LHC Injectors Upgrade

Which beams in the injectors fulfill HL-LHC Upgrade Scenario (US) 1 goals?

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Agenda

- Summary of US1 beam parameters: from US1 glossary to last iteration
- Possible production schemes
  - 3-splitting
  - BCMS
- Summary of issues in the injectors:
  - PSB
    - Space charge
  - PS
    - Space charge
    - Headtail instabilities
    - Transition crossing
    - Longitudinal instabilities
    - Electron cloud (not currently an issue)
  - SPS
    - Space Charge
    - Maximum available RF power during acceleration, instabilities and matching voltage
    - Electron cloud

Glossary: upgrade scenario 1 - LHC: 25 ns, 160 d/y

Running periods: Approximate one year long shutdowns are expected every 3 to 4 years for cryo-maintenance during the LHC operation after 2021.

	J	F	M	A	M	J	J	S	O	N	D	Peak_L	Int.L year	Int.L Cul
2021														400 [a)]
2022														
2023														
2024												$6x10^{34}$ [b)]	160	
2025												$6x10^{34}$	160	
2026												$6x10^{34}$	160	
2027														
2028												$6x10^{34}$	160	
2029												$6x10^{34}$	160	
2030												$6x10^{34}$	160	
2031														
2032												$6x10^{34}$	160	
2033												$6x10^{34}$	160	
2034												$6x10^{34}$	160	
2035												$6x10^{34}$	160	
													Reach Goal	2000

Hypothesis	- No crab cavity - Assuming NO levelling - Hubner factor used - Crossing angle adjusted for 12 sigma long range beam-beam separation						
Performance	Overall Physics operation (years)	Ib (10^{11}) [c)]	β* (m)	ε (μm) [c)]	Int.L/y (fb^{-1})	Int.L over 10y (fb^{-1})	Total Int. L (fb^{-1})
Upgrade Scenario 1 BASELINE	10	1.5	0.15	1.5	160	1600	2000
Alternative Upgrade Scenario 1	10	1.2	0.15	1	160	1600	2000

- Note a) The starting point changed from 400 fb^{-1} to 300 fb^{-1}

- 25 ns operation assumed as baseline

- Beam parameters are given at start of collision; 20% blow up and 5% losses have to be assumed from SPS extraction to LHC start of physics and with squeezed optics.

Assumptions for beam parameter estimation

- **US1 injectors:**
  - Brightness curve of Linac4 (as presented in Giovanni's talk)
  - all upgrade proposed for PSB/PS done (2 GeV + RF) + Linac4
  - SPS: *no 200 MHz power upgrade (?)*, assumed e-cloud solved - possibly with aC coating of vacuum chambers (see Hannes talk)
- **For beam quality preservation:**
  - Max Laslett tune shift in PS < |0.31|
    Fully profiting from larger longitudinal emittances for PSB-PS transfer (to be tested in 2014)
  - Max Laslett tune shift in SPS < |0.21|
  - Max intensity in SPS@extraction if 200 MHz LLRF upgrade only (PIC): 1.45 10^{11} p/b
  - Max intensity in SPS@extraction if 200 MHz full upgrade only: 2.00 10^{11} p/b
- **Losses and emittance blow up:**
  - LHC: 20% Emittance blow up, 5% losses
  - SPS: 10% Emittance blow up and losses
  - PSB/PS: 5 % Emittance blow up and losses
  - *No blow-up or losses in transfer between machines*

Performance summary (US1-LHC vs. US1-LIU)

	Ib(10^{11})	ε (μm 1σ norm)	
US1 requirements (LHC collision/**injection Baseline**)	1.5/**1.58**	1.5/1.25	LHC
US1 requirements (LHC collision/injection Alternate)	1.2/1.26	1/0.83	
US1 NEW requirements (LHC collision/injection Alternate)	**> 1.45e11**	**> 1.8**	
Linac4 + 2 GeV + SPS LLRF upgrade US1 (PS Standard scheme – 72 bchs)	**1.45**	1.37	LIU at SPS extraction
Linac4 + 2 GeV + full SPS upgrade (PS Standard scheme – 72 bchs)	**2.0**	**1.88**	
Linac4 + 2 GeV + SPS LLRF upgrade (PS BCMS scheme – 48 bchs)	**1.45**	0.91	
Linac4 + 2 GeV + full SPS upgrade (PS BCMS scheme – 48 bchs)	**2.0**	**1.37**	

200 MHz RF Upgrade necessary to match the preferred requirements of LHC-US1 with unchanged longitudinal parameters at LHC injection. Basically LIU US1 ≣ LIU US2

Large bunch intensity in LHC more important than low emittances

LHC25ns Production Scheme today and after LS1

Production scheme:

a) Double batch injection from PSB (**4 + 2 bunches, 6 bunches for PS at h=7**)

b) Up to 4 batches of **72 bunches** each transferred to the SPS (288 bunches)

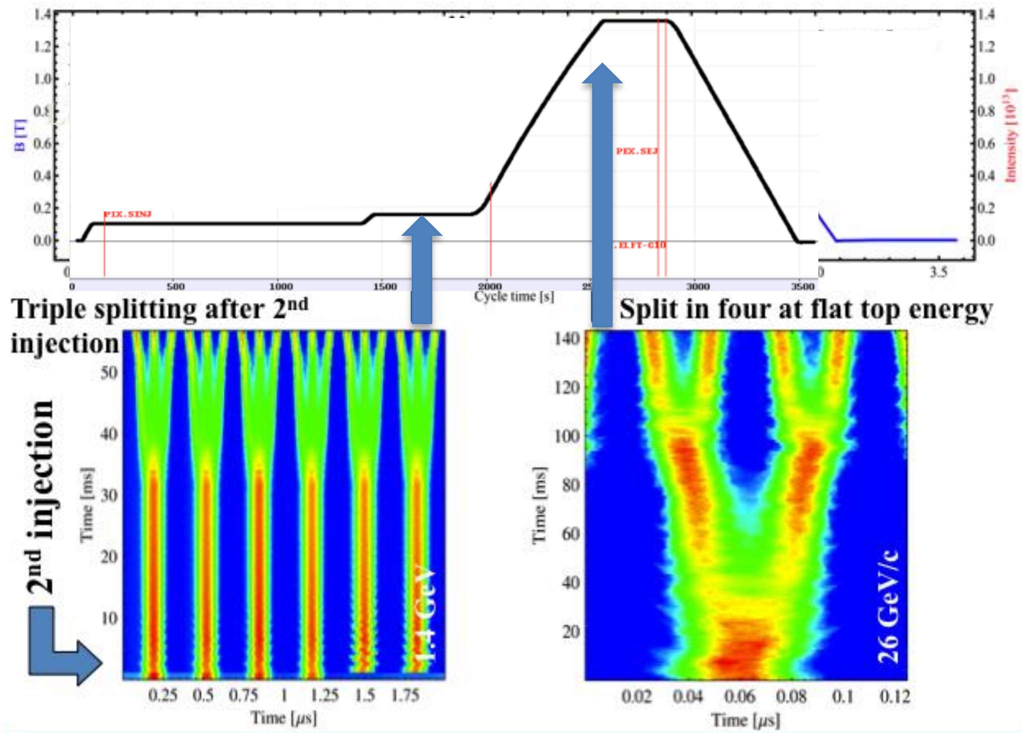
Transverse emittance produced in the PSB, longitudinal in the PS

Multiturn proton injection in PSB

RF gymnastics in PS:

-**Triple splitting@2.5 GeV/c**

- Acceleration
- 2 x Double splittings
  - (1 Double splitting for 50 ns)
- Bunch rotation



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

- ➢3 RF systems in PSB
- ➢5 RF systems in PS
- ➢2 RF systems in SPS

LHC 25(50)ns alternative Production in PS

Production scheme:

a) Double batch injection from PSB (**4 + 4 bunches, 8 bunches for PS at h=9**)

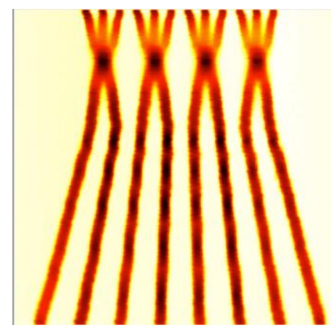
b) Up to 5 batches of **48 bunches** each transferred to the SPS (240 bunches)

Transverse emittance produced in the PSB, longitudinal in the PS

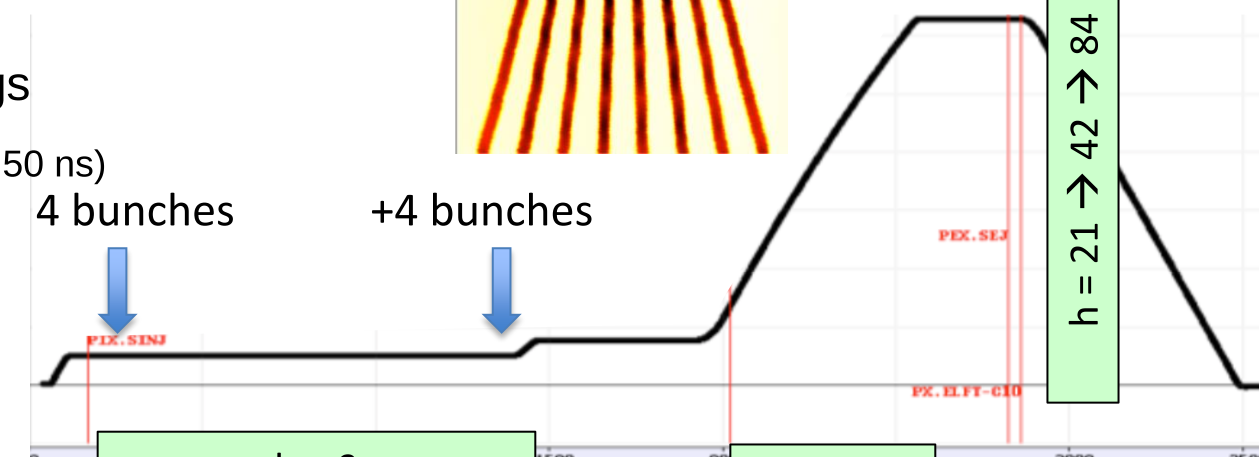
- Multiturn proton injection in PSB with **shaving**
- RF gymnastics in PS@2.5 GeV/c:
  - Batch compression
  - Bunch merging
  - Triple splitting
- Acceleration
- 2 x Double splittings

  (1 Double splitting for 50 ns)
- Bunch rotation

h = 9 → 10 → 11 → 12 → 13 → 14 → 7 → 21



h = 21 → 42 → 84



h = 9

h = 21

Challenges of the traditional schemes

High intensity injected in PSB:

- every PSB bunch is split 12 times (to get finally 72 bunches at 25 ns spacing, less for BCMS)
- Space-charge issue with Linac2 injection
- Today limited brilliance due to multiturn injection process

Long waiting time at PS injection:

- Space-charge issue.
- Headtail instability.

Long waiting time at SPS injection:

- Space-charge.
- TMCI instabilities (not any ore an issue, see Hannes's talk)

Many RF systems involved:

- Longitudinal instabilities and limitations to be overcome in all the machines

Beam quality is an issue:

- PS-SPS very sensitive to difference in relative bunch population
- LHC final luminosity very sensitive to degradation of transverse emittance

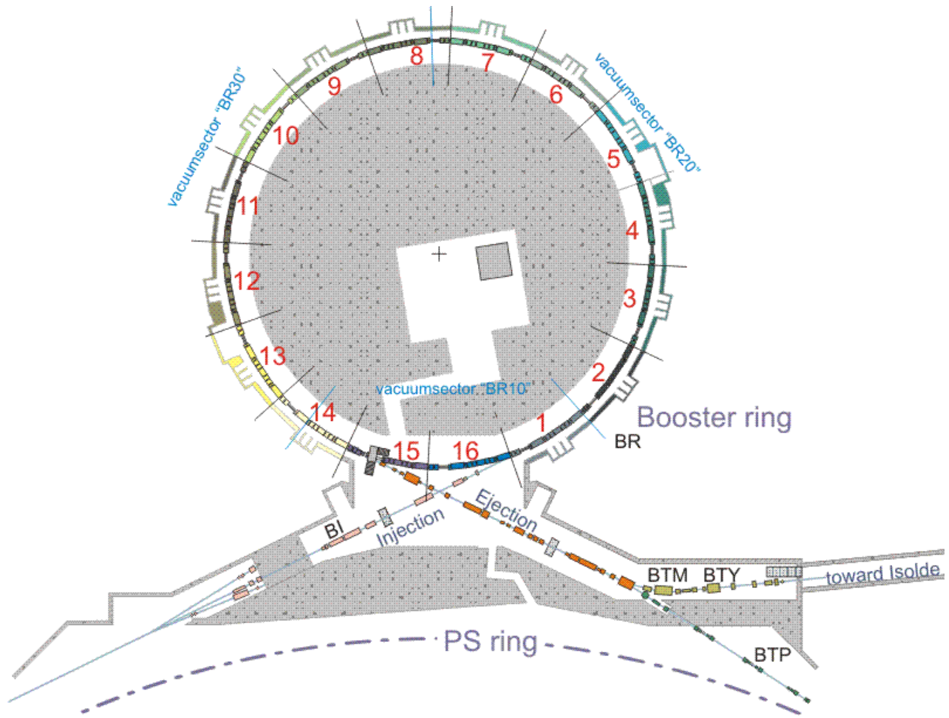
Issued analysed to preserve beam quality

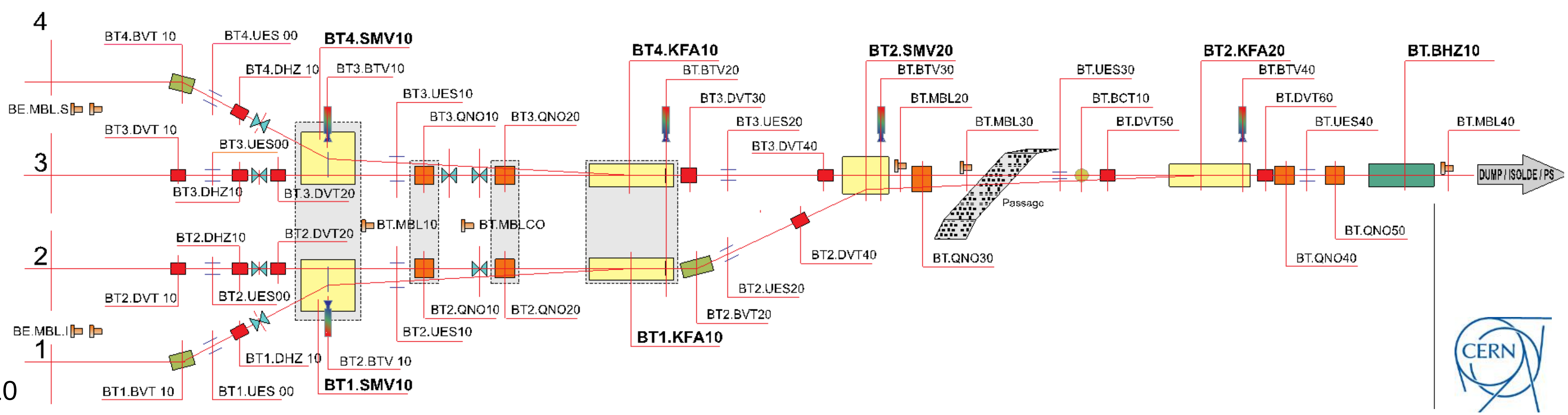
- Possible production schemes
  - 3-splitting
  - BCMS
- Issues common for the two schemes:
  - PSB
    - Space charge → L4 connection
  - PS
    - Space charge → PSB@2 GeV
    - Headtail instabilities → Transverse damper
    - Transition crossing
    - Longitudinal instabilities → Finemet cavity
    - Electron cloud → Transverse damper
  - SPS
    - Space Charge → well matched to PS space charge
    - Maximum available RF power → 200 MHz LL and HL upgrade
    - Electron cloud → effect on emittance or intensity?

PSB @ 2 GeV

PSB extraction energy upgrade requires (only main elements cited) :

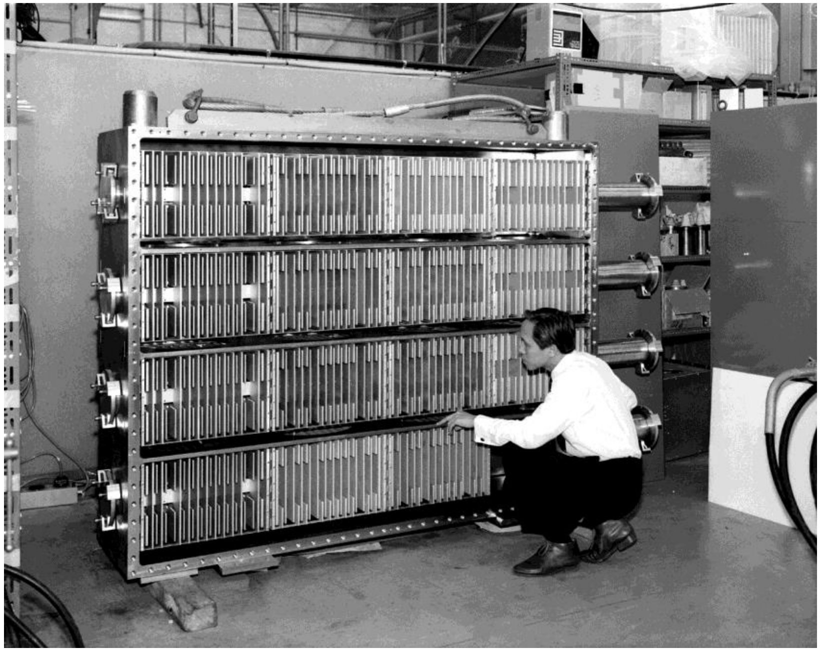
- New main power supply (POPS-like)
- Main Magnet cooling
- Main Magnet power distribution
- New extraction elements
- New transfer line elements
- New external beam dump
- New RF system

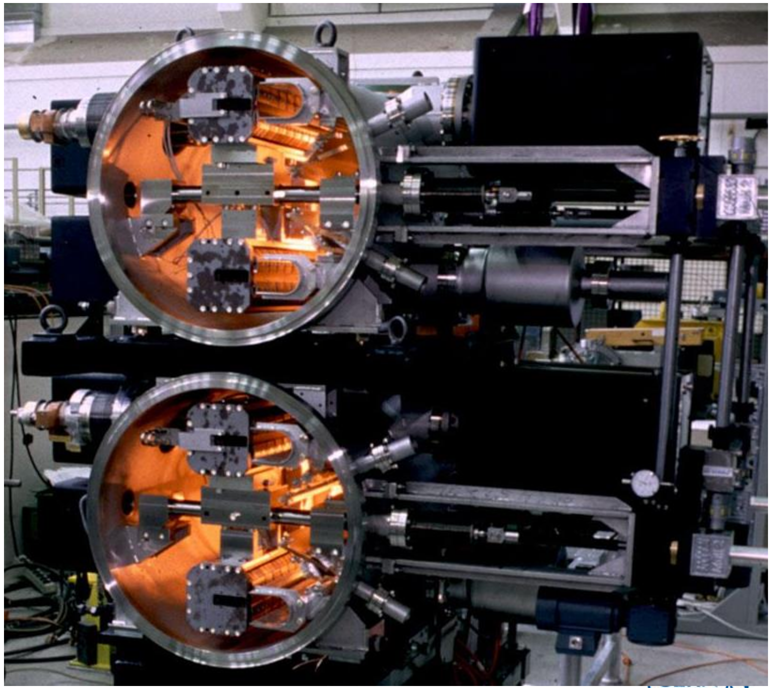




PSB 2 GeV extraction elements

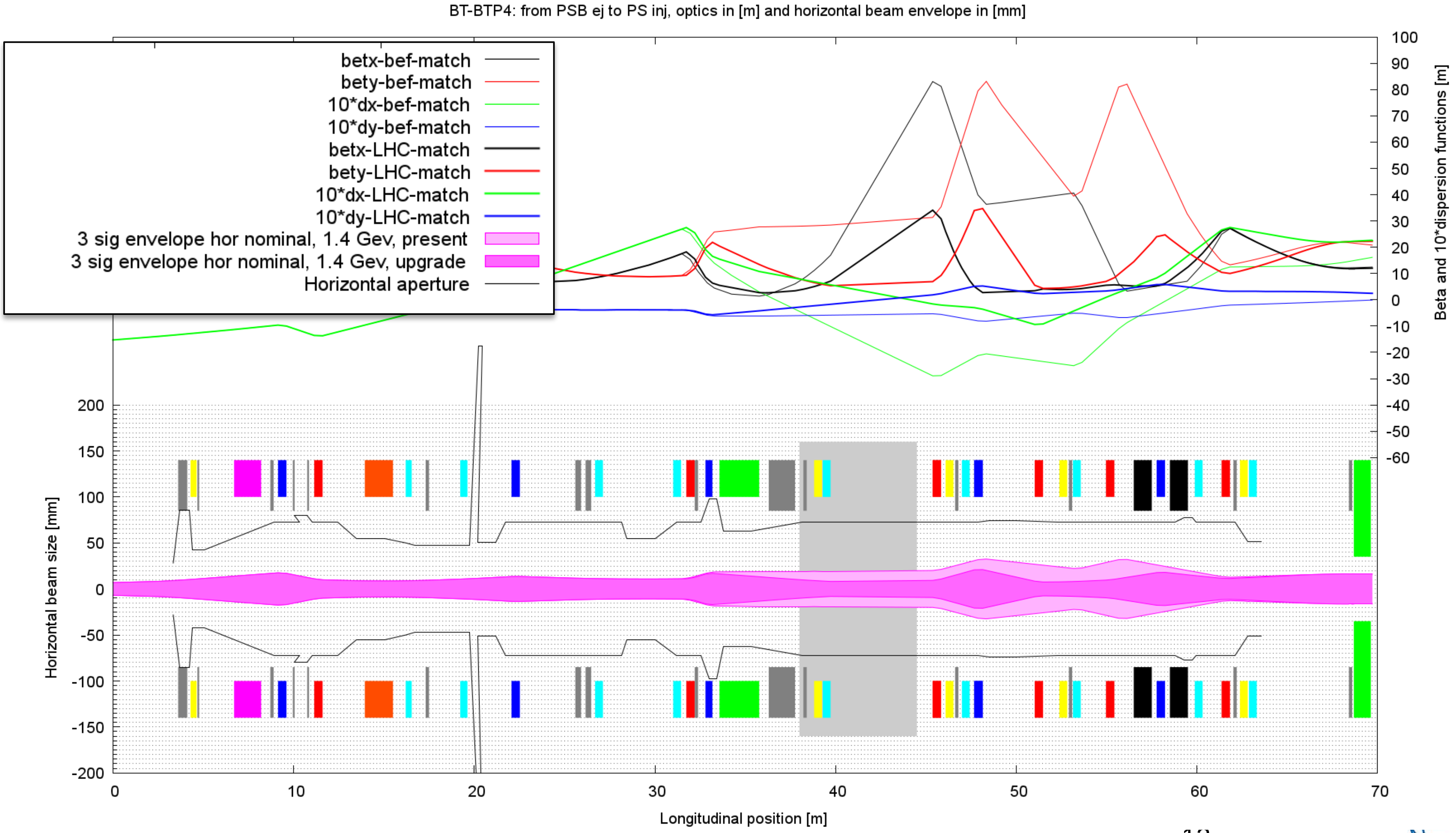
- PSB extraction bumpers → OK with present system
- PSB extraction kickers → at the limit – to be measured which field can be reached in ferrites
- PSB extraction septa: bus bars to be reinforced, magnets to be cooled in parallel to deal with increased RMS current
- PSB recombination kickers → to be replaced





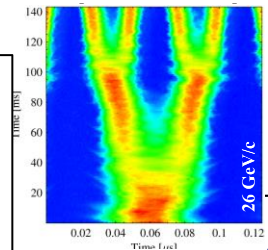
BT-BTP: LHC optics

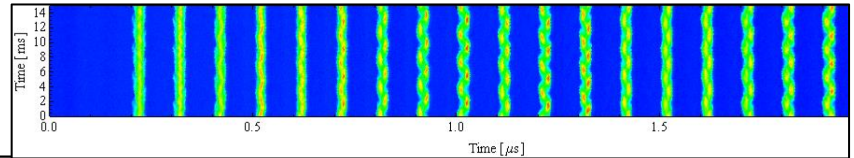
New optics design to reduce injection mis-match (horizontal Dispersion)



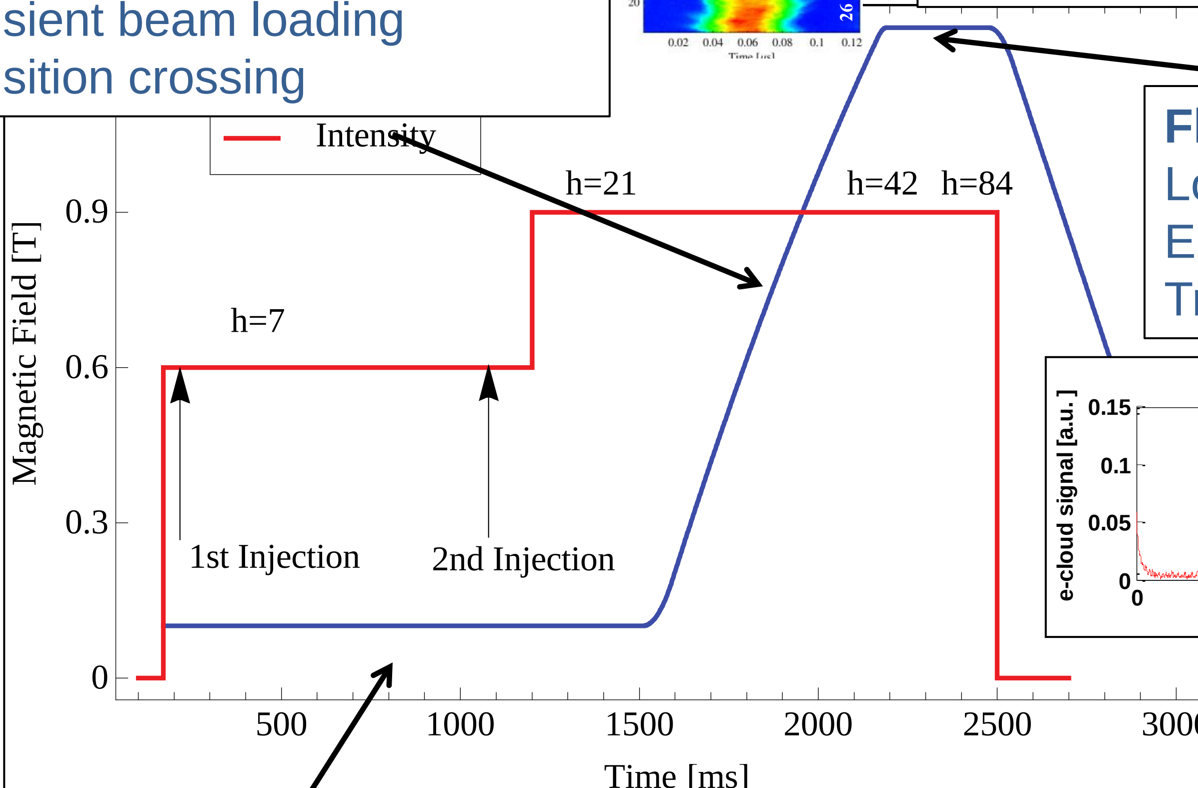
PS intensity limitations

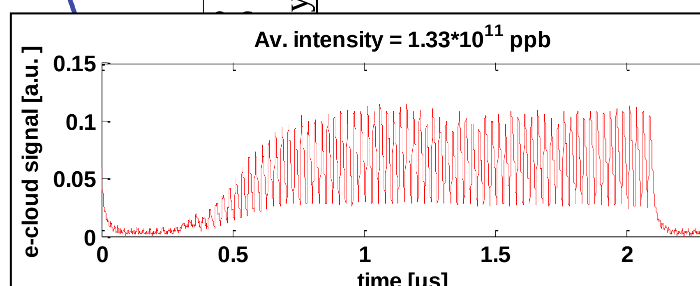
Acceleration/Bunch splittings
Longitudinal CBI
Transient beam loading
Transition crossing

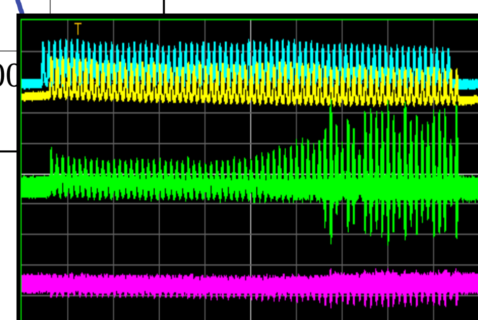




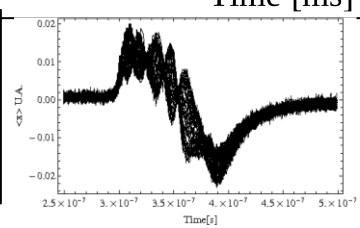
Flat top:
Longitudinal CBI
Electron cloud
Transverse instabilities



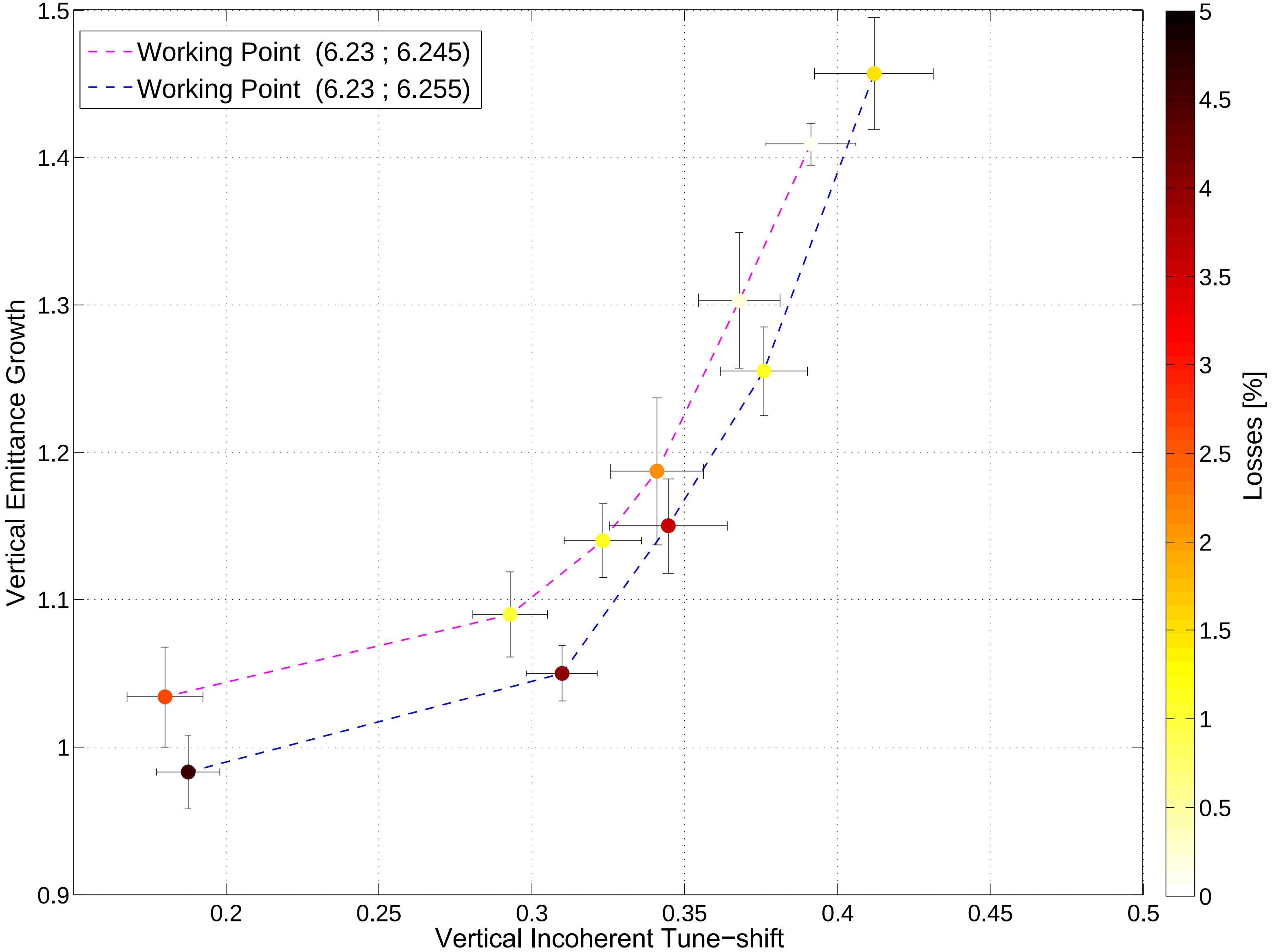




Injection flat bottom:
Space charge
Headtail instability



Space charge issue: Vertical growth vs. Tune-spread vs. Losses



2 GeV flat bottom

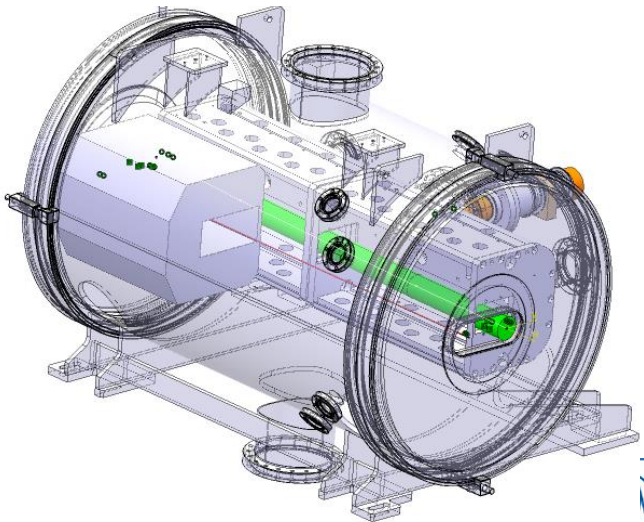
2 GeV injection needed to reduce space-charge-induced transverse emittance blow-up experienced by the first batch on the flat bottom

(N.B.: fourth injection energy increase since PS construction
50 MeV - 800 MeV - 1 GeV – 1.4 GeV)

2 GeV injection requires:

- New injection elements and power converters: septum, kicker, injection bumpers
  Studies started in 2012 for installation during LS2

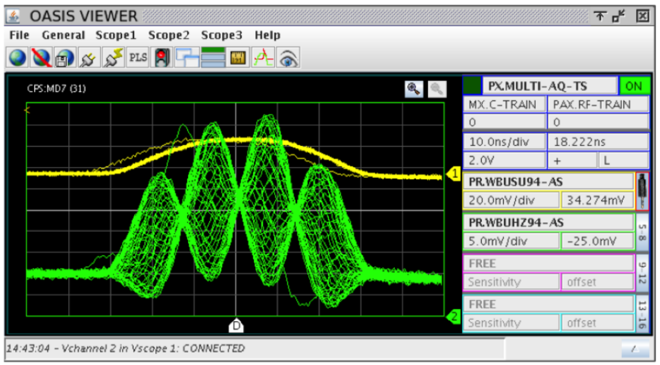
- New magnets and power converters for orbit correctors and lattice quadrupoles used at low energy



N.B.: *no new MPS required for upgrade.*

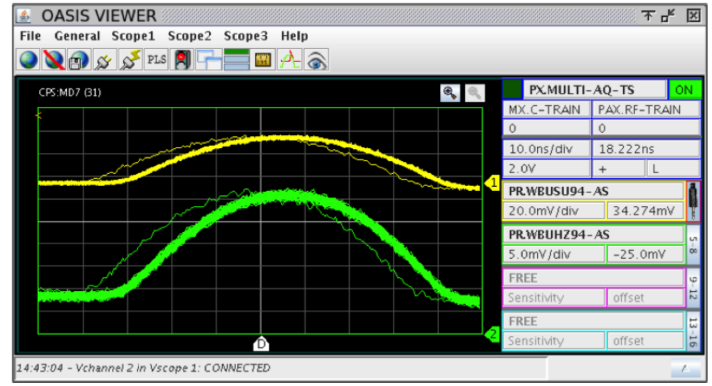
Headtail instabilities

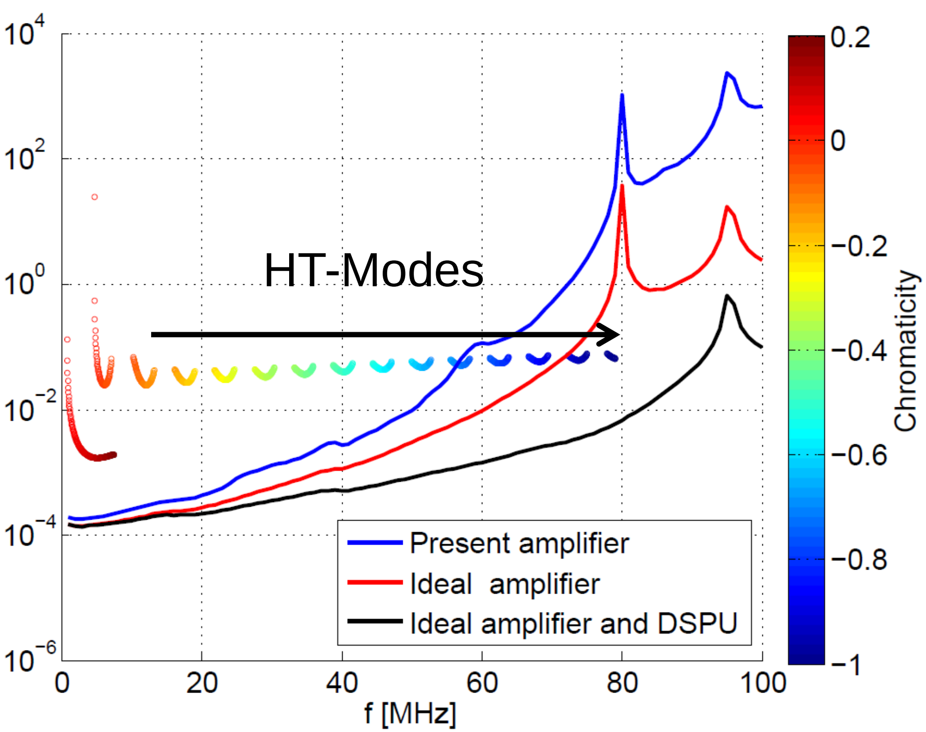
Headtail instab. no T-damper



$E_k = 2\ \text{GeV}$

Headtail instab. with T-damper





Headtail instabilities on injection flat bottom currently cured by introducing linear coupling

T-Damper/TFB 2012-2013 studies:

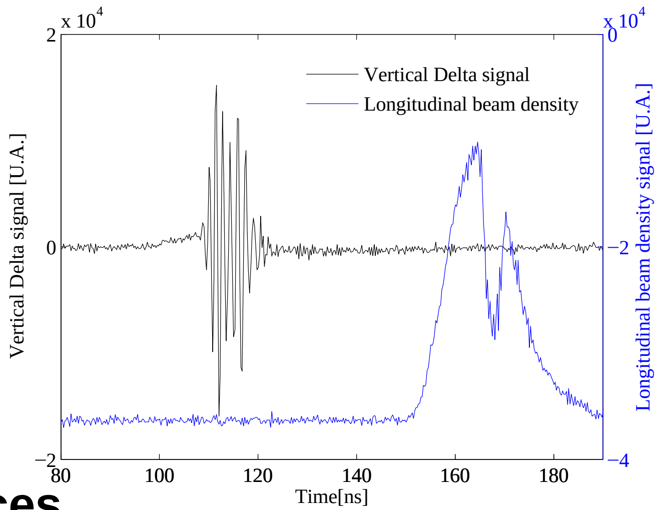
- cured headtail at 1.4 GeV
- power upgrade for 2 GeV
- future chromaticity control needed to avoid high order modes

Transition crossing

One fast vertical instability extensively studied on single bunch beams.

HL-LHC-type should be stable at transition.

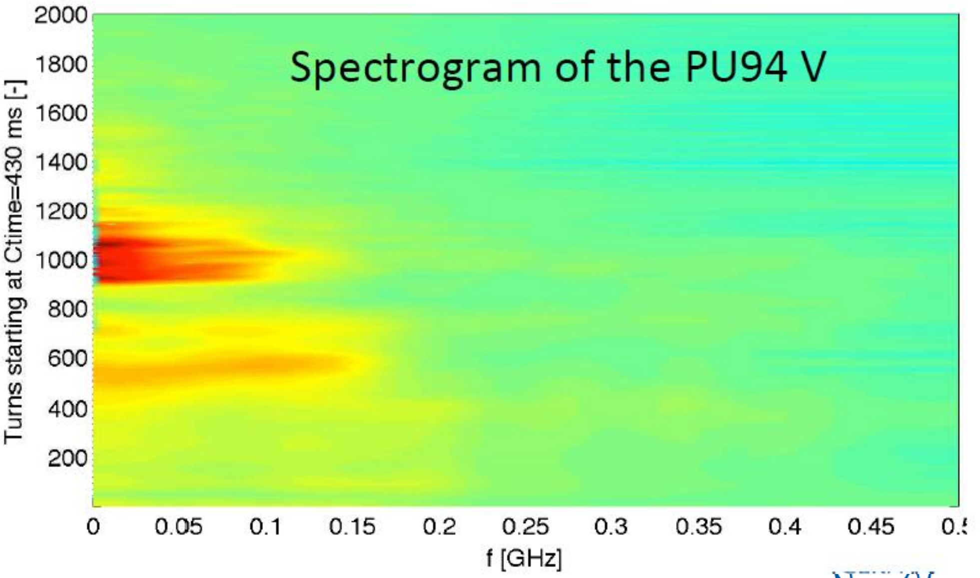
TOF-like single bunch beam



Future Studies with small longitudinal emittances
Minor influence of initial transverse emittance

A "new" fast single bunch transition instability with ≈4.5e11 ppb and 0.25-0.3 eVs. Further analysis needed.

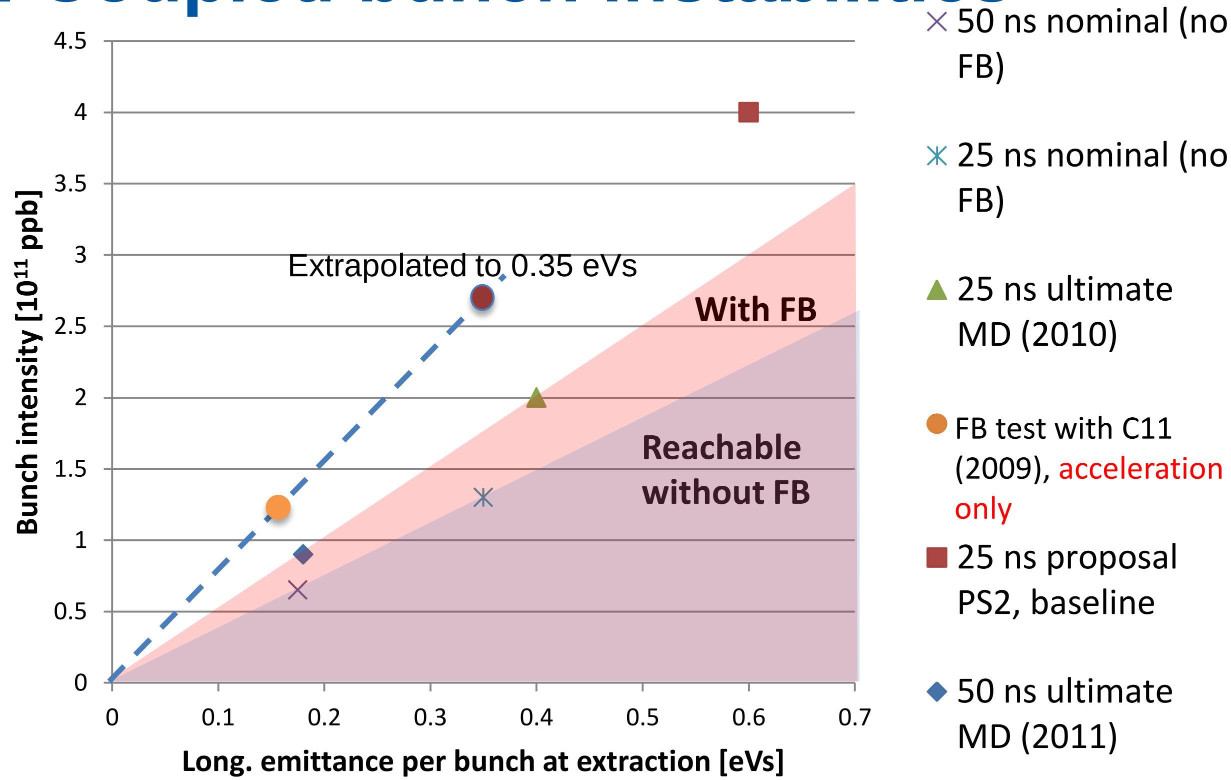
The TFB did not have any effect (spectrum beyond 100 MHz).



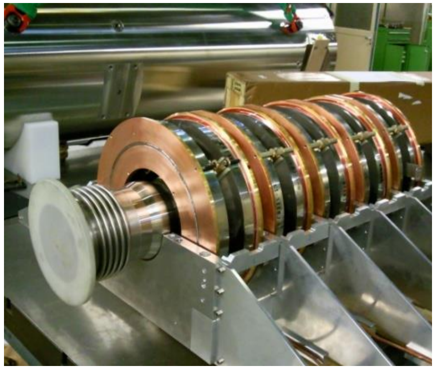
Longitudinal Coupled bunch instabilities

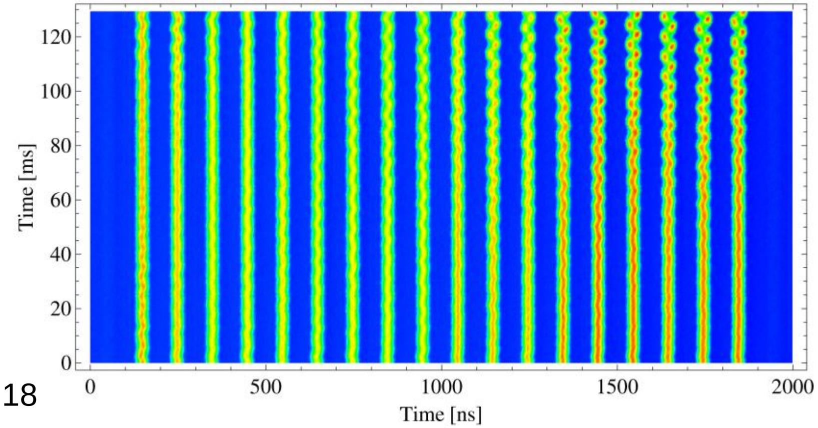
Longitudinal CB instabilities appear after transition

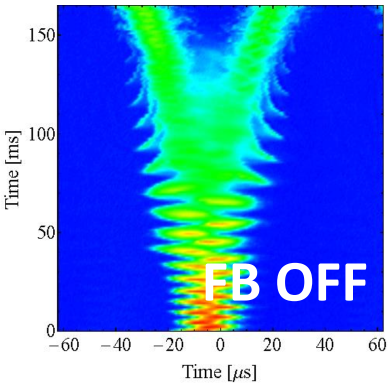
With new dedicated longitudinal damper possible to reach **more than 2.5e11 p/b** at extraction.

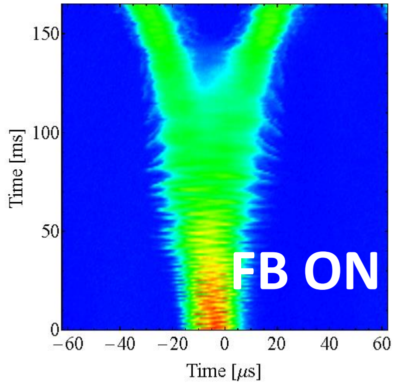


Finemet cavity installed during LS1









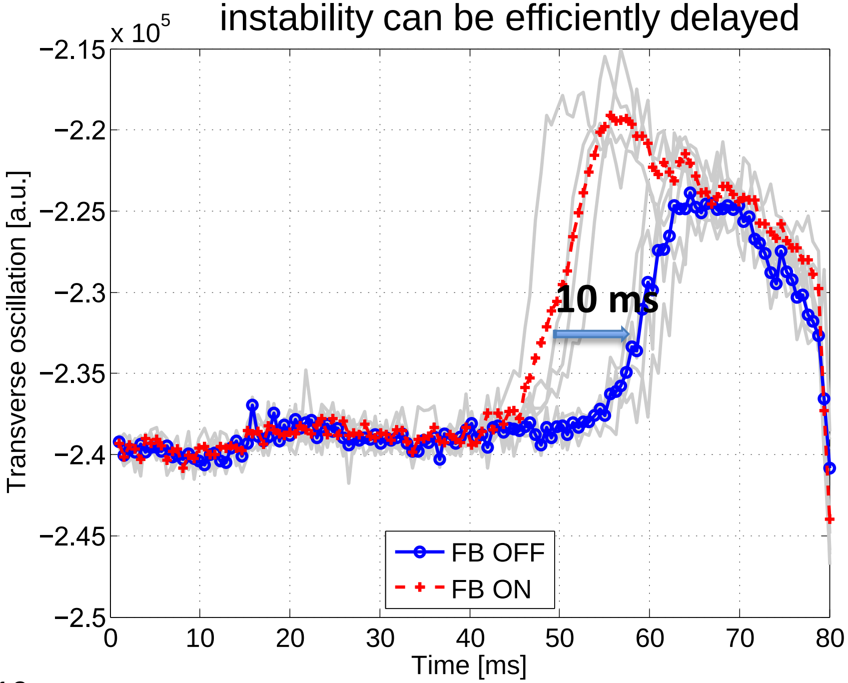
e-cloud instabilities: simulations and T-damper

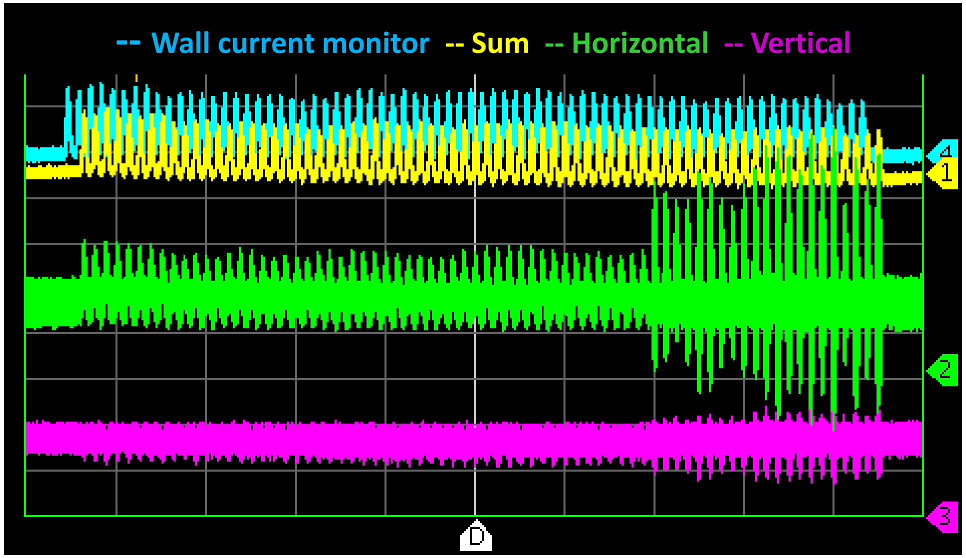
e-cloud observed for 25 ns beam production but no influence on beam quality

Transverse instability observed together with e-cloud if bunches shorter than nominal or kept in the machine for time longer than needed.

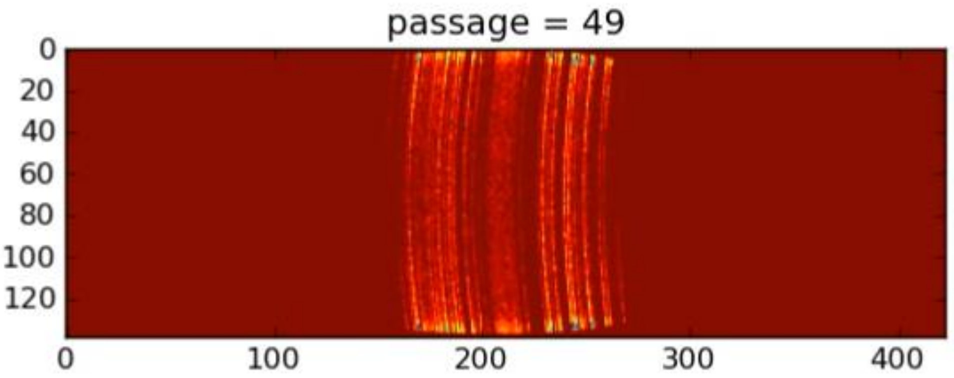
Shorter batches a la BCMS suffering less

Damper/TFB tests proved that instability can be efficiently delayed

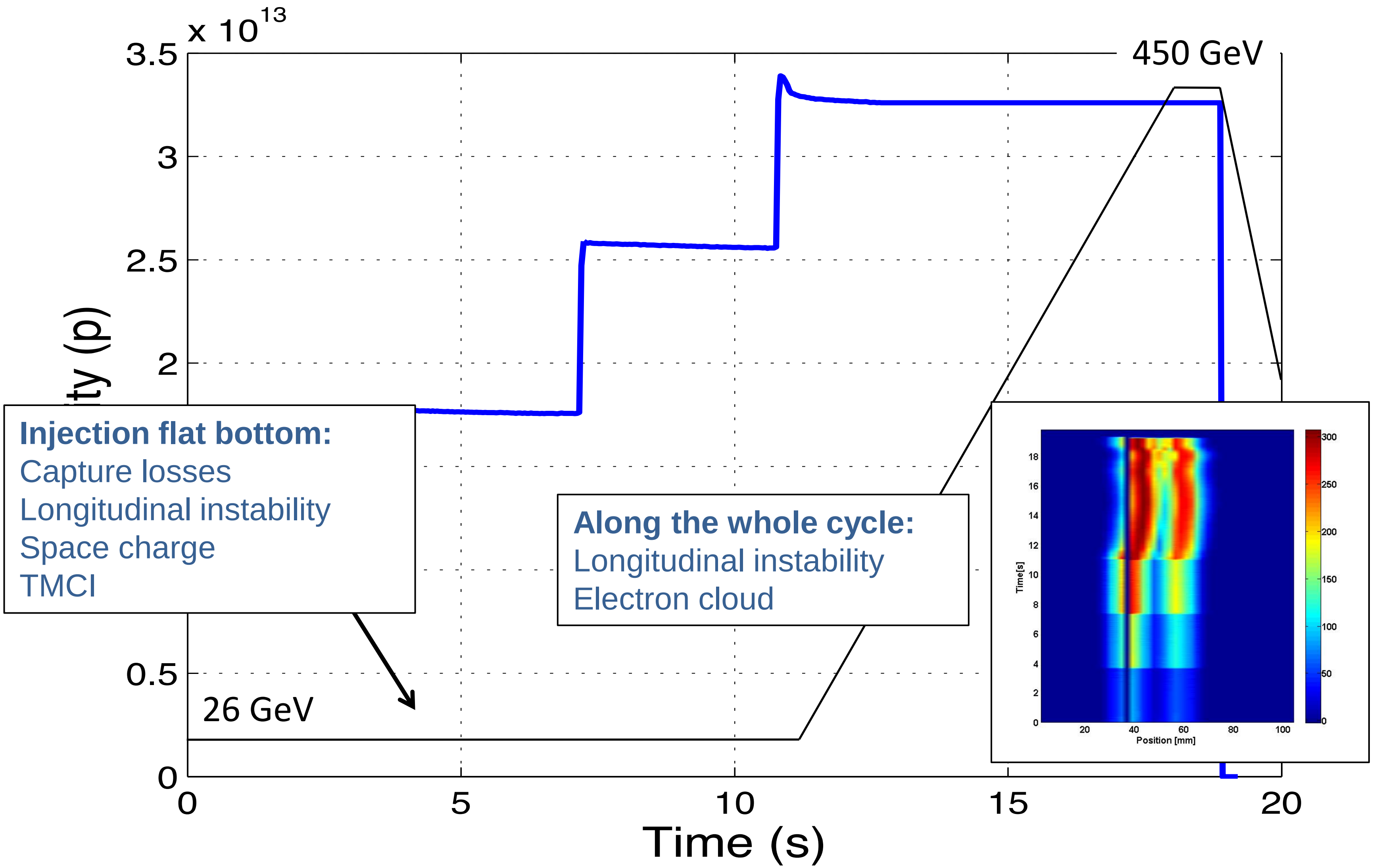




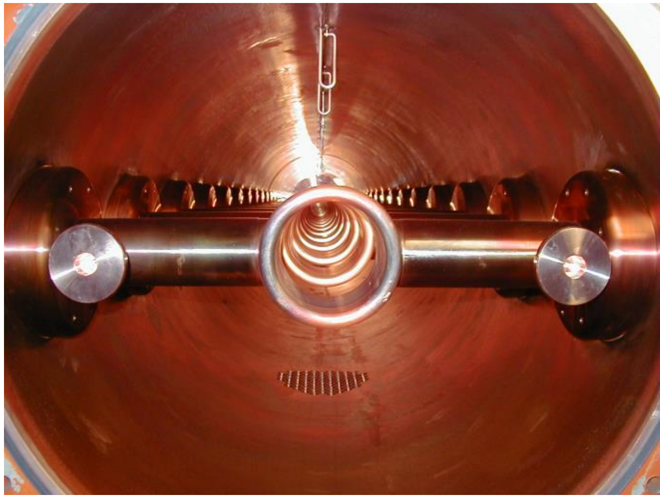
Pycloud simulations for combined function magnets established to predict future operation



SPS intensity limitations



SPS 200 MHz RF system

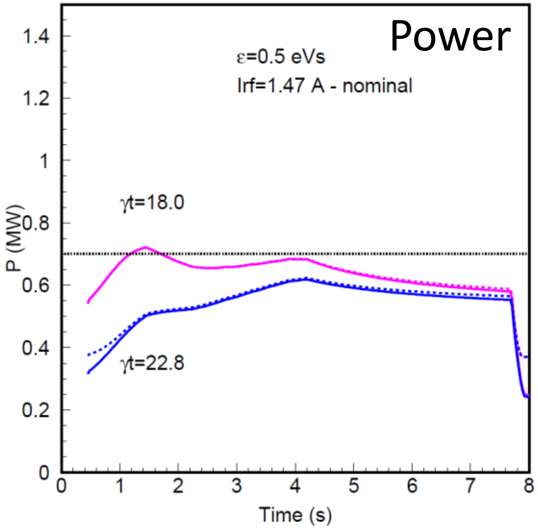


4 Travelling Wave cavities:

- 2 cavities of 5 sections
- 2 cavities of 4 sections

Power/cavity limit:

- 700 kW for full ring (FT/CNGS & LHC beams) – continuous mode
- (1.0-1.1) MW for 50% full ring (LHC beam)
  - in principle possible in pulsed mode (after consolidation), but never tested and used for high intensities
  - need completely new SPS LLRF included in the PICS
  - reduced reliability



Voltage: now maximum 7.5 MV

Maximum Power limit reached also during acceleration.

Longitudinal instabilities and RF upgrade

SPS 200 MHz LLRF upgrade (pulsing at 1.05 MW):

1.45e11 ppb with no performance degradation of extracted beam

SPS 200 MHz full upgrade:

4→6 (shorter) cavities

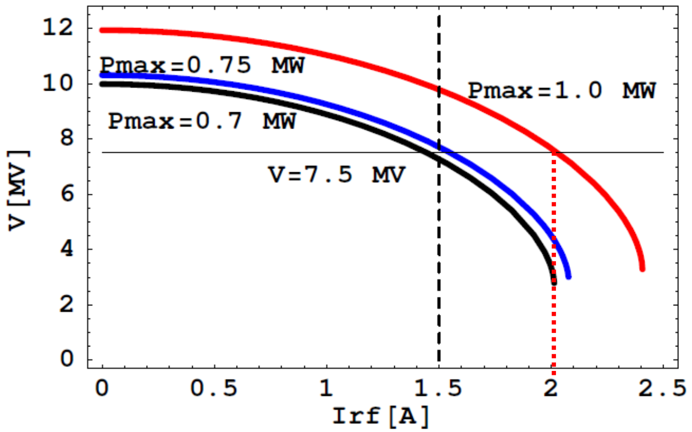
- Will allow 10 MV at extraction for 3 A RF current
- 20% less impedance

Will give ×2 intensity range

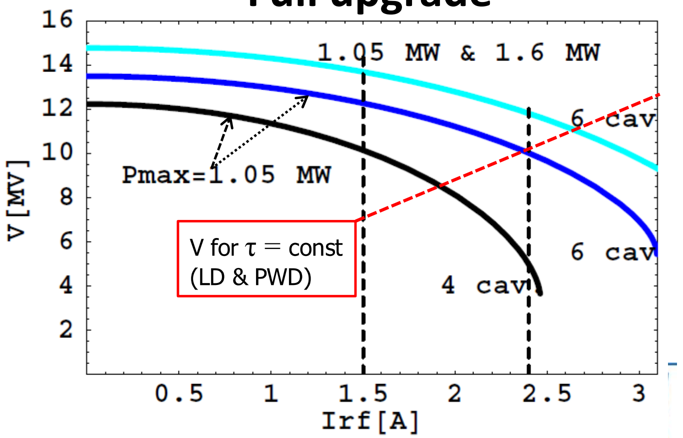
- **2.0e11 p+/b for 25 ns w/o performance degradation**
- Unknown is beam stability with high intensity (combination of single- and coupled-bunch effects)

More details in Hannes and Heiko talks, in particular Heiko will tell why increasing the power even more does not necessarily helps

Today



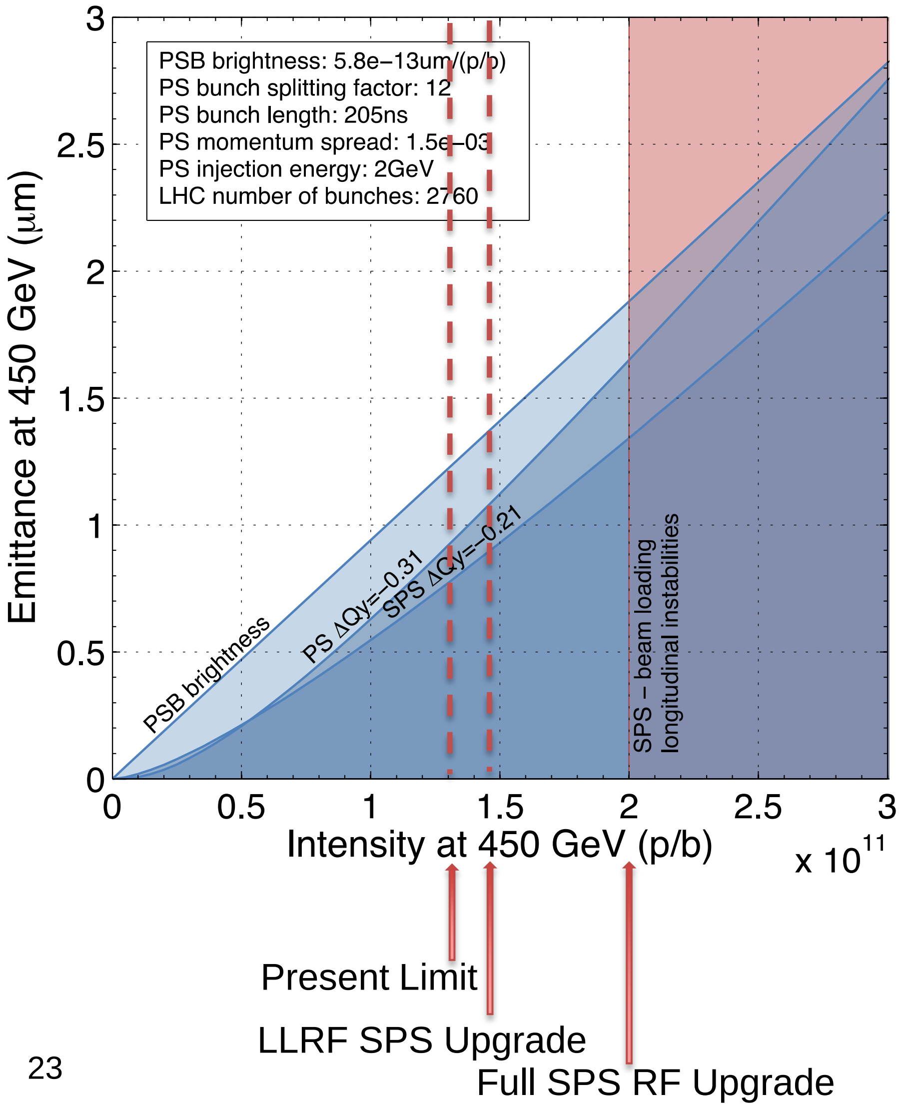
Full upgrade



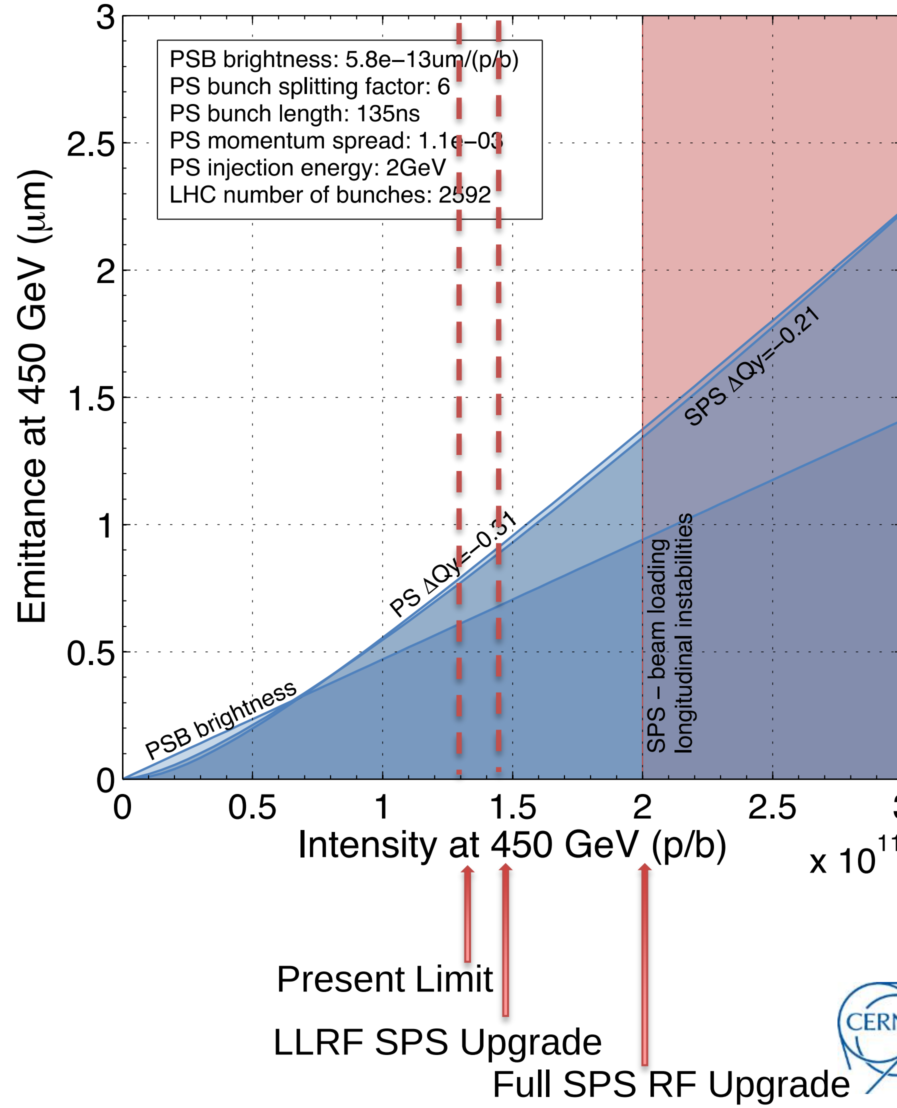
Standard scheme and BCMS schemes

Assuming longer bunches than today for PSB-PS transfer (to be tested in 2014)

Linac4 – Standard scheme – 2GeV – 25ns



Linac 4 – BCMS – 2GeV – 25ns



Risk analysis

	Y2-N200	Y2-Y200
PSB/PS Beam transfer@2GeV	Commissioning new PSB important elements plus extraction-injection	Commissioning new PSB important elements plus extraction-injection
Longer bunches for PSB/PS transfer	To be tested to assess full gain for Space charge limit	To be tested to assess full gain for Space charge limit
FB PS – headtail	Headtail ~ as today	Headtail ~ as today
FB PS – SC	Confortable for large emittances	Confortable for large emittances
Transition crossing	Should be OK	Should be OK but more studies needed
E-cloud PS	Damper if needed. Eventually BCMS should be better	Damper if needed. Eventually BCMS should be better
SPS - SC	Limit in PS	Limit in PS
SPS 200 MHz upgrade @ extraction	1.45e11	2e11
E-cloud in SPS	Assumed as solved. Eventually BCMS should be better	Assumed as solved. Eventually BCMS should be better

Conclusions

- US1 requirements can be fulfilled with both main injector upgrades: PSB@2GeV and 200 MHz RF power upgrade
  - 200 MHz Power upgrade necessary to match the requirements of preferred LHC-US1 scenario with unchanged longitudinal parameters at LHC injection (bunch length in particular)

- “Matching” of maximum Laslett tune shift currently achieved during normal operations with L4 and PSB@2GeV in all injectors
  - Possible to produce a large range of emittances, down to 1 μm if needed for some intensities
  - 2 GeV introduces also margin for emittance blow-up not included here (as blow-up during beam transfer or underestimation of current space charge limits)