Electron cloud simulation with PyECLOUD

G. Iadarola, G. Rumolo

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Outline

- **Introduction on Electron Cloud Effect**
- **PyECLOUD:**
    - Overview
    - MP size management
    - Convergence and performances
- **PyECLOUD at work for LHC studies:**
    - SEY reconstruction from heat-load measurements
    - Benchmarking with stable phase shift measurements
    - PyECLOUD – HEADTDAIL simulation of EC induced instabilities

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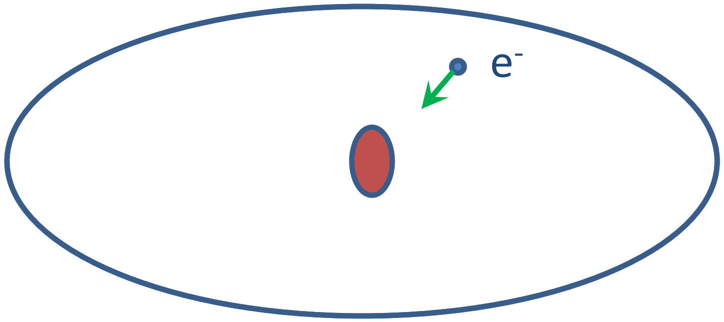
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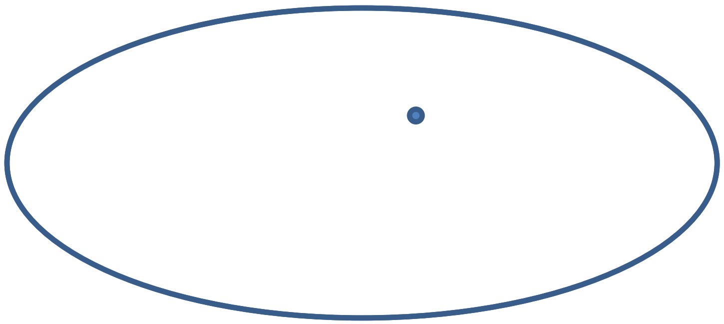
Secondary electron emission



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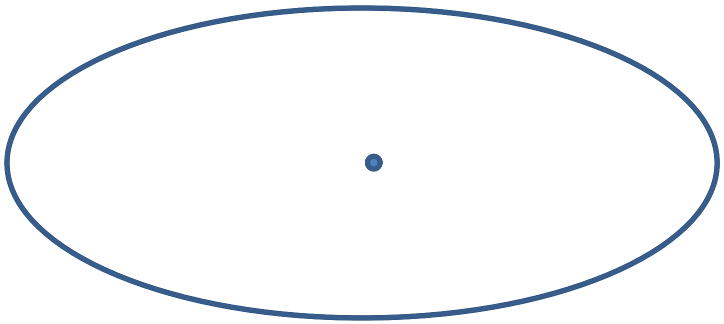

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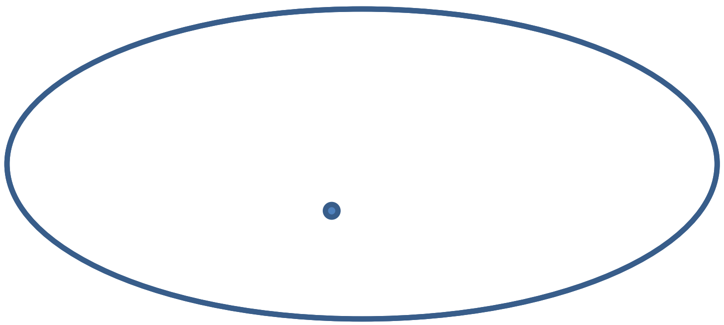

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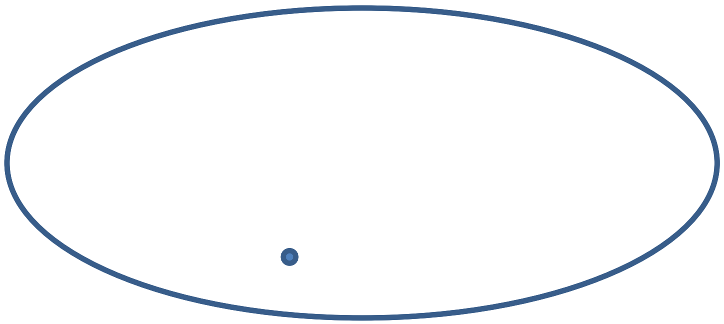

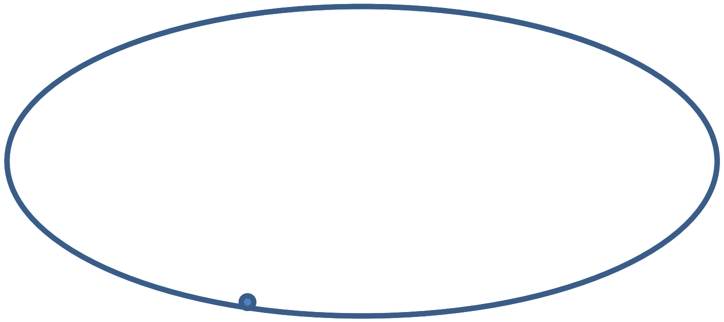

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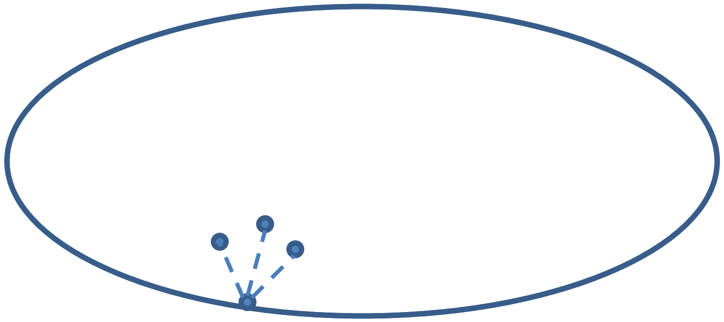
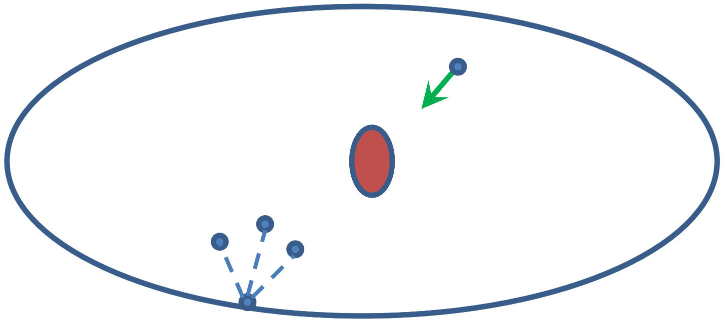
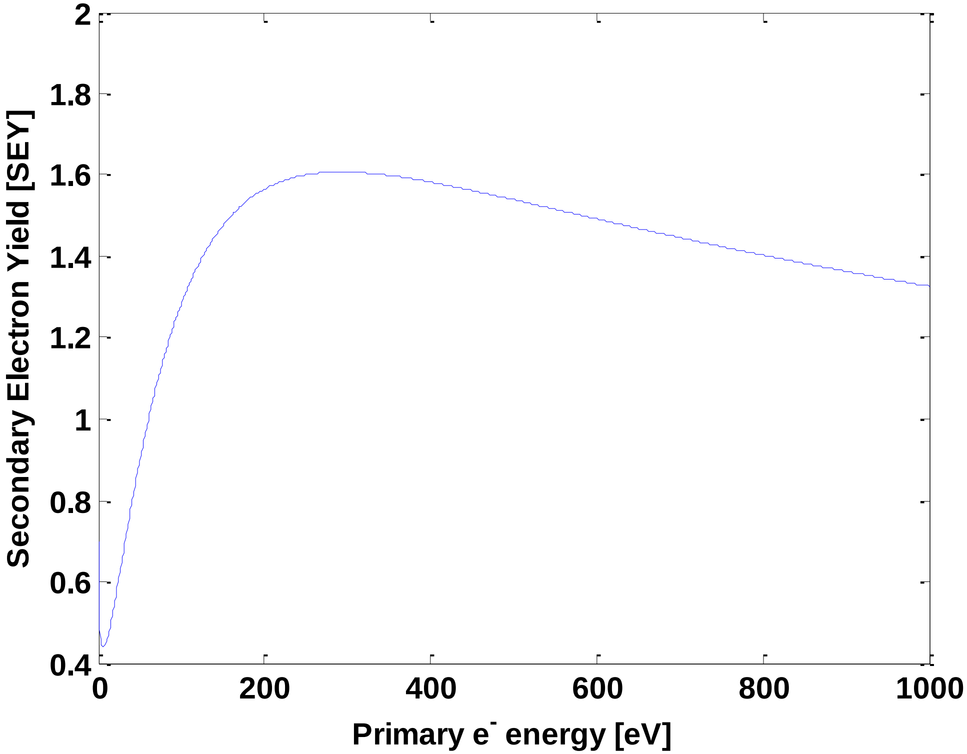


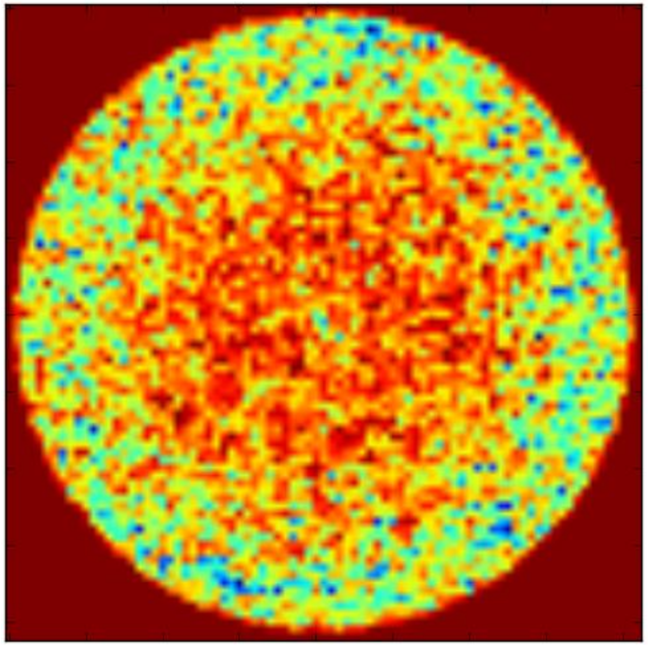


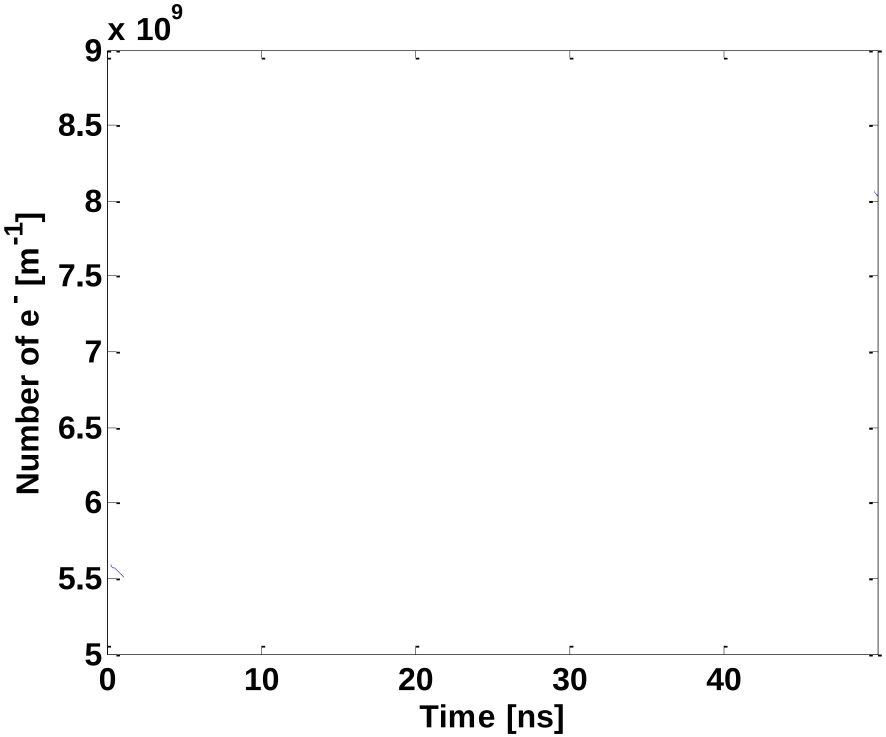


The **Secondary Electron Yield** of the chamber's surface is basically the ratio between emitted and impacting electrons and is function of the energy of the primary electron.

Electron cloud build-up

Beam pipe transverse cut





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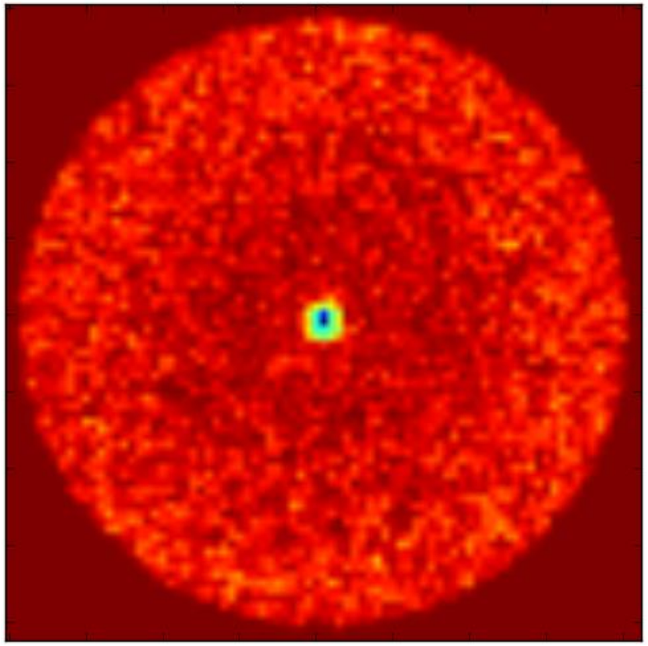

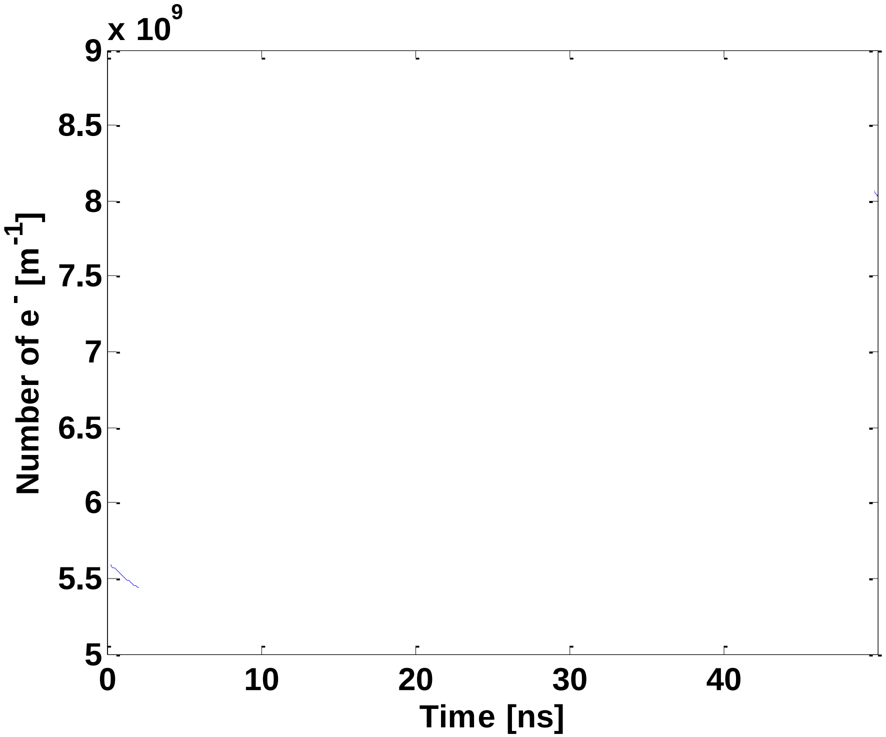

- **During the bunch passage** the electrons are accelerated by the beam **"pinched" at the center of the beam pipe**

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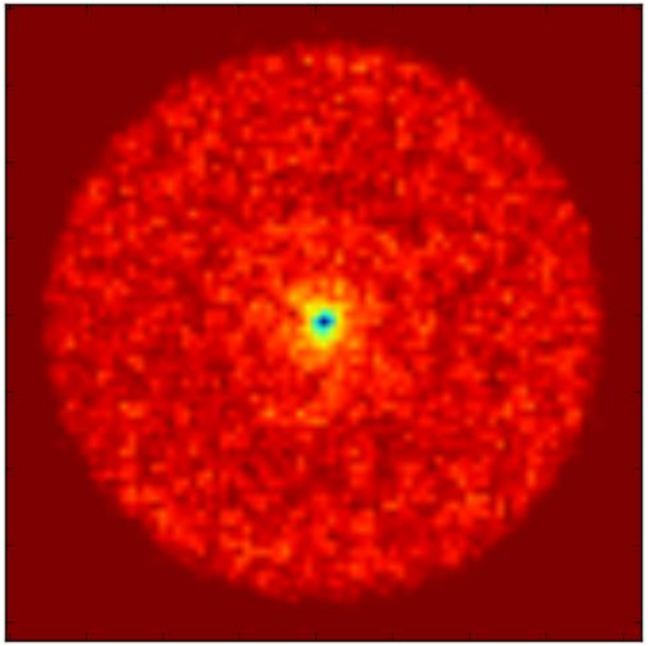

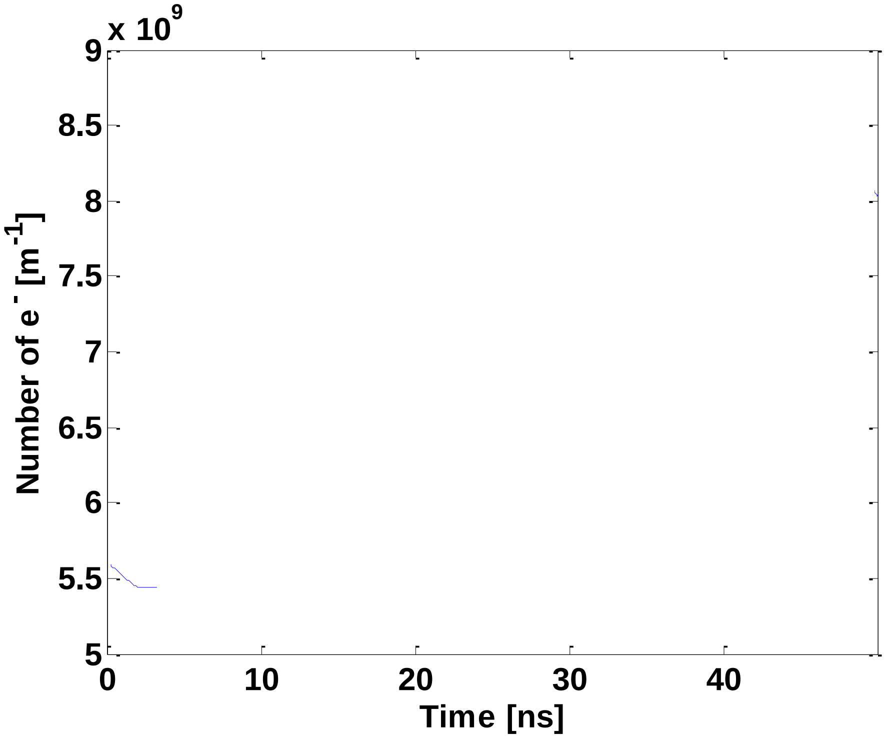

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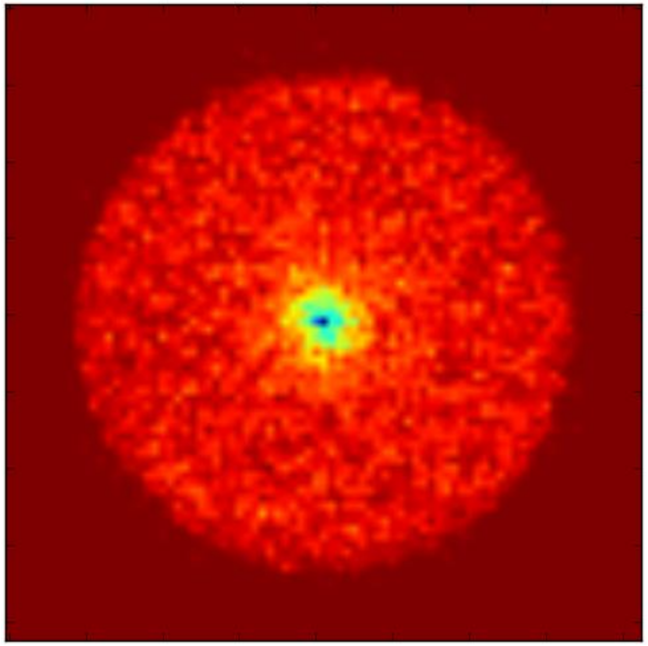

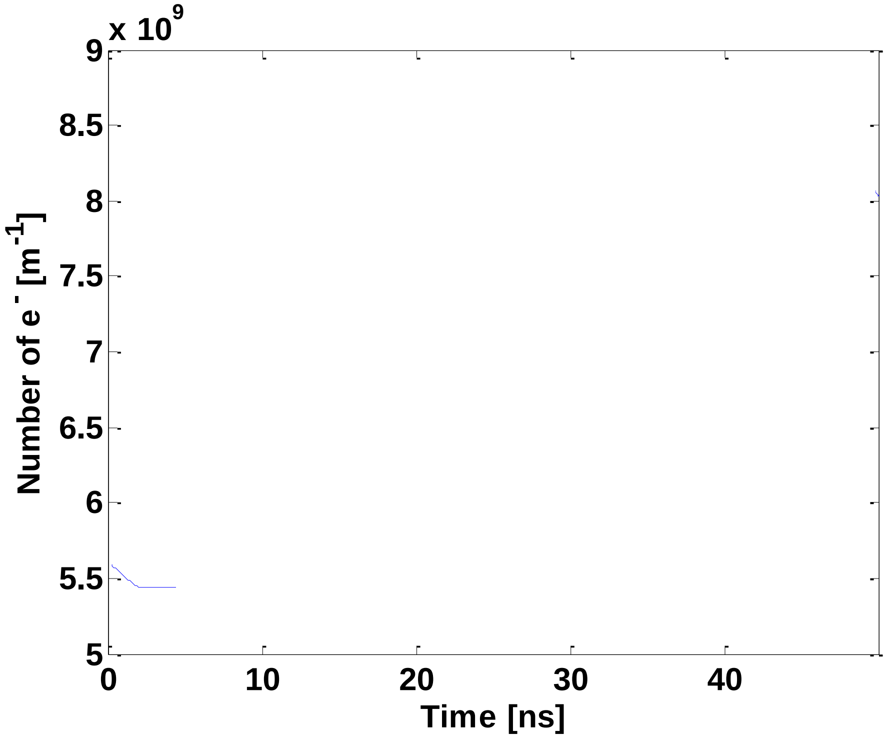

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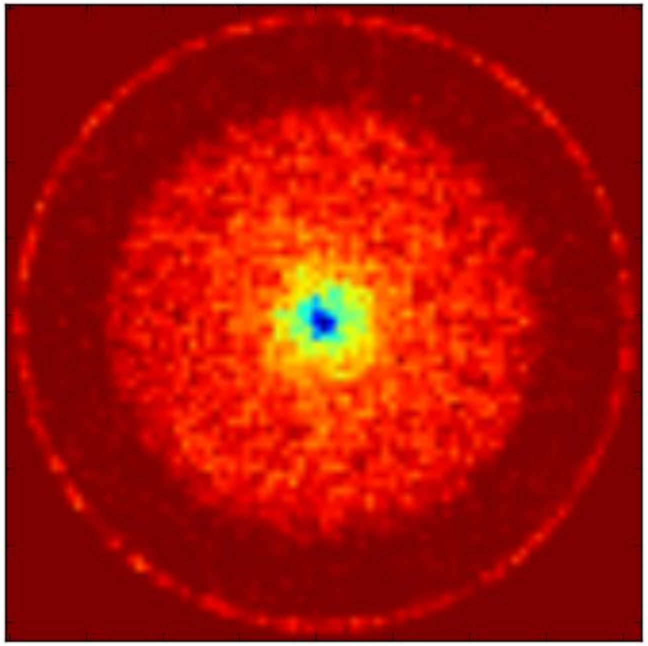

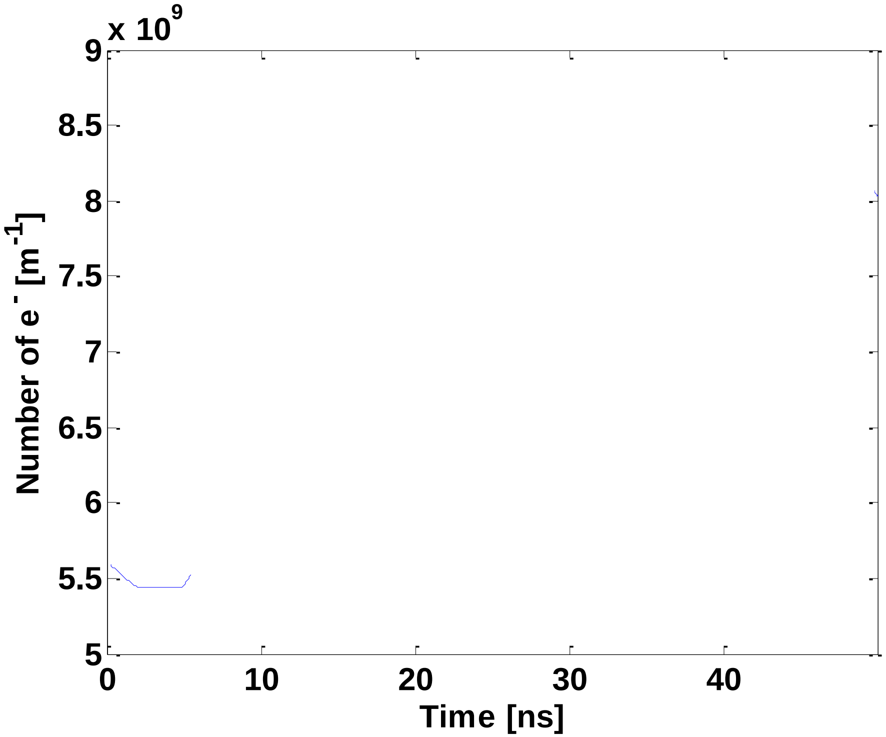

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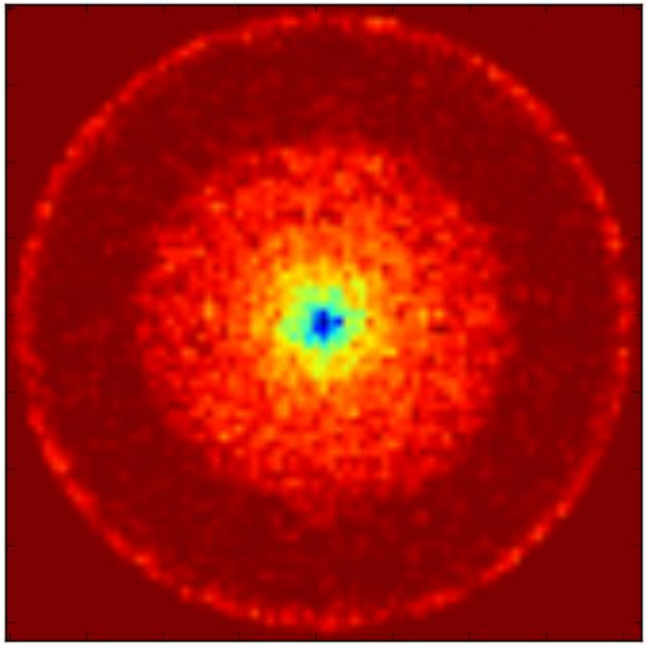

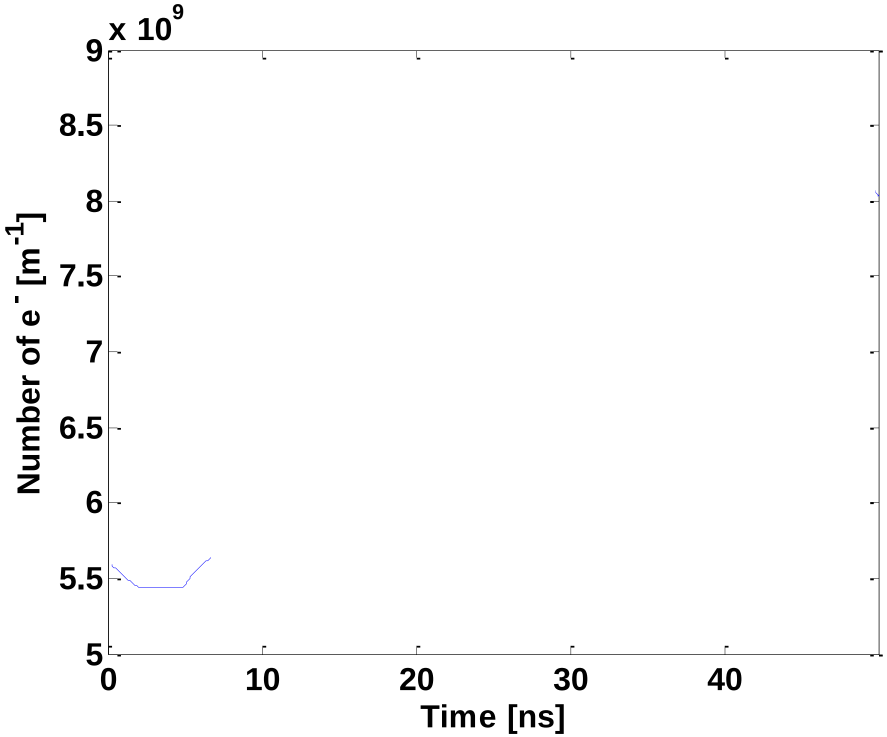

- **After the bunch passage** the electrons **hit the chamber's wall (with E~100eV)**
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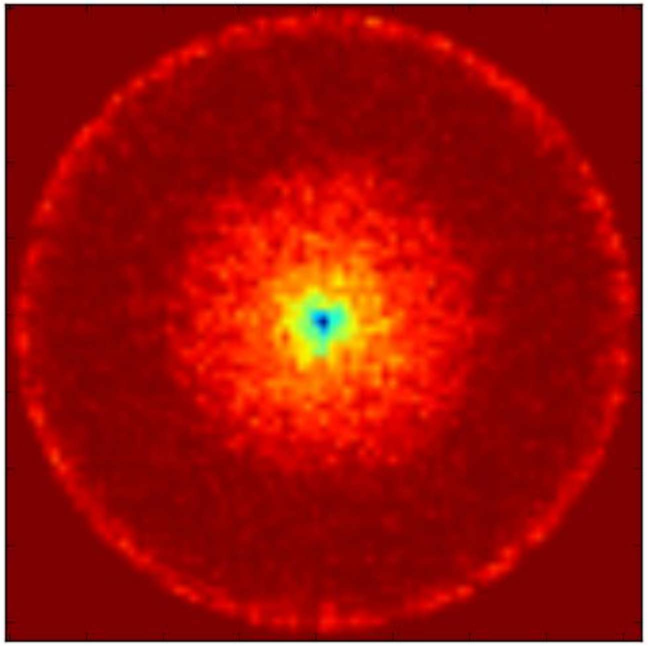

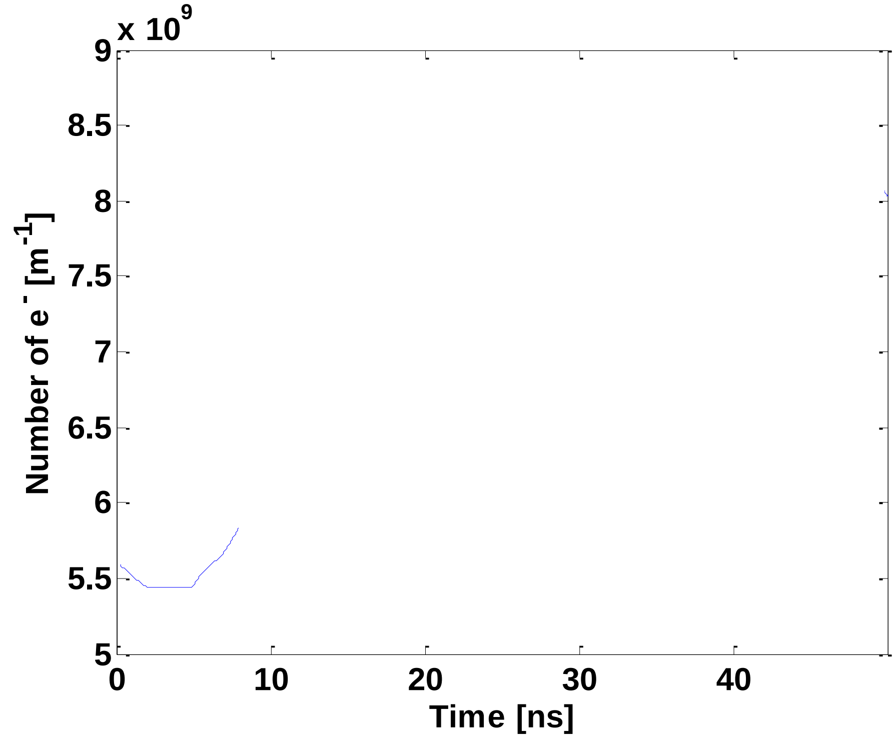

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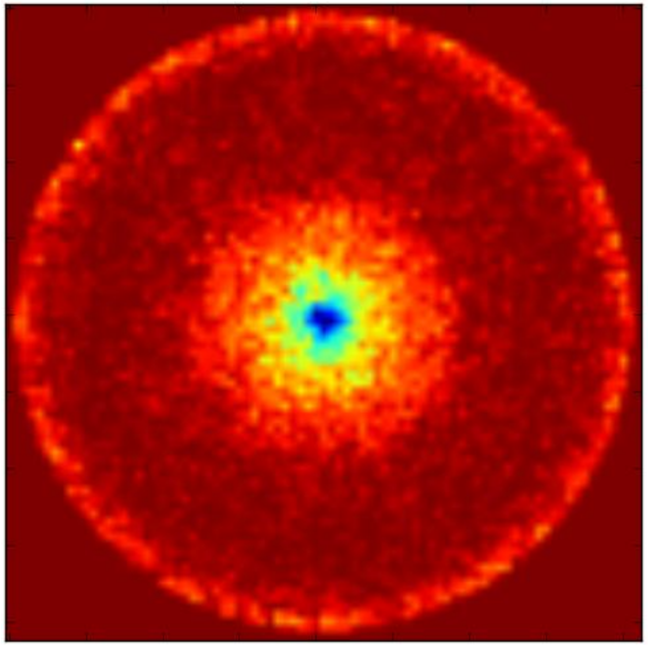

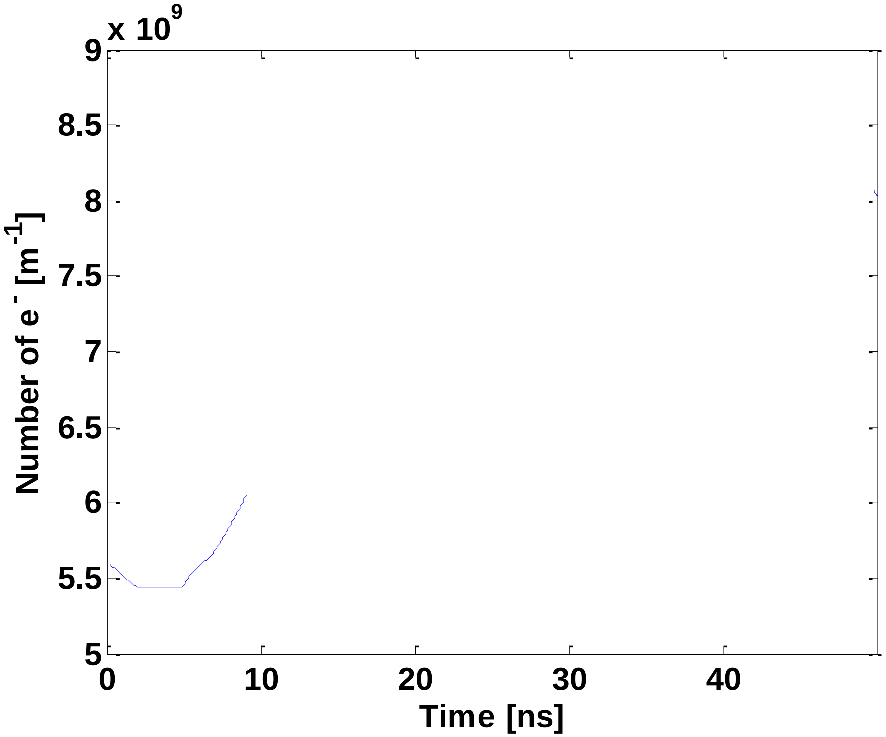

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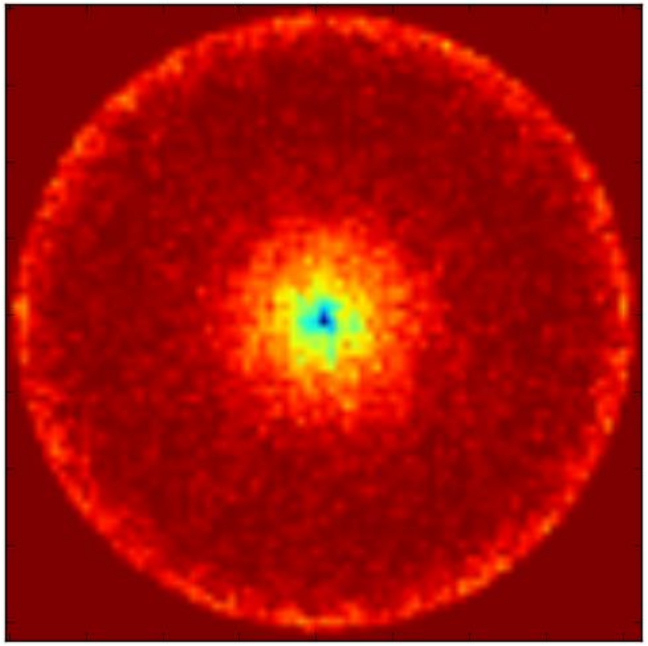

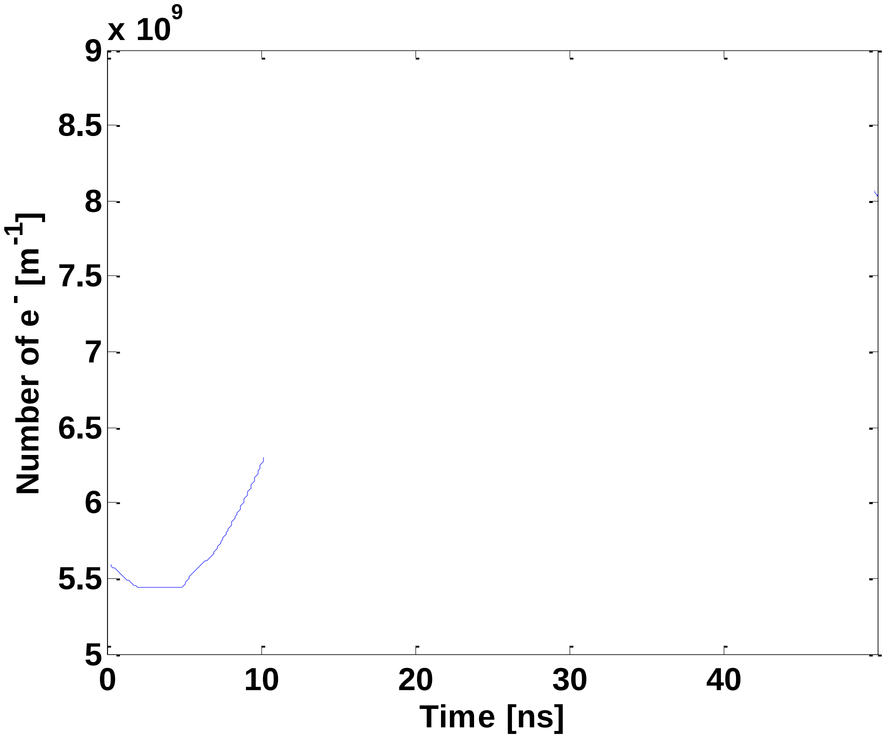

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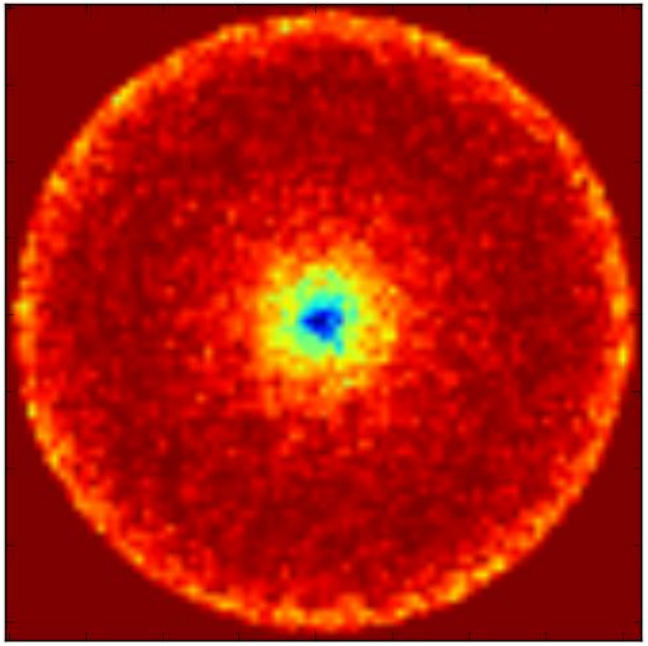

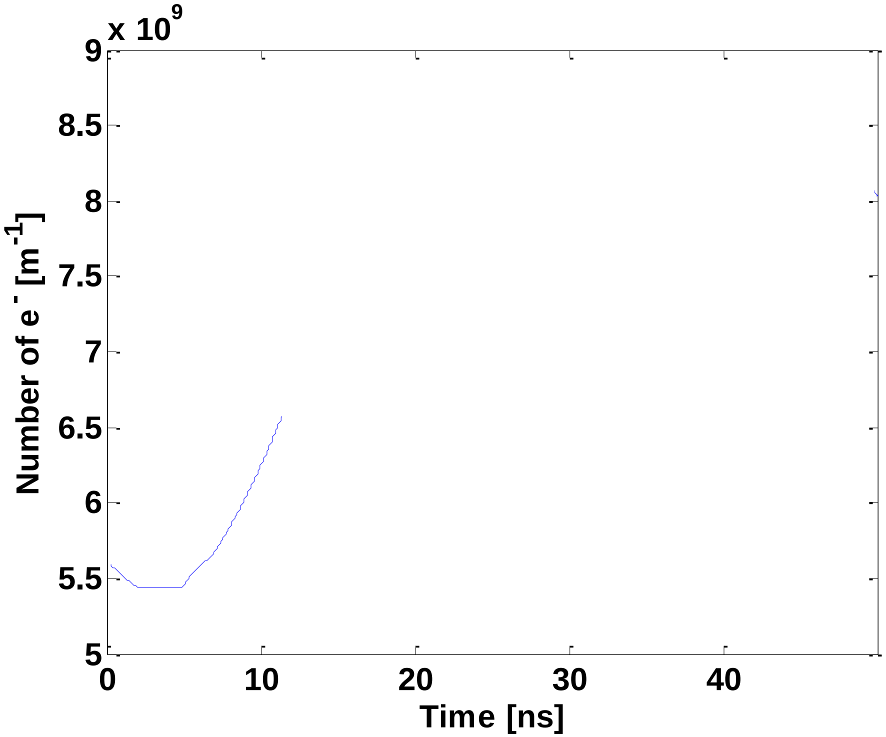

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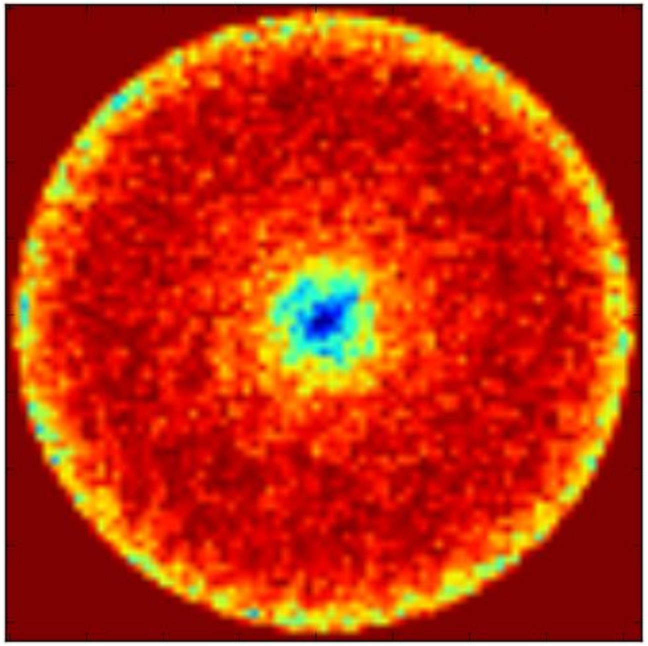

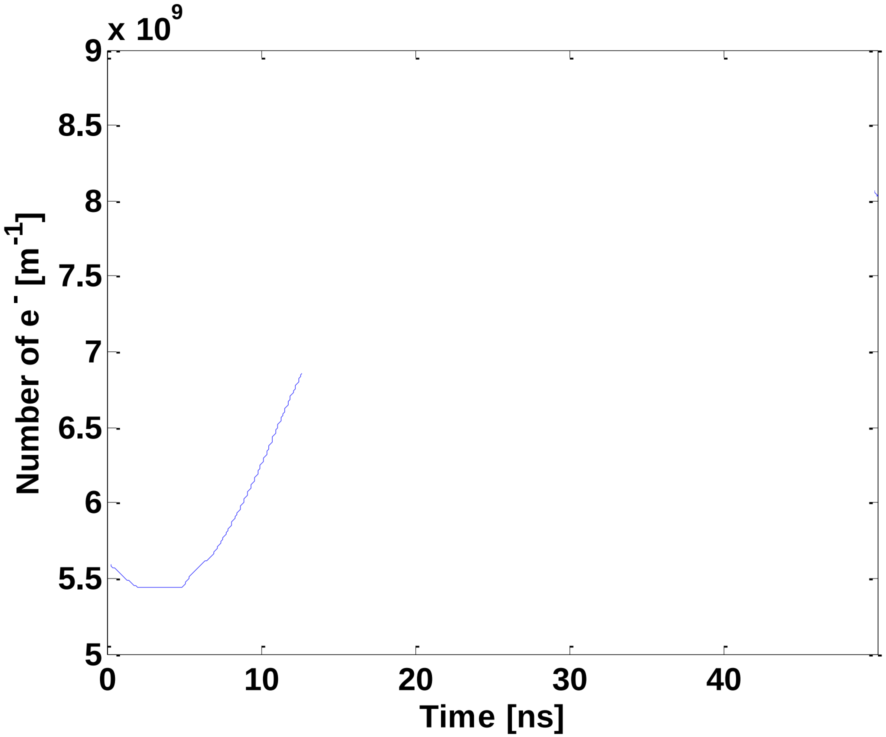

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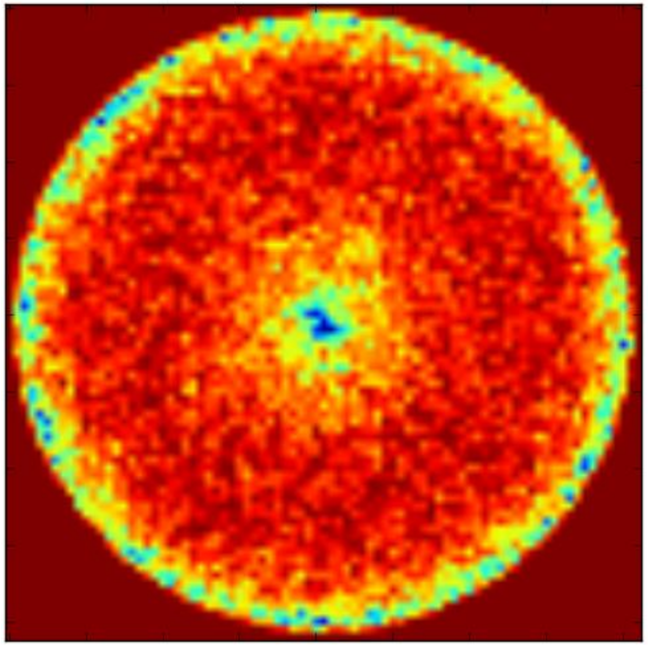

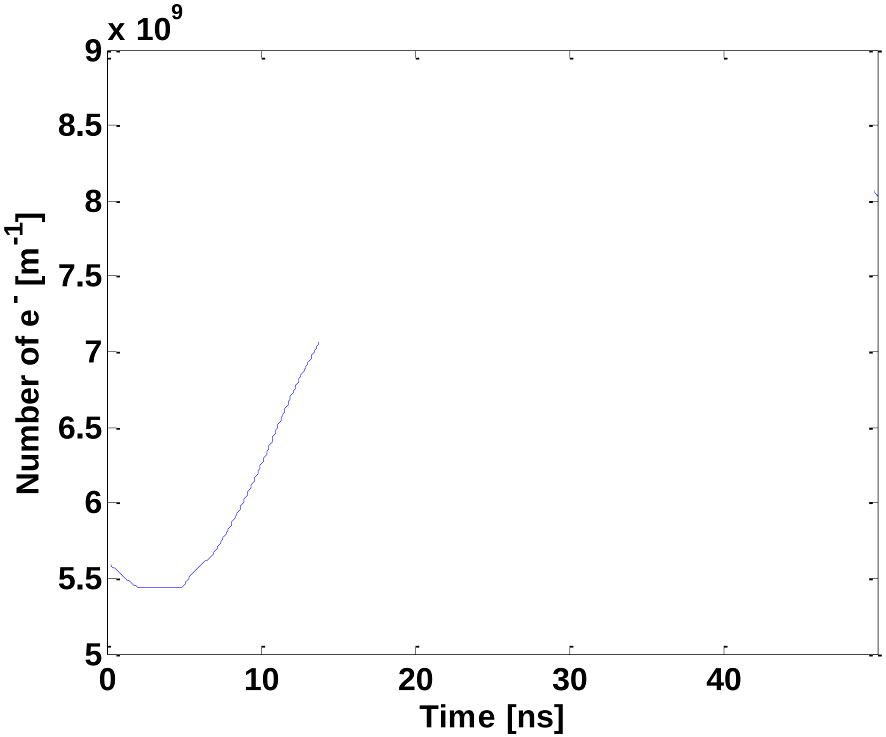

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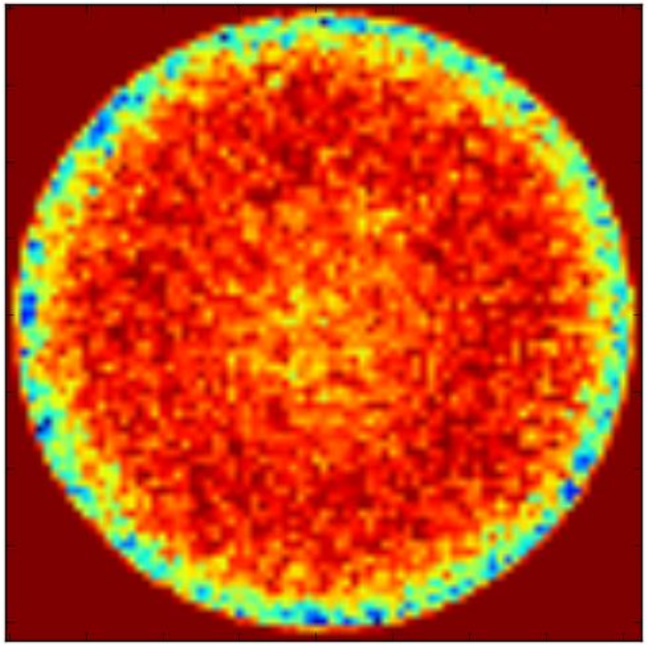

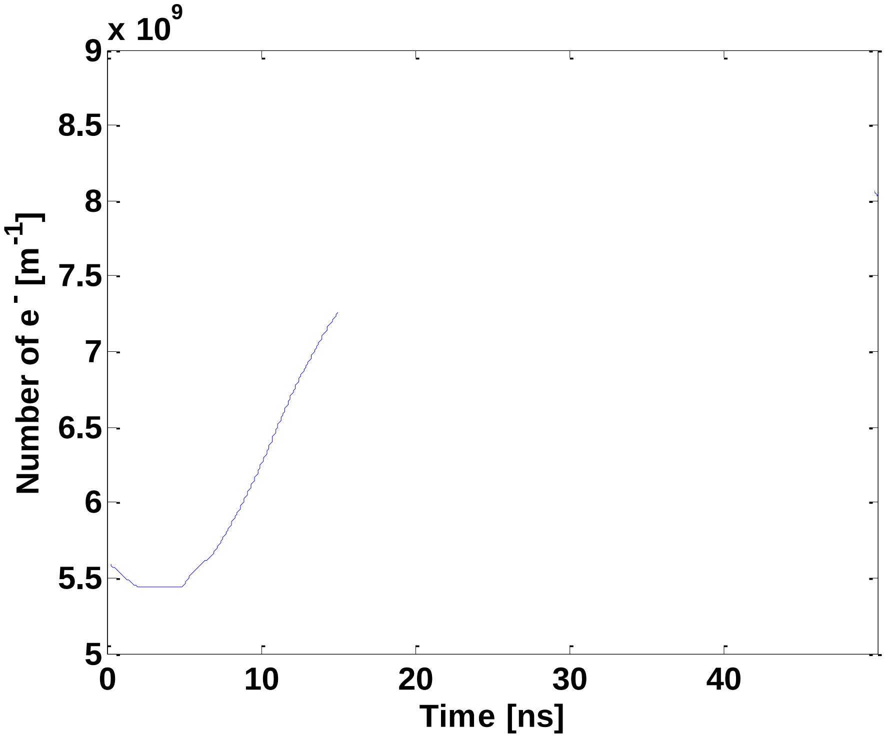

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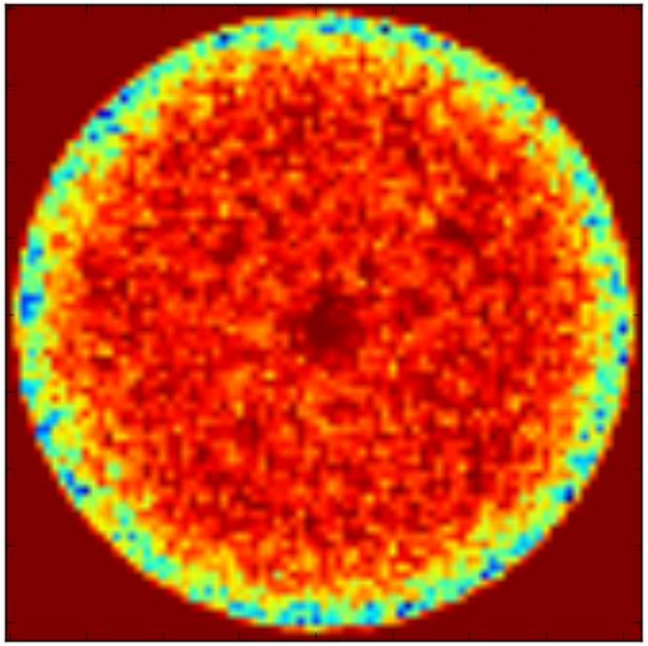

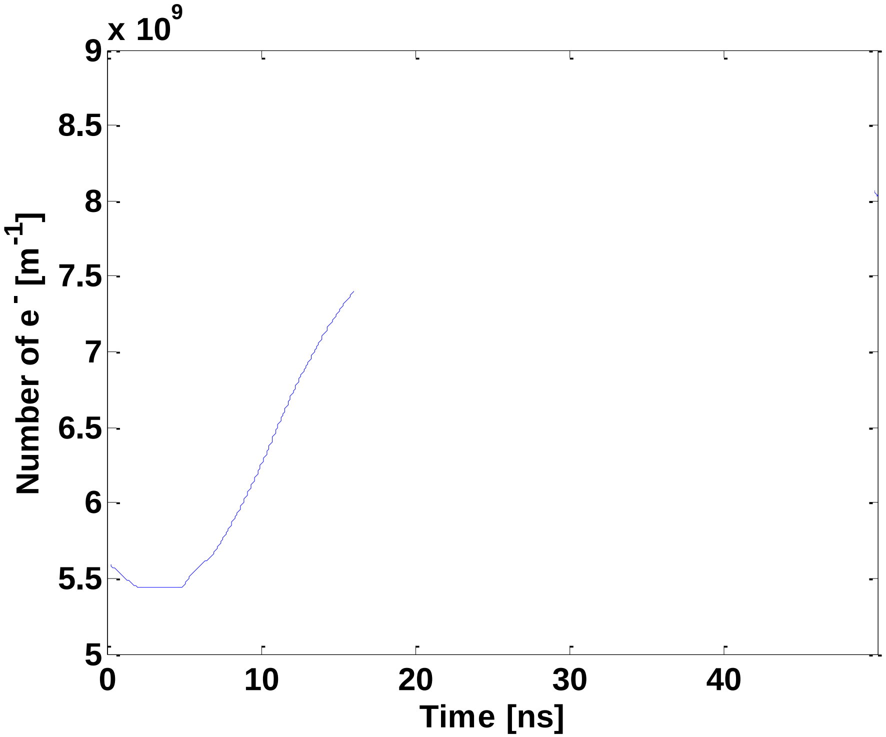

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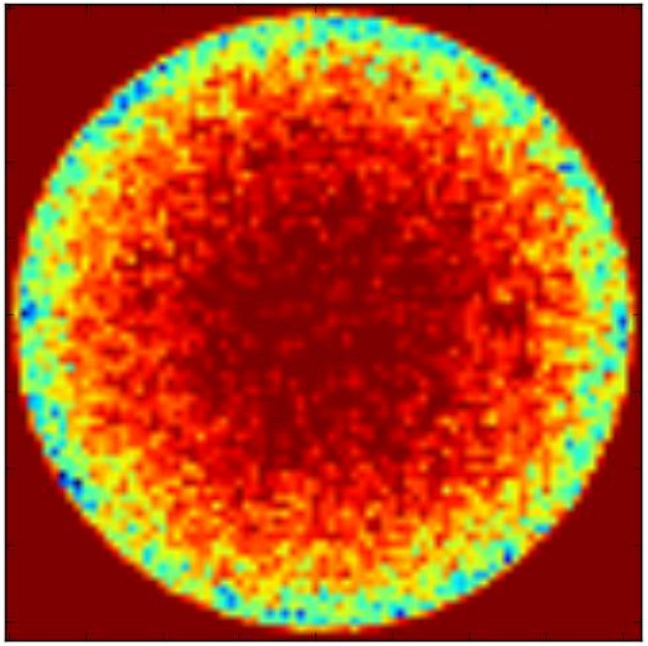

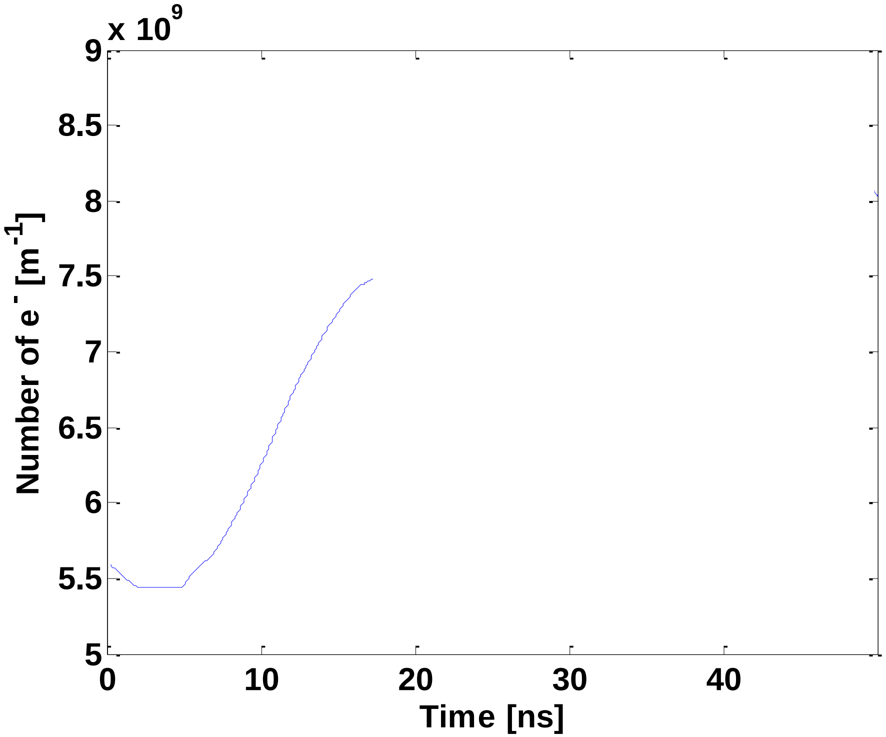

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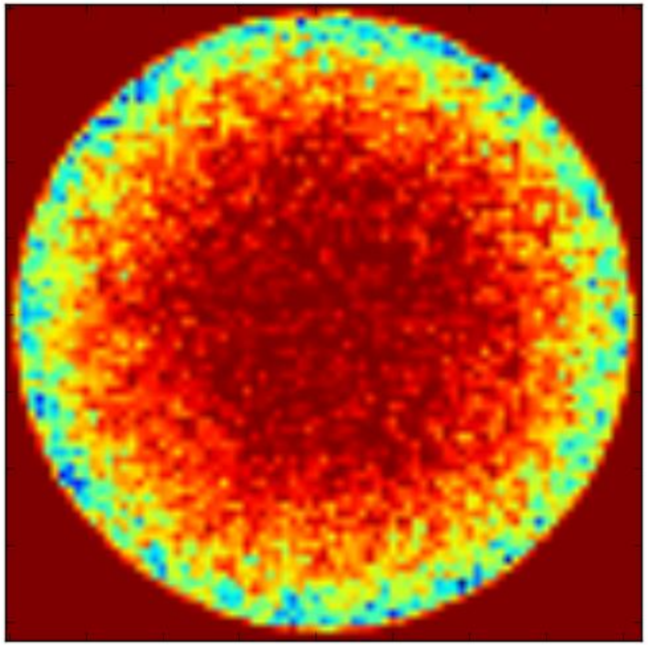

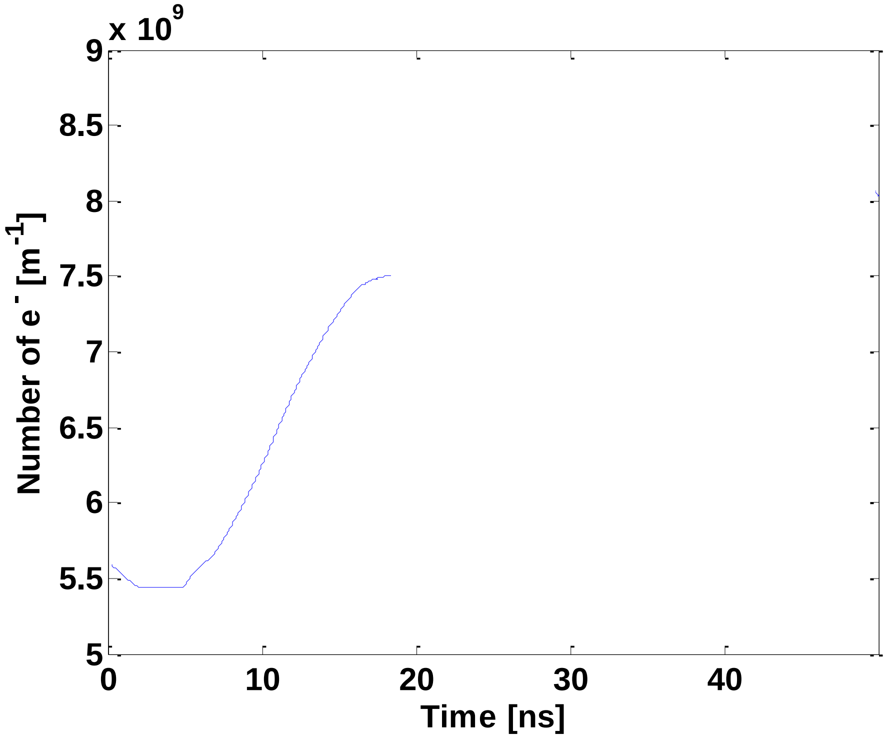

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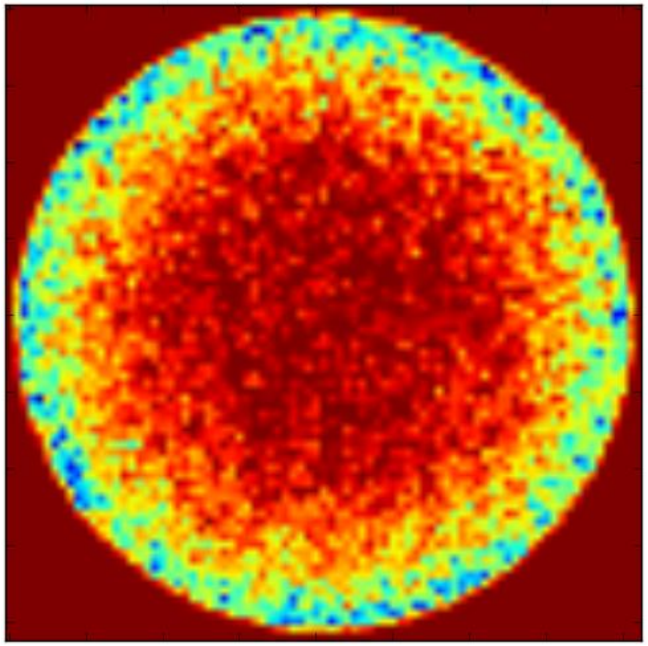

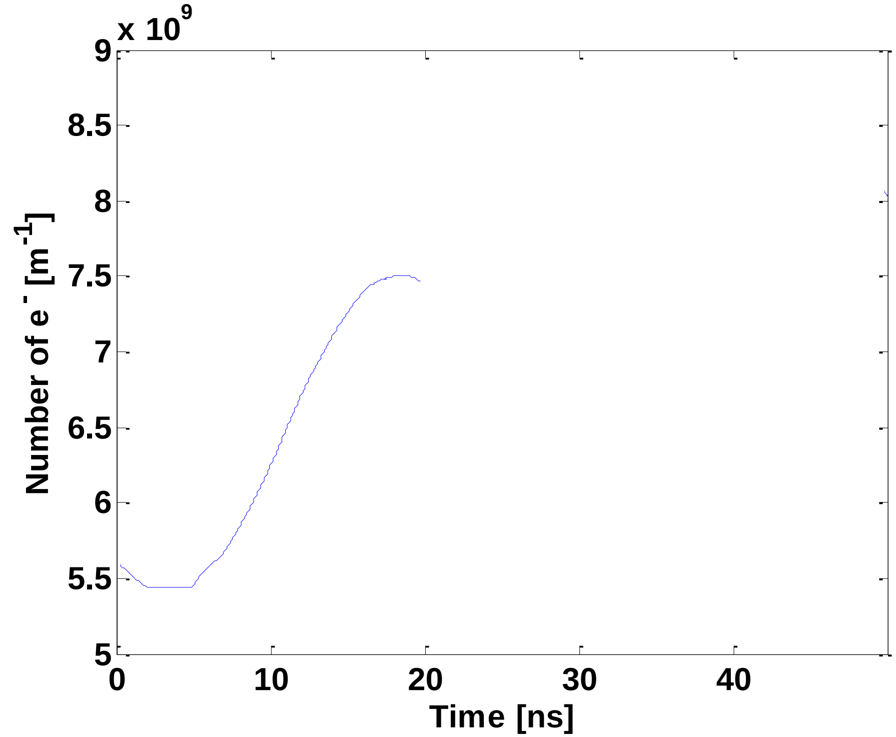

- Secondary electrons are emitted with **smaller energies (E~1eV)** and, if they **hit the wall before the following bunch passage, they are absorbed** without generation of further secondaries
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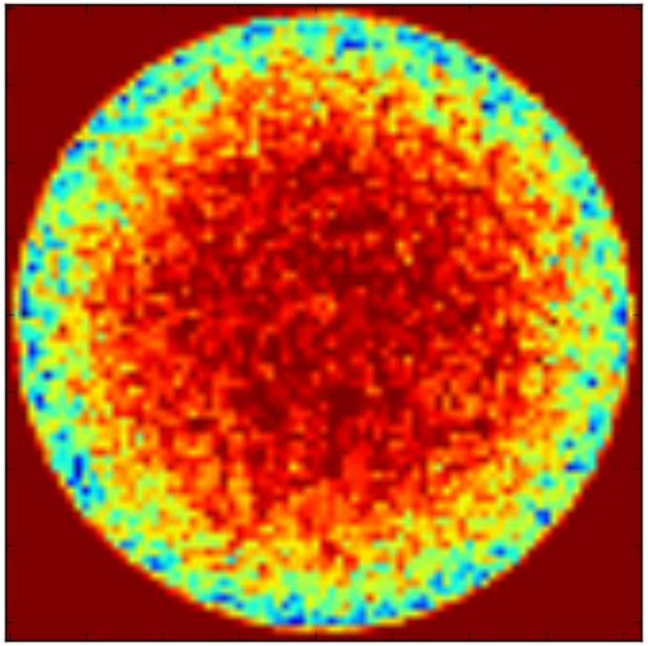

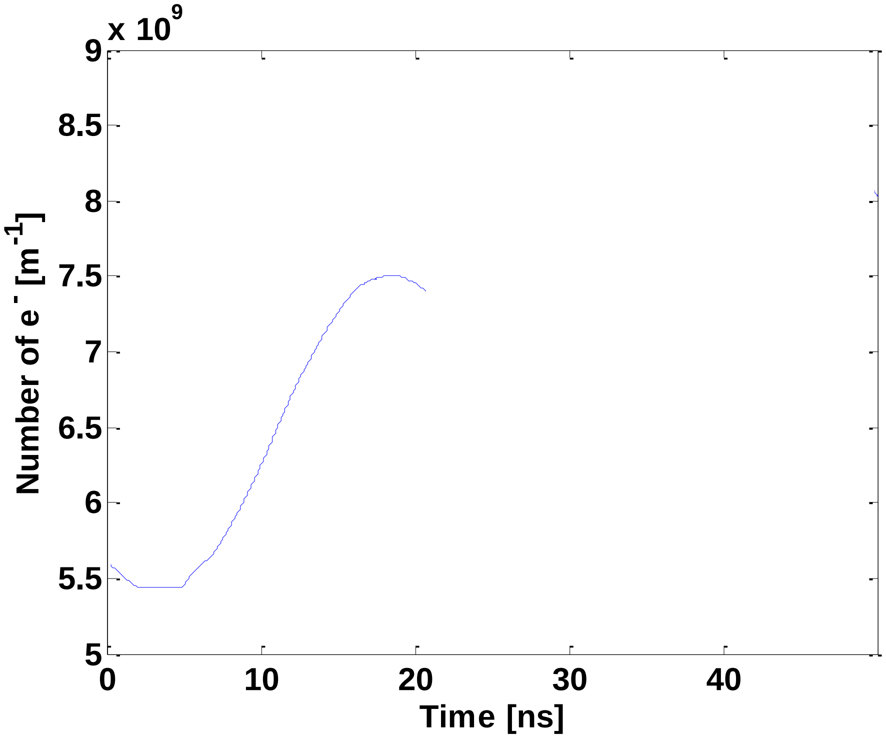

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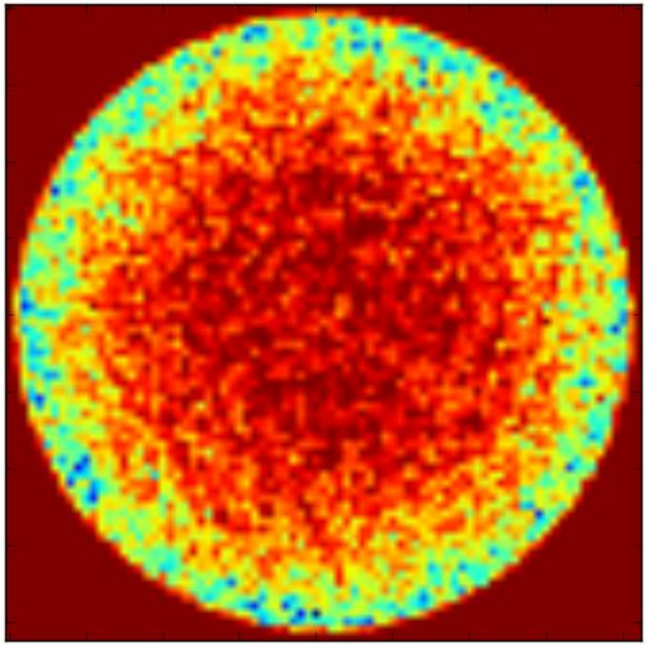

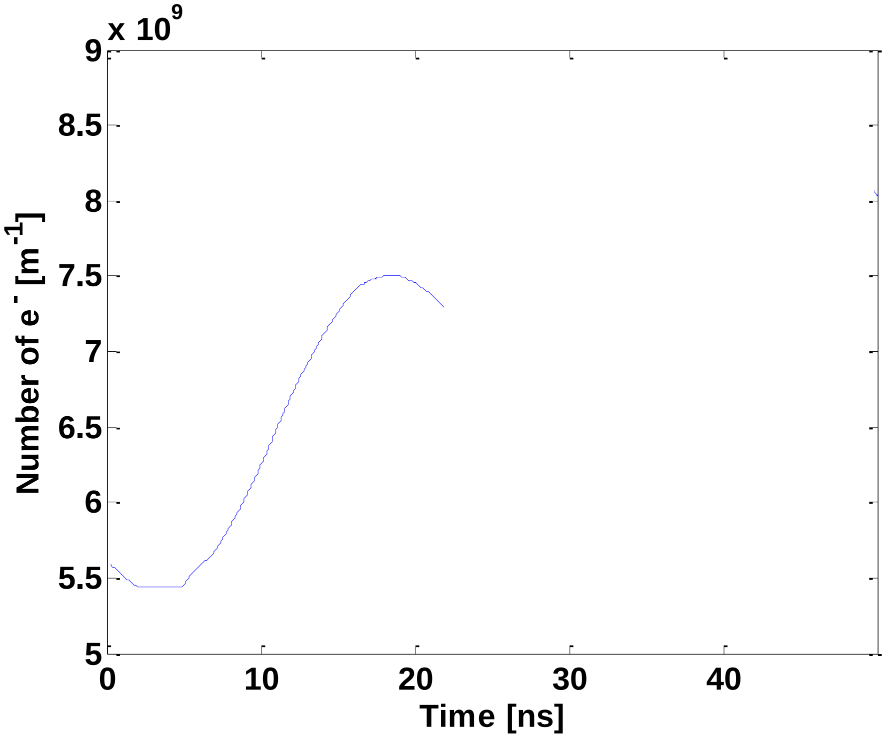

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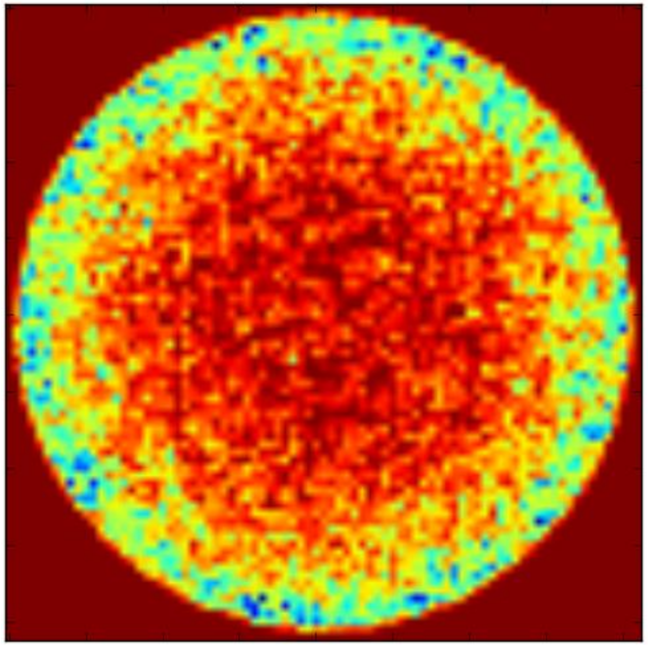

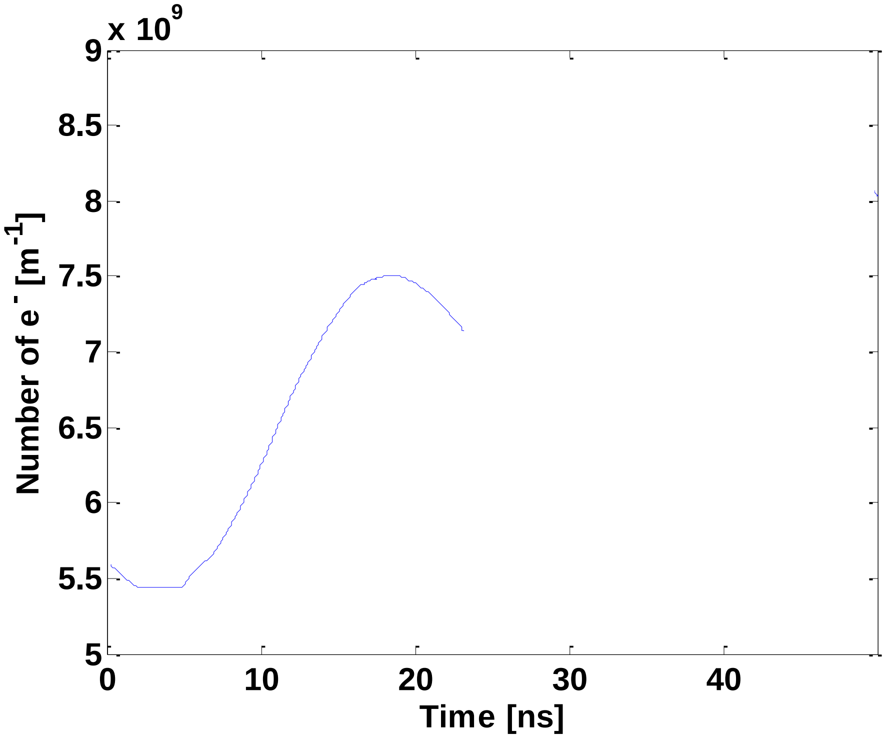

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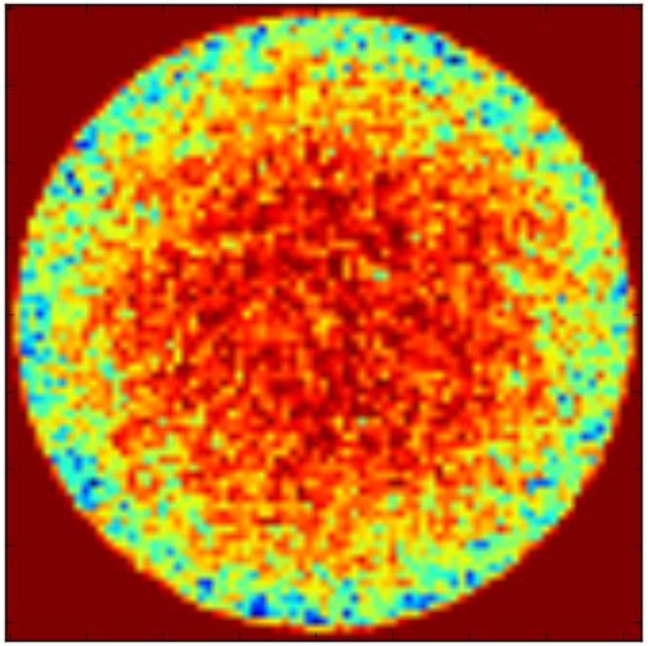

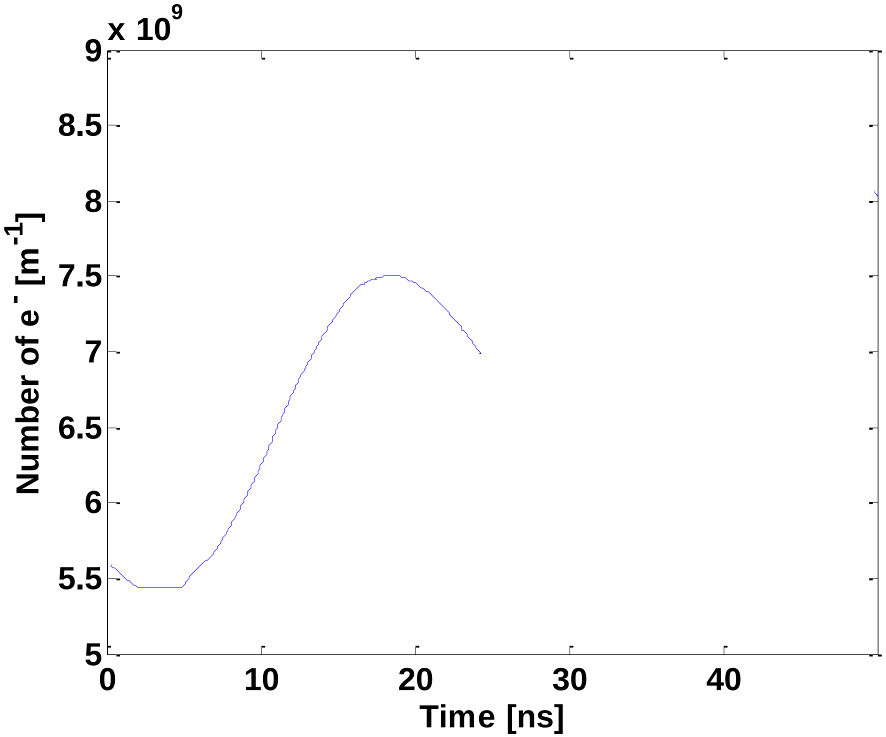

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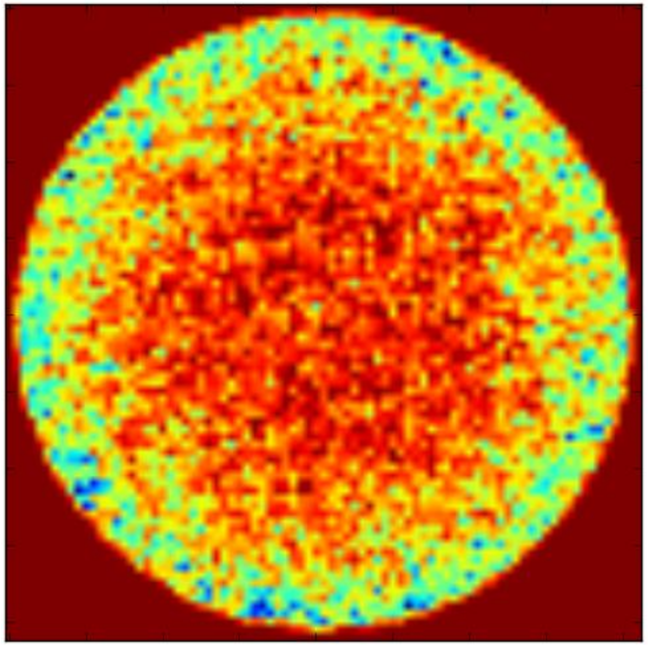

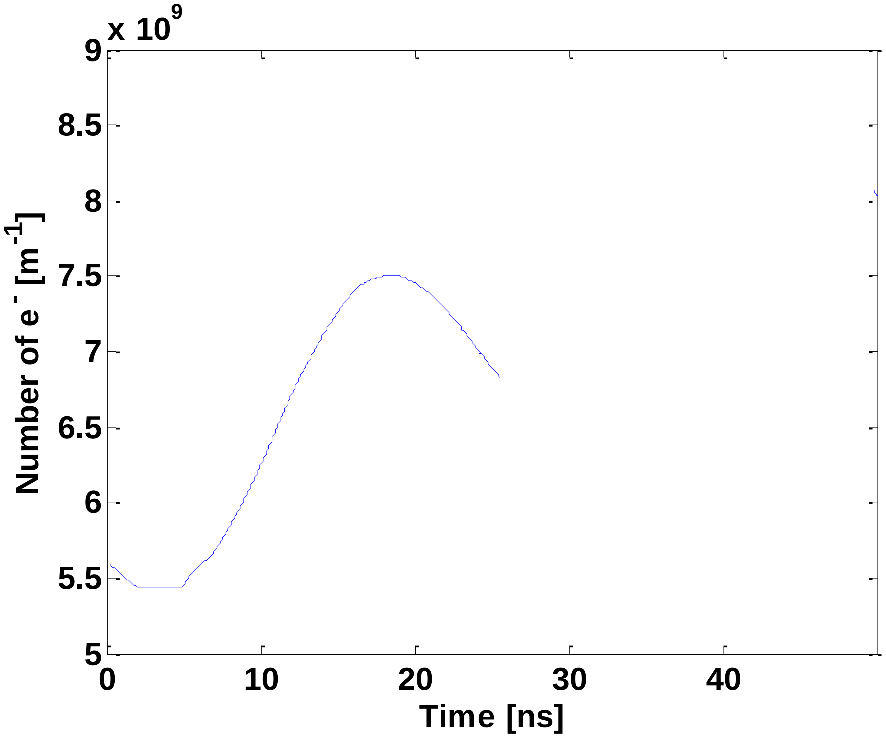

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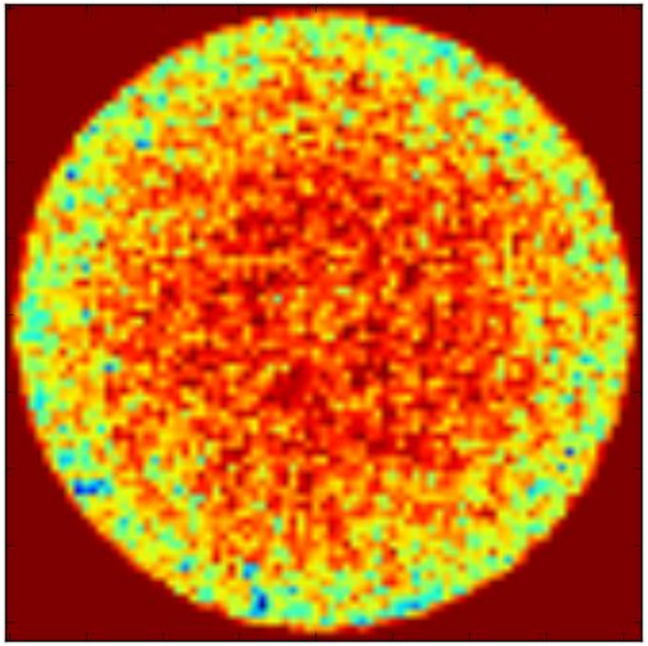

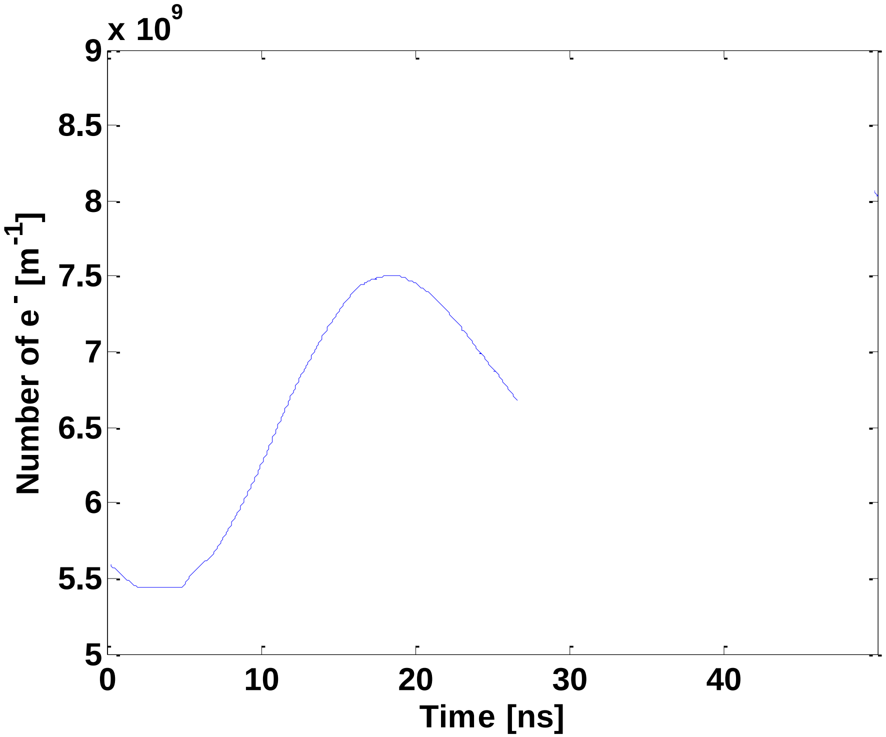

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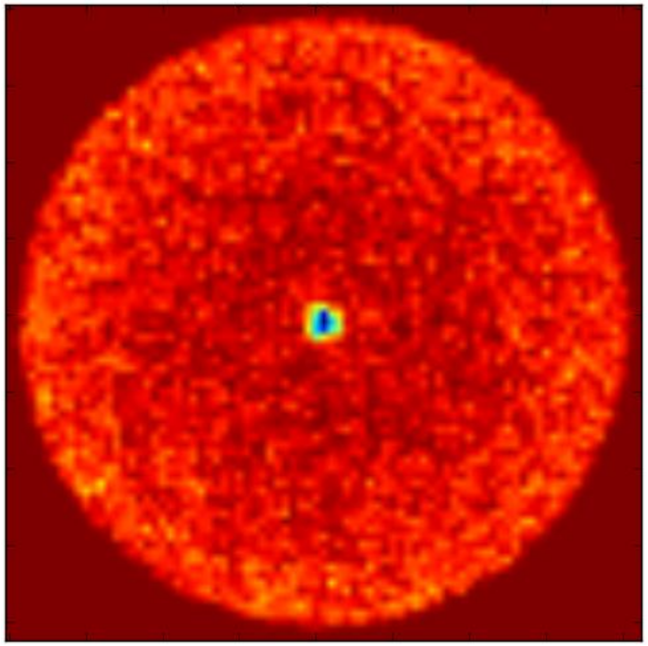

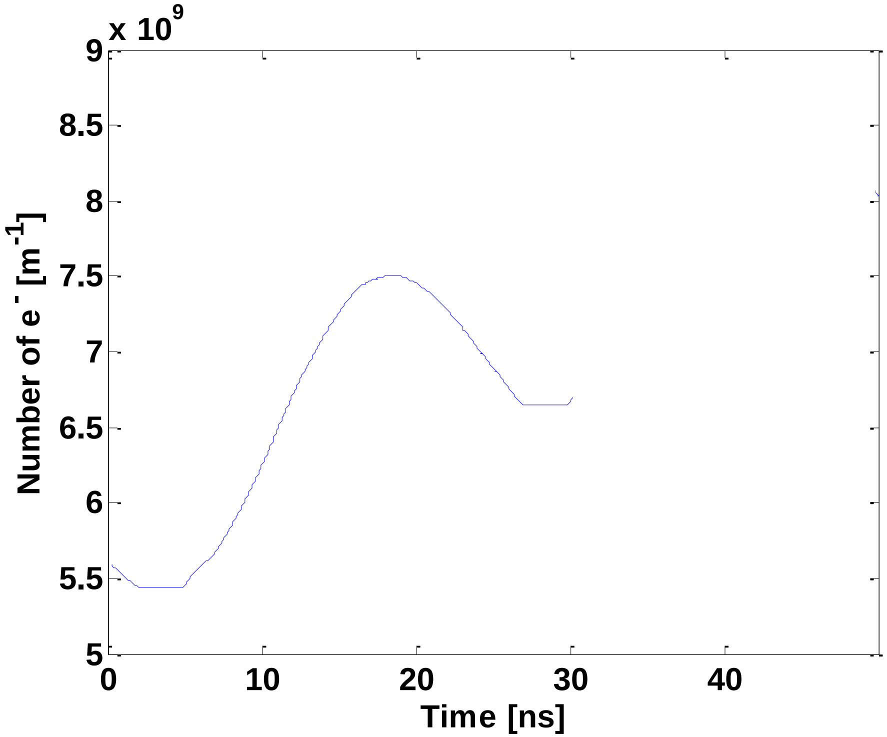

- **Another bunch passage can interrupt the decay** before reaching the initial value
- In these cases **avalanche multiplication** is observed between bunch passages

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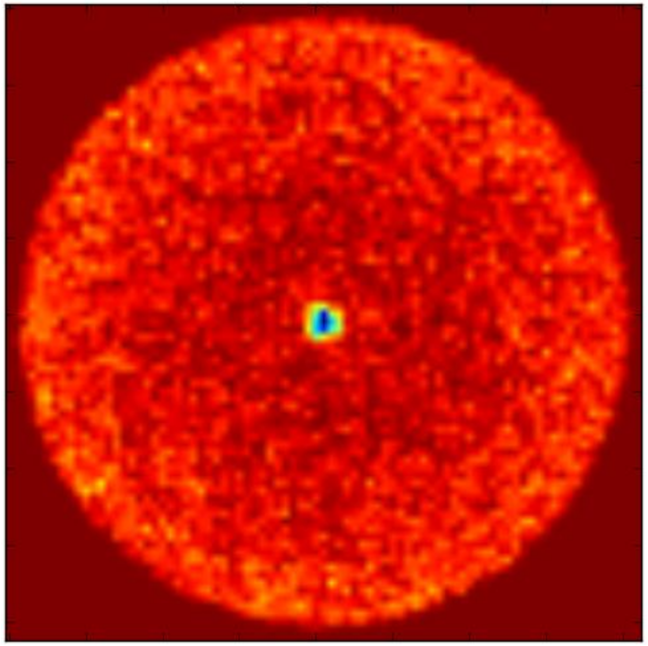

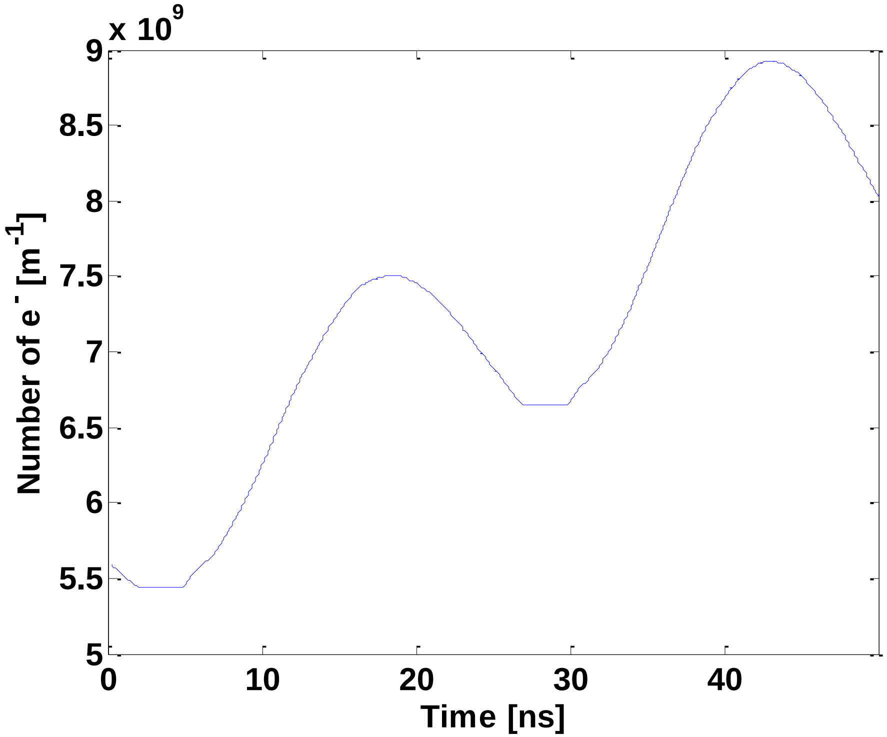

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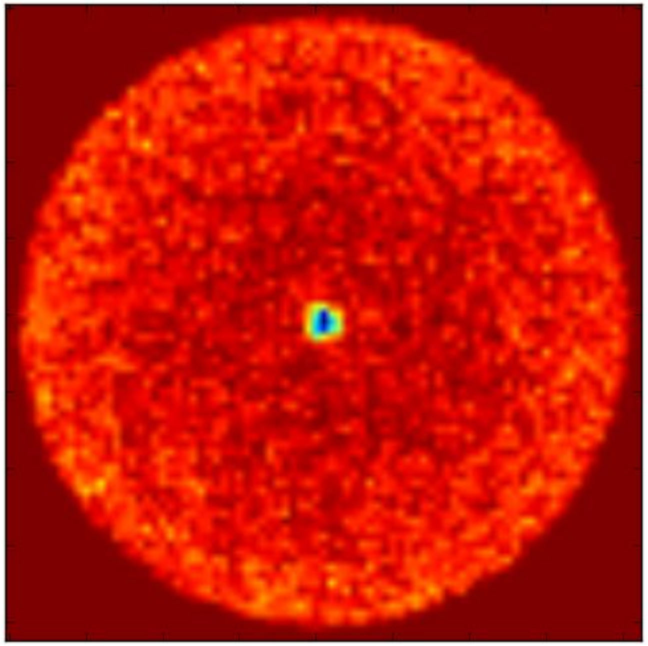
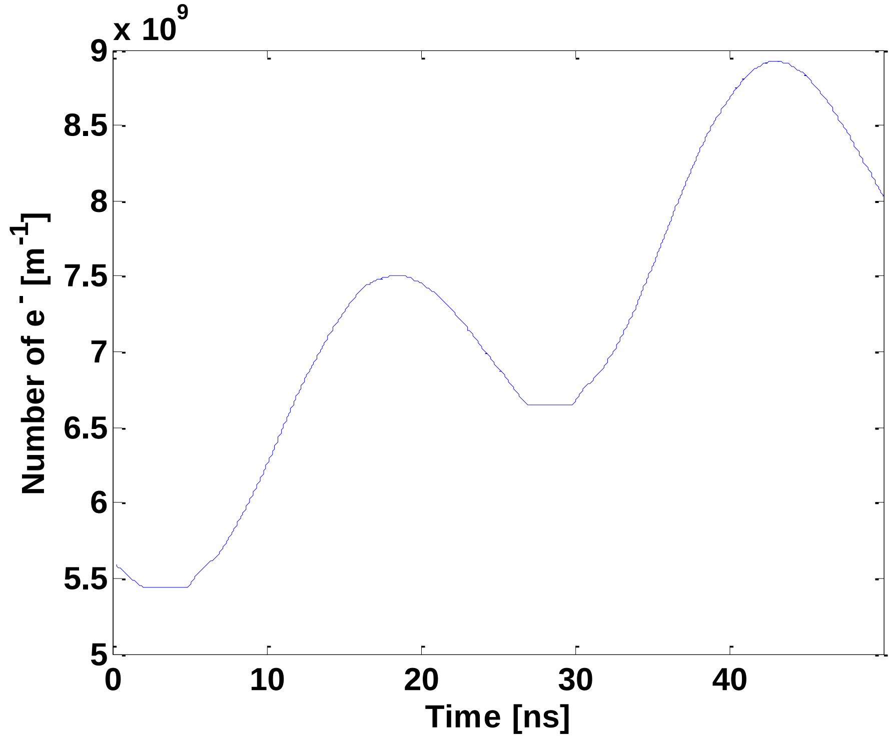
Electron cloud build-up

Beam pipe transverse cut





- **Strong impact on beam quality** (EC induced instabilities, particle losses, emittance growth)
- **Dynamic pressure rise**
- **Heat load** (on cryogenic sections)

Outline

- **Introduction on Electron Cloud Effect**
- **PyECLOUD:**
  - Overview
  - MP size management
  - Convergence and performances
- **PyECLOUD at work for LHC studies:**
  - SEY reconstruction from heat-load measurements
  - Benchmarking with stable phase shift measurements
  - PyECLOUD – HEADTDAIL simulation of EC induced instabilities

ECLOUD
• Developed at CERN since **1997** (mainly by F. Zimmermann, G. Bellodi, O. Bruning, G. Rumolo, D. Schulte)
• Pioneering work which defined a **physical model for the EC build-up**
• **FORTRAN 77** code
• **Scarcely modular** (difficult to maintain, develop and debug)

From ECLOUD to PyECLOUD

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• **FORTRAN 77** code	• **Python** code
• **Scarcely modular** (difficult to maintain, develop and debug)	• **Strongly modular** (much easier to develop and maintain)
	• **Several improvements** introduced with better performances in terms of **reliability, accuracy, efficiency, and flexibility**

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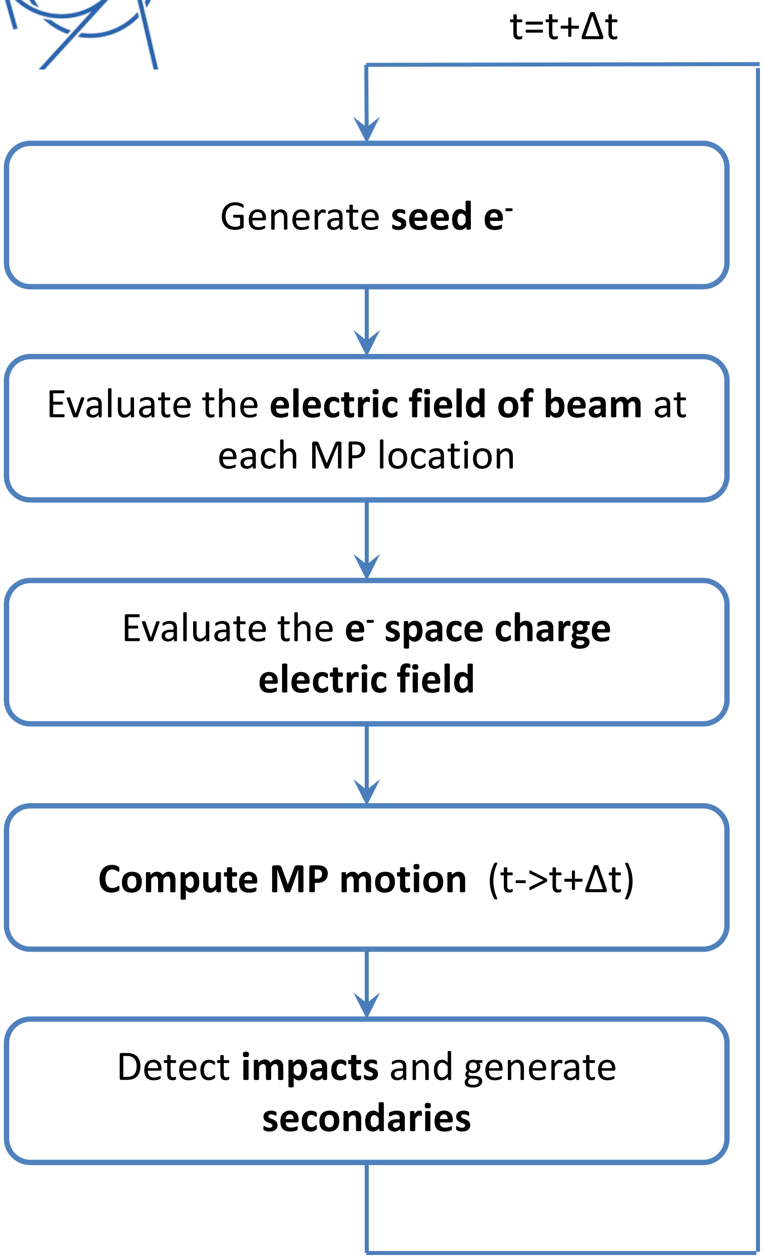
PyECLOUD flowchart



PyECLOUD is a **2D macroparticle (MP) code** for the simulation of the **electron cloud build-up** with:

- **Arbitrary shaped chamber**
- **Ultra-relativistic beam**
- **Externally applied (uniform) magnetic field**

PyECLOUD flowchart

t=t+Δt

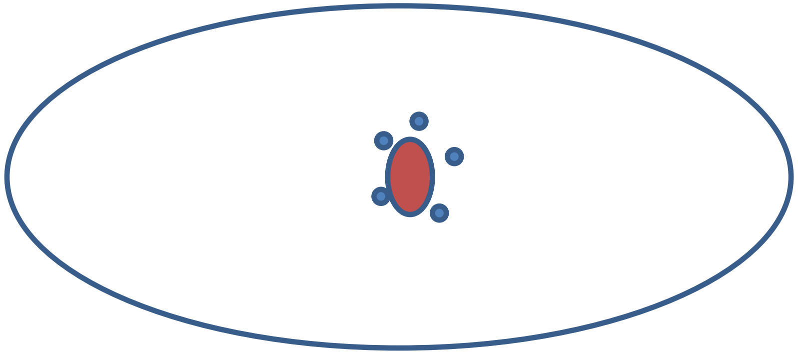
Generate **seed e⁻**

Evaluate the **electric field of beam** at each MP location

Evaluate the **e⁻ space charge electric field**

Compute MP motion (t->t+Δt)

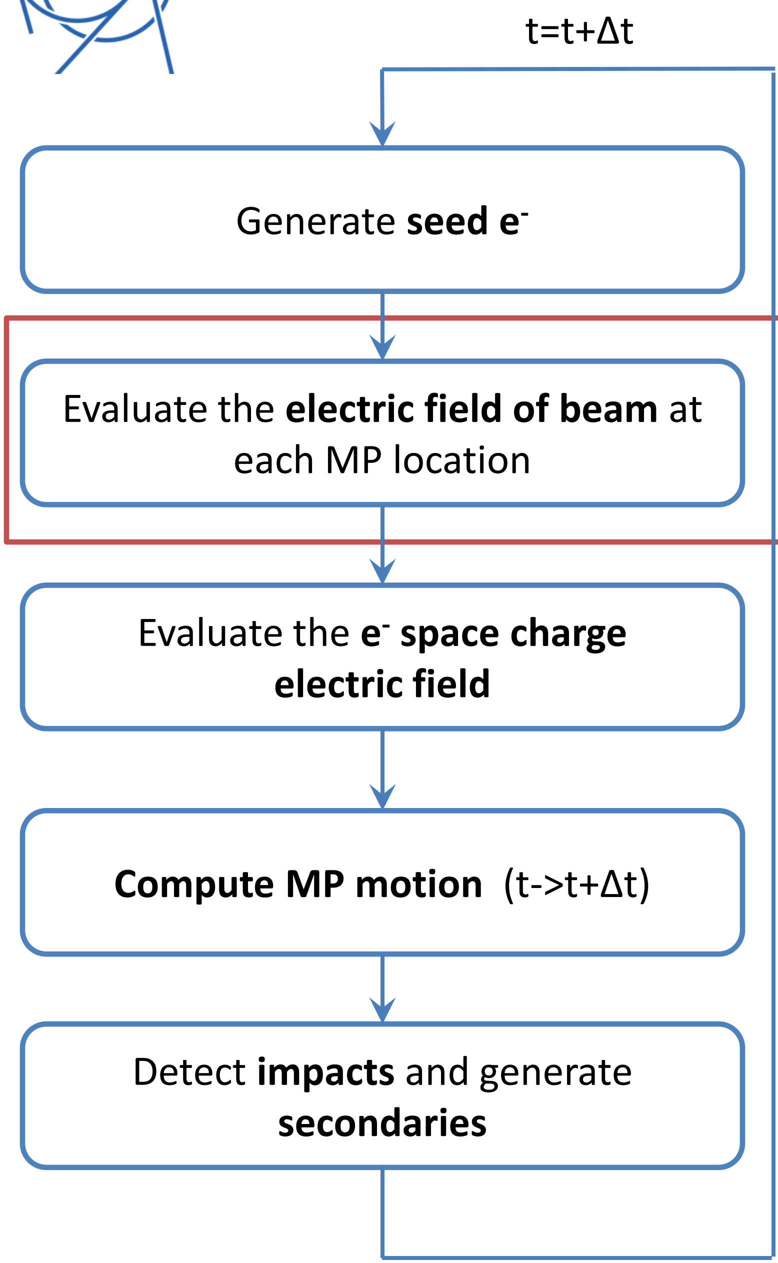
Detect **impacts** and generate **secondaries**

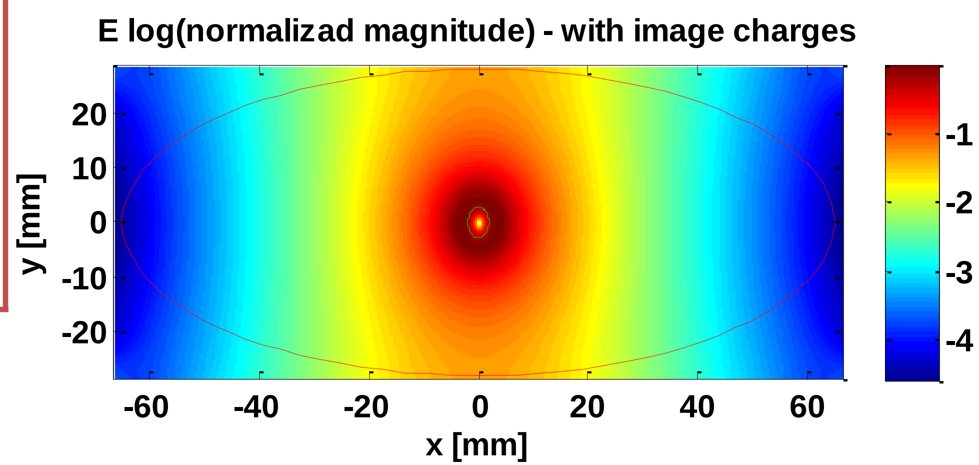


Evaluate the number of **seed e⁻** generated during the current time step and **generate the corresponding MP**:

- **Residual gas ionization** and **photoemission** are implemented

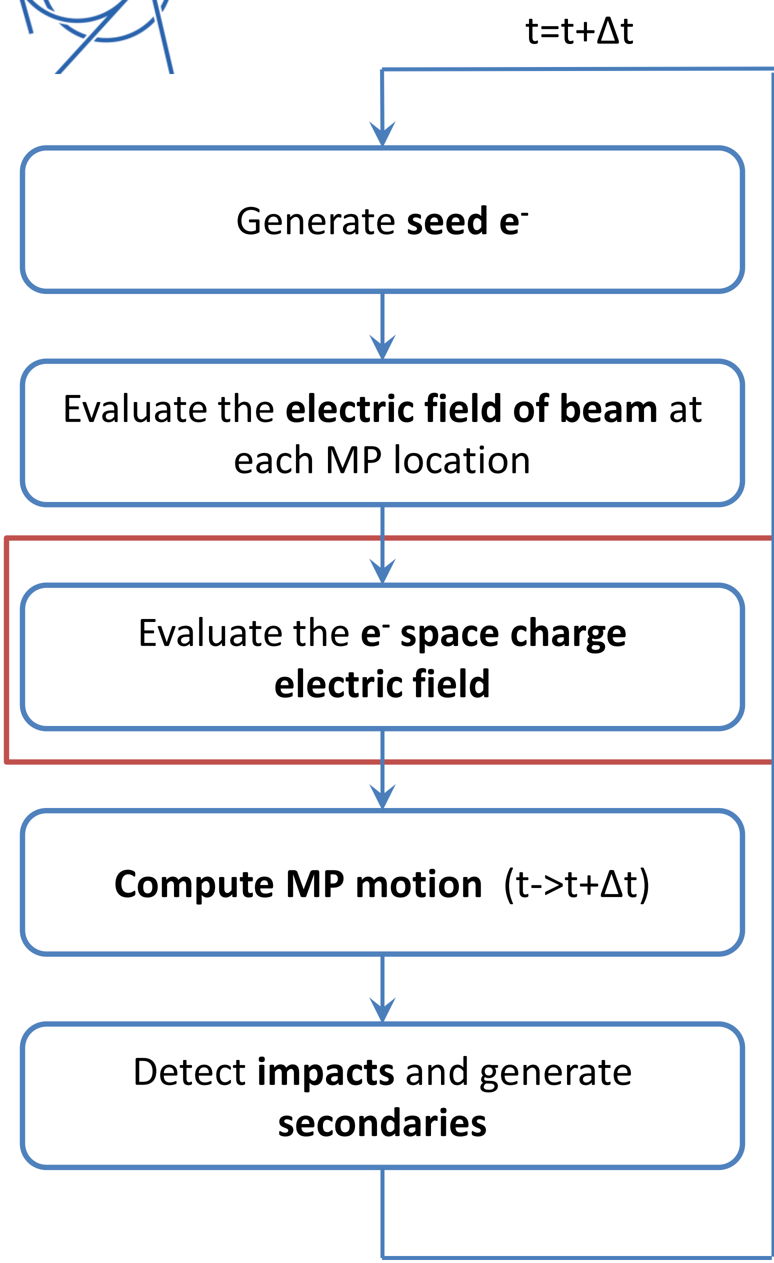
PyECLOUD flowchart

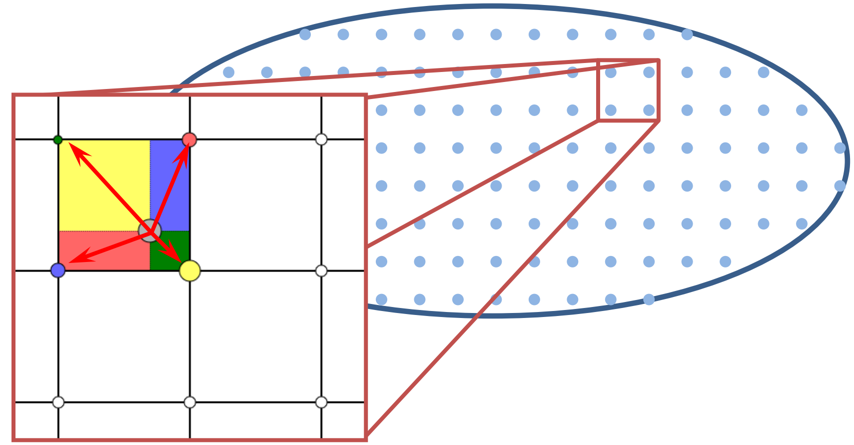




- The **field map** for the relevant chamber geometry and beam shape is **pre-computed on a suitable rectangular grid and loaded from file** in the initialization stage
- When the field at a certain location is needed a **linear (4 points) interpolation algorithm** is employed

PyECLOUD flowchart

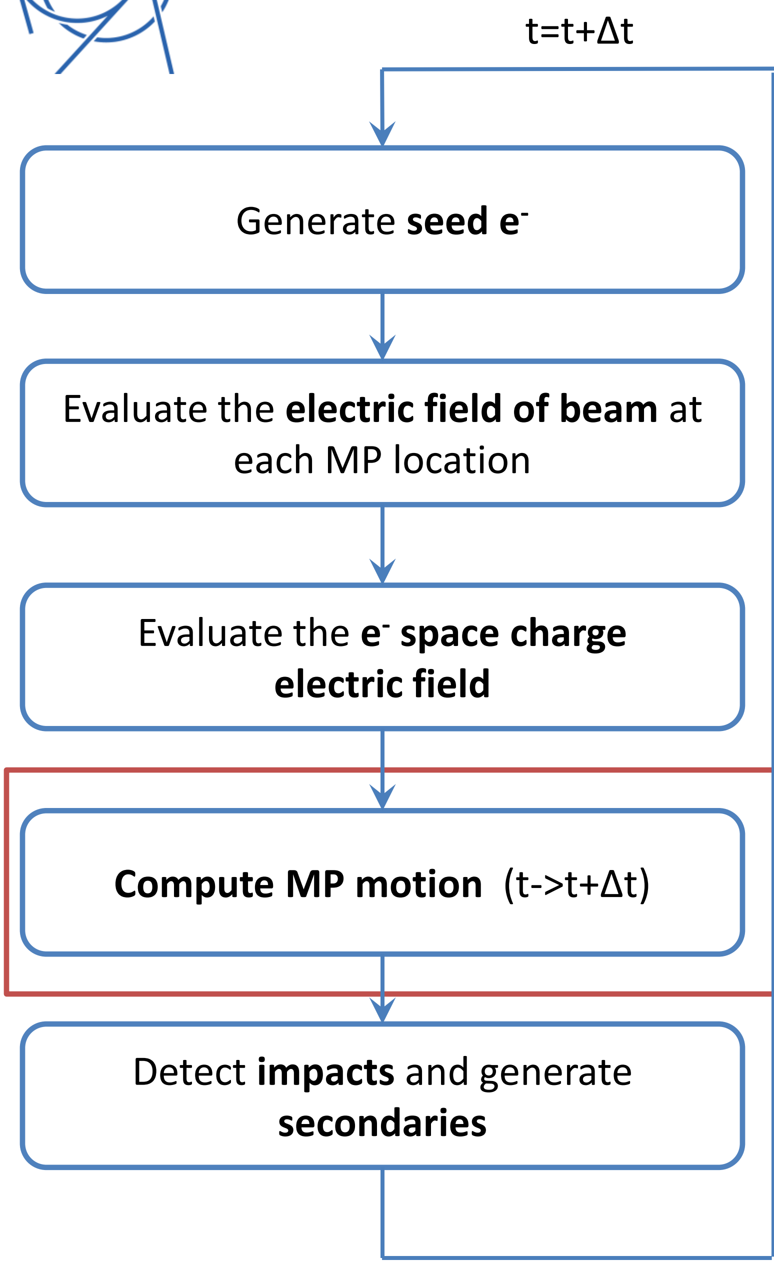


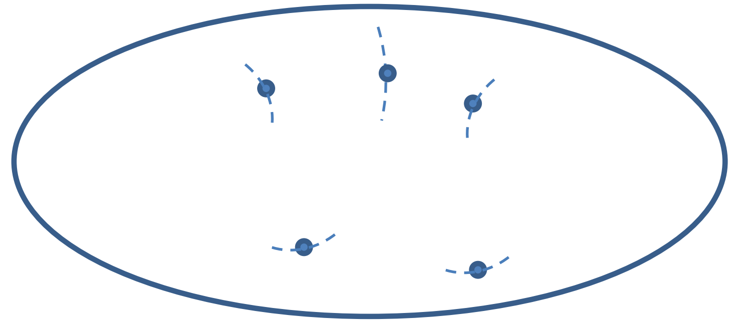


Classical **Particle In Cell (PIC) algorithm:**

- **Electron charge density** distribution ρ(x,y) computed **on a rectangular grid**
- Poisson equation solved using **finite difference method**
- Field at MP location evaluated through **linear (4 points) interpolation**

PyECLOUD flowchart





The dynamics equation is integrated in order to **update MP position and momentum**:

$$\frac{d\mathbf{v}(t)}{dt} = -\frac{q}{m}\left[\mathbf{v}(t) \times \mathbf{B}\left(\mathbf{r}(t), t\right) + \mathbf{E}\left(\mathbf{r}(t), t\right)\right]$$

PyECLOUD flowchart

t=t+Δt

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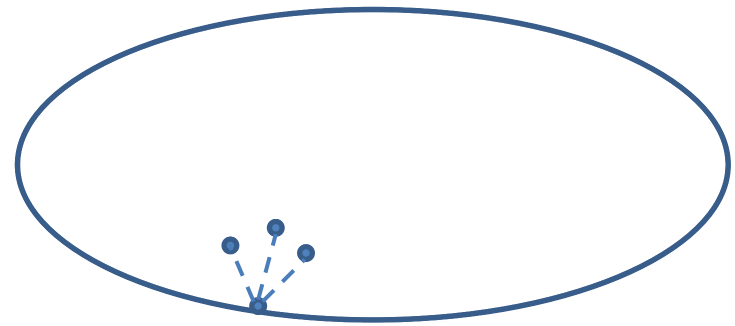

- When a MP hits the wall theoretical/empirical models are employed to generate **charge, energy and angle of the emitted charge**
- According to the number of emitted electrons, MPs can be **simply rescaled** or **new MP can be generated**

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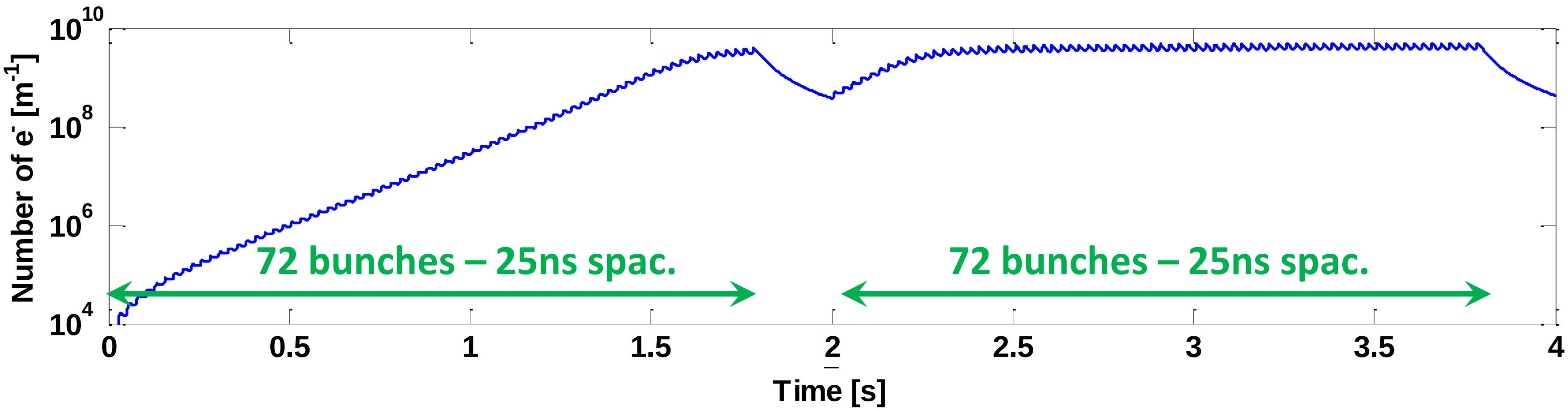
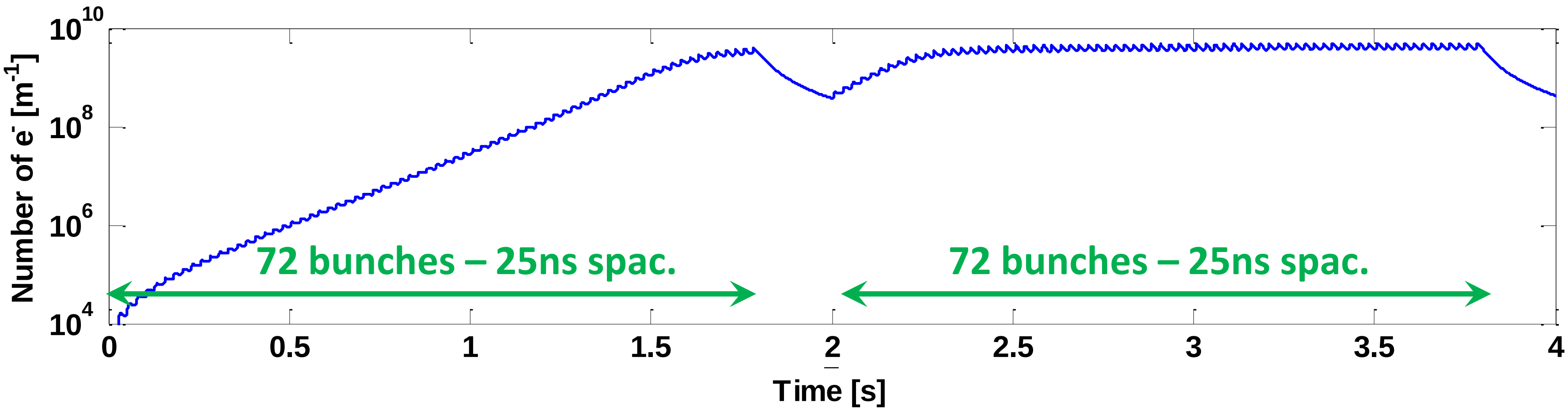
Macroparticle size management

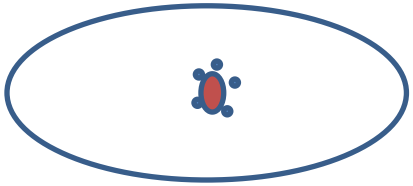


- In an electron-cloud buildup, due to the multipacting process, **the electron number extends over several orders of magnitude**
- It is practically **impossible to choose a MP size that is suitable for the entire simulation** (allowing a satisfactory description of the phenomenon and a computationally affordable number of MPs)

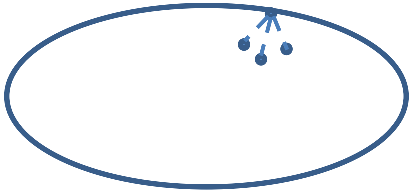
Macroparticle size management



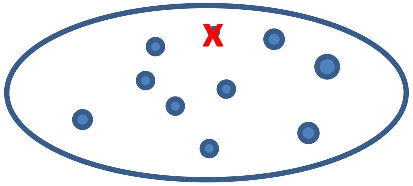
A **reference MP size N_{ref}** is used to **"take decisions"**:



1) **Seed MP generation:** the generated MPs have size N_{ref}



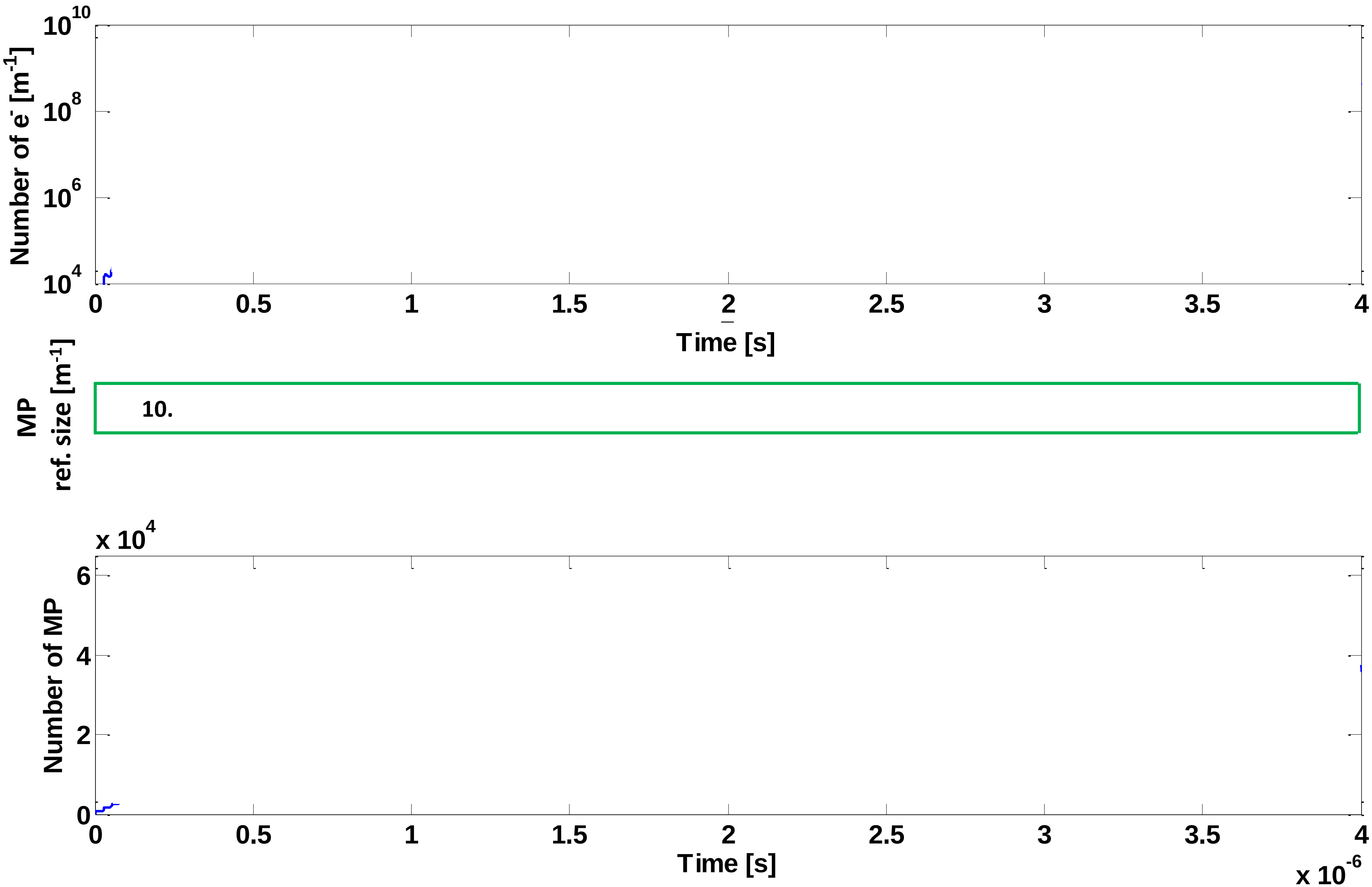
2) **Secondary MP emission**: additional true secondary MPs are emitted if the total emitted charge is $>1.5N_{ref}$



3) **MP cleaning**: at each bunch passage a clean function is called to eliminate all the MPs with charge $<10^{-4}N_{ref}$

Macroparticle size management

The **reference MP size N_{ref}** is adaptively changed during the simulation:



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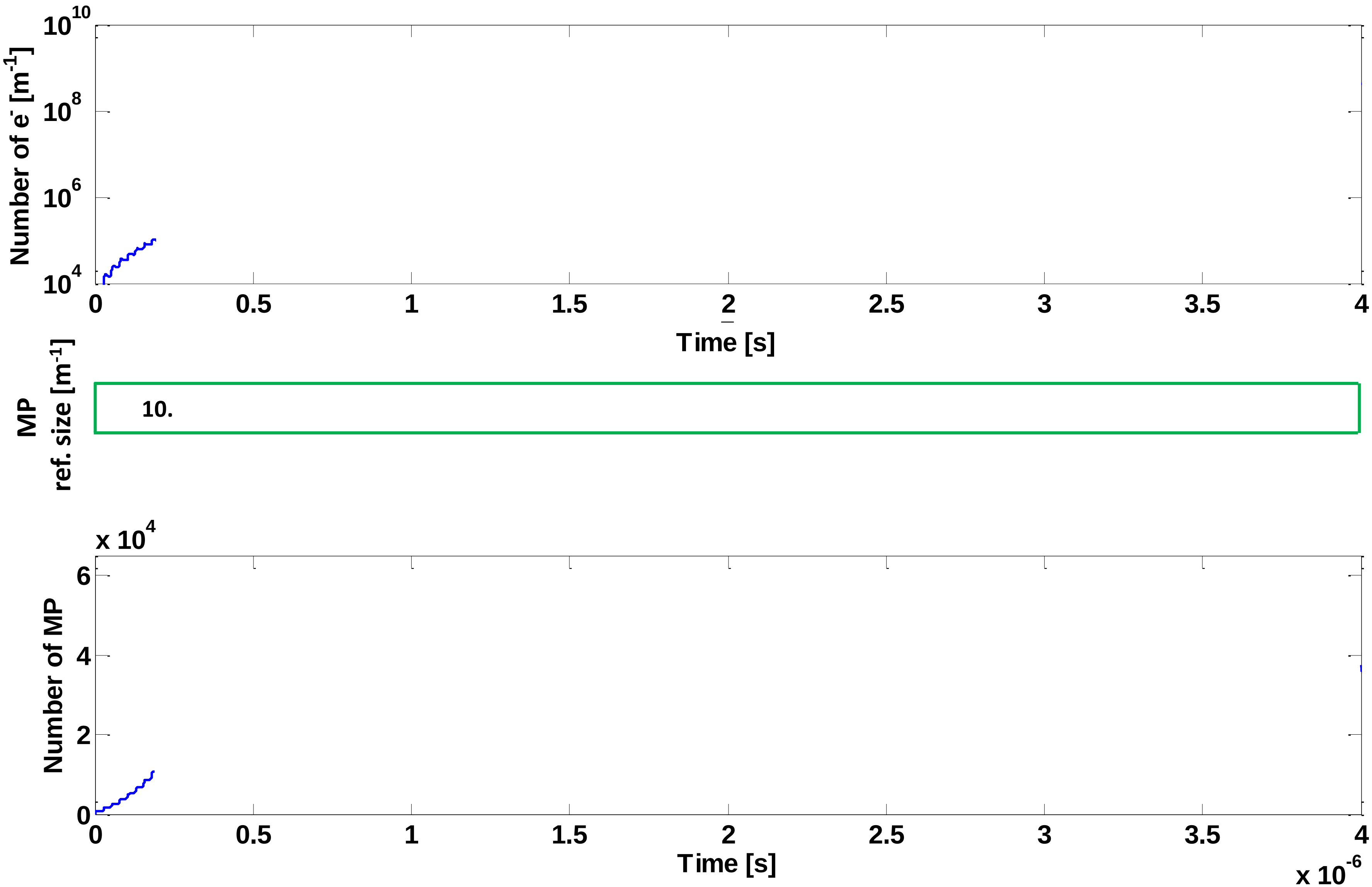

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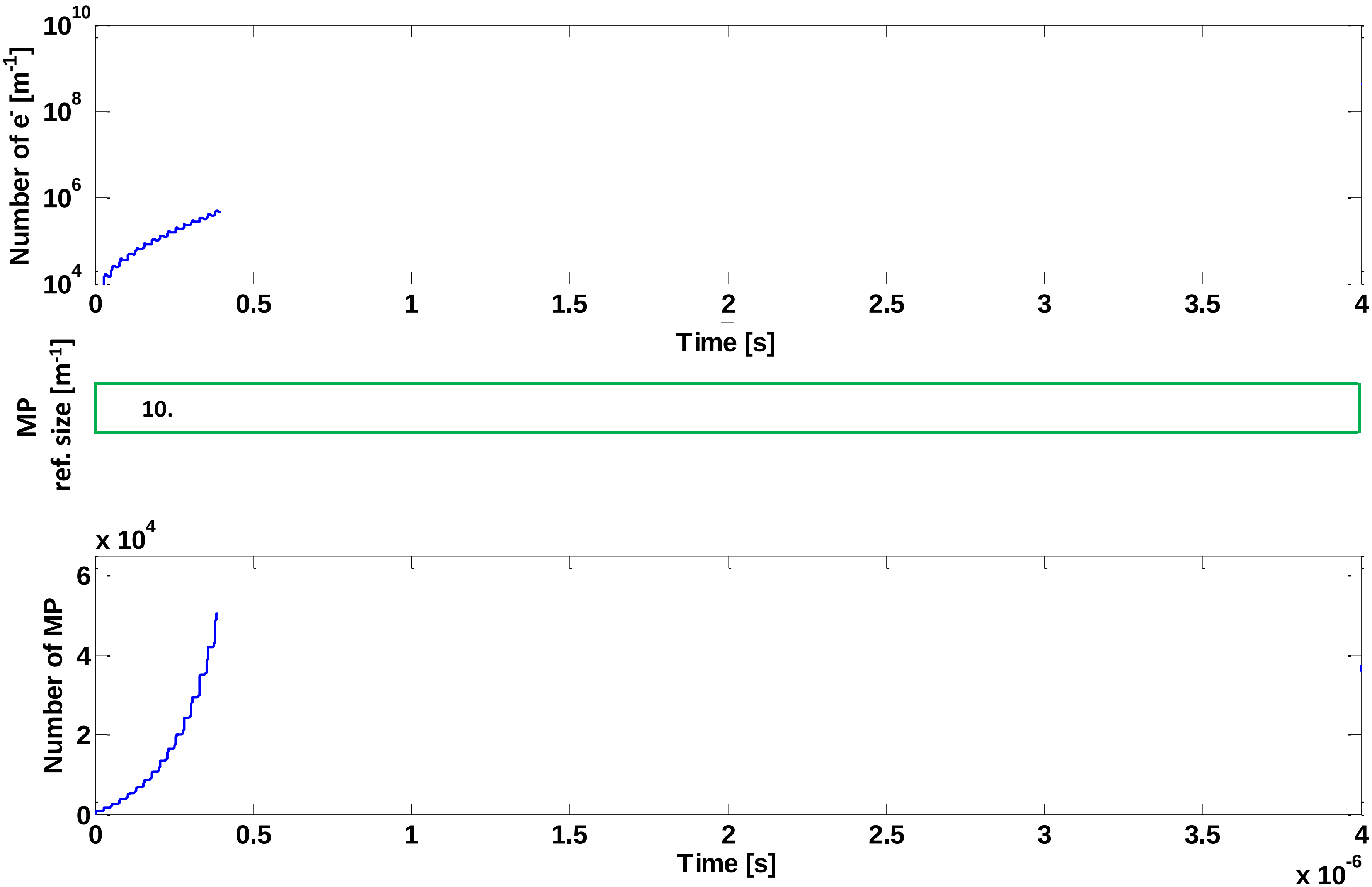

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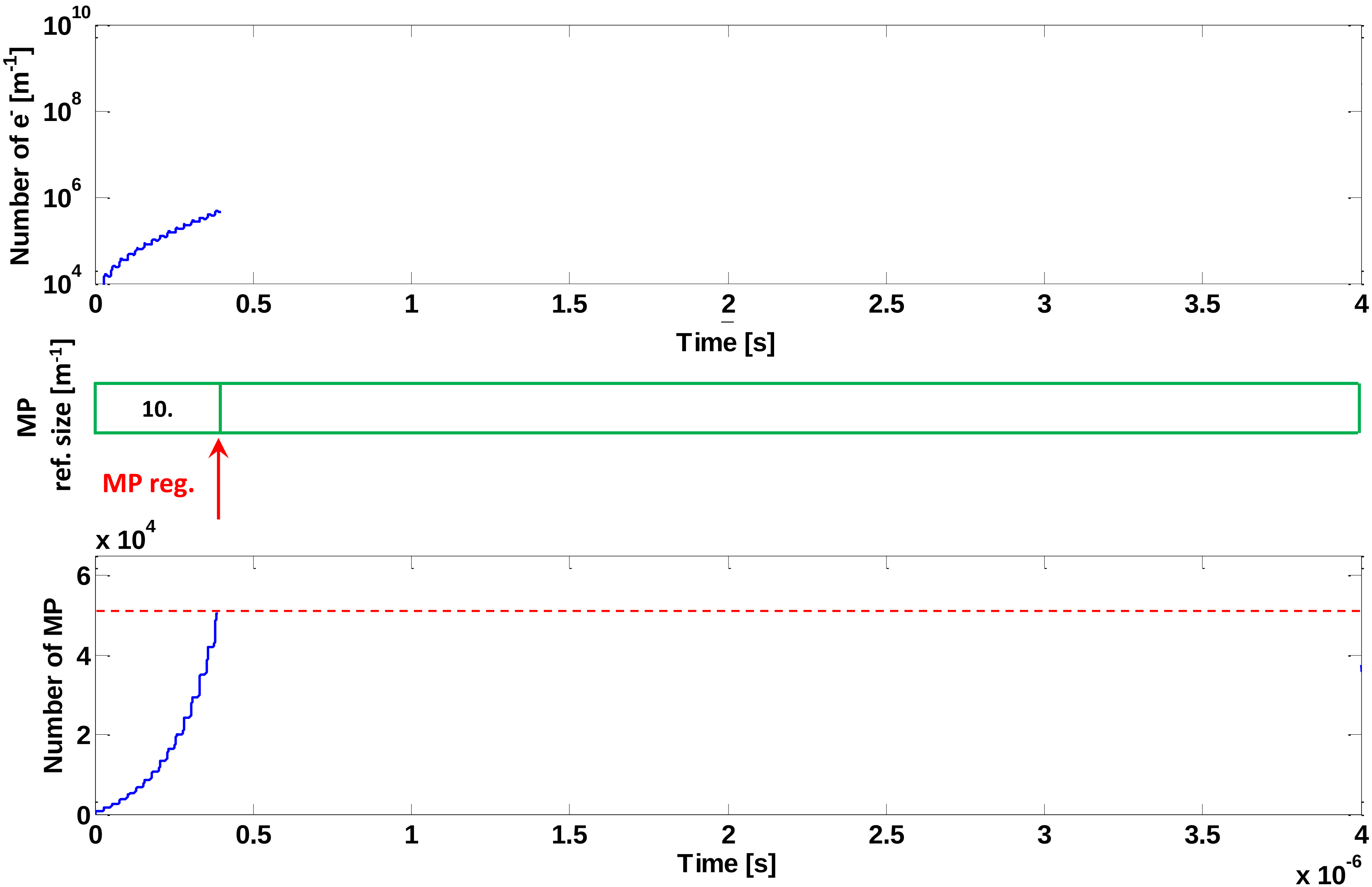

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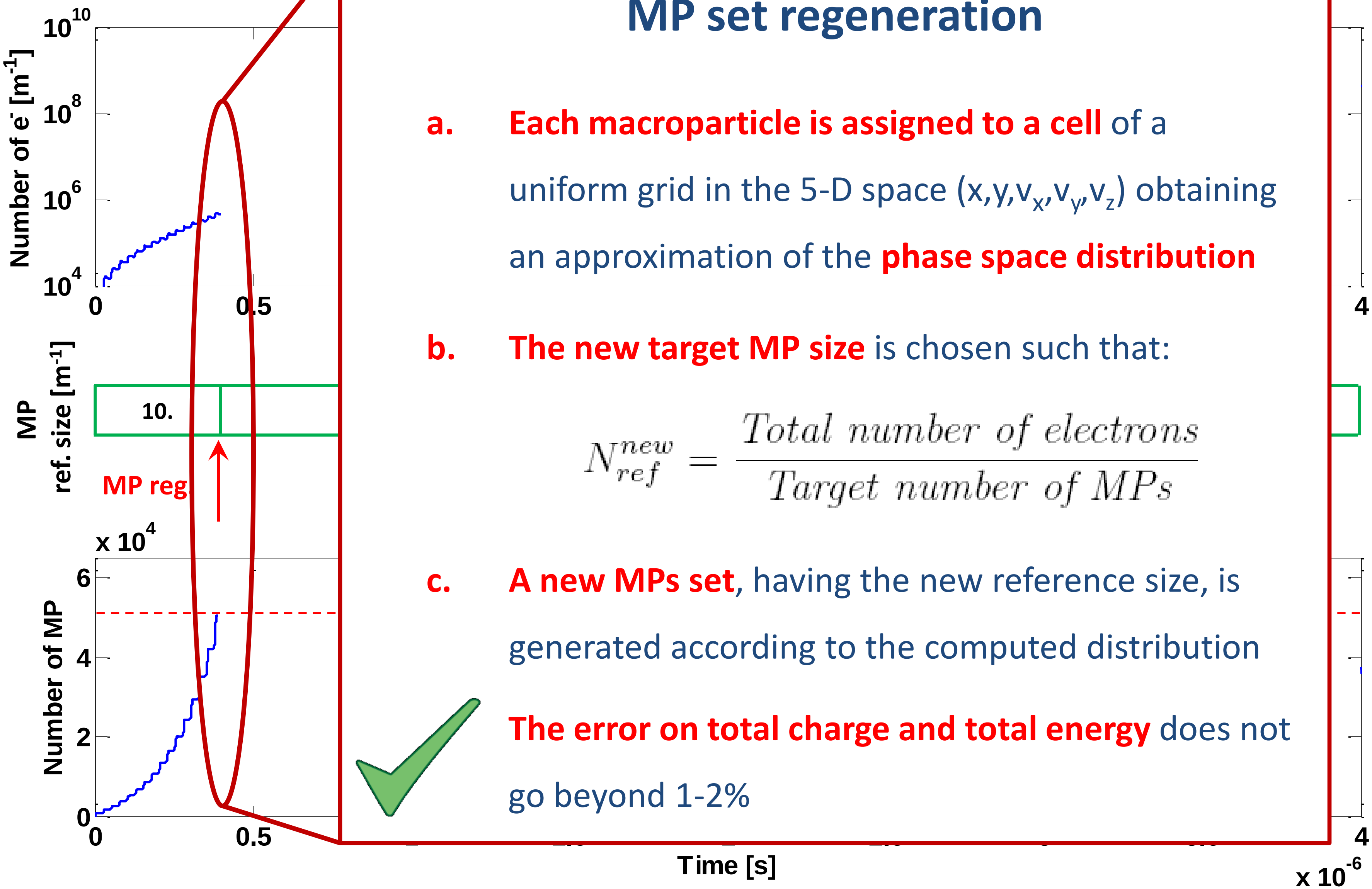

MP set regeneration

a. **Each macroparticle is assigned to a cell** of a uniform grid in the 5-D space (x,y,v_x,v_y,v_z) obtaining an approximation of the **phase space distribution**

b. **The new target MP size** is chosen such that:

$$N_{ref}^{new} = \frac{Total\ number\ of\ electrons}{Target\ number\ of\ MPs}$$

c. **A new MPs set**, having the new reference size, is generated according to the computed distribution

✔ **The error on total charge and total energy** does not go beyond 1-2%

Macroparticle size management

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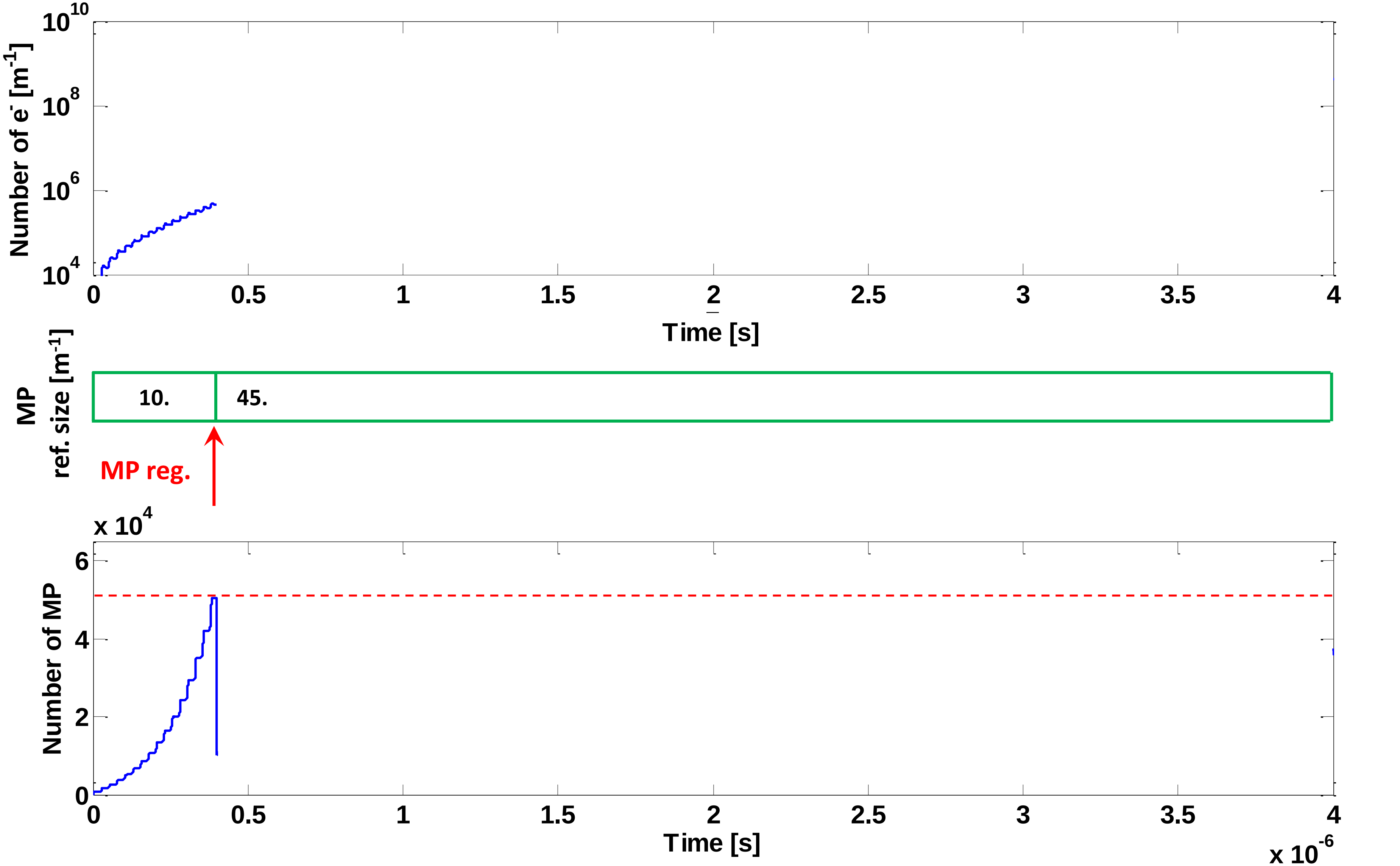

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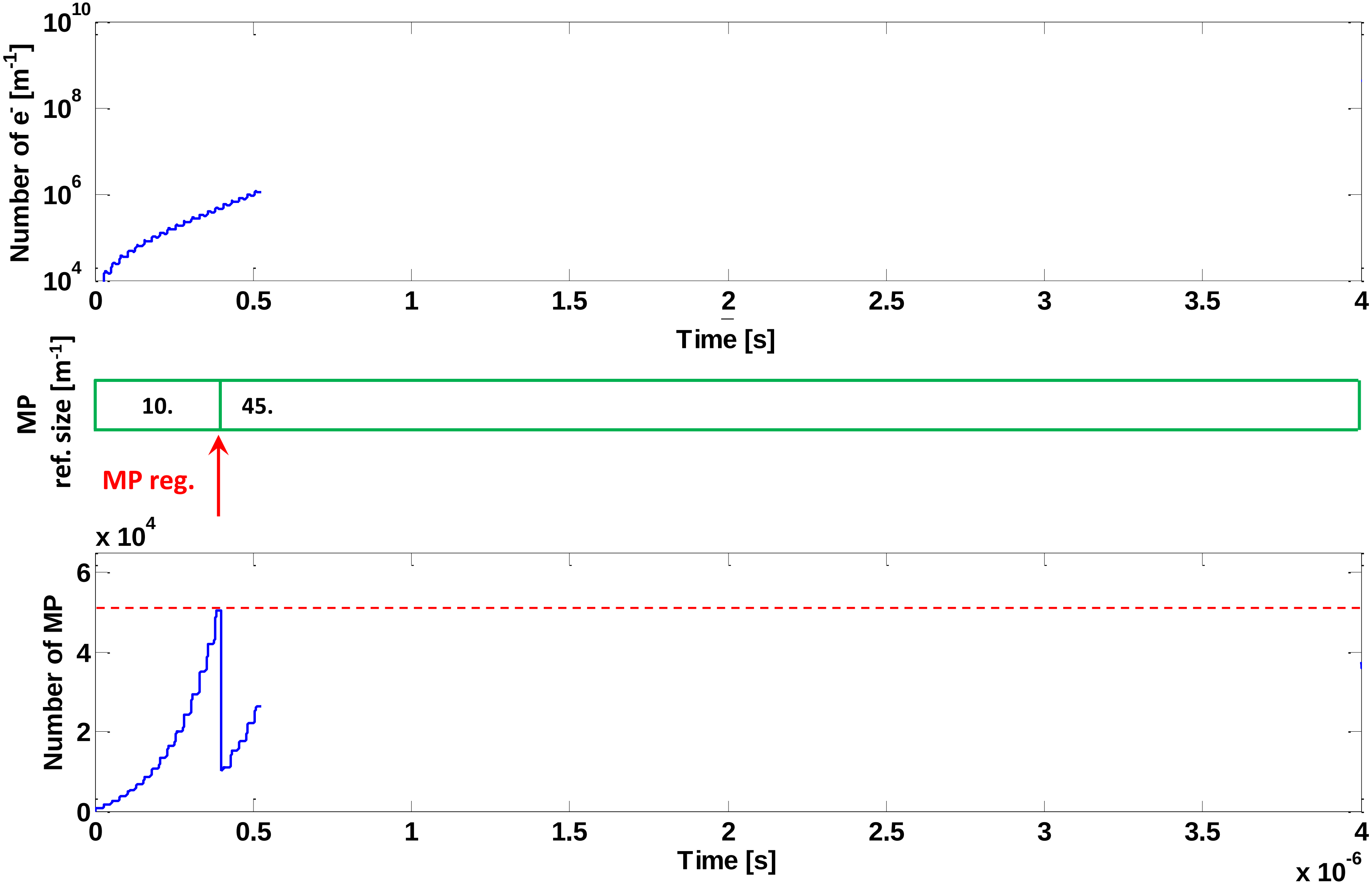

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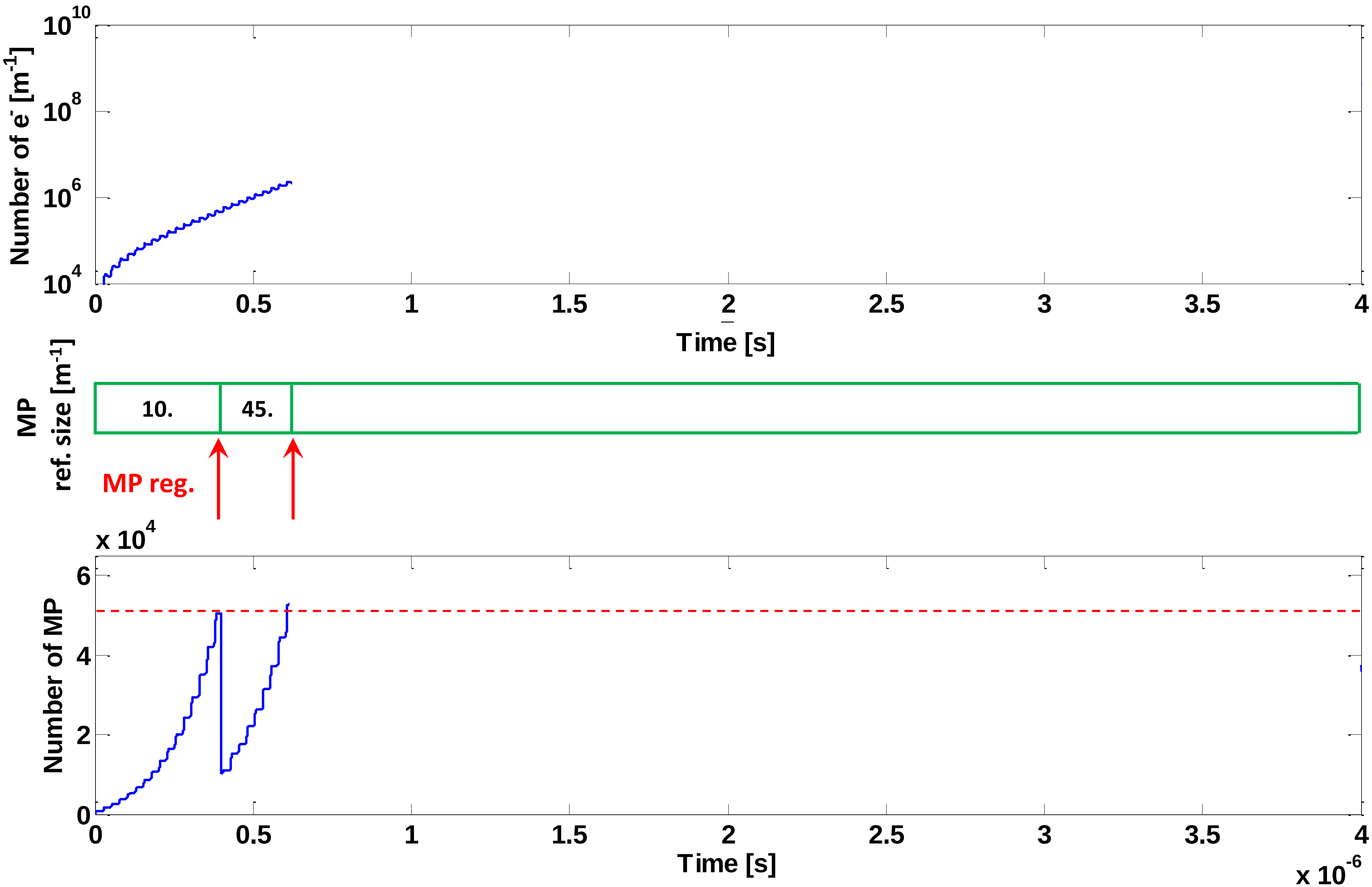

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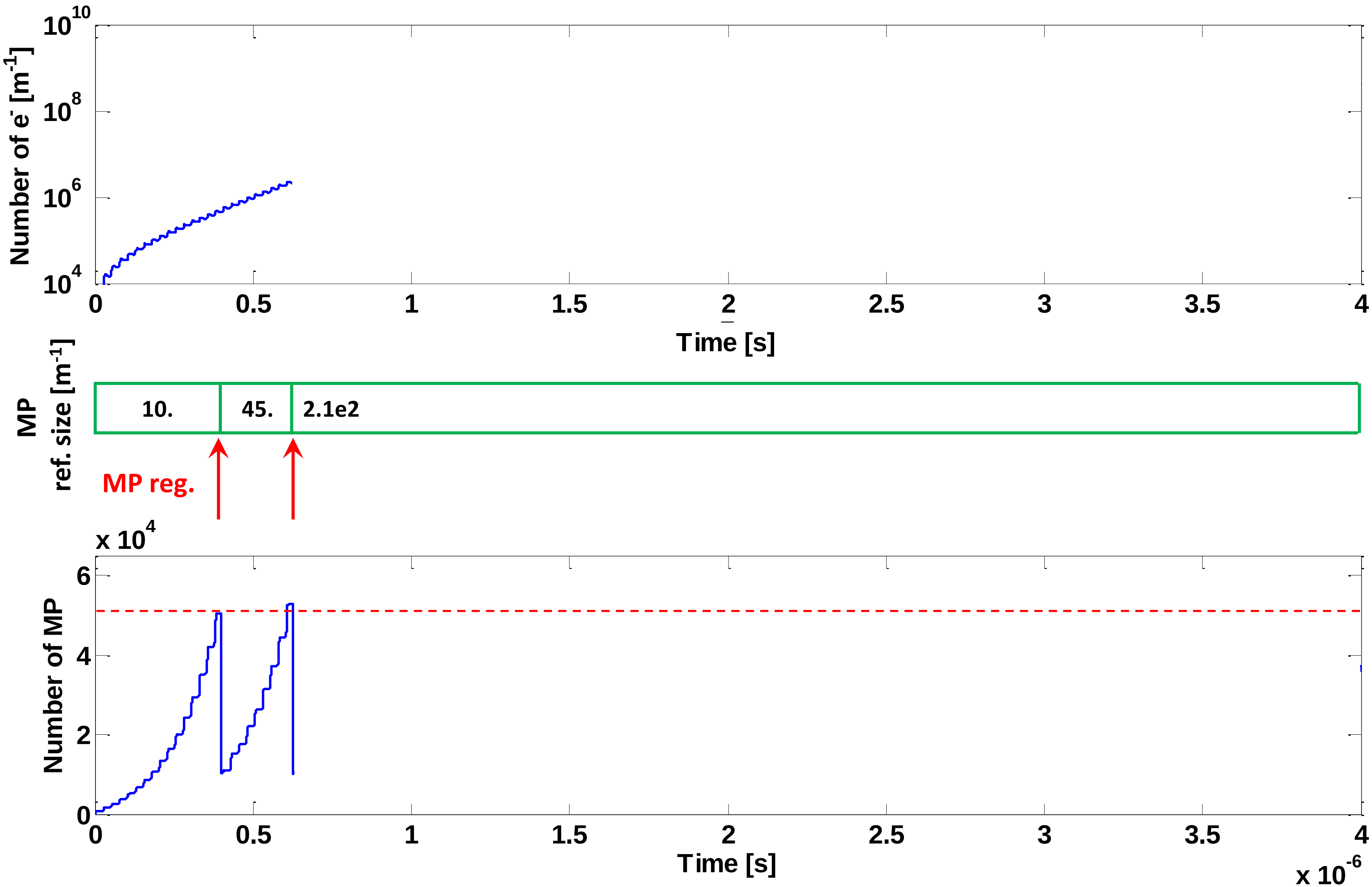

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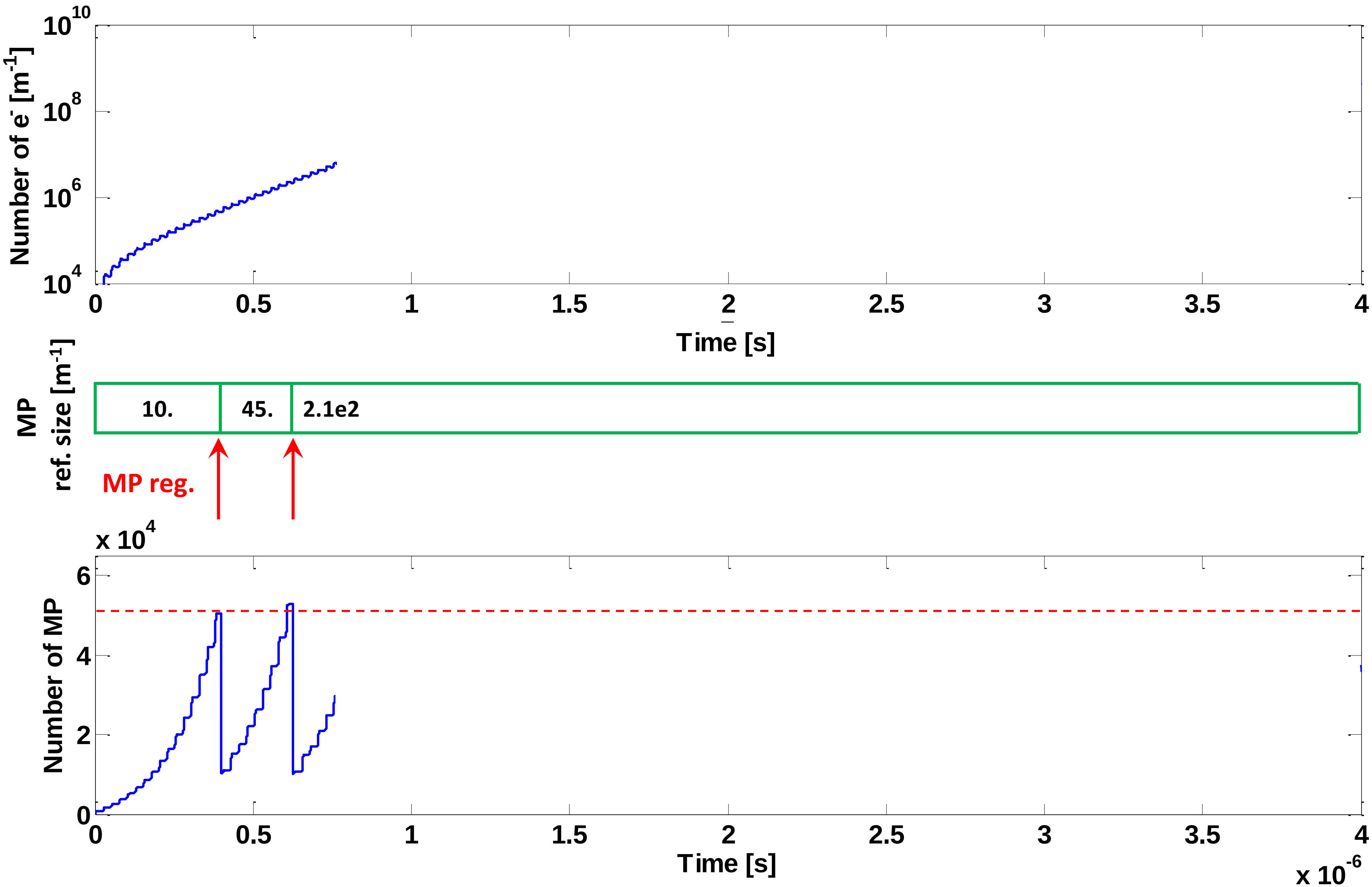

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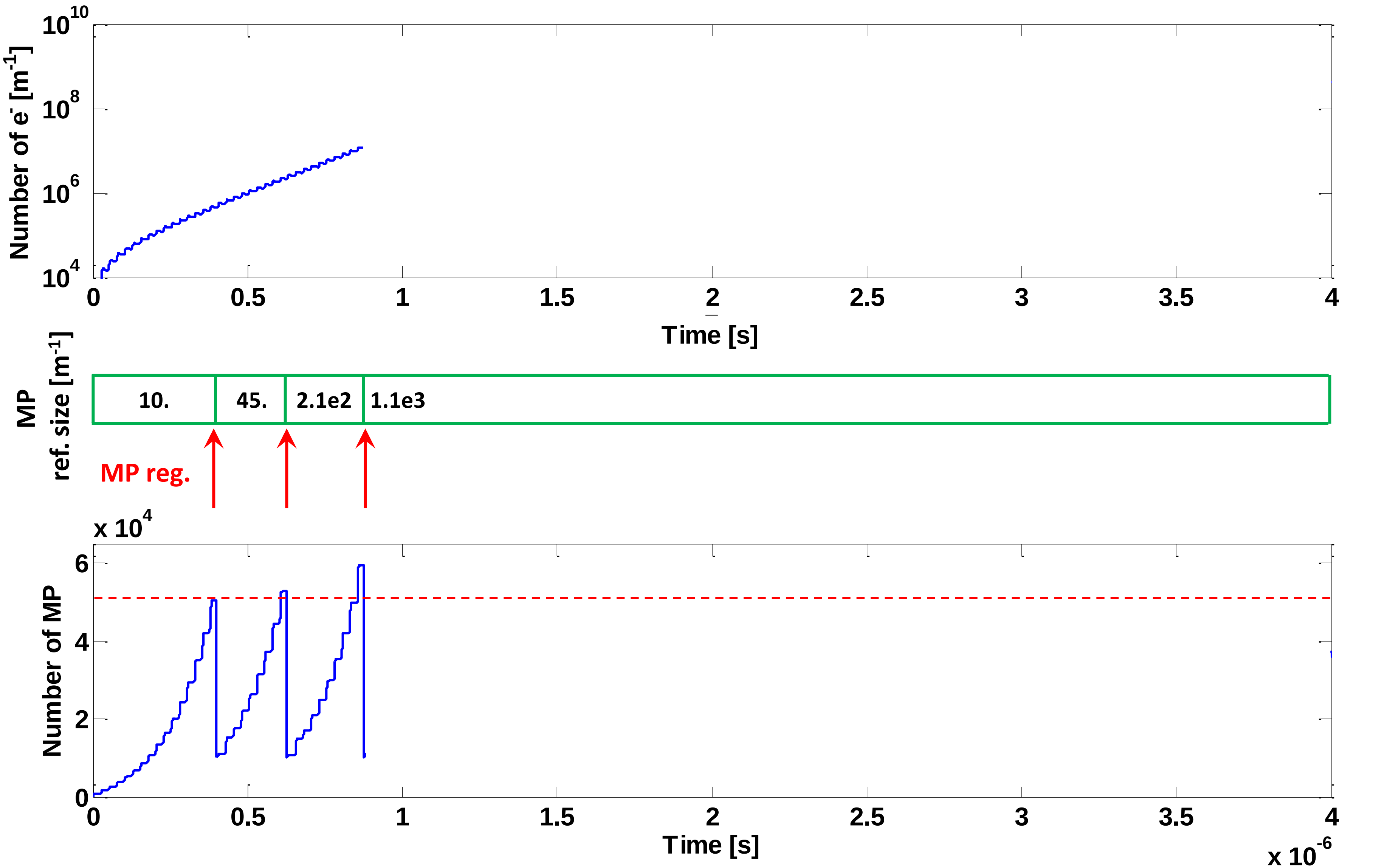

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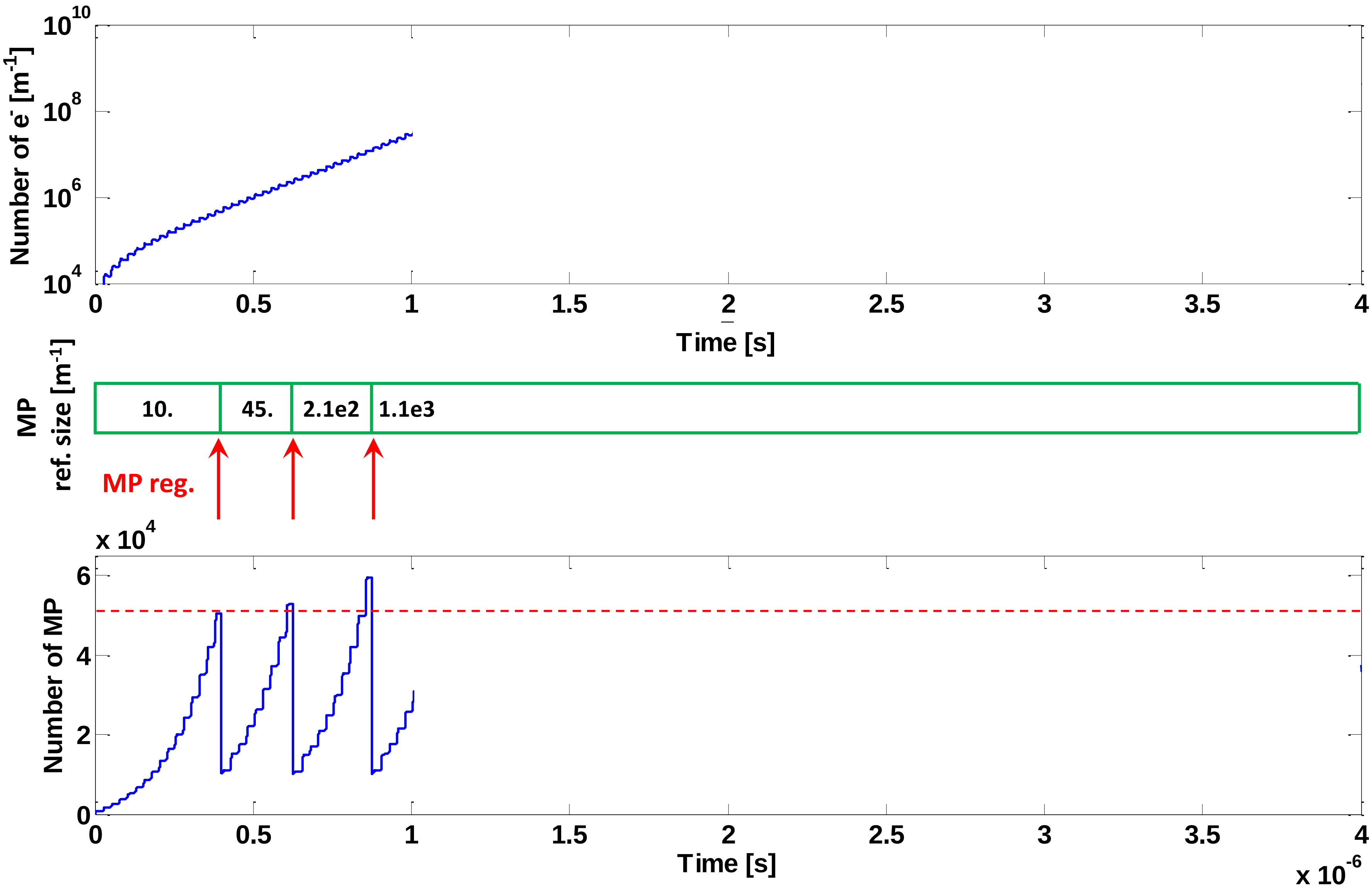

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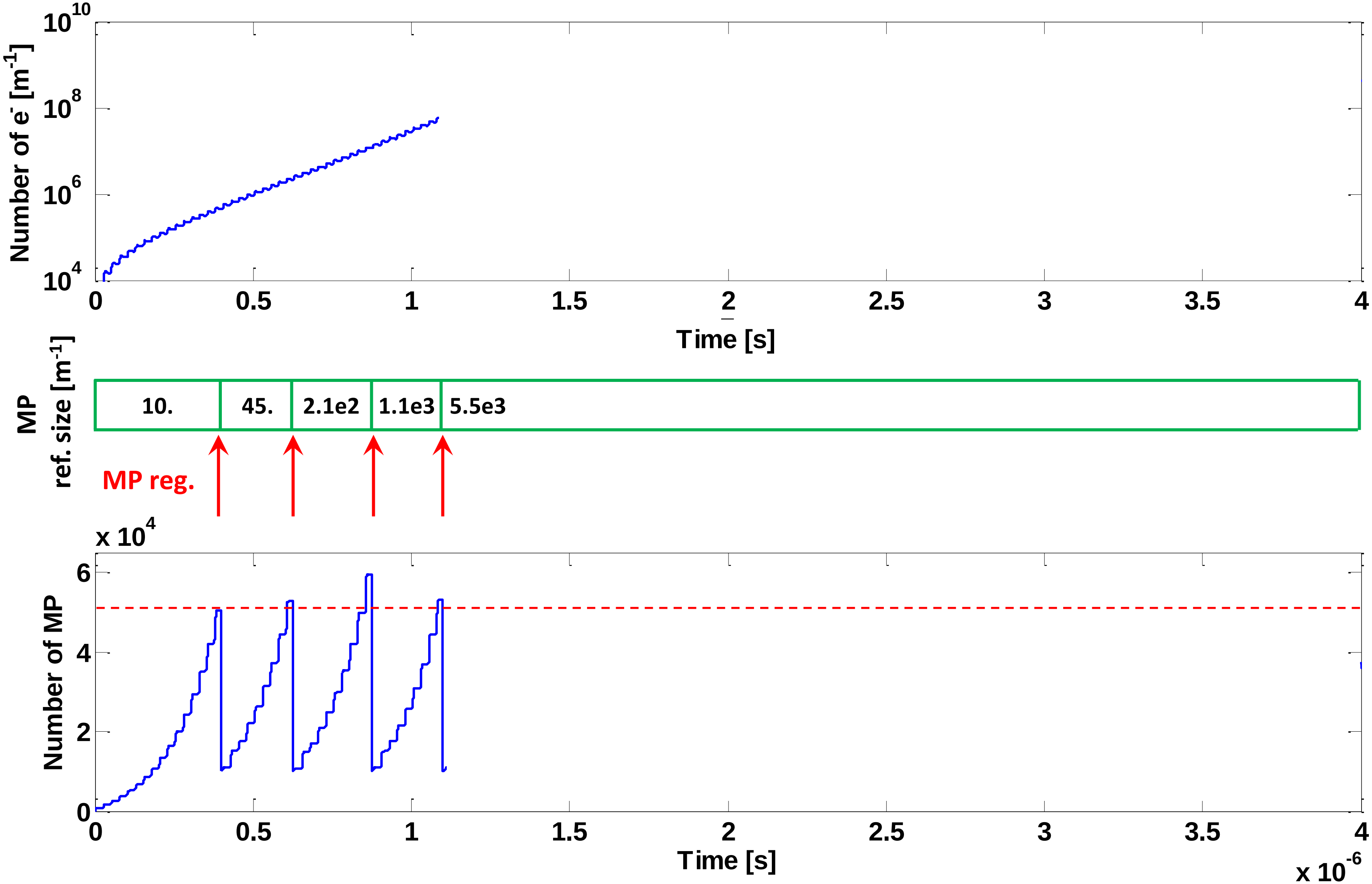

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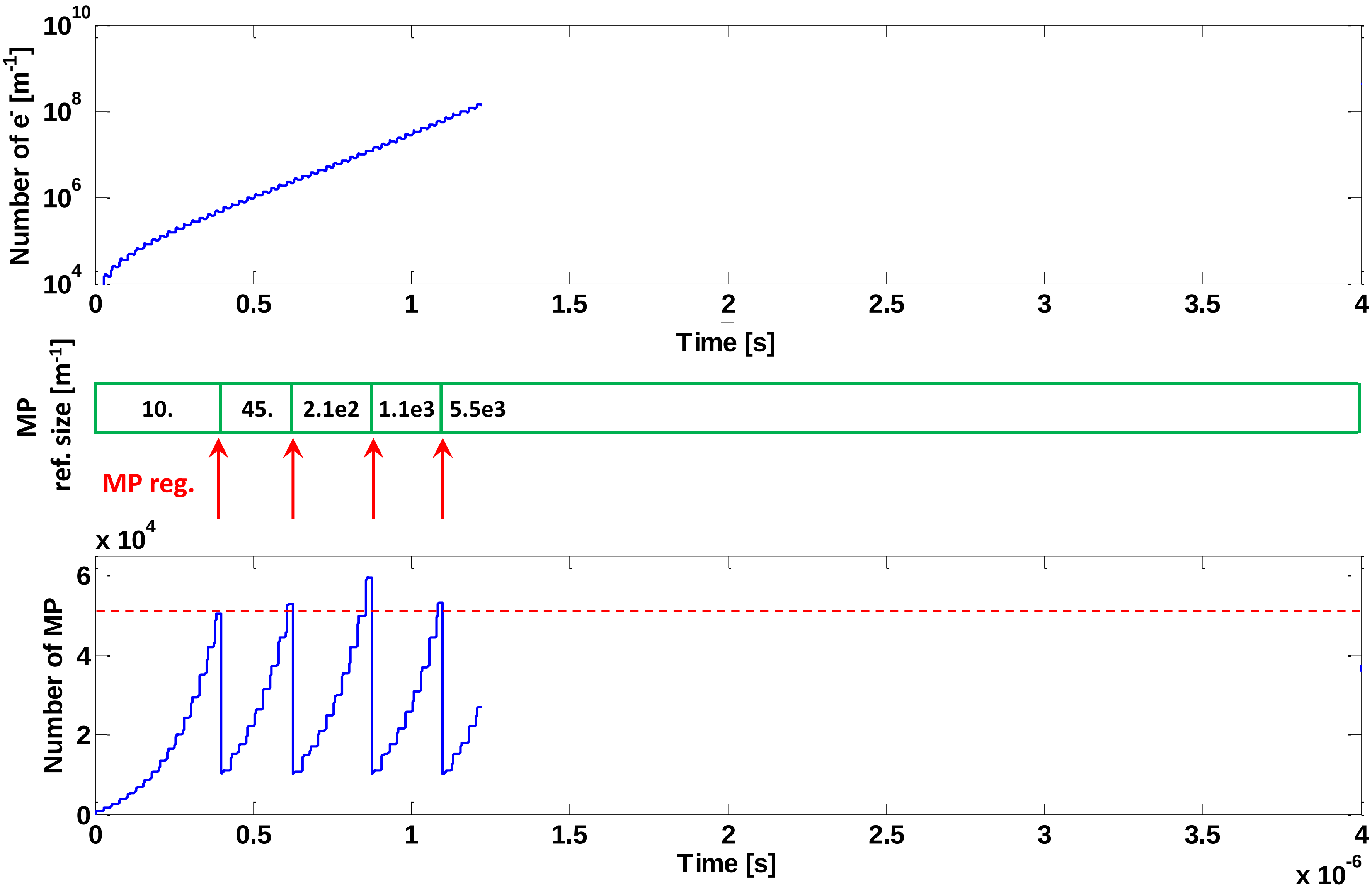

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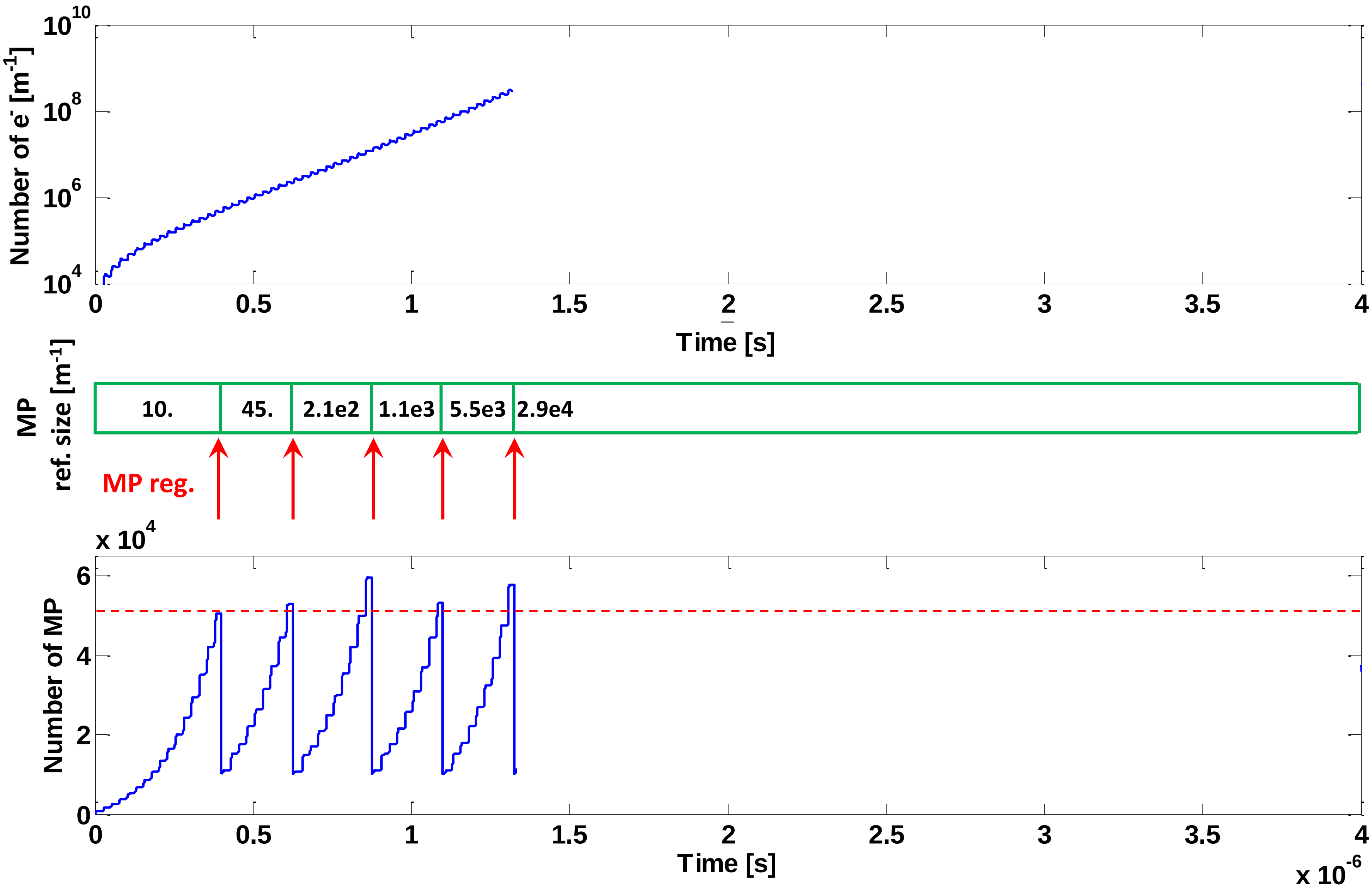

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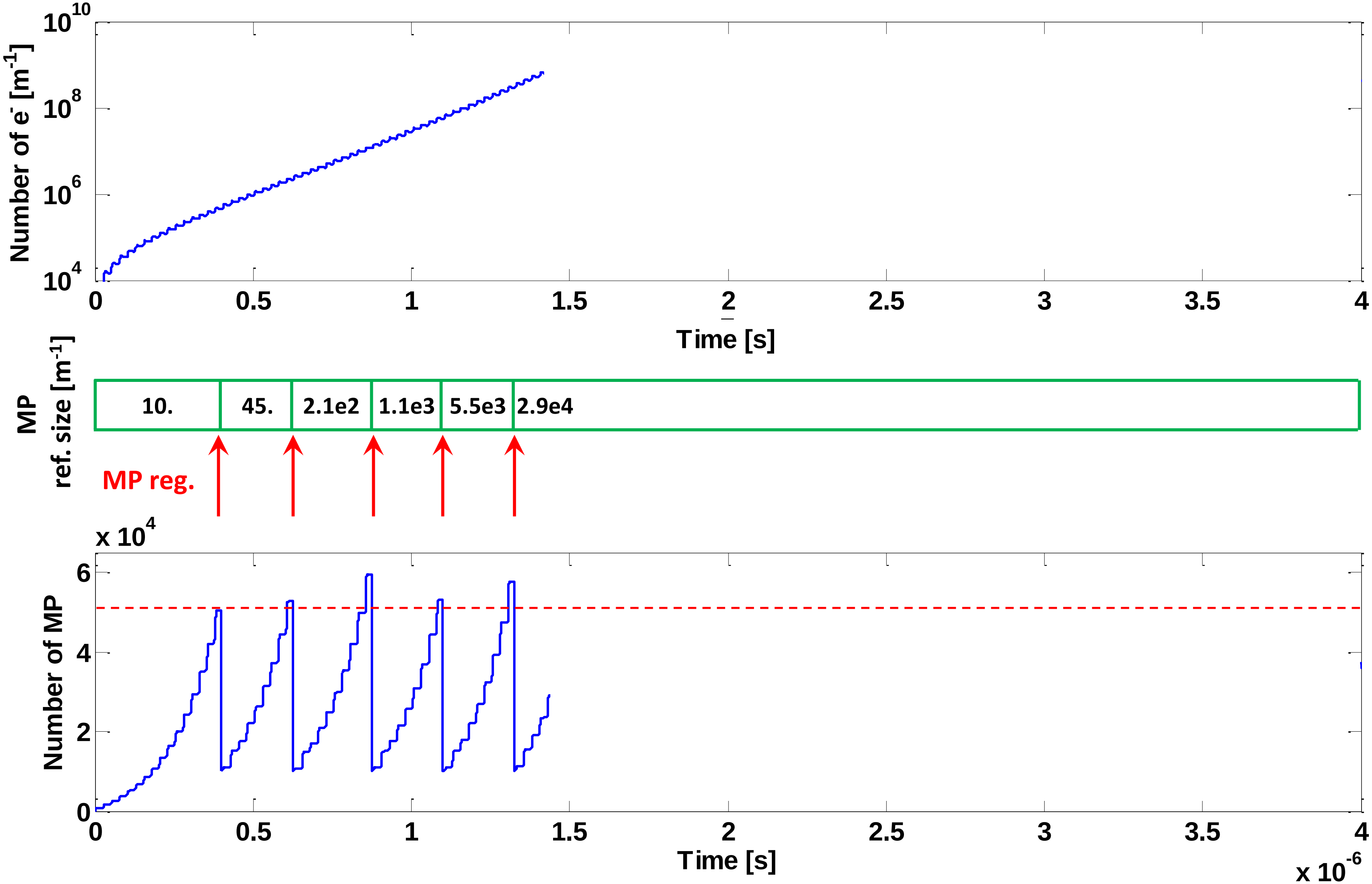

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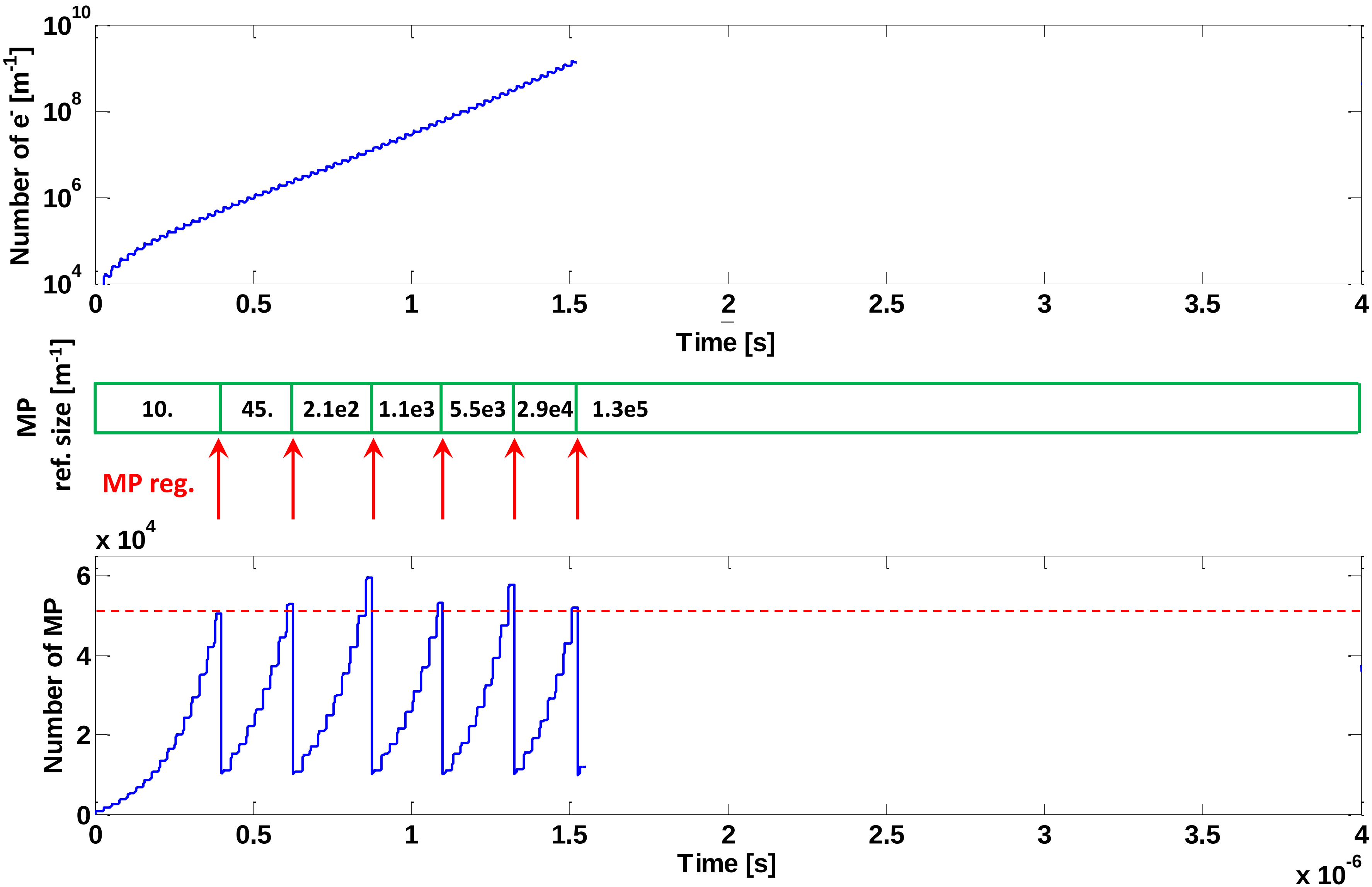

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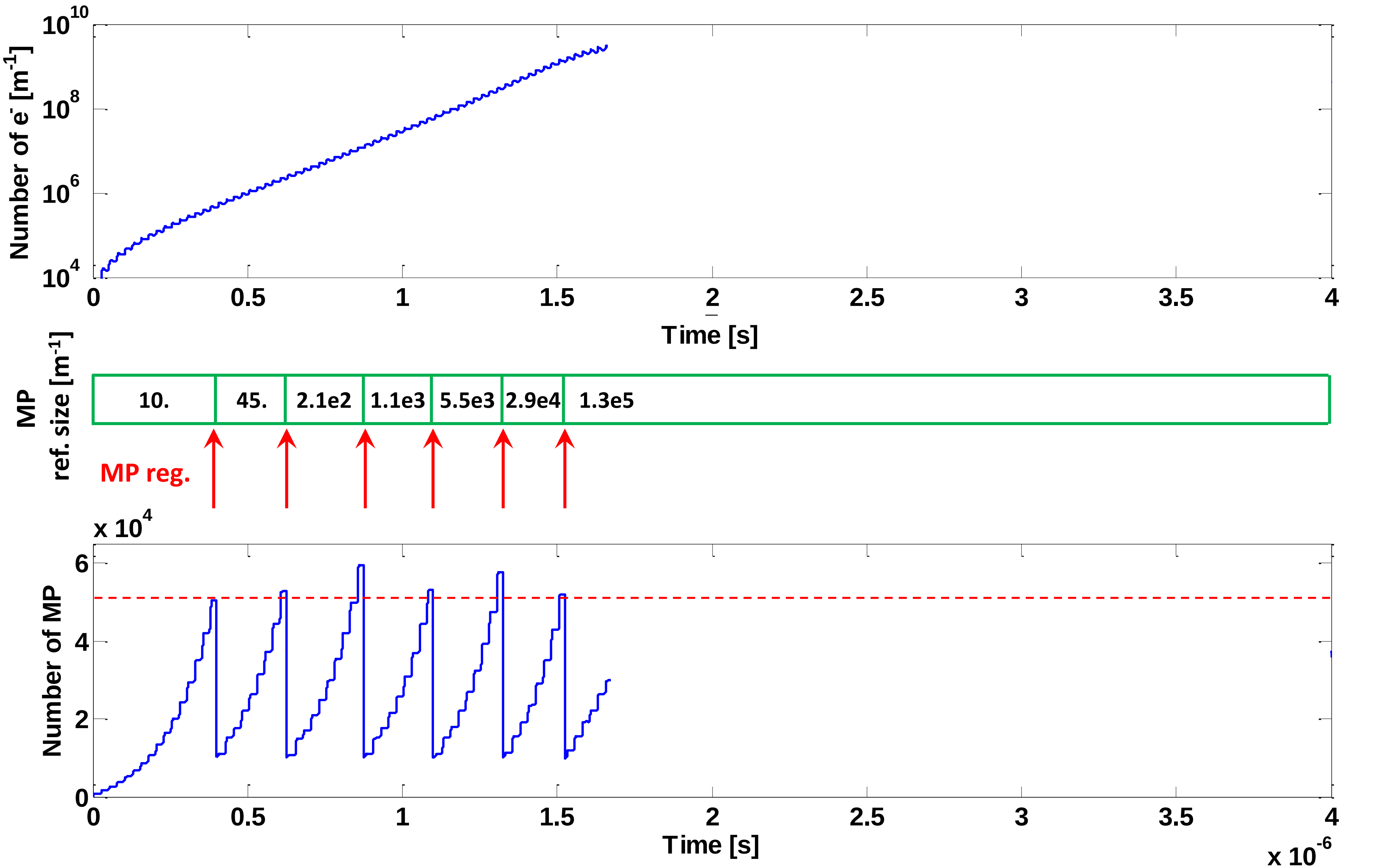

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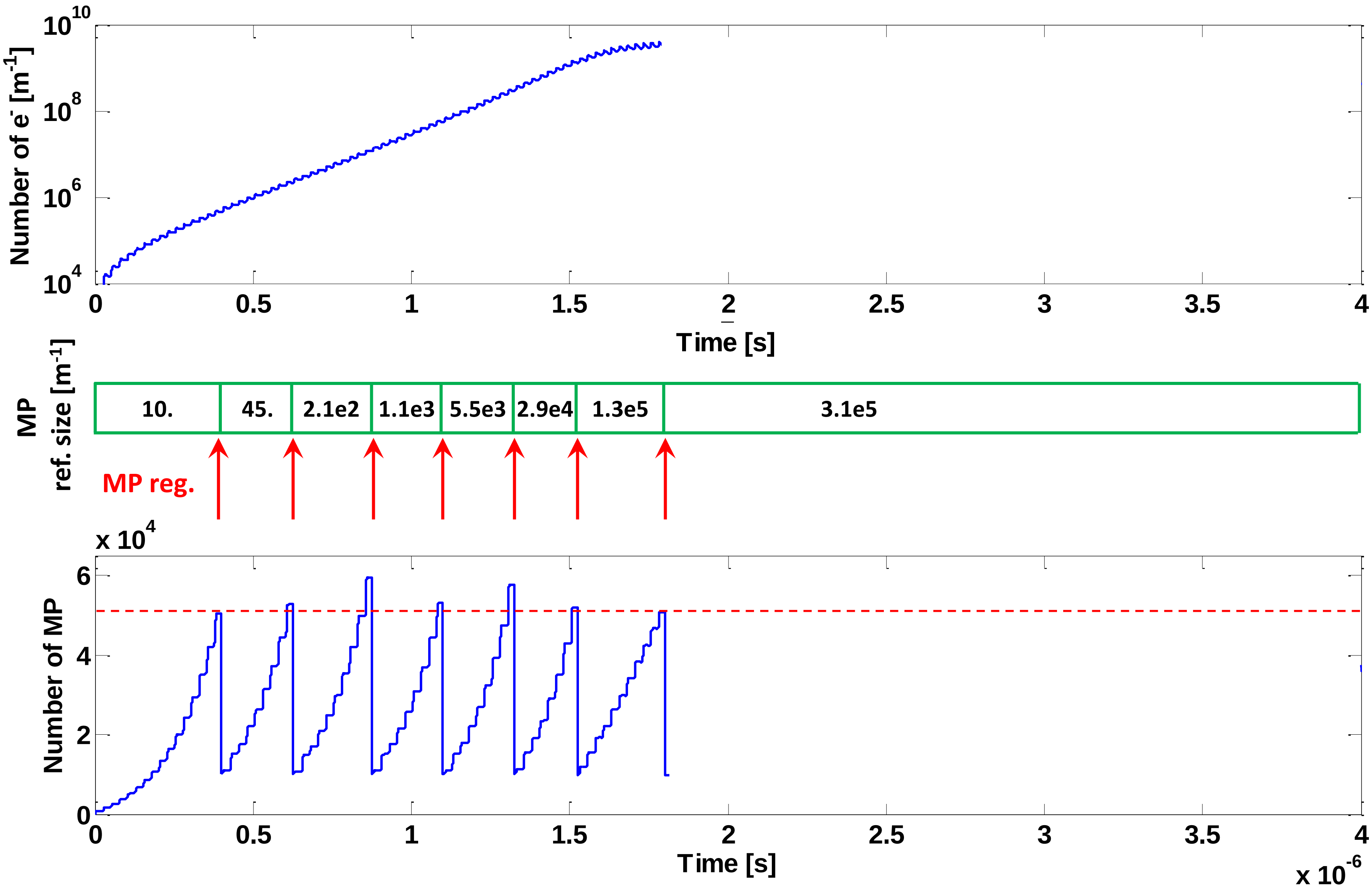

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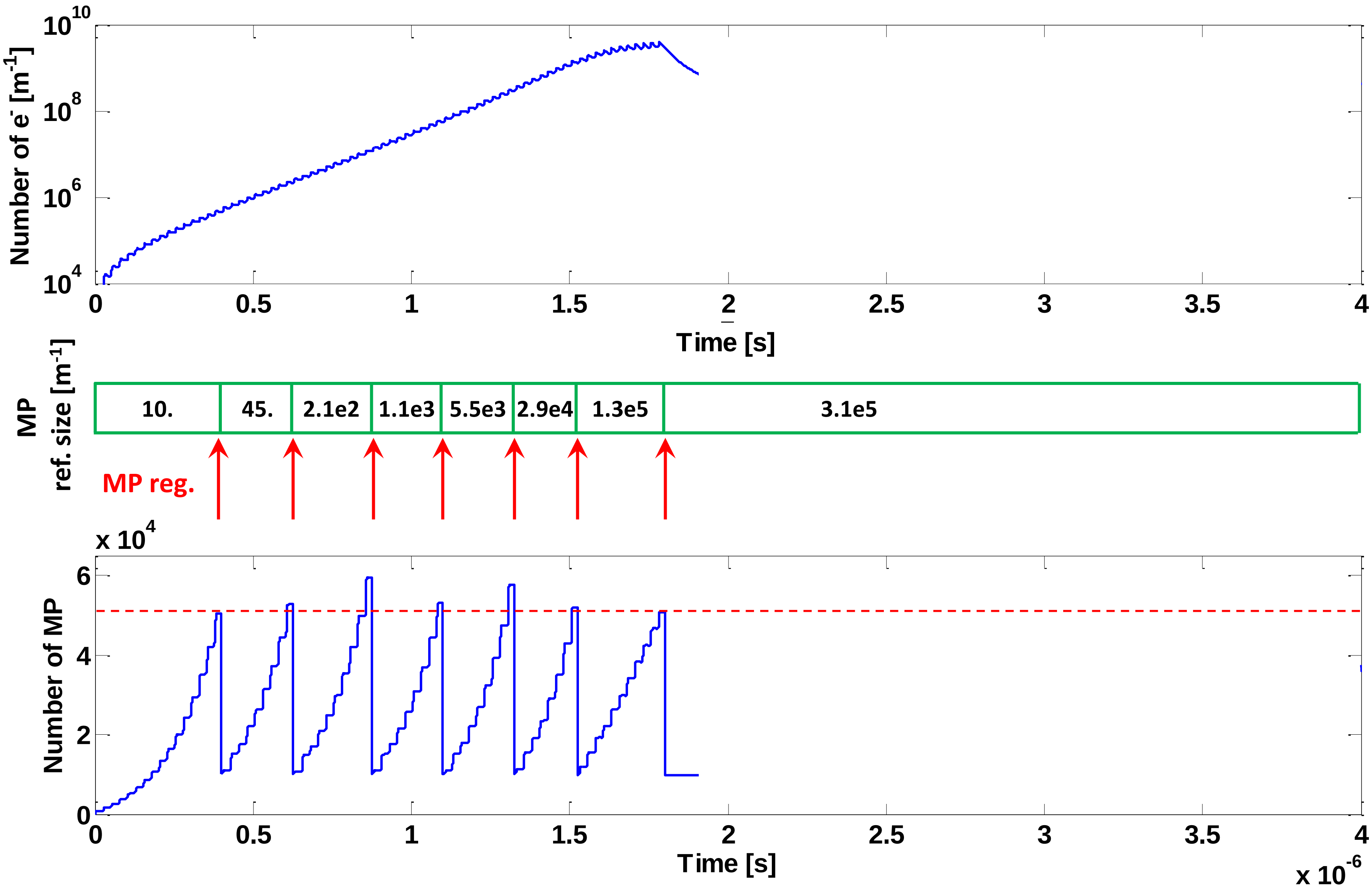

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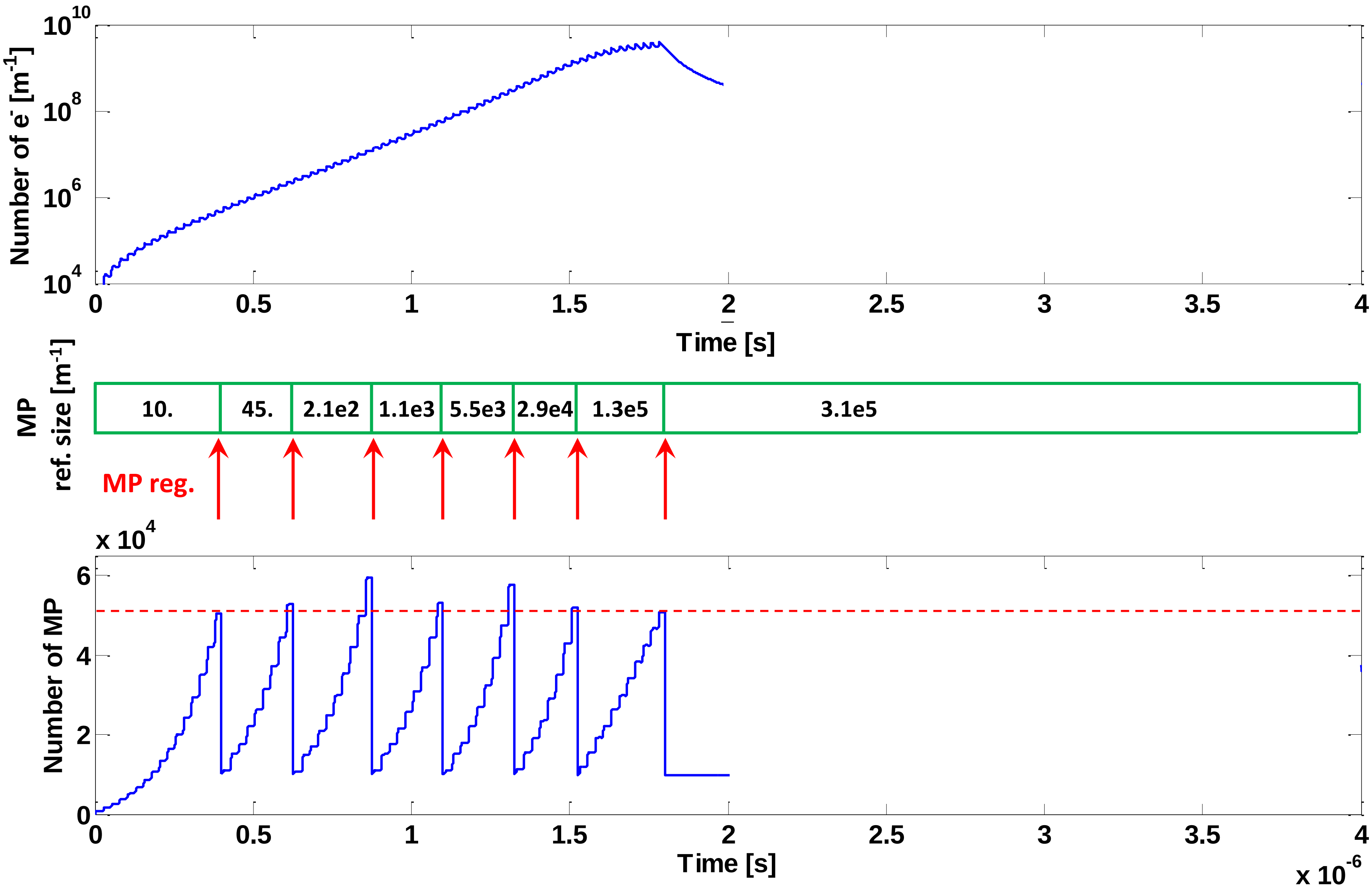

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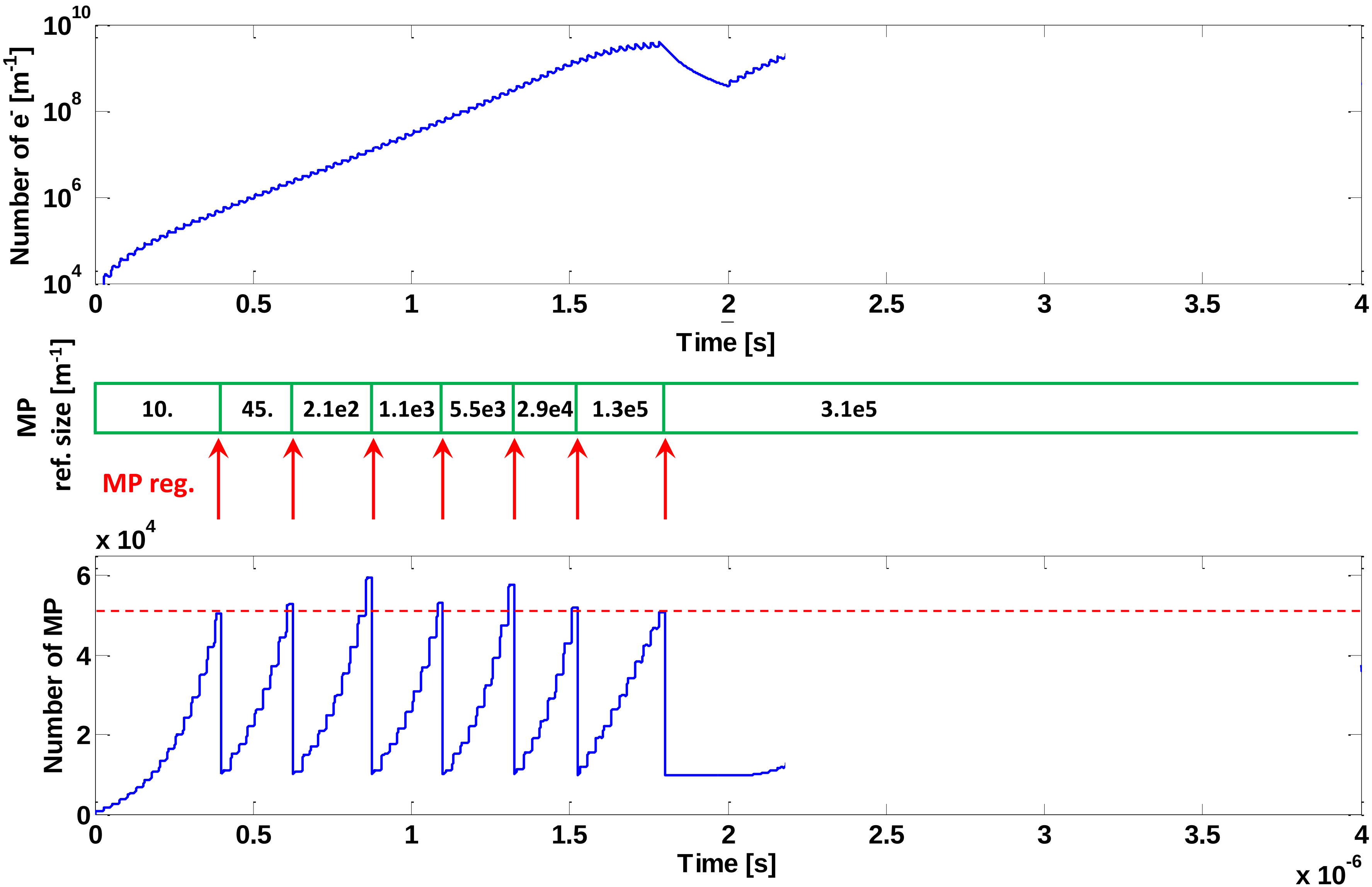

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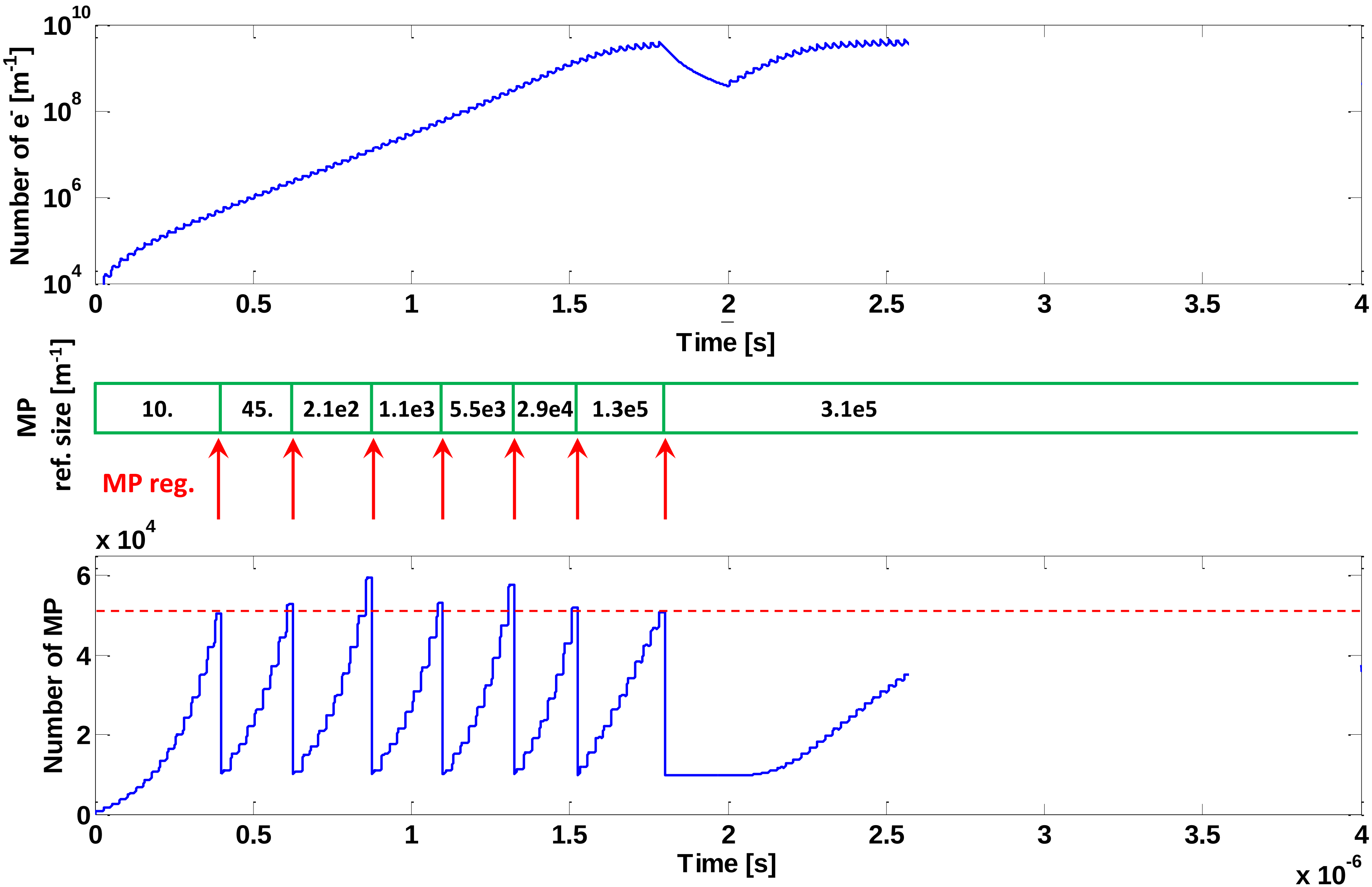

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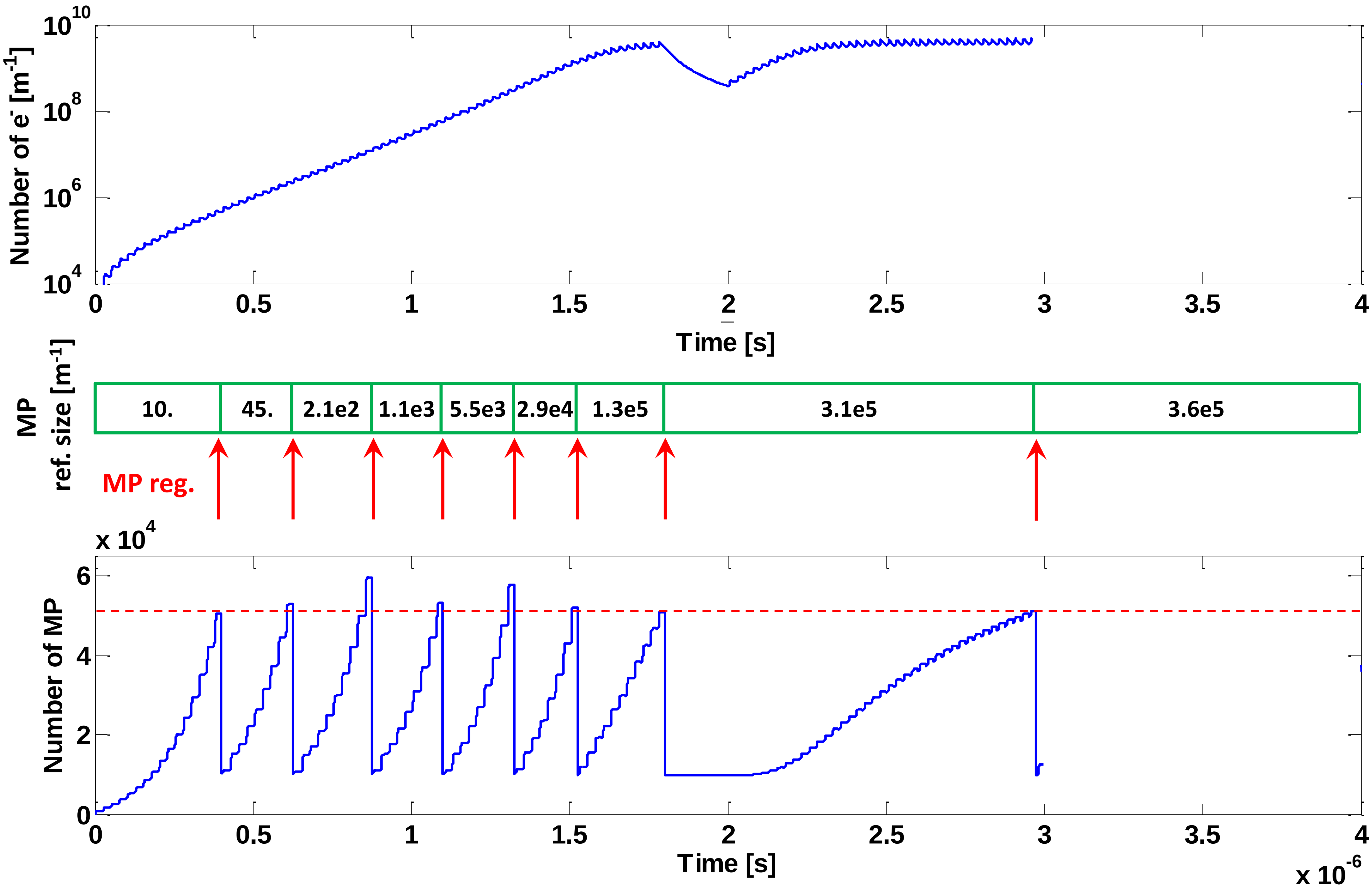

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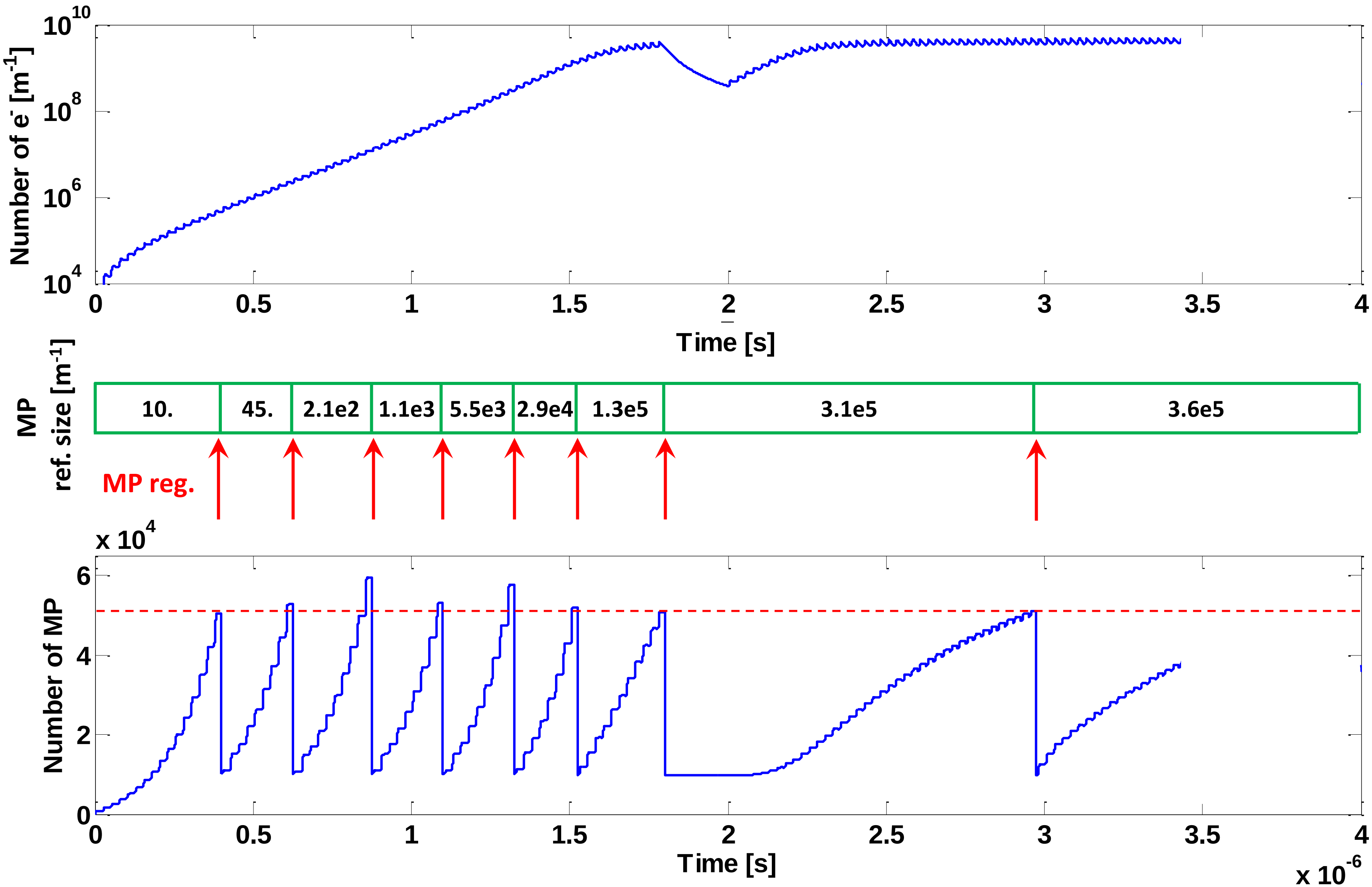

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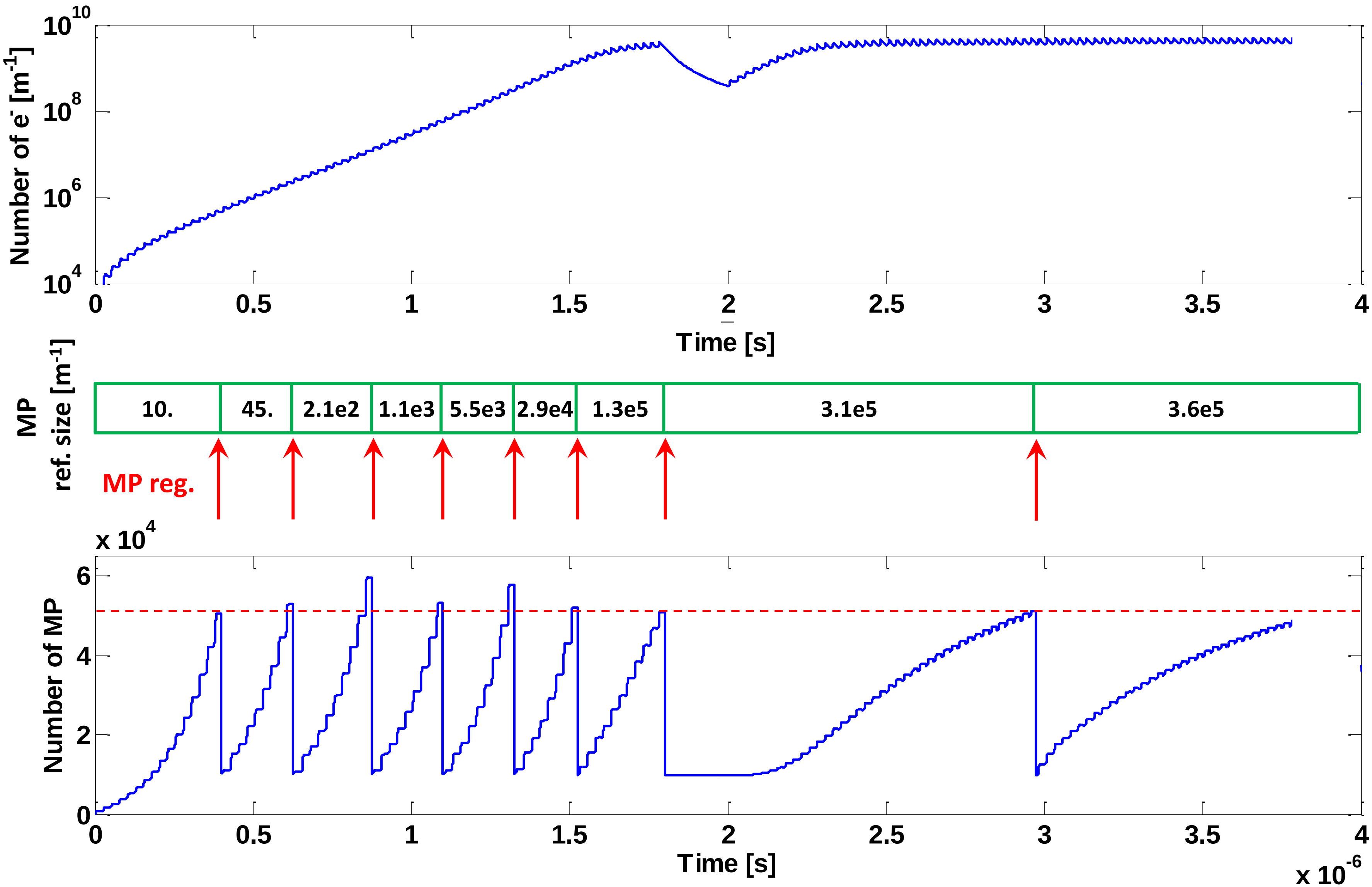

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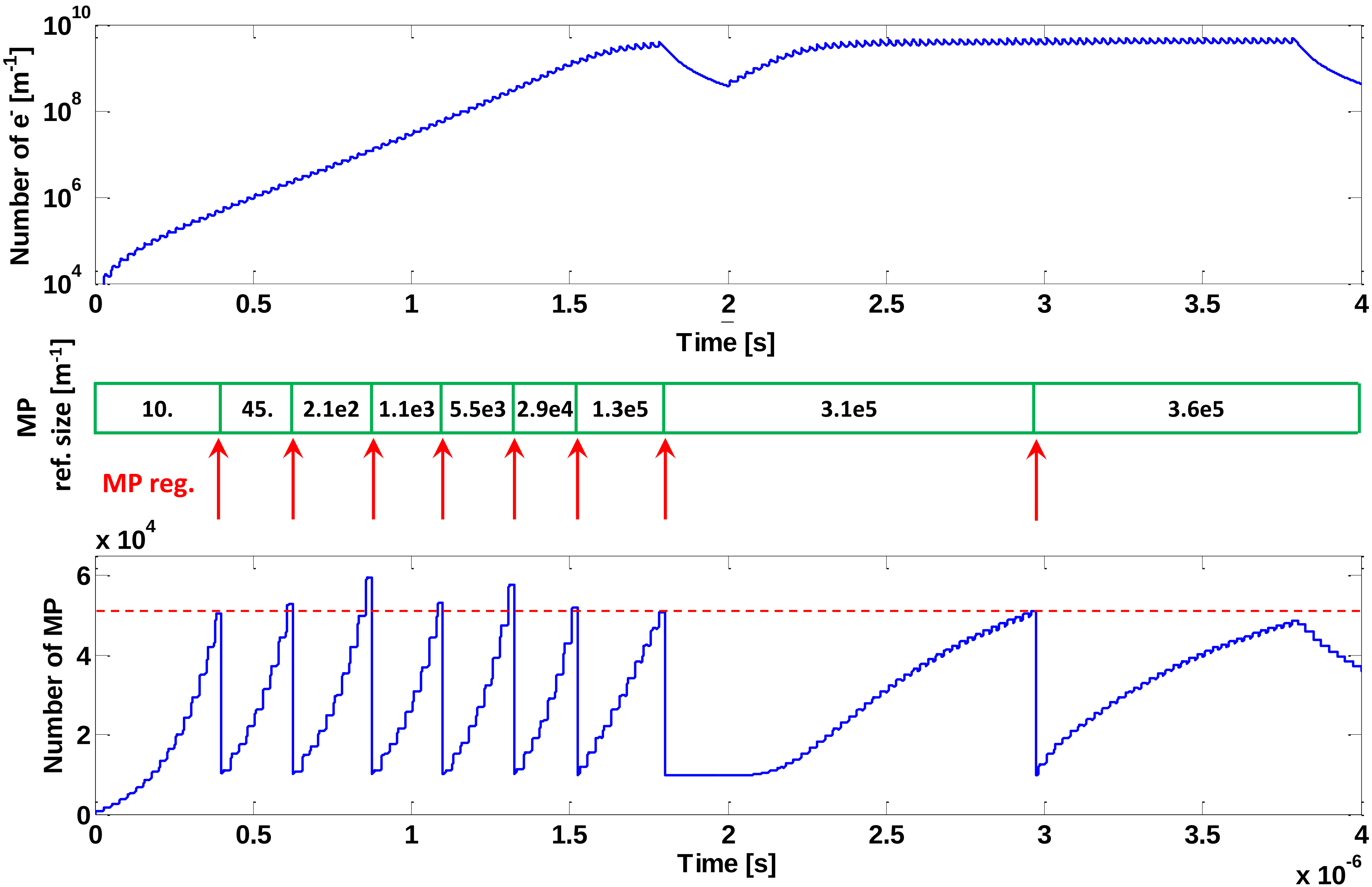

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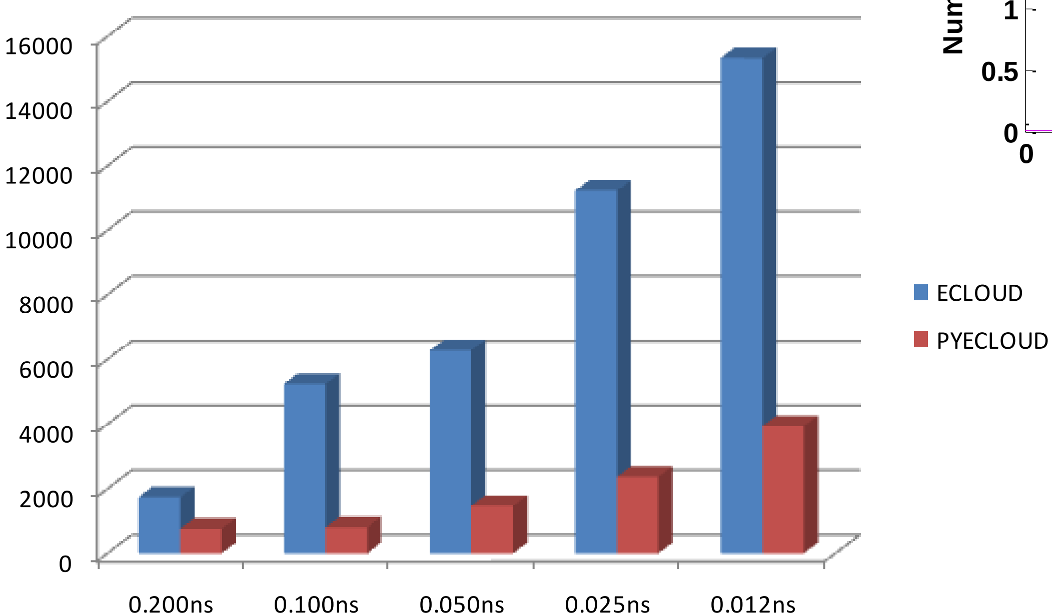
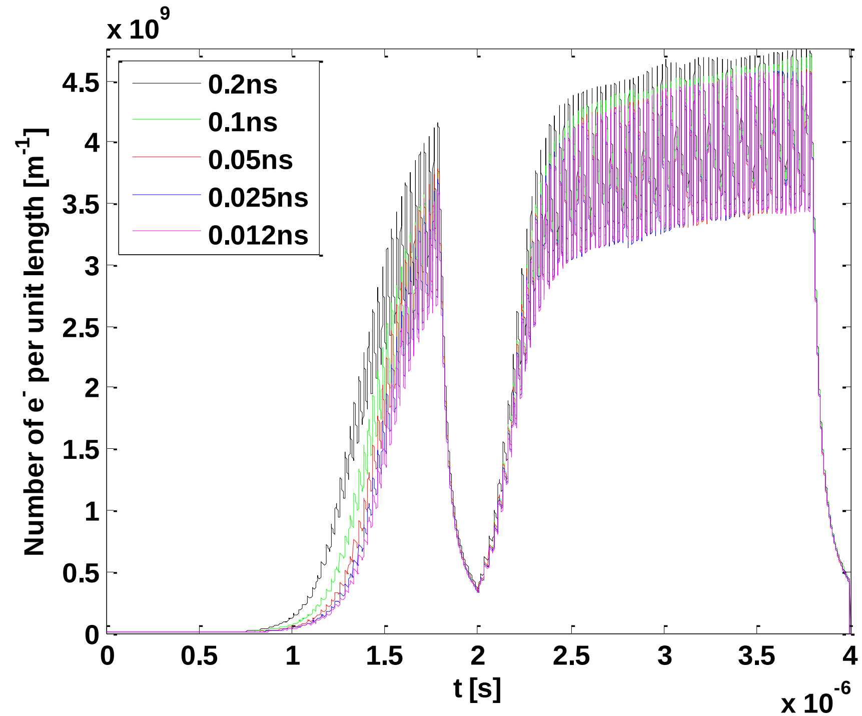
Convergence and performances

The **newly introduced features had a significant impact** on convergence and speed performances.

Timestep	ECLOUD	PYECLOUD
0.2 ns	29 min	12 min
0.1 ns	1h 27 min	13 min
0.05 ns	1h 45 min	24 min
0.025ns	3h 7 min	40 min
0.012ns	4h 15 min	1h 6 min





SPS MBB bending magnet, SEY_{max} = 1.5, nominal 25ns beam, E=26GeV

PyECLOUD at work

Several studies at CERN are/have been employing the new code:

Proton Synchrotron (PS):

- **Study on EC dependence on the Bunch Profile** (C. Bhat)
- **Benchmarking of shielded pickup measurements** (S. Gilardoni, G. Iadarola, M Pivi, G. Rumolo, C. Y. Vallgren)

Super Proton Synchrotron (SPS):

- **Scrubbing optimization studies** (G.Iadarola, G. Rumolo)
- **Intensity upgrade studied** (G.Iadarola, G. Rumolo)
- **Benchmarking of Strip Detector measurements** (H. Bartosik, G.Iadarola, H. Neupert, M. Driss Mensi, G. Rumolo, M. Taborelli)

Large Hadron Collider (LHC):

- **Benchmarking of bunch-by-bunch energy loss data from stable-phase shift** (J. F. Esteban Muller, G.Iadarola, G. Rumolo, E. Shaposhnikova)
- **Map formalism study for scrubbing optimization** (O. Dominguez, F. Zimmermann)
- **Pressure observations vs. simulations benchmarking** (O. Dominguez, F. Zimmermann)
- **Background study for 800mm chamber close to ALICE** (V. Baglin, O. Dominguez, G. Iadarola, G. Rumolo)
- **Heat load benchmarking for the cryogenic arcs** (G. Iadarola, H. Maury Cuna, G. Rumolo. F. Zimmermann)
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$>10^4$ simulations run so far

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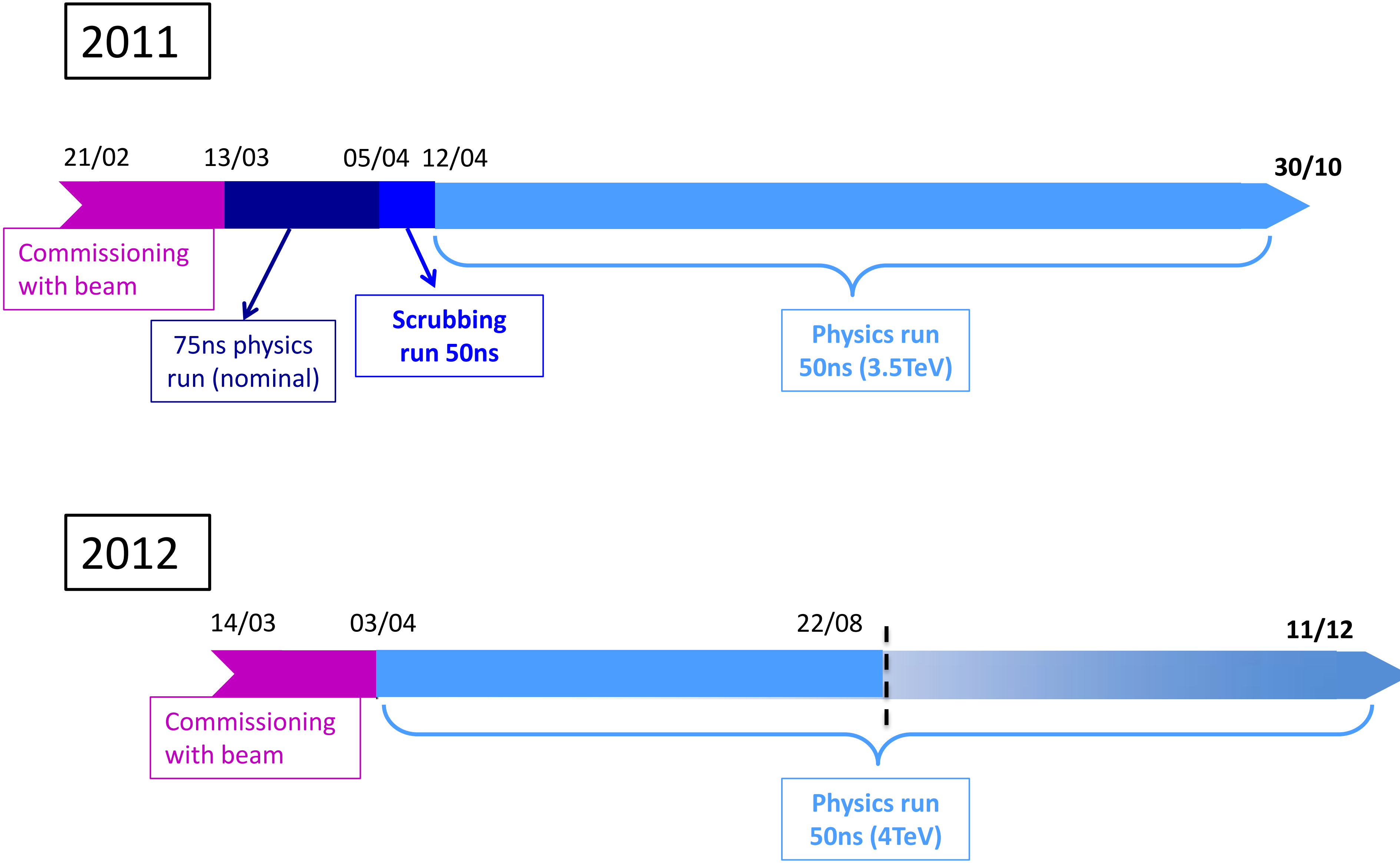
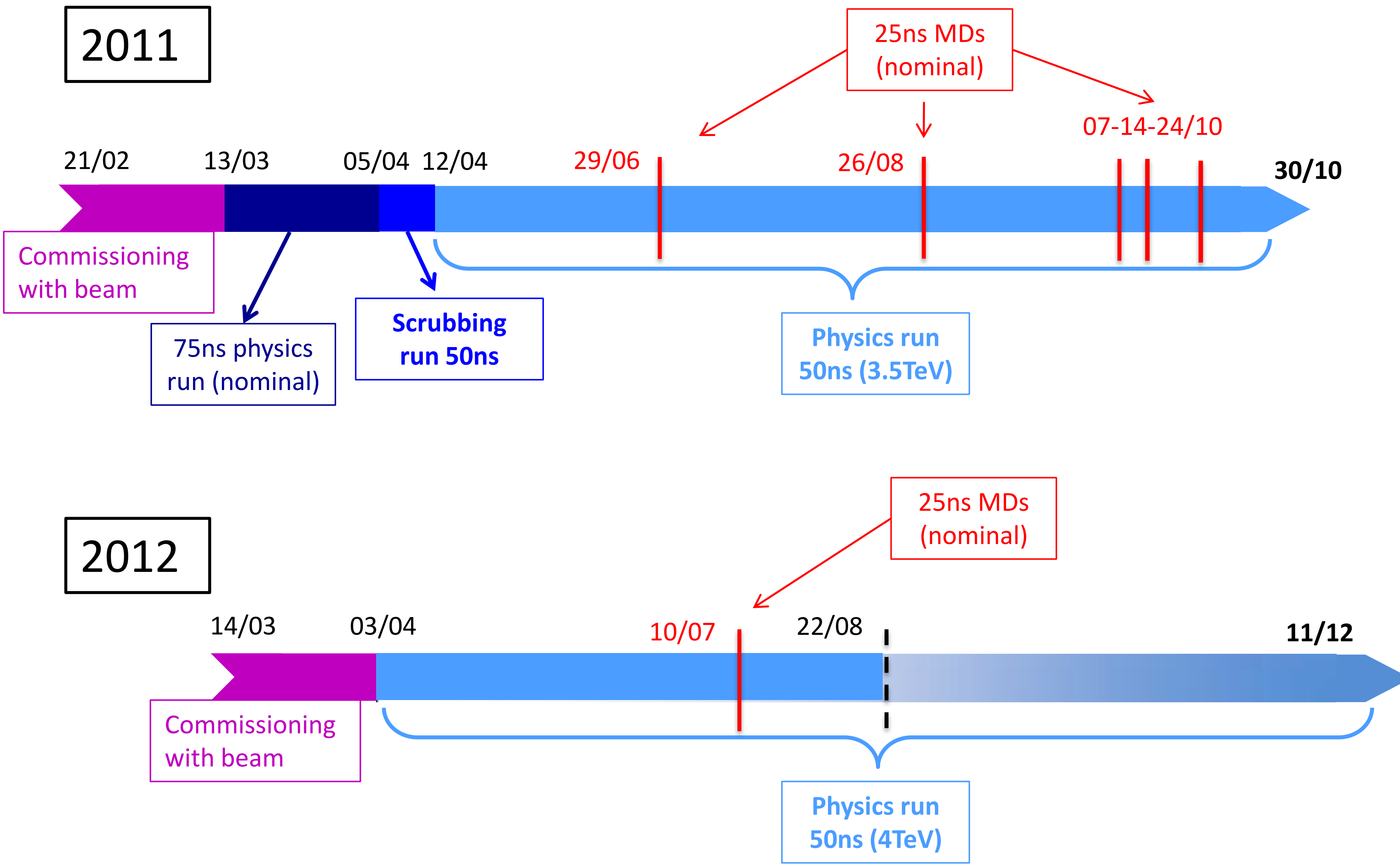
- **PyECLOUD at work for LHC studies:**
  - SEY reconstruction from heat-load measurements
  - Benchmarking with stable phase shift measurements
  - PyECLOUD – HEADTDAIL simulation of EC induced instabilities

EC observations in the LHC



EC observations in the LHC



EC observations in the LHC

2011

21/02 13/(

Commissioning with beam

75ns p run (no

0/10

2012

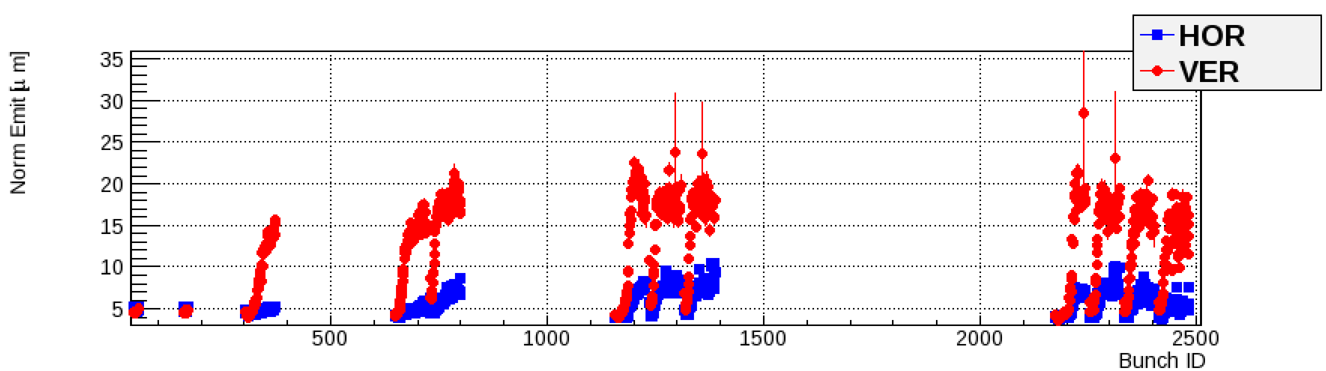
14/

Commi with be

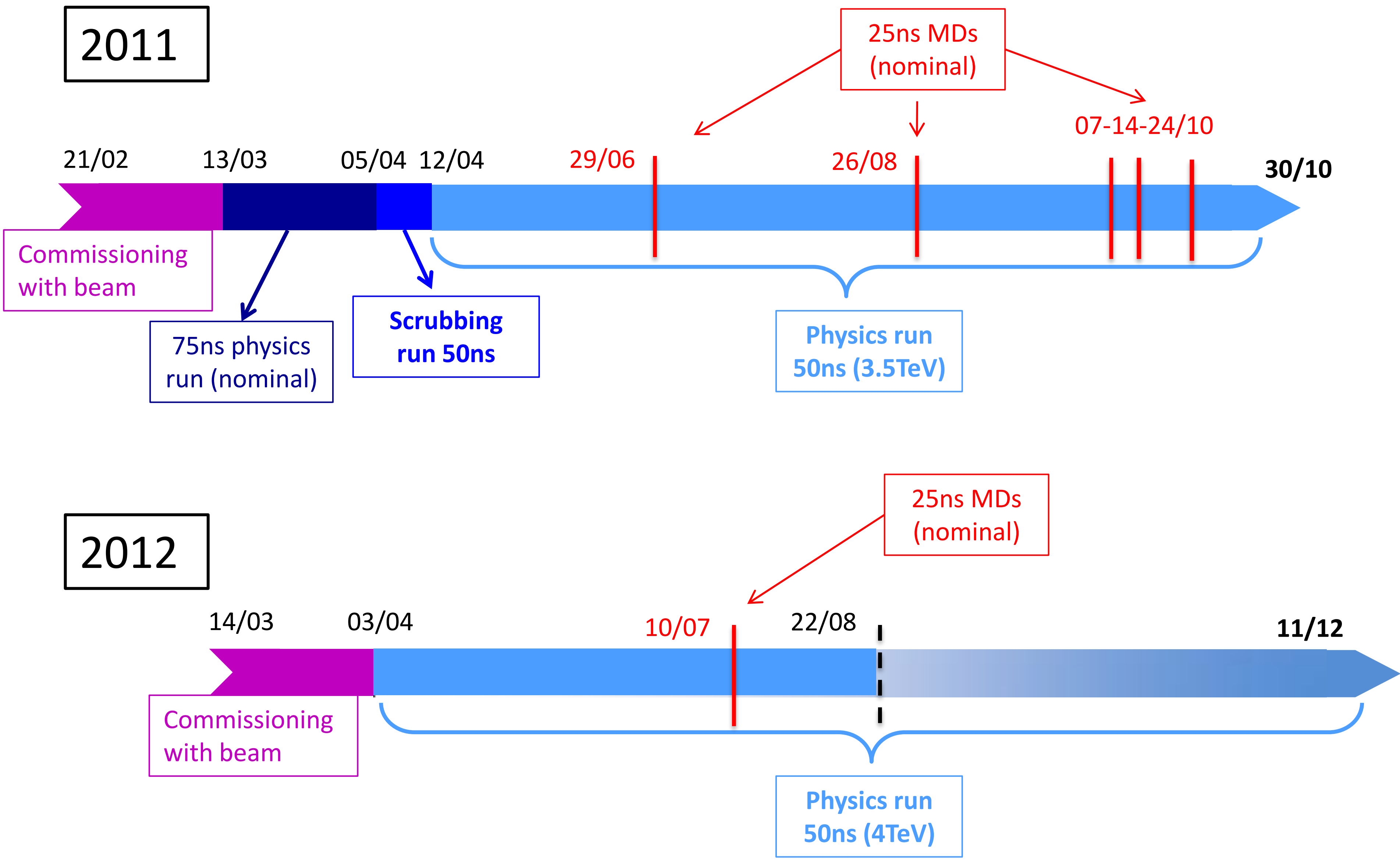
11/12

Indication that a **severe EC** is developing in the LHC arcs **with 25ns** bunch spacing:

- **Heat load** on the cryo-magnets beam screens
- Dynamic **pressure rise**
- Effects on the beam (especially last bunches of the trains):
  - **Fast instabilities** (avoidable with high chromaticity settings)
  - **Particle losses** (together with bunch shortening)
  - Transverse **emittance growth**



EC observations in the LHC



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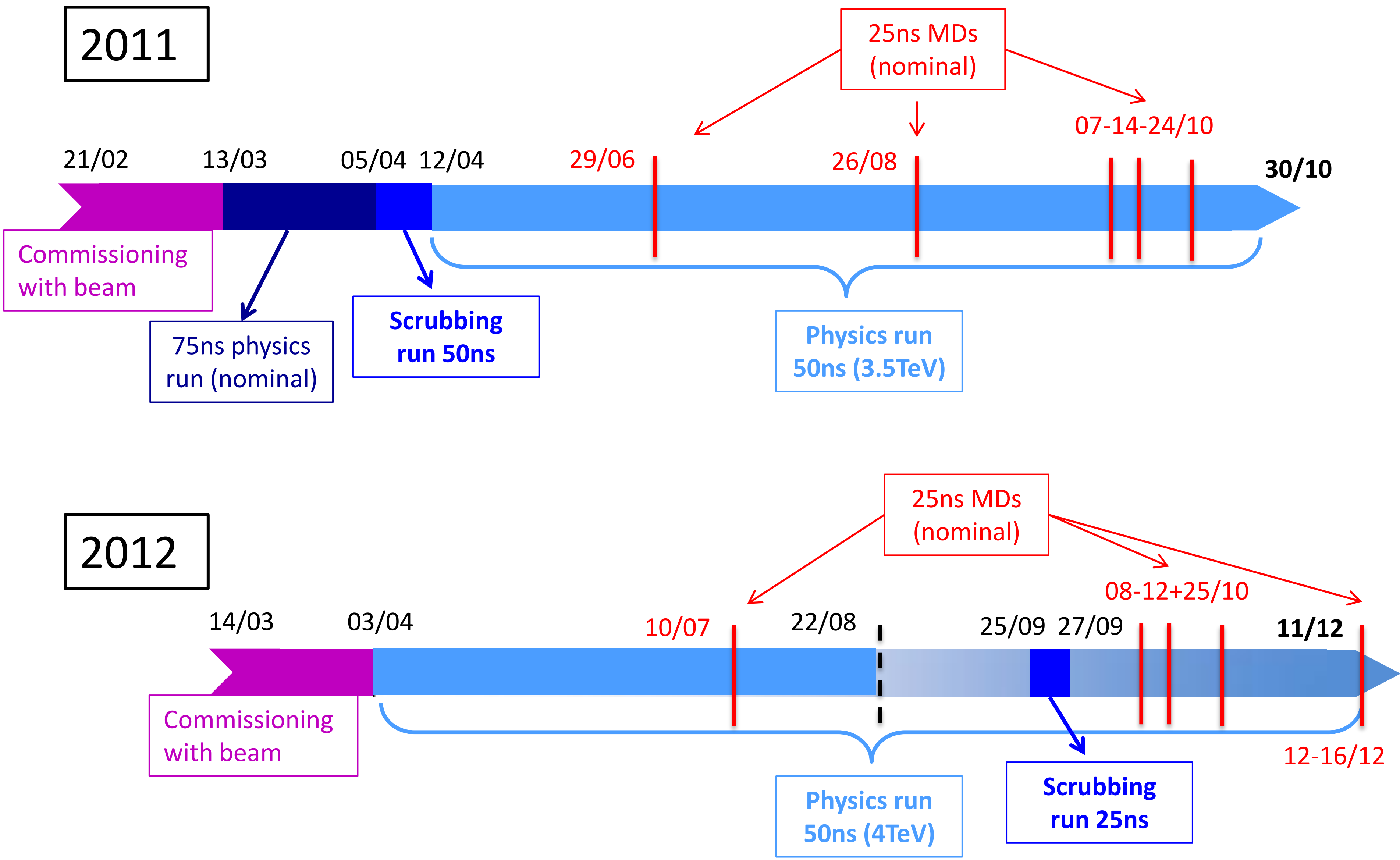

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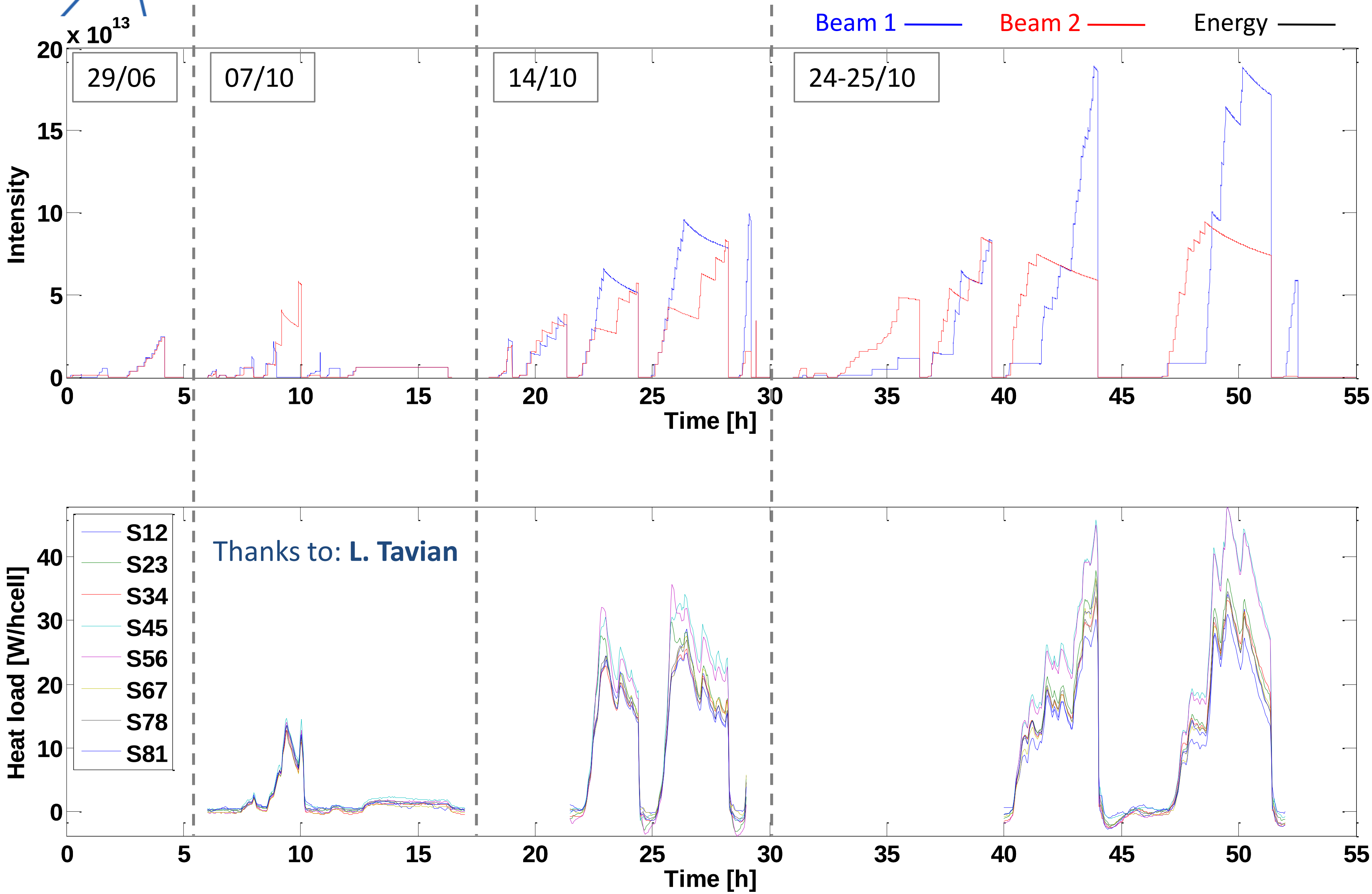
Estimation of the SEY in the LHC arcs



Estimation of the SEY in the LHC arcs

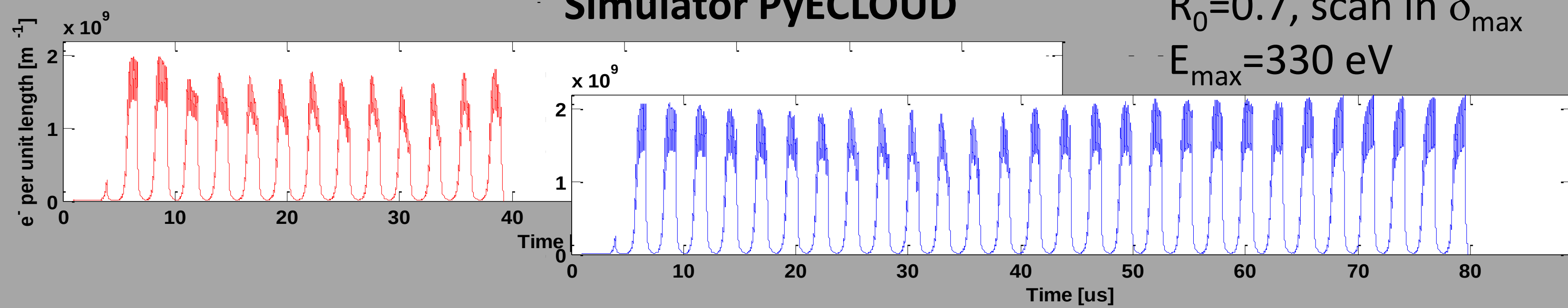
Measured Bunch-by-bunch **intensity & length** (B1)

Measured Bunch-by-bunch **intensity & length** (B2)

Simulator PyECLOUD

R_0=0.7, scan in δ_{max}

E_{max}=330 eV



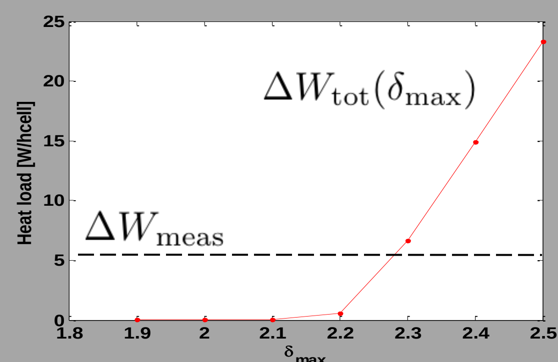
$\Delta W_{\mathrm{sim1}}(\delta_{\mathrm{max}})$

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

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

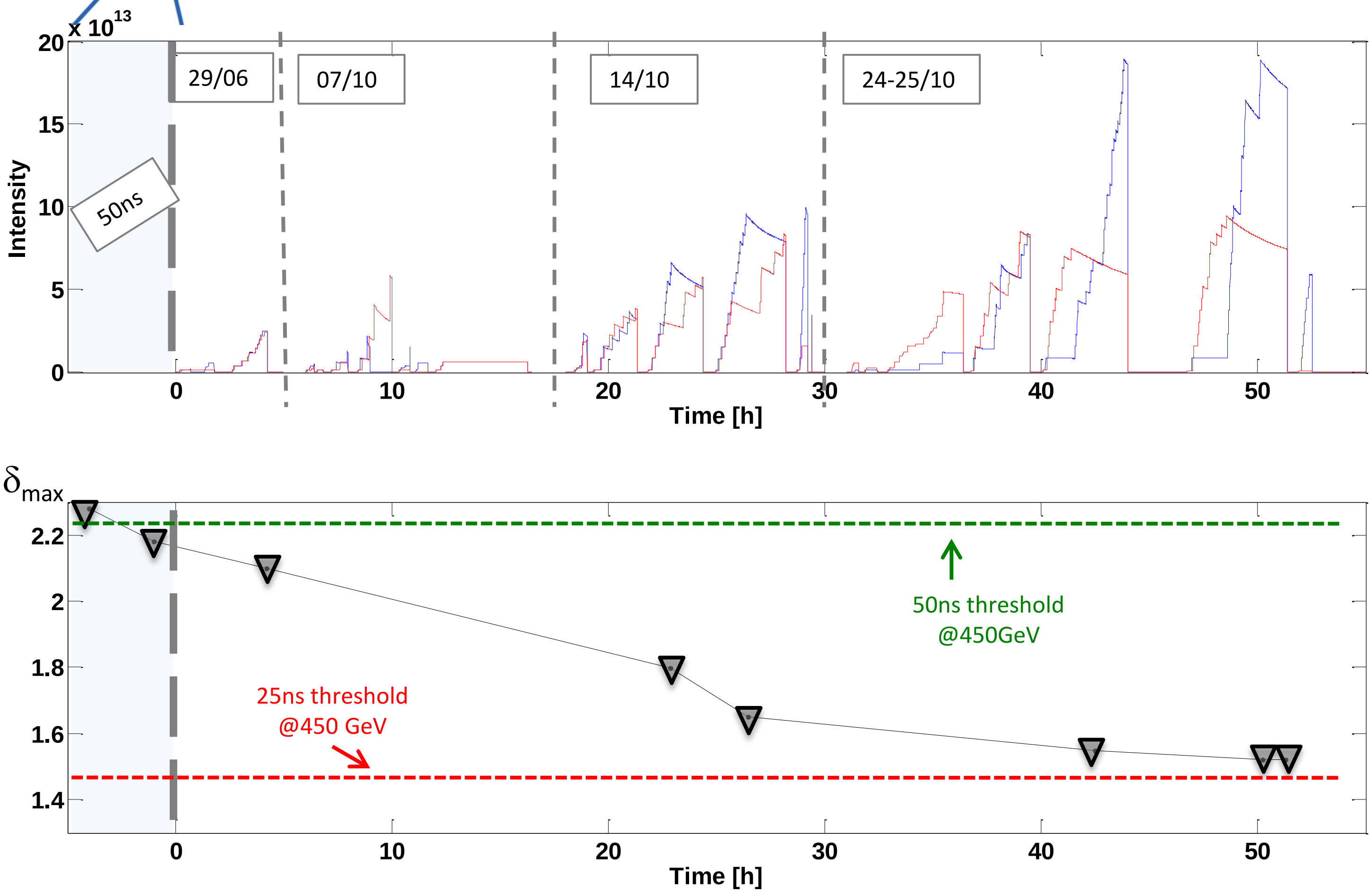
Measured heat load

ΔW_{meas}

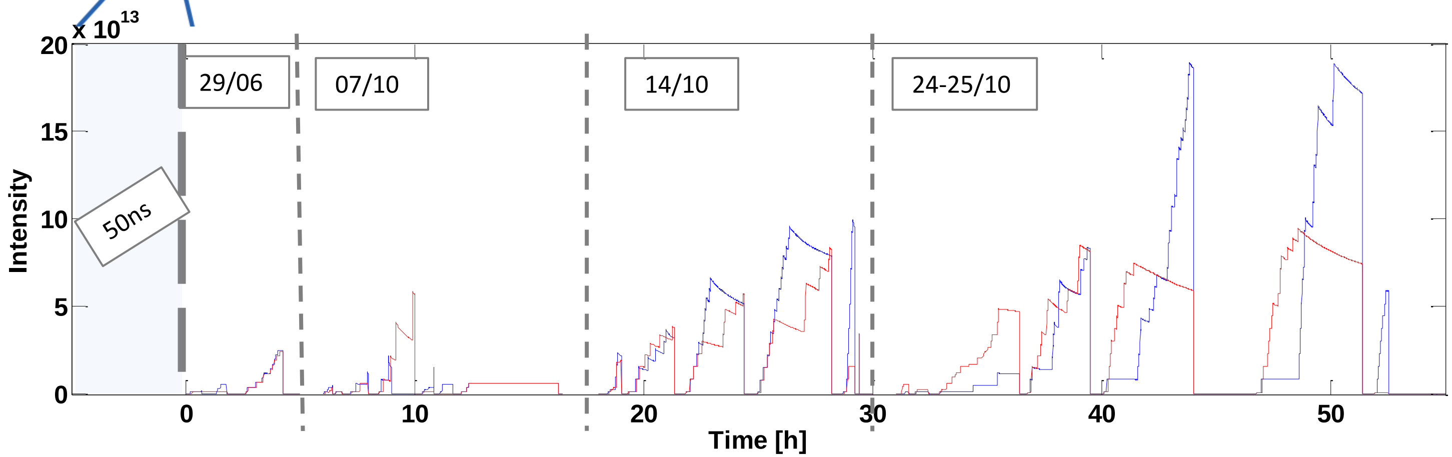


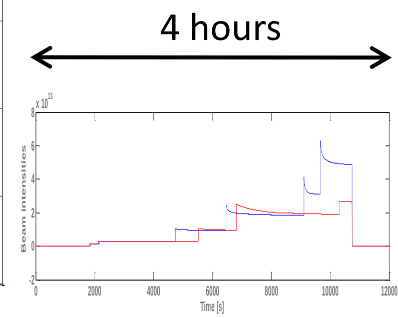
δ_{max}

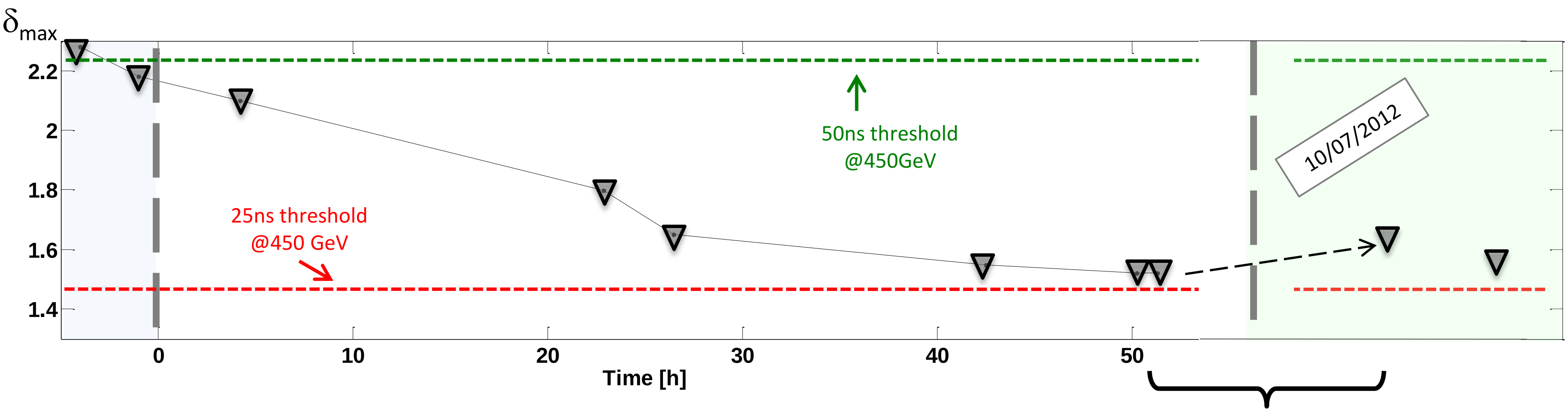
Estimation of the SEY in the LHC arcs



Estimation of the SEY in the LHC arcs







3w p operation (50ns) 2011 + ions + Winter shut-down + 3m operation (50ns) 2012

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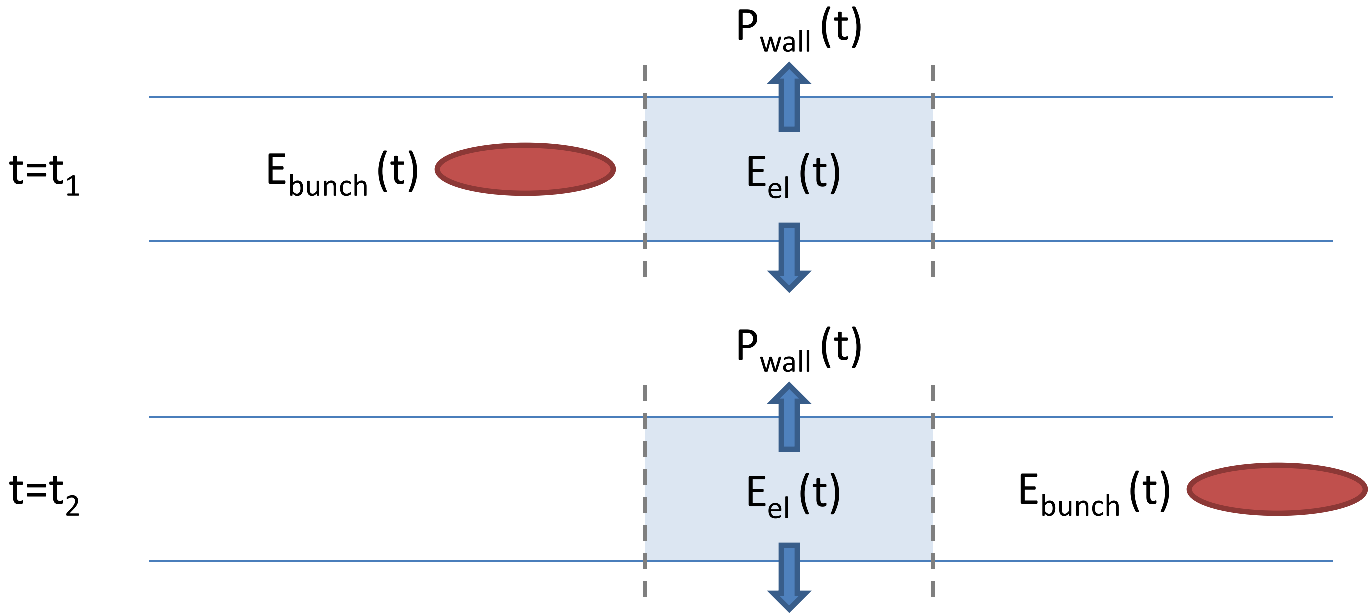
Bunch by bunch energy loss

PyECLOUD estimates the **bunch by bunch energy loss**, with a simple energy balance:



$$[E_{bun}(t_2) + E_{el}(t_2)] - [E_{bun}(t_1) + E_{el}(t_1)] = \int_{t_1}^{t_2} P_{wall}(t)dt$$

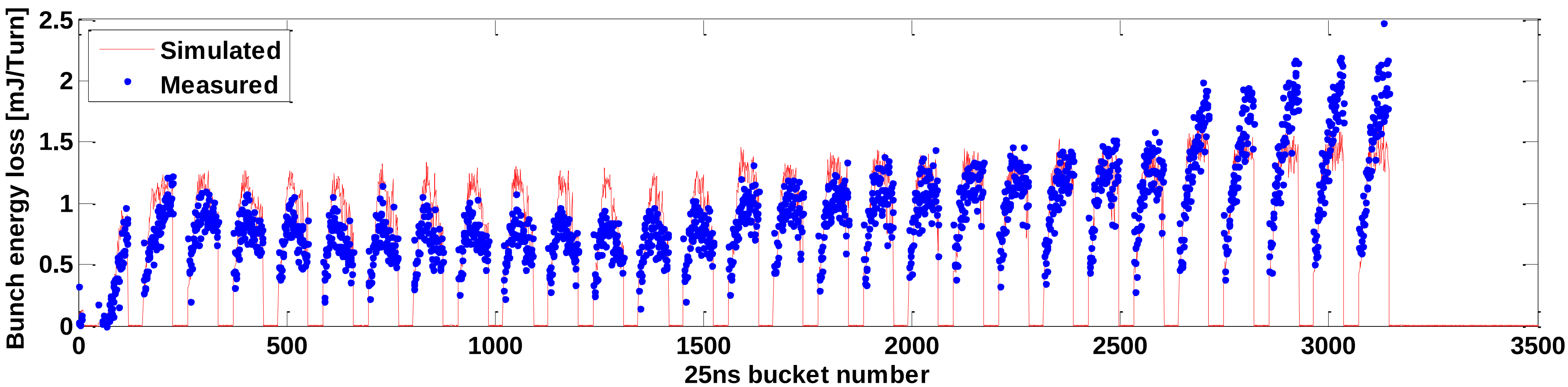
$$E_{bun}(t_1) - E_{bun}(t_2) = [E_{el}(t_2) - E_{el}(t_1)] + \int_{t_1}^{t_2} P_{wall}(t)dt$$

Bunch en. loss — e^- en. gain (electrostatic + kinetic) — En. transferred to walls

Bunch by bunch energy loss

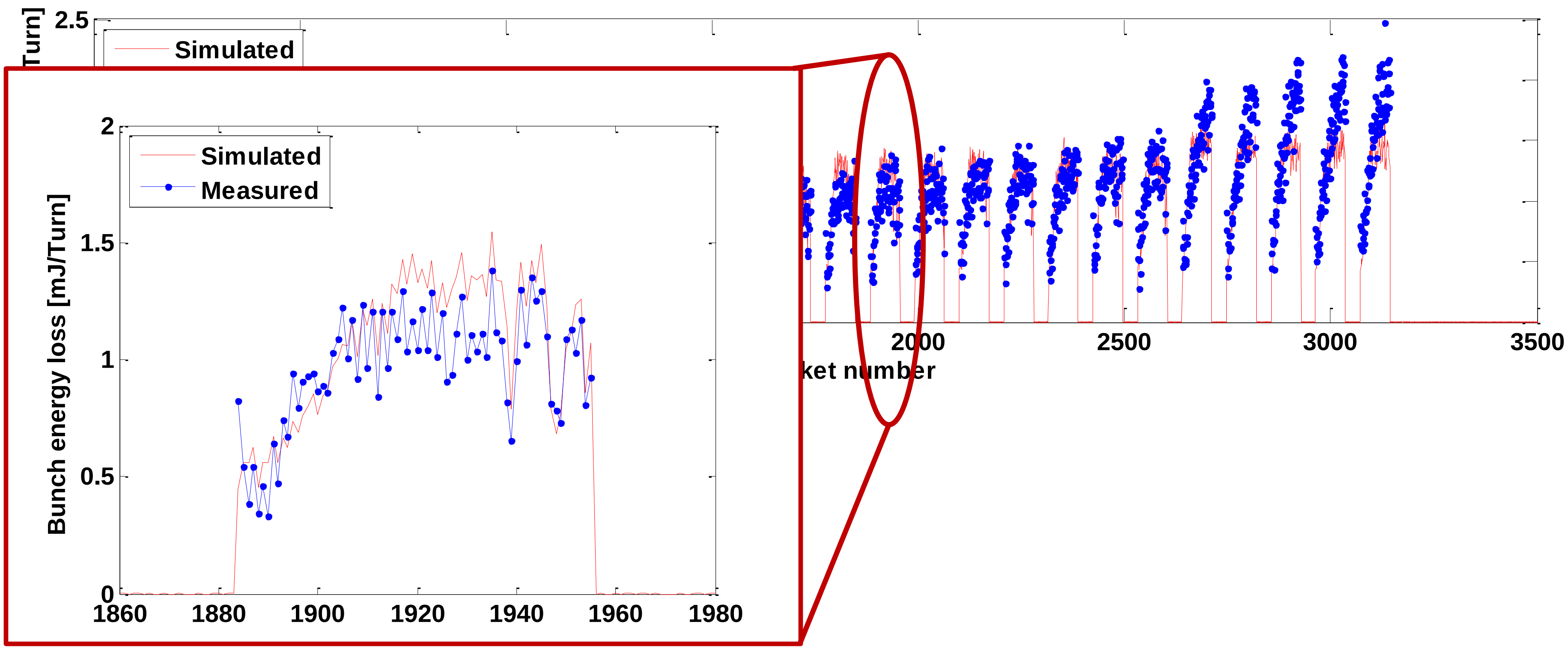
Simulation results could be **benchmarked with measured bunch by bunch energy loss**

(stable phase shift measurements).



Thanks to **J. Esteban-Müller and Elena Shaposhnikova**

Simulation results could be **benchmarked with measured bunch by bunch energy loss** (stable phase shift measurements).



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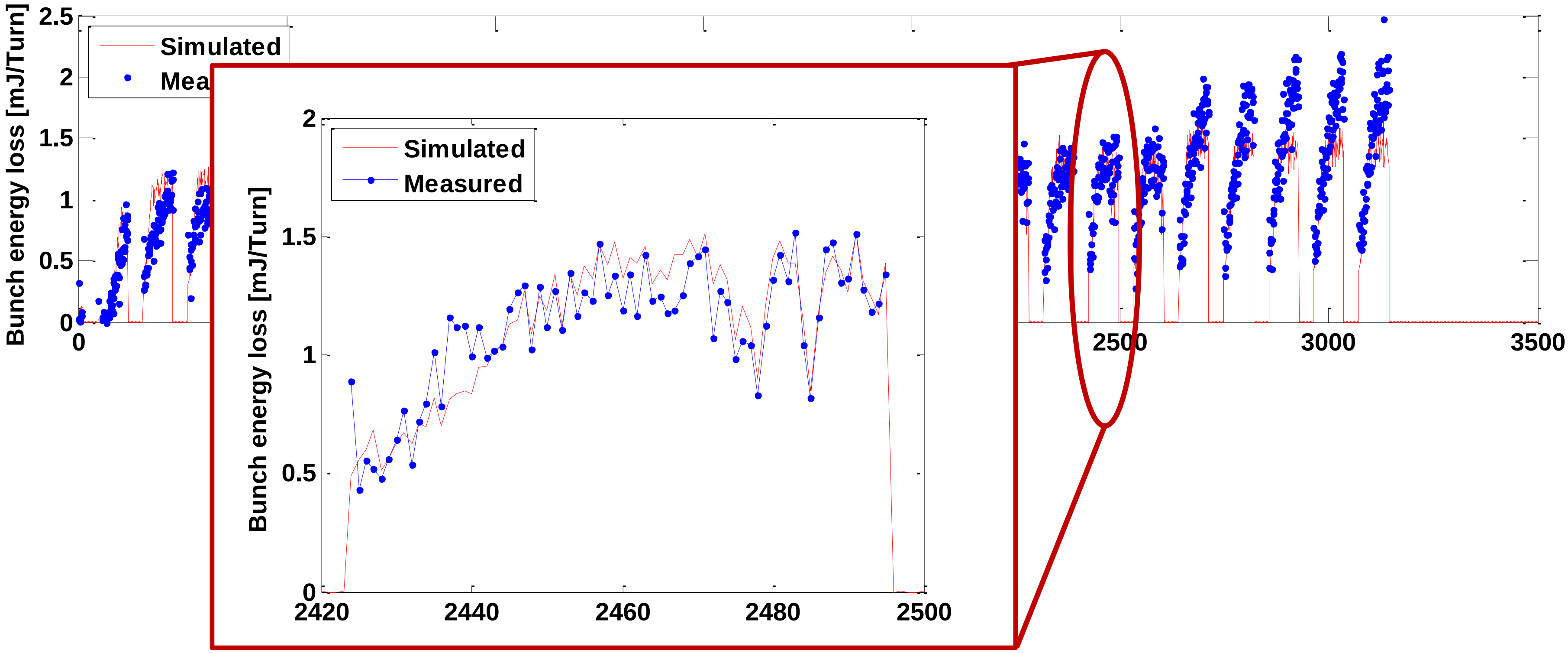

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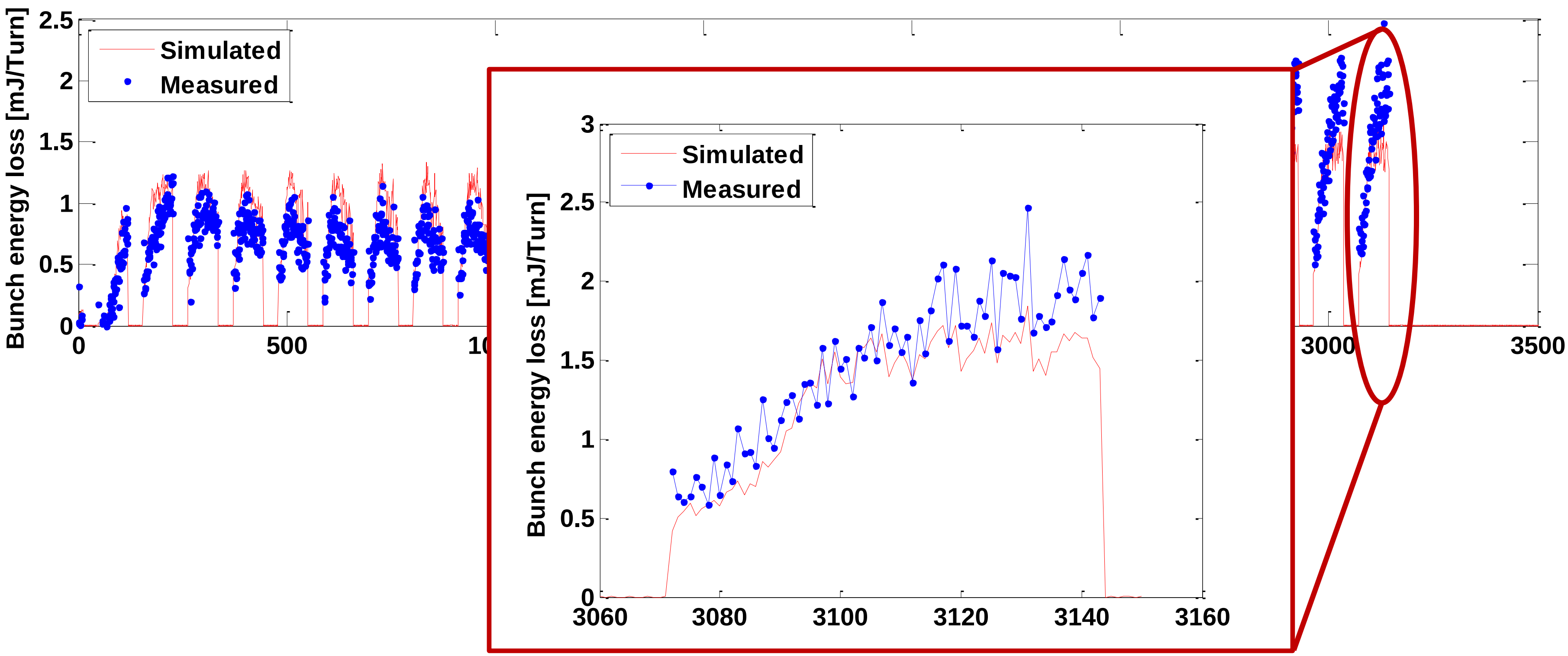

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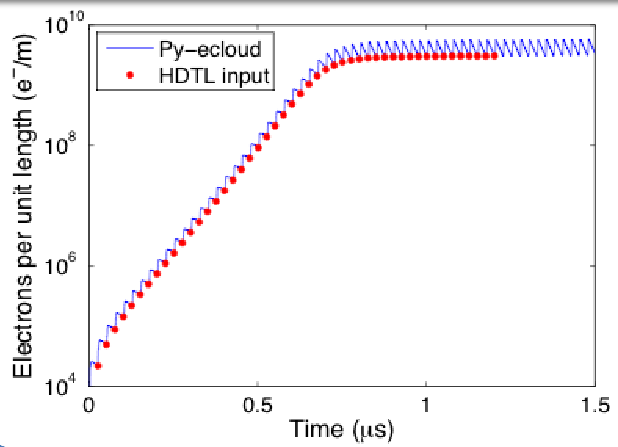
Bunch by bunch energy loss

PyECLOUD

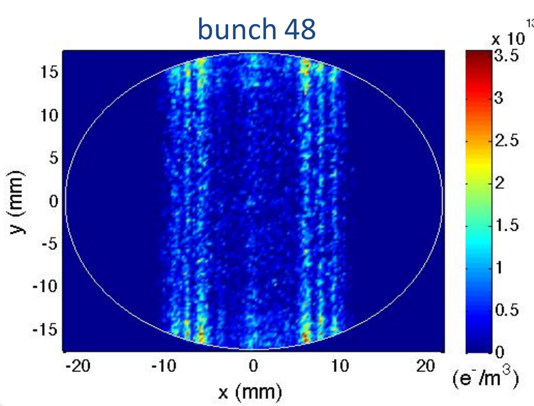
1x



- **Single passage of 48 bunches**
- **Equal bunch intensities (1.0e11p/b)**
- **Transverse emittance of ε_x=ε_y=3.5µm**
- **Electrons move in dipole field**
- **Beam screen approximated as ellipse**

48x

e^- distribution at bunch entrance



Thanks to **H. Bartosik**

48x

HEADTAIL

- **e^- distribution from PyECLOUD**
- **e-cloud reset after bunch passage**
- **Electrons move in dipole field**
- **Each bunch simulated individually**
- **Simulation of 500 turns**

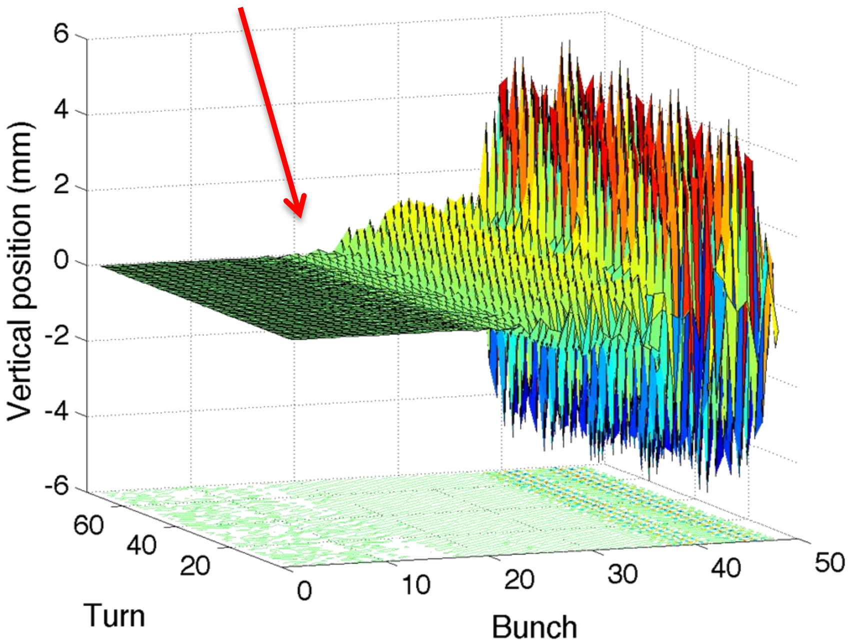
Bunch by bunch energy loss

PyECLOUD

- Single passage of 48 bunches

Measurement

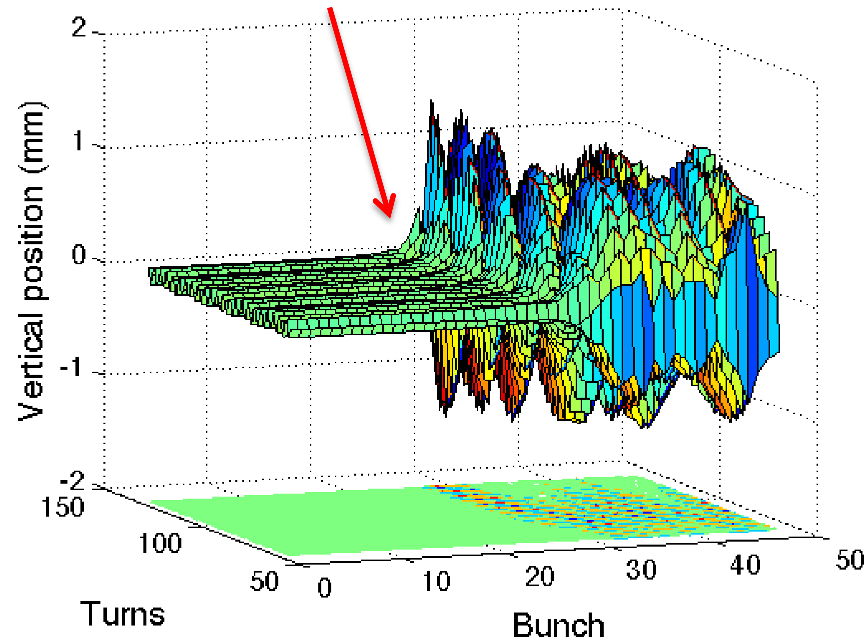
~ bunch 25 is the first unstable

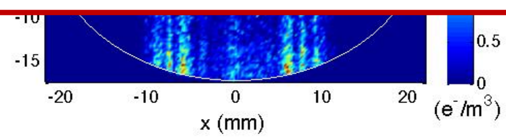


Thanks to **W. Hofle**

Simulation

bunch 26 is the first unstable





- Each bunch simulated individually
- Simulation of 500 turns

Summary

- A new Python code for the simulation of the e-cloud build-up has been developed
- The structure of PyECLOUD has been presented (with a closer look to MP size management)
- PyECLOUD has been used to reconstruct the SEY evolution of the LHC beam screen, and benchmarked with stable phase shift maeasurements

Future plans

- Arbitrary shaped chamber with non-uniform SEY (already implemented, test ongoing)
- Non uniform magnetic field map (e. g. quadrupoles, combined function magnets)
- Integration with HEADTAIL for self-consistent simulations

Thanks for your attention!