HL-LHC Parameter Space and Scenarios

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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 ➔ $\Delta Q = 0.02 - 0.03$

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

3) 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)

Potential Performance Limitations for the LHC

beta*:

1) Aperture ➔ interaction with WP3 of the HL-LHC: $\beta^* < 0.2$m

2) Chromatic aberrations & optics matchability

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

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

Presentation by
Stephane Fartoukh on Monday

3) Geometric reduction factor:

➔ moderate increase of L with reduced β^*

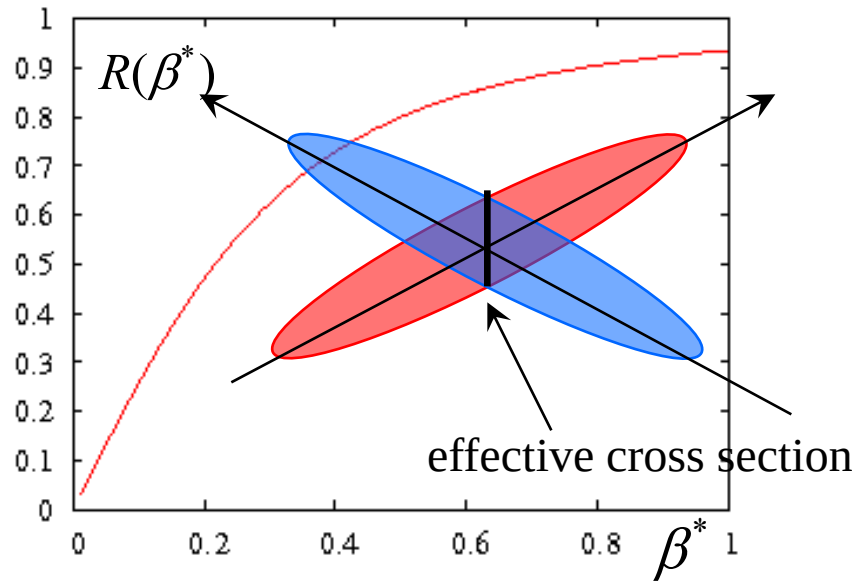
➔ margin for L leveling with Crab Cavities

Geometric Reduction Factor: R

geometric luminosity reduction factor:

Piwinski angle

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

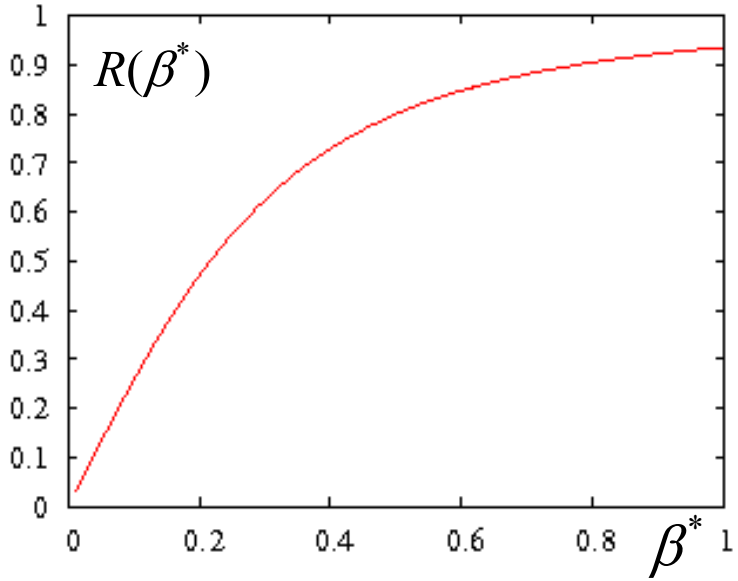


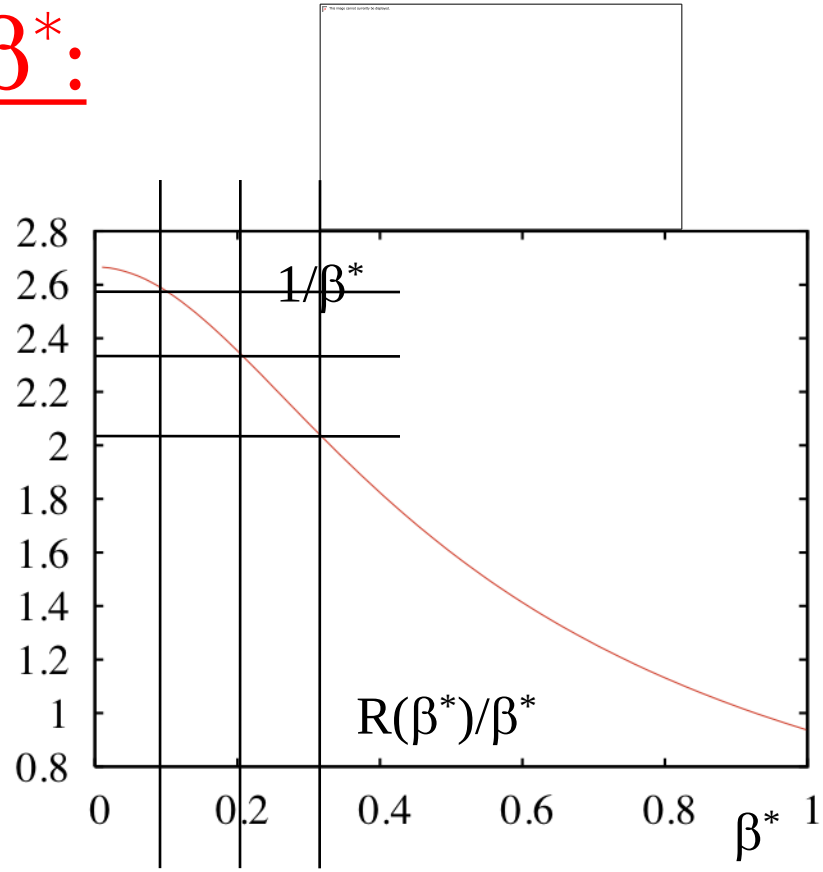
large crossing angle:

- ➔ 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^*:

Geometric reduction factor



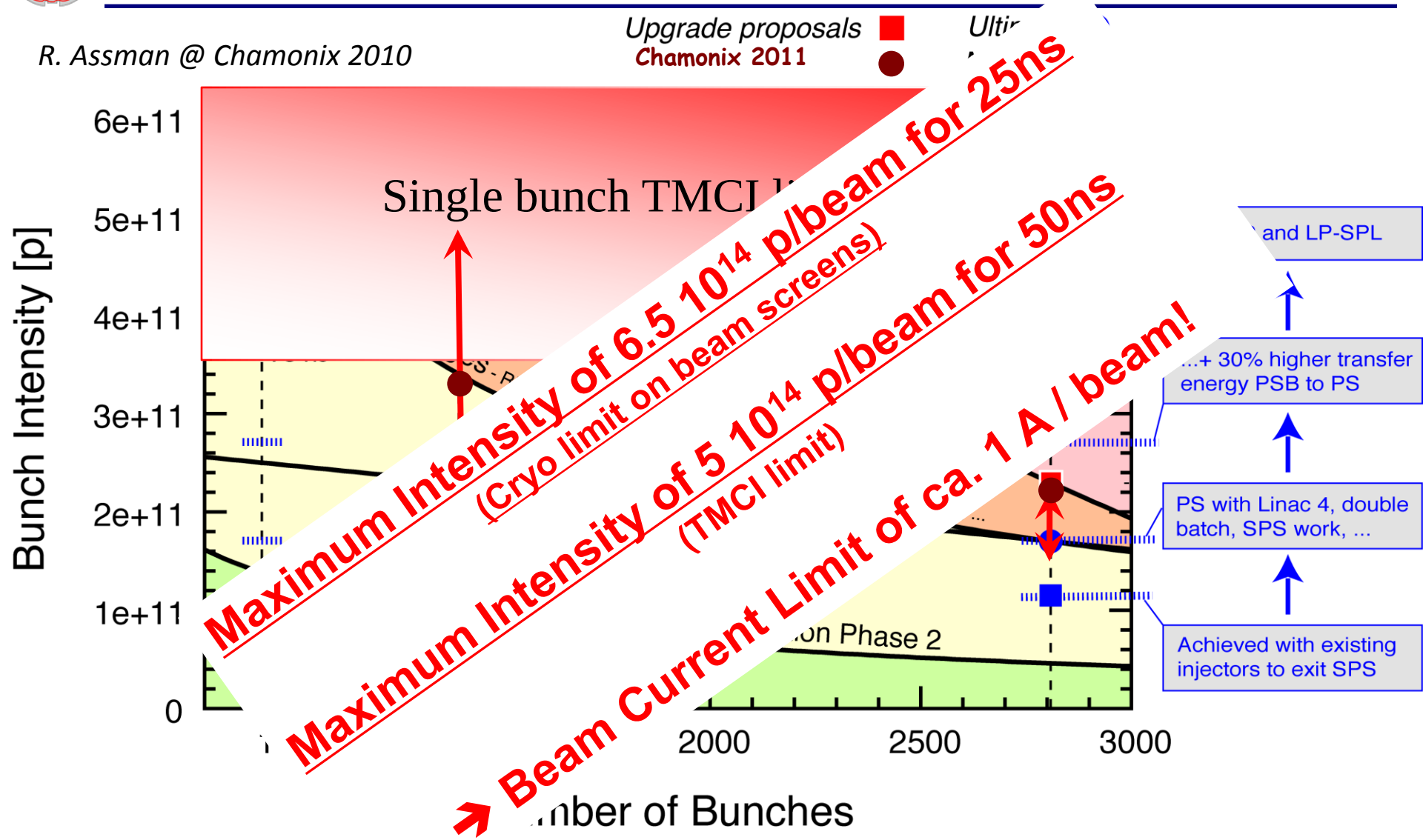


small β^*: ➔ moderate increase of L with decreasing β^*

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

Summary of LHC Intensity Limits (7 TeV)



Ideal scenario: no in ections included!

Note: Some assumptions and conditions apply…

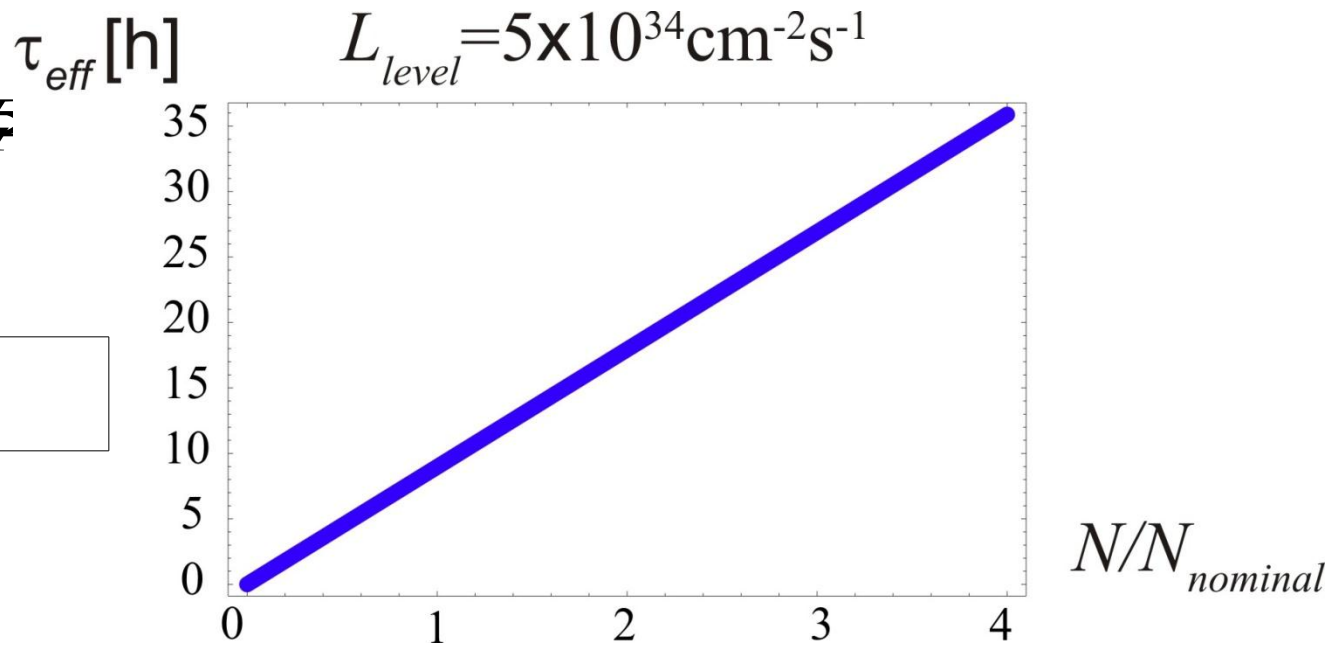
Upgrade Considerations: Beam Lifetime

F. Zimmermann, Chamonix 2011

- For given luminosity τ_{eff} scales with total beam current

$$\frac{dN_{tot}}{dt} = \frac{N_{tot}}{\tau_{eff}} = n_{IP} \sigma L$$

$$\tau_{eff} = \frac{N_{tot}}{n_{IP} \sigma L_{lev}}$$



(σ=100 mbarn) τ_{eff} = 13.9 hours for 5 10^{14} p/beam:

➔ argument for HL-LHC scenarios with maximum beam current

Upgrade Considerations: Beam Lifetime

Run length assuming leveled luminosity:

➔ virtual luminosity of $k * 5\ 10^{34}\ cm^{-2}\ sec^{-1}$ ➔ $T_{level} = (1-1/\sqrt{k}) * \tau_{eff}$

Assuming: $1.8\ 10^{11}$ ppb @ 25ns & $3.5\ 10^{11}$ ppb @ 50ns (➔ $\approx 5\ 10^{14}$ p/beam)

➔ τ_{eff} = 13.9 hours for $5\ 10^{14}$ p/beam:

k = 2: ➔ T_{level} = 4.1 h

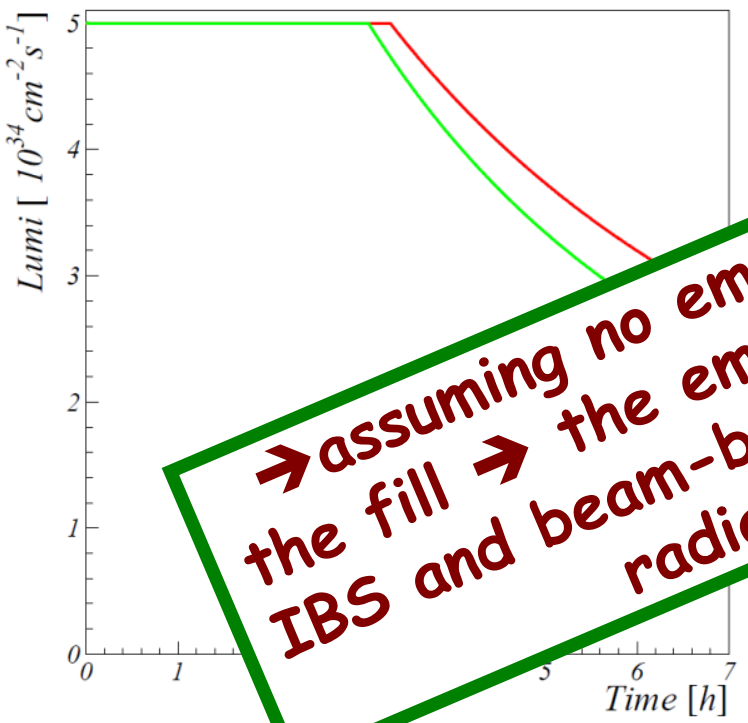
k = 3: ➔ T_{level} = 5.9 h

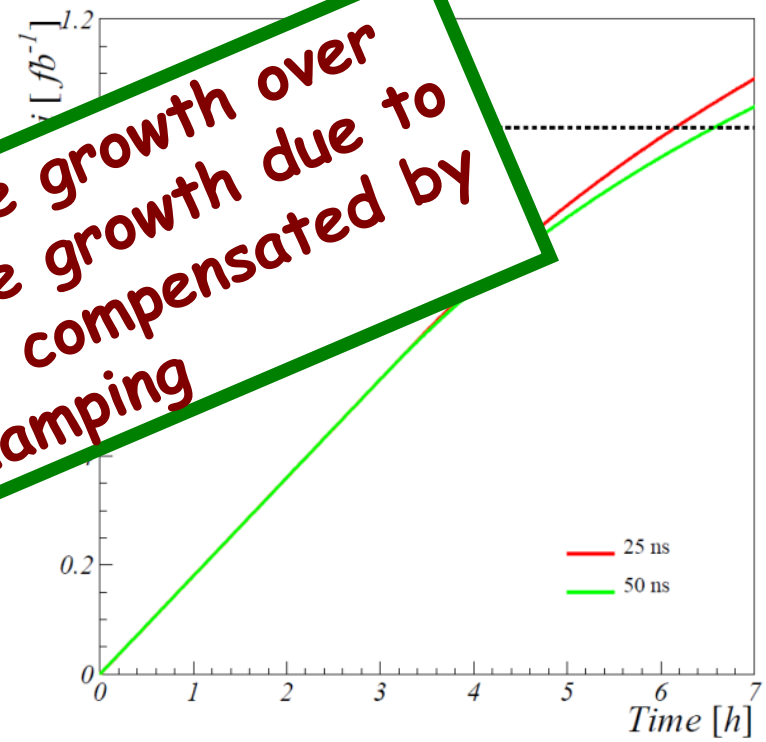
k = 4: ➔ T_{level} = 7.0 h

Upgrade Considerations: Integrated Luminosity

Integrated luminosity: run with luminosity decay

[Stephan Fartoukh]





➔assuming no emittance growth over the fill ➔ the emittance growth due to IBS and beam-beam is compensated by radiation damping

➔ L_{int} = ca 0.4 fb^{-1} over 3 h for a luminosity decay to 2.5 10^{34} cm^{-2} s^{-1}

Upgrade Considerations: Integrated Luminosity

Integrated luminosity: leveling to constant luminosity

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

➔

(σ=100 mbarn)

➔ integrated luminosity directly proportional to total current

➔ L_{int} = 0.4 fb^{-1} per fill for N_{tot} = 5 10^{14} ppb over 3h and k = 1

➔ L_{int} = 0.4 + 0.73 fb^{-1} per fill for N_{tot} = 5 10^{14} ppb over 7h and k = 2

➔ L_{int} = 0.4 + 1.25 fb^{-1} per fill for N_{tot} = 5 10^{14} ppb over 10h and k = 4

➔ argument for HL-LHC scenarios with maximum 'k'

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: $200\ fb^{-1}$ to $300\ fb^{-1}$ per year
- Total integrated luminosity: ca. $3000\ fb^{-1}$

HL-LHC Performance Estimates

nominal bunch length and minimum β*: 'HL-LHC Kickoff+'

minimum β*

OK for HL goals ('k' = 4)

(Even better if emittances can be further reduced: still a factor 1.2 to 2.5 wrt beam-beam limit)

→results in maximum fill length of

7 + 3 h and

1.7 fb^{-1} per fill

5.6 10^{14} and 4.6 10^{14} p/beam

ficient room for leveling
th Crab Cavities)

l luminosity (25ns) of
/ 0.37 10^{34} cm^{-2} s^{-1}

10^{34} cm^{-2} s^{-1} ('k' = 4)

l luminosity (25ns) of
/ 0.37 10^{34} cm^{-2} s^{-1}

.7 10^{34} cm^{-2} s^{-1} ('k' = 4.5)

(Leveled to 5 10^{34} cm^{-2} s^{-1})

Parameter					
N					
n_b					
beam current [A]					
x-ing angle [μrad]					
beam separation [σ]					
β* [m]					
ε_n [μm]					
ε_L [eVs]					
energy spread					
bunch length [m]					
IBS horizontal [h]					
IBS longitudinal [h]					
Piwinski parameter					
geom. reduction					
beam-beam / IP					
Peak Luminosity	1 10^{34}	**7.4 10^{34}**	**8.4 10^{34}**		
Events / crossing	19	**141**	**257**	**95**	**190**

Emittance Margin for SPS to HL-L

- IBS growth @ injection: ca. 10% in 20min f ess of 9 1 ad

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

➔ density close to HL-LHC g

➔ expect similar growth f

Presentation by Verena Kain on Monday

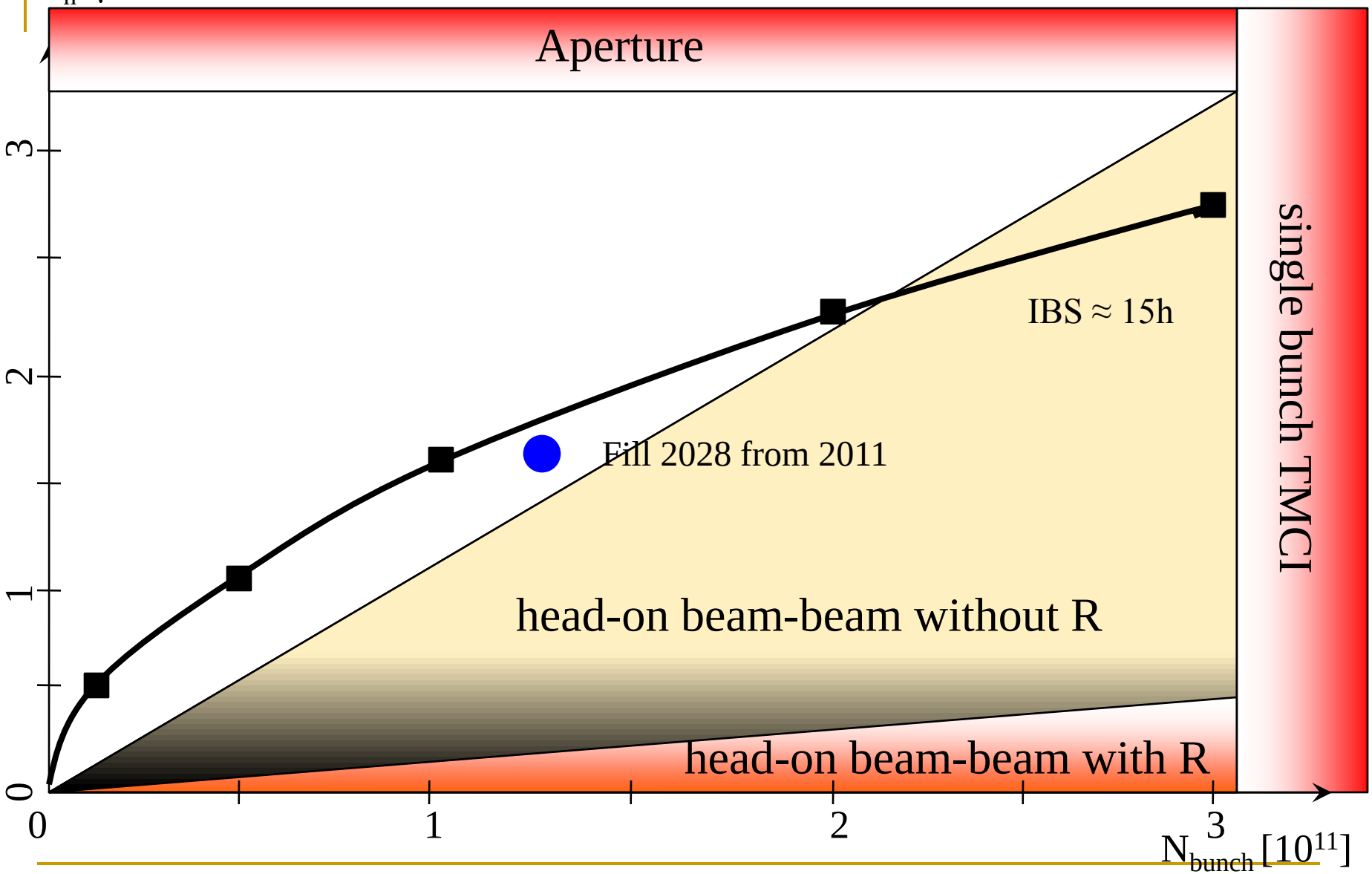
- Growth @ ramp ted to damper gain and tune feedback

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

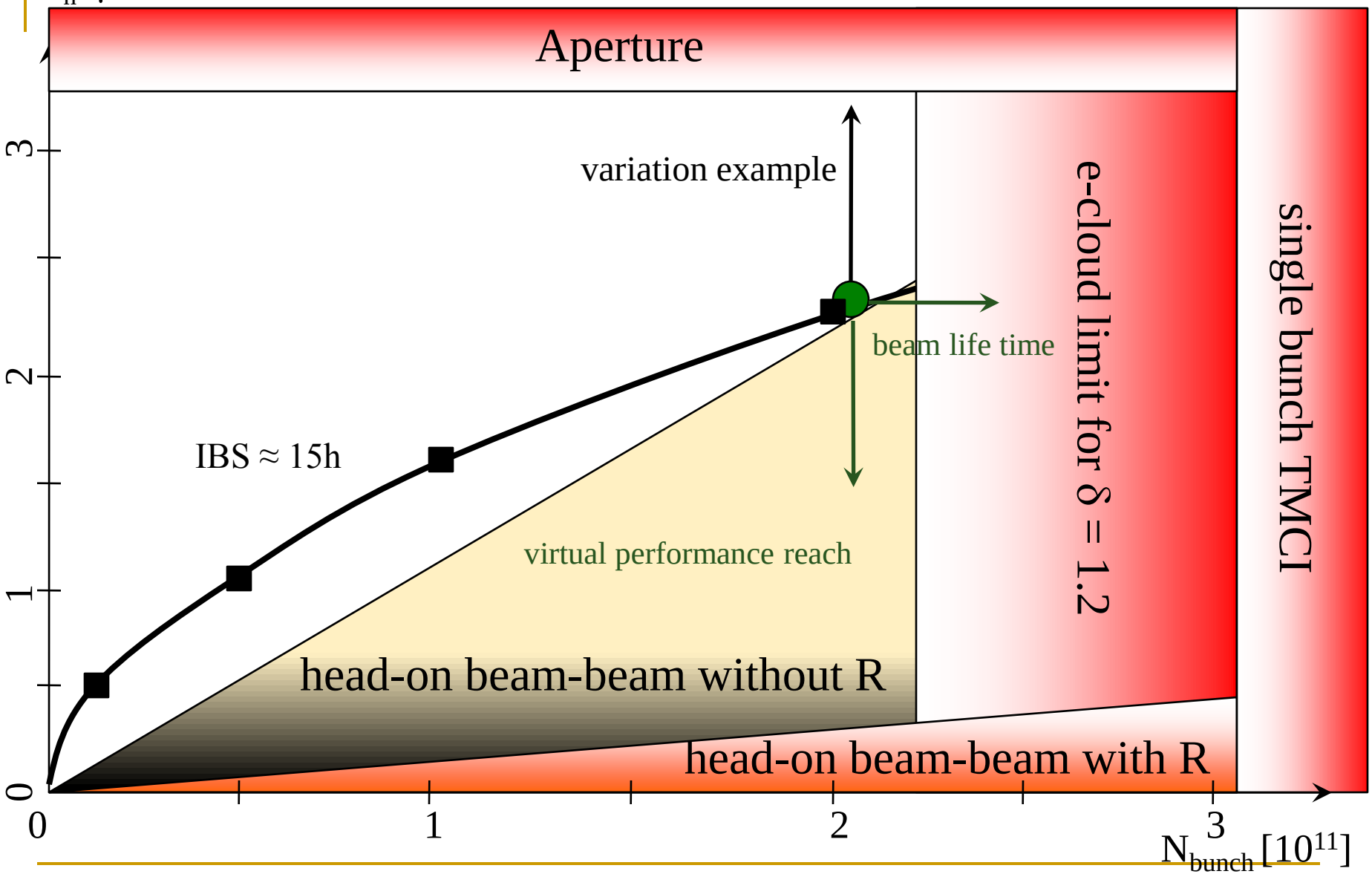
Assume for now 10% to 20% emittance growth between SPS extraction and HL-LHC luminosity production

should be able to find better solution for HL-LHC

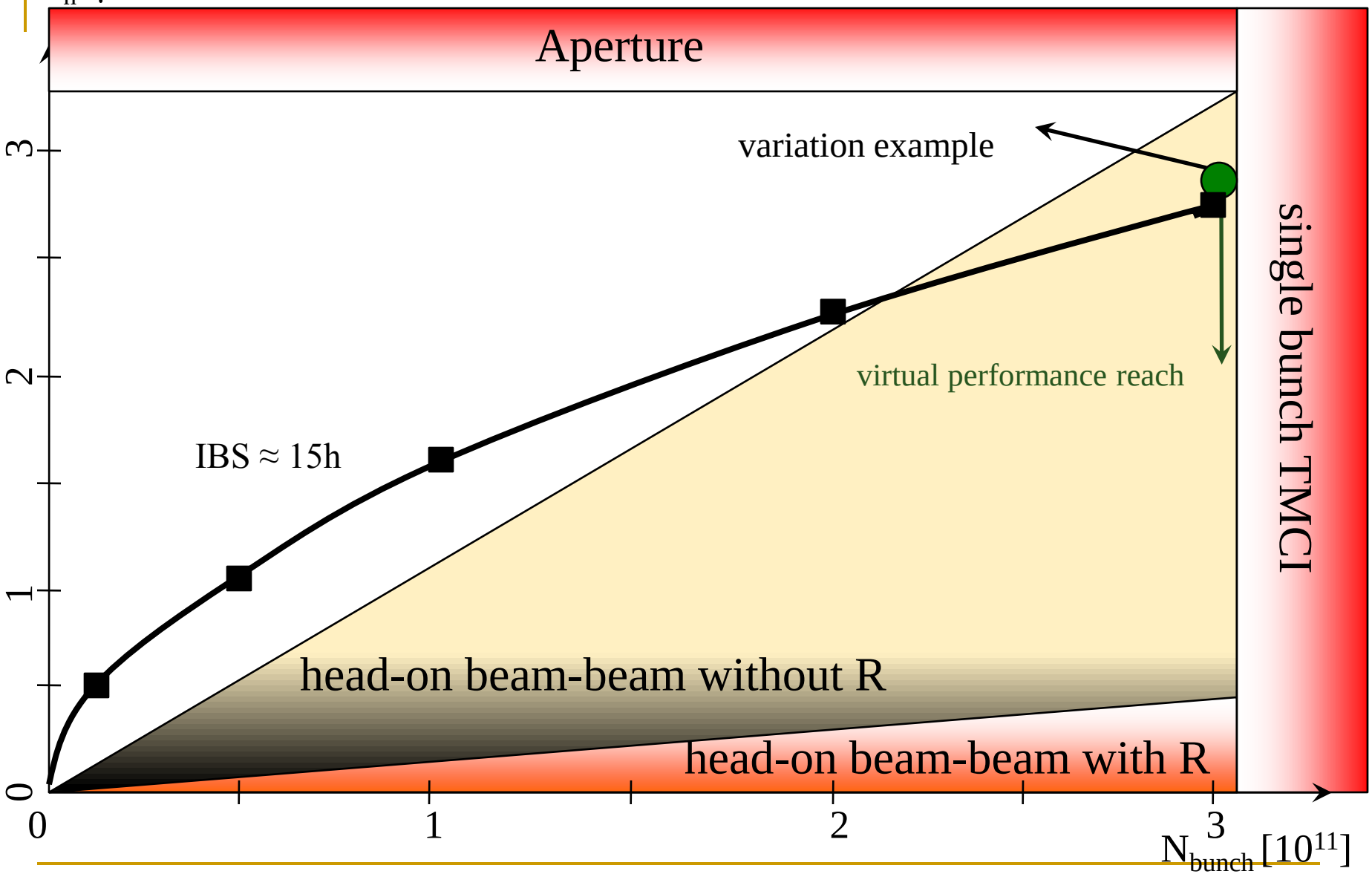
HL-LHC Parameter Space



HL-LHC Parameter Space: 25ns



HL-LHC Parameter Space: 50ns



HL-LHC Performance Estimates

variation examples:

Parameter	nominal	minimum β* 25ns	minimum β* 50ns
N	1.15E+11	**2.0E+11**	**2.5E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.02**	**0.64**
x-ing angle [μrad]			
beam separation [σ]			
β* [m]			
ε_n [μm]			
ε_L [eVs]			
energy spread			
bunch length [m]			
IBS horizontal [h]			
IBS longitudinal [h]	61 -> 60	**35**	**24**
Piwinski parameter	0.68	**2.5**	**2.5**
geom. reduction	0.83	**0.37**	**0.37**
beam-beam / IP	3.10E-03	**2.7E-03**	**3.4E-03**
Peak Luminosity	1 10^{34}	**5.6 10^{34}**	**4.4 10^{34}**
Events / crossing	19	**106**	**165**

At limit for HL goals

➔implies maximum fill length

of 4h+3h and

ca. 1.1 fb^{-1} per fill

5.6 10^{14} and 3.5 10^{14} p/beam

➔ Not sufficient room for leveling (with Crab Cavities)

'irtual luminosity (25ns) of
= 5.6 / 0.37 10^{34} cm^{-2} s^{-1}

= 15 10^{34} cm^{-2} s^{-1} ('k' = 3)

'irtual luminosity (50ns) of
= 4.4 / 0.37 10^{34} cm^{-2} s^{-1}

= 11.9 10^{34} cm^{-2} s^{-1} ('k' = 2.4)

Upgrade Considerations: Integrated Lum sity

Phase	Days	Co
Commissioning	21	
Scrubbing run	10	
5 MDs	22	
6 Technical stops		ys TS plus 1 very with beam)
Special requests		EM/ALPHA Intermediate energy run Luminosity scans
Intensity ramp		
Total high	~130	
Ion	4	
	24	
	290	

requires between 150 and 230 fills per year to reach 250 fb^{-1} per year!

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

➔ implies 1 to 1.5 fills per day for previous scenarios

M. Lamont March 2011

Upgrade Considerations: Integrated Lu[illegible]osity

Machine Efficiency:

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

Example 1: k = 4 ➔ 1 fill per d[illegible] of 10h:

- ➔ 221 fills for reach[illegible] — 5 10^{14} p/beam
- ➔ fill-length= [illegible]
- ➔ Efficier[illegible]

Example[illegible] fills per day with run length of 7h:

[illegible]aching 250 fb^{-1} — 5 10^{14} p/beam

[illegible]ume = 3h + 4h = 7h

[illegible]iency = 43%

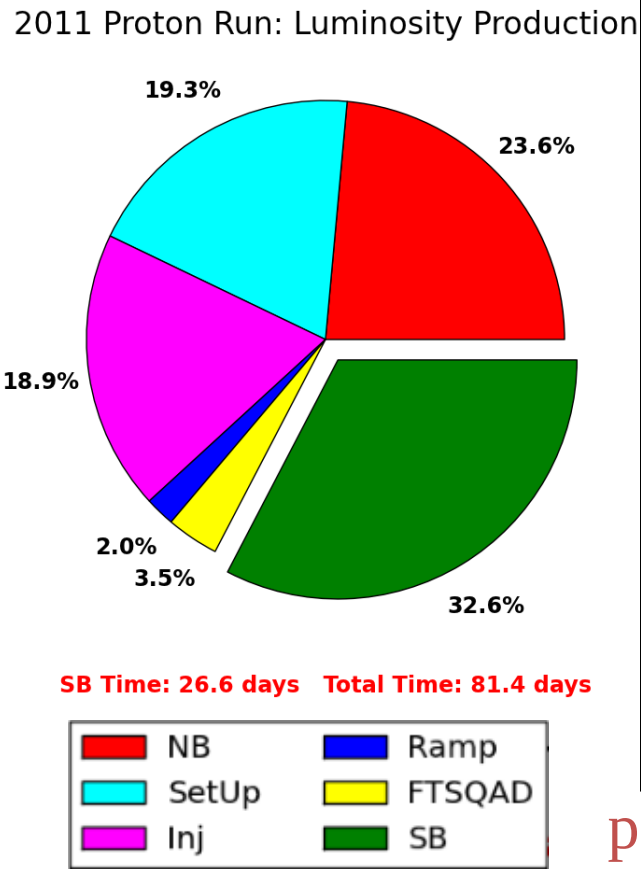
➔ **compared to machine efficiency of 23% - 33% during 2011 operation**

➔ **independent of number of involuntary beam dumps**

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

[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] run length; Turnaround etc.

compared [illegible] 0.2 – 0.24 in ATLAS and CMS

and 0.26 – 0.32 with leveling

from LHC operation in 2011

➔ **250 fb-1 per year is very ambitious with L_{peak} = 5 10^{34} cm^{-2} s^{-1}**

➔ **maximize peak performance reach for HL-LHC!**

Upgrade Considerations: Integrated Luminosity

Machine Efficiency:

➔ average Turnaround time of ca. 5 hours

➔ minimum fill-to-fill time = leveling time + 3h + turnaround time

➔ Efficiency = number of fills per day * fill-to-fill time / 24 h

➔ allows comparison with LHC operation: Efficiency = L_{oper} / L_{theor}

Example 1: k = 4 ➔ 1 fill per day with run length of 10h:

➔ fill-to-fill time = 3h + 7h + 5h = 15h

➔ Efficiency = 1 * 15 / 24 = 63%

$5\ 10^{14}$ p/beam

Example 2: k = 2 ➔ 1.5 fills per day with run length of 7h:

➔ fill-to-fill time = 3h + 4h + 5h= 12h

➔ Efficiency = 1.5 * 12 / 24 = 75%

$5\ 10^{14}$ p/beam

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 63% to 75% 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 ≤ 5 hours**

Ion Operation during HL-LHC:

- ALICE is preparing an upgrade bid for 10nb^{-1}
  -scaling 2011 and 2012 performance to 7 TeV
  ca. 500 μb^{-1} per year for a four week run

- Doubling number of bunch
  -will double the injectio performance
  -resulting emittance ction might reduce
  performance re
  g @ 7 TeV can partially compensate
  oling a la RHIC might help

- D
  euterons is requested by ALICE, it will most likely
  uled after LS3 (development of source and injector
  be challenging before LS2).

running ALICE in dedicated ion mode during HL-LHC reduces time available for p-p physics by ca. 30 days

Summary:

- Small β^* optics solutions open the door for HL-LHC performance with leveling ➔ we need Crab cavities!
  ➔ optics design requires information on required configurations (ALICE;LHCb)!

- Bunch intensities: assuming total limit of 1 A in the LHC
  2 10^{11} ppb for 25ns and 3.5 10^{11} ppb for 50ns operation

- Bunch spacing:
  -25ns clearly preferred for event pileup but requires larger current wrt 50ns -
  50ns is a very attractive backup scenario for avoiding e-cloud problems
  (in the SPS and the LHC!)

- integrated luminosity:
  -250 fb^{-1} is extremely challenging; requires high availability and reliability
  ➔ how much time can one assume for HL-LHC physics! (MDs, TS, Pb etc.)
  150d; average fill length of 7h to 10h and average Turnaround time of ca. 5h
  ➔ ca. 70% efficiency [time required for physics fills / run 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!

Potential Performance Limitations for the LHC

Bunch Intensity:

1) Beam-Beam interaction ➔ limit for beam brightness and Θ?

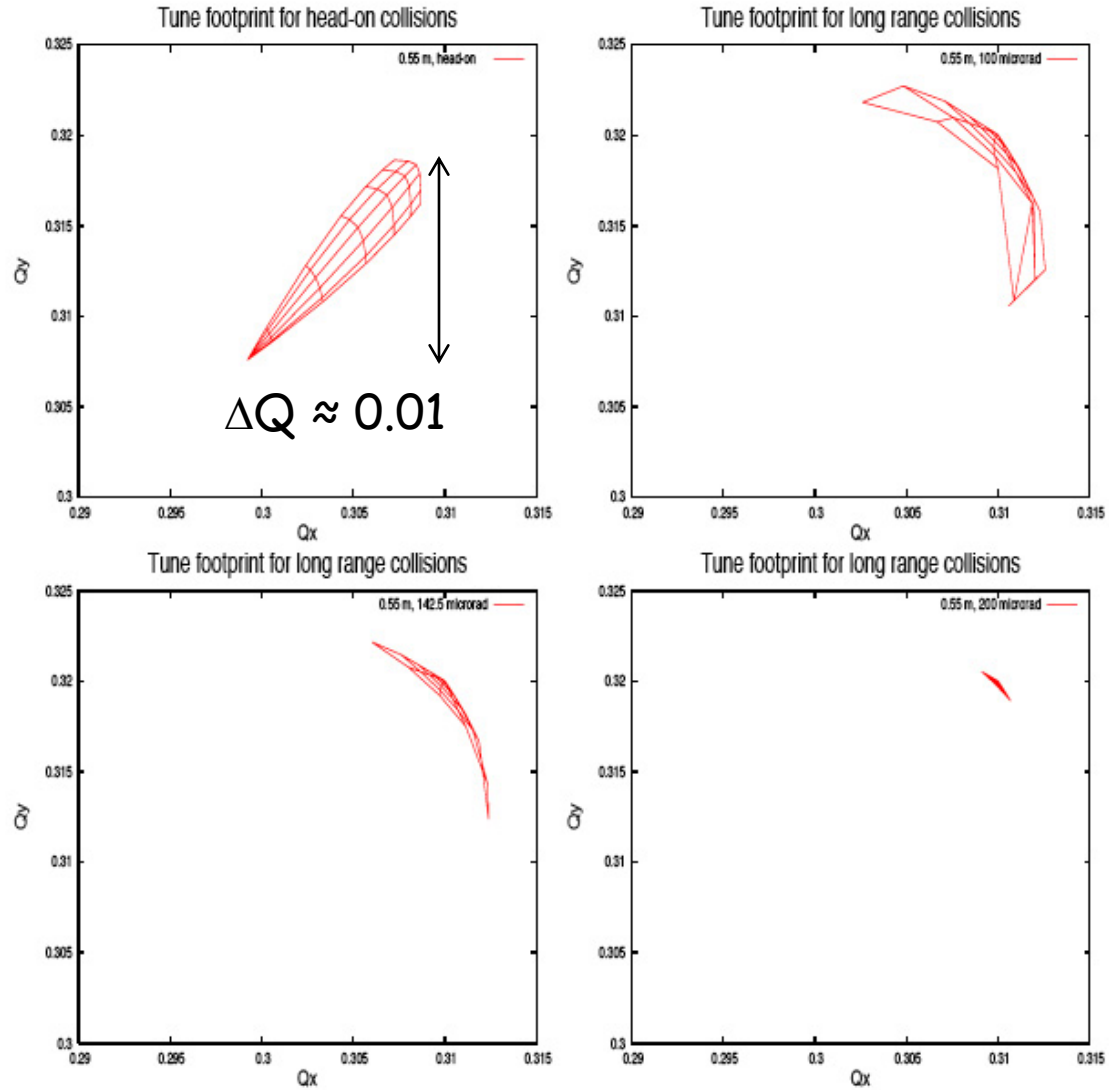
➔ no limit found yet for head-on
➔ long range:
➔ losses for $d < 6\sigma$
➔ instabilities for tight settings with $d < 10\sigma$

Presentation by
Werner Herr on Monday

LHC Challenges: Long-Range Beam-Beam

- Tune spread due to head-on beam-beam interaction wo x-ing:

$$\xi_{beam-beam} = \frac{r_p}{4\pi} \cdot \frac{N_b}{\varepsilon_n}$$



- Long range interactions:

Crossing angle configurations:

Top Left:	only head-on
Top right:	= 200μrad (≈ 7σ)
Bottom left:	= 285μrad (≈ 10σ)
Bottom right	= 400μrad (≈ 13σ)

Werner Herr et al, LPN 416

LHC Challenges: Beam-Beam Interaction

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

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

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

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

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

→ 3 head-on/bunch ➔ $\xi_{beam\text{-}beam} < 10^{-2}$ ➔ $N < 3.6\ 10^{11}$

@ $\varepsilon_n = 3.75\ \mu m$ rad

➔ $N < 2.4\ 10^{11}$

@ $\varepsilon_n = 2.5\ \mu m$ rad

Assuming head-on collisions!

LHC Challenges: Beam-Beam Interaction

Design report: $\Delta Q_{\ldots} < 0.01$

Maximum beam brightness of 10×10^{10} ppb/μmrad

(compared to 8×10^{10} ppb/μmrad in Rende's presentation on Tuesday)

Minimum emittance of $\varepsilon_n = 3.75$ μm rad for $3.6\ 10^{11}$ ppb

(single bunch TMCI limit)

Minimum emittance of $\varepsilon_n = 2.5$ μm rad for $2.4\ 10^{11}$ ppb

(e-cloud limit for 25ns)

Long-range BB separation > 10 σ

(geometric reduction factor from crossing angle will affect BB tune shift)

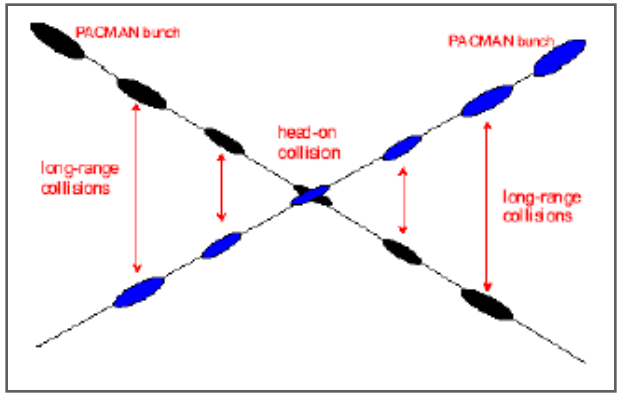
Potential Performance Limitations for the LHC

Number of bunches:

1) electron cloud effect ➔ limit depends on bunch spacing

2) Total beam power ➔ dedicated task in HL-LHC project
➔ for now we assume a limit of ca. 1 A per beam

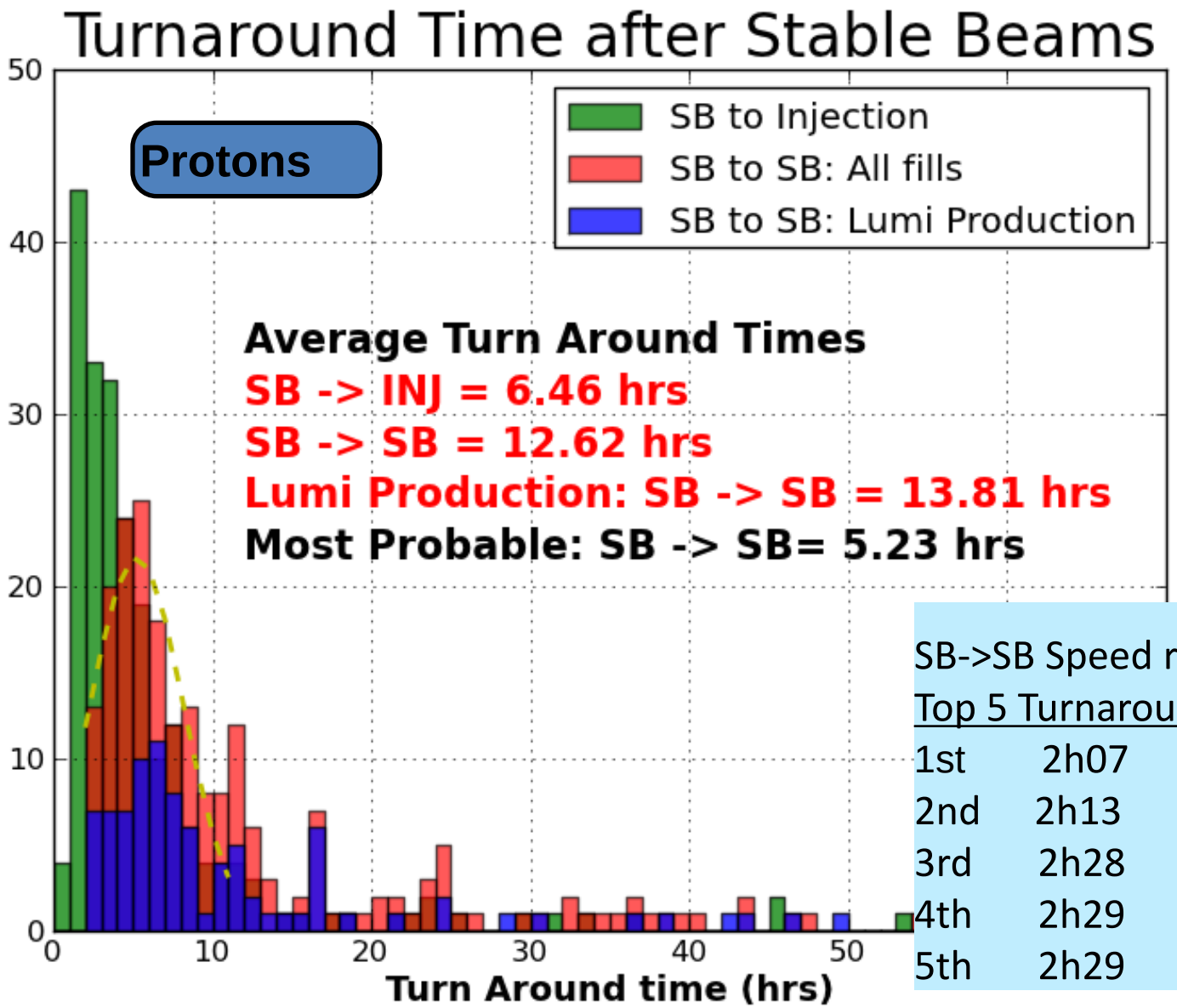
1) Cleaning efficiency ➔ cryo collimators



2) Long range beam-beam:
ca. 30+ /IP for 25ns bunch spacing

5) Injector performance depends on bunch spacing ➔ different brightness for 25ns & 50ns bunch spacing options

Performance: Turnaround



SB->SB Speed records

Top 5 Turnaround times

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

Upgrade Considerations: Machine Efficiency

LHC Operation: theoretical maximum integrated luminosity

- ➔ average Turnaround time of ca. 5 hours @ 3.5 TeV (2.5 h minimum)
- ➔ Peak luminosity: 1.1 10^{33} cm^{-2} sec^{-1}
- ➔ Luminosity lifetime: ca. 20h (35h) exponential ($[1+t/tau]^{-2}$) decay

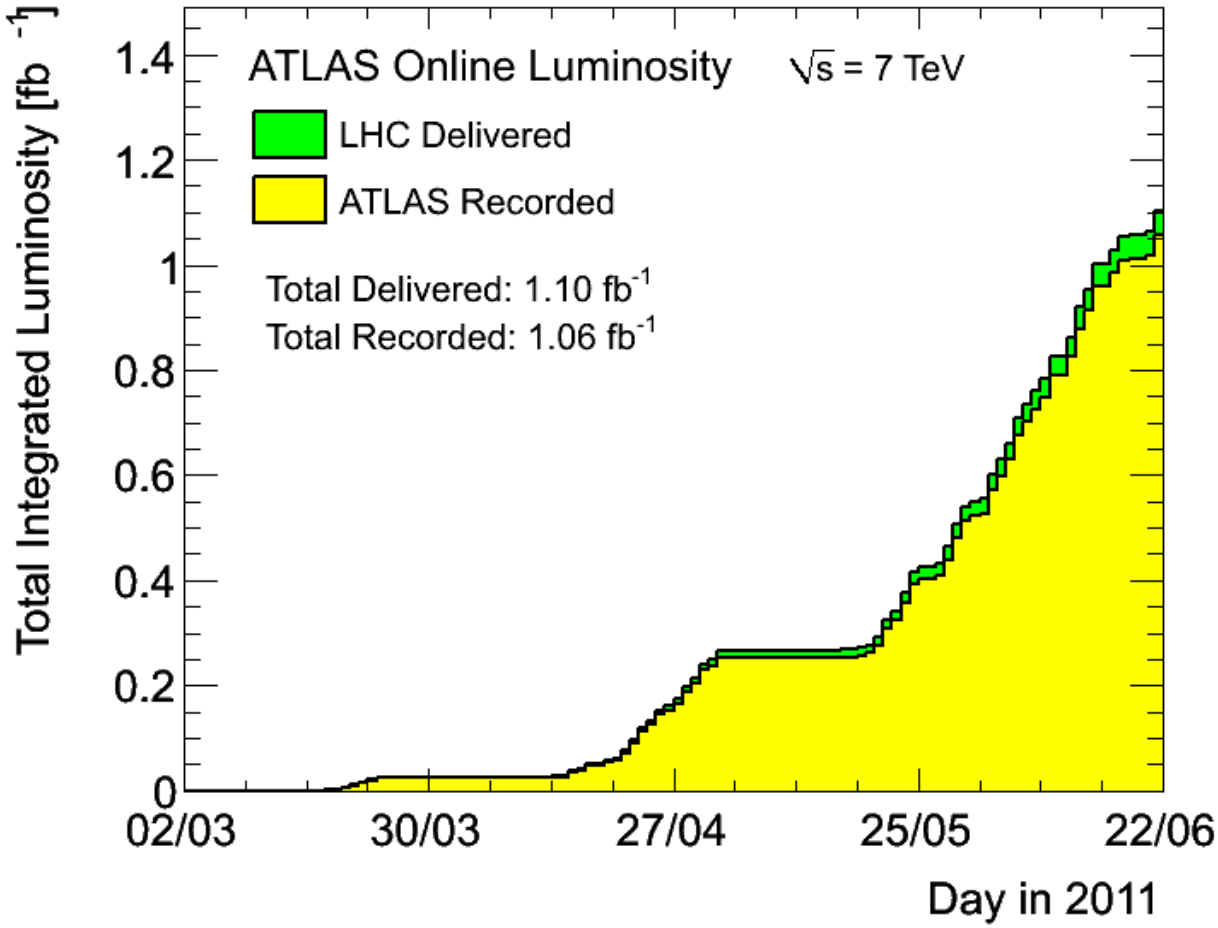
  Can't be explained by burn off (ca. 30h from DR restgas and IBS)!
- ➔ optimum fill length of ca. 14h with rather broad peak
- ➔ minimum fill-to-fill length: 2.5h + 14h = 16.5h
- ➔ integrated luminosity / fill: ca. 40 pb^{-1} (40 pb^{-1}) (fill 1883) (44 pb^{-1})
- ➔ integrated luminosity / day: ca. 58 pb^{-1} (58 pb^{-1}) (65 pb^{-1})
- ➔ integrated luminosity / week: 405 pb^{-1} (405 pb^{-1}) (450 pb^{-1})

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%

Potential limitations: high brightness operation:

No Leveling:

- ➔ ca. 0.6 fb^{-1} in 7 hours for start luminosity of 5 10^{34} cm^{-2} s^{-1}:
  - ➔ 12 hour minimum fill-to-fill time for 5 h turnaround time
  - ➔ need 2.8 fills per day
  - ➔ 1.7 fb^{-1} per day
  - ➔ 250 fb^{-1} in 150 days
  - ➔ requires 100% efficiency to reach HL goals!

Upgrade Considerations: Integrated Luminosity

HL-LHC running scenarios:

➔ Assume average run length is reduced to premature end of fills

➔ assume on average 25% shorter than ideal fill length

➔ average fill time of 5h to 7.5h

$5\ 10^{14}$ p/beam

➔ 1.33 * 1 fills per day for k = 4

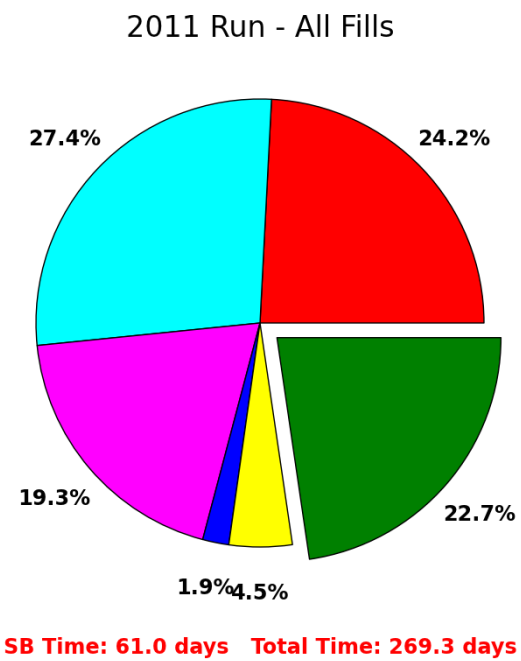
Efficiency = 1.33 * 1 * (0.75* [3h+7h]+5h) / 24 = 70% (63%)

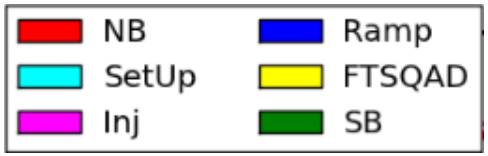
➔ 1.33 * 1.5 fills per day for k = 2

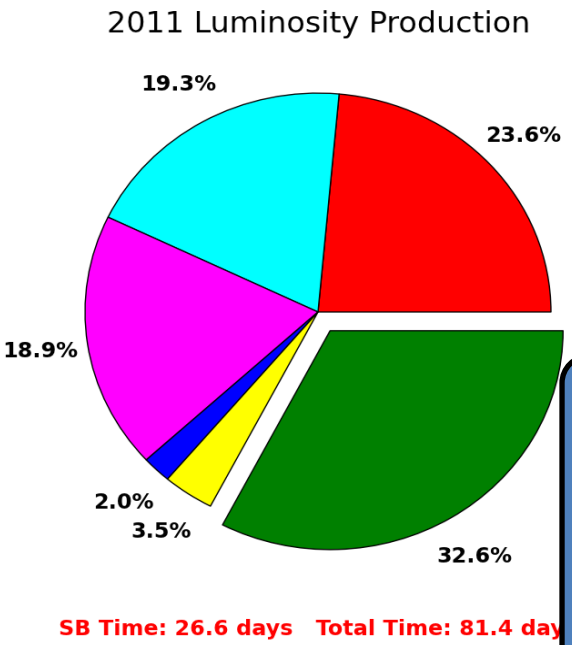
Efficiency = 1.33 * 1.5 * (0.75* [3h+4h]+5h) / 24 = 85% (75%)

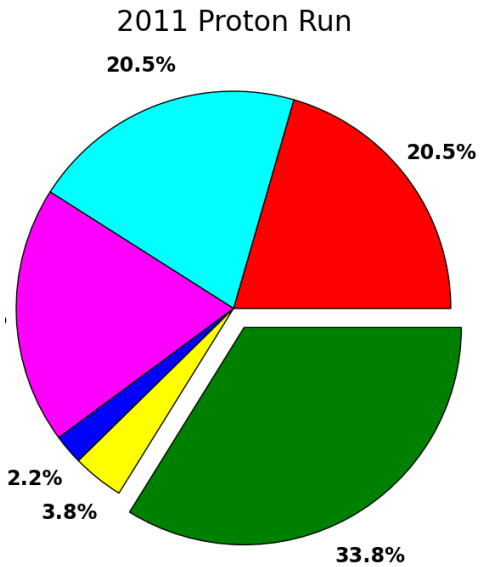
[Alick Macmpherson; Evian 2012]

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

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

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