LHC Accelerator Physics Issues

White Paper activities:

-consolidation → overall accelerator complex reliability

-new injector projects:

-LINAC4 → LP SPL (replacement for LINAC2)

-PS2 with LPSPL as injector

→ larger brightness and higher than ultimate beam intensities

LHC IR Upgrade Options

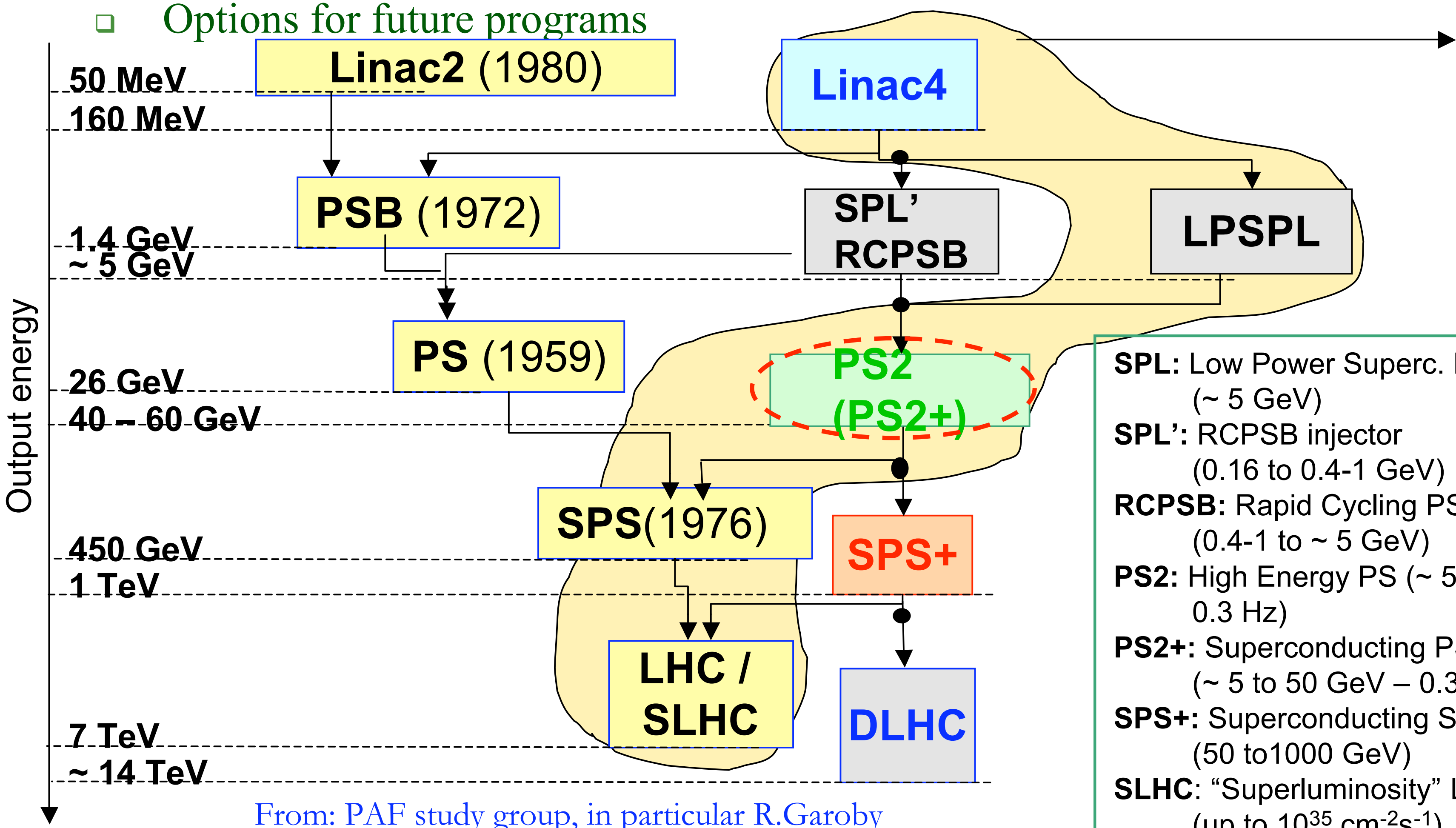
-large aperture triplet magnets

-opening the option for operation with $\beta^* < 0.5$ (e.g. 0.25m)

-aiming for maximum integrated luminosity!

White Paper Upgrade Path

- 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: Low Power 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)

LHC IR Upgrade Options

- Phase 1: consolidation of 'ultimate' performance with $L > 10^{34} cm^{-2} sec^{-1}$

  -large aperture NbTi triplet magnets using existing spare dipole cables with the goal of introducing additional margins for the LHC operation

  -no modifications of the experiment interface and cryogenic infrastructure

  -opening the option for operation with $\beta^* = 0.25m$ and the LHC 'ultimate' beam parameters yielding a performance reach of $L = 3 \times 10^{34}\ cm^{-2}\ sec^{-1}$

  (2011 / 2012 shut down)

- Phase 2:

  -aims at operation beyond ultimate luminosity (the goal is integrated L!!!)

  -implies operation in extremely radiation hard environment (35 MGy/year[@])

  (less than 1 year lifetime for magnets with nominal triplet layout!)

  ➔ new magnet technology and /or special protection / absorber elements

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[@]N. Mokhov et al LPR 633 for ($L = 10\ 10^{34}\ cm^{-2}\ sec^{-1}$)

LHC IR Upgrade Options

- Phase 2 magnet R&D:

  magnet R&D for Nb_3Sn triplet magnet technology is done in close collaboration with USLARP and the FP6 CARE ESGARD program

  ➔ the USLARP collaboration performed already several promising short magnet tests (1m) and plans for the construction of a working full scale (ca. 4m) prototype by the end of 2009

  ➔ a FP7 JRA aims at the development of a 13T Nb_3Sn dipole magnet

- Phase 2 collimation R&D: done in collaboration with USLARP and FP7

  ➔ Jaw robustness and Z for ultimate beam intensities & cleaning efficiency

- absorber and protection R&D: still without a clear project structure and a clear definition of project milestones (TAS & TAN design for $L = 10^{35}$ cm^{-2} sec^{-1} & radiation in ventilation from cleaning insertions)

LHC IR Upgrade Options

- Phase 2 options:

  the current studies look for a 10 fold increase in the peak luminosity & identified 2 different options (doubling the bunch number not possible[@]):

  ES: Low β^* (8cm[@] → 14cm[$]) with 'ultimate' beam parameters requiring significant hardware modifications in the IR & detector regions (25ns)

  LPA: operation with larger than 'ultimate' beam intensities and 'flat bunches' but without modifications in the detector regions (50ns)

- additional measures required for the Phase 2 upgrade:

  -upgrade of the cryogenic plants for IR1 & IR5 (additional new plants)
  -improved shielding and protection of triplet magnets
  -both Phase 2 options require additional measures that go beyond magnet R&D and that could benefit already the Phase 1 upgrade

  → Choice for Phase 2 implementation depends on validity of these measures

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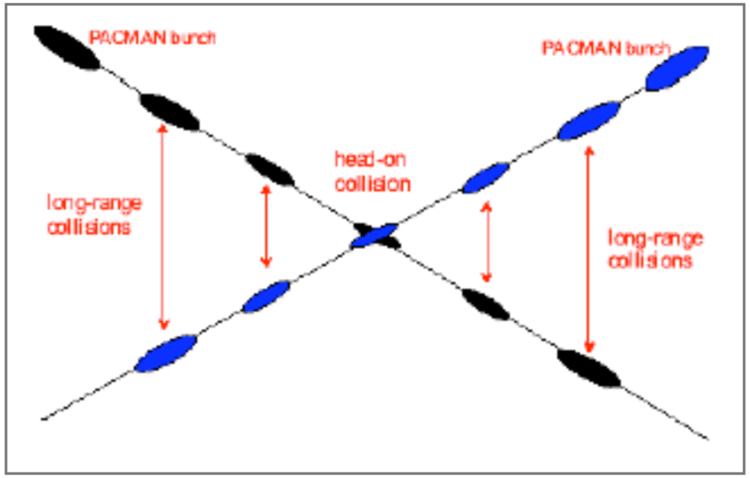
[@]LUMI'06 workshop [$]BEAM'07 workshop

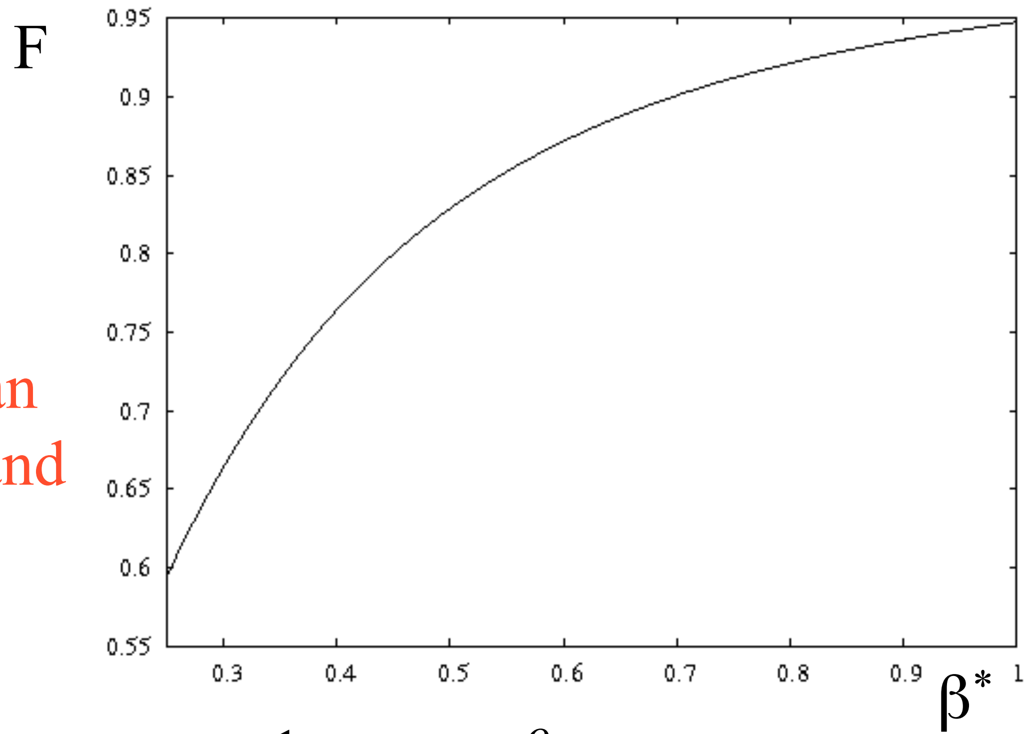
Additional Measures for the IR Upgrades

Minimizing the luminosity loss due to the crossing angle at the IP:



Unwanted IPs require operation with a crossing angle ➔ long range b-b interactions

The crossing angle results at the IP in an increase of the effective cross section and thus a reduction of the luminosity.



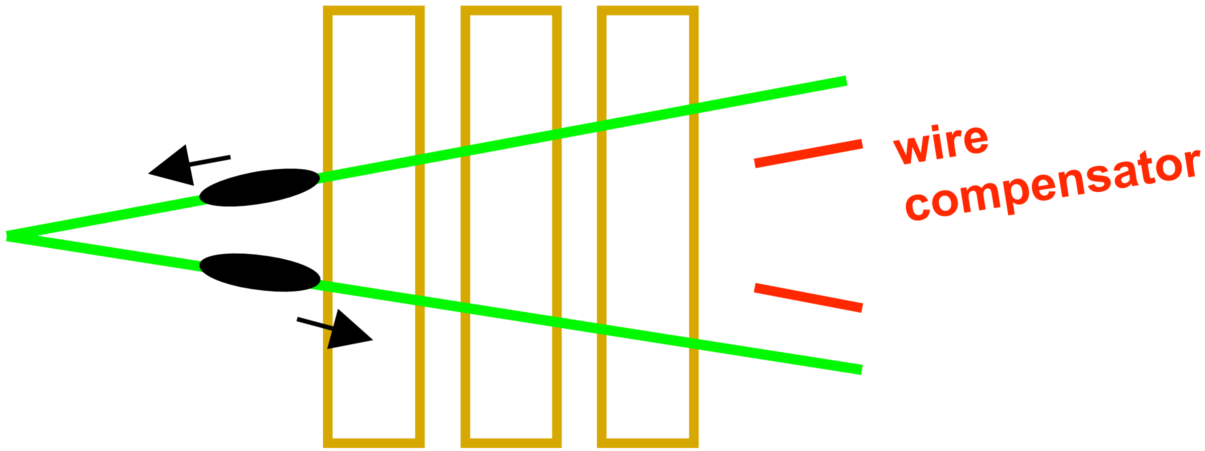
$$F = \frac{1}{\sqrt{1+\phi^2}}; \quad \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$ Piwinski angle

Assuming a constant normalized beam separation the reduction factor decreases with decreasing β^*!

Additional Measures for the IR Upgrades

Minimizing the luminosity loss due to the crossing angle at the IP:

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



➔ new proposal and technology! ➔ requires MDs (USLARP & CERN[@])

➔ could potentially reduce the required crossing angle

➔ similar proposal for head-on collisions: electron lens[#]

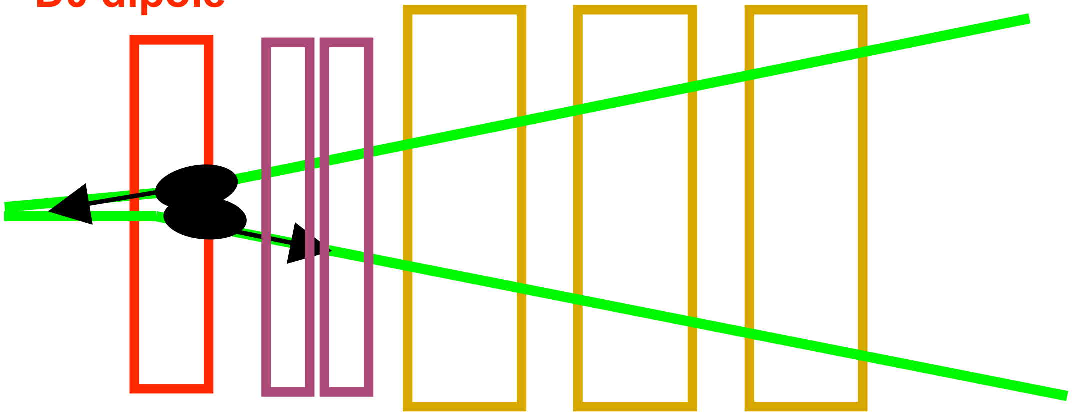
(➔ larger operation margins)

[@]Machine Studies in the SPS; [#] FNAL & USLARP at LUMI'06

Additional Measures for the IR Upgrades

Minimizing the luminosity loss due to the crossing angle at the IP:

2) reduce the crossing angle at the IP via dipole magnets deep inside the detectors (slim dipole option)

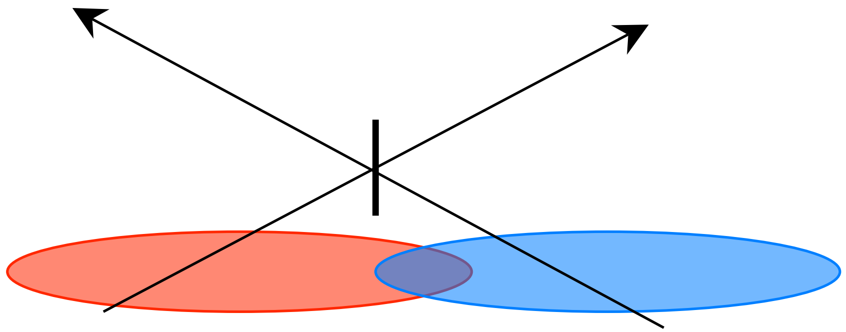


- ➔ requires magnet integration inside the detectors (back scattering/calorimetry!)
- ➔ impact on detector performance and physics reach?!
- ➔ requires new magnet technology (new R&D effort in addition to triplet)
- ➔ implies parasitic collisions at 4 σ for 25ns bunch spacing
- ➔ similar proposal exists for slim quadrupole magnets

Additional Measures for the IR Upgrades

Minimizing the luminosity loss due to the crossing angle at the IP:

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



➔ requires high precision RF technology and control

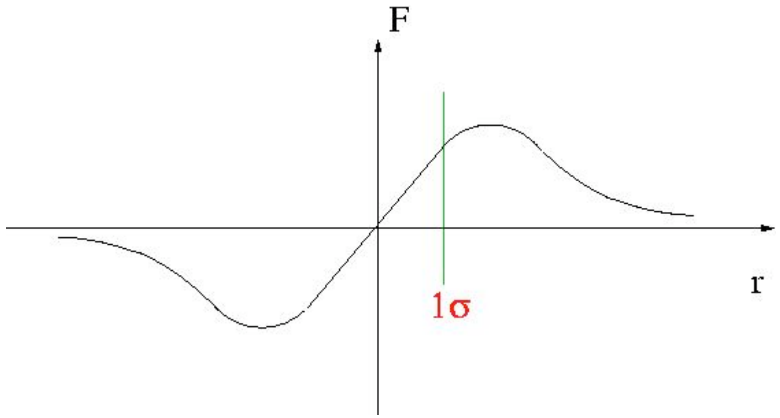
➔ currently used in KEK B-factory

➔ no experience with operation in proton machines (noise!)

➔ requires prototyping and machine studies (lead time & resources?)!

Additional Measures for the IR Upgrades

Minimizing the effect of the head-on beam-beam collisions at the IP:



➔ compensate the head-on beam-beam force by additional e^-/p^+ interactions (opposite sign of the p^+/p^+ b-b force)

➔ development of a prototype 'electron lens' at FNAL

➔ this new tool is currently studied / tested in Tevatron (and RHIC in 2008)

➔ still open issues: Tevatron observes significant operation improvements when using the lens as a fast quadrupole but no successful operation as b-b lens yet

➔ not yet included in the Phase 2 upgrade options (but interesting if it works!)

Additional Measures for the IR Upgrades

operation with large Piwinski parameter:

F. Zimmermann Beam'07

$$L_{Gauss} \approx \frac{1}{2} \frac{f_{coll} \cdot \nu}{r_p \cdot \beta^*} \cdot \Delta Q_{tot} \cdot N_b$$

$$L_{flat} \approx \frac{1}{\sqrt{2}} \frac{f_{coll} \cdot \nu}{r_p \cdot \beta^*} \cdot \Delta Q_{tot} \cdot N_b$$

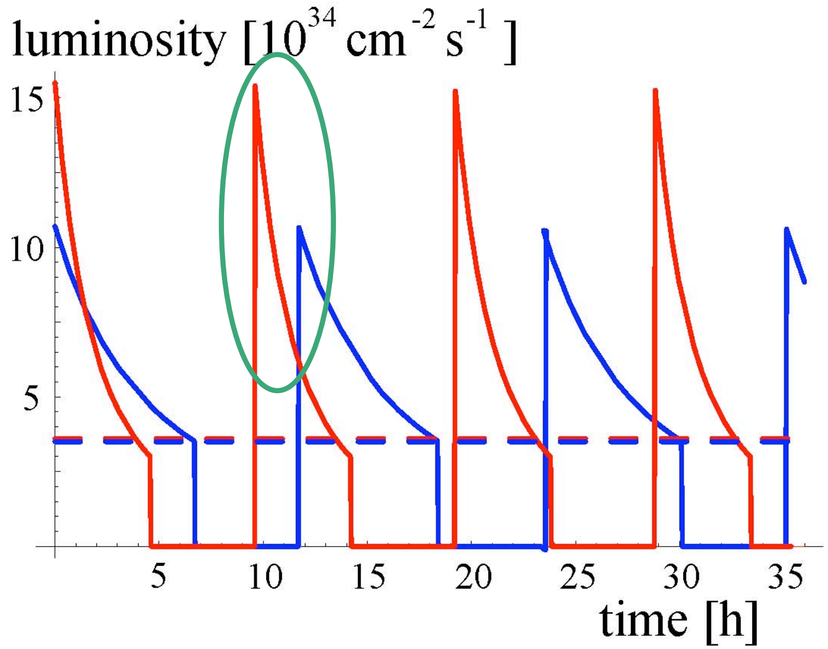
- ➔ 40% higher luminosity for flat bunch profile
- ➔ operation in 'large Piwinski angle' regime allows increase of bunch intensity independent of bb tune spread

- ➔ inefficient use of bunch current (only linear increase of L with N_b)
- ➔ increased luminosity lifetime
- ➔ allows increase of bunch current beyond beam-beam limit
- ➔ efficiency of method depends partly on 'flatness' of the bunch distribution
- ➔ feasibility and efficiency not yet demonstrated in real operation
  (could be tested in RHIC or in the LHC during first years of operation)

Additional Measures for the IR Upgrades

luminosity leveling:

(plot from F. Zimmermann in Beam'07)



- ➔ potential loss of integrated luminosity due to initial luminosity tuning
- ➔ short luminosity life time
- ➔ high event rate at beginning of run

- ➔ changing the luminosity during a physics run can counter act the above problems for the price of a small loss in integrated luminosity (ca. 10% for T_{turn} = 5h [G. Sterbini & J-P Koutchouk Beam'07])
- ➔ luminosity variation can be done either via β^* (difficult in operation [Tevatron]) or crossing angle adjustments

- ➔ feasibility and efficiency not yet demonstrated in real operation

Summary Additional Measures for the IR Upgrades

- the following measures are in addition to larger triplet apertures!
- minimizing the luminosity loss due to crossing angle:
  - → compensation of long range b-b encounters with wire compensators
  - → early separation scheme with integrated dipole magnets
  - → bunch rotation with crab cavities
- minimizing effect of head-on beam-beam collisions: → 'electron lens'
- maximizing luminosity via bunch current: → flat beam operation
- maximizing usable integrated luminosity: → luminosity leveling
- improved triplet magnet protection: → magnetic TAS; absorbers & masks

Phase 2 Beam Parameter Options[@]

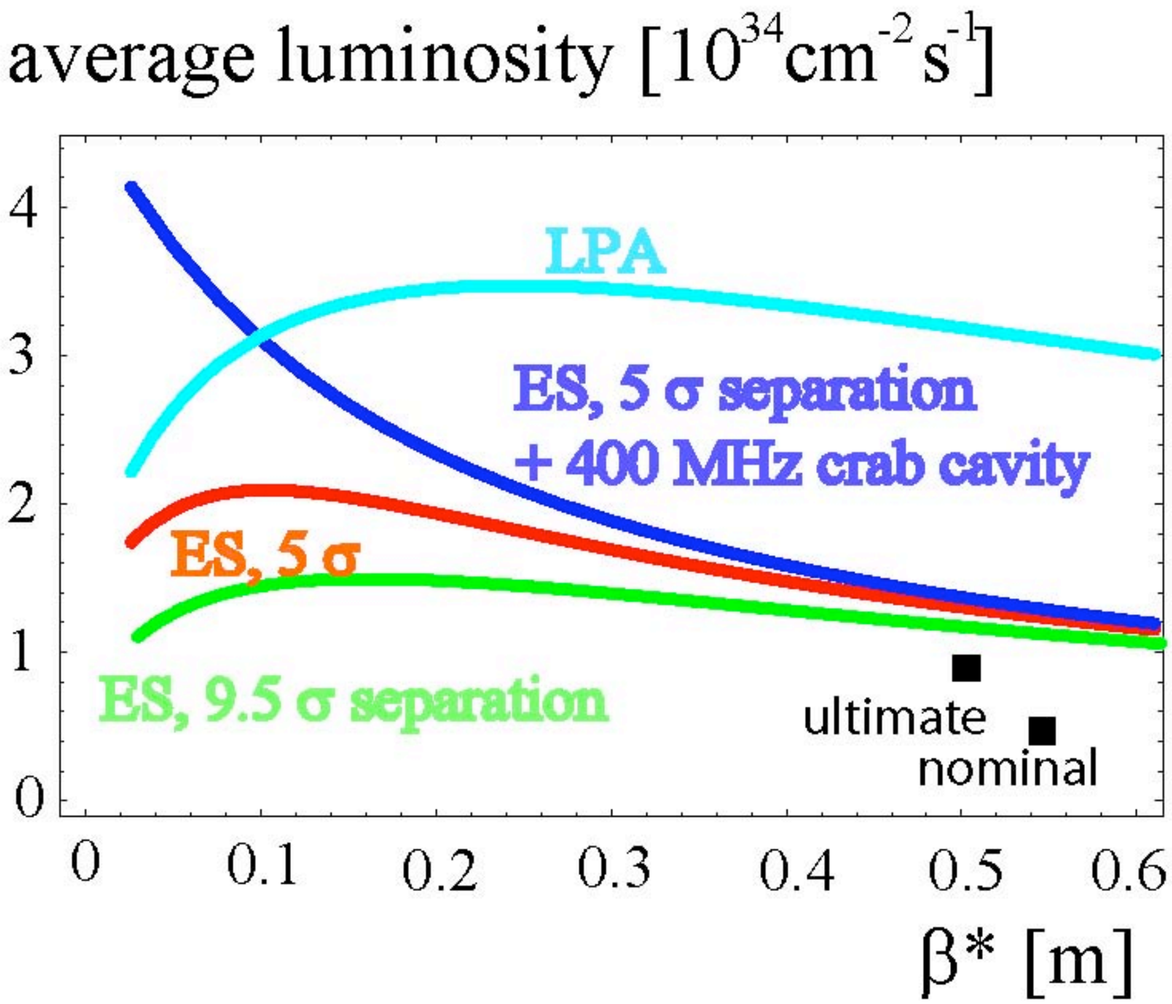
Summary of the nominal, 'ultimate' and Phase2 upgrade beam parameters

parameter	nominal	ultimate	ES (25ns)	LPA (50ns)
Protons per bunch	$1.15\ 10^{11}$	$1.7\ 10^{11}$	$1.7\ 10^{11}$	$4.9\ 10^{11}$
Total beam current	0.58 A	0.86 A	0.86 A	1.22 A
Longitudinal bunch profile	Gauss	Gauss	Gauss	Flat
β^* at the IPs	0.55m	0.5m	8cm (→14cm)	25cm
Full crossing angle at the IPs	285μrad	315μrad	0μrad	381μrad
Peak luminosity [$cm^{-2}\ sec^{-1}$]	$1\ 10^{34}$	$2.3\ 10^{34}$	$15.5\ 10^{34}$	$10.7\ 10^{34}$
Peak events per crossing	19	44	294	403
Initial luminosity lifetime	25h	14h	2.2h (wo leveling)	4.5h (wo leveling)
Stored beam energy	370MJ	550MJ	550MJ	780MJ
Additional requirements	-	-	Large aperture triplet magnets	Large aperture triplet magnets
			Efficient absorbers / radiation hard	Efficient absorbers / radiation hard
			(wire compensators)	(wire compensators)
			D0	
			Crab cavities	
			luminosity levelling	flat beam operation
			Cryoplant upgrade	Cryoplant upgrade

@LUMI'06 workshop proceedings

Phase 2 Luminosity Potential

F. Zimmermann at Beam'07



-average luminosity over one physics run assuming optimum run length

-2 different optimization branches

-both requiring different technologies and operation modes

-estimates done without luminosity leveling

-Phase 2 might provide average luminosity increase by a factor 3 to 4 wrt ultimate performance in most optimistic scenario

LHC Performance Evolution: Integrated Luminosity@

- nominal: $L = 10^{34}$ cm^{-2} sec^{-1}

➔ T_{turn} = 10h; τ_{lumi} = 15h ➔ $L_{integrated}$ = 70 fb^{-1}

➔ T_{turn} = 5h; τ_{lumi} = 15h ➔ $L_{integrated}$ = 80 fb-1 ➔ weak impact of T_{turn}

- ultimate: $L = 2.3 \times 10^{34}$ cm^{-2} sec^{-1}

➔ T_{turn} = 10h; τ_{lum} = 10h ➔ $L_{integrated}$ = 127 fb^{-1}

➔ T_{turn} = 5h; τ_{lumi} = 10h ➔ $L_{integrated}$ = 155 fb^{-1} ➔ moderate impact of T_{turn}

- Phase IIa: $L = 15.5 \times 10^{34}$ cm^{-2} sec^{-1} (Lumi'06 in Valencia)

➔ T_{turn} = 10h; τ_{lum} = 2.5h ➔ $L_{integrated}$ = 374 fb^{-1}

➔ T_{turn} = 5h; τ_{lumi} = 2.5h ➔ $L_{integrated}$ = 535 fb^{-1} ➔ big impact of T_{turn} (50%)

- Phase IIb: $L = 6.2 \times 10^{34}$ cm^{-2} sec^{-1} (BEAM'07 at CERN)

➔ T_{turn} = 5h; τ_{lumi} = 7h ➔ $L_{integrated}$ = 370 fb^{-1} ➔ still significant impact of T_{turn}

➔ only efficient with luminosity leveling and if $T_{turn} \leq 5$h

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@O Brüning at Beam'07 assuming 200 days of operation per year

Accelerator Physics Wish list for SLHC

- Phase 2 collimation ✔

- magnet R&D ✔: large aperture triplet (NbTi + Nb_3Sn) and 'slim' magnets

- additional measures:
  -continue LRBB wire studies with goal of demonstrating feasibility
   and quantifying gains in operation ✔
  -continue BB electron lens studies with goal of demonstrating feasibility
   and quantifying gains in operation ✔
  -demonstrate feasibility of 'flat beam' operation and luminosity leveling
  -design R&D and prototyping of a CRAB cavity for the LHC
  -demonstration of the feasibility for using CRAB cavities in proton machines
  -shielding improvements (TAS / TAN)

- LHC injector complex:
  -SPS upgrade measures:
   (e.g. damper and feedback system for curing electron cloud instabilities)
  -studies towards a PS2 ✔ (White Paper)