PS potential performance with a higher injection energy

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for the PS-LIU

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PSB Energy Upgrade Task Force

The role of the PS in the LHC beams production

- **Conserve the transverse emittances produced in the PSB:**
  - Causes of blow-up:
    - Laslett tune shift due to space charge: < |0.3|
      → **Blow-up of first batch waiting for the second batch injection**
      → Can be beaten by increasing the injection energy
      (Chamonix 2010 proposal from M. Giovannozzi, reason of the previous PSB extraction energy upgrade from 1 to 1.4 GeV)
  - Injection mis-steering/oscillations.
  - Other effects: head-tail instability at injection energy, TMCI at transition crossing, electron cloud at extraction.
- **Define the longitudinal structure of the beam**
  - 25-50-75-150 ns bunch spacings are defined by RF gymnastics in the PS.
  - Longitudinal beam quality can be spoiled by:
    coupled bunch instability, transient beam loading...

What kind of beam we could produce at 2 GeV (I)

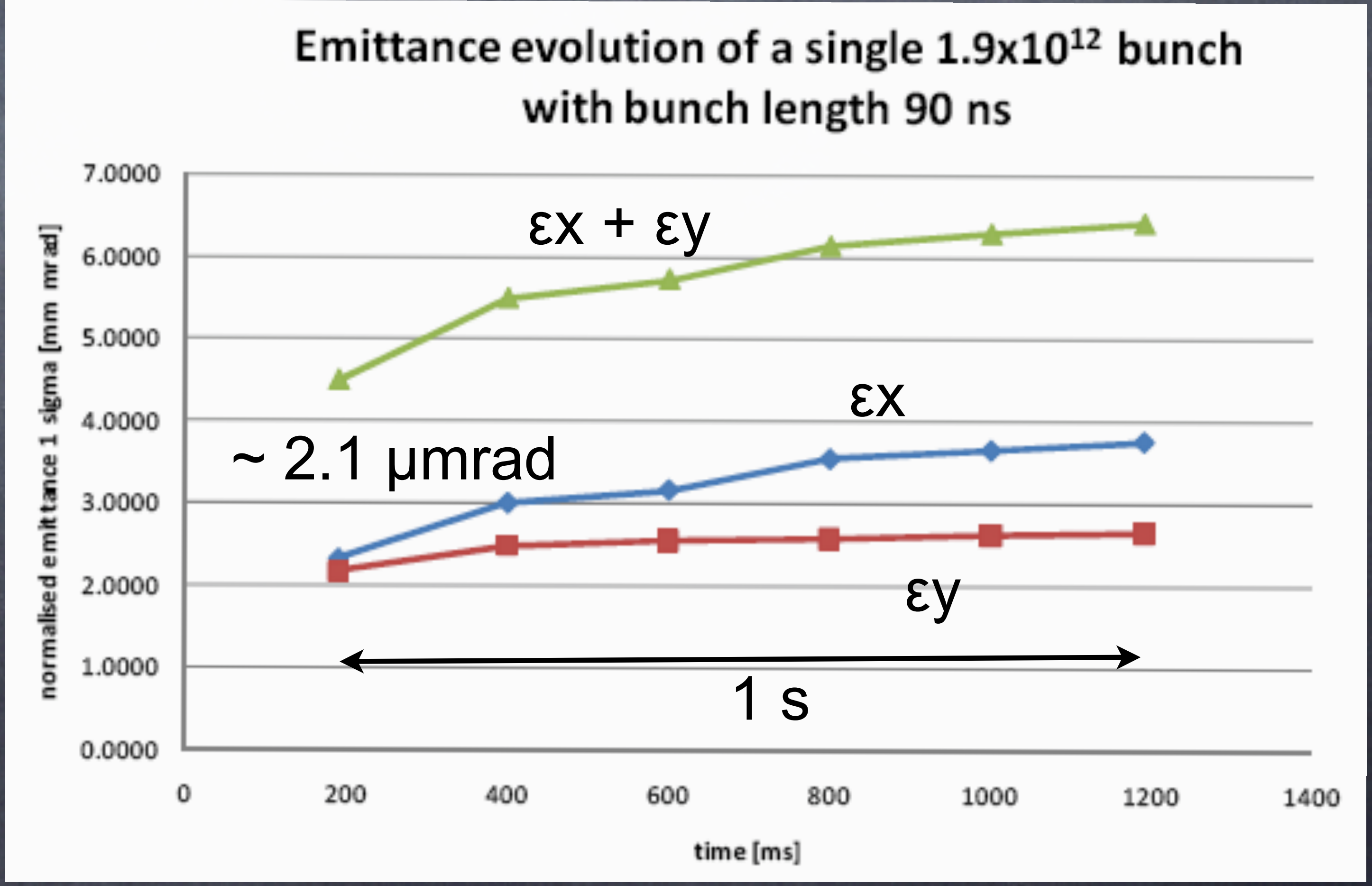
From 2010 tests/LHC beam operation:

- For Laslett tune shift below |0.3|, no-significant transverse emittance blow-up observed.
- Large Laslett tune shift might be acceptable, tests done with **ΔQx ~ -0.34** and **ΔQy~ -0.56** (**to be further studied, not in full agreement with past studies from E. Metral et al.**).
- Tests with ultimate-like beams showed that more than 1.7 10^{11} ppb peak performance is achievable with 25 ns and 50 ns bunch spacing, but only reduced beam quality and operationally not maintainable.

$$\Delta Q_y^{\mathrm{MDLHC25}} @\mathrm{PSinj} = -0.338$$

Test early 2010 (S. Hancock et al.):

$160 \cdot 10^{10}$ ppb (at PS ejection)
135 ns and 0.9 eVs
εx,y≈ 2.5 μmrad → **~ 10% blowup**



Test end 2010:

$190 \cdot 10^{10}$ ppb (at PS ejection)
90 ns
Increase total emittance (εx + εy) ~40%

$$\begin{cases} \Delta Q_x^{\mathrm{LHC25MD}} @\mathrm{PS\_FT} = -0.34 \\ \Delta Q_y^{\mathrm{LHC25MD}} @\mathrm{PS\_FT} = -0.56 \end{cases}$$

What kind of beam we could produce at 2 GeV (II)

Achievable with Linac4 (at PS ejection. max, 72 bunches for the 25 ns, 36 for 50 ns) in the hypothesis $\varepsilon_{(x,y)} \not\propto$ ppb:

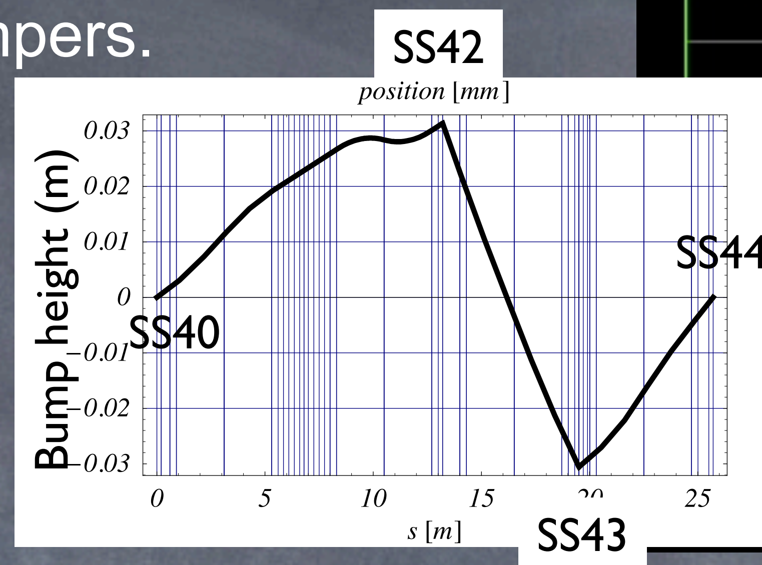
Intensity PS ej. (ppb)	Bunch spacing	$\varepsilon_{(x,y)}$ PS ej. (1 σ norm) **no blow-up**	Laslett ΔQx	Laslett ΔQy	ε_l @ PSB	PSB int. per ring **(assuming 5-10% losses)**	Comment
$3.0 \cdot 10^{11}$	25 ns (DB)	2.5 μm rad	-0.24	**-0.37**	< 2 eVs (160 ns)	~ $400 \cdot 10^{10}$	Optimistic from Low εL
$1.5 \cdot 10^{11}$	25 ns (SB)	2.5 μm rad	-0.18	-0.28	1.4 eVs (120 ns)		Limited by L4 brightness
$1.9 \cdot 10^{11}$	25 ns (DB)	2.5 μm rad	-0.14	-0.22	< 2 eVs (160 ns)	~ $240 \cdot 10^{10}$	Pessimistic lower limit
$3.0 \cdot 10^{11}$	50 ns (DB)	2.5 μm rad	-0.11	-0.17	< 2 eVs (160 ns)	~ $190 \cdot 10^{10}$	Optimistic from Low εL
$1.9 \cdot 10^{11}$	50 ns (DB)	2.5 μm rad	-0.07	-0.11	< 2 eVs (160 ns)	~ $125 \cdot 10^{10}$	Pessimistic lower limit
$1.7 \cdot 10^{11}$	25 ns (DB)	1.5 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $220 \cdot 10^{10}$	Minimum $\varepsilon_{(x,y)}$
$2 \cdot 10^{11}$	25 ns (DB)	1.8 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $250 \cdot 10^{10}$	Minimum $\varepsilon_{(x,y)}$
$2.7 \cdot 10^{11}$	50 ns (DB)	1.1 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $170 \cdot 10^{10}$	Minimum $\varepsilon_{(x,y)}$
$3.5 \cdot 10^{11}$	50 ns (DB)	1.5 μm rad	-0.3	-0.3	< 2 eVs (160 ns)	~ $220 \cdot 10^{10}$	Beyond limits RFwise

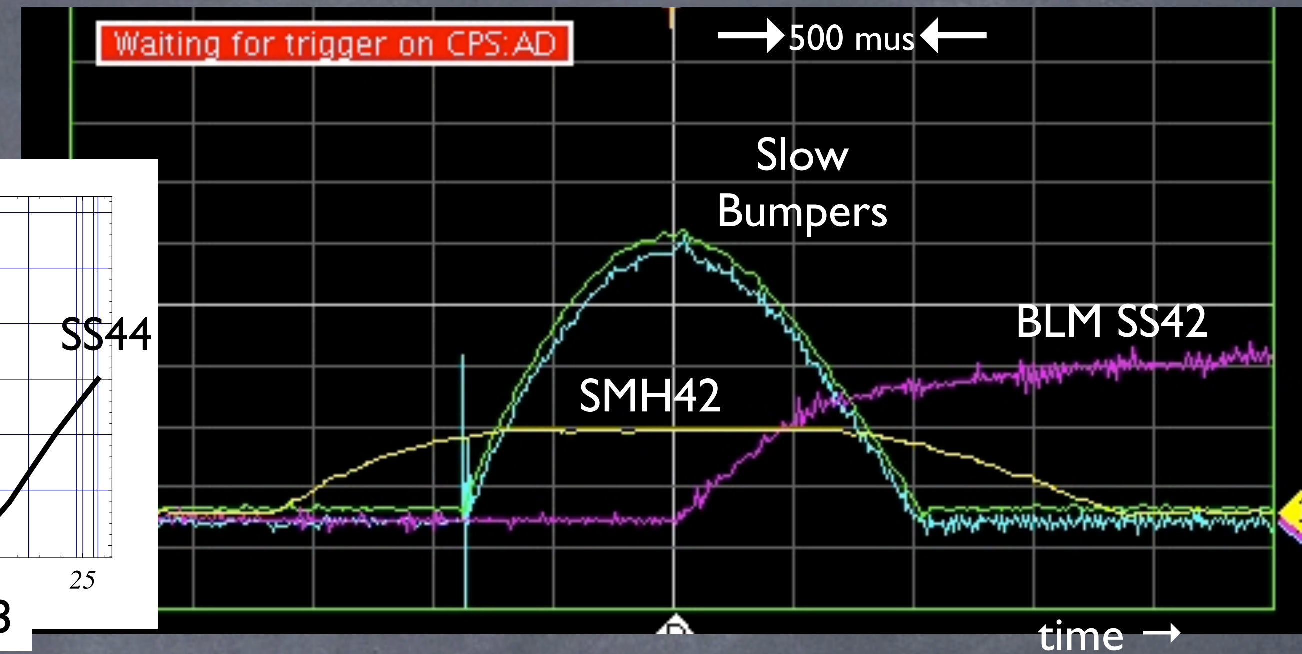
Goal for longitudinal parameters:

- Intensity variation along the batch < than ± 10%.
- 0.35 eVs at extraction (SPS injection).

2 GeV Injection

Current injection composed by:
- 4 independent dipole bumpers.
- Magnetic septum.
- Kicker.





Bumper magnets have some margin for the 2 GeV operation
- **New design to avoid captive vacuum chamber.**
- One bumper will be installed in the septum vacuum tank and it will have a septum-like design.

Kicker should be operated at 2 GeV in short circuit mode to avoid changing the power converter.
- Kicker was not modified during the 1 to 1.4 GeV upgrade.
- First test showed ~10% emittance blow up due to ripple on kicker flat top: could be cured by transverse damper.
- Possible to inject only the LHC-type beams at 2 GeV with the existing kicker (not much margin left however).
- **Eventual supplementary kicker needed in SS53 if extra kick is needed.**

Septum should be exchanged, too short and no margin.
- Problem of bumper in same SS.
- Change of the injection point.
- Consolidation of power converter already foreseen.
- **New design with septum-like bumper in septum vacuum under study.**

New injection conceptual design will be frozen in february together with BT/BTP upgrade

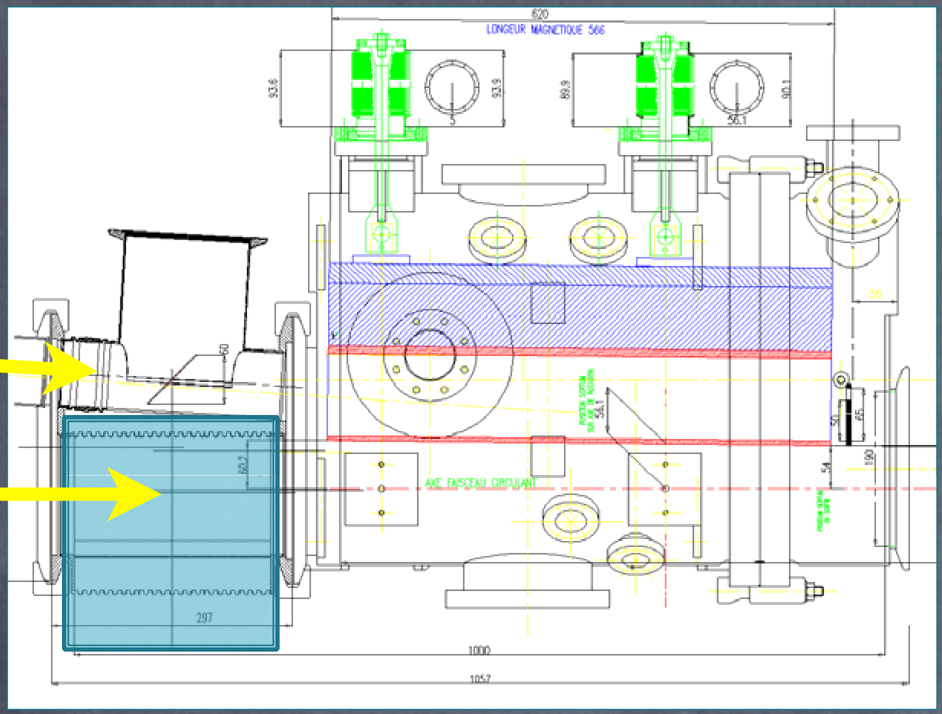
New septum design

Current design

Proposed for 2 GeV
(from M. Hourican)

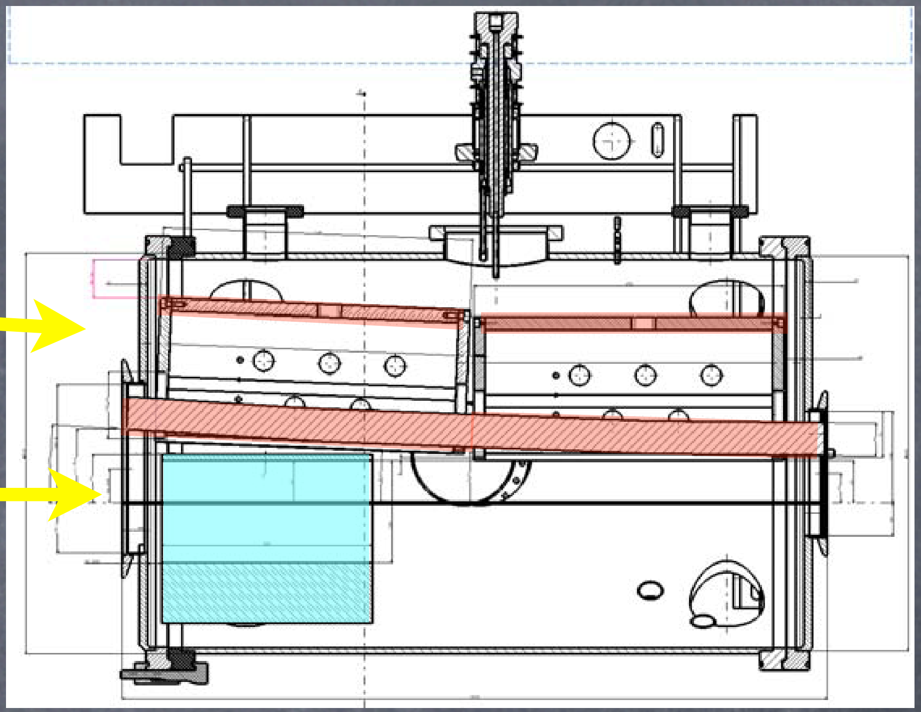
BTP beam

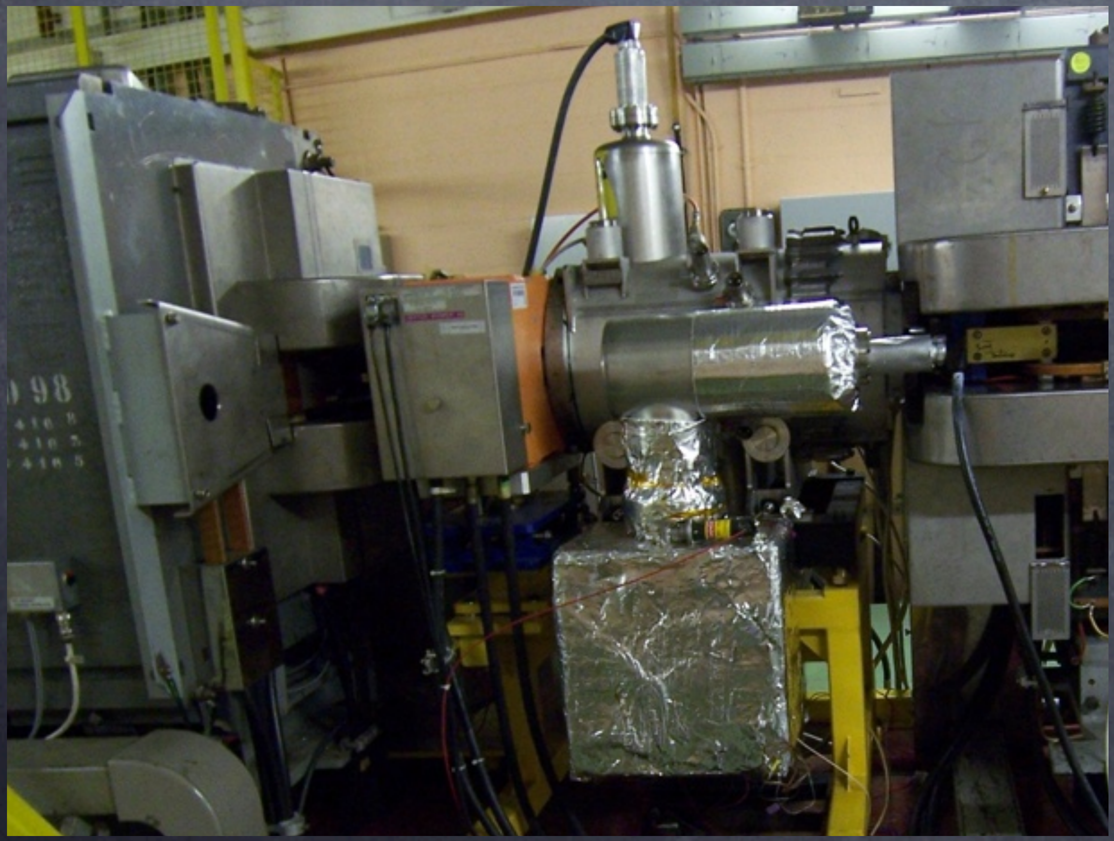
PS beam

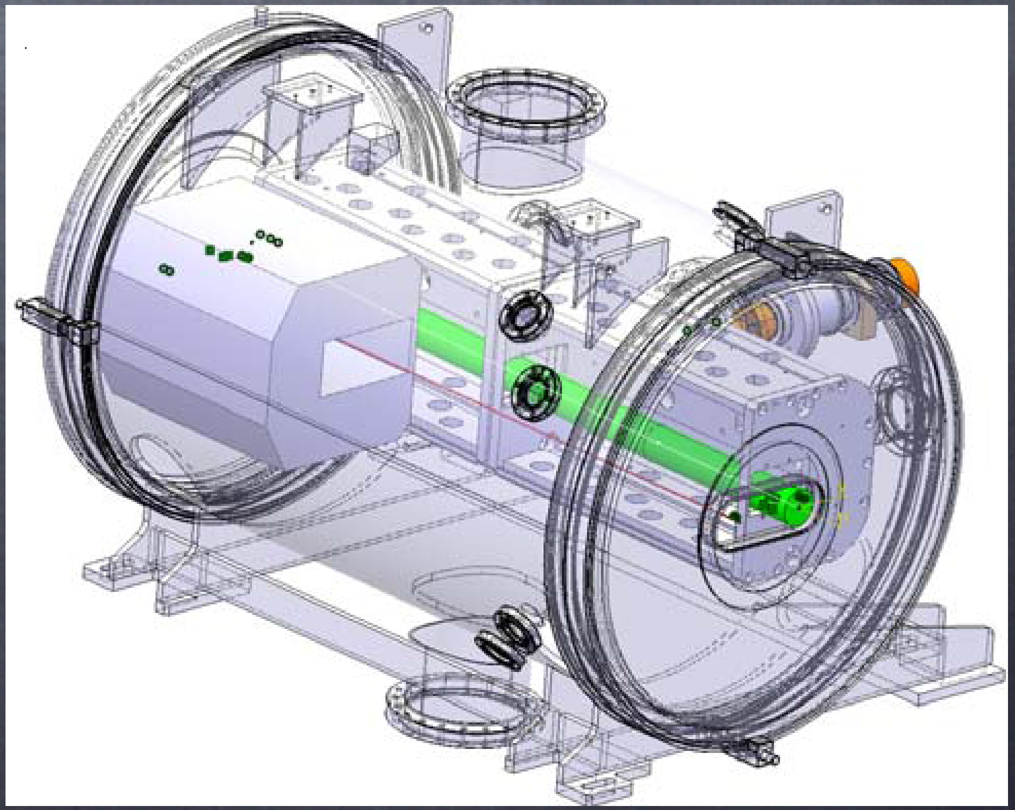


BTP beam

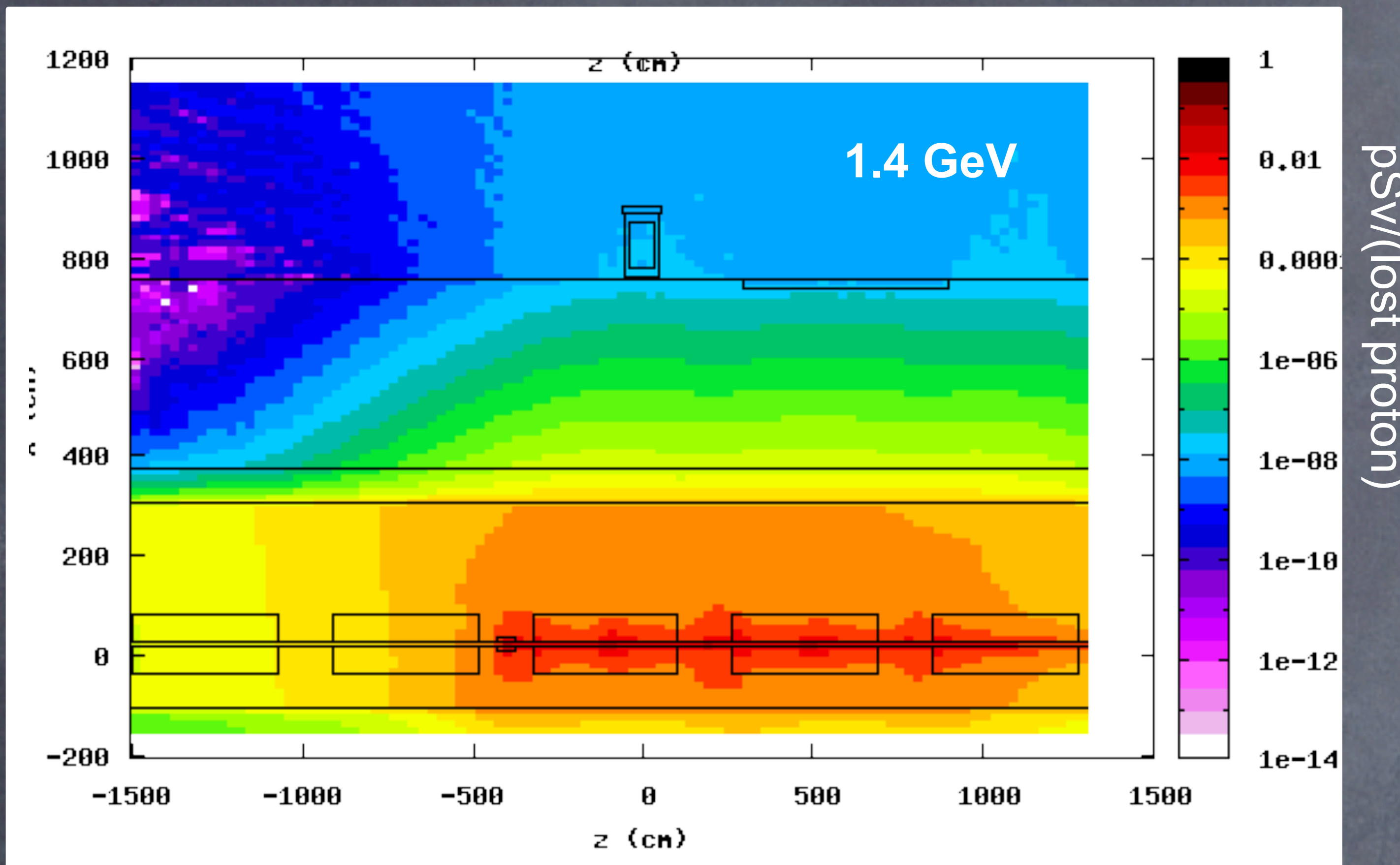
PS beam

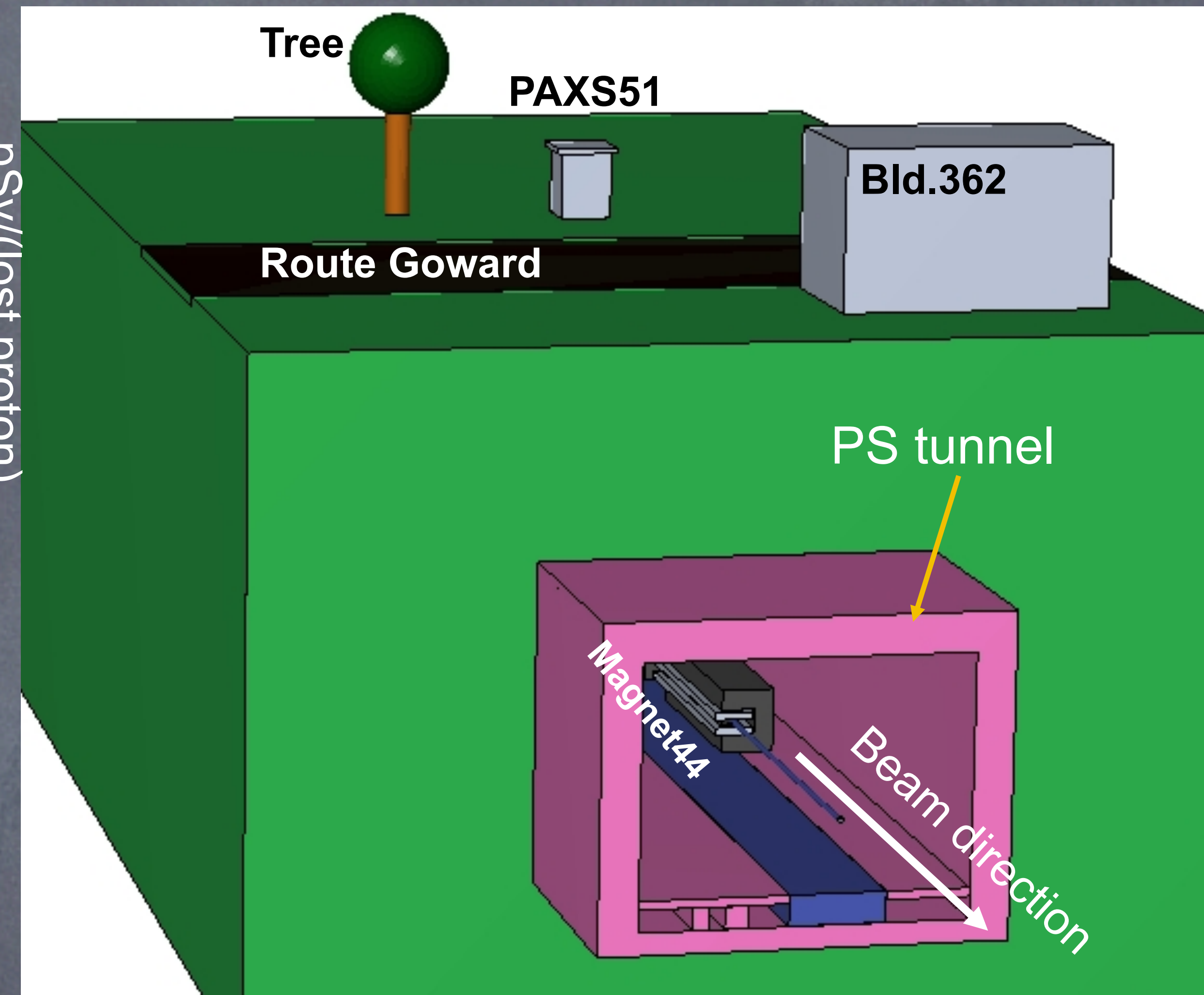






Losses at injection





Courtesy of S. Damjanovic, RP

Fluka simulations showed that the activation of materials and on Route Goward would increase **when going to 2 GeV <u>assuming the same losses as at 1.4 GeV</u>**

- Losses should be reduced thanks to the reduced physical emittances.
- Losses happen during the decrease of the injection bump → implement a faster bump.
- **LHC beam-type losses at injection are small even today.**
- **Issue if FT beams are going to be injected at 2 GeV (current baseline for LIU).**

Implement new shielding on top of route Goward (needed in any case for today high-intensity beams)

Flat bottom blow-up/instabilities

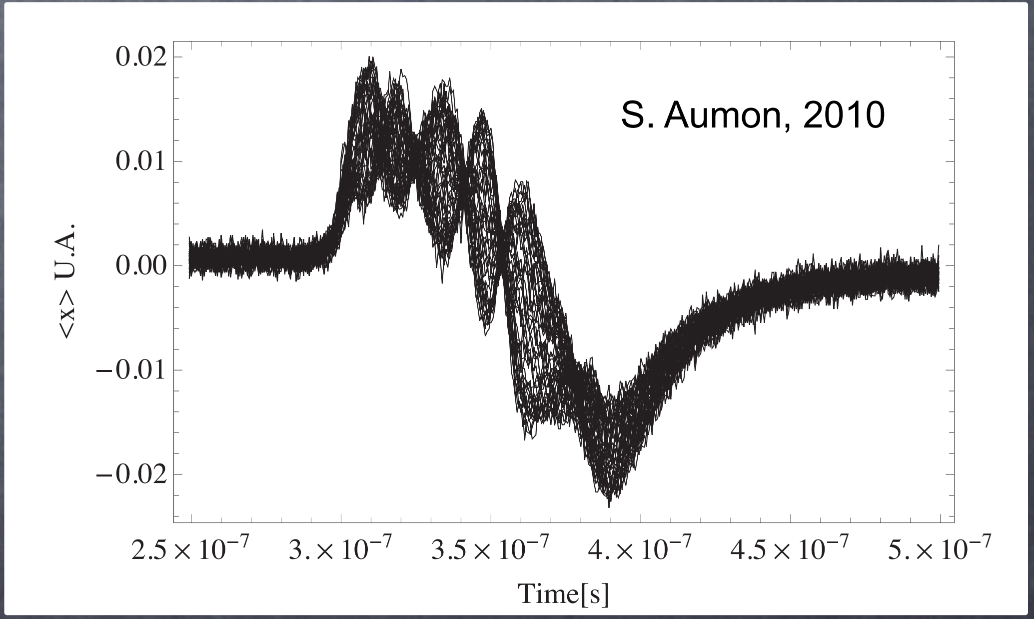
- Transverse blow-up due to space charge needs further studies. Not completely clear yet the mechanism which blow-up the emittance for a large Laslett nor the growth rate. Also the limit on the tune shift of |0.3| merits to be revised.

- If emittance blow up grow rate of the order of 1 s, PSB second injection could arrive after 900 ms.
- Tests with very large tune shift done (order of |0.56| in H plane), showed large emittance blow-up on a long time scale.

- Growth rate of head-tail instabilities at the flat bottom scales like N/γ→ issue for the first batch waiting for the second → 50% faster instabilities if twice the intensity at 2 GeV

Observed during 2010 tests with large Laslett tune shift beams:

- Instability rise time was very fast, few 10-20 ms.
- Instability fall time was very fast, few 10-20 ms.
- No significant emittance transverse blow-up was observed.

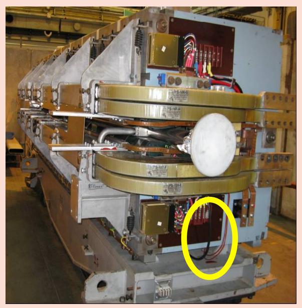
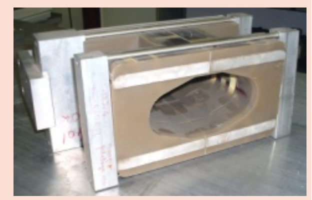
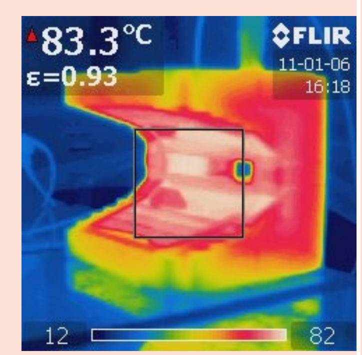
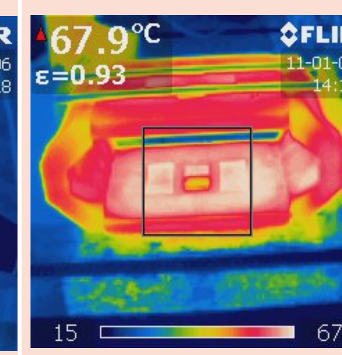


Might cause emittance blow up but also beam losses

Could be cured with:
- Octupoles (not any longer) but octupoles available in the PS.
- Linear coupling as done today by skew quadrupoles.
- Working point adjustment not done today but sextupoles available (PFW) or dedicated ones could be installed.
- Transverse feedback which is available but not operational.

From 2010 experience, this was not a limitation but needs to be carefully studied in any case

Performances of magnets/PO used at low energy

	DHZ	DVT	QFN – QDN	QFN - QDN	QSK + DVT	QSK
Use	H dipole correctors	V dipole correctors	Lattice quadrupoles (1)	Lattice quadrupoles (2)	Combined function skew quadrupole	Skew quadrupoles
Number of magnets	100	5	20	20	25	20
View						
Power converters		To be consolidated	To be consolidated	To be consolidated	To be consolidated	To be consolidated
For 2 GeV	Ok (MD to confirm)	Ok (MD to confirm)	OK (MD to confirm)	OK (MD to confirm)		

Magnets have been tested in 2010 with maximum RMS which seems to be compatible with operation at 2 GeV except Skew quadrupoles used to damp the HEADTAIL instability

Power converters should be renovated in any case, new specifications for more flexible operation at 2 GeV will be provided

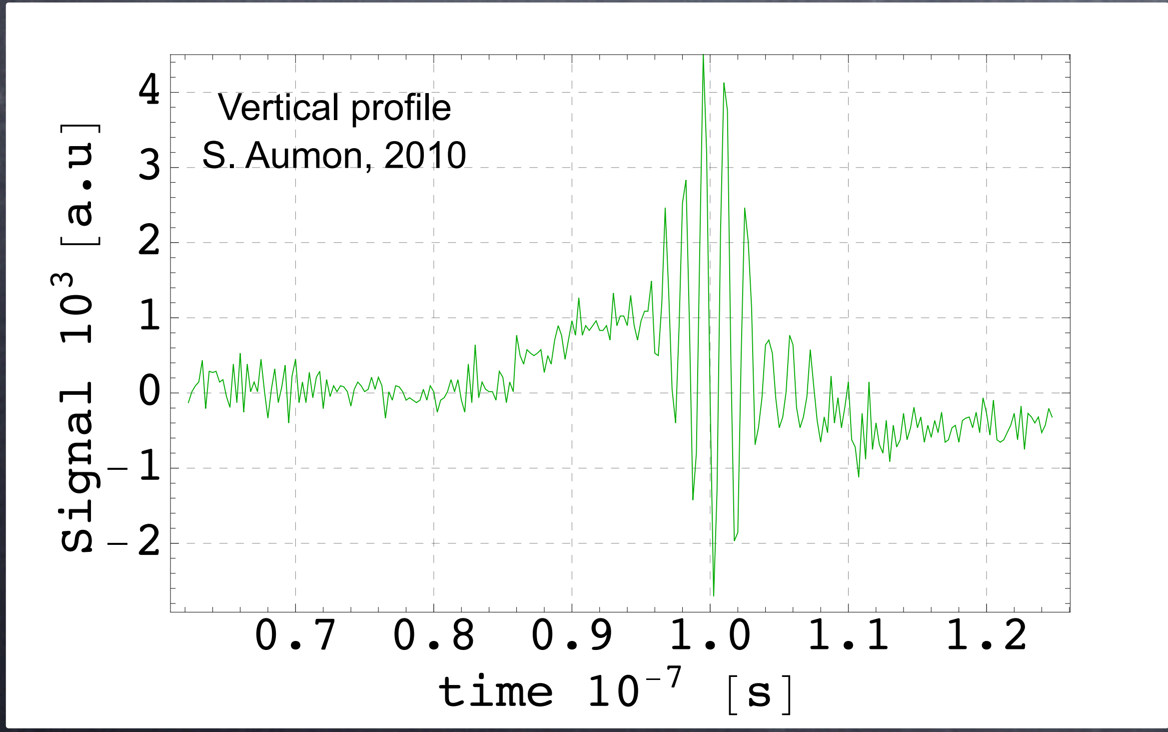
Transition

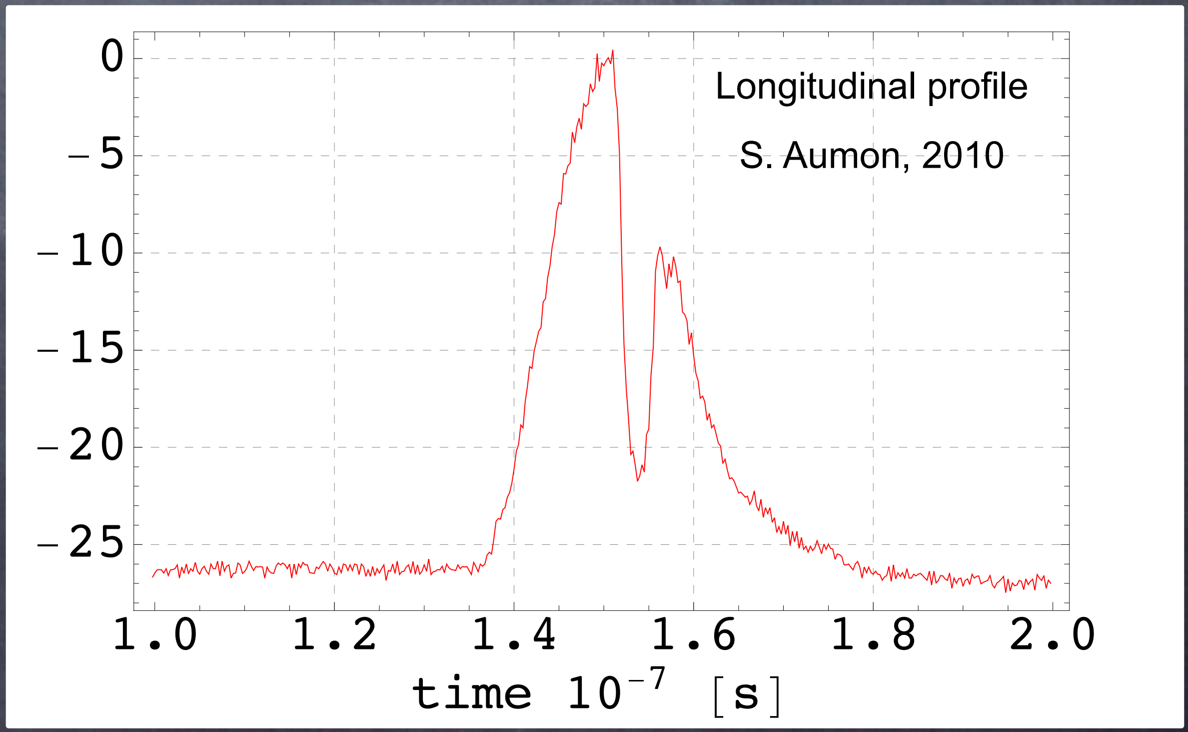
Longitudinal plane: no limitations at transition crossing expected for (beyond) ultimate beams

- Peak current only allows an estimation, no direct scaling.
- No problem up to $2 \cdot 10^{11}$ ppb (at PS ej.) during ultimate LHC25 tests (good for crossing transition with up to $4 \cdot 10^{11}$ ppb at ej. with LHC50).
- Peak current of ultimate beams below present limitations (with e.g. TOF or AD beams).

Beam	Int. [10^{11} ppb] at ejection	Intensity [10^{11} ppb]	Long. emittance ε_l [eVs]	Pk. current at γ_{tr} [A]
LHC25, nominal	1.3	5.2	0.65	8.4
LHC25, ultimate	2.1	8.4	0.65	14
LHC50, nominal	1.3	2.6	0.65	4.2
LHC50, beyond ult.	3.0	6.0	0.65	9.7
SFTPRO/CNGS		17	1.4	15
AD		40	2.3	23
TOF		89	2.6	40

The TMCI instability observed on the TOF beam, and causing vertical losses, has a threshold beyond themore-than-ultimate LHC beam, stable for ~2 x 10^{12} ppb (2010 results). Further studies will be done. Might cause $\varepsilon_{(x,y)}$ blow-up. Transverse emittance blow-up observed during 2010 tests with ultimate beam.



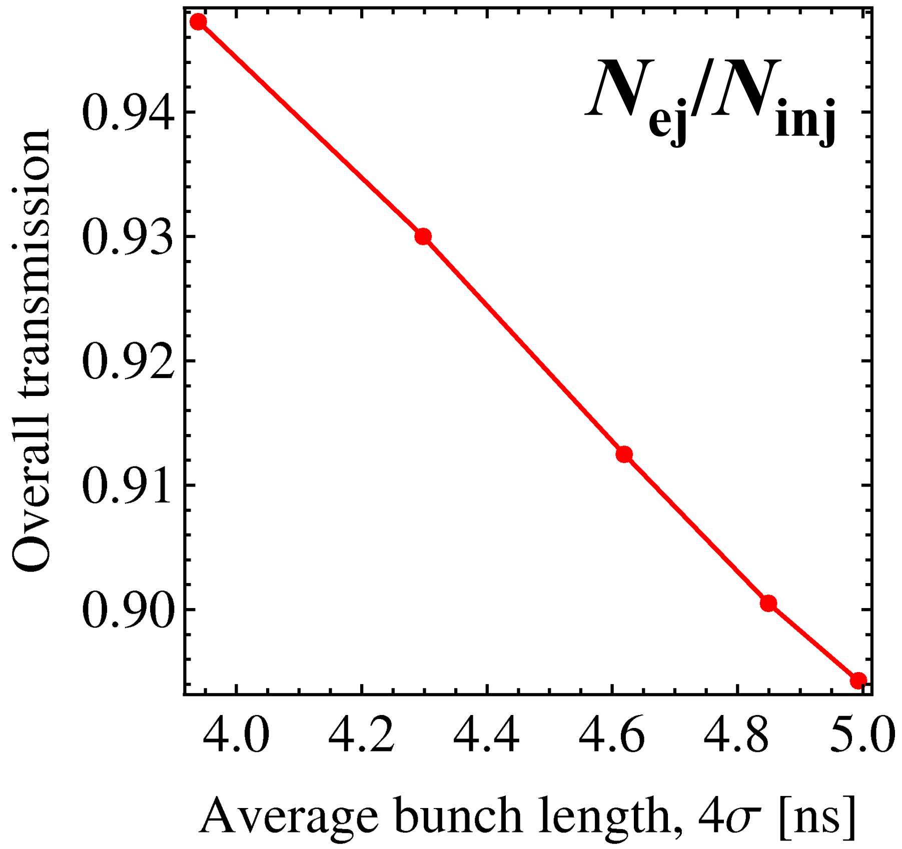


Longitudinal emittance at extraction: constraint for the SPS on beam quality

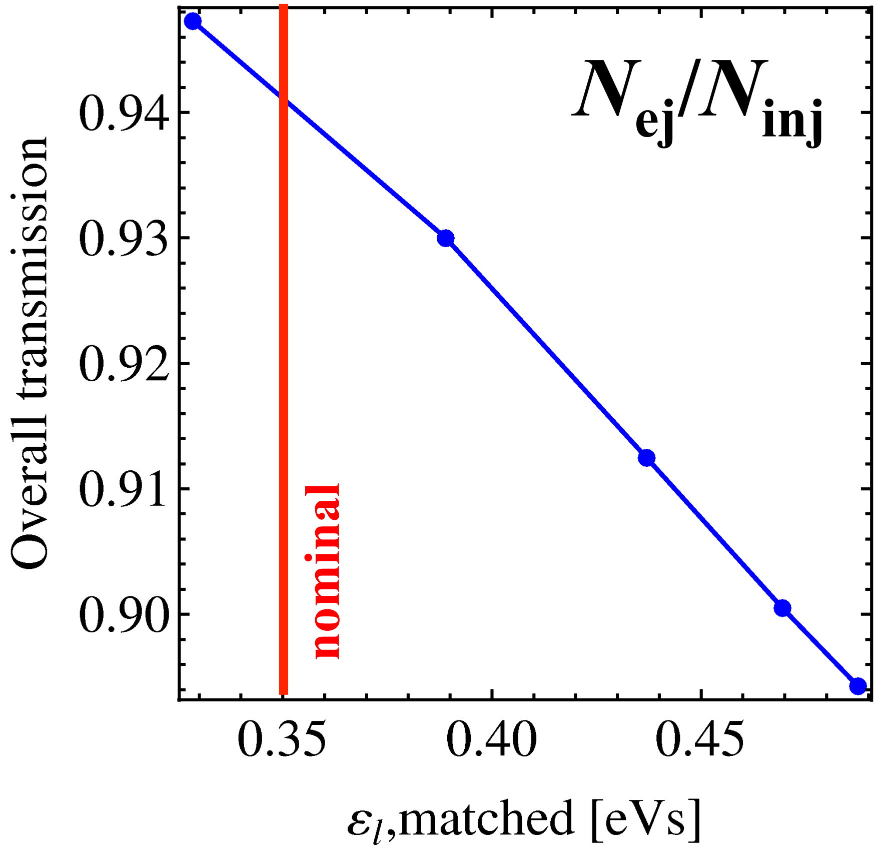
Long. beam quality required for SPS? Is ε_l = 0.35 eVs written in stone?

→ **Dependence of beam transmission in SPS from injected beam quality:**

Versus 4σ bunch length



Versus longitudinal emittance



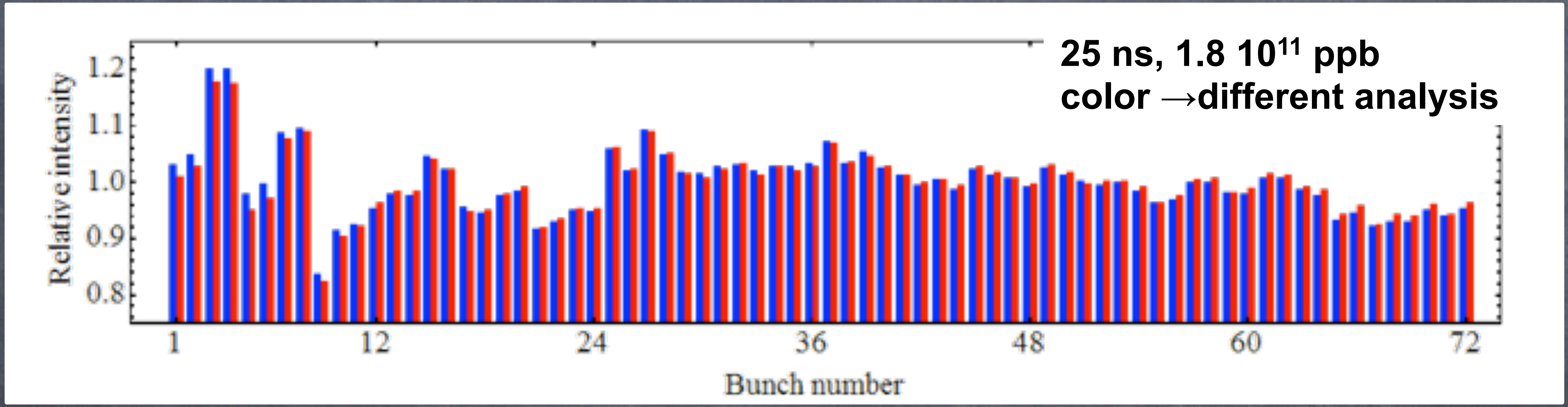
→ **No increase in bunch length at PS-SPS transfer permissible**

→ **Generate the same bunch length with larger ε_l? More bunch rotation V_{RF}?**

→ **Systematic MDs in 2011 evaluating that route**

Sources of longitudinal beam parameter degradation

- **Transient beam loading causes relative intensity errors of up to 20% (± 10%) per splitting**
  - Pattern well understood from RF manipulations.
  - Distributed problem since all the RF systems are used for splitting, i.e. contributed to the final spread.
  - Bunch length and longitudinal emittance also affected with consequences for the SPS.



- **Coupled bunch instability observed during acceleration and at flat top, longitudinal emittance blow-up:**
  - Mode spectrum very similar for the same average longitudinal density (25 ns or 50 ns) ~ N/ε_l .
  - Very different mode spectra during acceleration and on the flat-top depending on bunch spacing (25 ns or 50 ns).
    → Impedance change of 10 MHz cavities due to gap relay closing.

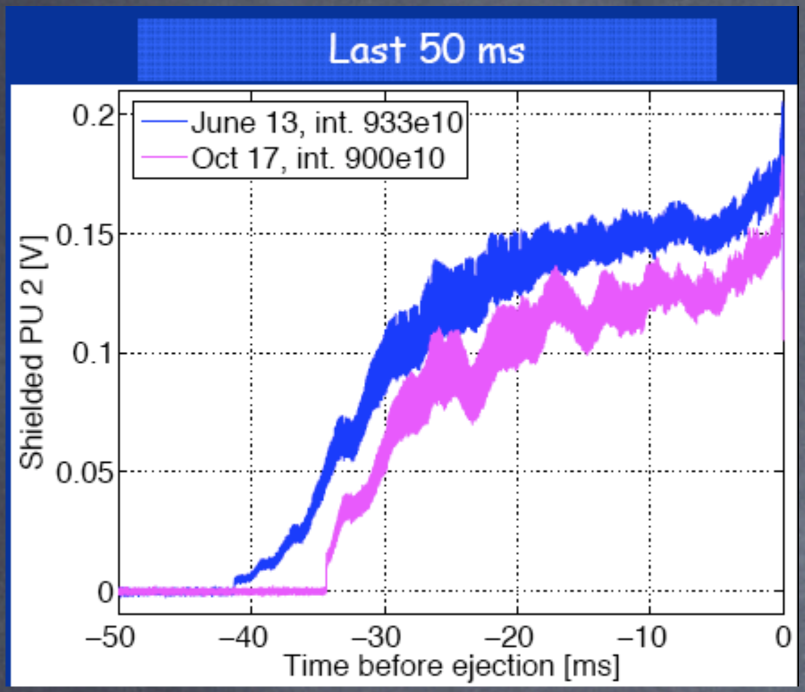
Summary of RF-HW interventions

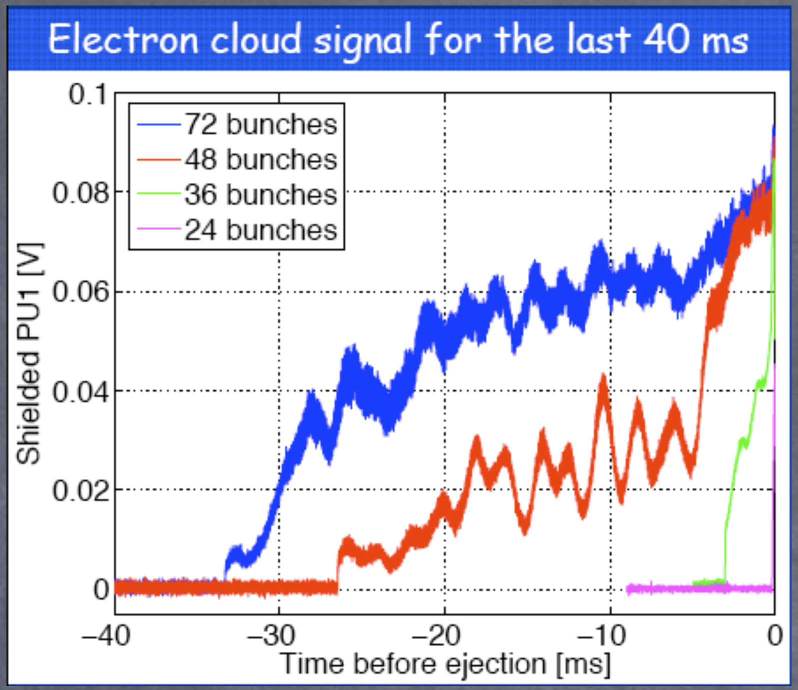
Priority	Item	When	Remarks
[1]	**New coupled-bunch FB**	**2012**	**ongoing, budgeted**
2	Dedicated kicker cavity	2015-2020	on consolidation list
10 MHz			
[1]	**1-turn delay FB**	**2011**	**budgeted, prototype tests in 2011**
1	**Renovate FB amplifiers**	**2011-2015 (?)**	**study until end 2011**
1	**Slow phase loops around each cavity**	**2013-2014**	
2	New power amplifier (1 tube/gap)	2014-2018 (?)	study until end 2012
20 MHz			
1	**1-turn delay FB**	**2012**	**study until mid 2011**
2	Slow phase loops around each cavity	2012	
40 MHz			
[1]	**Automatic tuning system**	**2011**	
1	**1-turn delay FB**	**2012**	**study until mid 2011**
2	New feedback amplifier in grooves	2014	study until end 2012, priority to be redefined after first study 2011
2	Slow phase loops around each cavity	2012	
3	Study more voltage per cavity	2013	shut-down time with infrastructure (water, etc.) needed
3	New power supplies	2014-	can be specified after voltage tests
80 MHz			
1	**1-turn delay FB**	**2012**	**study until mid 2011**
1	**Automatic tuning system - PLC, prot./ions switching**	**2011-2012**	
2	Slow phase loops around each cavity	2012	
2	New feedback amplifier in grooves	2014	study until end 2012, priority to be redefined after first study 2011
2	Fast ferrite tuner	2016	feasibility study by end 2011
3	Study more voltage per cavity	2013	shut-down time with infrastructure (water, etc.) needed
3	New power supplies	2014-	can be specified after voltage tests
3	Extra 80 MHz cavity		

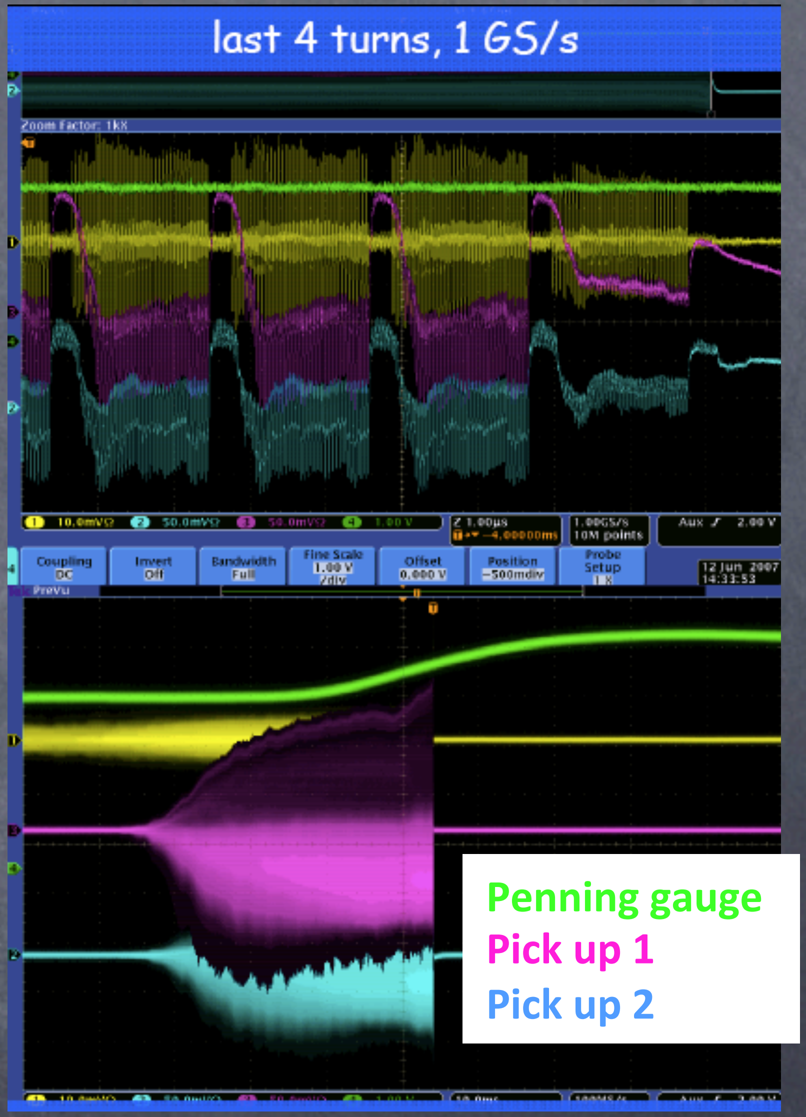
- The years of completion are crudely estimated as well, some of the items may only be fully implemented beyond 2017
- Items with priorities in brackets indicate activities already ongoing before the LIU framework started
- The priorities may change according to the outcome of the studies proposed

Flat top (transverse)

Electron Cloud: dedicated electron cloud measurements were set up and conducted in the PS. An electron cloud signal is observed after the second double splitting, with little conditioning effect over 1 year run. (F. Caspers, T. Kroyer, E. Mahner)







Electron cloud was observed but not clear yet if any deleterious effect on the beam. Might become more critical with higher brillance.

New studies in 2011 since direct impact on the time available for the last RF manipulation

- Transverse instabilities at flat top observed in 2001, 2004 and again 2006.

- Appears in the horizontal plane with rise times of the order of few ms.
- Probably related to electron cloud (why mainly horizontal and why not cured by chromaticity).
- Coupled bunch or single bunch effect?
- Full bunch length must be below 11 ns with the present intensities.
- Threshold of 4.5 x 10^{10} ppb for a bunch length of 10 ns.

Beam instrumentation

- If the upgrades aim to smaller emittance to get larger brillance, the injectors should be able to precisely measure them.

In PS, ongoing revision of emittance measurement devices:

- BWS: the precision on the small emittance beams was not good enough.

- BWS: cannot measure emittance bunch-by-bunch.

- Matching with PSB should be optimised as much as possible to preserve emittance. Current system had to be revised for the 2 GeV case.
May be install a turn-by-turn measurement. With new SMH42, should revise the profile detectors in the injection region.

- TT2 OTR screens should be revised for higher-brilliance beams.

- Need to improve intensity measurement to better evaluate losses between machines.

- Need to measure the extraction trajectory or beam radial position before extraction.

New dedicated PU could be installed to measure on large h, beyond the h=21 limit of today

Revision of the systems might lead to an important upgrade of some of them

MDs during 2011

- Injection/matching studies (dedicated MD required).

Energy

- Acceleration on h=7 to study machine and hardware performances at 2 GeV with LHC-type beam.
- Study of HW limitations of the low energy correctors/quadrupoles at 2 GeV.
- Study of injection working point using the PFW (tune and chromaticity control).
- Study of RF manipulations at 2 GeV.
- Emittance evolution on 2 GeV long flat bottom (headtail instabilities, space charge).
- Double injection separated by less than 1.2 s.
- Emittance grow-up after transition crossing (also TMCI related studies).
- Electron cloud studies during phase rotation before extraction.
- Longitudinal instability during acceleration and on the flat-top.
- Study of bunch length/longitudinal emittance optimum/margin for transfer to SPS.

HW System summary

System	Impact at 2 GeV	Impact	Comments
Injection elements	Not possible to inject	High	Promising design exists already
Low energy correctors	Worst orbit at injection	Low	Will be tested in MDs
Low energy skew quadrupoles	Not Damping Headtail instability	High	Will be tested in MDs
Low energy quadrupoles	Control tune at injection	Low	Will be tested in MDs PFW could be used
Transverse damper	To be studies	Medium (damp injection errors and help in Headtail)	Would be necessary if too large ripple of injection kicker
New RF coupled-bunch feedback	Not reproducible results with unequal bunches + ghost bunches	Medium (depends on LHC requirements)	Required
1 turn delay feedback for transient beam loading during bunch splitting manipulations	Not reproducible results with unequal bunches + ghost bunches	Medium (depends on LHC requirements)	Required
Improved shielding on top of route Goward	cannot inject non-LHC beams at 2 GeV	Not clear yet	Depends on the decision on upgrade non-LHC beams

System study/upgrade useful also in case of no upgrade to 2 GeV

Conclusions

- The injection energy increase could lead to $3.0 \cdot 10^{11}$ ppb to SPS with an emittance of 2.5 μmrad (1 σ normalized) for the 25/50 ns (Double batch, 72/36 bunches with 6 PSB rings) or smaller emittances could be produced at the price of the intensity per bunch for the 25 ns.
- Revise the limit of the emittance blow-up due to the Laslett tune shift to determine the maximum intensity at injection.
- Maximum intensity per bunch will depend on how far the RF limitations can be pushed.
- To be studied : evaluate the maximum intensity per bunch deliverable within ε(x,y)~2.5 μm rad (1 σ norm) with 25 ns for scheme with 48 bunches (Single batch, 4 PSB rings) → Laslett induce blow-up not there.
- A large number of studies is foreseen for this year, both as MDs as on the simulation side to better extrapolate the limits to the 2 GeV upgrade.
- Studies are progressing concerning the HW changes necessary for the higher injection, in particular for the RF and the elements used at injection energy.
- Non-LHC beams have been analyzed, with some concerns about the eventual increase of the radiation levels in the ring.

spare

Laslett tune shift

$$\Delta Q_x = \frac{R_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z} \oint \frac{\beta_x(s)ds}{\sigma_x(s)\left[\sigma_x(s)+\sigma_y(s)\right]}$$

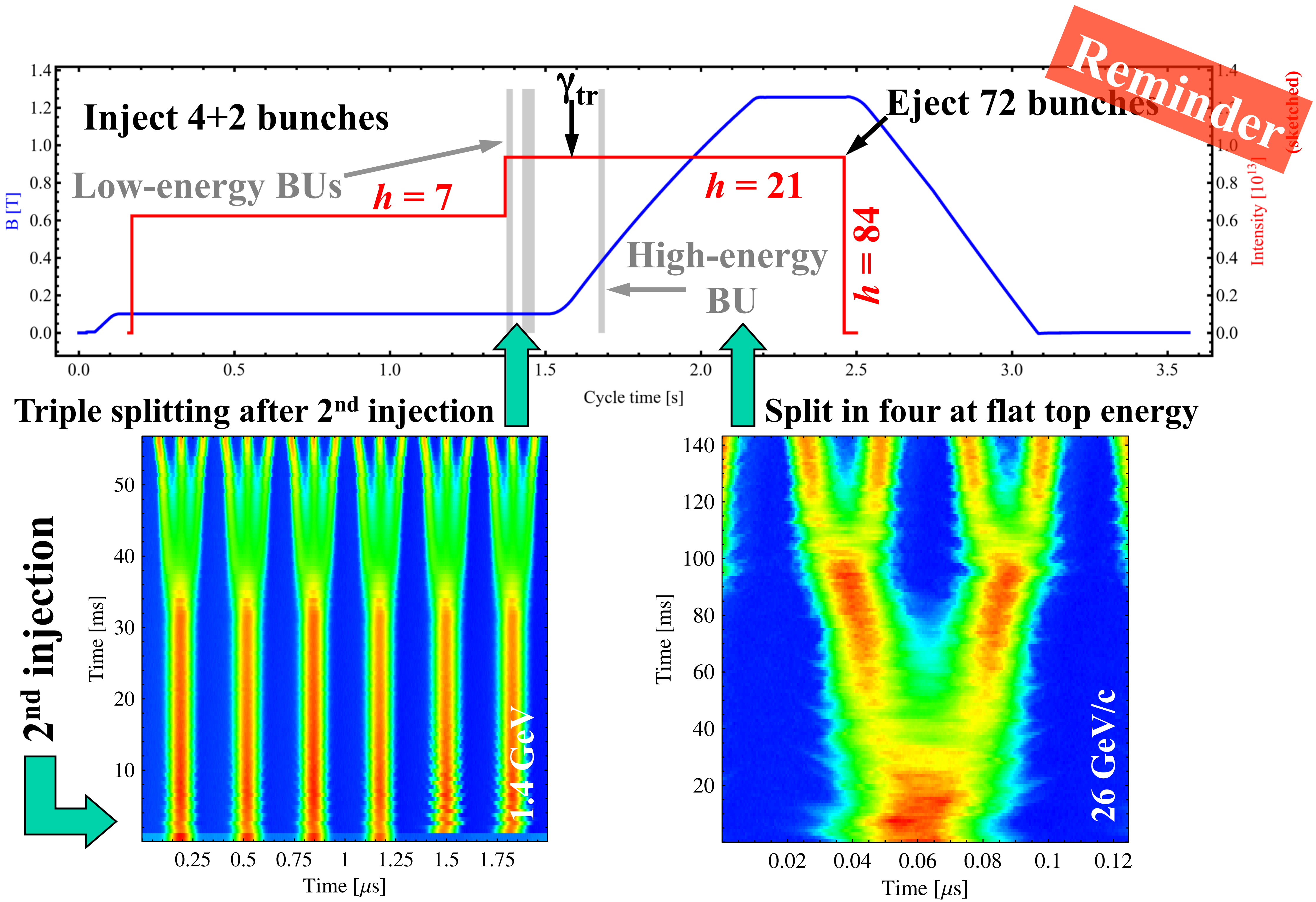
$$\Delta Q_y = \frac{R_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z\sqrt{\epsilon_y}} \oint \frac{\sqrt{\beta_y(s)}ds}{\sigma_x(s)+\sigma_y(s)}$$

$$\begin{cases} \sigma_x(s) = \sqrt{\epsilon_x\beta_x(s) + D_x^2(s)\left(\frac{\delta p}{p_0}\right)^2} \\ \sigma_y(s) = \sqrt{\epsilon_y\beta_y(s)} \end{cases}$$

$$\epsilon_{x,y} = \frac{\epsilon_{xn,yn}}{\beta\gamma}$$

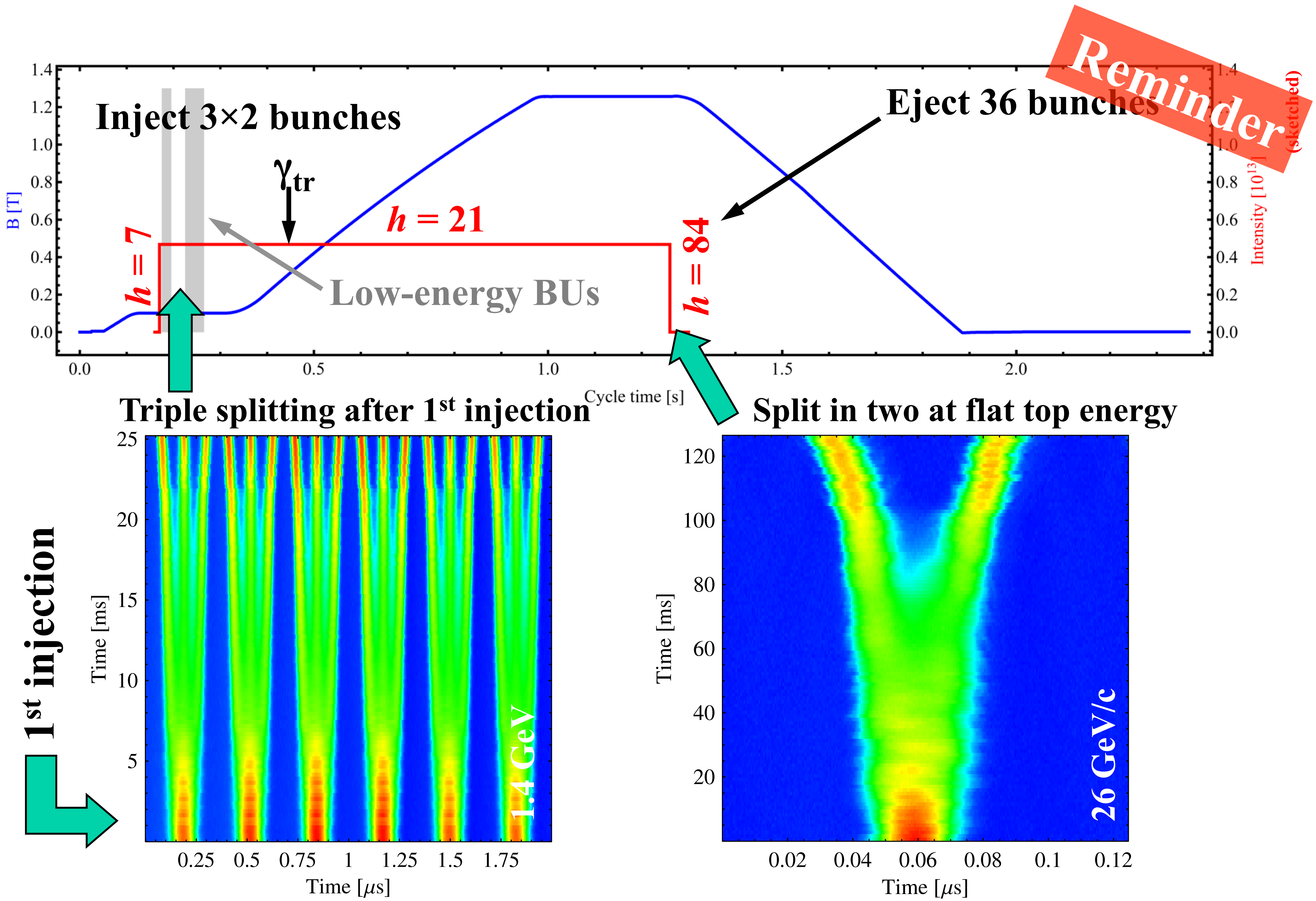
$1/\beta\gamma^2$ $1/\sigma_z$ $1/\varepsilon$

Reminder on double batch LHC beams (25 ns here)



→ **Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72**

Reminder on single batch LHC beams (50 ns here)



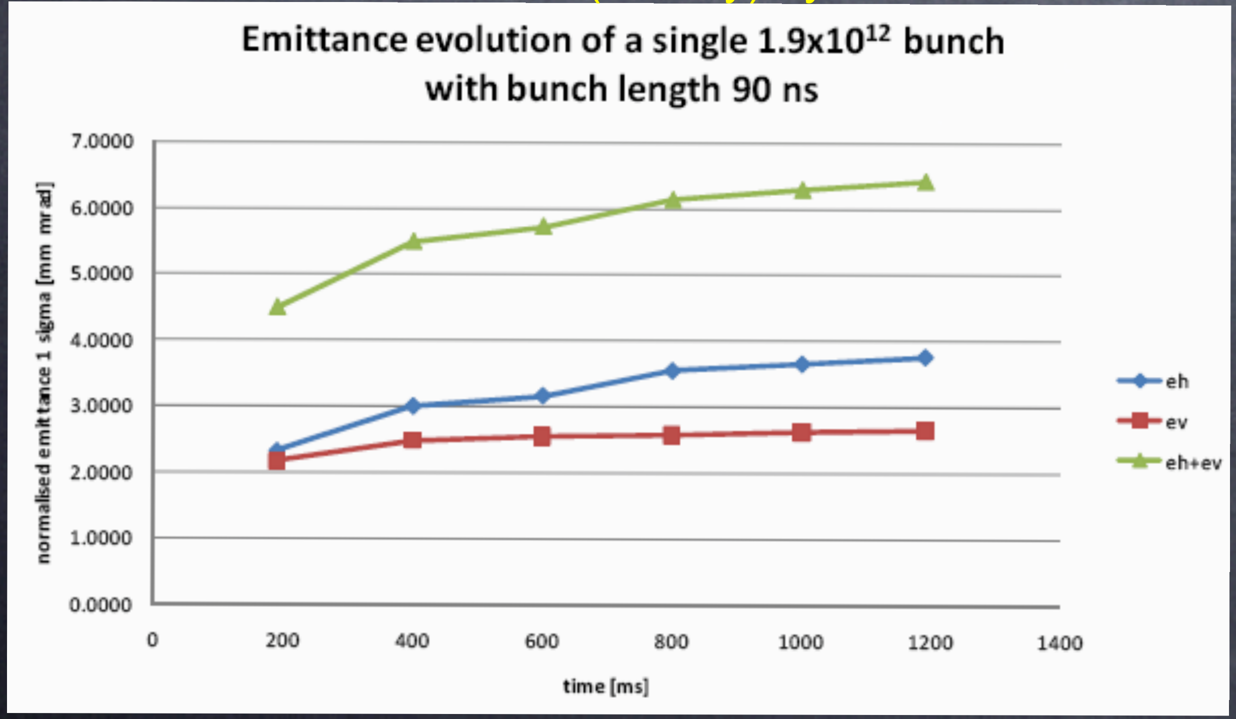
→ Each bunch from the Booster divided by 6 → 6 × 3 × 2 = 36

Do we have any margin?

From 2010 MDs, on June 24th there was a first joint PSB/PS MD (S. Hancock, A. Findlay, et al) on the LHC25 single-batch intensity limit at PS injection. The beam was produced in the PSB from the LHC50. The ~1.6e12 p accelerated on h=1 are re-bucketed in one of the two available buckets of h=2, instead of being equally split between the two.
This gave more than 1.6E12 p longitudinally confined in 135 ns and 0.9 eVs, and transversely in $\varepsilon_{x,y} \approx 2.5\mu m$.
This beam was injected into the PS on a 3 bp cycle and a transverse emittance increase of only 10% was observed at the end of the flat bottom, with no discernible blow up in the longitudinal plane.
No correction of working point implemented to try reducing the blow-up

$$\Delta Q_y^{\mathrm{MDLHC25}} \mathrm{@PSinj} = -0.338$$

On Sunday Nov 21st there was an MD at the SPS to measure the emittance growth at flat bottom in extreme conditions of space charge (S. Gilardoni, R. Steerenberg, H. Damerau, S. Hancock)
The same beam type as on June 24th was used from the PSB, i.e. LHC50 rebucketed from h=1 to h=2 instead of split before extraction, but with higher intensity. This beam was also compressed adiabatically after injection into the PS (from 130ns to 95ns) in order to further increase the space charge effect.
An increase of total emittance ($\varepsilon_x + \varepsilon_y$) by ~40% is observed over 1s, scan of working point needed.



$$\begin{cases} \Delta Q_x^{\mathrm{LHC25MD}} \mathrm{@PS\_FT} = -0.34 \\ \Delta Q_y^{\mathrm{LHC25MD}} \mathrm{@PS\_FT} = -0.56 \end{cases}$$

Summary of RF-HW interventions

Priority	Item	When	Remarks
(1)	New coupled-bunch FB	2012	ongoing, budgeted
2	Dedicated kicker cavity	2015-2020	on consolidation list
	10 MHz		
(1)	1-turn delay FB	prototype tests 2011	
1	Renovate FB amplifier	2011-2015?	study until end of 2011
1	Slow phase loops around each cavity	2013-2014	
2	New power amplifier (1 tube/gap)	2014-2018?	study until end of 2012
	20 MHz		
1	1-turn delay FB	2012	study until mid 2011
2	Slow phase loops around each cavity	2012	
	40 MHz		
(1)	Automatic tuning system	2011	
1	1-turn delay FB	2012	study until mid 2011
2	New feedback amplifier in grooves	2014	study until end 2012, priority to be redefined after first study 2011
2	Slow phase loops around each cavity	2012	
3	Study more voltage per cavity	2013	shut-down time with infrastructure (water, etc.) needed
3	New power supplies	2014-	can only be specified after voltage tests
	80 MHz		
1	1-turn delay FB	2012	study until mid 2011
1	Automatic tuning system (PLC, prot./ions switching)	2011-2012	
2	Slow phase loops around each cavity	2012	
2	New feedback amplifier in grooves	2014	study until end 2012, priority to be redefined after first study 2011
2	Fast ferrite tuner	2016	feasibility study by end 2011
3	Study more voltage per cavity	2013	shut-down time with infrastructure (water, etc.) needed
3	New power supplies	2014-	can only be specified after voltage tests

Note:
- The years of completion are crudely estimated as well, some of the items may only be fully implemented beyond 2017
- Items with priorities in brackets indicate activities already ongoing before the LIU framework started
- The priorities may change according to the outcome of the studies proposed