LHC Injectors Upgrade

Can we ever reach the HL-LHC requirements with the injectors?

H. Bartosik, G. Iadarola, Y. Papaphilippou, G. Rumolo, E. Shaposhnikova

Acknowledgements: G. Arduini, T. Argyropoulos, J. Bauche, T. Bohl, K. Cornelis, P. Costa Pinto, H. Damerau, R. de Maria, J. Esteban Müller, R. Garoby, S. Gilardoni, B. Goddard, S. Hancock, W. Höfle, M. Meddahi, B. Mikulec, M. Taborelli, H. Timko, R. Wasef

Agenda

- **Assumptions on LIU upgrades**
- **Achievable brightness in the PSB**
- **Challenges in the PS**
- **Challenges in the SPS**
  - TMCI at injection
  - Space charge
  - Longitudinal instabilities and beam loading
  - Electron cloud in the SPS
- **Summary of expected performance after implementation of all US2 upgrades**

Assumptions on LIU upgrades

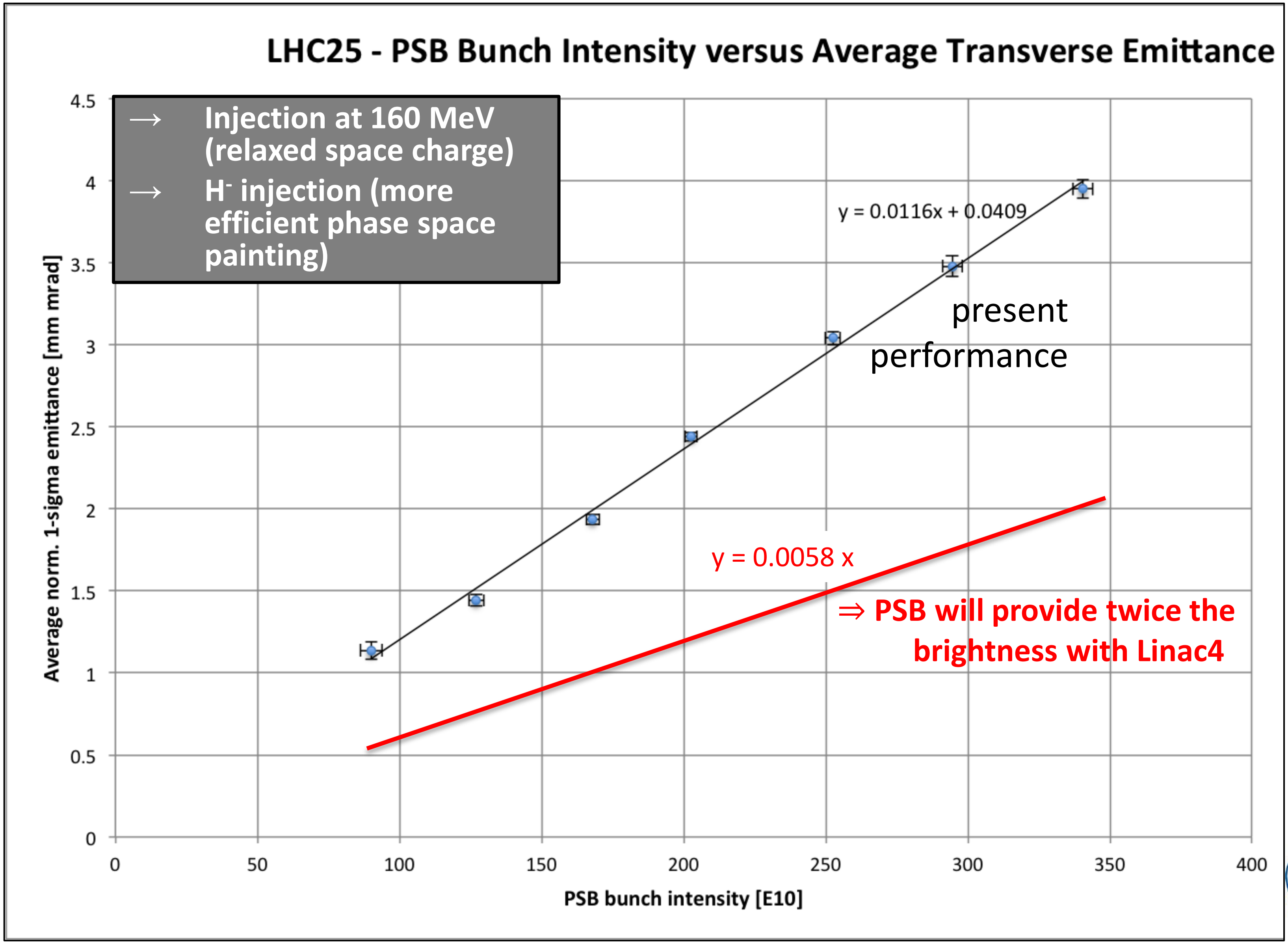
- **Upgrade scenario 2 for the injectors**
  - All upgrades for PSB and PS (2 GeV + RF) + Linac4
  - Full SPS 200 MHz RF upgrade
  - SPS e-cloud mitigation

- **Assumptions on beam quality preservation**
  - PSB: 5% losses and 5% emittance blow-up
  - PS: 5% losses and 5% emittance blow-up
  - SPS: 10% losses and 10% emittance blow-up

  } as achieved in 2012 operation with 50 ns beams

see presentation of G. Rumolo …

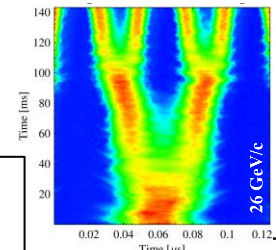
PSB brightness

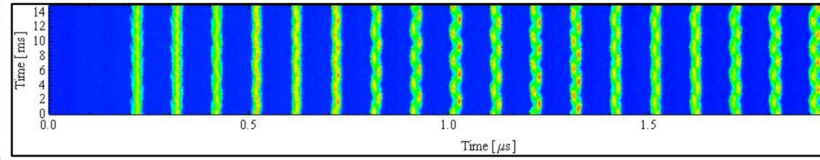


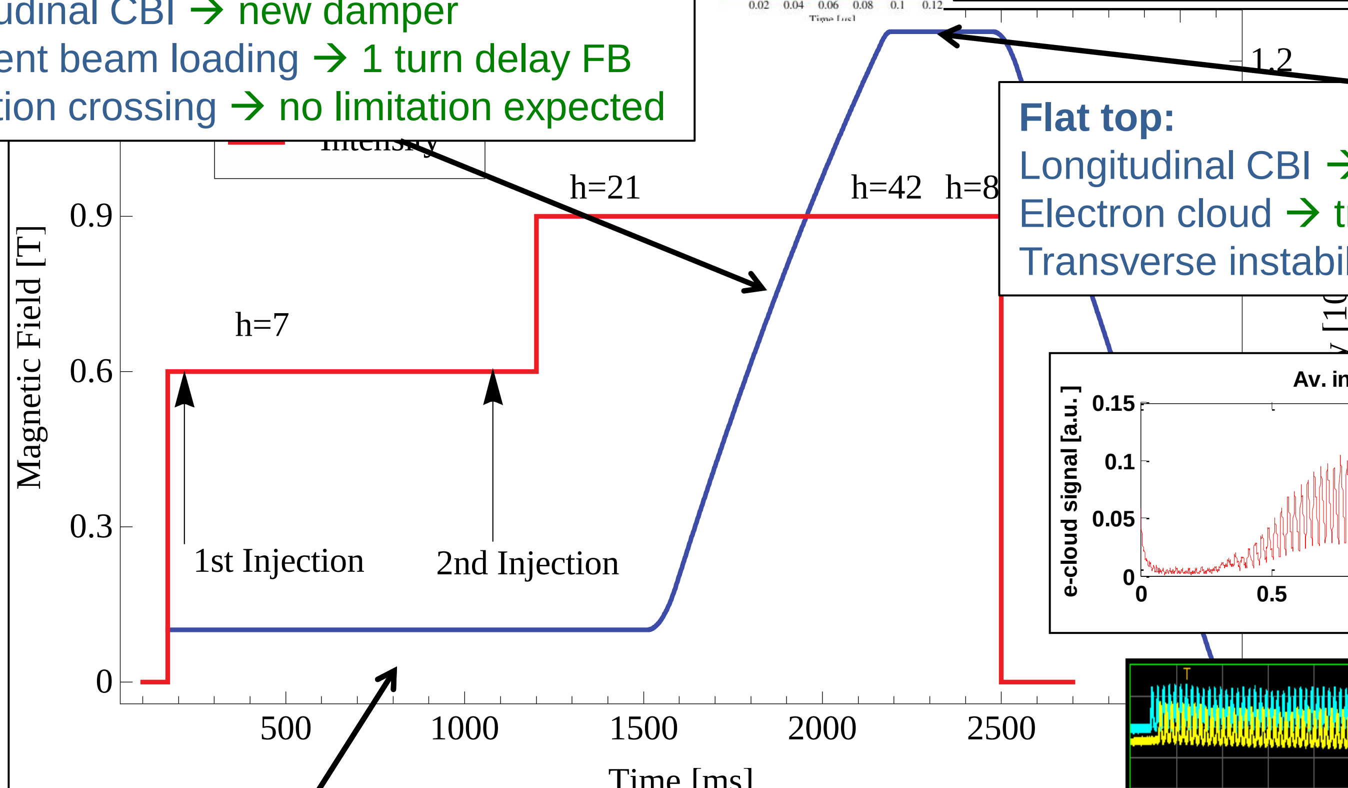
see presentation of S. Gilardoni …

Challenges in the PS

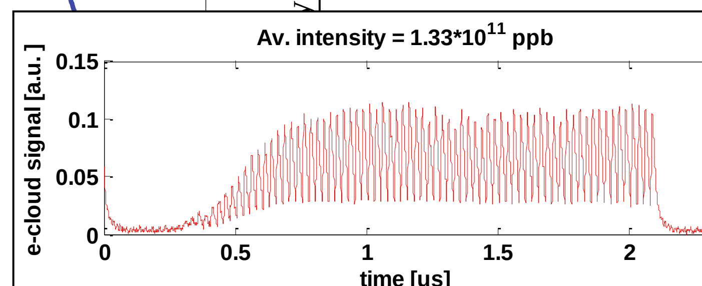
Acceleration/Bunch splittings
Longitudinal CBI → new damper
Transient beam loading → 1 turn delay FB
Transition crossing → no limitation expected



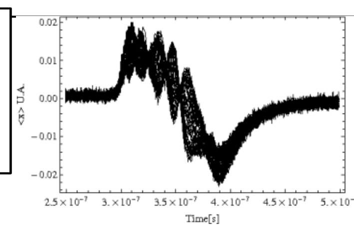


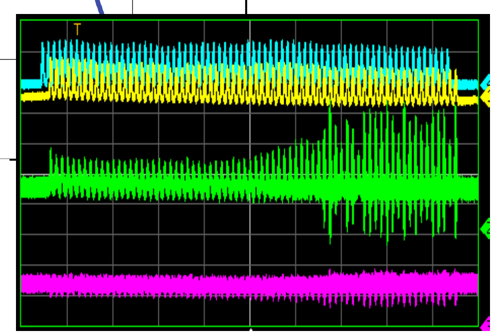


Flat top:
Longitudinal CBI → new damper
Electron cloud → transverse FB
Transverse instabilities → transverse FB



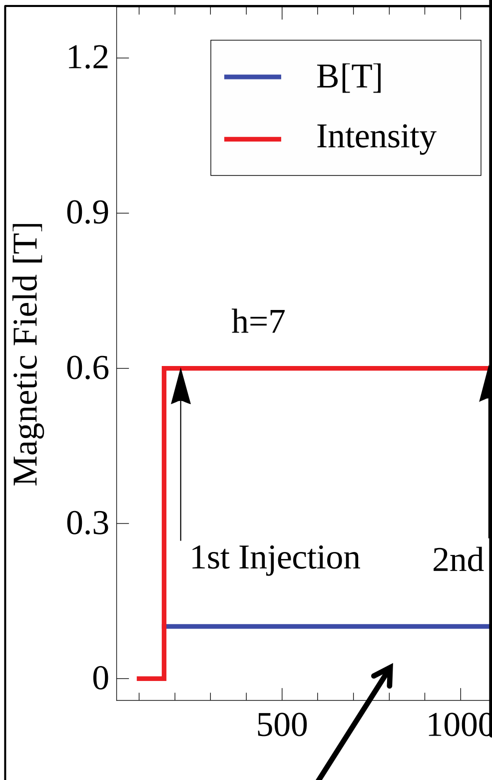
Injection flat bottom:
Space charge
Headtail instability → transverse FB



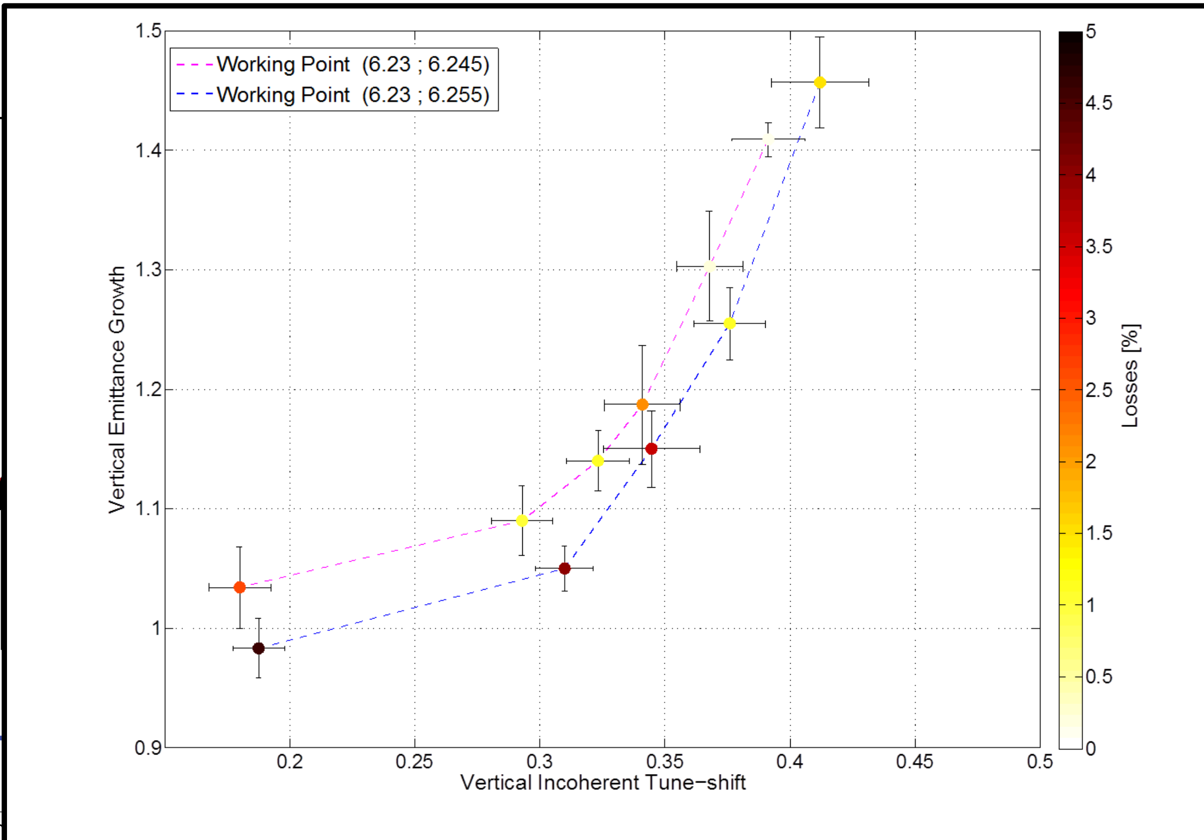


see presentation of S. Gilardoni …

Challenges in the PS



⇒ ΔQy≈0.31 is acceptable in the PS

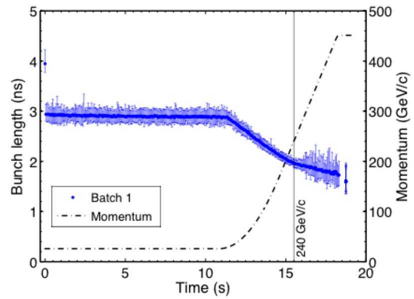


Injection flat bottom:

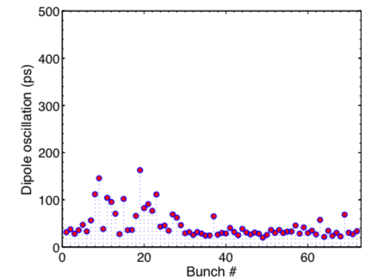
Space charge → higher brightness with 2 GeV

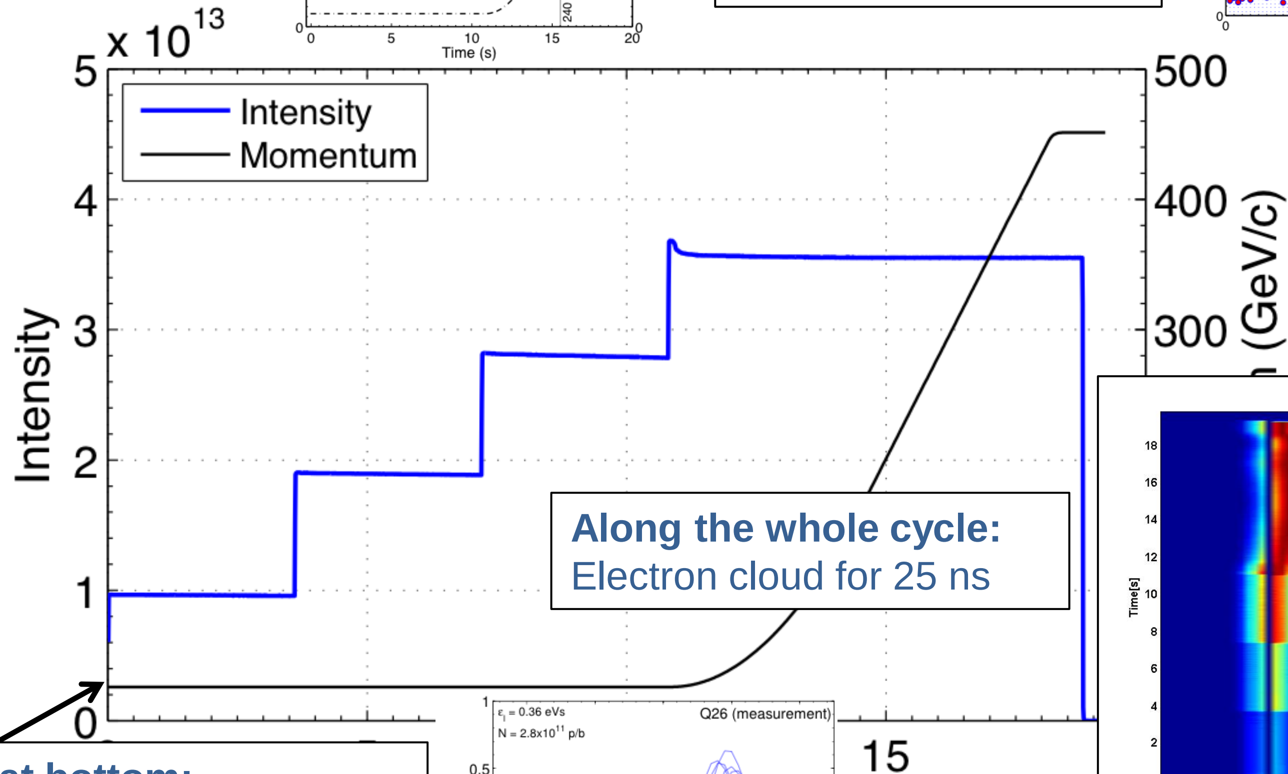
Headtail instability → transverse FB

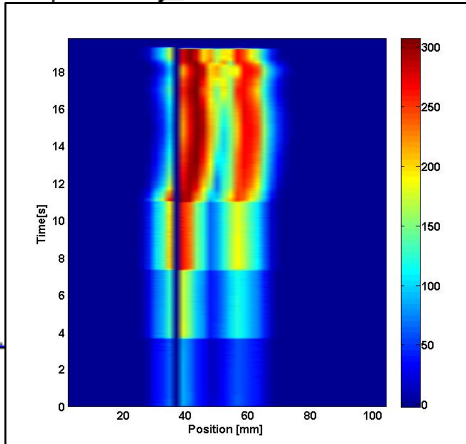
SPS limitations overview



Ramp and flat top:
Longitudinal instability
Beam loading
RF power

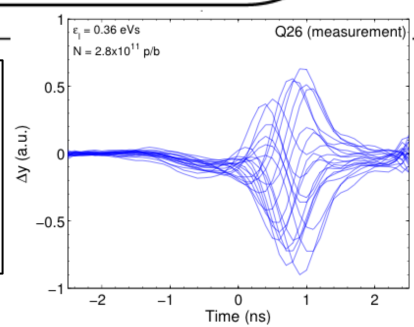






Along the whole cycle:
Electron cloud for 25 ns

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



SPS instability scaling and Q20 optics

- **TMCI in the vertical plane at injection**

threshold intensity: $N_{th} \sim |\eta| \varepsilon_l / \beta_y$

η	slip factor
ε_l	longitudinal emittance
β_y	vertical beta-function

- **Longitudinal instabilities**

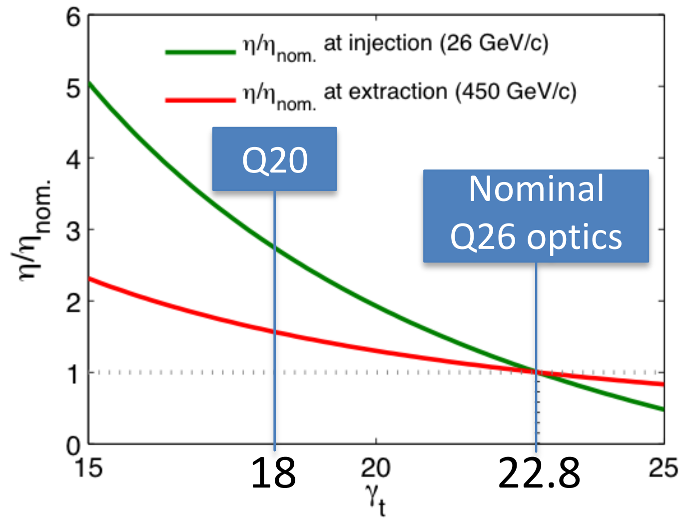
loss of Landau damping: $N_{th} \sim |\eta| \varepsilon_l^{5/2}$

- **Electron cloud instability**

threshold intensity: $N_{th} \sim |\eta|$

⇒ **Raise instability threshold by increasing η!**

η relative to nominal SPS optics



- **Q20 low γ_t optics**
  - Q_x/Q_y = 20.13/20.18 (nominal Q26 optics: Q_x/Q_y = 26.13/26.18)
  - 3 (1.6) times higher η at injection (extraction) compared to Q26
  - Larger dispersion in arcs → reduction of space charge tune shift
- **Q20 successfully used for LHC filling since October 2012**

TMCI at SPS injection

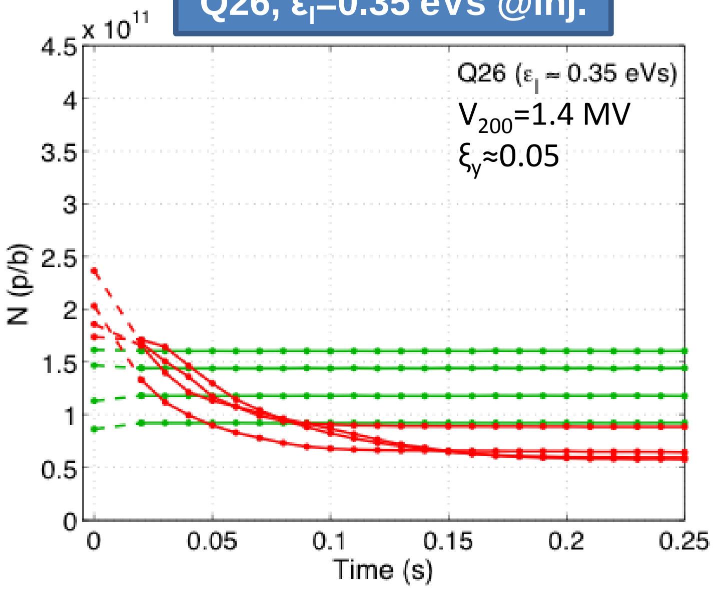
- **Fast vertical instability at injection with low chromaticity**
- **Mitigation by Q20 optics**

  ⇒ η/β_y about 2.5 times higher than in Q26!

  ⇒ No intensity limitation due to single bunch TMCI within the LIU/HL-LHC parameter space

$N_{th} \sim |\eta| \varepsilon_l/\beta_y$

Q26, ε_l=0.35 eVs @inj.



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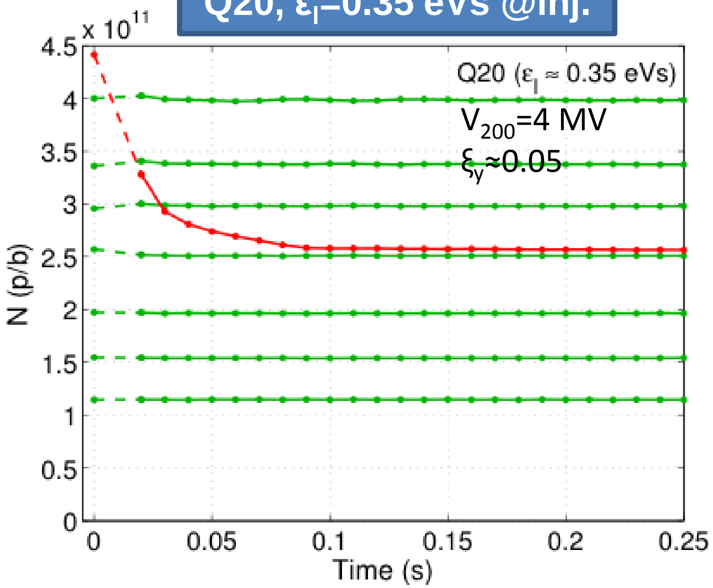


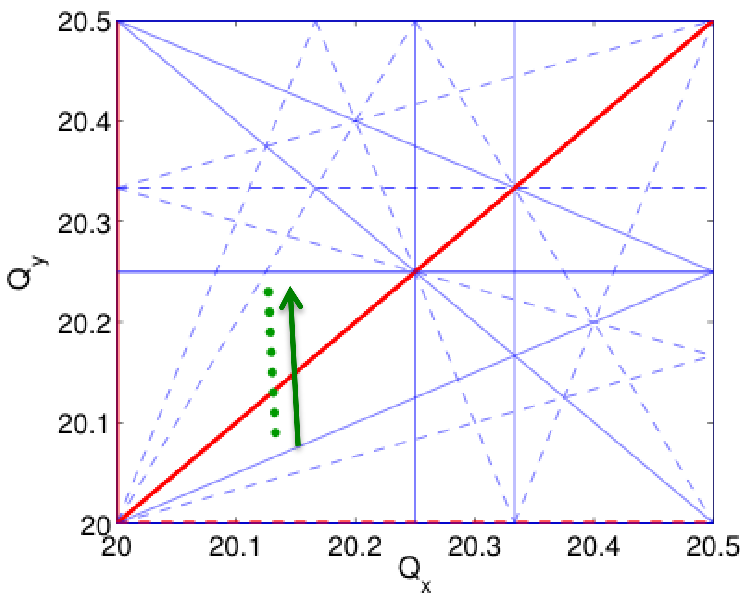
… measurements !

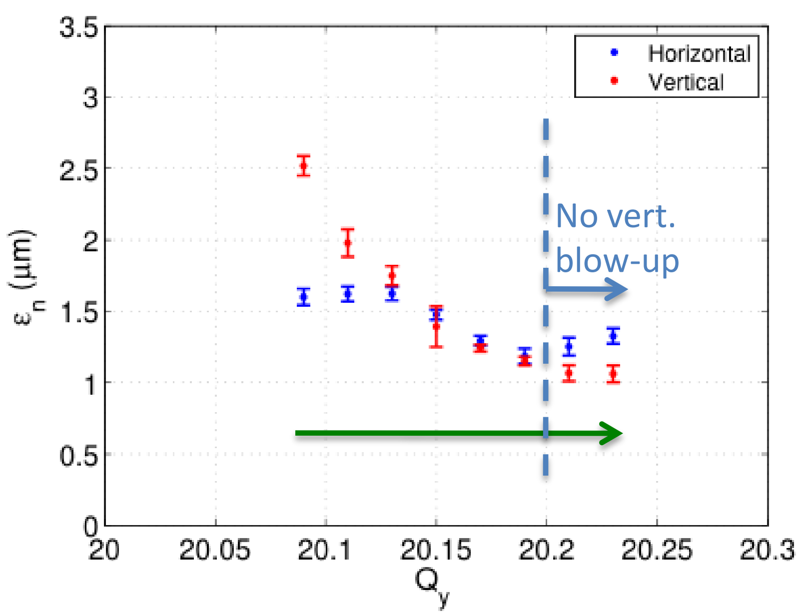
Space charge tune shift - SPS

- **50 ns BCMS beam on Q20 LHC filling cycle**
  - Single batch with N ~ 2x10^{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

Q26 would have around 15% larger tune shift due to smaller dispersion …





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Expect (Q20)
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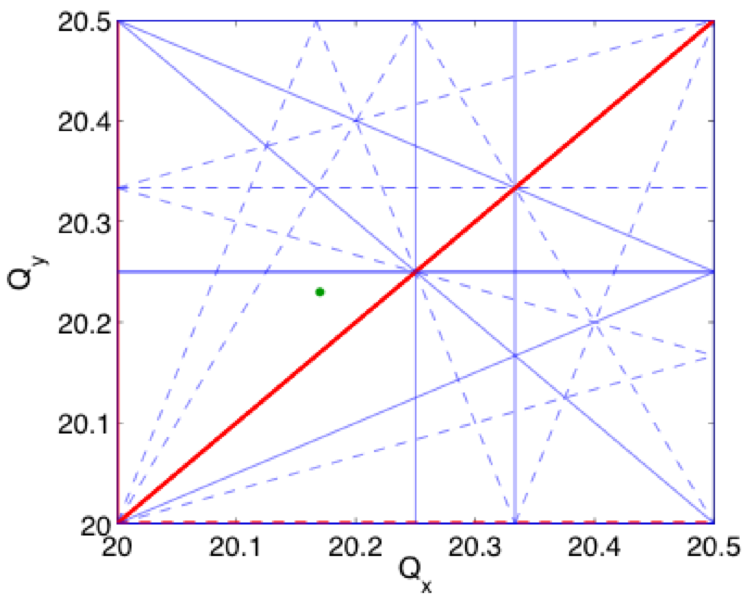
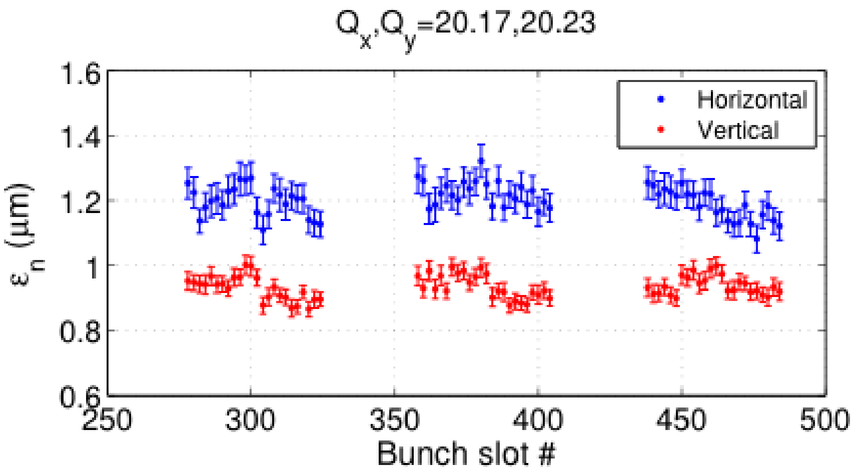
ΔQ_y ~ 0.20

Q26 would have around 15% larger tune shift due to smaller dispersion …

- **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 **ΔQ_y = 0.21** → considered as present maximum

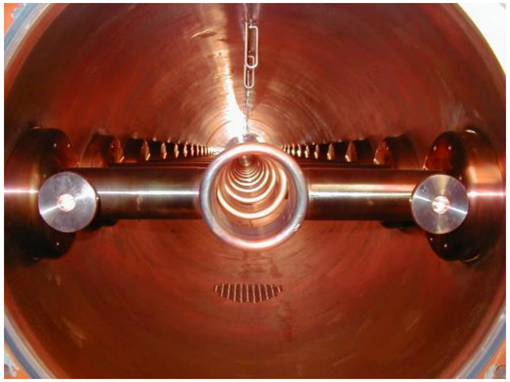


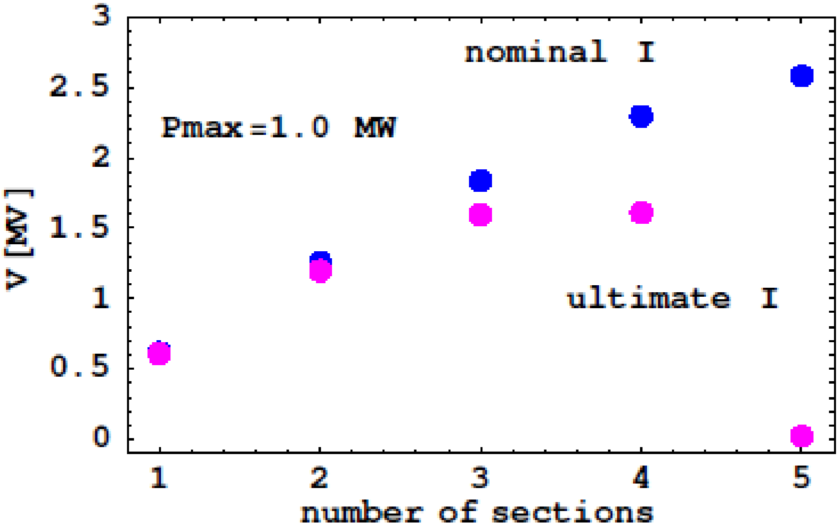


Bunch-by-bunch Wire Scanner measurements not calibrated

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**

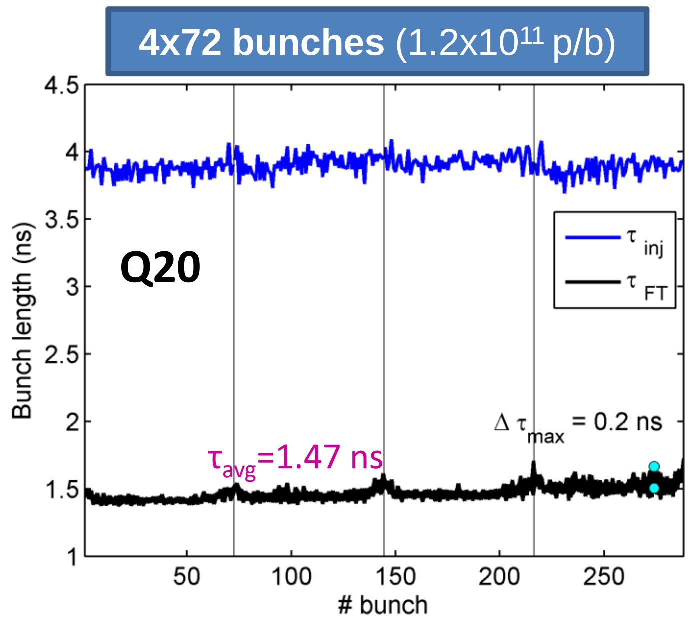


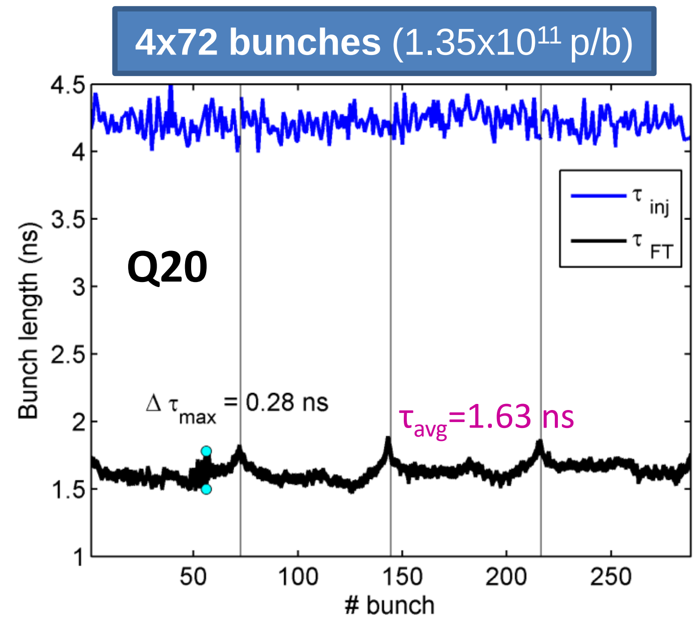


Bunch length at SPS flat top

- **Maximum RF voltage at flat top used for shortening bunches before extraction**
  - Stability of Q26 optics is achieved with smaller longitudinal emittance in Q20 (less blow-up needed)
  - For same stability (but smaller longitudinal emittance) same bunch length in both optics

- **Measured bunch length increase with intensity**
  - Due to instabilities (or controlled longitudinal emittance blow-up) and larger emittance from PS
  - Here: 11 % increase in τ_{avg} for 12% in intensity!
  - Reference point: N~1.35x10[11] p/b, bunch length ~ 1.7 ns in Q20 optics (BQM max 1.9 ns)



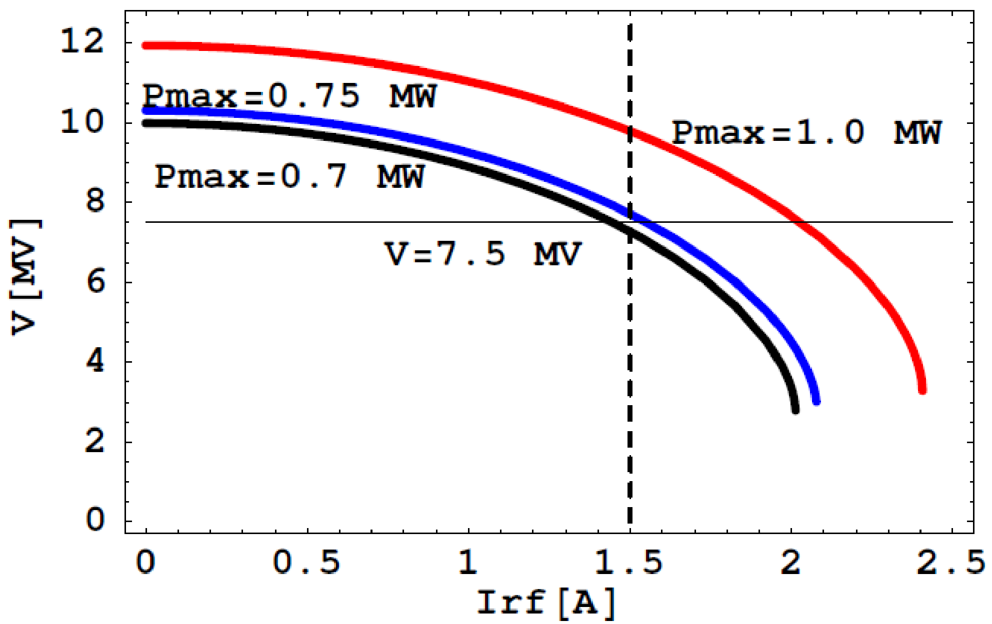


Estimation of maximum intensity from SPS

- **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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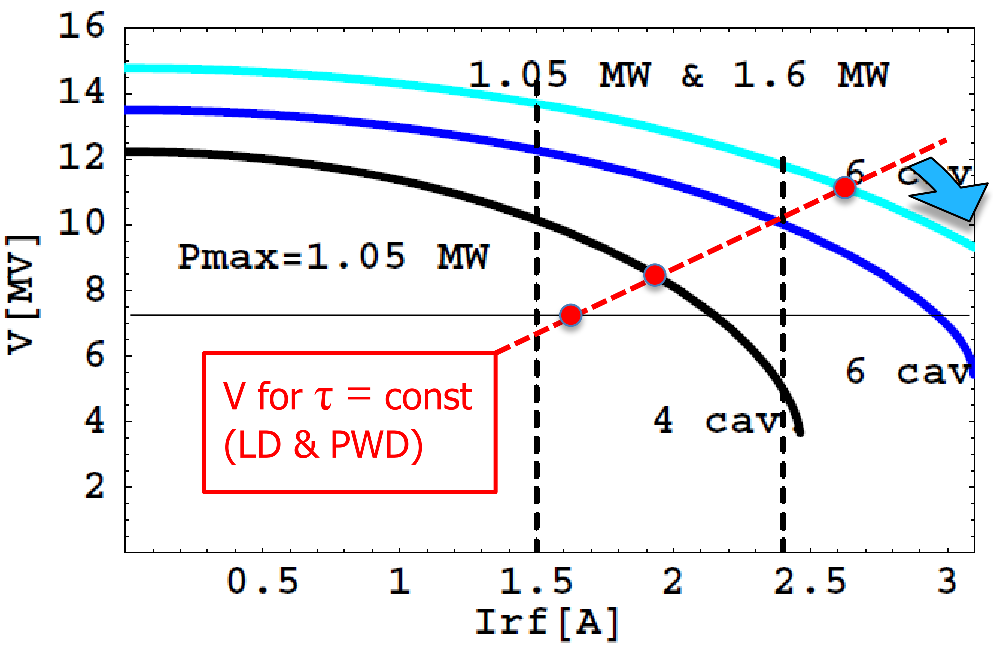
  - larger ε_l to avoid loss of Landau damping (LD): V ~ N
  - to compensate potential well distortion (PWD): V ~ N

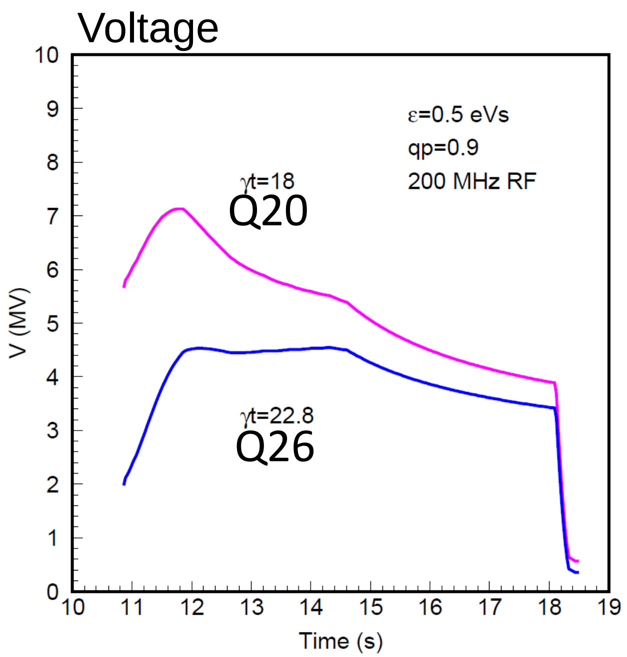
  } Otherwise longer bunches at extraction and losses in LHC
- **After LLRF upgrade: 4 cavities, 1.05 MW pulsing → 1.45x10^{11} p/b**
- **After full RF upgrade: 4 cavities with 1.05 MW & 2 cavities with 1.6 MW → <u>2.0x10^{11} p/b</u>**

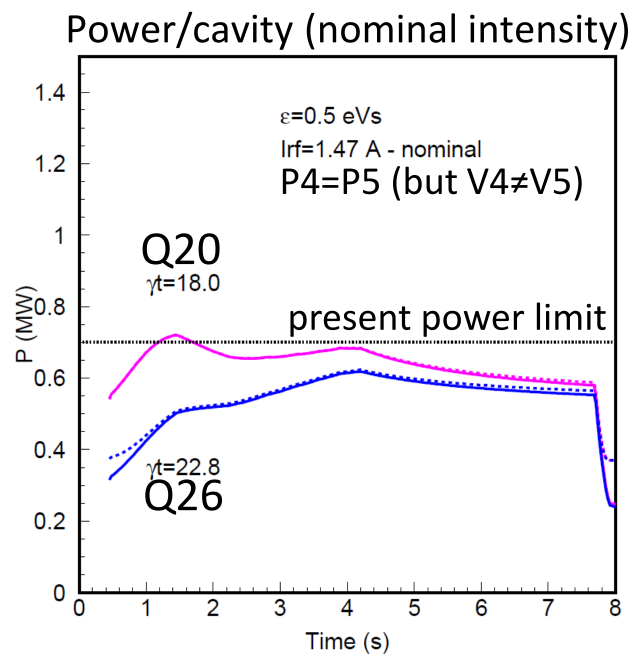


Scaling to preserve bunch length at extraction based on presently achieved performance and understanding of stability scaling …

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

Required RF power/cavity during acceleration



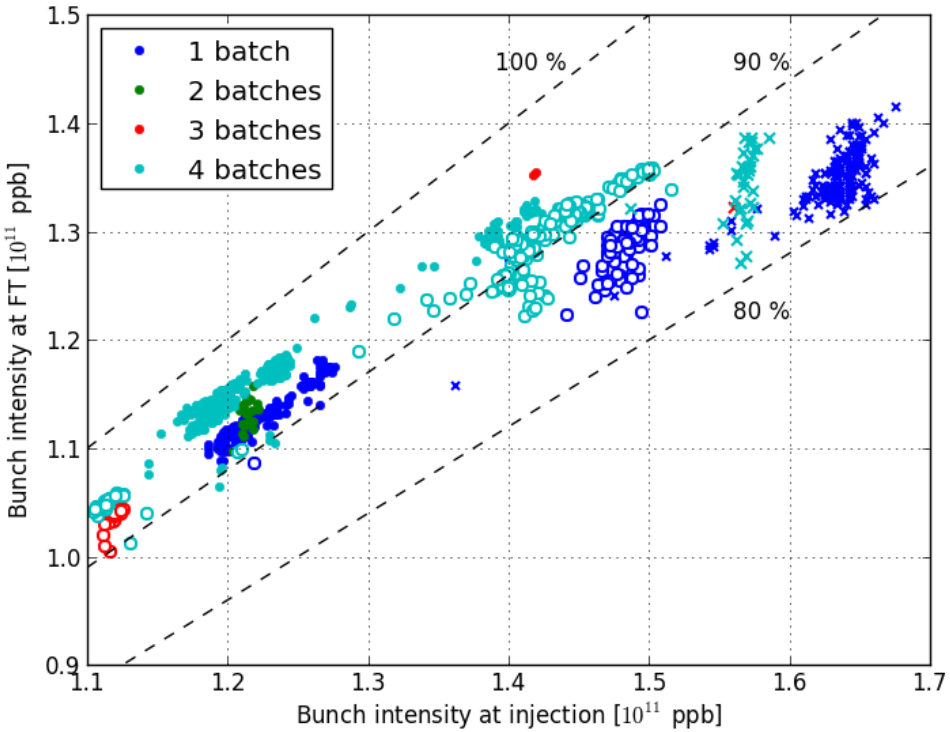


- **RF power with present RF system is at the limit for intensities above nominal**
- **More RF voltage and power needed for higher than nominal intensity**
  - Due to beam loading and higher required voltage for larger longitudinal emittance (→ beam stability)
  - Even more in Q20 compared to Q26 due to higher required voltage (η is larger)

further details in the presentation of H. Damerau

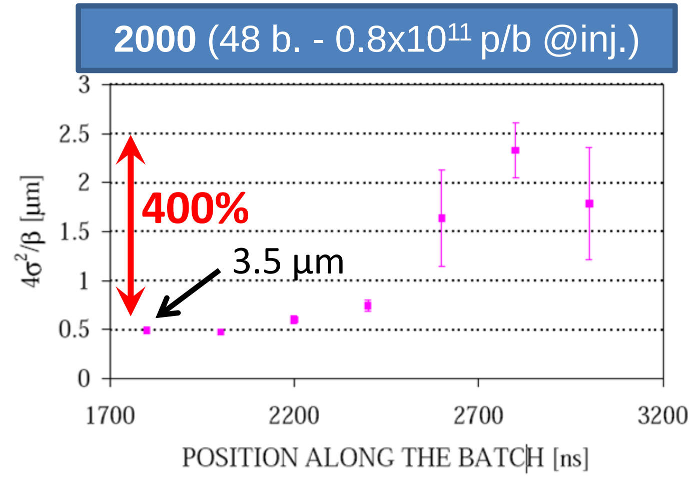
SPS transmission as function of intensity

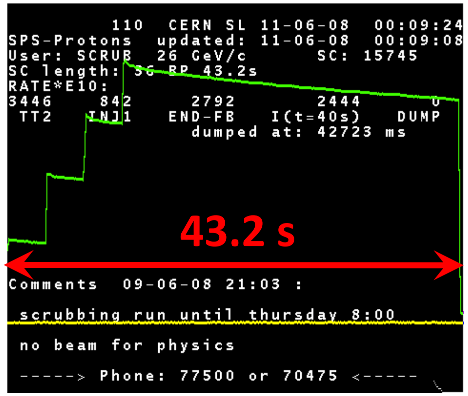
- **MDs in the end of 2012 for higher intensity with 25 ns beam in Q20**
- **Transmission decreasing for higher intensity!**
  - Related to longitudinal distribution from PS and beam loading?
  - Observed fast losses on flat bottom → due to e-cloud?

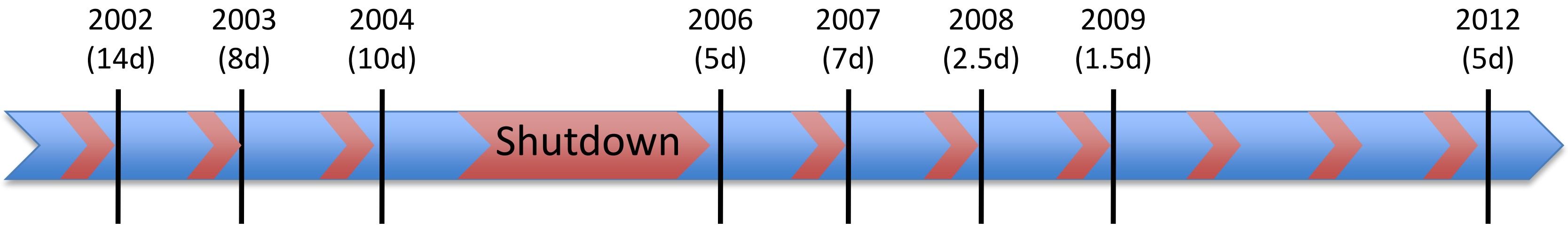


E-cloud and scrubbing in the SPS

- **Strong limitation due to e-cloud in the past**
  - Instabilities at injection + incoherent effects
  - Emittance blow-up along the batch
  - High chromaticity needed for beam stability
  - Pressure rise around the machine
- **Situation improved gradually due to scrubbing**
  - Secondary Electron Yield reduction by the e-cloud itself
- **Scrubbing runs since 2002**
  - Performed at 26 GeV in cycling mode (~40 s cycle length)
  - Typically limited by heating and/or outgassing
  - ~1-2 weeks periods
- **SPS scrubbing history**



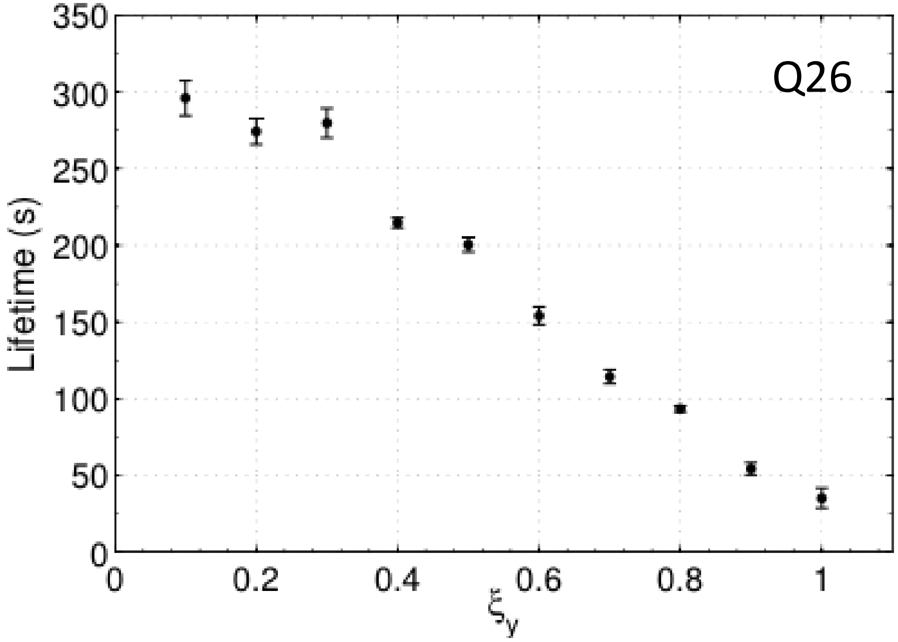




The 25 ns beam with nominal intensity in 2012

- **Measurements on long flat bottom cycle (22 s)**
- **Different vertical chromaticity settings**
  - No instability with low vertical chromaticity
  - Best life time with chromaticity $\xi_y \leq 0.3$

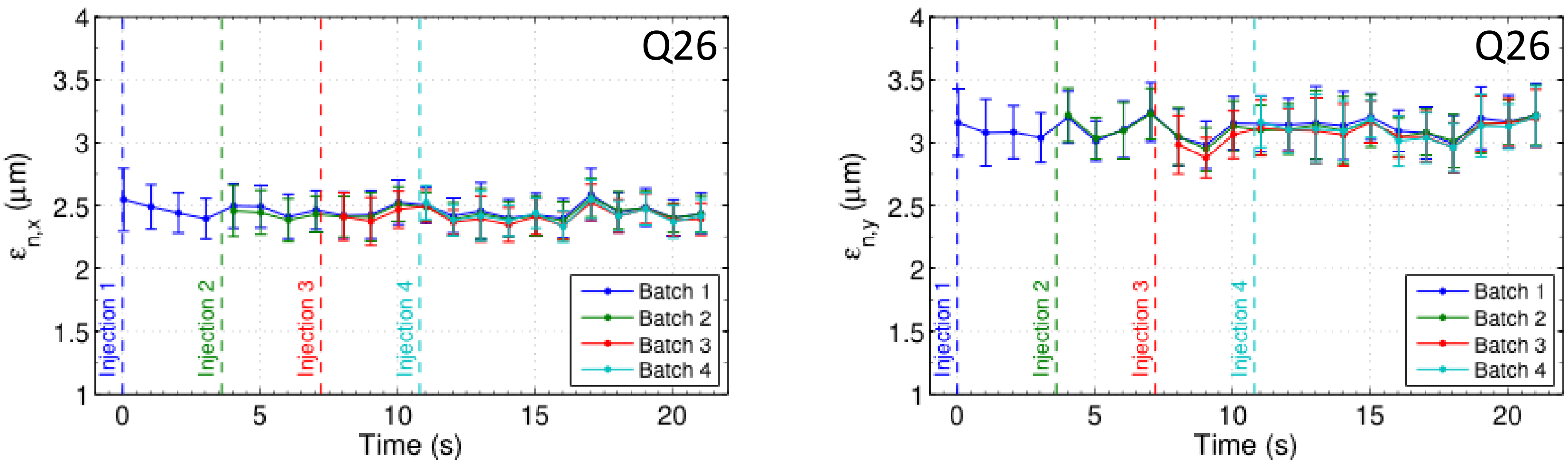
4x72 bunches (1.15×10^{11} p/b @inj.)



The nominal 25 ns beam in 2012

- **Measurements on long flat bottom cycle (22 s)**
- **Different vertical chromaticity settings**
  - No instability with low vertical chromaticity
  - Best life time with chromaticity $\xi_y \leq 0.3$
- **No measurable emittance growth with 4 batches stored for more than 10 s**
- **This situation should be achieved for US2 beam parameters …**

4x72 bunches (1.15x10^{11} p/b @inj.)

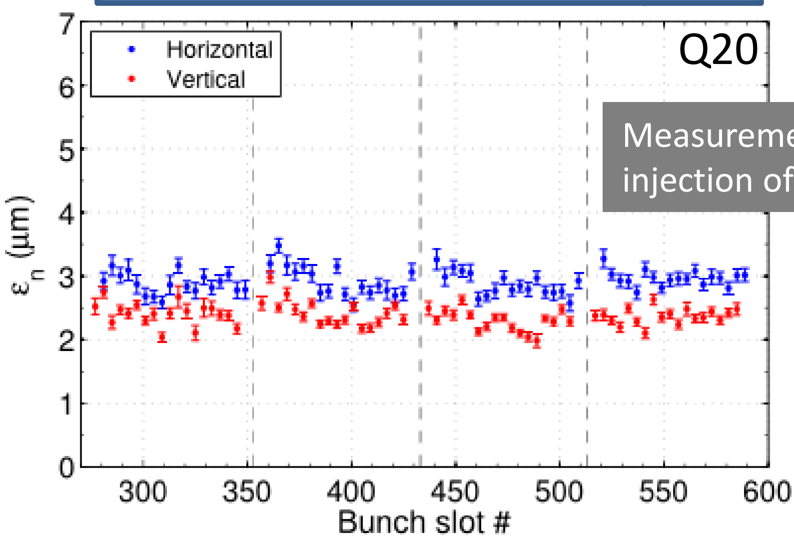


Bunch-by-bunch Wire Scanner measurements not calibrated

Indications for e-cloud effects in 2012?

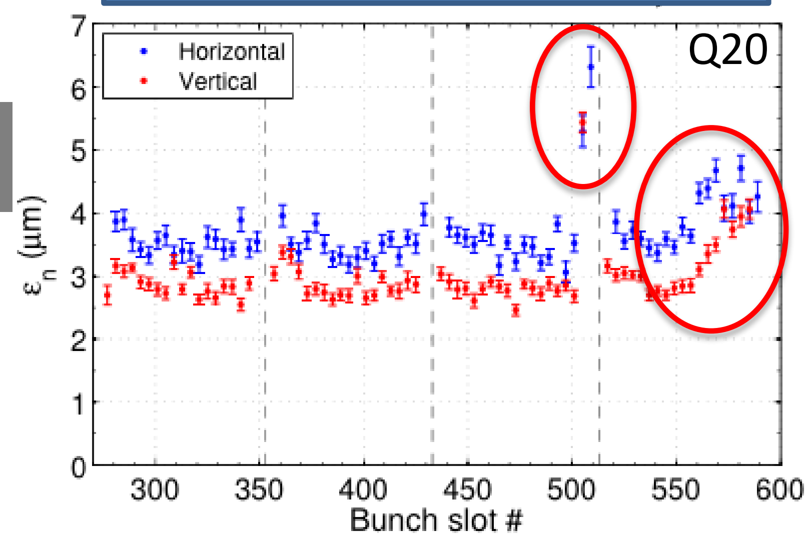
- **MD studies in the end of 2012 for increasing intensity of 25 ns beam in SPS with Q20**
- **No problem up to 1.3x10^{11} p/b @ injection**
- **Bunches in the tails of 3rd and 4th batch show blow-up for 1.4x10^{11} p/b @ injection**
  - SPS was never scrubbed for this high intensity ...
  - Additional scrubbing step needed? (e-cloud stripes in dipoles move outwards for higher intensity)

4x72 bunches (1.3x10^{11} p/b @inj.)



Measurements after injection of 4th batch

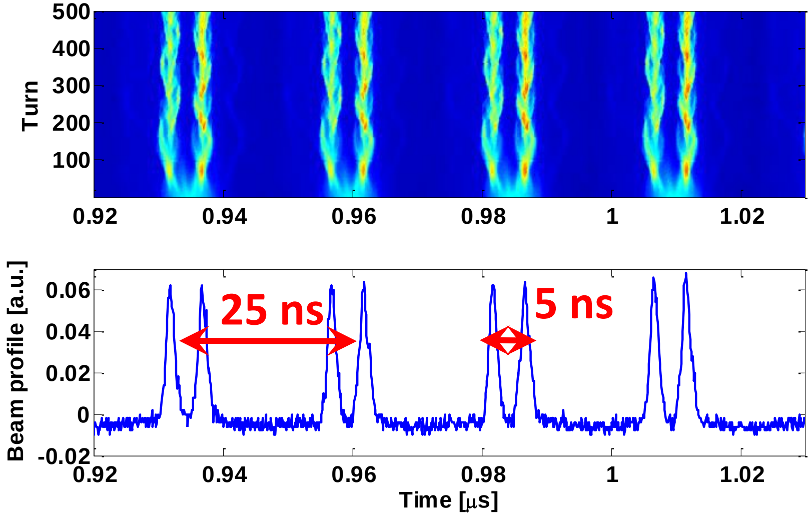
4x72 bunches (1.4x10^{11} p/b @inj.)

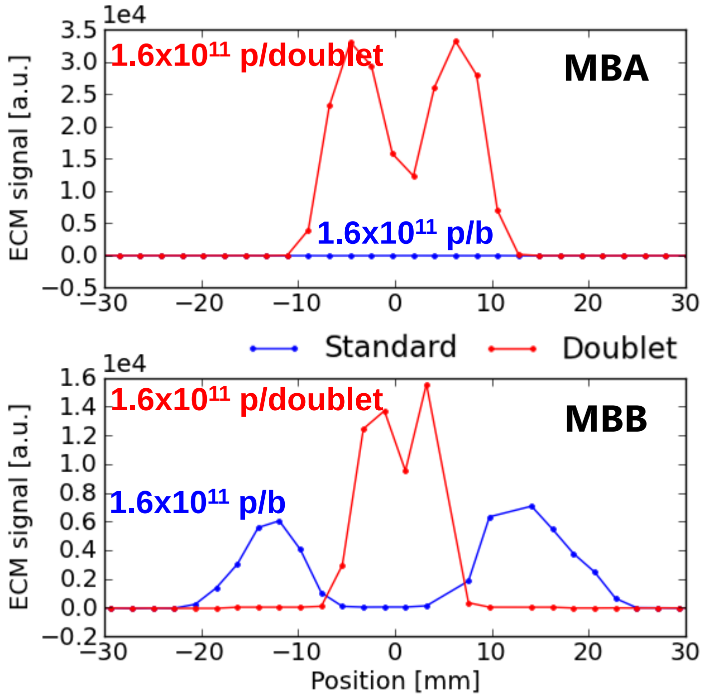


Bunch-by-bunch Wire Scanner measurements not calibrated

Doublet beam: the future of 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 $1.6x10^{11}$ p/doublet
- Clear enhancement on e-cloud detectors compared to standard 25 ns beam measured





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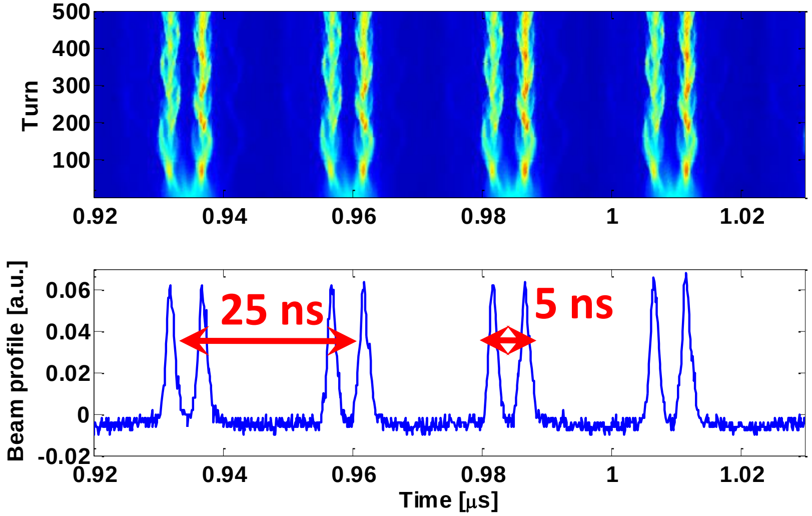
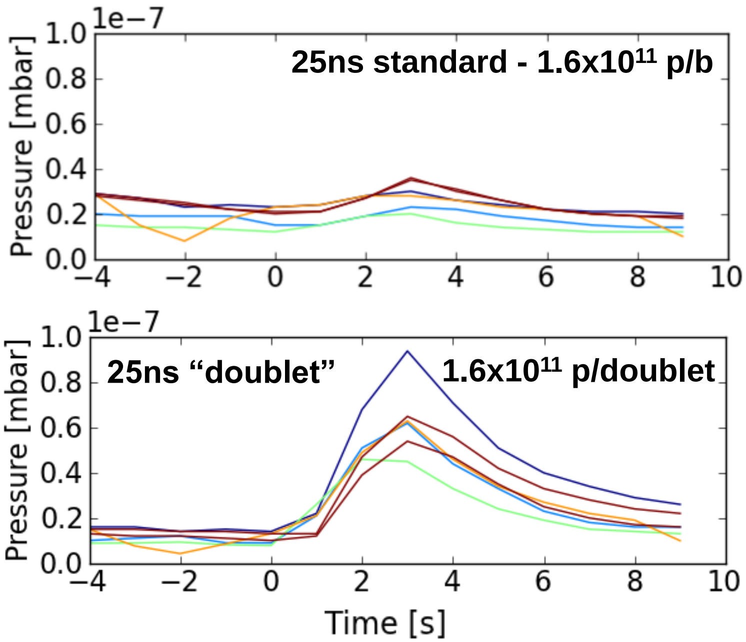
- Capturing each bunch in 2 neighboring 200 MHz buckets
- Successfully tested in MDs at the end of 2012/13 run with 1.6×10^{11} p/doublet
- Clear enhancement on e-cloud detectors compared to standard 25 ns beam measured
- Enhanced pressure rise compared to standard 25 ns beam measured in the arcs



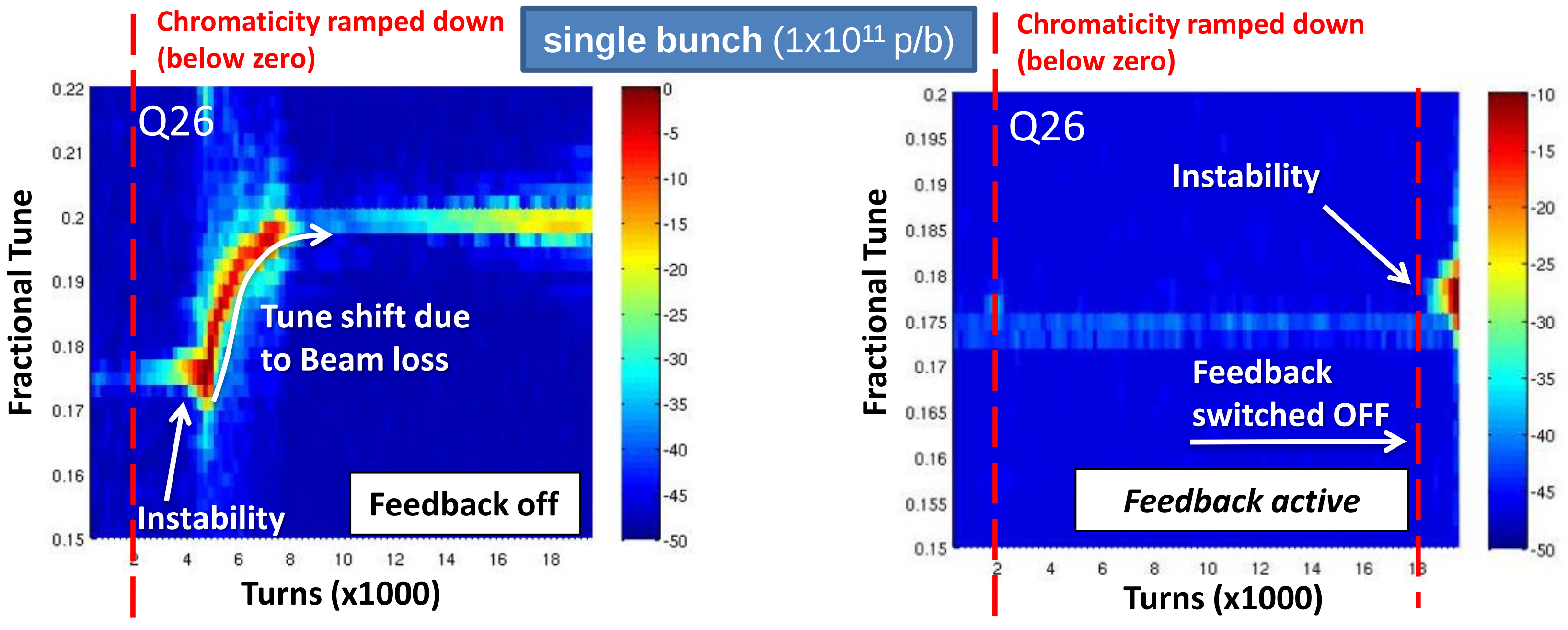


High bandwidth transverse feedback (CERN/LARP)

see also LIU SPS High Bandwidth Feedback review

- **High bandwidth (intra-bunch) feedback could help**
  - fight electron cloud instabilities
  - improve beam quality during scrubbing → faster and more efficient machine scrubbing
  - avoid running with high chromaticity settings → better beam lifetime and emittances
  - stabilize the scrubbing beam (present damper cannot cope with “pi-mode” oscillations of doublets)

- **MD studies in 2012/2013 using a 200 MHz stripline pickup as kicker**
  - Feedback stabilizes the bunch → clearly works for dipole mode

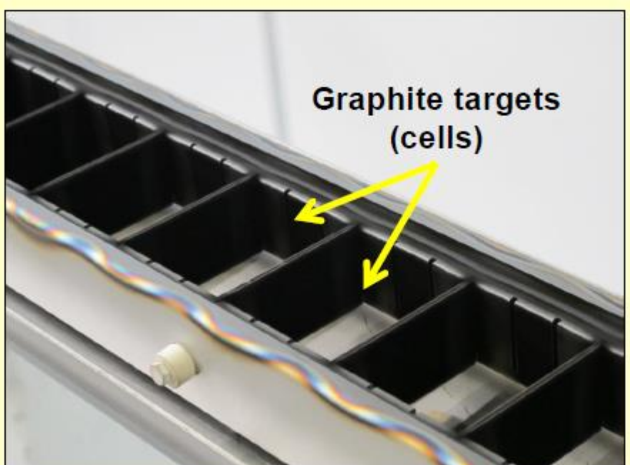


E-cloud suppression by coating with a-C

- **Thin film of a-C provides low Secondary Electron Yield**
  - Suppression of e-cloud in prototype chambers demonstrated with beam in SPS
  - 4 SPS half cells (including quadrupoles) with a-C coating ready for the startup in 2014 → further tests with beam

- **Possible coating campaign**
  - Objective: coat at least 90% of the SPS circumference
  - Elements to coat (in order of priority)
    - MBB Dipoles (35%)
    - Quadrupoles (QD+QF = 10%)
    - MBA Dipoles (35%) + Straight Sections (20%)
  - Technique: coat actual beam pipes by DC Hollow Cathode sputtering

by mid 2015: decide if coating should be applied or scrubbing is sufficient



Scrubbing or coating? A possible strategy …

Oct.
Nov.
2014
Mar.
2015
Jun.

SCRUBBING RUN I (2 weeks)
beams: nominal intensity
Goal: recover the 2012 performance
Risk: mixed with machine start-up

SCRUBBING RUN II (2 weeks)
beams: 2e11 p/b, scrubbing beam, …
Scrubbing successful for high intensity?

YES

LIU-SPS Review: coating?
(after data analysis!)

NO

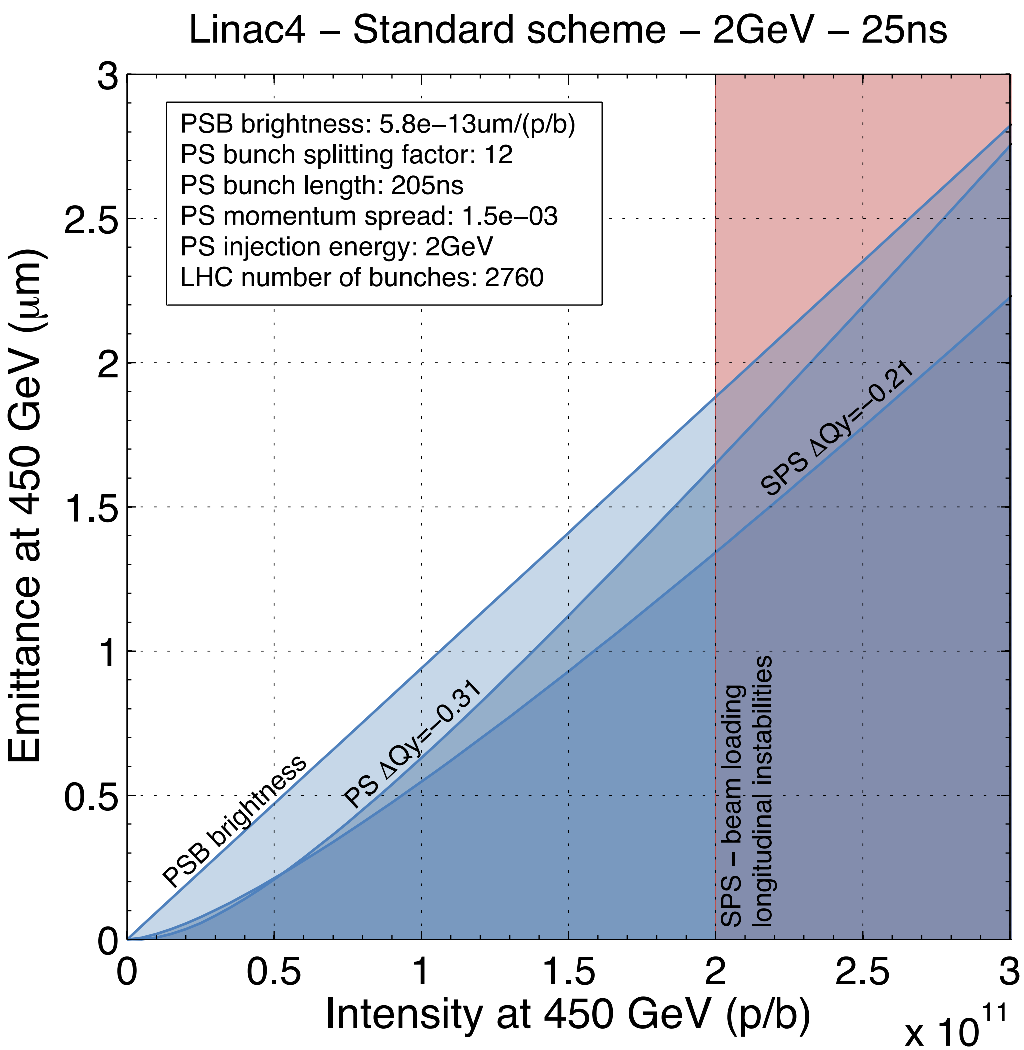
a-C coating (during LS2)

Scrubbing qualification: No degradation for 2e11 p/b with 4x72 bunches and 6x48 bunches

Results from the 4 coated half cells

Simulations for higher brightness beams (from Linac4)

Standard scheme (72 bunches / PS batch)

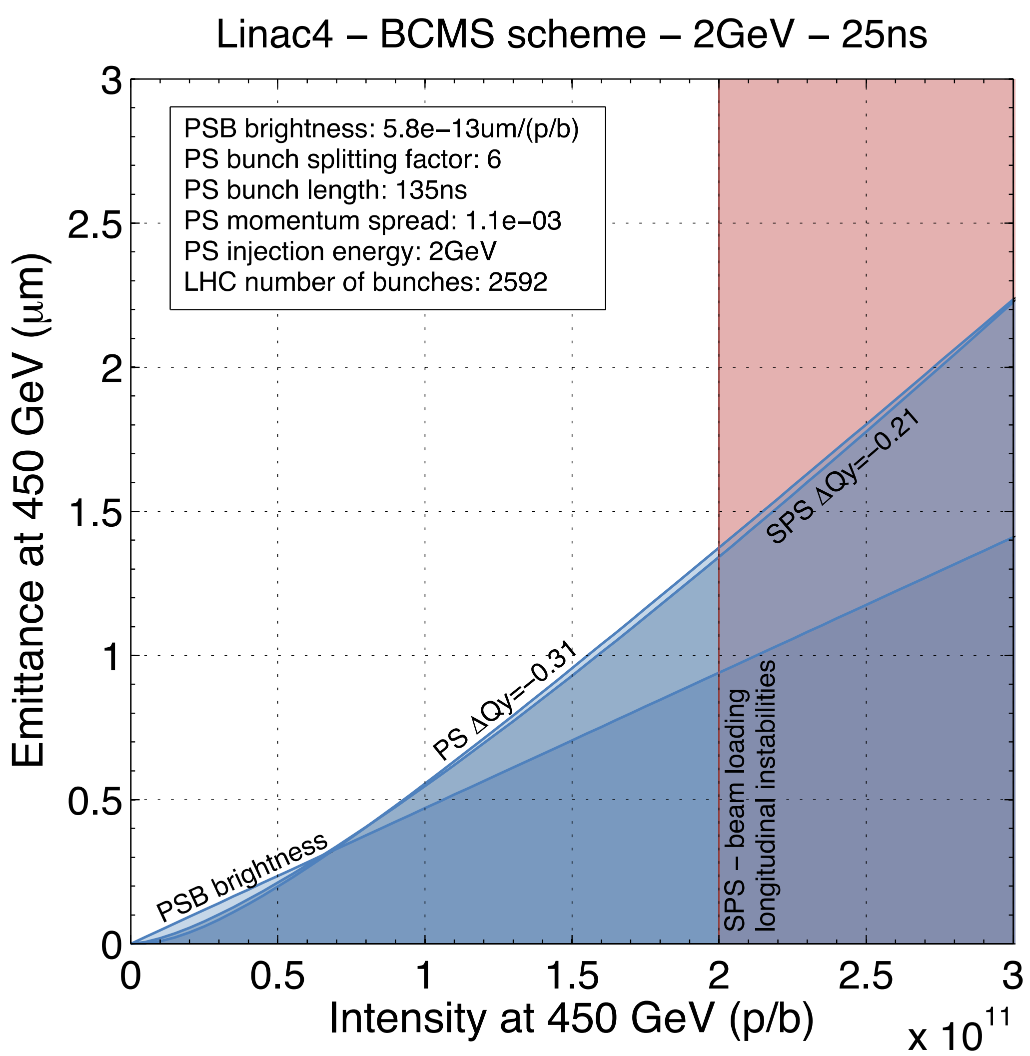


- **LIU upgrades**
  - SPS 200 MHz upgrade
  - SPS e-cloud mitigation
  - PSB-PS transfer at 2 GeV

- **Limitations standard scheme**
  - SPS: longitudinal instabilities + beam loading
  - PSB: brightness

- **Performance reach**
  - 2.0×10^{11}p/b in 1.88μm (@ 450GeV)
  - 1.9×10^{11}p/b in 2.26μm (in collision)

BCMS scheme (48 bunches / PS batch)



- **LIU upgrades**
  - SPS 200 MHz upgrade
  - SPS e-cloud mitigation
  - PSB-PS transfer at 2 GeV
- **Limitations BCMS scheme**
  - SPS: longitudinal instabilities + beam loading
  - PS: space charge
  - SPS: space charge
- **Performance reach**
  - 2.0×10^{11} p/b in 1.37μm (@ 450GeV)
  - 1.9×10^{11} p/b in 1.65μm (in collision)

Comparison of LIU and HL-LHC parameters

		PSB						
		N (10^{11} p)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU-US2	Standard	29.55	1.55	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.55, 0.66)
	BCMS	14.77	1.13	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.35, 0.44)
HL-LHC		34.21	1.72	0.16	1.4	650	$1.8 \cdot 10^{-3}$	(0.58, 0.69)

		PS (double injection)						
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	E (GeV)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU-US2	Standard	28.07	1.63	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.16, 0.28)
	BCMS	14.04	1.19	2.0	1.48	135	$1.1 \cdot 10^{-3}$	(0.19, 0.31)
HL-LHC		32.50	1.80	2.0	3.00	205	$1.5 \cdot 10^{-3}$	(0.18, 0.30)

		SPS (several injections)						
					after filamentation (ϵ_z=0.35 eVs, B_l=4 ns @inj)			
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	$\delta p/p_0$	$\Delta Q_{x,y}$
LIU-US2	Standard	2.22	1.71	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.09, 0.16)
	BCMS	2.22	1.25	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.12, 0.21)
HL-LHC		2.57	1.89	26	0.42	3.0	$1.5 \cdot 10^{-3}$	(0.10, 0.17)

		LHC					
		N (10^{11} p/b)	$\epsilon_{x,y}$ (μm)	p (GeV/c)	ϵ_z (eVs/b)	B_l (ns)	bunches/train
Post-LS1	Standard	2.00	1.88	450	0.60	1.65	72
	BCMS	2.00	1.37	450	0.60	1.65	48
HL-LHC		2.32	2.08	450	0.65	1.65	72

Summary and conclusions

US2	Intensity @SPS extraction	Normalized transverse emittance @SPS extraction
HL-LHC baseline	2.32×10^{11} p/b	2.08 µm
HL-LHC alternative	1.58×10^{11} p/b	1.08 µm
LIU - standard scheme (72 bunches/PS batch)	2×10^{11} p/b	1.88 µm
LIU - BCMS scheme (48 bunches/PS batch)	2×10^{11} p/b	1.37 µm

- **Can we ever reach the HL-LHC requirements with the injectors?**
  - LIU does not match HL-LHC 'point-like' beam parameter requirements
  - However, LIU parameters are sufficiently close to reach integrated luminosity goal of 270 fb^{-1}/year!

  ⇒ See presentation of R. de Maria!

- **Intensity limitation of injectors due to RF power and longitudinal instability in the SPS**
  - Possible improvement depending on success of identifying and reducing longitudinal impedance

- **It is assumed that the SPS e-cloud limitation will be successfully eliminated**
  - Either by scrubbing or by a-C coating (to be decided by mid 2015)

LHC Injectors Upgrade

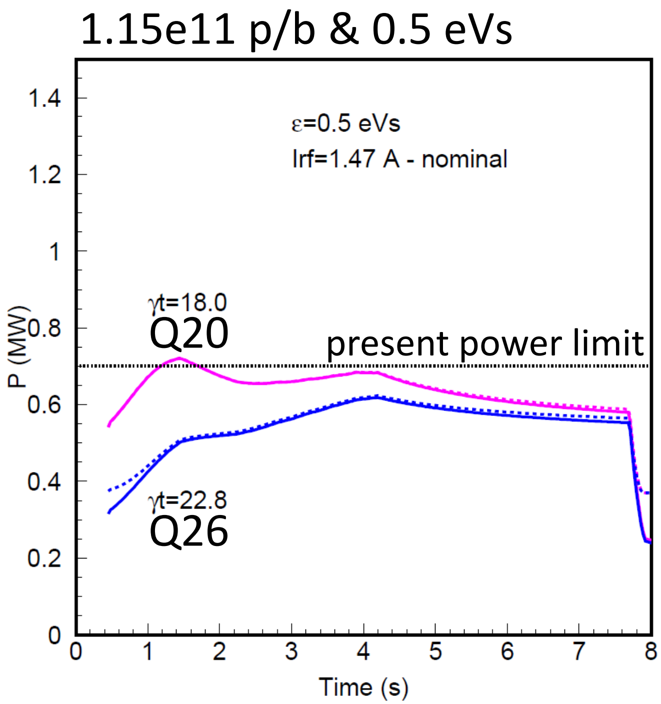
Thank you for your attention!

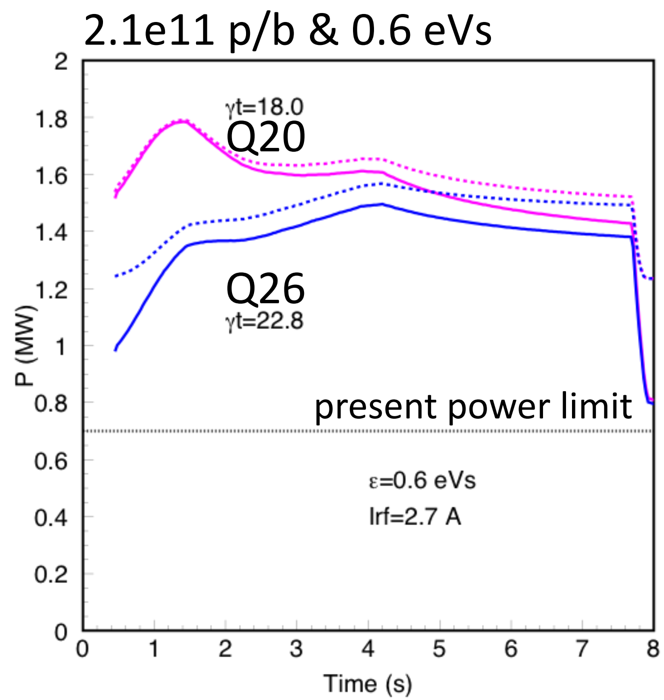
CERN

LHC Injectors Upgrade

Back-up slides

Required RF power/cavity during acceleration





- **for present situation of SPS 200 MHz cavity configuration**