LHC experience with different bunch spacings in 2011 (25, 50 & 75 ns): Electron cloud aspects

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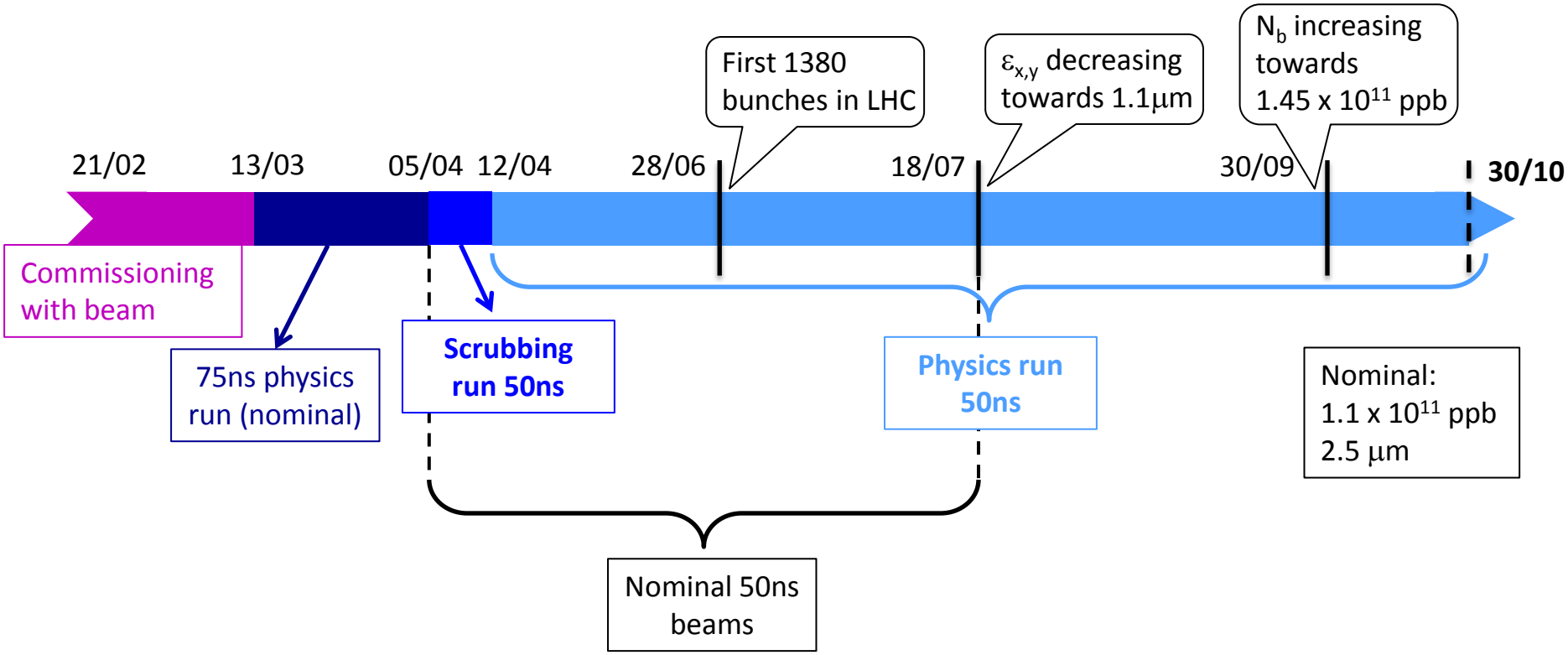
Introduction

Focus of this talk → Results of the analysis of the 2011 electron cloud observations and measurements



Introduction

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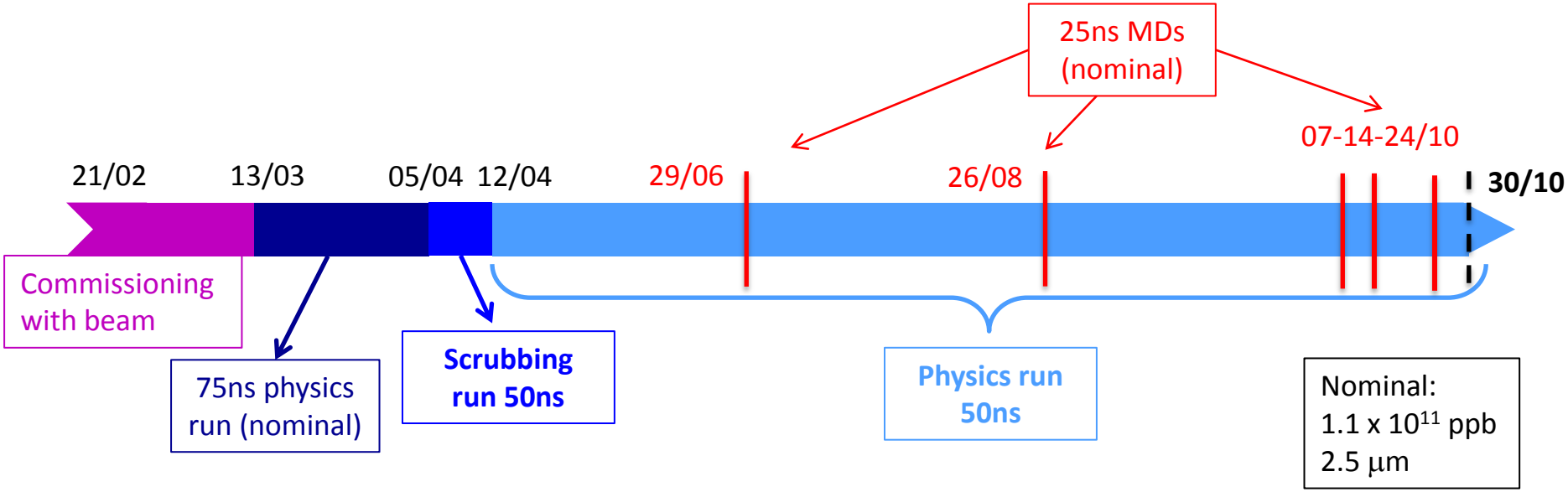


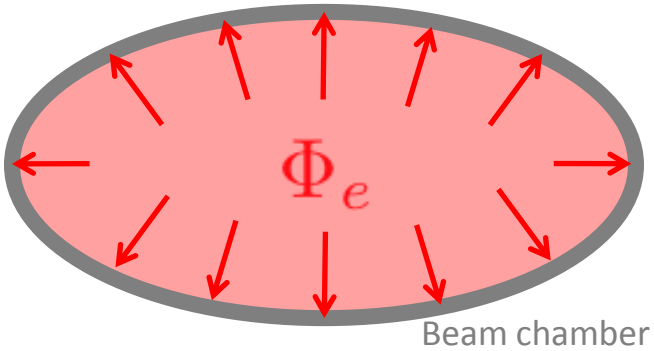
- 75ns operation → no electron cloud observations in 2011
- 50ns operation
  - ⟶ Observations during scrubbing
  - ⟶ Physics operation with residual electron cloud activity
- 25ns MDs: evolution of δ_{max} in the arcs and uncoated SS
- Estimation of scrubbing time and closing remarks

Electron cloud observables

PRESSURE RISE

$$\Delta P = kT \frac{\int \eta_e(E)\Phi_e(E)dE}{S_{\text{eff}}}$$

Electron flux to the chamber wall Φ_e

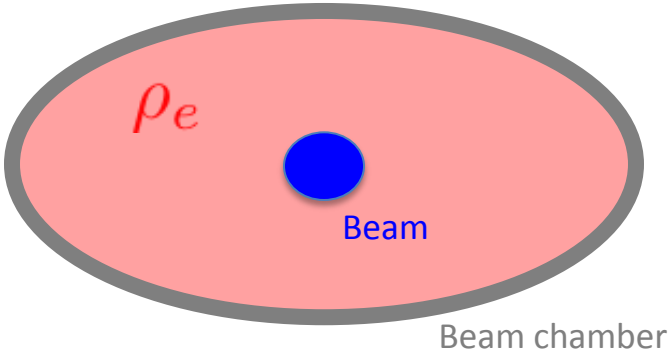


POWER ON THE CHAMBER WALL

$$\Delta W = \int \Phi_e(E) E dE \quad \begin{cases} \propto \Delta T \\ \propto \sin \Delta\varphi_s \end{cases}$$

Electron cloud observables

Electron cloud with density ρ_e around the beam



COHERENT INSTABILITY

- Affects only the last bunches of each batch
- Can be single or coupled bunch

$$\tau_{\text{inst}} \propto \frac{1}{\rho_e}$$

INCOHERENT EMITTANCE GROWTH

- Causes degrading lifetime and slow beam loss
- Typically associated to bunch shortening and loss pattern increasing along the batch

$$\frac{\Delta\epsilon_{x,y}}{\Delta t} \propto \rho_e$$

Scrubbing run in 2011

⇒ The **scrubbing run** took place in the week 5–12 April 2011

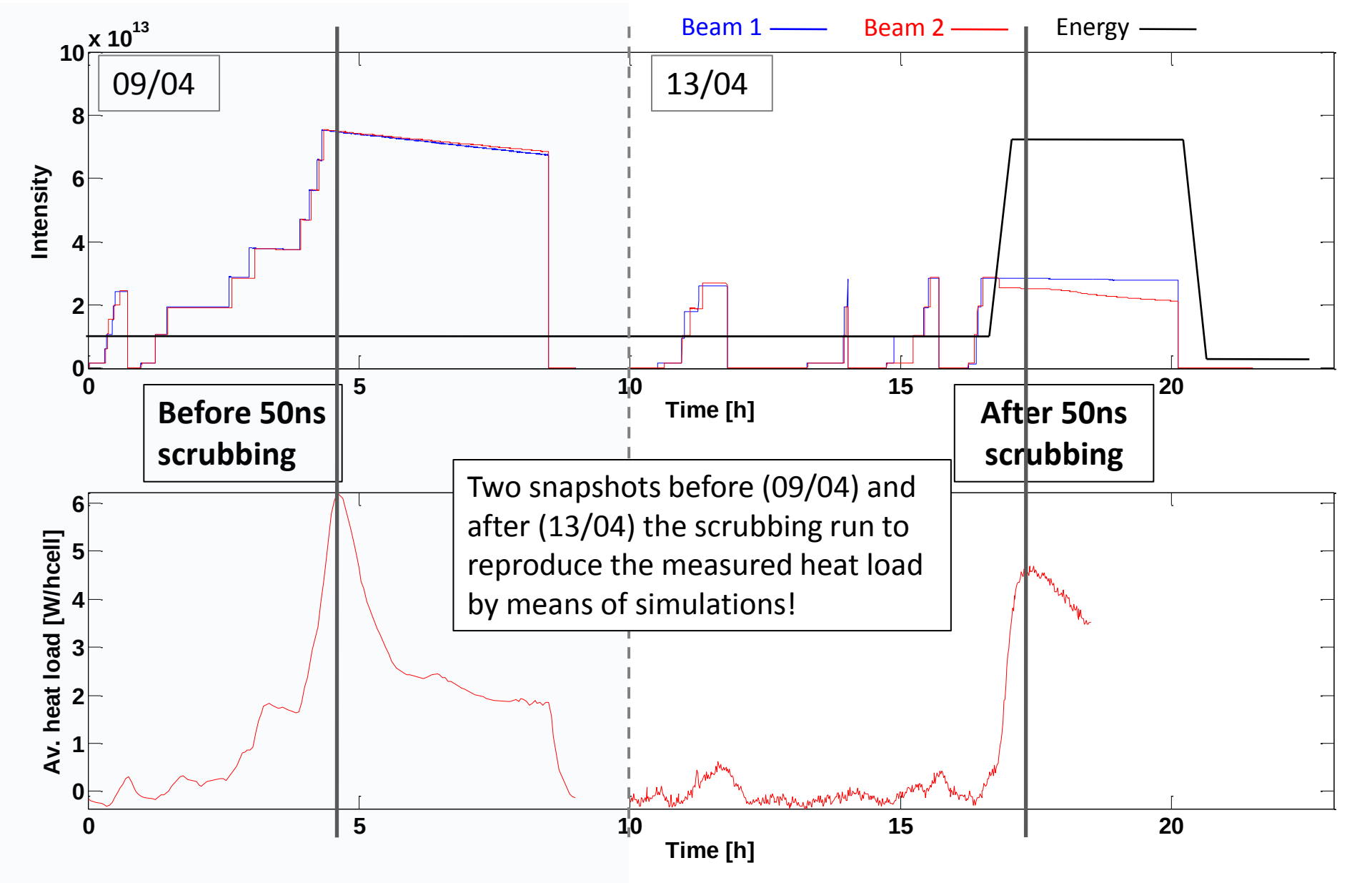
- Nominal 50ns spaced beams with up to 1020 bunches per beam injected into the LHC and stored at 450 GeV/c

⇒ Very efficient **machine cleaning**

- The dynamic vacuum decreased by one order of magnitude over 17h of effective beam time (i.e. 72h machine time)
- The heat load on the beam screen in the arcs
  - → significant at the beginning of the scrubbing run
  - → within measurement resolution at the end
- The average stable phase decreased by one order of magnitude
- Instabilities and emittance growth, visible during the first fills, disappeared later even with low chromaticity settings

⇒ After scrubbing, **physics with 50ns** and stable beams with **1380** bunches per beam on 28 June 2011

δ_{max} in the arcs: estimation technique



Two snapshots before (09/04) and after (13/04) the scrubbing run to reproduce the measured heat load by means of simulations!

δ_{max} in the arcs: estimation technique

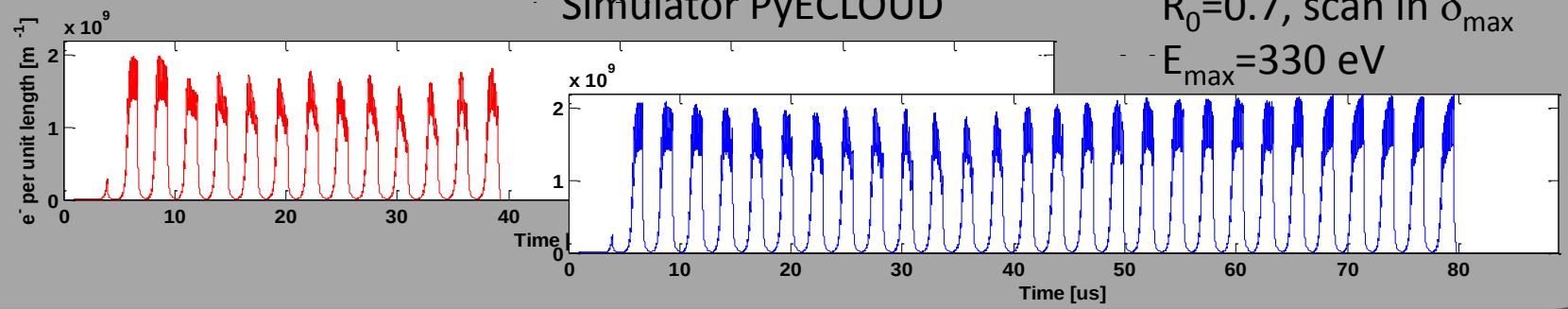
fastBCT + bunch-by-bunch b-length (B1)

fastBCT + bunch-by-bunch b-length (B2)

Simulator PyECLOUD

R_0=0.7, scan in δ_{max}

E_{max}=330 eV



$\Delta W_{\mathrm{sim1}}(\delta_{\max})$

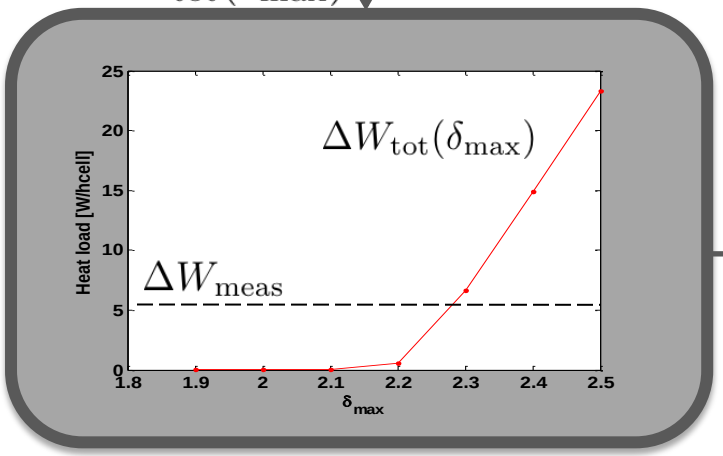
$\Delta W_{\mathrm{sim2}}(\delta_{\max})$

$\Delta W_{\mathrm{tot}}(\delta_{\max})$ **Total simulated heat load**

$\Delta E_{b1}(\delta^*_{\max})$
$\Delta E_{b2}(\delta^*_{\max})$ [mJ/turn]

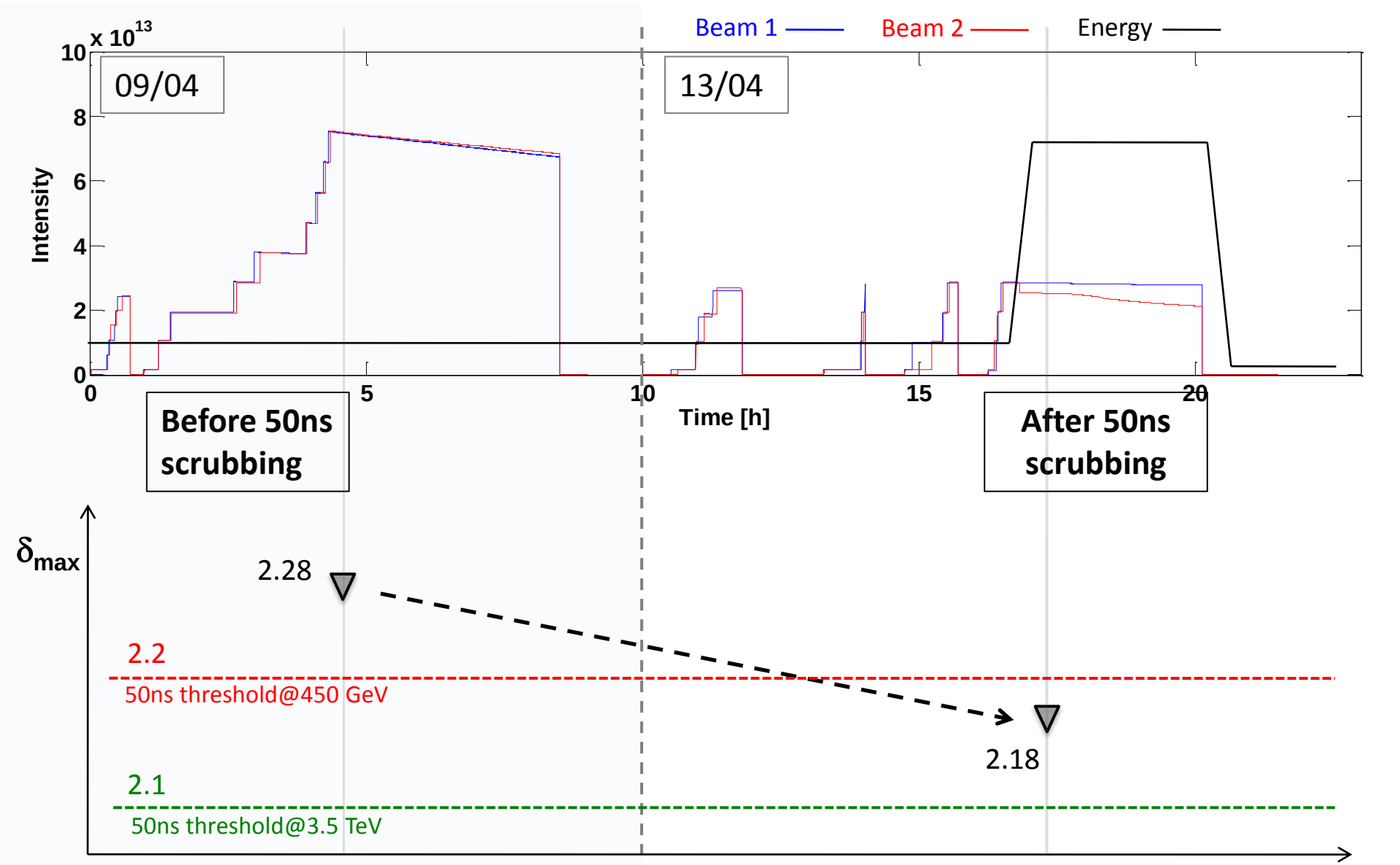
Measured heat load

ΔW_{meas}



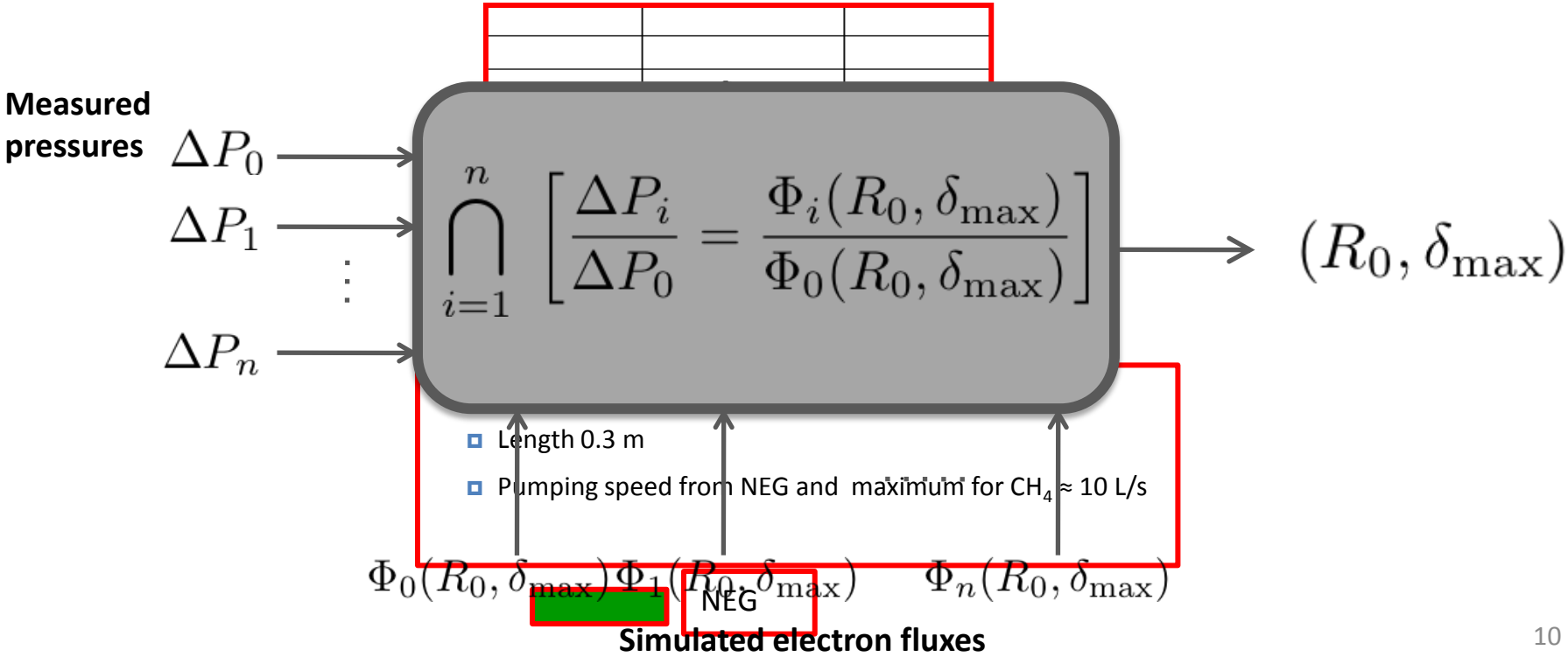
$\delta^*_{\max}$

δ_{max} in the arcs: results (50ns)



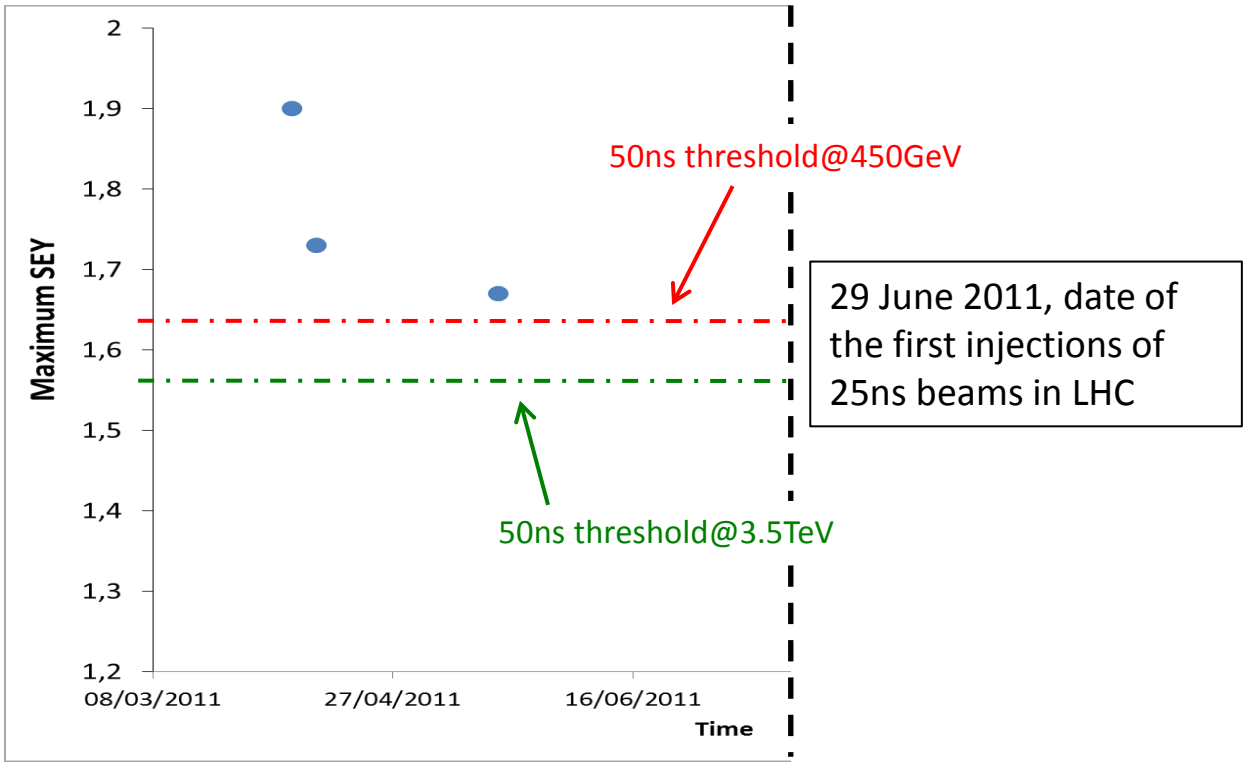
δ_{max} in uncoated straight sections: estimation technique

- The evaluation of δ_{max} is done in the field-free regions in proximity of the pressure gauges
  - Used Beam1 data from gauges (Cu): VGI.141.6L4.B and VGPB.2.5L3.B
  - A solution (R_0, δ_{max}) is found comparing the pressure rises ΔP_i measured at different injections with the electron fluxes Φ_i from simulations



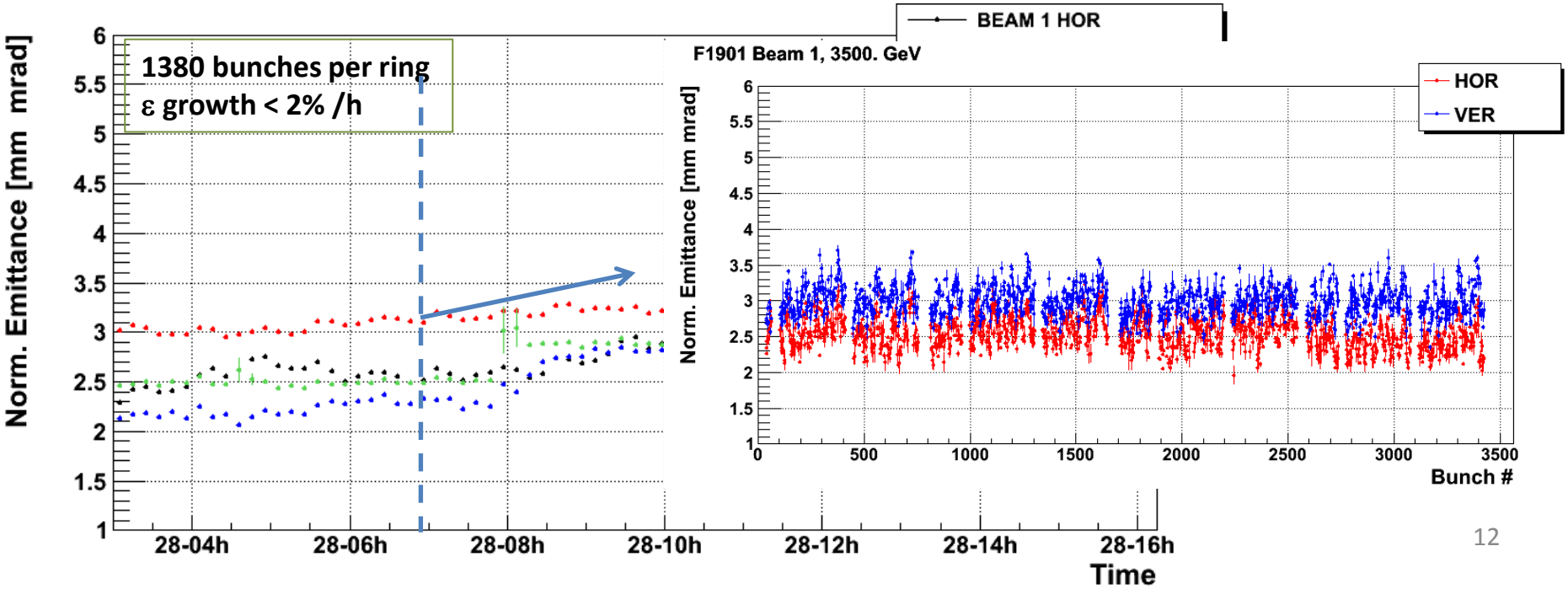
δ_{max} in uncoated straight sections: results (50ns)

- Pressure rise measurements with 50ns beam to estimate δ_{max} in the field-free regions in proximity of the pressure gauges (**R_0 ≈0.2–0.3**)
  - Measurements done **at the beginning** and **at the end of the scrubbing run**
  - Measurements done **during the 50ns operation** of LHC (19 May)
  - As expected, we are approaching the δ_{max} **thresholds for 50ns beams**



LHC operation with 50ns beams

- By end-June 2011, LHC was filled with 1380 bunches per beam
  - Nominal 50ns beams not suffering from obvious electron cloud limitations, very low rate emittance growth
  - No typical pattern along the batches as from electron cloud
- Reduction of transverse emittances and increase of bunch current (from July onwards) did not cause any significant return of the electron cloud
  - Consistent with expected electron cloud behaviour (weak dependence on transverse emittances, decrease with bunch current in dipoles)
- Pressure rise from electron cloud only survived in a wide common StSt beam pipe (close to ALICE)



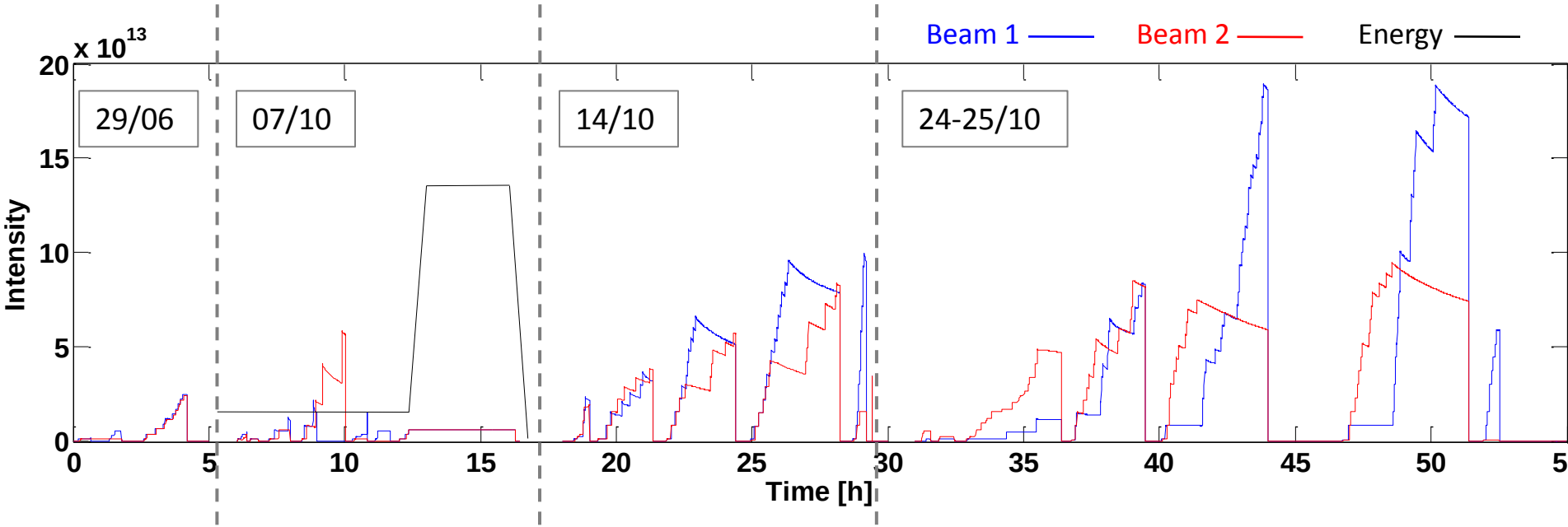
Summary 50ns run (before 25ns beam in LHC)

	δ_{max} (last estimated)	δ_{max} (threshold @450 GeV)	δ_{max} (threshold @3.5 TeV)
Straight section (uncoated)	**1.66**	**1.63**	**1.58**
Beam screen (arcs)	**2.18**	**2.2**	**2.1**

Nominal beam
1.1×10^{11} ppb

* Thresholds in the arcs do not change significantly at least up to $N_b = 1.8 \times 10^{11}$ ppb

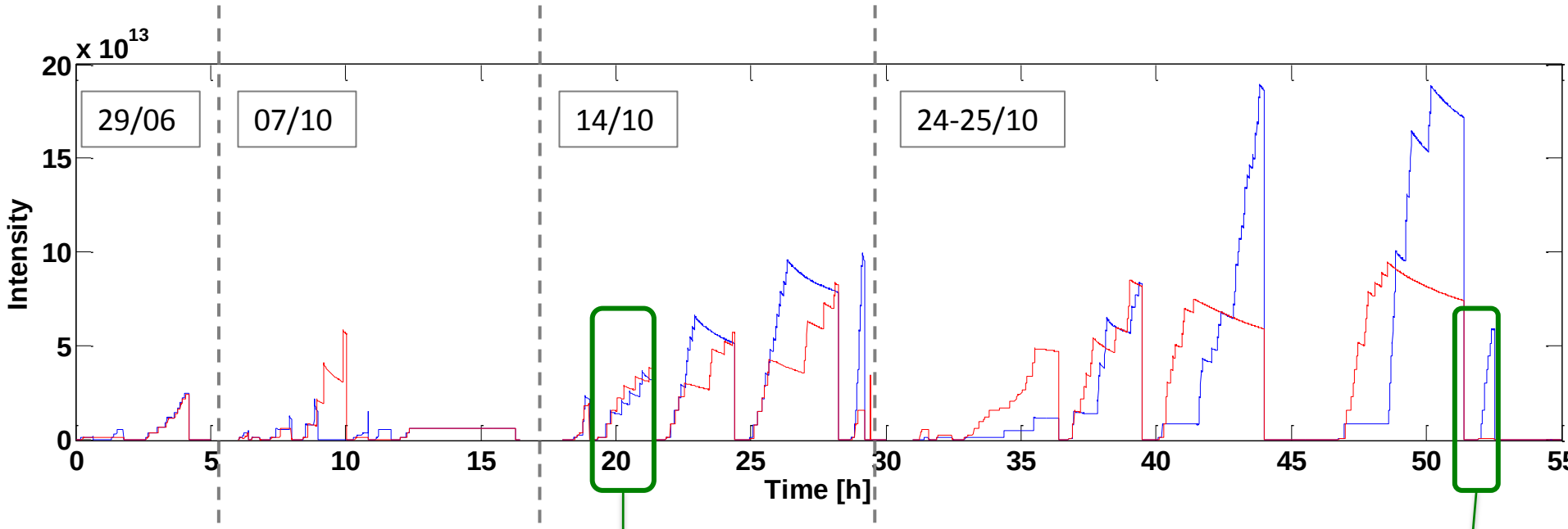
25ns experience in 2011



DATE	SHORT DESCRIPTION
29 June	Injections of **9 x 24b trains per beam** with different spacings between them
26 August	Two attempts to inject a **48b train** with damper on and off: fast instability dumps the beam within 500 turns in both cases (SBI and CBI)
7 October	High chromaticity ($Q'_{x,y}$ ≈15): Injection tests with **trains of 72-144-216-288 bunches** from the SPS + ramp to 3.5 TeV & 5h store with **60b (12+24+24) per beam**
14 October	High chromaticity: injection of up to **1020 bunches** per beam in **72b trains** (decreasing spacings between trains at each fill: 6.3–3.2–1 μs)
24-25 October	Injection of up to **2100 bunches** in Beam 1 and **1020** in Beam 2 (1μs train spacing)

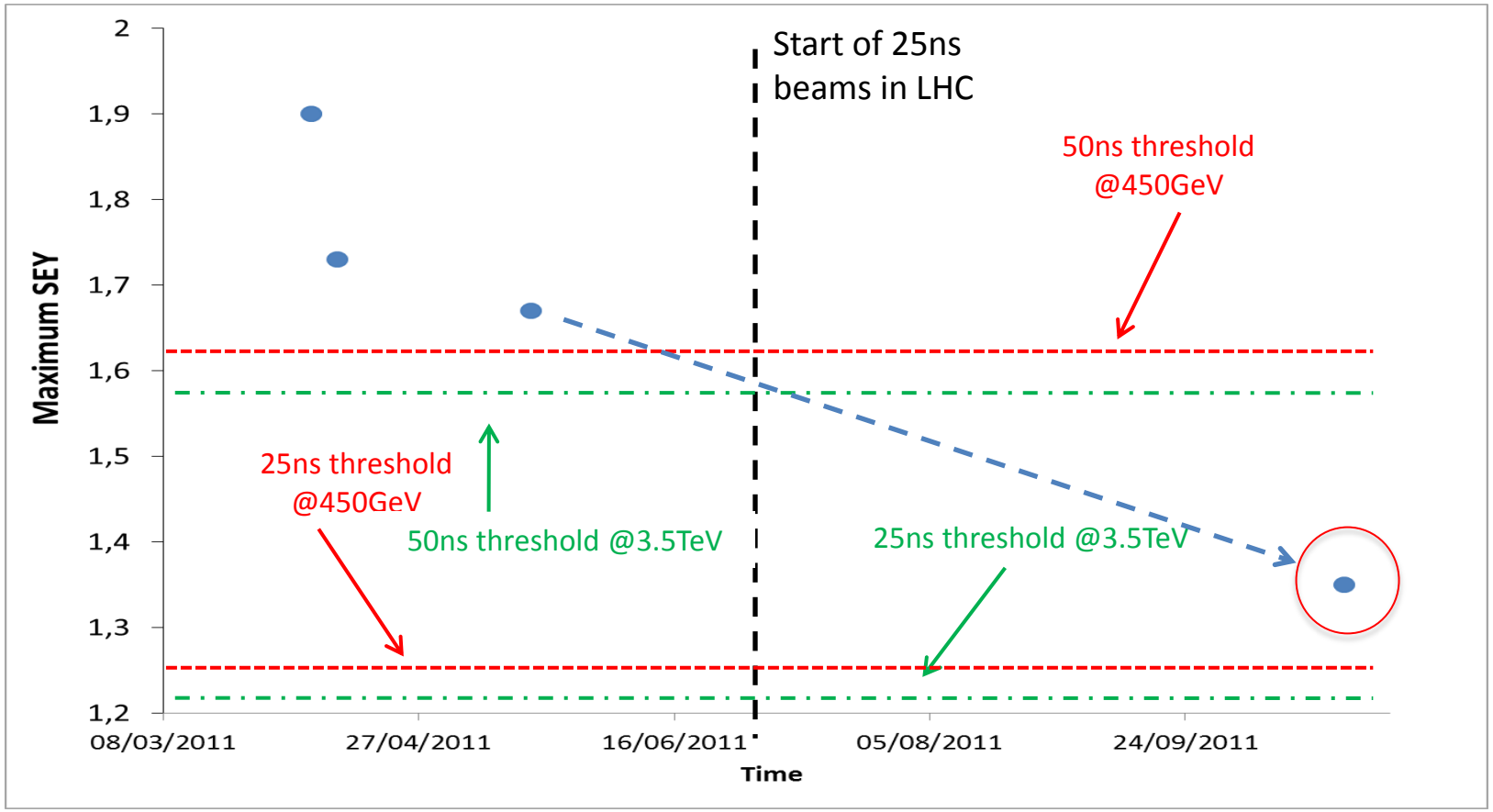
Scrubbing

δ_{max} in the uncoated sections: results (25ns)



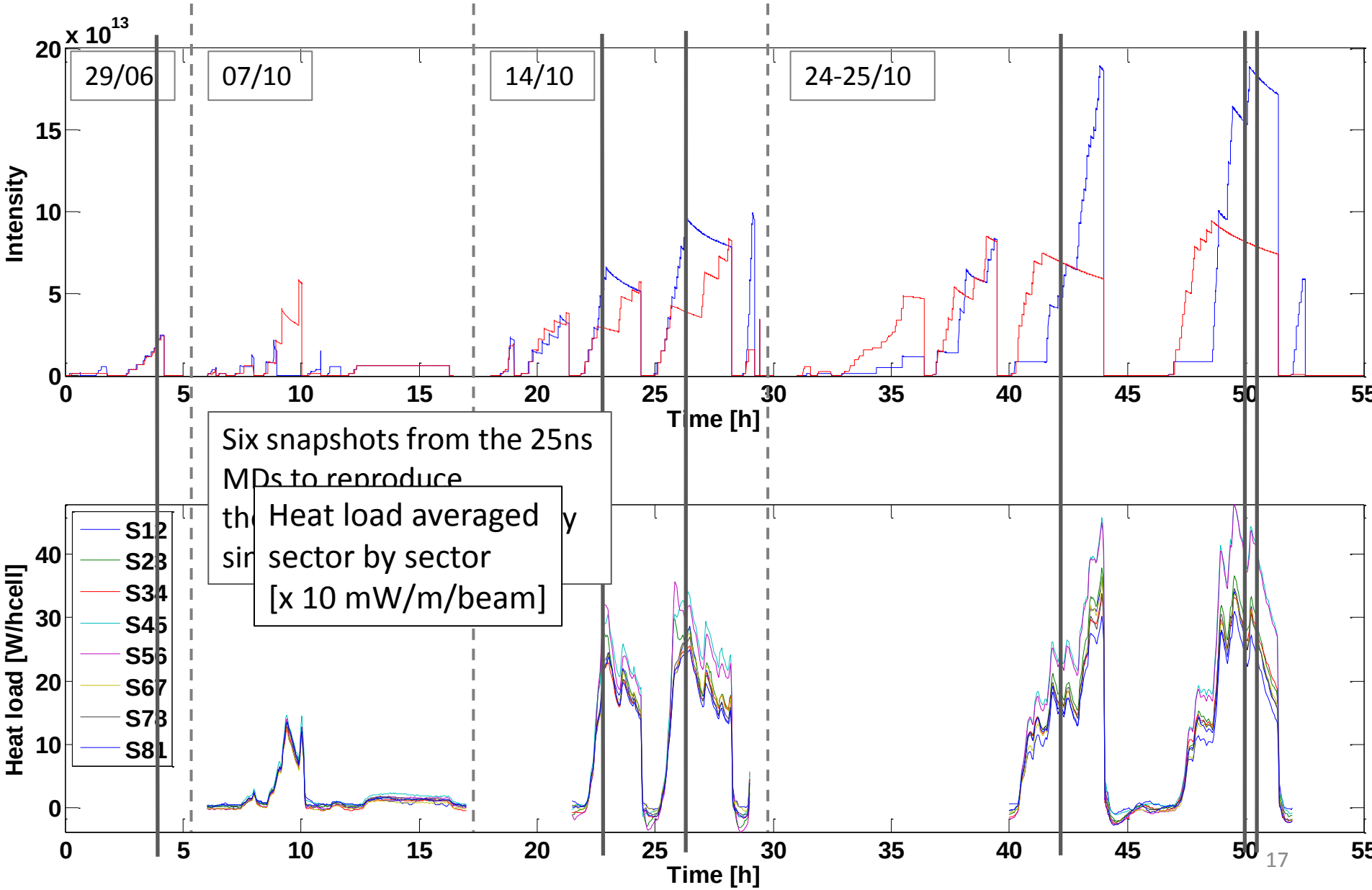
- Attempt made on 14 October to take pressure rise measurements on a dedicated fill with decreasing spacings (4—3—2—1 μs), but hard to use data for the δ_{max} estimation due to rapid evolution of beam and vacuum
- After considerable 25ns scrubbing, on the morning of the 25 October, 8 x 72b batches with different spacings could be injected for Beam 1 and remain stable to allow the pressure values to level

δ_{max} in the uncoated sections: results (25ns)



- Scrubbing with 25ns beam (~40h) has lowered δ_{max} to 1.35 !
- Again, we are not far from the threshold for 25ns beams, but further scrubbing is needed

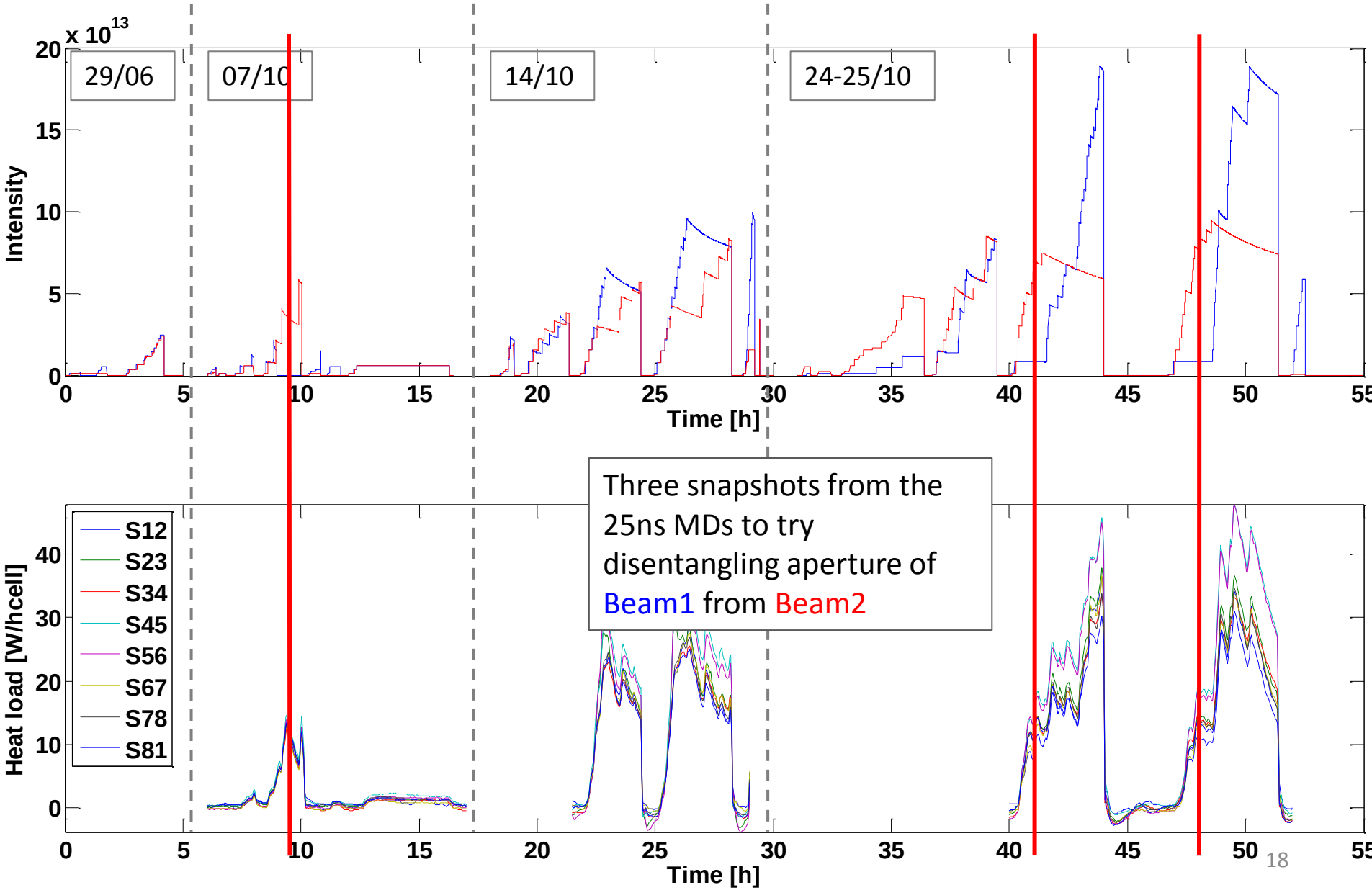
δ_{max} in the arcs: results (25ns)



Six snapshots from the 25ns MDs to reproduce the [illegible] y sin[illegible]

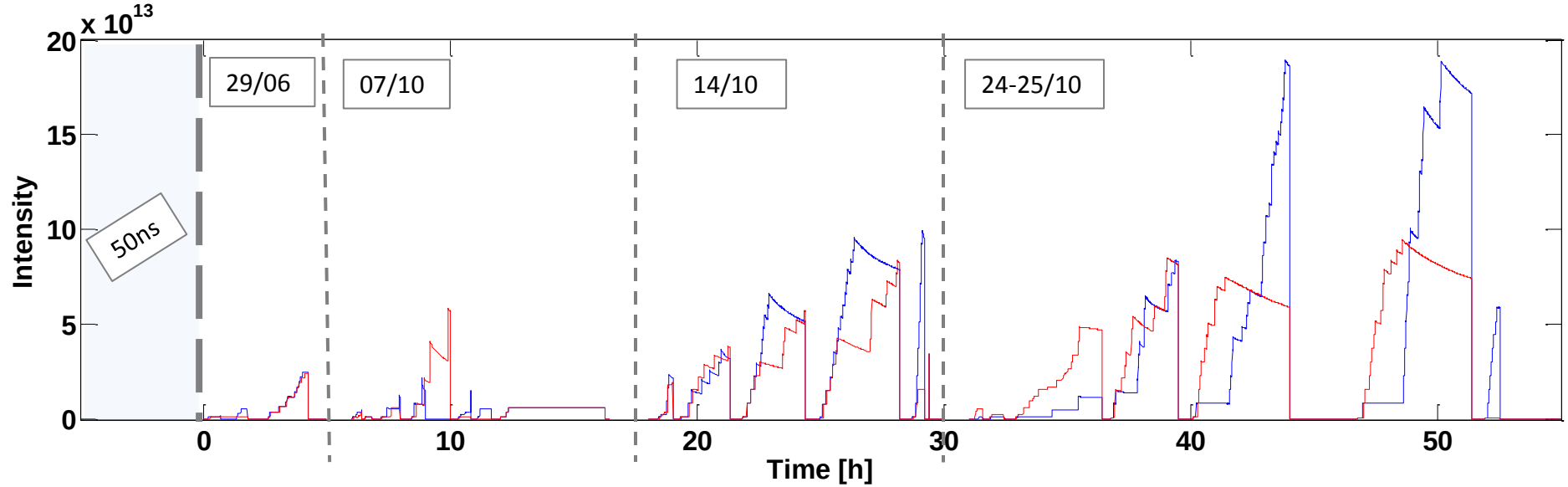
Heat load averaged sector by sector [x 10 mW/m/beam]

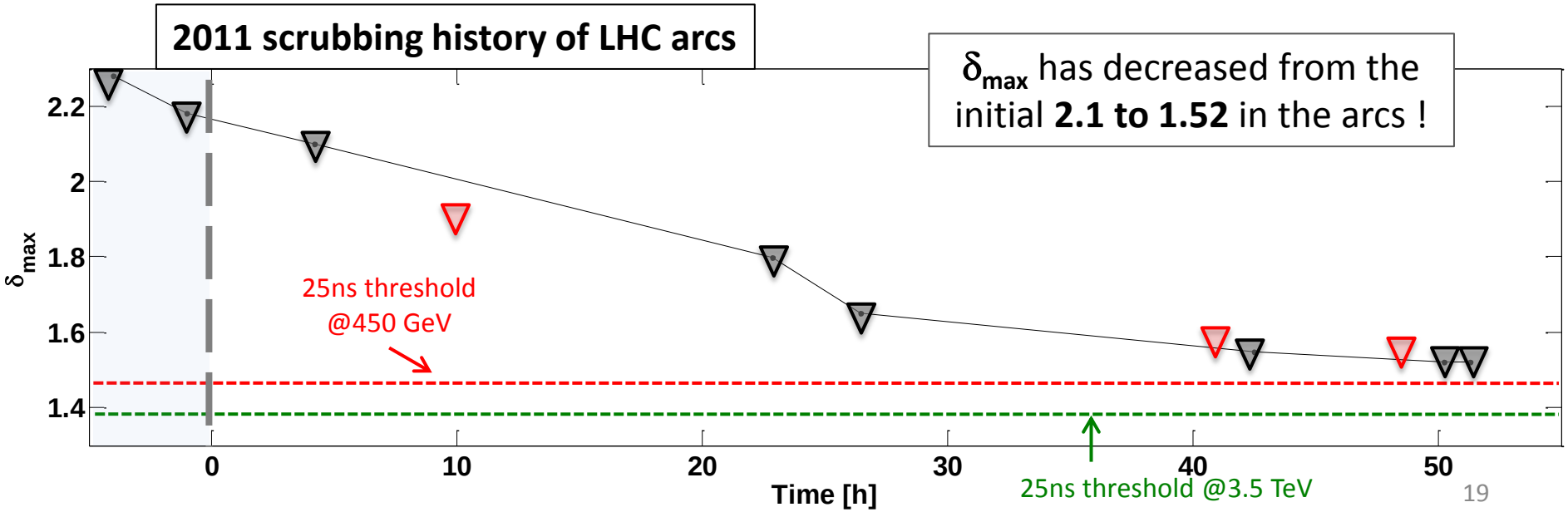
δ_{max} in the arcs: results (25ns)



Three snapshots from the 25ns MDs to try disentangling aperture of Beam1 from Beam2

δ_{max} in the arcs: results





Not only heat load and pressure rise, **the beam sees the electron cloud**, too, and it consequently…

⇒ Loses energy

⇒ Gets unstable and is quickly lost or exhibits emittance growth

⇒ Has a bad lifetime with a pattern degrading towards the tail(s) of the batches

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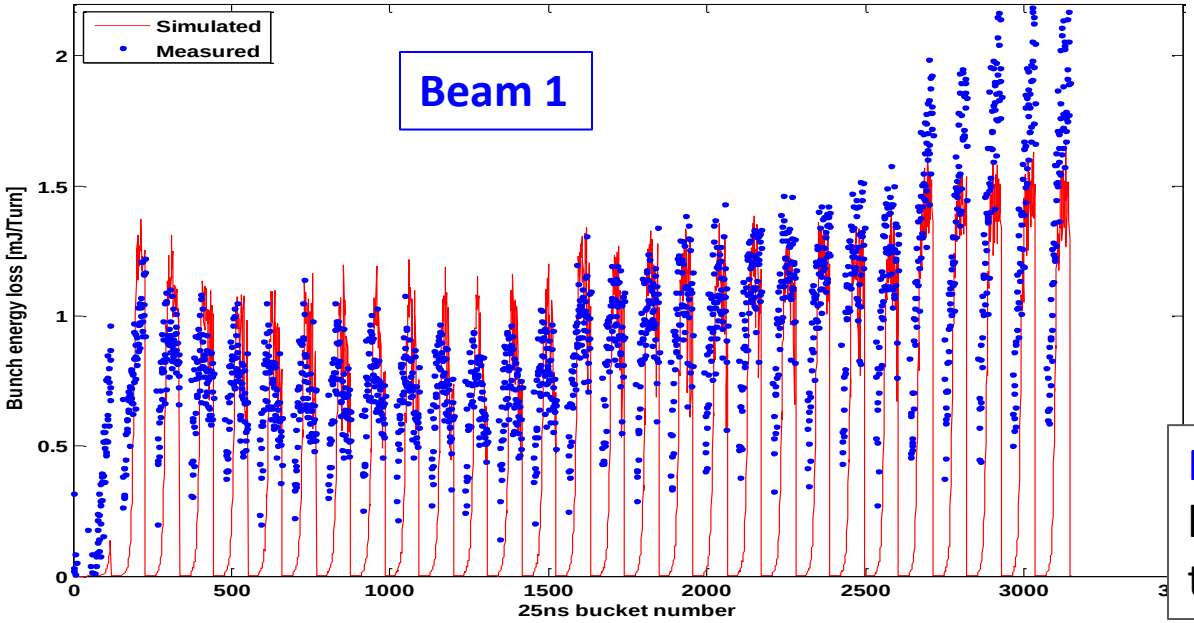
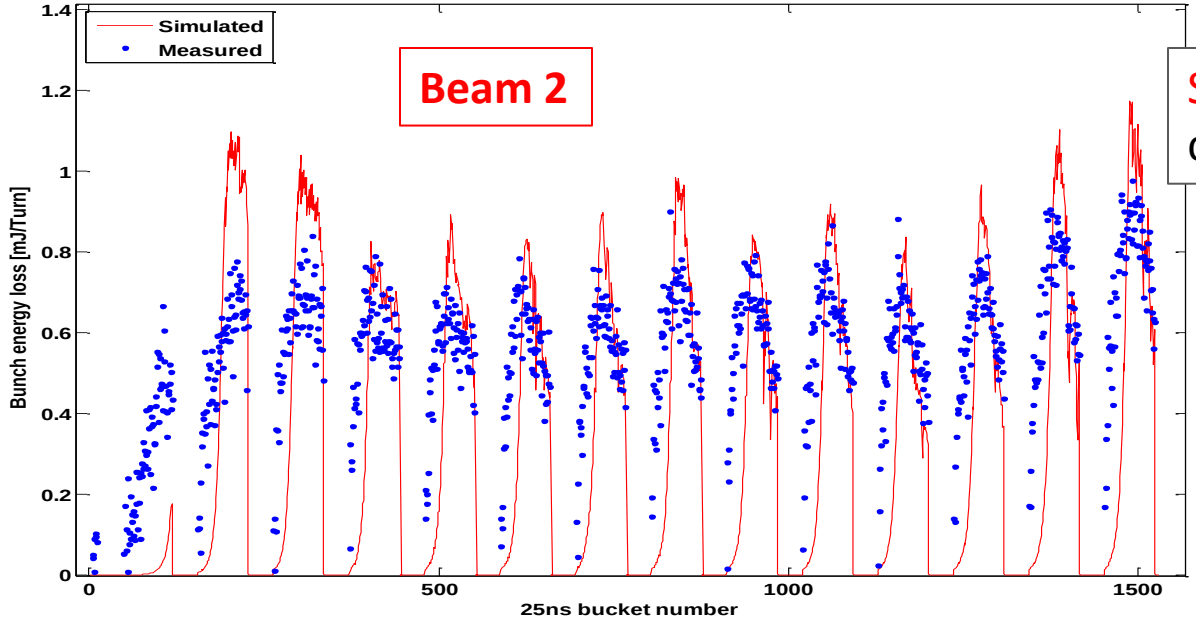
Beam observables: energy loss





Measurements ◆ → the energy loss per bunch is obtained from the stable phase shift

Simulations – → We use the test case the last fill on the 25 October

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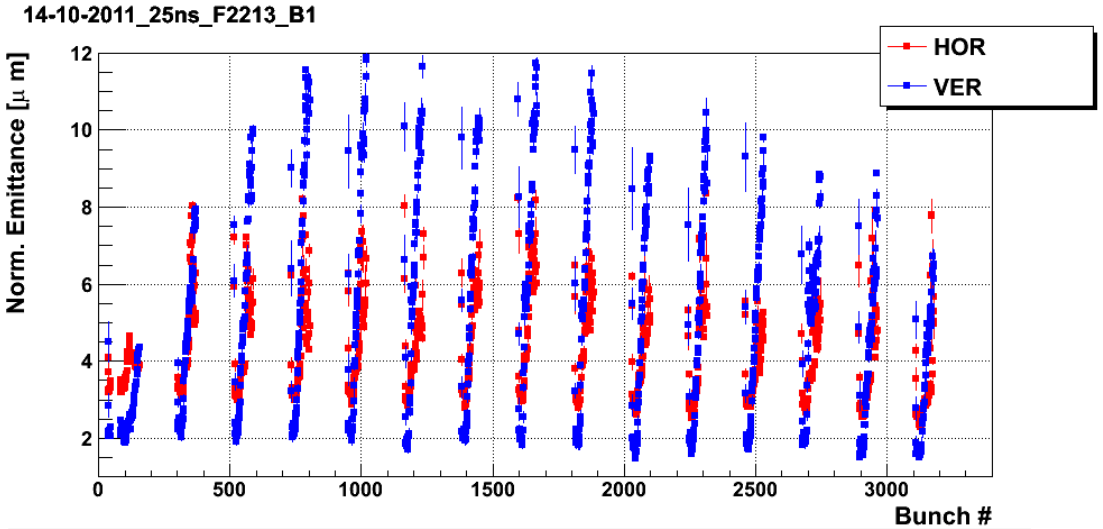
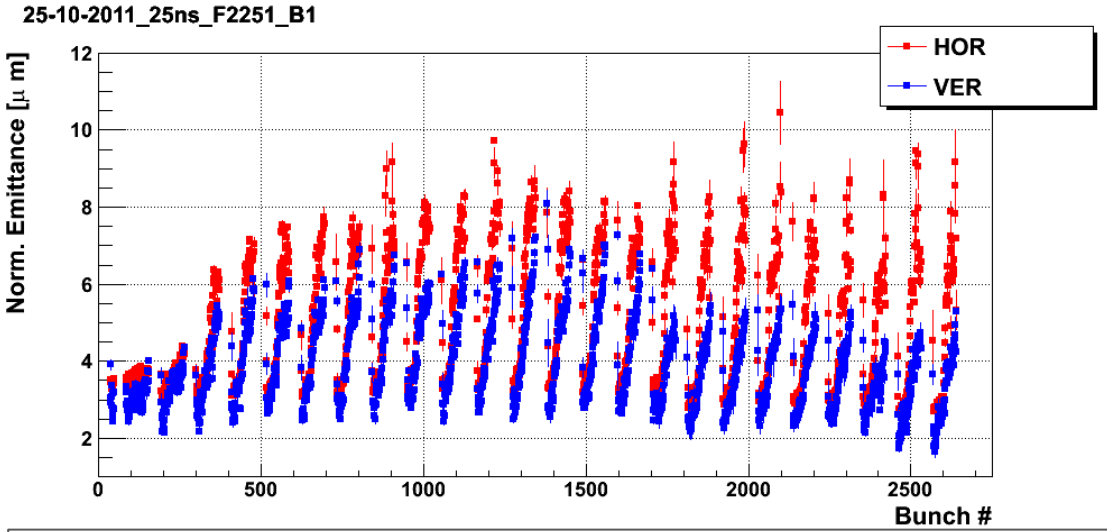
Beam observables: emittance growth



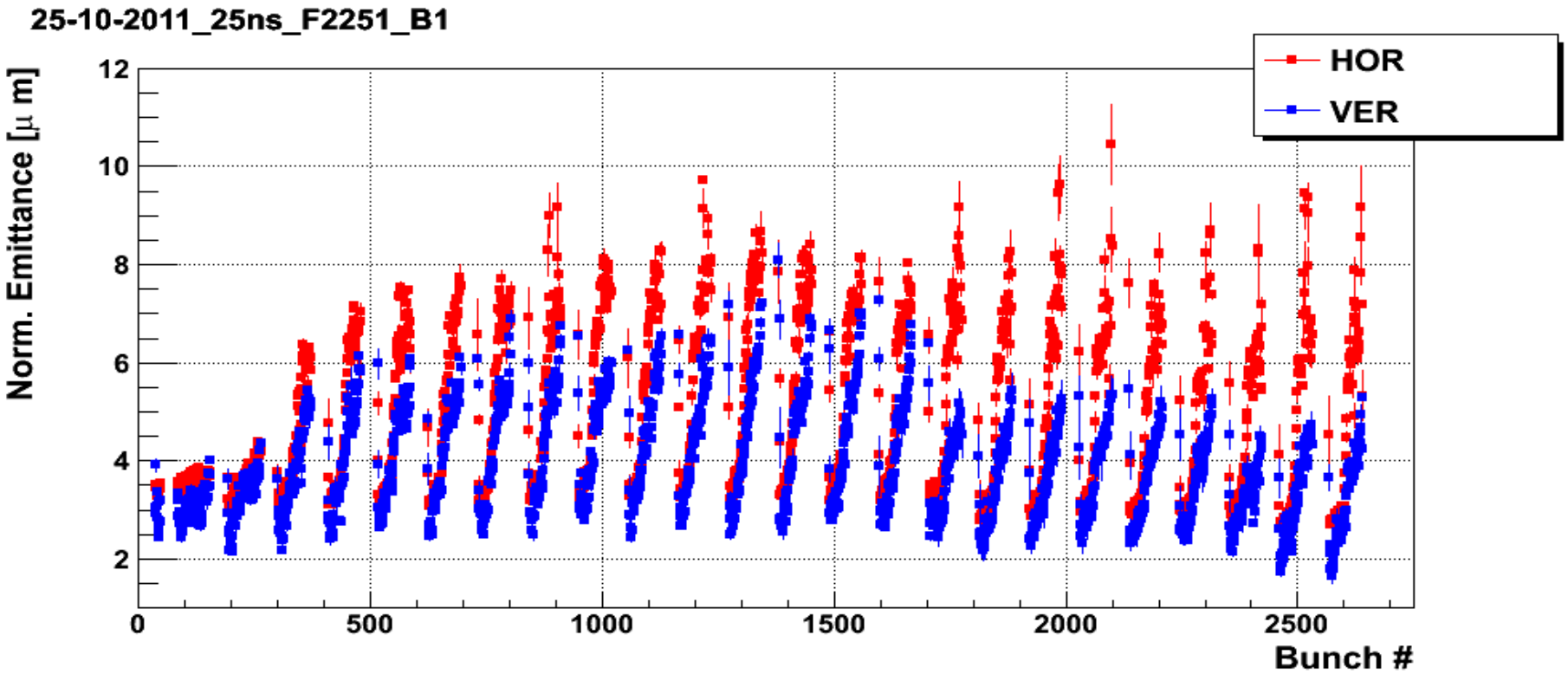
14 October → batches injected with 3.6 μs spacing, $Q'_{x,y}$=15

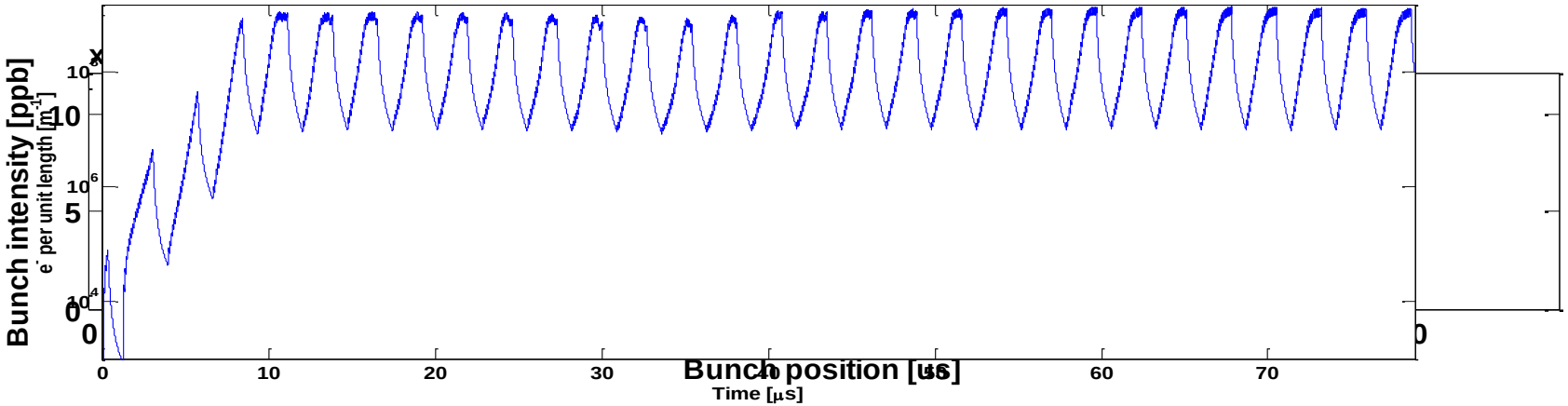


24-25 October → batches injected with 1 μs spacing, Q'_x=3, Q'_y=15

- The benefits from scrubbing have been visible on the 25ns beam:
  - The effect of the electron cloud has gradually moved later later along the trains, in spite of the closer spacing!
  - First 1 – 2 trains seem to be hardly affected now
  - In general, improvement in vertical
- Both beams are still unstable in the two planes, or anyway affected by emittance growth

Beam observables: emittance growth





Not only heat load and pressure rise, **the beam sees the electron cloud**, too, and it consequently…

⇒ Loses energy

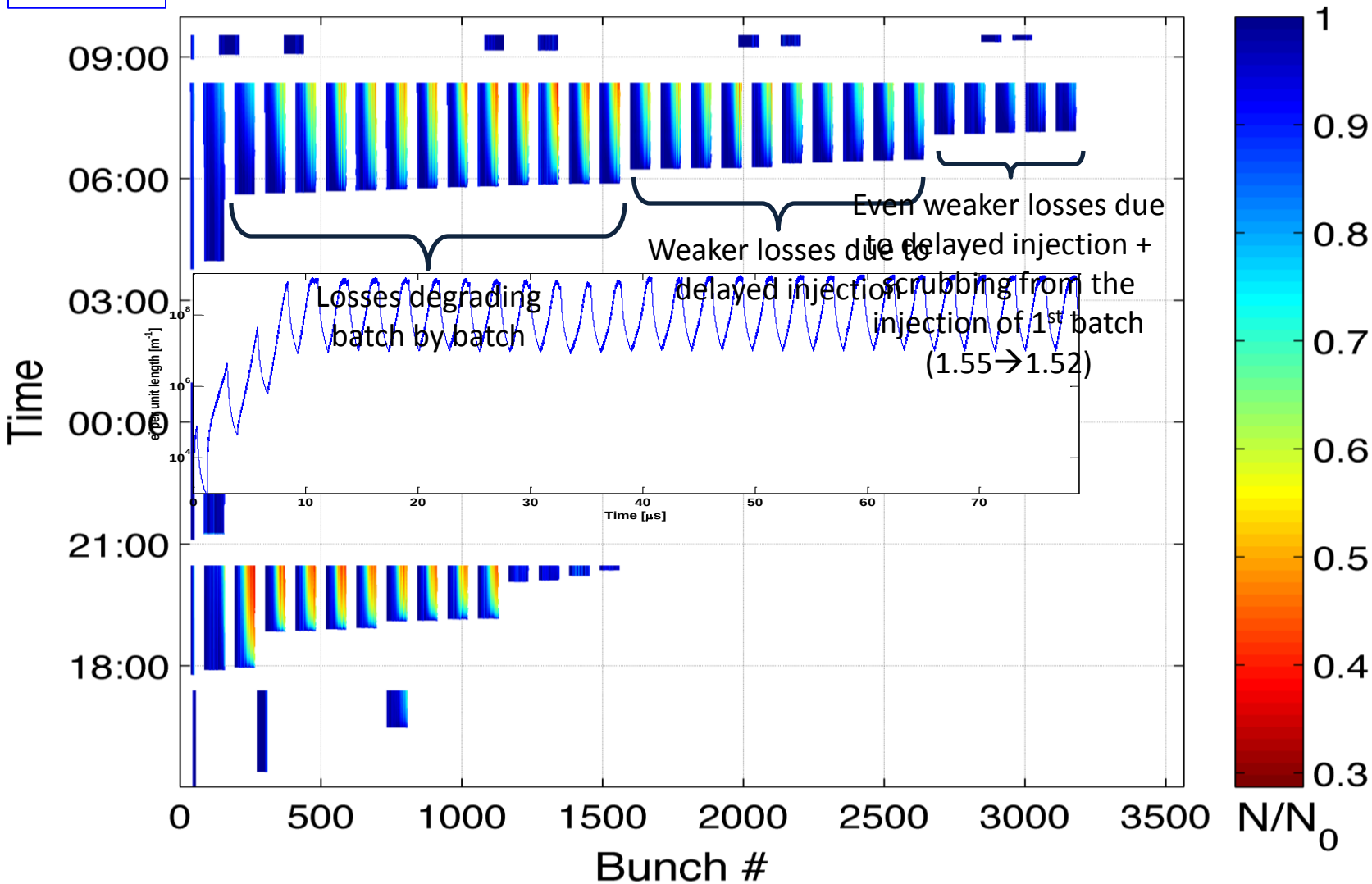
⇒ Gets unstable and is quickly lost or exhibits emittance growth

⇒ Has a bad lifetime with a pattern degrading towards the tail(s) of the batches

Beam observables: beam losses

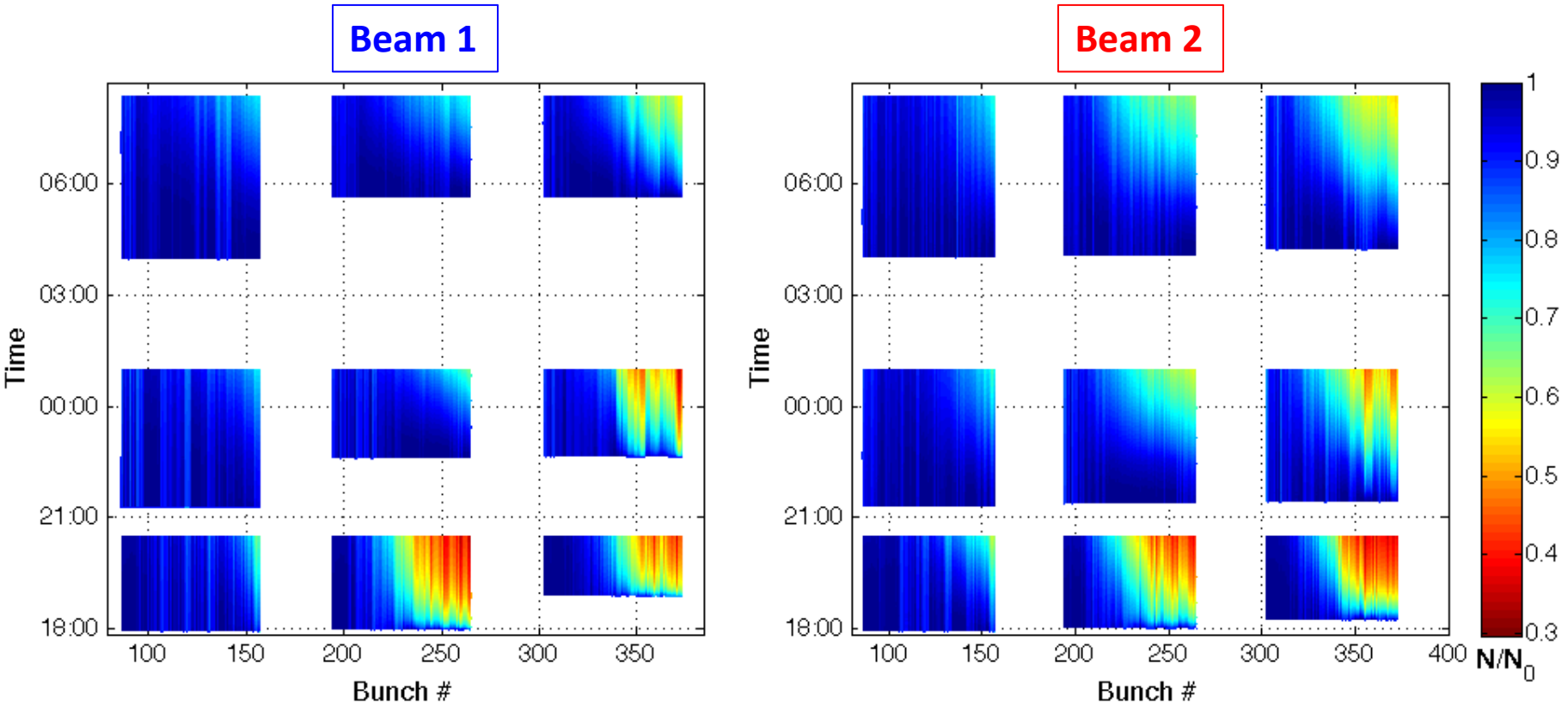
24 October → batches injected with 1 μs spacing

Beam 1



Beam observables: beam losses

24-25 October → first three batches injected of last three fills



- At this point the behaviour of the two beams is very similar
- This suggests similar electron cloud rise and saturation value
- It is consistent with the δ_{max} estimation made for beam 2 with the heat load data

Summary 25ns MDs

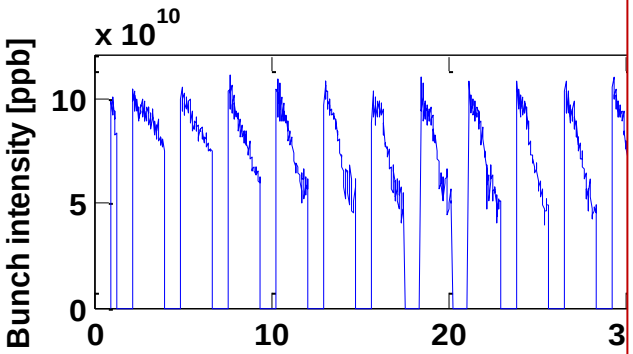
	δ_{max} (last estimated)	δ_{max} (threshold @450 GeV)	δ_{max} (threshold @3.5 TeV)
Straight section (uncoated)	**1.35**	**1.25**	**1.22**
Beam screen (arcs)	**1.52**	**1.45**	**1.37**

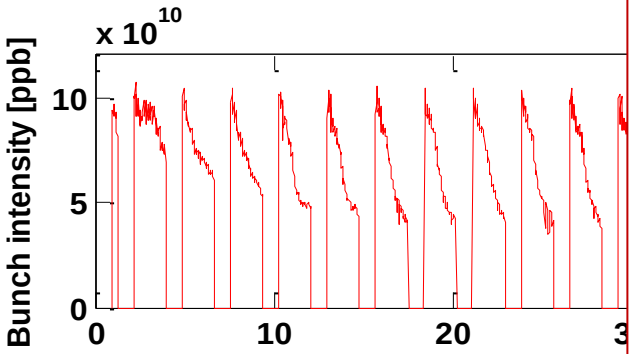
⇒ We still need to scrub by an additional ~0.15 to ensure ecloud-less operation of 25ns beams

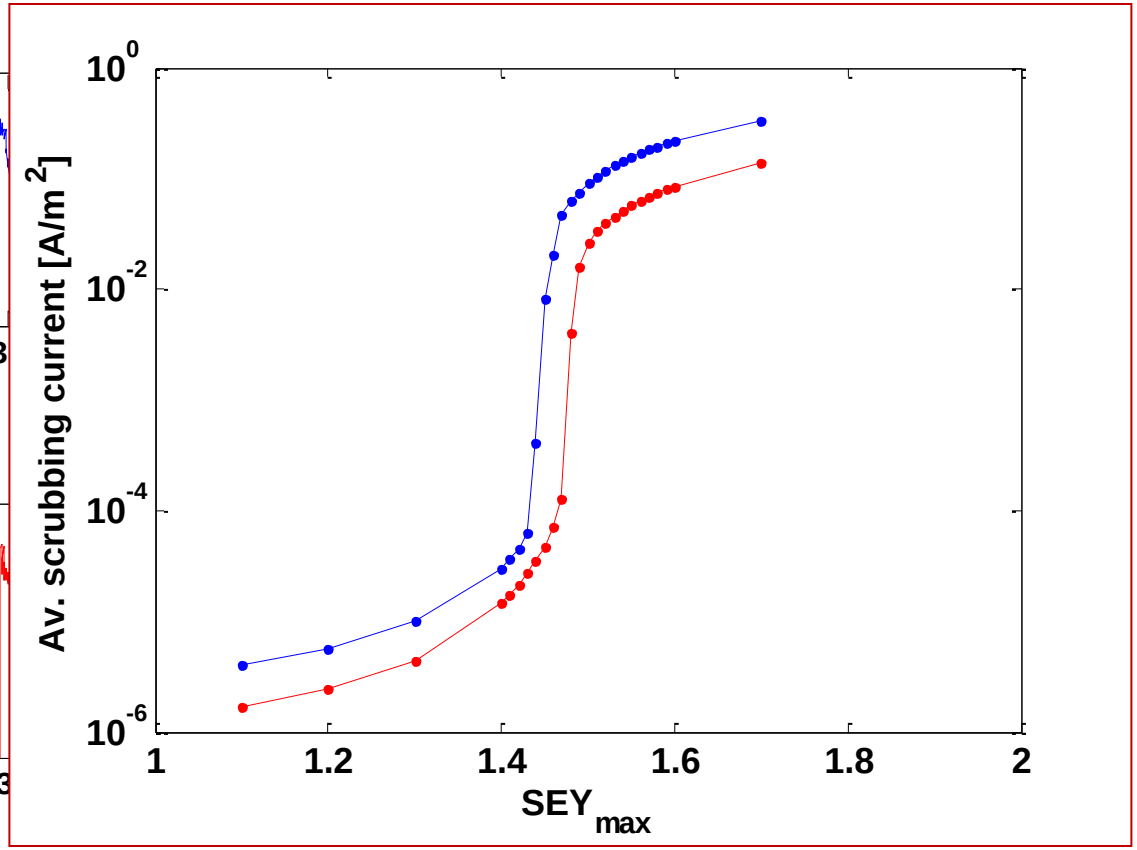
⇒ Based on our models and lab measurements, we will try giving a rough estimation of how long we need to scrub the arcs

Estimation of the scrubbing time

- ⇒ Structure of the scrubbing beam
  - ✓ Conservative assumption: the beam at the end of the last 25ns fill in 2011
- ⇒ Map the electron current density to the beam screen wall J_e [A/mm^2] as a function of δ_{max}





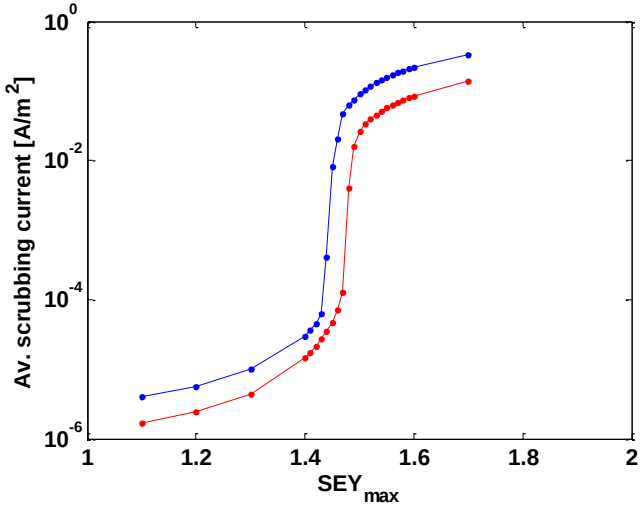


Estimation of the scrubbing time

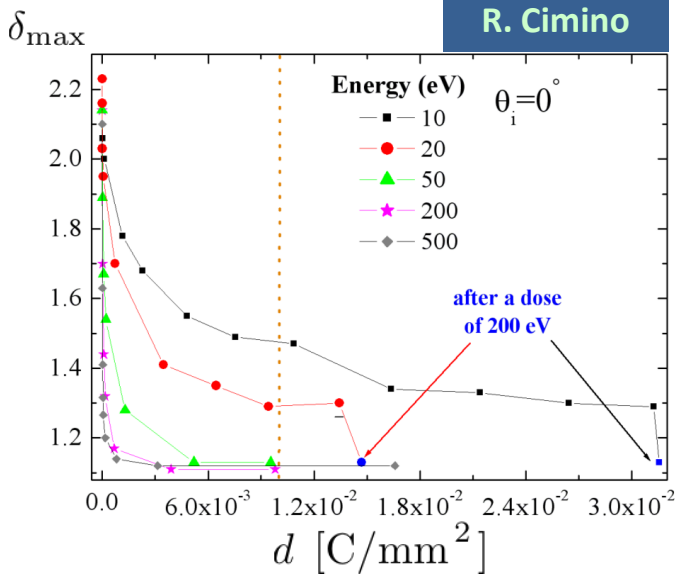
$$\delta_{\max}(t_n) \longrightarrow J_e(t_n)$$

$$d(t_n + \Delta t) = d(t_n) + J_e(t_n) \cdot \Delta t$$

$$d(t_n + \Delta t) \longrightarrow \delta_{\max}(t_{n+1})$$

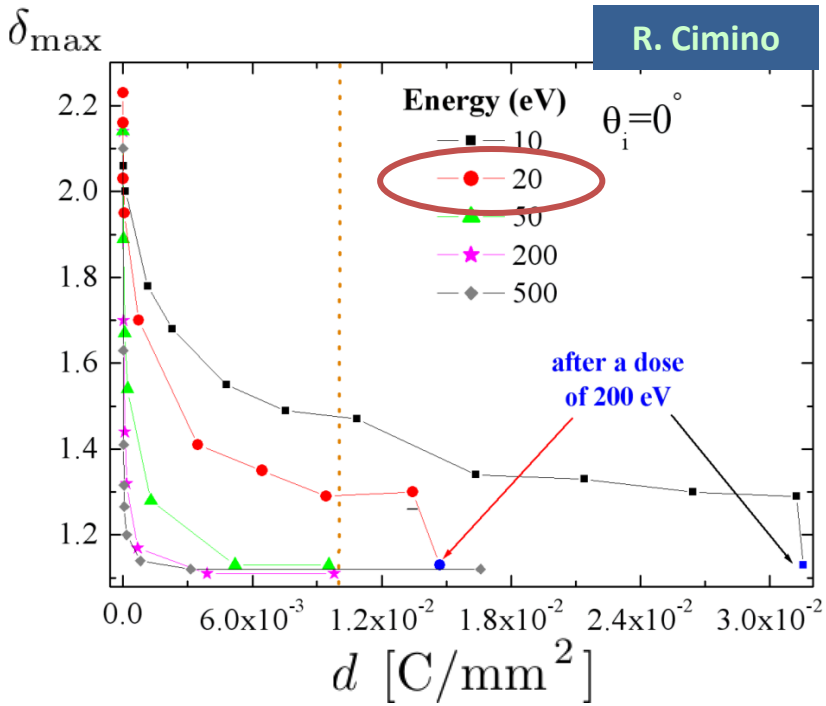


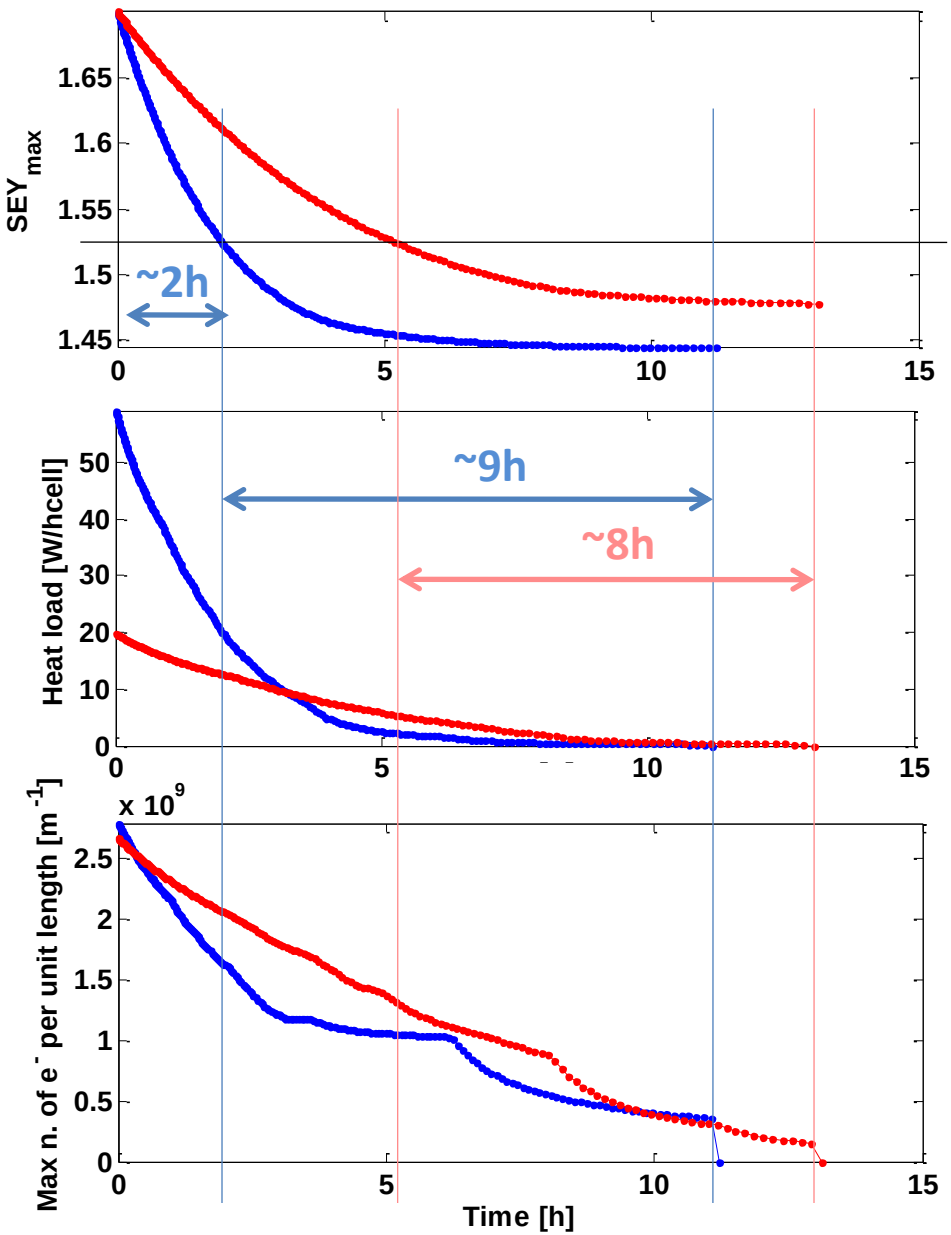
R. Cimino



Estimation of the scrubbing time: results

It took ~2.8h of equivalent beam 1 to go from δ_{max} 1.65 to 1.52





Probably realistic to assume at least 20h beam time

Estimation of the scrubbing time: considerations

- ⇒ Based on our best knowledge at the moment, scrubbing the LHC arcs with the 25ns beam we had during the last 2011 fill could take about **20h effective beam time**
- ⇒ This lowers the electron cloud by “only” one order of magnitude, therefore does not guarantee running without incoherent effects already at the end of the calculated scrubbing time (it can take longer)
- ⇒ The total effective scrubbing time is actually longer because we will need to dump and refill more times, and finally ramp, to extend the reach of the scrubbing efficiency and cover the needed range
- ⇒ The corresponding machine time could be about **1w**
- ⇒ Towards the end of the scrubbing process, only the last trains reach saturation and scrub. This can be optimized
  - ⊙ Inject in trains of 288b from the SPS, or at least (288 + N*72)
  - ⊙ Cause more uncaptured beam (like in the SPS)
  - ⊙ Minimize the length of the abort gap to possibly use multi-turn effects (e.g. with overinjection)

Concluding remarks

	δ_{max} (estimated)	Threshold δ_{max} (50ns, 450 GeV)	Threshold δ_{max} (50ns, 3.5 TeV)	Threshold δ_{max} (25ns, 450 GeV)	Threshold δ_{max} (25ns, 3.5 TeV)
Straight section (uncoated)	**1.35**	**1.63**	**1.58**	**1.25**	**1.22**
Beam screen (arcs)	**1.52**	**2.2**	**2.1**	**1.45**	**1.37**

⇒ After the 25ns MDs, the LHC beam chambers have been cleaned to δ_{max} **values well below the build up threshold for nominal 50ns beams**

⇒ If the present level of machine conditioning was preserved, **'ecloud-less' operation of LHC with 50ns beams** up to high intensities should be possible in 2012

⇒ Only 2-3 days of scrubbing with 25ns beams for 50ns operation could be sufficient – just to clean parts of the LHC open to air and check the conditioning of the arcs

⇒ Scrubbing of the arcs for 25ns operation could take up to **2 weeks machine time** (including also test ramps)

Thank you for your attention

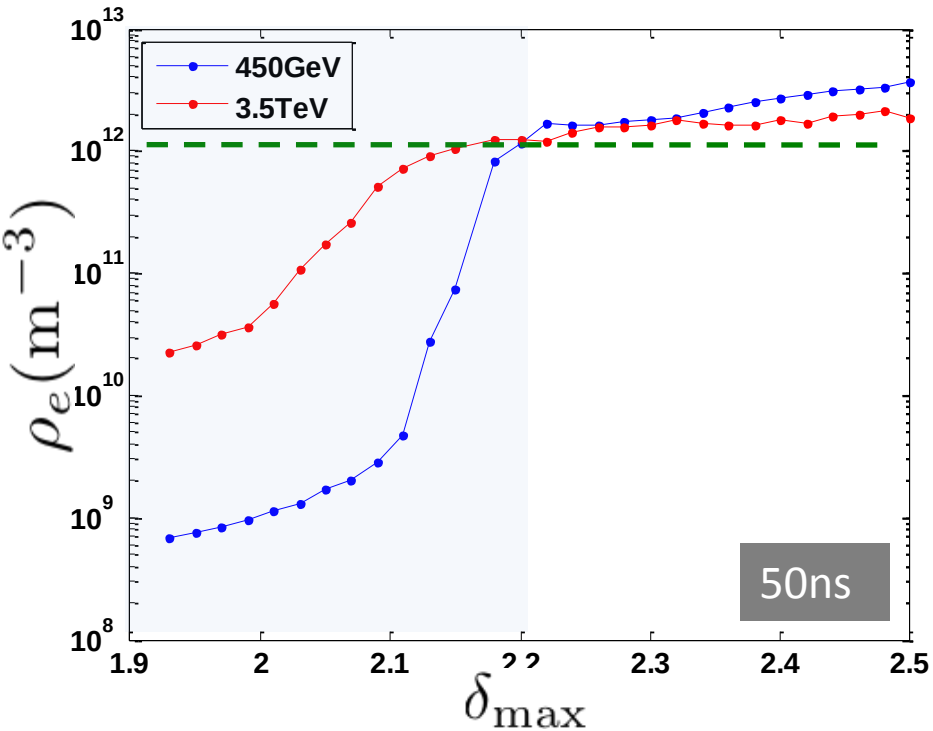
Very special thanks to **G. Iadarola, H. Bartosik, O. Dominguez, J. Esteban-Müller,** and **F. Roncarolo** for their careful off-line analysis of large amounts of MD data and the huge simulation effort that improved the general understanding of electron cloud and scrubbing!

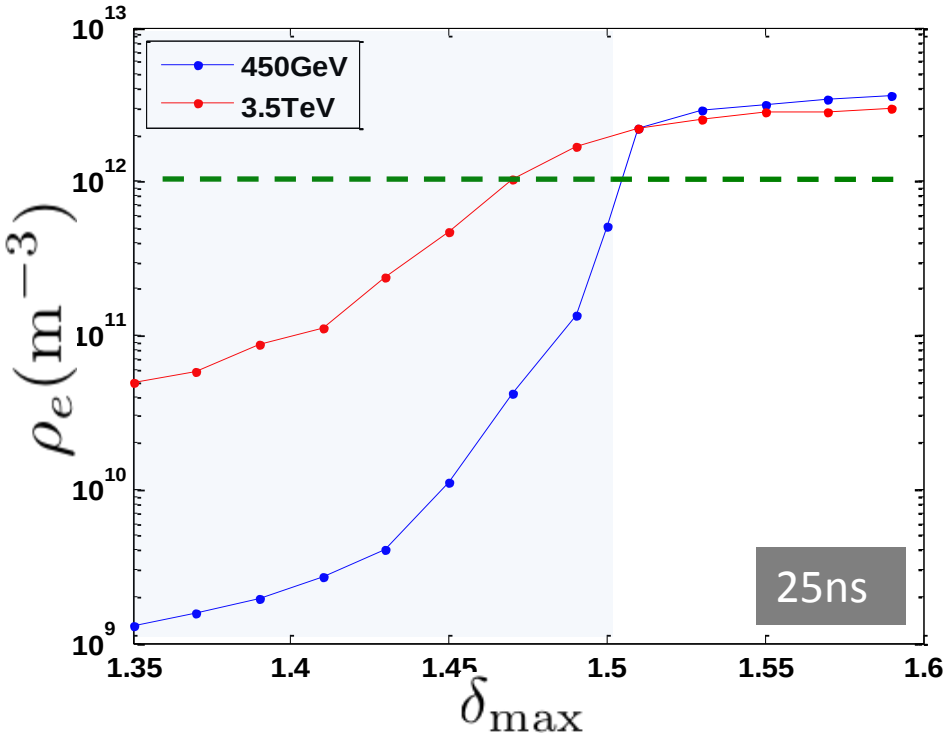
Many thanks to G. Arduini, V. Baglin, P. Baudrenghien, G. Bregliozzi, S. Claudet, G. Lanza, G. Papotti, E. Shaposhnikova, L. Tavian for all the beautiful data they kindly provided us with and the numerous discussions

Thanks to B. Goddard, V. Kain, K. Li, H. Maury-Cuna, E. Métral, S. Redaelli, B. Salvant, F. Zimmermann, and all those who promoted and/or actively participated in the MDs

SPARE SLIDES

Instability and emittance growth: predictions





- Calculated coherent ECI threshold for central density in dipoles is around $\rho_e=10^{12}$ m^{-3} for nominal intensity and Q'=0 at 450 GeV (simulations were run assuming the whole LHC made of dipoles)
- It can be stabilized with chromaticities $Q'_{x,y}>15$, but emittance growth due to electron cloud + chromaticity remains!
- Right plot shows that with 25ns beams stability could be achieved only for $\delta_{max} \leq 1.5$

Estimation of the scrubbing time

- ⇒ Curve of the decrease of δ_{max} with the integrated electron dose deposited on the wall, $d=J_e\Delta t$ [C/mm²]
- ⇒ Depends on material and electron energy, several measurements done in the past (two examples illustrated here)
- ⇒ If we use the 500eV curve (left plot) we end up with scrubbing times in the machine much lower than those measured → perhaps an indication that the real δ_{max} in the machine are lower than we believe (R_0=1.0 instead of 0.7?)