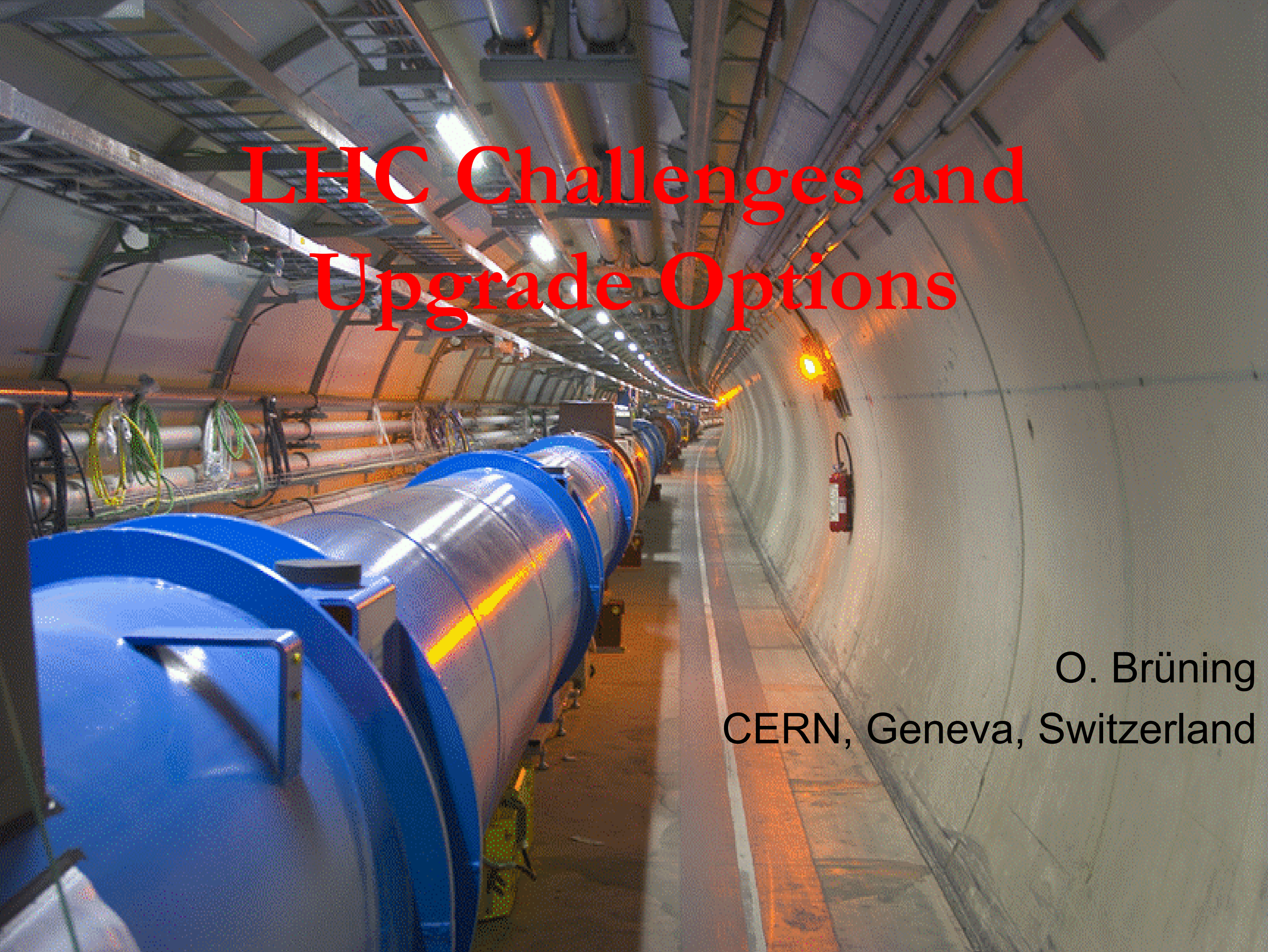
LHC Challenges and Upgrade Options



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- Main challenges for the LHC operation
- LHC parameters
- Upgrade options

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

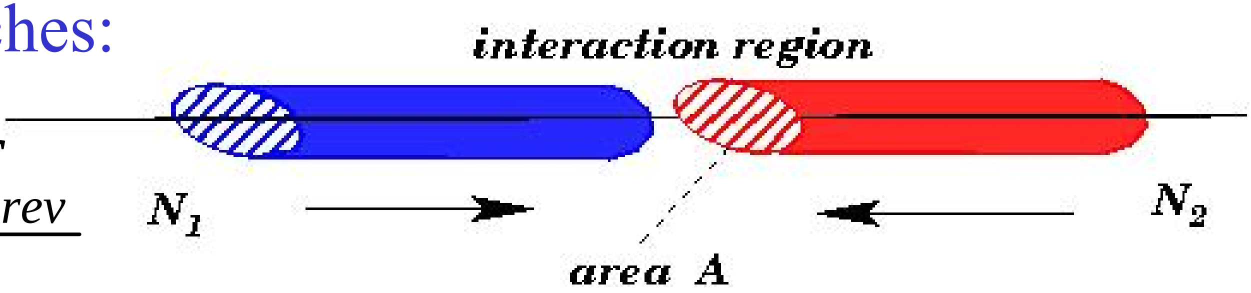
- Integrated luminosity: $L = \int L(t)\, dt$

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

Introduction: Instantaneous 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

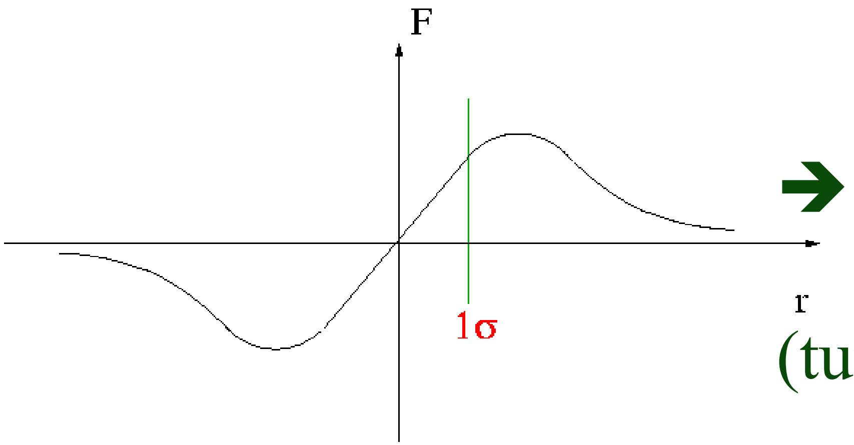
$L = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$ small β at IP and high collision energy

Introduction: Maximizing Luminosity I

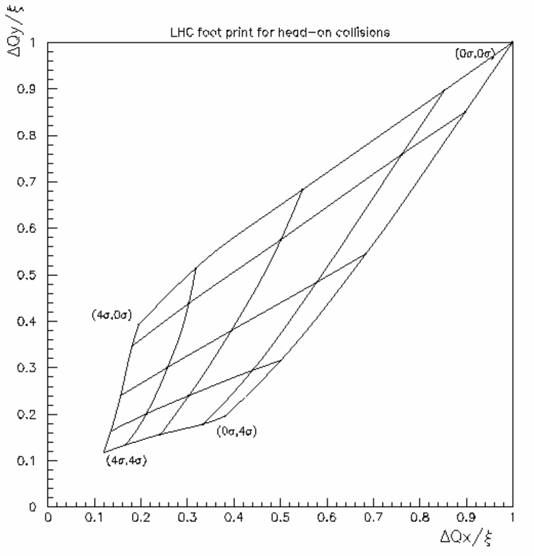
🟩 Number of particles per bunch:

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

➔ limited by beam-beam interaction



➔ frequency spread (tune foot print)



➔ tune foot print & resonances impose a limit for: N / ε_n

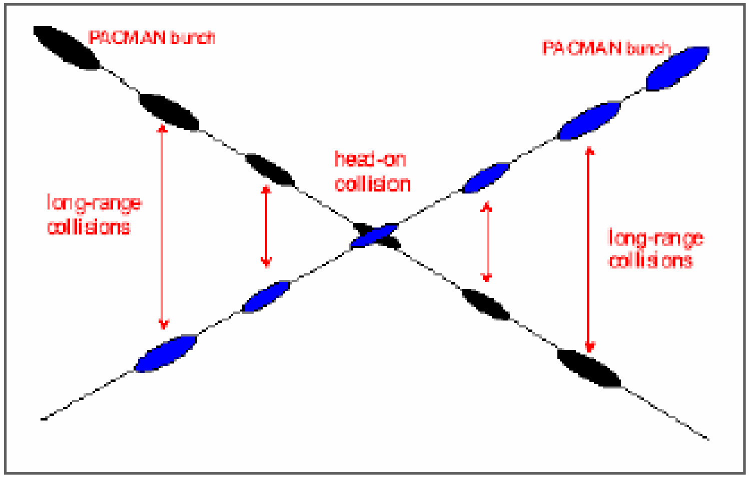
LHC with 3 head-on experiments ➔ $N < 1.5\ 10^{11}$

(ε_n limited by magnet aperture)

Introduction: Maximizing Luminosity II

- Number of bunches:

-operation with more than 115 bunches implies additional unwanted collisions!

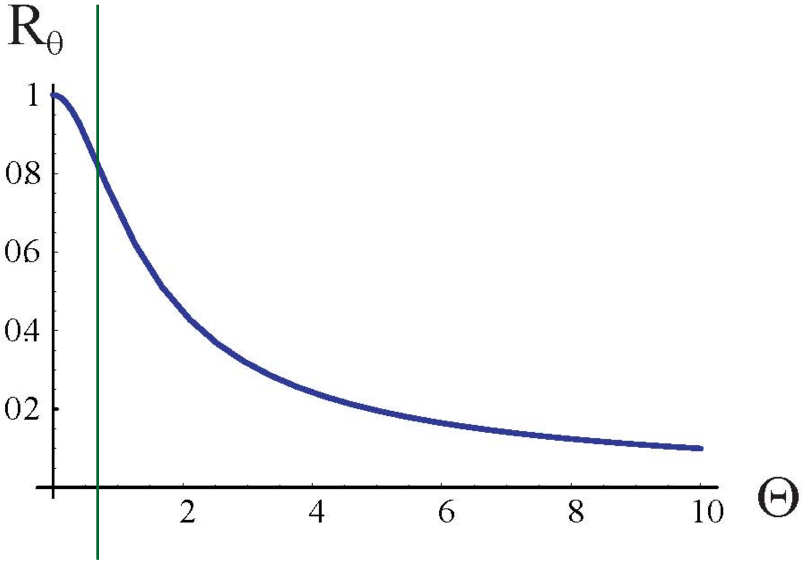


➔ operation requires crossing angle has to be increased for large n_b

➔ triplet aperture reduction and luminosity reduction!

-geometric luminosity reduction factor:

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



Introduction: Maximizing Luminosity III

- beam size at the IP:

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

small beam size at the IP implies large beam divergence:

$$\sigma_{IP} = \sqrt{\beta_{IP} \cdot \varepsilon} \qquad \sigma'_{IP} = \sqrt{\frac{\varepsilon}{\beta_{IP}}}$$

➔ large beam size inside the triplet magnets (proportional to $1/\beta_{IP}$)

Nominal LHC triplet magnets: 200 T/m operational gradient
(235 T/m peak field on test stand ➔ margin for 200 kW heat load)
coil aperture of 70mm (50mm for beam screen) ➔ 7T / 8.3 T
(at the limit of NbTi magnet technology) ➔ $\beta_{IP} > 0.55$m

LHC Challenges

- operation at the beam-beam limit:

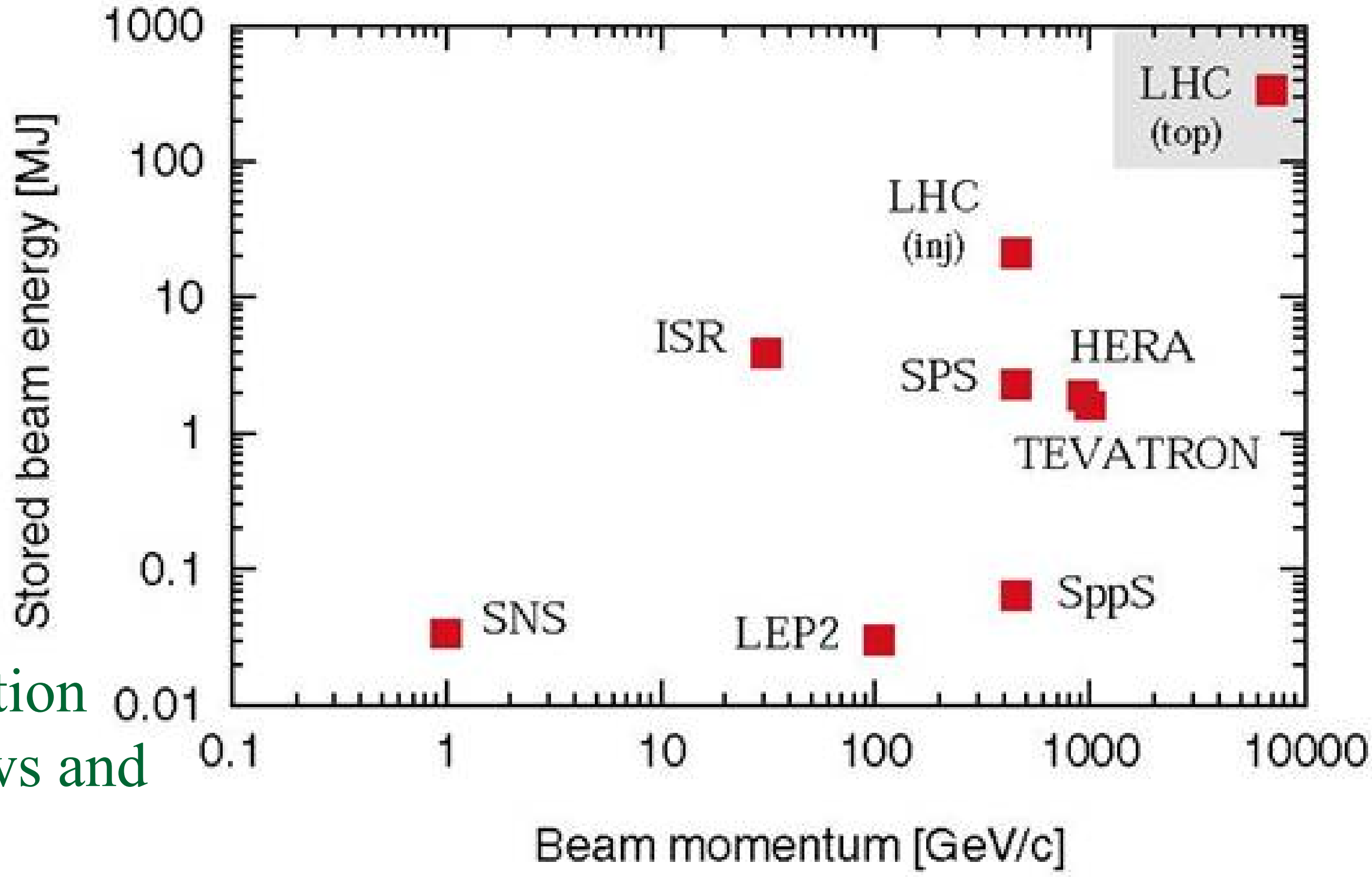
  beam lifetime; beam halo and background

- total beam power:

  factor 200 higher than in past storage rings

LHC Challenges: Beam Power

- 🟩 Unprecedented beam power: → Machine protection System!



- → potential equipment damage in case of failures
- → beam must never reach sensitive equipment!
- → 2 stage collimation system (136 jaws and absorbers)
- → with robust jaws (Fiber reinforced Graphite jaws)

LHC Challenges

- operation at the beam-beam limit:

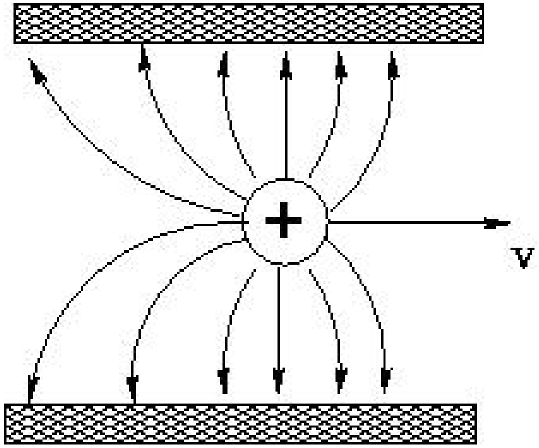
  beam lifetime; halo and background

- total beam power in cold environment (2K):

  factor 200 higher than in past storage rings

- collective effects:

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)

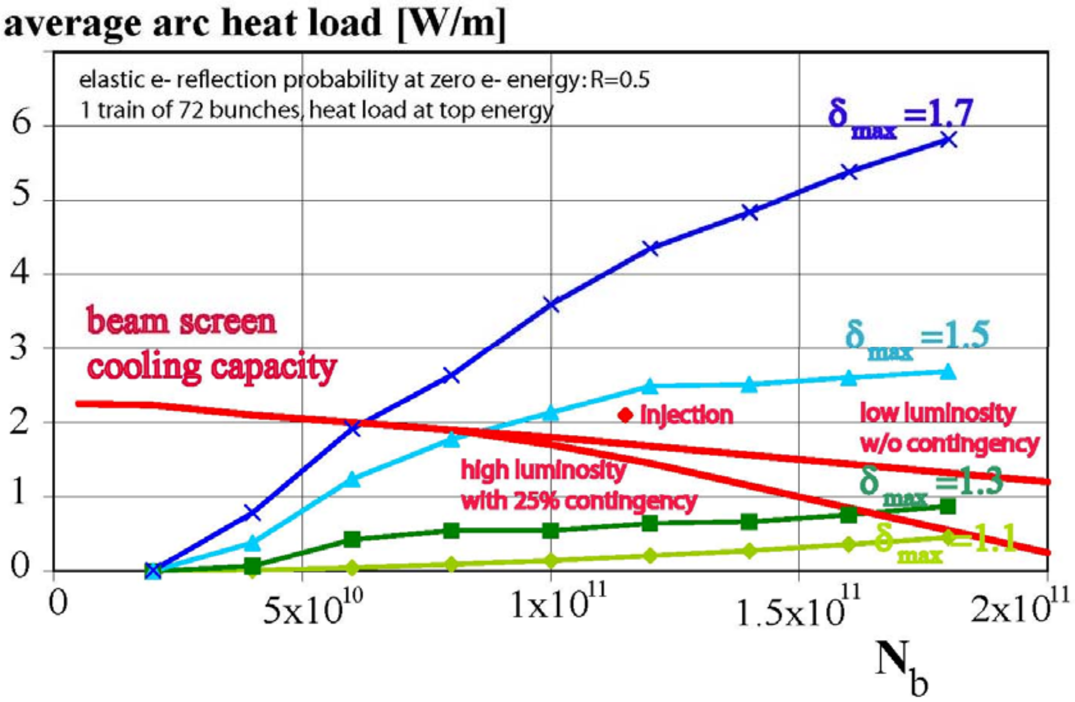
LHC Challenges

- operation at the beam-beam limit:
  beam lifetime; halo and background
- total beam power in cold environment (2K):
  factor 200 higher than in past storage rings
- collective effects:
- electron cloud effect:

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 (beam size)



➔ effect disappears for low bunch currents or large bunch Spacing

➔ secondary emission yield decreases during operation (beam scrubbing)

[F. Zimmermann / CERN]

LHC Challenges

- operation at the beam-beam limit:
  beam lifetime; halo and background

- total beam power in cold environment (2K):
  factor 200 higher than in past storage rings

- collective effects:

- electron cloud effect:

- old injector complex and long ‘turn around’ time for LHC:
  minimum of 1h loss for each failed ramp

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 & small R factor
events / crossing	1 ←→ 4	detector efficiency
peak luminosity	$0.1*10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$	
luminosity lifetime	56h	long physic runs ==> efficiency
E[TeV]	8.14	10 T dipole field (slightly too optimistic)
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	$1.0*10^{34}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$	
luminosity lifetime	15h	1 physics run per day
E[TeV]	7	
E[MJ]	366	quench & damage potential (200 x)!

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_{IP} values
     - ➔ some gain in luminosity if the crossing angle does not need to be increased proportionally
   - ➔ provides aperture space for dedicated absorbers

   - ➔ allows larger collimator jaw opening! (collective effects)

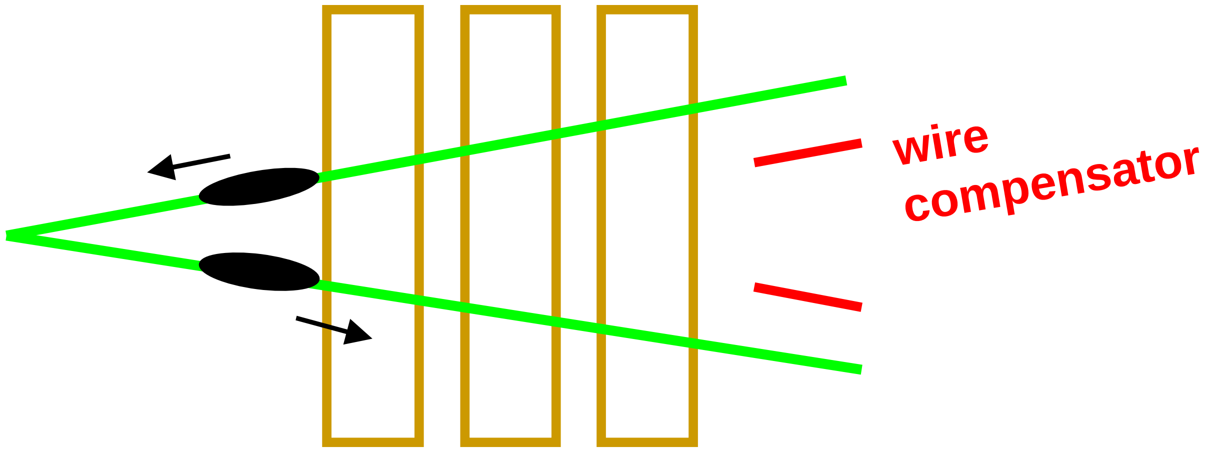
Phased final focus upgrade approach:

- ➔ Phase a: low gradient final focus layouts (existing NbTi)
  (magnet lifetime limited by radiation dose)
- ➔ Phase b: new magnet technology (Nb3Sn [USLARP])
  (higher peak field and more radiation hard)

Additional Phase1 Upgrade Options

- minimize detrimental effect of beam-beam interactions:

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



➔ new proposal and technology! ➔ requires machine studies

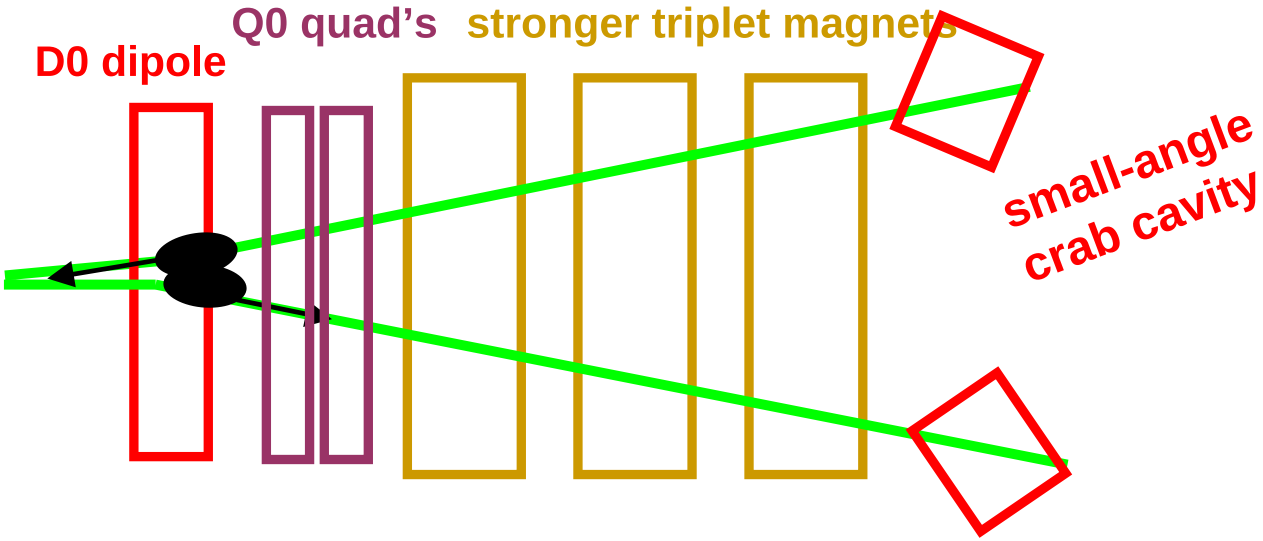
➔ could potentially reduce the required crossing angle

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

Additional Phase1 Upgrade Options

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

2) 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

Additional Phase1 Upgrade Options

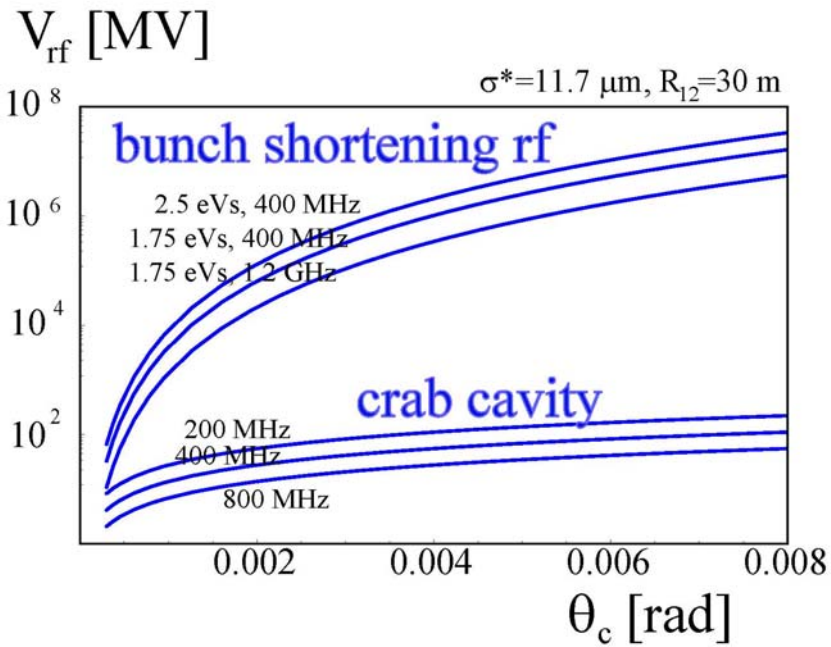
- minimize luminosity loss due to geometric reduction factor:

3) shorter bunch length

➔ expensive in terms of RF

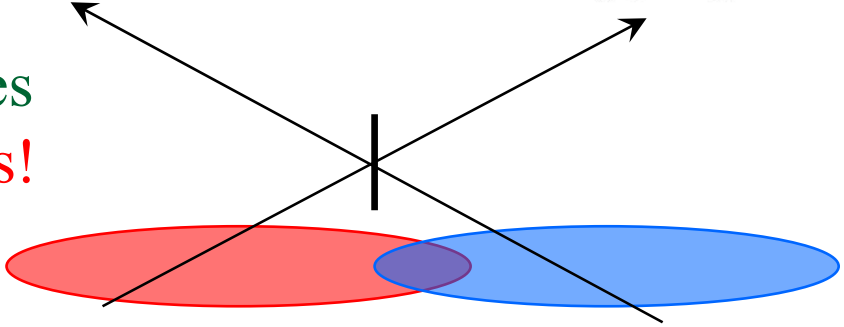
$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

[F. Zimmermann]



4) bunch rotation via crab cavities

➔ new technology for protons!



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

parameter	symbol	ultimate	25 ns, small β*	50 ns, long	
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	$\beta*$ [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 / 2.6	6.7 / 2.9	←
extent luminous region	σ_l [cm]	4.3	3.7	5.3	
comment			D0 + crab (+ Q0)	wire comp.	

W. Scandale and F. Zimmermann LUMI'06

Summary Upgrade Options for 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

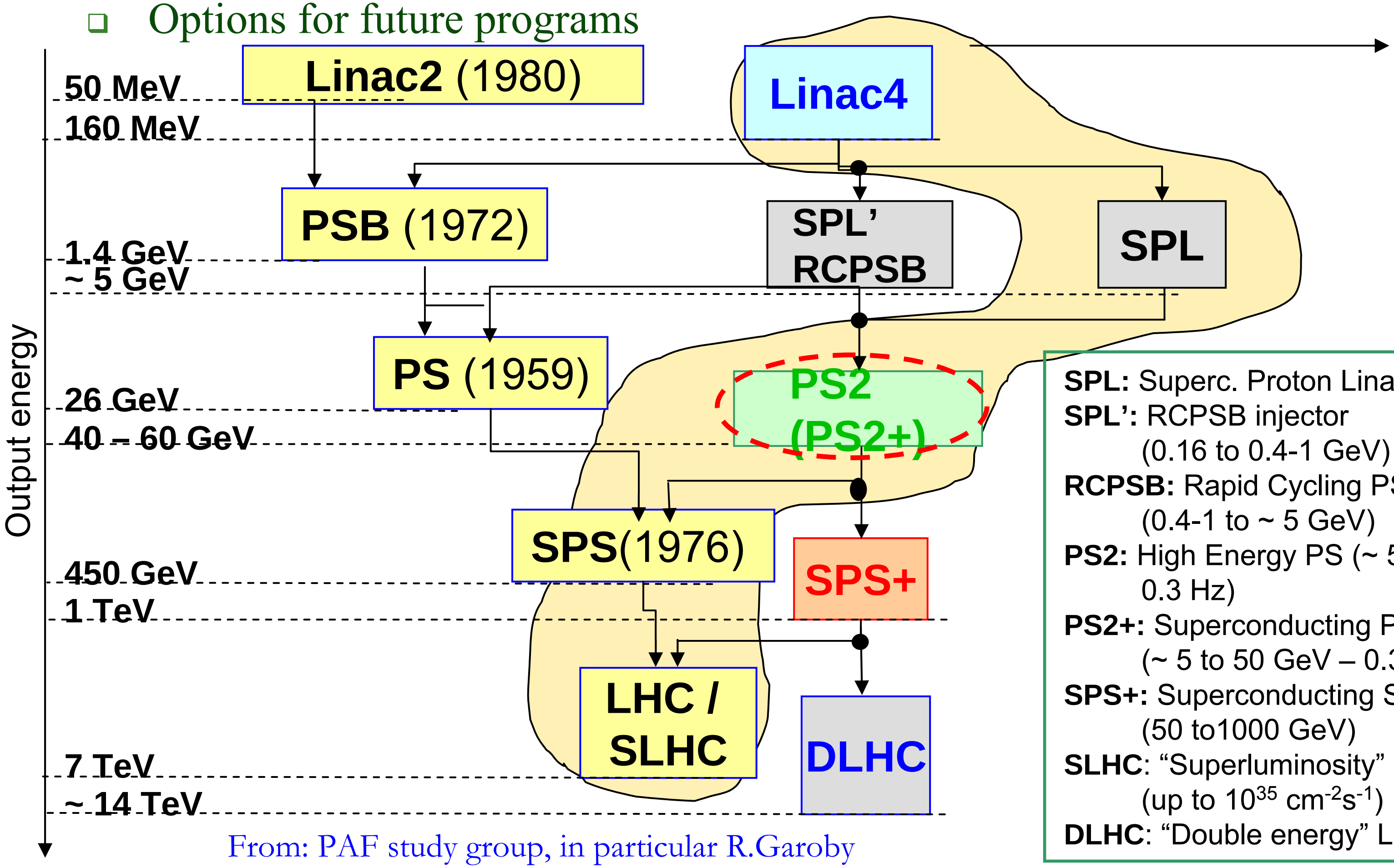
  3) replacement for main proton linac: LINAC4
  → overcomes bottleneck for 'ultimate' LHC parameters
  → solves maintenance problem for existing LINAC2
  → SPL (second phase) could 'bypass' PSB (space charge)

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

→ CERN 'White Paper'

Upgrade Options: Phase 2 White Paper

- Proton Accelerators for the Future (PAF) study – identified upgrade scenarios
  - Reliable operation for the LHC (allow ultimate LHC beam)
  - Options for future programs



From: PAF study group, in particular R.Garoby

SPL: Superc. Proton Linac (~ 5 GeV)
SPL': RCPSB injector
(0.16 to 0.4-1 GeV)
RCPSB: Rapid Cycling PSB
(0.4-1 to ~ 5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
PS2+: Superconducting PS
(~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS
(50 to1000 GeV)
SLHC: "Superluminosity" LHC
(up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (~14TeV)

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