LHC Injectors Upgrade

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Collective effects and limitations in the PS

Giovanni Rumolo, on behalf of the LIU-PS project team

Special thanks to S. Aumon, E. Benedetto, H. Damerau, S. Gilardoni, S. Hancock, A. Huschauer, G. Iadarola, E. Métral, R. Steerenberg, C. Yin-Vallgren

Outline

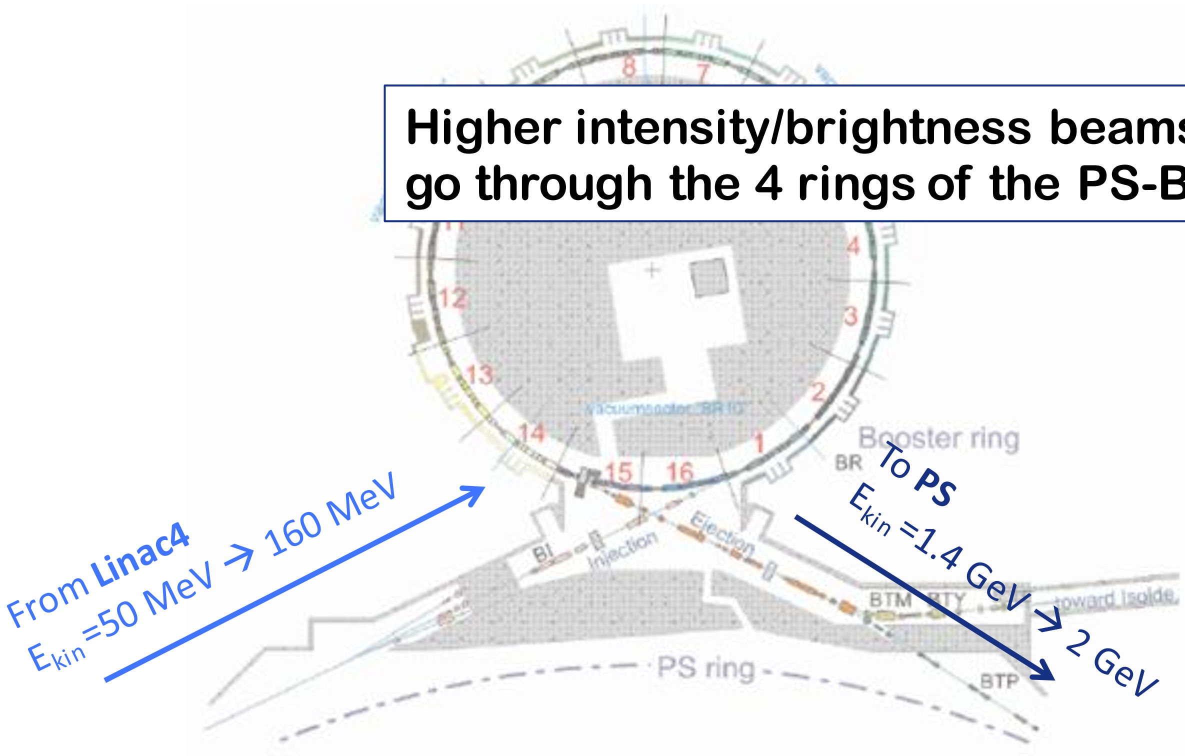
1. High intensity/brightness LHC (and physics) beams in the PS

2. Several collective phenomena
   - Space charge at injection
   - Coherent beam instabilities along the cycle
   - Electron cloud at flat top

3. Summary and outlook

Higher brightness beams in the PS

Higher intensity/brightness beams in the PS ring go through the 4 rings of the PS-Booster ….



1. Linac 4 will allow for production of higher brightness beams in the PSB
   → Higher injection energy (160 MeV)
   → H^- injection
2. Higher extraction energy into the PS (2 GeV)
   → Eases PS injection (weaker space charge, transversely smaller beams)

Higher brightness beams in the PS

LASLETT TUNE SHIFT

$$\Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{\frac{3}{2}} \gamma^2 \beta \sigma_z} \oint \frac{\beta_{x,y}(s) ds}{\sqrt{\epsilon_{x,y}\beta_{x,y}(s)}(\sqrt{\epsilon_x \beta_x(s)} + \sqrt{\epsilon_y \beta_y(s)})}$$

If we assume that:

⇒ The optics at the PS injection remains the same

⇒ The bunch length does not change

$$\frac{(\gamma^2\beta)_{2\,\mathrm{GeV}}}{(\gamma^2\beta)_{1.4\,\mathrm{GeV}}} = 1.63$$

⇒ $\frac{N_b}{\epsilon_x \epsilon_y}$ up to 63% larger

Higher brightness beams in the PS

LASLETT TUNE SHIFT

$$\Delta Q_{x,y} = \frac{r_p N_b}{(2\pi)^{\frac{3}{2}}\ \gamma^2 \beta\ \sigma_z} \oint \frac{\beta_{x,y}(s) ds}{\sqrt{\epsilon_{x,y}\beta_{x,y}(s)}(\sqrt{\epsilon_x \beta_x(s)} + \sqrt{\epsilon_y \beta_y(s)})}$$

$$\frac{N_b}{\epsilon_x \epsilon_y} \quad \text{up to 63\% larger}$$

PS and higher brightness beams…

⇒ What are the problems posed by space charge @PS injection?

⇒ Can there be other limitations from collective instabilities (impedance, electron cloud) elsewhere along the cycle?

Space charge at injection (1.4 GeV)

	N_b (x 10^{10} p)	$\varepsilon_{x,y}$ (μm)	$4\sigma_t$ (ns)	ΔQ_y
LHCINDIVhigh	40	1.7	90	**-0.2**
LHC50nom (DB)	80	1.1	180	**-0.26**
LHC50ult (DB)	120	1.8	180	**-0.26**
LHC25 (DB)	160	2.5	180	**-0.26**
AD	400	9.0/5.0	185	**-0.28**
TOF	800	12.0/8.0	230	**-0.31**
MD beams				
LHC50 SB rebucketed	150.0-190.0	2.5-3.0	130	**-0.34**
LHChighbright	70	2.0	95	**-0.25**

Double batch LHC beams, 1.2sec @FB (LHC50nom, LHC50ult, LHC25)

Physics beams, short FB (AD, TOF)

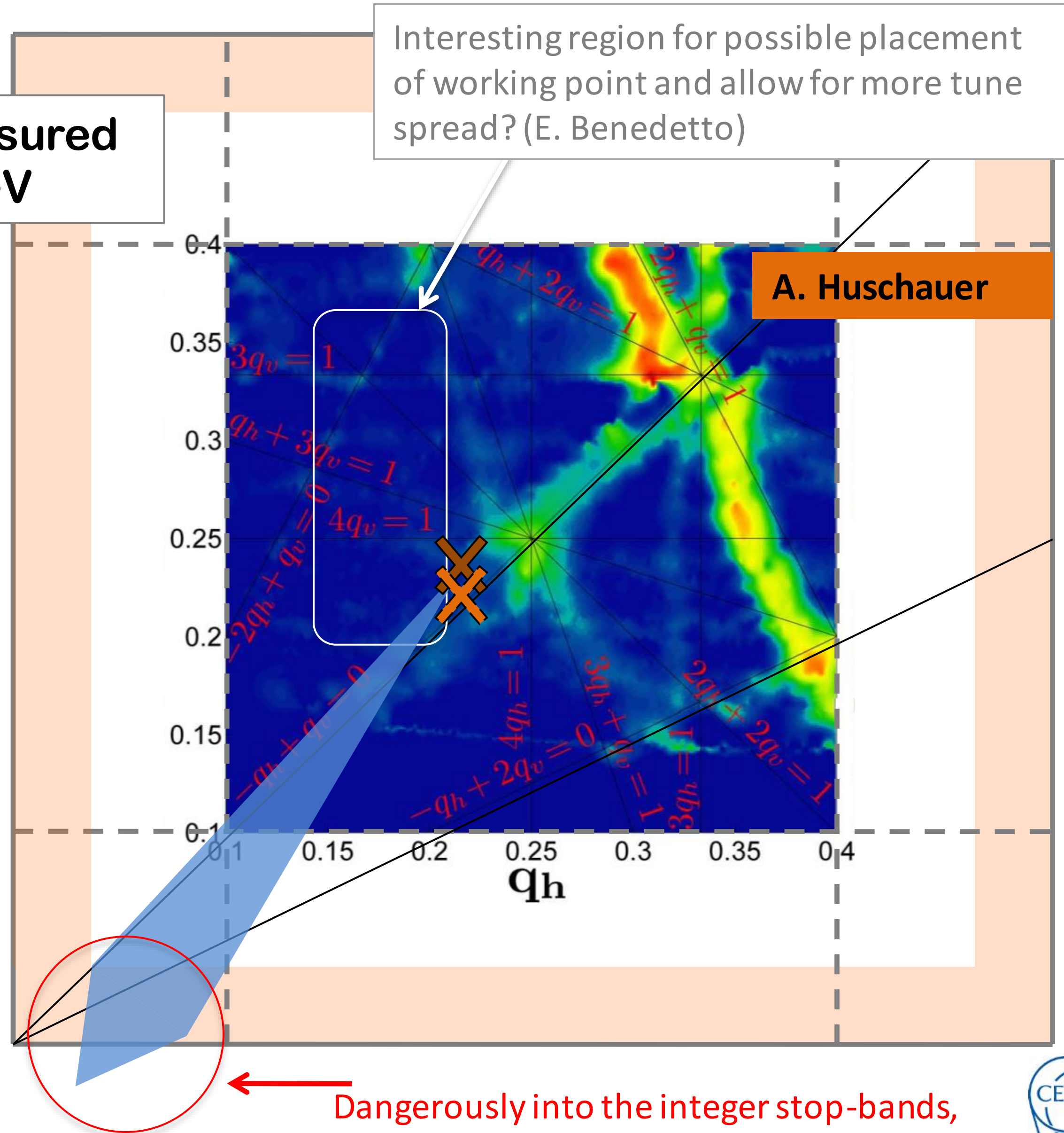
For space charge studies @FB after bunch rotation (LHC50 SB rebucketed, LHChighbright)

Space charge at injection (1.4 GeV)

LHC beams in the measured tune diagram @ 1.4 GeV

Working point

- ⇒ Nominal (0.21,0.24)
- ⇒ Coherent tune shift about (-0.003,-0.01), as measured by S. Aumon
- ⇒ Incoherent tune spread (-0.2,-0.26)

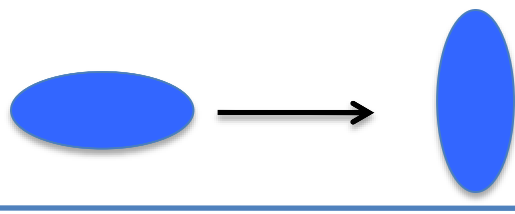


Dangerously into the integer stop-bands, maybe formula overestimates tune spread?

Extreme space charge MD (2010)

	N_b (x 10^{10} p)	$\varepsilon_{x,y}$ (μm)	$4\sigma_t$ (ns)	ΔQ_y
LHC50 SB rebucketed	150.0-190.0	2.5-3.0	130	**-0.34**

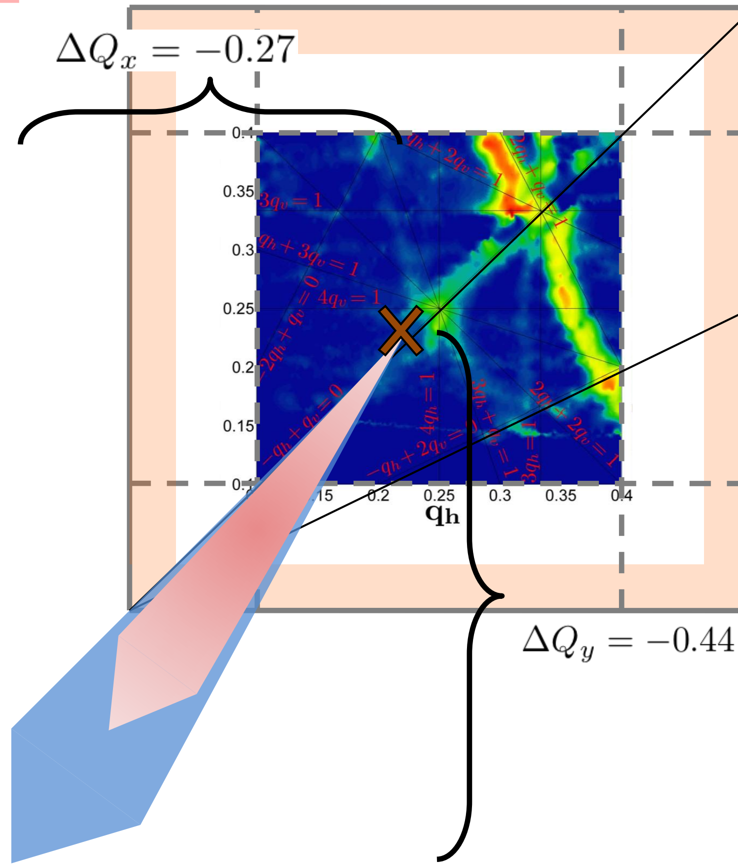
H. Damerau, S. Gilardoni, S. Hancock, R. Steerenberg



Bunch adiabatically shortened with 10MHz cavity **@1.4 GeV** FB (130ns → 90ns)

Huge tune spreads in both horizontal and vertical plane, however no loss observed

Emittance growth measured on a 1.2sec plateau



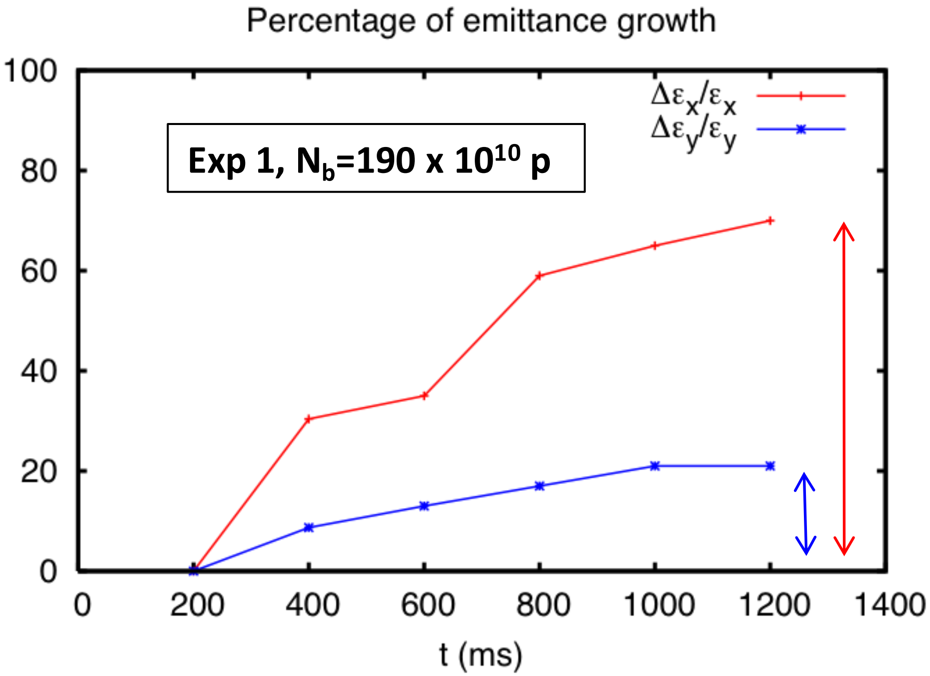
Extreme space charge MD (2010)

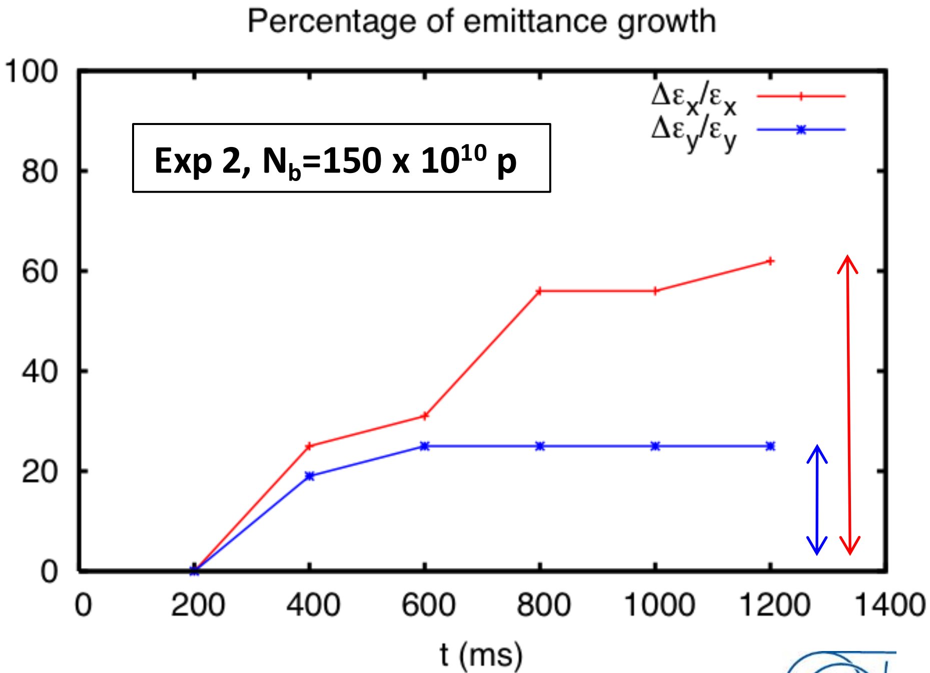
	N_b (x 10^{11} p)	$\varepsilon_{x,y}$ (μm)	$4\sigma_t$ (ns)	ΔQ_y
LHC50 SB rebucketed	150.0-190.0	2.5-3.0	130	**-0.34**

20% ε_y growth over 1.2sec

65% ε_x growth over 1.2sec

H. Damerau, S. Gilardoni, S. Hancock, R. Steerenberg





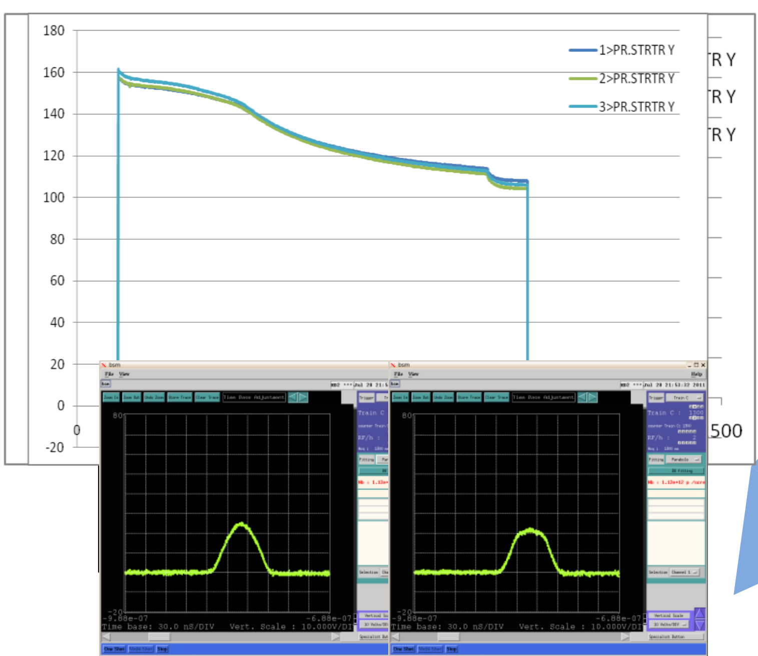
Space charge MDs at 2 GeV

Shortened bunch @2GeV

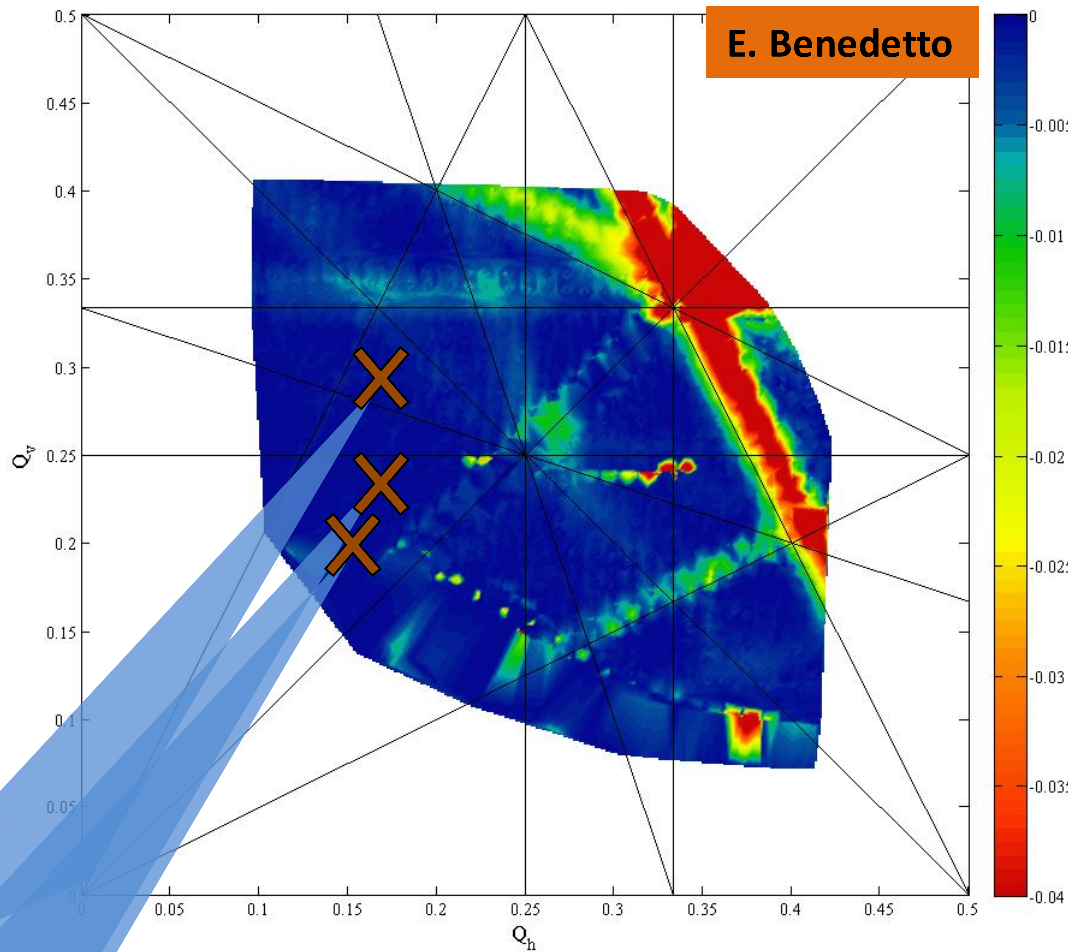
→ ΔQ_x = -0.19, ΔQ_y=-0.27

→ Three working points analyzed

- Q_x=0.15, Q_y=0.196
- Q_x=0.17, Q_y=0.23
- **Q_x=0.17, Q_y=0.30**



TUNE SCAN @ 2 GeV

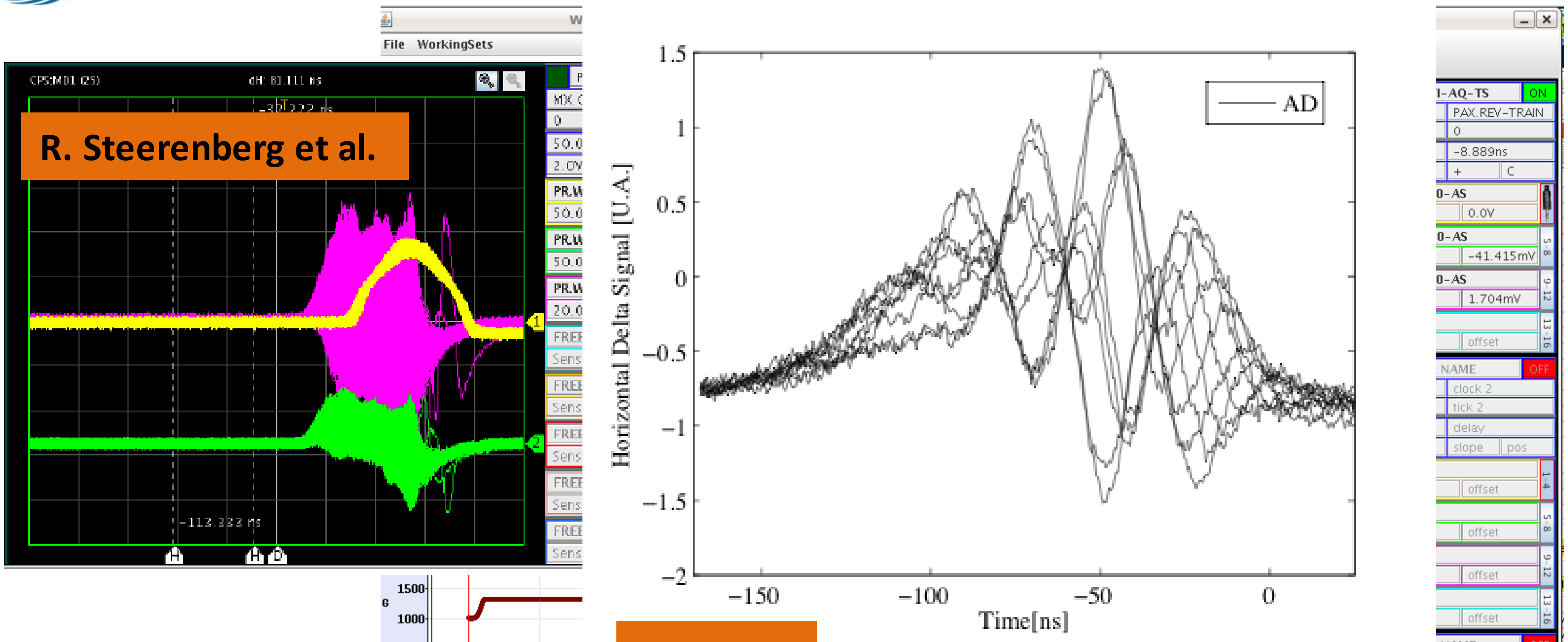


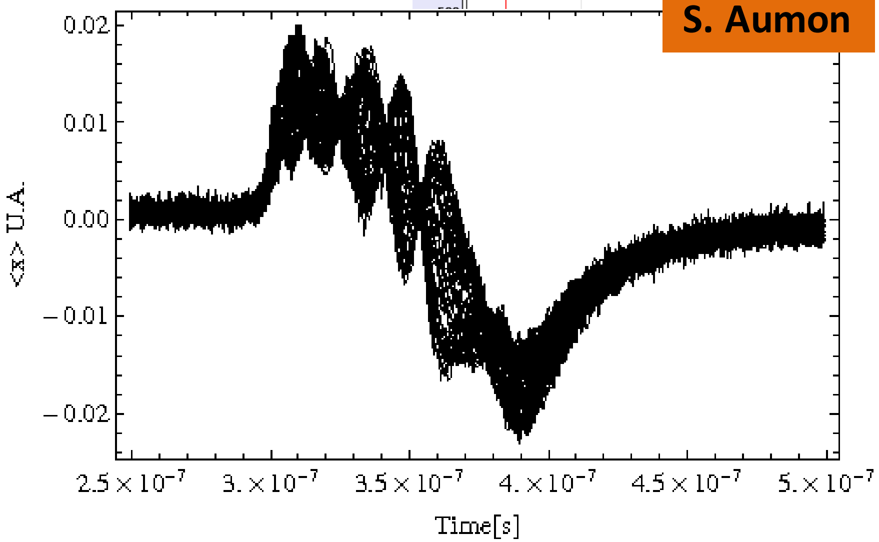
To be noted that the injection optics for the PS upgrade will be actually different !
→ see talk by J. Borburgh

An overview on the PS coherent instabilities

- Transverse headtail instabilities at flat bottom
- Fast instabilities at transition
- Longitudinal coupled bunch instabilities
- Electron cloud

Headtail instabilities at flat bottom

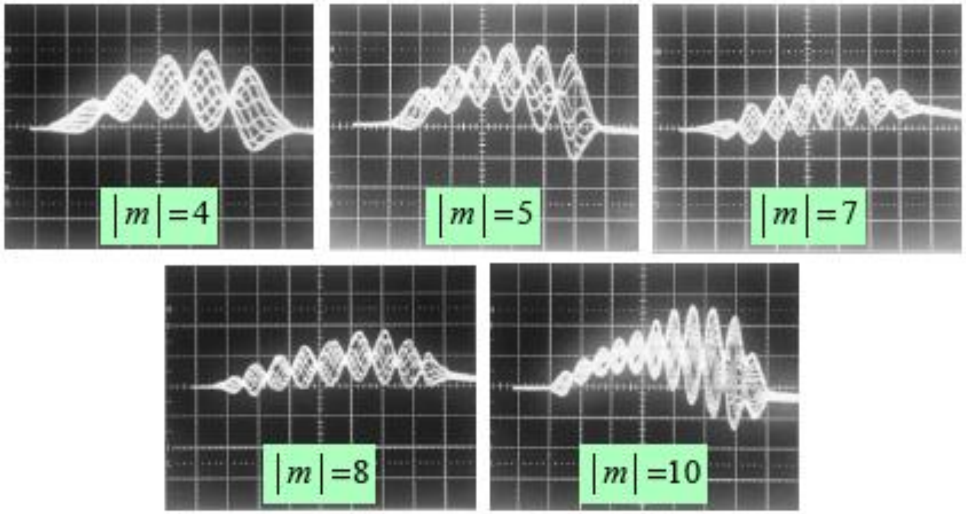


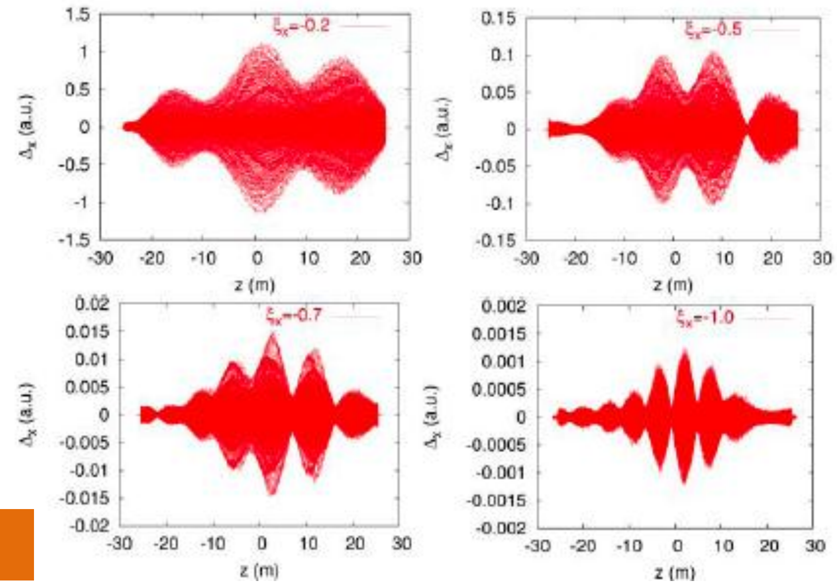


- **Head-tail type instabilities** at flat bottom (4-5 nodes, depending on ξ) have been observed on several occasions

- Depends on the **working point**, in particular seems to be cured through **linear coupling** above the tune diagonal, but not below

Headtail instabilities at flat bottom





E. Métral, G. Rumolo, et al.

- Explained like **single bunch instabilities** due to the **resistive wall impedance**
- **HEADTAIL code** was successfully used for reproducing the evolution and the patterns with numbers of nodes consistent with the chromaticity values

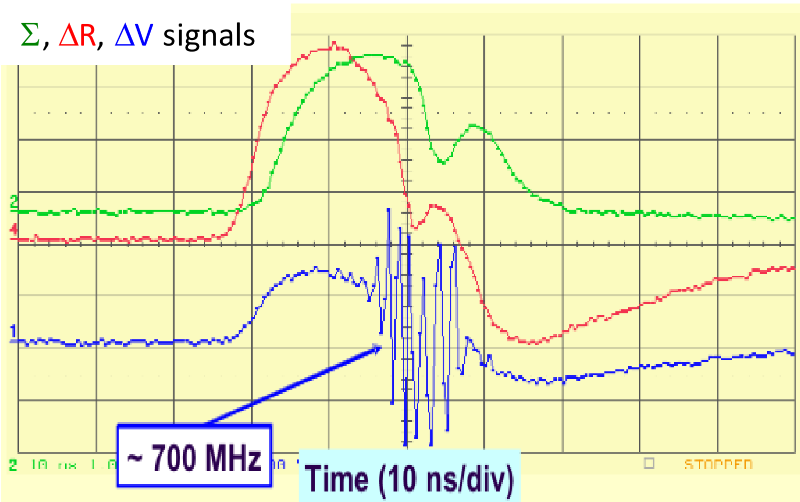
  ⇒ More MDs needed

  ⇒ HEADTAIL simulations multi-bunch and with space charge

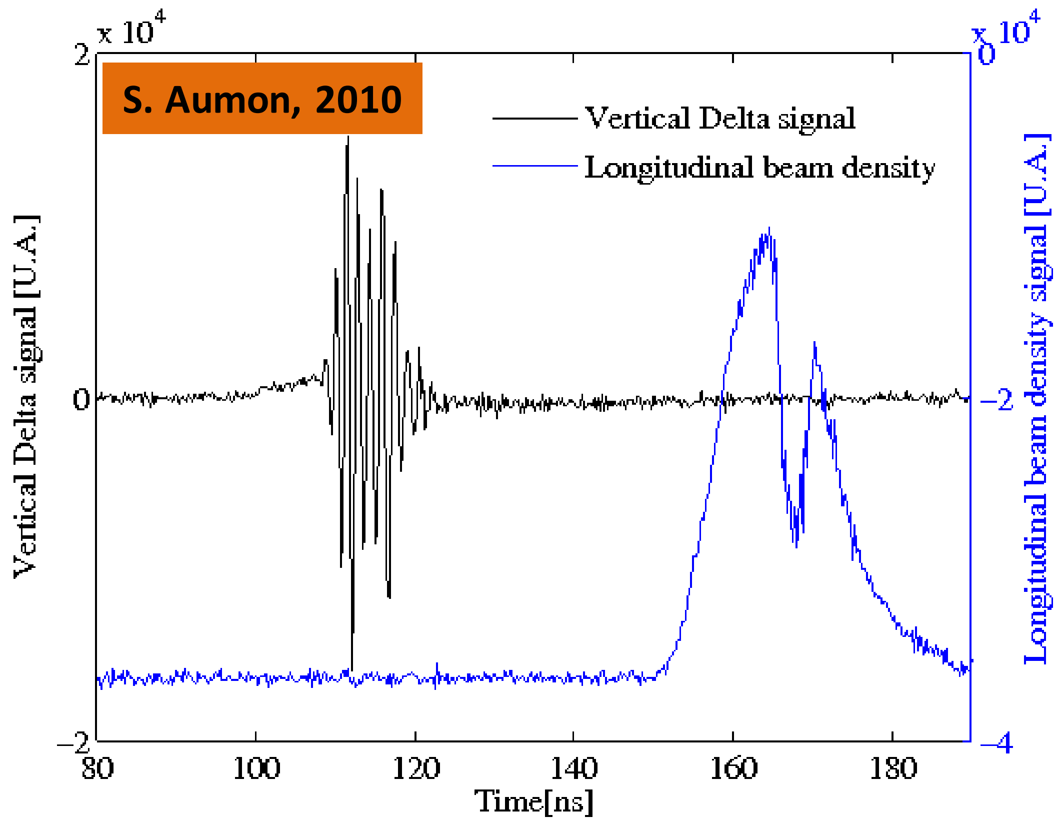
  ⇒ Transverse feedback system? (PSB and SPS need one!)

- Transverse headtail instabilities at flat bottom
- Fast instability at transition
- Longitudinal coupled bunch instabilities
- Electron cloud

Fast instability at transition



E. Métral et al., 2003



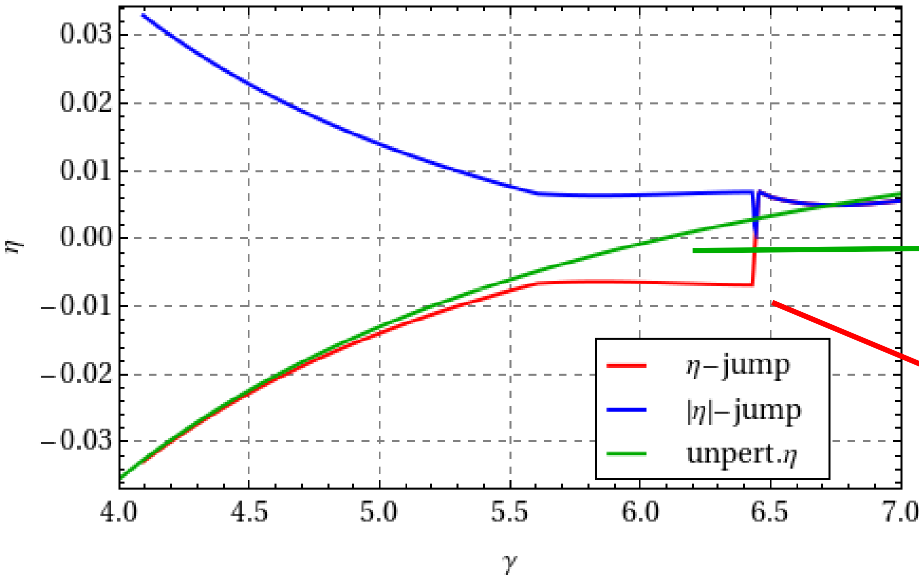
- TOF becomes unstable when crossing transition above a certain intensity threshold, which

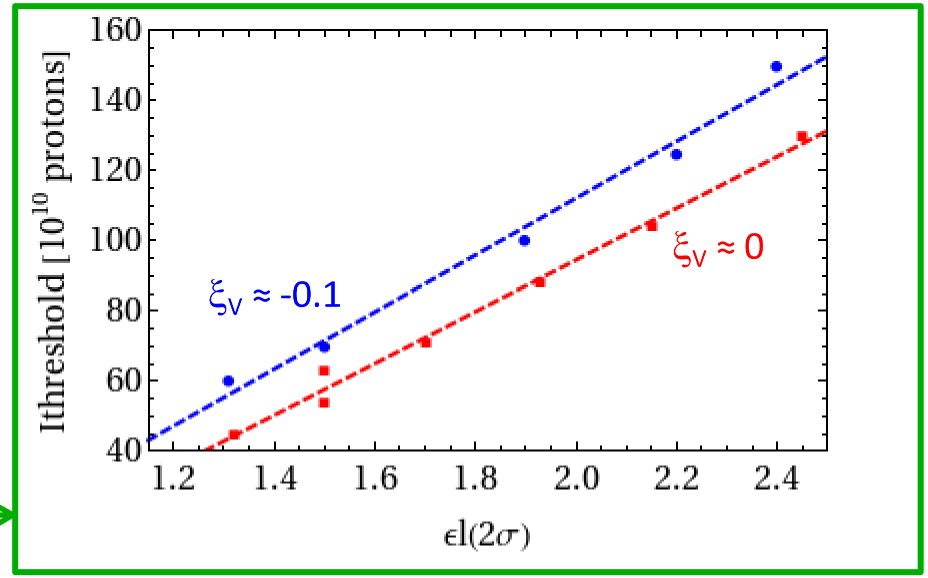
→ depends on bunch longitudinal emittance

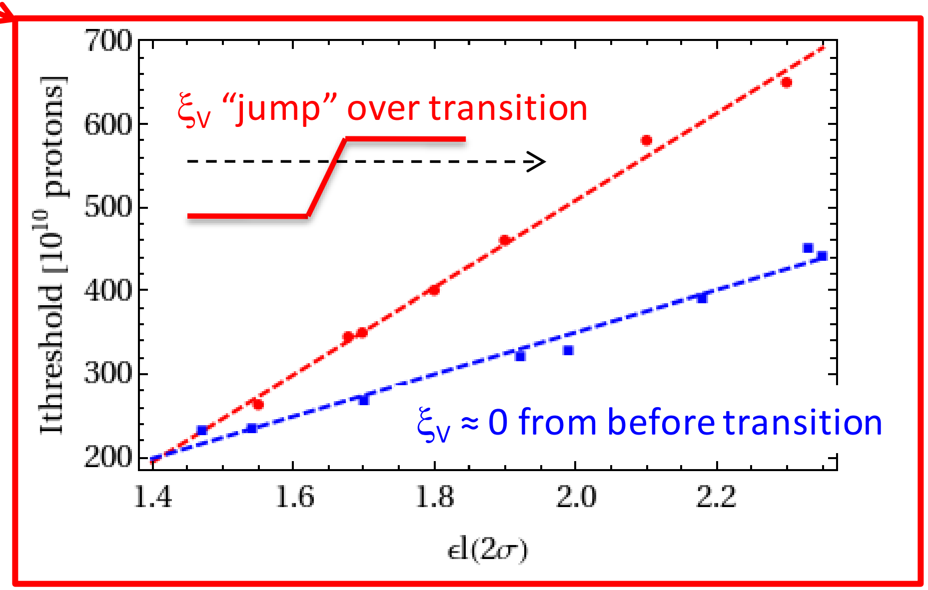
→ depends on gamma jump scheme

Fast instability at transition

S. Aumon, 2011







γ–jump scheme

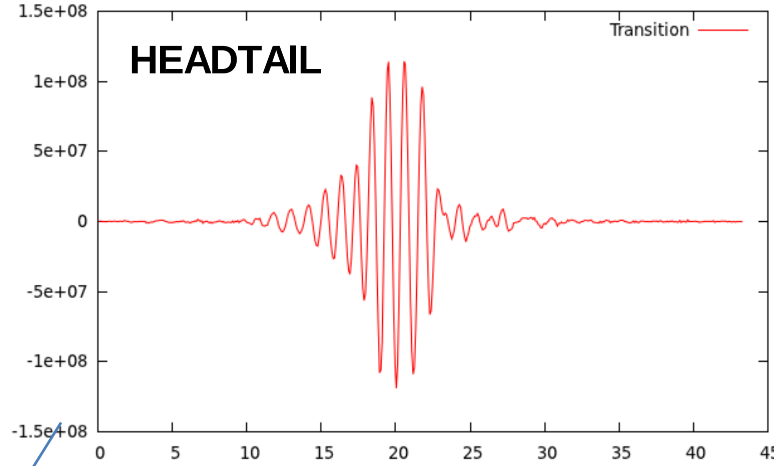
- → low thresholds if jump not applied
- → thresholds 4 to 6 times higher, depending on the ξ_V trim, when γ–jump scheme in place
- → anyway thresholds proportional to ε_z

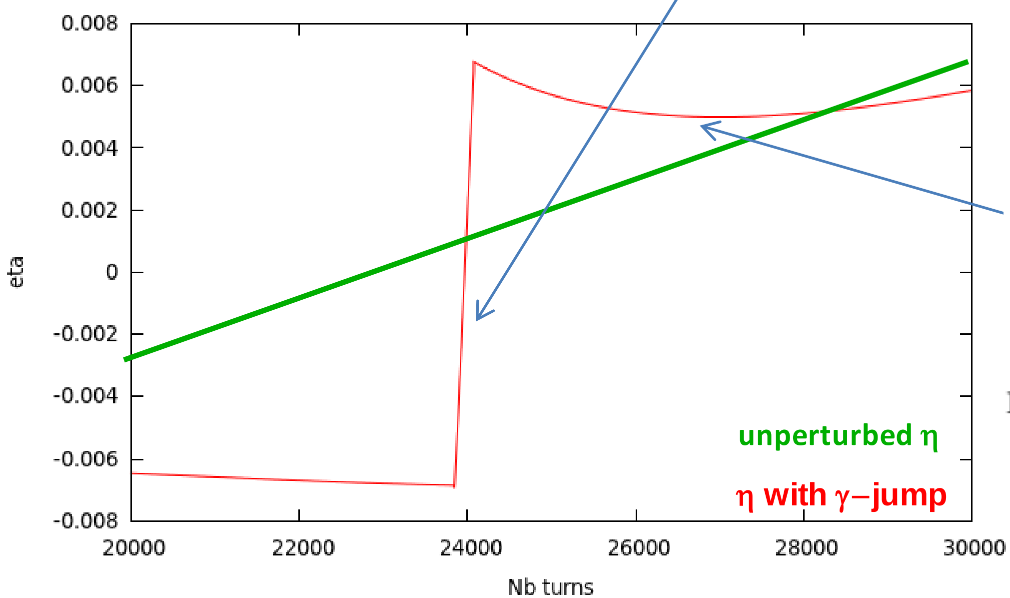
Fast instability at transition

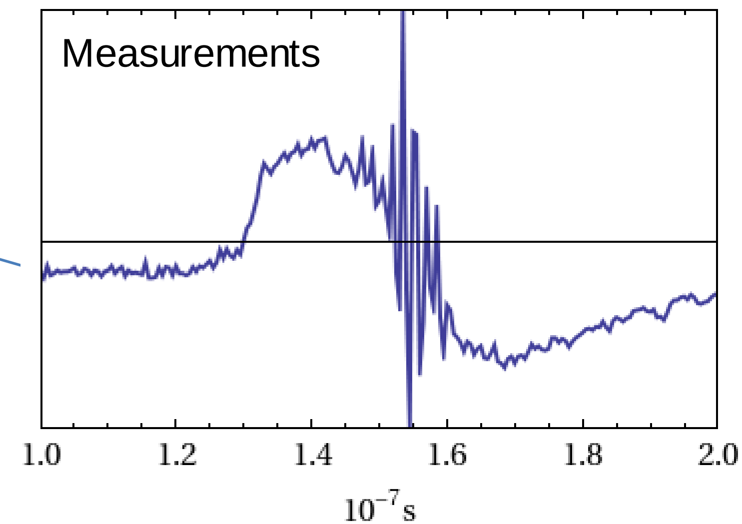
HEADTAIL simulations

→ can be done on the accelerating ramp, with and without γ–jump scheme

→ reproduce quite accurately the instability evolution using a **broad band impedance model of 2 MΩ/m at 1 GHz**







S. Aumon, 2011

- Transverse headtail instabilities at flat bottom
- Fast instability at transition
- Longitudinal coupled bunch instabilities
- Electron cloud

Longitudinal coupled bunch instabilities

- **Longitudinal coupled bunch instabilities** with both 25ns and 50ns beams observed (previously also with 75ns and 150ns beams)
  - ✓ During the ramp
  - ✓ At flat top when ramping down h=21 during bunch splitting
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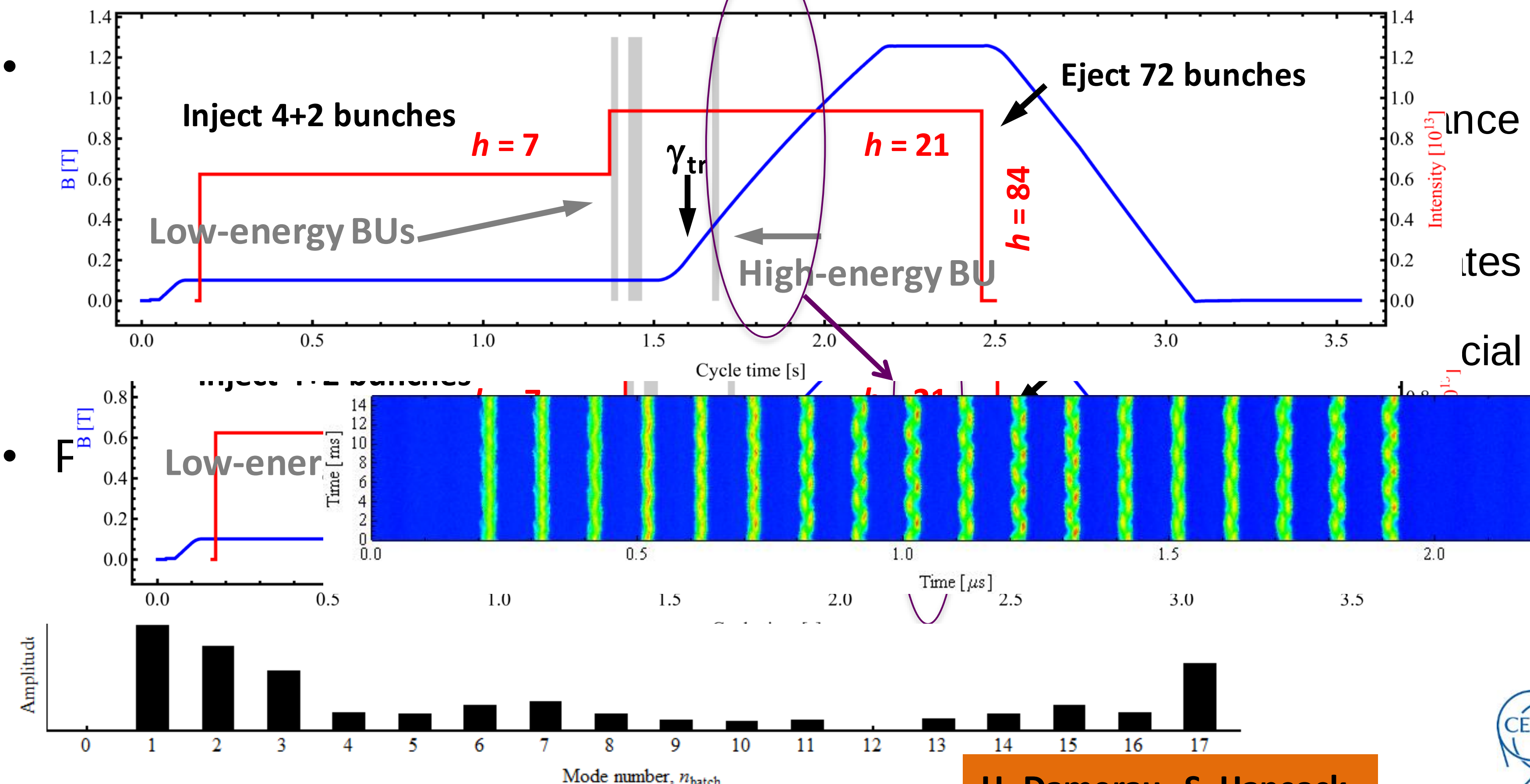

H. Damerau, S. Hancock

- Transverse headtail instabilities at flat bottom
- Fast instability at transition
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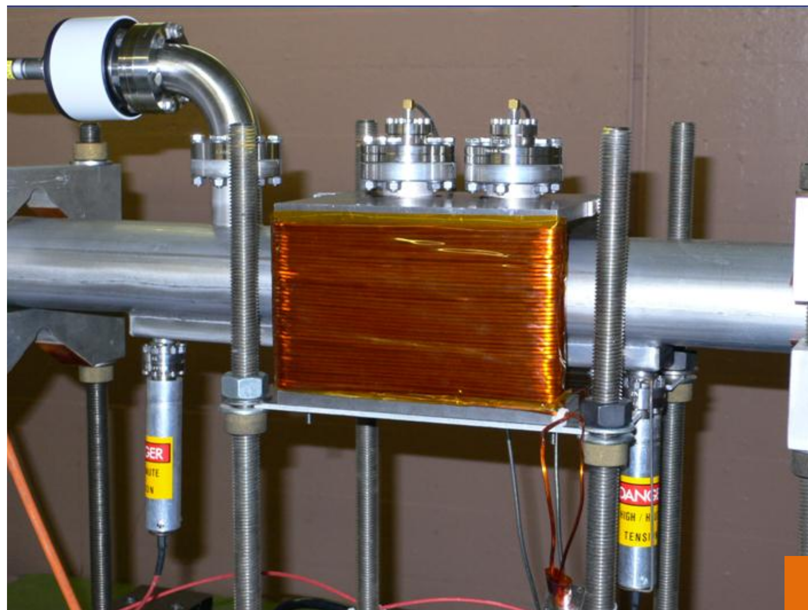
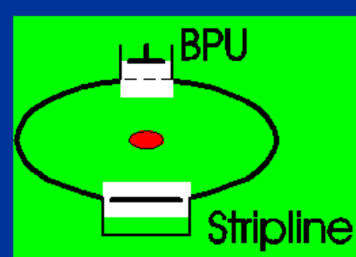
Electron cloud

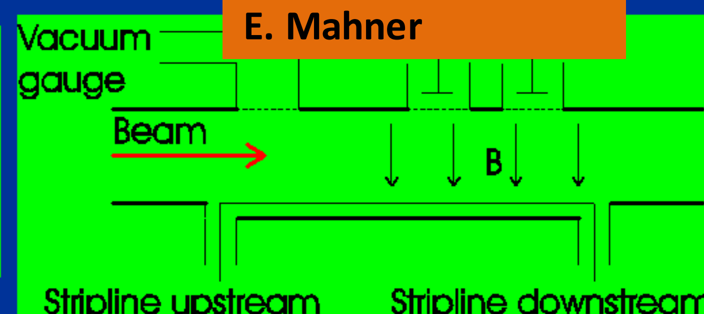
Electron cloud can be measured in the PS thanks to a shielded button pick up (with stripline for possible clearing voltage applied)



F. Caspers, T. Kroyer, E. Mahner

- PS elliptical vacuum chamber with dimensions 1050 x 146 x 70 mm.
- Special antechamber for clearing electrode without aperture reduction.
- Material: stainless steel 316 LN





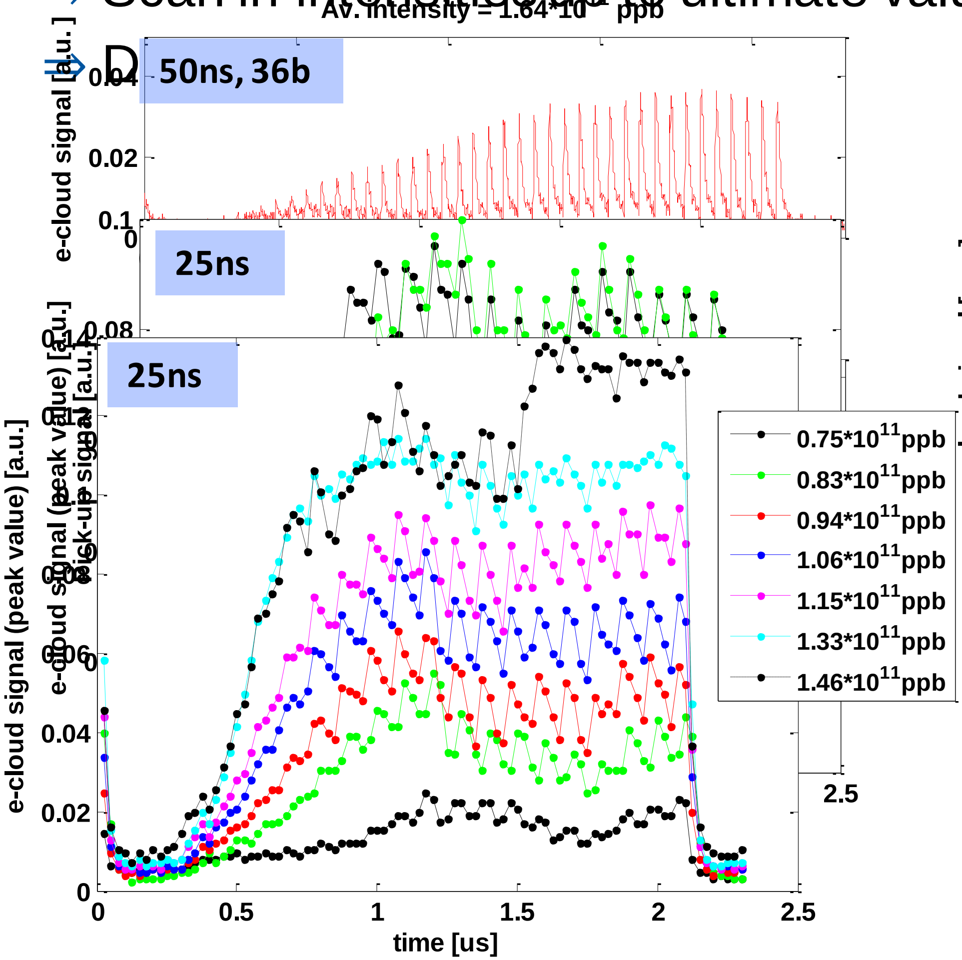
Electron cloud

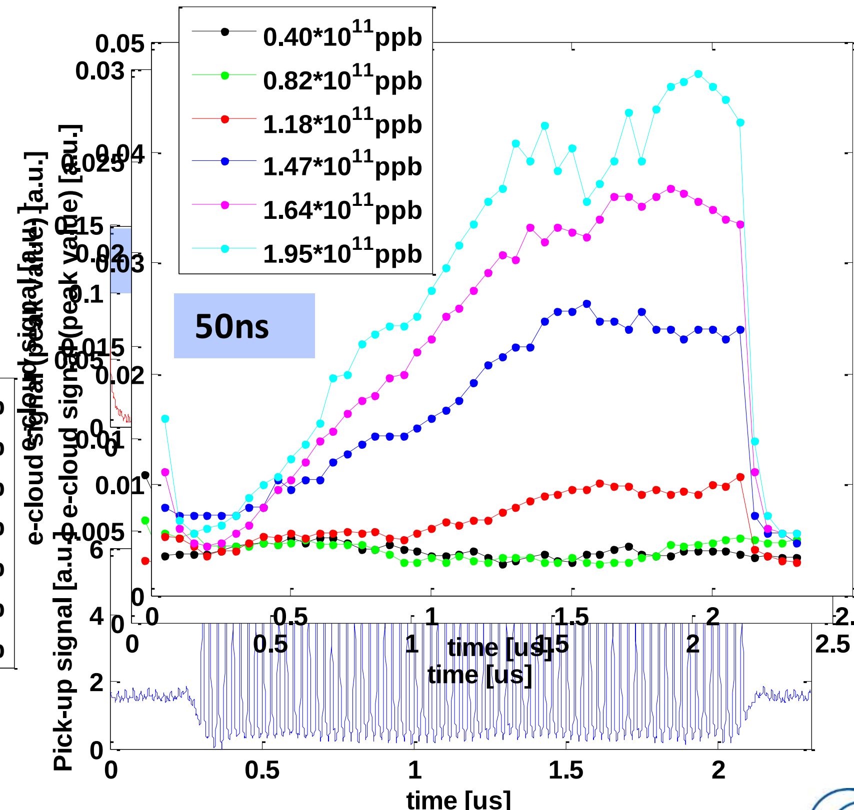
Recent systematic scans taken with

⇒ 50ns and 25ns beams

⇒ Scan in intensities up to ultimate values

⇒ D





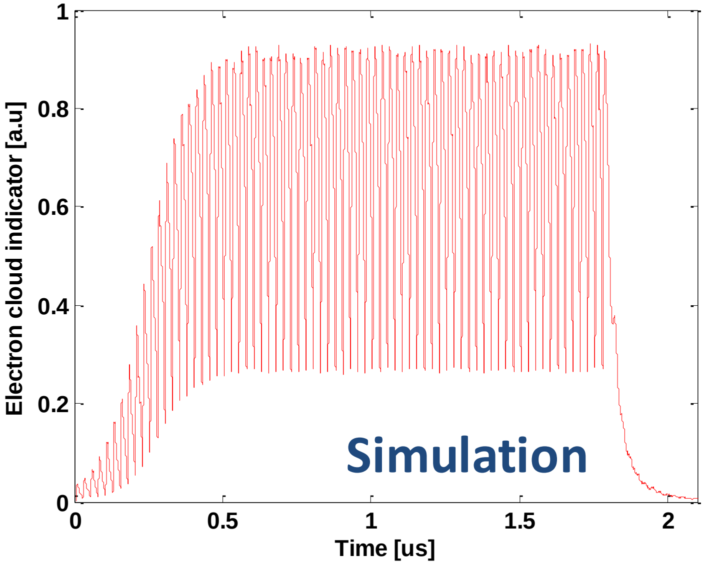
G. Iadarola, C. Yin-Vallgren

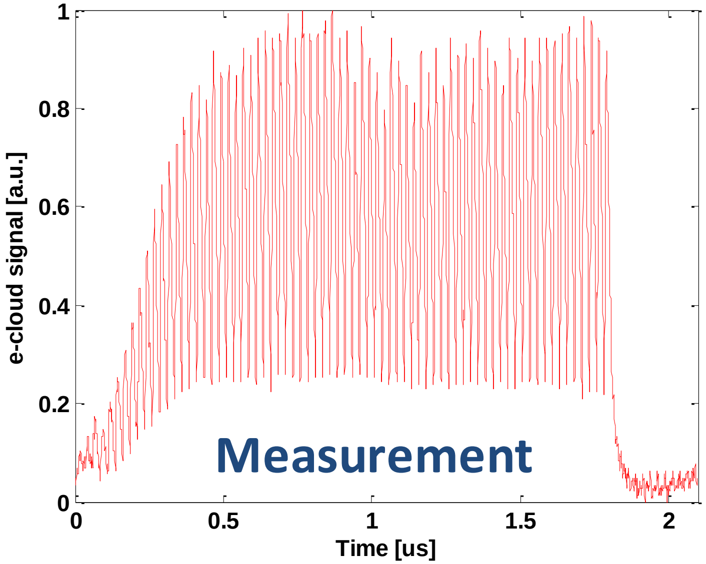
Electron cloud

Simulations ongoing with the build up code ***PyECLOUD***

⇒ Flux to the wall for a 25ns case (N_b=1.33 x 10^{11} ppb, bunch length=4ns)

⇒ First estimation of the inner surface properties of the PS beam chamber



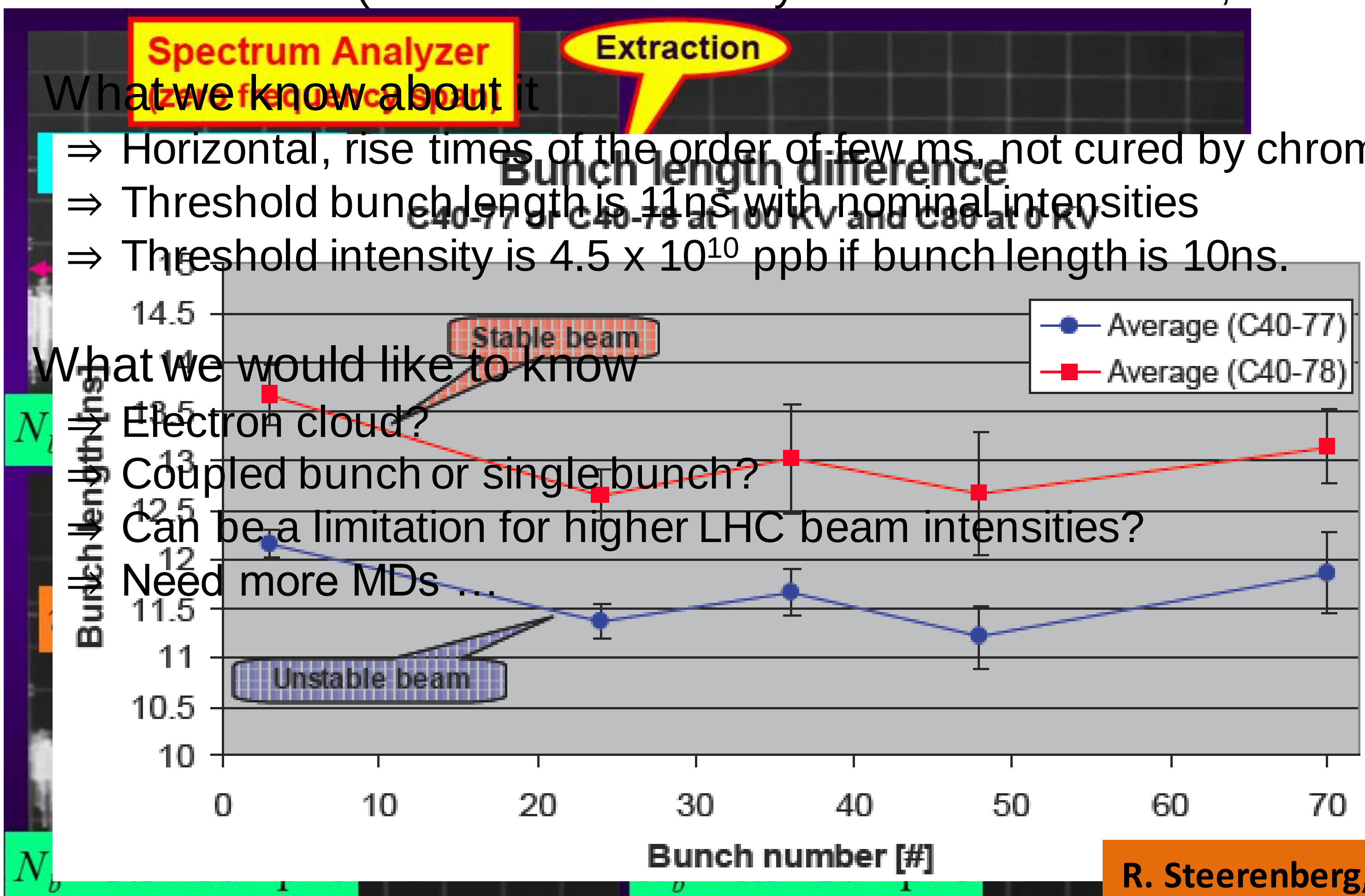


	δ_{max}	R_0	Beam in the gap
Simulation	1.6	0.5	5%

G. Iadarola, C. Yin-Vallgren

Transverse instabilities at flat top (electron cloud?)

- **Transverse instabilities at flat top** observed in
  - ✓ 2001 (special cycle with 25ns bunches of 10ns stored for 100ms)
  - ✓ 2004-2006 (bunches adiabatically shortened to 10-11ns, instead of 12.5ns)



- What we know about it
  - ⇒ Horizontal, rise times of the order of few ms, not cured by chromaticity
  - ⇒ Threshold bunch length is 11ns with nominal intensities
  - ⇒ Threshold intensity is 4.5 x 10^{10} ppb if bunch length is 10ns.

- What we would like to know
  - ⇒ Electron cloud?
  - ⇒ Coupled bunch or single bunch?
  - ⇒ Can be a limitation for higher LHC beam intensities?
  - ⇒ Need more MDs …

R. Steerenberg, et al.

Wrap up and outlook

1. **Space charge at PS injection**
   - → Eased by injection at 2 GeV
   - → Lots of studies ongoing (MDs and simulations)
   - ➜ Full impact to be understood via detailed simulations (Space Charge Working Group, F. Schmidt) and future MDs
2. **Collective instabilities along the cycle**
   - → Transverse headtail instabilities
   - → Fast instability at transition
   - → Longitudinal coupled bunch instabilities during the ramp and at flat top
   - → Horizontal instabilities at flat top
   - ➜ Pose limitations for high brightness beams, need for more studies (MDs, PS impedance model, extended simulations), hardware solutions (transverse and longitudinal feedbacks), alternative production schemes
3. **Electron cloud at flat top**
   - ➜ So far not a problem, effort ongoing to characterize the chamber walls (δ_{max}, R_0) to extrapolate behavior for higher brightness beams

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN