LHC Injectors Upgrade Project Overview

R. Garoby for the LIU Project Team

- **Introduction**
- Planned actions
- Status of investigations
- Estimated beam characteristics
- Planning
- Summary

LIU Project Objectives

Mandate

"The LHC Injectors Upgrade should plan for delivering reliably to the LHC the beams required for reaching the goals of the HL-LHC. This includes LINAC4, the PS booster, the PS, the SPS, as well as the heavy ion chain."

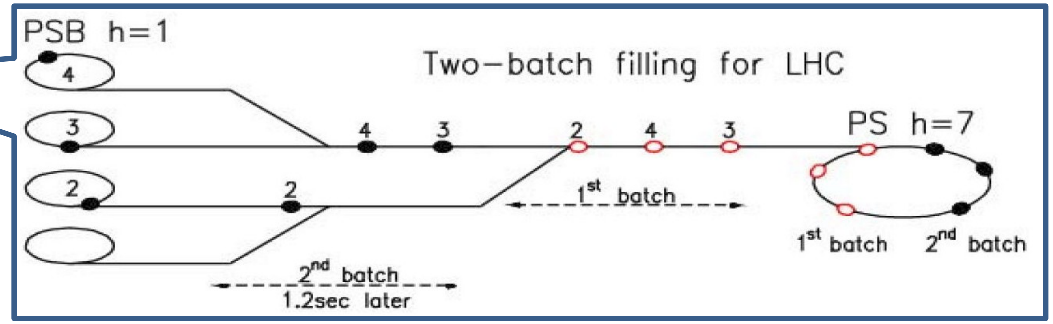
Implementation

The LIU Project will:

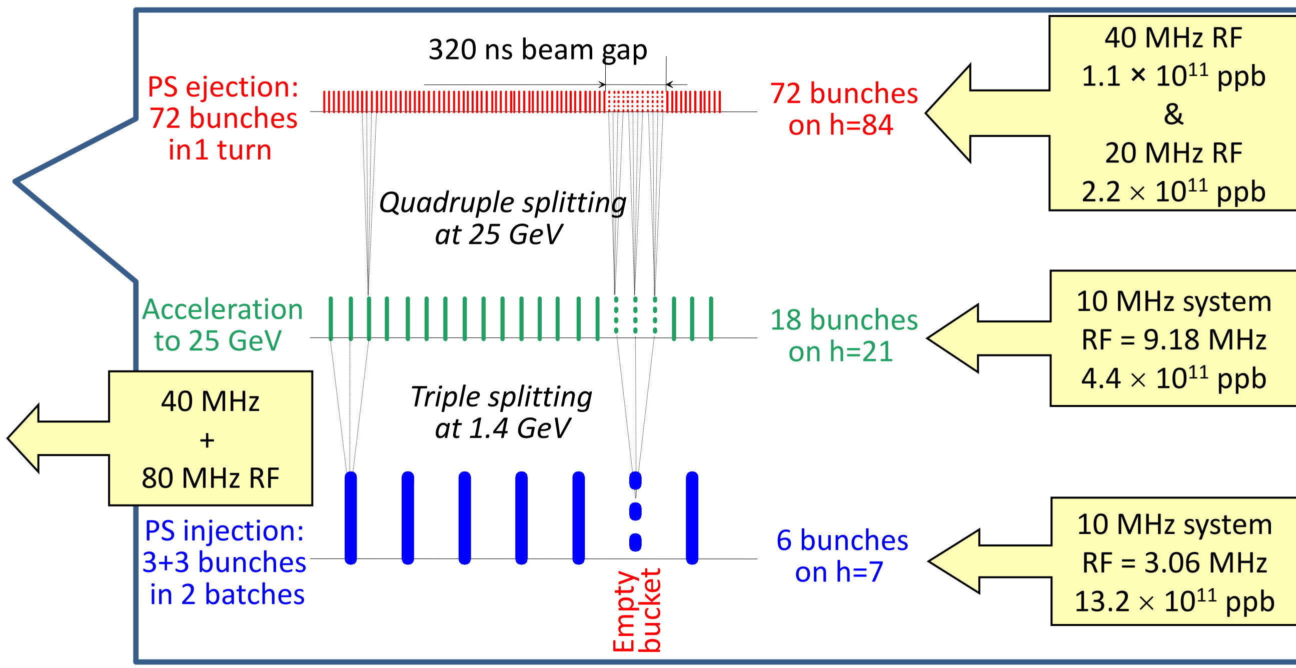
- Analyse the status of the injectors and the HL-LHC requirements,
- Propose an upgrade path for the injectors, exploiting the work done by the Task Forces on the „PSB energy upgrade" and „SPS upgrade" and by the Working Group on the SPS upgrade,
- Organize the upgrades (WBS with resources and planning) and take care of their implementation,
- Take care of hardware and beam commissioning.

Generation of LHC beam in the PS complex

1. Division by 2 of the intensity in the PSB (one bunch per ring and double batch filling of the PS)



2. Increase of the injection energy in the PS (from 1 to 1.4 GeV)
3. Quasi-adiabatically splitting of each bunch 12 times in the PS to generate a train of bunches spaced by 25 ns
4. Compression of bunches to ~4ns length for bunch to bucket transfer to the SPS
5. Stacking of 3-4 PS batches in the SPS and acceleration to 450 GeV



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Principles of action

To increase performance

Brightness ↗

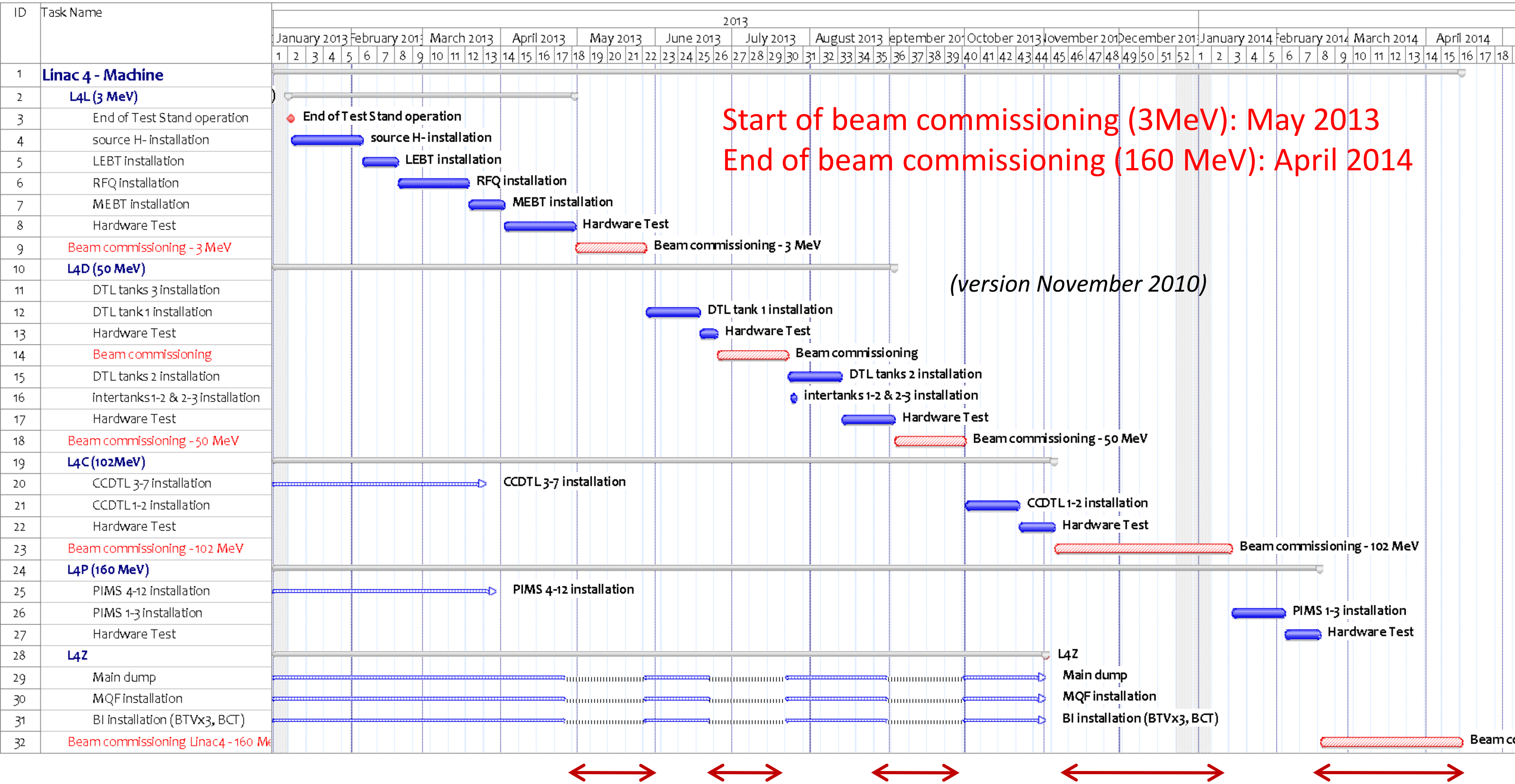
- ⇒ **Increase injection energy in the PSB from 50 to 160 MeV, Linac4 (160 MeV H^-) to replace Linac2 (50 MeV H^+)**
- ⇒ **Increase injection energy in the PS from 1.4 to 2 GeV, increasing the field in the PSB magnets, replacing power supply and changing transfer equipment**
- ⇒ **Upgrade the PSB , PS and SPS to make them capable to accelerate and manipulate a higher brightness beam (feedbacks, cures against electron clouds, hardware modifications to reduce impedance…)**

To increase reliability and lifetime (until ~2030!)
(tightly linked with consolidation)

- ⇒ **Upgrade/replace ageing equipment (power supplies, magnets, RF…)**
- ⇒ **Procure spares**
- ⇒ **Improve radioprotection measures (shielding, ventilation…)**

Linac4: Commissioning schedule

M. Vretenar



5 commissioning stages: 3 MeV 10 MeV 50 MeV 100 MeV 160 MeV

In 2013/14 (15 months), 6.5 months of beam commissioning, 3 months of HW tests, 5.5 months of installation

Upgrade Work Packages

PSB	Management (M resources)
	Beam Dynamics
	Magnets
	Magnetic Measurements
	RF
	Beam Intercepting Devices
	Power Converters (PSB)
	Power Converters (Injection)
	Vacuum System
	Beam Instrumentation
	Commissioning
	Injection
	Extraction, Transfer
	Controls
	Electrical Systems
	Cooling & Ventilation
	RP and Safety
	Transport and Handling
	Survey

PS	Management (M resources)
	Beam Dynamics
	Magnets
	RF
	EPC
	Beam instrumentation
	Intercepting device
	Vacuum system
	Injection
	Controls
	Electrical system
	Cooling and ventilation
	Transport
	Civil engineering
	RP
	Machine Interlocks
	Alarms
	Access doors
	Survey
	OP

SPS	Management (M resources)
	Beam dynamics studies and
	MKDV/H impedance reduction
	Beam instrumentation
	Extraction protection upgrade
	New high bandwidth damper
	Existing damper power upgrade
	Existing damper removal to
	RF 200 MHz upgrade
	ecloud mitigation: aC coating
	New collimation system
	New MKE and extraction channel upgrade
	Beam dump upgrade
	TL protection upgrade

+ Consolidation…

PS injector – RCS option

Tentative RCS parameters

=> Same beam characteristics than PSB @ 2GeV
=> Shorter PS § SPS injection flat bottoms

Energy range	160 MeV to 2 GeV
Circumference	(200x 4/21) π m ≈ 119.68 [illegible]
Repetition rate	~10 Hz
RF voltage	60 k[illegible]
Harmonics	[illegible]
Frequency range	[illegible] [illegible]jection)
Beam param[illegible] (for [illegible]	[illegible]ycle (3.25 10^{12} p/p) [illegible] μm [illegible]2×0.27 eVs (determined by [illegible] for most cases)
[illegible]	[illegible]d symmetry 21 cells, 5 cells/arc, 2 cells/straight section
[illegible]	$3.5 < Q_{H,V} < 4.5$
L[illegible] section (4x)	2 x 2.35 m
Rel[illegible]stic gamma at transition	~4
Maximum magnetic field	< 1.3 T

Benefits:

- Competitive cost wrt PSB consolidation and upgrade (? Study in progress…)
- Reliability (new hardware / modern design)
- Commissioning decoupled from physics operation

K. Hanke

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PS injector: RCS feasibility study

Beam characteristics:

- for all PS users: equivalent to PSB at 2 GeV
- for ISOLDE: ~ 7 10^{13} p/s @ 2 GeV (today: ~10^{13} p/s @ 1.4 GeV)

Feasibility report with cost estimate: end of July

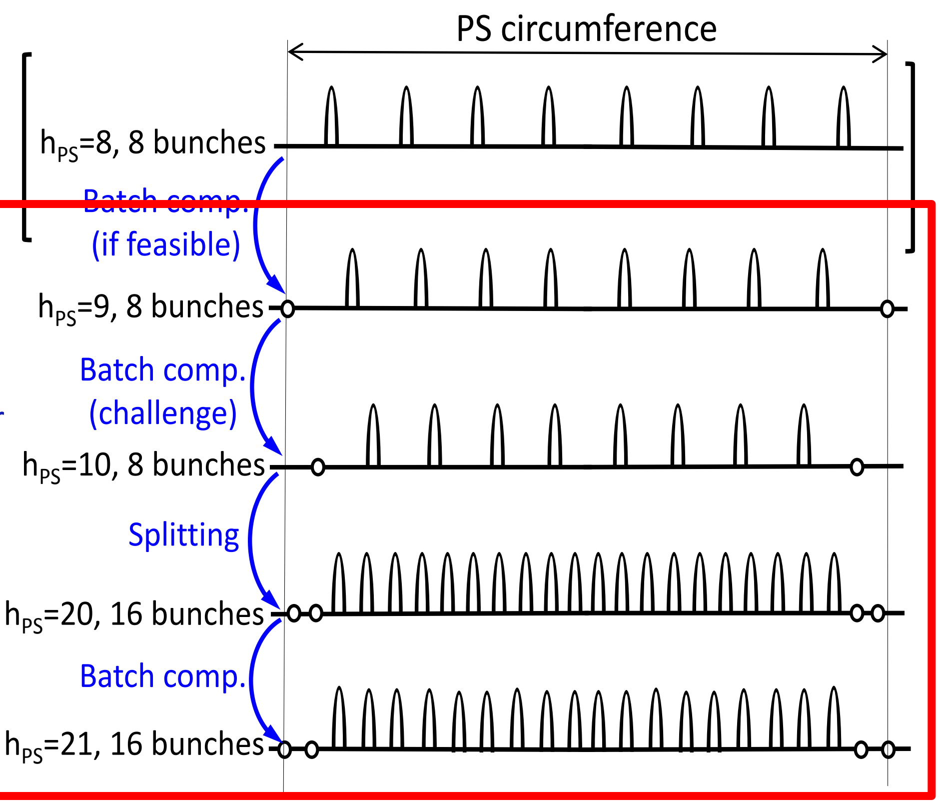
PS Longitudinal: Batch Compression (1/2)

Batch Compression Schemes in the PS

Compression to h_{PS} = 10 and generation of 64 bunches

- Injection and first acceleration with h_{PS}=8 or h_{PS}=9
- Potential brightness increase: 12/8 = 1.50*
  - Corresponds to PSB upgrade: 1.4 GeV to 1.77 GeV
  - Brightness per bunch for 25 ns trains out of PSB
    - ε^*=2.5 μm and 2.23 10^{11} or
    - ε^*=1.90 μm and 1.7 10^{11}
- Estimate of longitudinal parameters at injection for 25 ns trains
  - Every bunch split into 8 LHC bunches with 0.35 eVs
  - 1.6 eVs per injected bunch allows a factor 1.75 blow-up

*) With h_{PS}=8 at injection, compared to present situation with Linac2 and double batch PSB to PS transfer

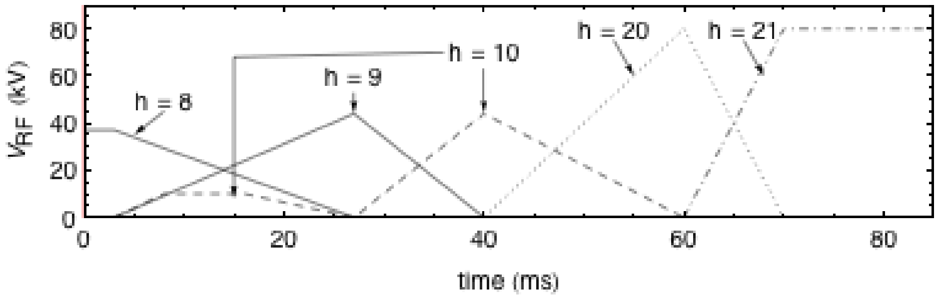


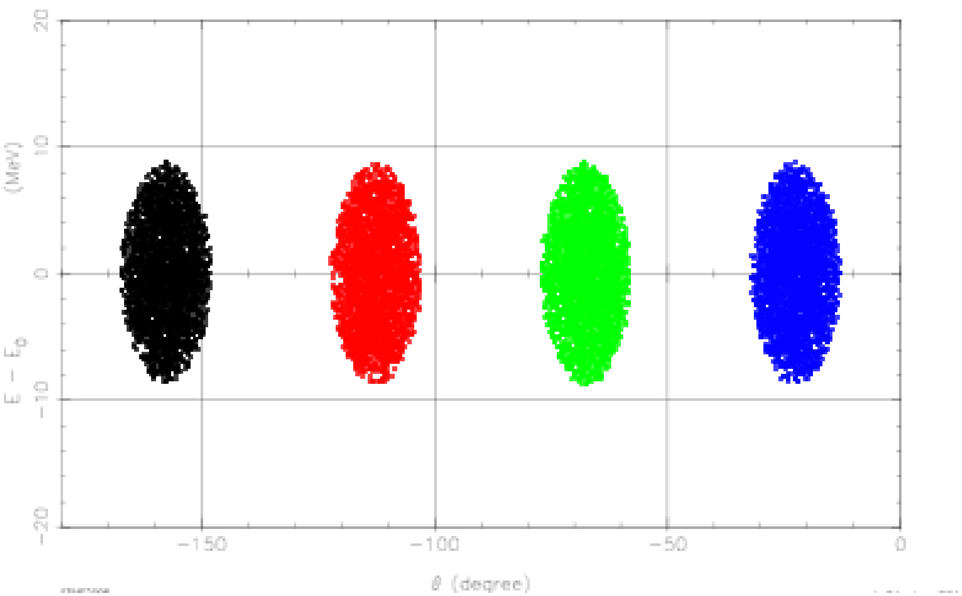
RF gymnastics at an appropriate intermediate energy (hypothesis 2.5 GeV)
(Injection and first acceleration with h_{PS}=8 or h_{PS}=9)

MD tests – H. Damerau, S. Hancock – May 2011

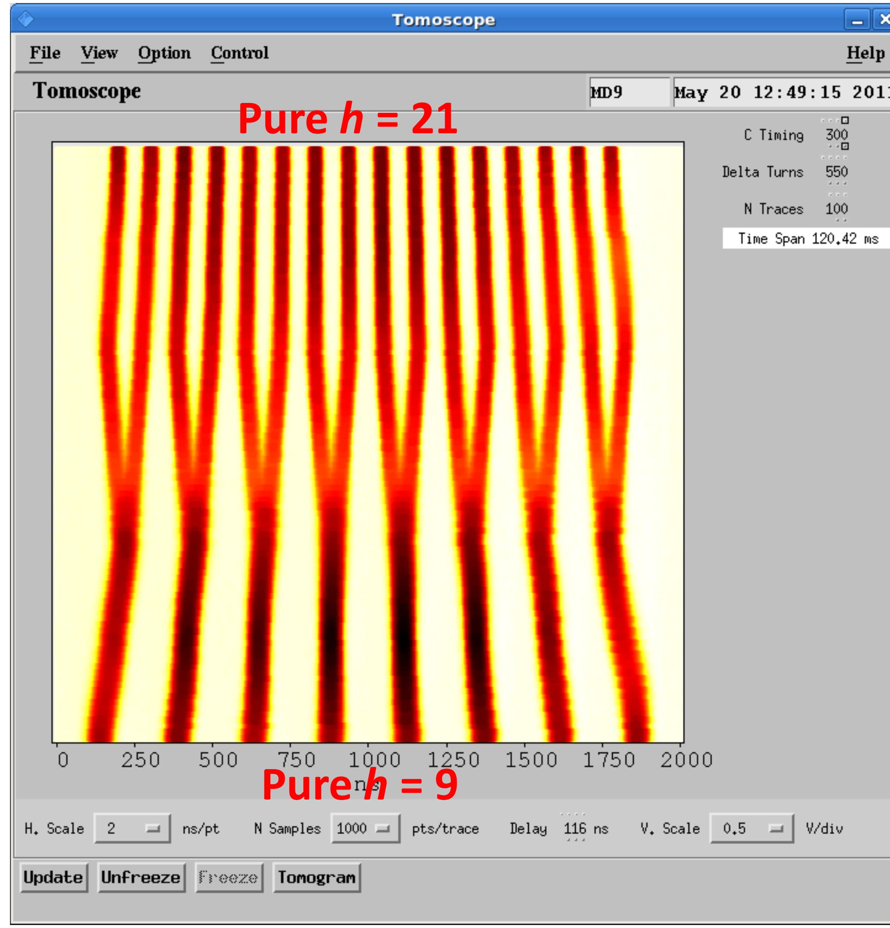
PS Longitudinal: Batch Compression (2/2)

Simulation (C. Carli)





MD result at 2 GeV (H. Damerau, S. Hancock)



- RF gymnastics OK up to intermediate energy
- Significant effort required to reach 26 GeV and make beam available for the SPS (RF preparation § beam adjustment) **=> Need for precise measurement of transverse emittances before continuing**

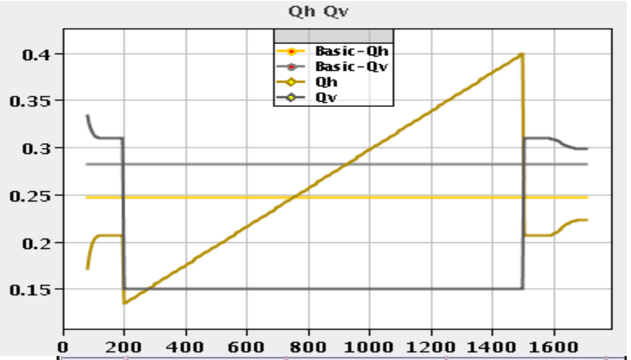
Transverse: Principle of Working Point Scans

E. Benedetto

GOAL: Identify dangerous resonance lines in tune diagram

Loss measurement for different WPs:

- Low intensity beam (not SC-dominated) → 130 x 10^{10} protons
- Large emittance (to fill the chamber & provoke immediate losses)
- Long flat bottom @ 1.4 GeV
- Tune program:
  - Scan between (0.1 - 0.4)
  - Vertical tune constant
  - Sweep of the horizontal tune



Slope in the intensity signal indicates importance of the crossed resonance line

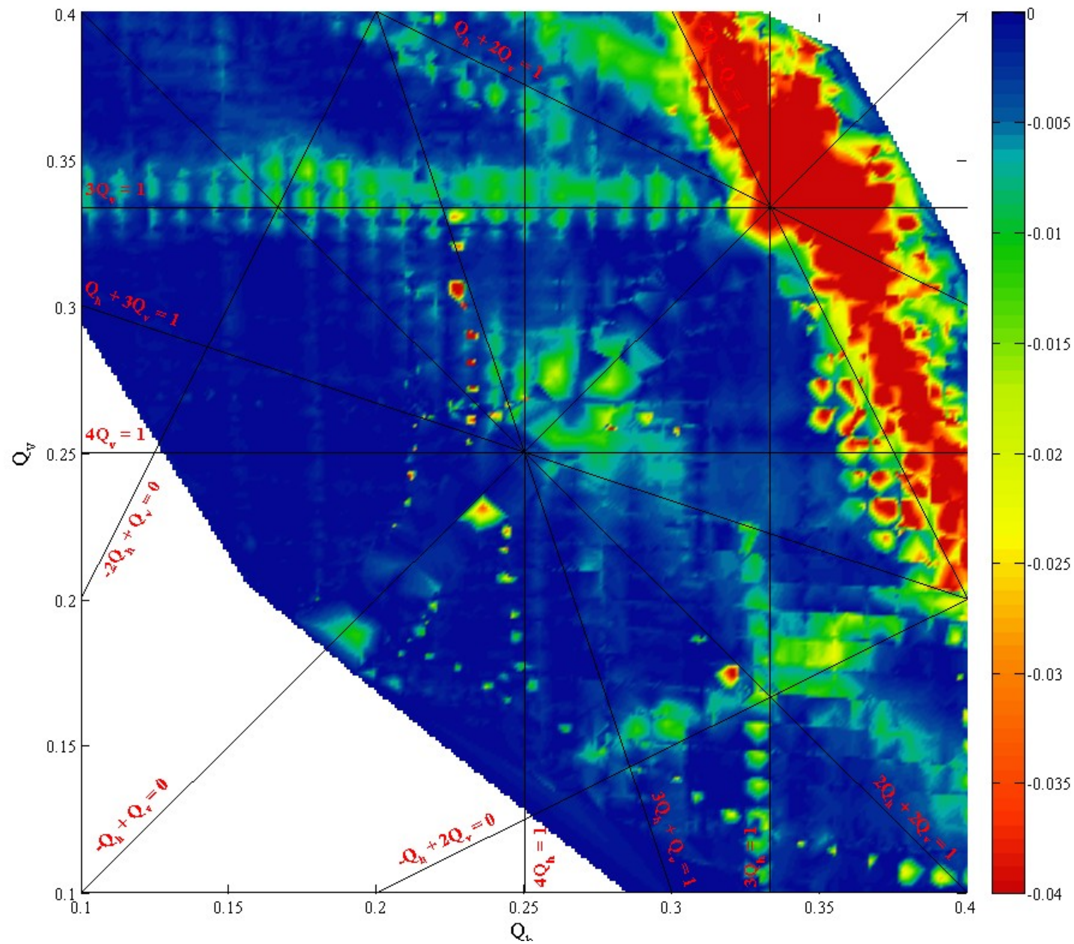
Transverse: PS Tune Scans

2 GeV

E. Benedetto

⇒ w/o PFW : no surprises

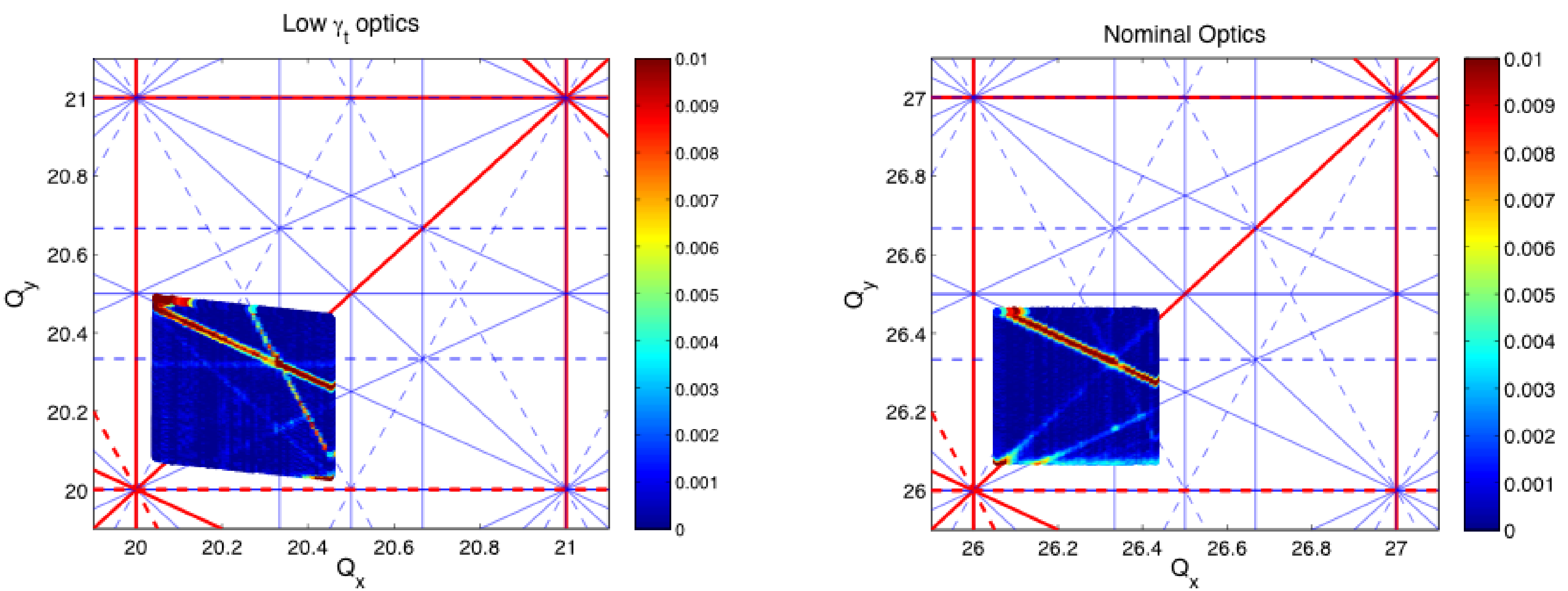
⇒ with PFW ongoing



Transverse: SPS Tune Scans

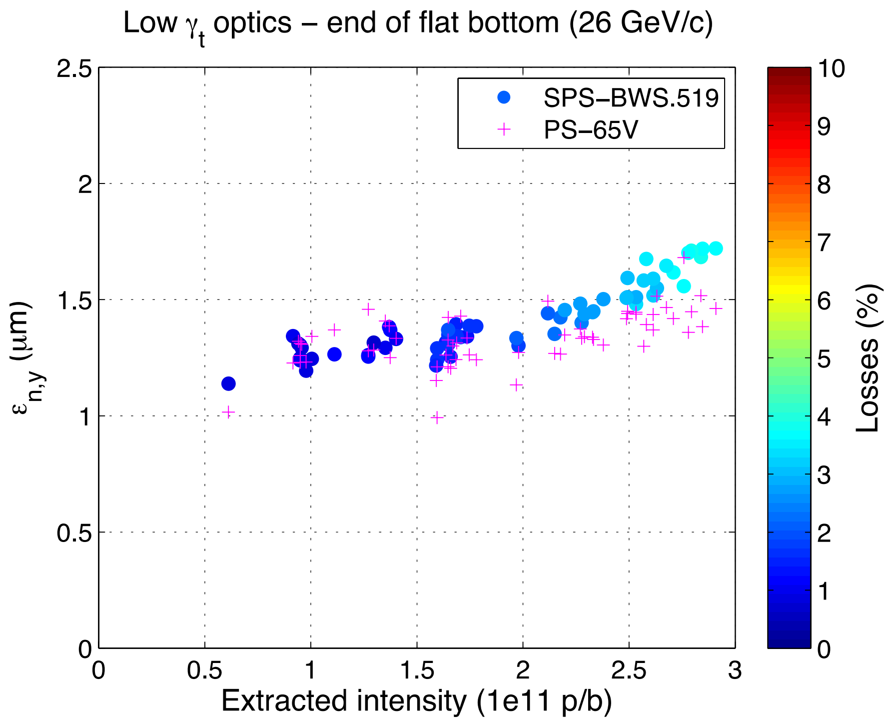
H. Bartosik

- Identified resonances in the low γ_t optics
  - normal sextupole resonance Qx+2Qy is the strongest
  - skew sextupole resonance 2Qx+Qy quite strong !!??
  - normal sextupole Qx-2Qy, skew sextupole resonance at 3Qy and 2Qx+2Qy fourth order resonances visible
- Identified resonances in the nominal optics
  - normal sextupole resonance Qx+2Qy is the strongest
  - Coupling resonance (diagonal, either Qx-Qy or some higher order of this), Qx-2Qy normal sextupole
  - skew sextupole resonance 2Qx+Qy weak compared to Q20 case
  - It seems that the stop-band width of the vertical integer is stronger than in Q20 optics

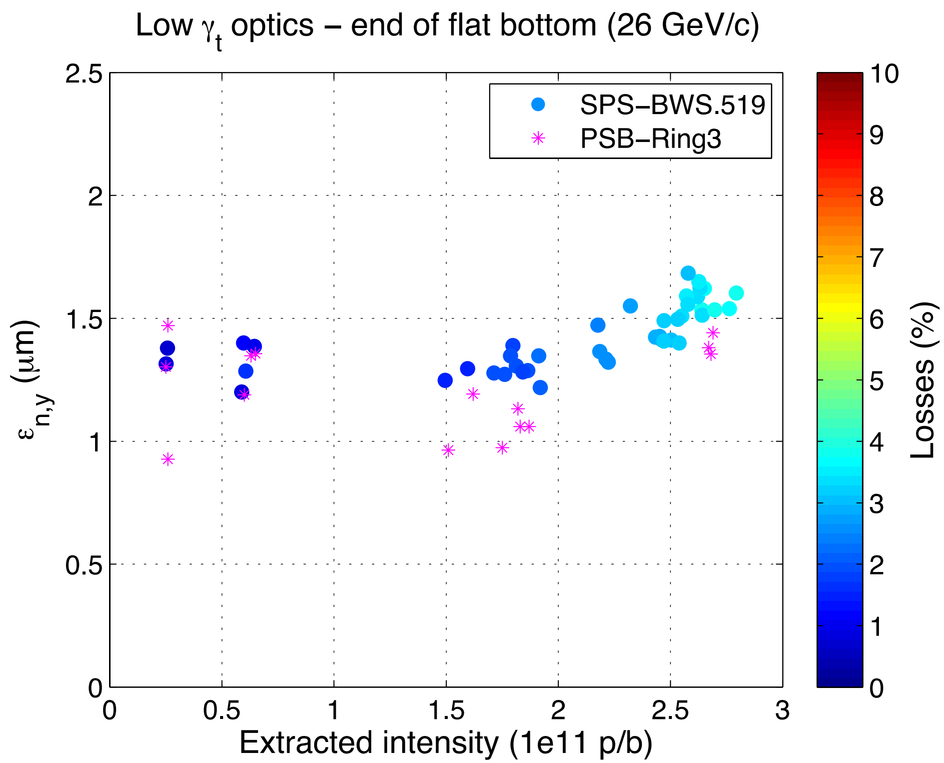


Transverse emittance measurement: debugging…

A. Guerrero
§ B. Mikulec



Emittance preservation (?) between PS @ 26 GeV and SPS flat bottom



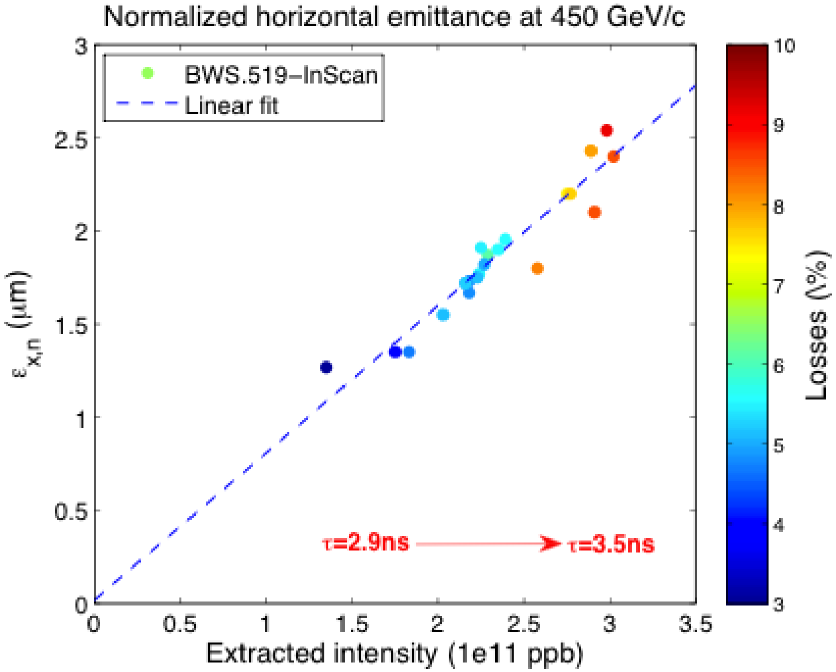
Emittance Blow-up (?) between PSB and SPS flat bottom

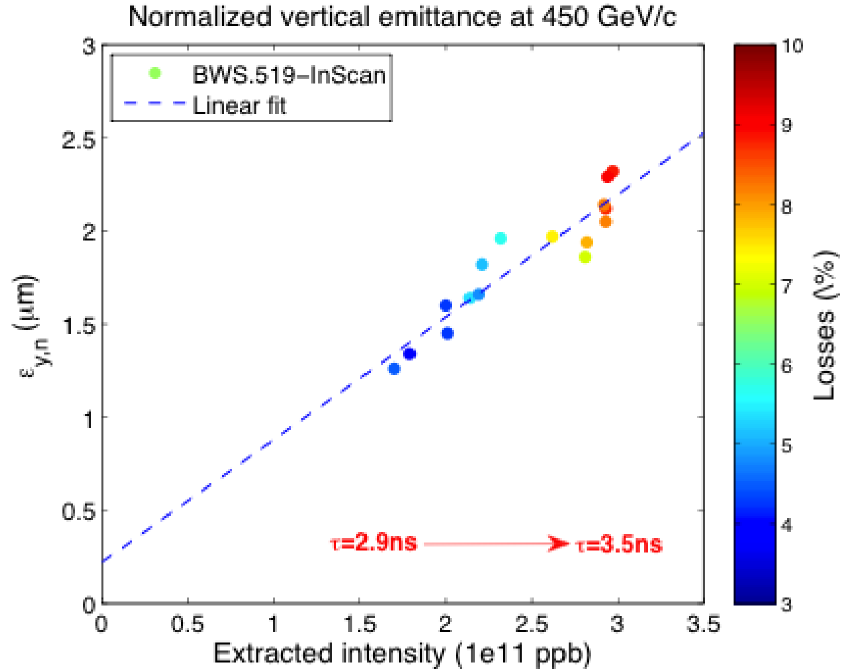
Transverse: emittances vs intensity in SPS

H. Bartosik

Measurement of single bunch emittances
- In scan with "reference" wire scanner BWS.519 at flat top
- Long cycle (~10s injection plateau, ~10s acceleration)
- Losses along the cycle extracted from DC-BCT measurement

PS bunch length increasing with intensity
- T=2.9ns @ 1.5e11 p/b, T=3.5ns @ 3e11 p/b
- Emittances in PSB: ~ 1μm < 1.5e11p / ~ 1.1μm @ 2e11p / ~ 1.3μm @ 3e11p (Well adjusted beam in the PSB!)



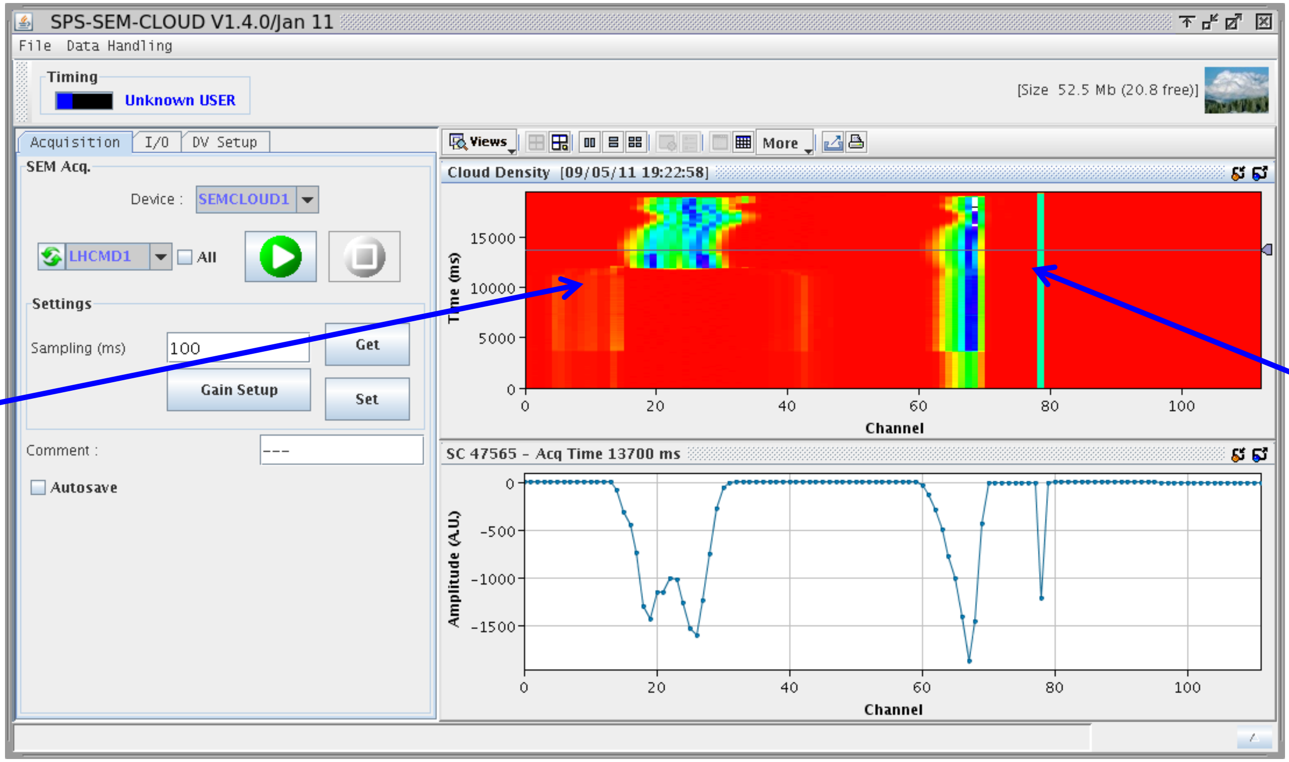


SPS: e-cloud with 25 ns bunch train

M. Taborelli

- Electron cloud measured at all the liners
  - Signal already visible with 1 batch on both stainless liners
  - No signal visible on the a-C coating liner
  - Half signal clearly visible on the half coated chamber
  - Effect of the clearing electrode checked scanning points on a grid of voltage vs. magnetic field values

Clearing electrode: it was switched off in the middle of cycle



Half-coated liner, only stripe on StSt visible

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Caveat…

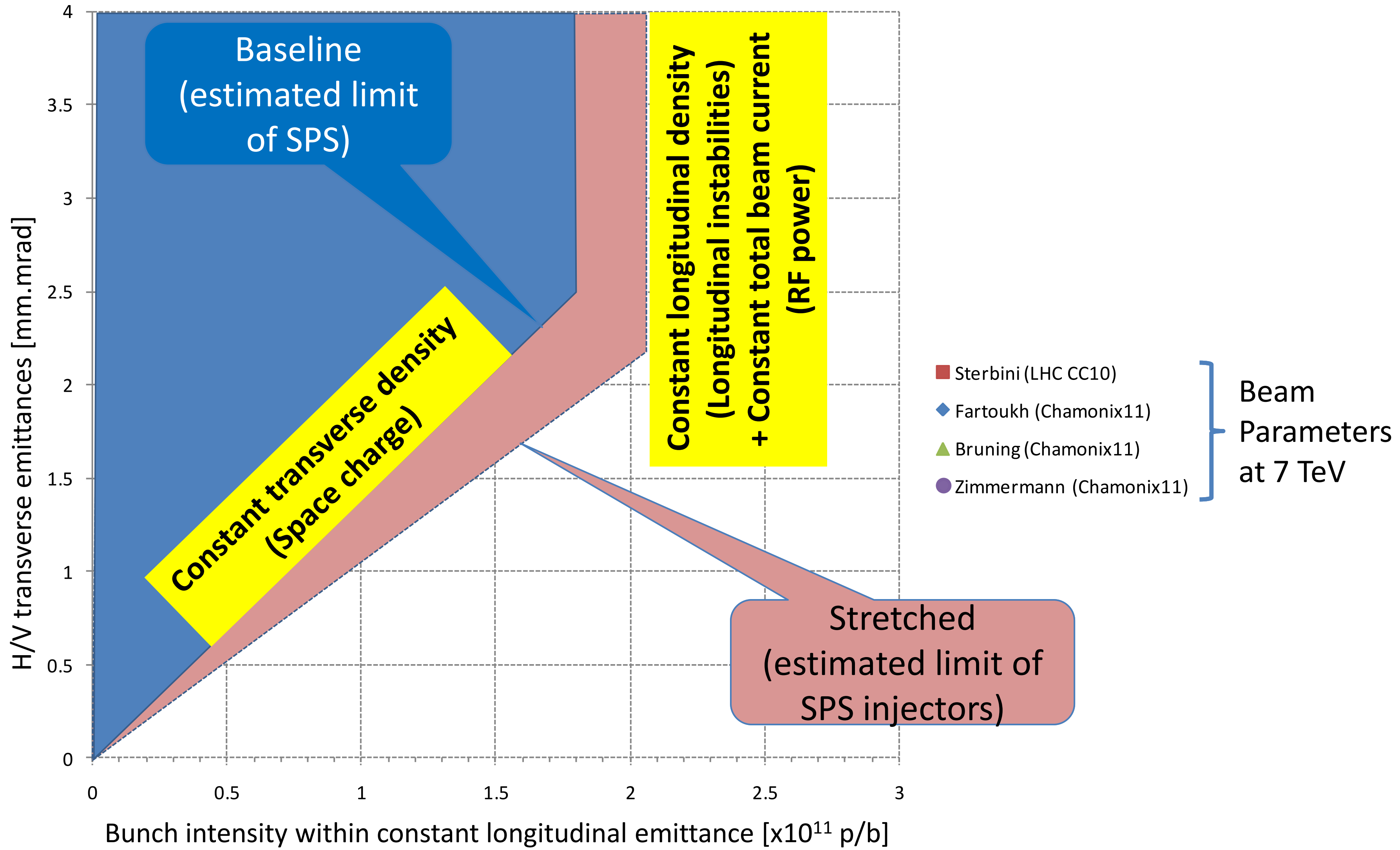
- Beam parameters are given at injection in LHC: beam loss and blow-up inside the LHC are not accounted for.

- All necessary improvements are implemented in the injectors (Linac4, PSB to PS transfer at 2 GeV, coupled bunch instabilities suppressed, e-cloud suppressed, hardware upgraded…)

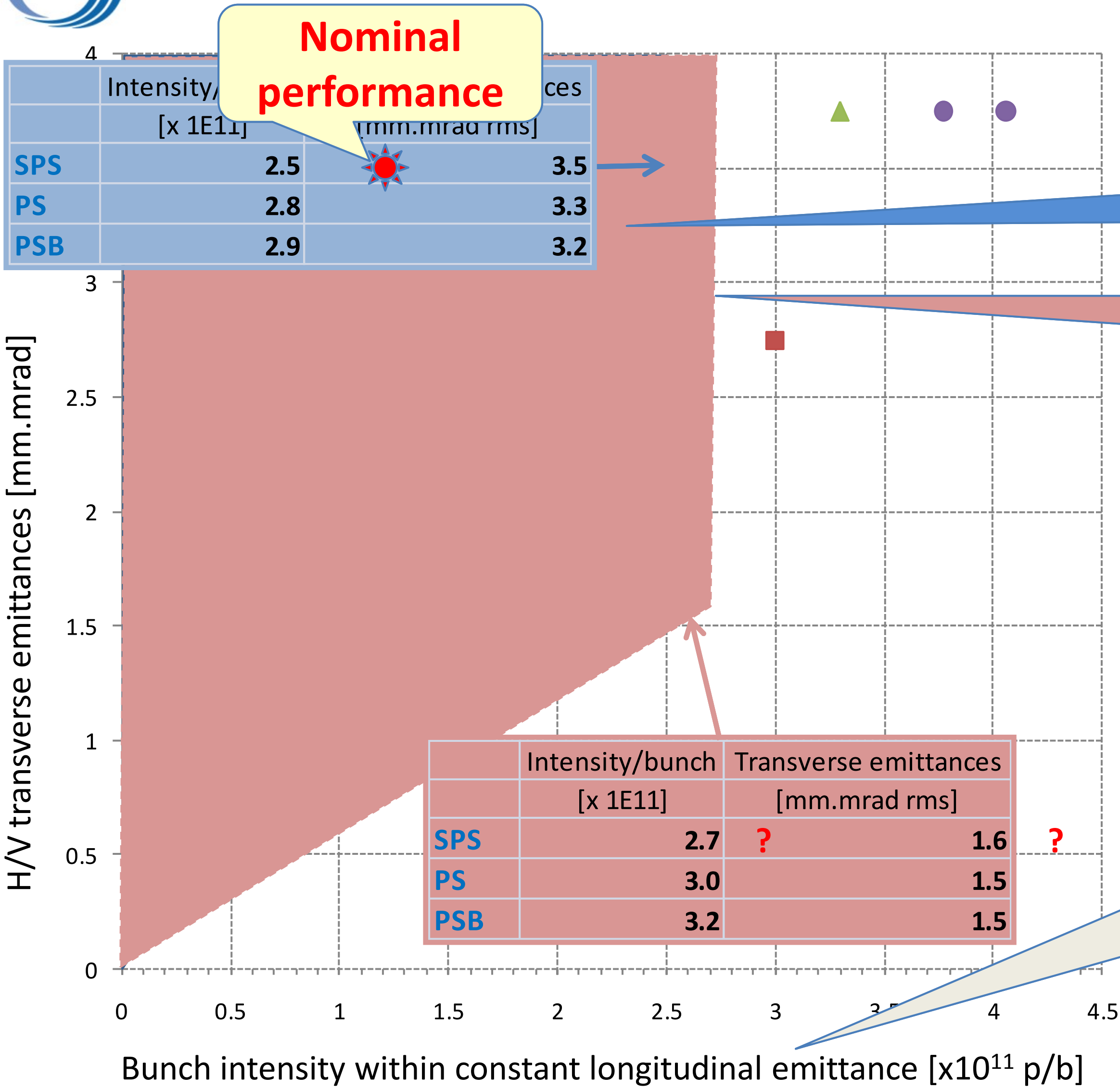
- Estimated beam degradation in the accelerator chain (based on observations in 2010):
  - ✓ PS: 5 % beam loss, 5 % transverse blow-up
  - ✓ SPS: 10 % beam loss, 5 % transverse blow-up.

- RF gymnastics being kept, imperfections are unchanged:
  - ✓ +-10 % fluctuation of all bunch parameters within a given PS bunch train.
  - ✓ Traces of ghost/satellite bunches.

Beam parameters: Comments



Beam parameters at LHC injection [50 ns]



	Intensity/	ces
	[x 1E11]	[mm.mrad rms]
SPS	2.5	3.5
PS	2.8	3.3
PSB	2.9	3.2

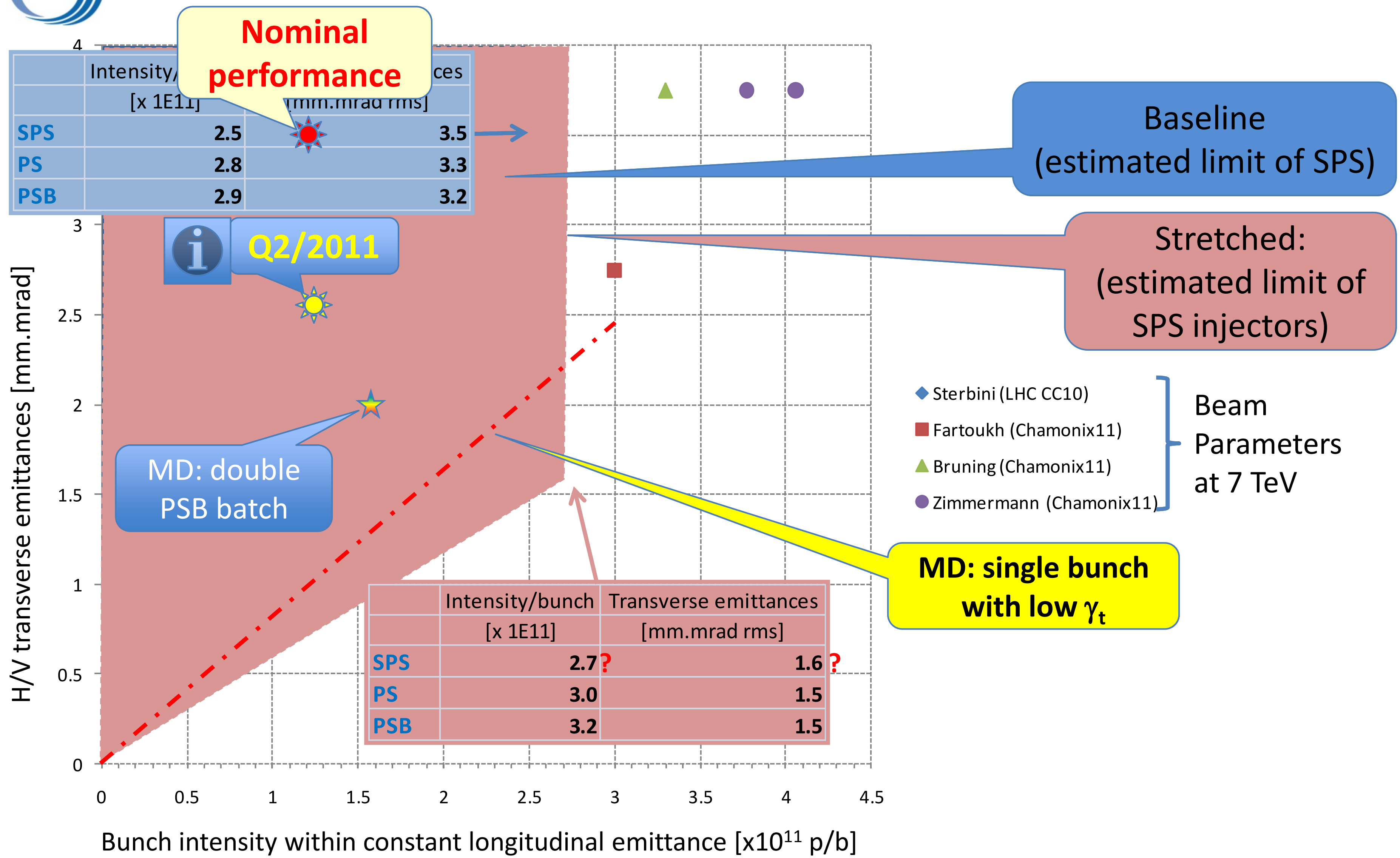
	Intensity/bunch	Transverse emittances
	[x 1E11]	[mm.mrad rms]
SPS	2.7	1.6
PS	3.0	1.5
PSB	3.2	1.5

Baseline (estimated limit of SPS)

Stretched: (estimated limit of SPS injectors)

< ½ longit. emittance wrt 25 ns during acceleration in the PS => Less Landau damping + e-clouds effects ?

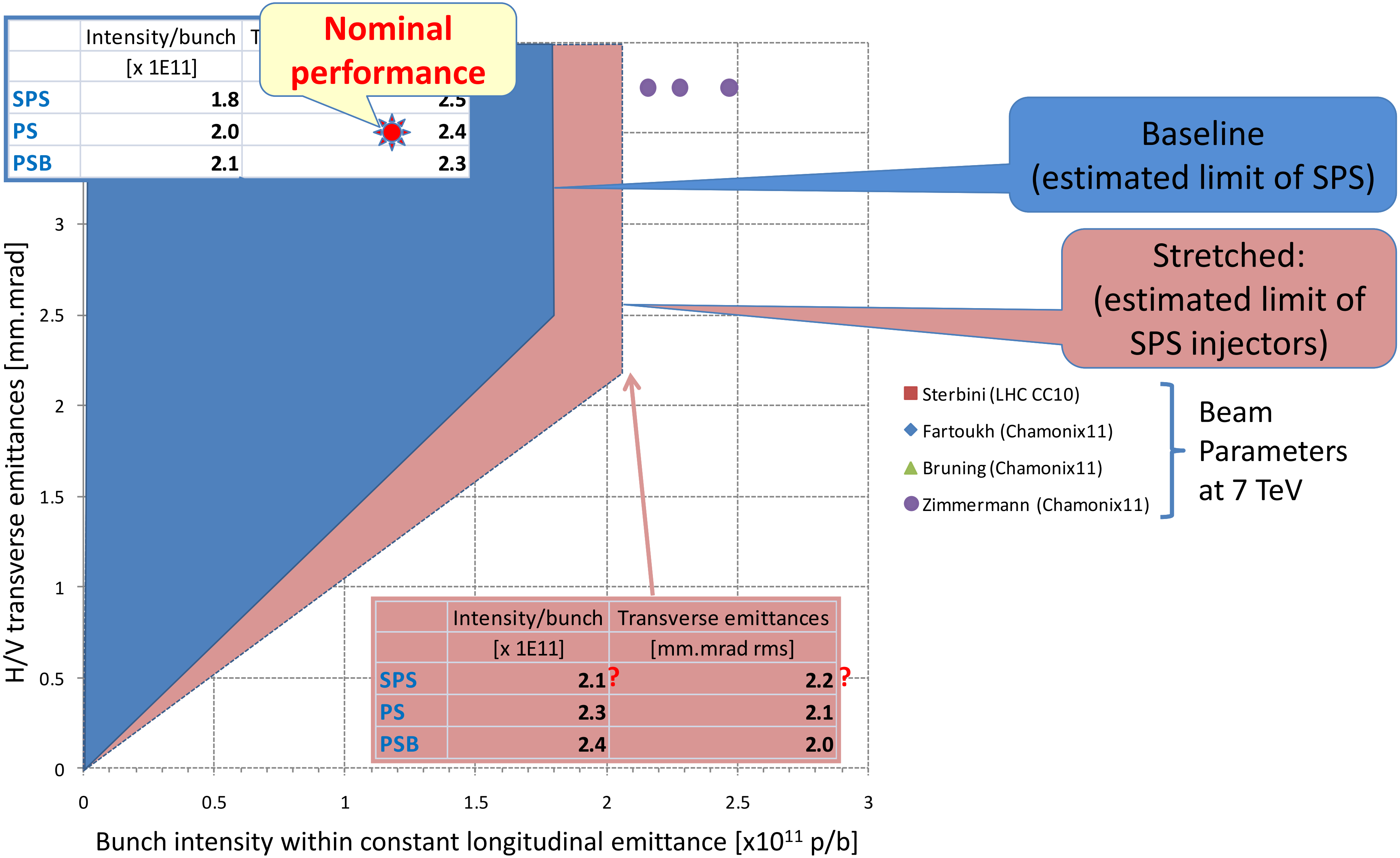
Beam parameters at LHC injection [50 ns]



	Intensity/	…ces
	[x 1E11]	[mm.mrad rms]
SPS	2.5	3.5
PS	2.8	3.3
PSB	2.9	3.2

	Intensity/bunch	Transverse emittances
	[x 1E11]	[mm.mrad rms]
SPS	2.7?	1.6 ?
PS	3.0	1.5
PSB	3.2	1.5

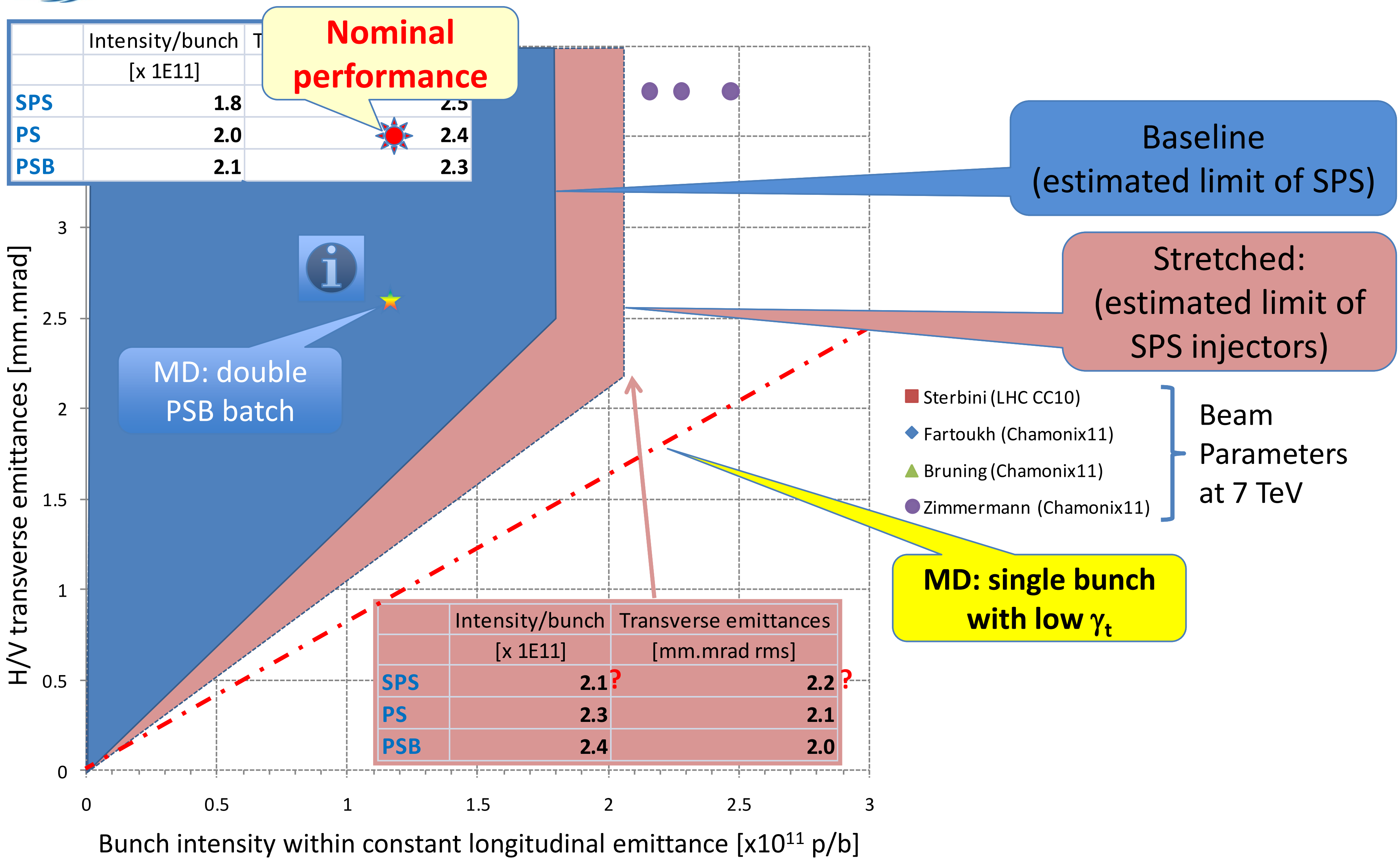
Beam parameters at LHC injection [25 ns]



	Intensity/bunch [x 1E11]	T
SPS	1.8	2.5
PS	2.0	2.4
PSB	2.1	2.3

	Intensity/bunch [x 1E11]	Transverse emittances [mm.mrad rms]
SPS	2.1?	2.2?
PS	2.3	2.1
PSB	2.4	2.0

Beam parameters at LHC injection [25 ns]



	Intensity/bunch [x 1E11]	T
SPS	1.8	2.5
PS	2.0	2.4
PSB	2.1	2.3

	Intensity/bunch [x 1E11]	Transverse emittances [mm.mrad rms]
SPS	2.1 ?	2.2 ?
PS	2.3	2.1
PSB	2.4	2.0

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Overall LIU Planning

	Linac4	PS injector, PS and SPS	Beam characteristics at LHC injection
2011 - 2012	Continuation of construction…	• Beam studies § simulations • Investigation of RCS option • Hardware prototyping • Design § construction of some equipment • TDR	25 ns, 1.2 10^{11}p/b, **~2.5 mm.mrad** 50 ns, 1.7 10^{11}p/b, **~2.2 mm.mrad** 75 ns, 1.2 10^{11} p/b, $\leq$ 2 mm.mrad
2013 – 2014 (Long Shutdown 1)	• Linac4 beam commissioning • Connection to PSB ?	• PSB modification (H^- injection) ? • PSB beam commissioning ? • Modifications and installation of prototypes in PS and SPS	
2015 - 2017	• Progressive increase of Linac4 beam current	• If Linac4 connected: progressive increase of PSB brightness • Some improvement of PS beam (Injection still at 1.4 GeV) • Equipment design § construction for PS injector, PS and SPS • Beam studies	• Limited gain at LHC injection (pending PS and SPS hardware upgrades)
2018 (Long Shutdown 2)		• Extensive installations in PS injector, PS and SPS • Beam commissioning	
2019 –2021			After ~1 year of operation: beam characteristics for HL-LHC…

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Summary

- ☞ **MDs during 2011-2012 are essential to refine the knowledge and understanding of the injectors and to check the potential of upgrades.**
- ☞ **Preliminary requirement/First goal: getting confidence in beam instrumentation => Extensive debugging: progressing well, but time – consuming...**
- ☞ **Recent observations in 2011 tend to demonstrate that the accelerators perform better than in the previous years. Not fully understood.**
- ☞ **Need to interact with HL-LHC for selecting reachable beam parameters which are sufficient for HL-LHC to reach its goals.**
- ☞ **Irrelevant to the decision to connect Linac4 to the PSB during LS1 and to the choice between PSB/RCS, the beam characteristics specified for LIU will be met some time after the end of LS2 (~2020).**

THANK YOU
FOR YOUR ATTENTION!

Why is today's beam better than nominal?

Simple! No more blow-up along the accelerators cascade…

- PSB:
  - Improved (achromatic) optics in the Linac2 to PSB transfer line since 2005 [http://khanke.home.cern.ch/khanke/papers/2006/ab_note_2006_001.pdf]
- PS:
  - Injection trajectories
  - Working point along the whole cycle
  - Transition
- PS to SPS:
  - Transverse matching with better optics in TT2-TT10

WARNING: NO MARGIN LEFT!