!!!

  LHC upgrade studies could provide means for overcoming Limitations of nominal configuration
  ➔ R&D results should be available shortly after commissioning!

- radiation limit of triplet magnets (700fb^{-1}) might be reached by 2013

  ➔ one needs to prepare a replacement now
  larger triplet aperture will also reduce collimator impedance!

- 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

Upgrade Options

- CERN identified 3 main options for the LHC upgrade and grouped them according to their impact on the LHC infrastructure into three phases (2001):

Phase 0: performance upgrade without hardware modifications

Phase 1: performance upgrade with IR modifications

Phase 2: performance upgrade with major hardware modifications

Ultimate Parameters (Phase0)

Parameters	nominal	'Ultimate'	
# bunches	2808	2808	
N / bunch	$1.15 * 10^{11}$	$1.7*10^{11}$	beam-beam
β^*	0.55m	0.5m	impedance
ε_n	1.75μm	1.75μm	
σ^*	16μm	16.7μm	
σ_L	7.55cm	7.55cm	
full crossing angle	285μrad	> 315μrad	triplet aperture
events / crossing	19.2	44.2	detector efficiency?
peak luminosity	$1.0*10^{34}cm^{-2}sec^{-1}$	$2.4*10^{34}cm^{-2}sec^{-1}$	
L lifetime	15h	10h	1 physics run per day
E[TeV]	7	7 -> 7.45	
E[MJ]	366	541	quench & damage risk

Phase1 Upgrade Options

- increase mechanical aperture of the final focus quadrupoles:

1) New final focus magnets with larger aperture:

→ allows smaller β^* → higher luminosity

→ larger peak field for constant gradient and higher radiation

→ a) new magnet technology (Nb_3Sn [USLARP])

→ b) low gradient final focus layouts (existing NbTi)

→ implies larger crossing angle

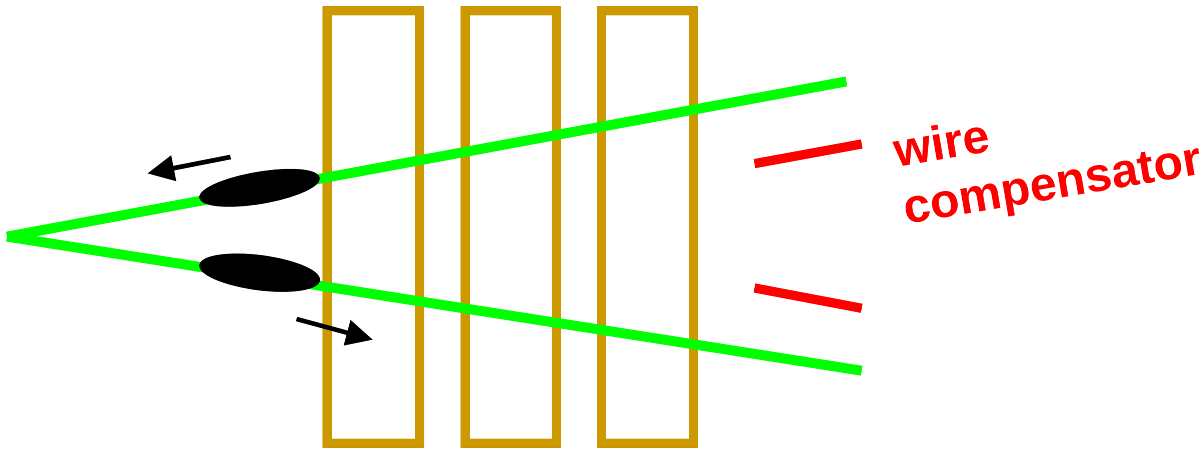
$$sep[\sigma] \approx \theta_c \cdot \frac{\sqrt{\beta^*}}{\sqrt{\varepsilon}}$$

→ reduction of luminosity

Phase1 Upgrade Options

- minimize detrimental effect of beam-beam interactions:

2) Compensate long range beam-beam effects ➔ smaller x-in angle



➔ new proposal and technology! ➔ requires machine studies

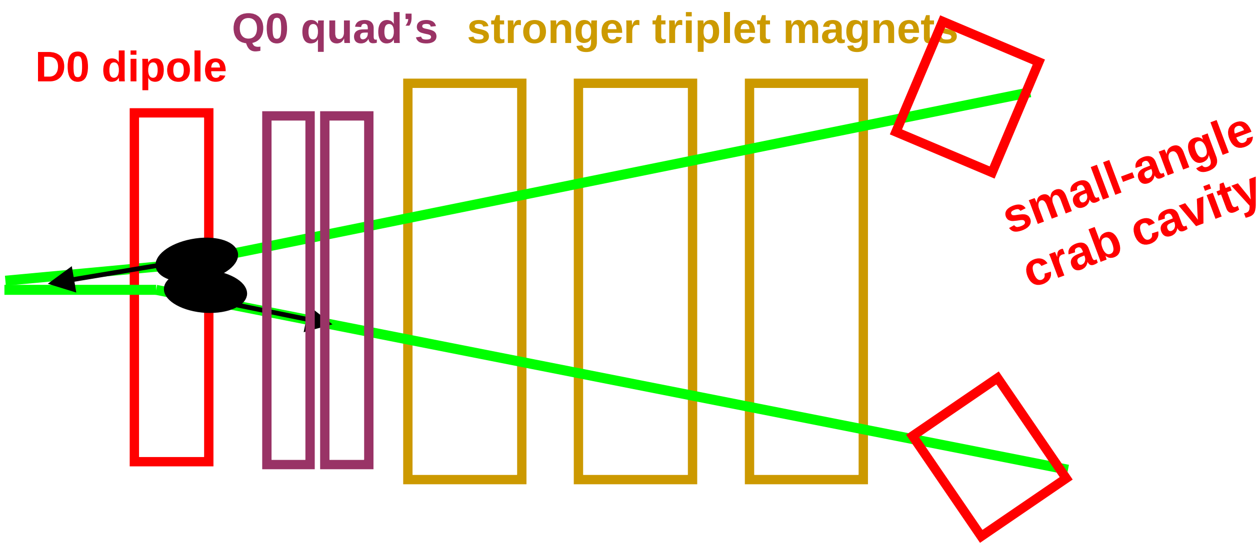
➔ can not improve dynamic aperture beyond beam separation (6σ)

➔ similar proposal for head-on collisions (➔ larger operation margins)

Phase1 Upgrade Options

- minimize luminosity loss due to crossing angle at the IP:

  3) early separation scheme in order to minimize geometric reduction:



➔ requires magnet integration inside the detectors (back scattering!)
➔ requires new magnet technology
➔ implies parasitic collisions at 4 σ for 25ns bunch spacing

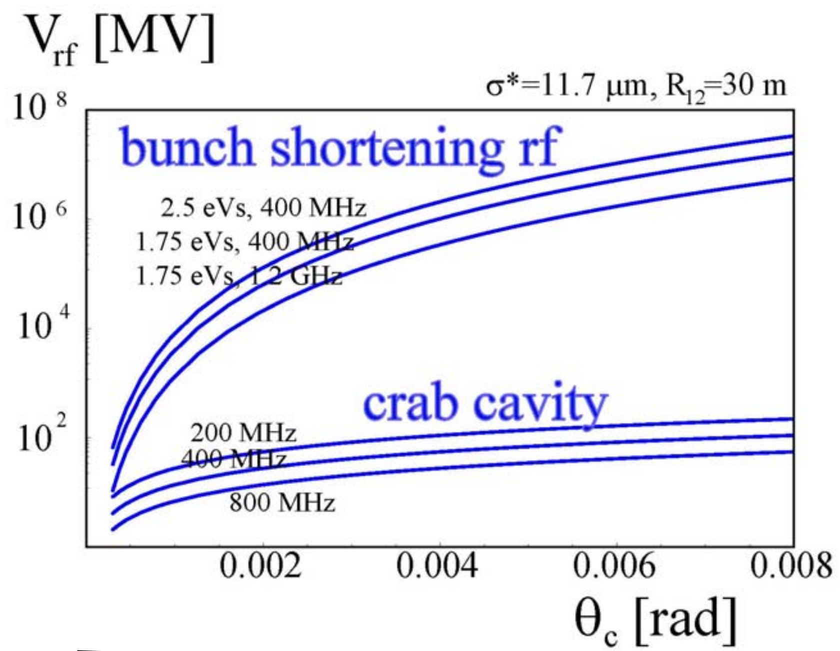
Phase1 Upgrade Options

- minimize luminosity loss due to geometric reduction factor:

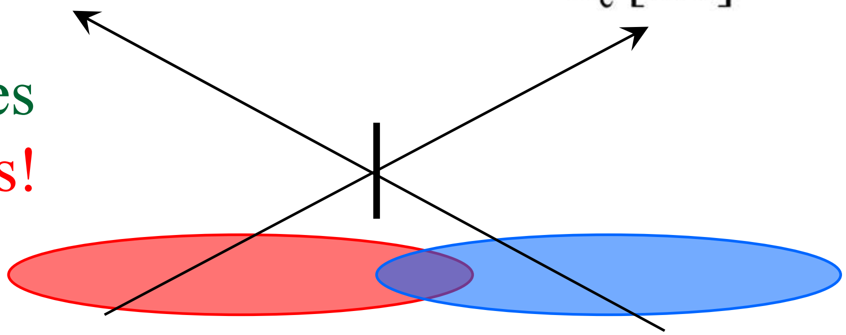
4) shorter bunch length
➔ expensive in terms of RF

$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

[F. Zimmermann]



5) bunch rotation via crab cavities
➔ new technology for protons!



Scenarios for L = 10^{35} cm^{-2} sec^{-1}

parameter	symbol	ultimate	25 ns, small β*	50 ns, long
transverse emittance	ε [μm]	3.75	3.75	3.75
protons per bunch	N_b [10^{11}]	1.7	1.7	4.9
bunch spacing	Δt [ns]	25	25	50
beam current	I [A]	0.86	0.86	1.22
longitudinal profile		Gauss	Gauss	Flat
rms bunch length	σ_z [cm]	7.55	7.55	11.8
beta* at IP1&5	β* [m]	0.5	0.08	0.25
full crossing angle	θ_c [μrad]	315	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.75	0	2.0
Luminosity reduction		0.8	0.86	0.45
peak luminosity	L [10^{34} $cm^{-2}s^{-1}$]	2.3	15.5	10.7
peak events per crossing		44	294	403
initial lumi lifetime	τ_L [h]	14	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} $cm^{-2}s^{-1}$]	0.91	2.4	2.5
	$T_{run,opt}$ [h]	17.0	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} $cm^{-2}s^{-1}$]	1.15	3.6	3.5
	$T_{run,opt}$ [h]	12.0	4.6	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	1.04 (0.59)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.25	0.36
image current heat	P_{IC} [W/m]	0.33	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.06 (0.56)	0.09 (0.9)
extent luminous region	σ_l [cm]	4.3	3.7	5.3
comment			D0 + crab (+ Q0)	wire comp.

Upgrade Options: Phase 1

- final choice depends on main motivation for upgrade:

    1) Overcome limitations in nominal LHC
    2) Increase luminosity by one order of magnitude

- need to keep all technical options alive until LHC startup

- prepare for a staged upgrade scenario:

    1) First upgrade in order to overcome potential bottlenecks in LHC operation
    2) Second upgrade to push performance by factor 10

Upgrade Options: Phase 2

- CERN identified 3 main areas for consolidation efforts:

  1) New Multi Turn Extraction for the PS ➔ smaller losses

  2) PS magnet renovation and replacement (PS2):
     ➔ program for refurbishing and replacing 50 magnets until 2008 ➔ not a long term solution ➔ PS2 project

  3) replacement for main proton linac: LINAC4
     ➔ overcomes bottleneck for 'ultimate' LHC parameters
     ➔ solves maintenance problem for existing LINAC2
     ➔ SPL (second phase) could 'bypass' PSB (space charge)

  4) magnet renovation in the SPS
     ➔ program for refurbishing and replacing SPS magnets

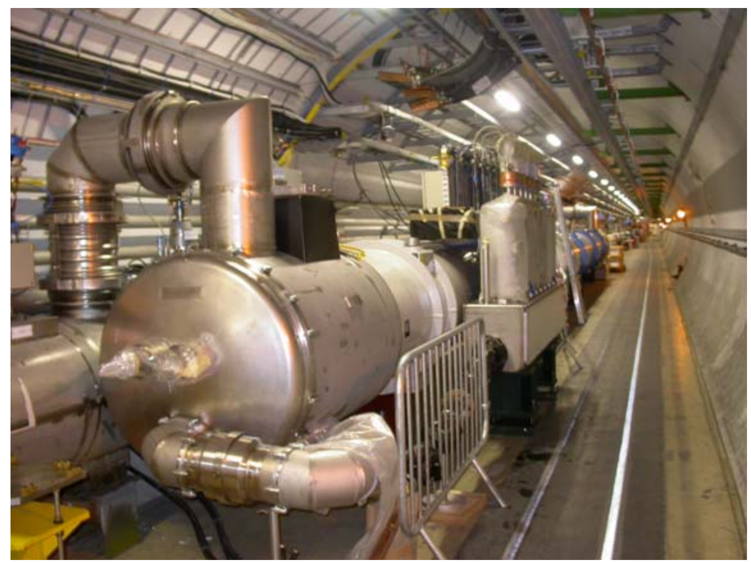
➔ CERN 'White Paper'

LHC Installation

cryogenic distribution in 12

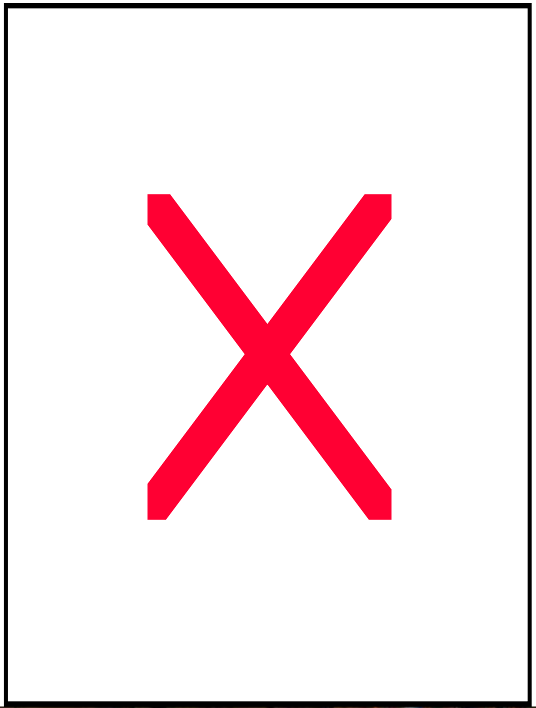
superconducting link

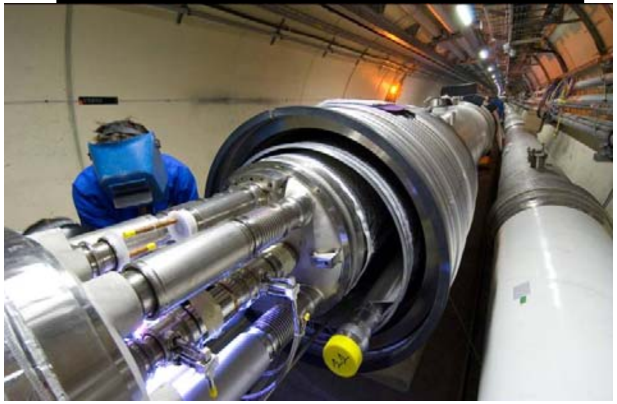
Q6 with cryogenic connection in IR8

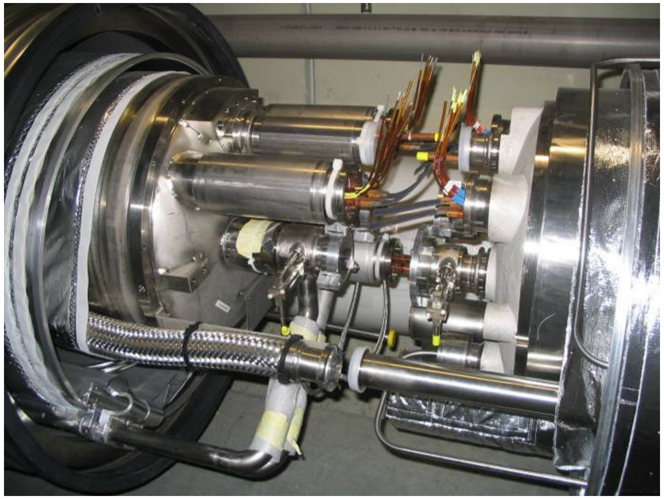


electrical distribution in IR8

LHC Installation





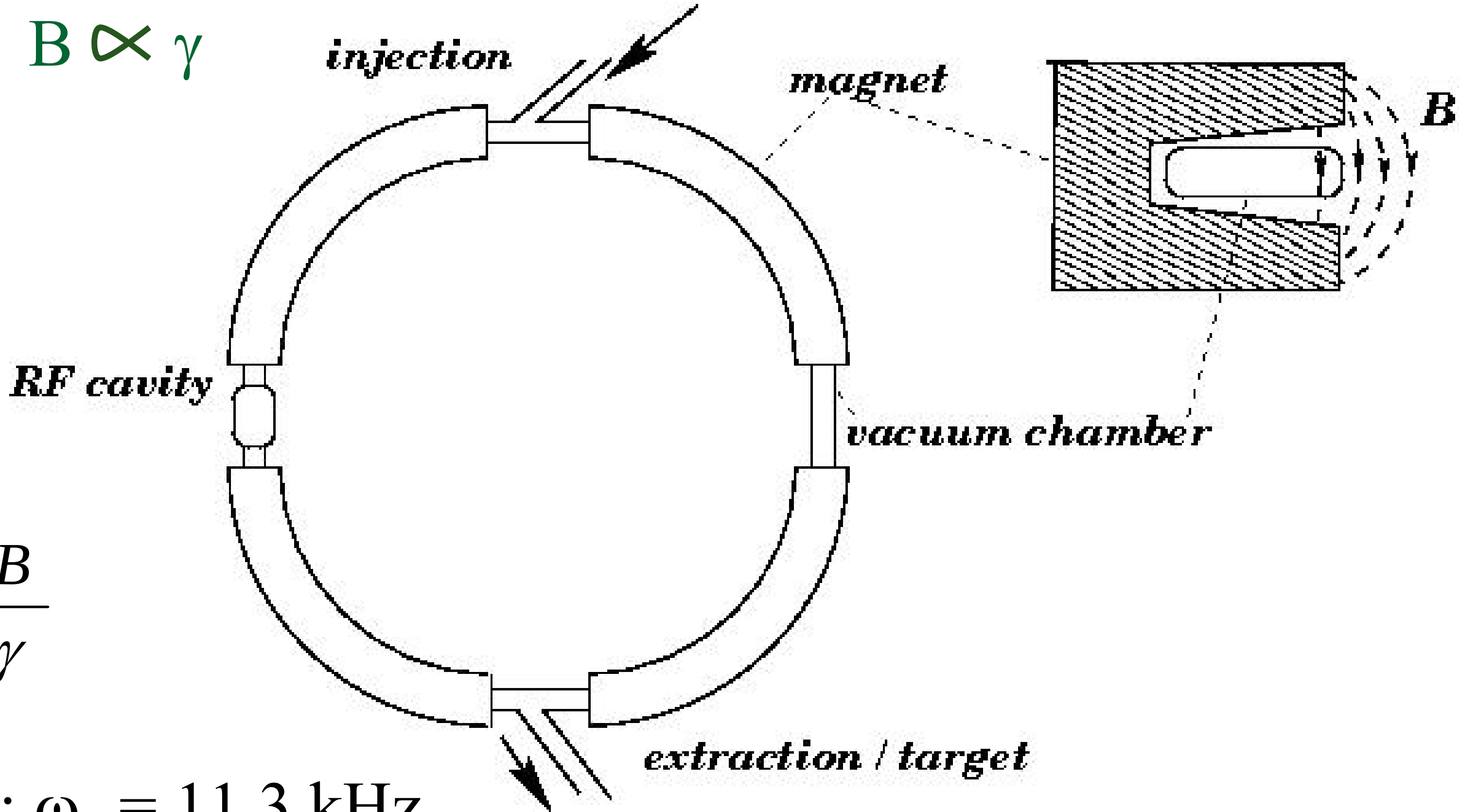


Introduction: the LHC is a Synchrotron

- R = constant:

$$r = \frac{m_0}{q} \cdot \frac{\gamma}{B} \cdot v$$

v = c → B ∝ γ



$$\omega_0 = \frac{q}{m_0} \cdot \frac{B}{\gamma}$$

LHC / LEP: ω_0 = 11.3 kHz