LHC Injectors Upgrade

The high intensity/high brightness upgrade program at CERN: status and challenges

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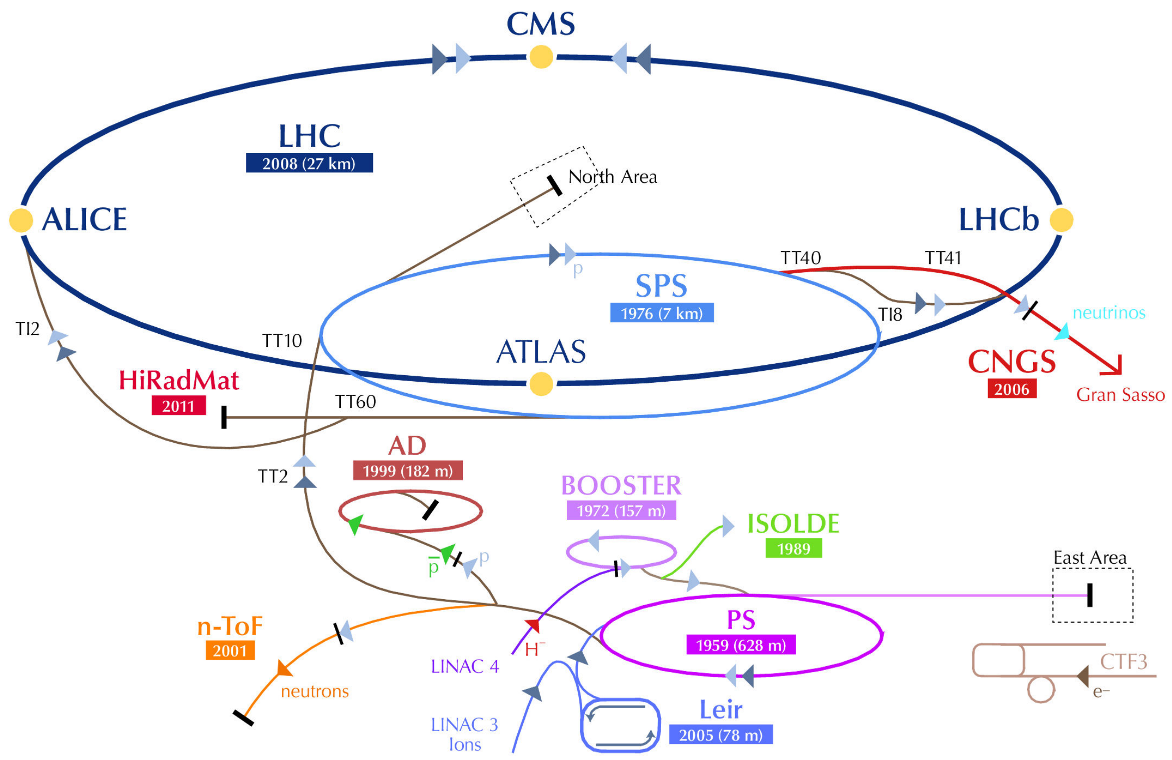
LHC injectors upgrade Goals



"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…"   (This is the mandate … **Upgrade of Brightness**)

+ determine possible improvements for high intensity beams.

HL-LHC* beam parameters, today vs tomorrow

*High Luminosity - LHC

Param. @ LHC collision	Nominal[1] 25 ns	Today * 50 ns	HL-LHC[1] 25 ns	HL-LHC[1] 50 ns
Int/bunch	1.15E11	~1.6E11	2.2E11	3.5E11
Bunches	2808	1374	2808	1404
Beam current [A]	0.58		1.12	0.89
ε_n[μm]	3.75	~ 2.4	2.5	3.0
β*[m]	0.55	0.6	0.15	0.15
Peak Lumi [cm^{-2} s^{-1}]	$1\ 10^{34}$	$7.74\ 10^{33}$	$9\ 10^{34}$	$9\ 10^{34}$

*Non official values
[1]O. Bruning, HL-LHC/LIU day, 30/03/2012

Goal of HL-LHC ~ 300- 250 fb^{-1} per year

Today we produce about 1 fb^{-1} per week

LHC25ns Production Scheme as today

25 ns is bunch spacing required by the LHC (today LHC uses 50 ns bunch spacing)

Production scheme:

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

b) 4 batches of 72 bunches each transferred to the SPS

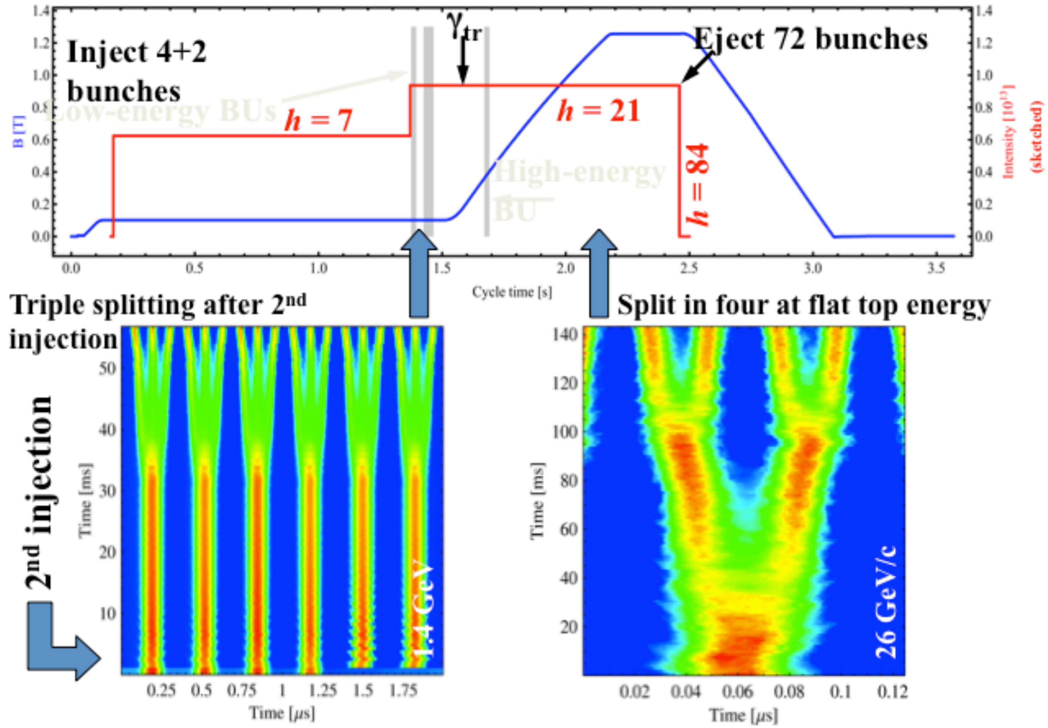
Transverse emittance produced in the PSB, longitudinal in the PS

- Multiturn proton injection in PSB
- RF gymnastics in PS:
  - Triple splitting
  - Acceleration
  - 2 x Double splittings
  - Bunch rotation

➢ 3 RF systems in PSB

➢ 5 RF systems in PS

➢ 2 RF systems in SPS



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

Challenges of this scheme

High intensity injected in PSB:

- every PSB bunch is split 12 times (to get finally 72 bunches at 25 ns spacing)
- Space-charge issue. **See B. Mikulec & A. Molodozhentsev presentation**
- Limited brilliance due to multiturn injection process

Long waiting time at PS injection:

- Space-charge issue. **See A. Molodozhentsev presentation**
- Headtail instability.

Long waiting time at SPS injection:

- Space-charge.
- TMCI instabilities. **See H. Bartosik presentation**

Many RF systems involved:

- Longitudinal instabilities and limitations to be overcome in all the machines **See E. Shaposhnikova presentation**

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

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Goal of HL-LHC ~ 250 fb^{-1} per year

Today we produce about 1 fb^{-1} per week

Basic Principles of the Injector upgrade

To increase performance (soon extended for heavy ions) : **Increase Brightness**

Overcome main limitations of LHC injectors (brief intro summary):

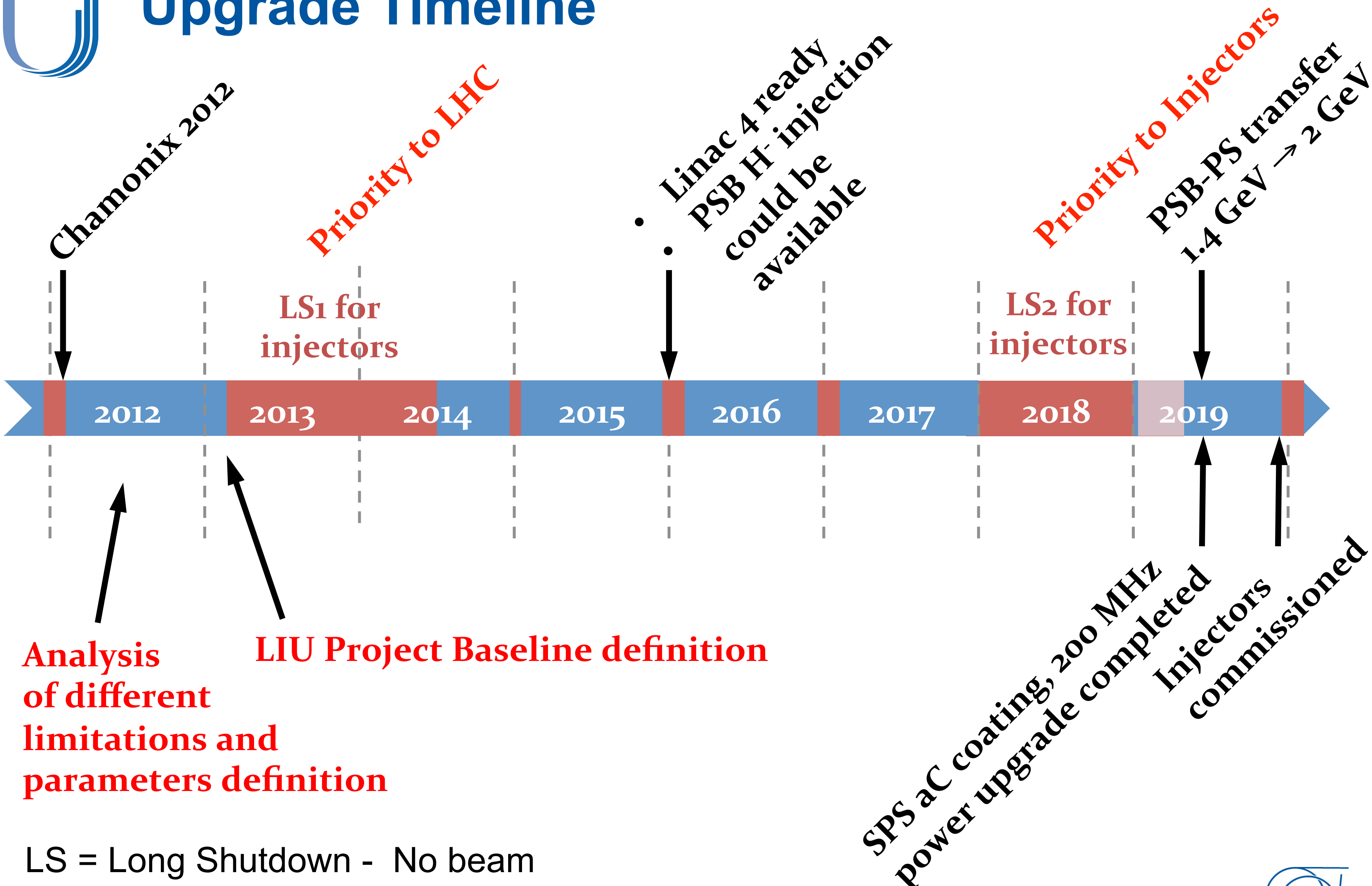
- Space charge current limitations
  - **PSB injection : Increase injection energy in the PSB from 50 to 160 MeV**
    Linac4 (160 MeV H^-) to replace Linac2 (50 MeV H^+)
    Prove operation with Laslett larger than |0.36| @ 160 MeV (today |0.7|, required max. |0.5|)
  - **PS injection: Increase injection energy in the PS from 1.4 to 2 GeV**
    Prove operation with Laslett larger than |0.3| @ 2 GeV (today |0.28|, required max. |0.34|)
  - **SPS injection** if confirm current operational limit
    Prove operation with Laslett larger than |0.15|
- Transverse/Longitudinal stability limits
  - TMCI @ SPS
  - Transient beam loading and CBI in the PS
  - RF limitations in SPS
- Electron cloud related issues
  - Wideband transverse damper in PS
  - SPS vacuum chamber coating+scraping+wideband damper

To increase reliability and lifetime (until ~2030!)

PS	is 53 years old
PSB	is 40 years old
SPS	is 36 years old

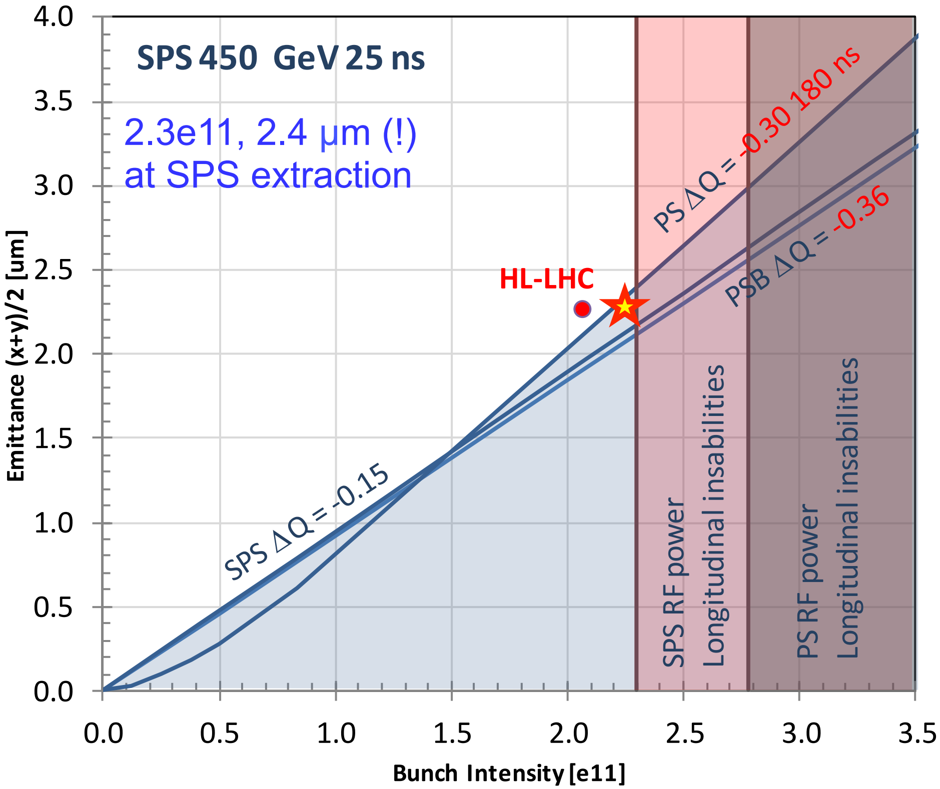
- Upgrade the PSB , PS and SPS to make them capable to accelerate and manipulate a higher brightness beam (feedbacks, cures against electron clouds, hardware modifications to reduce impedance, improve beam instrumentations…)

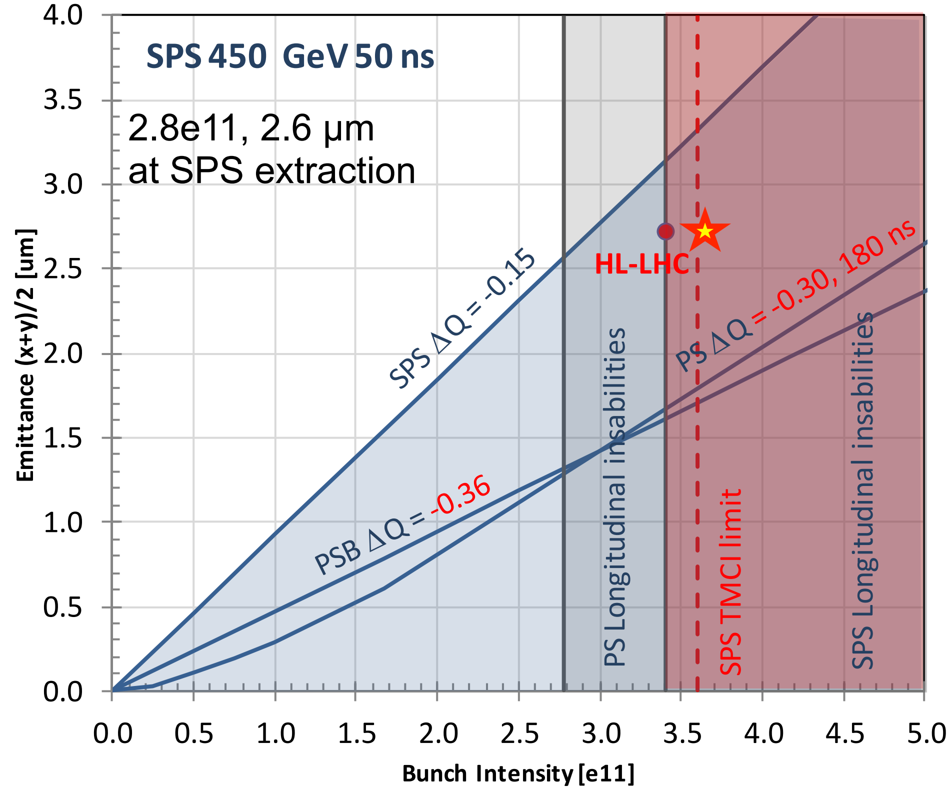
Upgrade Timeline



‘Conceivable’ improvements for stretch goals?

Goal: reduce losses (and SPS blowup) at the possible minimum





Will be **real challenge** to achieve with x2 beam intensities wrt today

Assumed **optimistic** budgets for losses and emittance blowup

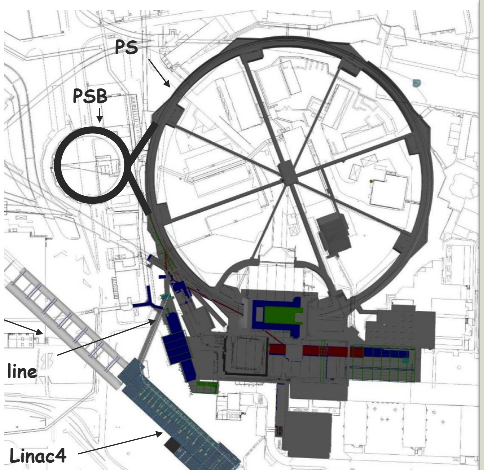
Stretch	PSB	PS	SPS	LHC
loss %	5	3	8	3
blowup %	5	5	5	10

Linac 4

Linac4: new 160 MeV H^- linac injector for the CERN accelerator complex, to replace the 50 MeV p^+Linac2.

Goals: double brightness (I/ε) in the PS Booster from higher injection energy (factor 2 in $\beta\gamma^2$) for the LHC Luminosity Upgrade (>2020) + advantages of H^- + more intensity for other users + modern and more reliable injector.

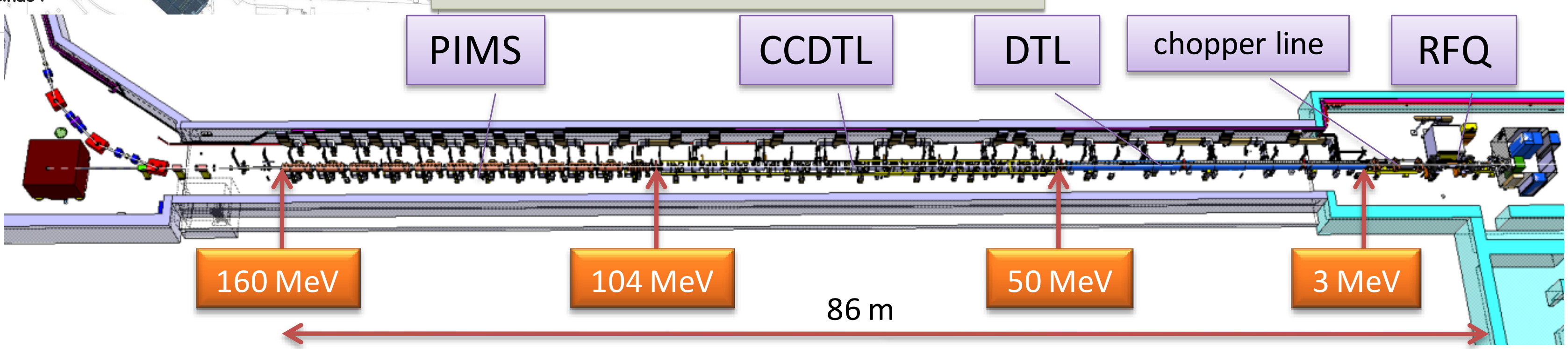
Status: building and infrastructure completed, accelerator installation starting.



Ion species	H^-	
Output Energy	160	MeV
Bunch Frequency	352.2	MHz
Max. Rep. Frequency	2	Hz
Max. Beam Pulse Length	0.4	ms
Max. Beam Duty Cycle	0.08	%
Chopper Beam-on Factor	65	%
Chopping scheme:	222 transmitted /133 empty buckets	
Source current	80	mA
RFQ output current	70	mA
Linac pulse current	40	mA
Tr. emittance (source)	0.25	π mm mrad
Tr. emittance (linac exit)	0.4	π mm mrad
Max. repetition frequency for accelerating structures	50	Hz

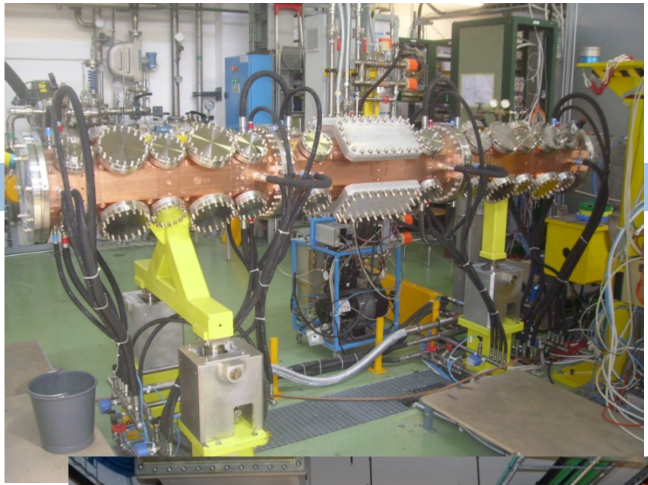
Presentation of J.B. Lallement

	Energy [MeV]	Length [m]	RF Pow. [MW]	Focusing
RFQ	0.045 - 3	3	0.6	RF
DTL	3 - 50	19	5	112 PMQs
CCDTL	50 - 102	25	7	14 PMQs, 7 EMQs
PIMS	102 - 160	22	6	12 EMQs

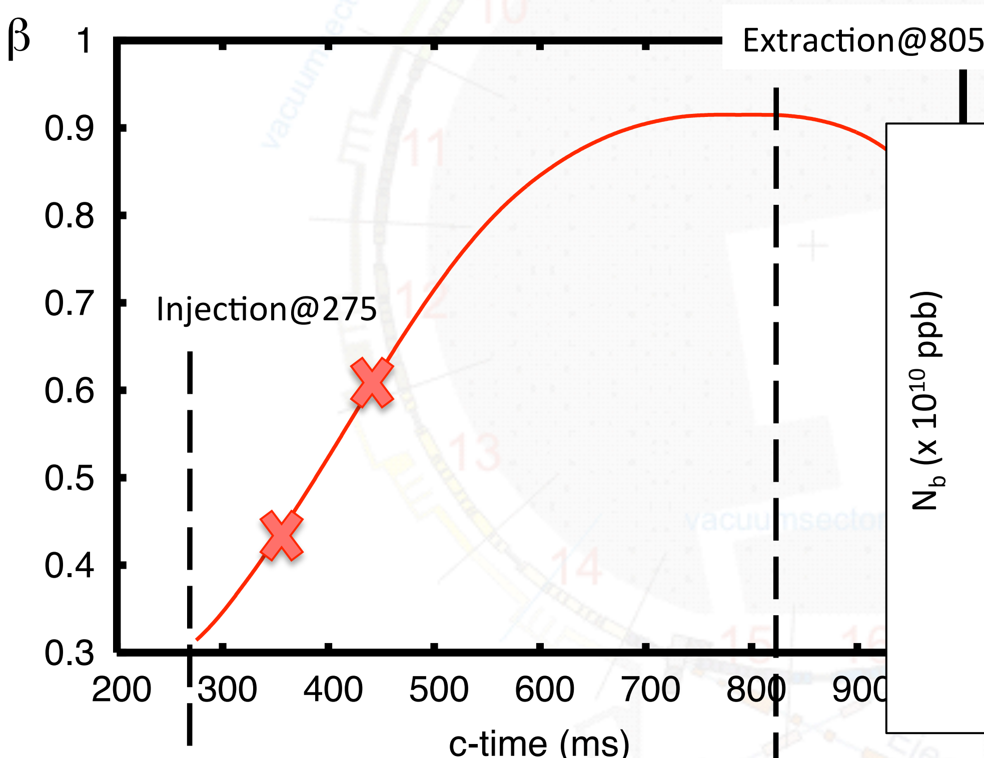


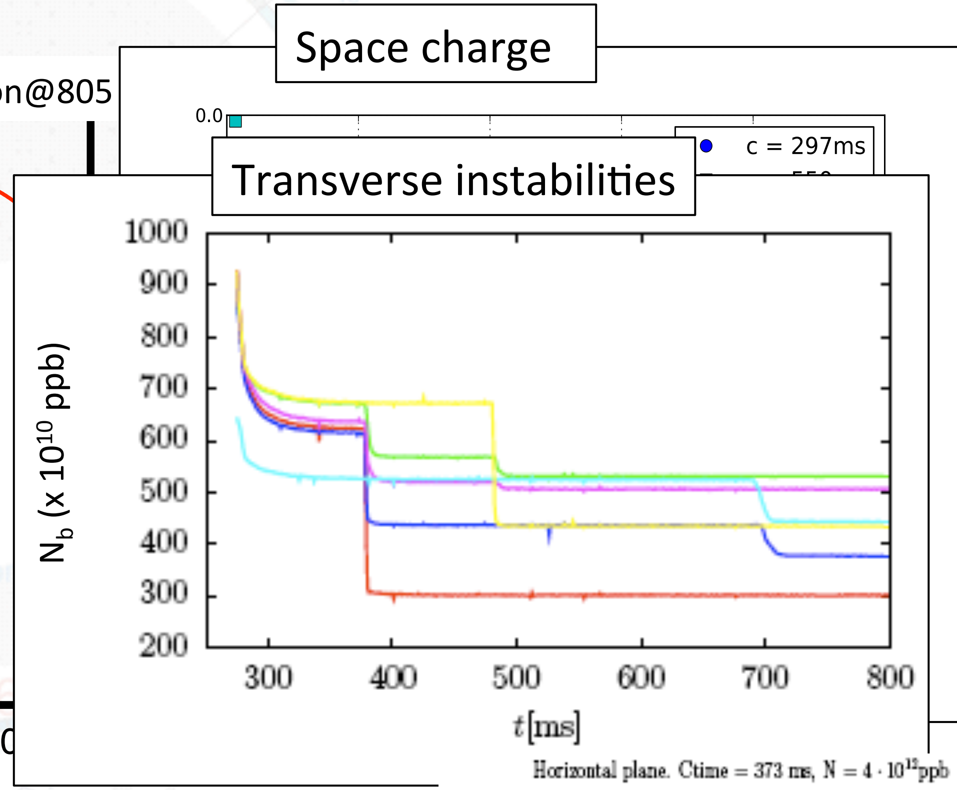
Linac4 - Status

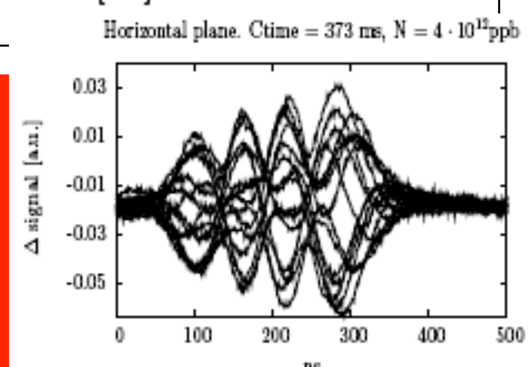
- Installation of infrastructure (electricity, cooling, ventilation, racks, cabling, RF Network) to be completed in Autumn.
- Injector up to 3 MeV (Ion source, LEBT, RFQ, MEBT line) installed in a dedicated test stand and starting beam commissioning.
- Accelerating structures being assembled or delivered at CERN; after RF testing will be installed in the tunnel from end 2013.
- Commissioning in the tunnel from mid-2013 (3 MeV line), followed by DTL in 1st half 2014 (delayed because of long 2013/14 LHC shut-down), CCDTL in 2nd half 2014, PIMS at early 2015.
- Connection to the PS Booster only at the next long LHC shut-down (2017/18), preceded by a series of beam tests and improvements to reliability.



PSB intensity limitations

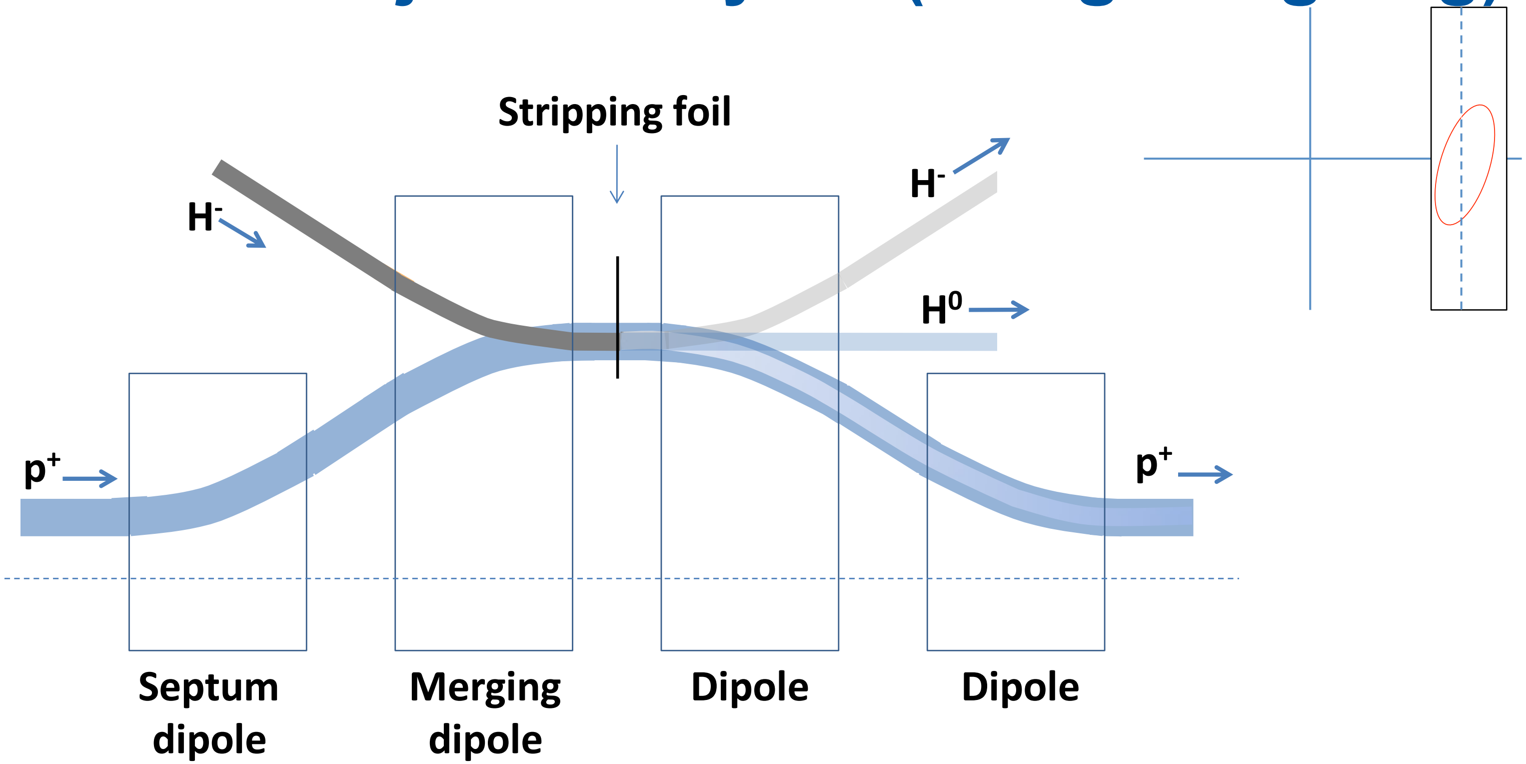


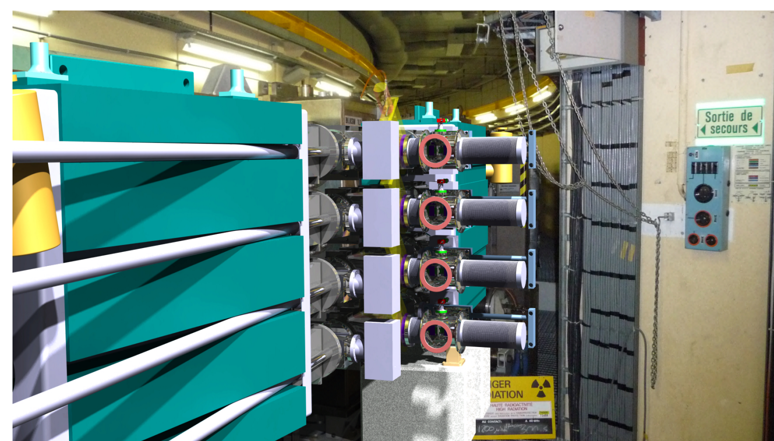




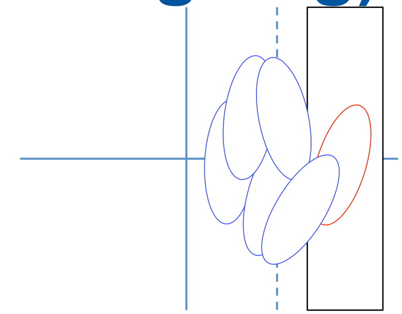
- Space charge (losses, emittance blow up)
- Instabilities along the cycle (efficiency of the transverse feedback system)
- LHC beams presently not limited by these effects
- Limit today due to injection transverse painting

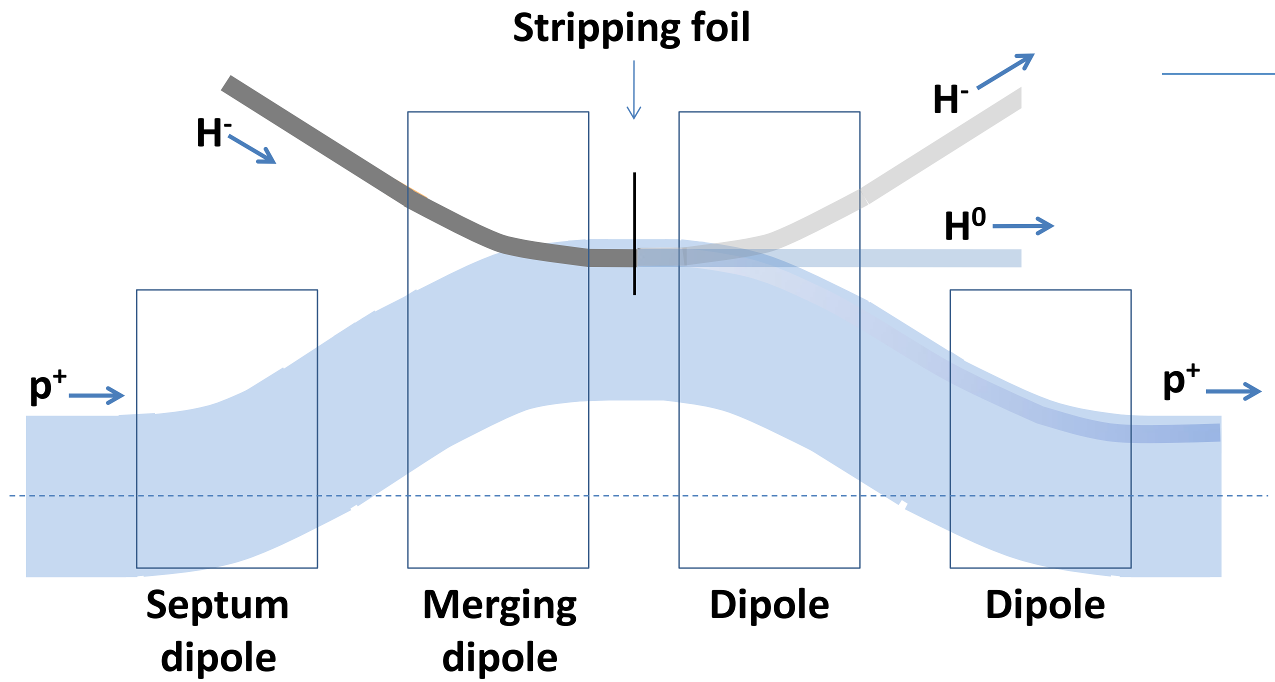
L4-PSB H^- injection layout (design ongoing)

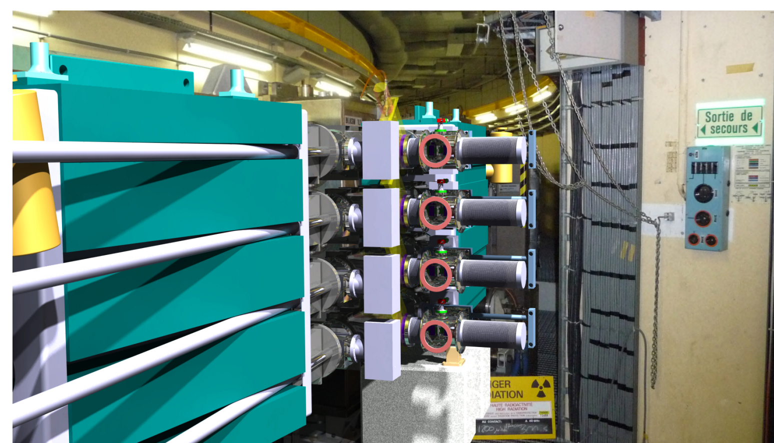




L4-PSB H$^-$ injection layout (design ongoing)







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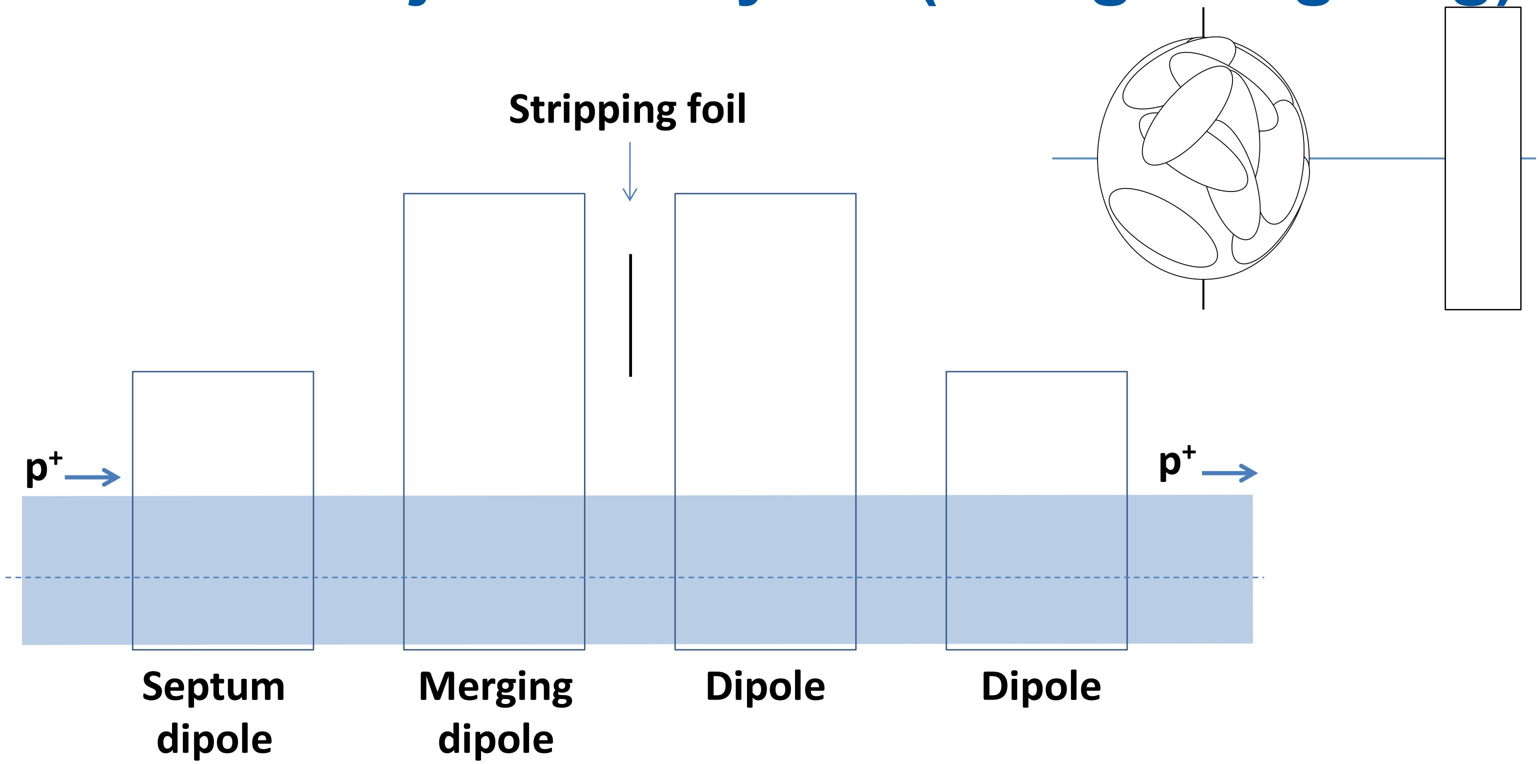
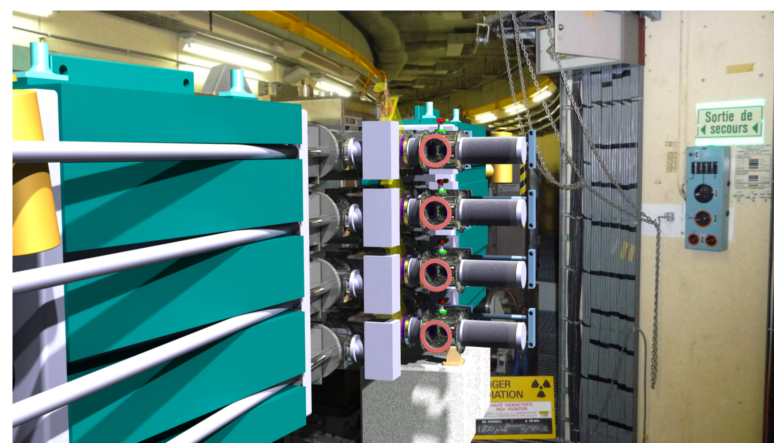
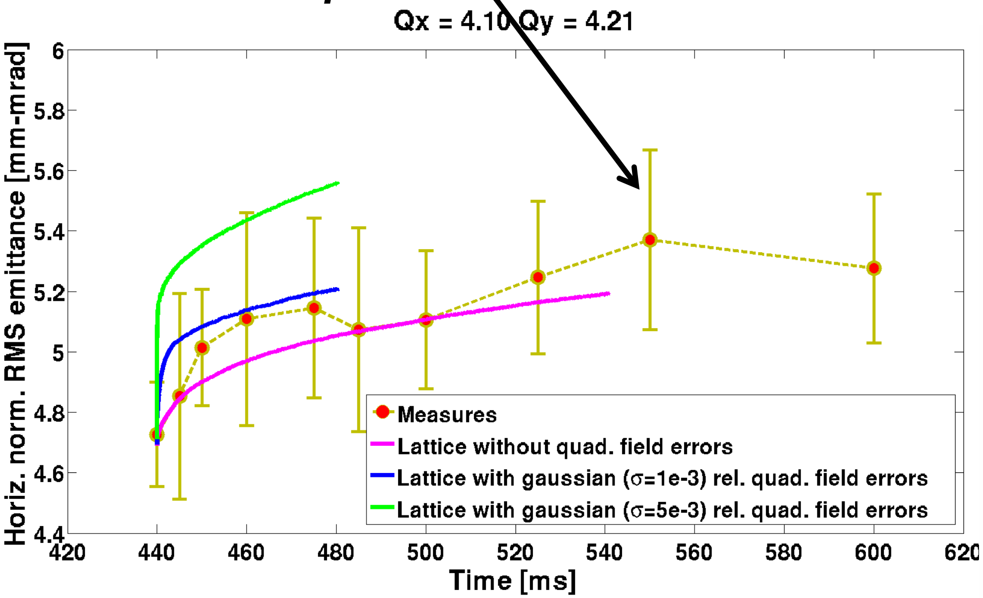




Space charge: PTC-Orbit studies

Measurements to be improved

See A. Molodozhentsev presentation for progress in Space charge studies



Effect of [1,0,4] resonance

W_{kin} = 160MeV

LHC25 beam

$B_f \sim 0.4$

$Q_x = 4.10 / Q_y = 4.21$

#0 → measurements

#1 → ideal lattice

#2, #3 → lattice with RANDOM errors $\{\delta K1\}_{QM}$

#2 : 1Sigma = 1.0×10^{-3} (relative value)

#3 : 1Sigma = 5.0×10^{-3}

Gaussian generator (no cut)

Machine model to be improved

Courtesy V.Forte

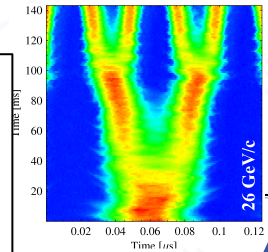
Studies progressing to:

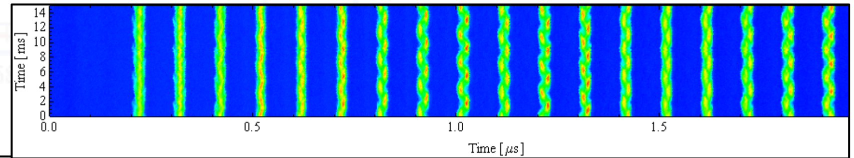
a) Improve understanding of transverse emittance blowup due to space charge
b) Eventually improve resonance compensation used in normal operation and propose one for 160 MeV operation
c) Beta-beating compensation during injection process
d) Understand if lattice symmetry-breaking due to space requirements of the new H^- injection might reduce machine performances

Acceptable agreement between experimental data and simulation results (LHC25 beam)

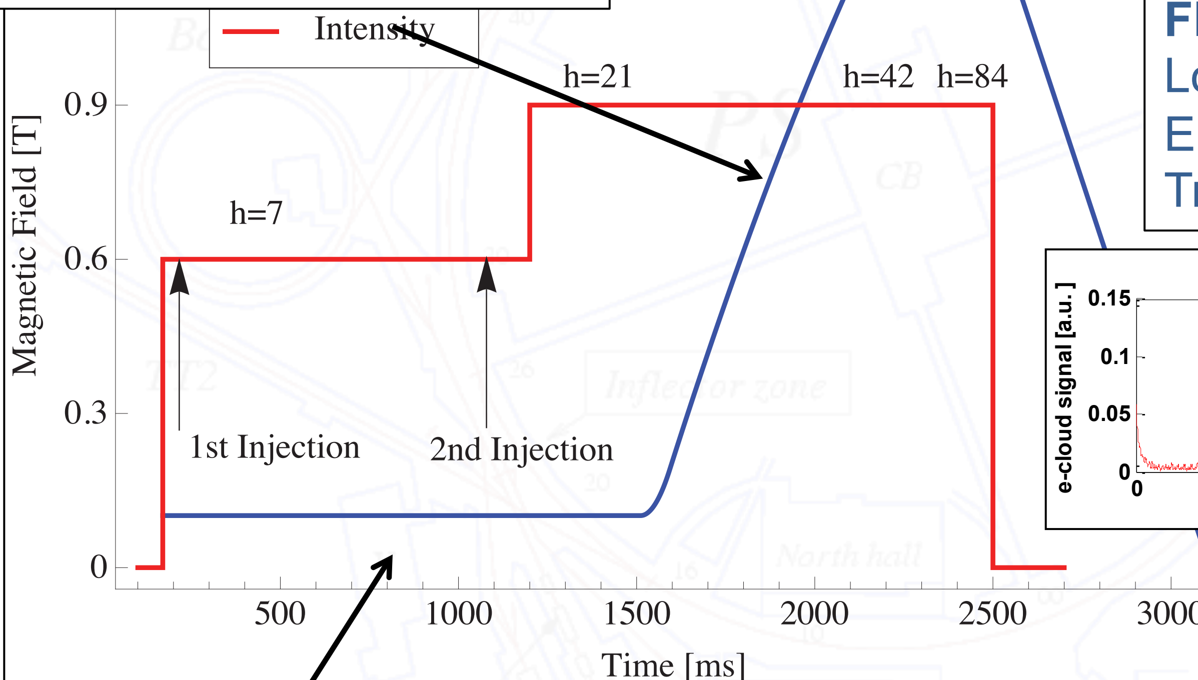
Maximum random error of the PSB quadrupole magnets ~ 1.0×10^{-3} (1σ)

PS intensity limitations

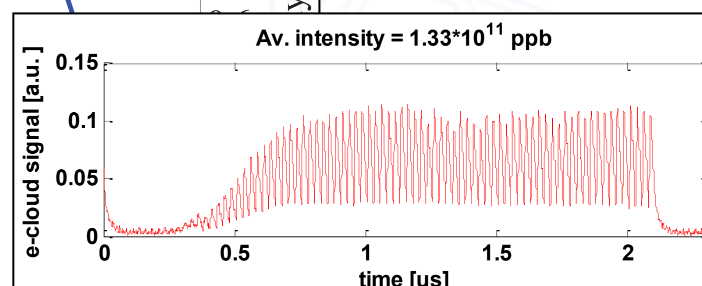


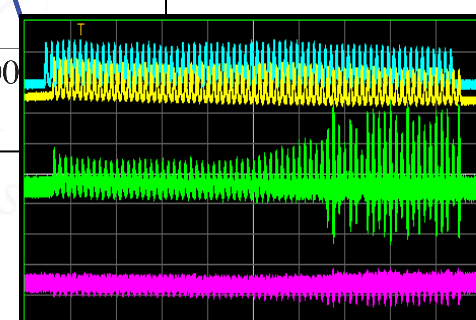


Acceleration/Bunch splittings
Longitudinal CBI
Transient beam loading
Transition crossing

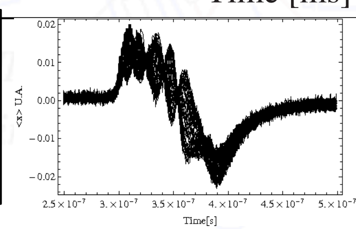


Flat top:
Longitudinal CBI
Electron cloud
Transverse instabilities





Injection flat bottom:
Space charge
Headtail instability

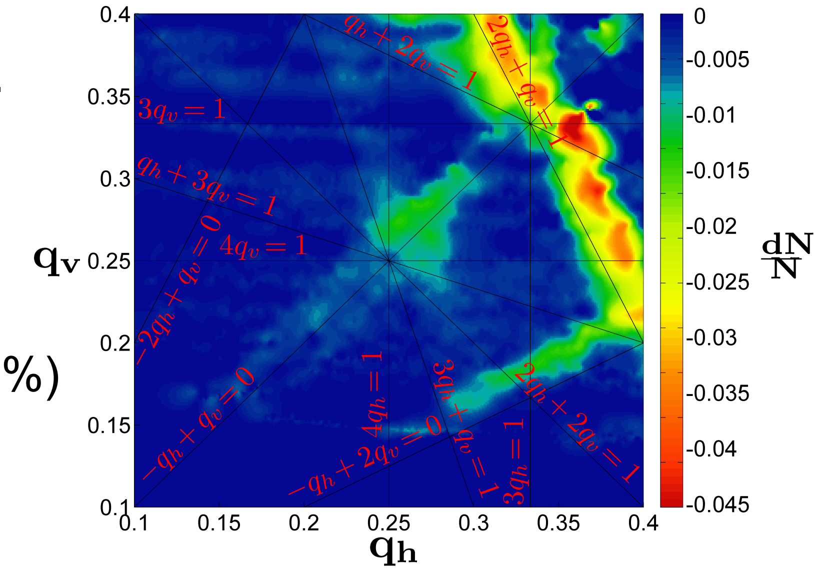


Space Charge at injection (1.4 GeV - 2 GeV)

Study to determine largest acceptable tune spread.

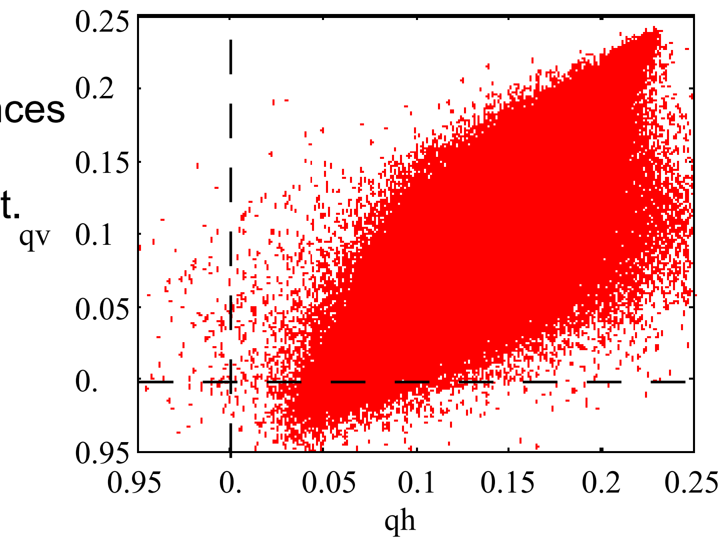
Today max acceptable: ΔQy ~|0.3| @ 1.4 GeV
HL-LHC max needed: ΔQy ~|0.34| @ 2 GeV

Goal: demonstrate that possible to inject a beam with ΔQ>|0.3| with limited emittance blowup (max 5%)



How the problem is approached:

- Experimental studies:
  - ✓ Learn from operational beams experience. Current Laslett at about -0.28 with Qy=0.23
  - ✓ Tune scan to identify via beam losses dangerous resonances
  - ✓ Driving terms measurements
  - – Understand the effect of the integer resonance and scan it.
  - – Compensate resonances (as done already in 1975 with injection at 50 MeV)



- Simulation studies:
  - – PTC–Orbit simulations
  - ✓ Lack of good magnetic error model
    - No error tables from magnetic measurements (à la LHC) available from 195
    - Opera©-based magnetic error simulations starting from construction tolerances fed in PTC-Orbit

PS intensity limitations

Injection flat bottom:
Space charge
Headtail instability

→ Cured by introducing linear coupling
Encouraging tests two weeks ago of T-damper
Eventually possible to use octupoles

Acceleration/Bunch splittings
Longitudinal CBI
Transient beam loading
Transition crossing

→ Longitudinal Feedback (kicker)
Implemented after LS1

→ Not an issue

Flat top:
Longitudinal CBI
Electron cloud
Transverse instabilities

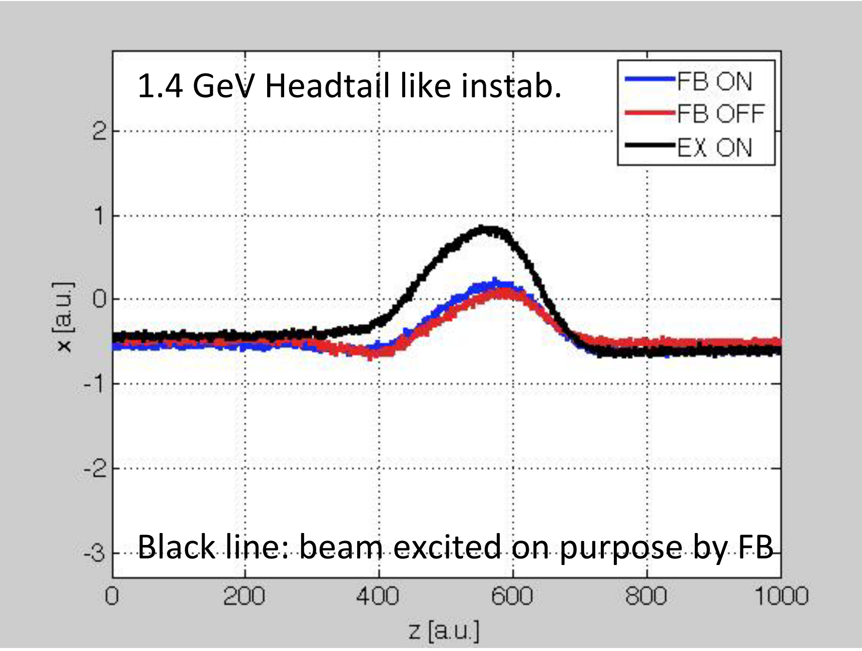
→ Encouraging tests last week of T-damper

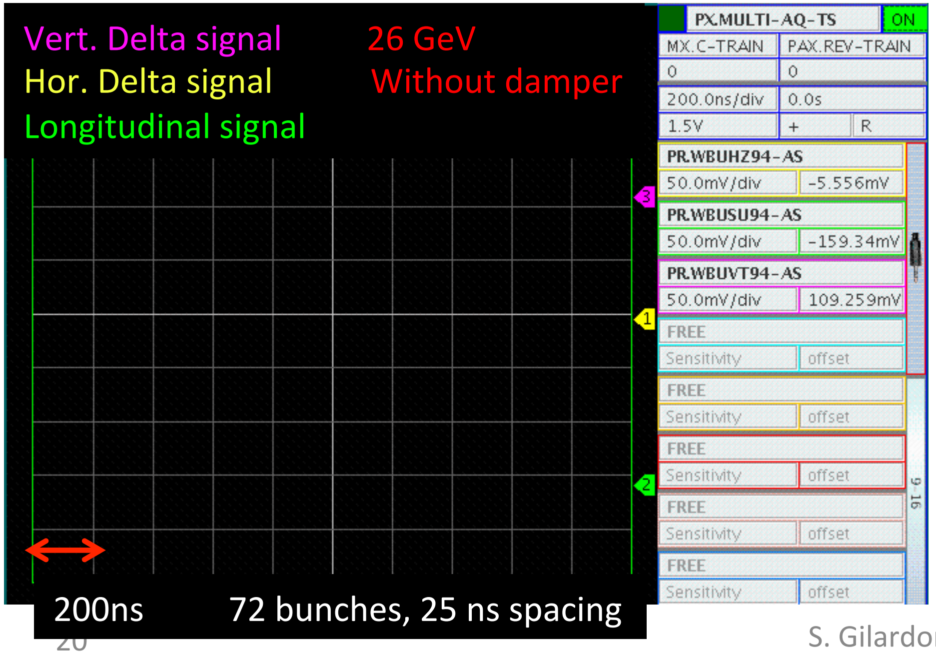
Damper commissioning

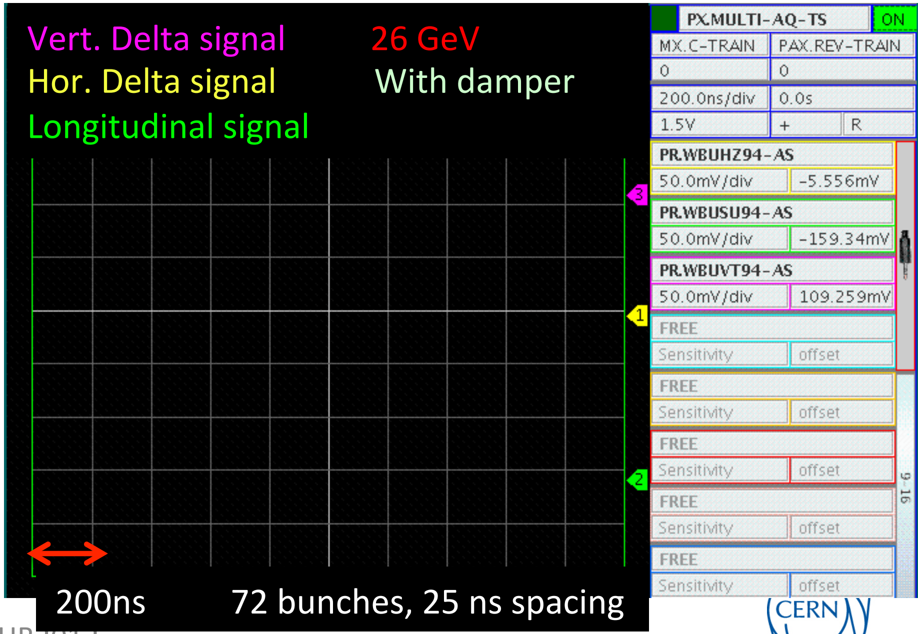
Damper/TFB tests proved:

- Can damp headtail instab. at injection
- Can damp injection oscillations
- Can damp high energy instabilities

Results presented today @CERN





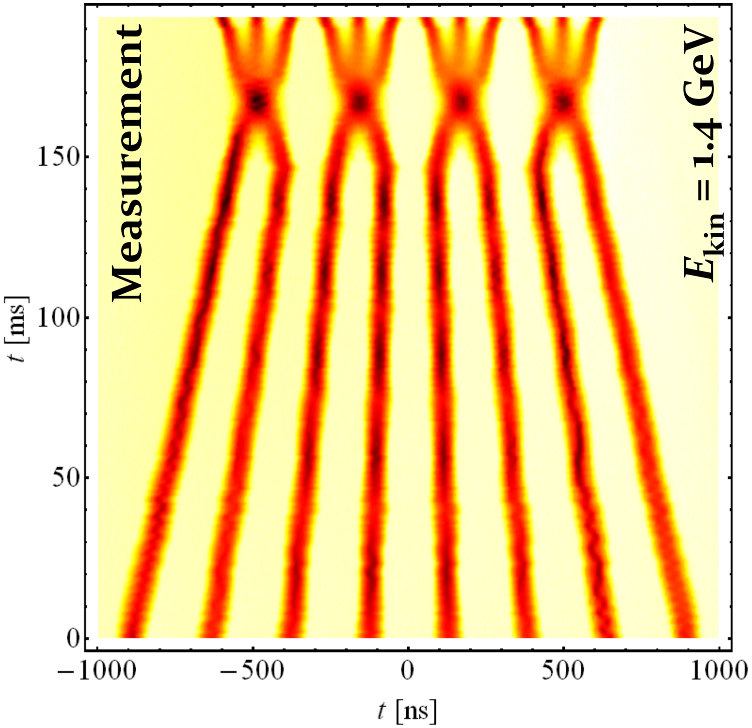


Batch compression and bunch merging

More evolved RF manipulations schemes from *h* = 9 to 21 to increase LHC brightness after LS1

Most ‘simple’ scheme: *h* = 9 → 10 → 11 → 12 → 13 → 14 → 7 → 21

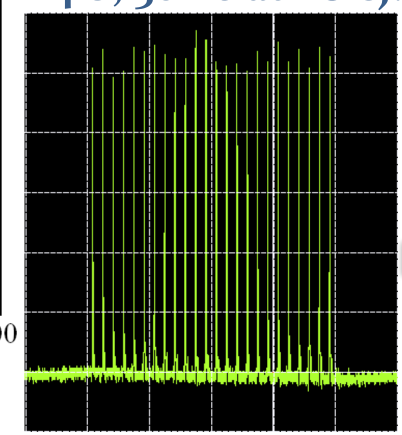
Pure *h* = 21

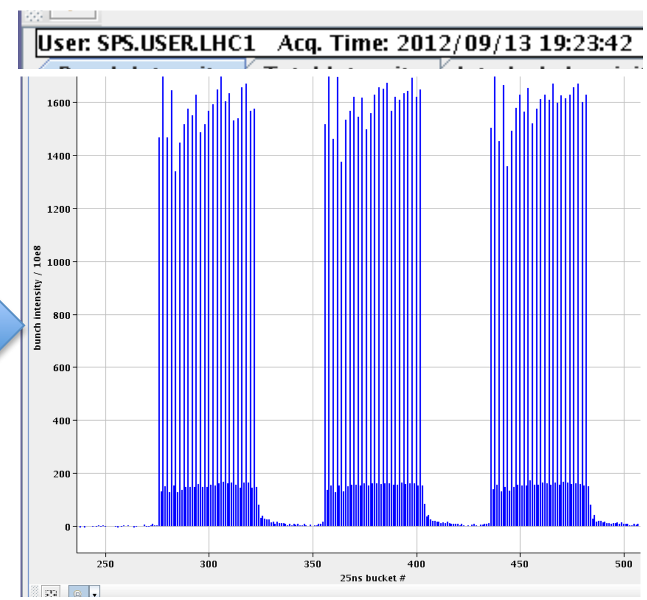


Pure *h* = 9

	25 ns	50 ns
Splitting ratio PS ejection/injection	6	3
Batch length from PS	48	24

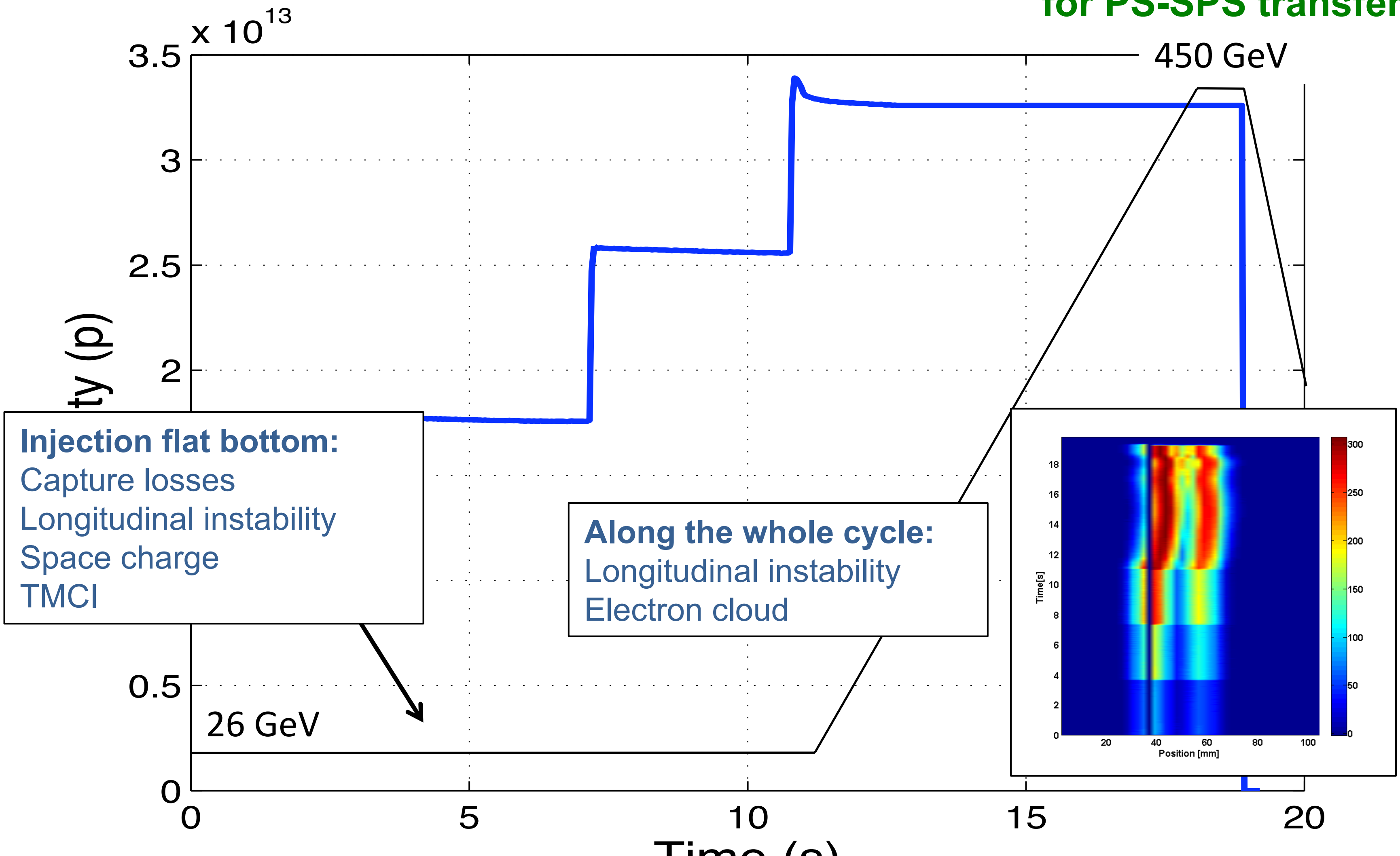
24 b, 50 ns at PS ej.





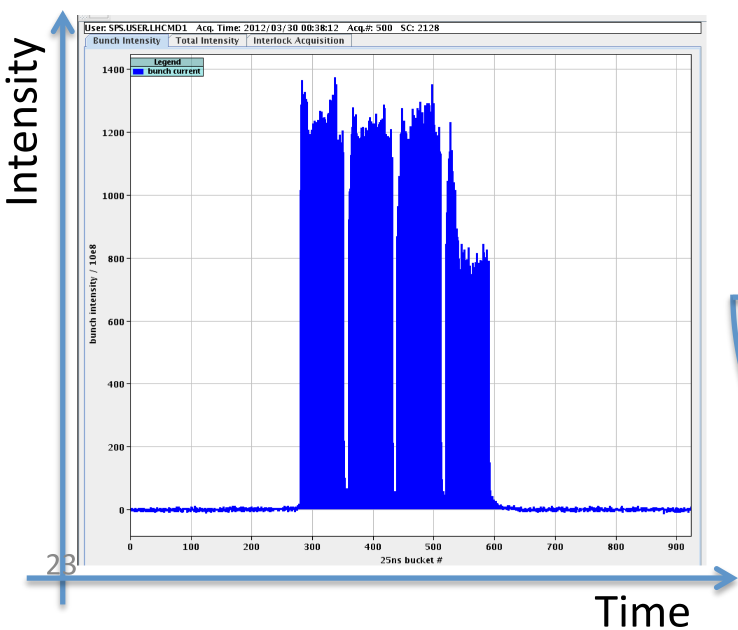
SPS intensity limitations

See Helga's presentation for PS-SPS transfer

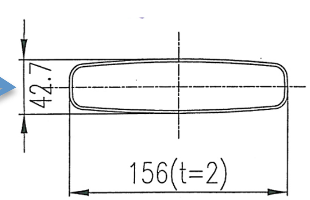


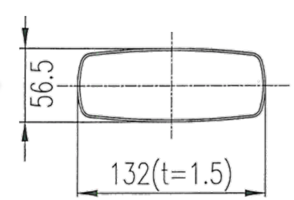
Electron cloud in SPS

- SPS: has been a major performance limit (beamloss, vacuum, ecloud instability and incoherent emittance growth)
  - Presently **not a limitation for 50 ns** bunch spacing (**well scrubbed**)
  - **Serious for 25 ns** beam: scrubbing difficult (StSt chambers)
  - **Robust solution developed with aC coating** of vacuum chambers inside the magnets (LIU baseline)
  - High bandwidth feedback could cure eC-instab. – would help scrubbing



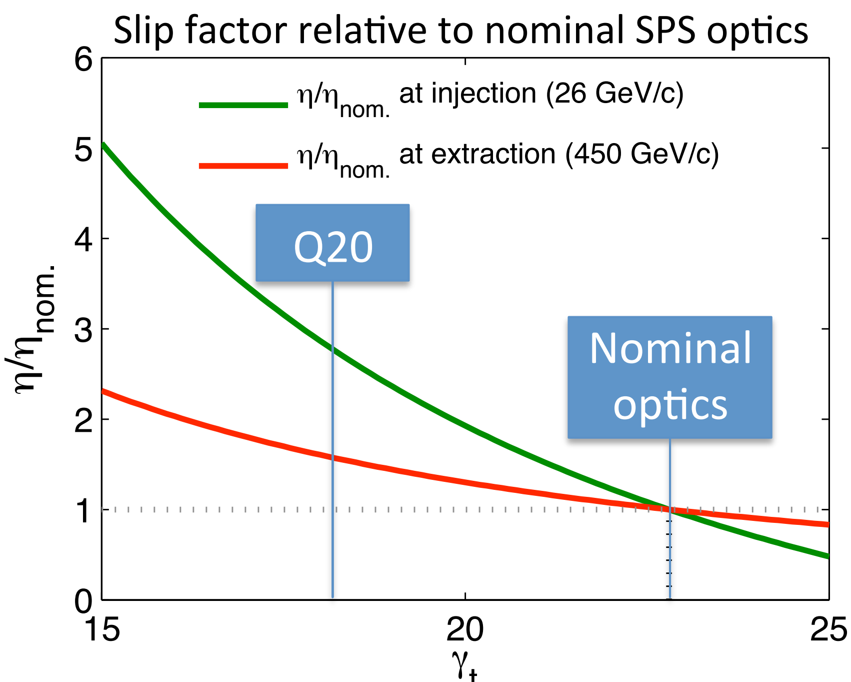
Beampipe profile	SEY threshold @ 1.1 10^{11} p/bunch	SEY threshold @ 2.5 10^{11} p/bunch
ID 156 (LSS)	1.4	1.1
ID 130 (LSS)	1.45	1.05
MBA (Dipole)	1.4	1.45
MBB (Dipole)	1.15	1.25





Low gamma-transition SPS optics

- Present intensity limitations for LHC p+ beams:
  - TMCI at injection → N_{th} 1.6x10^{11}p/b (small Q'): $\mathbf{N_{th} \sim \eta\varepsilon_l/\beta_y}$
  - Longitudinal instability (N_{th}~3x10^{10}p/b for 50 ns): $\mathbf{N_{th} \sim \eta\varepsilon_l^2}$
- Instability thresholds scale with slip factor $\eta=1/\gamma_t-1/\gamma$



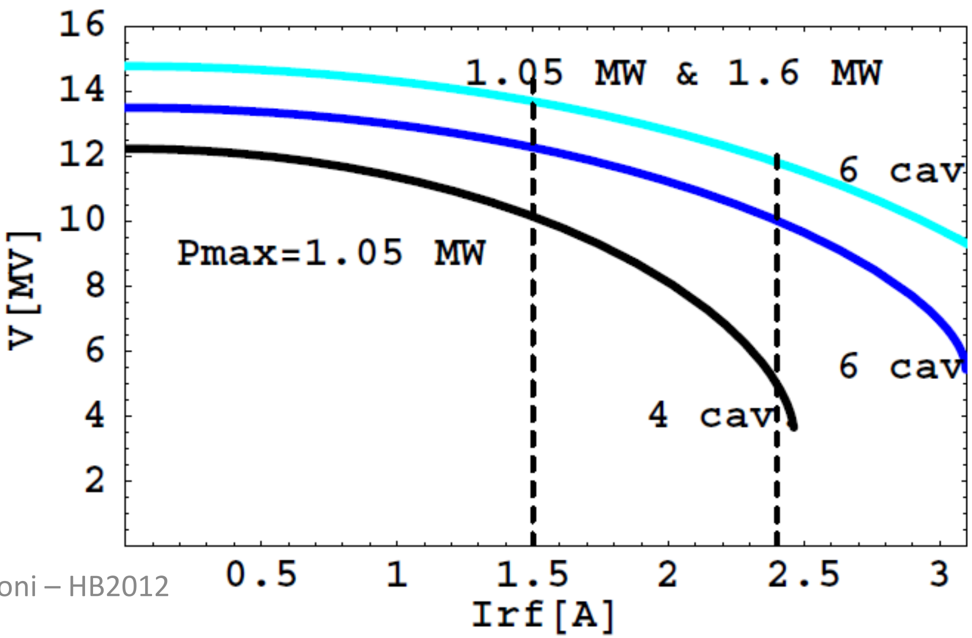
γ_t reduced from 23 to 18 by changing integer Q_x from 26 to 20 ("Q20" optics).
See presentation of Hannes

About 3 times higher η at injection

Big increase in TMCI and longitudinal instability thresholds
Presently being deployed operationally in SPS for regular LHC filling

Longitudinal instabilities and RF upgrade

- Longitudinal stability: 25 ns beam unstable at 2-3e10 p+/b
  - Presently mitigated with long. emittance blowup (0.6 eVs) and 800 MHz
- Need ≥0.9 eVs for 25 ns stability with x2 nominal I_b (Q26)
  - Q20: instability thresholds higher, but need smaller εl to get same bunch length for given V_{RF}
- SPS 200 MHz upgrade: ×2 power, 4→6 (shorter) cavities
  - Will allow 10 MV at extraction for 3 A RF current (now 1.5 A)
  - 20% less impedance
- Will give ×2 intensity range
  - 2.3e11 p+/b for 25 ns
  - >3.4e11 p+/b for 50 ns
  - Unknown is beam stability with high intensity (combination of single- and coupled-bunch effects)



See E. Shaposhnikova presentation

Planned SPS upgrades (as example to describe the large impact of the upgrade on the injectors)

- Double power of 200 MHz RF system
- Power and low-level control upgrade of 800 MHz RF system
- Ecloud mitigation – in-situ aC coating of all dipole and quadrupole vacuum chambers;
- Deployment of low gamma-transition “Q20” optics
- Major Improvement of beam size, orbit and loss monitoring, plus other new or upgraded BI systems;
- New High Bandwidth transverse feedback system;
- Upgraded pickups for present high power damper system;
- Upgraded passive protection devices in extractions and transfer lines TI 2 and TI 8 (relocation plus new devices);
- Improved vacuum sectorisation – arcs and near critical equipment;
- Complete impedance reduction of MKE and dump kickers.

Baseline

Ongoing studies/Options

- New transverse beam tail scraper system
- Improvement/replacement of beam dump system
- New low-impedance extraction kickers
- New faster injection kickers (for ions)
- Upgraded transfer line collimation system
- Upgrade extraction protection beam diluters
- Improved electrostatic septa
- New high energy orbit correction system

Present and future SPS performance (in terms of beam power for Neutrino beams)

	Operation		SPS record		After LIU (2020)	
					Aim	Study
	LHC	CNGS	LHC	CNGS	LHC	post-CNGS
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity/10^{11}	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS beam intensity/10^{13}	2.3	4.4	3.75	5.3	6.35	7.0*
PS beam intensity/10^{13}	0.6	2.3	1.0	3.0	1.75	4.0*
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2/2.4*
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	6.0/7.2
PS momentum [GeV/c]	26	14	26	14	26	14
average current [μA]	0.17	1.17	0.28	1.4	0.47	1.9/1.6
power [kW]	77	470	125	565	211	747/622

*Feasibility including operational viability (especially in the PS) remains to be demonstrated

Main present limitations for high intensity CNGS-type beam (Neutrino production beams)

- **In all machines:**
  - Beam losses leading to radiation issues; already now at the limit in PS → present (2012) operation with lower total intensity of $4x10^{13}$
- **In the SPS:**
  - longitudinal beam stability (leading to uncontrolled longitudinal emittance blow-up)
  - maximum available power at 200 MHz (750 kW for full ring) and therefore voltage (7.5 MV) due to beam loading
  - equipment (extraction kicker, …) heating
  - large transverse (vertical) emittance at injection
  - injection below transition
  - no bunch-to-bucket transfer, debunched beam component

LIU plans and specific studies required for high intensity CNGS-type beam

LHC Injectors Upgrade (LIU), also beneficial for the CNGS-type beam:

- **Linac4**
- Increase of injection energy, new beam controls and upgrade of transverse dampers in **PSB** and **PS,** replacement of RF system in the **PSB**, upgrade of LLRF in the **PS,** improved beam instrumentation in all accelerators and TLs
- **SPS:**
  - Upgrade of the 800 MHz (2015): 1→ 2 cavities, new FB and FF systems
  - Upgrade of the 200 MHz RF system (2020) : 4 → 6 cavities.
  - Impedance reduction (by 20% for 200 MHz RF - 2020, serigraphy of extraction kickers - 2015)

Studies

- **PS:**
  - Loss reduction and related activation,
  - Transition crossing
  - Debunching-rebunching and Multi-turn Ejection at $4x10^{13}$ p/p
  - Operational compatibility with different users, spares policy…
- **SPS:**
  - Use of the 800 MHz RF system (Landau cavity) for beam stability
  - Optimum transition crossing
  - Need for collimation system for loss localisation
  - New optics with lower transition energy (under implementation for the LHC beam)

Conclusions

Upgrade of LHC beams in injectors requires:

a) improve understanding of current limits due to space charge → improve machine modeling, understand resonances…

b) overcome current limitations of RF systems, in particular in PS and SPS

c) Major improvement of many subsystems, including beam instrumentation, vacuum, etc…

Goal: Main interventions during 2018 to start commissioning for HL-LHC in 2019 of basically 4 new machines (L4+PSB@2GeV + PS +SPS) to fully profit from performances of L4.

Non-LHC beams for neutrino production are challenging in some different ways, but will profit from the from the LIU planned activities

Spares

O. Brüning, HL-LHC/LIU Day, 30 March 2012

Parameter	nominal	…ninimum β^* 25ns	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

Translated for the injectors …

B. Goddard, HL-LHC/LIU Day, 30 March 2012

25 ns	PSB inj	PSB extr/PS inj	PS extr/SPS in		
Energy GeV	0.16	2			
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

- Space charge in the PSB (ΔQ>0.36) ?
- Space charge in the PS (ΔQ>0.28) ?

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+]			4.2	3.9	3.5
Ib in LHC [e11 p+]			4.2	3.9	3.5
Exyn [mm.mrad]			2.5	2.7	3.0

- Longitudinal instabilities in the PS?
- Space charge in the SPS (ΔQ>0.15) ?

Assumptions for beam losses and emittance conservation

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

Translated for the injectors …

B. Goddard, HL-LHC/LIU Day, 30 March 2012

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					2808
Ib [e11 p+]					2.2
Ib in LHC [e					2.2
Exyn [mm.					2.5

50 ns					
Energy Ge					7000
Nb					1404
Ib [e11 p+]					3.5
Ib in LHC [e					3.5
Exyn [mm.					3.0

- **Space charge in the PSB, PS, SPS (acceptable ΔQ)**
  - → Do we fully understand the effects and do we have simulation tools (benchmarked with our machines) for predictions ?
- **Longitudinal instabilities in the PS**
- **Longitudinal instability and TMCI in the SPS**
  - → Is Q20 optics enough to raise these thresholds above the requested values?
- **Electron cloud effects with larger intensity (PS & SPS)**
  - → Can we rely on scrubbing or do we need coating ?
  - → High bandwidth transverse feedback system ?

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

Limits: space charge/brightness

- PSB at 160 MeV
  - **Very confident** to run with **ΔQy ≈ -0.3** (and reasonable hope for ΔQy ≈ -0.36, or 1.4 um/2.4e12 p+)
- PS at 2 GeV
  - **Very confident** to run with ΔQy > -0.26 (and reasonable hope to increase to ΔQy ≈ -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] ≈ -1.22 N_b [e12] / ΔQy, with Q20 optics at 26 GeV
  - Present **assumption** is to run with ΔQy ≈ -0.15
  - Gives 1.2e11 p+/um or 1.6 um for 2.0e11 p+
  - Need to increase to ΔQy ≈ -0.18 – 0.20 for 50 ns beam, or 1.2 um for 2e11 p +

Fundamental question: why different space-charge limits for different machines?

Examples of Operational Beams (1.4GeV)

Beam	LHC-50	TOF	AD
Intensity [xE10 ppb]	105	650-850	400
ε horizontal, normalized, 1σ [π.mm.mrad]	1.08	14.5	9
ε vertical, normalized, 1σ [π.mm.mrad]	1.34	7	5
Bunch Length (4σ) [ns]	180	250	180
Δp/p (1σ) [xE-3]	1.25	1.75	1.56
Working point	(6.235 ; 6.245)	(6.14 ; 6.26)	(6.21 ; 6.25)
Max. Laslett Tune-spread $\Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{3/2} \gamma^3 \beta^2 \sigma_z} \oint \frac{\beta_{x,y}(s) ds}{\sigma_{x,y}(s)[\sigma_x(s) + \sigma_y(s)]}$	(0.19 ; 0.28)	(0.18 ; 0.29)	(0.18 ; 0.27)

- Currently no significant emittance blow-up nor losses are observed for operational beams that cannot be cured by increasing the vertical tune and adapting the horizontal to remain near the diagonal
(recent change Qx: 6.21->6.235 , Qv: 6.23-> 6.245)