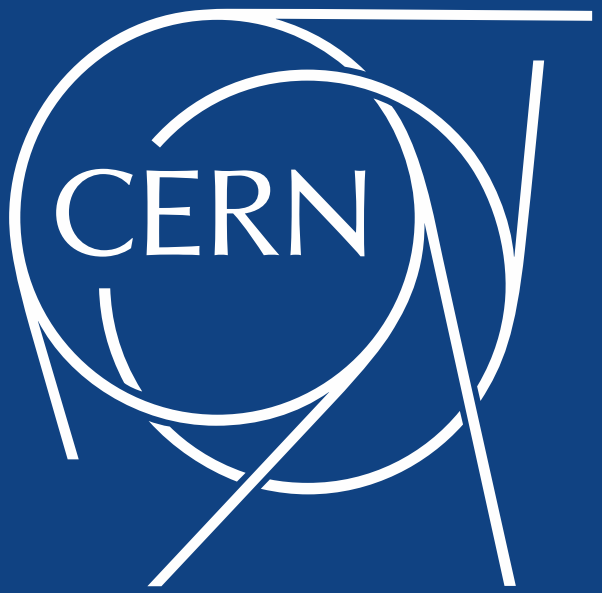
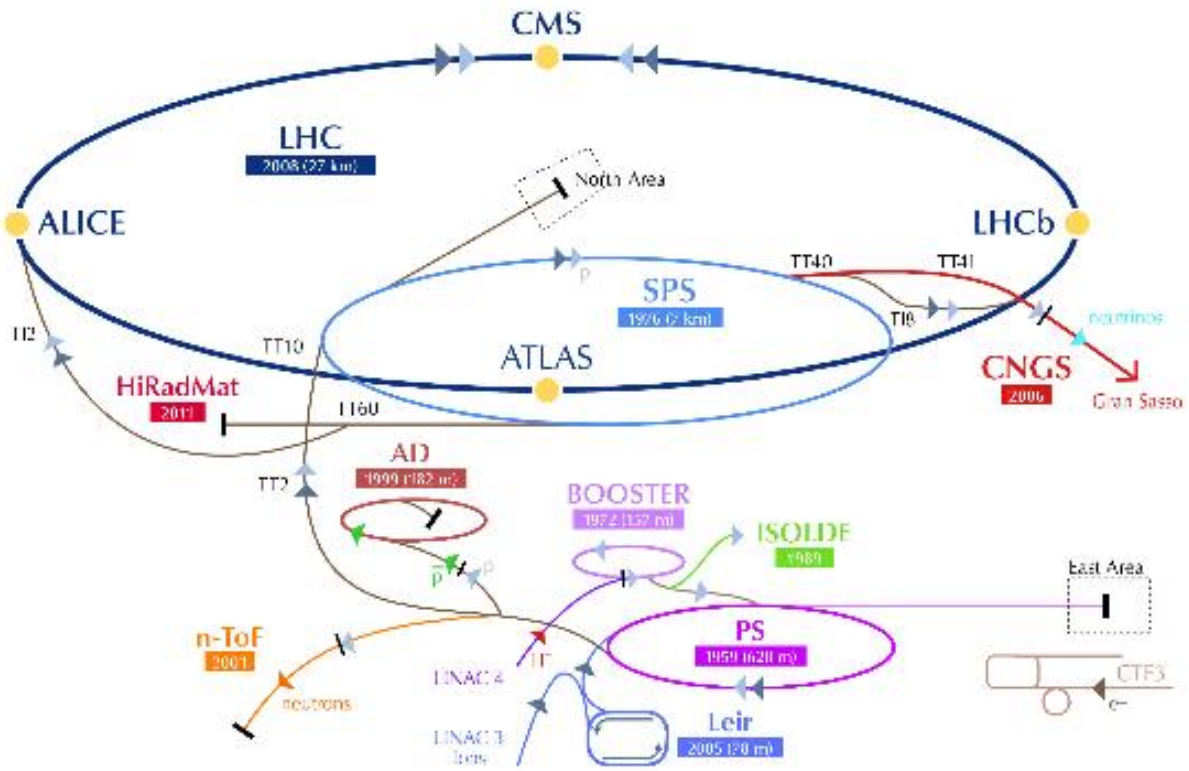

CERN

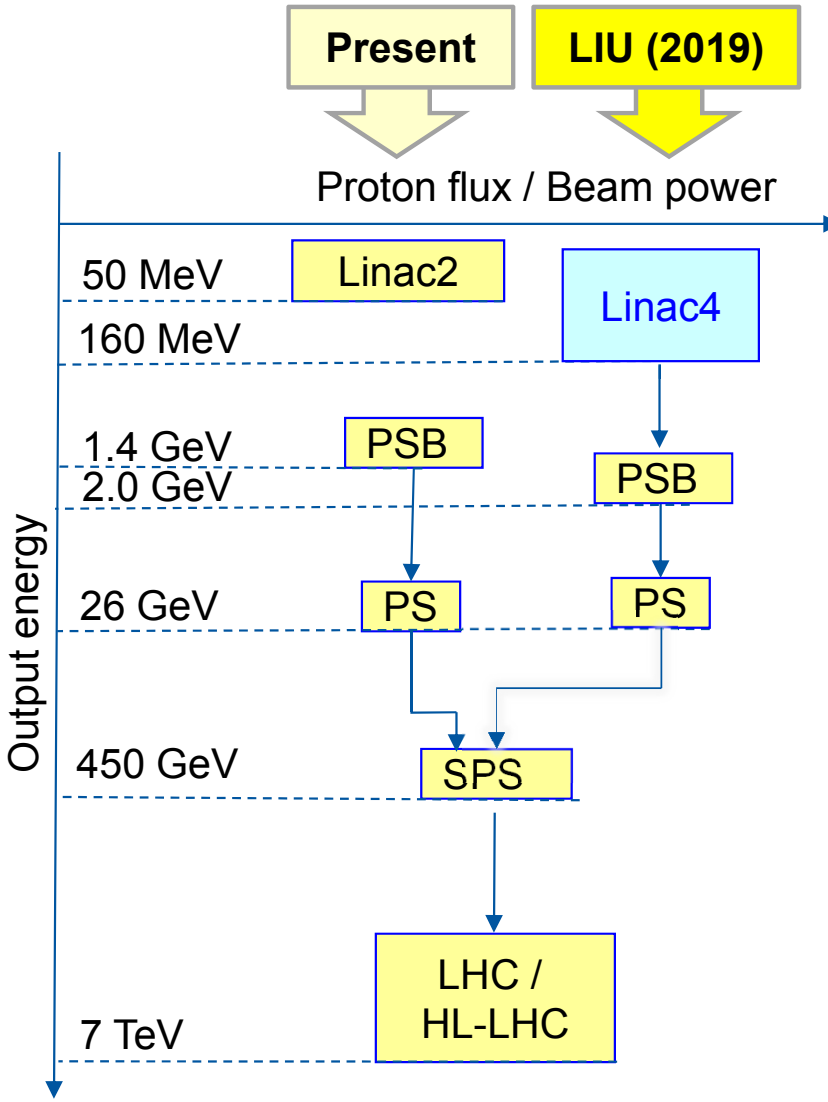
Long-term beam losses in the CERN injector chain

S. Gilardoni – CERN –BE/ABP

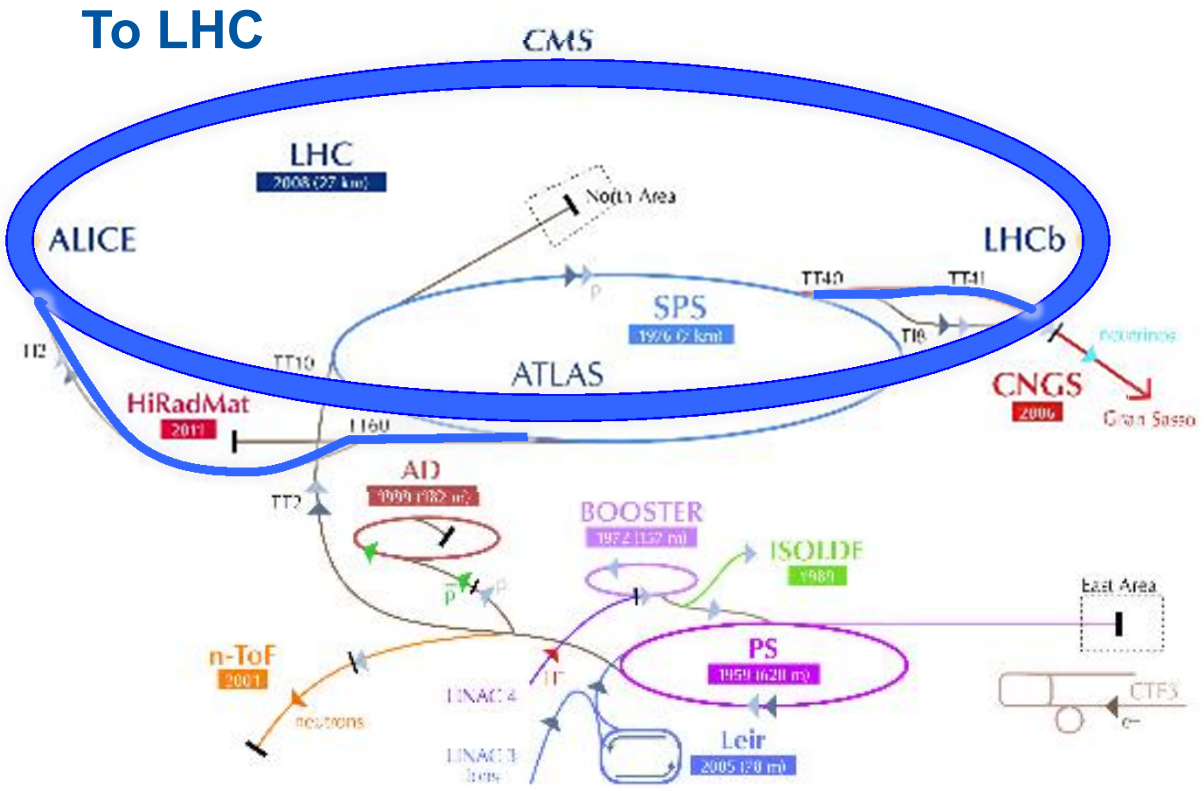
In collaboration with:
G. Arduini, H. Bartosik, E. Benedetto, H. Damerau, V. Forte, M. Giovannozzi, B. Goddard, S. Hancock, K. Hanke, A. Huschauer, M. Kowalska, M. J. McAteer, M. Meddahi, E. Métral, B. Mikulec, Y. Papaphilippou, G. Rumolo, E. Shaposhnikova, G. Sterbini, R. Wasef

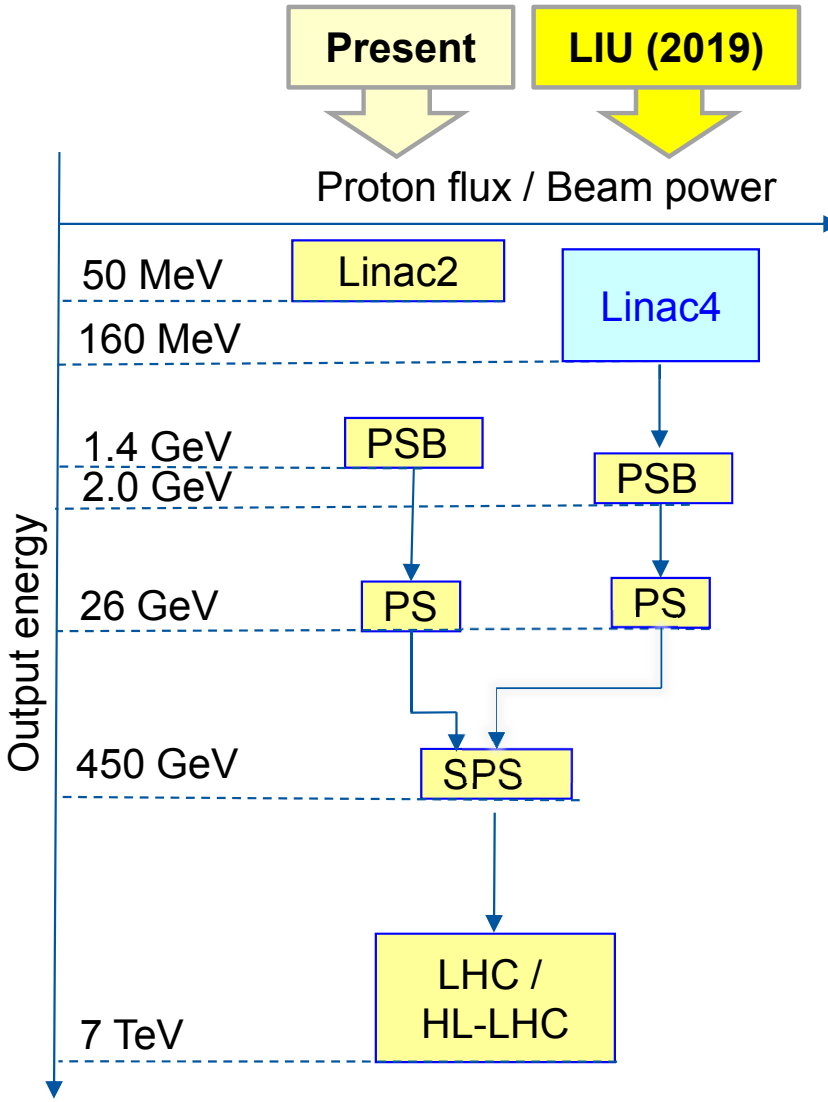
LHC injectors (today vs tomorrow)





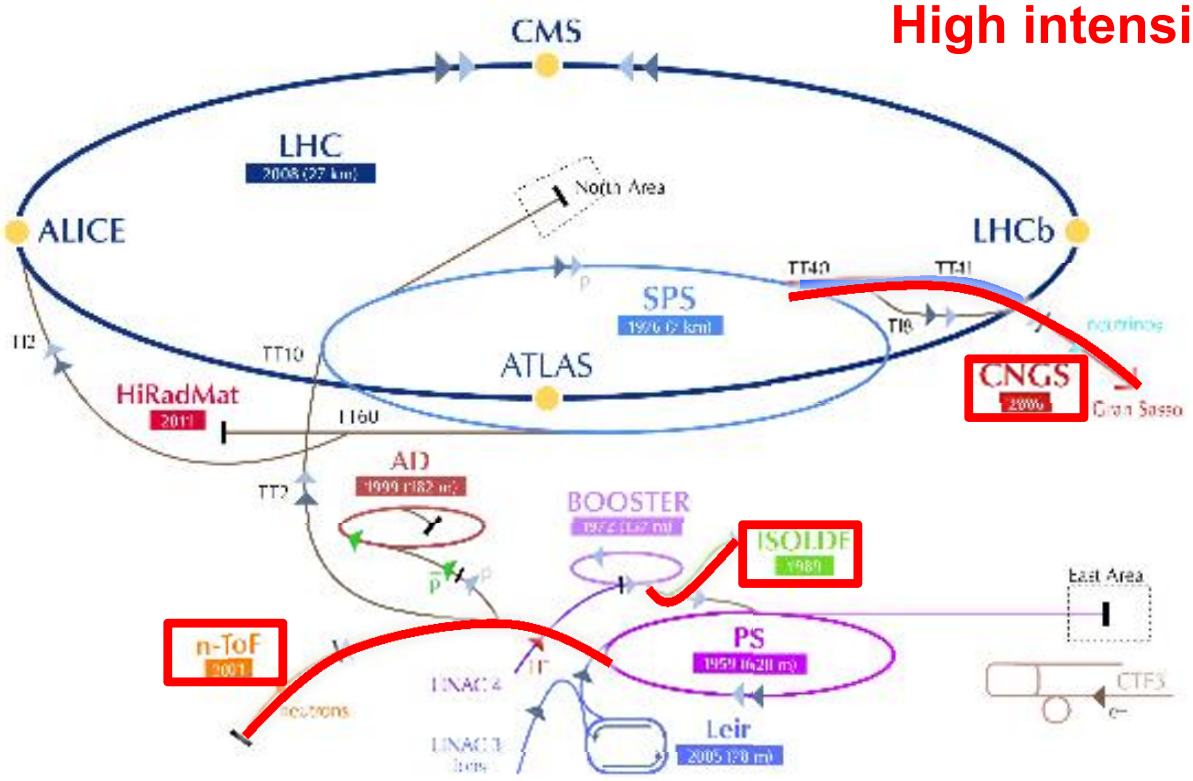
LHC injectors (today vs tomorrow)



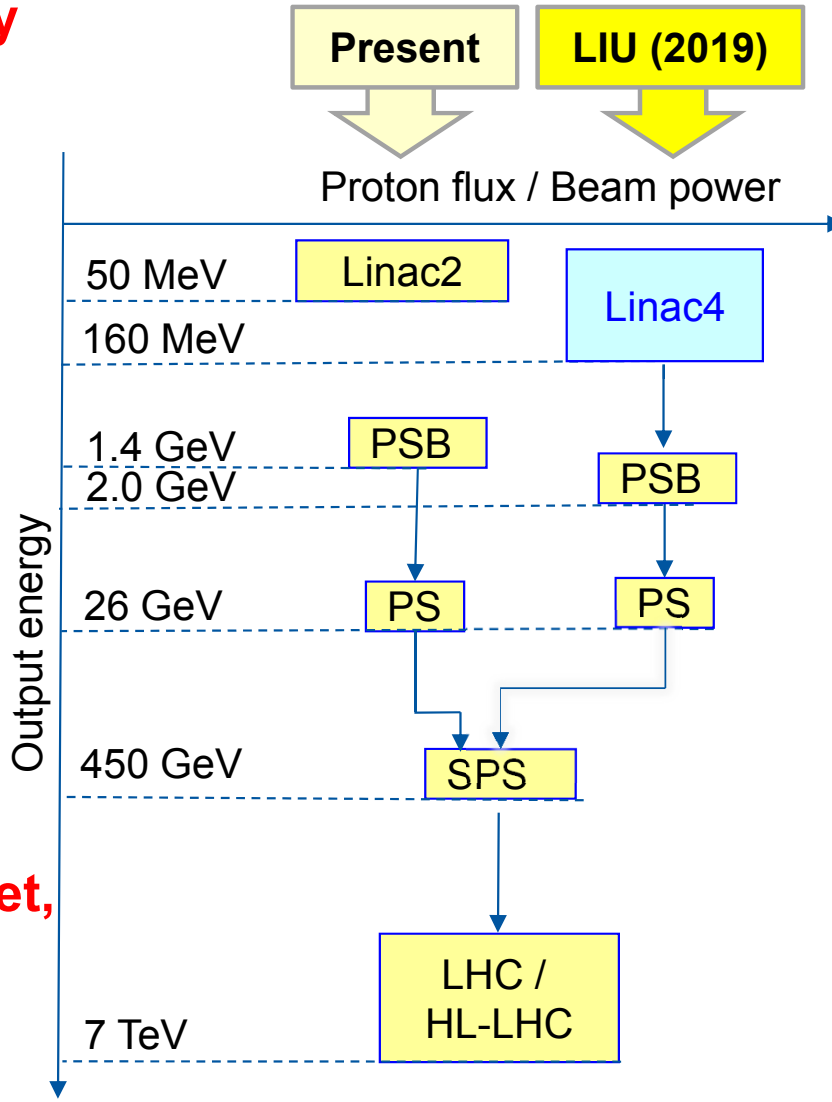


LHC-type beams: maximum intensity with minimum emittance compatible with the collider needs.

LHC injectors (today vs tomorrow)

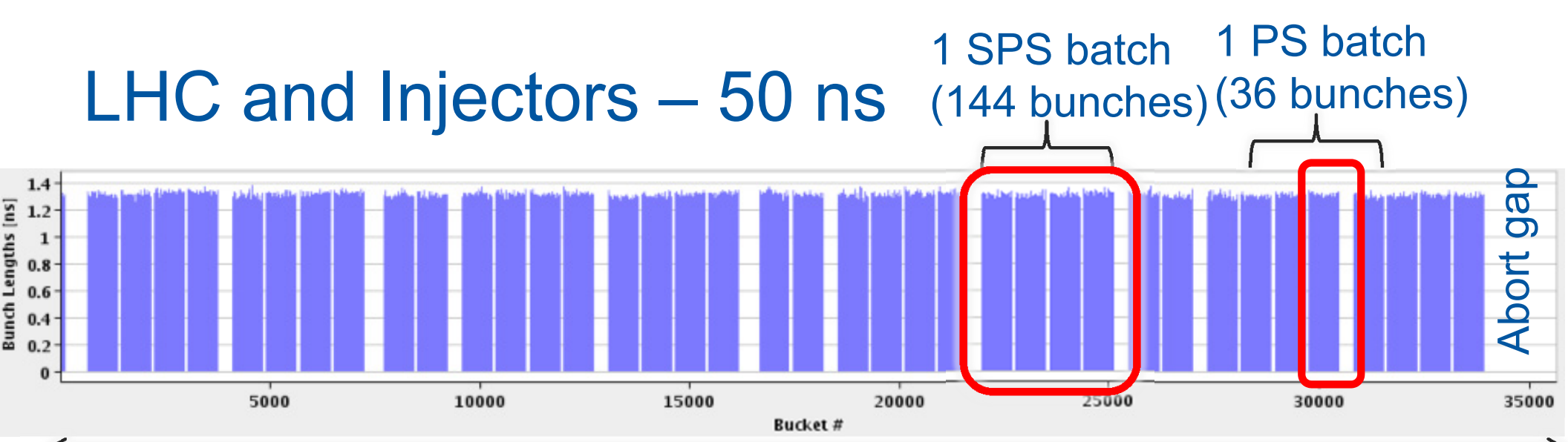


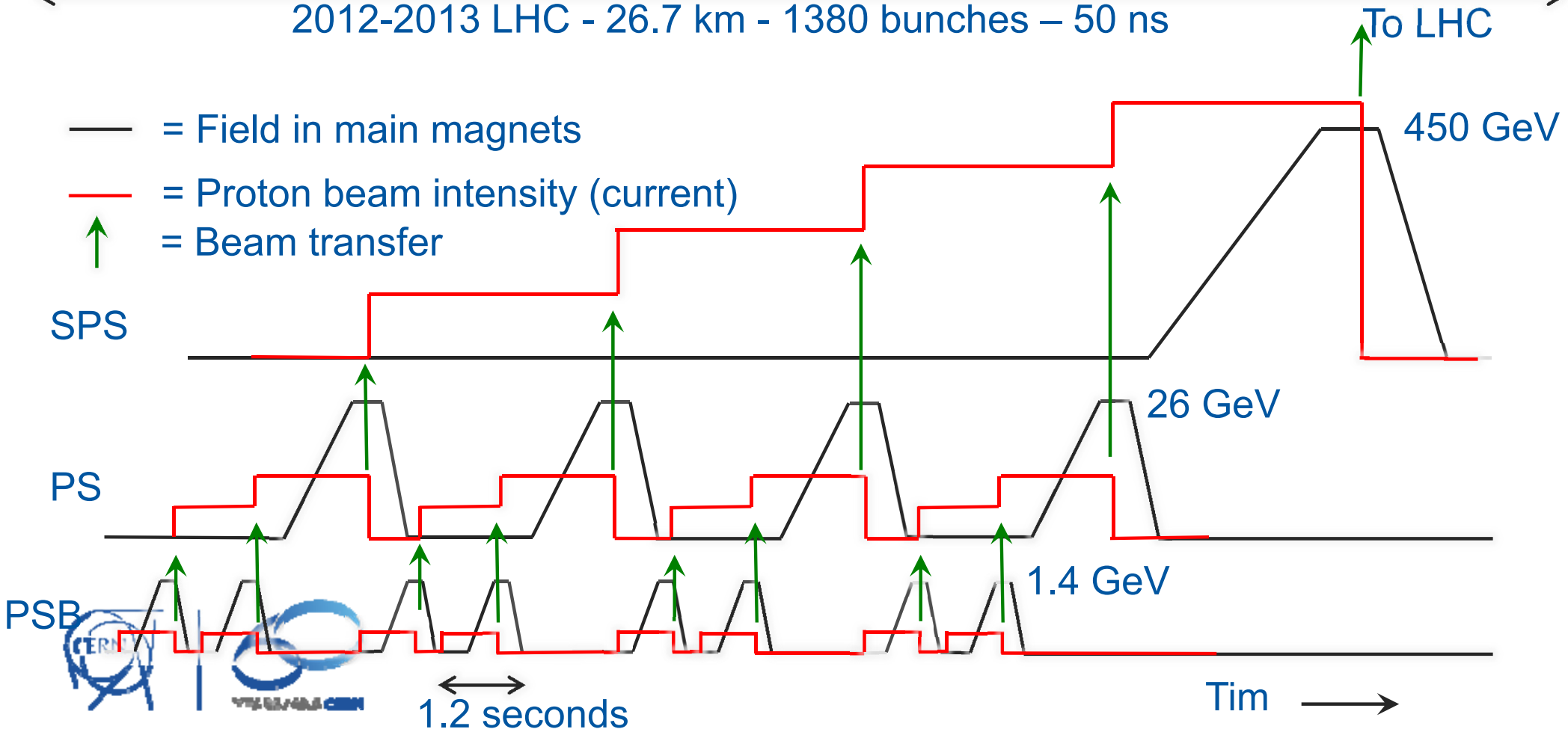
High intensity



High intensity beams: maximize protons on target, minimizing losses
(emittance compatible with machine apertures)

LHC and Injectors – 50 ns





LHC25(50)ns Production Scheme

Production scheme:

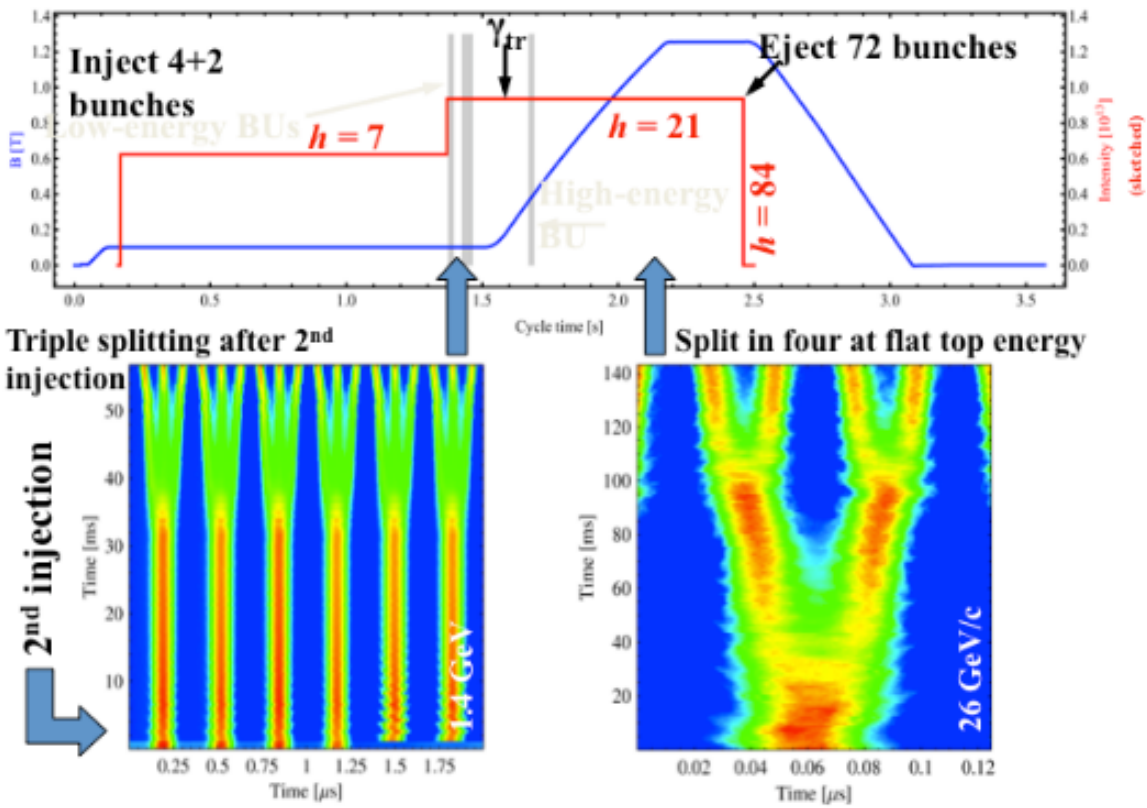
a) Double batch injection from PSB (**4 + 2 bunches, 6 bunches for PS at h=7**)

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

- Multi-turn proton injection in PSB
- RF gymnastics in PS:
  - Triple splitting
  - Acceleration
  - 2 x Double splittings
    - (1 Double splitting for 50 ns)
  - Bunch rotation

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



LHC 25(50)ns BCMS

BCMS "**B**atch **C**ompression, **M**erging and **S**plitting in PS"

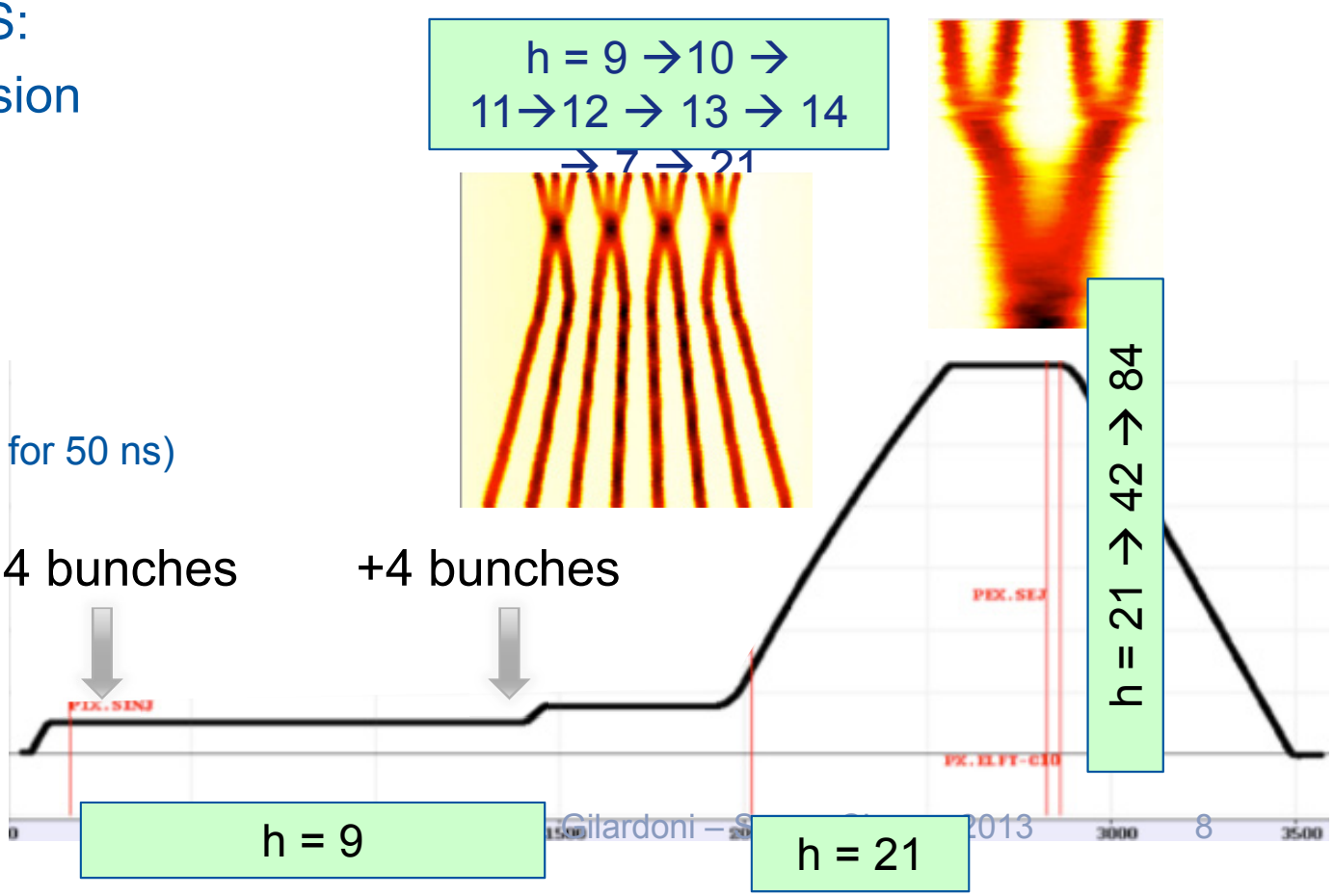
Production scheme:

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

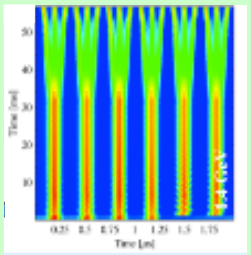
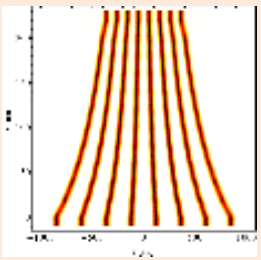
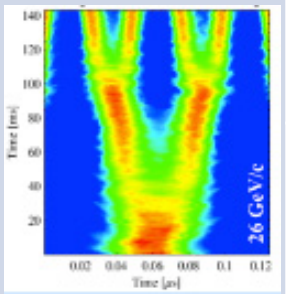
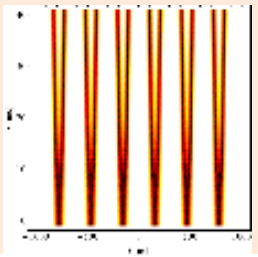
b) Up to 5 batches of 48 bunches each transferred to the SPS (240 bunches)

Transverse emittance produced in the PSB, longitudinal in the PS

- Multiturn proton injection in PSB with **shaving**
- RF gymnastics in PS:
  - Batch compression
  - Bunch merging
  - Triple splitting
- Acceleration
- 2 x Double splittings
  (1 Double splitting for 50 ns)
- Bunch rotation

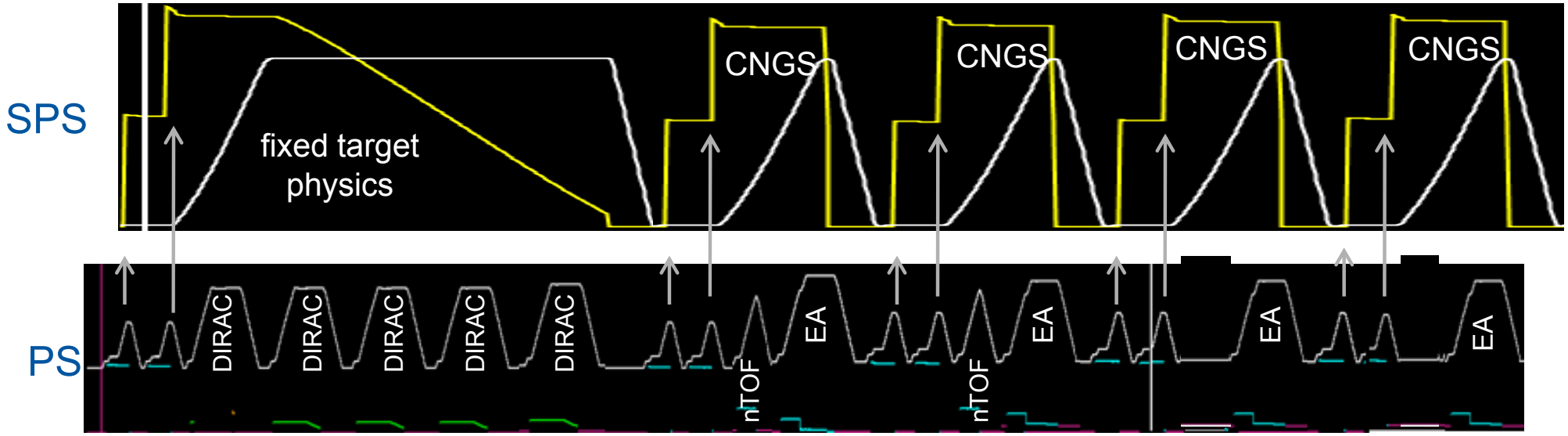


Catalogue of Possible production schemes - 25 ns

Schemes 25 ns	PSB – PS bunches	RF gym. in PS	RF gym. at injection	RF gym. at extraction	b/Train to SPS	SPS injections
3-spitting (standard scheme)	4 + 2	/3 ↗ /2 /2			72	4
BCMS	4 + 4	+2C/3↗/2 /2			48	5
BCS	4 + 4	C ↗ /2 /2			32	5
8b+4e	4 + 2	/2 ↗ /2 /2			48	5

/ Splitting C Batch Compression + Merging ↗Acceleration to 26 GeV/c

Scheme for Neutrino (high-intensity) beam production



protons delivered @ SPS extraction *

From R. Steerenberg

Facility	Protons delivered	% of total
CNGS	$3.9 \times 10^{+19}$	79.6%
LHC type	$1.1 \times 10^{+18}$	2.3%
rest	$8.9 \times 10^{+18}$	18.1%
Total	$4.9 \times 10^{+19}$	

* RP survey 2012

The SPS was delivering 450 kW peak power on target, 350 kW on average.

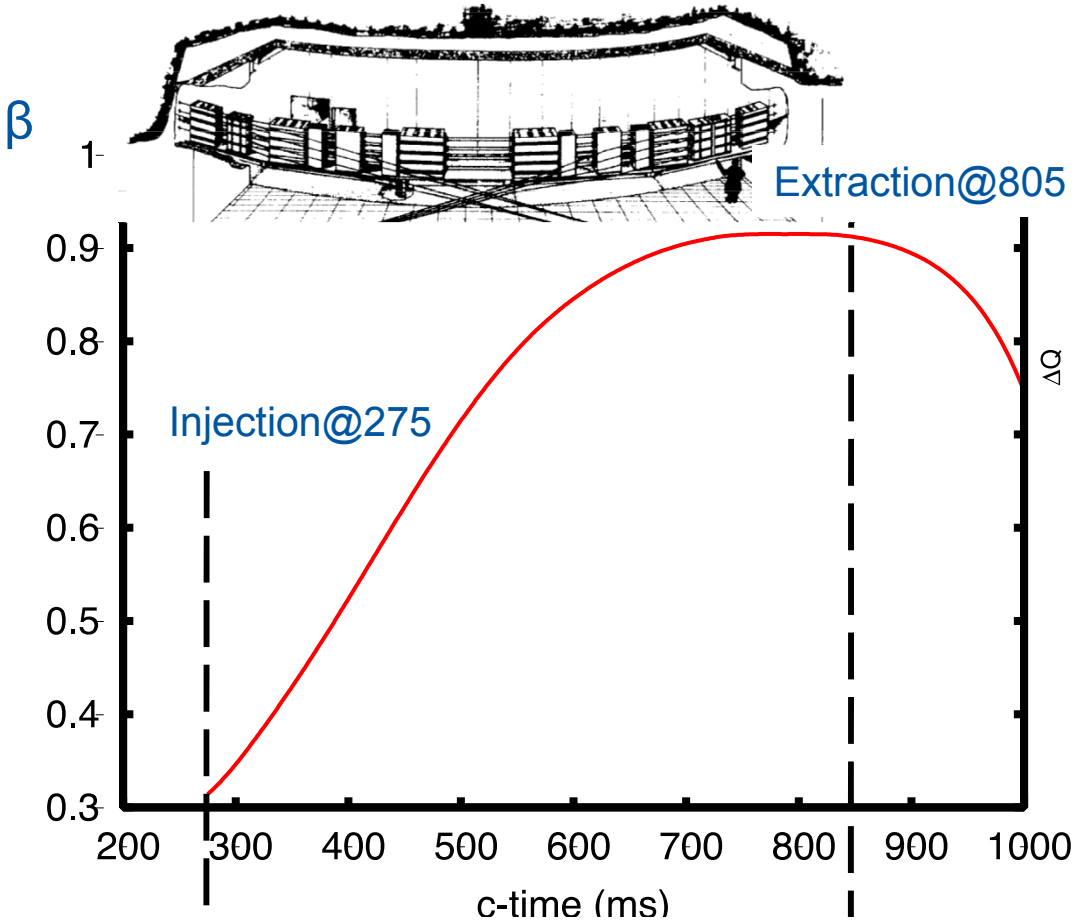
The number of protons taken by LHC during 2012 is less than the number of protons lost in the injectors for CNGS.

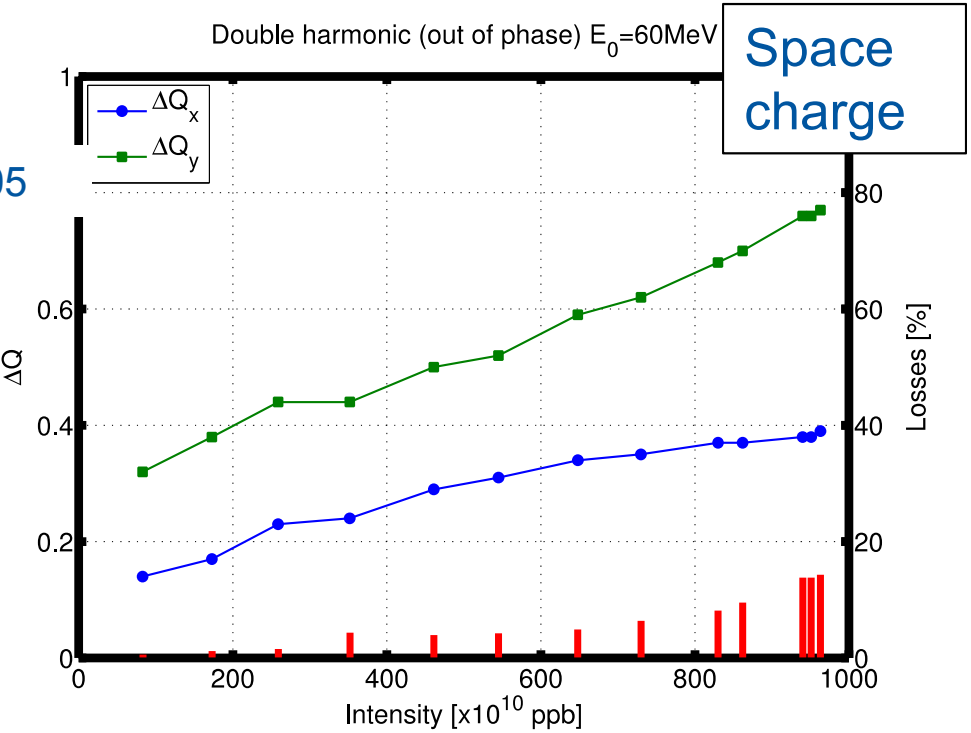
In the PS, about 8-12% of the total CNGS intensity is lost.

The complex in few numbers

	Operation		Record		After LIU (2020)	
	LHC	CNGS	LHC	CNGS	Aim LHC	Study 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	2.5	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	1.95	4.0(*)
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2/2.4(*)
SPS cycle length [s]	22.8	6.0	21.6	6.0	21.6	6.0/7.2
PS momentum [GeV/c]	26	14	26	14	26	14

PSB intensity limitations

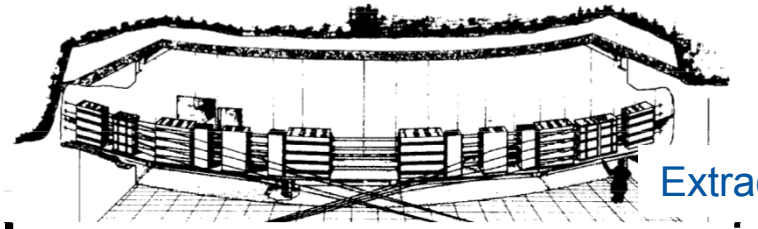




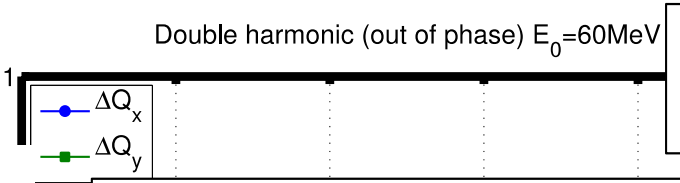
Space charge

- Losses during injection process:
  - Conventional multi-turn injection (40-50% losses)
  - Losses at injection septum and longitudinal capture
- Space charge (losses, emittance blow up)

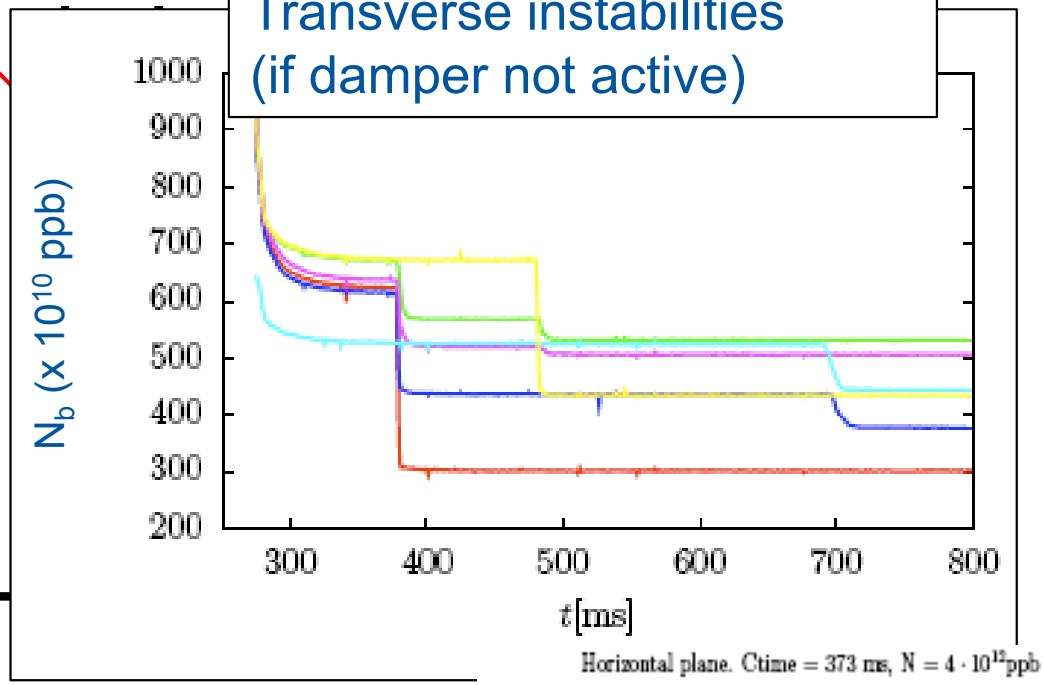
PSB intensity limitations

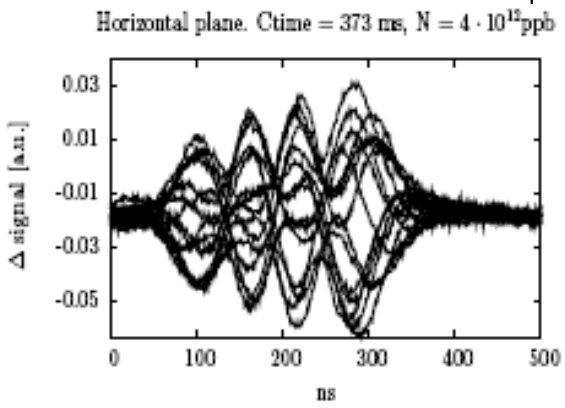


Space charge



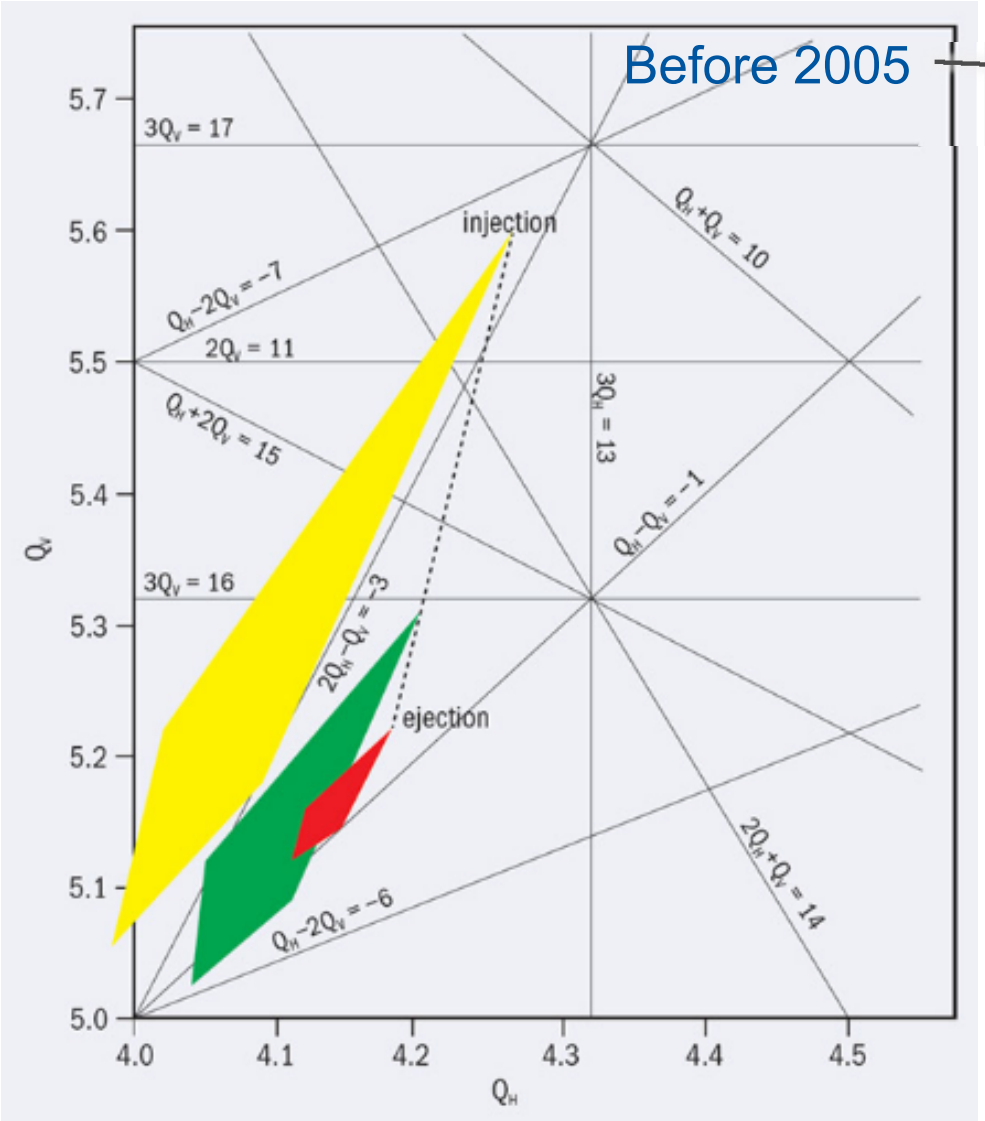
Transverse instabilities (if damper not active)

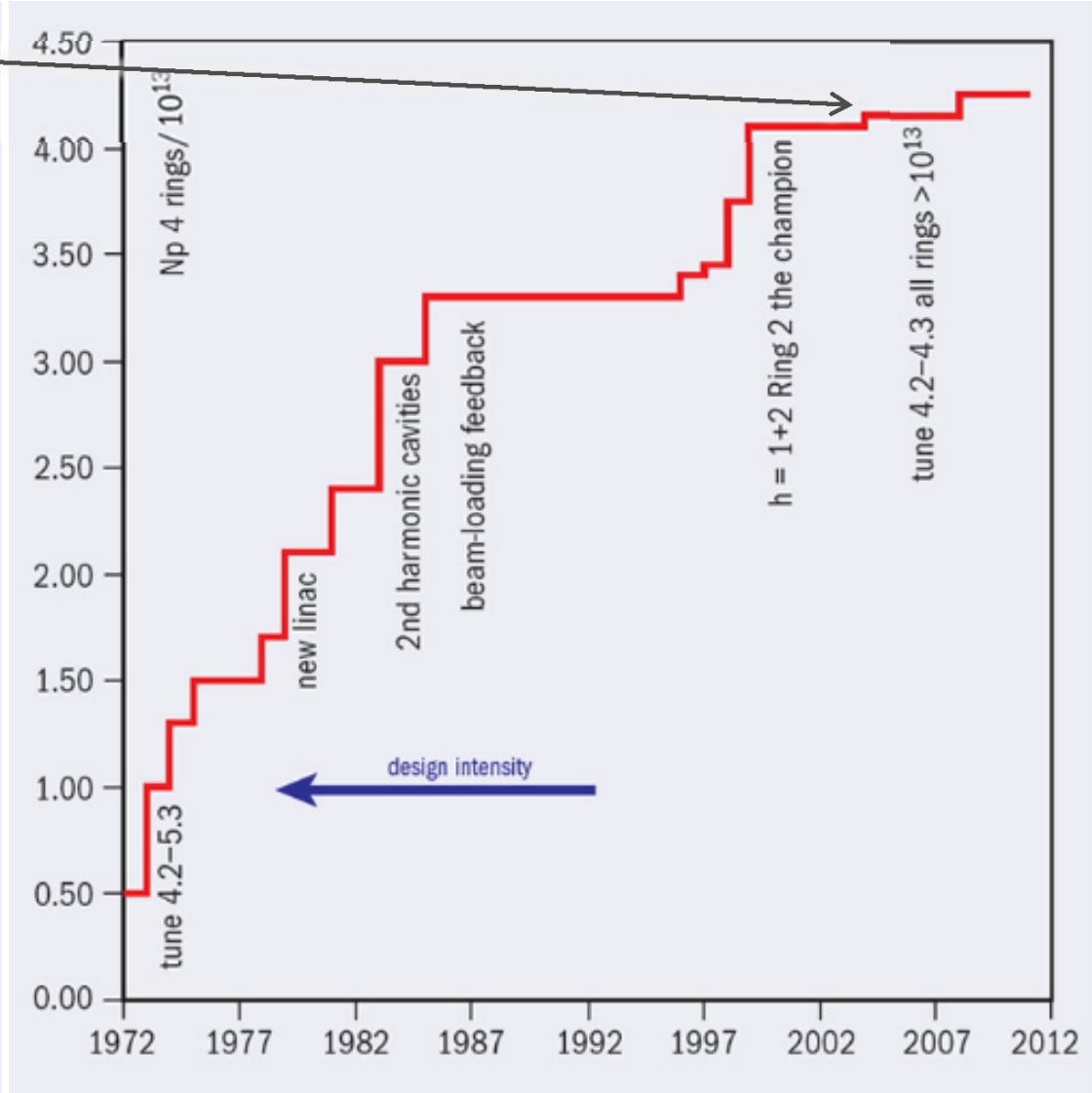




- Losses during injection process:
  - Conventional multi-turn injection (40-50% losses)
  - Losses at injection septum and longitudinal capture
- Space charge (losses, emittance blow up)
- Instabilities along the cycle (efficiency of the transverse feedback)
- **Brightness from PSB limited for LHC beams but no issue with intensity**

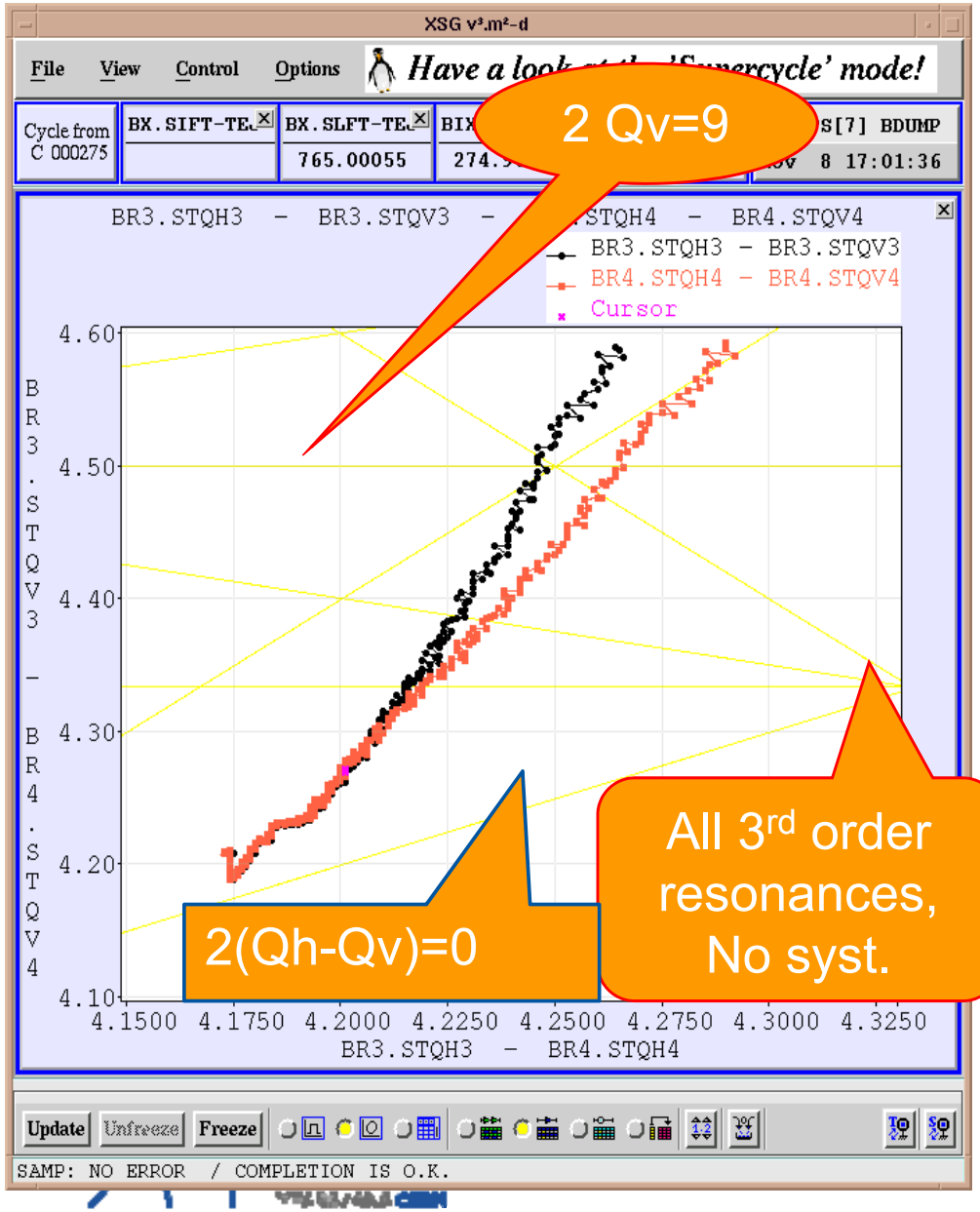
PSB: choice of working point (I/II)



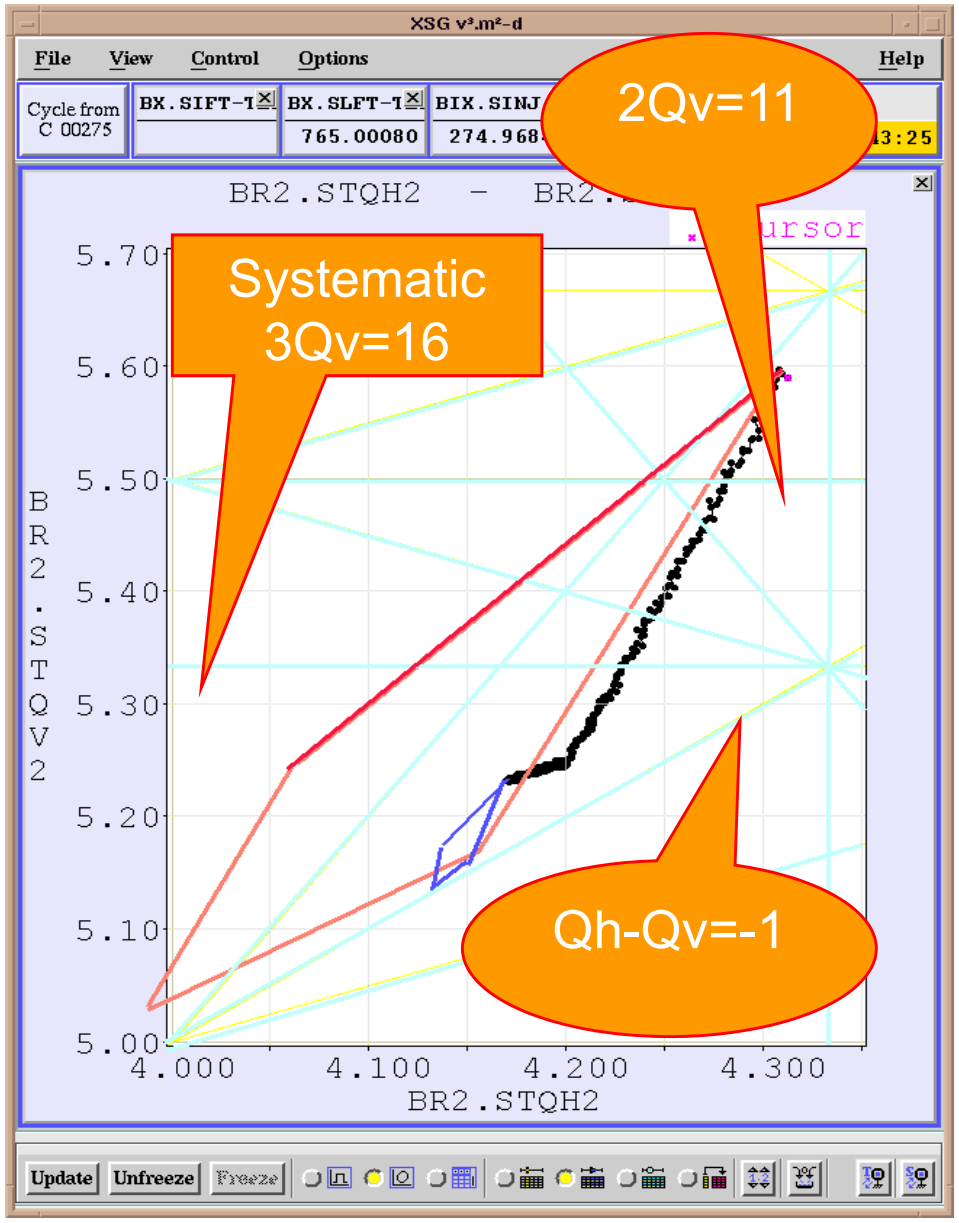


Choice of working point (II/II)

Low WP 4,17 4,23



High WP 4,17 5,23



H.W.P. versus L.W.P.

- HWP: R2 good performances ; two bad: R1 and R4
- LWP: quasi all rings equal. 5% more intensity.

- LWP: orbit correction needed and done, change vertical shaving dipole and Transfer line matching.

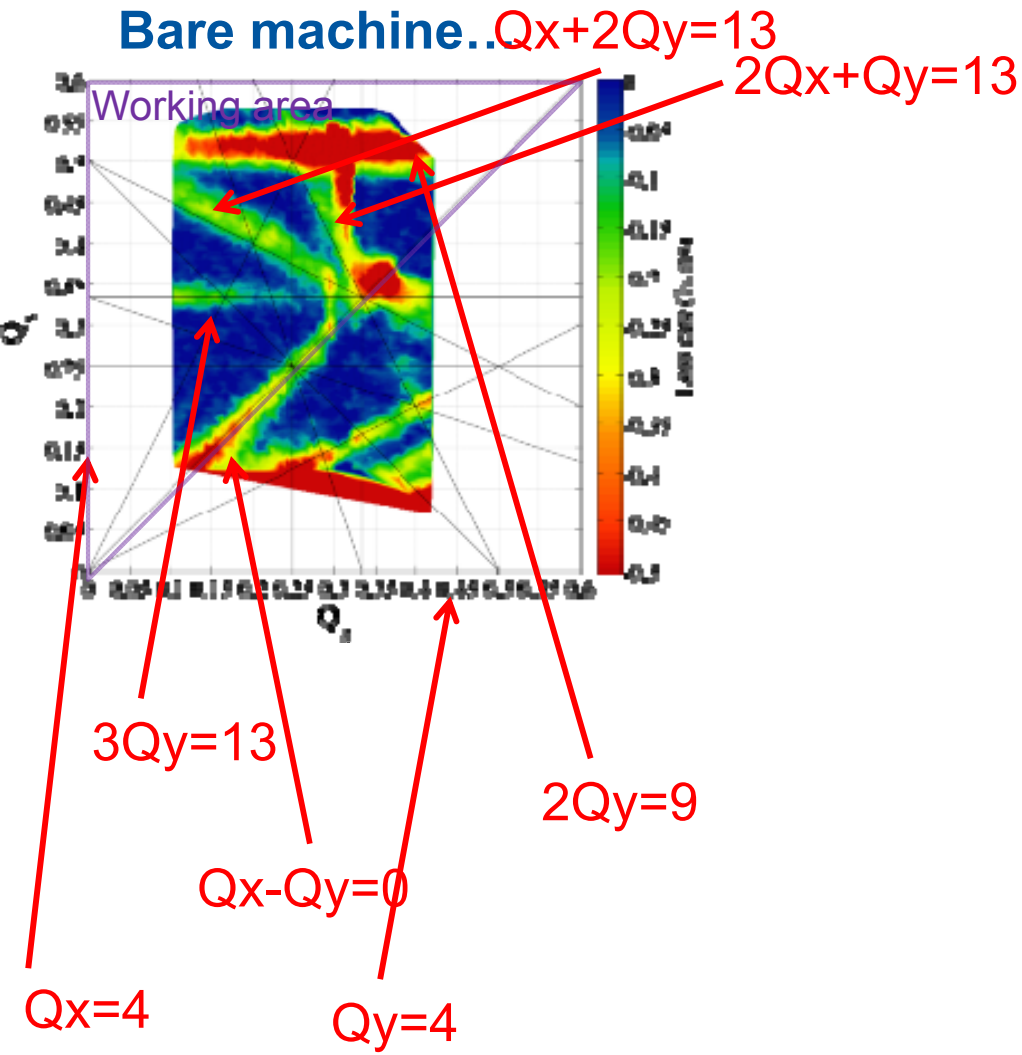
- Strength and effects of resonances are much smaller especially for outer rings

- Limitation: Montague resonance
- Vertical emittance of the LHC beam is a bit larger.

PSB R2 resonance compensation and tr. feedback regulation effects at 160 MeV

- The PSB presents visible resonances up to the sextupolar order in the working area.
- Multipoles are present to compensate them…

Bare machine…



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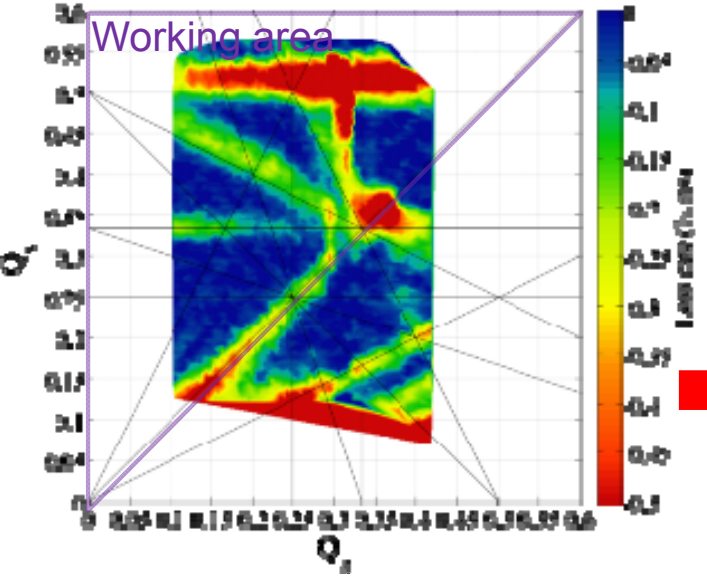
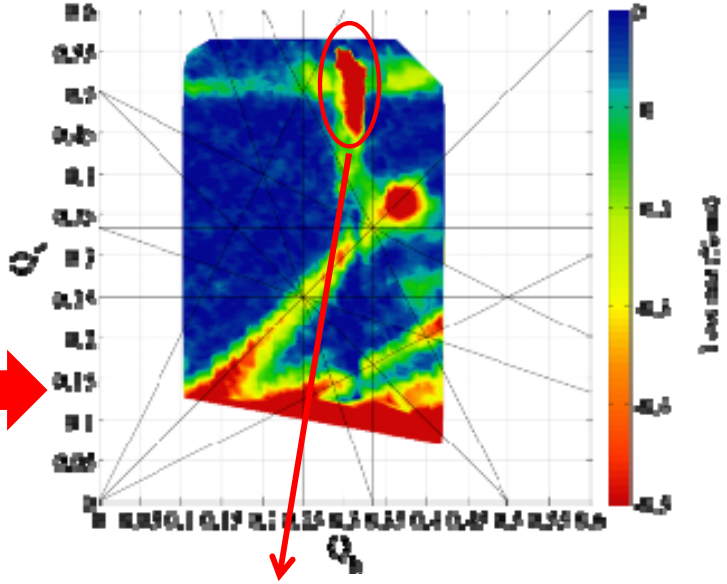


…after few iterations…



Beam instability

PSB R2 resonance compensation and tr. feedback regulation effects at 160 MeV

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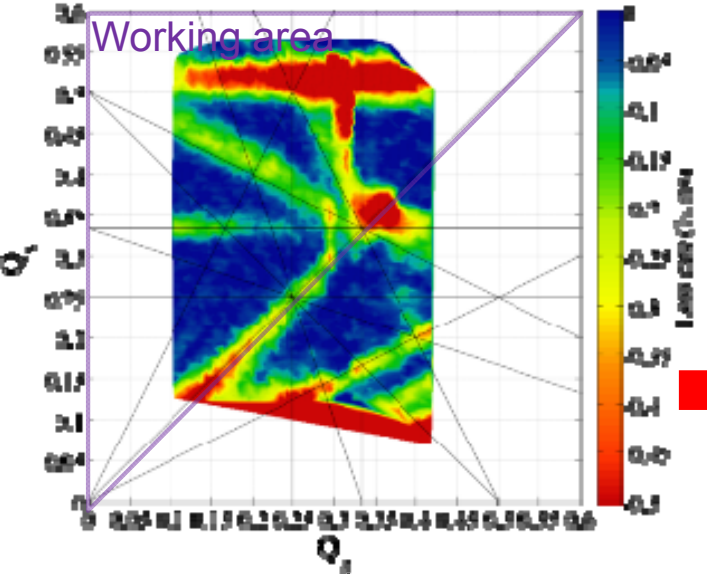
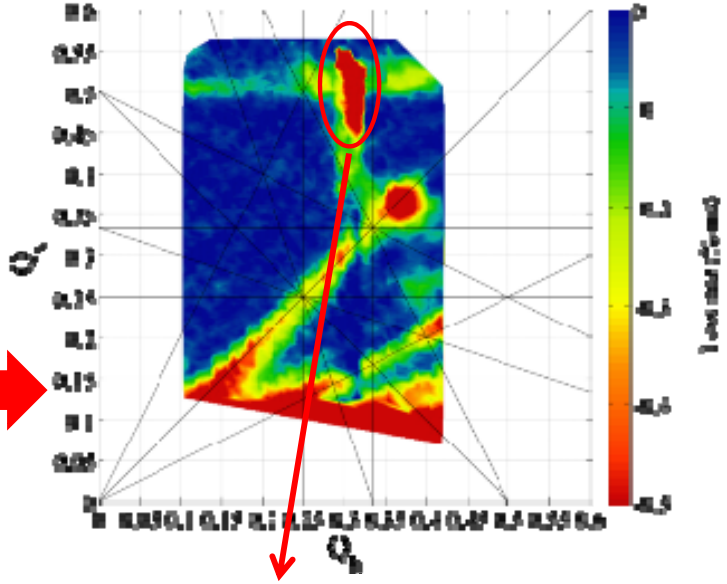
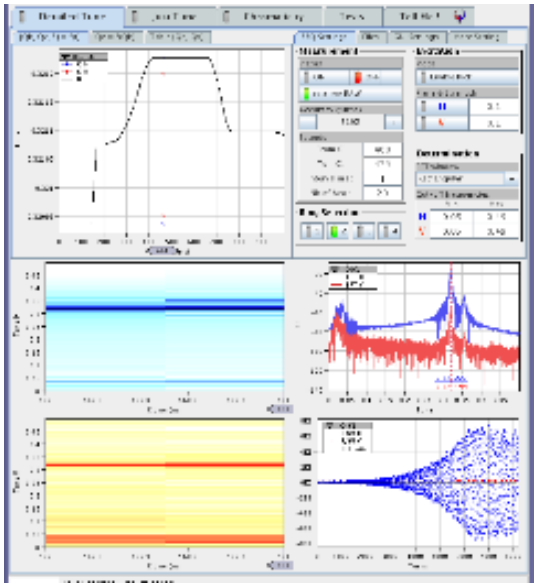


…after few iterations…



Beam instability



PSB R2 resonance compensation and tr. feedback regulation effects at 160 MeV

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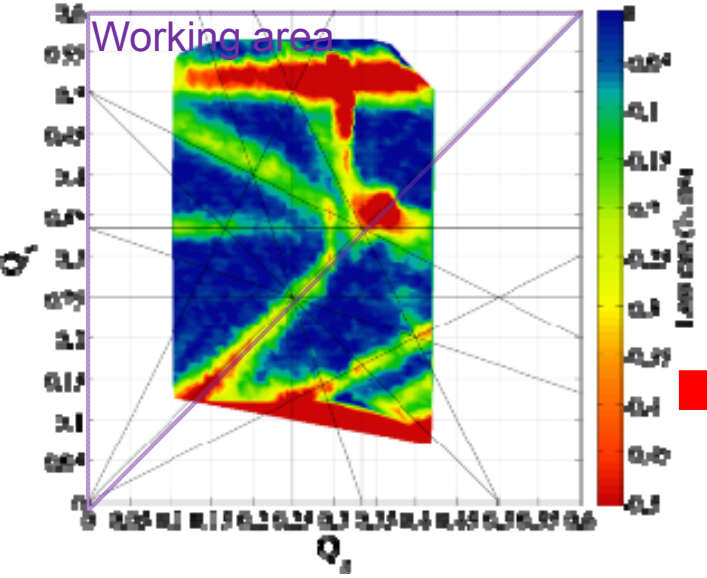
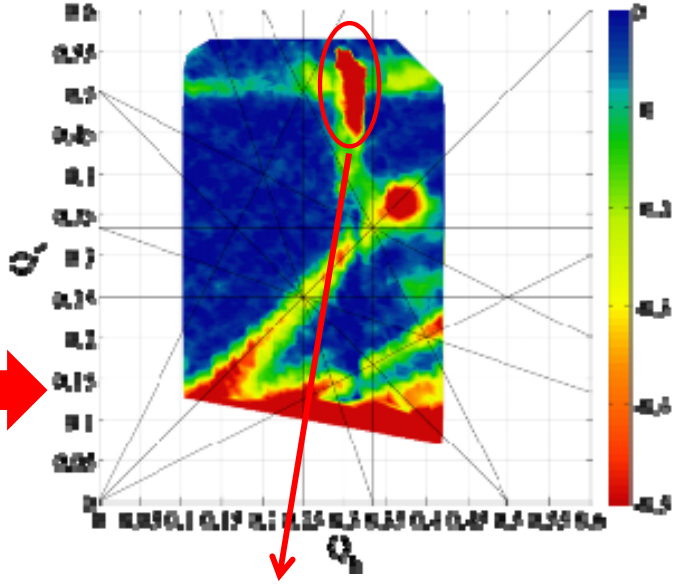
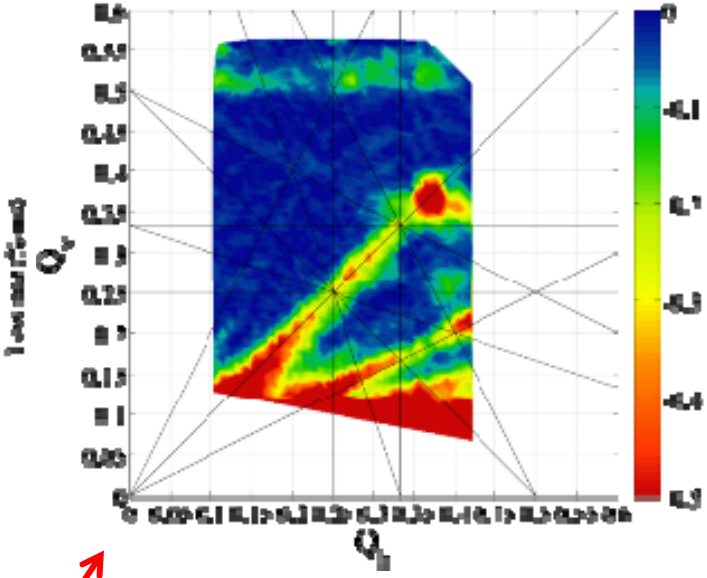
Bare machine…



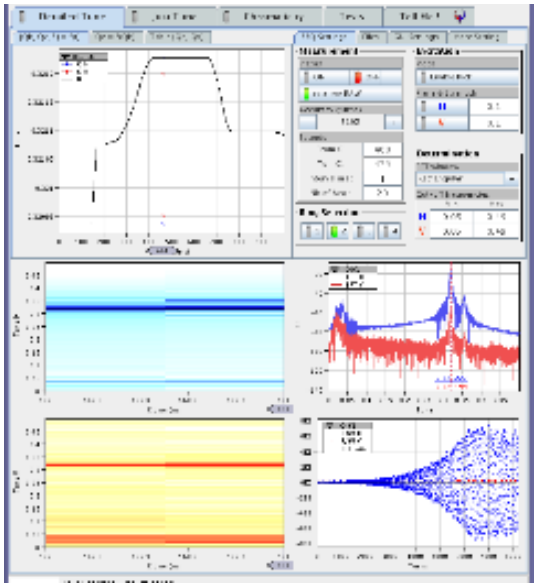
…after few iterations…



…the final result.



Beam instability



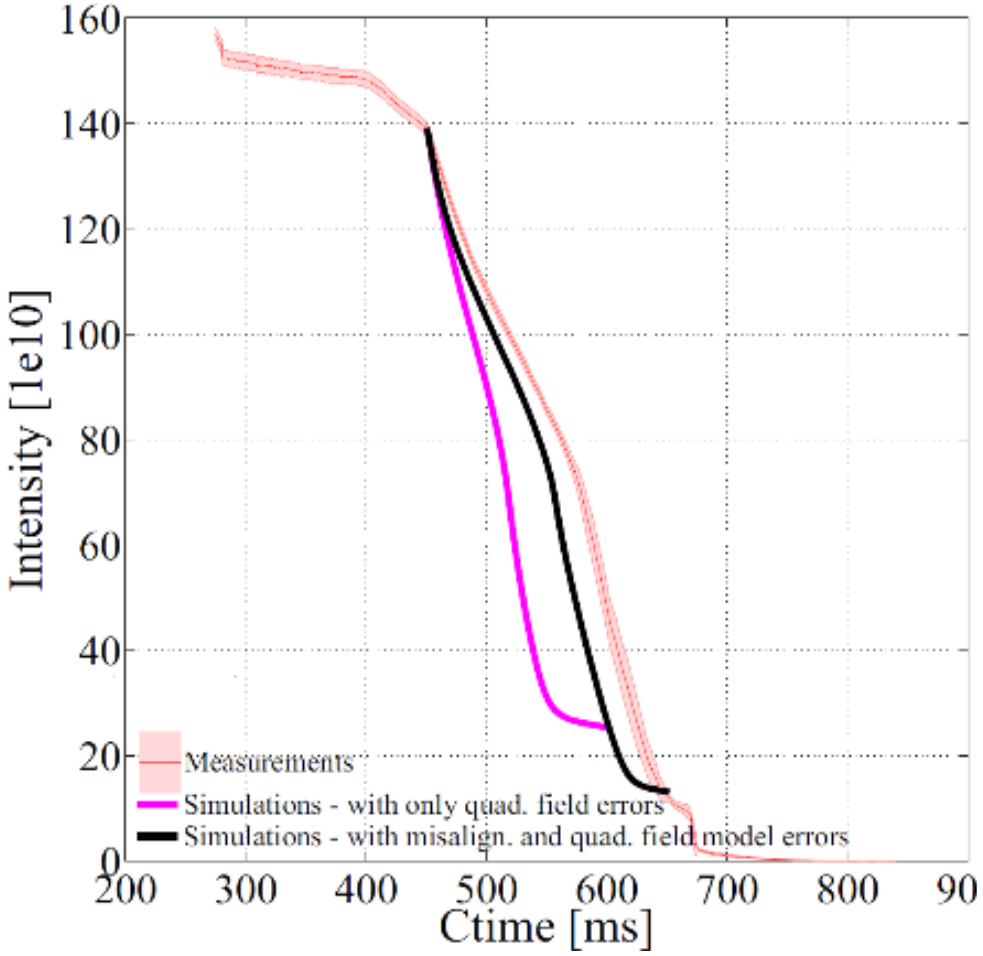
…cured adjusting the tr. feedback…

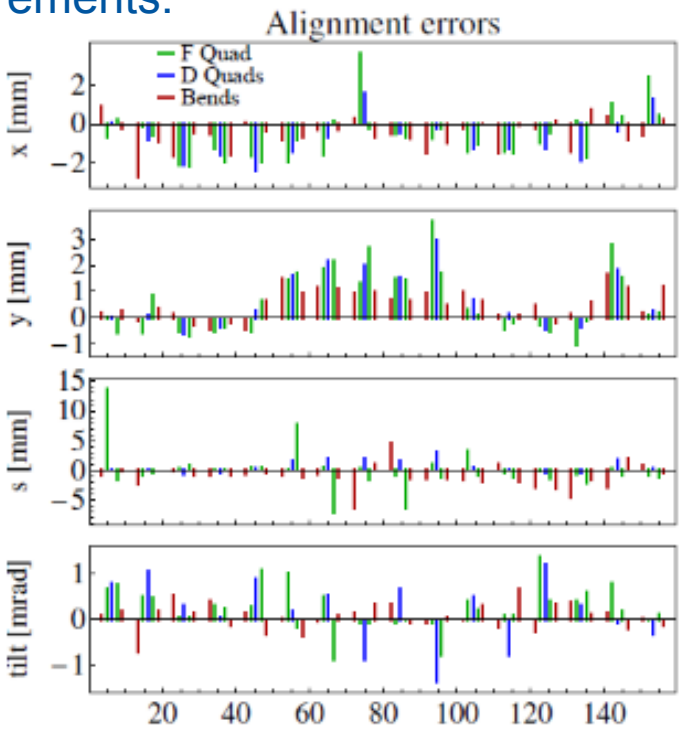
End September 2014 tests

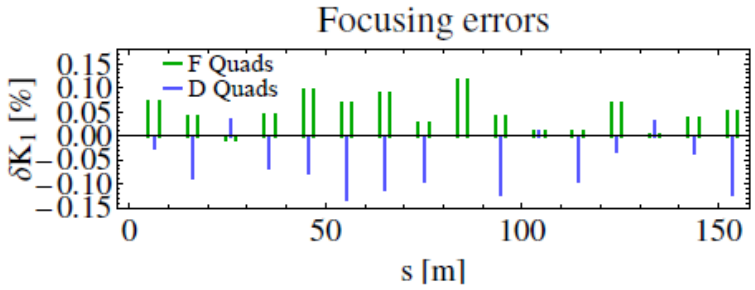
See E. Benedetto talk

PSB R2 long term losses by space charge

- Big effort to evaluate losses due to space charge (main bottleneck in the machine) and resonance lines interactions (like the 2Qy=9 half-integer).
- Optimization of the optics model through beam-based measurements.

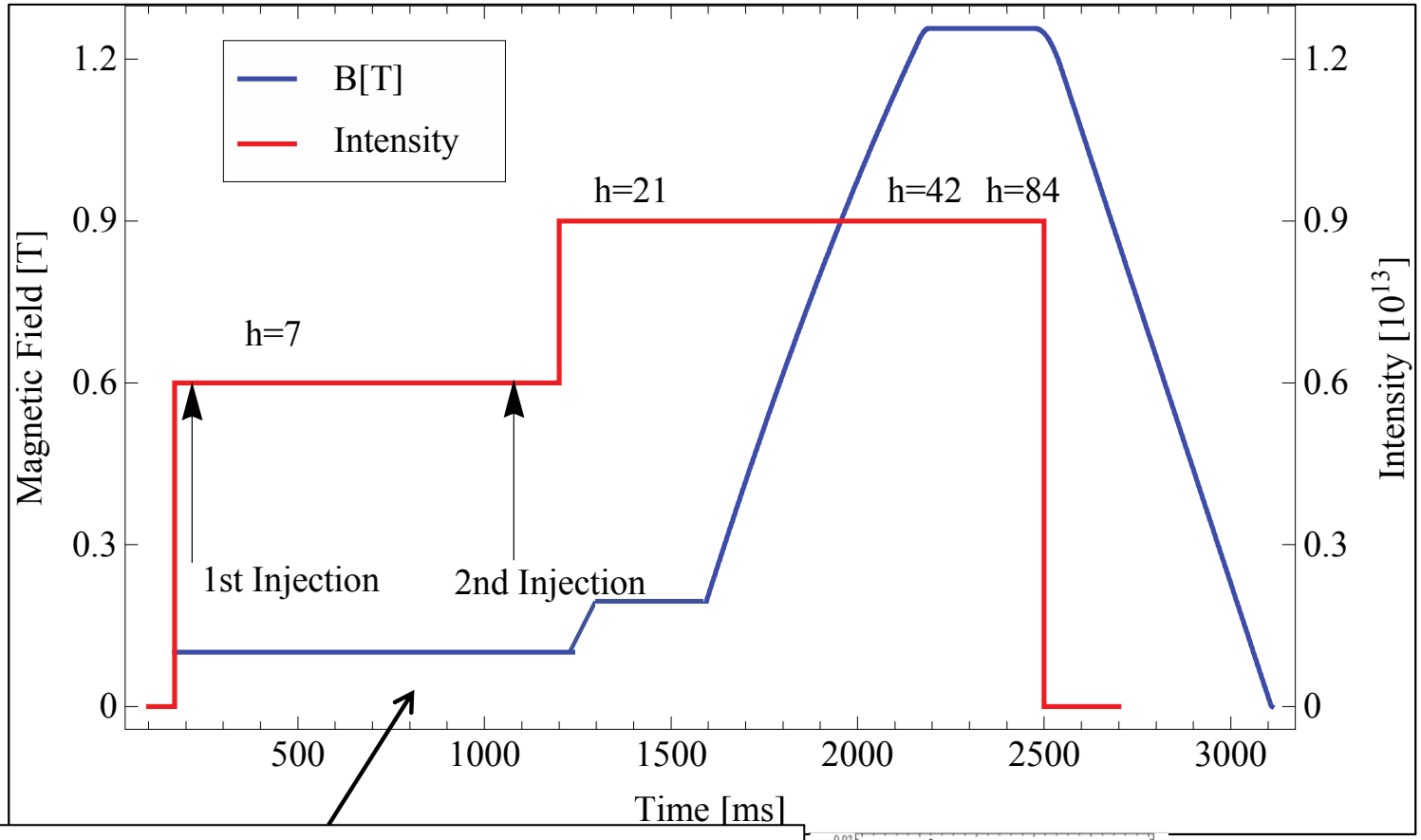






Reference:
V. Forte et al., "CERN PS Booster Space Charge Simulations with a Realistic Model for Alignment and Field Errors", IPAC'14, Dresden, Germany, TUPRI029

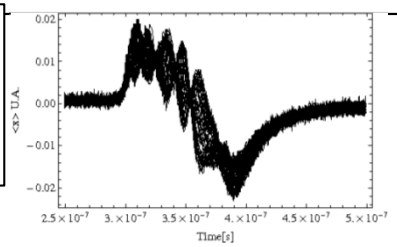
PS brightness limitations overview



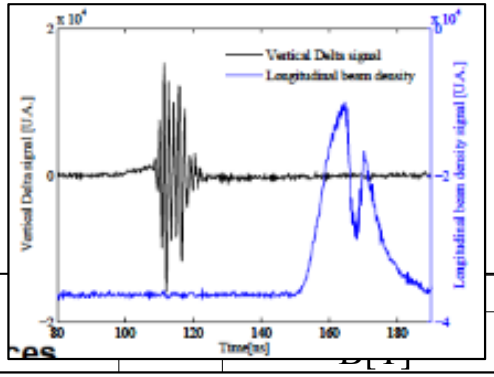
Injection flat bottom:

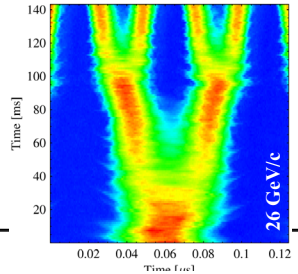
Space charge → Injection @2GeV

Headtail instability → Transverse FB



PS brightness limitations overview



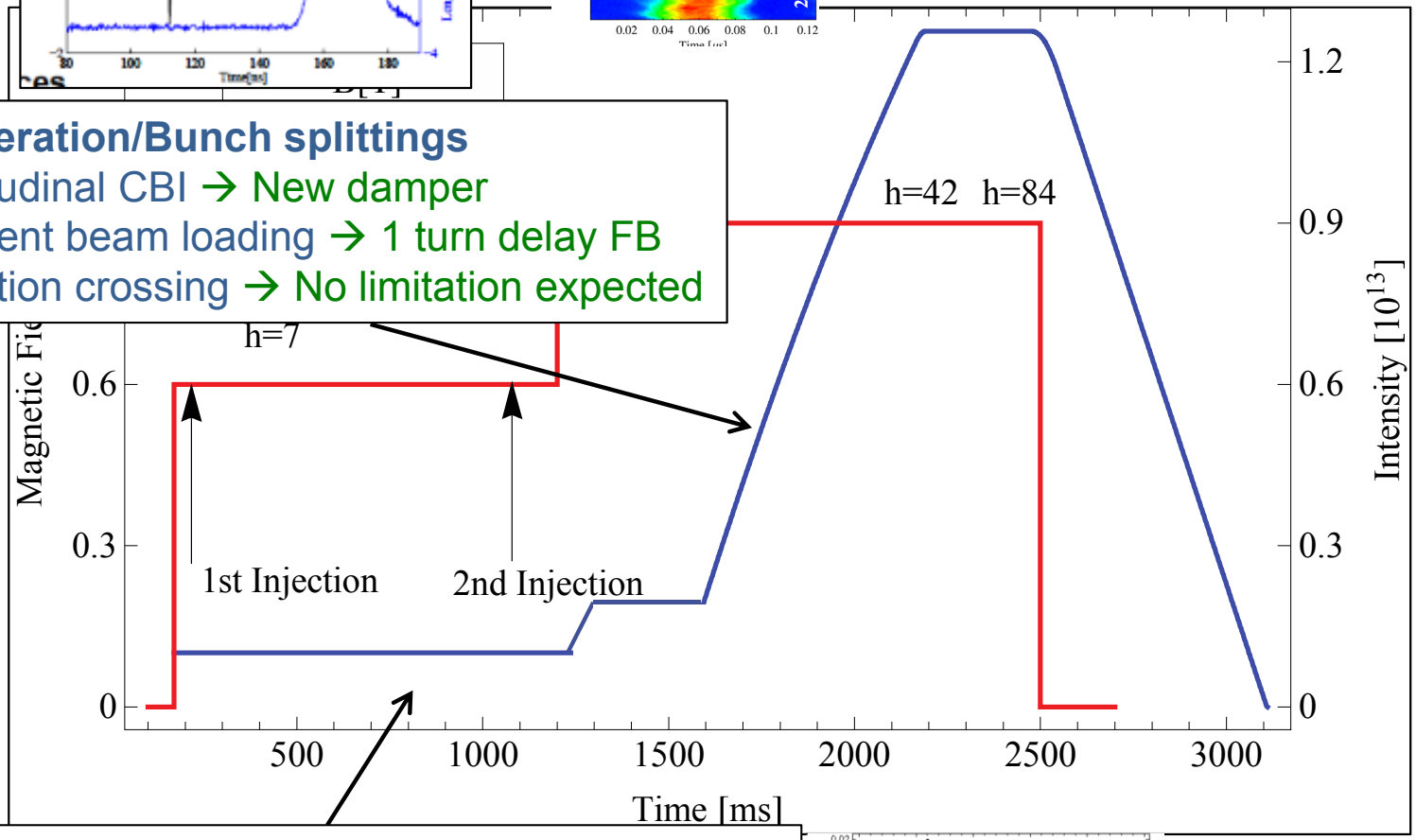


Acceleration/Bunch splittings

Longitudinal CBI → New damper

Transient beam loading → 1 turn delay FB

Transition crossing → No limitation expected



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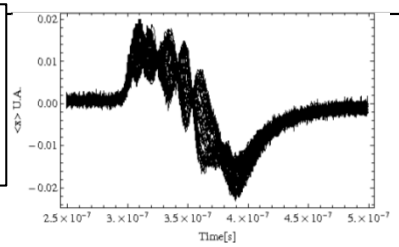
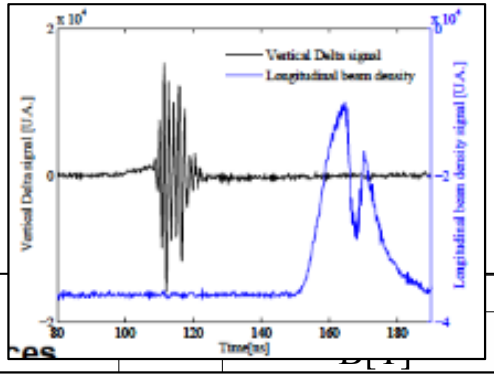
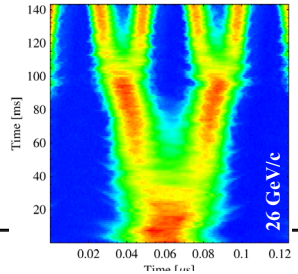
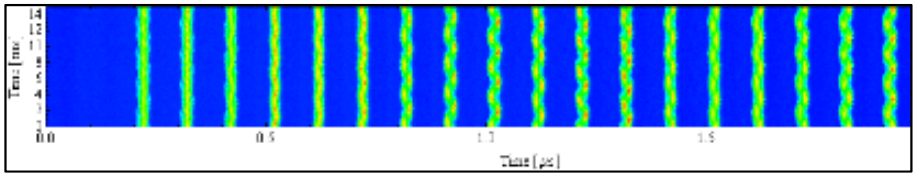


PS brightness limitations overview

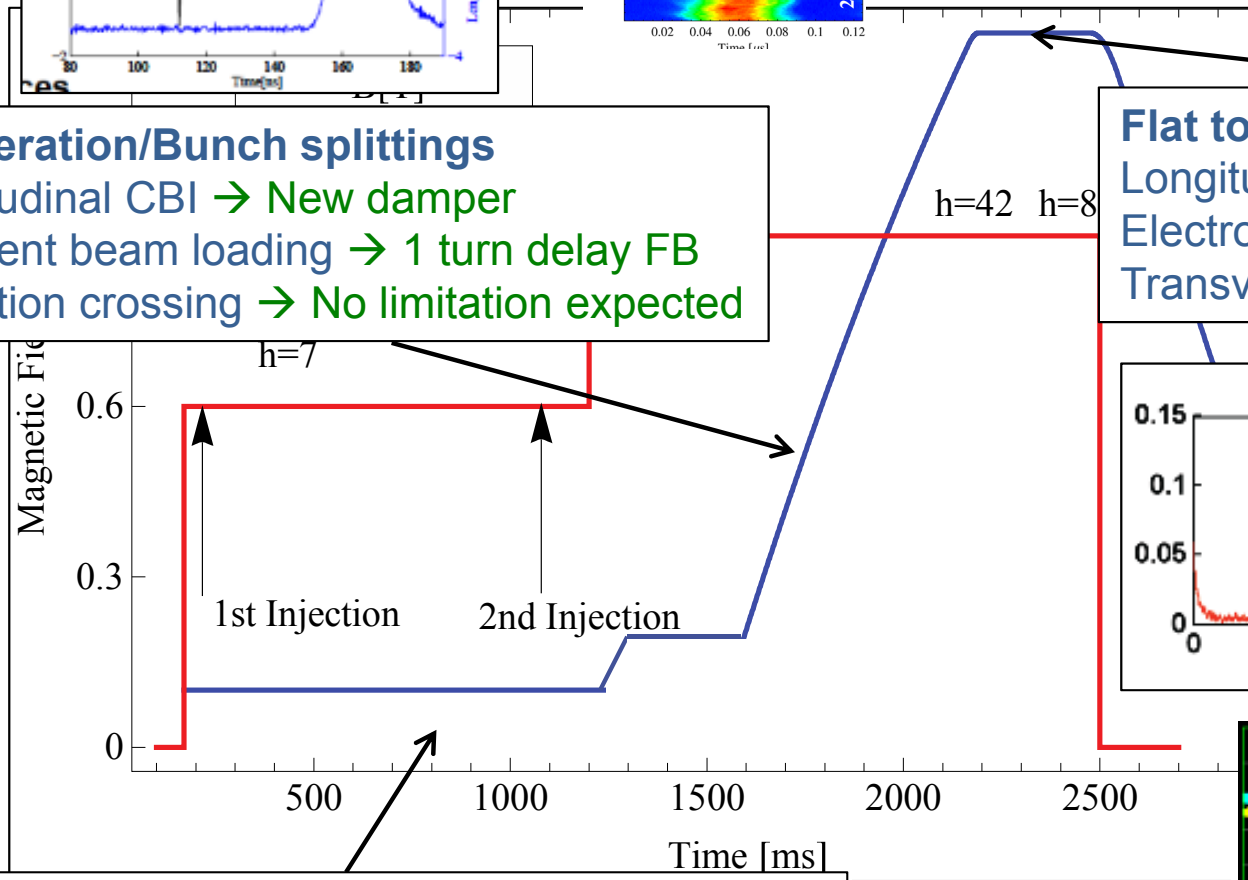


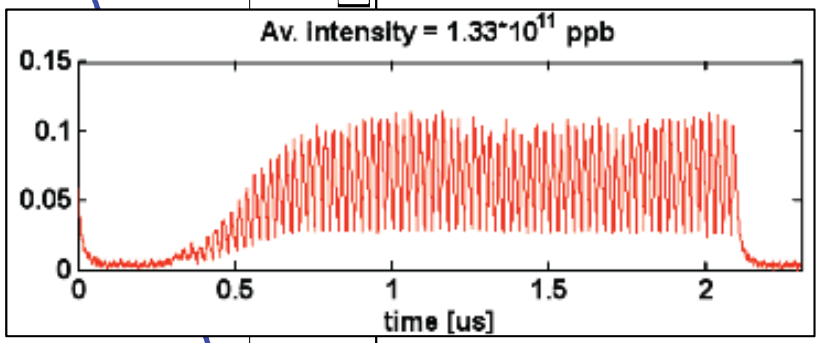


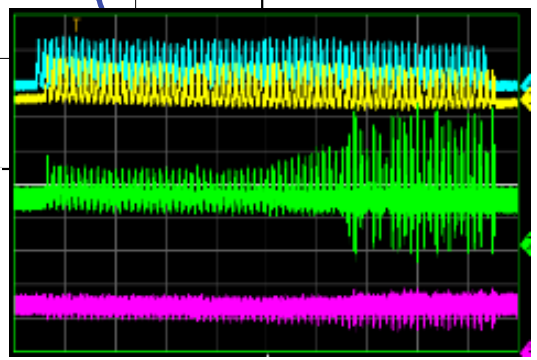


Acceleration/Bunch splittings
Longitudinal CBI → New damper
Transient beam loading → 1 turn delay FB
Transition crossing → No limitation expected

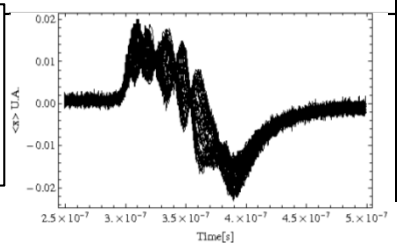
Flat top:
Longitudinal CBI → New damper
Electron cloud → Transverse FB
Transverse instabilities → Transverse FB



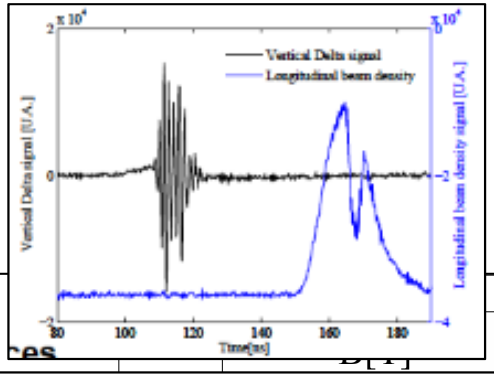


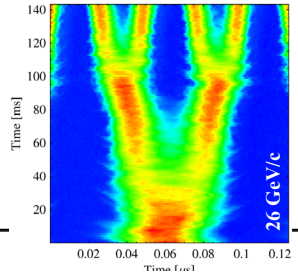


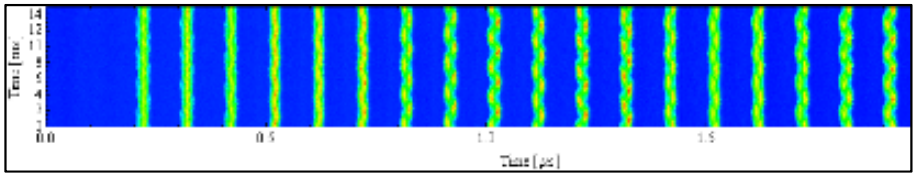
Injection flat bottom:
Space charge → Injection @2GeV
Headtail instability → Transverse FB



PS brightness limitations overview





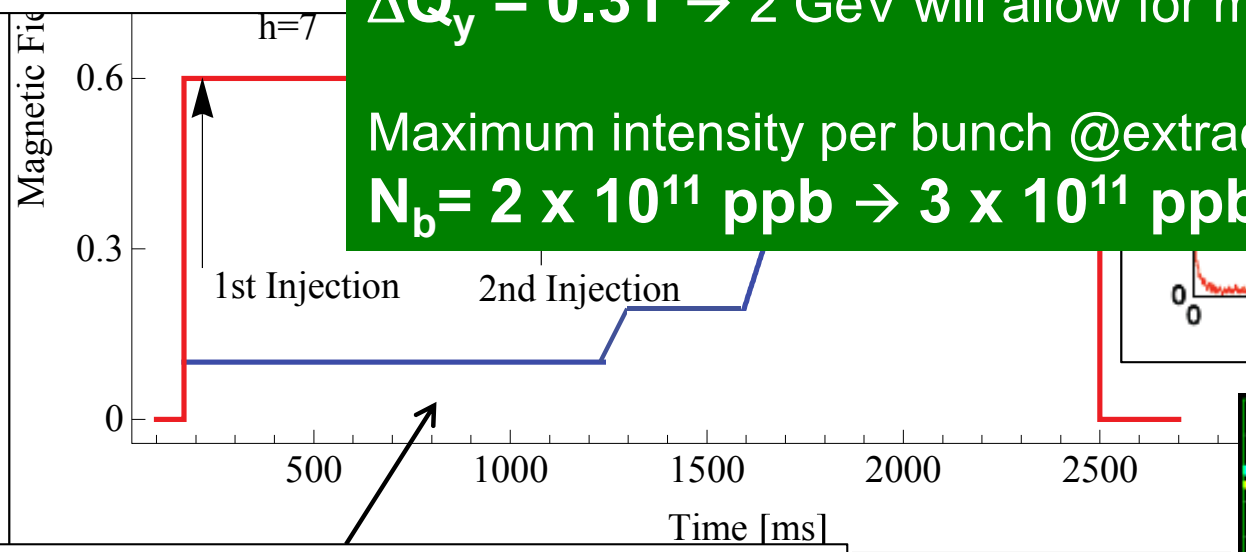


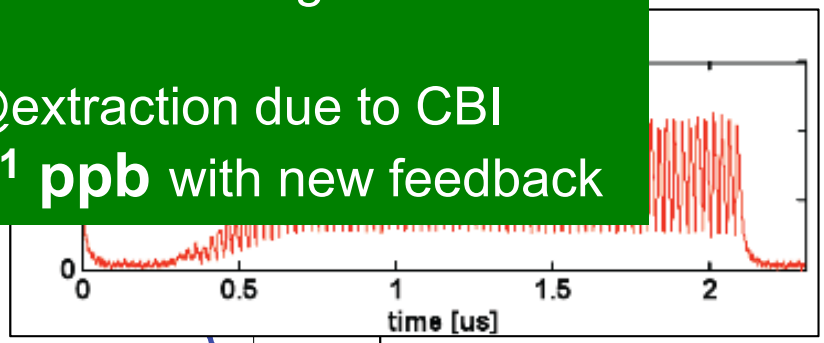
Acceleration/Bunch splittings
Longitudinal CBI → New damper
Transient beam loading
Transition crossing → N

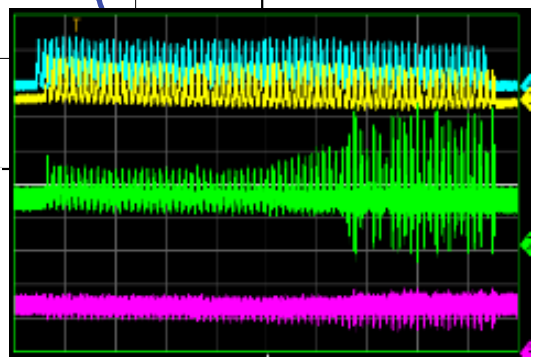
Flat top:
Longitudinal CBI → New damper
verse FB

Maximum SC tune spread @injection
$\Delta Q_y = 0.31$ → 2 GeV will allow for more brightness

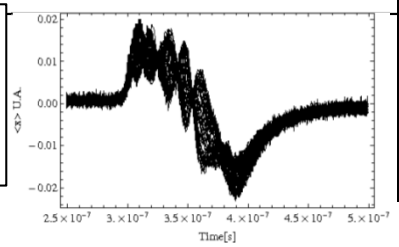
Maximum intensity per bunch @extraction due to CBI
$N_b = 2 \times 10^{11}$ ppb → 3×10^{11} ppb with new feedback



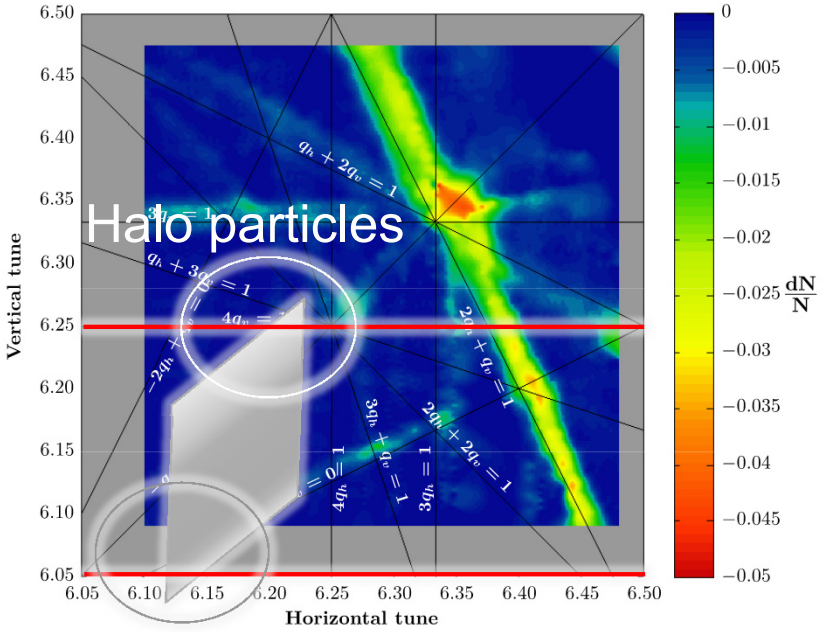


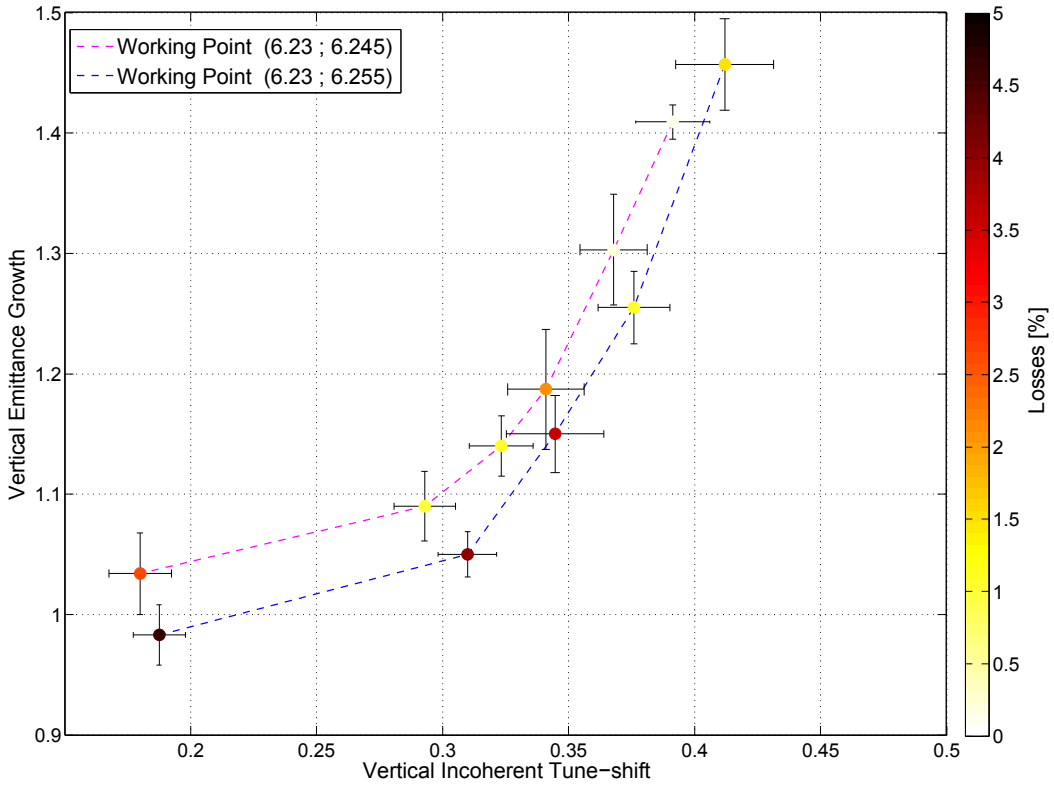


Injection flat bottom:
Space charge → Injection @2GeV
Headtail instability → Transverse FB



Space-charge: current limitations





The beam tune-spread is trapped between the 4Qy=25 and the integer.

➔ If one increases the vertical tune to avoid emittance growth due to the integer, the beam loss increases because of the 4th order resonance

➔ Choice of working point is a compromise between beam loss and emittance blow-up

4Qy resonance mitigation

- The preferred hypothesis is that the 4th order resonance is **a structure resonance driven by space charge**.

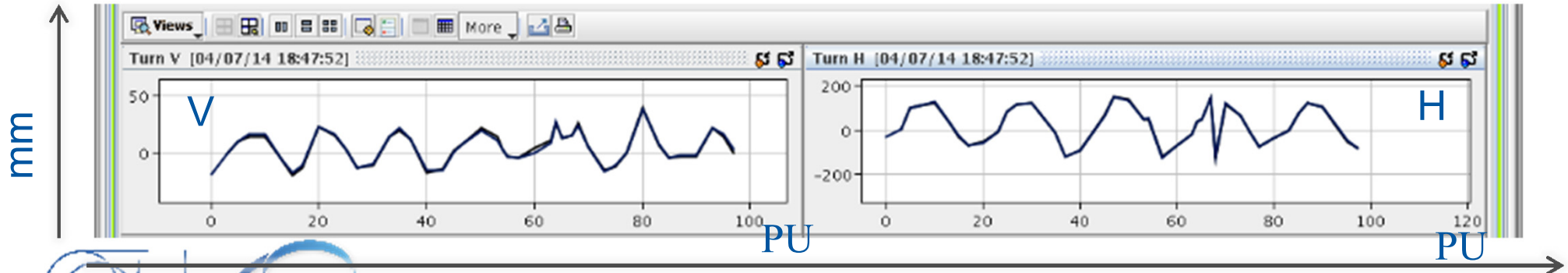
- The resonance is driven by the space charge force modulation which has a harmonic (8x6.25=50) of the symmetry of the machine (50x ”FD DF”)

➔ If one **changes the vertical integer tune**, then the space charge harmonic should be different from the lattice one, and shouldn’t be excited anymore. (ex: 8*7.25=58).

- A proposed mitigation is under-study, where the integer tunes are changed from (6,6) to (5,7). A measurement campaign started in 2014 and the first results seem to be very promising.

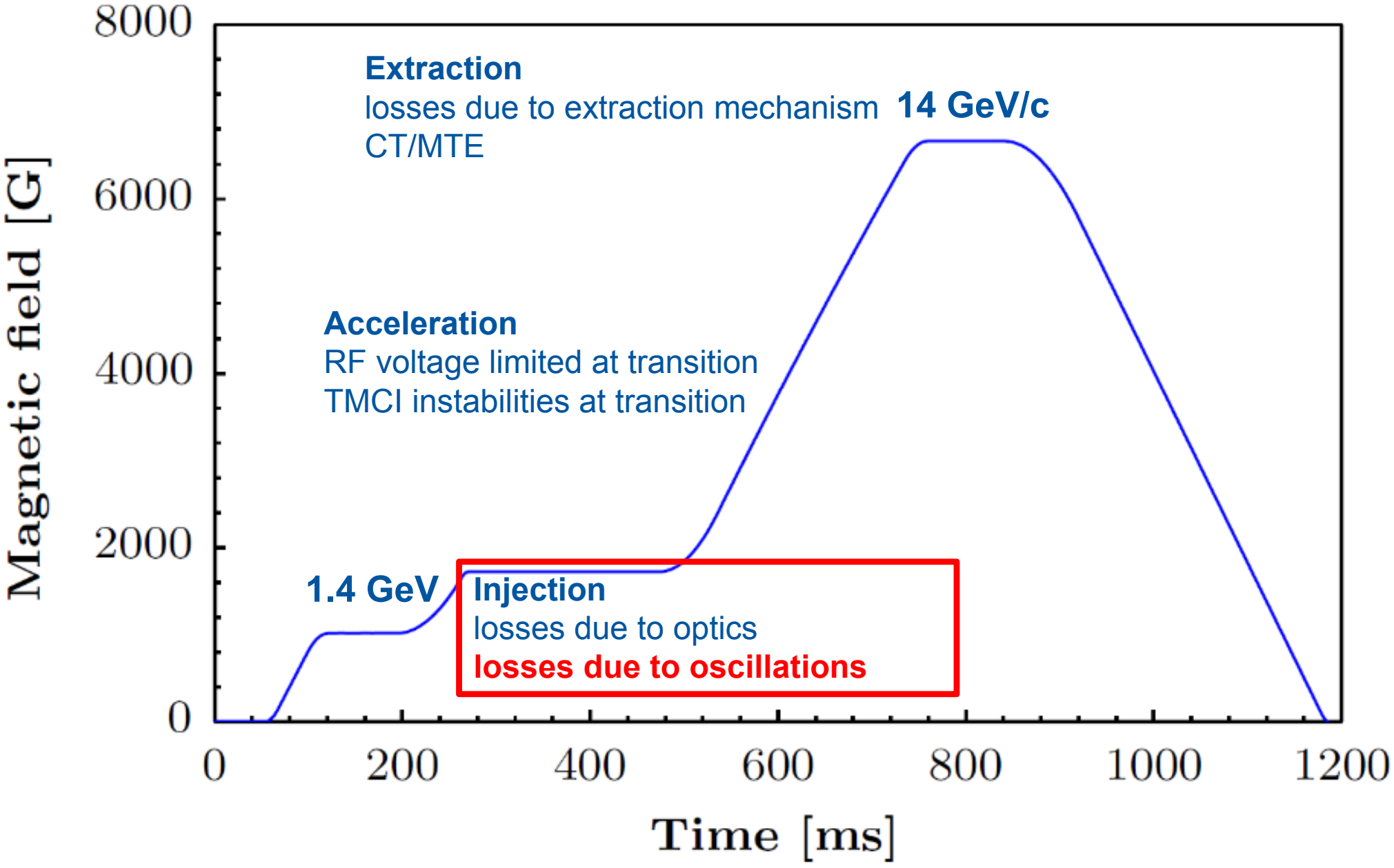
8>Qv> 7 closed orbit

6>Qx>5 closed orbit



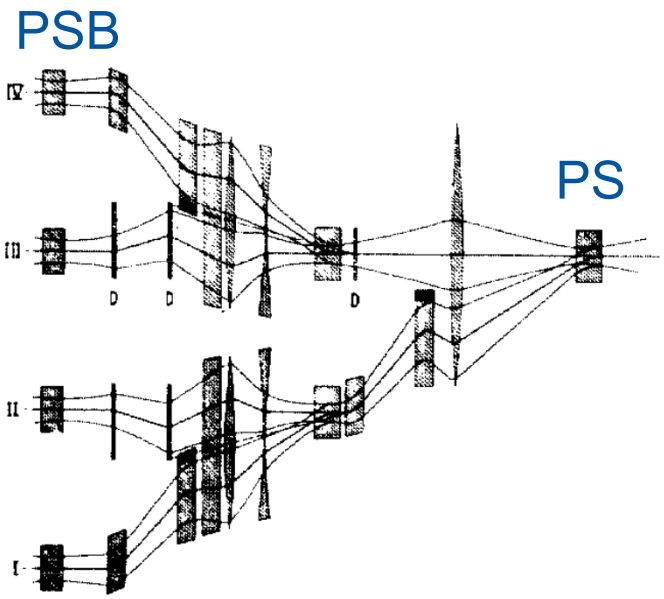
Measured closed orbit with the split tunes optics

PS Limitations for high-intensity beams: what we learned from the CNGS run

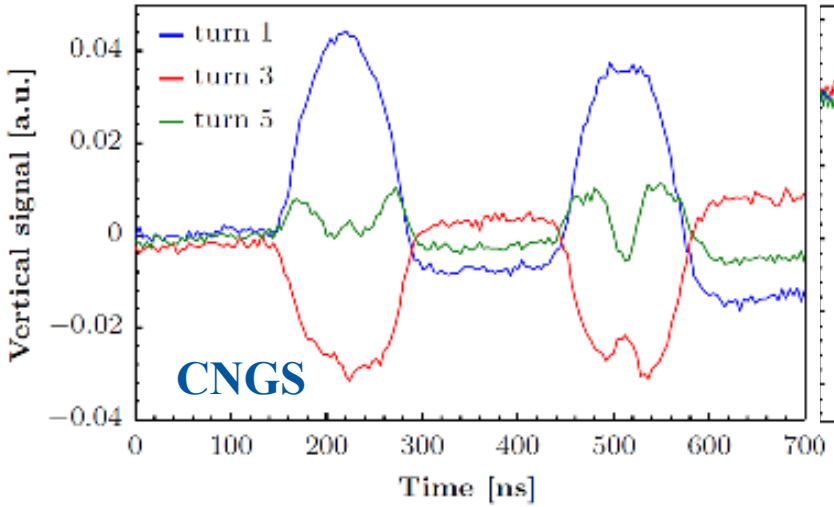


Injection oscillations at PS injection

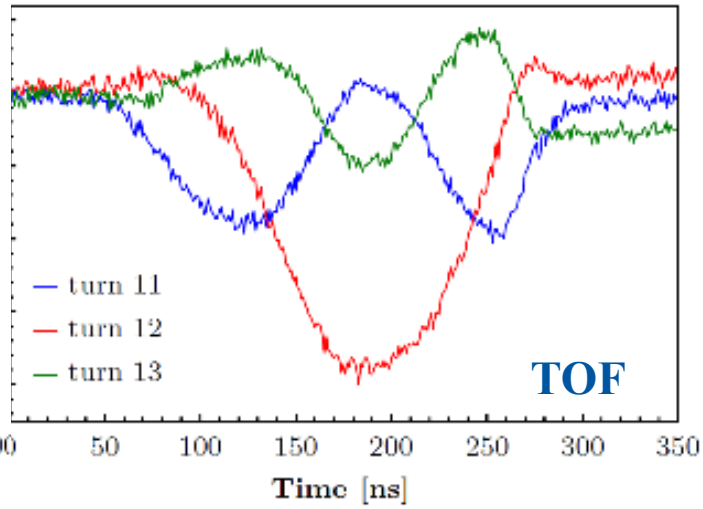
- Fast buildup of intra-bunch oscillations (few turns after injection)
- Oscillations primarily observed in vertical plane
  - PSB recombination is in the vertical plane
- Oscillations contribute to beam loss at injection
- Visible each time the beam is injected
- Effect due to **image charges/currents** (indirect space charge) associated to an injection error



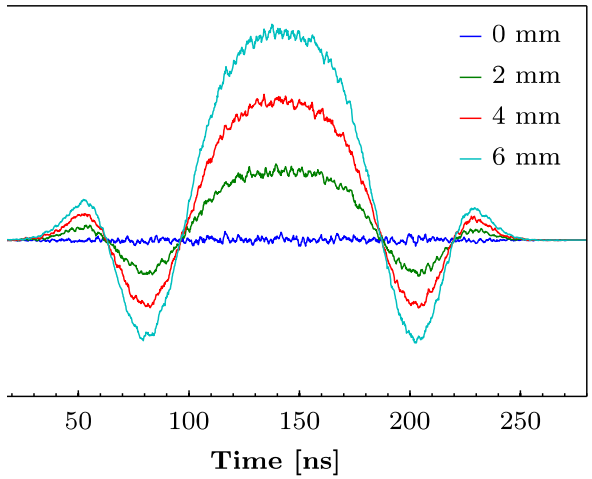
$I_p = 375 \cdot 10^{10}$ ppb (Meas.)



$I_p = 700 \cdot 10^{10}$ ppb (Meas.)

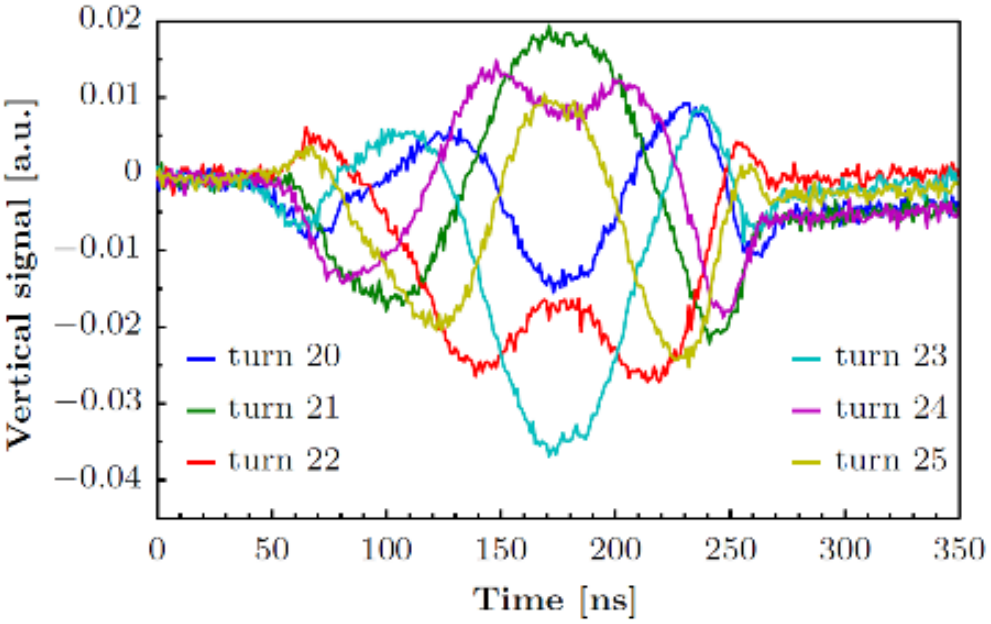


Simulations

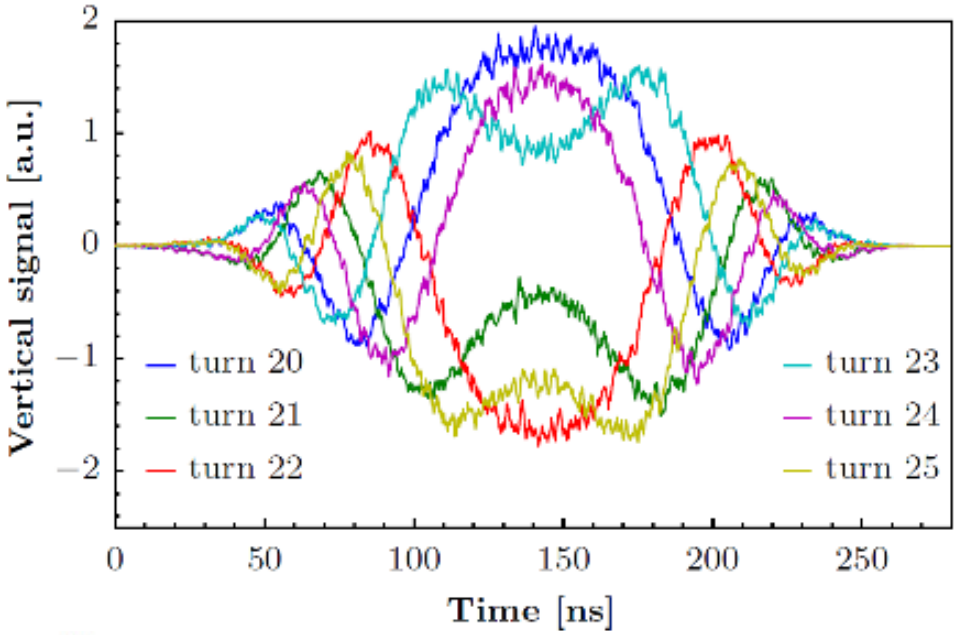


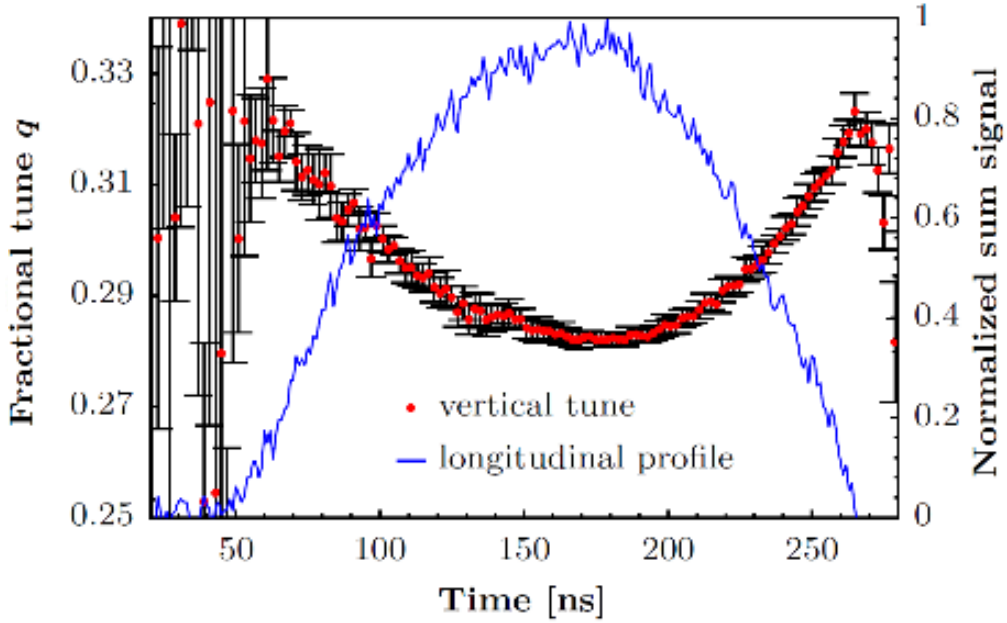
Injection oscillations: comparison

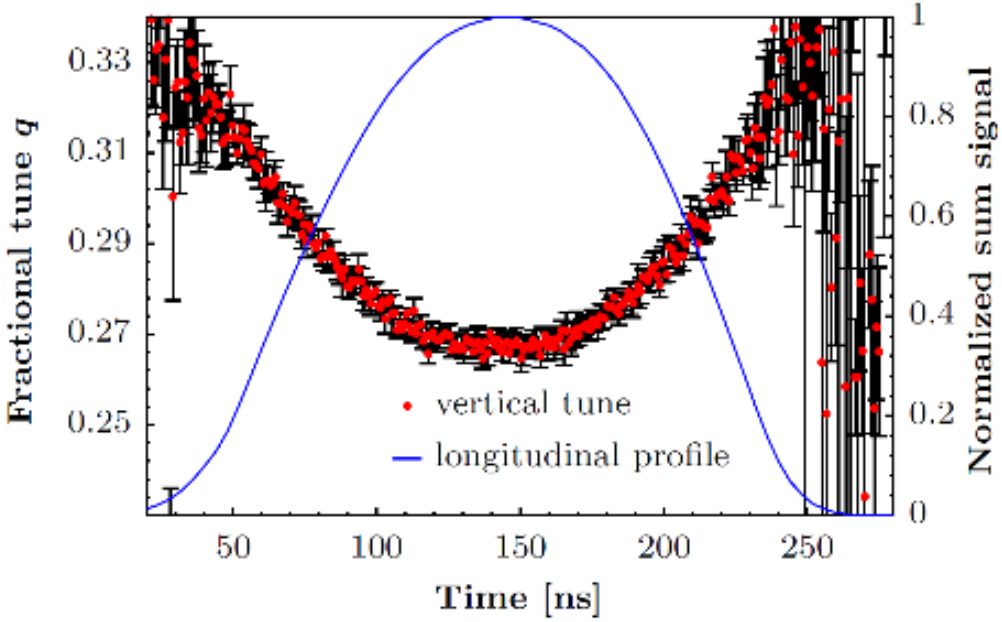
measurement



simulation

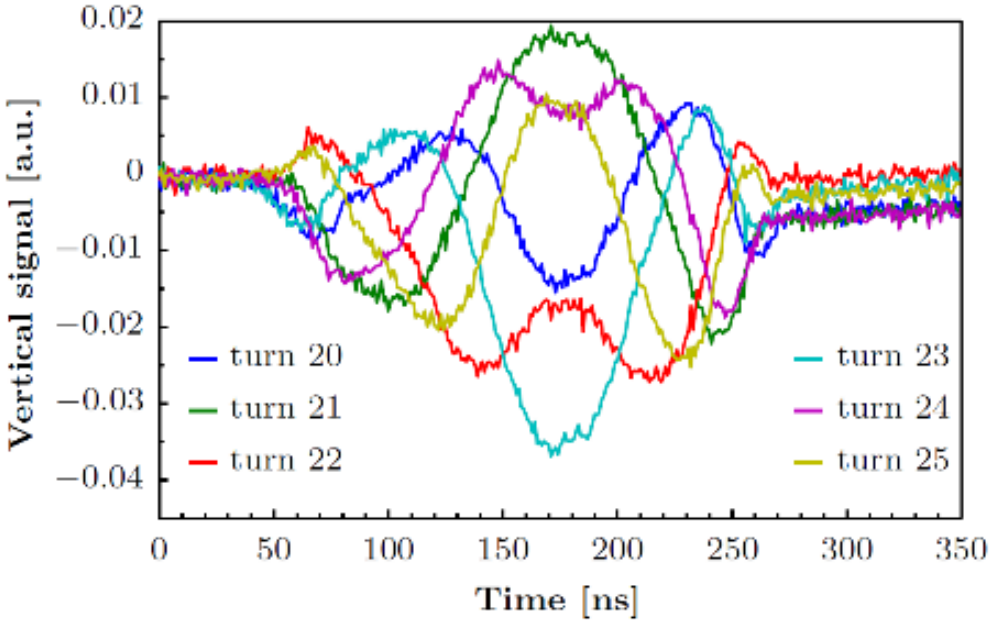


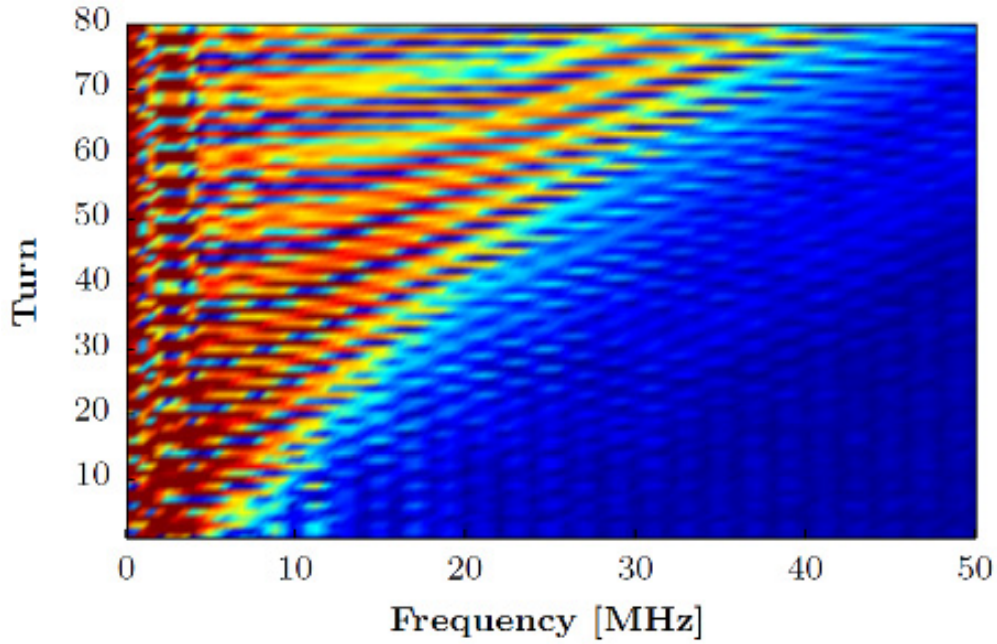




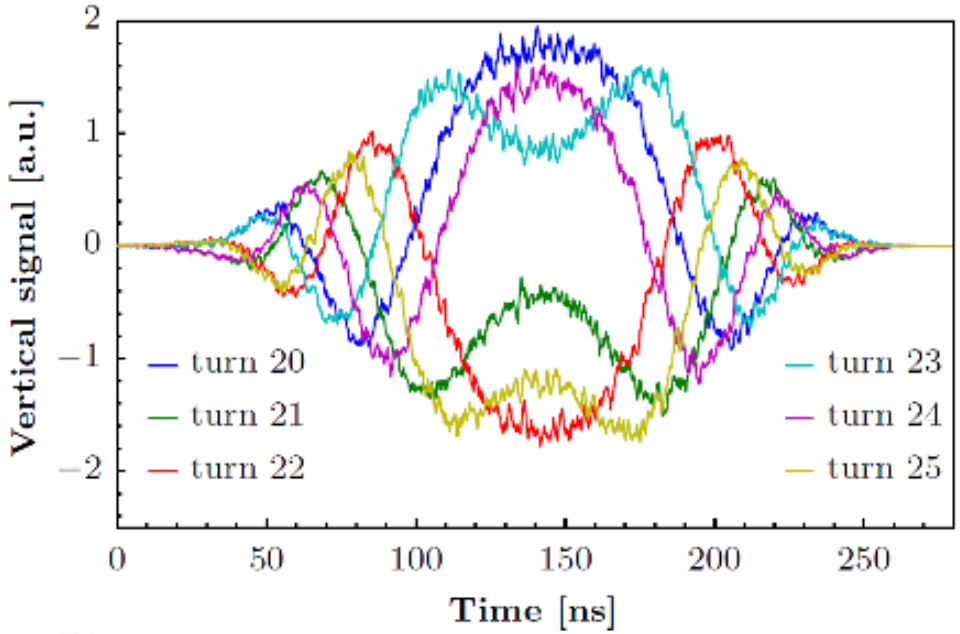
Injection oscillations: comparison

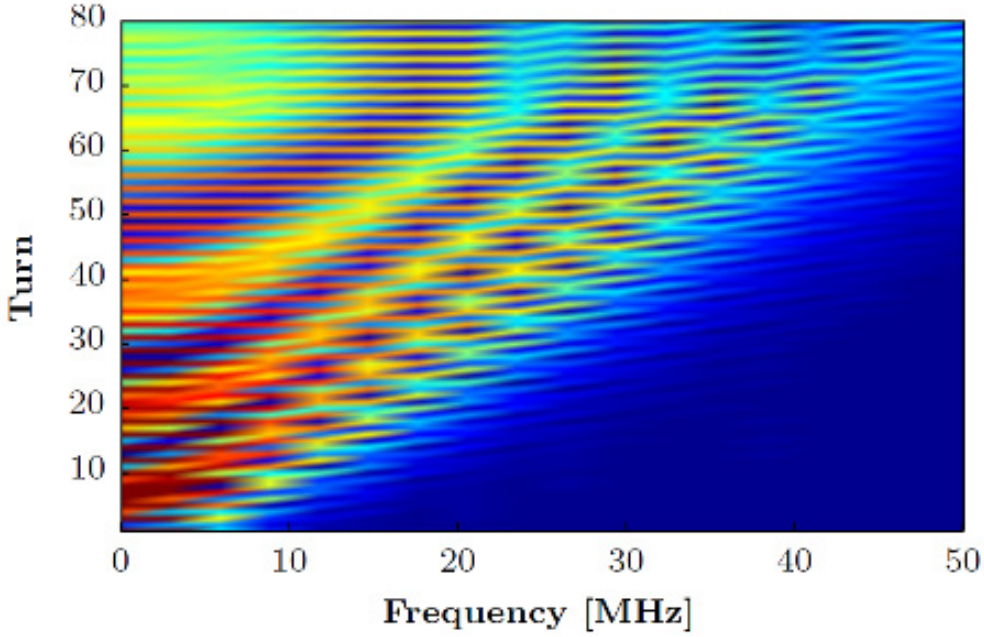
measurement





simulation

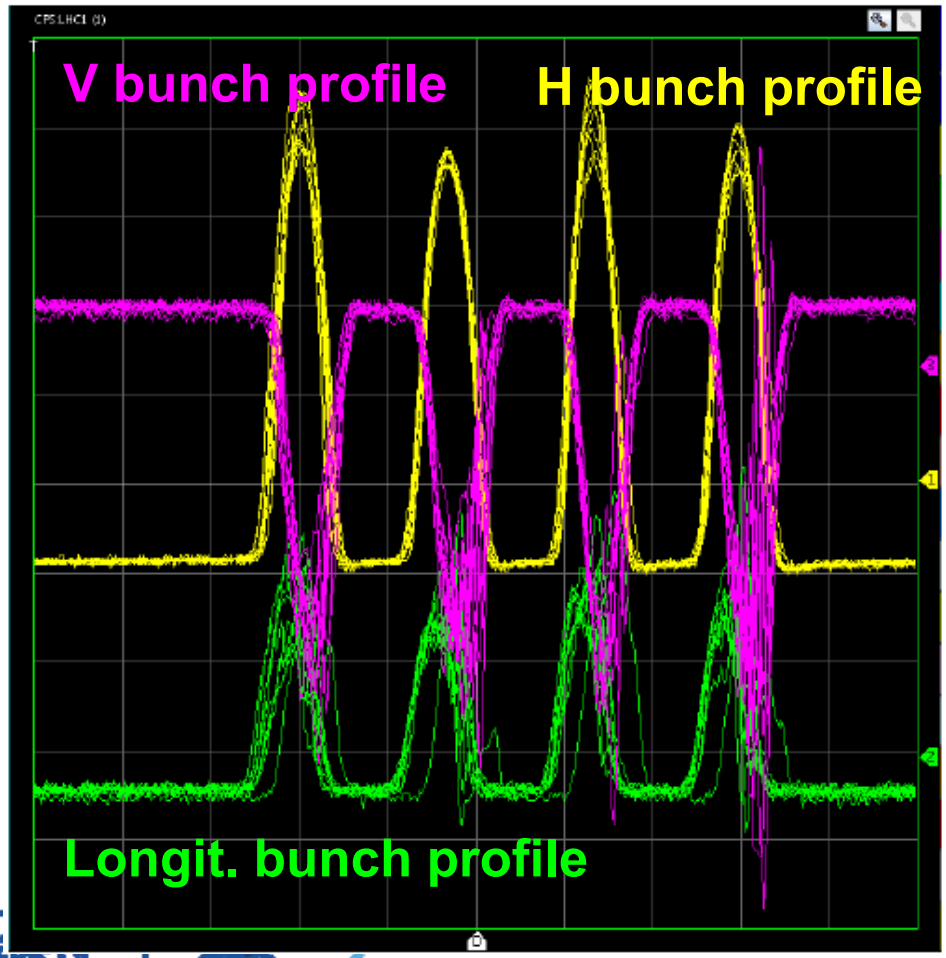




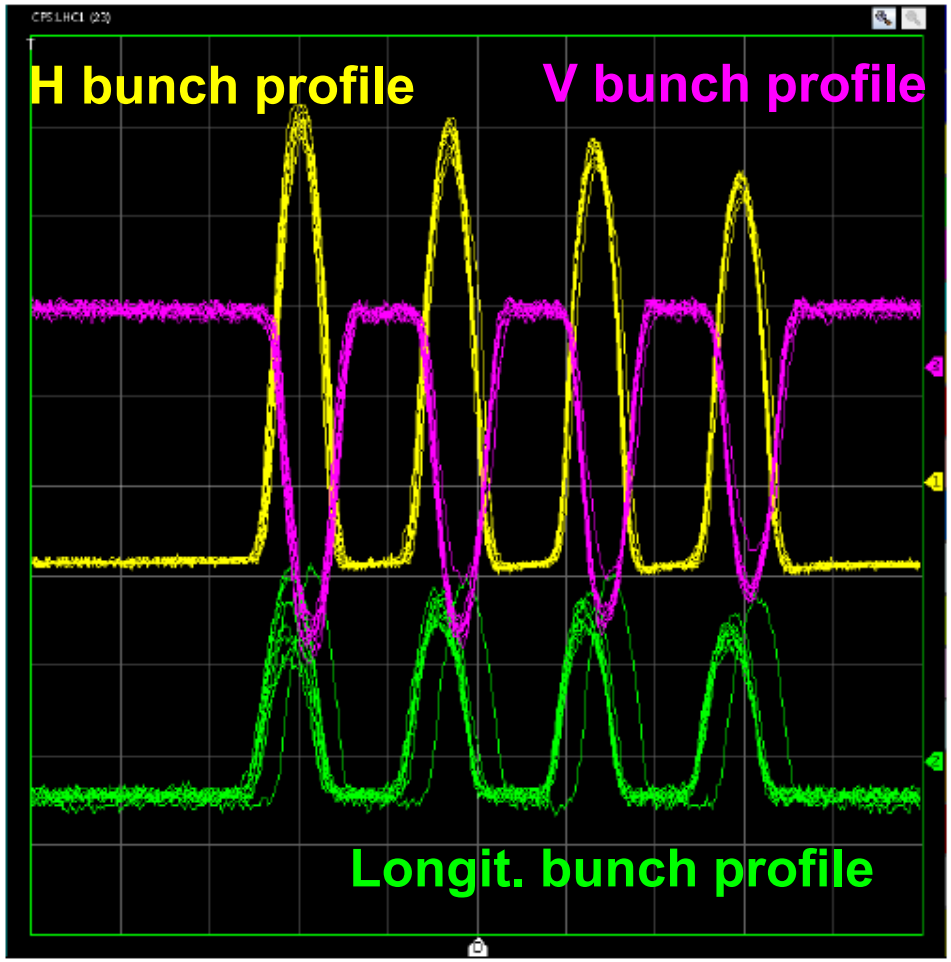
Last week results

Injection oscillations observed also on LHC-beams.
Damper can effectively cope with that.

Transverse damper OFF



Transverse damper ON



Continuous Extraction (CT, 70's): the principle

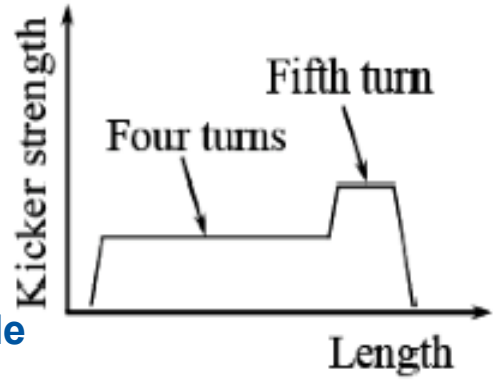
- Horizontal tune set to 6.25 phase advance per turn of 90° .

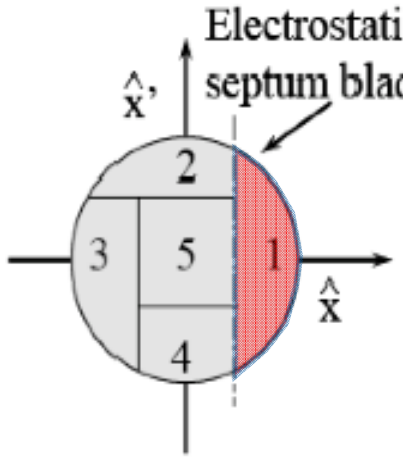
- The beam is de-bunched (PS main RF - 10 MHz, SPS main RF 200 MHz)
  - **Capture losses at SPS injection**

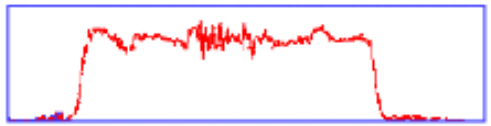
- A part of the proton beam is pushed by a slow and a fast bumps beyond the blade of an electrostatic septum.
  - **Instantaneous losses around the ring due to scattering with septum blade**

- The sliced beam that receives the kick of the electrostatic septum is extracted during the current machine turn. The rest is extracted with the same mechanism within the next 4 turns.

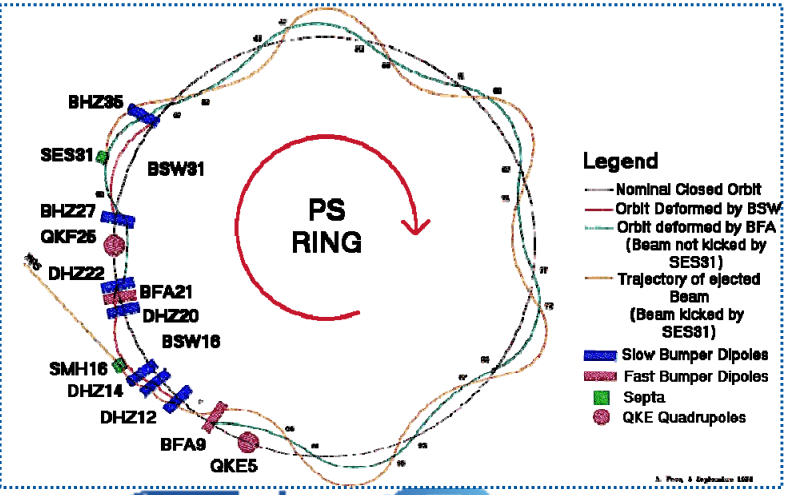
- The five beam slices feature the same intensity but different optical parameters.
  - **Mismatch at SPS injection**

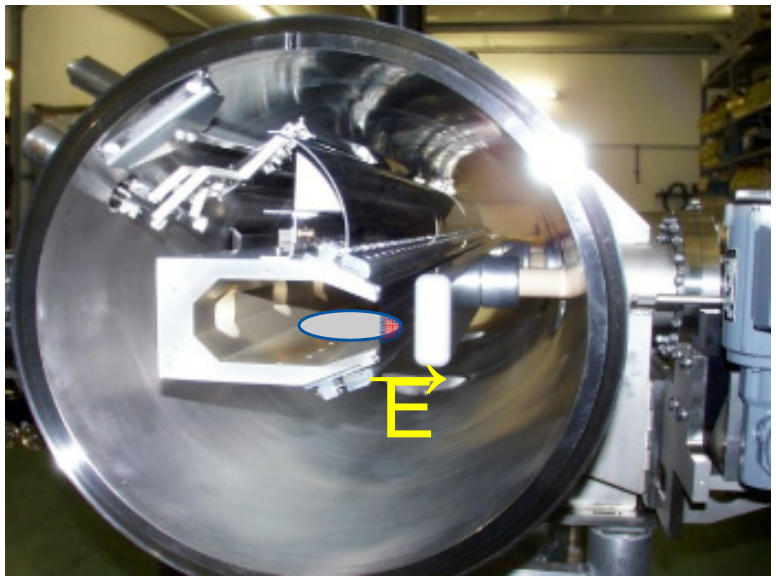




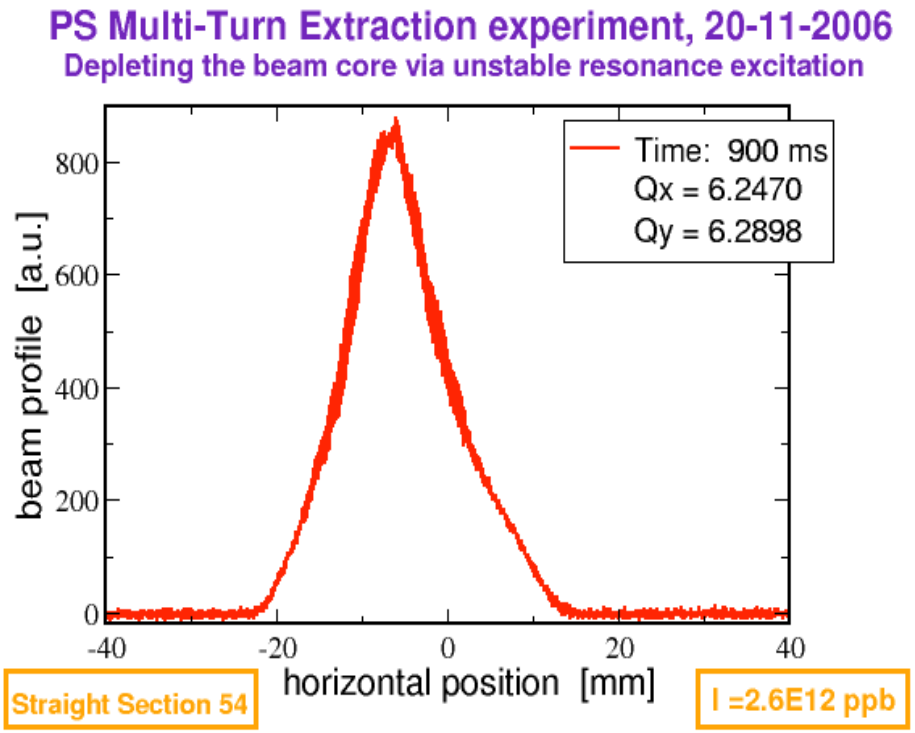


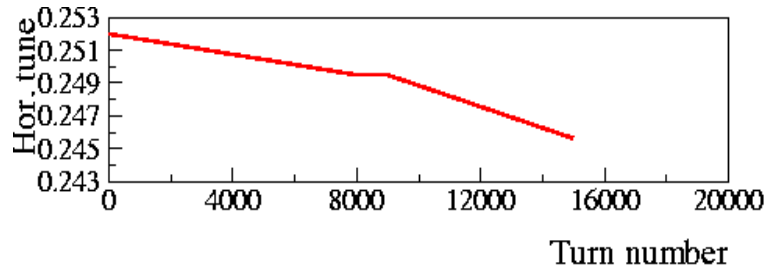
← Five PS turns →

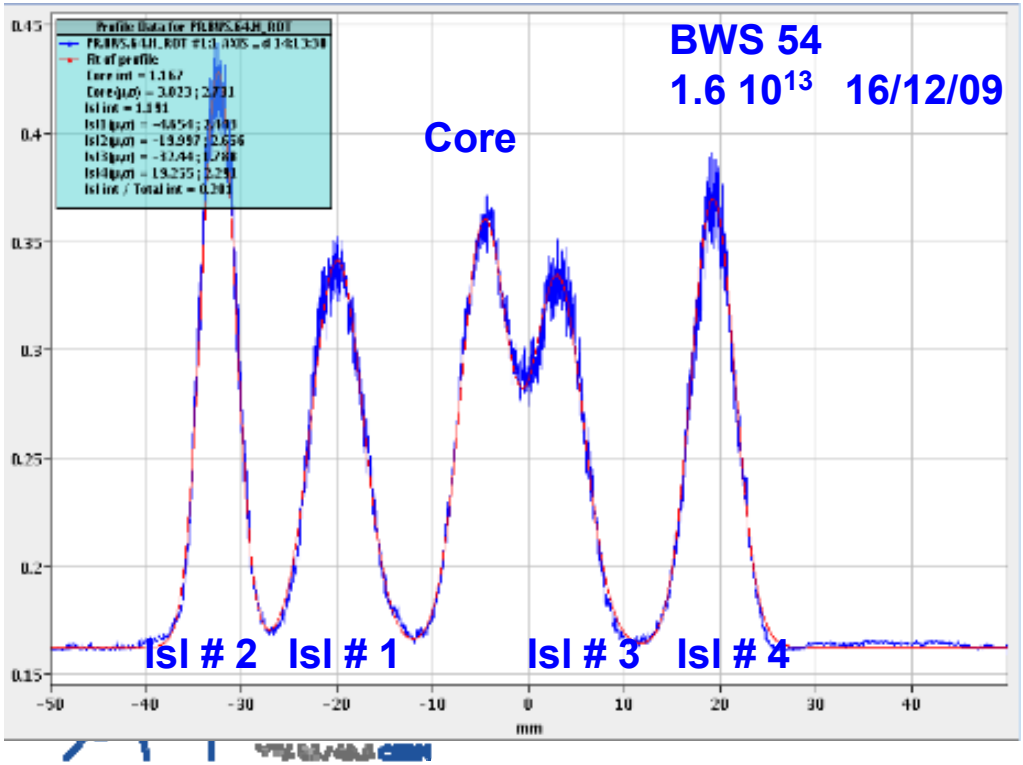


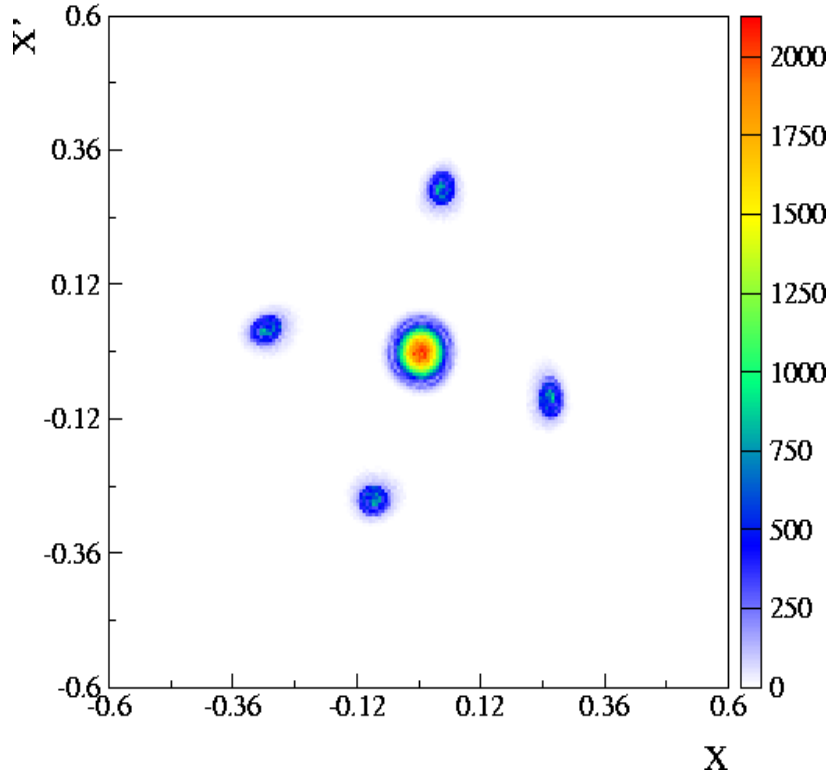


MTE: Multi-Turn extraction

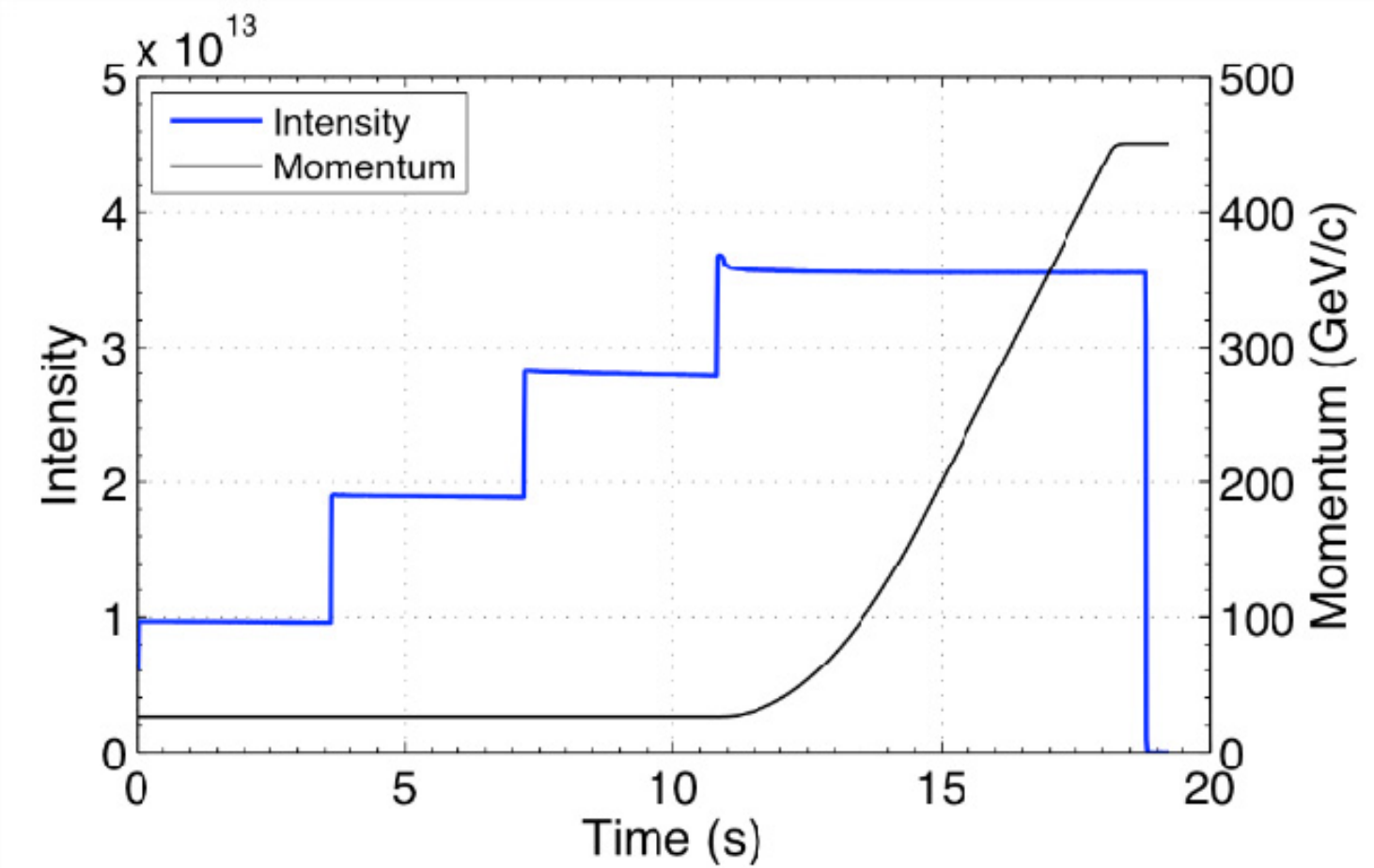




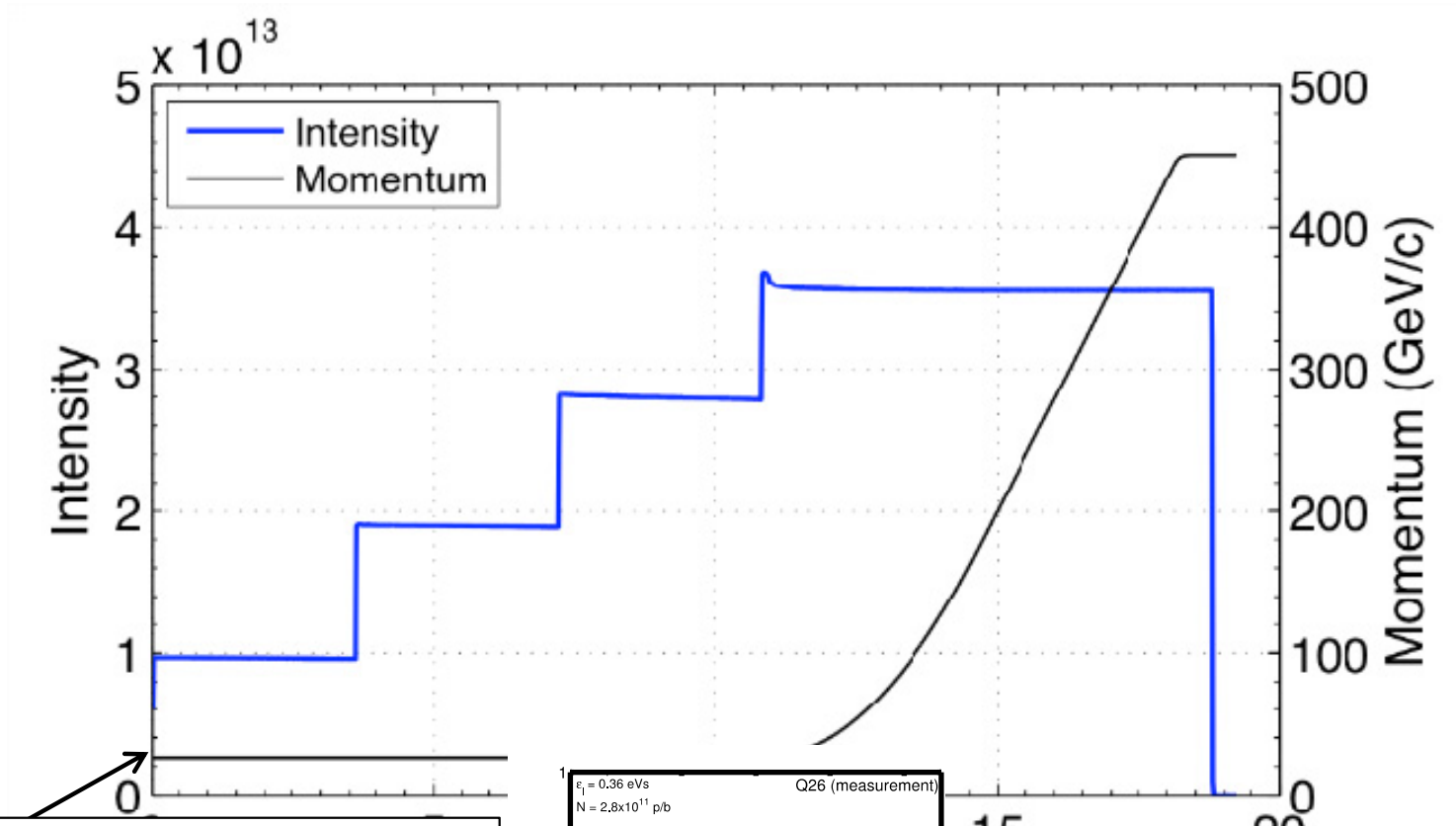


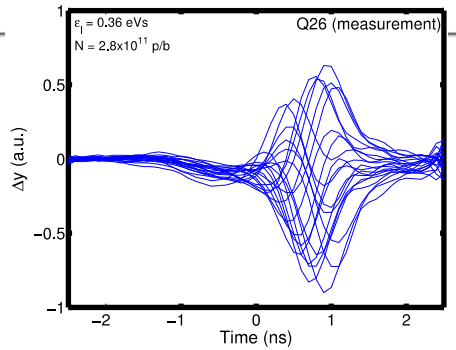


SPS limitations overview – LHC beams



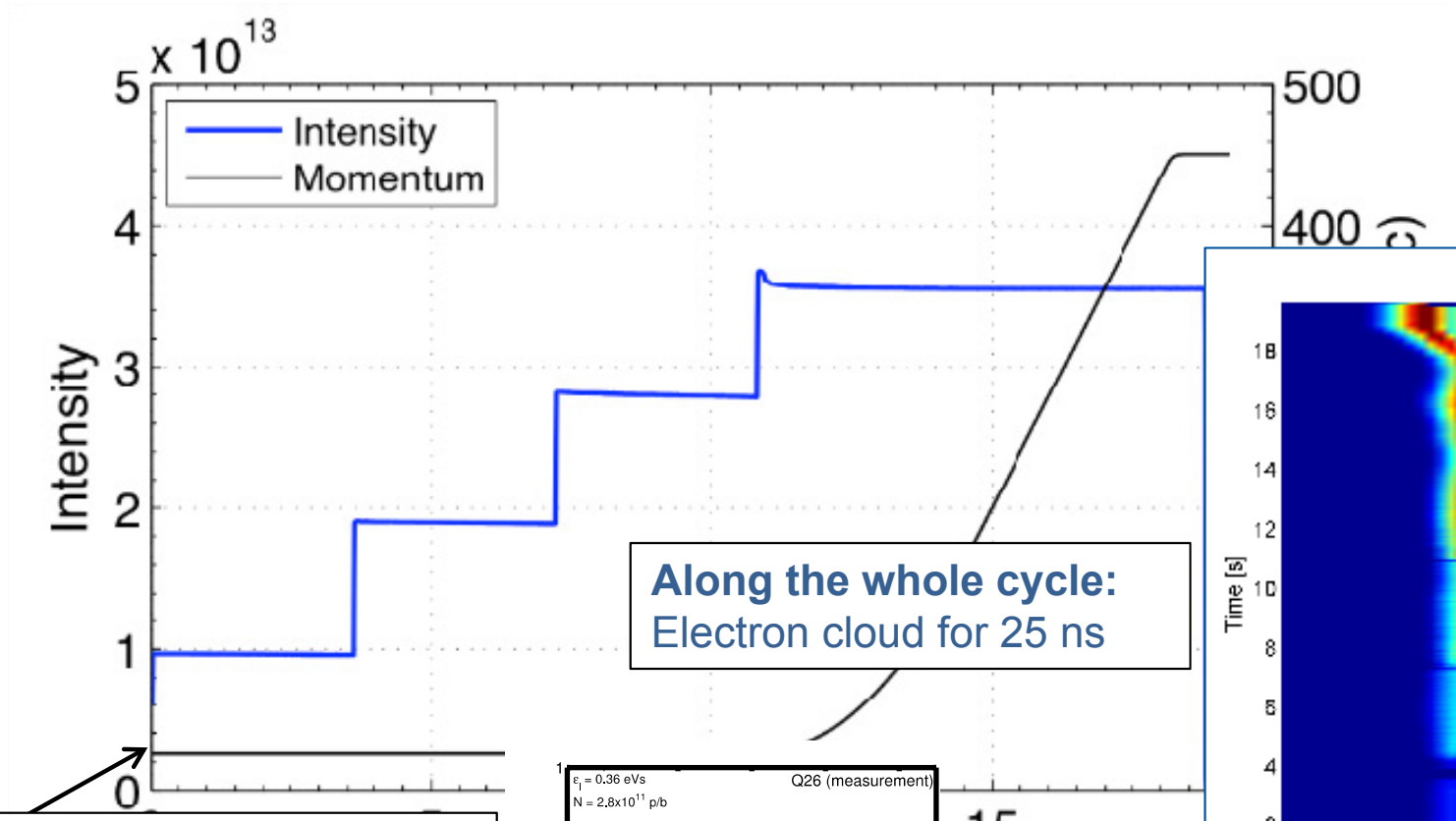
SPS limitations overview – LHC beams



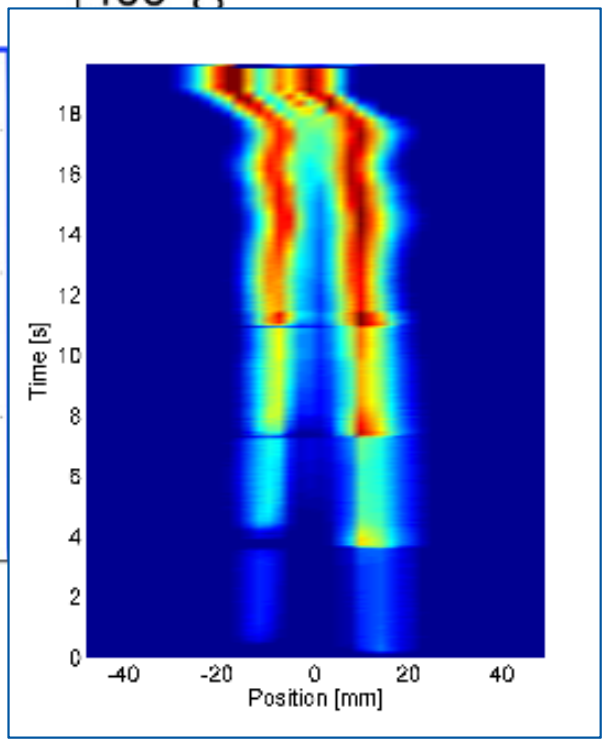


Injection flat bottom:
Capture losses, incoherent losses
Space charge
TMCI

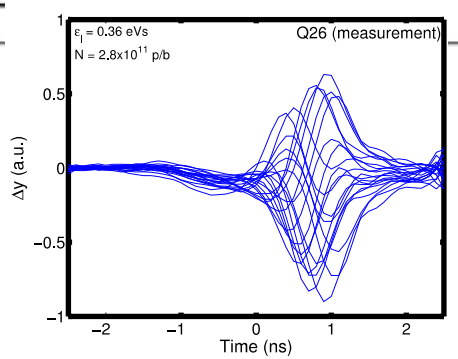
SPS limitations overview – LHC beams



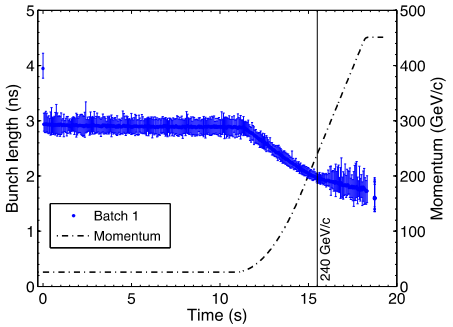
Along the whole cycle:
Electron cloud for 25 ns



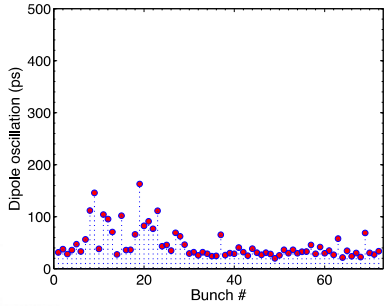
Injection flat bottom:
Capture losses, incoherent losses
Space charge
TMCI

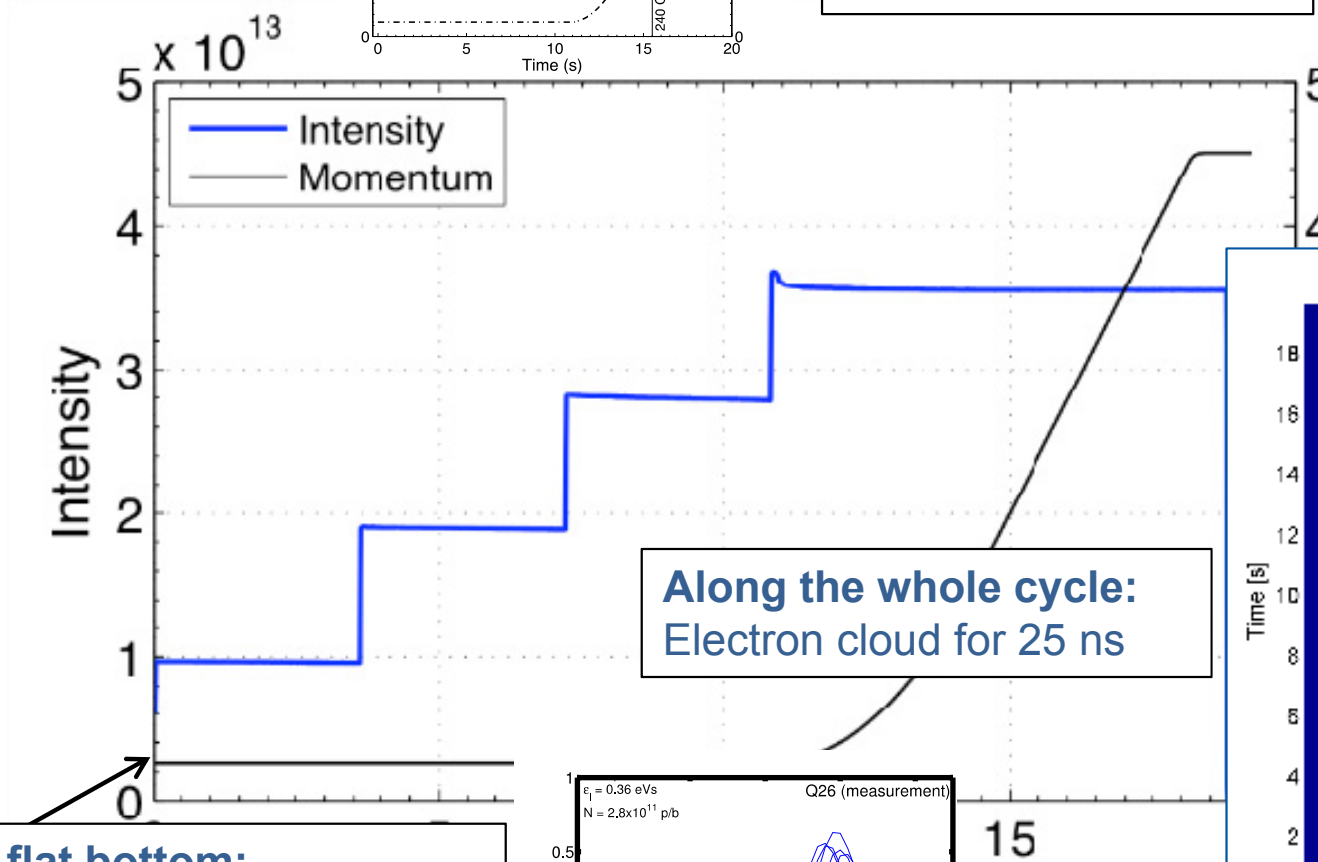


SPS limitations overview – LHC beams

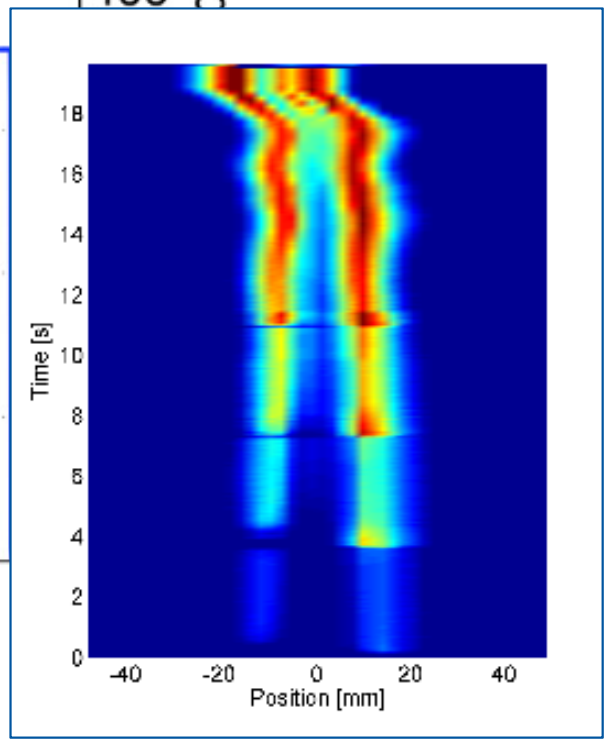


Ramp and flat top:
Longitudinal instability
Beam loading
RF power

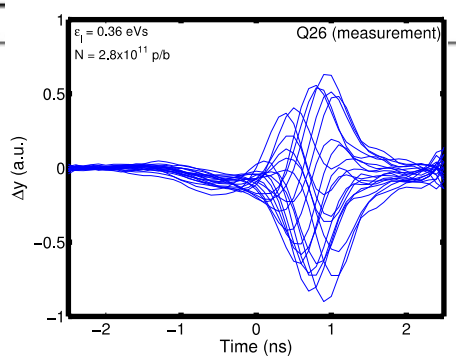




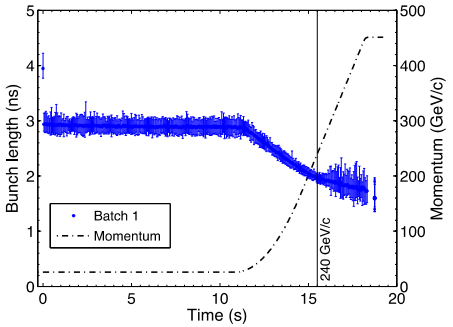
Along the whole cycle:
Electron cloud for 25 ns



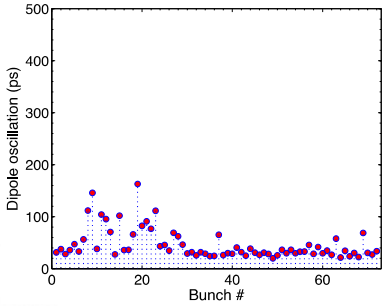
Injection flat bottom:
Capture losses, incoherent losses
Space charge
TMCI

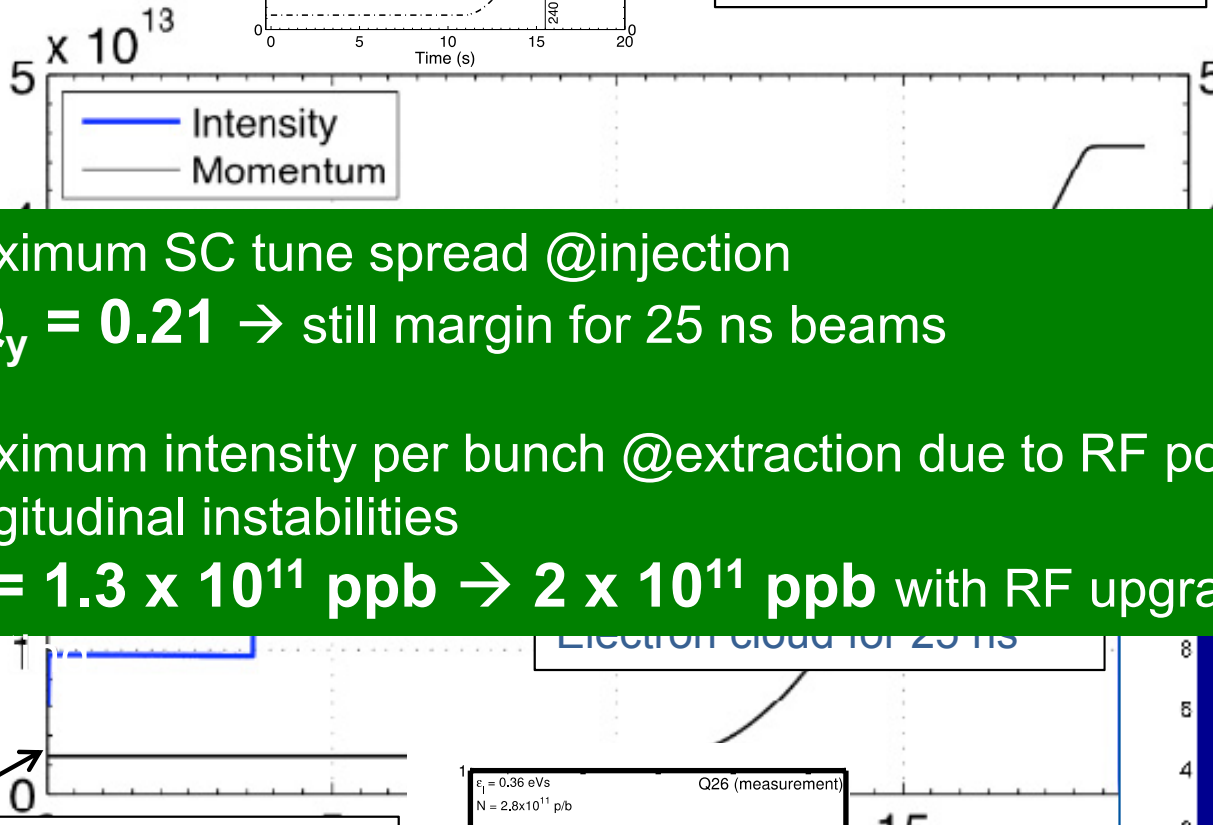


SPS limitations overview – LHC beams



Ramp and flat top:
Longitudinal instability
Beam loading
RF power

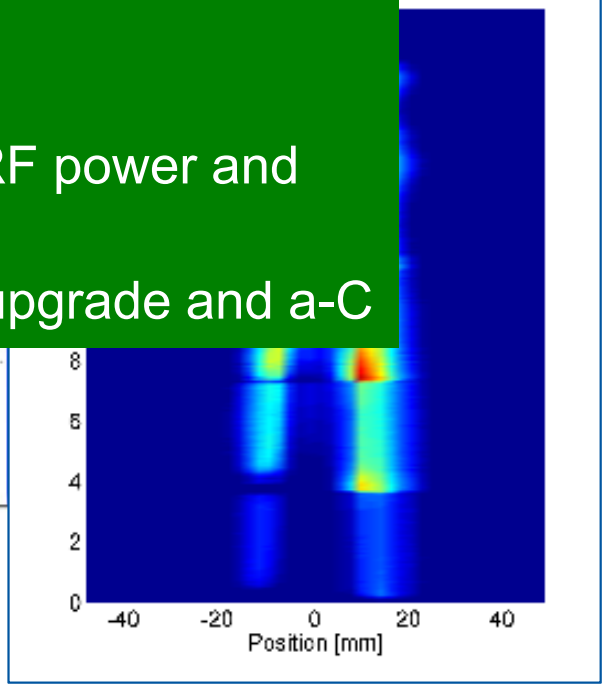




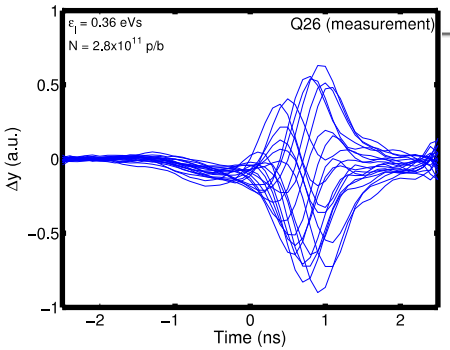
Maximum SC tune spread @injection
ΔQ_y **= 0.21** → still margin for 25 ns beams

Maximum intensity per bunch @extraction due to RF power and longitudinal instabilities
N_b= 1.3 x 10^{11} ppb → 2 x 10^{11} ppb with RF upgrade and a-C

Electron cloud for 25 ns



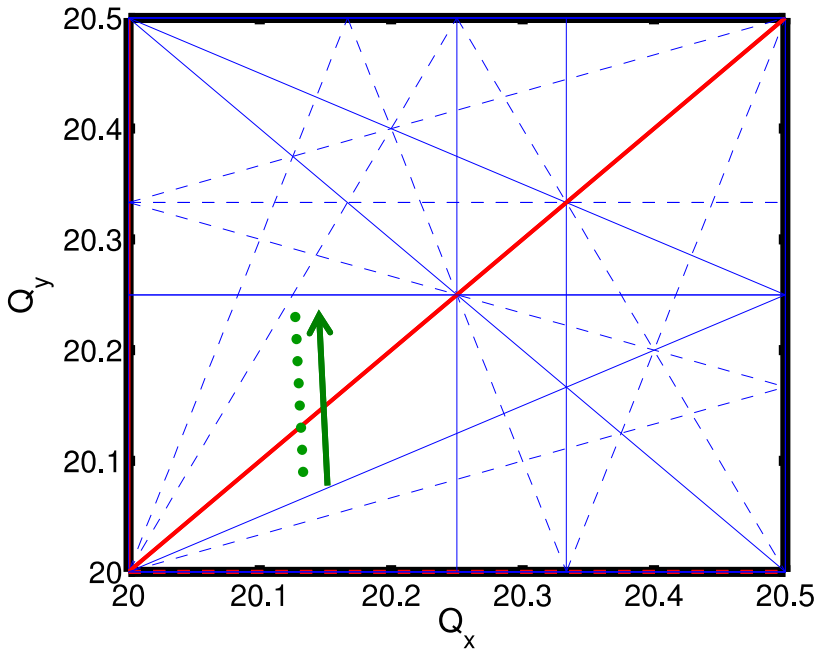
Injection flat bottom:
Capture losses, incoherent losses
Space charge
TMCI

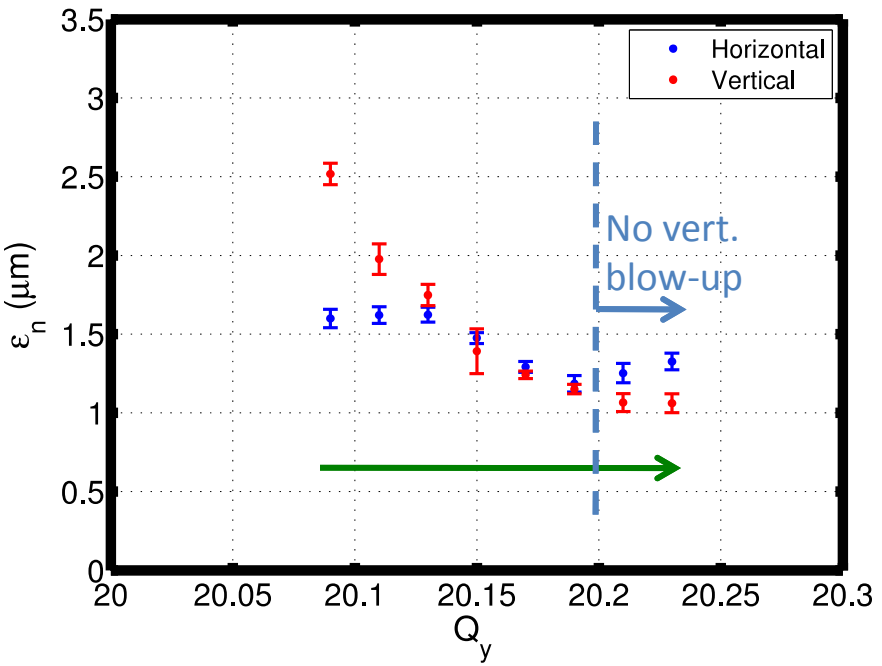


Space charge tune shift – SPS

- **50 ns BCMS beam on LHC filling cycle**
  - Single batch with N ~ 2×10^{11} p/b @inj. and ε_n~ 1.1 μm
  - Measurements for different tunes
  - Average of 5 measurements at the end of flat bottom
  - No (vertical) blow-up for $Q_y \geq 0.21$ → consistent with expected tune shift

Expect (Q20)
ΔQ_x ~ 0.11
ΔQ_y ~ 0.20





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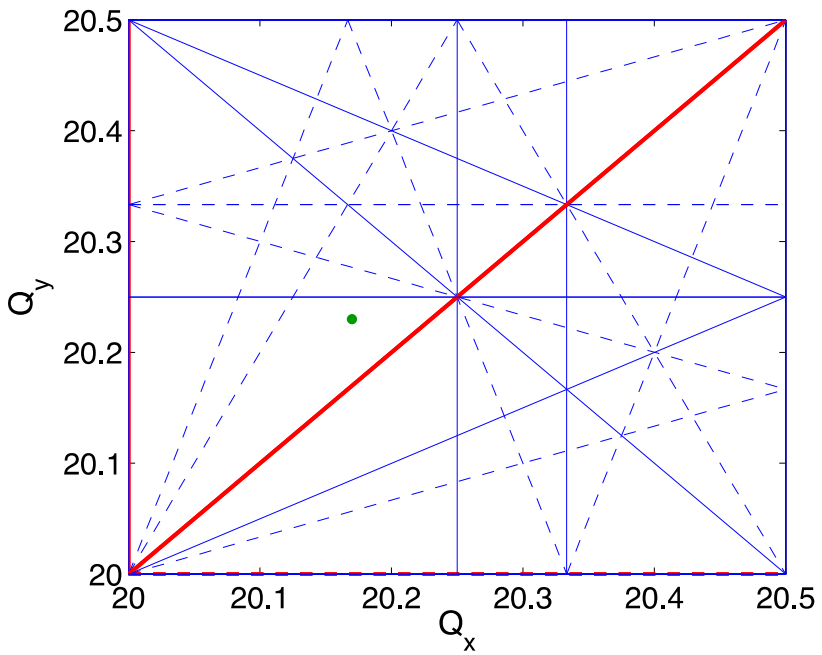
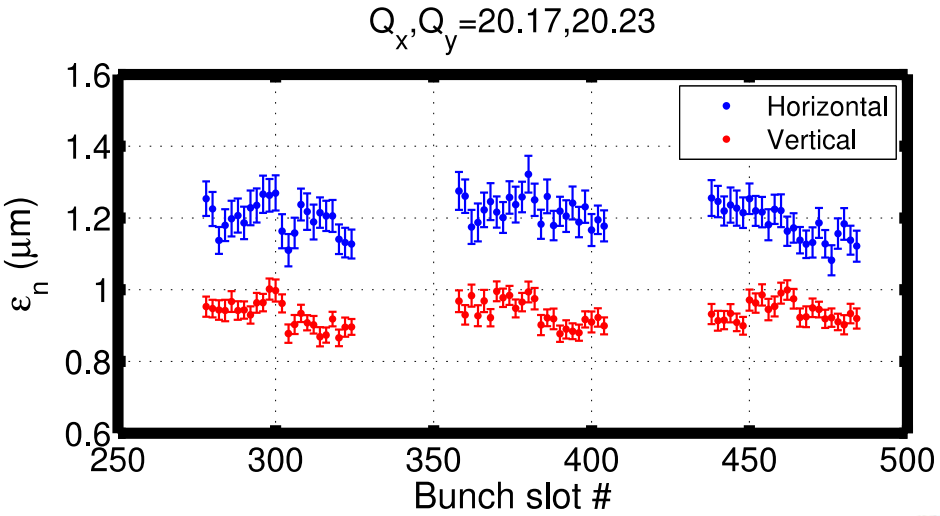
ΔQ_x ~ 0.11
ΔQ_y ~ 0.20

- **Measurement at end of flat bottom with 3 BCMS batches**
  - Similar emittances for all batches (different storing times)**! Transmission around 95% (without scraping)**
  - During LHC filling with BCMS beam had even **$\Delta Q_y = 0.21$** → considered as present maximum

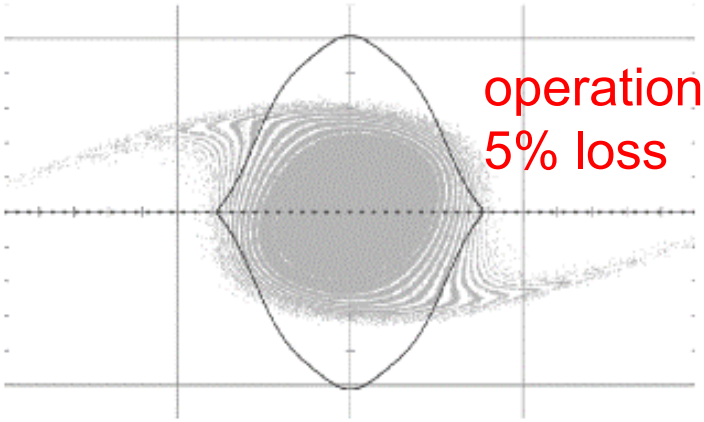




Bunch-by-bunch Wire Scanner measurements not calibrated

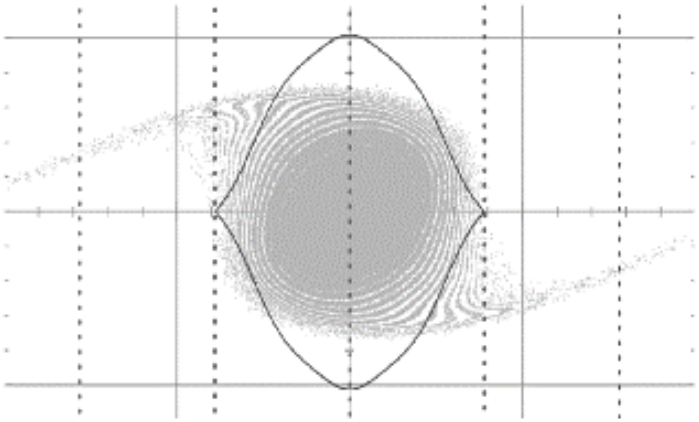
Capture loss due to PS bunch shape (after rotation in longitudinal phase space)

Shape can be improved by higher PS voltage: => tails are less populated but losses are there!



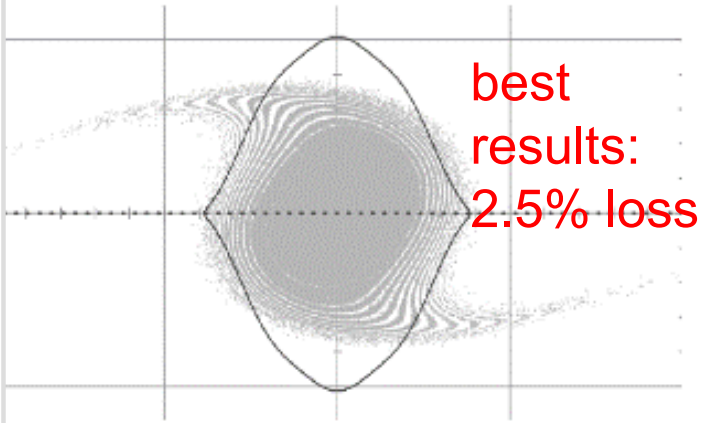
operation: 5% loss

(a) $V_{40\ MHz} = 300$ kV, $V_{80\ MHz} = 600$ kV



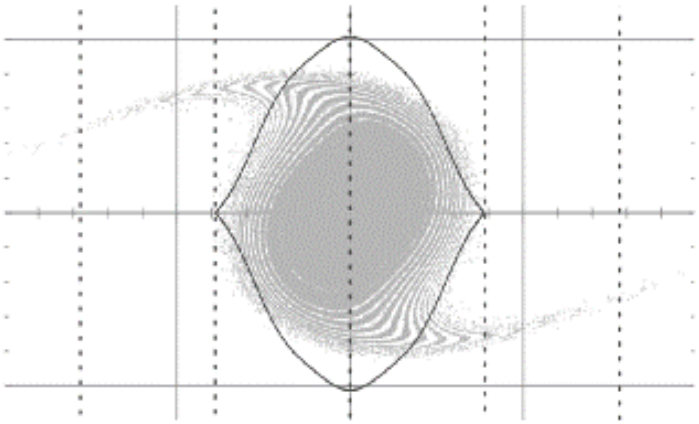
(b) $V_{40\ MHz} = 300$ kV, $V_{80\ MHz} = 900$ kV

H. Timko et al., ESME simulations of realistic bunch distribution from PS tomography (no intensity effects included)



best results: 2.5% loss

(c) $V_{40\ MHz} = 600$ kV, $V_{80\ MHz} = 600$ kV

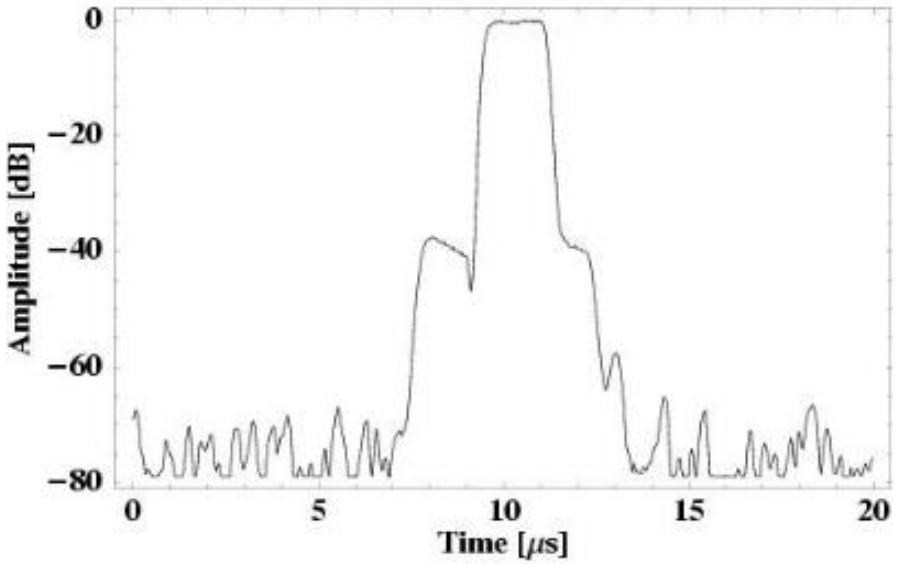


(d) $V_{40\ MHz} = 600$ kV, $V_{80\ MHz} = 900$ kV

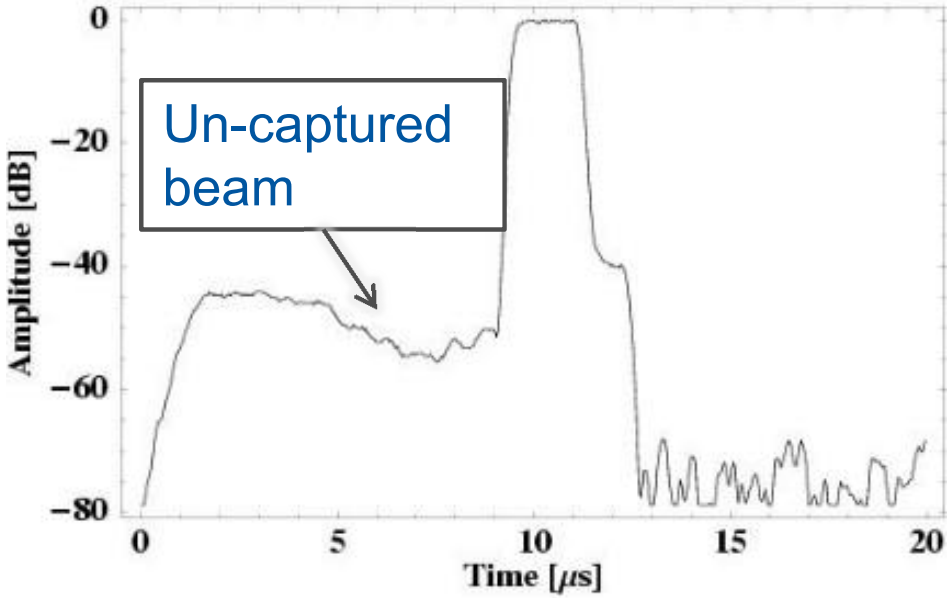
H. Timko et al., Phys. Rev. ST Accel. Beams 16 (2013) 051004

Capture losses: un-captured beam after injection

Uncaptured beam is always moving to the left.
Energy loss (dp/p < 0) due to resistive impedance?



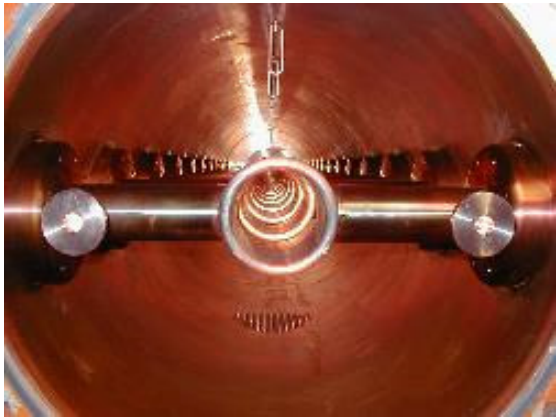
Injection at 26 GeV/c



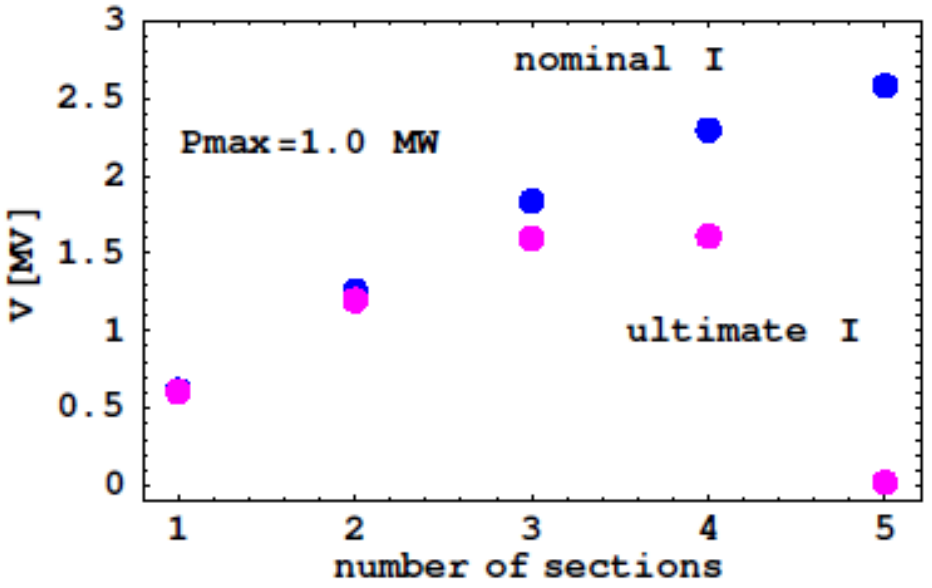
A few seconds later

SPS 200 MHz travelling wave RF cavities

- **Present situation:**
  - 2 cavities of 5 sections
  - 2 cavities of 4 section
- **Power/cavity limit**
  - Presently 0.7 MW (continuous mode)
  - Around 1.05 MW for ½ ring in pulsed mode with new LLRF



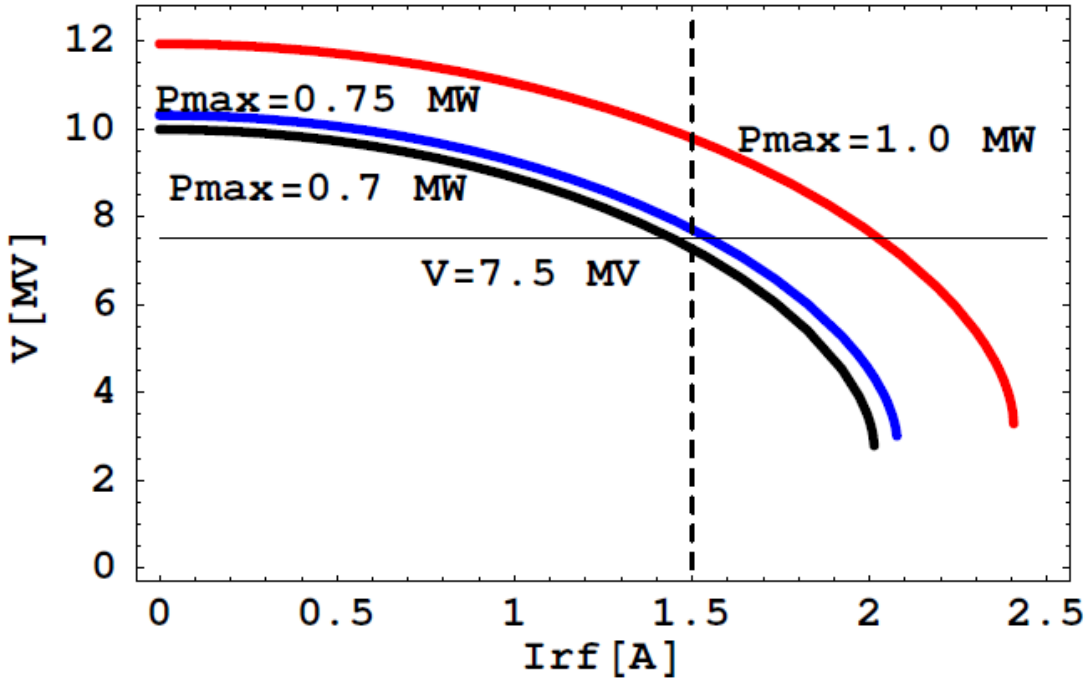
- **Beam loading: less voltage available for higher intensity!**
  - 5-section cavities are less efficient for high intensity due to beam loading
- **Upgrade:**
  - **rearrange the 4 existing cavities into 6**
    - 2x4+4x3 = 20 sections, with 2 spare sections
    - gives also 20% less impedance
  - **2 additional new power plants with 1.6 MW each**



Estimation of maximum intensity from SPS

- **Present situation: 4 cavities, 0.7 MW & 7.5 MV available → 1.3x10^{11} p/b**
- **Higher voltage required for higher intensity**
  - larger ε_l to avoid loss of Landau damping (LD): V ~ N
  - to compensate potential well distortion (PWD): V ~ N

} Otherwise longer bunches at extraction and losses in LHC



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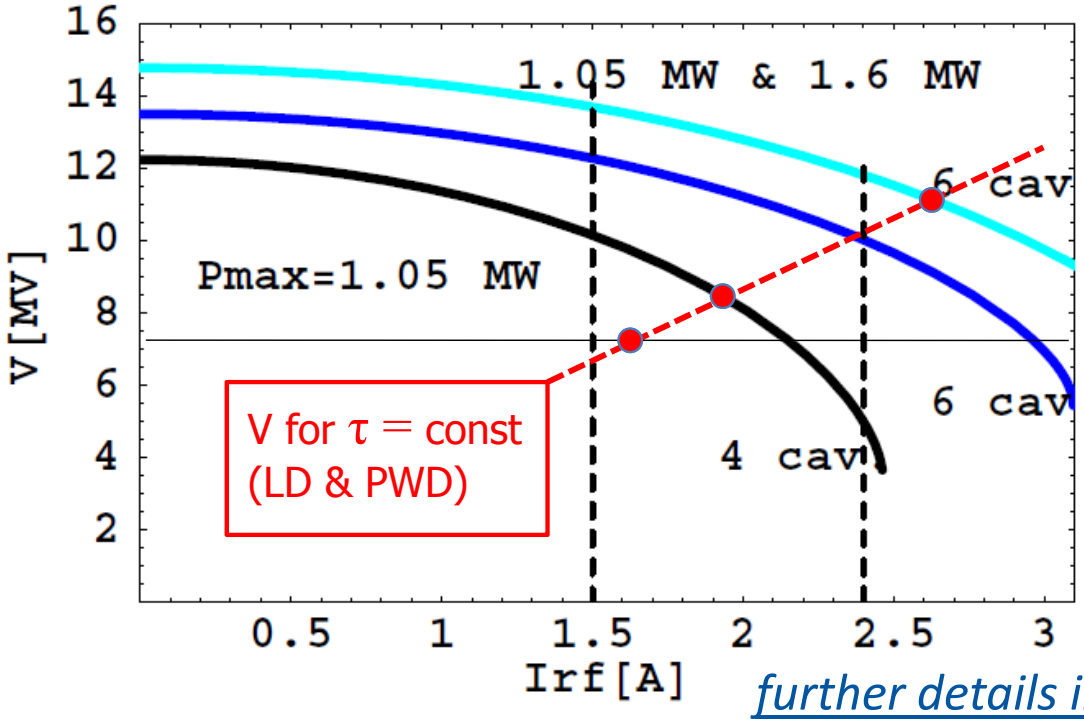
- **After full RF upgrade: 4 cavities with 1.05 MW & 2 cavities with 1.6 MW → 2.0x10^{11} p/b**



Scaling to preserve bunch length at extraction based on presently achieved performance and understanding of stability scaling …

further details in the presentation of H. Damerau

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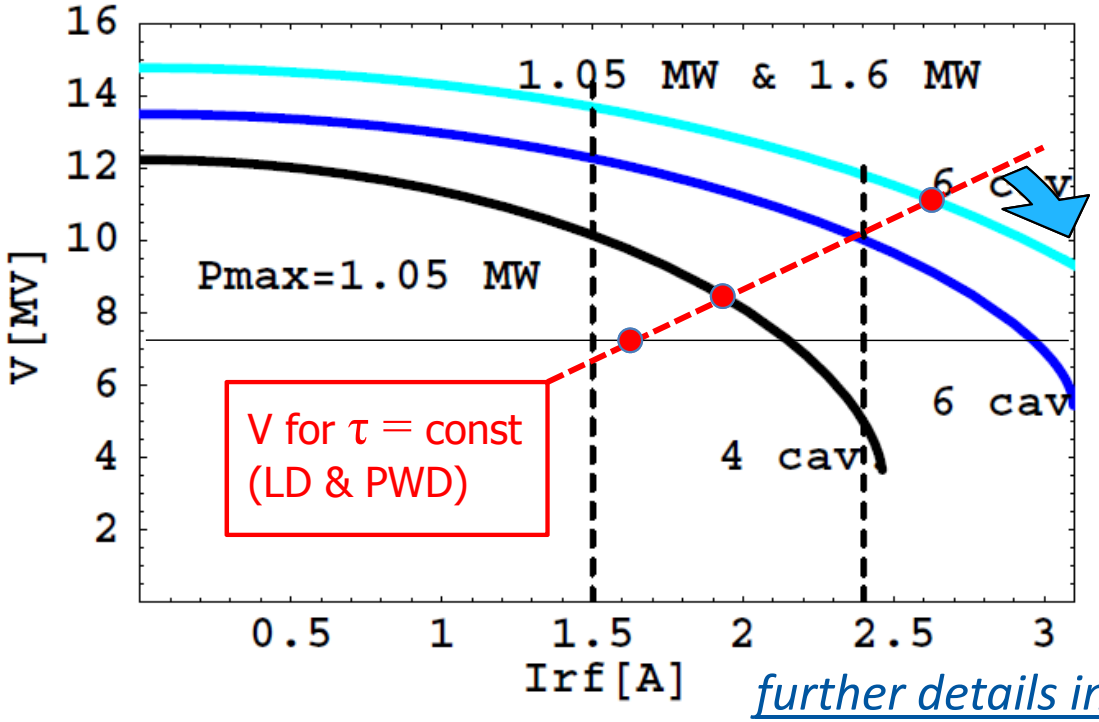


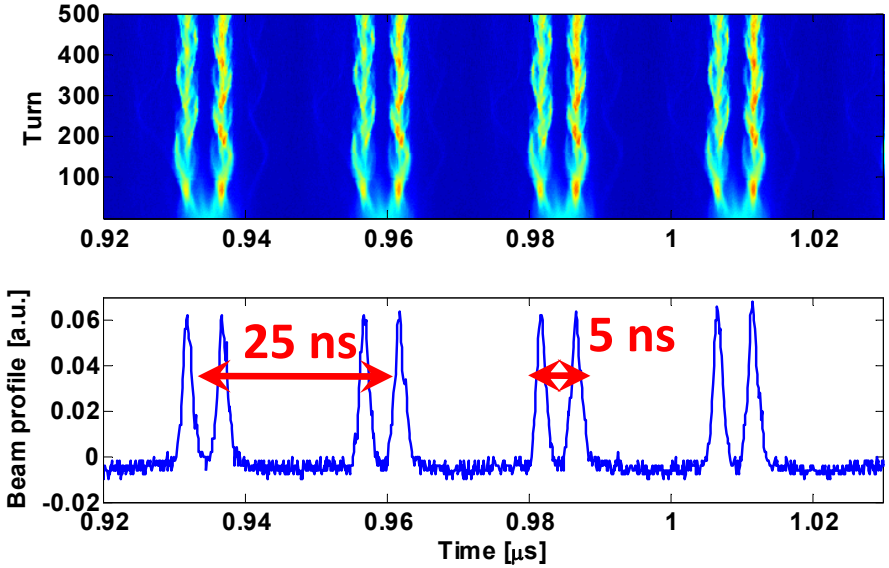
Scaling to preserve bunch length at extraction based on presently achieved performance and understanding of stability scaling …

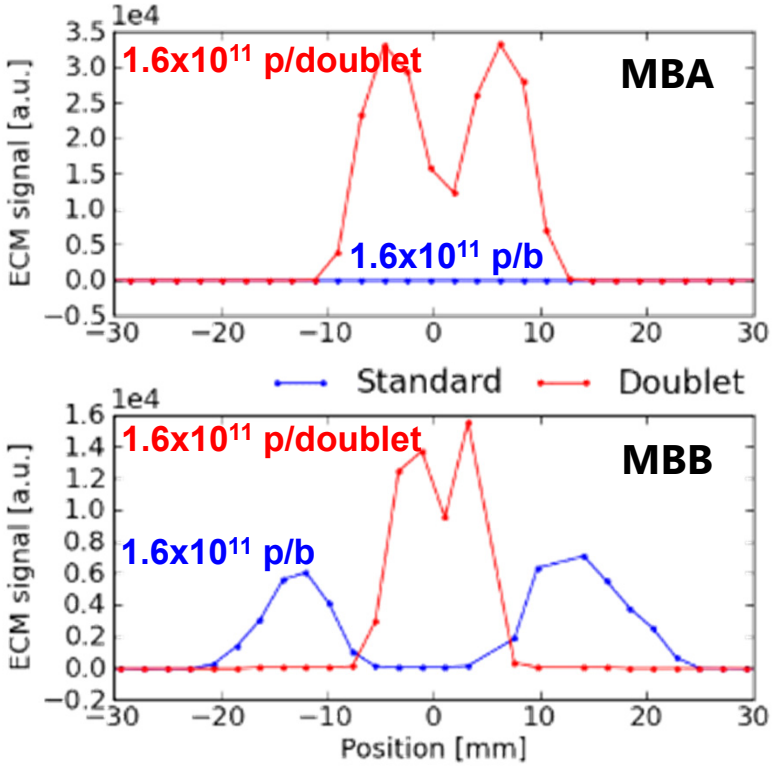
Ongoing efforts within LIU SPS to identify impedance sources in view of possible impedance reduction campaign, but not easy !

further details in the presentation of H. Damerau

e-cloud: Doublet beam, a possible boost to scrubbing

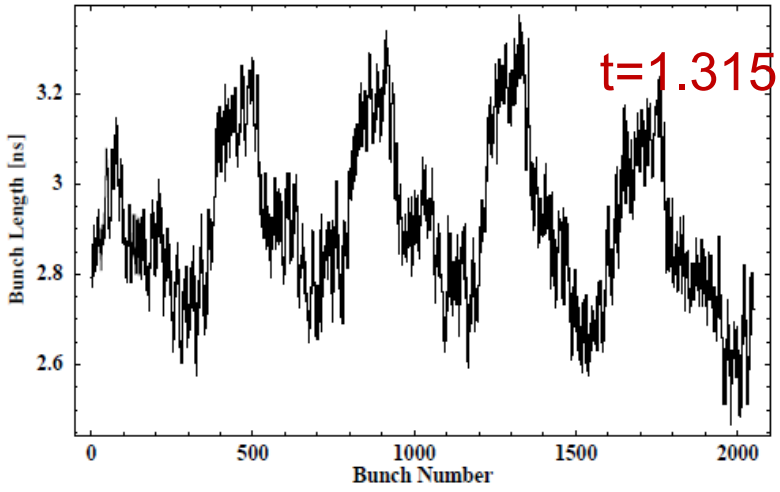
- Injection of long bunches into SPS (with 25 ns spacing)
- Capturing each bunch in 2 neighboring 200 MHz buckets
- Successfully tested in MDs at the end of 2012/13 run with 1.6×10^{11} p/doublet
- Clear enhancement on **e-cloud detectors** compared to standard 25 ns beam measured

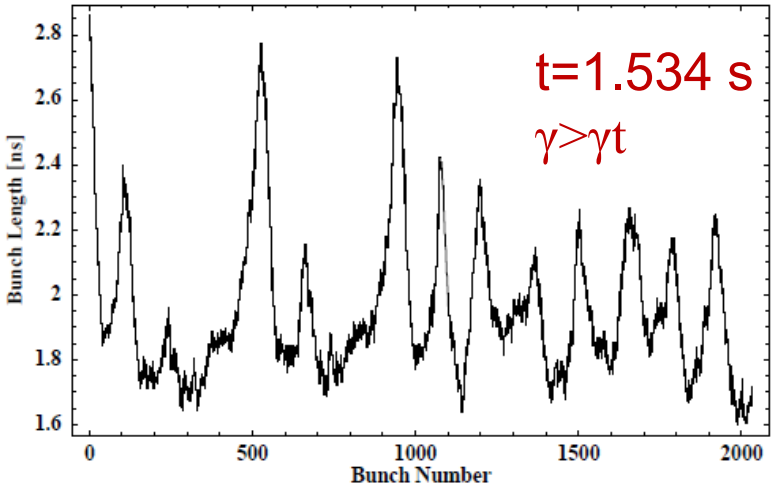


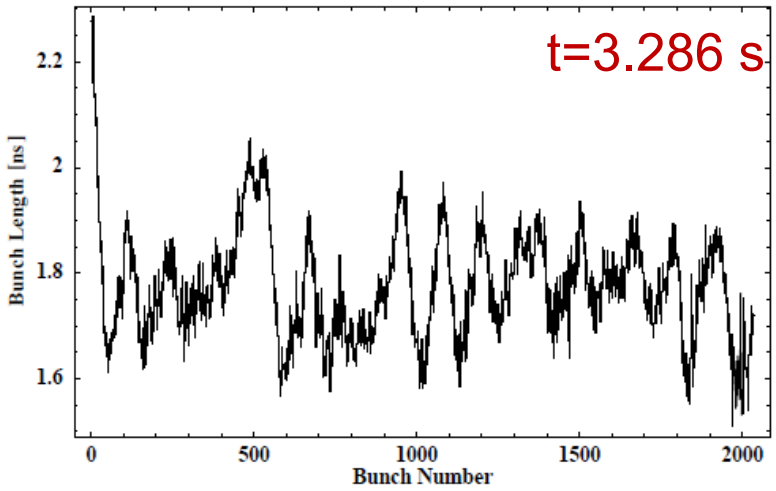


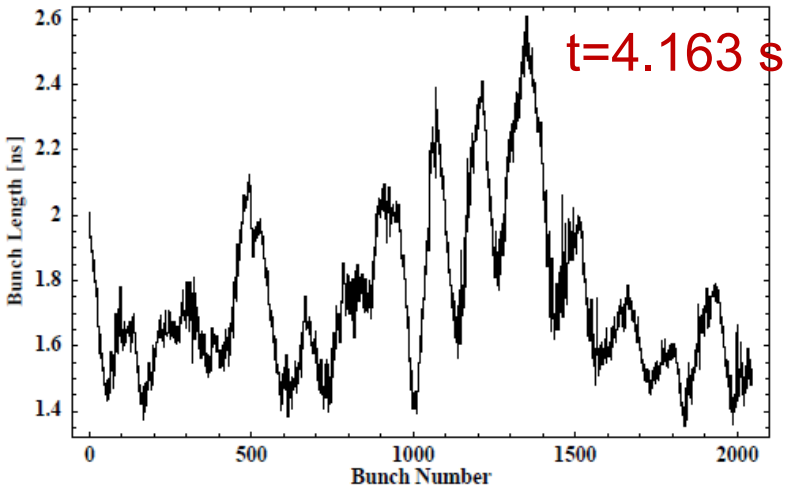
Bunch length along the batch during cycle for high intensity beam

5.6x10^{13} injected, 15% losses







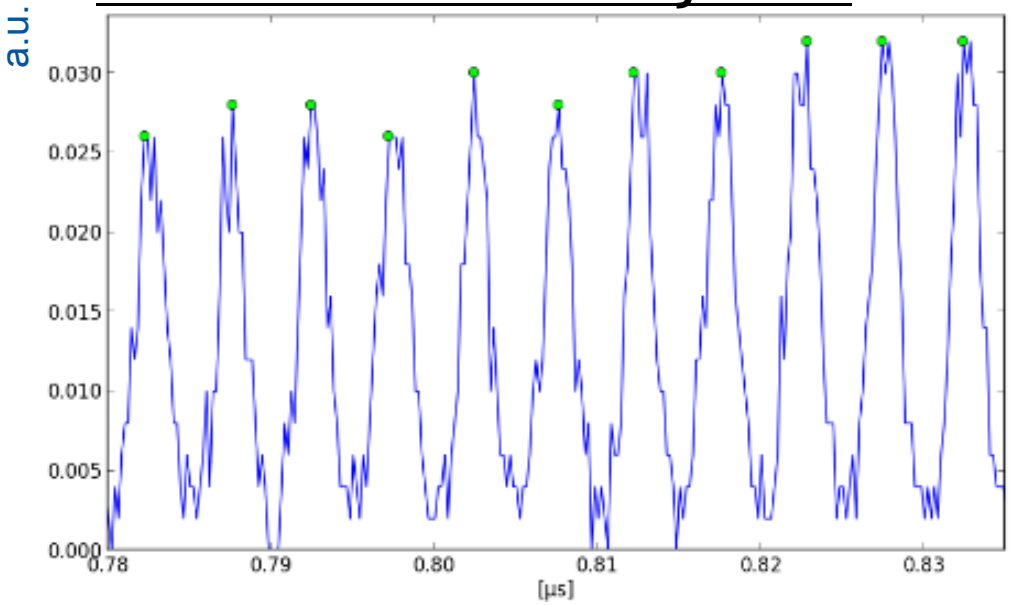


(AB-Note-2005-034 RF, T. Bohl et al.)

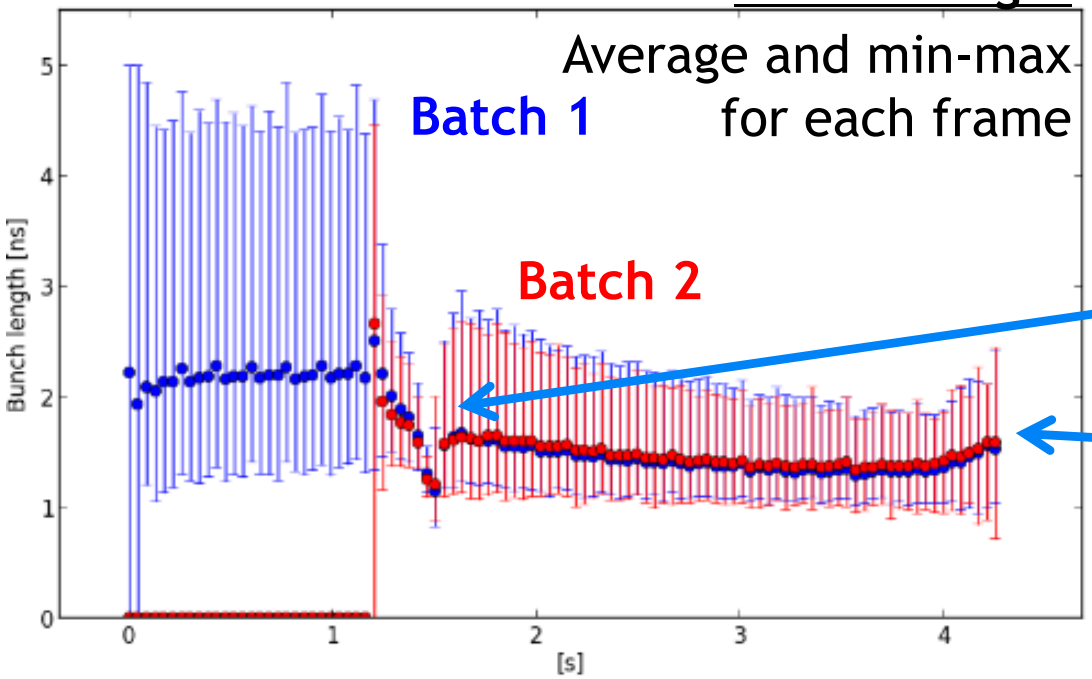
Nominal CNGS Cycle

- Injected beam is practically debunched
- Bunches not well defined after injection

Beam structure after injection



Bunch Length

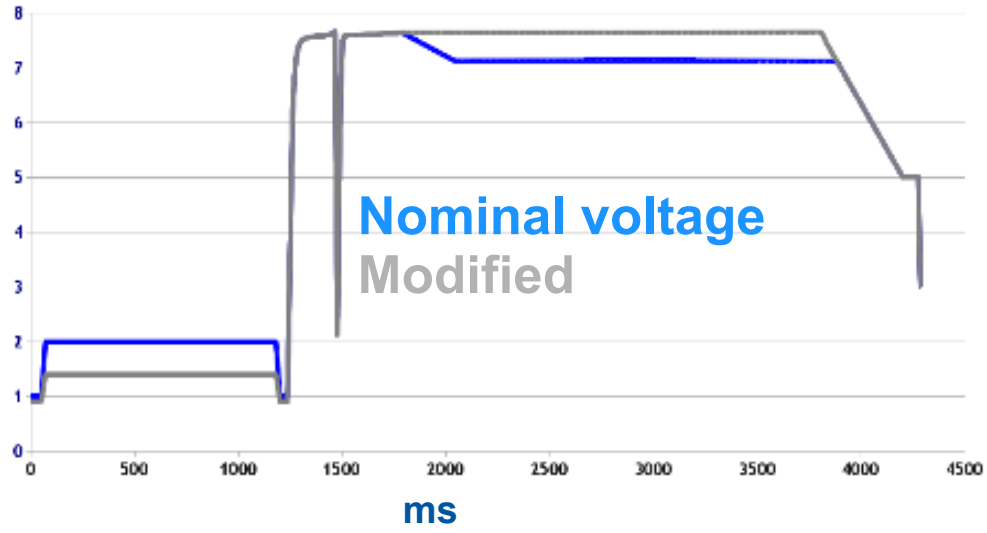


- transition
- instability at the end of the cycle

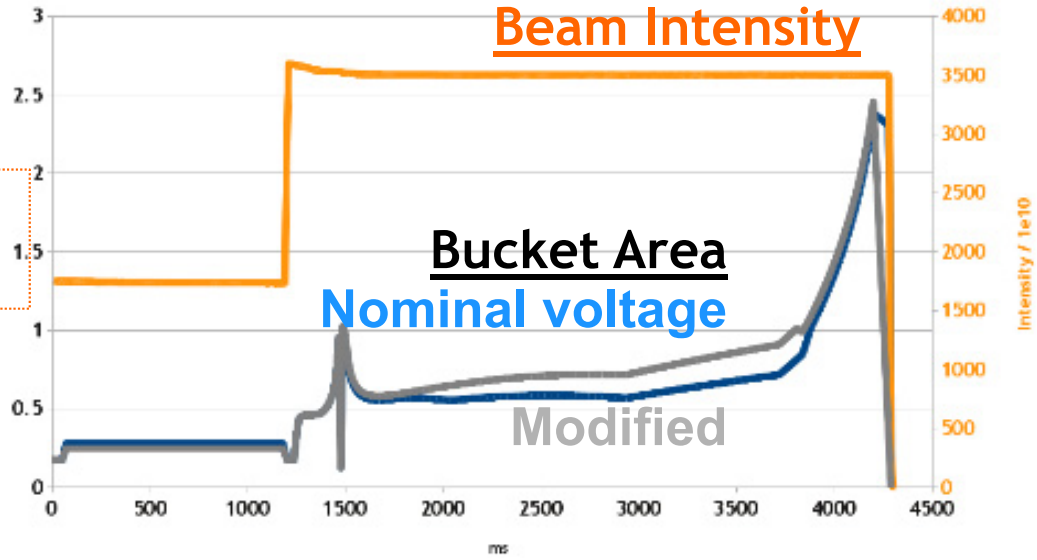
C. Lazaridis

Reducing beam losses

- Losses due to instabilities around 2.8 s in the cycle
  - Maximum 200 MHz RF voltage
- Tried reducing voltage to improve stability
  - Constant bucket area
  - Increasing synchrotron frequency spread inside the bunch



For intensities ~3.7x10^{13} losses are 3.5%
$\Rightarrow$ 0.2% reduction in high-energy losses



C. Lazaridis

Summary injectors losses

- LHC beam losses produced by:
  - Space charge at injection (PSB – PS – SPS)
  - Transverse instabilities (PSB – PS)
  - Longitudinal instabilities (PS – PSB)
  - Insufficient RF power (SPS)
  - Not optimized bunch shape at transfer (PS ➔ SPS)
- High intensity beam losses produced by:
  - Mechanical aperture (PSB – PS – SPS) and optics mismatch at injection (PS ➔ SPS)
  - Beam instabilities (or oscillations PSB ➔PS)
  - Extraction mechanism (PS ➔ SPS)
  - Absence of bunch-to-bucket transfer (PS ➔ SPS)