LHC Injectors Upgrade

Update of achievable beam characteristics at injection in LHC

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LHC Injectors Upgrade

Contents

- LIU understanding of final* HL-LHC requirements
- Experience with beam until end 2011
- Limitations and mitigations in the injector chain
  - Space charge, electron cloud, beam loading, longitudinal stability, TMCI
- Expected injector chain performance after upgrades
  - Areas still requiring performance improvement
- Possible variant directions in parameter space
- Unknowns, risks and remaining issues
- Conclusion

**after LS3*

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Requirements from HL-LHC (at 10:00 today)

Target: 250-300 fb^{-1} per year

Parameter	nominal	minimum β* 25ns	minimum β* 50ns
N	1.15E+11	**2.0E+11**	**3.3E+11**
n_b	2808	2808	1404
beam current [A]	0.58	**1.02**	**0.84**
x-ing angle [μrad]	300	475	520
beam separation [σ]	10	10	10
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.5	2.5
energy spread	1.00E-04	1.00E-04	1.00E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	**25**	**17**
IBS longitudinal [h]	61 -> 60	**21**	**16**
Piwinski parameter	0.68	**2.5**	**2.5**
geom. reduction	0.83	**0.37**	**0.37**
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**
Peak Luminosity	1 10^{34}	**7.4 10^{34}**	**8.4 10^{34}**
Events / crossing	19	**141**	**257**

at LHC collision

LHC Injectors Upgrade

Requirements from HL-LHC (at 10:35 today)

Target: 250-300 fb^{-1} per year

Parameter	nominal	minimum β* 25ns	minimum β* 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	480	550
beam separation [σ]	10	10	10
β^* [m]	0.55	**0.15**	**0.15**
ε_n [μm]	3.75	2.5	3.0
ε_L [eVs]	2.51	2.5	2.5
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	**20.0**	**20.7**
IBS longitudinal [h]	61 -> 60	**15.8**	**13.2**
Piwinski parameter	0.68	**2.54**	**2.66**
geom. reduction	0.83	**0.37**	**0.35**
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**
Peak Luminosity	1 10^{34}	**9.0 10^{34}**	**9.0 10^{34}**
Events / crossing	19	**171**	**340**

at LHC collision

LHC Injectors Upgrade

Required parameters through injector chain

- Assumptions made on emittance blowup* and beam loss. :
  - PSB flat bottom-extr: 5% emittance blowup, 5% beamloss
  - PS inj-extr: 5% emittance blowup, 5% beamloss
  - SPS inj-extr: 10% emittance blowup, 10% beamloss (incl. scraping)
  - LHC inj-flat top: 10% emittance blowup, 10% beamloss

- Total assumed beamloss 27% (PSB flatbottom to LHC flat-top), and total emittance growth 33% (or $\Delta\varepsilon \approx 0.7$ um with 2.5 um in LHC)

- For comparison, 2011 operation saw about 13% beamloss (PS injection to LHC flat-top), with $\Delta\varepsilon$ of about 60% (0.4 – 0.5 um to SPS extraction, and $\Delta\varepsilon$ 0.5 – 0.6 um LHC)

* rather simplistic as several processes will give fixed absolute $\Delta\varepsilon$

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Resulting required parameters through injector chain

25 ns	PSB inj	PSB extr/PS inj	PS extr/SPS inj	SPS extr/LHC inj	LHC top
Energy GeV	0.16	2	26	450	7000
Nb	1	1	72	288	2808
Ib [e11 p+]	35.2	33.5	2.7	2.4	2.2
Ib in LHC [e11 p+]	2.9	2.8	2.7	2.4	2.2
Exyn [mm.mrad]	1.9	2.0	2.1	2.3	2.5

50 ns	PSB inj	PSB extr/PS inj	PS extr/SPS inj	SPS extr/LHC inj	LHC top
Energy GeV	0.16	2	26	450	7000
Nb	1	1	36	144	1404
Ib [e11 p+]	28.0	26.7	4.2	3.9	3.5
Ib in LHC [e11 p+]	4.7	4.4	4.2	3.9	3.5
Exyn [mm.mrad]	2.2	2.4	2.5	2.7	3.0

	PSB	PS	SPS	LHC
loss %	5	5	10	10
blowup %	5	5	10	10

Using Oliver's numbers timestamped at 10:35:00 30/4/2012

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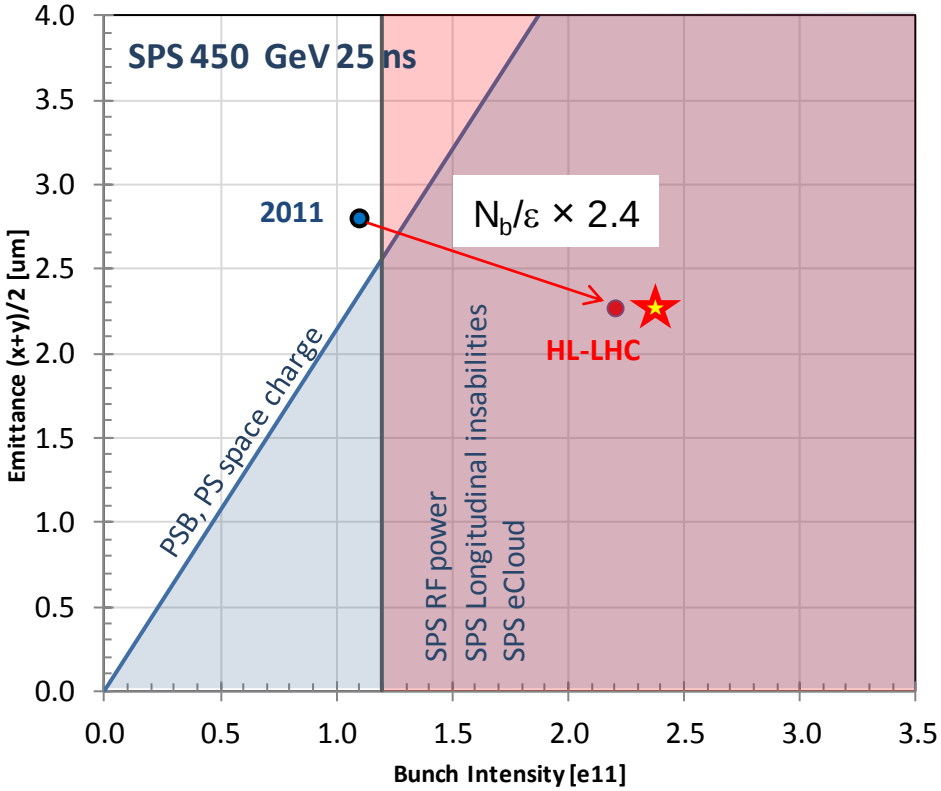
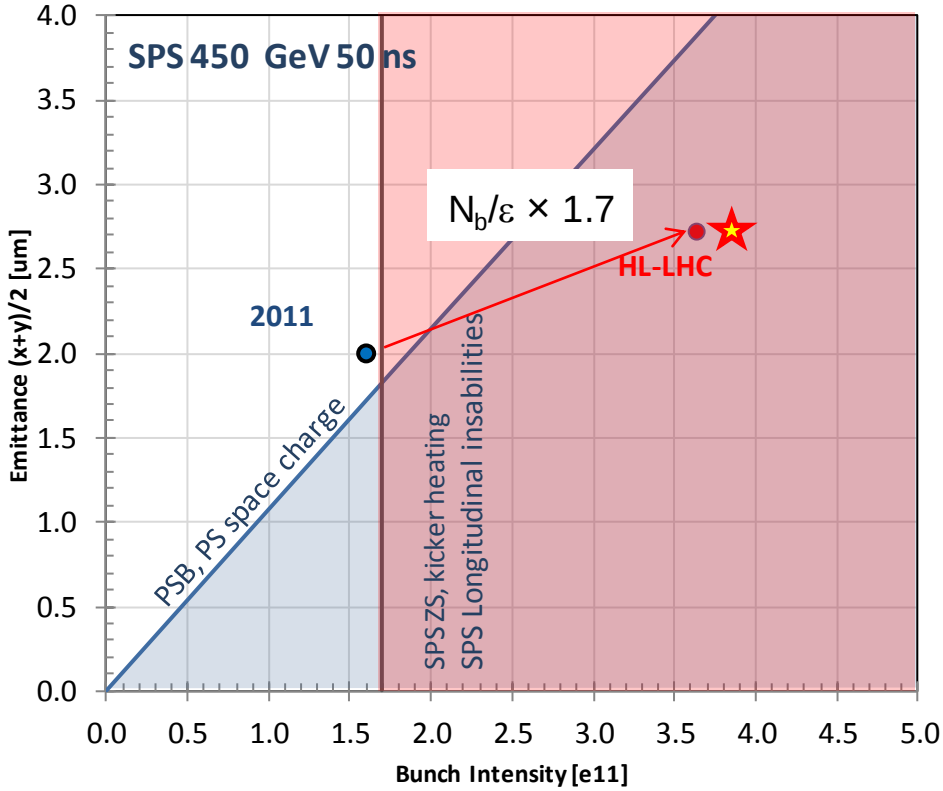
2011 to post-LS2





- 2011 : 1.5e11 with 2.5 um for 50 ns (at LHC flat-top)
  - Around 1.1 e11 with 2.8 um for 25 ns, extracted from SPS
- Large improvement still required for either 25 or 50 ns beam
  - ×2.4 in brightness for 25 ns...

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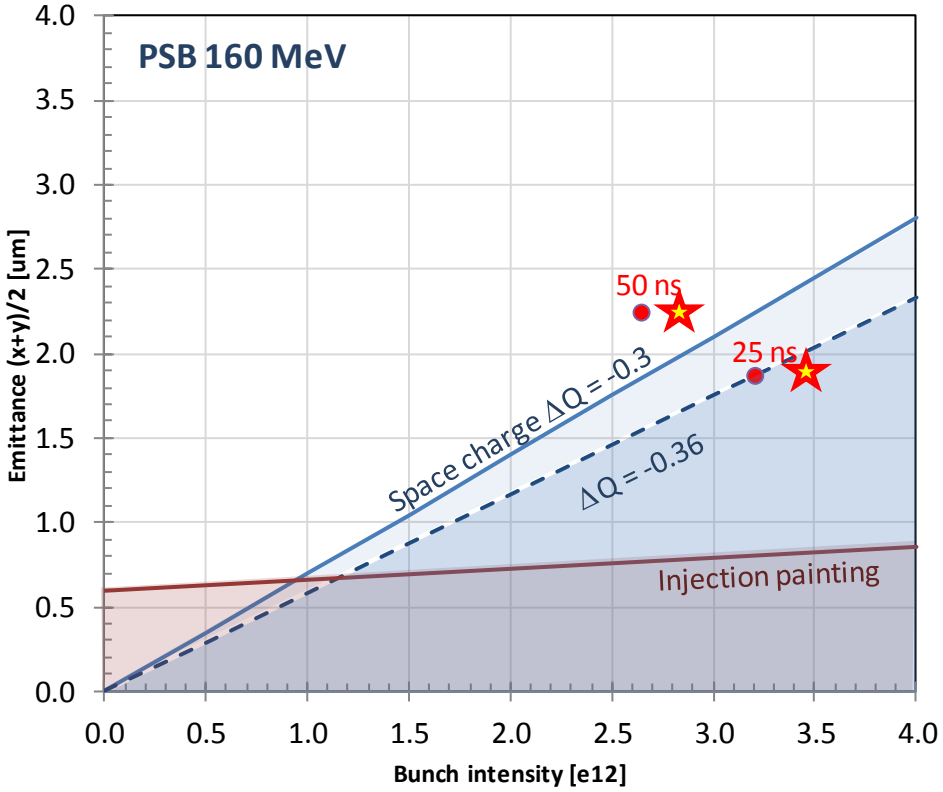
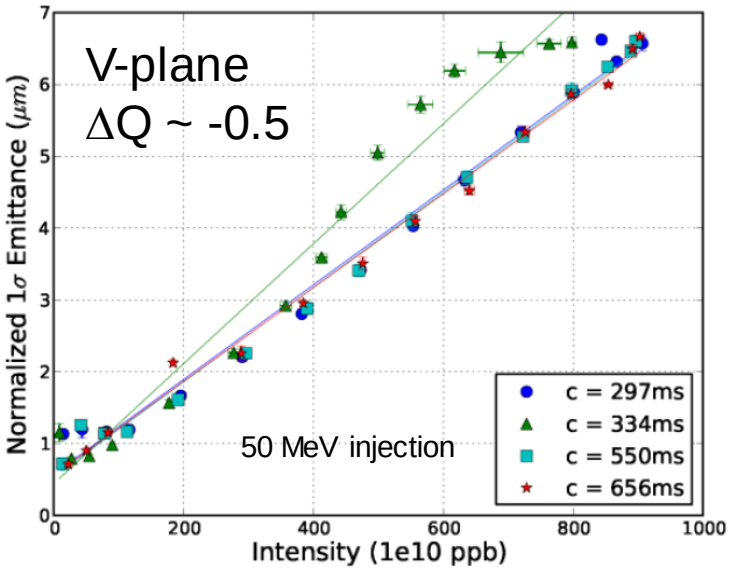
PSB brightness/SC limit

Expected PSB brightness limit at injection energy of 160 MeV



Tune spreads calculated from Laslett formula: gave -0.3 as a conservative value. Extrapolate observed brightness behaviour to 160 MeV



B.Mikulec et al., ATS Note 013,2012

PSB not expected to be a limit for 50 ns, and good prospect to run with ΔQ at -0.36 for 25 ns

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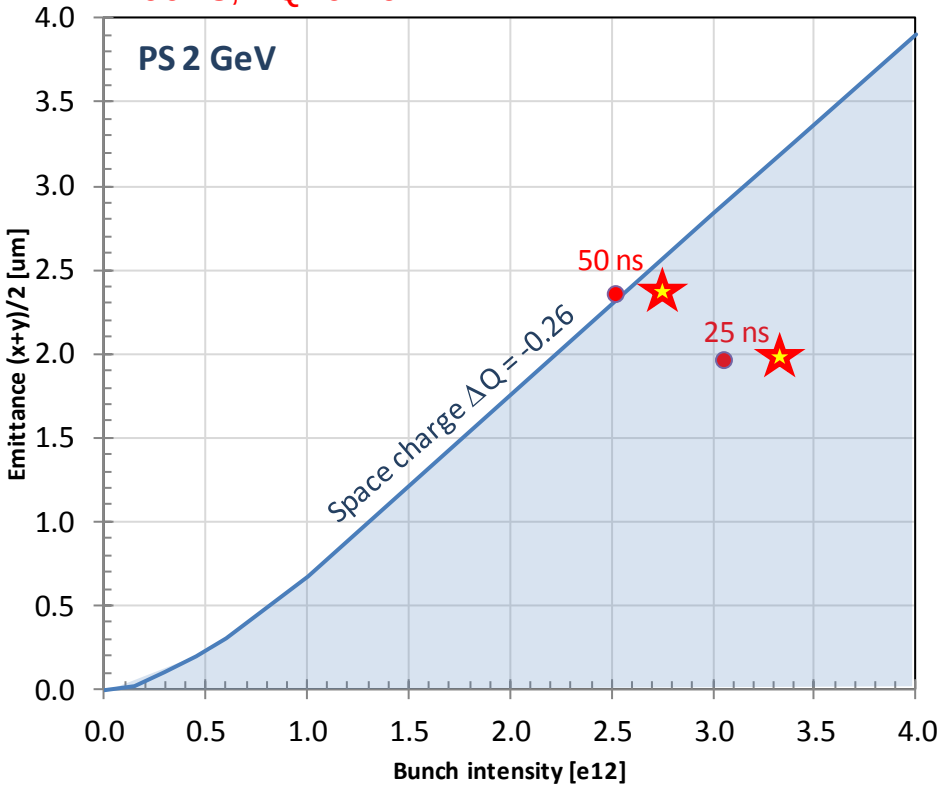
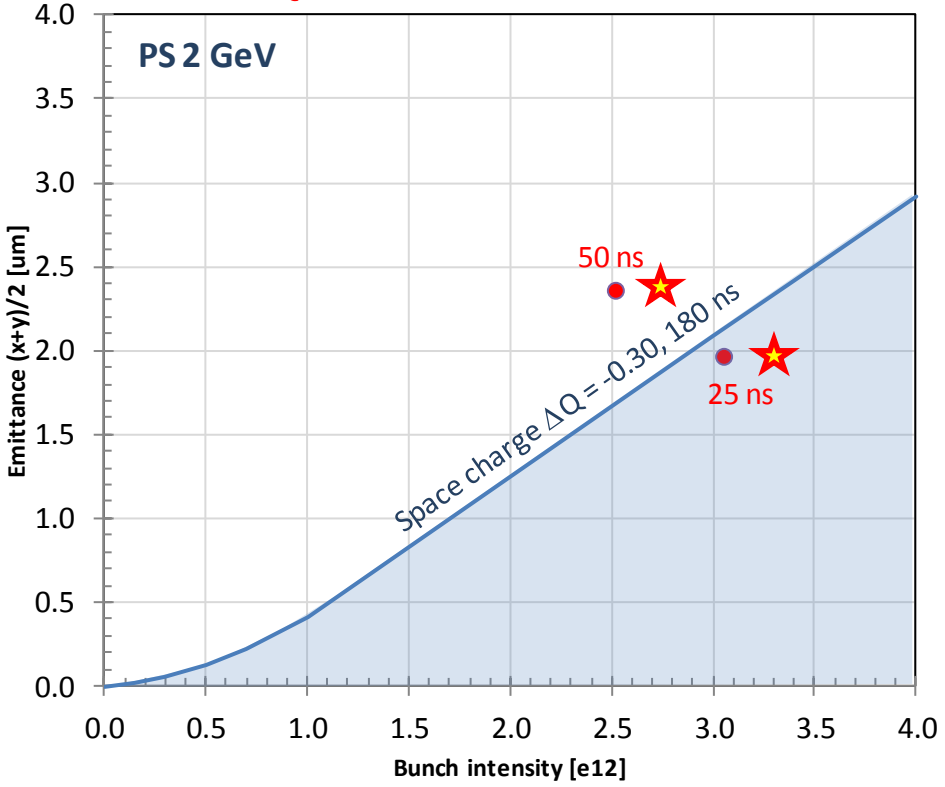
PS brightness/SC limit

Injection energy of 2 GeV (h=7, no compression, dp/p = 0.0013)

160 ns, ΔQ -0.26



180 ns, ΔQ -0.30



$$\Delta Q_y = \frac{r_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z}\frac{1}{\sqrt{\varepsilon_y}}\oint\frac{\sqrt{\beta_y(s)}}{\sqrt{\beta_y(s)\varepsilon_y}+\sqrt{\beta_x(s)\varepsilon_x+\sigma^2_{\Delta p/p}D^2_x(s)}}ds$$

Pushing ΔQ_v to -0.30, with long (180 ns) bunches is probably feasible
Then looks OK for 50 ns, and close to requirement for 25 ns

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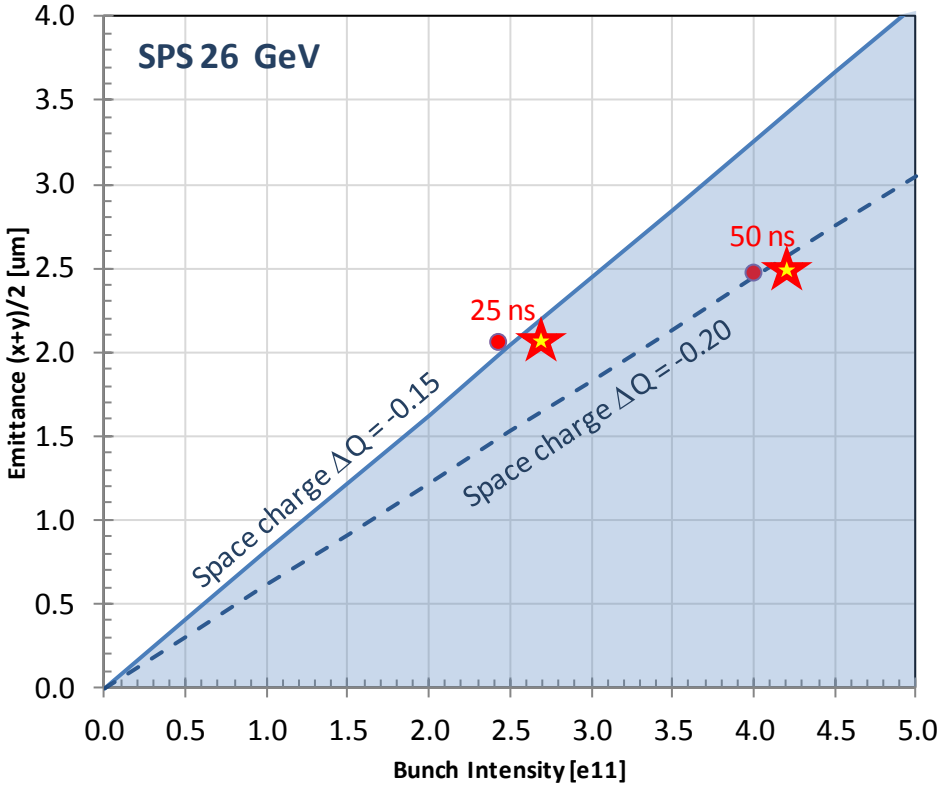
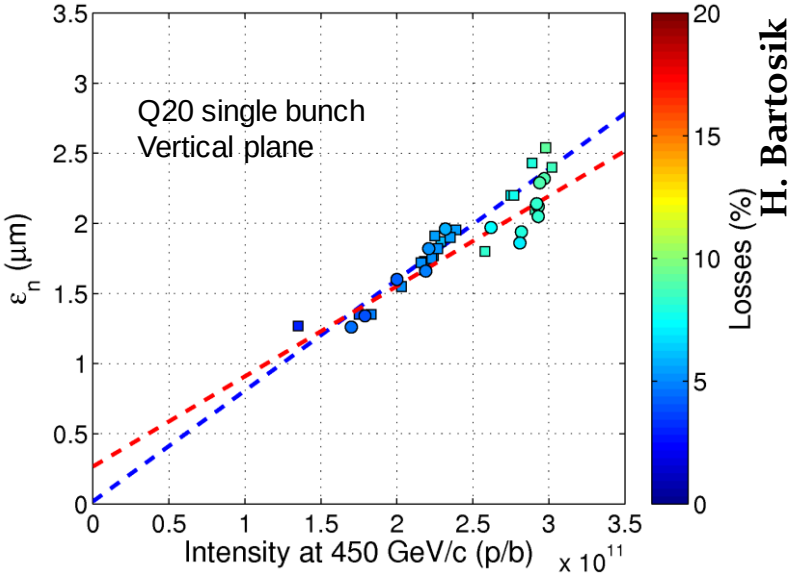
SPS brightness/SC limit

Postulated SPS brightness limit at injection energy of 26 GeV (Q20)



Single bunch….reached ΔQ_y -0.19 in MD with Q20 from Laslett formula



SPS needs to run at ΔQ ~ -0.15 for 25 ns beam, and at around -0.20 for 50 ns

Big question here is whether single bunch performance translates to multibunch, although should gain from working point optimisation

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Limits: space charge/brightness

- PSB at 160 MeV
  - **Very confident** to run with $\Delta Qy \approx -0.3$ (and reasonable hope for $\Delta Qy \approx -0.36$, or 1.4 um/2.4e12 p+)
- PS at 2 GeV
  - **Very confident** to run with $\Delta Qy \approx -0.26$ (and reasonable hope to increase to $\Delta Qy \approx -0.30$, with 180 ns long bunches, giving 1.6 um/2.4e12 p+)
  - Then looks reasonably well matched to what PSB can provide
- SPS: ε_{xy} [um] $\approx -1.22\ N_b$ [e12] / ΔQy, with Q20 optics at 26 GeV
  - Present **assumption** is to run with $\Delta Qy \approx -0.15$
  - Gives 1.2e11 p+/um or 1.6 um for 2.0e11 p+
  - Need to increase to $\Delta Qy \approx -0.18 - 0.20$ for 50 ns beam, or 1.2 um for 2e11 p+

- For 25 ns: suggests limit will be in PSB or PS
- For 50 ns: PS could deliver <1.0 um for 2.0e11, so limit still in SPS

LHC Injectors Upgrade

Other limitations

- SPS TMCI : single bunch
  - With Q20 looks like being above ~3.6e11 per bunch (Q'=0)
  - Assumed not to be an issue
- PS longitudinal coupled bunch instability
  - New coupled-bunch FB with a dedicated kicker cavity should increase limits from present ~1.7e11 to about 3e11 p+/b
  - Much more of an issue for performance reach with 50 ns
- PS beam loading in 10,20,40 MHz RF systems
  - Limited by transient phase for splitting – not a hard limit but will affect bunch-to-bunch quality – more critical for 50 ns beam
  - Limit expected to be ~3e11 per bunch, for 25 and 50 ns spacing
- PS-SPS transfer parameters – studies ongoing
  - Main motivation is longitudinal stability margin in PS. Need to make sure losses do not degrade (too much) with the larger emittance.

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SPS longitudinal instabilities

- Longitudinal stability: 25 ns beam unstable at 2-3e10 p+/b
  - Presently mitigated with long. emittance blowup (0.6 eVs) and 800 MHz
- Need $\geq$0.9 eVs for 25 ns stability with x2 nominal I_b (Q26)
  - Maybe gain from lower impedance (200 MHz and kickers), x2 800 MHz V.
  - Need to answer whether major upgrade of MKE kickers (open C core) is necessary – quantify effect of such a change?
  - Would be very beneficial to transfer longer (e.g. 1.8 ns) bunches to LHC (but need to mitigate capture losses in LHC) -> MD
  - Q20: instability thresholds higher, but need smaller ε_l to get same bunch length for given V_{RF}
- After upgrade, expect factor 2 intensity possible wrt 2011
  - 2.3e11 p+/b for 25 ns, and >3.4e11 p+/b for 50 ns
  - Main unknown is beam stability with high intensity (combination of single- and coupled-bunch effects)

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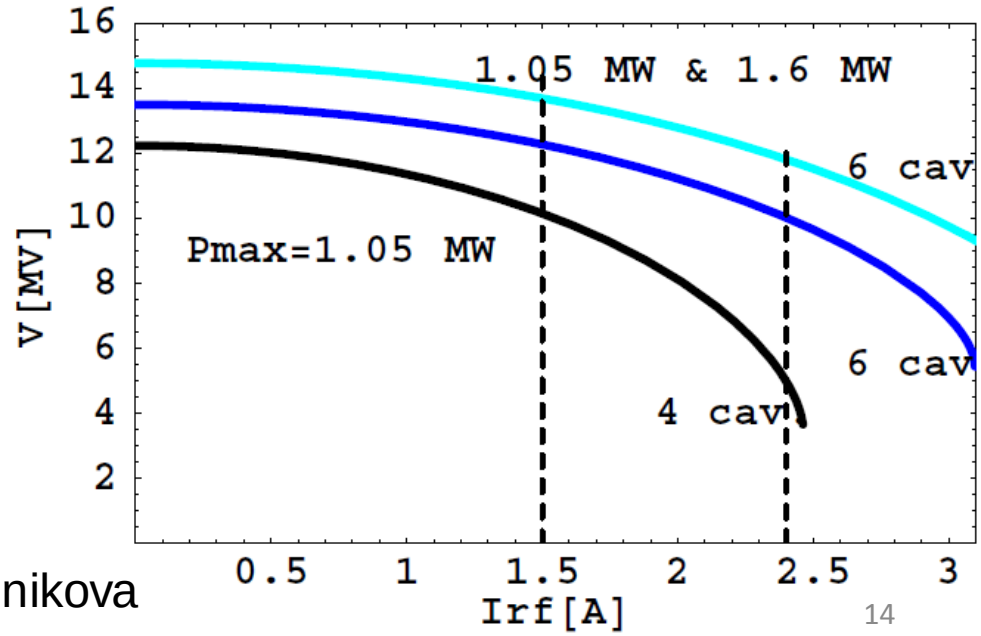
SPS beam loading

- SPS 200 MHz: x2 power, 4→6 (shorter) cavities, -20% impedance
  - Will allow 10 MV at extraction for 3 A RF current (now 1.5 A)
  - Need to operate existing power plants in pulsed mode (0.75→1.05 MW)
- After upgrade: same voltage available as now (if pulsed) for 2.3e11 p+/b (25 ns) and 4.6e11 p+/b (50 ns).
  - With larger emittance more V_{RF} needed for same bunch length
  - Will anyway have 10% longer bunches for 2x nominal I, with 10 MV



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‘Operational’ limitations

- Mainly in SPS (to date)
  - Heating of extraction kickers: should be ‘solved’ with final shielded MKE in LS1. Expect limit to be at least twice present beam power. Backup solution of open C core MKE kickers will definitely solve this problem
  - ZS sparking: interference with slow extracted FT beams. Difficult to solve – ‘ppm’ ion trap and main voltage modulation being studied. Last resort is ZS off and retracted during LHC beam, which strongly impacts beam to North Area. Major concern.
  - Outgassing of dump and impact on injection kickers MKP vacuum: extra differential pumping and sectorisation planned. Effect is mainly a limitation for scrubbing and setting up, rather than LHC filling. Should be manageable

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ecloud

- PS: observed but not yet a limitation.
  - Studies are ongoing to investigate HL-LHC regime
  - Mitigations being investigated (coating, double bunch rotation, …)
- SPS: expected to be major performance limit (beamloss, vacuum, ecloud instability and incoherent emittance growth):
  - More serious for 25 ns beam (but present for 50 ns)
  - Expected to be removed when machine is aC coated (LIU baseline)
  - Scrubbing for 25 ns will be tough…StSt chambers, OP limitations…
  - HBW feedback could cure vertical single bunch ECI

Beampipe profile	SEY threshold @ 1.1 10^{11} p/bunch	SEY threshold @ 2.5 10^{11} p/bunch
ID 156 (LSS)	1.4	1.1
ID 130 (LSS)	1.45	1.05
MBA (Dipole)	1.4	1.45
MBB (Dipole)	1.15	1.25

LHC Injectors Upgrade

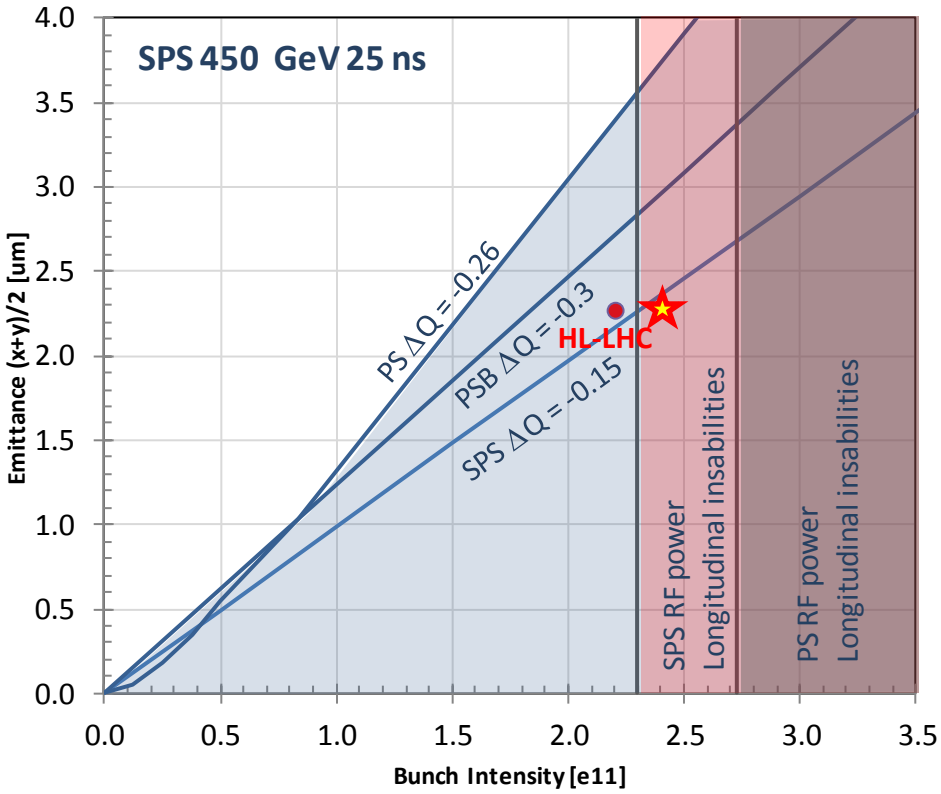
Putting it together

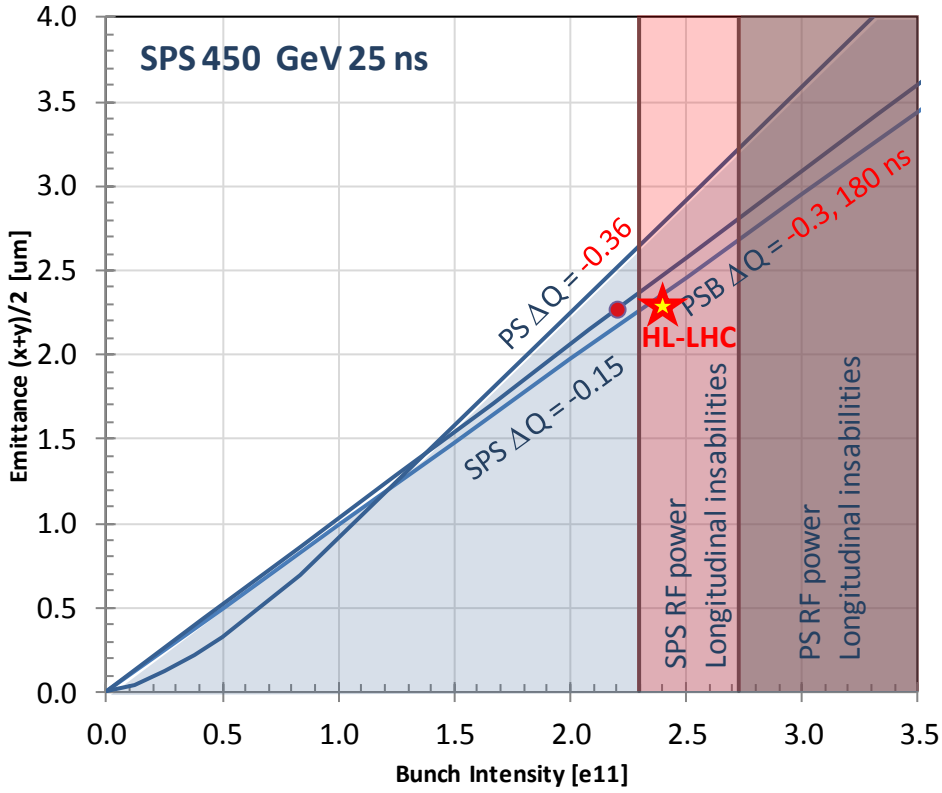
- Assume here:
  - ΔQ of -0.36 possible in PSB
  - ΔQ of -0.30 possible in PS
  - ΔQ of -0.15 possible in SPS (most speculative)
  - No limitation from ecloud after aC coating
  - Twice present beam current (2.3e11 for 25 ns, 3.5e11 for 50 ns) possible after SPS RF upgrade
  - Intensity per bunch limited to 3e11 p+ in PS from longitudinal coupled bunch instability and beam loading, with new feedback system in place

LHC Injectors Upgrade

25 ns after LIU upgrade

- At Chamonix, announced limit of 2.2e11 p+/b in 3.5 um



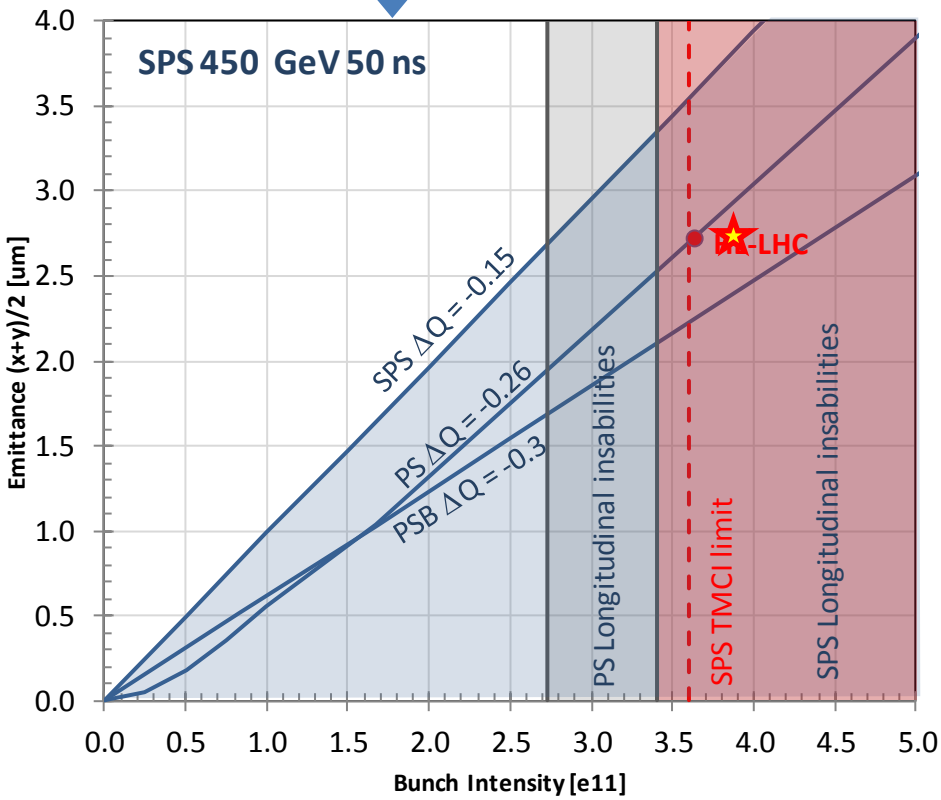


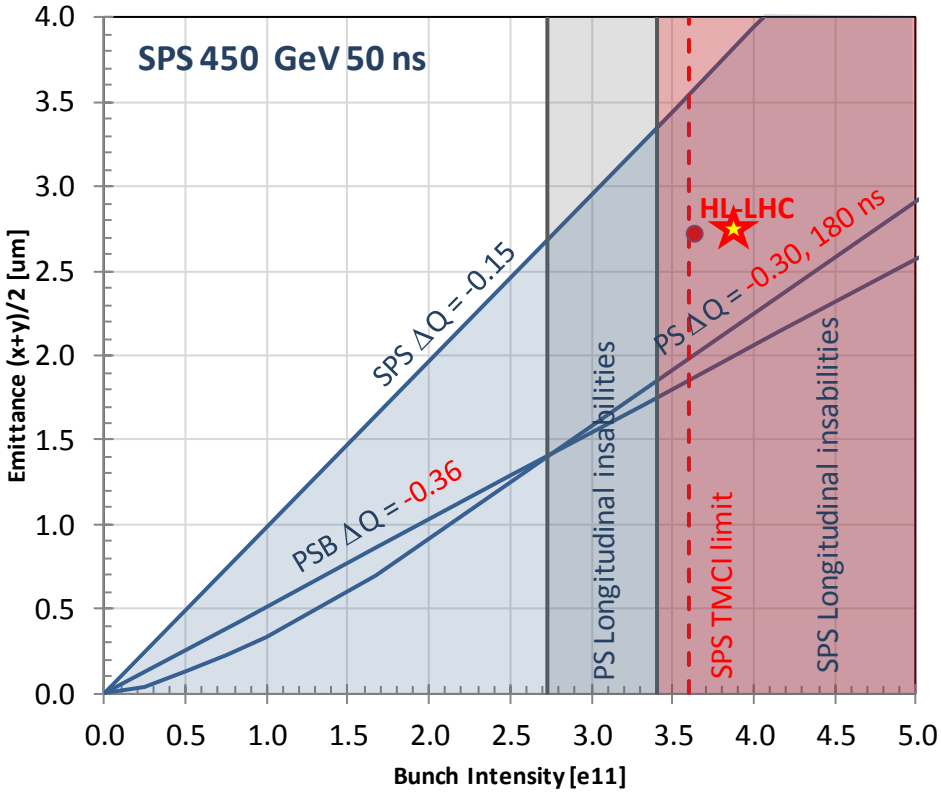
- Pushing 'reasonably' on PSB and PS space charge, and bunch length at 2 GeV in PS, 2.2e11 in 2.5 um seems feasible. Close to HL-LHC target of 2.2e11 in 2.3 um.

LHC Injectors Upgrade

50 ns after LIU upgrade

- At Chamonix, announced 2.7e11 p+/b in 2.7 um. Unchanged





- No change from pushing on PSB and PS space charge limits
- Intensity limited by longitudinal instabilities in PS (and then SPS), and emittance by brightness in SPS at $\Delta Q = -0.15$
- Both 'limits' are informed guesses at the present

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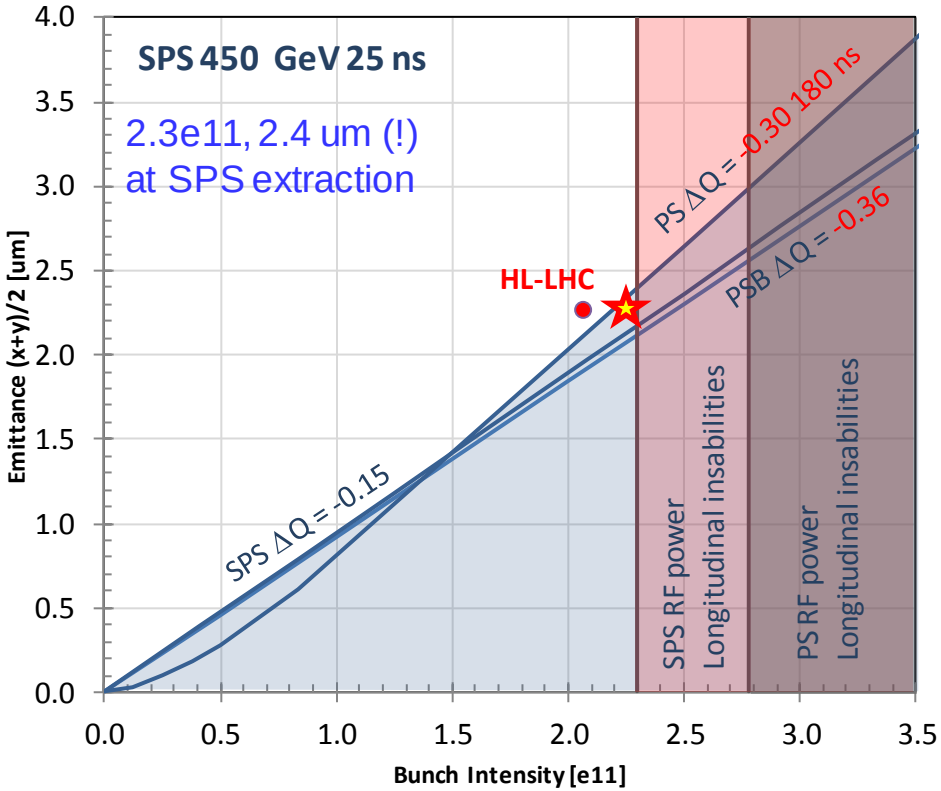
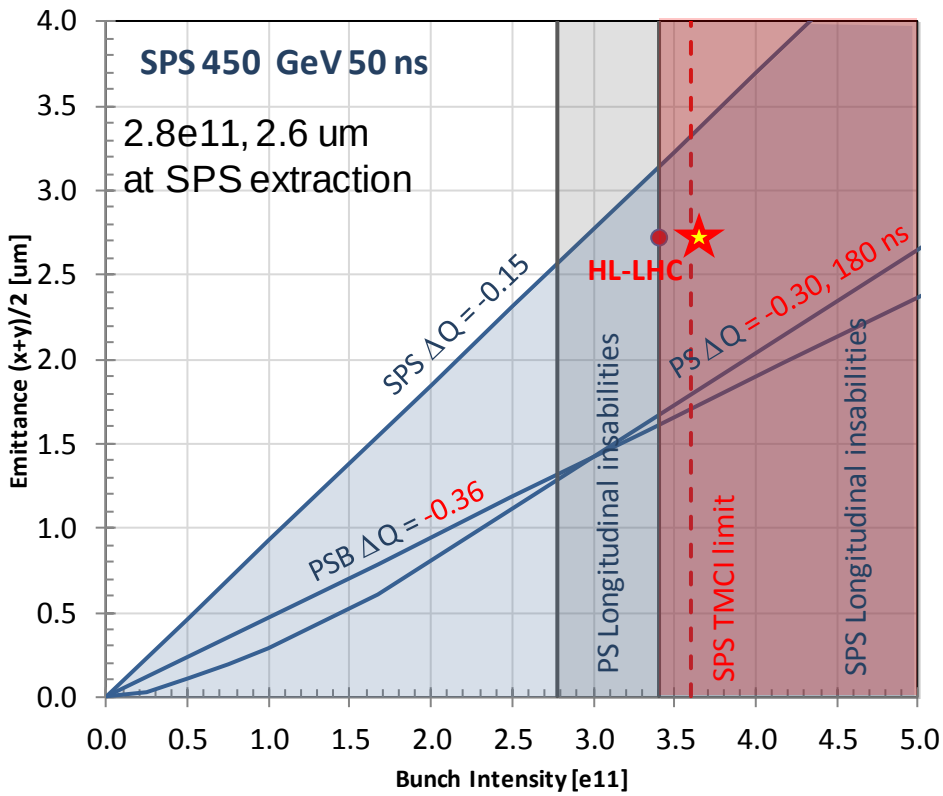
‘Conceivable’ improvements?

- Reduce losses (and SPS blowup) even further!?





- Will be **real challenge** to achieve with x2 beam intensities
- Consider as “stretch” goal - also for HL-LHC…!

Stretch	PSB	PS	SPS	LHC
loss %	5	3	8	3
blowup %	5	5	5	10

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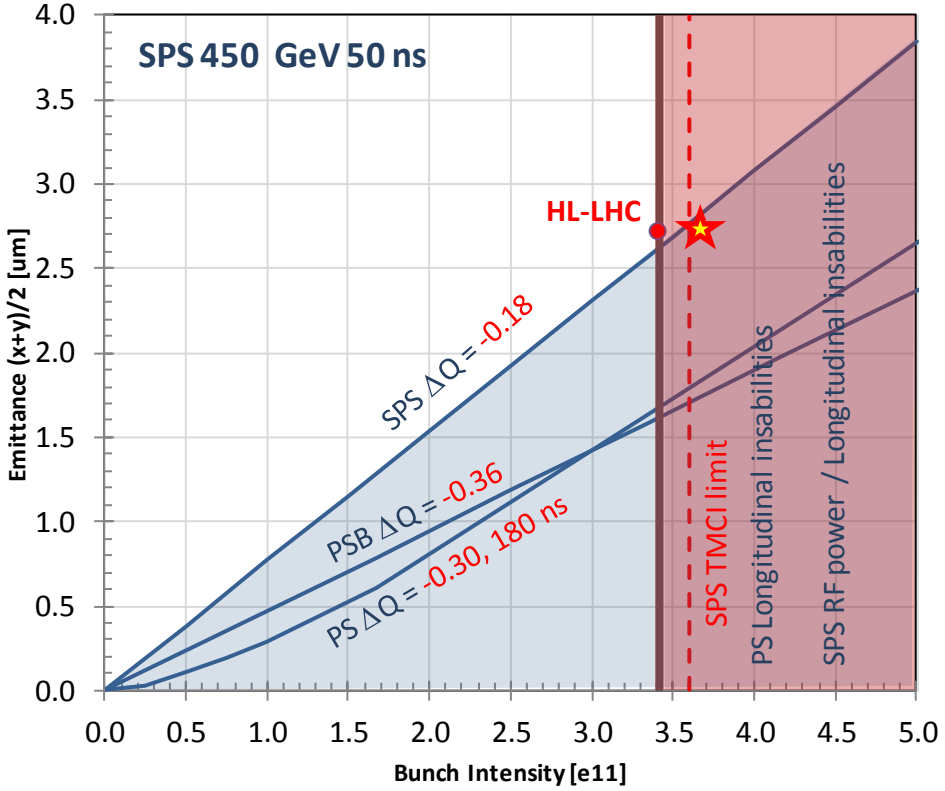
Hope for 50 ns?

- Losses + blowup: need to be brought to "stretch" levels
- Longitudinal stability in PS: would need 3.7e11 p+/b
- SPS tune shift: would need to run at $\Delta Q = -0.18$



– But requires 20% improvement in PS long. stability reach (on top of the factor ~2 assumed possible wrt today!!).

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Conclusions (I)

- Baseline LIU does not reach HL-LHC requirements…
- To even get close, with all upgrades working:
  - Need ΔQ_y to be pushed in PSB and PS beyond present assumptions
  - Need "stretch" loss/blowup levels in injectors, with HL-LHC ≤10% blowup, and losses of around 3%...
  - Need substantial improvement in PS longitudinal stability reach
- Expected limits are different for 25 and 50 ns production
  - PSB performance sufficient with 160 MeV injection for both
  - 25 ns: PS (PSB) space charge tune shift (2 GeV injection fixed by PSB).
  - 50 ns: brightness in SPS, PS longitudinal stability, PS beamloading

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Unresolved questions/issues

- Electron cloud
  - aC coating or scrubbing in SPS: baseline is aC, final review end 2012.
  - Potential issue with aC of high vacuum pressure: being studied
  - Is ecloud going to be an issue in PS?
- Q20 operational deployment in SPS after LS1?
  - Need to get experience if we have any hope to push to required levels
- Prospects for increasing (already ambitious) target for PS longitudinal stability (1.7e11 -> 3.0e11 -> 3.7e11 p+/b)
- Prospect for PS reaching -0.30, and PSB -0.36 in space charge tune shift

LHC Injectors Upgrade

Table of dreams – updated (I)

25 ns	Ib [e11]	Exy [um]	scaled I_b^2/e_{xy}
HL-LHC target (LHC flat-top)	**2.0**	**2.5**	**1.00**
LIU scenario (SPS extraction)			
LIU baseline (>LS2)	2.3	3.6	0.68
+ PS ΔQ to -0.30, PSB DQ to -0.36 (>LS2)	2.2	2.5	0.89
+ "stretch" blowup/losses (>LS3)	2.3	2.4	1.18

50 ns	I [e11]	Exy [um]	scaled I_b^2/e_{xy}
HL-LHC target (LHC flat-top)	**3.3**	**3.0**	**1.00**
LIU scenario (SPS extraction)			
LIU baseline (>LS2)	2.7	2.7	0.55
+ PS longitudinal stability 3.7e11 (>LS3)	3.3	3.3	0.67
+ SPS ΔQ to -0.18 (>LS3)	3.3	2.8	0.79
+ "stretch" blowup/losses (>LS3)	3.4	2.6	1.05

Now including brightness dilution in LHC in final quality factor

LHC Injectors Upgrade

Table of dreams – updated (II)

25 ns	Ib [e11]	Exy [um]	scaled I_b^2/e_{xy}
HL-LHC target (LHC flat-top)	**2.2**	**2.5**	**1.00**
LIU scenario (SPS extraction)			
LIU baseline (>LS2)	2.3	3.6	0.56
+ PS ΔQ to -0.30, PSB DQ to -0.36 (>LS3)	2.2	2.5	0.74
+ "stretch" blowup/losses (>LS3)	2.3	2.4	0.97

50 ns	I [e11]	Exy [um]	scaled I_b^2/e_{xy}
HL-LHC target (LHC flat-top)	**3.5**	**3.0**	**1.00**
LIU scenario (SPS extraction)			
LIU baseline (>LS2)	2.7	2.7	0.49
+ PS longitudinal stability 3.7e11 (>LS3)	3.3	3.3	0.60
+ SPS ΔQ to -0.18 (>LS3)	3.3	2.8	0.70
+ "stretch" blowup/losses (>LS3)	3.4	2.6	0.93

Now including brightness dilution in LHC in final quality factor

LHC Injectors Upgrade

Conclusions (II)

- In theory*, not totally impossible to approach HL-LHC request for both 25 and 50 ns, providing
  1. Losses and blowup can be reduced to "stretch" levels (25 and 50 ns)
  2. PS can run with higher space charge tune shift, nearer $\Delta Q \approx -0.30$ with 180 ns bunch length, and PSB can run with $\Delta Q \approx -036$ (mostly for 25 ns)
  3. PS longitudinal stability can improve significantly above present expectation (today at 1.7e11, LIU baseline 3e11, need 3.7e11) (for 50 ns)
  4. SPS can increase brightness limit, to $\Delta Q \approx -0.18$ (for 50 ns)
- Also....we are taking for granted that all planned upgrades fully effective, and that we can approach single bunch limits with multi-bunch operation

*"The difference between theory and practice is in theory somewhat smaller than in practice"