Electron cloud and scrubbing

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

5th Evian Workshop, 2-4 June 2014, Evian, 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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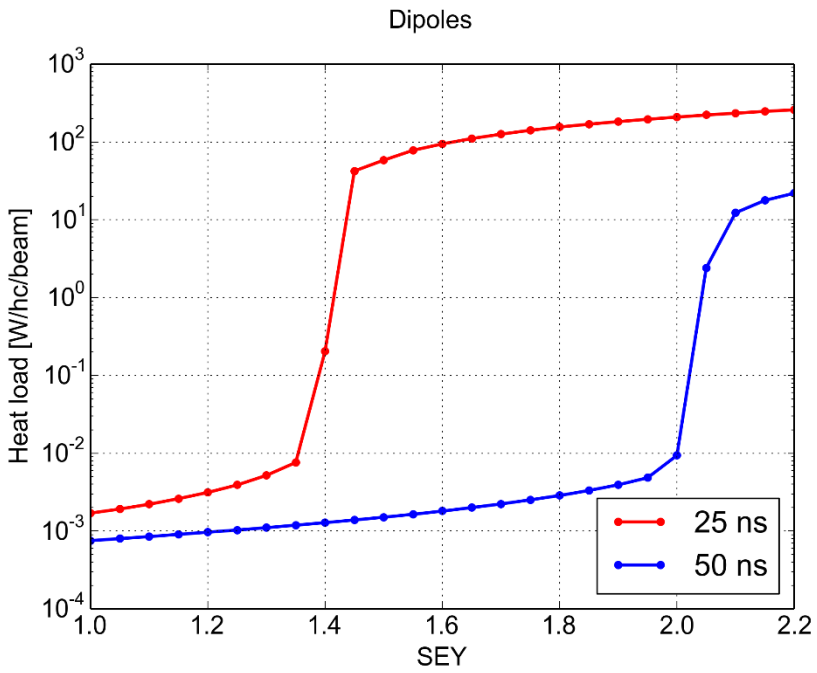
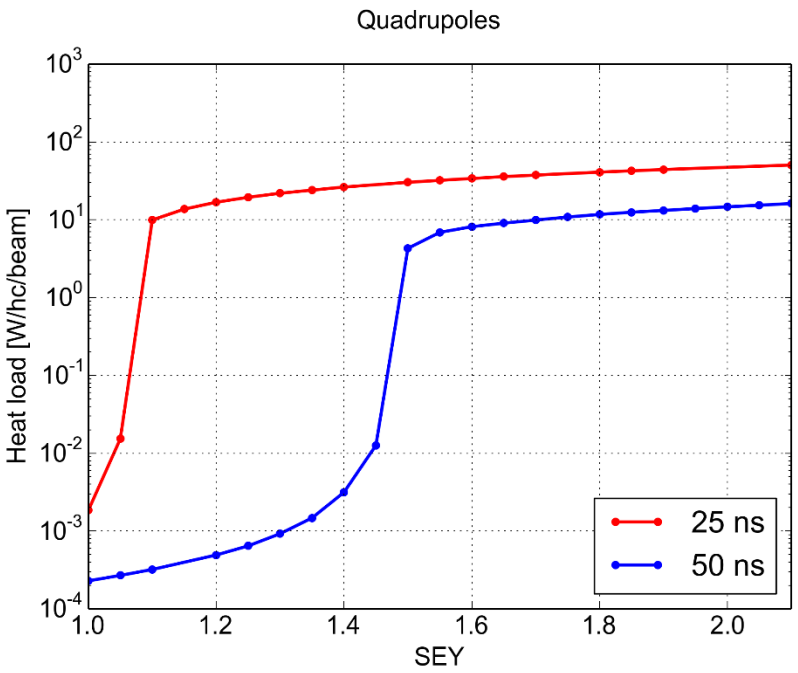
Run 1 experience: 50 ns vs 25 ns

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

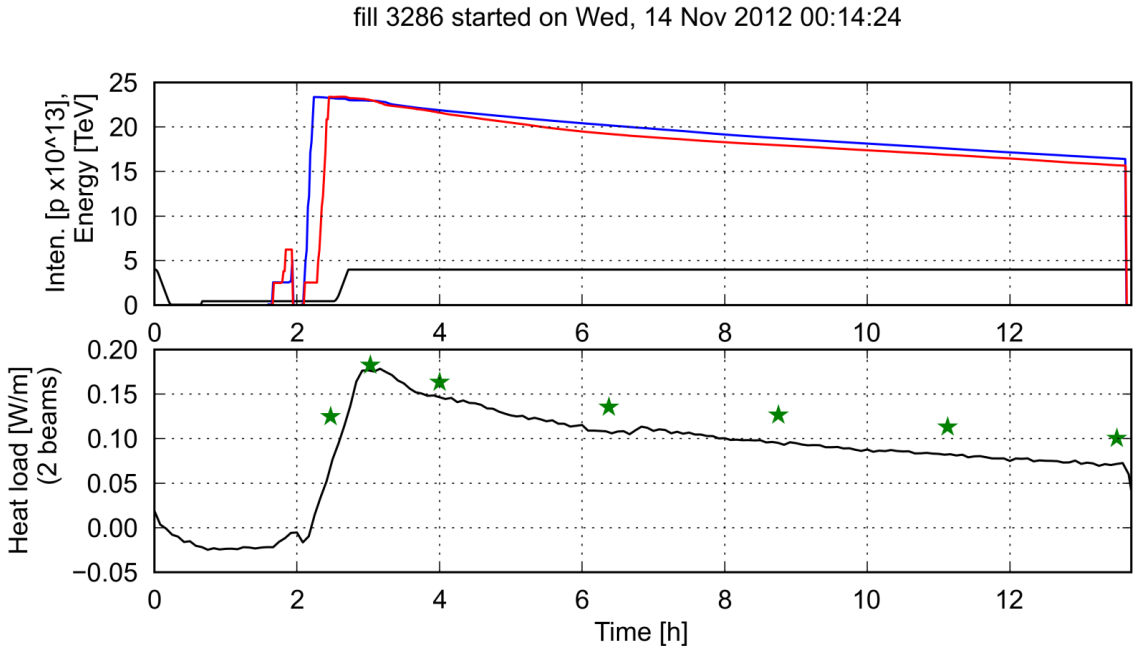
With **50 ns beams** we could have a practically **"e-cloud free" operation in 2012**, thanks to the scrubbing accumulated in 2011 in **4 days of scrubbing** with 50 ns beams + **2 days** of tests with 25 ns beams

Run 1 experience: 50 ns vs 25 ns

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

In 2012 **heat load measurements** on arc beam screens arcs confirm the **absence of any strong EC activity with 50 ns beams**

ns beams **looks unlikely** (also

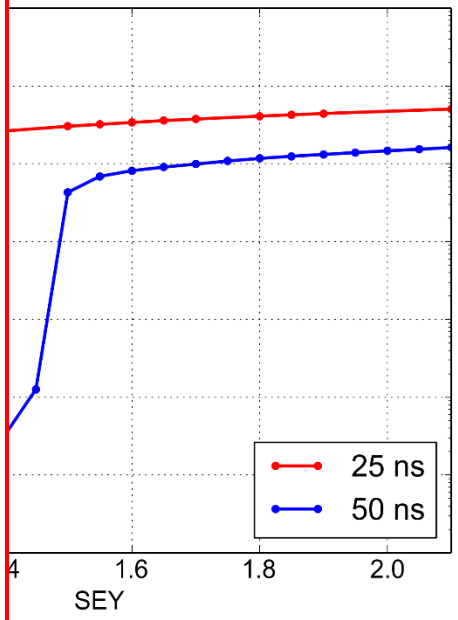


Heat load measurement from cryogenics

★ Estimation (impedance + synchrotron rad.)

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

Quadrupoles



, thanks to the scrubbing

with 25 ns beams

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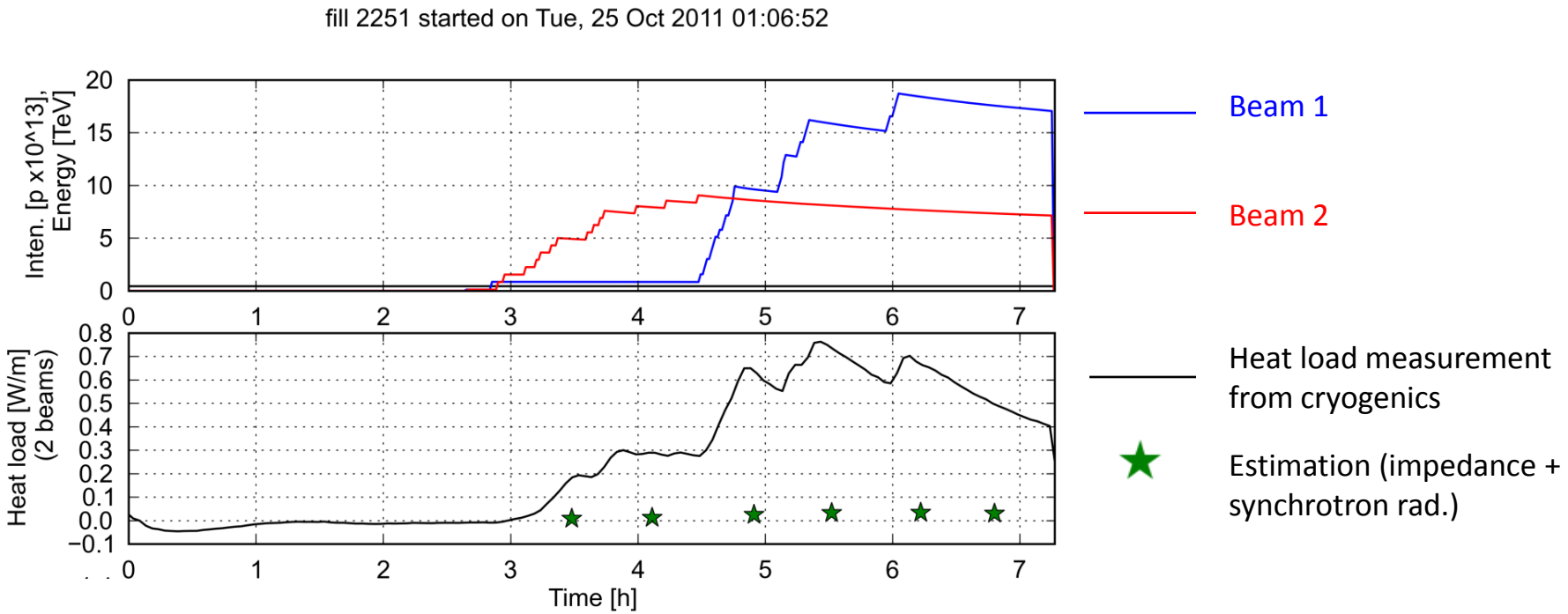
2011 experience with 25 ns beams: scrubbing tests

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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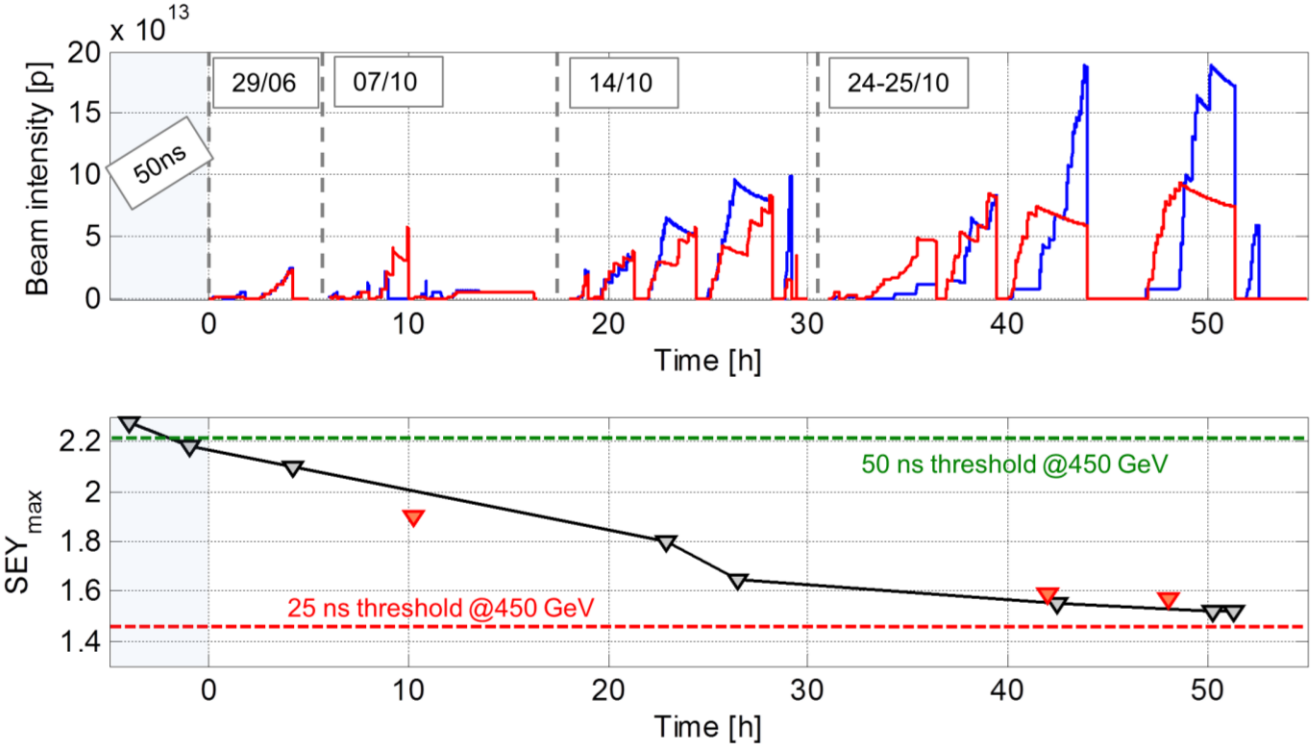

Reconstruction based on measured **beam parameteres, heat load meas. and PyECLOUD sims.**

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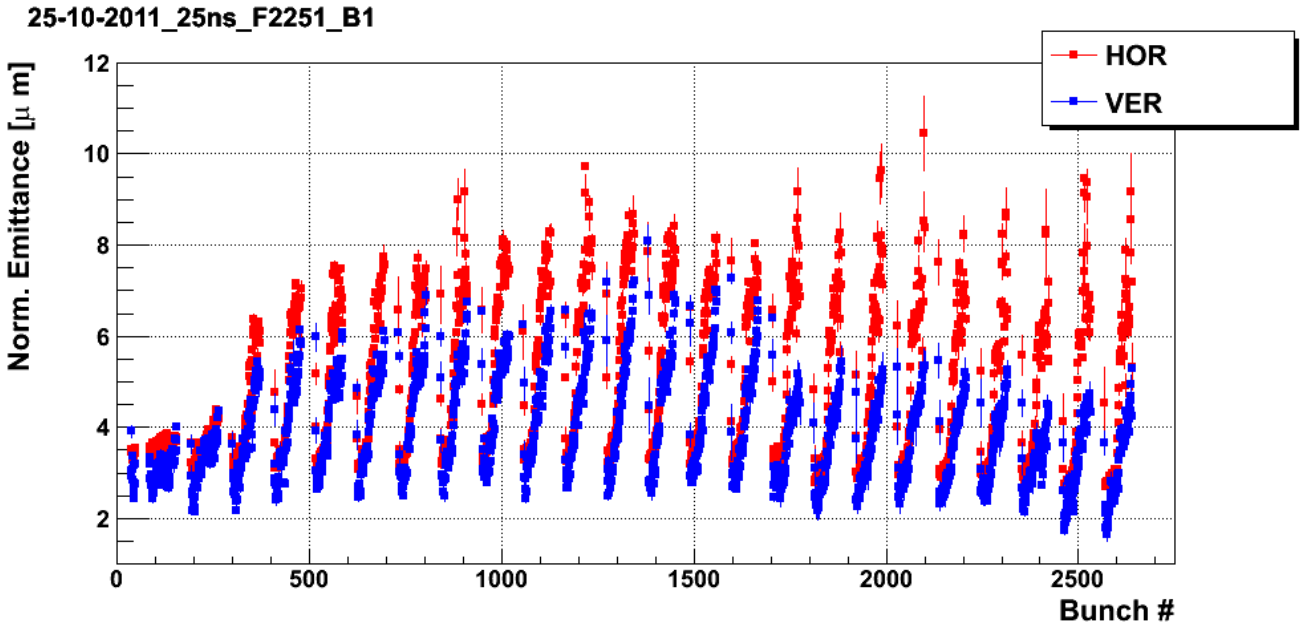
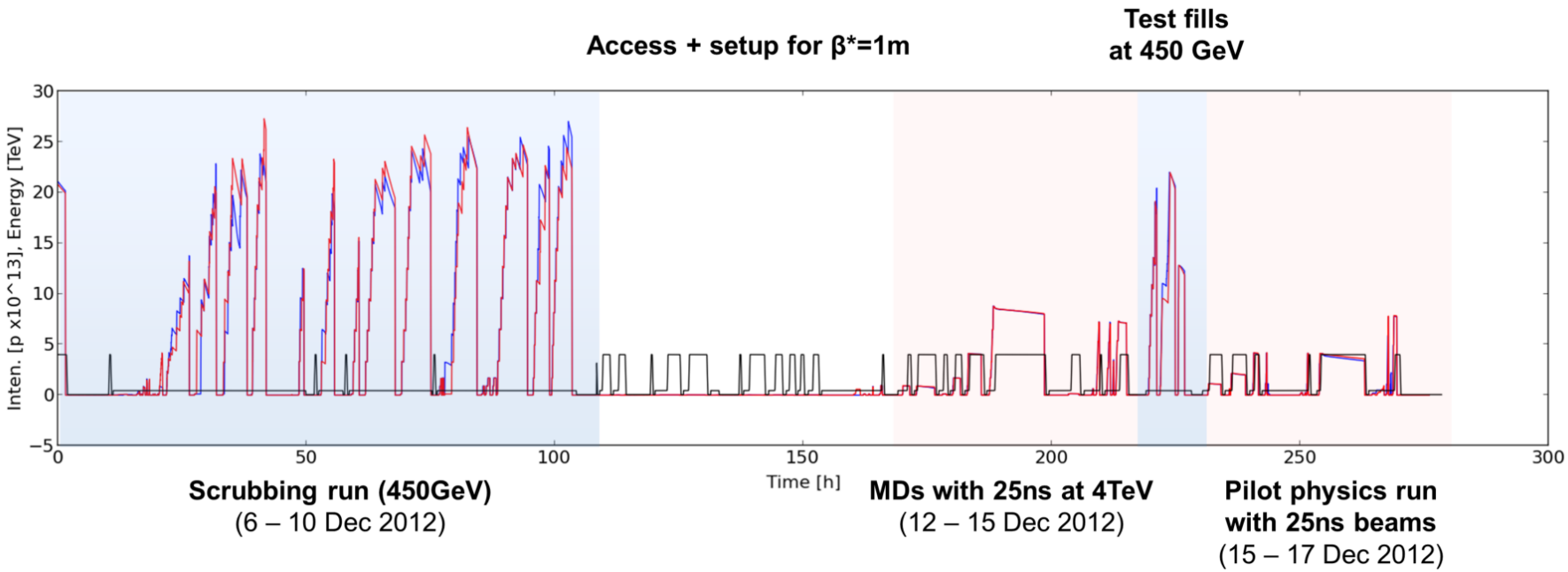
- **SEY in arc dipoles** could be lowered to ~1.5
- **Beam degradation still important** at the end of the scrubbing tests



Thanks to **F. Roncarolo**

The “25 ns run” in 2012

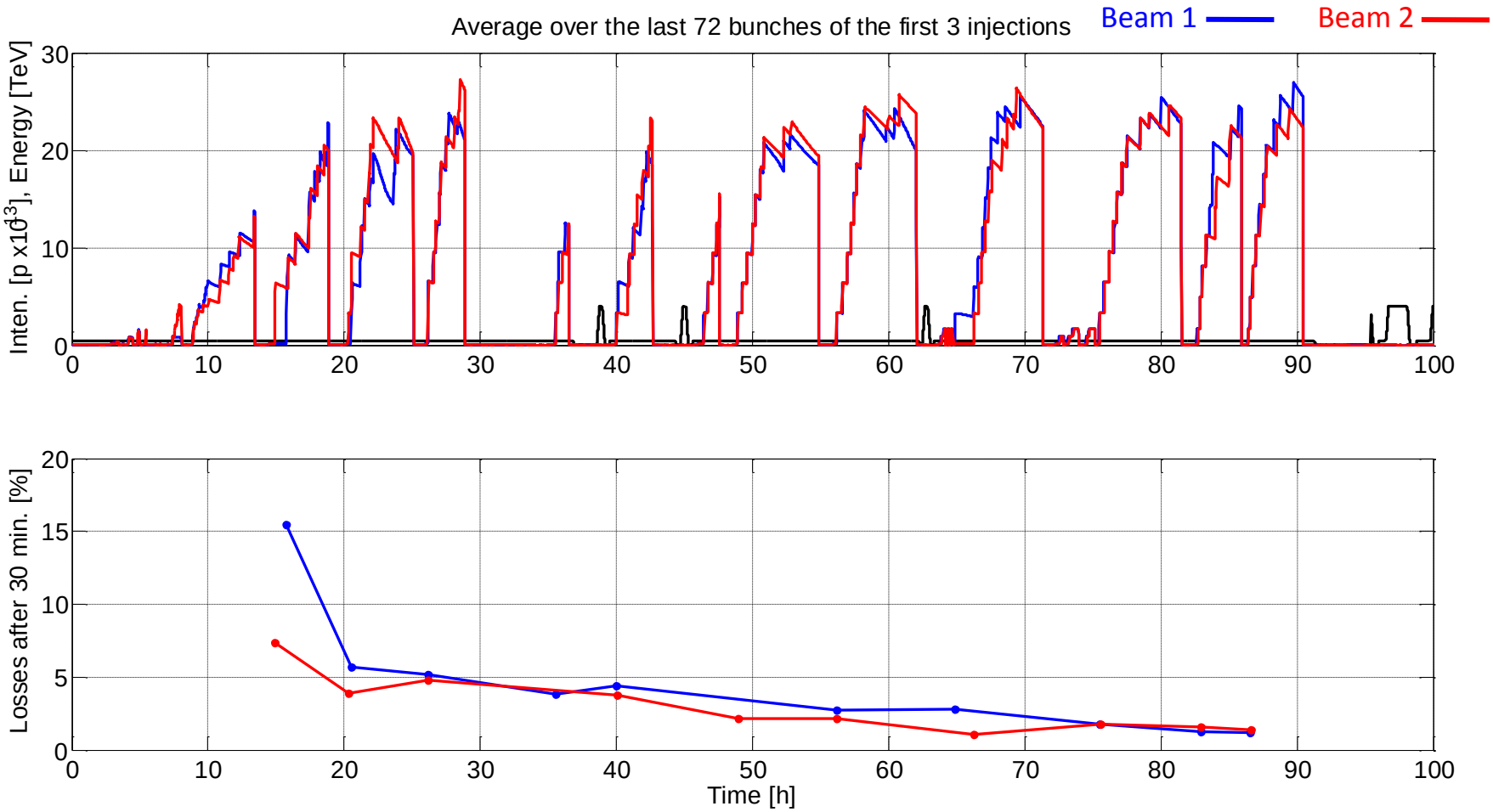
All experiments with 25 ns beams with large number of bunches were **concentrated in the last two weeks of the run**



The 2012 scrubbing 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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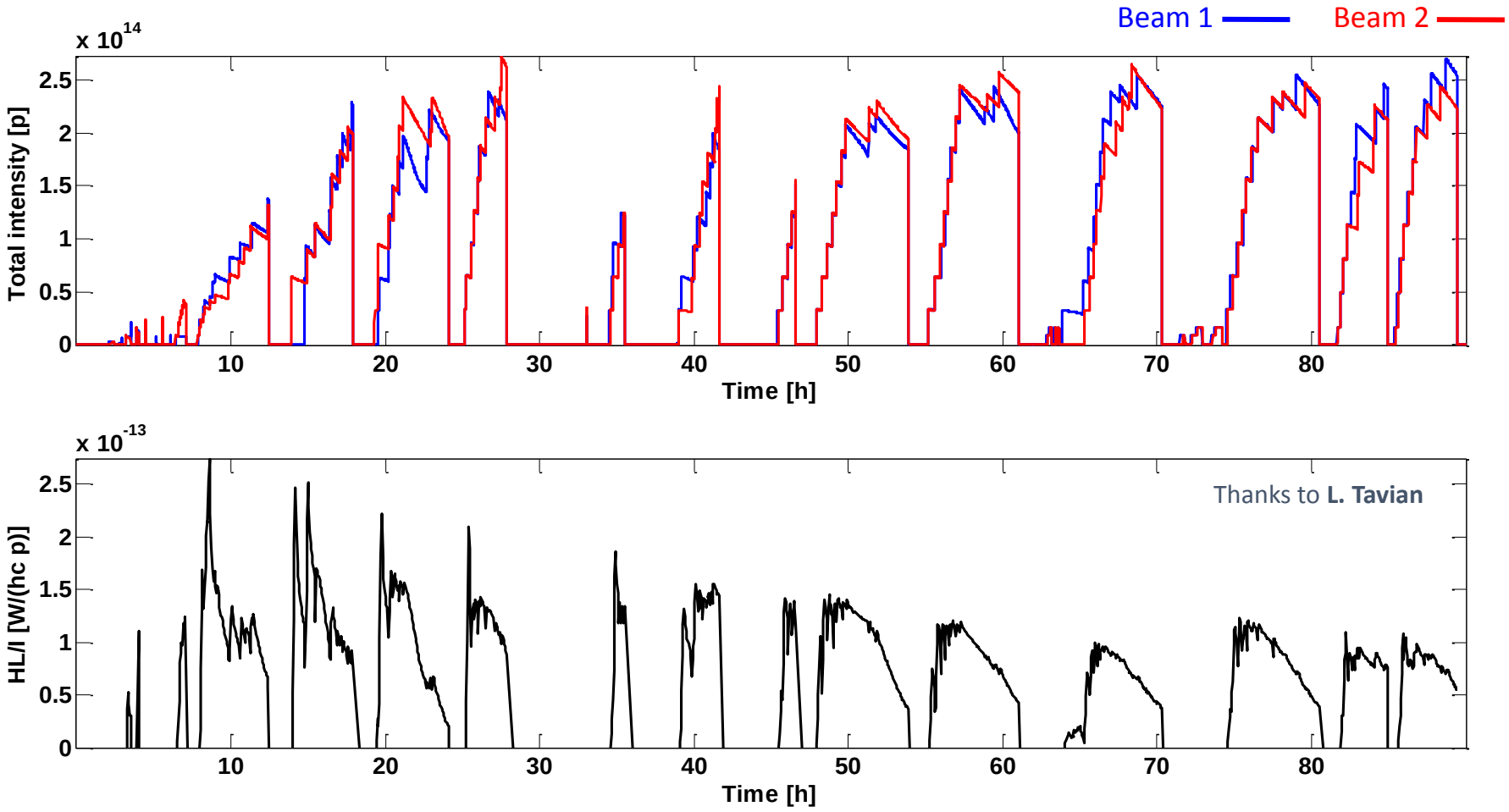

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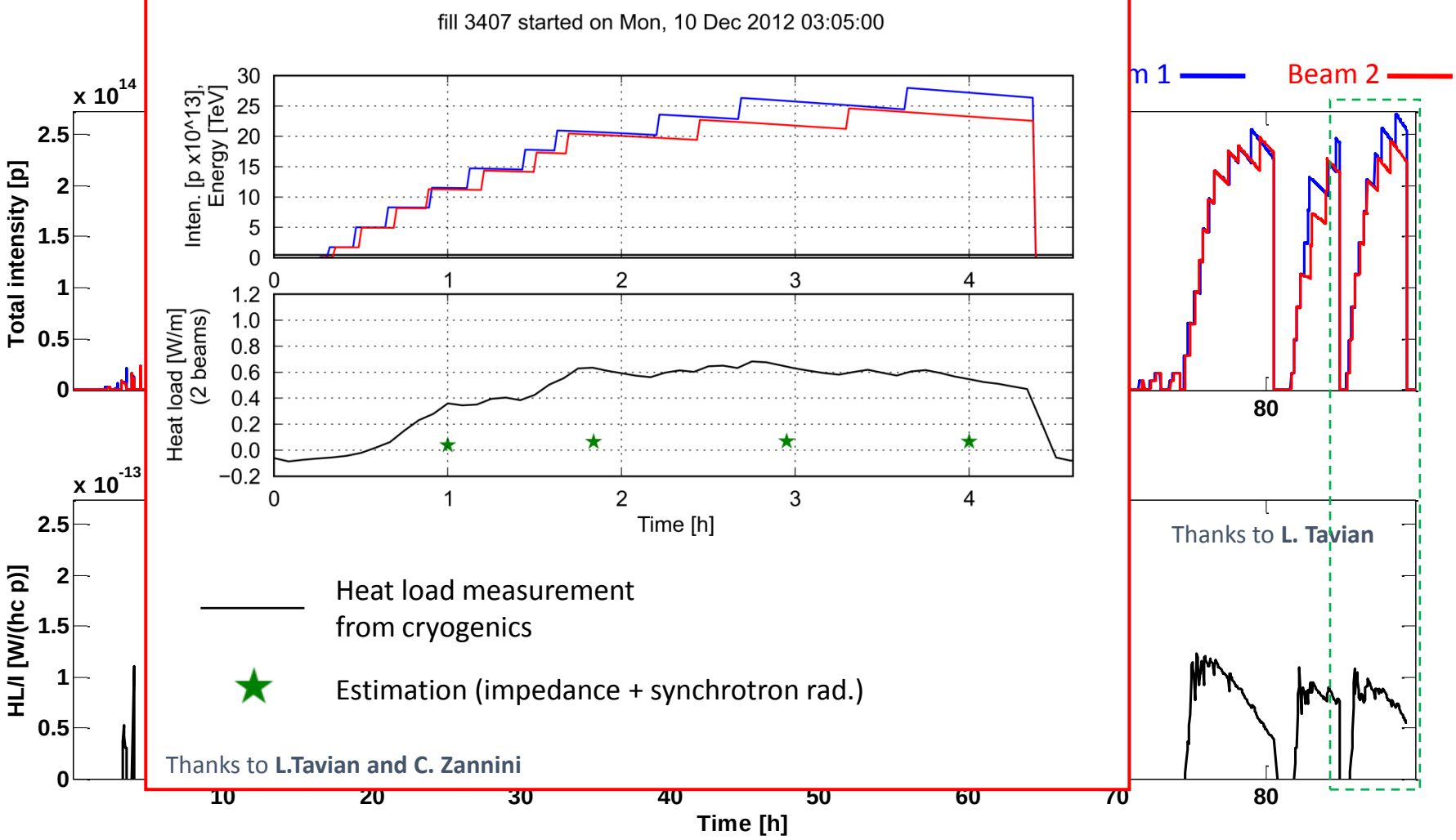
2.7x10^{14} p)

the arcs

e-cloud still there during the last fill



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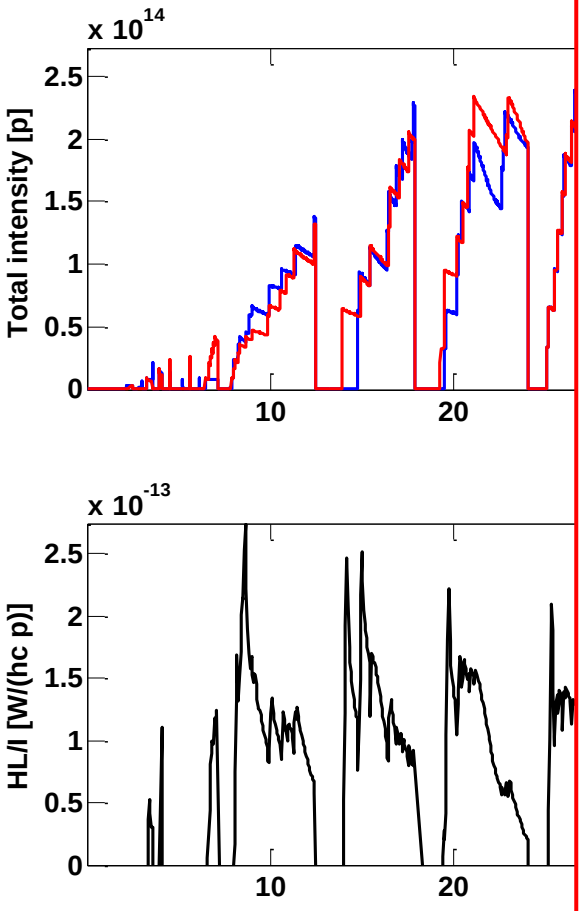
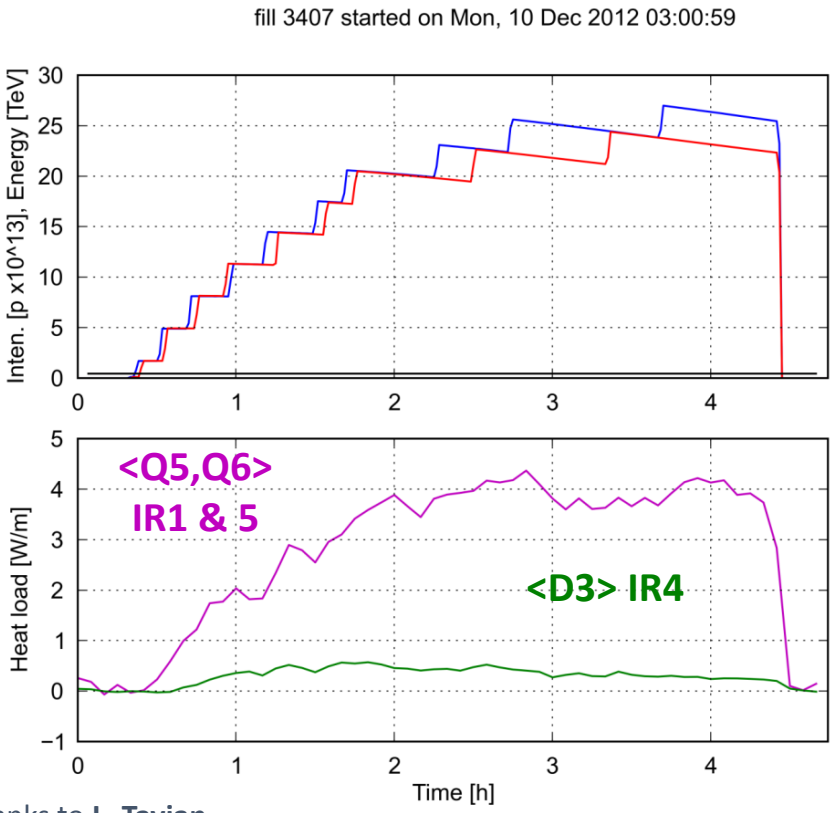
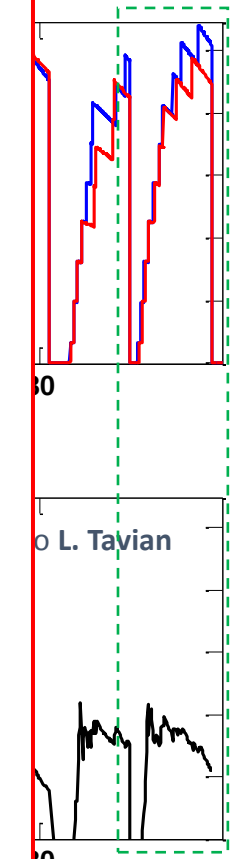


Heat load measurements on SAMs confirmed e-cloud **much stronger in quadrupoles** than in dipoles



Thanks to **L. Tavian**

Beam 2



o **L. Tavian**

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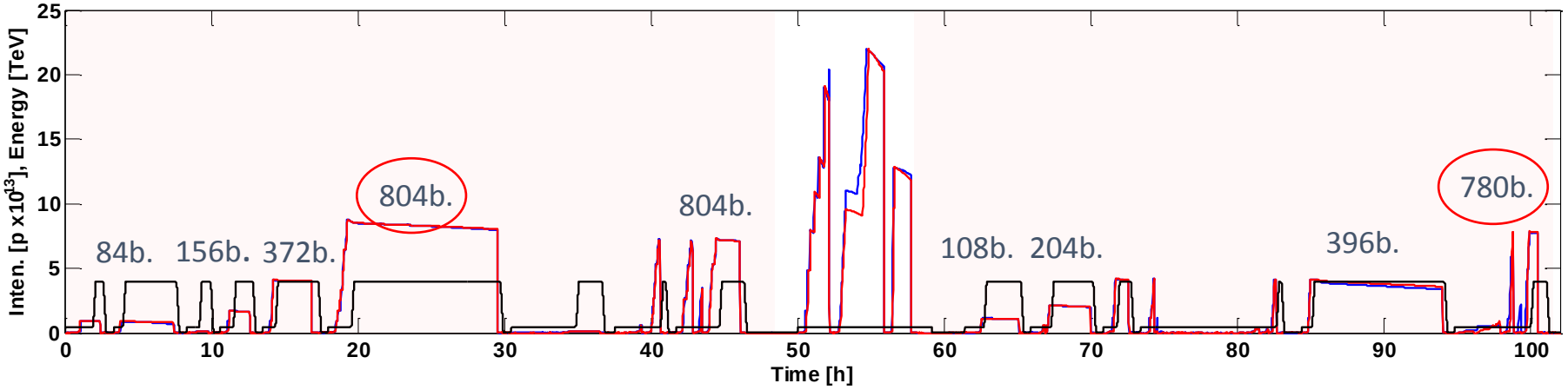
Experience with 25 ns beams at 4 TeV

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

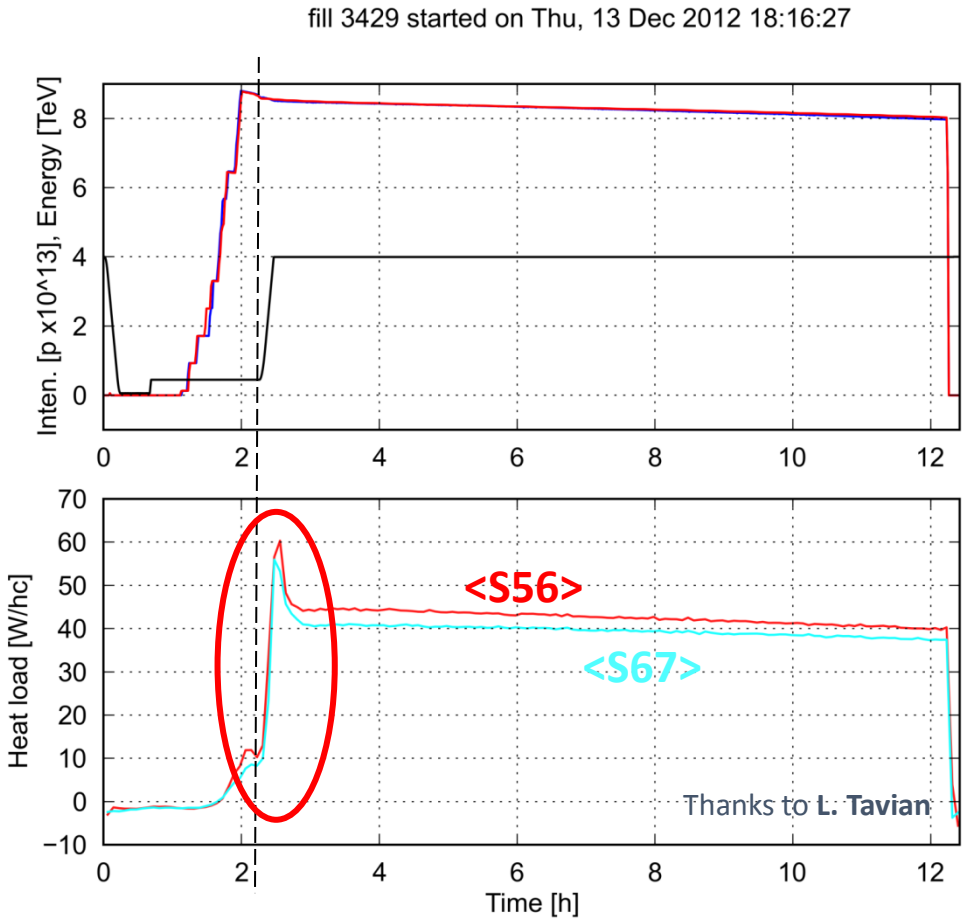


Machine Studies with 25 ns beams at 4TeV
(12 – 15 Dec 2012)

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

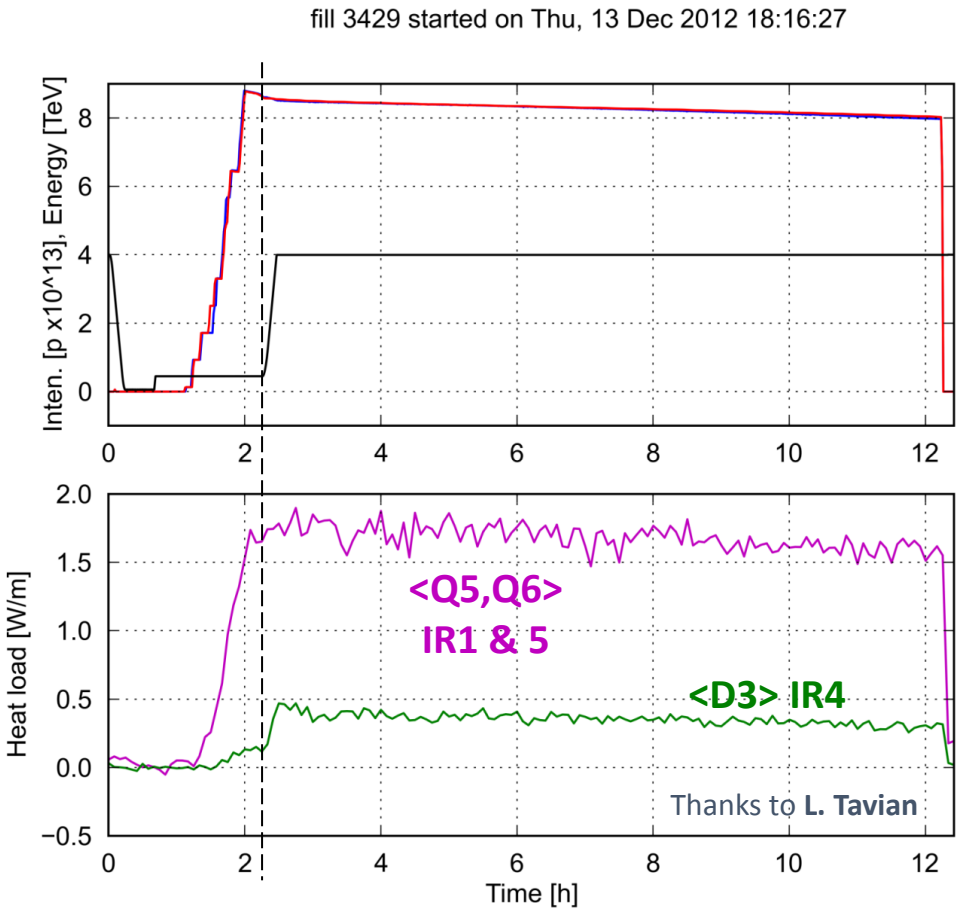
Heat load evolution during the ramp

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



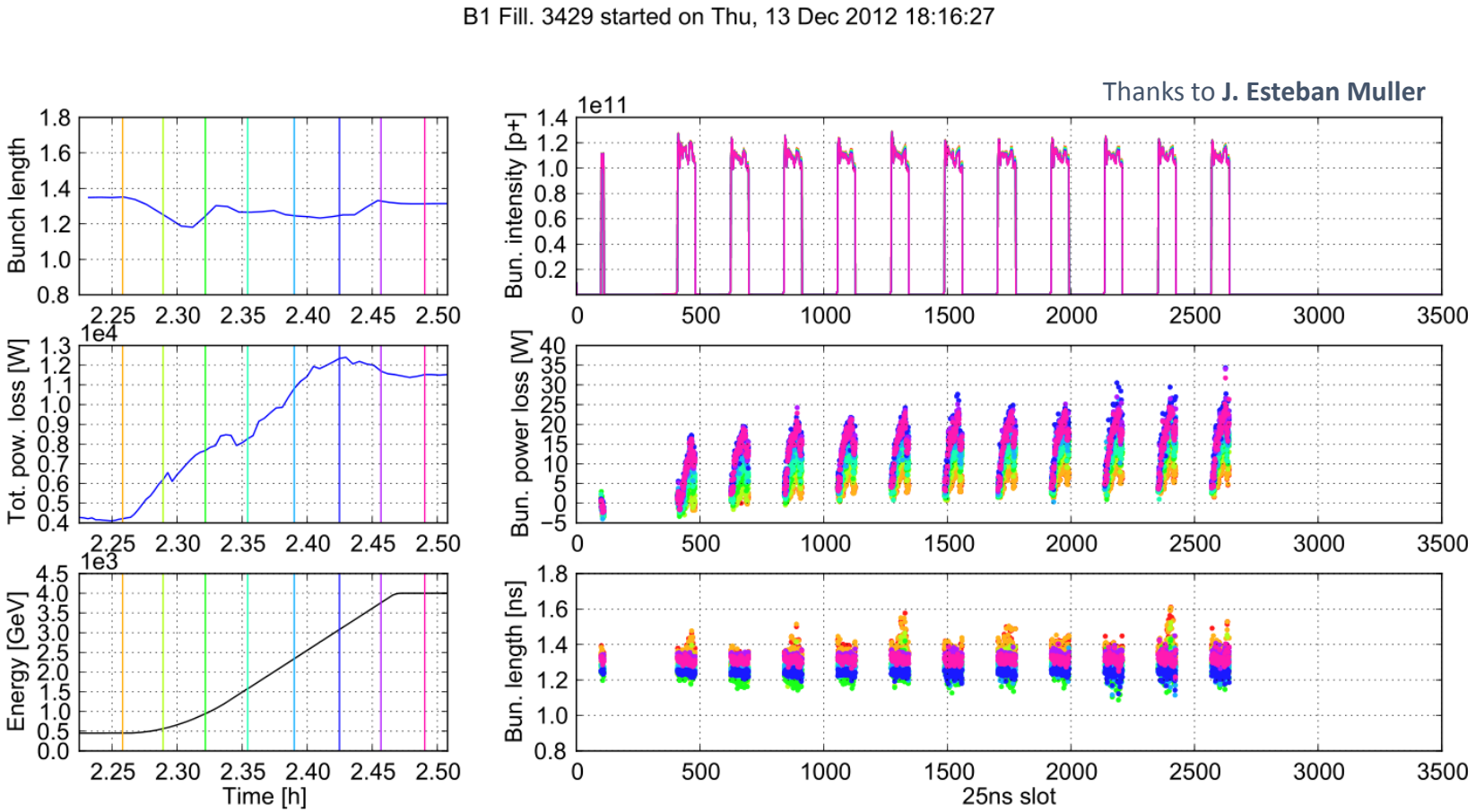
Heat load evolution during the ramp

- 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

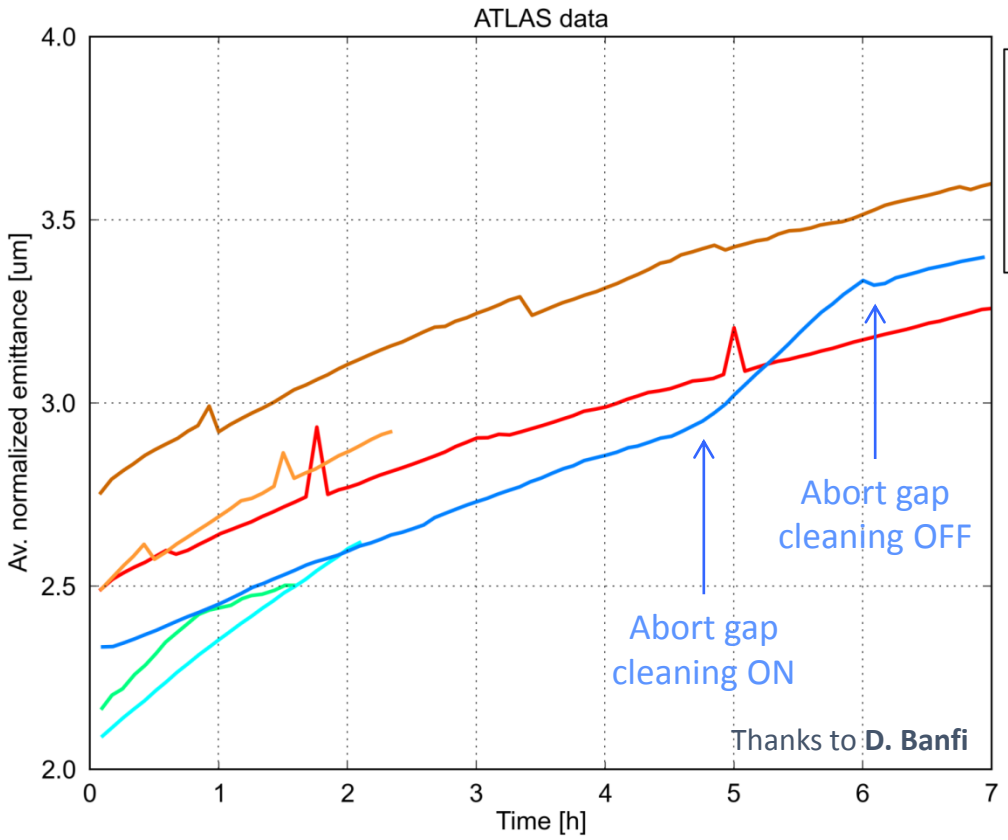
- A **strong enhancement on the heat load** is observed on the **energy ramp**
- SAMs show heat load **increase with energy in the dipoles but not in the quadrupoles**
- **Increase almost uniform along the ramp** → not only photoelectrons



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**



Fill 2736, 50 ns, 1374 b.
Fill 3000, 50 ns, 1374 b.
Fill 3286, 50 ns, 1374 b.
Fill 3441, 25 ns, 108 b.
Fill 3442, 25 ns, 204 b.
Fill 3453, 25 ns, 396 b.

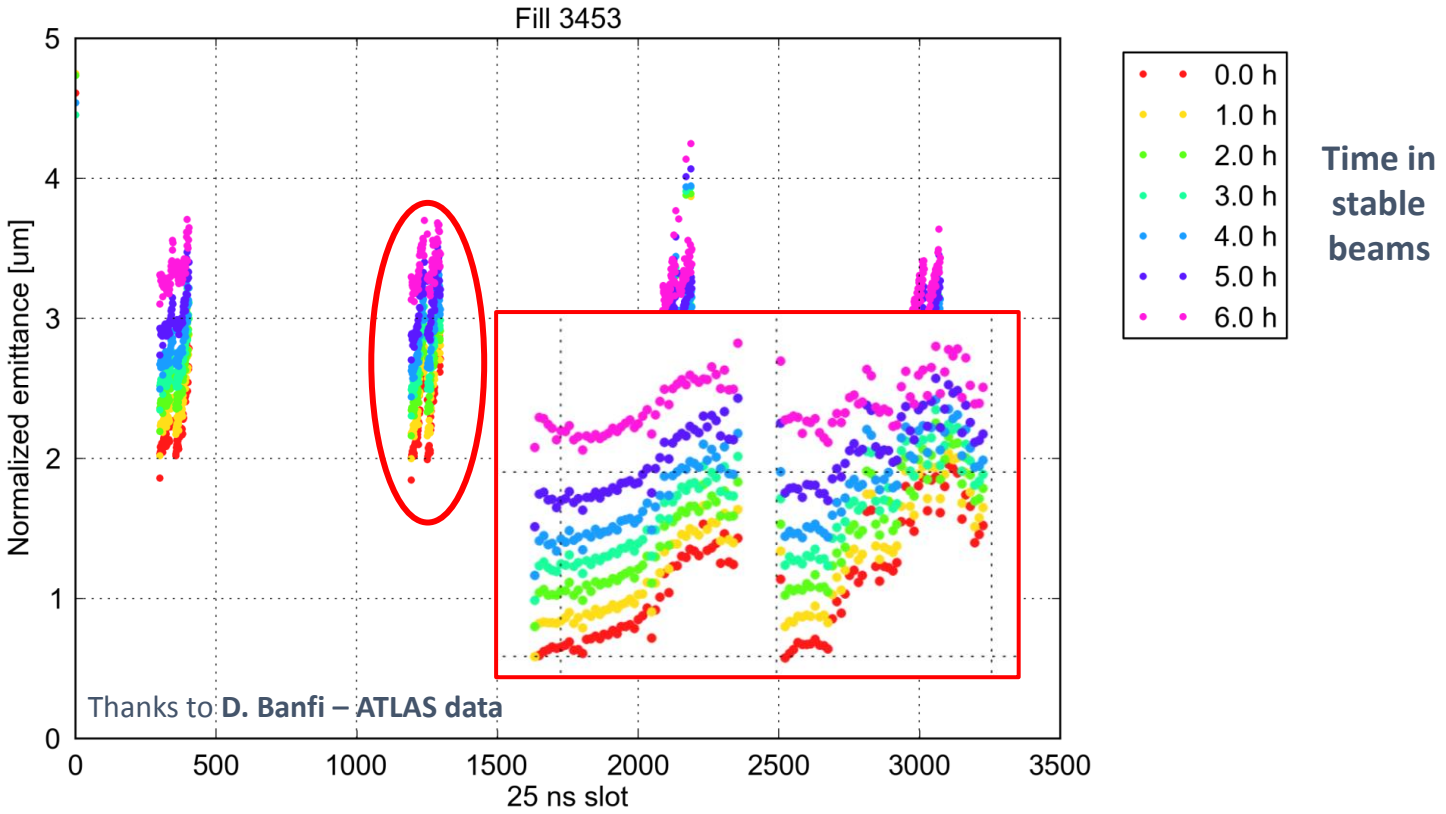
50 ns
1.45 – 1.6 x 10^{11} ppb

25 ns
1.0 – 1.1 x 10^{11} ppb

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)



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

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	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

→ **To cope with nominal number of bunches more scrubbing is mandatory**

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

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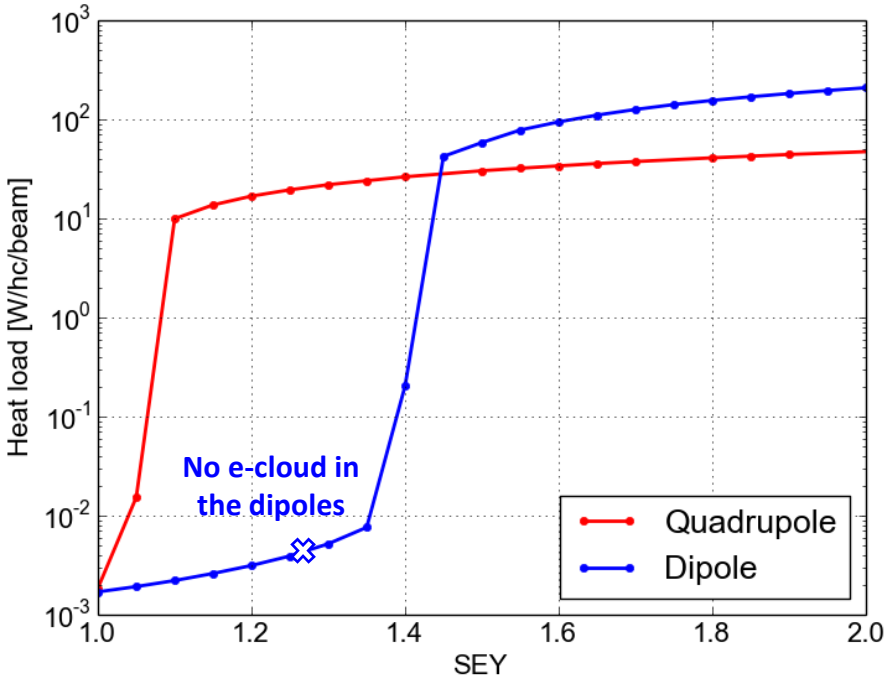
Scrubbing goals for 2015

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 mandatory**

→ 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

During LS1 several actions have been undertaken to **improve the effectiveness of scrubbing** and **gain more information on e-cloud** in LHC:

Cryogenics:

- → **SAM cooling capacity** (limiting scrubbing efficiency in 2012) increased by about x2
- → **Cooling capacity for Sector 34** restored to nominal (it was half in 2012)
- → **3 half cells in Sector 45 equipped with extra thermometers** for magnet-by-magnet heat load measurements

For details: S. Claudet and L. Tavian, at LBOC 08/10/2013

Vacuum:

- → **High sensitivity vacuum gauges** installed in the Sector 45 half cells equipped with thermometers
- → **Vacuum Pilot Sectors (Q5L8-Q4L8)** to be equipped with gauges and e-cloud detectors to study behavior of NEG coated vs unbaked Cu beam pipe

For details: V. Baglin, at LBOC 24/03/2014

Post-LS1 improvements

During LS1 several actions have been undertaken to **improve the effectiveness of scrubbing** and **gain more information on e-cloud** in LHC:

Injection kickers:

- → New design of beam screen, at capacitively coupled end, allows **24 screen conductors** → less beam induced heating
- → **NEG coated by-pass tubes**, and NEG cartridge added at interconnects → improved vacuum

For details: M. Barnes et al., at LBOC 21/01/2014, V. Baglin, at LBOC 24/03/2014

TDIs:

(during the 2012 Scrubbing Run heating could be kept under control by retracting the TDI between injections)

- → **Reinforced beam screen** (Stainless Steel)
- → Al blocks will have **Ti flash to reduce SEY**
- → **Temperature probes** installed (will allow monitoring heating during scrubbing)
- → **Mechanics disassembled and serviced** (should minimize risk of alignment problems observed during 2012 scrubbing)

For details: J. Uythoven, Minutes from the LIBD meeting on 18 March 2014, Edms nb.1367271

Post-LS1 improvements

During LS1 several actions have been undertaken to **improve the effectiveness of scrubbing** and **gain more information on e-cloud** in LHC:

New software tools for on-line scrubbing monitoring and steering:

- → **Beam screen heat load** (being developed by BE-OP and TE-CRG)
- → **Bunch-by-bunch energy loss** from RF stable phase (being developed by BE-OP and BE-RF)

For details: S. Popescu, at LBOC 06/05/2014

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

- → Being followed up by the LBOC
- → See next slides…

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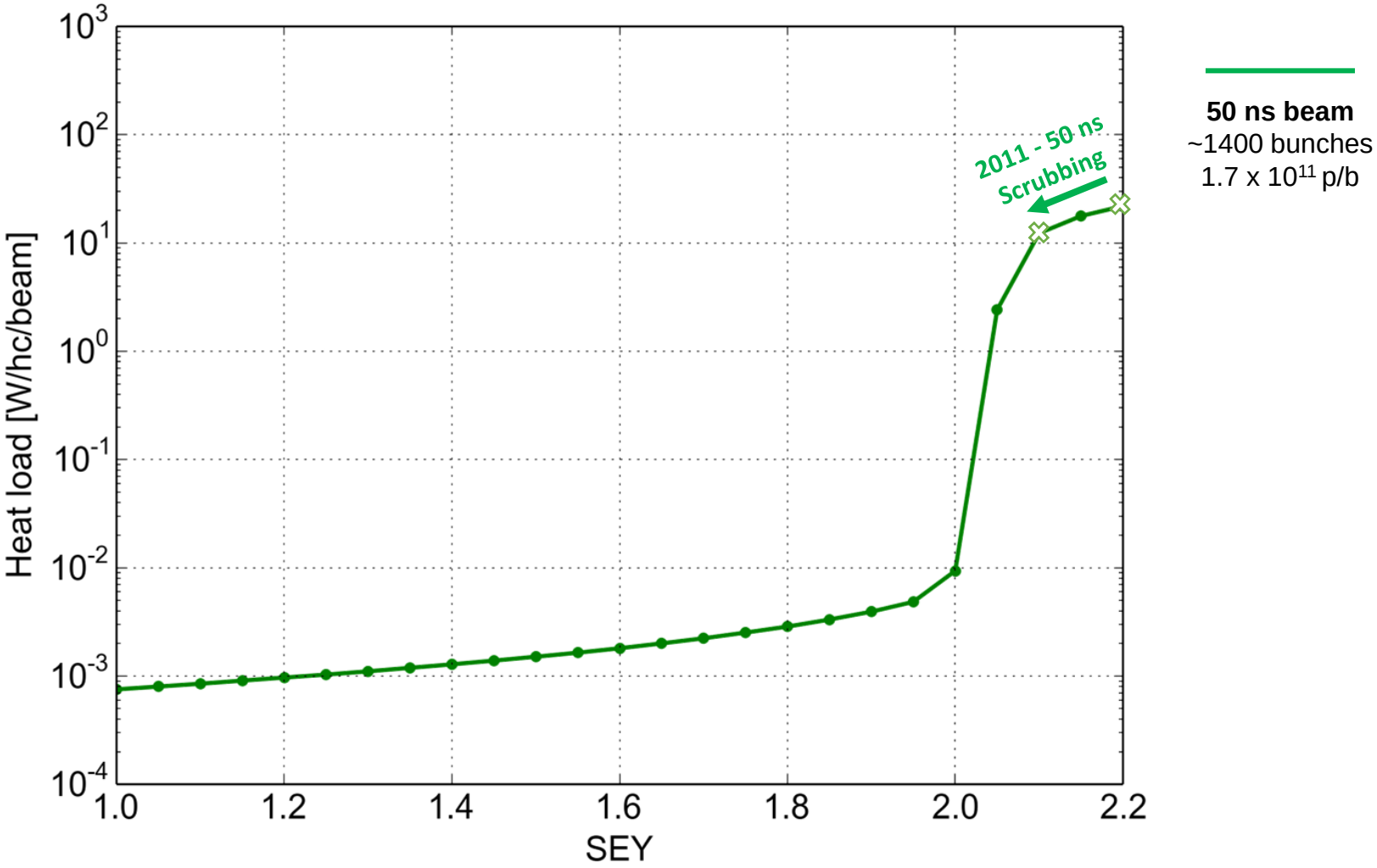
“Doublet” scrubbing beam: introduction

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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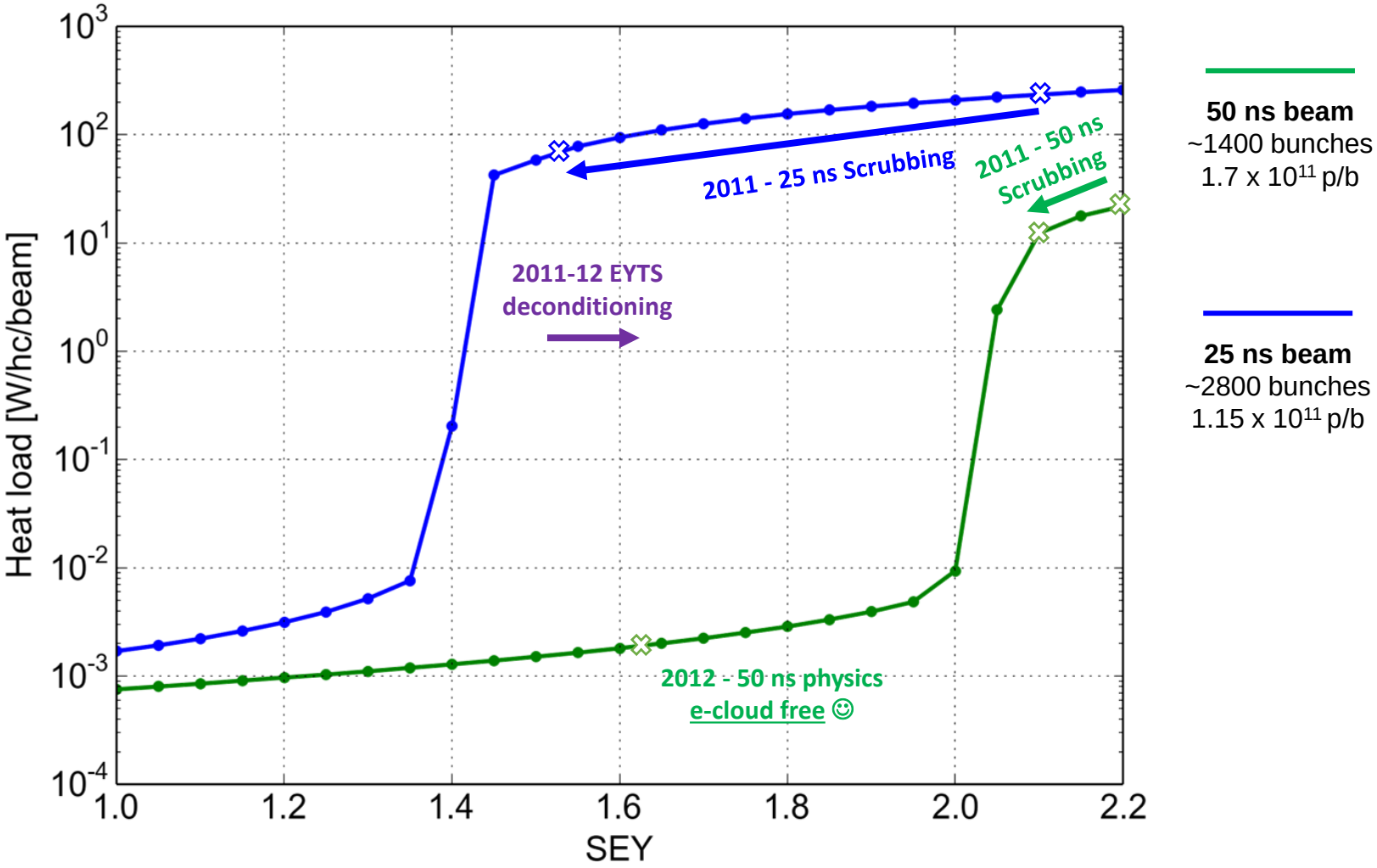

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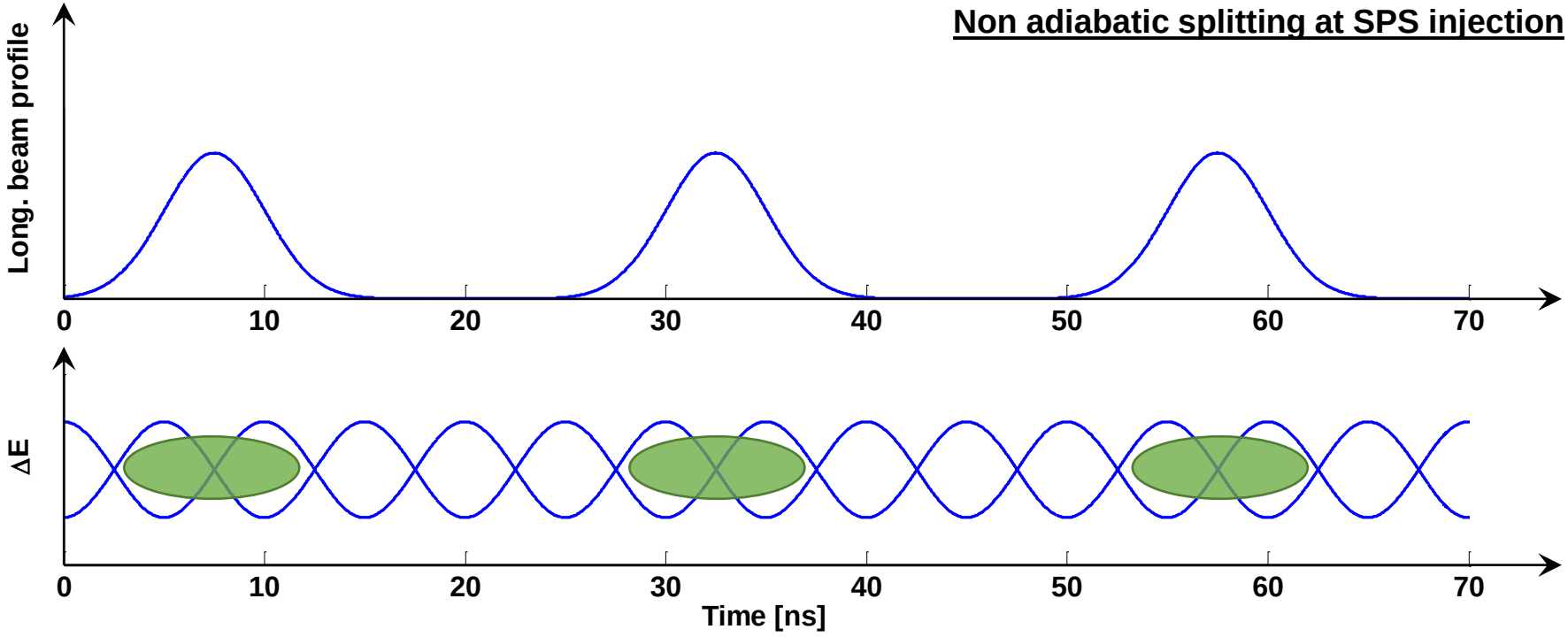
- Due to RF limitations in the PS it is **impossible to inject bunch-to-bucket into the SPS with spacing shorter than 25 ns**
- An alternative is to inject long bunches into the SPS and capturing each bunch in two neighboring buckets obtaining **a (5+20) ns “hybrid” spacing**



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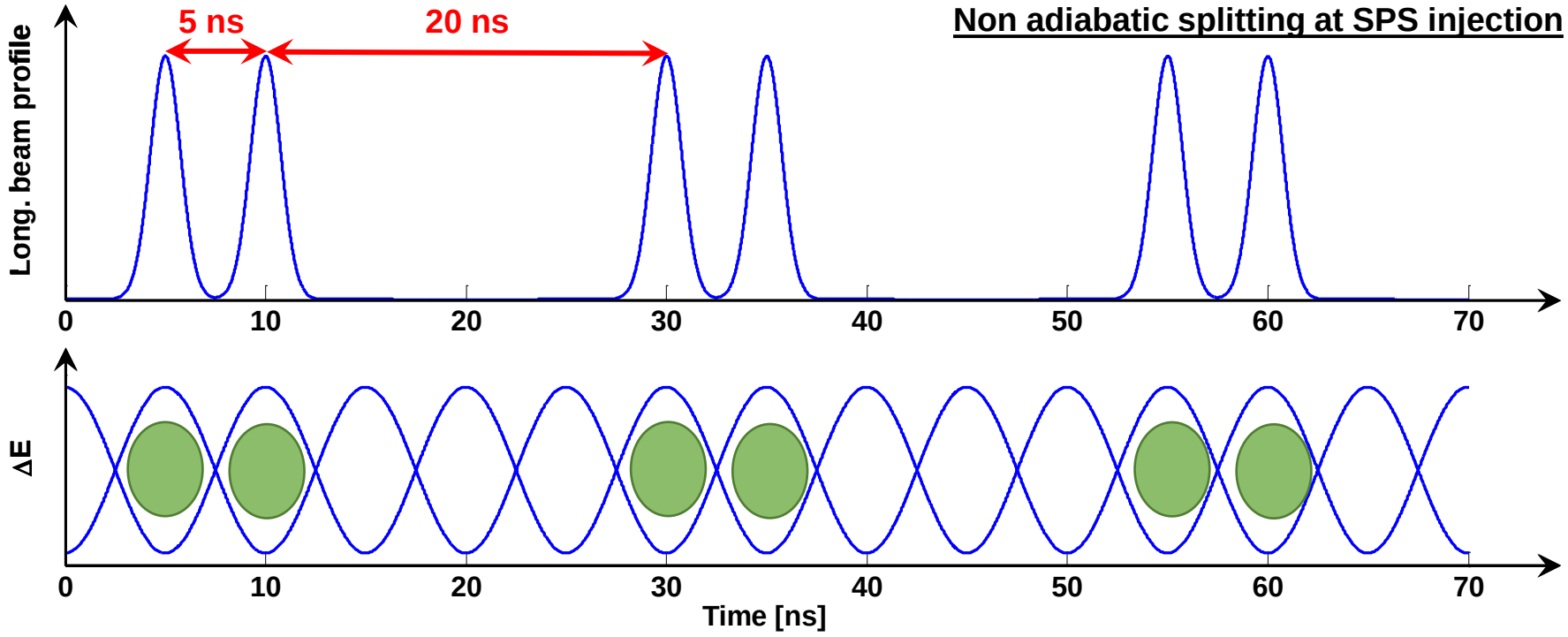
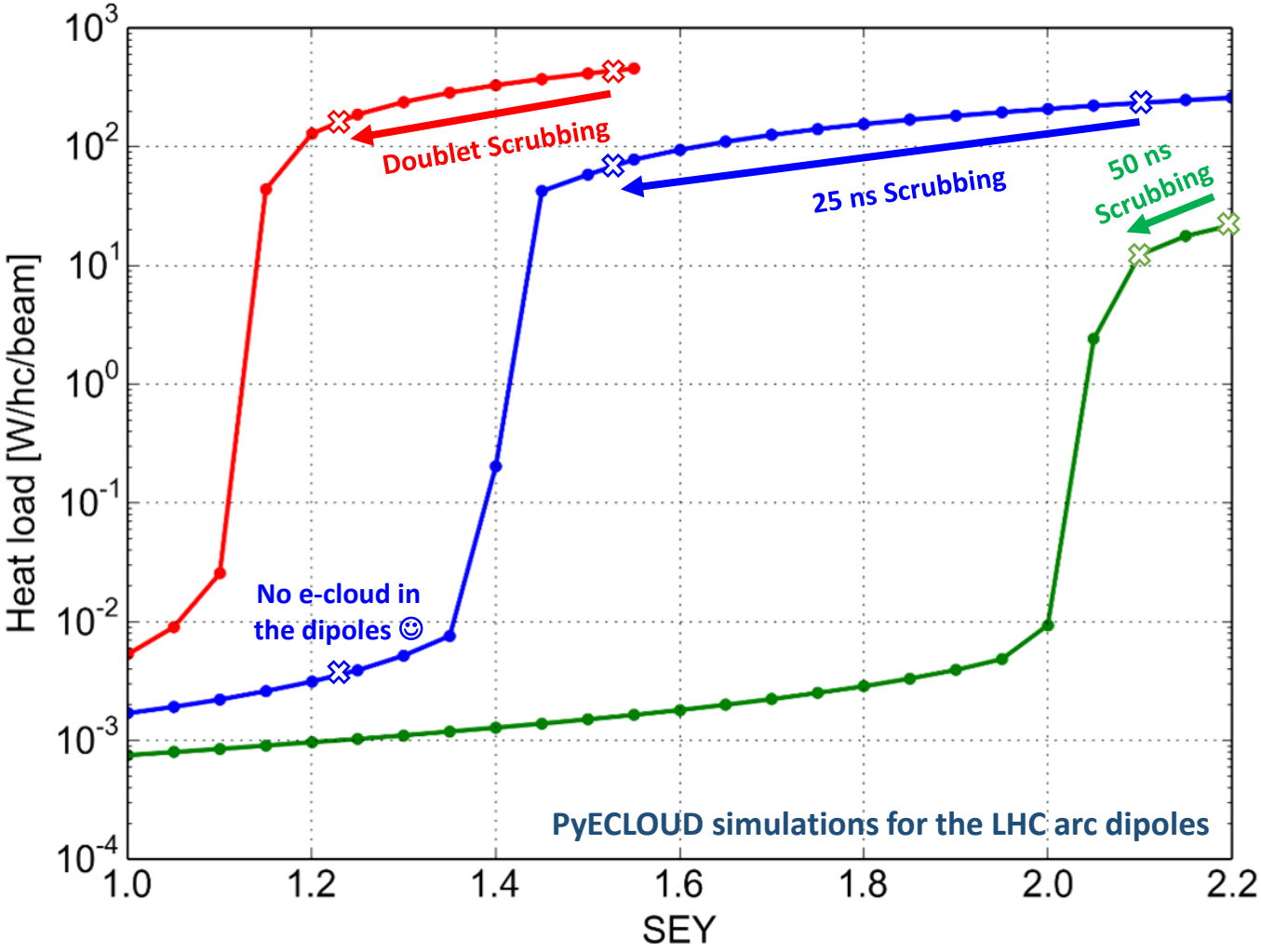


“Doublet” scrubbing beam: PyECLOUD simulation results

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



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

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

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

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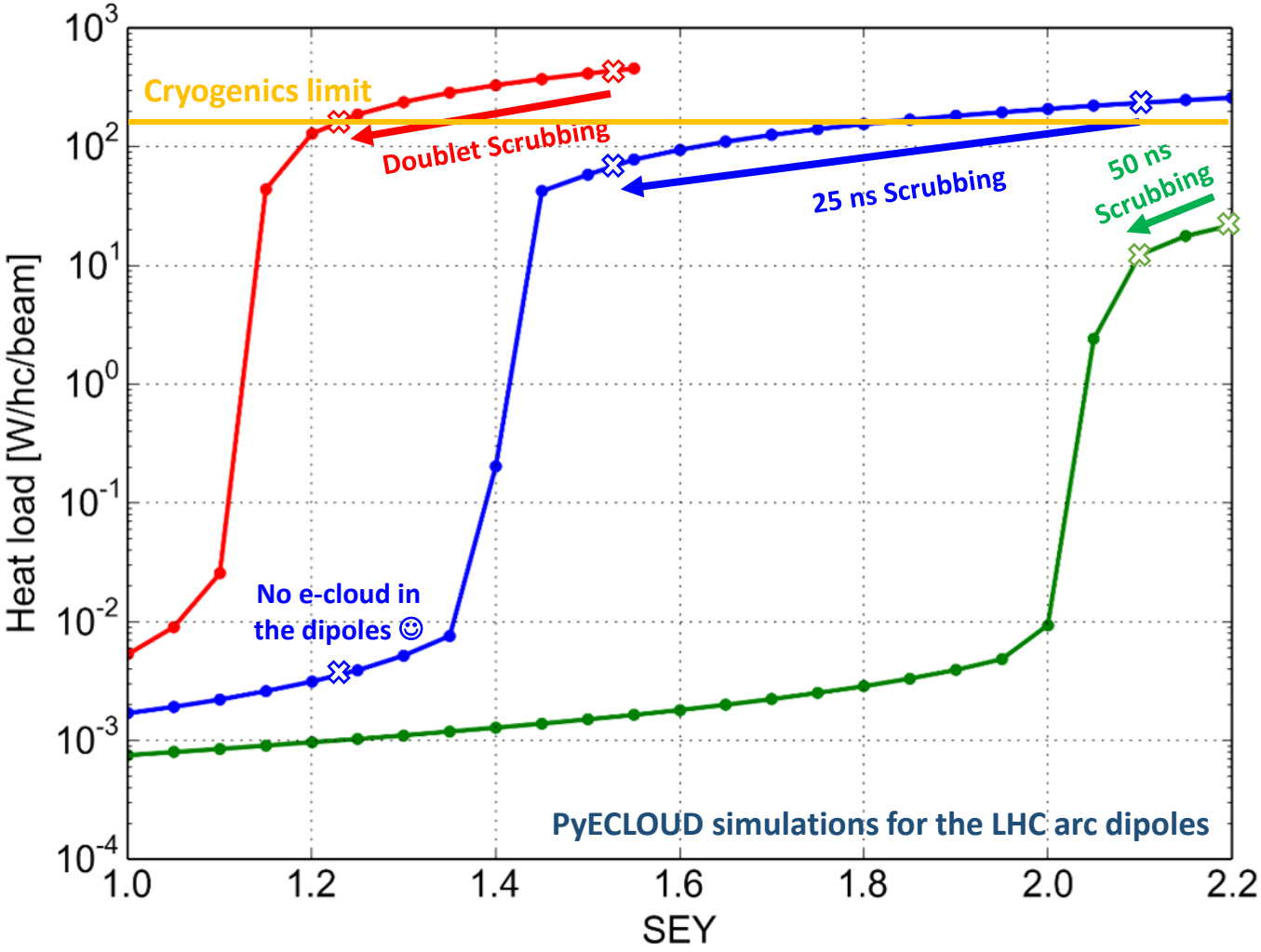

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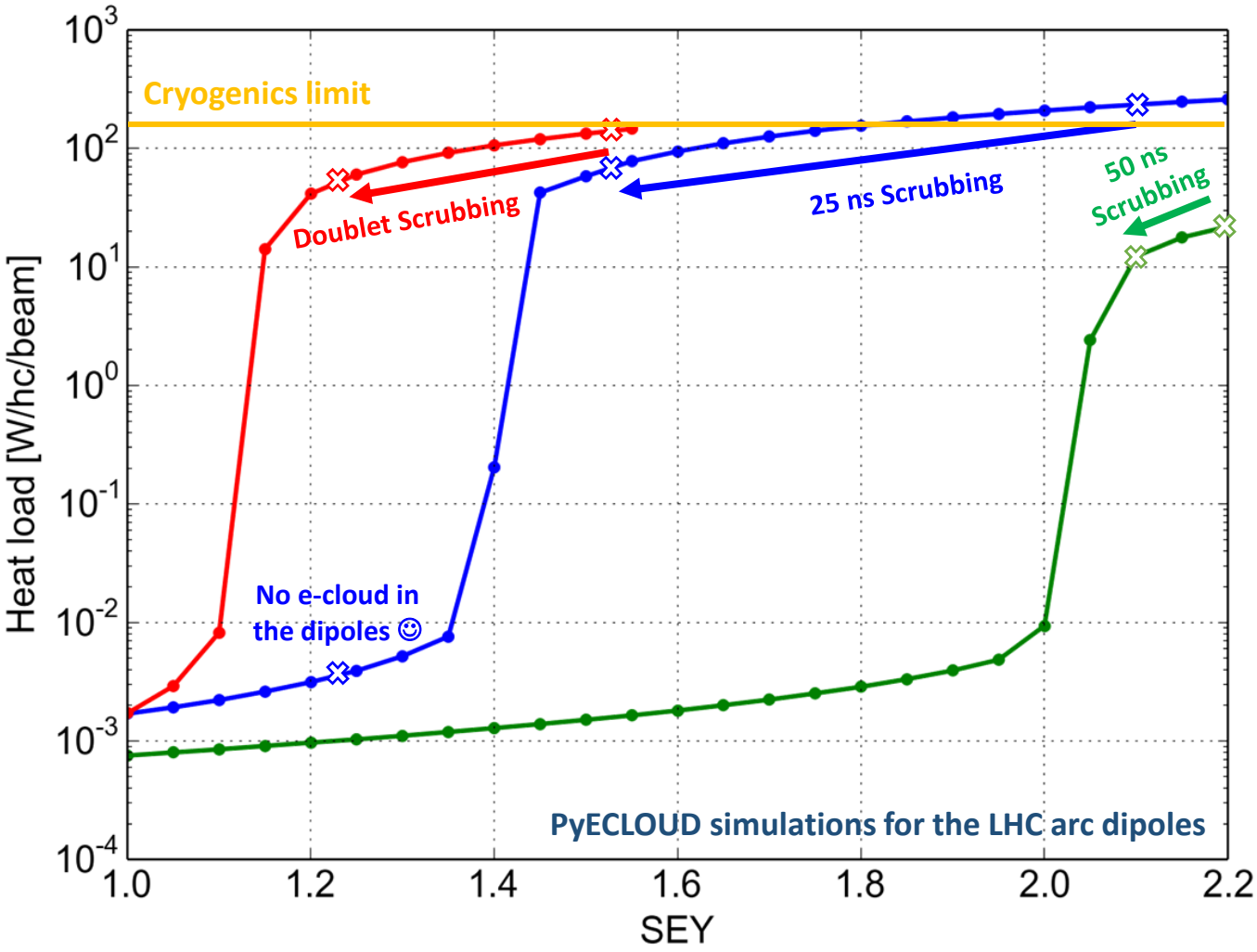


50 ns beam
~1400 bunches
1.7 x 10^{11} p/b

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

Doublet beam
~900 doublets
0.7 x 10^{11} p/b

“Doublet” scrubbing beam: PyECLOUD simulation results

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

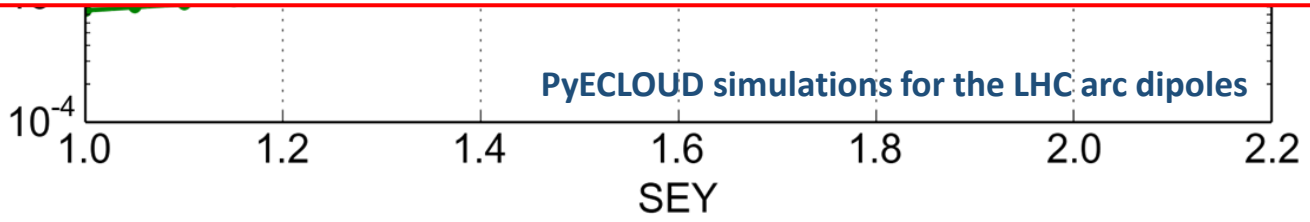
For example if: **$SEY_{dip} = SEY_{quad} = 1.45$**:

	$N_{bunches}$	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)



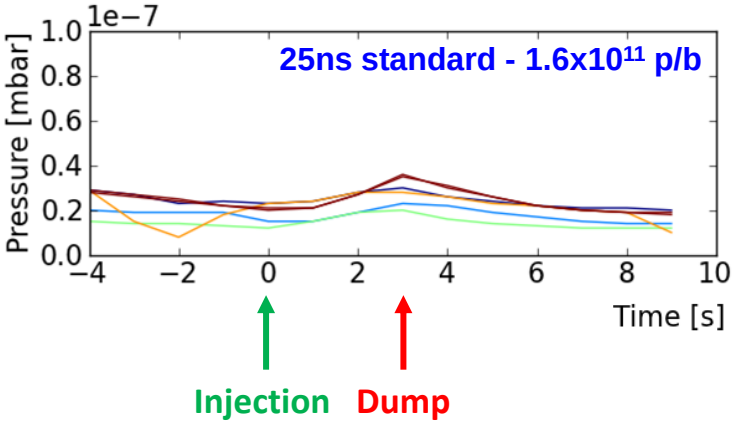
“Doublet” scrubbing beam: SPS tests

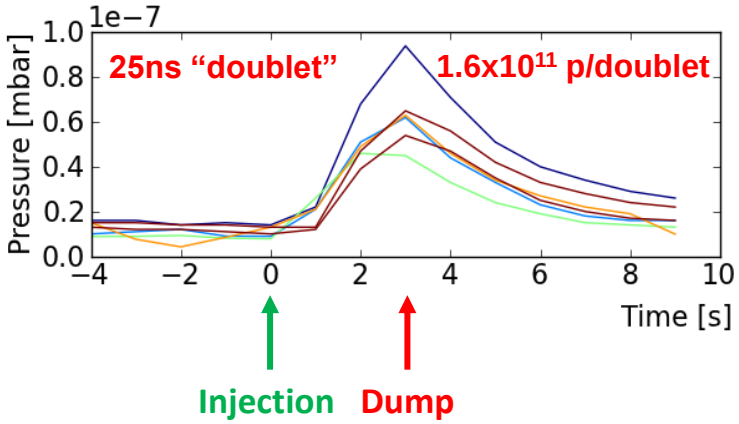
Production scheme and e-cloud enhancement **proved experimentally in the SPS** in 2012-13

→ 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**





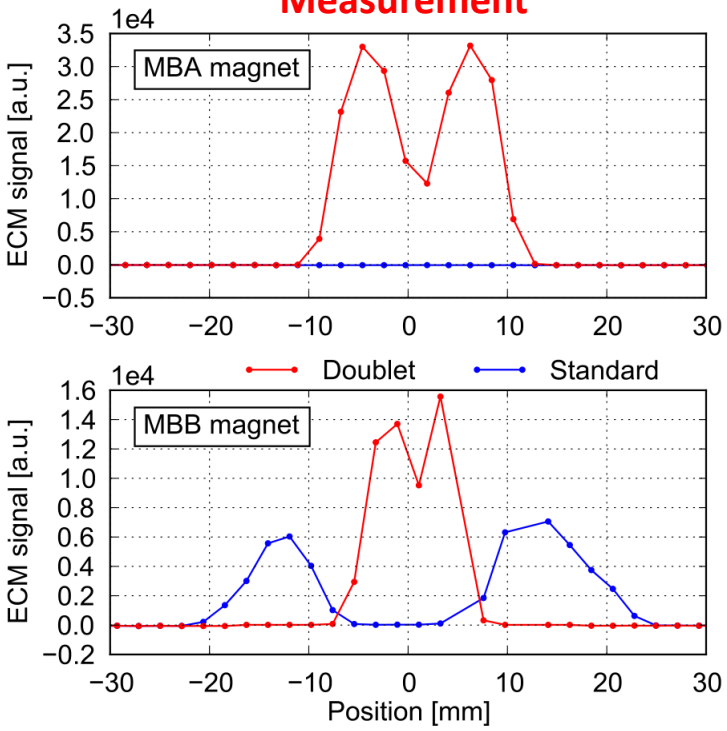
“Doublet” scrubbing beam: SPS tests

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

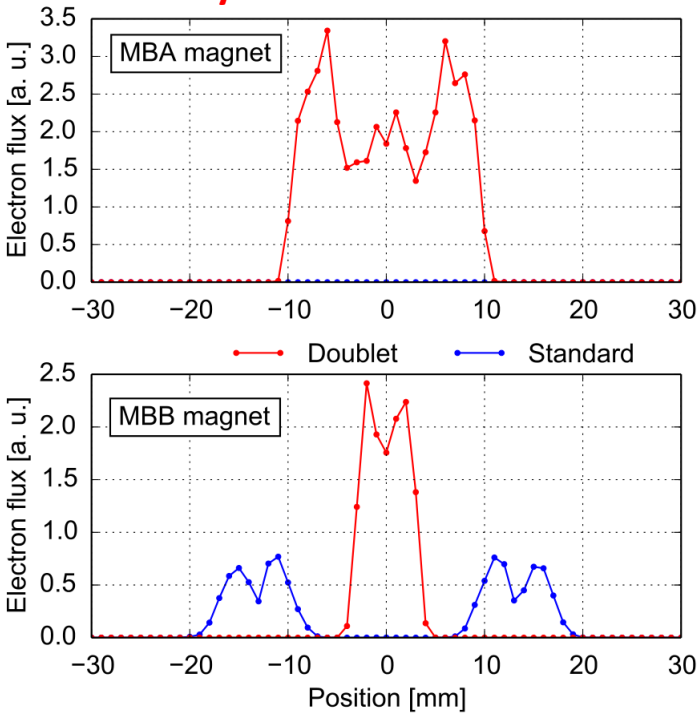
→ Stronger e-cloud visible both on **pressure rise** and on **dedicated detectors**

e-cloud detectors

Measurement



PyECLOUD simulation



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

→ **Important validation for our simulation models and tools**

“Doublet” beam: compatibility with LHC equipment

Reviewed within the LBOC → main conclusions:

Doublet production (for details: H.Bartosik et al., at LBOC 05/11/2013, E. Shaposhnikova al., at LBOC 03/12/2013)

- **Splitting at SPS injection is the most favorable scheme** (compared to splitting at high energy in SPS, or at LHC injection) both for beam quality and e-cloud enhancement

RF system (for details: P. Baudrenghien et al., at LBOC 26/11/2013)

- **No major issue**
- **Phase measurement will average** over each doublet

  → Low Pass Filter bandwidth to be optimized (being prepared in 2014)

- If bunch length from SPS stays below 1.8 ns **capture losses will not be larger than for standard 25 ns beam**

Transverse damper (ADT) (for details: G. Kotzian et al., at LBOC 26/11/2013)

- **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)

  → This kind of instabilities (if observed) will have **to be controlled with chromaticity and/or octupoles**

“Doublet” beam: compatibility with LHC equipment

Reviewed within the LBOC → main conclusions:

Beam instrumentation (for details: T. Lefevre et al., at LBOC 05/11/2013)

- **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 Quality Monitor (BQM) or LDM to be used for relative bunch intensity information
- **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

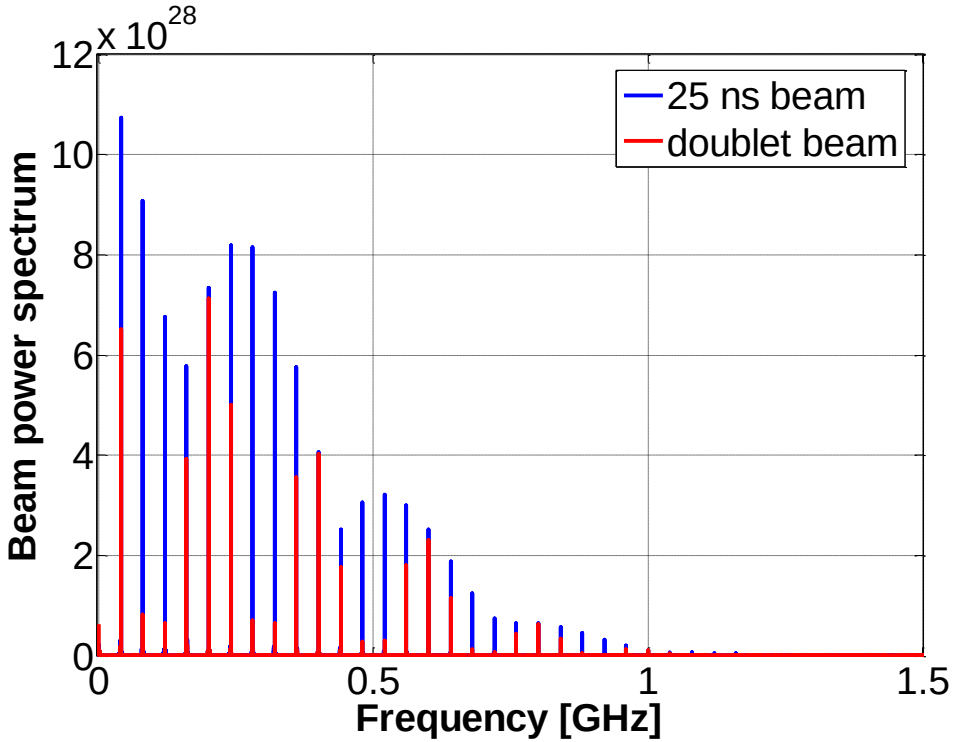
For details: J. Uythoven, Minutes from the LIBD meeting on 11 February 2014, Edms nb. 1355948

“Doublet” beam: 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**

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



Thanks to **C. Zannini**

Outline

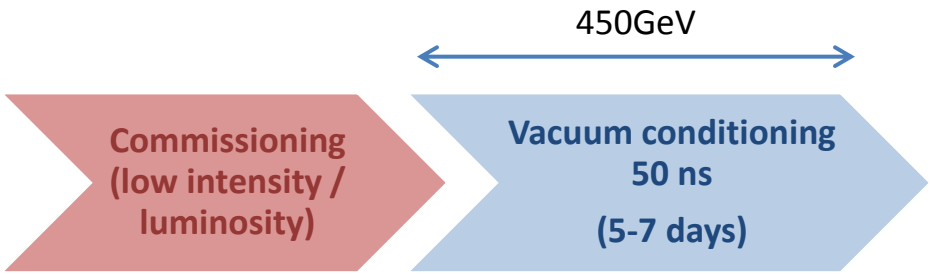
- **Run 1 experience**
  - 50 ns vs 25 ns
  - Scrubbing with 25 ns in 2011-2012
  - 25 ns beams at 4 TeV in 2012
- **Scrubbing in 2015**
  - Goals
  - Post-LS1 improvements
  - The “doublet” scrubbing beam
    (motivation, tests at SPS, compatibility with LHC equipment)
  - Scrubbing stages
  - Possible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

Scrubbing stages

Commissioning (low intensity / luminosity)

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

Scrubbing stages



First stores at 450 GeV with high intensity beams

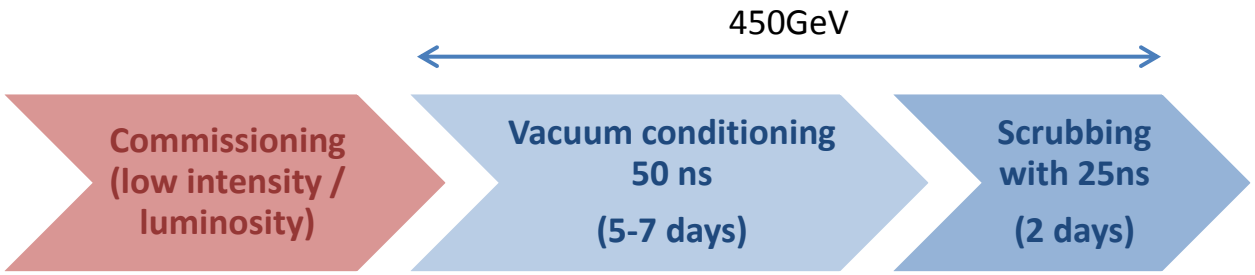
We will face dynamic pressure rise, heat load and possibly beam instabilities

Goals:

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

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

Scrubbing stages



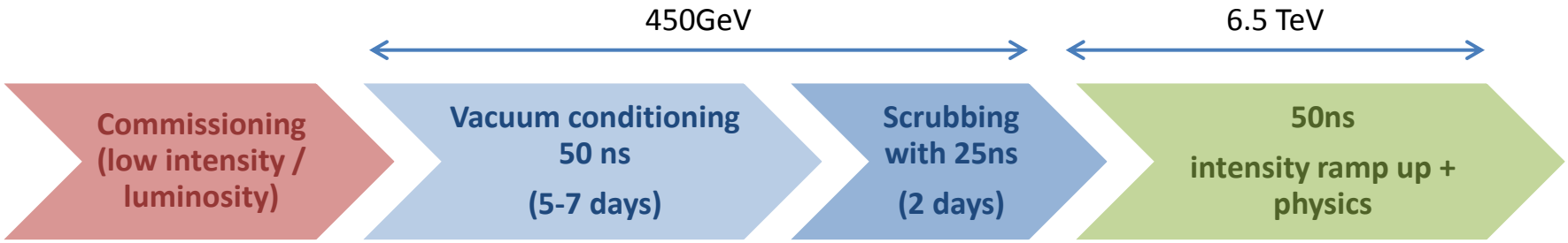
Switch to 25 ns when pressures, heat loads and instabilities are under control

Goal:

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

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

Scrubbing stages



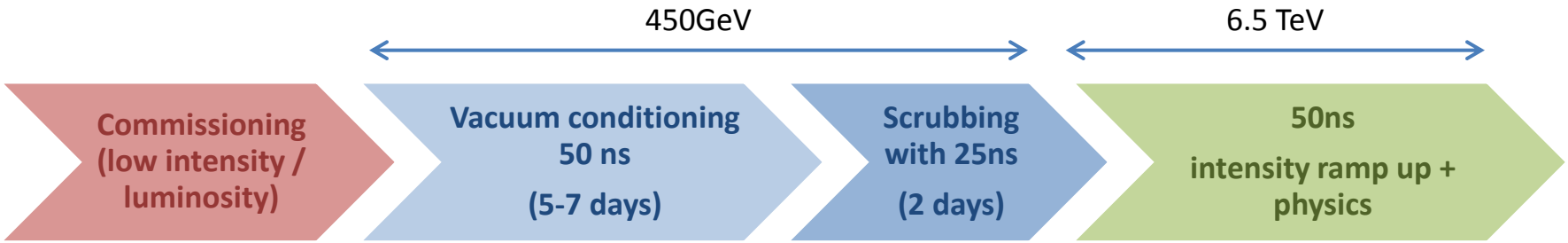
First ramps to 6.5 TeV with high intensity (50 ns) → synchrotron radiation and **photoelectrons**

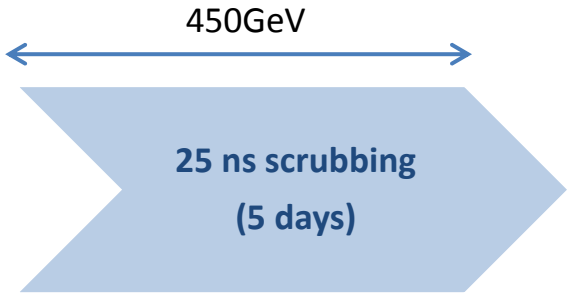
Goals:

- **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

Scrubbing stages





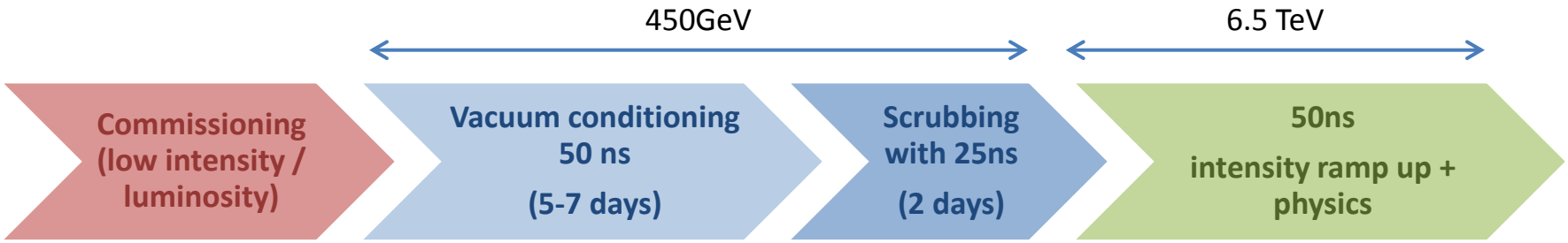
Scrubbing with 25 ns beams

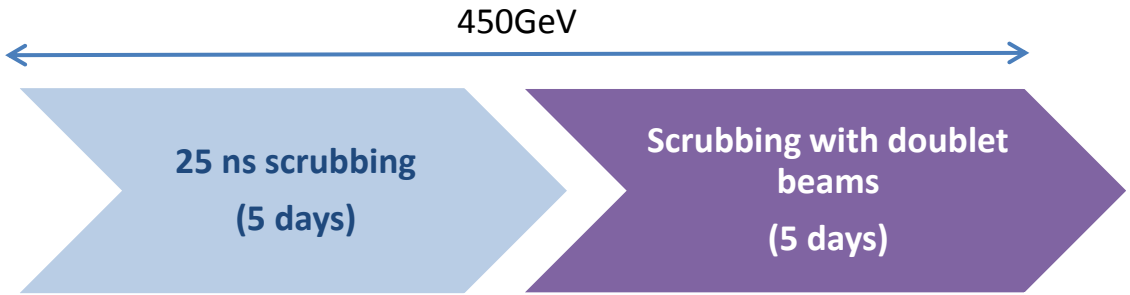
Goal:

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

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

Scrubbing stages



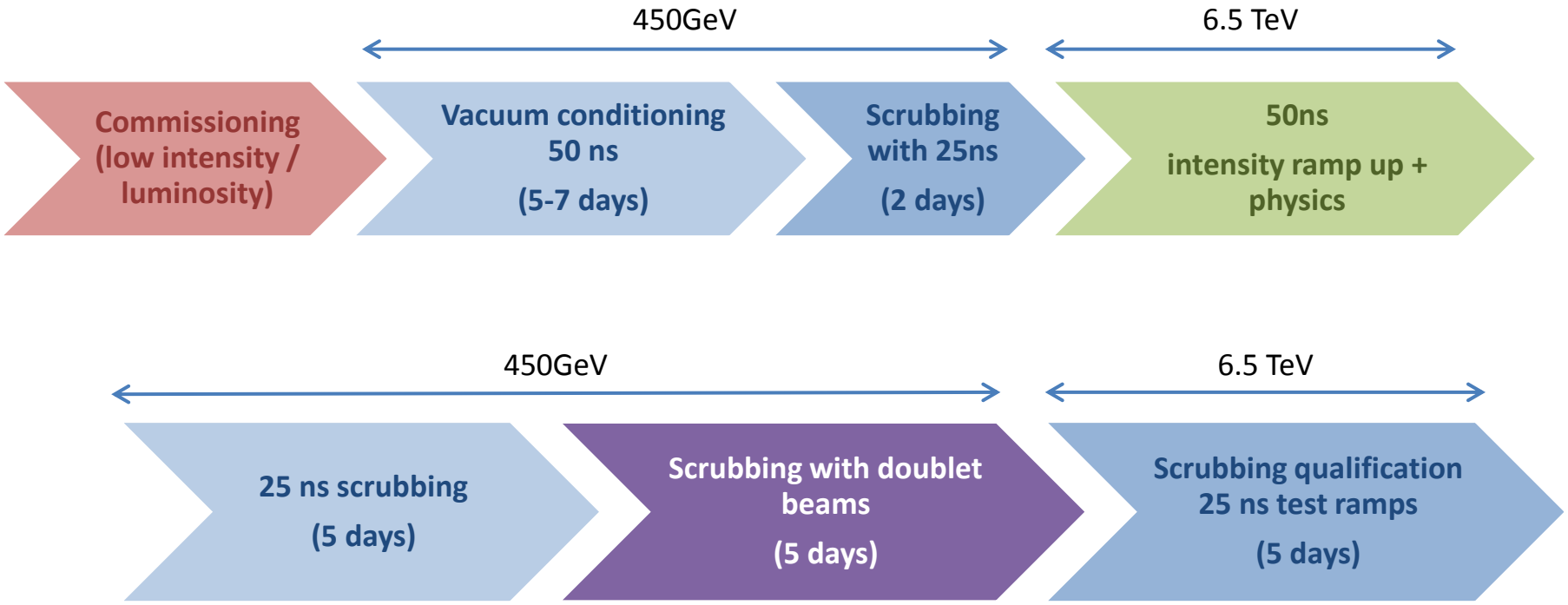


Scrubbing with doublet beam

Goal:

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

Scrubbing stages



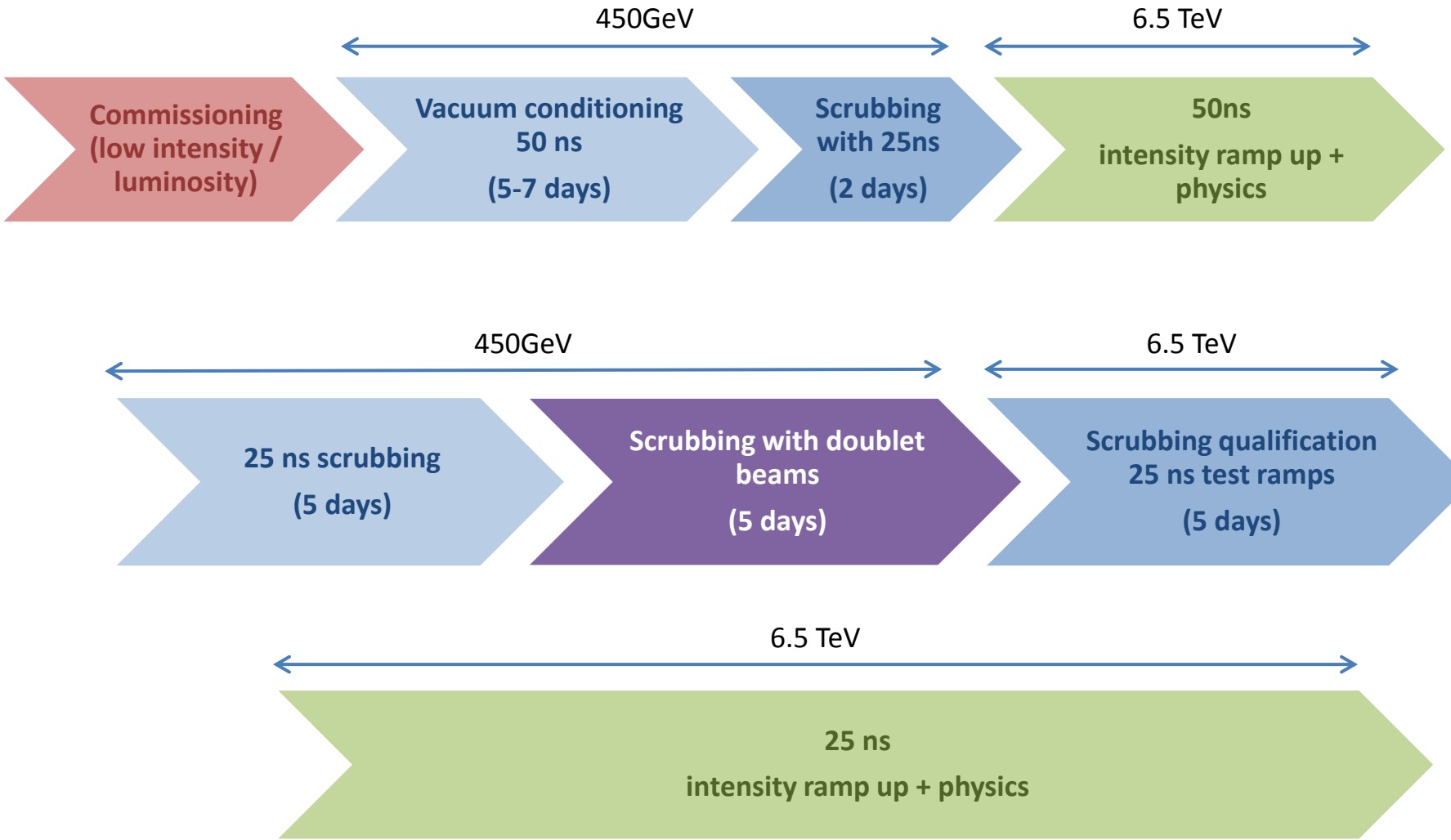
First ramps to 6.5 TeV with 25 ns beams

→ 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)

Scrubbing stages



Outline

- Run 1 experience
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  - 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

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**

Post scrubbing scenarios

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 talk by H. Bartosik)

- 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 **more scrubbing than in 2012 is mandatory**
- **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**

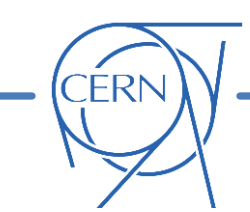
- Production scheme and e-cloud enhancement **proved experimentally at SPS in 2012-13**
- **Compatibility with LHC equipment** reviewed by the LBOC
  - → **No major showstopper** has been found
  - → Issue with **offset on interlock BPM in IR6** being followed up by BE/BI and TE/ABT

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

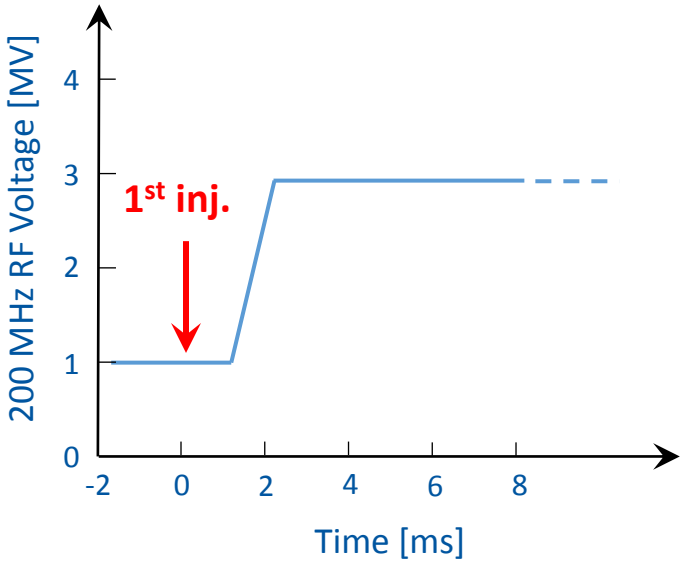
- Based on simulations → **to be validated experimentally** at SPS and (if needed) at LHC

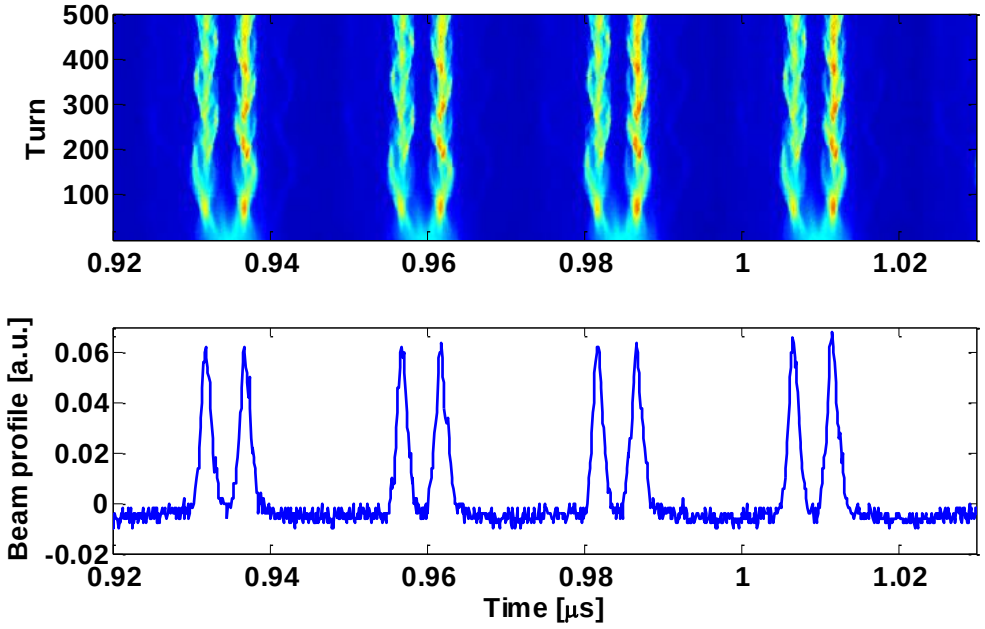


Thanks for your attention!

Tests of the 5 ns doublet beam in the SPS

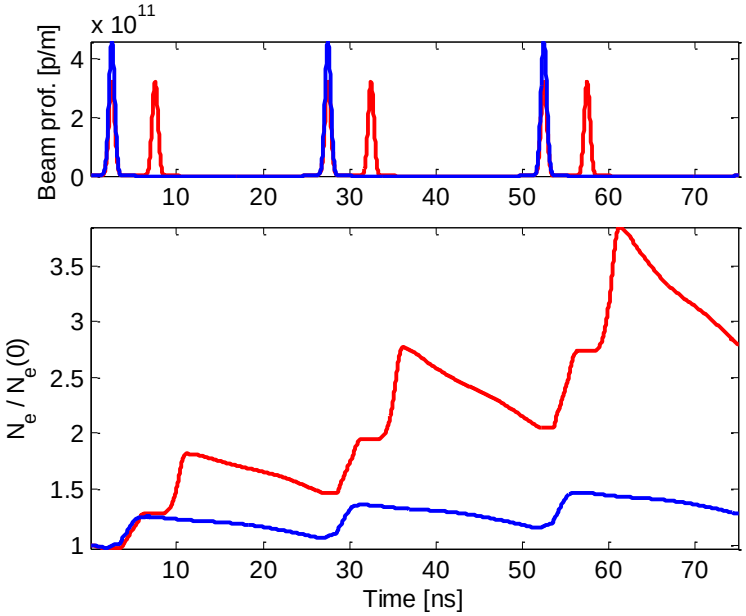
- First machine tests in the SPS at the end of 2012-13 run in order to
  - validate the doublet production scheme at SPS injection
  - obtain first indications about the e-cloud enhancement
- The production scheme has been successfully tested
  - for a train of up to (2x)72 bunches with 1.7e11 p/doublet

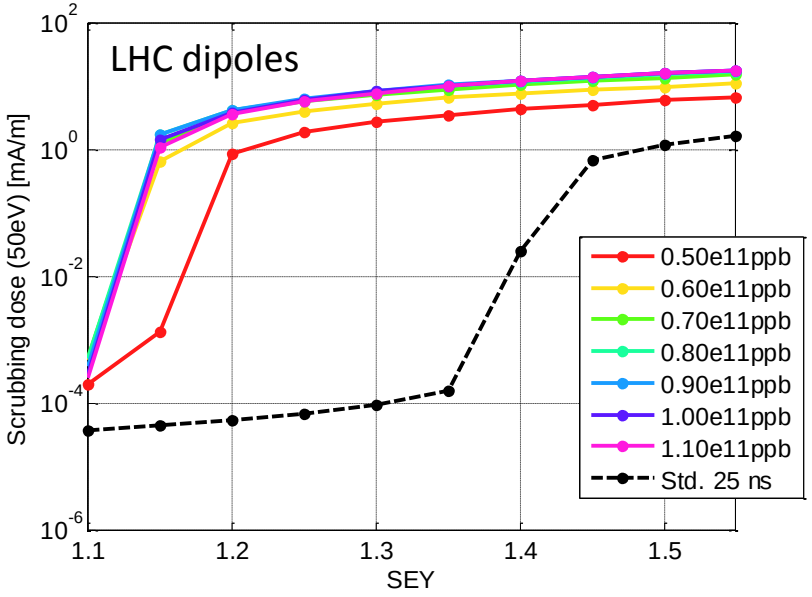




PyECLOUD simulations – 5 ns doublets

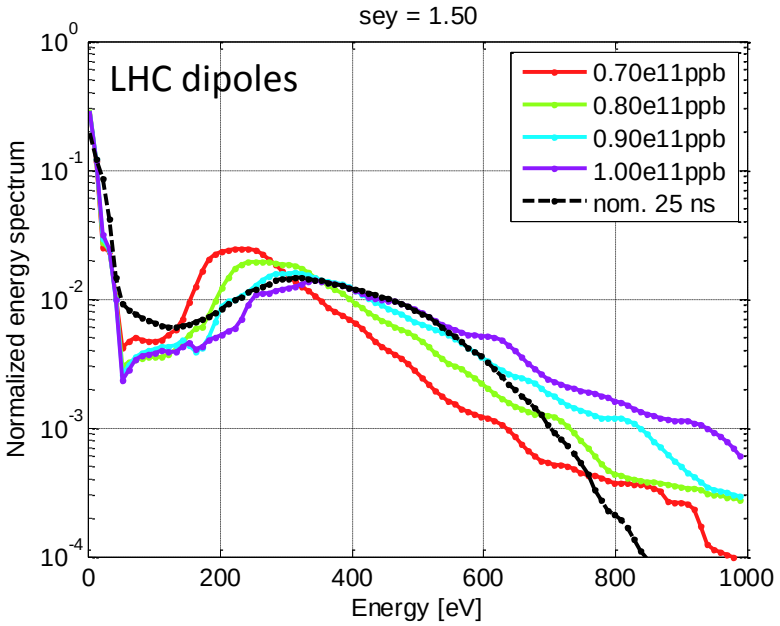
- The 5 ns doublet beam shows a much lower multipacting threshold compared to the standard 25 ns beam

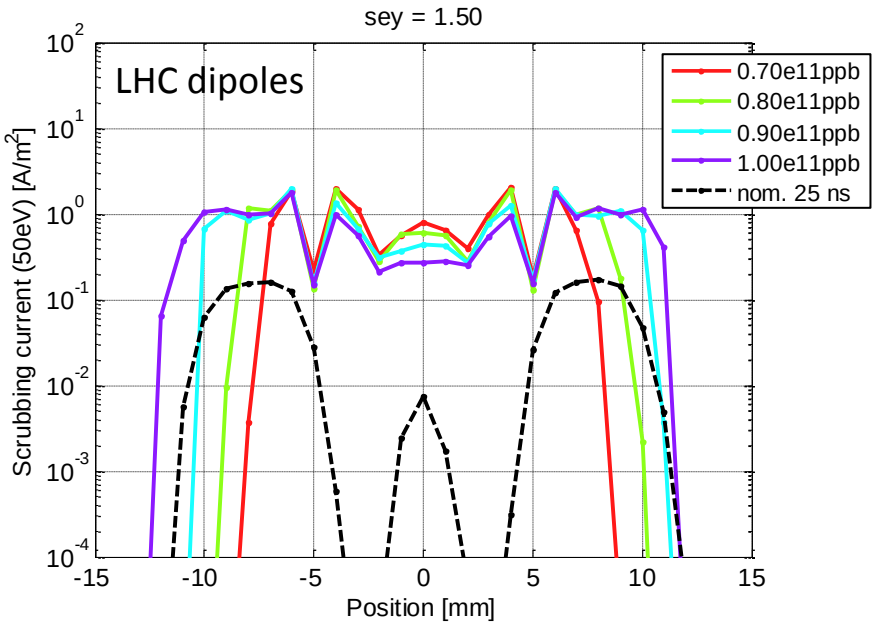


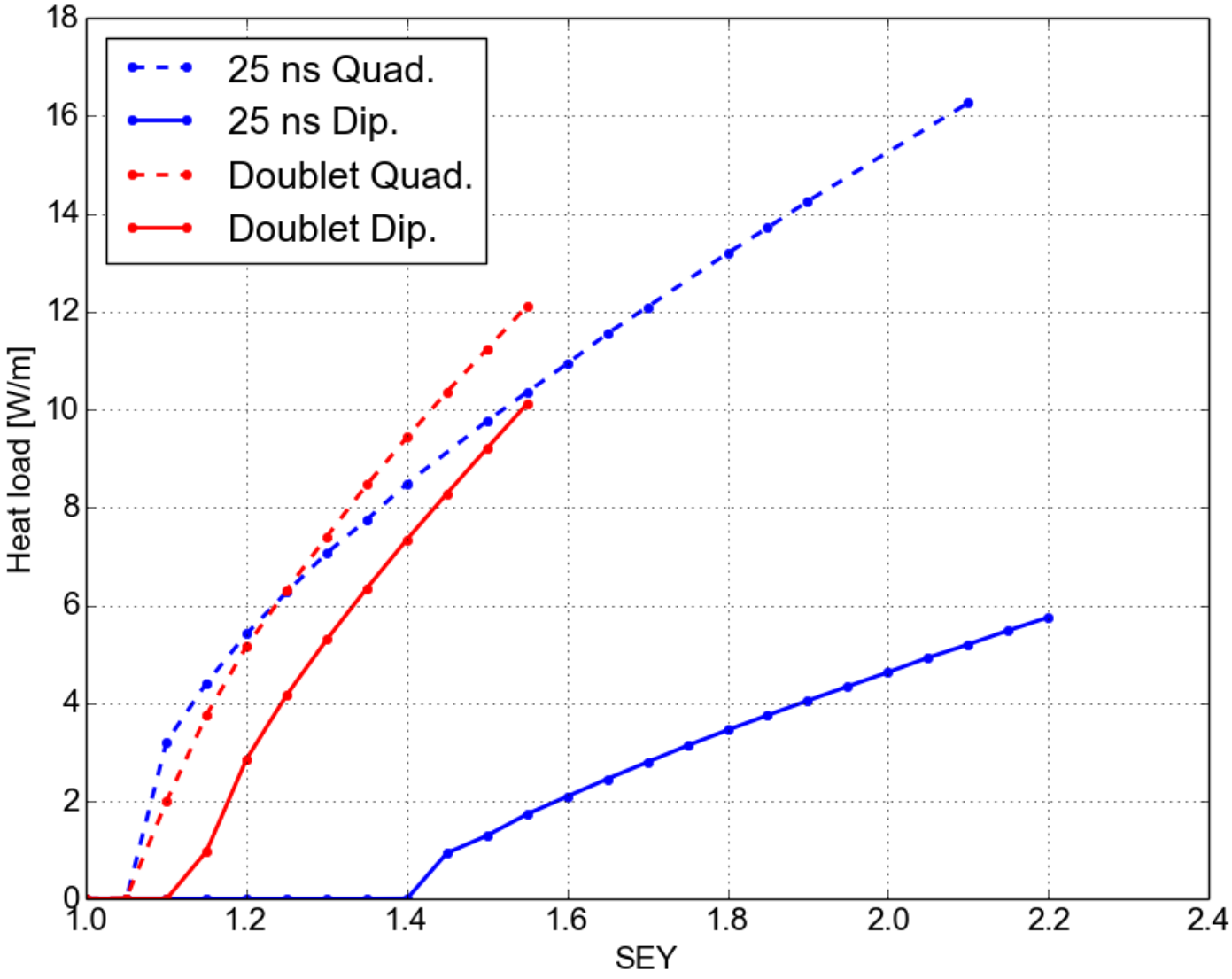


PyECLOUD simulations – 5 ns doublets

- 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

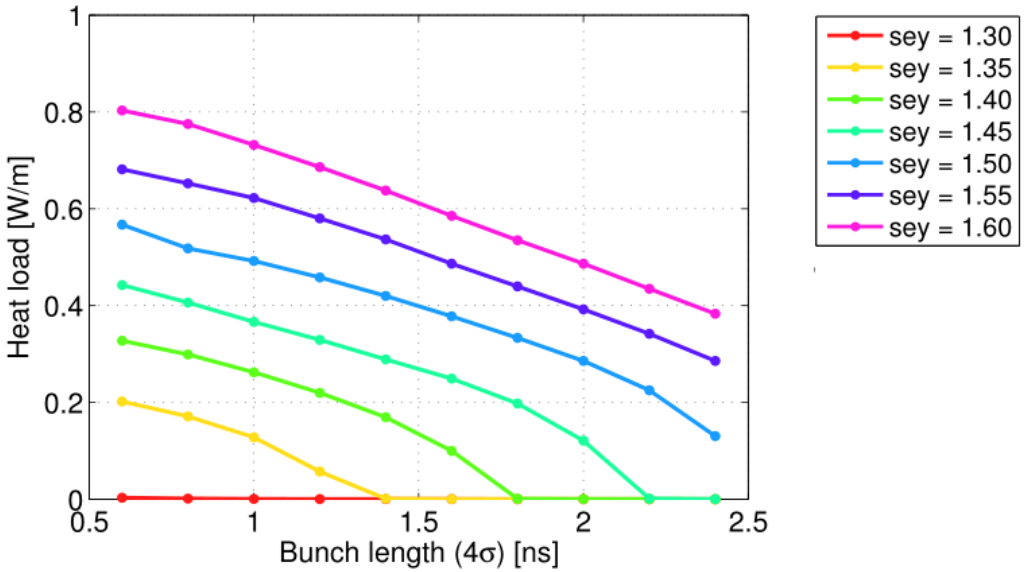


Figure 4.19: EC induced heat load as a function of the bunch length, for the LHC arc dipole magnets. Simulations for injection energy, 25 ns bunch spacing, different bunch intensities. No beam dependent seeding, uniform train of 640 bunches.

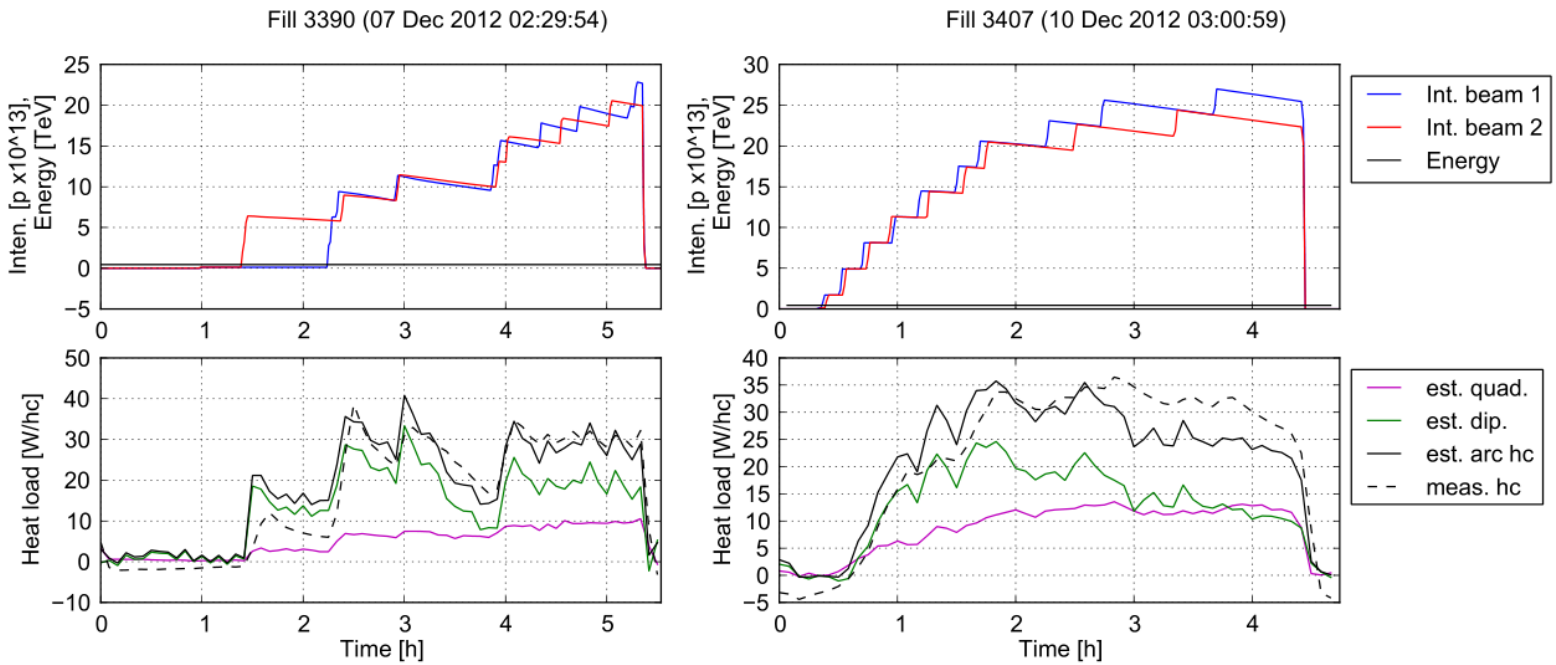


Figure 5.30: Curves in Fig. 5.29 rescaled to the lengths of the magnets in a regular LHC arc half-cell (purple and green), their sum (black continuous) and measured heat loads in the LHC arcs (black dashed).