LHC Performance Target

With input from many colleagues from WP2 and CERN groups

Based on discussions at the LHC Chamonix workshop in 2011 and the LIU – HL-LHC 'Brainstorming' meetings

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Performance optimization for the LHC

Luminosity (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s)$$

Event pileup & e-cloud

➔ 1) maximize bunch brightness (beam-beam limit) ➔ $[N_b/\varepsilon_n]$
➔ 2) minimize beam size (constant beam power; aperture)
➔ 3) maximize number of bunches (beam power; e-cloud)
➔ 4) compensate for 'R'

Operation at performance limit

➔ choose parameters that allow higher than design performance
➔ leveling mechanisms for controlling performance during run

Potential Performance Limitations for the LHC

Bunch Intensity:

1) Beam-Beam interaction ➔ limit for beam brightness and Θ?
➔ no limit found yet for head-on ➔ ΔQ = 0.02 – 0.03

3) Collective effects (e.g. TMCI) ➔ ca. 3.5 10^{11} ppb (single bunch)
[Elias Metral]

➔ heating of equipment (e.g. MKI) ➔ HL-TC

4) e-cloud effect ➔ depends on bunch spacing and SEY

➔ 50ns operation requires SEY < 2.1!
➔ e-cloud with 50ns bunch spacing has larger bunch limit than single bunch TMCI limit for all SEY values!
➔ 25ns requires SEY < 1.3 for 2 10^{11} ppb

LHC Challenges: e-cloud

F. Zimmermann, Chamonix 2011

25-ns bunch spacing   50-ns bunch spacing

-e-cloud heat load limit for 50ns larger than TMCI limit

-e-cloud heat load limit for 25ns compatible with bb limit if

$\delta_{max} < 1.3$

or with special bunch patterns that minimize e-cloud

(e.g. micro batches or satellite bunches)

-HL-LHC limit of the arc cryo system (upgrade) ➔ PLC

High Luminosity LHC

Emittance Margin for SPS to HL-L...

- IBS growth @ injection: ca. 10% in 20min ... ...ess of 9 10... ...ad

(Fill 2028: Bunch intensity 1.26 e+11; Bunch leng... ...ttance ~ 1.4 μm)

➔ density close to HL-LHC g...

➔ expect similar growth f...

- Growth @ ram... ...ed to damper gain and tune feedback?

- Growt... ...e: varies between zero and 10% depending on ... plane

Assume for now 10% to 20% emittance growth between SPS extraction and HL-LHC luminosity production

should be able to find better solution for HL-LHC!

Potential Performance Limitations for the LHC

emittance:

1) MADX simulation for IBS with beam parameters from Fill 2028:

(Bjorken-Mtingwa algorythm assumes Gaussian distributions)

➔ MADX-IBS growth rate ≈ 3 hours @ injection

(V_{RF} = 6 MV; τ_s = 1.15ns, ε_s = 0.38-0.53 eVs ➔ $\sigma_{\delta E/E} \approx 0.3\ 10^{-3}$)

➔ request for HL-LHC paramters IBS growth rate ≈ 9 hours

➔ $\varepsilon_{n,inj}(25ns) \geq 2.0\ \mu m$; $\varepsilon_{n,inj}(50ns) \geq 2.5\ \mu m$

2) Allow for 20% emittance growth during injection and ramp:

➔ $\varepsilon_{n,col}(25ns) \geq 2.5\ \mu m$; $\varepsilon_{n,col}(50ns) \geq 3.0\ \mu m$

LHC Challenges: Beam-Beam Interaction

- Design report: $\Delta Q_{\text{beam-beam}} < 0.01$

→ 3 head-on/bunch ➔ $\xi_{\text{beam-beam}} < 3.3\ 10^{-3}$ ➔ $N < 1.2\ 10^{11}$

2 head-on/bunch ➔ $\xi_{\text{beam-beam}} < 5\ 10^{-3}$ ➔ $N < 1.7\ 10^{11}$

@ nominal emittance: $\varepsilon_n = 3.75\ \mu\text{m rad}$

- Operation experience: $\Delta Q_{\text{beam-beam}} < 0.02 – 0.03$

→ 2 head-on/bunch ➔ $\xi_{\text{beam-beam}} < 13\ 10^{-3}$ ➔ $N < 3.7\ 10^{11}$

@ $\varepsilon_n = 3.0\ \mu\text{m rad}$

➔ $N < 3.1\ 10^{11}$

@ $\varepsilon_n = 2.5\ \mu\text{m rad}$

LHC Challenges: Beam-Beam Inte... n

- Operation experience: $\Delta Q_{beam\text{-}beam} < 0$ ...
- 3 head-on/bunch ➔ $\xi_{beam\text{-}beam} <$ ... .3 10^{11}

$\varepsilon_n = 3.0$ µm rad

➔ $N < 1.94\ 10^{11}$

@ $\varepsilon_n = 2.5$ µm rad

Assuming head ...

Consid... beam-beam tune shift will be reduced by ... reduction factor analogue to the ... nly true for round beams with alternate ... angle planes), this should still be OK.

2 Beam effects and long range beam-beam limitations
Need to be further assessed once the LHC operates with
25ns bunch spacing

High Luminosity LHC

Potential Performance Limitations for the LHC

beta*:

1) Aperture ➔ interaction with WP3 of the HL-LHC: $\beta^* = 0.15$m

2) Chromatic aberrations & optics matchability

➔ OK for $\beta^* \geq 0.3$m (Phase 1 solution)

➔ ATS squeezing mechanism for $\beta^* < 0.3$m

3) Geometric reduction factor:

➔ moderate increase of L with reduced β^*

➔ margin for L leveling (Crab Cavities? or dynamic β^*)

Upgrade Considerations: Beam L... time

Chamonix 2011

- For given luminosity τ ... current

$$\frac{dN_{tot}}{dt} = - \; N$$

$$N(t) = N_{tot}$$

$$t_{eff} = \frac{N_{tot}}{n_{IP} s \, L_{lev}}$$

τ_{eff}(25ns) = 17.2 hours

for 6.2 10^{14} p/beam and L_{level} = 5 10^{34} cm^{-2} s^{-1}

τ_{eff} (50ns) = 27.2 hours

for 4.9 10^{14} p/beam and L_{level} = 2.5 10^{34} cm^{-2} s^{-1}

$N_{nominal}$

4

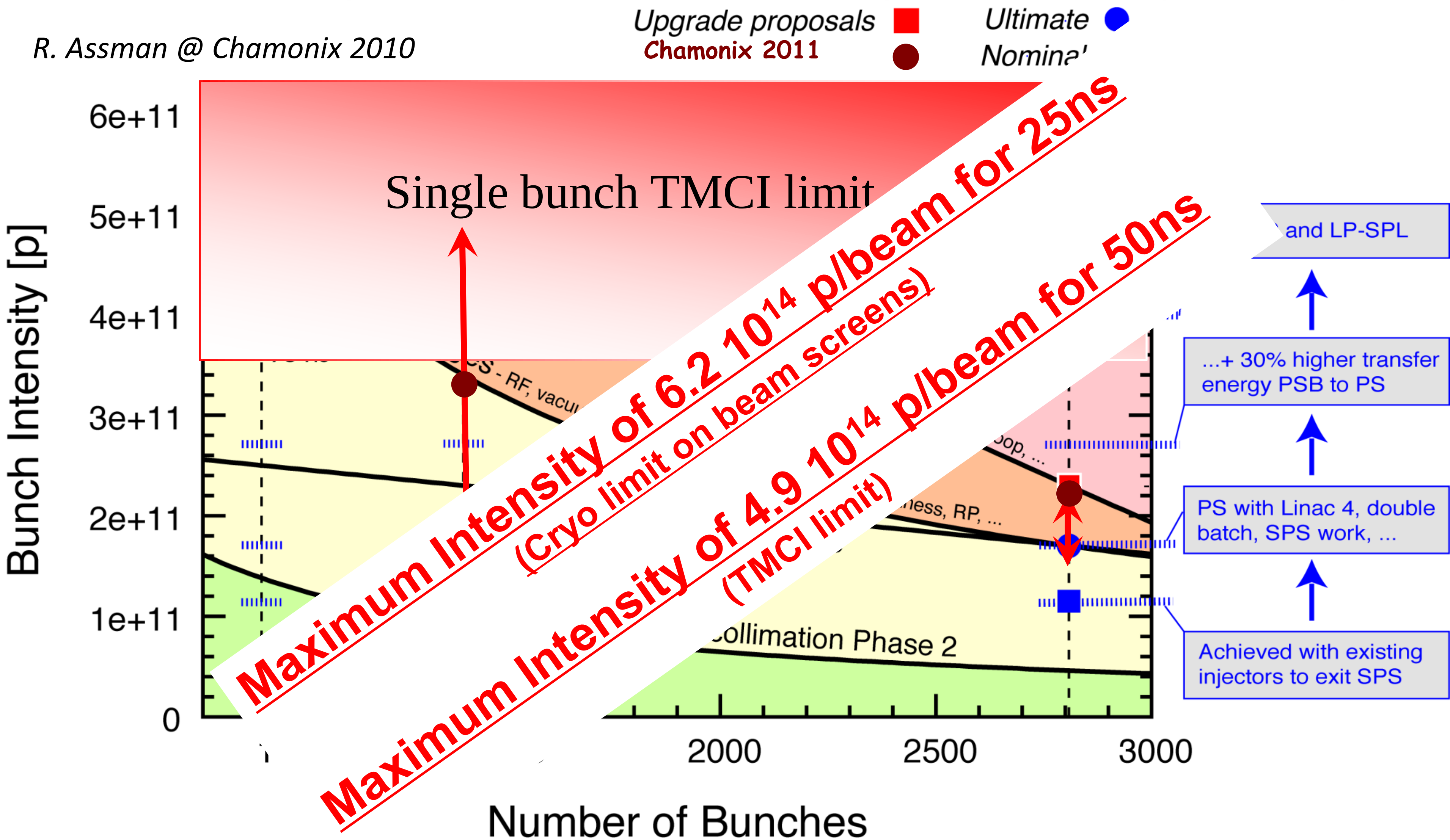
...nbarn)

➔ argument for ... narios with maximum beam current

High Luminosity LHC

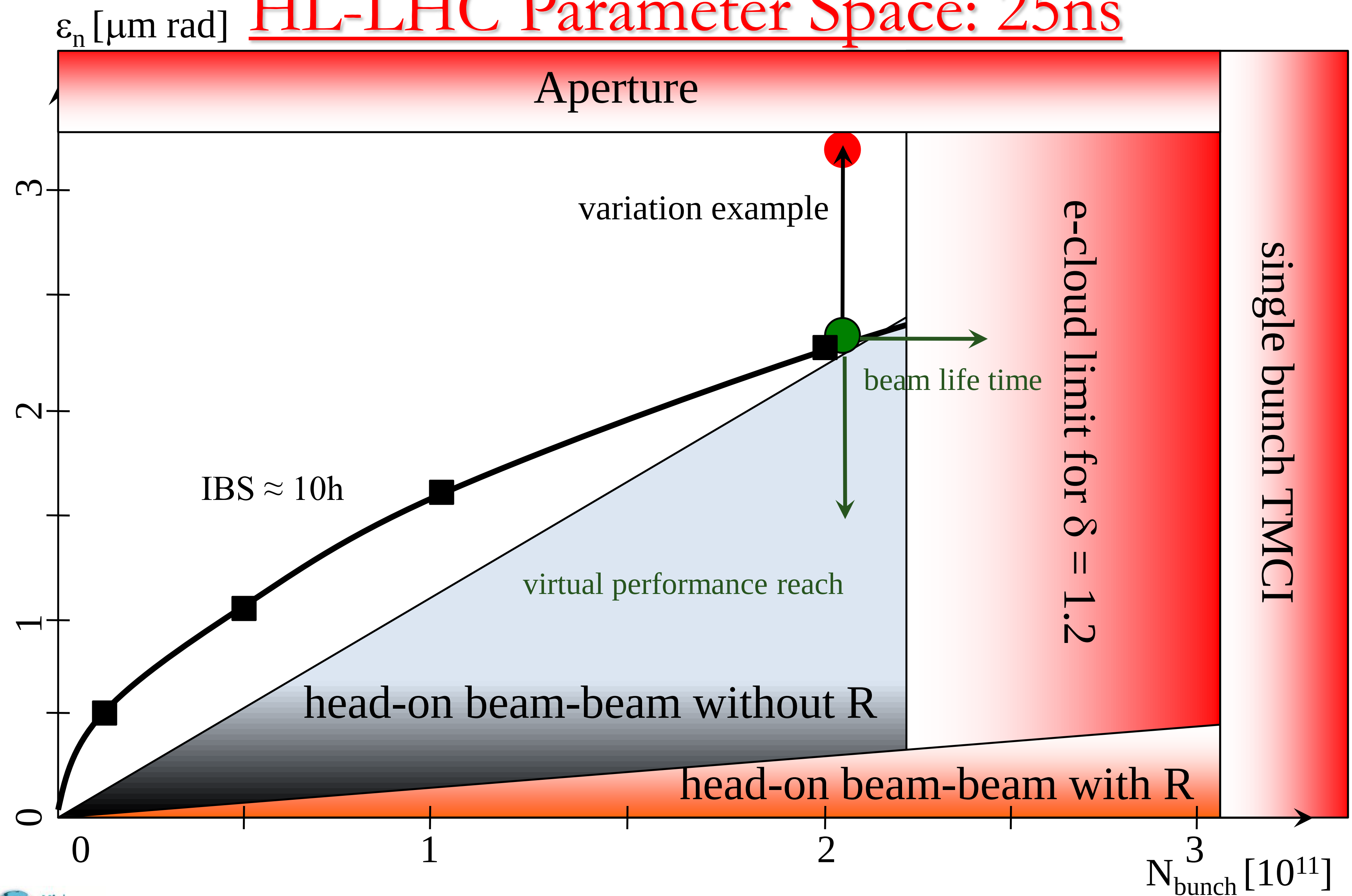
Summary of LHC Intensity Limits (7TeV)

R. Assman @ Chamonix 2010

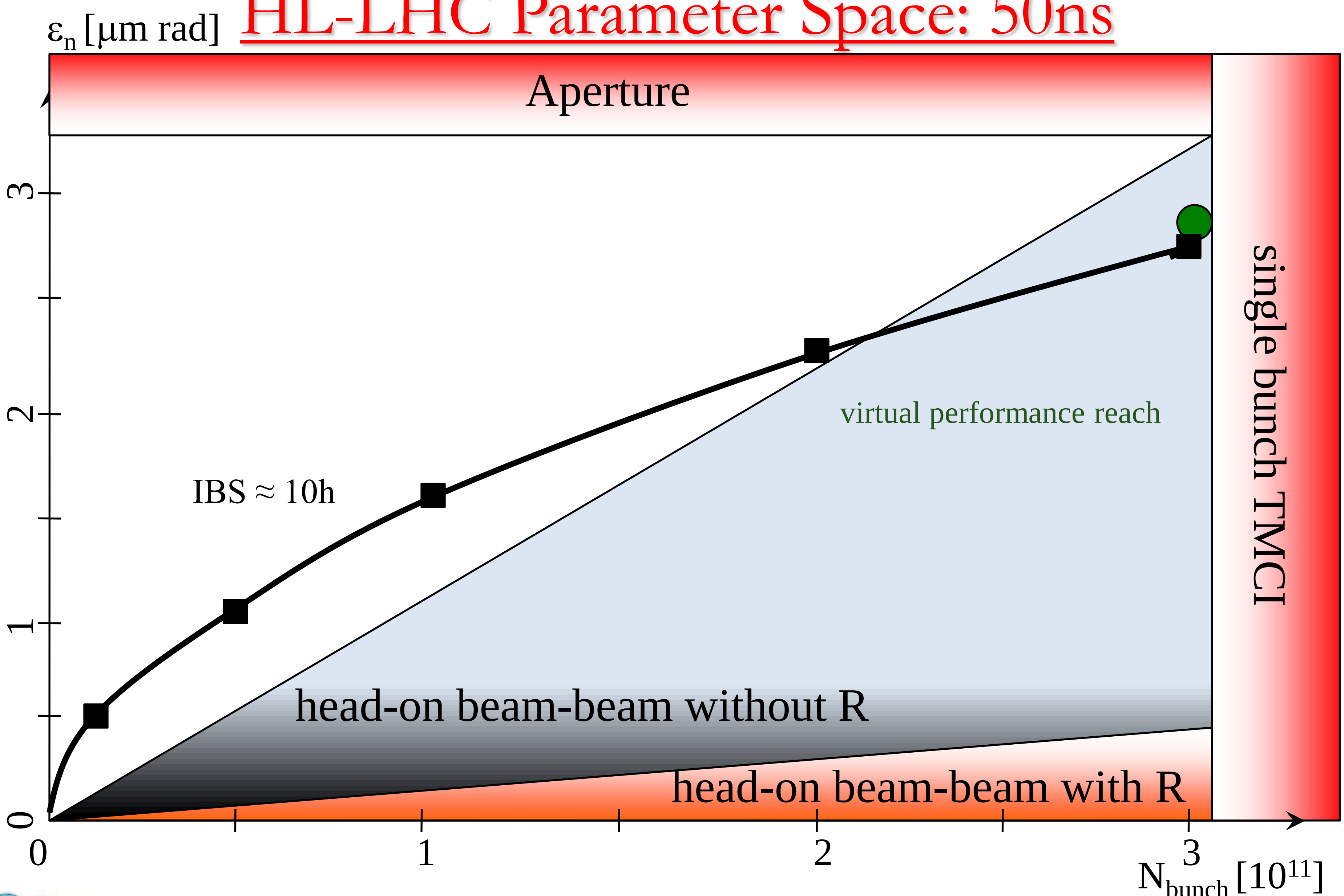


Ideal scenario: no imperfections included!

HL-LHC Parameter Space: 25ns



HL-LHC Parameter Space: 50ns



HL-LHC Performance Goals

- Leveled peak luminosity: $L = 5\ 10^{34}\ cm^{-2}\ sec^{-1}$
- Virtual peak luminosity: $L > 10\ 10^{34}\ cm^{-2}\ sec^{-1}$
- Integrated luminosity: 250 fb^{-1} per year
- Total integrated luminosity: ca. 3000 fb^{-1}

HL-LHC Performance Estimates

‘Stretched’ Baseline Parameters following 2nd HL-LHC-LIU:

Parameter	nominal	25ns	50ns
N	1.15E+11	**2.2E+11**	**3.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.12**	**0.89**
x-ing angle [μrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**18.5**	**17.2**
IBS longitudinal [h]	61 -> 60	**20.4**	**16.1**
Piwinski parameter	0.68	**3.12**	**2.85**
geom. reduction*	0.83	**0.305**	**0.331**
beam-beam / IP	3.10E-03	**3.3E-03**	**4.7E-03**
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**
Virtual Luminosity	$1.2\ 10^{34}$	**$24\ 10^{34}$**	**$26\ 10^{34}$**

Events / crossing (peak & leveled L) 19 -> 28 **207** **476** **140** **140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

→ sufficient room for leveling (with Crab Cavities)

Virtual luminosity (25ns) of $L = 7.4 / 0.305\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 24\ 10^{34}\ cm^{-2}\ s^{-1}$ (‘k’ = 5)

Virtual luminosity (50ns) of $L = 8.5 / 0.331\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ (‘k’ = 10)

*) without Hourglas effect

(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

Upgrade Considerations: Beam Lifetime

- Run length assuming leveled luminosity: $L \propto \frac{N_{tot}^2}{n_b}$

➔ virtual luminosity of $k * L_{level}$ ➔ $T_{level} = (1-1/\sqrt{k}) * \tau_{eff}$

➔ τ_{eff} = 17.2 hours for
6.2 10^{14} p/beam and
$L_{level} = 5\ 10^{34}\ cm^{-2}\ s^{-1}$:

k = 1.5 ➔ T_{level} = 3.1 h

k = 5.0 ➔ T_{level} = 9.3 h

➔ τ_{eff} = 27.2 hours for
4.9 10^{14} p/beam and
$L_{level} = 2.5\ 10^{34}\ cm^{-2}\ s^{-1}$:

k = 3.5 ➔ T_{level} = 12.7 h

k = 10.0 ➔ T_{level} = 18.8 h

Upgrade Considerations: Integrated Luminosity

- Integrated luminosity: leveling to constant luminosity

$L_{int} = L_{level} * T_{level}$

➔

$$L_{\text{int}} = \left(1 - \sqrt{L_{level}/L_{virt}}\right) \times \frac{N_{tot}}{n_{IP}\sigma}$$

(σ=100 mbarn)

➔ integrated luminosity directly proportional to total current

➔ k = 1.5; L_{int} = 0.57 fb^{-1} per fill for 25ns over 3.1h

➔ k = 3.5; L_{int} = 1.07 fb^{-1} per fill for 50ns over 12.7h

➔ k = 5.0; L_{int} = 1.71 fb^{-1} per fill for 25ns over 9.3h

➔ k = 10; L_{int} = 1.57 fb^{-1} per fill for 50ns over 18.8h

Upgrade Considerations: Integrated Luminosity

Phase	Days	Comment
Commissioning	21	
Scrubbing run	10	
5 MDs	22	4.5 days per slot
6 Technical stops	30	5 days (4 days TS plus 1 day recovery with beam)
Special requests	10	TOTEM/ALPHA Intermediate energy run Luminosity scans
Intensity ramp up	~39	
Total high intensity	~130	
Ion setup	4	
Ion physics	24	
TOTAL	290	

Can hope for ca. 150 days / year for HL-LHC operation

➔ implies 1.7 fb^{-1} /day
➔ ca. 1 to 3 fills per day

M. Lamont March 2011

HL-LHC Performance Estimates: Variation

- 25ns case:

L_{peak} (without CRAB cavities) = 7.4 10^{34} cm^{-2} sec^{-1}

$L_{virtual}$ (with CRAB cavities) = 24 10^{34} cm^{-2} sec^{-1}

T_{fill} (without CRAB cavities) = 3.1h

T_{fill} (with CRAB and perfect compensation) = 9.3 h

490 Fills per year without CRAB; 160 with CRAB

Efficiency = 39%

Upgrade Considerations: Integrated Lu sity

Machine Efficiency:

➔ Efficiency = number of fills per day * fill-le

Case 1: 25ns ➔ 1 to 2.14 fills

➔ 148 to 321 fills f

➔ fill-length=

➔ Efficie

6.2 10^{14} p/beam

Case 2: ls per day:

s for reaching 250 fb^{-1}

time = 13h to 19h

iency ≈ 75%

4.8 10^{14} p/beam

➔ compared to 25% - 35% during 2011 and 2012 operation

➔ independent of number of involuntary beam dumps

➔ independent of ratio of average run length and turnaround time!

Potential limitations: General worries

- How confident are we that average fill times are longer than 7h?
  - ➔ RF trips
  - ➔ QPS and PC trips
    - } ➔ *aging after 15+ years of operation?*
  - ➔ beam abort due to R2E ➔ **losses for operation with > 1A?**
  - ➔ UFO rate ➔ **cleaning?**

  - ➔ Very few operator initiated EOFs in 2010 and 2011 operation!!!!!!

- How confident are we that we can overcome e-cloud for 25ns?
  - ➔ HL-LHC goals require above ultimate intensities with sub-nominal ε_n
    - ➔ requires SEY of less than 1.3!
    - ➔ keep 50ns option alive!
    - ➔ apart from pile-up, 50ns has a high performance potential!

High Luminosity LHC

Other Topics for discussion in the afternoon

Bunch Intensity:

1) Limitations other than the LHC cryo system (e-cloud instability, Z heating; impact of bunch length etc.)
2) Maximum cryogenics cooling power in the arcs for HL-LHC with cryo upgrade.
3) Attainable average Turnaround time for the LHC.
4) Estimate for the attainable average fill length in the HL-LHC (ca. 5 hours in 2011 operation!).
5) Dynamic beta squeeze during physics?
6) Maximum tolerable Chromatic aberrations.

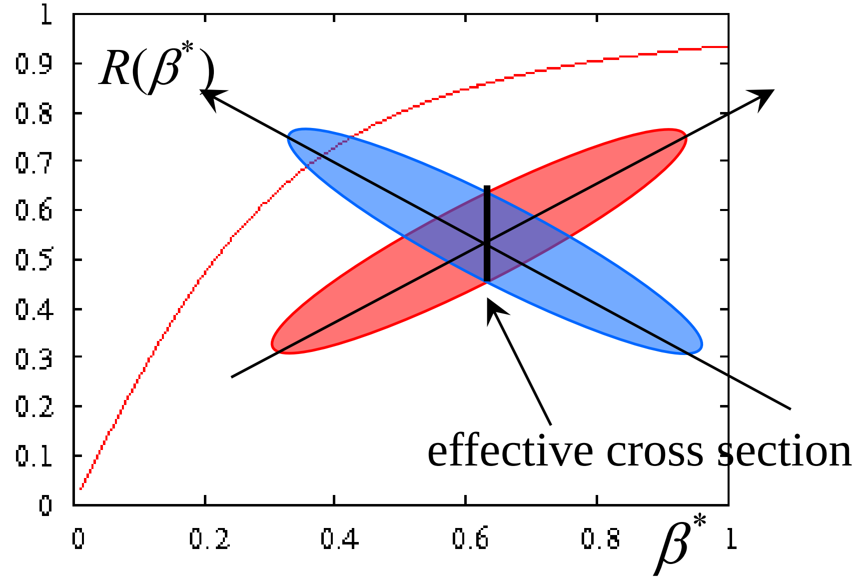
cern.ch

Geometric Reduction Factor: R

- geometric luminosity reduction factor:

Piwinski angle

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



large crossing angle:

➔ reduction of long range beam-beam interactions

➔ reduction of head-on beam-beam parameter

➔ reduction of the mechanical aperture

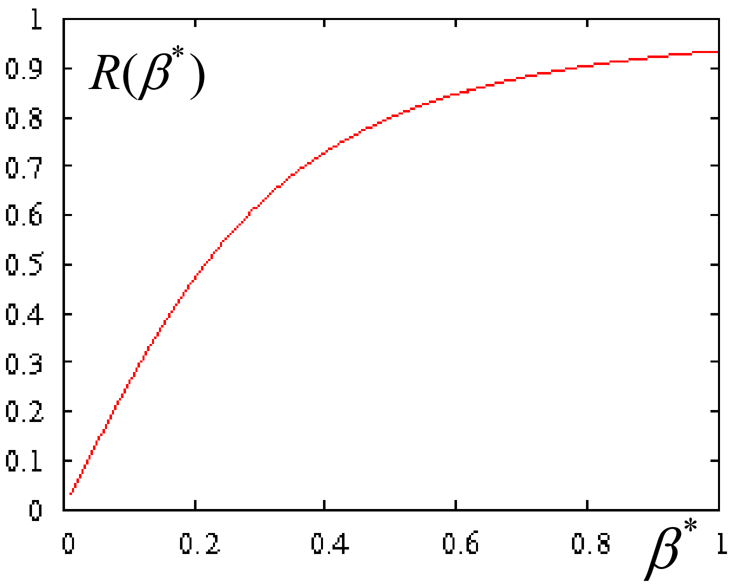
➔ reduction of instantaneous luminosity

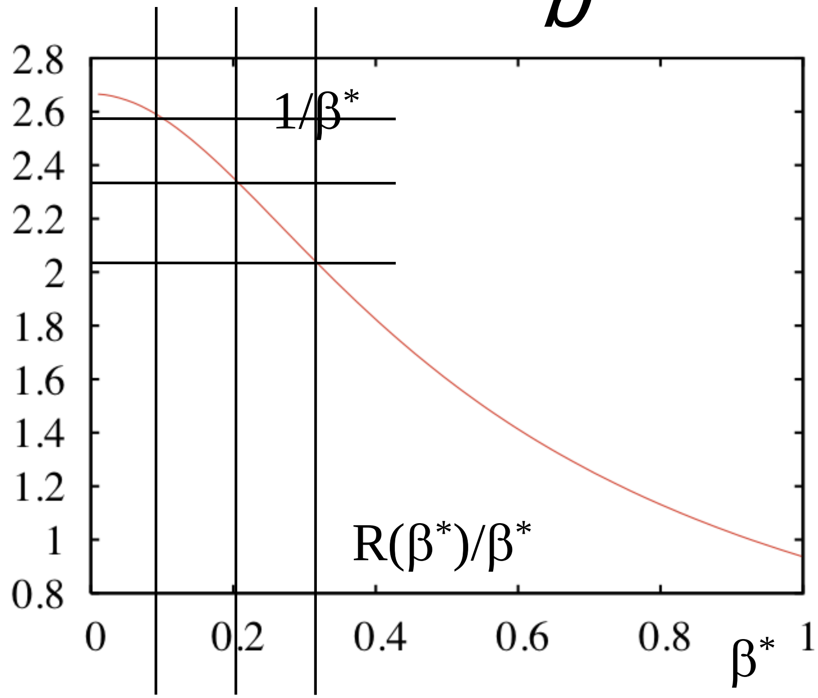
➔ inefficient use of beam current (machine protection!)

Luminosity versus β^*:

$$L \mu \frac{R(b^*)}{b^*}$$

- Geometric reduction factor





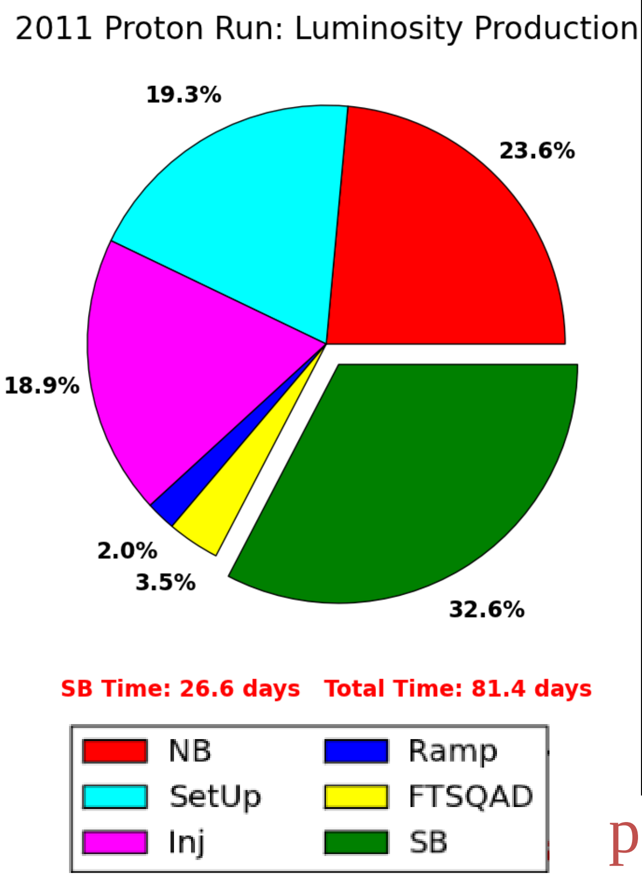
small β^*: ➔ moderate increase of L with decreasing β^*

ca. 40% for β^* 0.5m -> 0.25m
ca. 15% for β^* 0.3m -> 0.2m
ca. 10% for β^* 0.2m -> 0.1m

➔ gain in virtual luminosity reach with Crab Cavities

[Alick Macpherson]

LHC Availability and Performance in 2011



	Days	NB %	SET UP %	INJ %	RAMP %	FT+SQ +AD %	SB %
2011	299.3	25.7	30.5	17.4	1.7	4.3	**20.5**
2011-TS	277.9	23.3	29.5	18.7	1.9	4.7	**22.0**
p-p	156.6	22.0	20.4	19.2	2.2	3.8	**33.8**
p-p LP	**81.4**	23.6	19.3	18.9	2.0	3.5	**32.6**
Pb-Pb	**24.1**	25.0	20.8	13.6	2.2	5.5	**32.9**
MD	33.2	22.9	32.3	36.8	1.2	6.0	**0.8**
High ß	4.2	6.2	43.7	10.3	3.2	35.4	**1.1**

p-p, Pb-Pb runs do not include TS or MD time

Hubner factor: $H = 11.57 \times L_{Del} / (D \times L_{Peak})$ **$H_{\_Expected}$ = 0.2**

p-p (LP): 81.4 days $L_{Peak} = 2572$ $(\mu b.s)^{-1}$ $L_{Del} = 4.01\ fb^{-1}$ => **H = 0.22**

Pb-Pb: 24.1 days $L_{Peak} = 512$ $(b.s)^{-1}$ $L_{Del} = 167.6\ \mu b^{-1}$ => **H = 0.24**

Upgrade Considerations: Integrated Lum[illegible]osity

Machine Efficiency:

- ➔ Hübner Faktor: H
- ➔ integrated luminosity = H * L_{peak} * days

  - ➔ 250 fb^{-1} in 150 days with [illegible] s^{-2}
    - ➔ requires H = 0.[illegible]on run length; Turnaround etc.
  - ➔ 250 fb^{-1} in 1[illegible] L_{peak} = 2.5 10^{34} cm^{-2} s^{-2}
    - ➔ r[illegible], independent on run length; Turnaround etc.

com[illegible] – 0.32 with leveling (LHC operation 2011)

[illegible] Ferroluzzi; Chamonix 2012

➔ 25ns scenarios are ambitious but seem within reach

➔ 50ns scenarios seem out of reach for the performance goal of 250 fb^{-1}

STABLE BEAMS – often short !

➔ **Using LHC data from 2011 one obtains:**

-average run length = 4.6 hours

-most probable turnaround time = 5.23 hours

➔ **average Fill-to-Fill time = 9.8 hours**

-total number of physics fills = 99

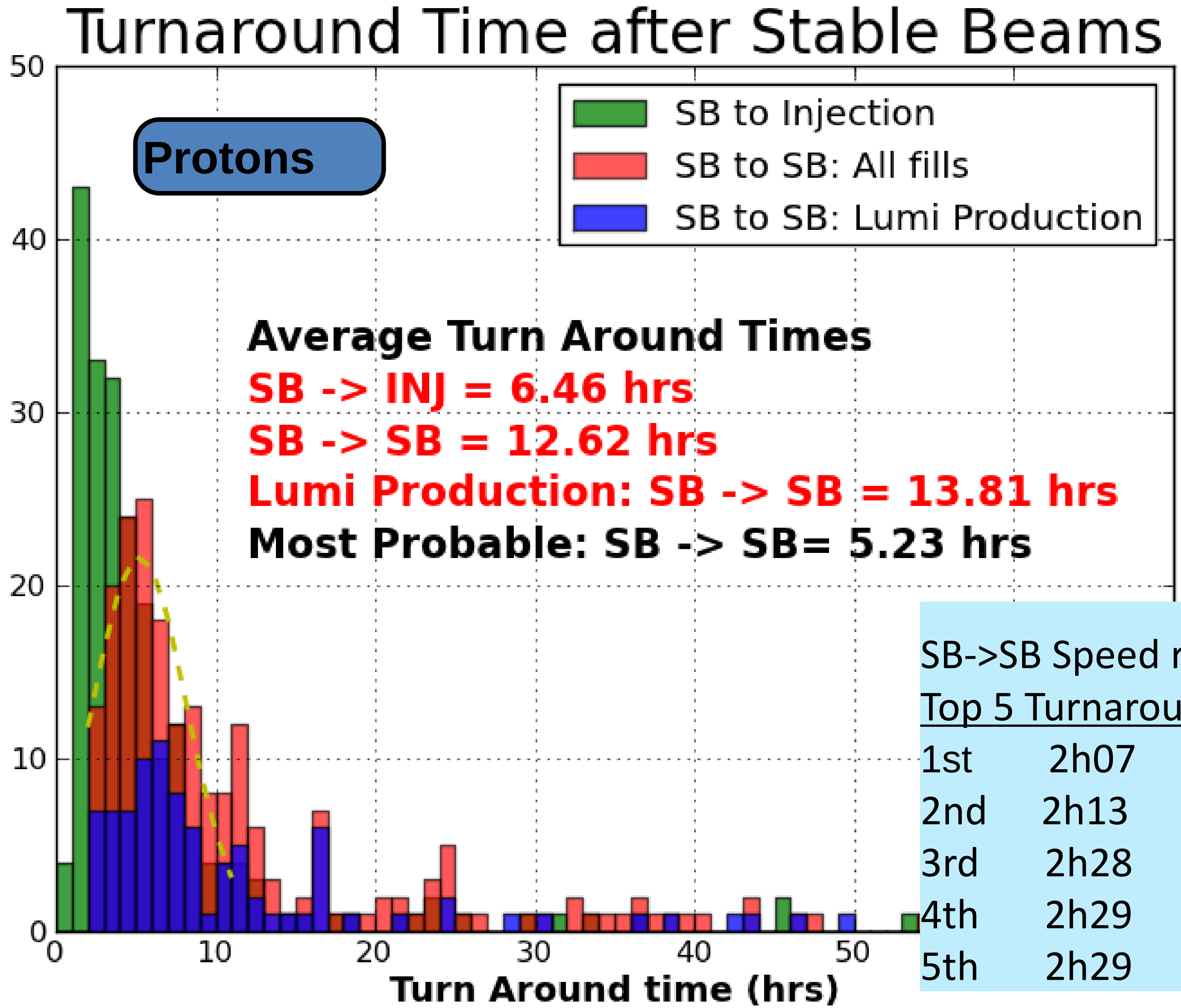
-total number of physics days = 80 (luminosity production period)

➔ **LHC efficiency in 2011 = 99*9.8/80/24 = 50%**

(compared to 38% to 78% for the HL-LHC scenarios!)

➔ **One should demonstrate in LHC operation that average fill length can be larger than desired fill length for HL-LHC (> 7 hours) and that average Turnaround time can be $\leq$ 5 hours**

Performance: Turnaround



SB->SB Speed records

Top 5 Turnaround times

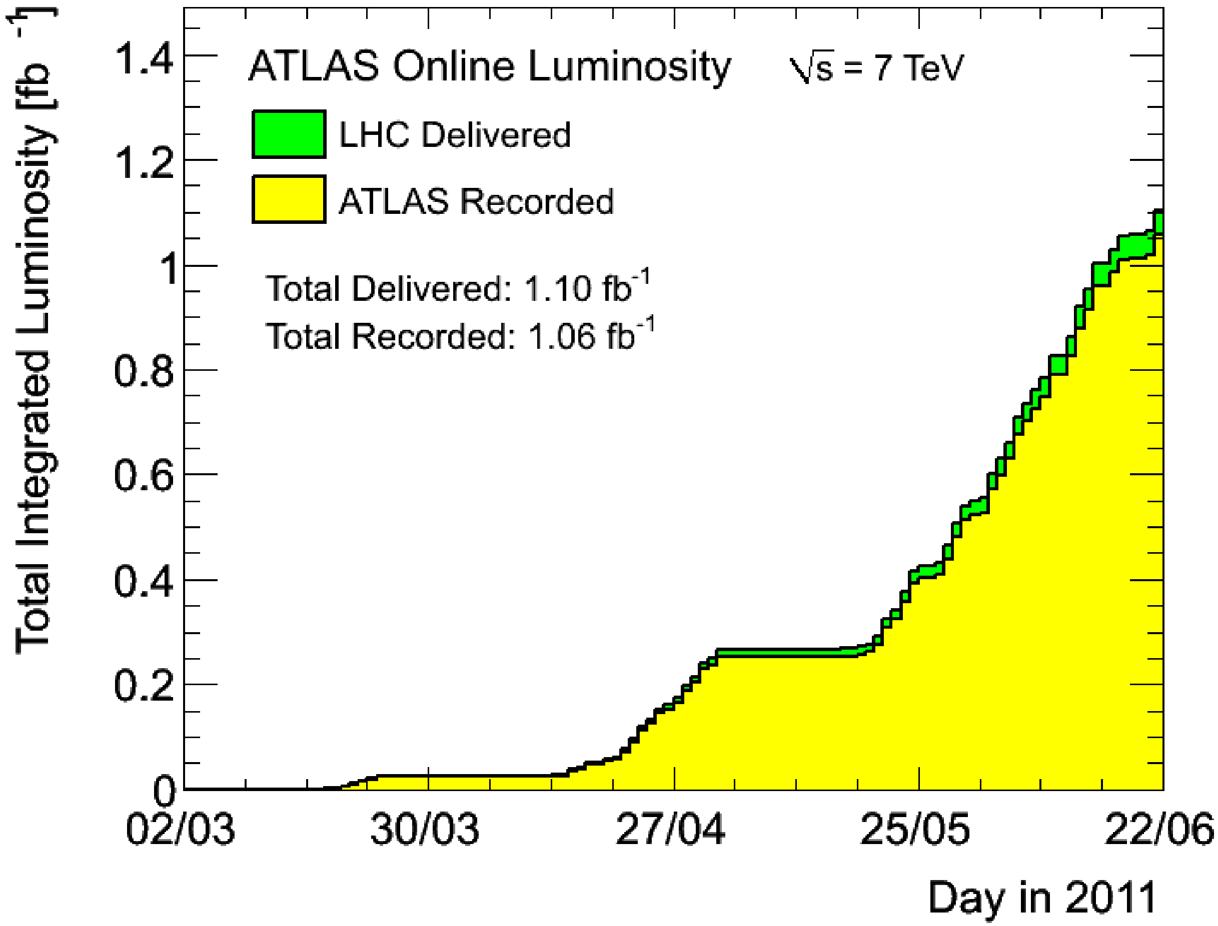
1st	2h07
2nd	2h13
3rd	2h28
4th	2h29
5th	2h29

Upgrade Considerations: Integrated Luminosity

LHC Operation:

650 pb^{-1} in last 4 weeks

800 pb^{-1} in last 5 weeks

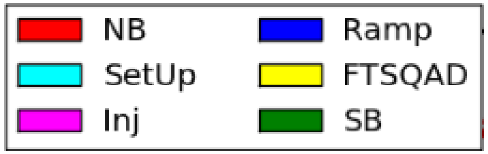


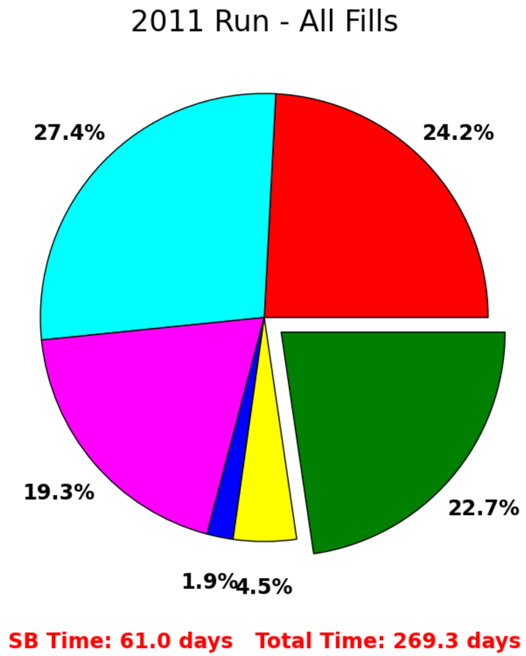
➔ obtained integrated luminosity per week over last month: ca. 163 pb^{-1}

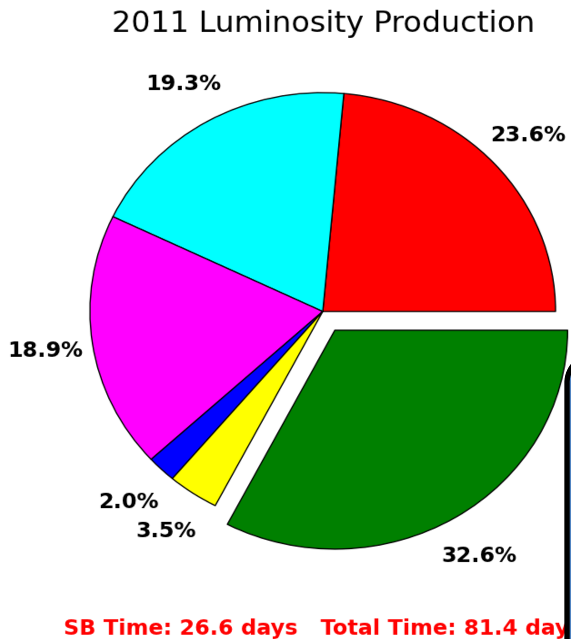
➔ LHC Efficiency: ca. 163 / 405 ➔ 40%

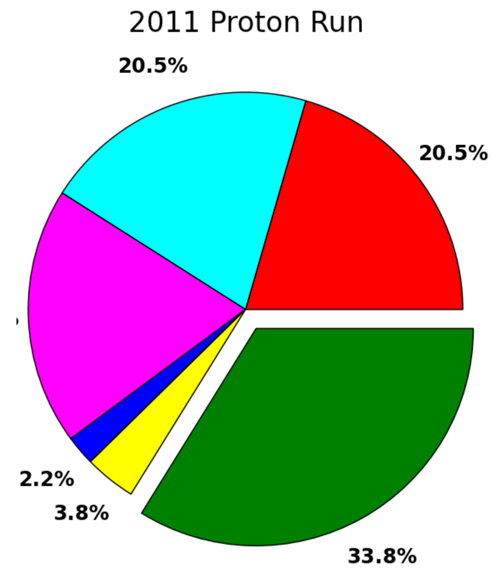
[Alick Macmpherson; Evian 2012]

LHC 2011 Run: Efficiency









- NB: based on Access
  (EIS Beam Status)
- All other categories use:
  - Beam mode
  - Beam presence
- Lumi Production =>1380b

<u>Hubner factor</u>

$H = 11.57 \times L_{Del} / (D \times L_{Peak})$

=> **H = 0.22**

D = 89.15 days

$L_{Peak} = 2572.0\ (\mu b.s)^{-1}$

$L_{Del} = 4.006\ fb^{-1}$