Scrubbing: Expectations and Strategy, Long Range Perspective

G. Iadarola and G. Rumolo

Acknowledgments:

G. Arduini, V. Baglin, D. Banfi, M. Barnes, H. Bartosik, P. Baudrenghien, E. Calvo, S. Claudet, J. Esteban-Müller, W. Hofle, L. Kopylov, G. Kotzian, T. Lefevre, E. Metral, S. Popescu, F. Roncarolo, B. Salvant, E. Shaposhnikova, J. Uythoven, M. Taborelli, G. Trad, L. Tavian, D. Valuch, J. Wenninger, C. Zannini

LHC Performance Workshop (Chamonix 2014), 22-25 September 2014, Chamonix, France

Outline

- **Run 1 experience**
  - 50 ns vs 25 ns
  - Scrubbing with 25 ns in 2011-2012
  - 25 ns beams at 4 TeV in 2012
- **Scrubbing in 2015**
  - Goals
  - Post-LS1 improvements
  - The “doublet” scrubbing beam
    (motivation, tests at SPS, compatibility with LHC equipment)
  - Scrubbing stages
  - Possible scenarios after scrubbing

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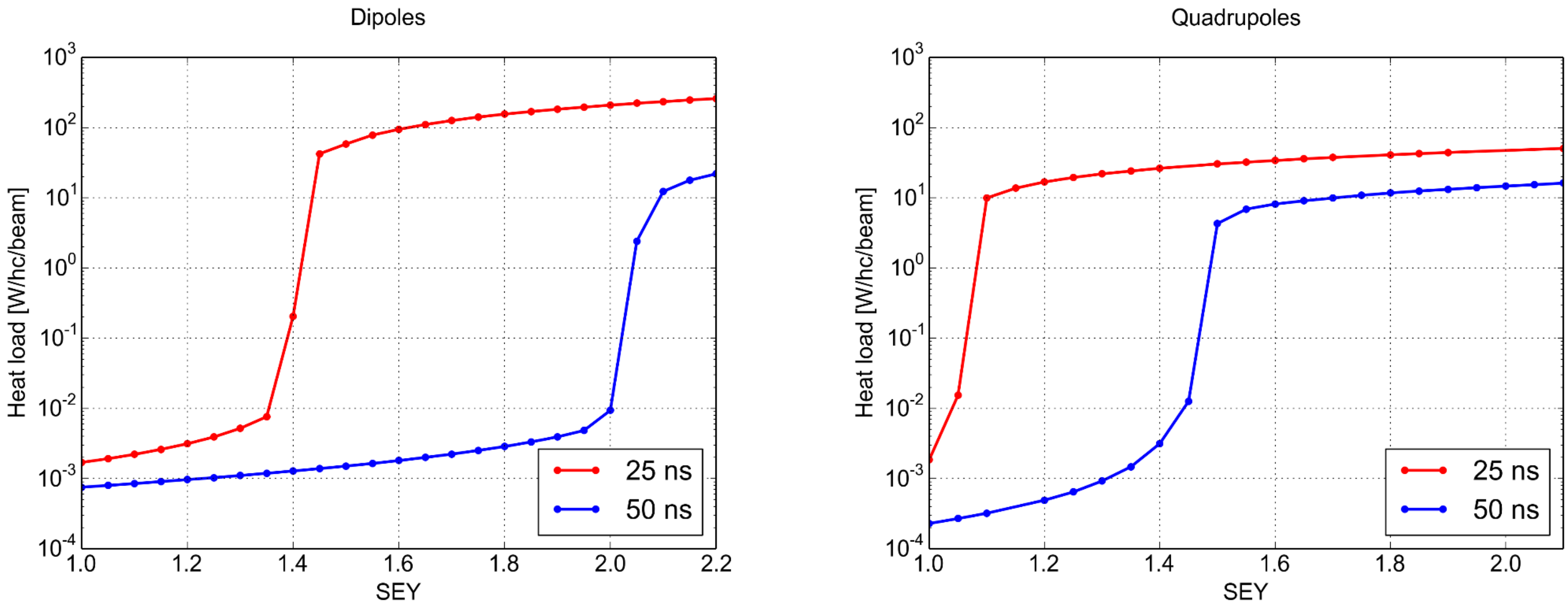
Run 1 experience: 50 ns vs 25 ns

The **"multipacting threshold"** for **25 ns beams is significantly lower** than for 50 ns

→ In particular, a full **e-cloud suppression in quadrupoles with** 25 ns beams **looks unlikely** (also given the Run 1 experience with the triplets)



PyECLOUD simulations

With **50 ns beams** we could have a practically **"e-cloud free" operation in 2012**, thanks to the scrubbing accumulated in 2011 in **4 days of scrubbing** with 50 ns beams + **2 days** of tests with 25 ns beams

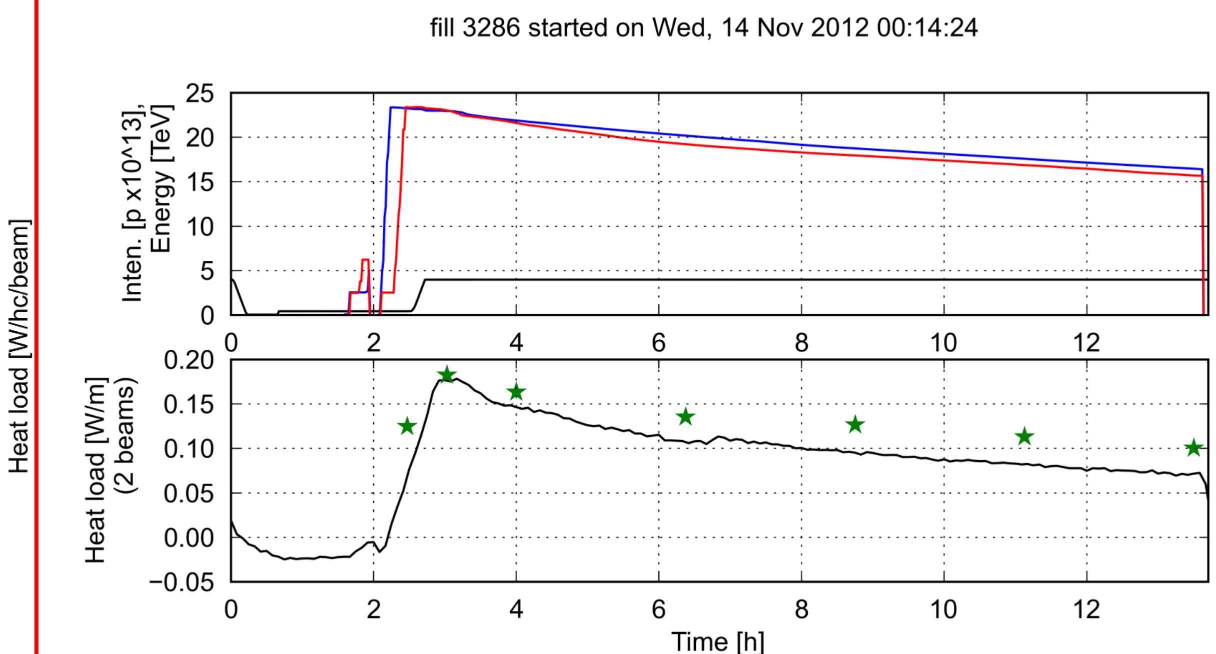
Run 1 experience: 50 ns vs 25 ns

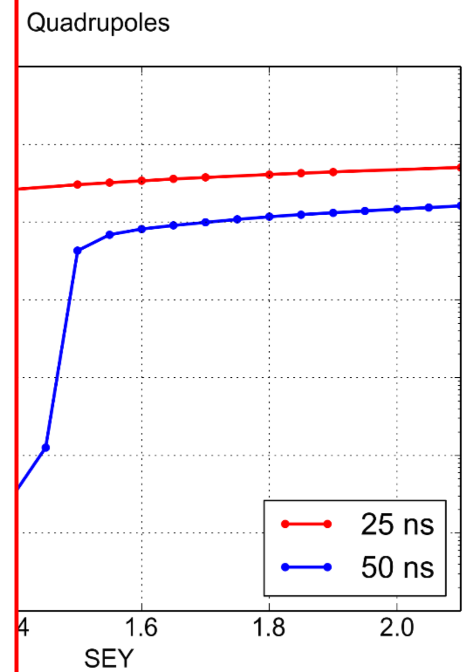
The **“multipacting threshold” for 25 ns beams is significantly lower** than for 50 ns

5 ns beams **looks unlikely** (also

In 2012 **heat load measurements** on the arc beam screens confirm

the **absence of any strong EC activity with 50 ns beams**





Heat load measurement from cryogenics

Estimation (impedance + synchrotron rad.)

, thanks to the scrubbing

with 25 ns beams

Thanks to **L. Tavian and C. Zannini**

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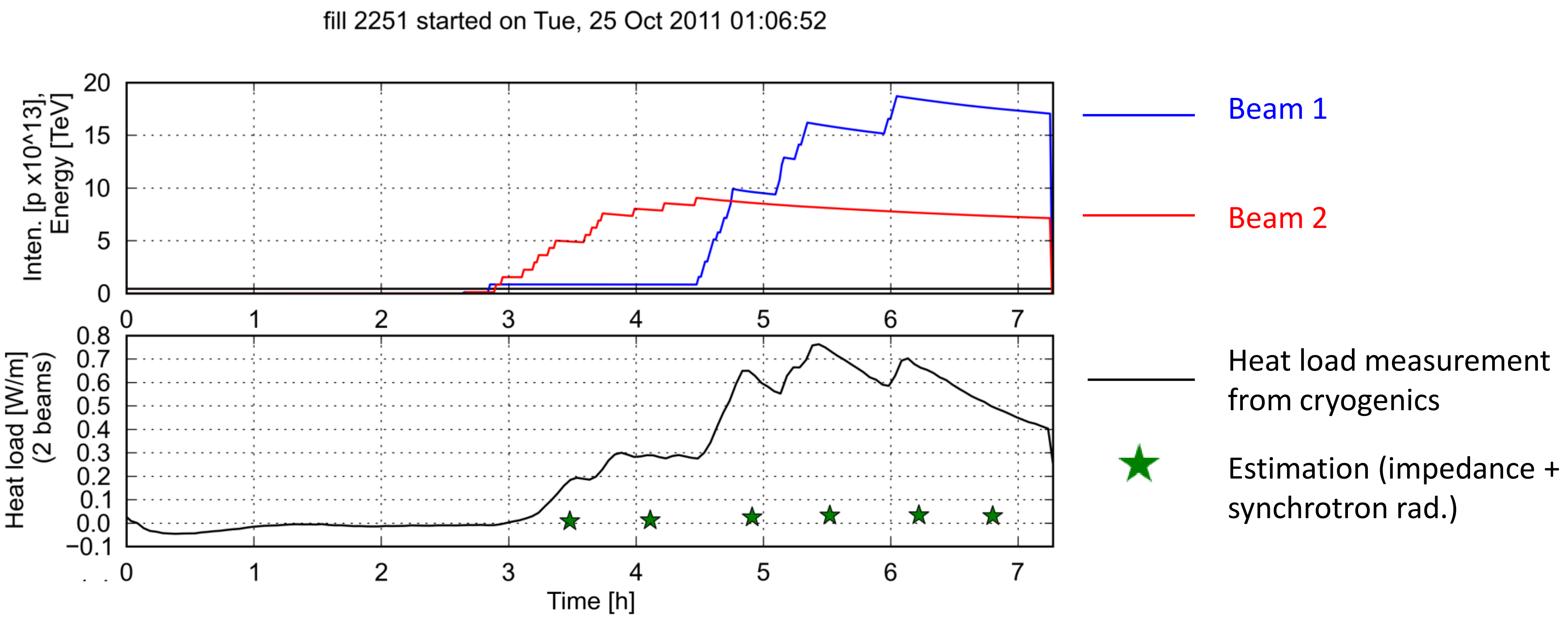
2011 experience with 25 ns beams: scrubbing tests

First scrubbing tests with 25 ns (450 GeV):

- Running with **high chromaticity to avoid EC driven instabilities**
- Injected up to **2100b.** for B1 and **1020b.** for B2
- Strong **heat load** observed in the cryogenic arcs



Thanks to **L. Tavian and C. Zannini**

Heat load due to e-cloud x15 stronger than heating due to impedance

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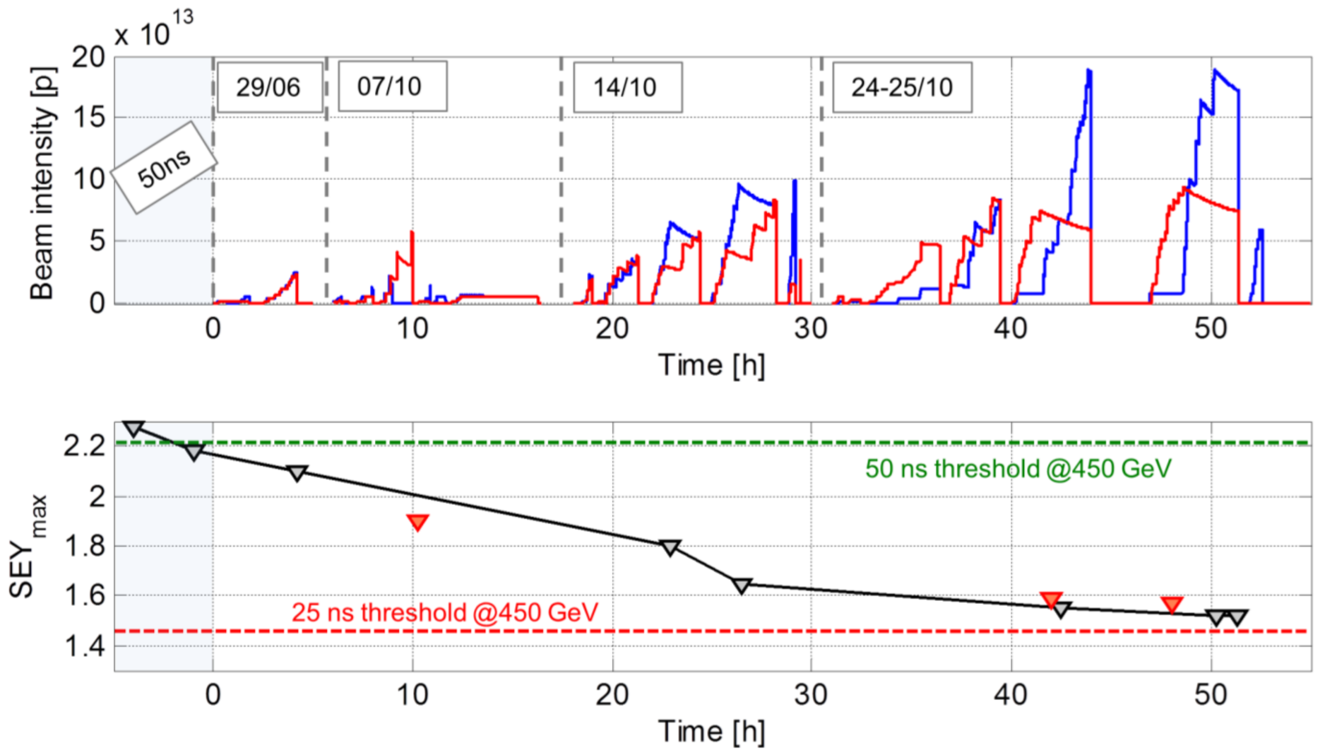

Reconstruction based on measured **beam parameters, heat load meas. and PyECLOUD sims.**

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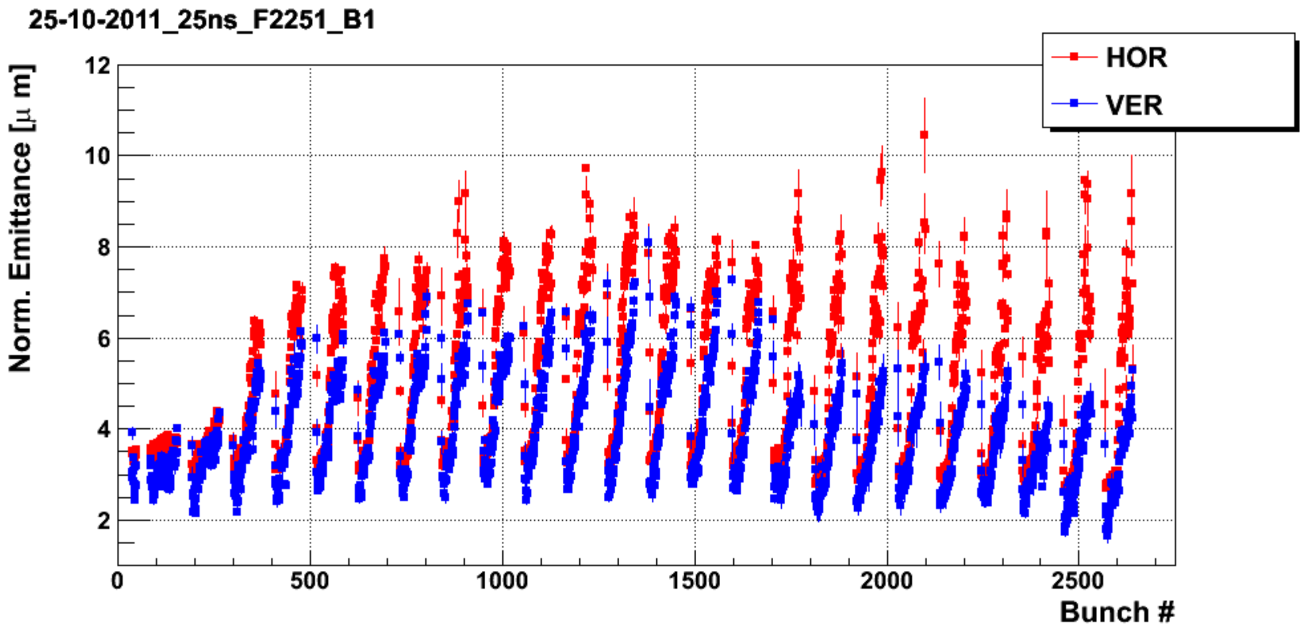
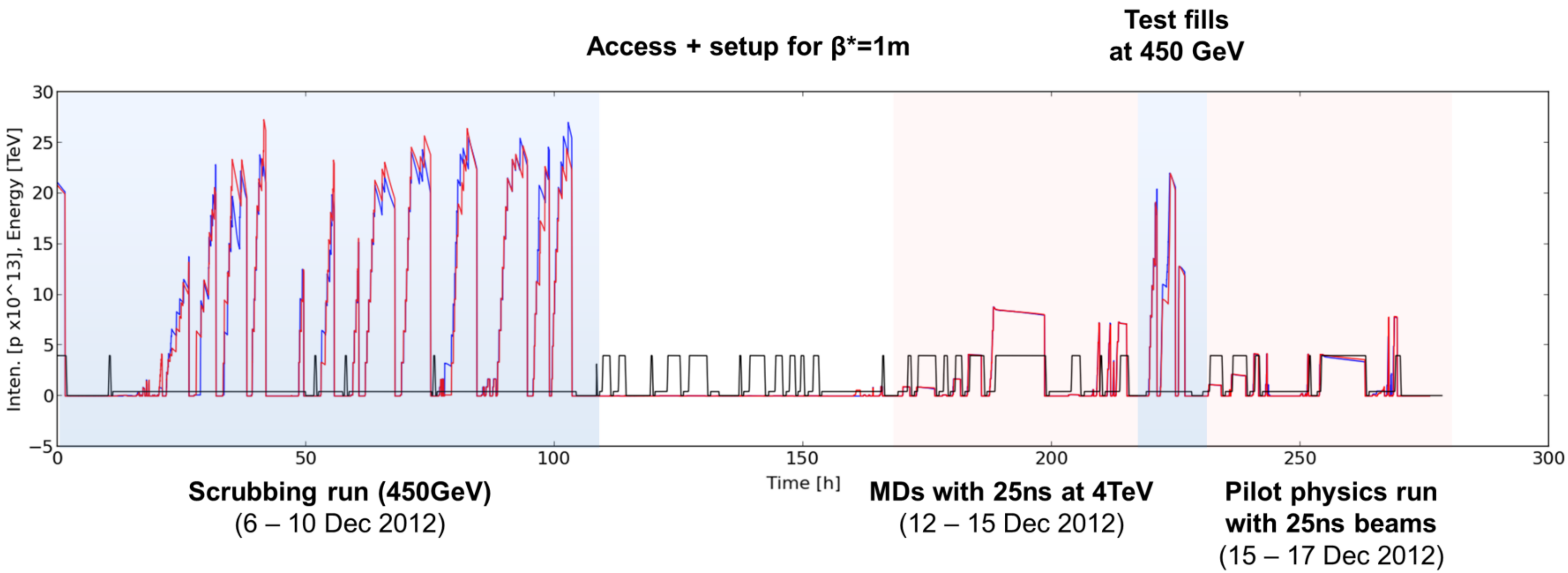
- Strong **heat load** observed in the cryogenic arcs
- **SEY in arc dipoles** could be lowered to ~1.5
- **Beam degradation still important** at the end of the scrubbing tests



Thanks to **F. Roncarolo**

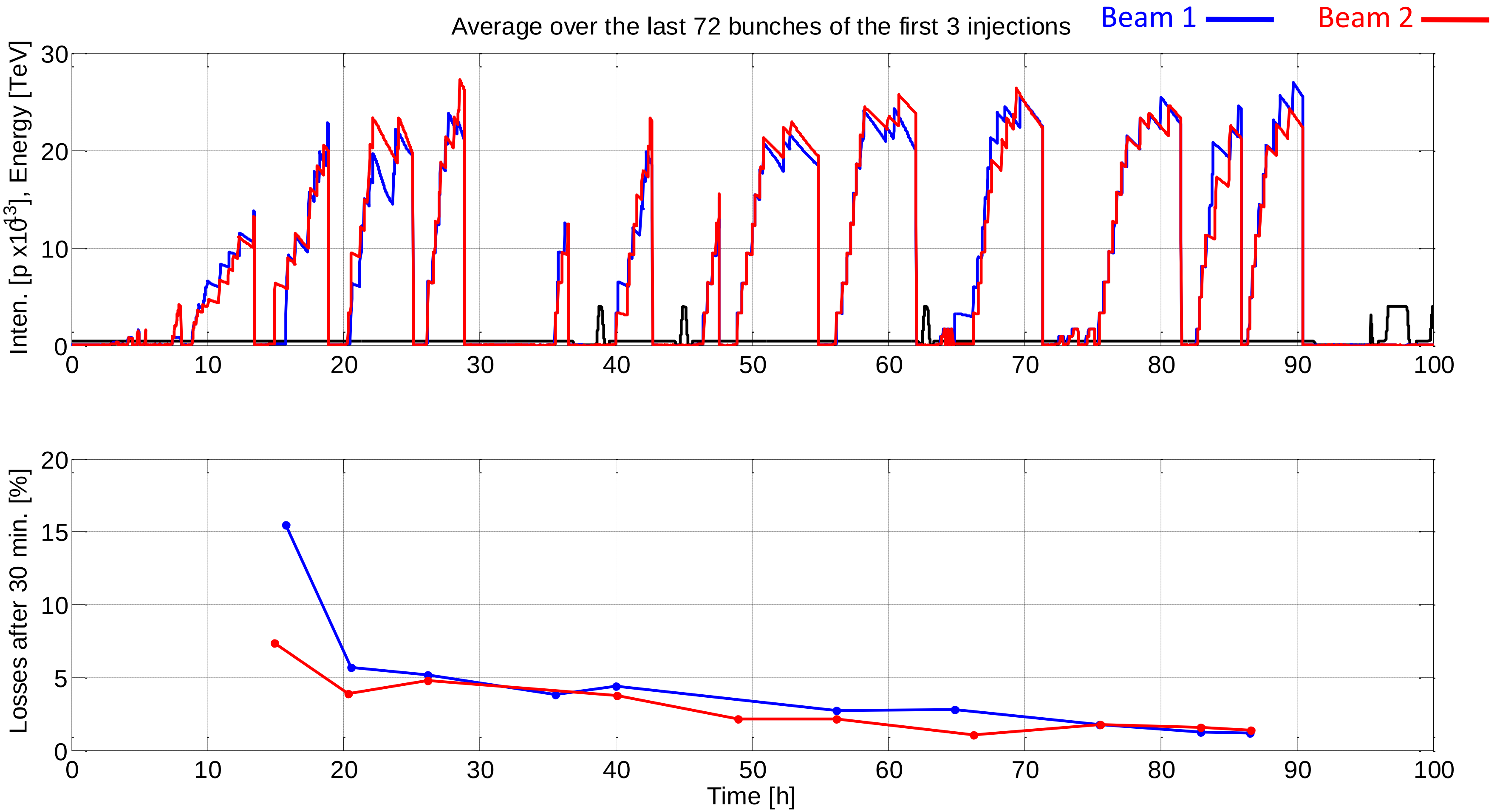
The “25 ns run” in 2012

All experiments with 25 ns beams with large number of bunches were **concentrated in the last two weeks of the run**



3.5 days of scrubbing with 25ns beams at 450 GeV (6 - 9 Dec. 2012):

- Regularly filling the ring with up to **2748b.** per beam (up to **2.7×10^{14} p**)
- Slow improvement visible on **beam quality** and **heat load in the arcs**



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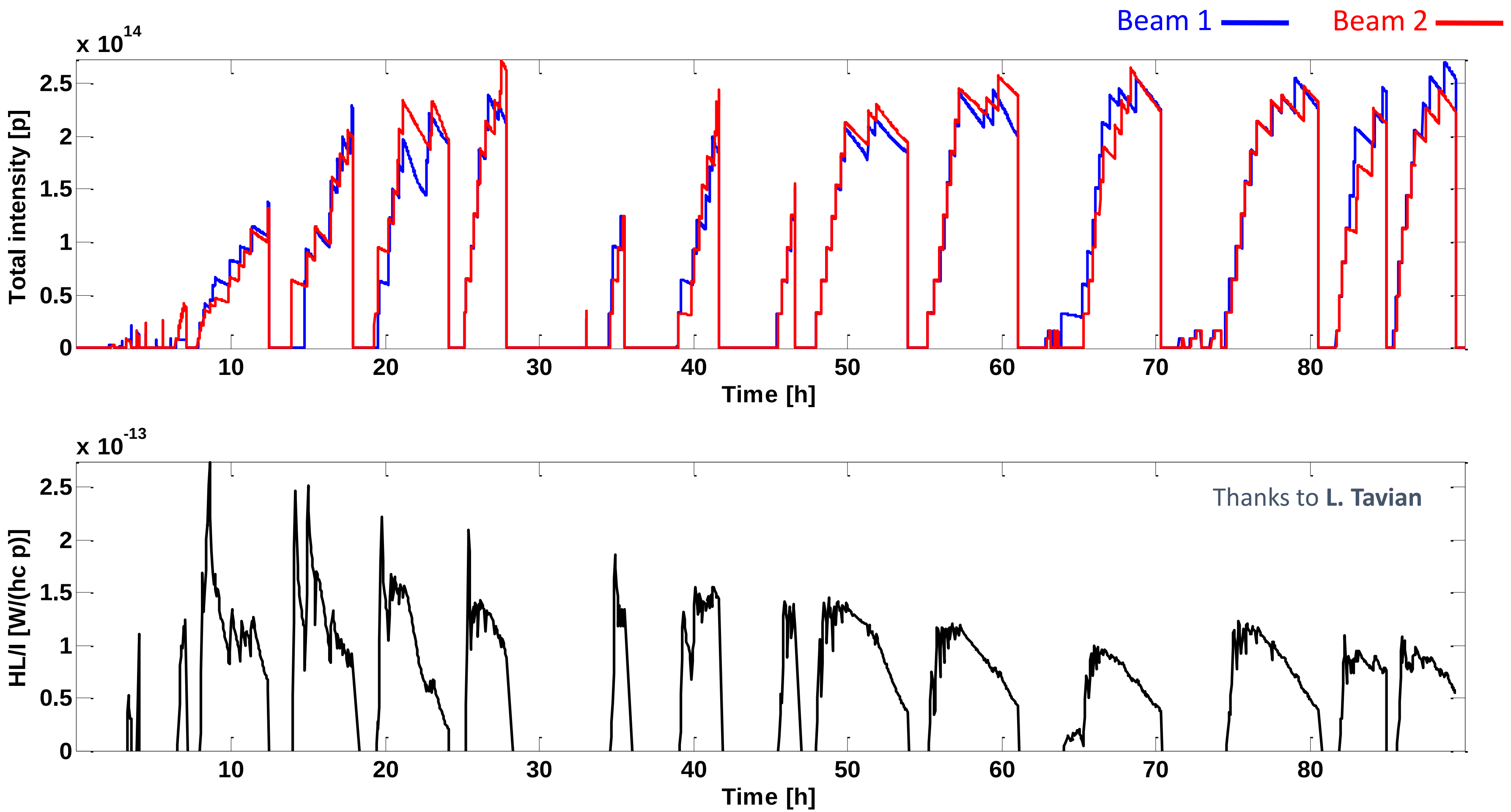
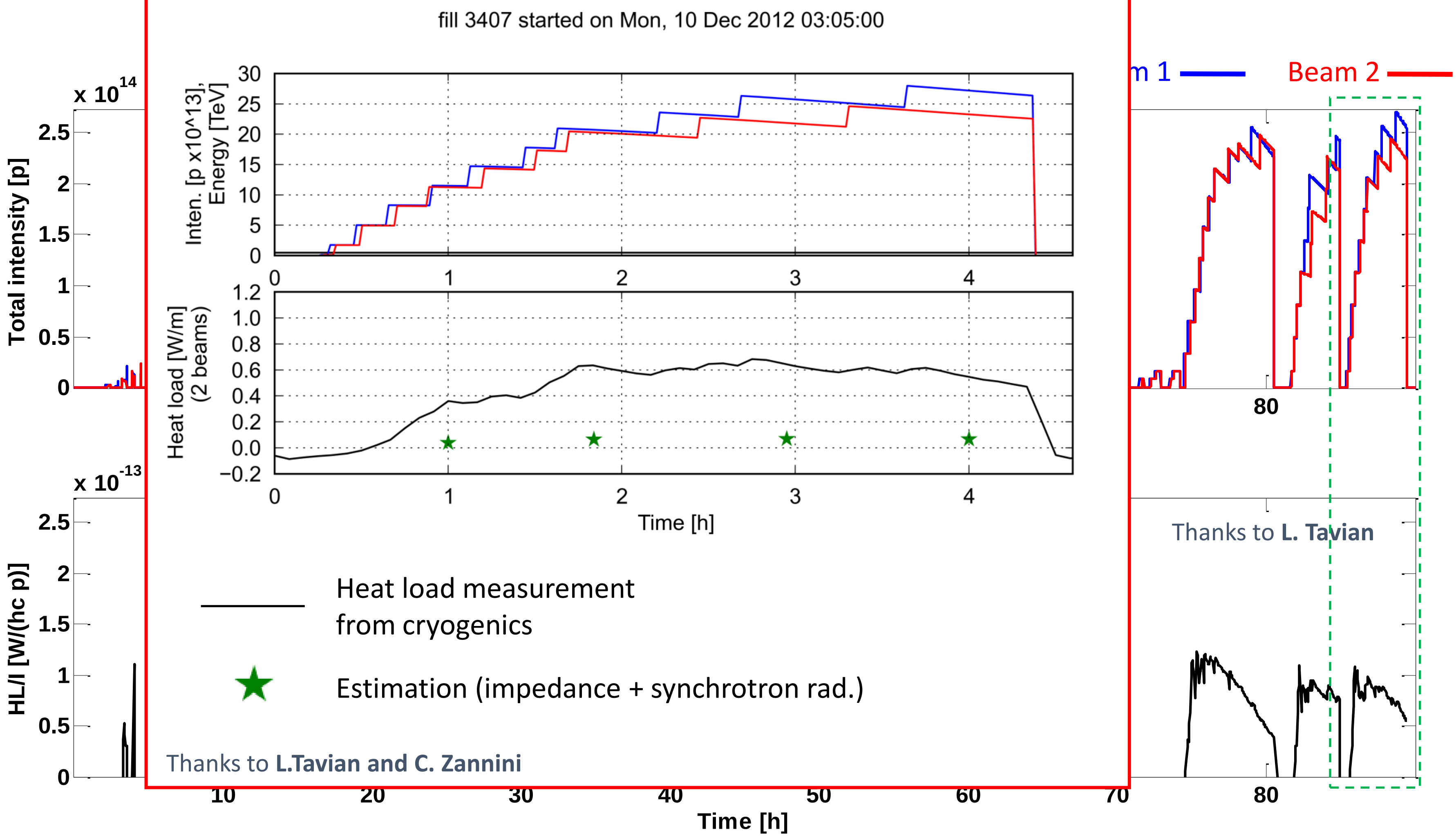


3.5 days of scrubbing with 25ns beams at 450 GeV (6 - 9 Dec. 2012):

2.7x10^{14} p)

the arcs

e-cloud still there during the last fill



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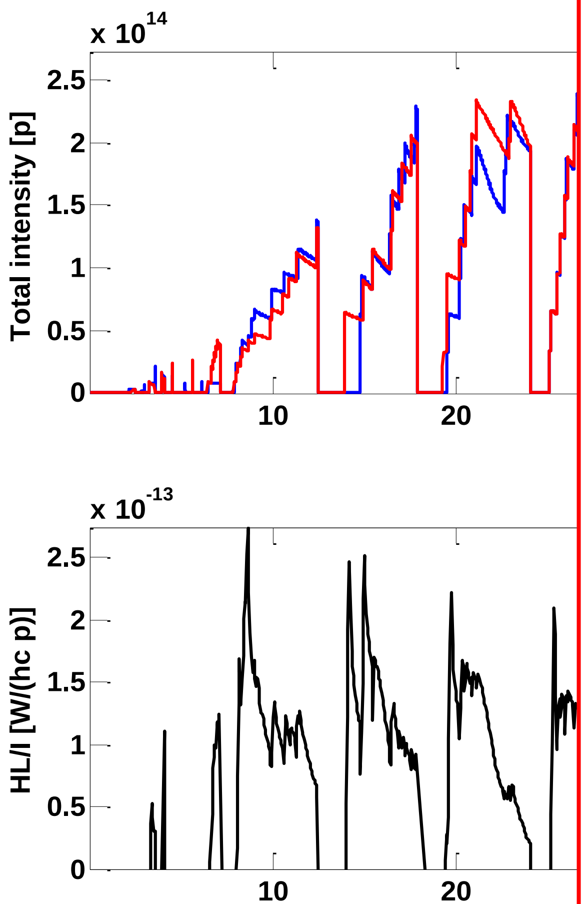
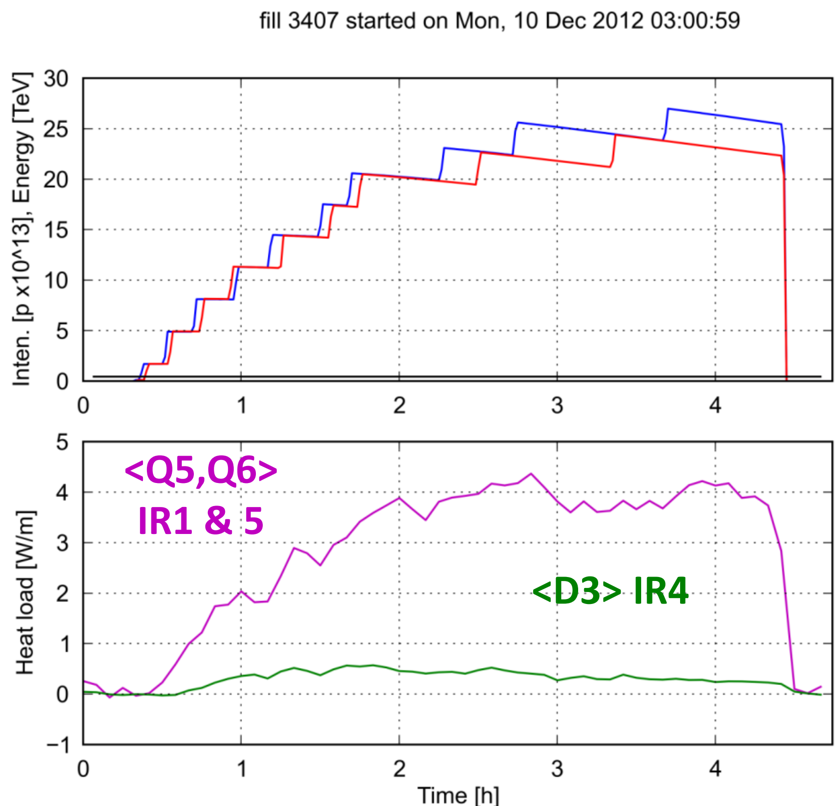
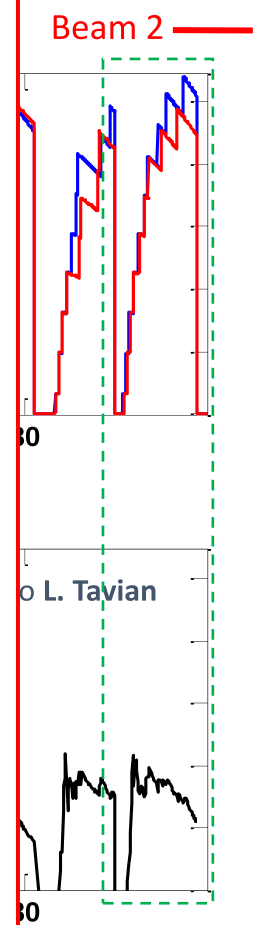


Heat load measurements on SAMs confirmed e-cloud **much stronger in quadrupoles** than in dipoles



Thanks to **L. Tavian**



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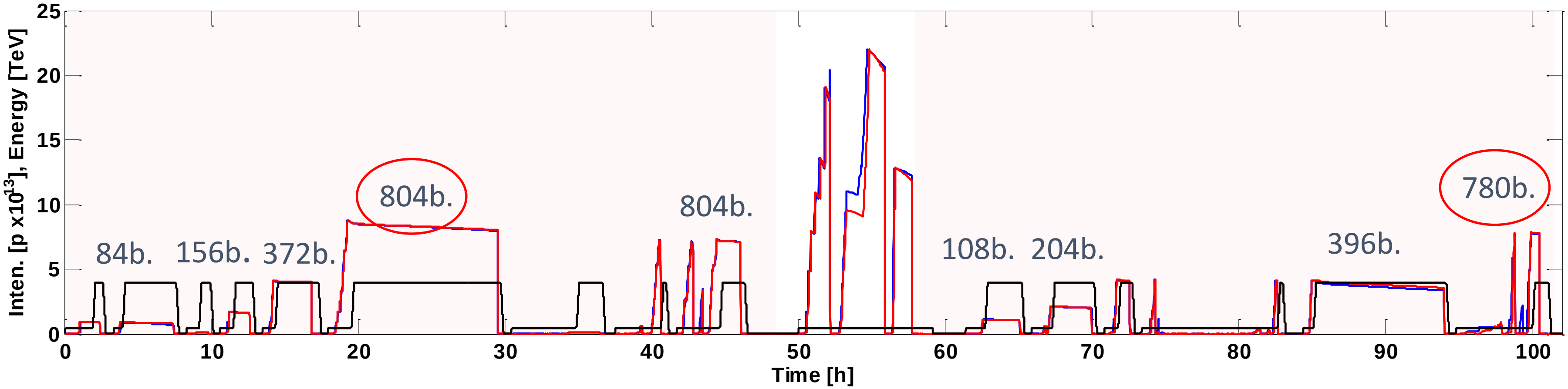
Experience with 25 ns beams at 4 TeV

The accumulated scrubbing made possible to have **machine studies and a pilot physics run with 25 ns at 4 TeV**



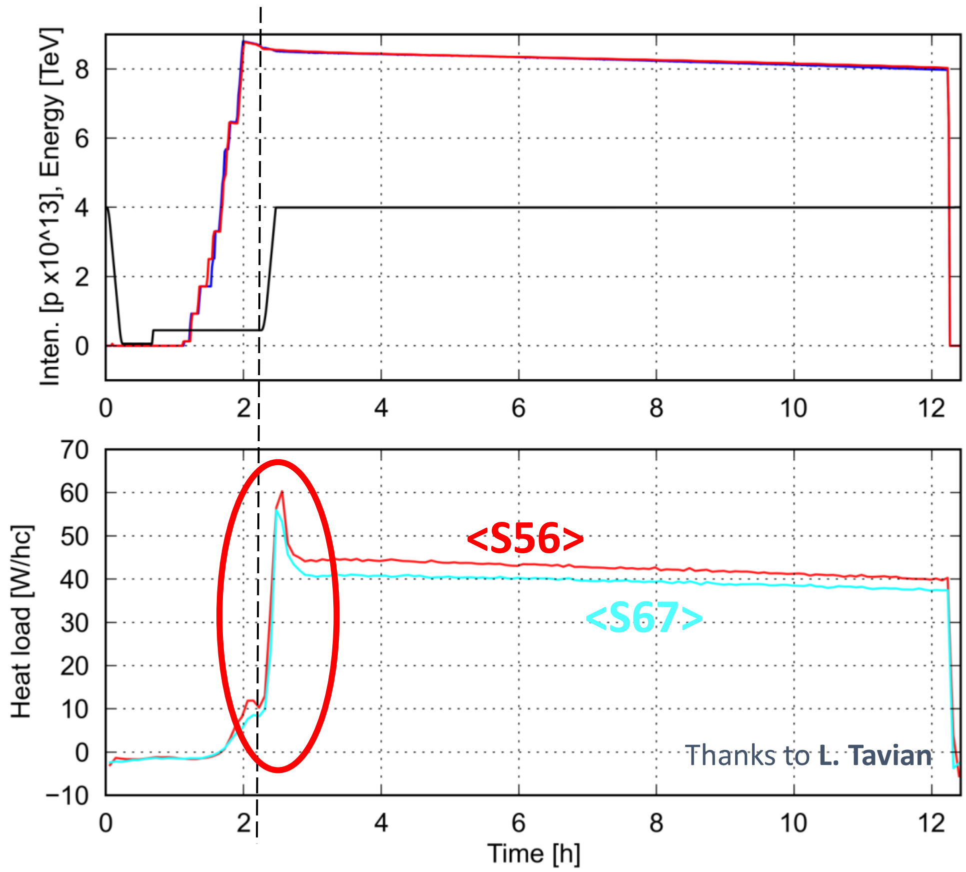
Machine Studies
with 25 ns beams at 4TeV
(12 – 15 Dec 2012)

Pilot physics run
with 25ns beams
(15 – 17 Dec 2012)

Heat load evolution during the ramp

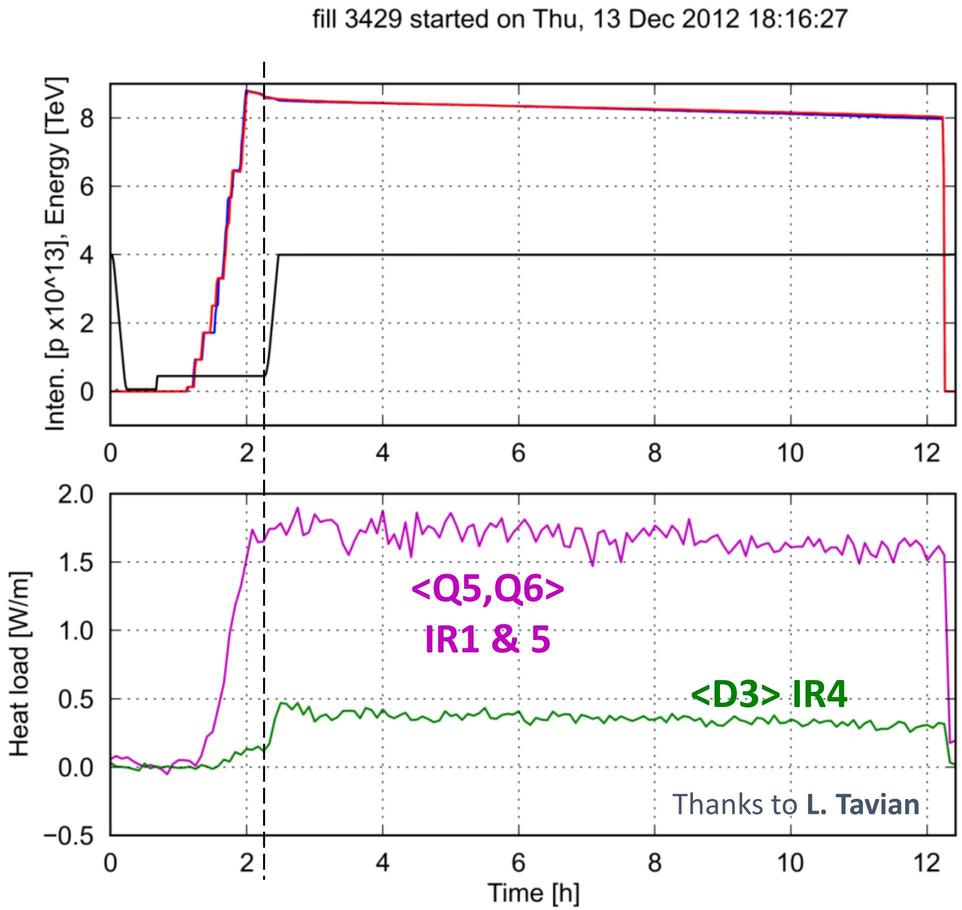
- A **strong enhancement on the heat load** is observed on the **energy ramp**

fill 3429 started on Thu, 13 Dec 2012 18:16:27



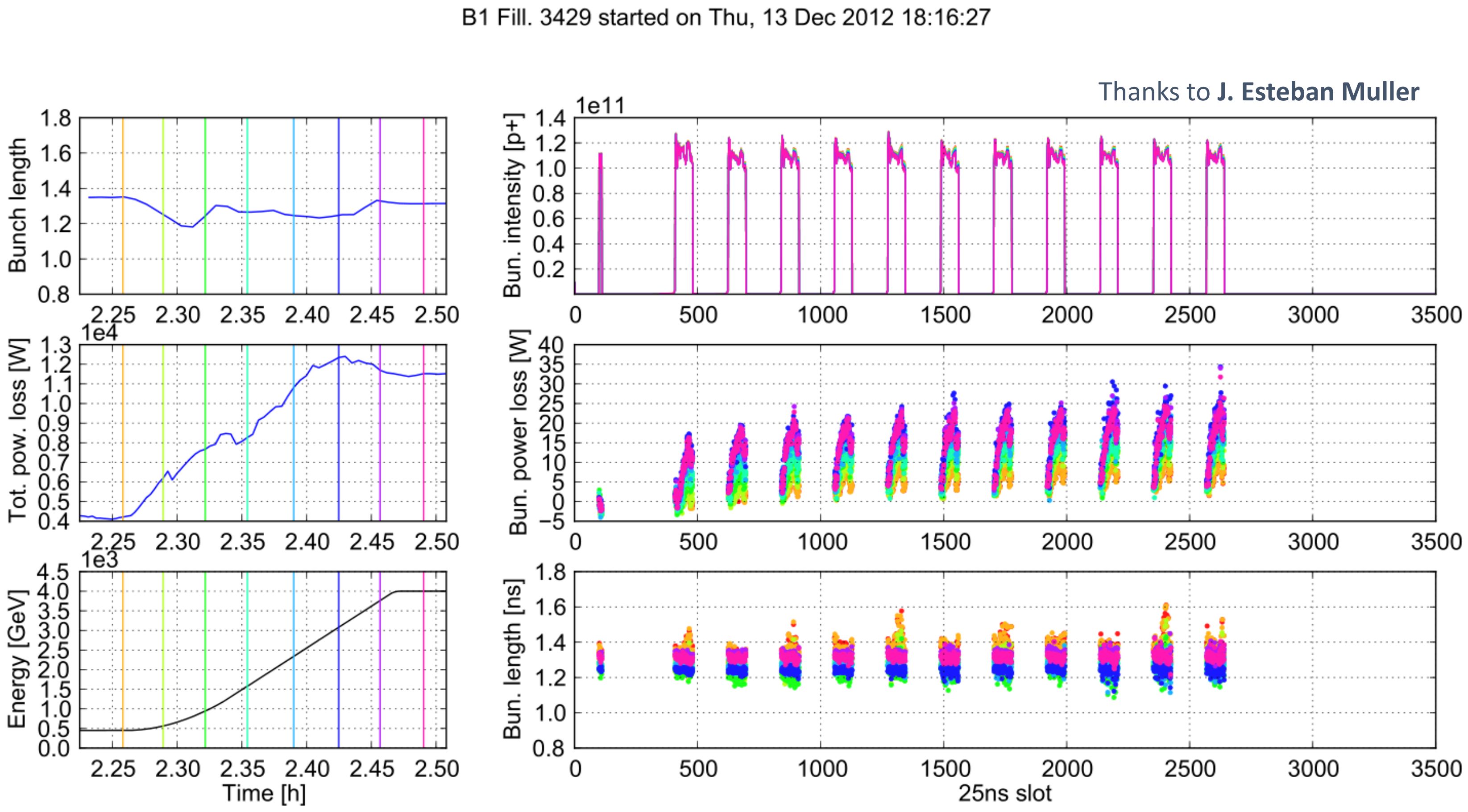
Heat load evolution during the ramp

- A **strong enhancement on the heat load** is observed on the **energy ramp**
- SAMs show heat load **increase with energy in the dipoles but not in the quadrupoles**



Heat load evolution during the ramp

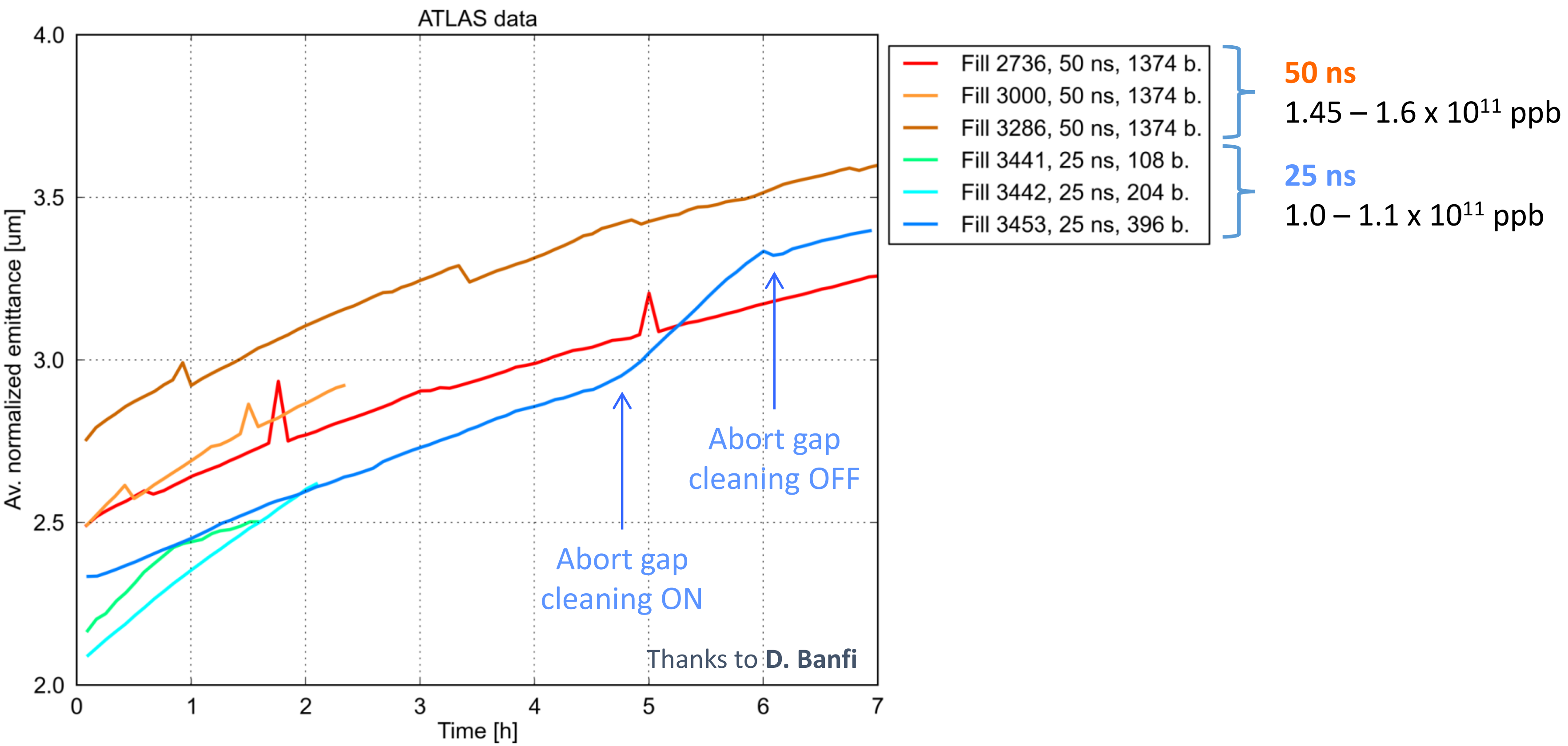
- A **strong enhancement on the heat load** is observed on the **energy ramp**
- SAMs show heat load **increase with energy in the dipoles but not in the quadrupoles**
- **Increase almost uniform along the ramp** → not only photoelectrons



Emittance blow-up with 25 ns beams at 4 TeV

Large electron cloud density in the arcs **does not show a strong effect on the beam** (due to **increased beam rigidity**)

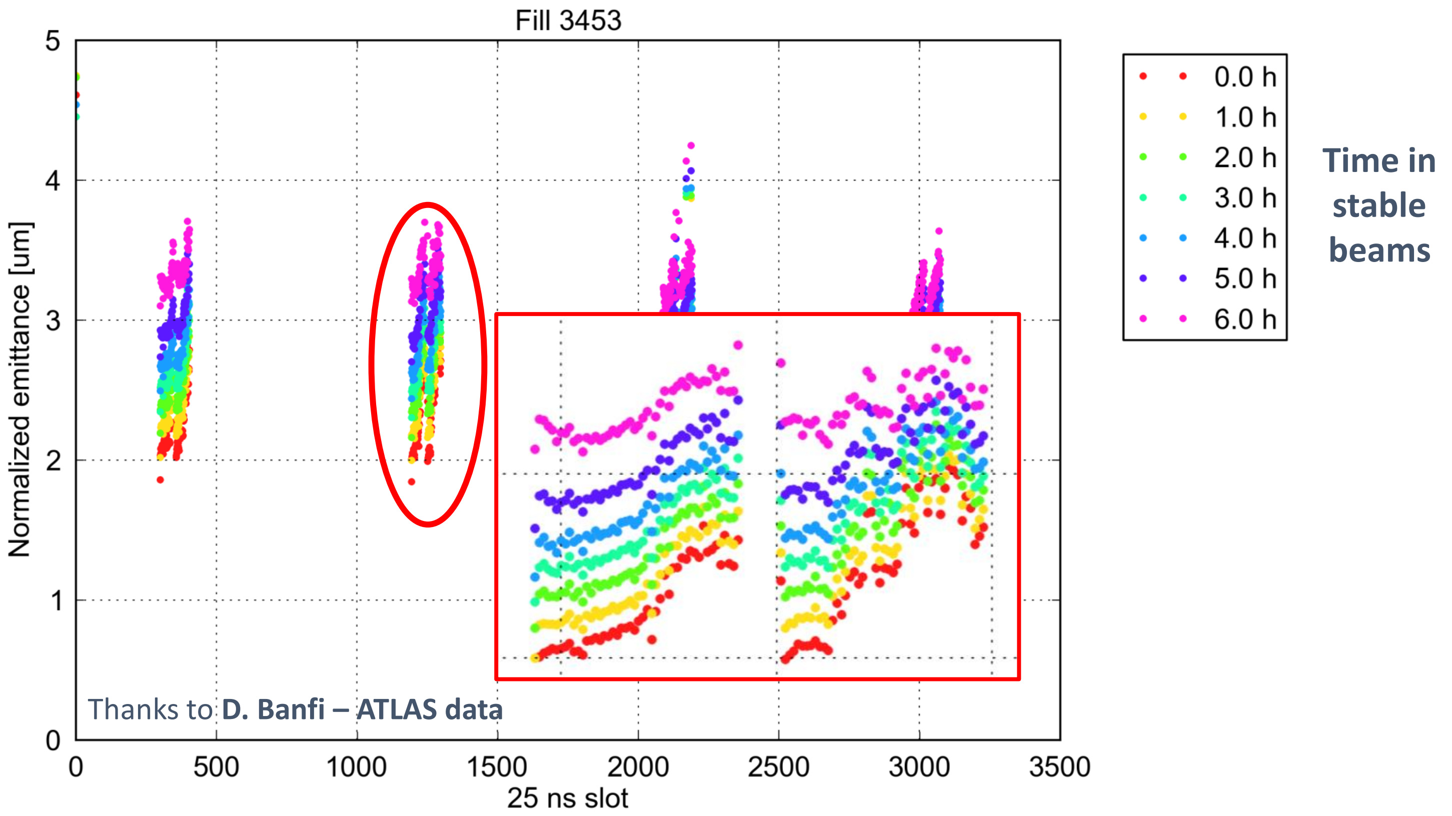
- **Emittance blow-up** in collision very similar to 50 ns → **likely not due to EC**



Emittance blow-up with 25 ns beams at 4 TeV

Large electron cloud density in the arcs **does not show a strong effect on the beam** (due to **increased beam rigidity**)

- **Emittance blow-up** in collision very similar to 50 ns → **likely not due to EC**
- Blow-up on trailing bunches is observed **mainly at injection energy** (BSRT)
- Blow up in **stable beams** more severe for brighter bunches at the **head of trains** (although they see less EC)



Thanks to **D. Banfi – ATLAS data**

Arc heat load after 2012 scrubbing: some extrapolation

Arc cooling capacity at 6.5 TeV will be **~160 W/hcell** [(1)]

	Measured in 2012 with 800b. @4TeV
Dipoles	40 W/hcell*
Quadrupole	5 W/hcell*
Total	**45 W/hcell**

* Estimated from SAMs

[(1)] S. Claudet and L. Tavian, at LBOC 08/10/2013

Arc heat load after 2012 scrubbing: some extrapolation

Arc cooling capacity at 6.5 TeV will be **~160 W/hcell** [(1)]

	Measured in 2012 with 800b. @4TeV	Rescaled to 2800 b.	Effect of tighter filling scheme	Effect of larger energy (6.5 TeV)
Dipoles	40 W/hcell*	(x3.4) 136 W/hcell	(x2) 272 W/hcell	(x1.6) 435 W/hcell
Quadrupole	5 W/hcell*	(x3.4) 17 W/hc	(x1) 17 W/hcell	(x1) 17 W/hcell
Total	**45 W/hcell**	**153 W/hc**	**289 W/hcell**	**450 W/hcell**

* Estimated from SAMs

→ more scrubbing is needed to cope with nominal number of bunches

[(1)] S. Claudet and L. Tavian, at LBOC 08/10/2013

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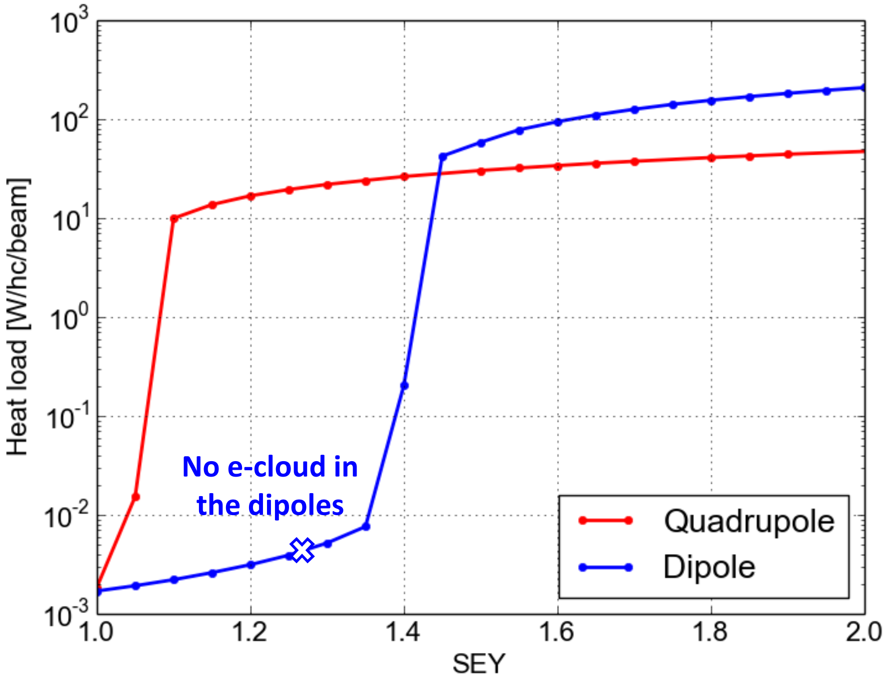
Scrubbing goals for 2015

Experience in Run 1 showed that the electron cloud can **limit the achievable performance with 25 ns** beams mainly through:

- **beam degradation** (blow-up, losses) at **low energy**
- **high heat load** on arc beam screens at **high energy**

To cope with nominal number of bunches **more scrubbing is necessary**

→ Main goal: e-cloud **suppression in the dipole magnets** (all along the fill)



- It would bring the **arc heat loads well within cooling capacity**
- It would significantly **improve beam quality preservation**

Post-LS1 improvements

The main limitations found during 2012 Scrubbing Run were **identified and mitigated** during LS1:

→ **Cryogenics:** increased cooling capacity for SAM modules and for Sector 34 (it was below nominal during Run 1)

→ **Injection kickers:** expected less beam induced heating (24 screen conductors) and better vacuum (NEG coated by-pass tubes, and NEG cartridge added at interconnects)

→ **TDIs:** Reinforced beam screen, improved vacuum, Al blocks will have Ti flash to reduce SEY, temperature probes installed, mechanics disassembled and serviced

New instrumentation will allow to **gain more information on e-cloud** in LHC and increase the scrubbing efficiency:

→ **3 half cells in Sector 45 equipped with extra thermometers** (for magnet-by-magnet heat load measurements) **and high sensitivity vacuum gauges**

→ **New software tools for on-line scrubbing monitoring and steering** (beam screen heat load and bunch-by-bunch energy loss from RF stable phase)

Possibility to use the **Scrubbing Beam** being developed for the SPS:

→ See next slides…

For more details see: G. Iadarola and G. Rumolo, “Electron cloud and scrubbing: perspective for 25 ns operation in 2015”, in the proceedings of the Evian 2014 Workshop, and references therein.

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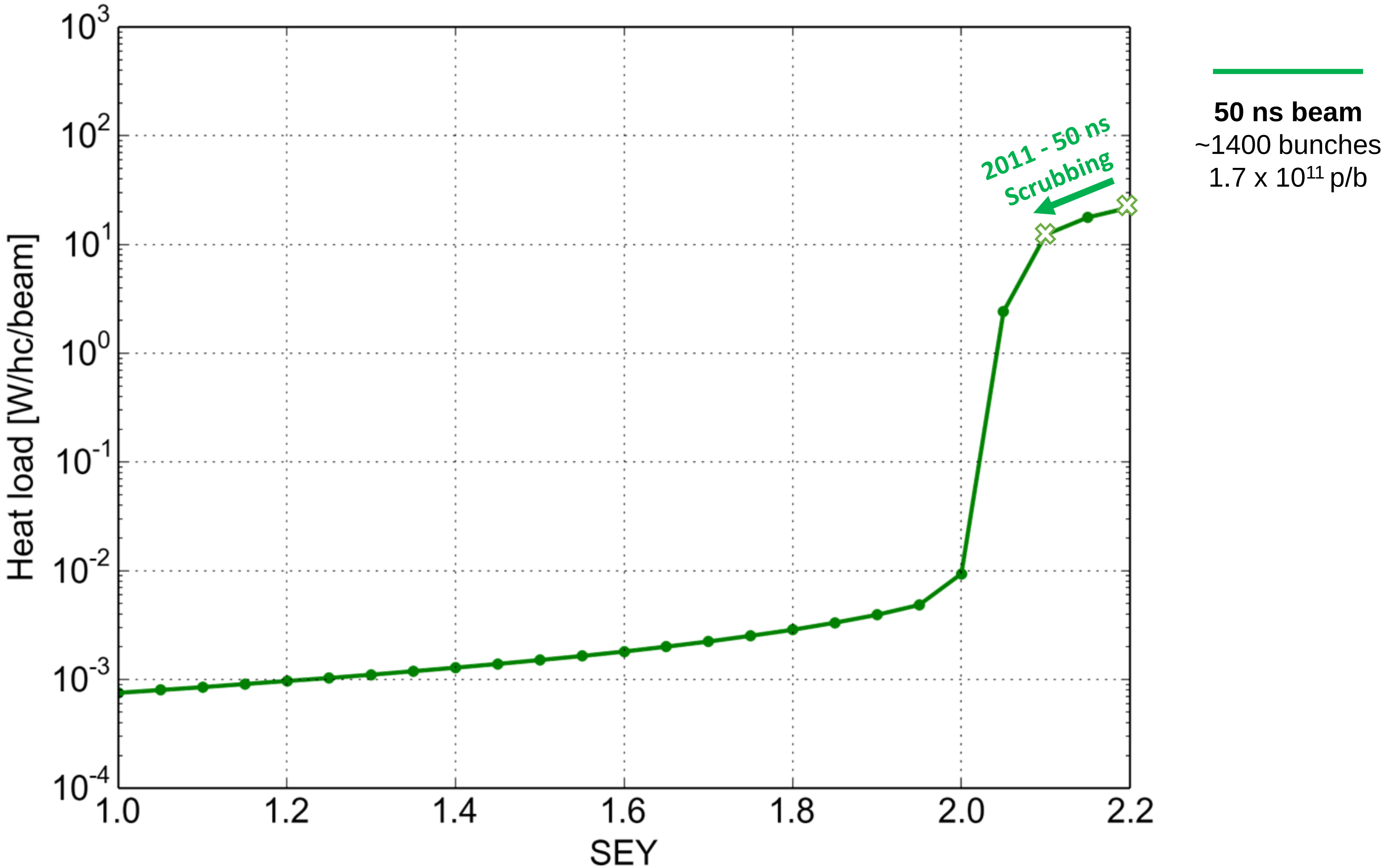
“Doublet” scrubbing beam: introduction

Scrubbing with 25 ns beam allowed to lower the SEY of the dipole chambers **well below the multipacting threshold for 50 ns → e-cloud free operation with 50 ns beams**



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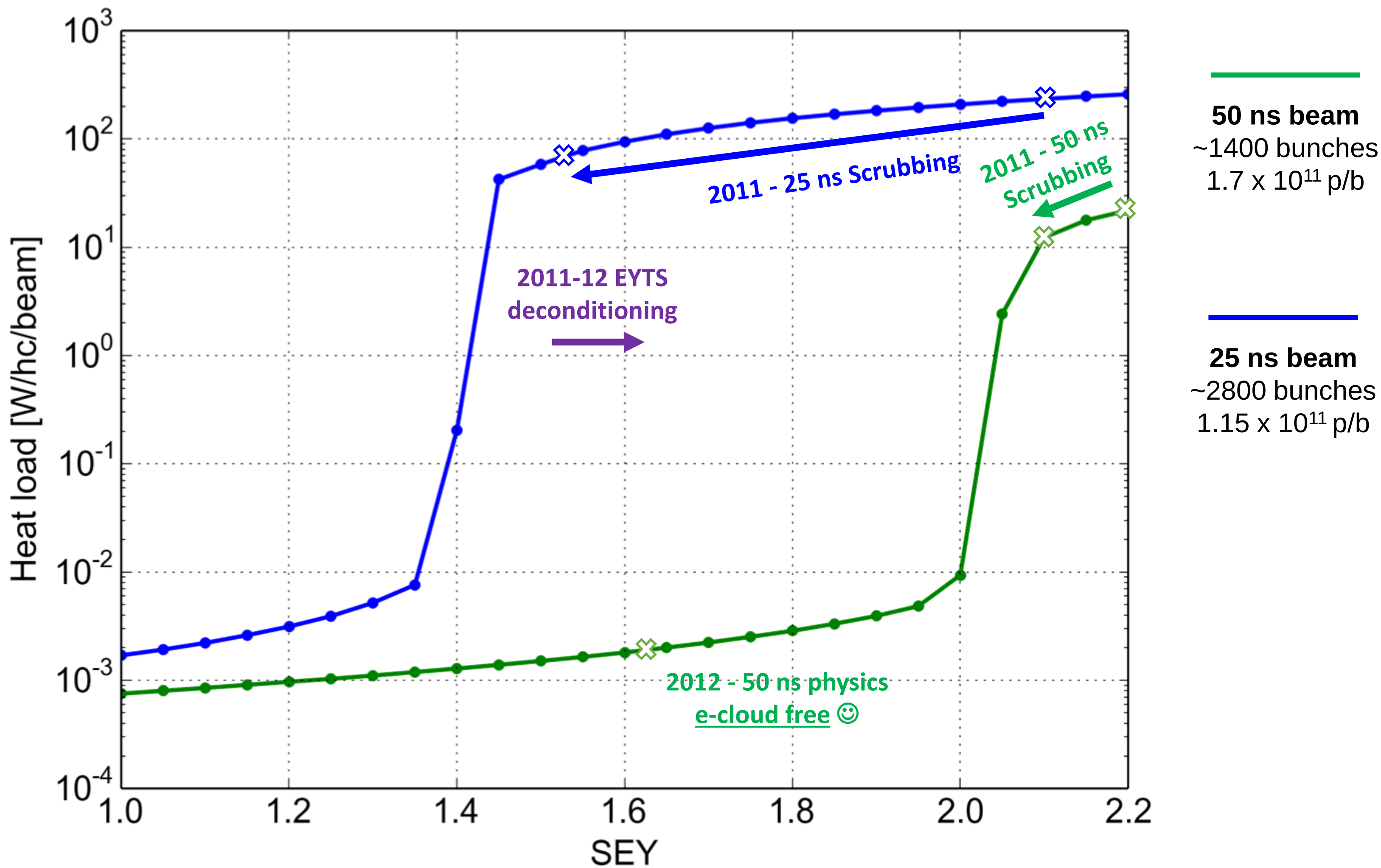
→ **Can we go to lower bunch spacing** (e.g. 12.5 ns) **to scrub for 25 ns operation?**



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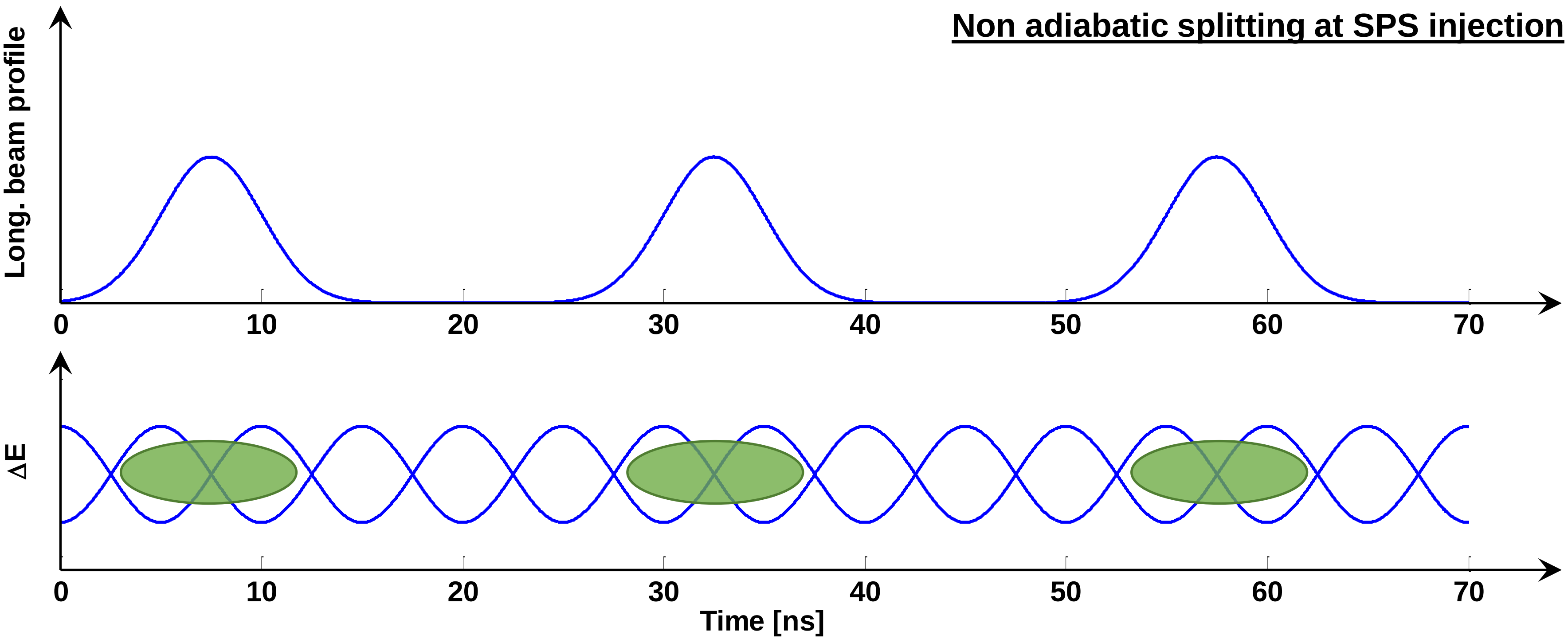
→ **Can we go to lower bunch spacing** (e.g. 12.5 ns) **to scrub for 25 ns operation?**

- Due to RF limitations in the PS it is **impossible to inject bunch-to-bucket into the SPS with spacing shorter than 25 ns**
- An alternative is to inject long bunches into the SPS and capturing each bunch in two neighboring buckets obtaining **a (5+20) ns “hybrid” spacing**



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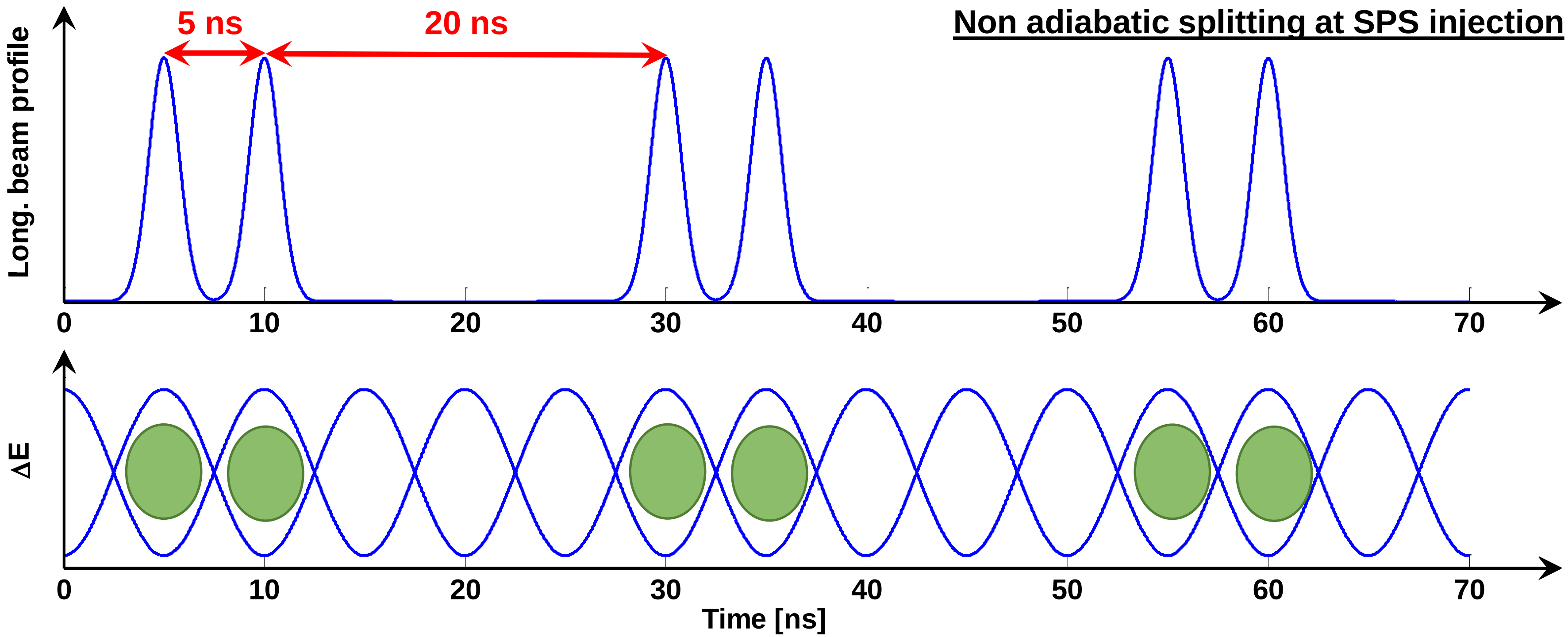
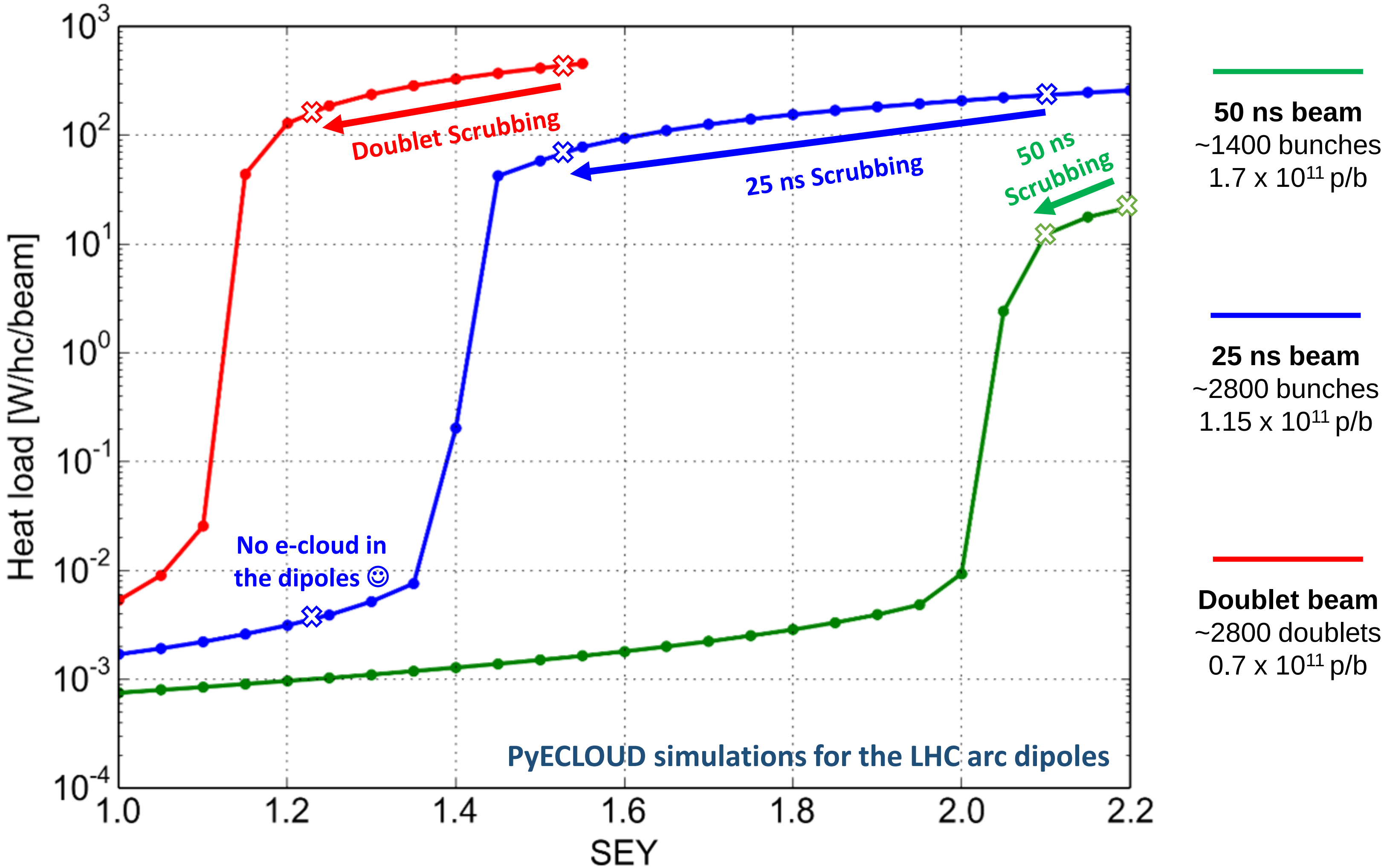


“Doublet” scrubbing beam: PyECLOUD simulation results

Buildup simulations show **a substantial enhancement of the e-cloud** with the “doublet” bunch pattern



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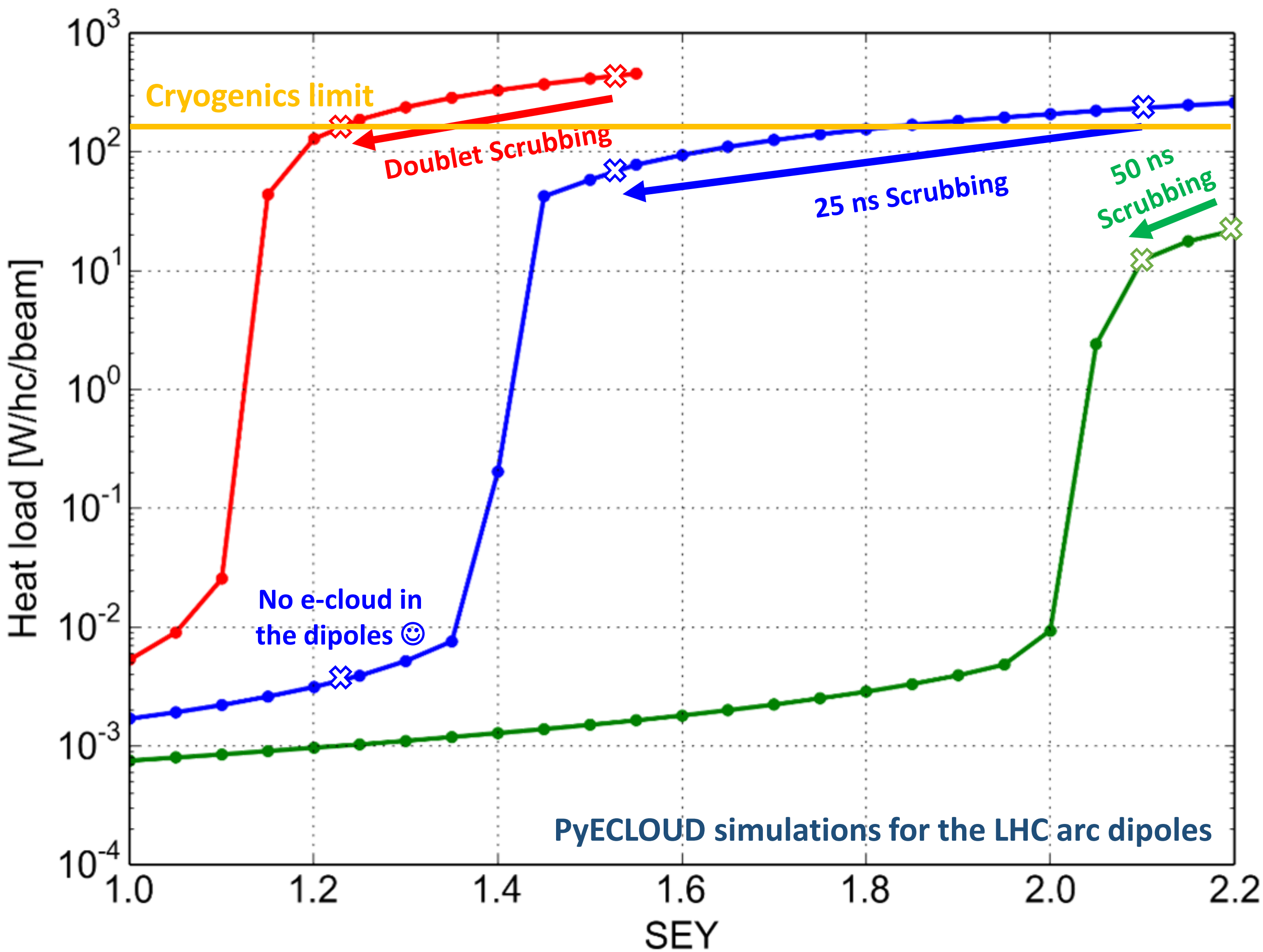

50 ns beam
~1400 bunches
1.7×10^{11} p/b

25 ns beam
~2800 bunches
1.15×10^{11} p/b

Doublet beam
~2800 doublets
0.7×10^{11} p/b

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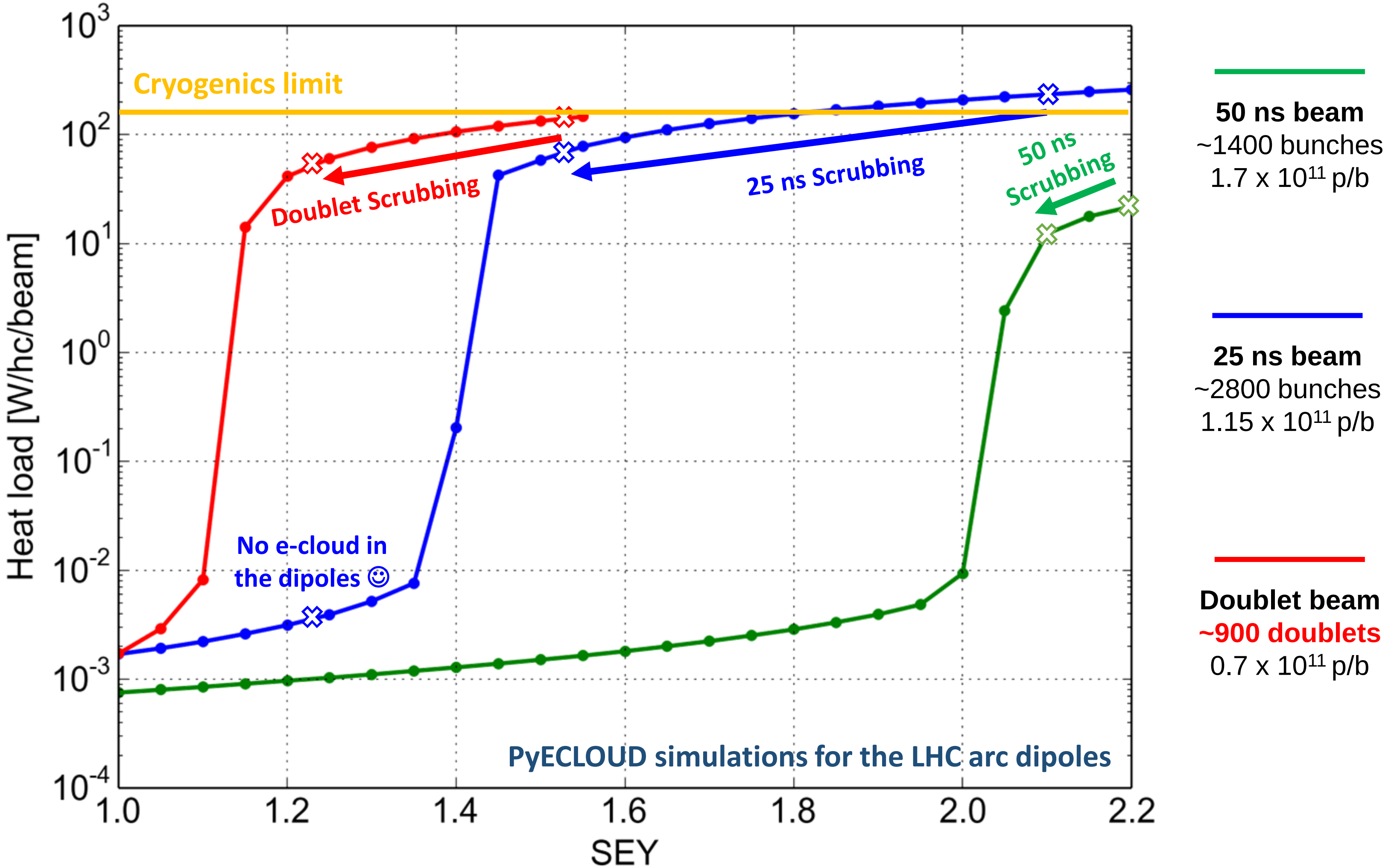

“Doublet” scrubbing beam: PyECLOUD simulation results

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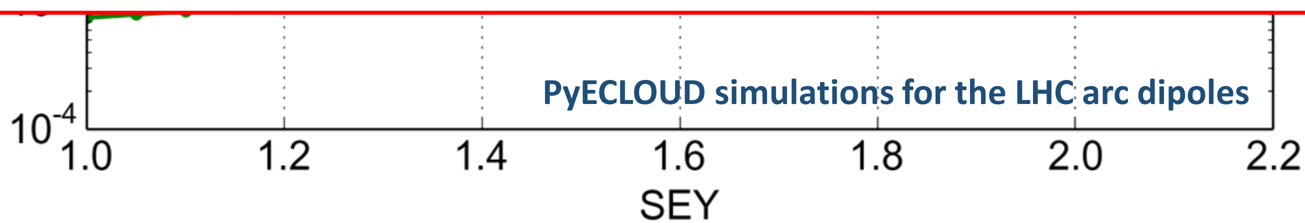
For example if: **SEY_{dip} = SEY_{quad} = 1.45**:

	$N_{bunches}$	Bunch int.	Total int.	Heat load	P_{dip}	P_{quad}	P_{TDI}*
Std. 25 ns beam	~2800	1.15 x 10^{11} p/b	3.2x 10^{14} p/beam	71 W/hc/beam	1 W/m	9.2 W/m	415 W
Doublet beam	~900	0.7 x 10^{11} p/b	1.2x 10^{14} p/beam	125 W/hc/beam	2.6 W/m	3.2 W/m	107 W

* Thanks to **N. Mounet and C. Zannini**

With the doublet beam:

- Arc beam screen **cooling capacity fully exploited**
- Stronger EC with significantly **lower total intensity**
- Scrubbing power much **better distributed along the arc**
- Lower intensity have a **positive impact on impedance heating** on sensitive elements (e.g. TDI)



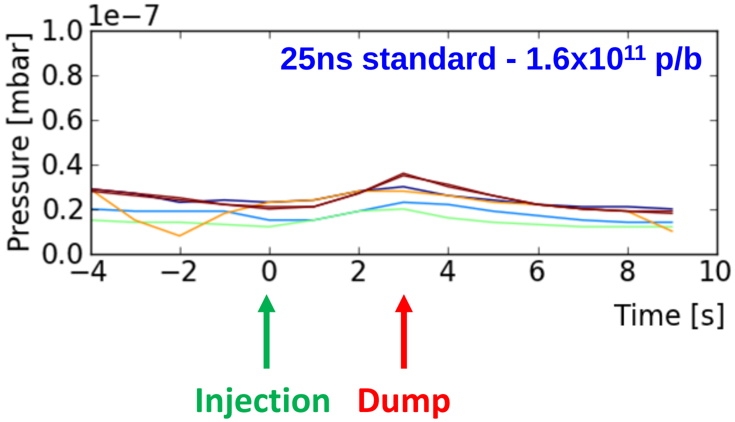
“Doublet” scrubbing beam: SPS tests

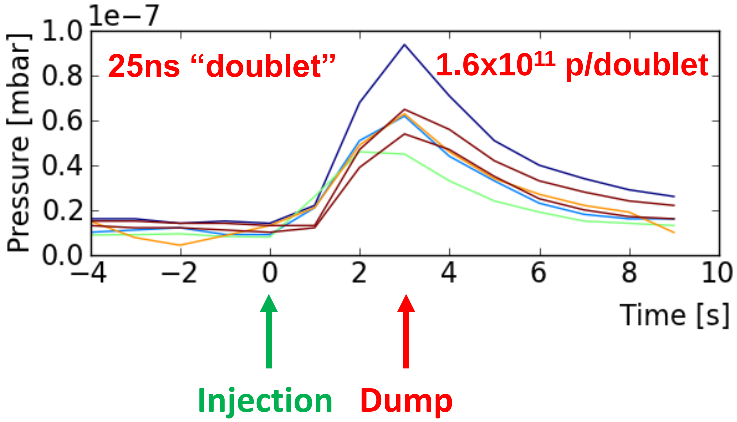
Production scheme and e-cloud enhancement **proved experimentally in the SPS** in 2012-13

→ Stronger e-cloud visible both on **pressure rise** and on **dedicated detectors**

Pressure in the SPS arcs

Thanks to **L. Kopylov, H. Neupert, M. Taborelli**





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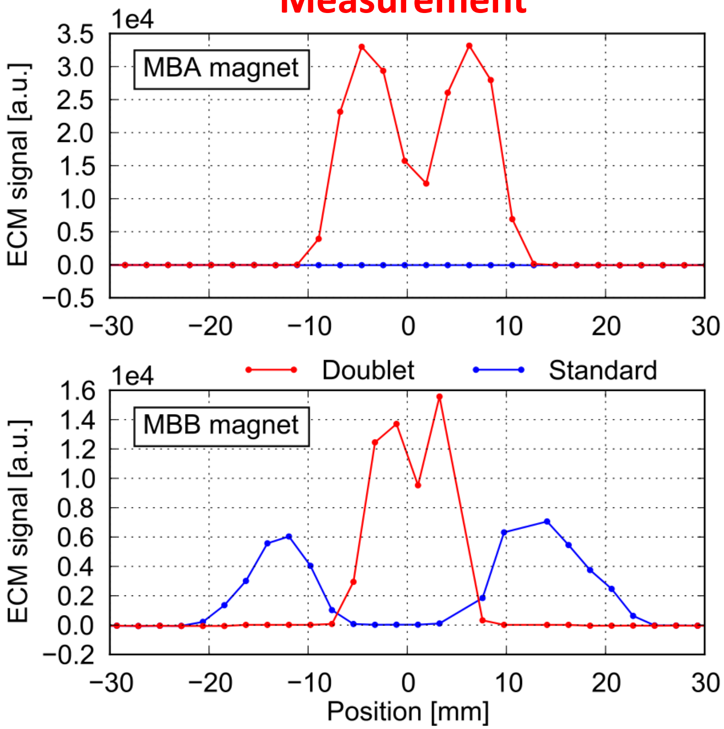
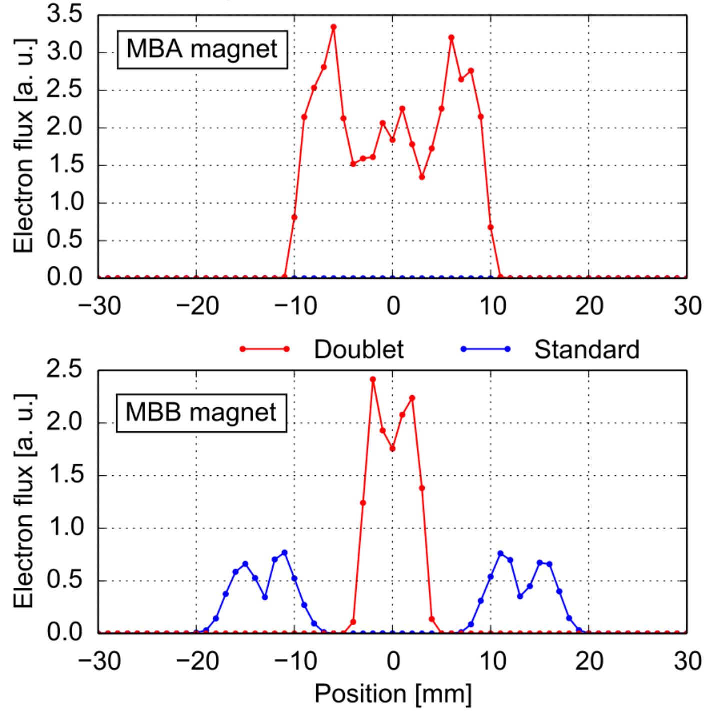
e-cloud detectors

Measurement



Thanks to **M. Mensi, H. Neupert, M. Taborelli**

PyECLOUD simulation



→ Important validation for our simulation models and tools

“Doublet” scrubbing beam: SPS tests

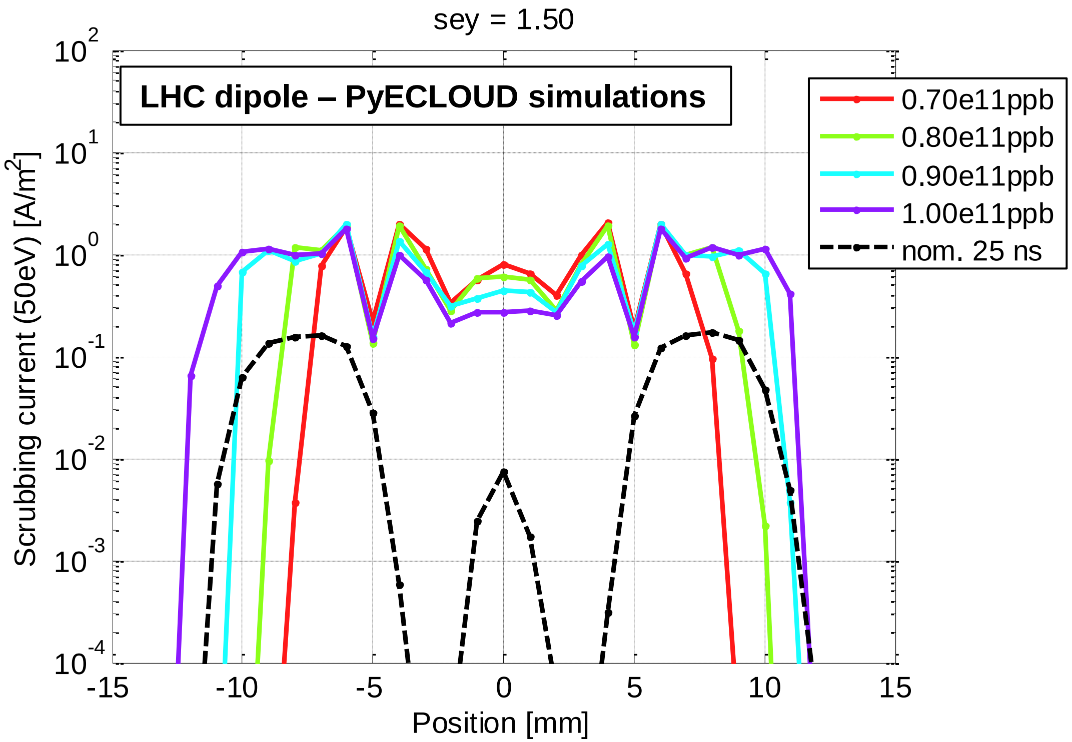
Production scheme and e-cloud enhancement **proved experimentally in the SPS** in 2012-13

→ Stronger e-cloud visible both on **pressure rise** and on **dedicated detectors**

e-cloud detectors

Reduced e-cloud region is a consequence of the relatively small bunch(let) intensity.

Fortunately, **for the LHC the effect is less strong** than for SPS



"Doublet" beam: compatibility with LHC equipment

Reviewed within the LBOC → main conclusions:

Doublet production:

- **Splitting at SPS injection is the most favorable scheme** (compared to splitting at high energy in SPS, or at LHC injection)

RF system:

- **No major issue (provided that bunch length from SPS stays below 1.8 ns)**
- **Phase measurement will average over each doublet**

Transverse damper (ADT):

- **Common mode oscillations** of the doublets would be **damped correctly**
- **The ADT will not react to pi-mode oscillations** (the two bunchlets oscillating in counter phase) → to be controlled with chromaticity and/or octupoles

Beam induced heating:

- **No additional impedance heating** is expected with the doublet beam (same total intensity)
- Beam power spectrum is modulated with $\cos^2$ function, **lines in the spectrum can only be weakened by the modulation**

For more details see: G. Iadarola and G. Rumolo, "Electron cloud and scrubbing: perspective for 25 ns operation in 2015", in the proceedings of the Evian 2014 Workshop, and references therein.

“Doublet” beam: compatibility with LHC equipment

Reviewed within the LBOC → main conclusions:

Beam instrumentation

- **No problem for:** Beam Loss Monitors (BLMs), DC Current Transformers (DCCTs), Abort Gap Monitors, Longitudinal Density Monitors (LDMs), DOROS and collimator BPMs
- BBQ (gated tune), Fast Beam Current Transformers (FBCTs), Wire Scanners, Beam Synchrotron Radiation Telescopes (BSRTs) **will integrate over the two bunchlets**
- **Beam Position Monitors (BPMs):** errors up to 2-4 mm, especially for unbalanced doublets in intensity or position

  → Use the synchronous mode and **gate on a standard bunch (for orbit measurement)**

- **Interlocked BPMs in IR6:** same issues as for other BPMs but they **need to be fully operational on all bunches** to protect aperture of dump channel

  → Being **followed up by TE-ABT and BE-BI. Possible strategy:**

  - Qualify the BPM behaviours by **measurement in the SPS (2014)** and **in the LHC (early 2015 single doublet)**
  - **Quantify the resulting error** in the interlocked BPM measurements
  - **Reduce the interlock** setting (presently 3.5 mm) accordingly

For more details see: G. Iadarola and G. Rumolo, “Electron cloud and scrubbing: perspective for 25 ns operation in 2015”, in the proceedings of the Evian 2014 Workshop, and references therein.

Outline

- **Run 1 experience**
  - 50 ns vs 25 ns
  - Scrubbing with 25 ns in 2011-2012
  - 25 ns beams at 4 TeV in 2012
- **Scrubbing in 2015**
  - Goals
  - Post-LS1 improvements
  - The “doublet” scrubbing beam
    (motivation, tests at SPS, compatibility with LHC equipment)
  - Scrubbing stages
  - Possible scenarios after scrubbing

Scrubbing stages

Commissioning (low intensity / luminosity)

~Week 21 (May)

The machine has been opened
Several newly installed components
→ Situation similar to 2010

Dates according to the present draft schedule (V0.4)

Scrubbing stages

450GeV

Commissioning (low intensity / luminosity)

Vacuum conditioning 50 ns

(5-7 days)

~Week 21 (May)

First stores at 450 GeV with high intensity beams

We will face dynamic pressure rise, heat load and possibly beam instabilities

Goals:

- **Vacuum conditioning** in newly installed equipment
- **First scrubbing** of arc beam screens

→ Situation similar to 2010/2011 scrubbing with 50 ns beams

Dates according to the present draft schedule (V0.4)

Scrubbing stages

450GeV

Commissioning (low intensity / luminosity) → **Vacuum conditioning 50 ns (5-7 days)** → **Scrubbing with 25ns (2 days)**

~Week 21 (May)

Switch to 25 ns when pressures, heat loads and instabilities are under control

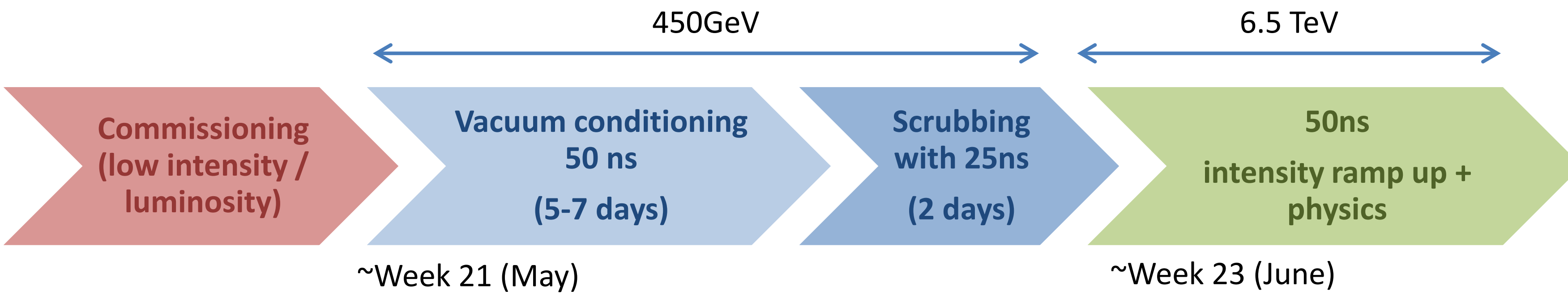
Goal:

- Lower the **SEY well below the threshold for 50 ns**

→ **Situation similar to 2011 MDs with 25 ns**

Dates according to the present draft schedule (V0.4)

Scrubbing stages



First ramps to 6.5 TeV with high intensity (50 ns) → synchrotron radiation and **photoelectrons**

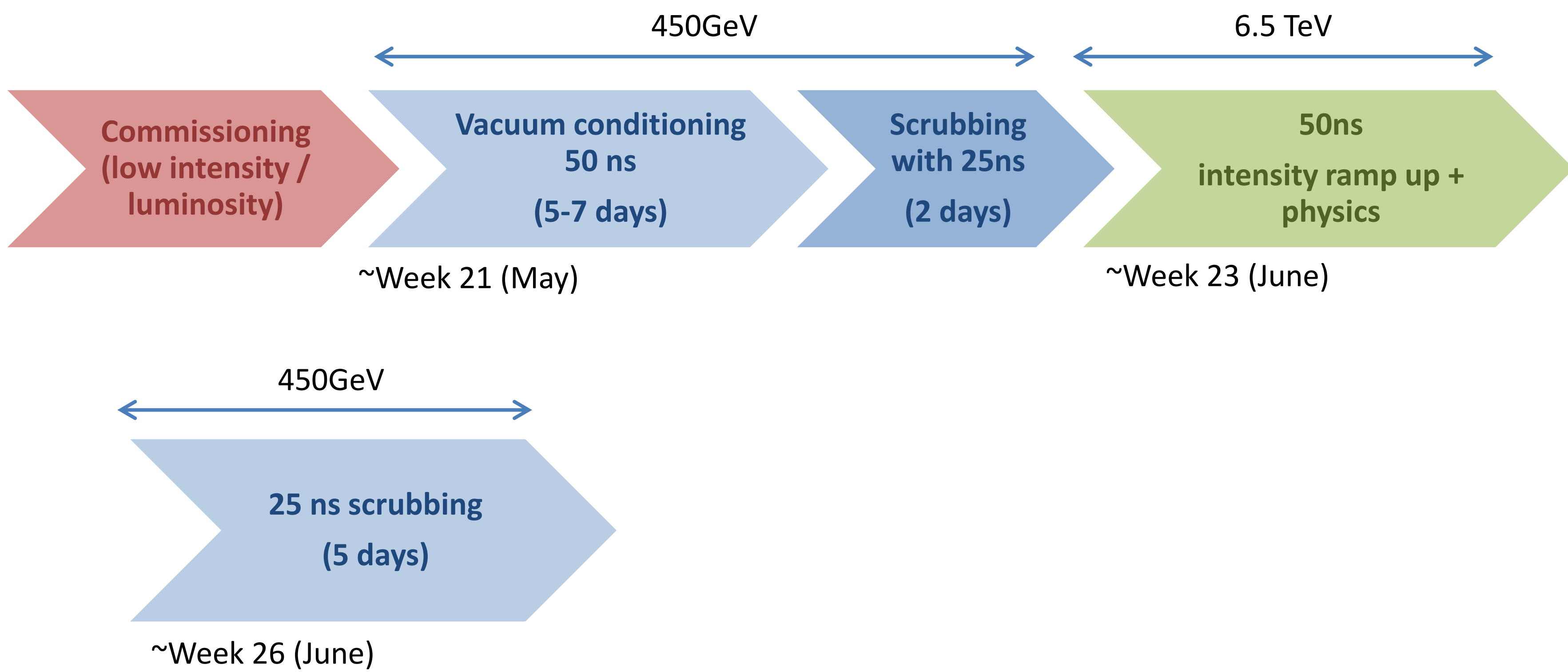
Goals:

- **Re-establish operation with high intensity beams**
- **Condition** chambers area interested by photoelectrons
- Deliver **luminosity with 50 ns**

Situation similar to 2012 startup with 50 ns

Dates according to the present draft schedule (V0.4)

Scrubbing stages



Scrubbing with 25 ns beams

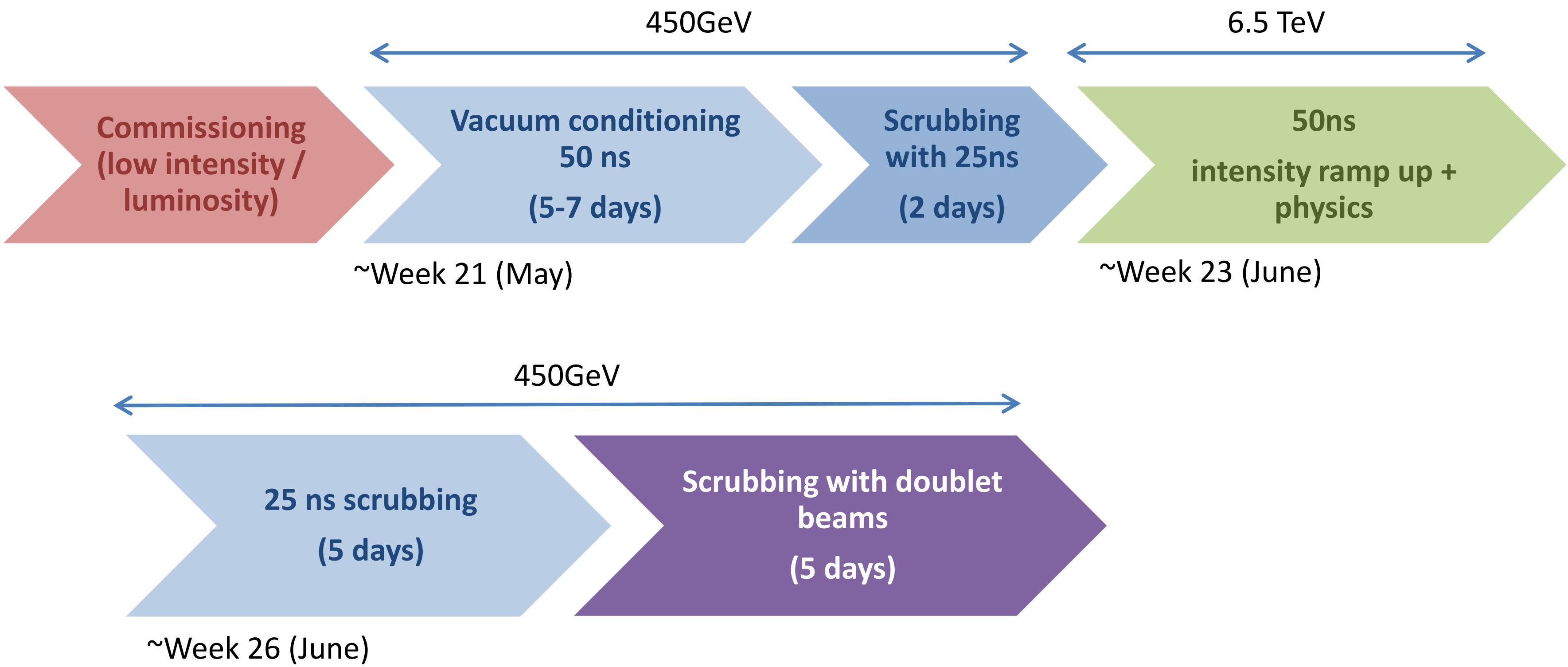
Goal:

- **Lower the SEY** enough to allow a safe operation and efficient scrubbing with doublet beam

→ **Situation similar to 2012 Scrubbing with 25 ns**

Dates according to the present draft schedule (V0.4)

Scrubbing stages



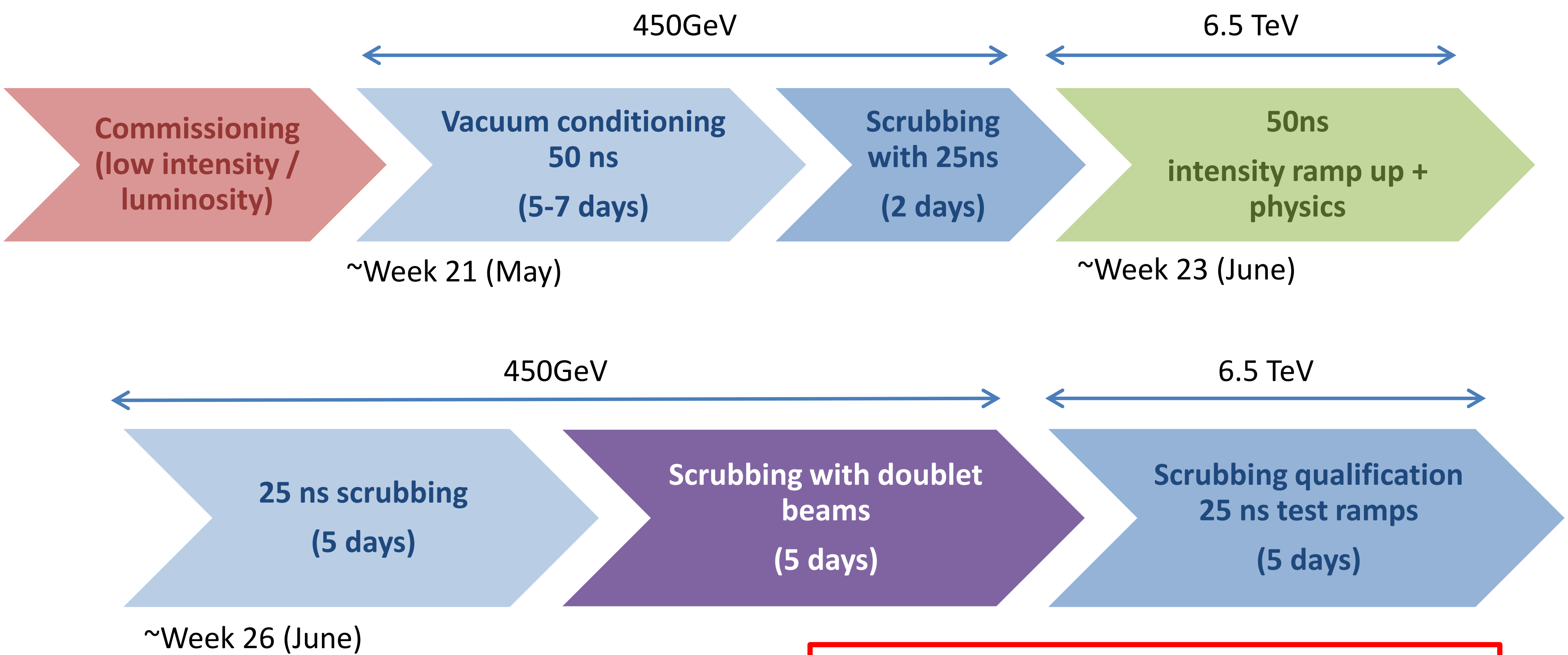
Scrubbing with doublet beam

Goal:

- Lower the **SEY in the dipoles below the threshold for 25 ns beams**

Dates according to the present draft schedule (V0.4)

Scrubbing stages



First ramps to 6.5 TeV with 25 ns beams

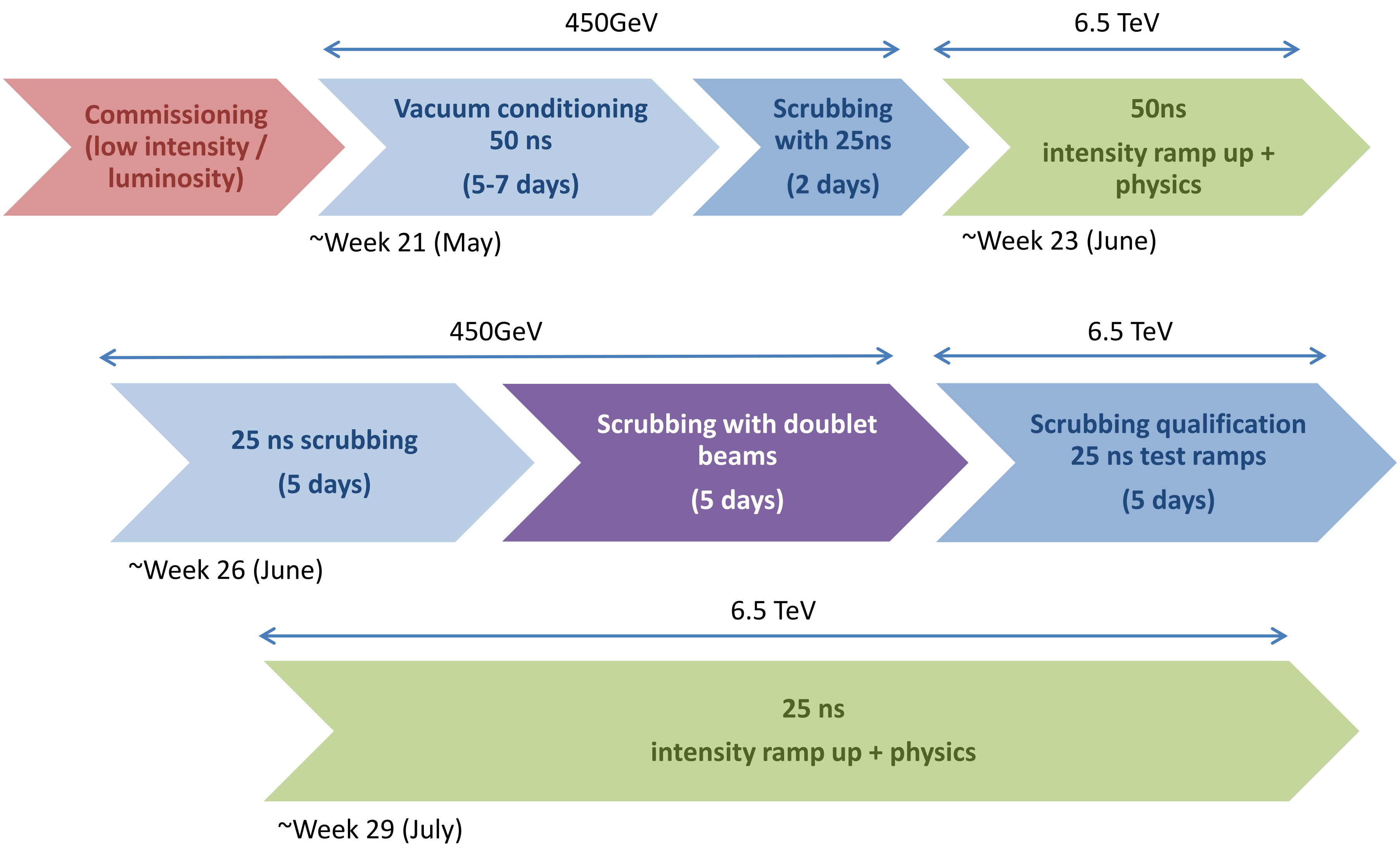
→ Intensity ramp-up will be needed

Goals:

- **Qualify e-cloud after scrubbing** (heat loads and beam degradation along the cycle)
- **Assess performance reach** with 25 ns beams
- **Further conditioning** (photoelectrons)

Dates according to the present draft schedule (V0.4)

Scrubbing stages



Dates according to the present draft schedule (V0.4)

Outline

- **Run 1 experience**
  - 50 ns vs 25 ns
  - Scrubbing with 25 ns in 2011-2012
  - 25 ns beams at 4 TeV in 2012
- **Scrubbing in 2015**
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    (motivation, tests at SPS, compatibility with LHC equipment)
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  - Possible scenarios after scrubbing

Post scrubbing scenarios

Scenario 1:

scrubbing is successful, i.e. after scrubbing heat load, instabilities, losses, blow-up are under control with sufficiently large number of bunches

→ **physics with 25 ns beams**

Remarks:

After scrubbing e-cloud will be strongly mitigated but **not completely suppressed:**

- Most probably e-cloud still present in arc **quadrupoles** and **inner triplets**
  → **Cooling capacity sufficient** to cope with it (perhaps not much margin SAMs?)
- If **beam degradation** is still observed at 450 GeV
  → **Long bunches at 450 GeV and at beginning of ramp** could help
- If we are still limited by **heat load** on ramp and/or at 6.5 TeV
  → Search **for optimal configuration** (max. luminosity within acceptable heat loads) in terms of **number of bunches** (length of the batches), **bunch intensity**, **bunch length**
- **Further conditioning** would anyhow be **accumulated while producing luminosity**

Scenario 2:

scrubbing insufficient (even with scrubbing beam), i.e. after scrubbing heat load and/or beam degradation limit to small number of bunches

→ **physics with low e-cloud pattern** (less bunches compared to std. 25 ns)

First option: (8b+4e) pattern

(made of short trains with 25 ns spacing, see talks by G. Rumolo and R. Tomas)

- Allows to store **up to ~1900b.** in the LHC
- Simulation show **smaller multipacting threshold** compared to std. 25 ns beam

  → **to be confirmed experimentally** (at the SPS) once this beam is available

Second option: 50 ns spacing

(the Run 1 operational beam)

- Allows to store **up to ~1380b.** in the LHC
- **Smaller multipacting threshold** compared to std. 25 ns beam and (8b+4e)

Summary and conclusions

Experience in Run 1 showed that the electron cloud can **limit the achievable performance with 25 ns** beams mainly through **beam degradation at low energy** and **high heat load** at **high energy**

- To cope with nominal number of bunches **we need more scrubbing than in 2012**
- **After LS1** several improvements (e.g. cryo, vacuum, injection) will allow for **better scrubbing efficiency**

"Doublet" Scrubbing Beam (5+20) ns being developed for the SPS looks **very attractive for LHC scrubbing**

- Production scheme and e-cloud enhancement **proved experimentally at SPS in 2012-13**
- **Compatibility with LHC equipment** reviewed by the LBOC
  - → **No major showstopper** has been found
  - → Issue with **offset on interlock BPM in IR6** being followed up by BE/BI and TE/ABT

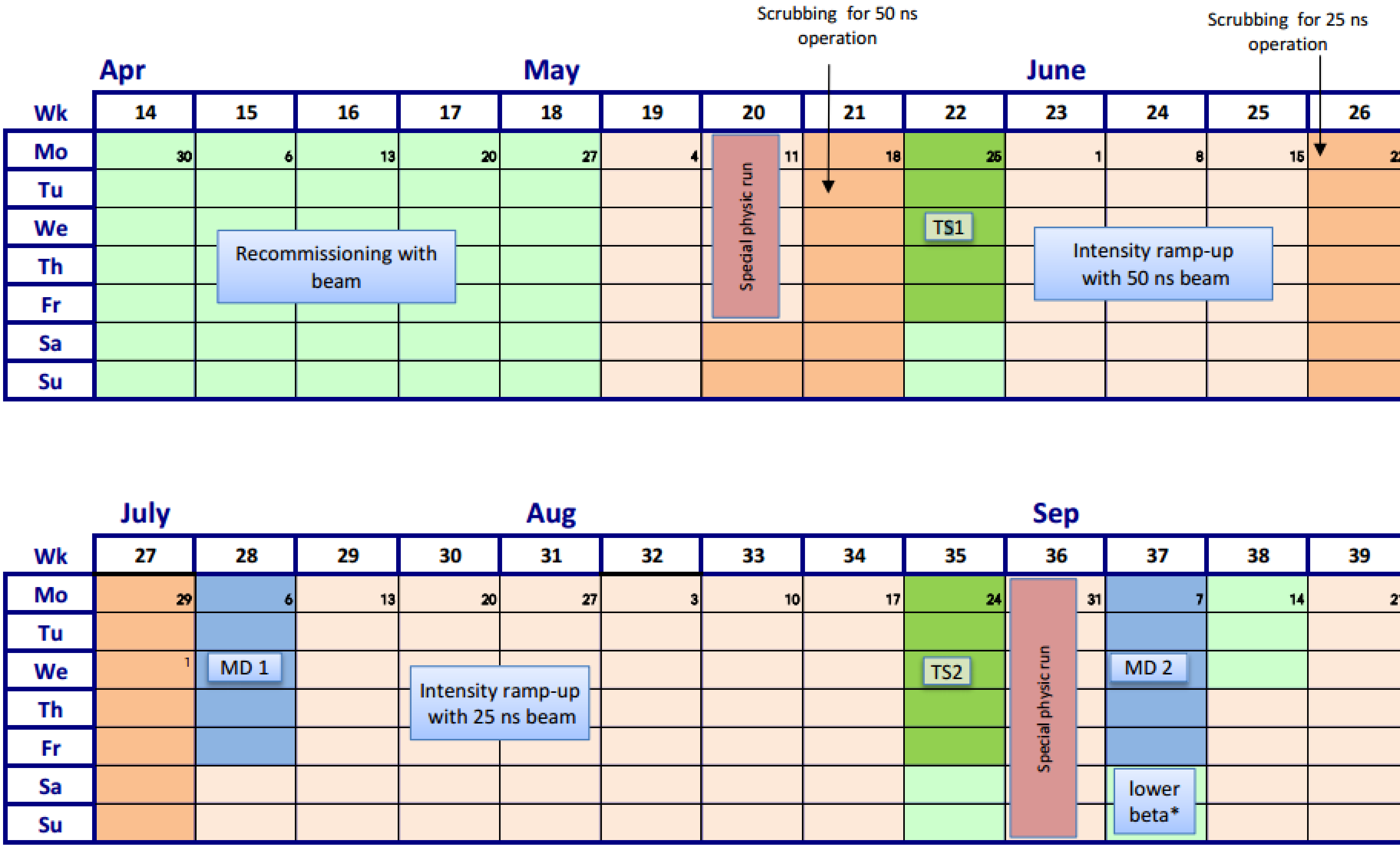
A **two stage scrubbing strategy** is proposed:

- **Scrubbing 1 (50 ns → 25 ns)** to allow for operation with **50 ns beams at 6.5 TeV**
- **Scrubbing 2 (25 ns → Doublet)** to allow for operation with **25 ns beams at 6.5 TeV**

If scrubbing insufficient even with scrubbing beam, **the 8b+4e scheme** could provide a significant e-cloud mitigation with 50% more bunches compared to 50 ns beam

- Based on simulations **→ to be validated experimentally** at SPS and (if needed) at LHC

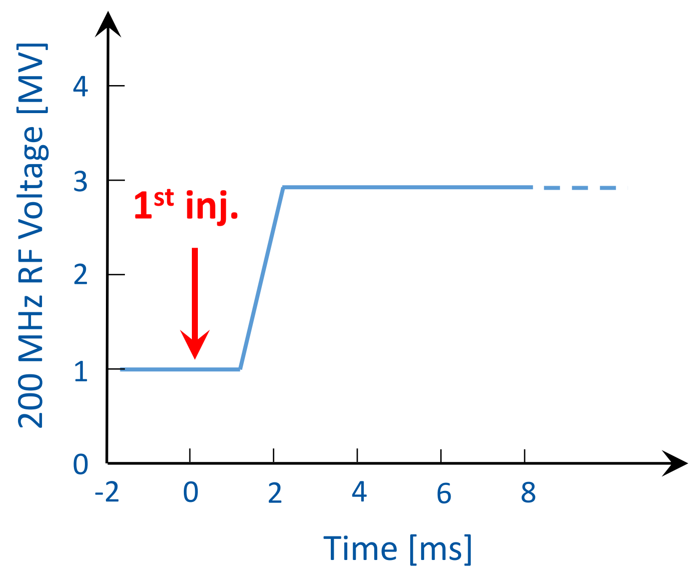
Thanks for your attention!

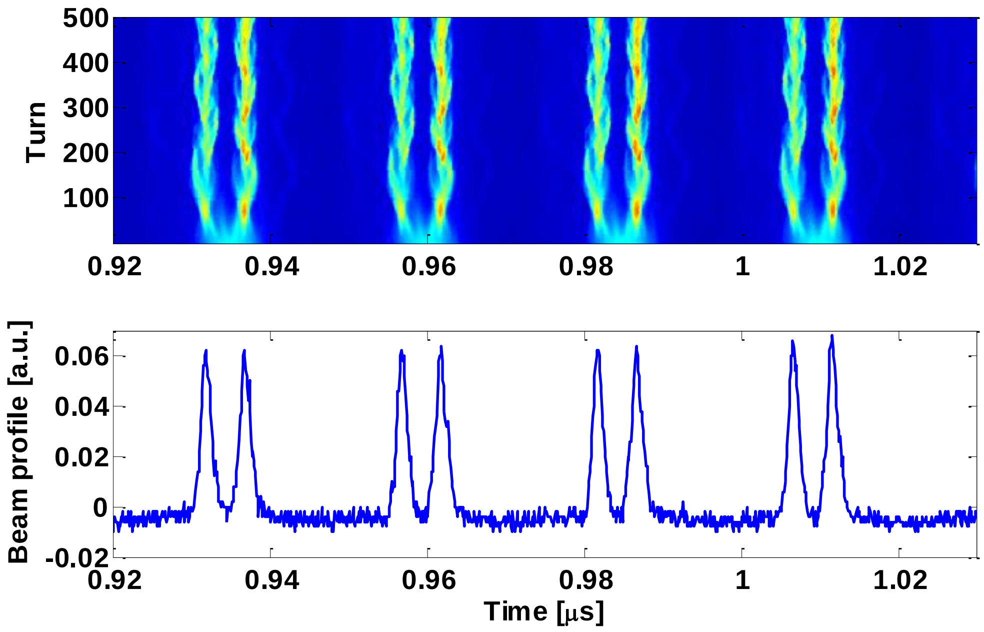


Scrubbing for 50 ns operation
Scrubbing for 25 ns operation
Apr
May
June
Wk
14 15 16 17 18 19 20 21 22 23 24 25 26
Mo
Tu
We
Th
Fr
Sa
Su
30 6 13 20 27 4 11 18 25 1 8 15 22
Special physic run
TS1
Recommissioning with beam
Intensity ramp-up with 50 ns beam
July
Aug
Sep
Wk
27 28 29 30 31 32 33 34 35 36 37 38 39
Mo
Tu
We
Th
Fr
Sa
Su
29 6 13 20 27 3 10 17 24 31 7 14 21
1
MD 1
Intensity ramp-up with 25 ns beam
TS2
Special physic run
MD 2
lower beta*

Tests of the 5 ns doublet beam in the SPS

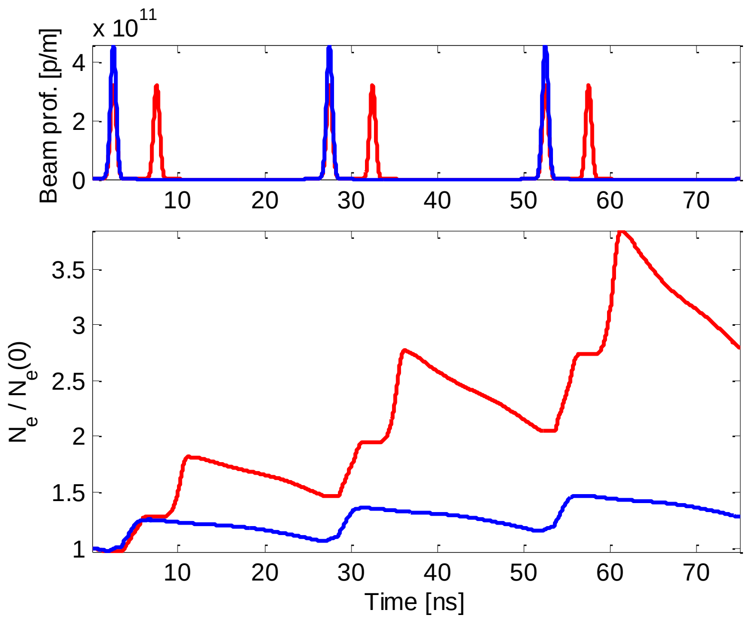
- First machine tests in the SPS at the end of 2012-13 run in order to
  - validate the doublet production scheme at SPS injection
  - obtain first indications about the e-cloud enhancement
- The production scheme has been successfully tested
  - for a train of up to (2x)72 bunches with 1.7e11 p/doublet

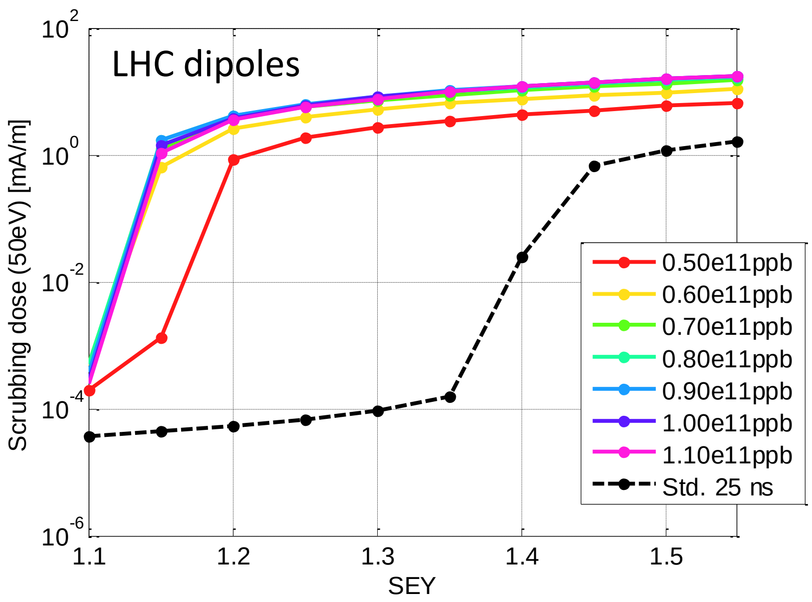




PyECLOUD simulations – 5 ns doublets

- The 5 ns doublet beam shows a much lower multipacting threshold compared to the standard 25 ns beam



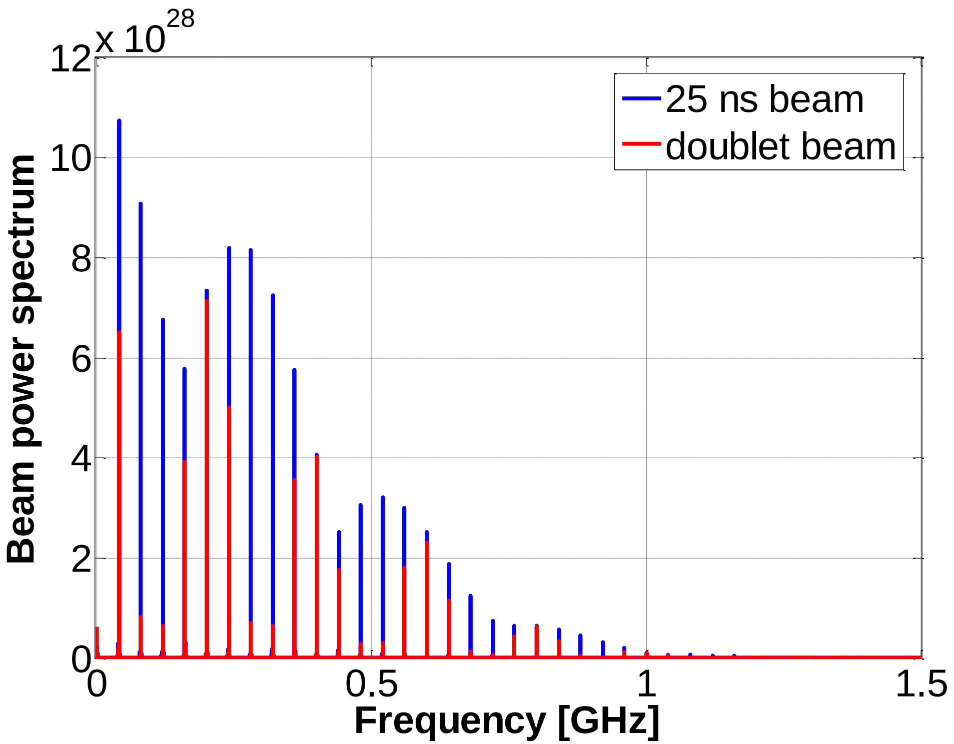


"Doublet" beam: beam induced heating

No additional impedance heating is expected with the doublet beam (same total intensity)

- Beam **power spectrum is modulated with cos² function**
- Lines in the spectrum **can only be weakened by the modulation**

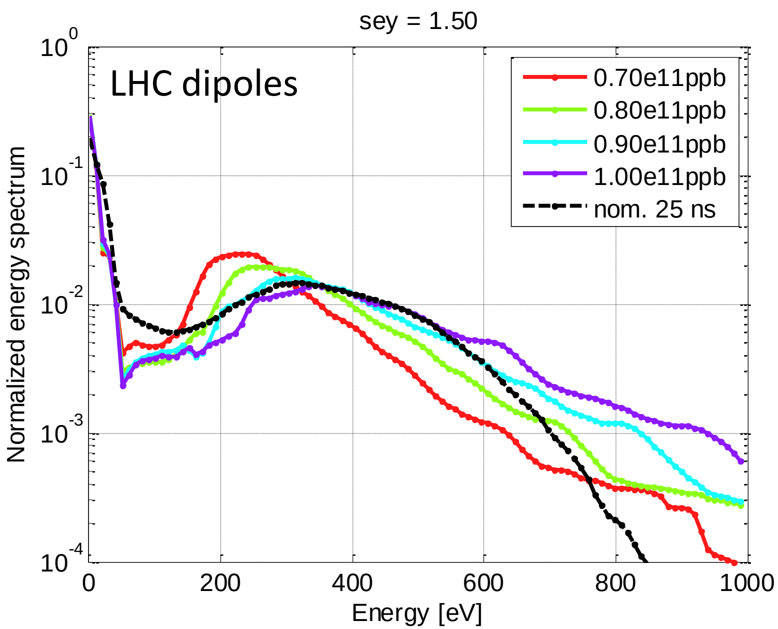
$$\Delta W = \frac{e\omega_0 N_d^2}{2\pi} \sum_{p=-\infty}^{\infty} |\Lambda(p\omega_0)|^2 \cos^2\left(\frac{p\omega_0 \tau_d}{2}\right) \mathrm{Re}\left[Z_{||}(p\omega_0)\right]$$

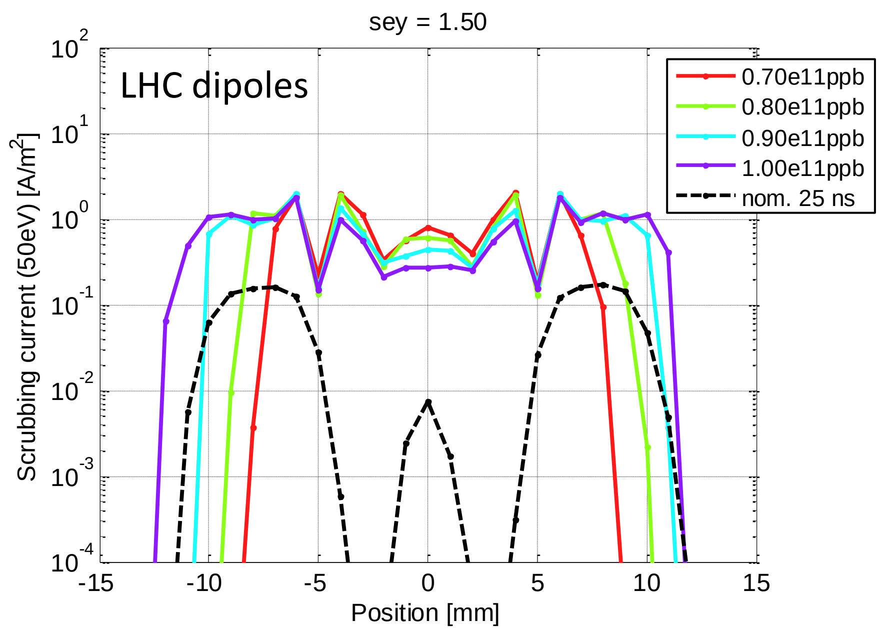


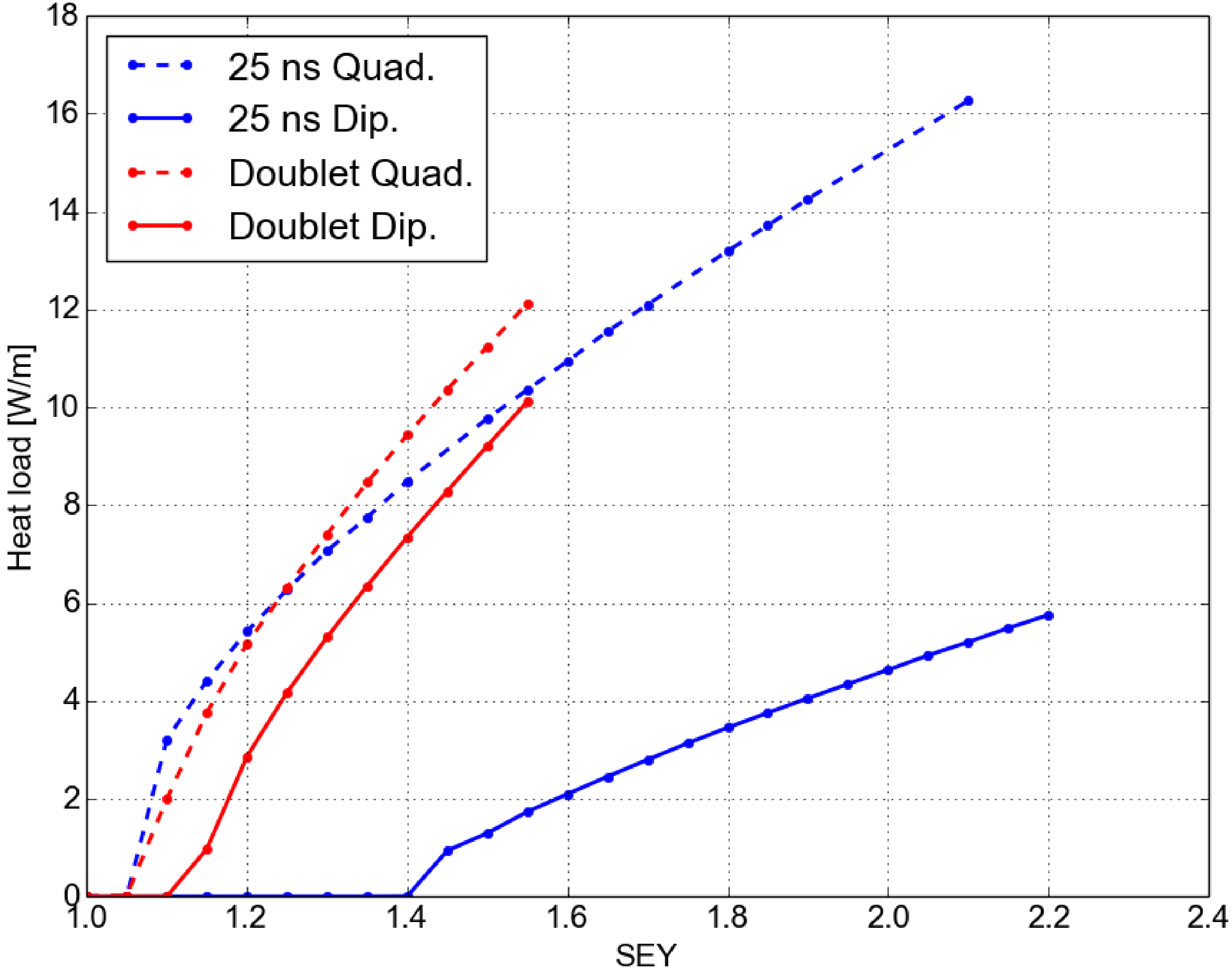
Thanks to **C. Zannini**

PyECLOUD simulations – 5 ns doublets

- The 5 ns doublet beam shows a much lower multipacting threshold compared to the standard 25 ns beam
- Efficient scrubbing with the doublet beam expected from e⁻ energy spectrum for a wide range of intensities
- Intensity larger than 0.8×10^{11} p/b preferable for covering similar horizontal region as the standard 25 ns beam with nominal intensity







25 ns Quad.
25 ns Dip.
Doublet Quad.
Doublet Dip.
Heat load [W/m]
SEY
0
2
4
6
8
10
12
14
16
18
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4

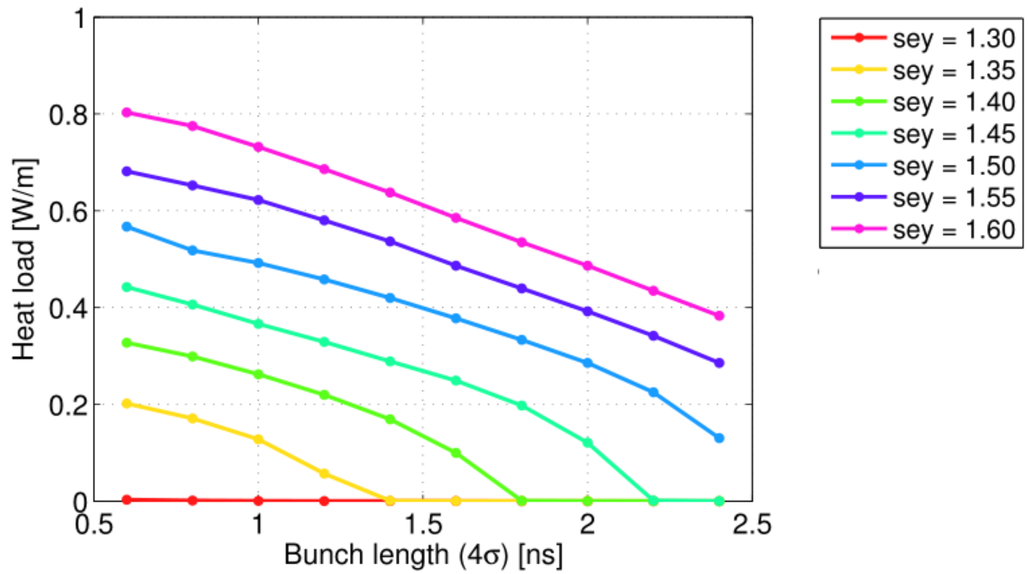


Figure 4.19: EC induced heat load as a function of the bunch length, for the LHC arc dipole magnets. Simulations for injection energy, 25 ns bunch spacing, different bunch intensities. No beam dependent seeding, uniform train of 640 bunches.

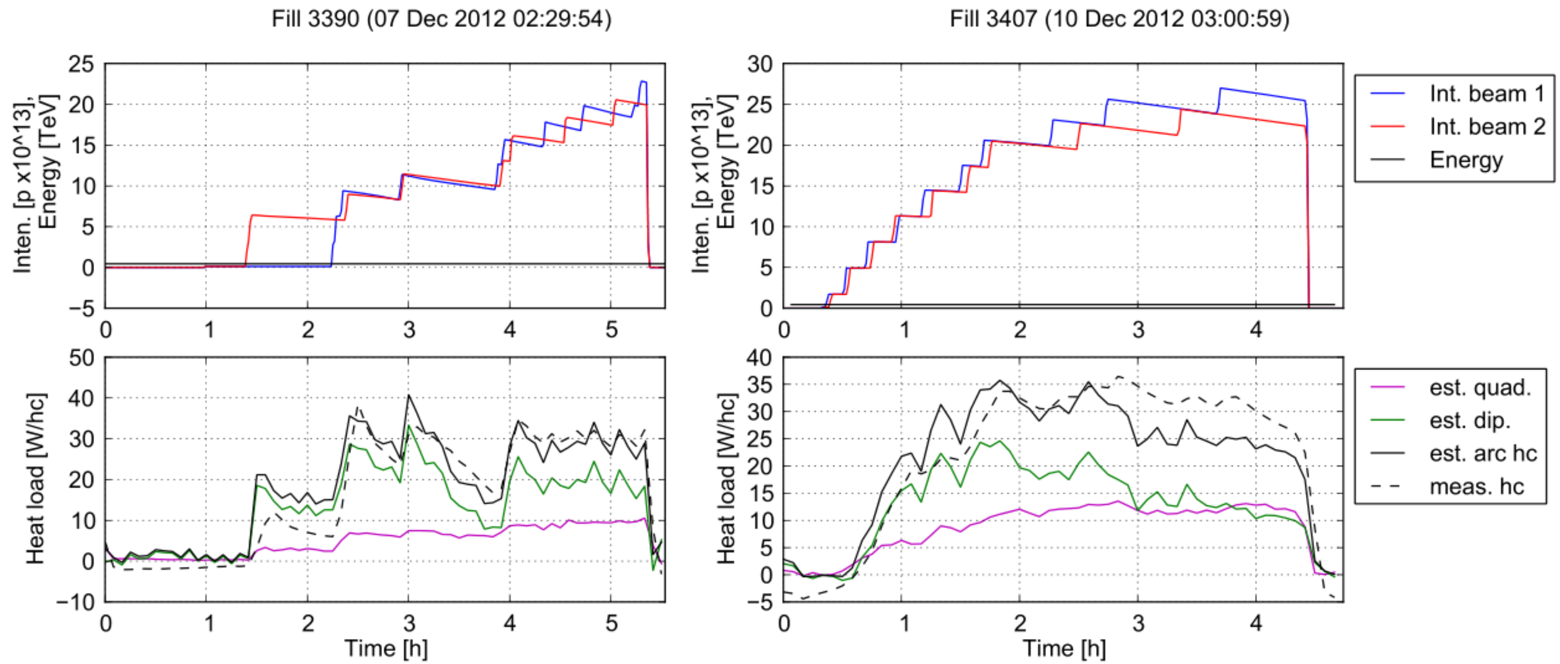


Figure 5.30: Curves in Fig. 5.29 rescaled to the lengths of the magnets in a regular LHC arc half-cell (purple and green), their sum (black continuous) and measured heat loads in the LHC arcs (black dashed).