(Classic) Ion-trapping in electron storage rings

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Introduction

- The residual gas in an accelerator can be ionized by several effects like collisions with the beam or synchrotron radiation

- The resulting ions can be trapped in the negative beam potential of the electron beam

- The ion cloud effect on the electron beam can be divided in two parts :
  - The effect of the electric field produced by the ion cloud distribution which leads to tune shift, tune spread, halo increase and emittance blow-up.
  - The oscillation of the ion cloud within the electron beam potential which can lead to an instability.

- Possible mitigations to clear the ions are:
  - Gap in the bunch train
  - Beam shaking
  - Clearing electrodes

- To design effective mitigation strategies it is crucial to understand the ion dynamics and all the elements which can affect the ion behaviour inside the accelerator

Overview

I] Some theory

- Transverse beam-ion interaction
- Longitudinal beam-ion interaction
- Effect of dipoles and magnetic mirror effect

II] Simulations: Ion dynamics

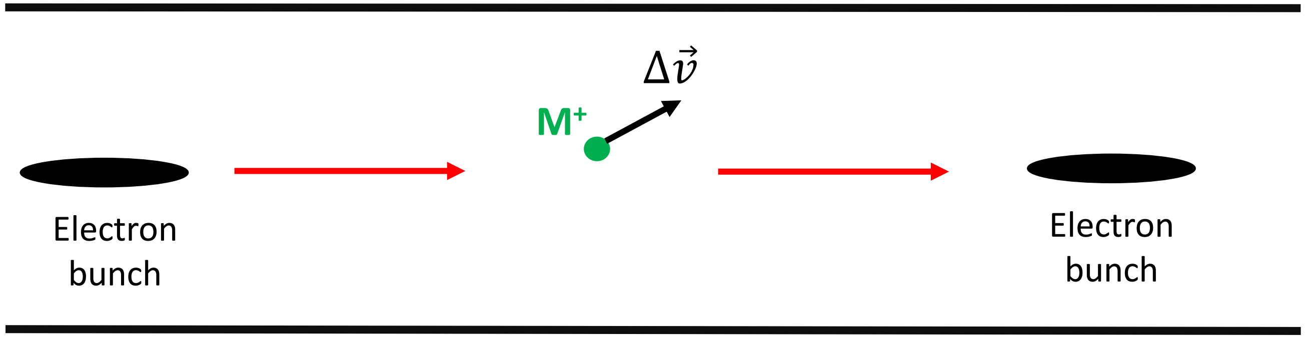
- A compact storage ring: ThomX
- A 3rd generation light source: Soleil
- A 4th generation light source: APS-U

III] Simulations: Mitigation strategies

- Clearing electrodes
- Clearing gaps

A model to describe the beam-ion interaction

The model gives the kick that an ion will feel when the electron beam is going through the beam pipe:



The model:

- Bassetti-Erskine formula[1] for transverse dynamics

Assumptions:

- “Strong-weak” model of the beam-beam interaction
- Electron bunch is supposed Gaussian

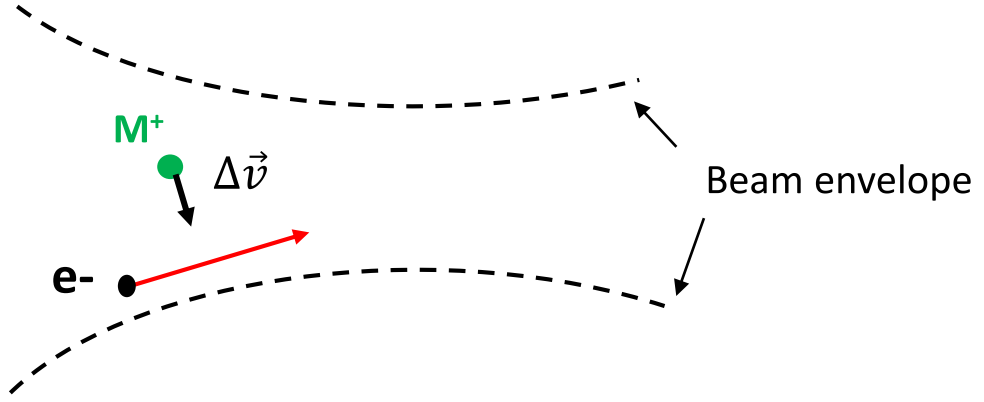
$$i\Delta v_x + \Delta v_y = \frac{-\overset{\text{Number of e- in a bunch}}{N}K\sqrt{\pi}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\left(w\left(\frac{\overset{\text{Ion position}}{x+iy}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - e^{-\left(\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)} w\left(\frac{\overset{\text{Beam size at the ion position}}{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right)$$

$$K = \frac{2r_pc^2}{v_eA}$$

[1] Bassetti and Erskine, Closed expression for the electrical field of a two-dimensional Gaussian charge. Technical report, 1980.

A model to describe the beam-ion interaction

The longitudinal part of the beam-ion interaction comes from the fact that the beam has a non-uniform transverse beam size:



The model:

- Bassetti-Erskine formula[1] for transverse dynamics
- Sagan formula[2] for longitudinal dynamics

Assumptions:

- "Strong-weak" model of the beam-beam interaction
- Electron bunch is supposed Gaussian
- The beam trajectory is quasi-parallel to the longitudinal axis

Energy spread

Dispersion function and derivative

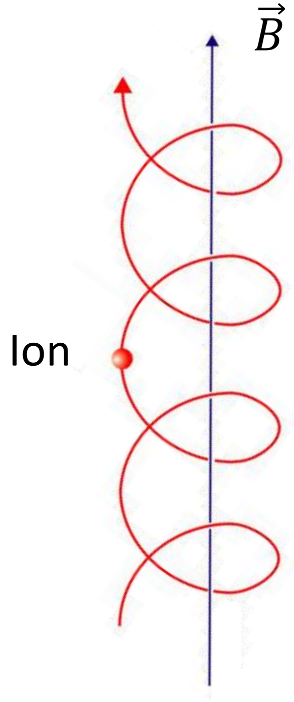
$$\Delta \mathrm{v}_s = (-\alpha_x \epsilon_x + \eta\eta' \sigma_\epsilon^2)\frac{\partial \Delta \mathrm{v}_x}{\partial x} - \alpha_y \epsilon_y \frac{\partial \Delta \mathrm{v}_y}{\partial y}$$

The ion dynamics are determined by the optics and the lattice design

[2] David Sagan. Some aspects of the longitudinal motion of ions in electron storage rings. Nucl. Instr. Meth. A, 1991.

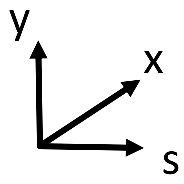
Effect of dipole magnets

The motion of a particle of charge q and mass m in an uniform and constant magnetic field $\vec{B}$ is the well known cyclotron motion:



$$\omega_c = \frac{qB}{m}$$

$$r_c = \frac{v_\perp}{\omega_c}$$

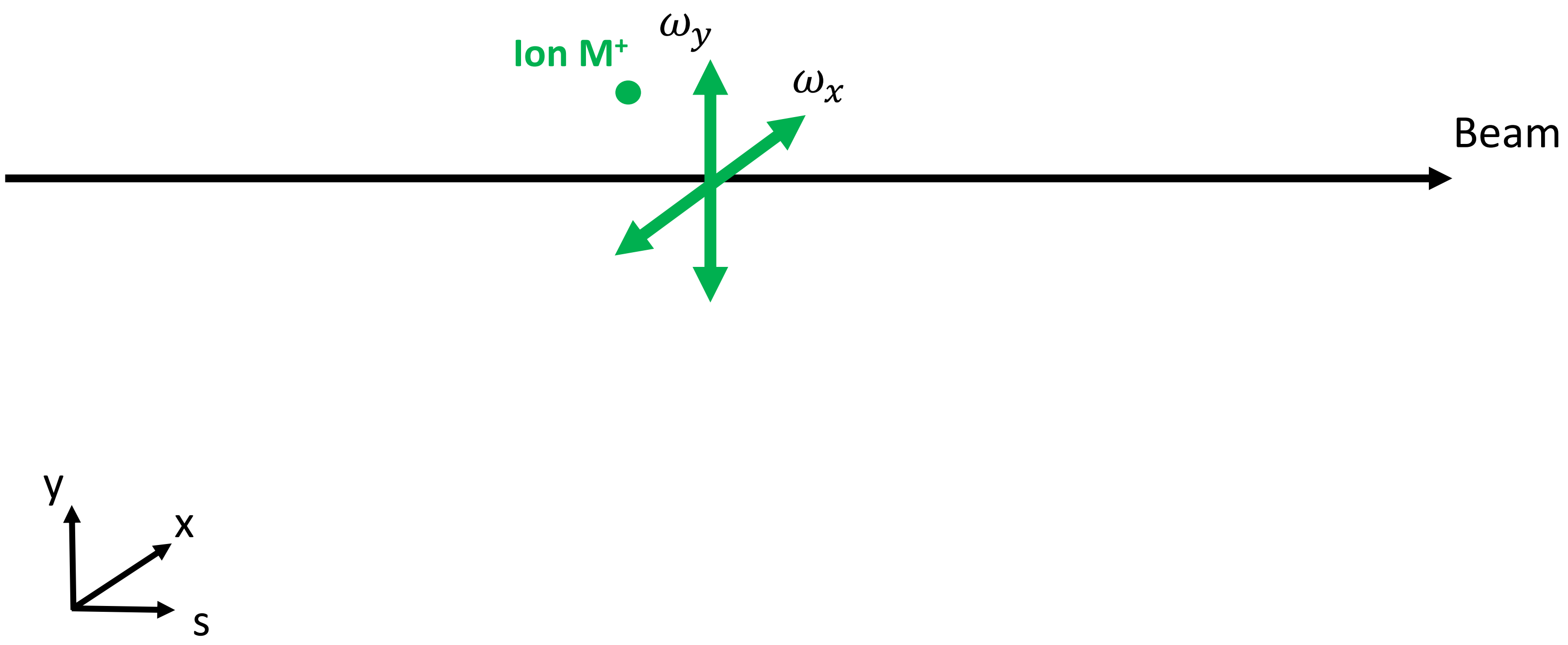


No global longitudinal displacement

Image: Eurofusion

Effect of dipole magnets

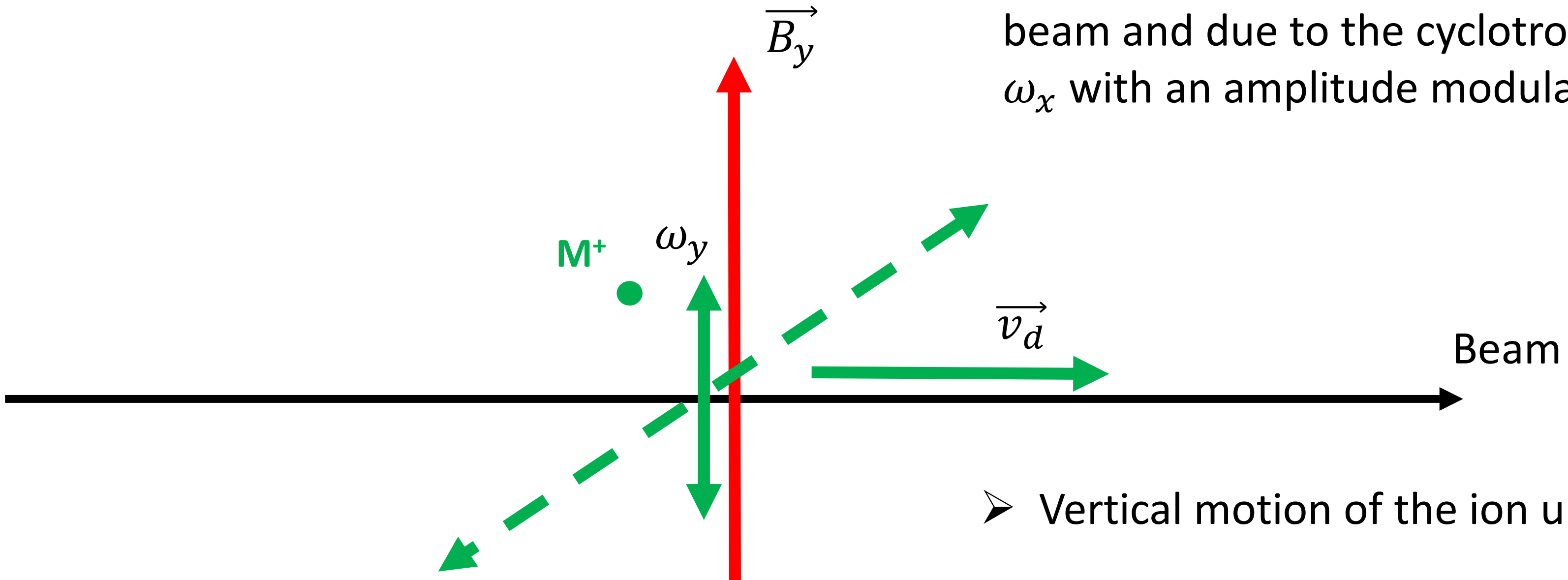
With the beam only, the ion is oscillating on both the horizontal plane and the vertical plane with respective pulsation ω_x and ω_y.

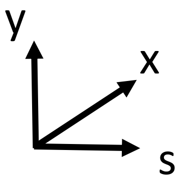


[3] Y. Miyahara, K. Takayama, and G. Horikoshi, Dynamical analysis on the longitudinal motion of trapped ions in an electron storage ring NIM Sec. A (1988).

Effect of dipoles magnets

With the beam and a dipole field, the resulting motion is a combination of the two motions:





- Horizontal motion of the ion is the sum of oscillations due to the beam and due to the cyclotron motion, so oscillation at pulsation ω_x with an amplitude modulation varying at pulsation ω_c
- Vertical motion of the ion unchanged, oscillation at pulsation ω_y
- The horizontal oscillations driven by the beam translates into a longitudinal drift velocity[3]:

$$v_d = (\omega_c x_0 + v_{s0})\,\frac{\omega_x^2}{\omega_c^2 + \omega_x^2}$$

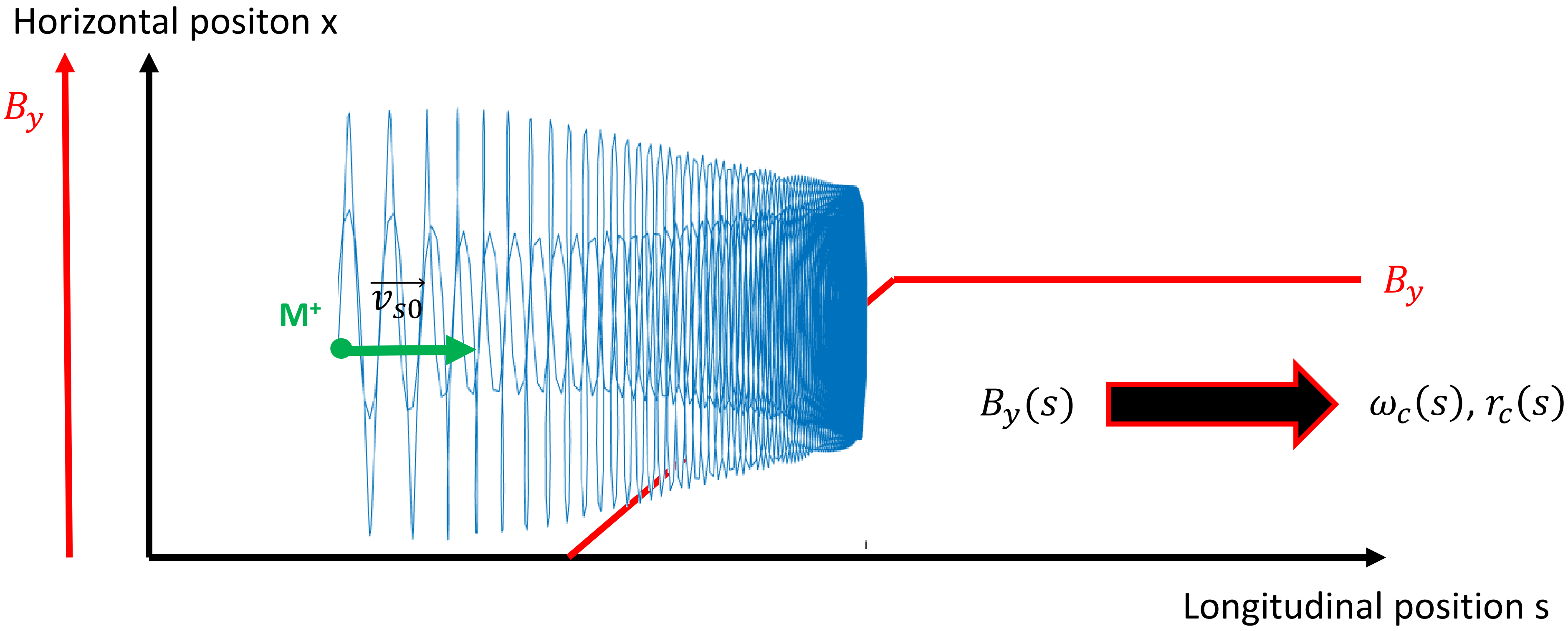
Alexis Gamelin [3] Y. Miyahara, K. Takayama, and G. Horikoshi, Dynamical analysis on the longitudinal motion of trapped ions in an electron storage ring NIM Sec. A (1988).

Magnetic mirror effect

An ion coming from a magnetic field free region which enters the dipole can be reflected by the fringe field:

- Condition for reflection: $v_{s_0} \leq \left| x_0 \sqrt{\omega_x \Omega(B_{max}) - \omega_x^2} \right| \approx \left| x_0 \frac{\omega_c(B_{max})}{\sqrt{2}} \right|$

$$\Omega = \sqrt{\omega_c^2 + \omega_x^2}$$



$B_y(s)$ ➡ $\omega_c(s)$, $r_c(s)$ and $v_d(s)$

[2] Y. Miyahara, K. Takayama, and G. Horikoshi, Dynamical analysis on the longitudinal motion of trapped ions in an electron storage ring NIM Sec. A (1988).

Magnetic mirror effect: Simulation

Condition for reflection:

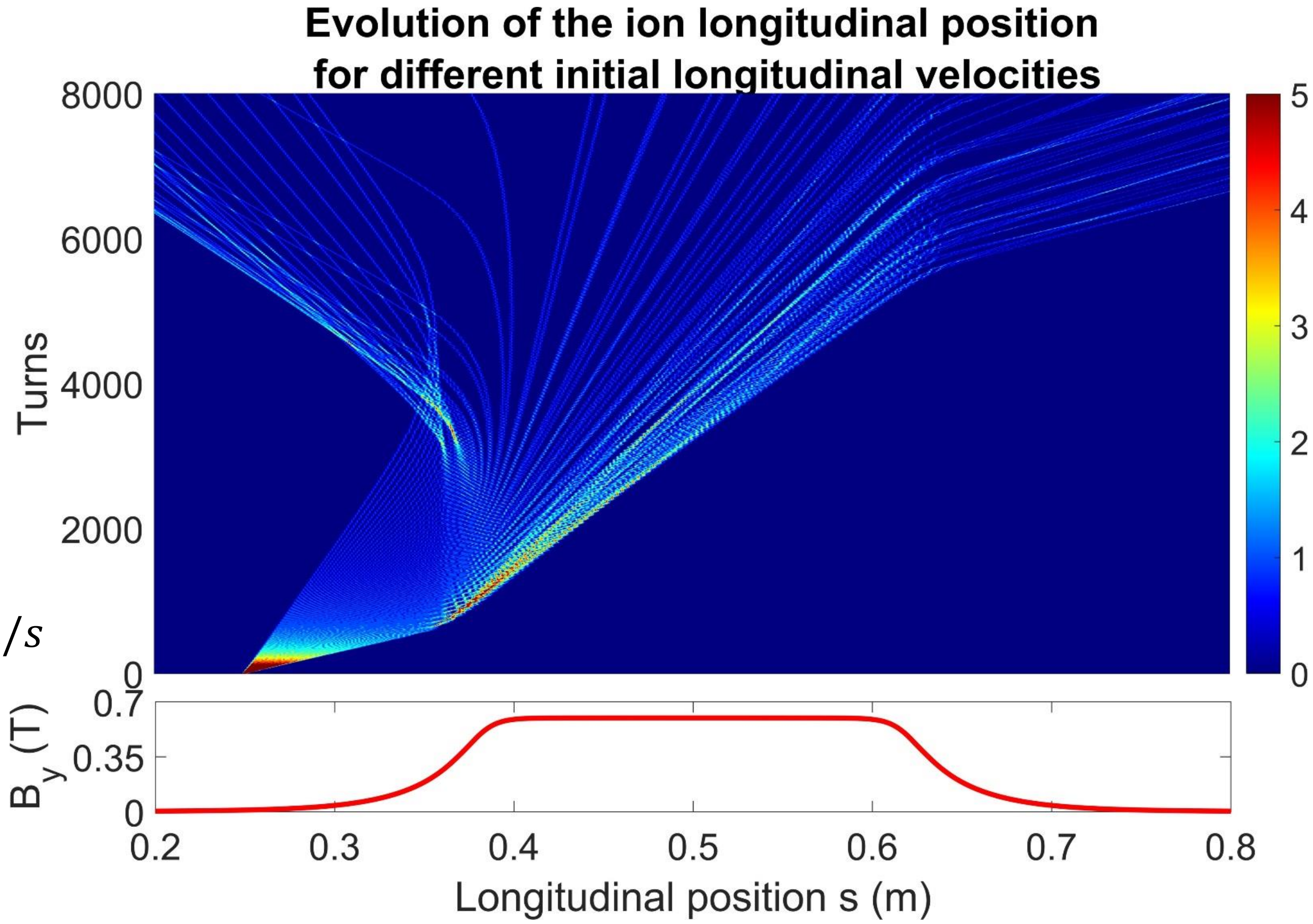
$$v_{s0} \leq \left| x_0 \sqrt{\omega_x \Omega(B_{max}) - \omega_x^2} \right| \approx \left| x_0 \frac{\omega_c(B_{max})}{\sqrt{2}} \right|$$

Simulation parameters:

$\omega_c = 2{,}6\ MHz$ $\omega_x = 2{,}1\ MHz$

$x_0 = 1\ mm$ $B_y = 0{,}6\ T$

- Analytic calculation: $v_{s0} = 1350\ m/s$
- Tracking: $v_{s0} = 1330\ m/s$


Evolution of the ion longitudinal position for different initial longitudinal velocities

NUAGE, ion cloud tracking

The following effects impact the ion cloud dynamics:

- Beam-ion interaction
- Ion trapping in magnetic field
- Clearing electrodes
- Gaps in bunch train

Included in

NUAGE a data parallel Matlab code for ion cloud tracking developed at LAL

Tracking in magnetic elements (dipoles, quadrupoles) by solving ODE

Interpolation of the 3D field maps of the clearing electrodes

- Ion cloud collective effects (self space charge, …)

Not included in NUAGE

In NUAGE, the ion cloud is defined at the start of the simulation (composition, number of ions, …) and tracked during a fixed time length. The simulation does not include the generation of new ions during the tracking.

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III] Simulations: Mitigation strategies

- Clearing electrodes
- Clearing gaps

A compact storage ring: ThomX

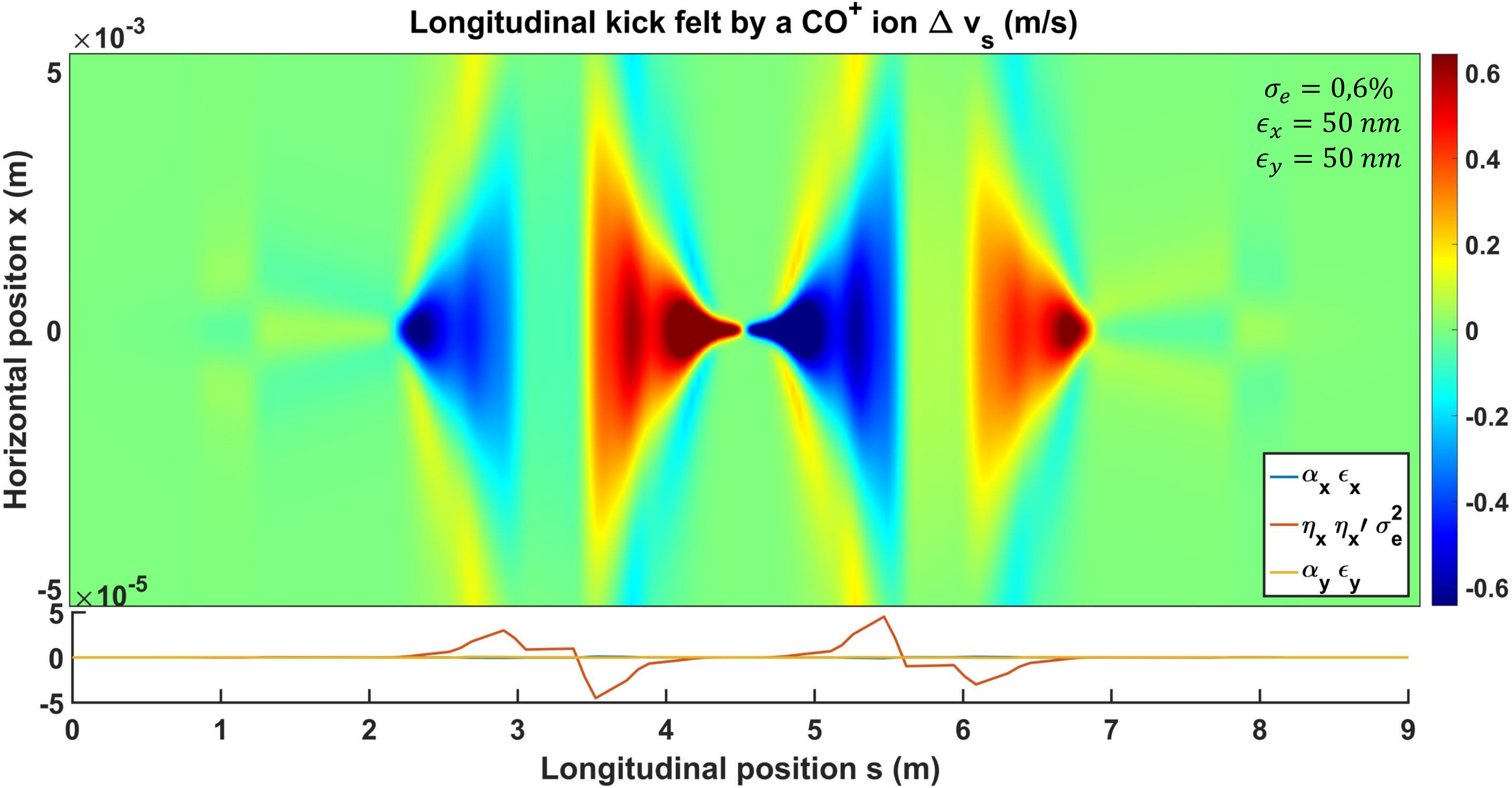
$$\sigma_e = 0{,}6\%$$

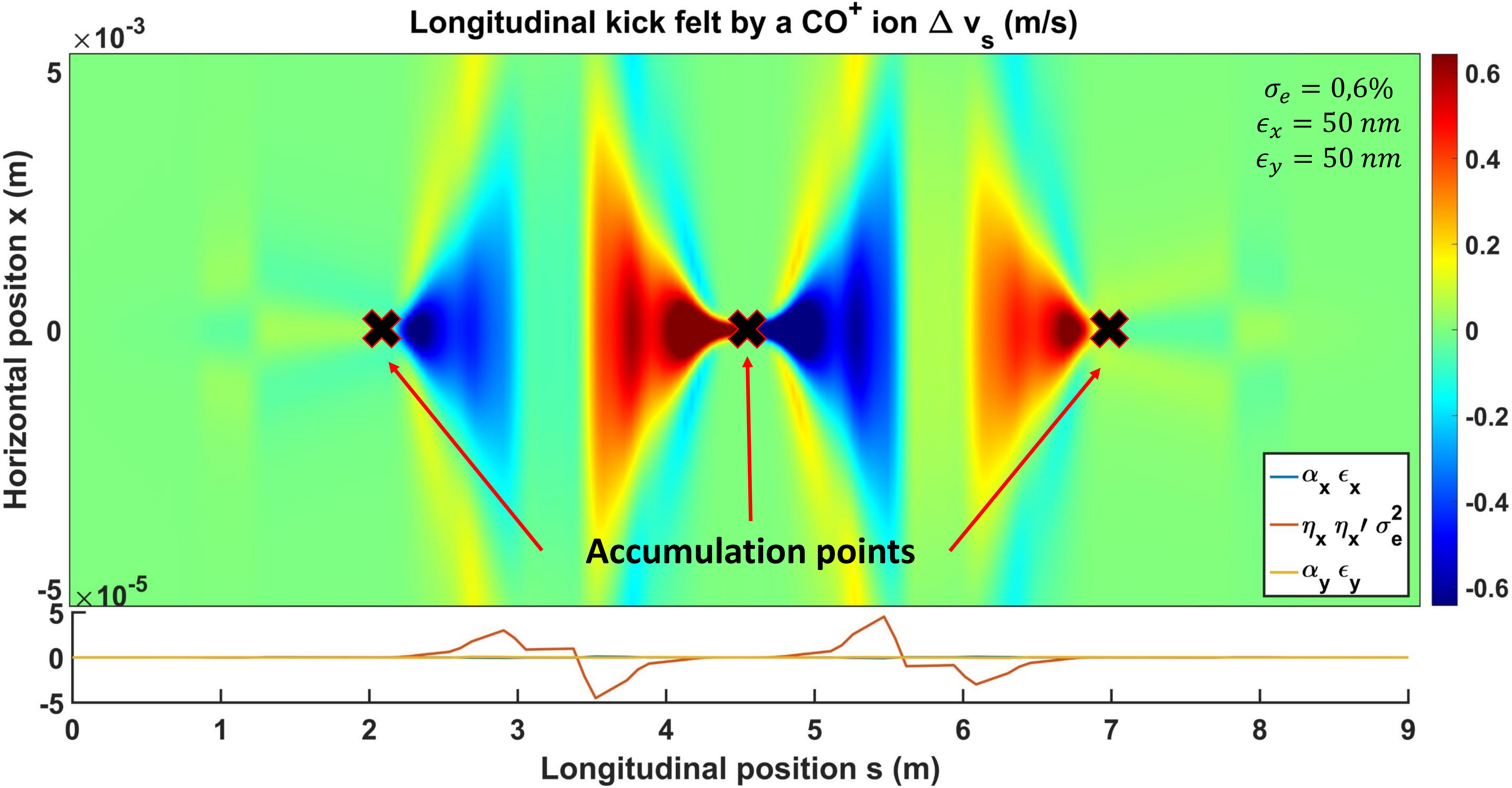
$$\epsilon_x = 50\ nm$$

$$\epsilon_y = 50\ nm$$

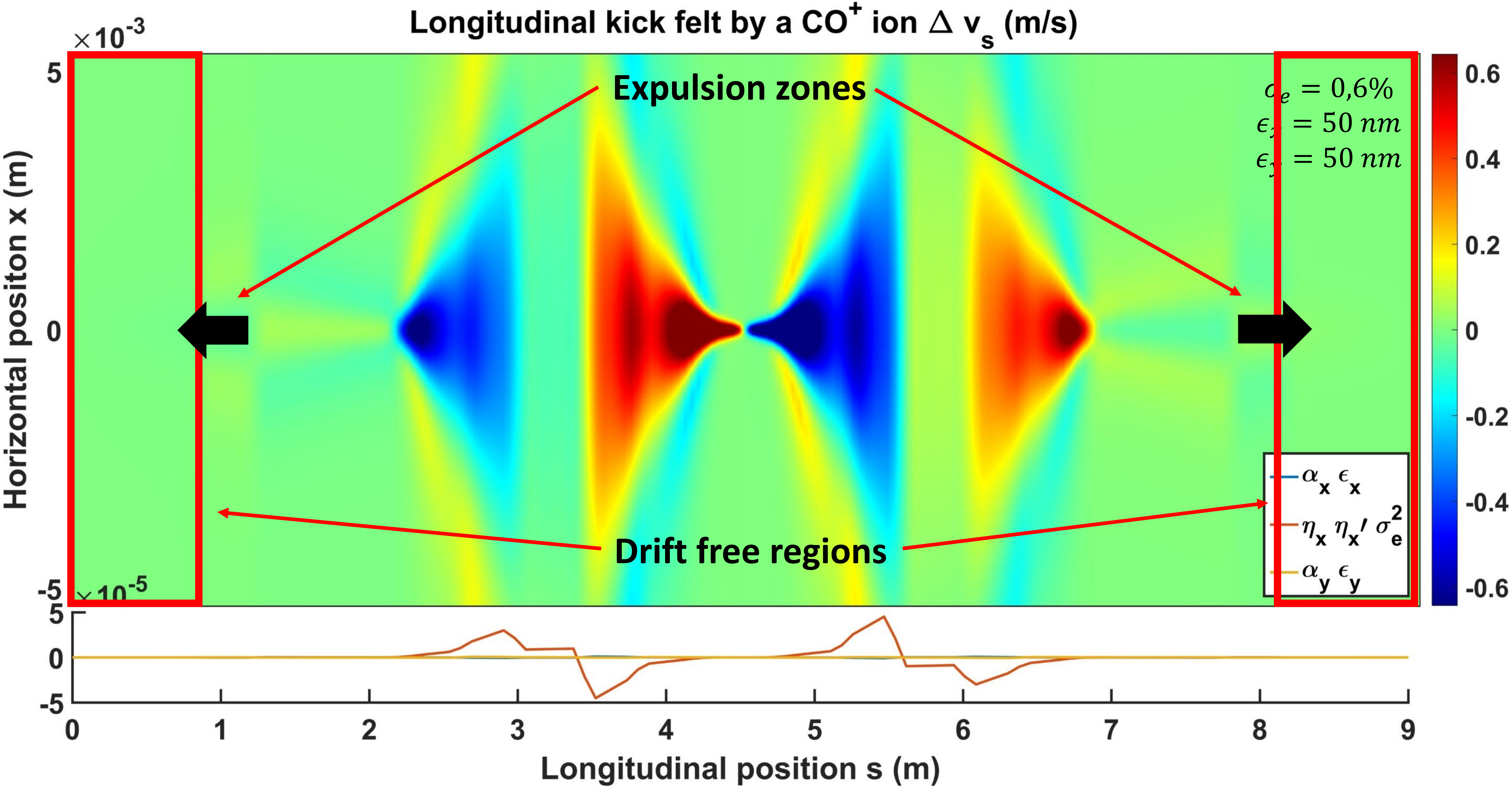
$$Q_{bunch} = 1\ nC$$

$$N_{bunch} = 1$$


Longitudinal kick felt by a CO$^+$ ion Δv_s (m/s)
$\times 10^{-3}$
5
0
-5
Horizontal positon x (m)
$\sigma_e = 0{,}6\%$
$\epsilon_x = 50\ nm$
$\epsilon_y = 50\ nm$
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
$\alpha_x\ \epsilon_x$
$\eta_x\ \eta_x'\ \sigma_e^2$
$\alpha_y\ \epsilon_y$
$\times 10^{-5}$
5
0
-5
0
1
2
3
4
5
6
7
8
9
Longitudinal position s (m)



Accumulation points

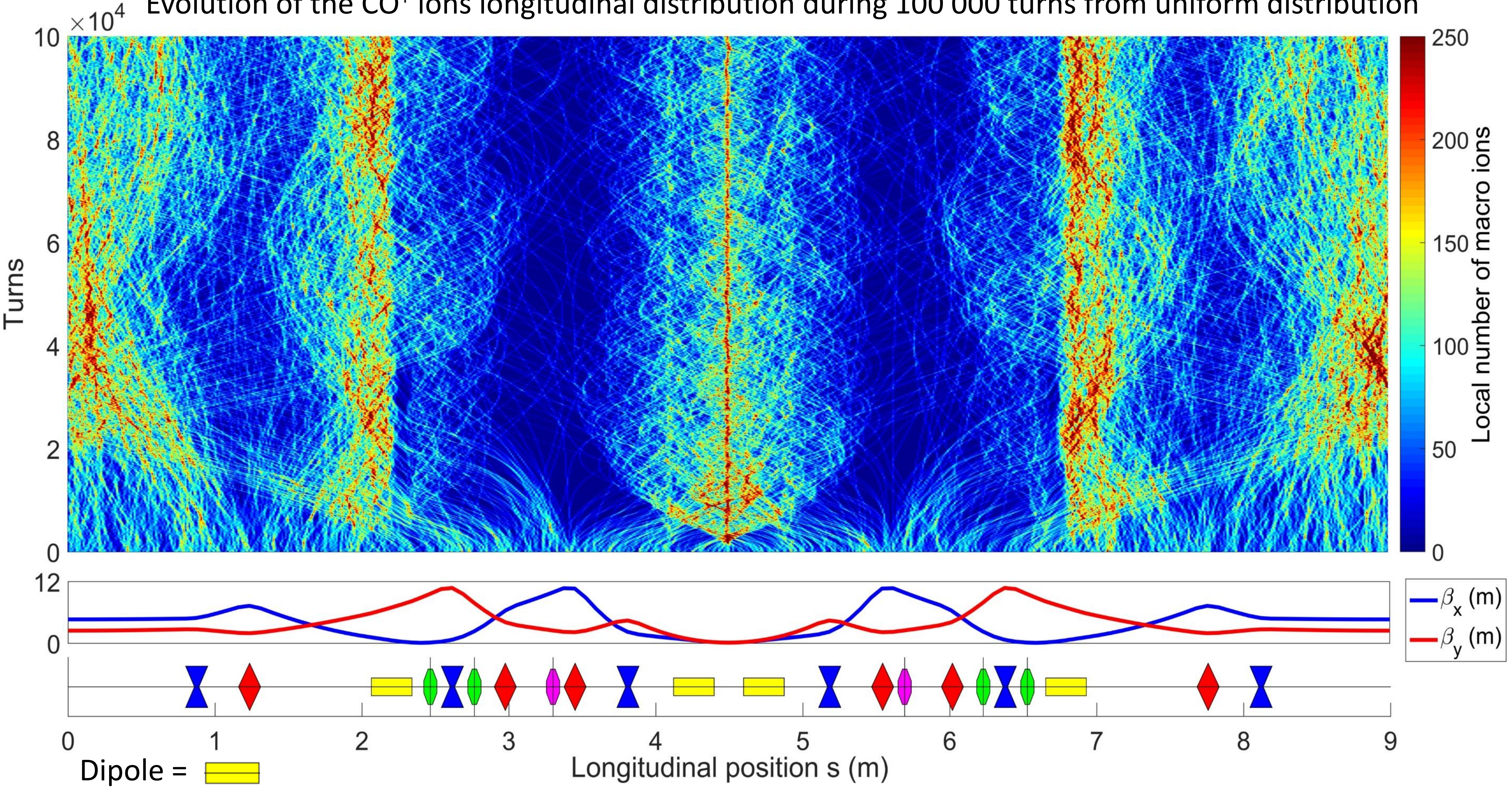


Expulsion zones

Drift free regions

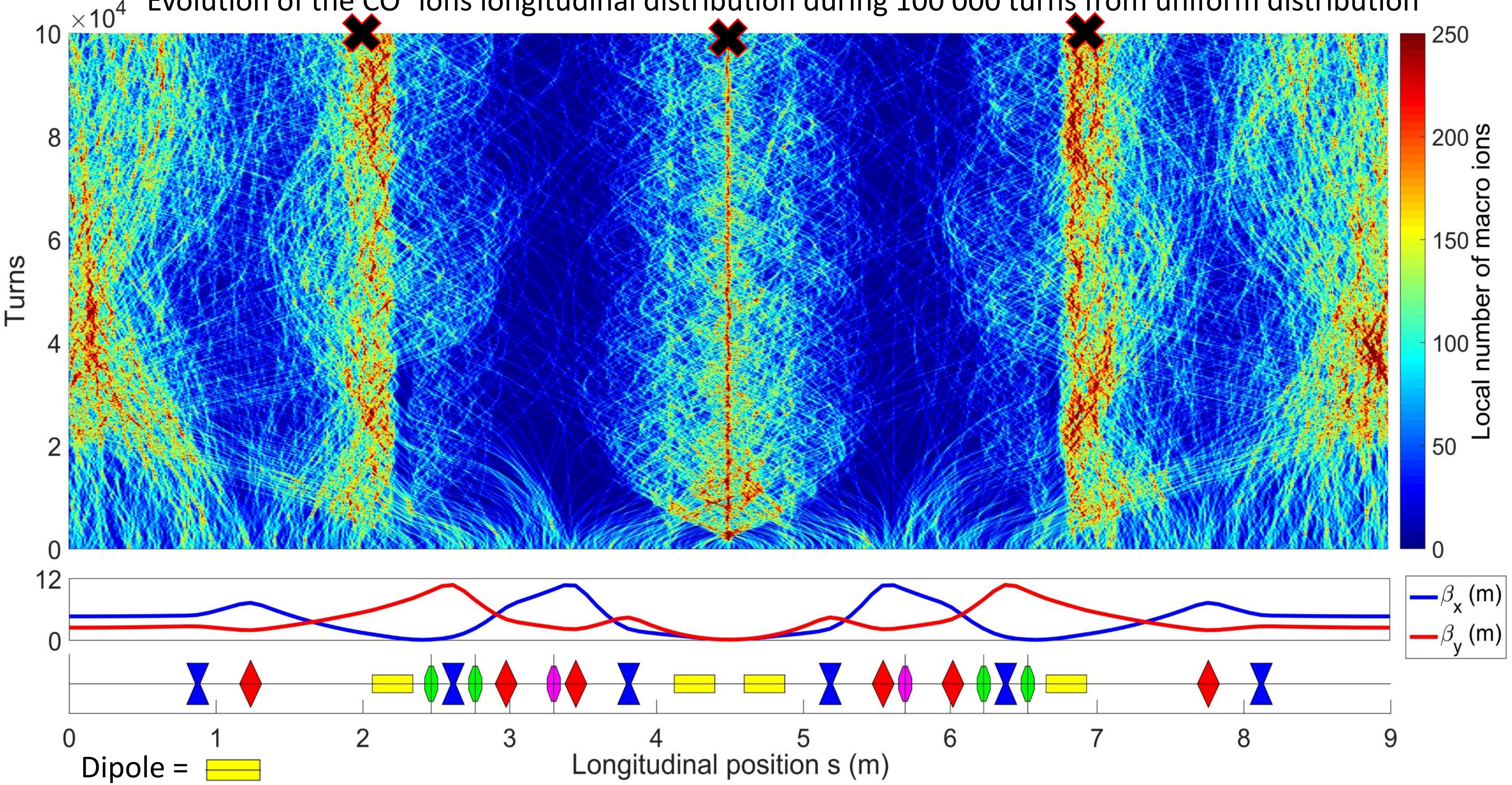
$\sigma_e = 0{,}6\%$
$\epsilon_x = 50\ nm$
$\epsilon_y = 50\ nm$

Evolution of the CO⁺ ions longitudinal distribution during 100 000 turns from uniform distribution



NUAGE simulation, number of macro ions at start : 100 000

Evolution of the CO⁺ ions longitudinal distribution during 100 000 turns from uniform distribution



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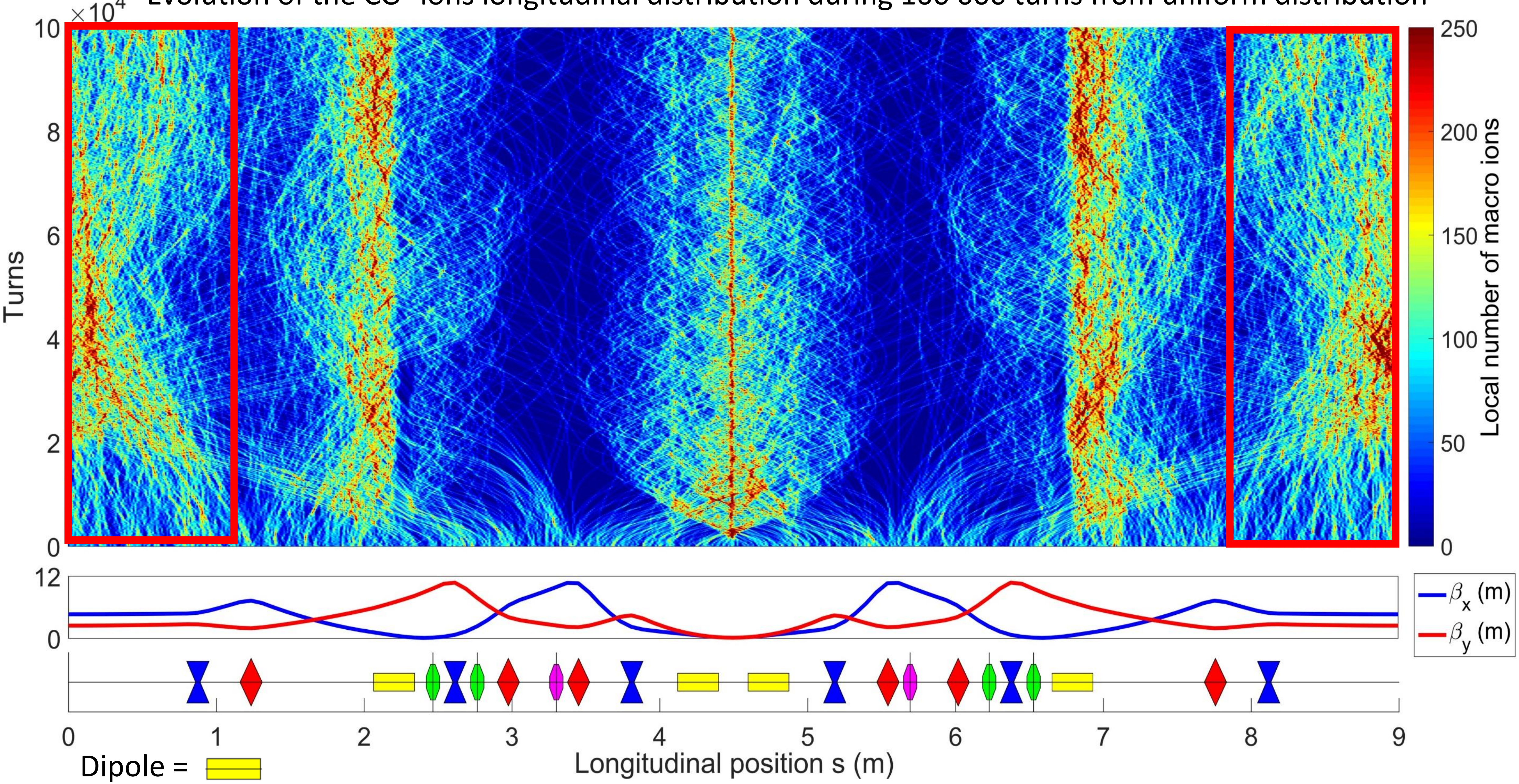


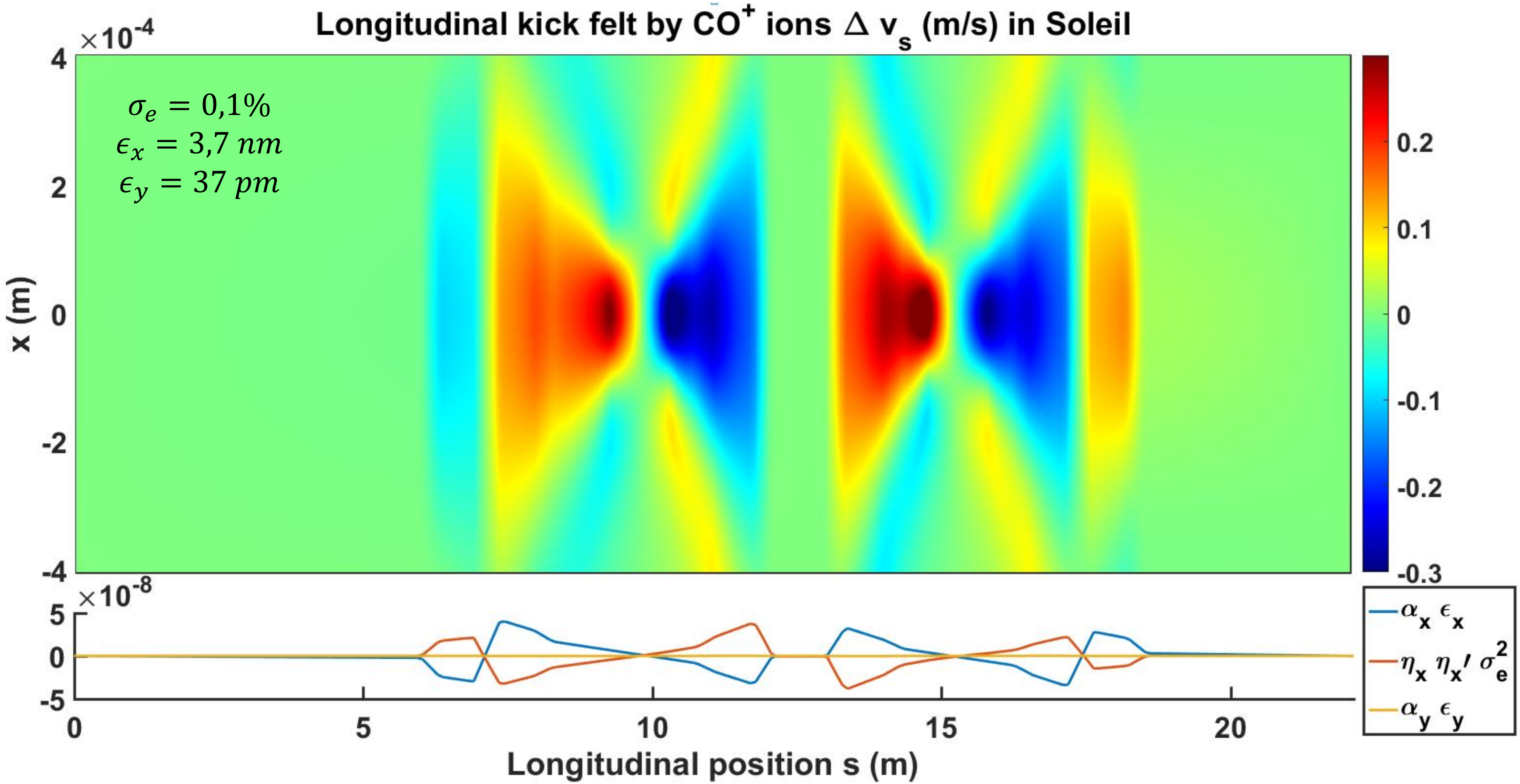
Dipole = 🟨

NUAGE simulation, number of macro ions at start : 100 000

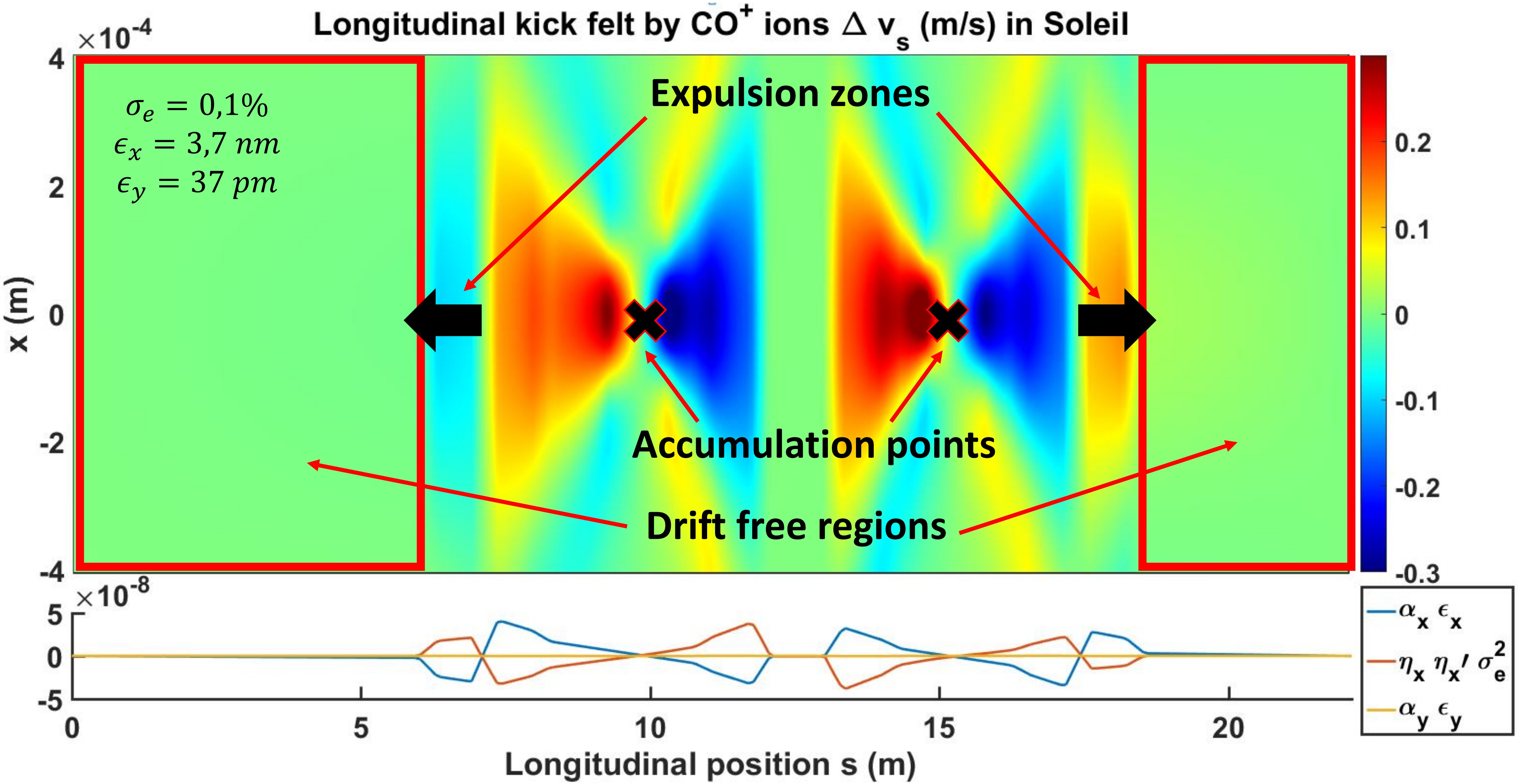
3rd generation light source: Soleil

$\sigma_e = 0{,}1\%$
$\epsilon_x = 3{,}7\ nm$
$\epsilon_y = 37\ pm$
$Q_{bunch} = 1{,}42\ nC$
$N_{bunch} = 416$
ΔL = 0,85 m

3rd generation light source: Soleil



3rd generation light source: Soleil



Longitudinal kick felt by CO$^+$ ions Δv_s (m/s) in Soleil

$\sigma_e = 0{,}1\%$
$\epsilon_x = 3{,}7\ nm$
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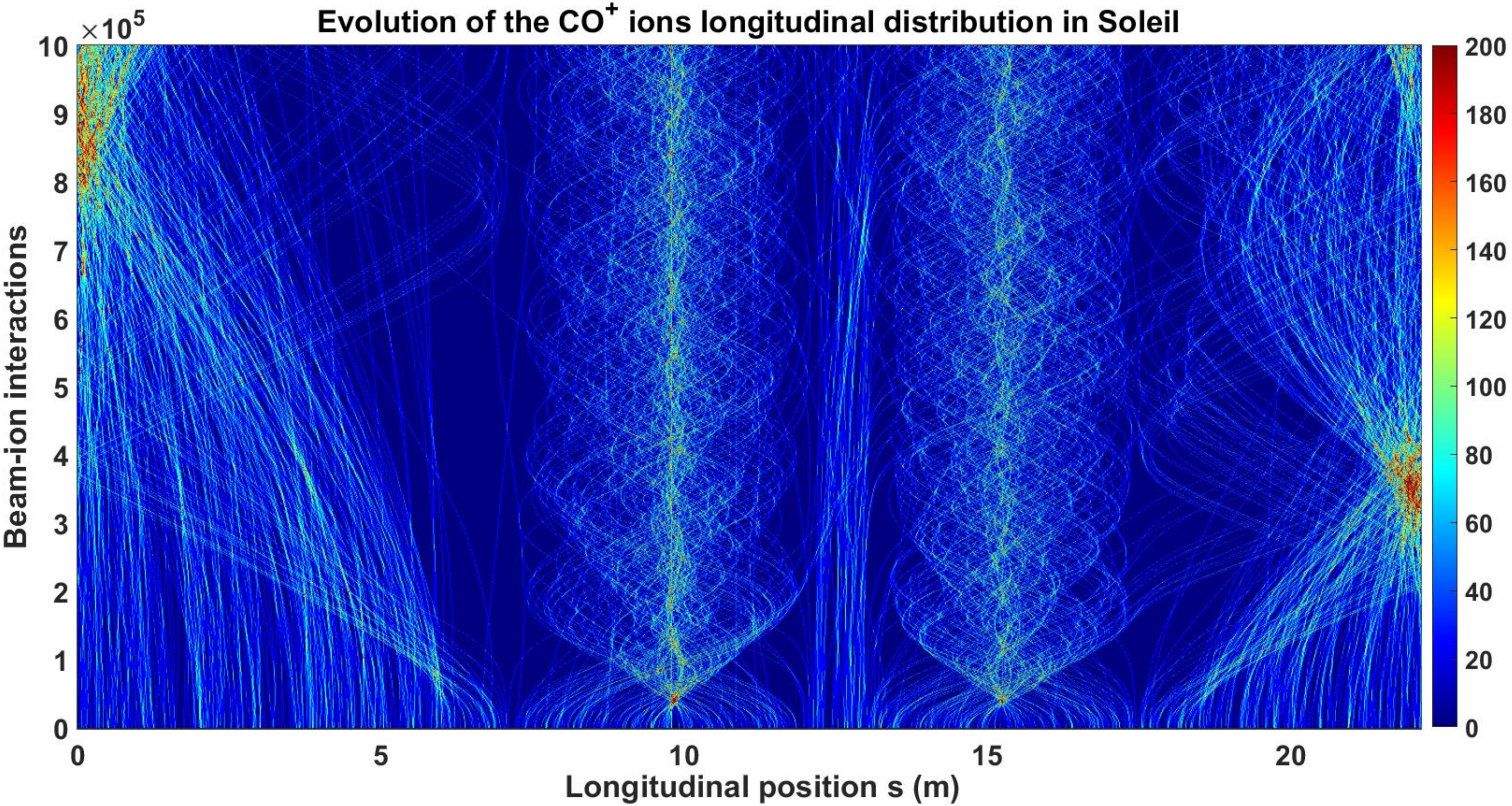
Expulsion zones

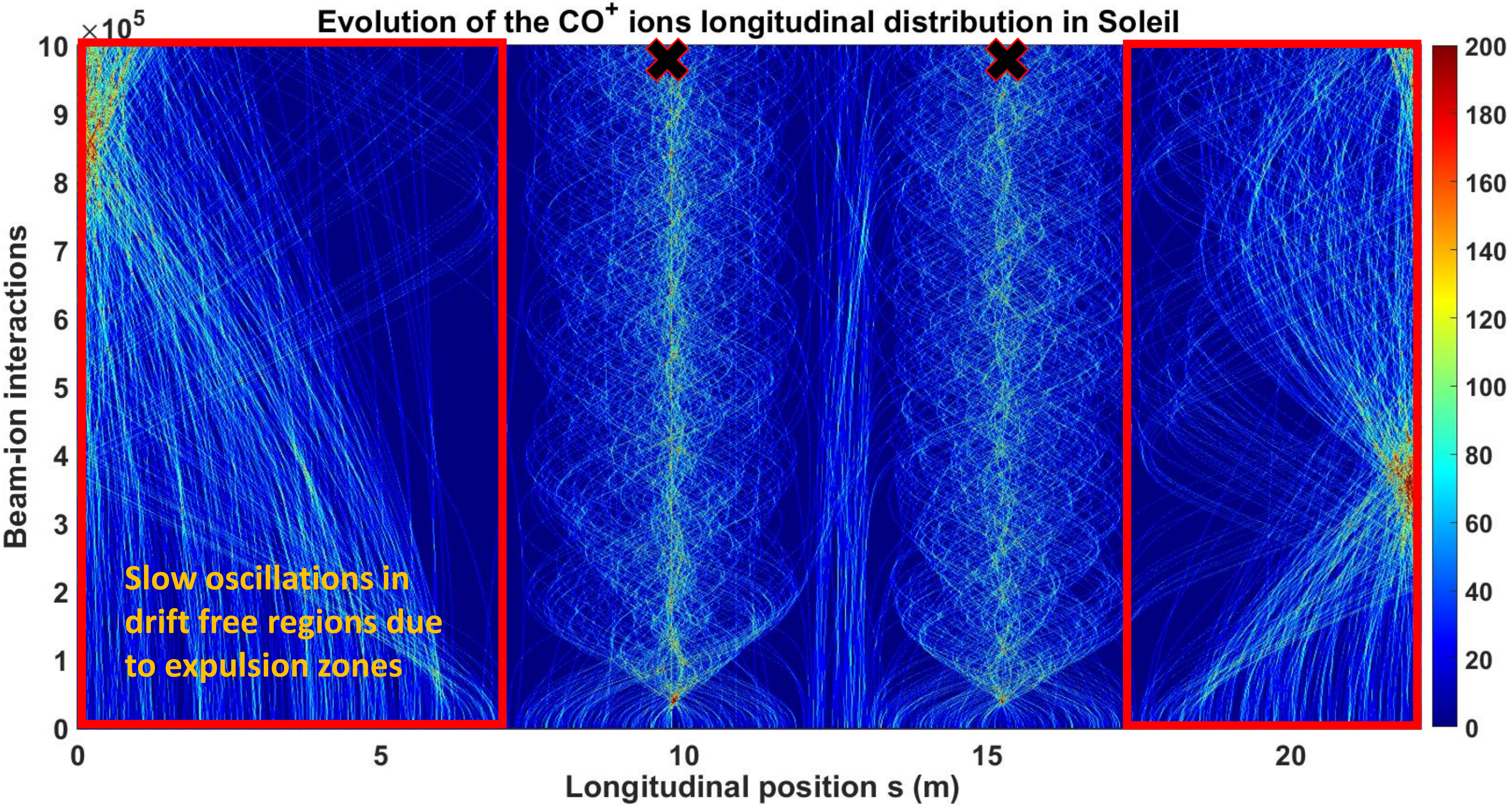
Accumulation points

Drift free regions

3rd generation light source: Soleil



3rd generation light source: Soleil



Slow oscillations in drift free regions due to expulsion zones

4th generation light source: APS-U

$\sigma_e = 0{,}13\%$

$\epsilon_x = 29\ pm$

$\epsilon_y = 29\ pm$

$Q_{bunch} = 2{,}27\ nC$

$N_{bunch} = 324$

$\Delta\mathrm{L}$ = 3,4 m

4th generation light source: APS-U

Condition for ion trapping in linear theory[5]:

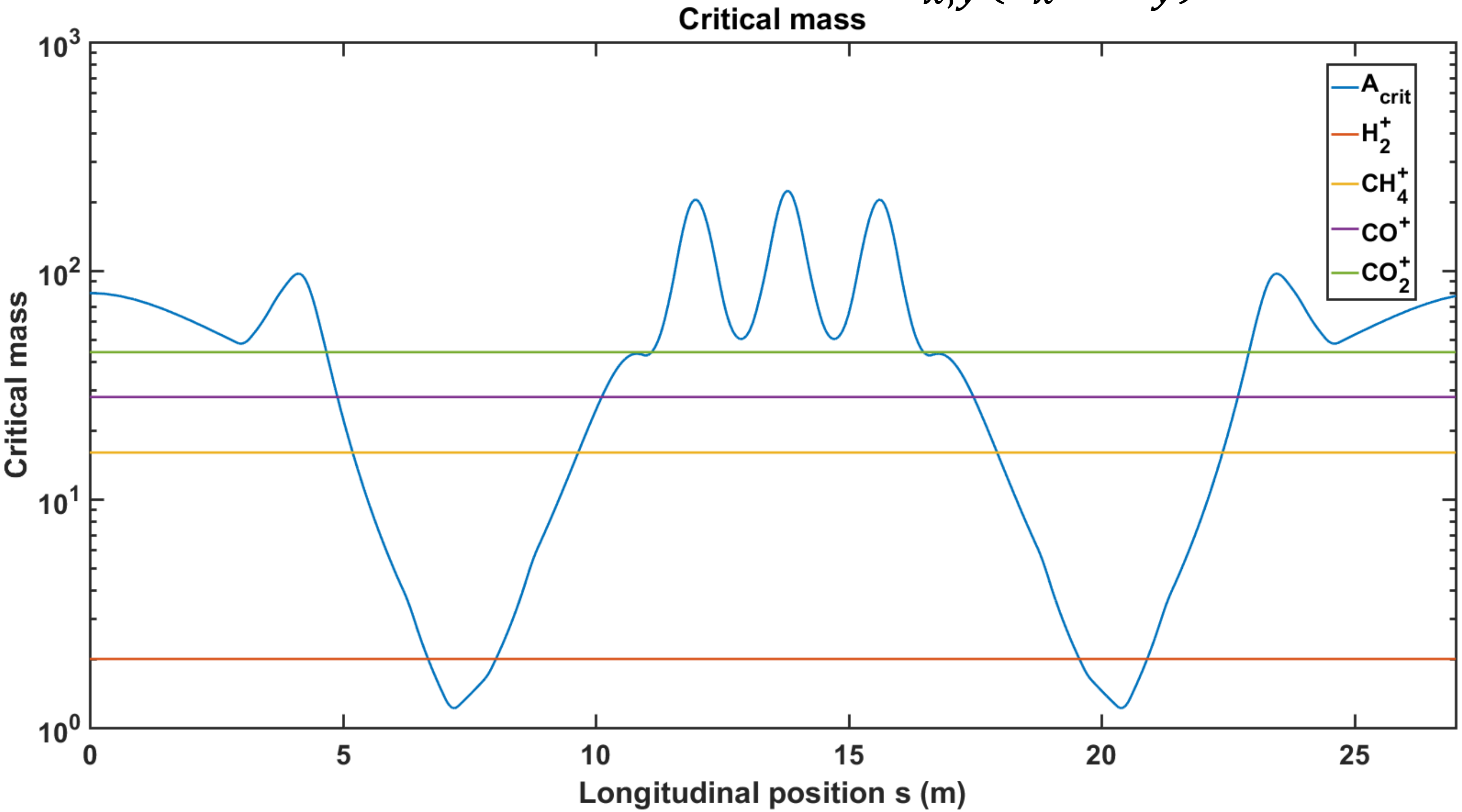
$$A_{ion} \geq \frac{n_e r_p \Delta L}{4\sigma_{x,y}(\sigma_x + \sigma_y)} = A_{crit}$$

<u>APS-U parameters:</u>

E = 6 GeV
ϵ_x = 29 pm
ϵ_y = 29 pm
Nb = 324
n_e = 1,4 x 10^{10}
ΔL = bunch spacing = 3,4 m
r_p = classic proton radius = 1,5 x 10^{-18} m

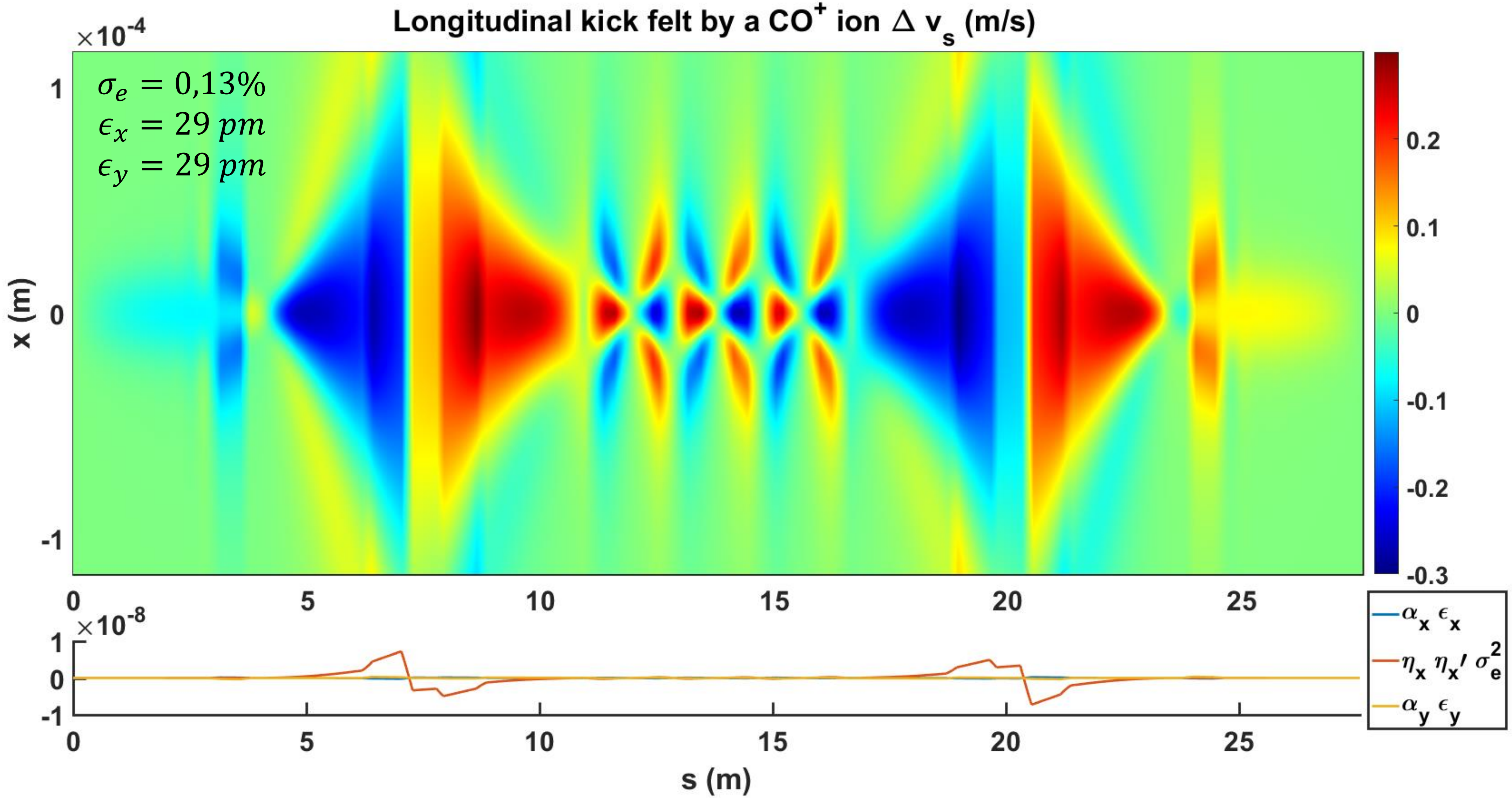
<u>Gas composition (simulations):</u>

H2: 43%
CO: 40 %
CO2: 13%
CH4: 4%

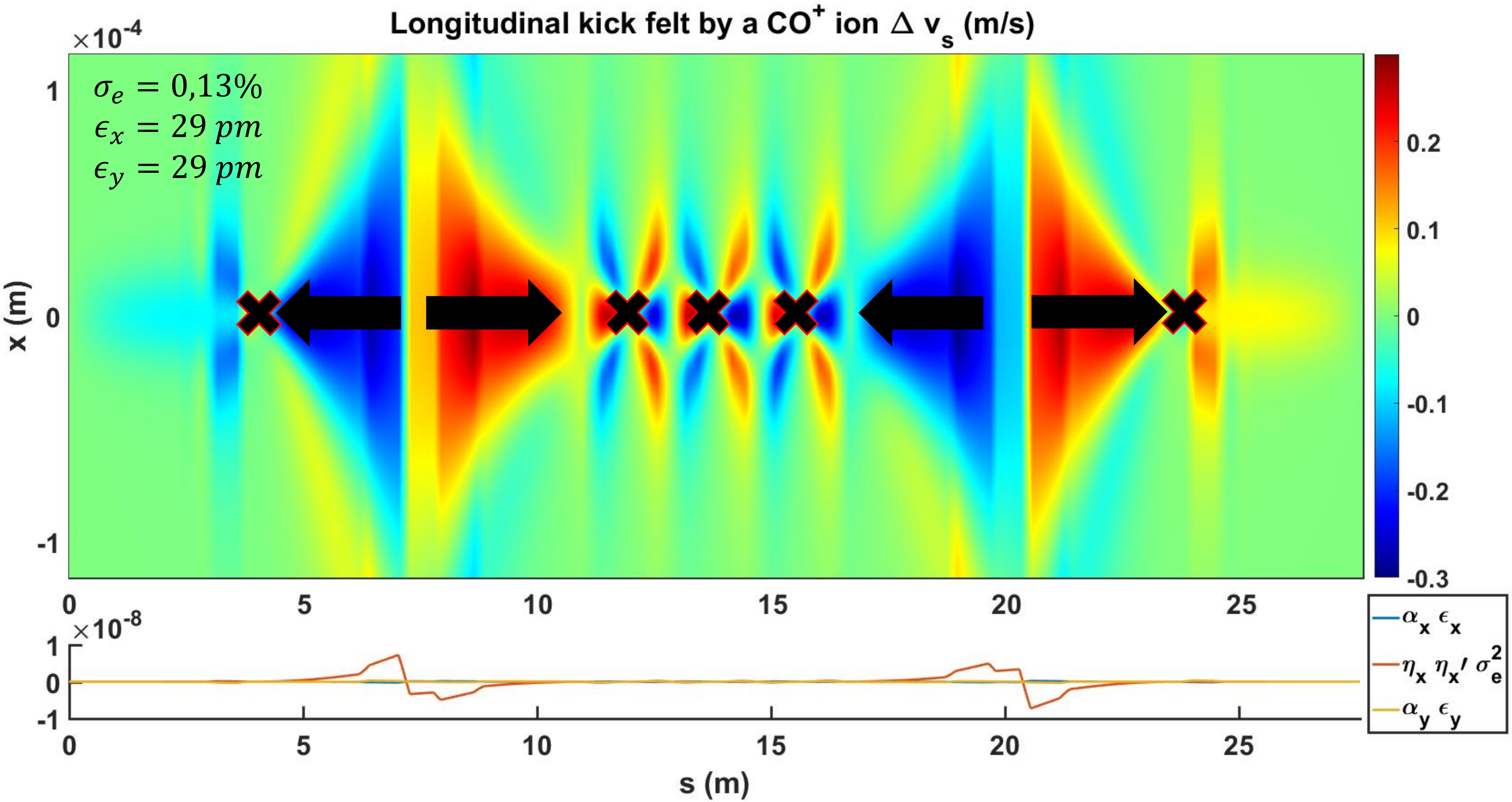


[5] G.H. Hoffstaetter, M. Liepe / Nuclear Instruments and Methods in Physics Research A 557 (2006) 205–212

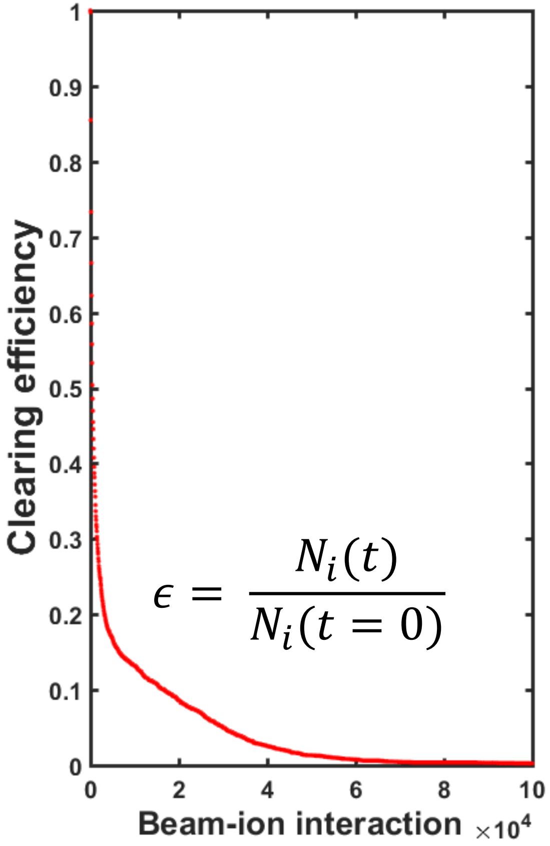
4th generation light source: APS-U



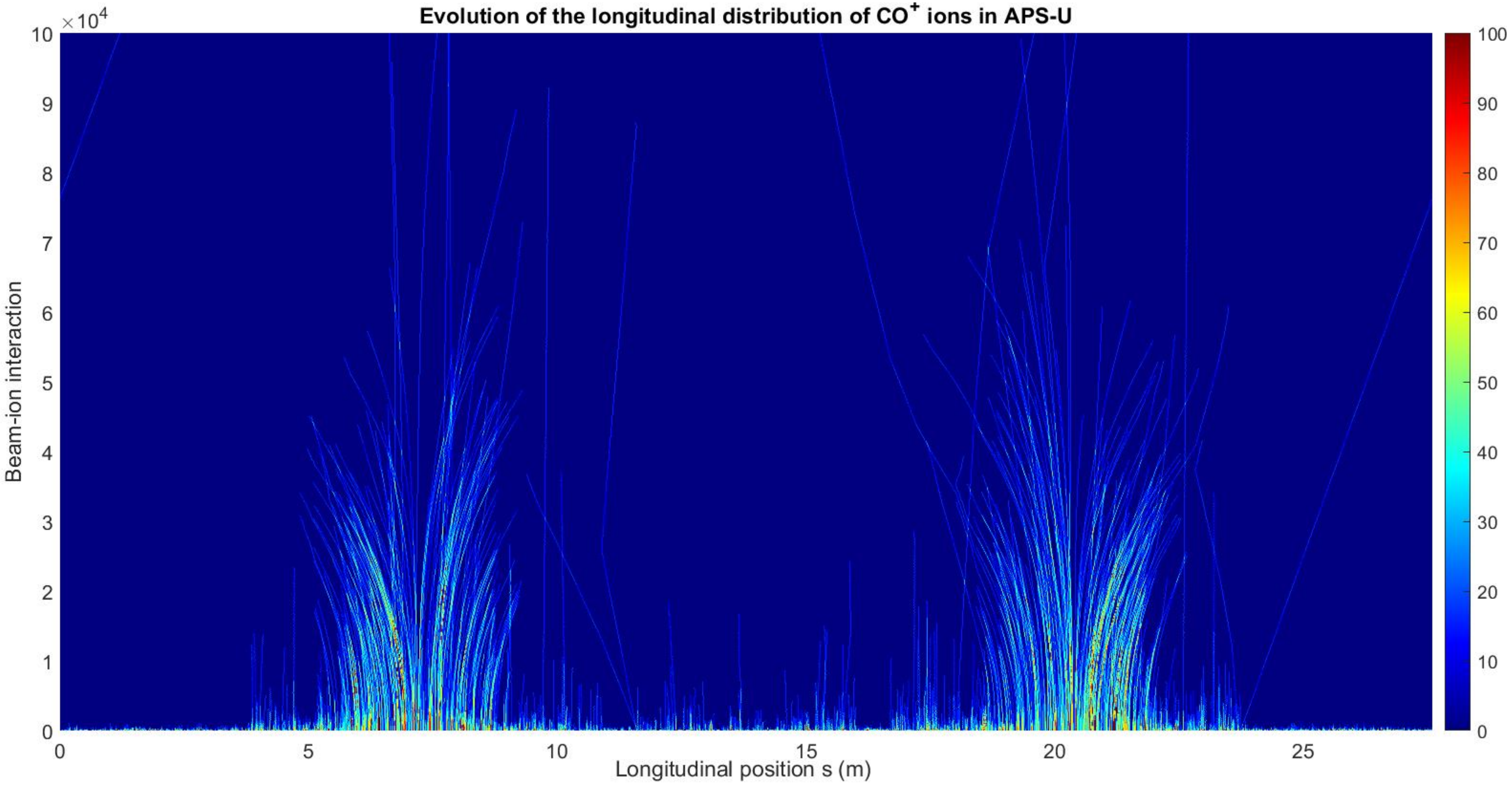
4th generation light source: APS-U



4th generation light source: APS-U



$$\epsilon = \frac{N_i(t)}{N_i(t=0)}$$



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III] Simulations: Mitigation strategies

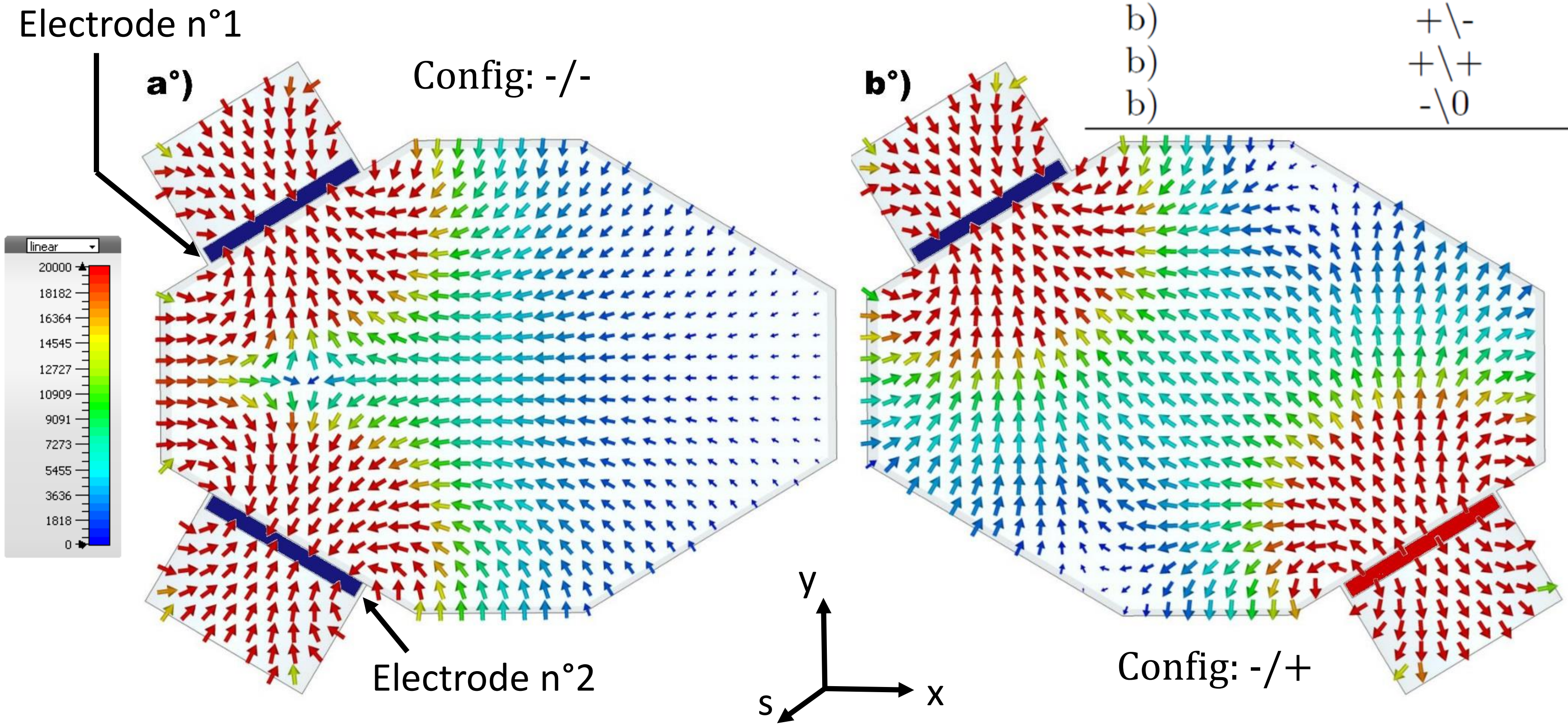
- Clearing electrodes
- Clearing gaps

Clearing electrode with longitudinal field

- ➢ Depending on the electrode geometry it is possible to generate a longitudinal field in addition to the transverse field

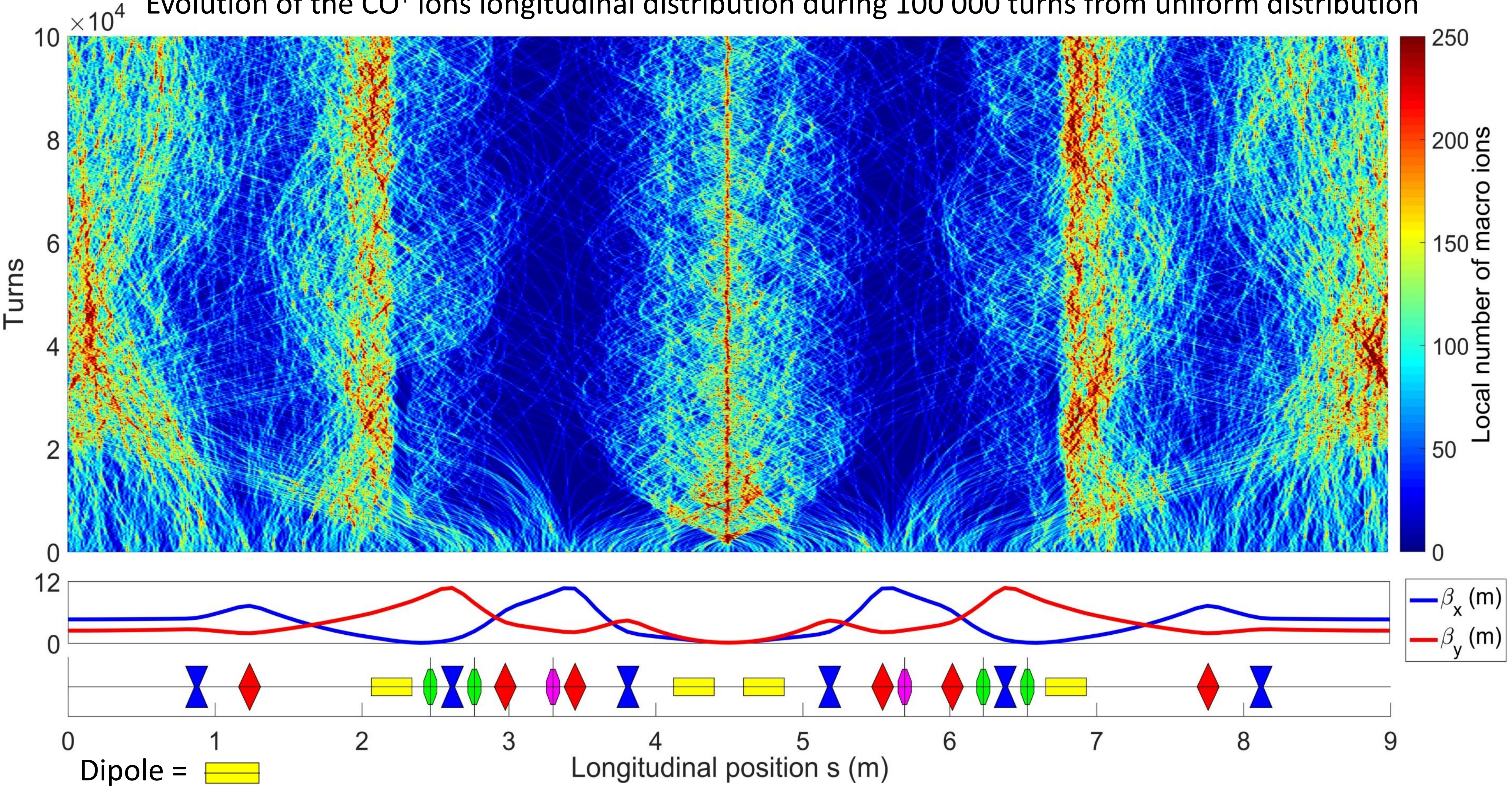
Simulation results for 500 V (CO+ ions):

Type	Configuration	% of ions remaining
a)	-\-	18 %
a)	+\-	33 %
a)	+\+	78 %
b)	-\-	29 %
b)	+\-	31 %
b)	+\+	94 %
b)	-\0	31 %



- ➢ The clearing efficiency could be improved further if the electrodes are designed with this idea in mind
- ➢ The electrodes can be button BPMs

Evolution of the CO⁺ ions longitudinal distribution during 100 000 turns from uniform distribution



Dipole = 🟨

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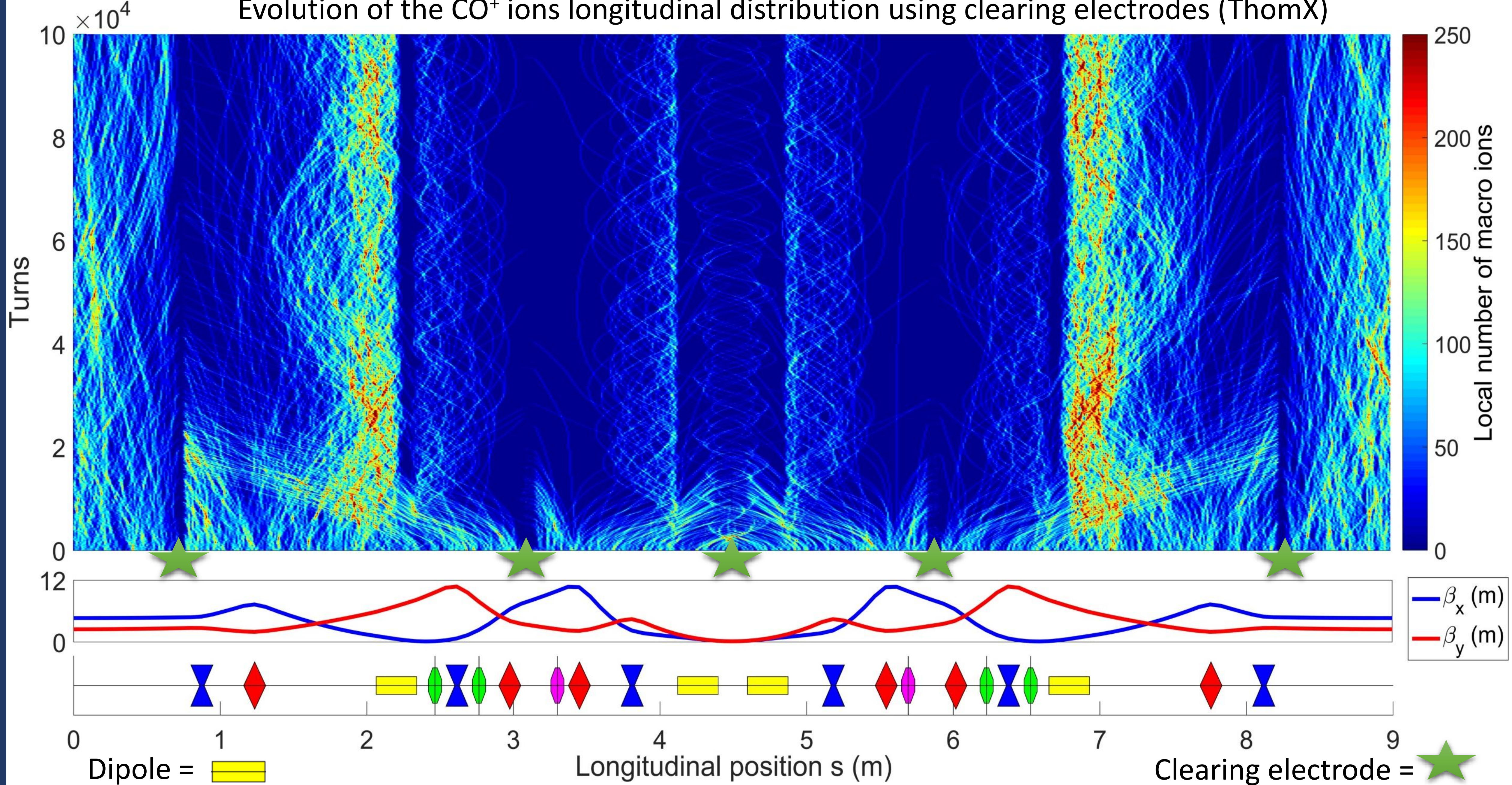
NUAGE simulation, number of macro ions at start : 100 000

Evolution of the CO⁺ ions longitudinal distribution using clearing electrodes (ThomX)



Dipole = 🟨

Clearing electrode = ★

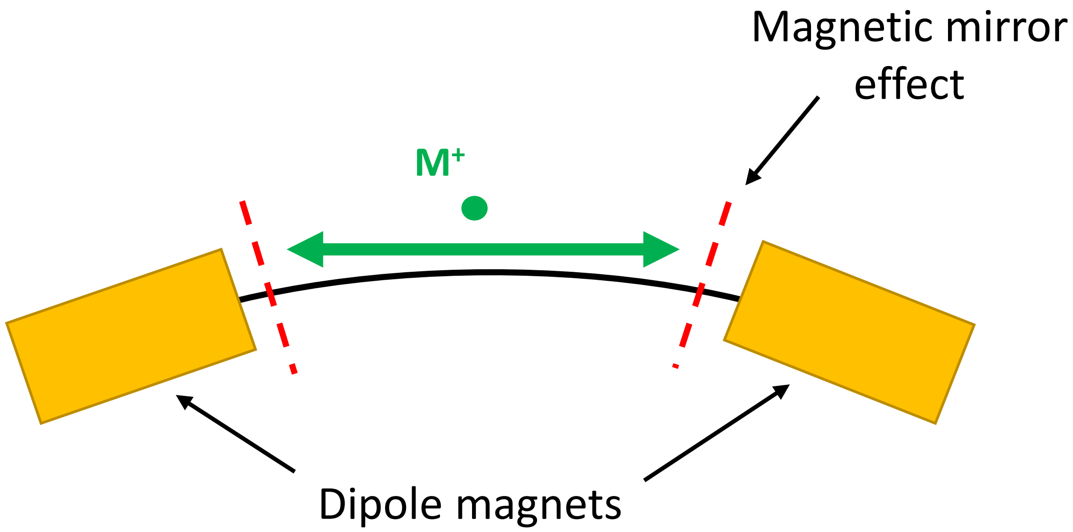
NUAGE simulation, number of macro ions at start : 100 000

Ion-Trapping due to dipoles

Two cases:

- Case a°) low velocity ion stuck in between two dipoles

$$v_s < v_{min}$$

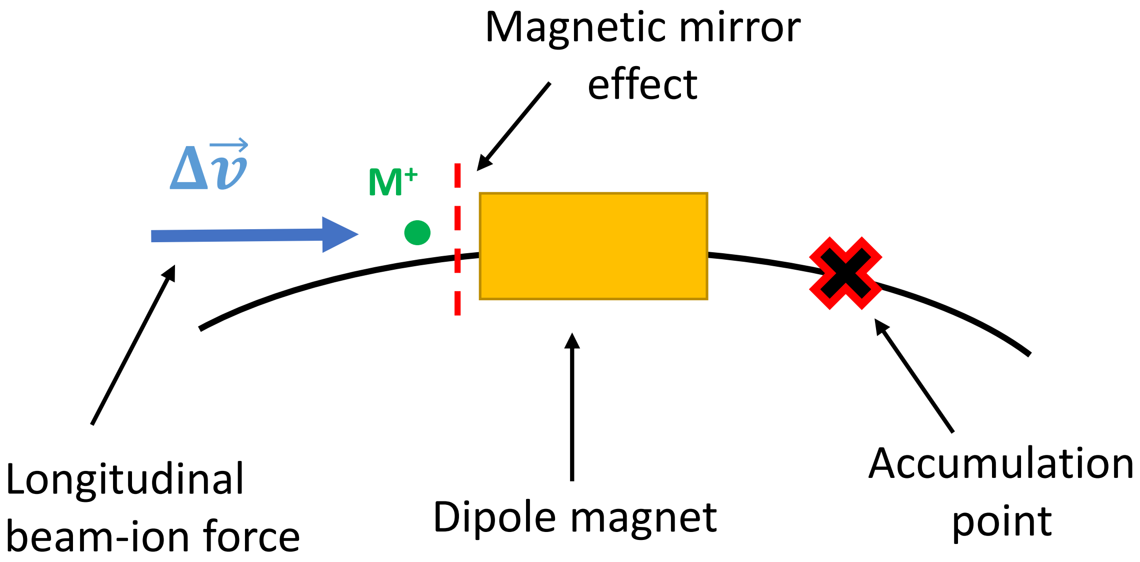

Magnetic mirror effect

Dipole magnets

- Case b°) accumulation point near dipole location

Accumulation around longitudinal position s_0 such as:

$$|\Delta v_s(s_0, x_0, y_0)| = |v_d(s_0, x_0)|$$

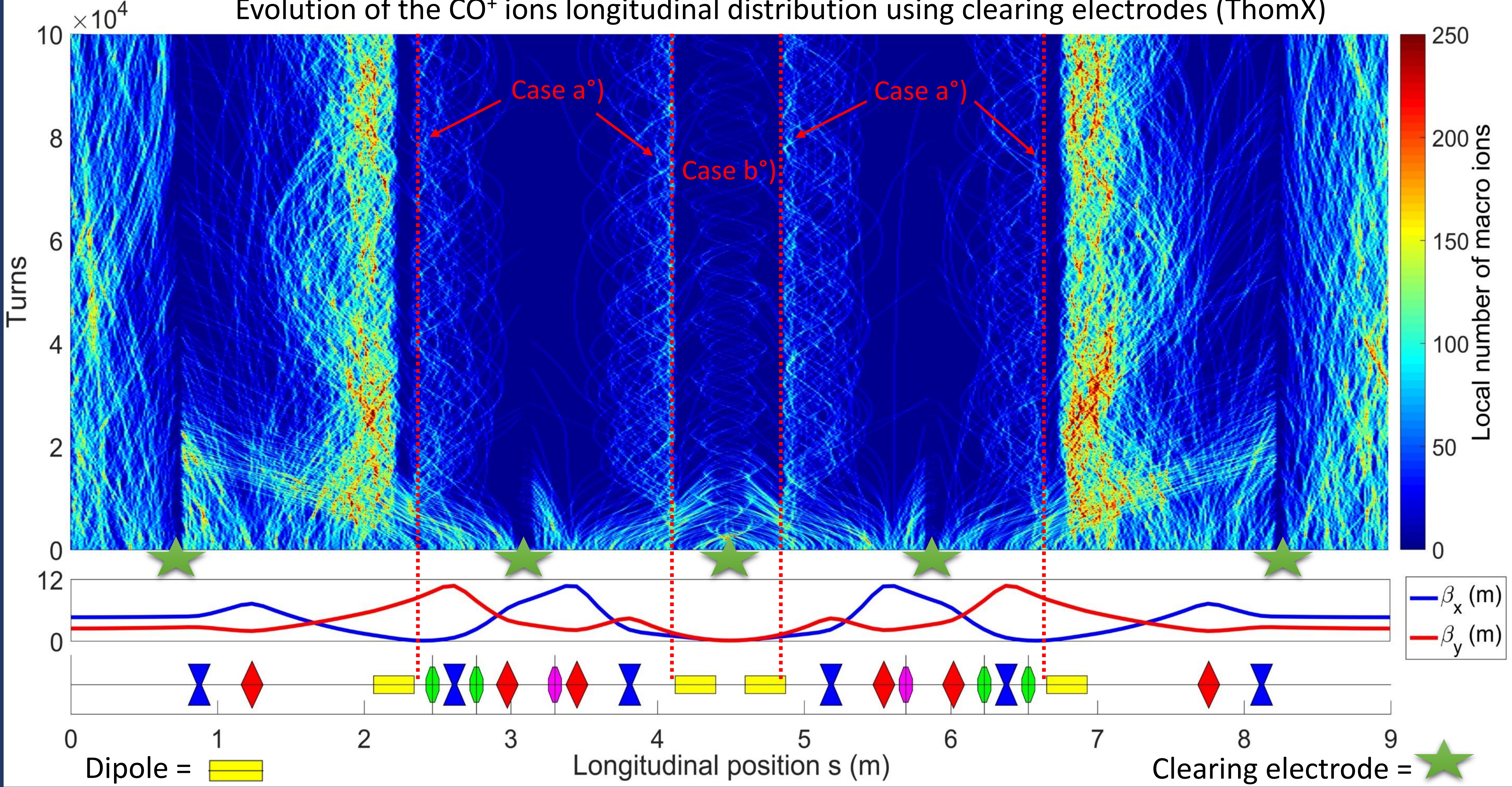

Magnetic mirror effect

Longitudinal beam-ion force

Dipole magnet

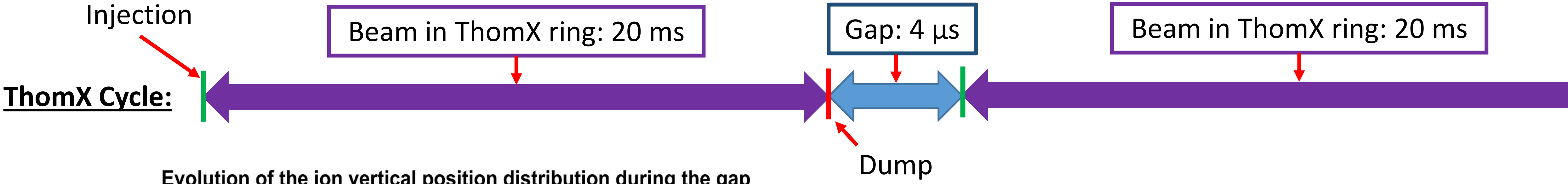
Accumulation point

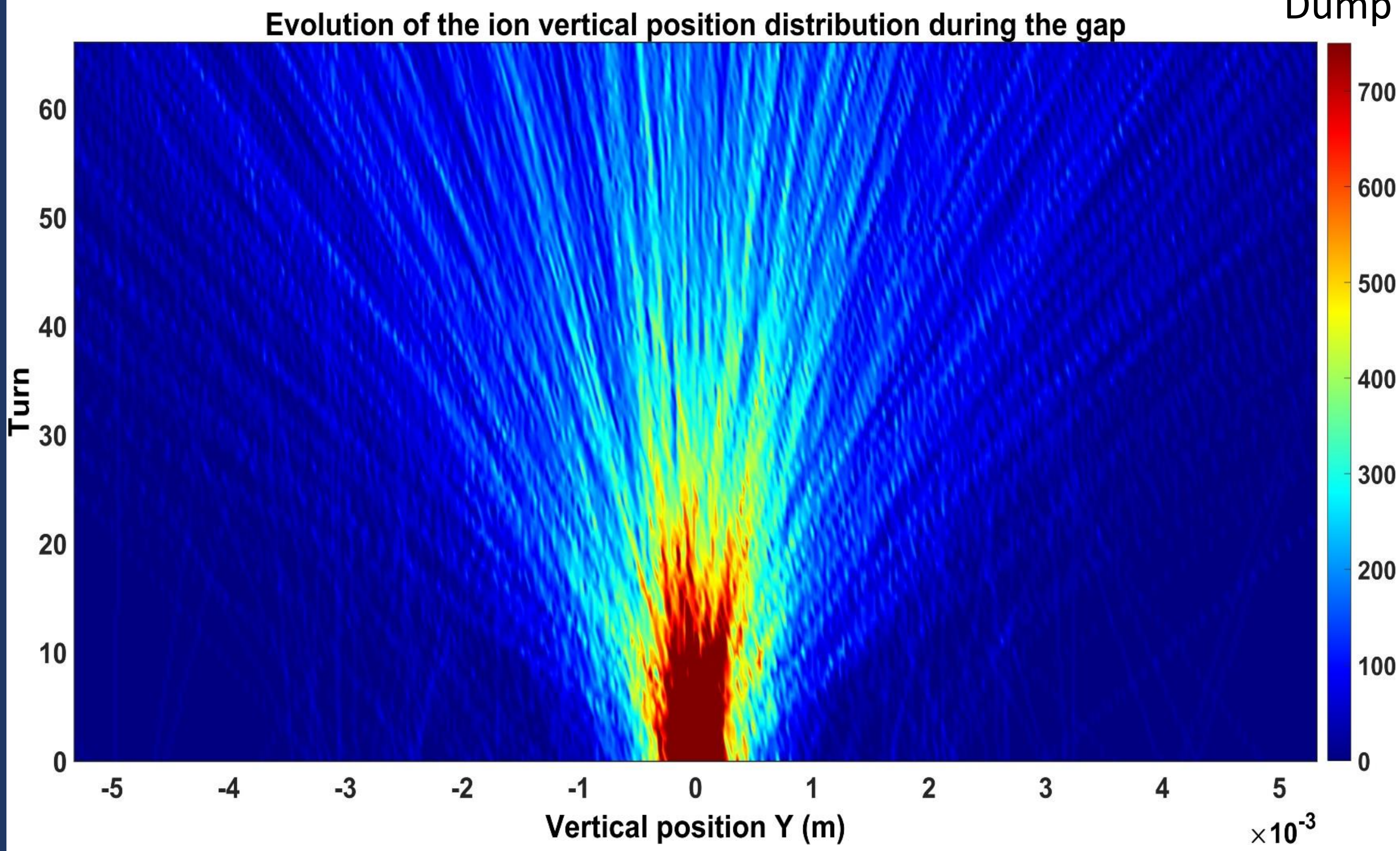
Evolution of the CO^+ ions longitudinal distribution using clearing electrodes (ThomX)



NUAGE simulation, number of macro ions at start : 100 000

Clearing gap, mixing ion positions





When there is no beam, ions are freed from beam potential well. The gap cleans a small part of the ions and « mix up » ion positions.

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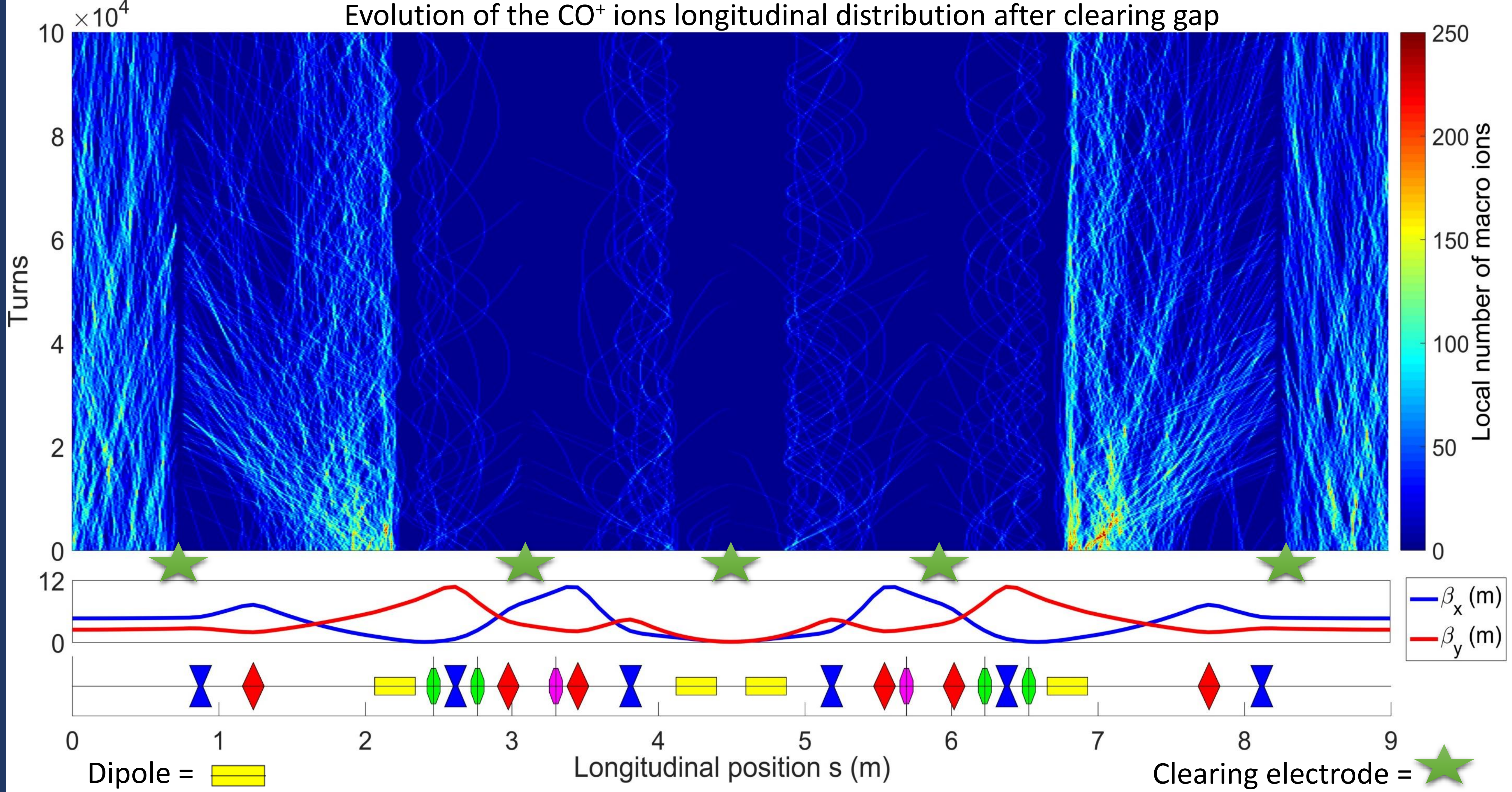
NUAGE simulation, number of macro ions at start : 39 000

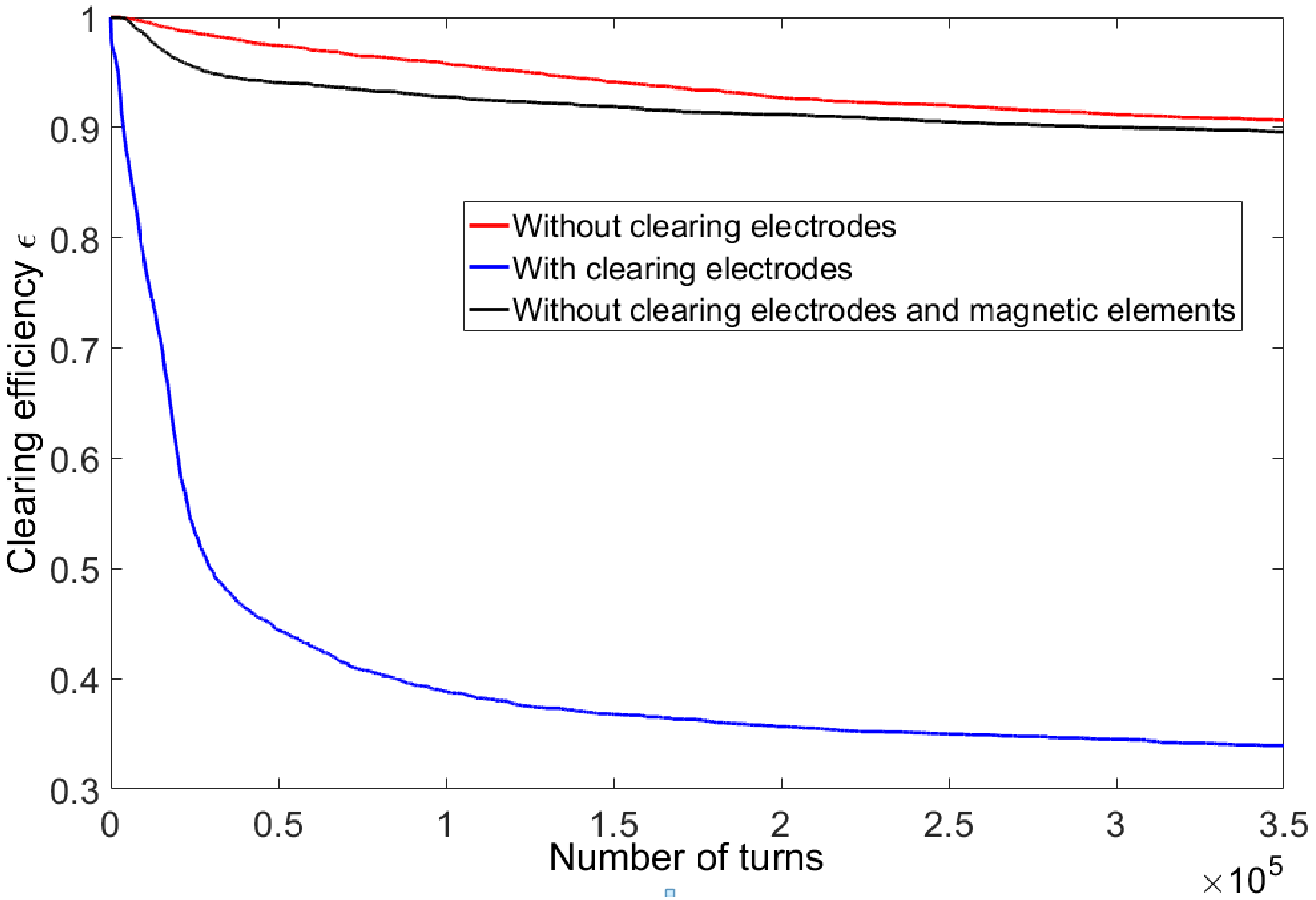
Evolution of the CO^+ ions longitudinal distribution after clearing gap



NUAGE simulation, number of macro ions at start : 39 000

Clearing efficiencies

- Clearing efficiency $\epsilon(t) = \frac{N_i(t)}{N_i(t=0)}$
- Effect of dipoles in total trapping ≈ 5 %
- Good positioning of a few electrodes at the nearest of the accumulation points allows to clear more than 50 % of all the ions generated

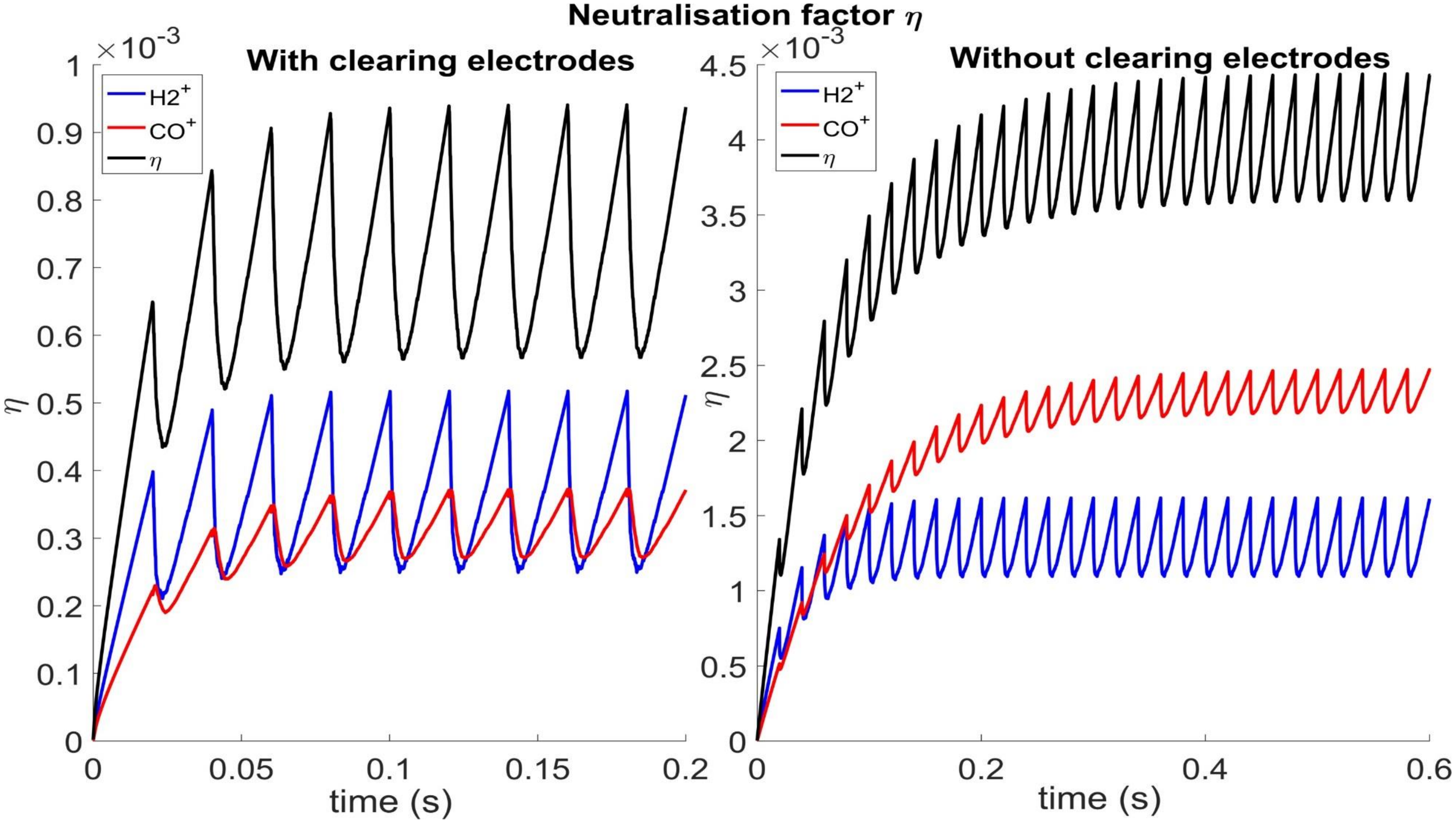


Neutralisation factor

Using the clearing efficiencies $\epsilon(t) = \frac{N_{ions}(t)}{N_{ions}(t=0)}$ computed by NUAGE and the known ionisation cross-section it is possible to get the neutralisation factor $\eta = \frac{n_{ions}}{n_{electrons}}$ which is the relevant quantity for the beam dynamics:

Initial residual vacuum:
$P_{tot} =$ 3 10^{-10} mbar
90 % H_2
10 % CO

$$\frac{\eta_{no\ clearing}}{\eta_{clearing}} \approx 4{,}5$$



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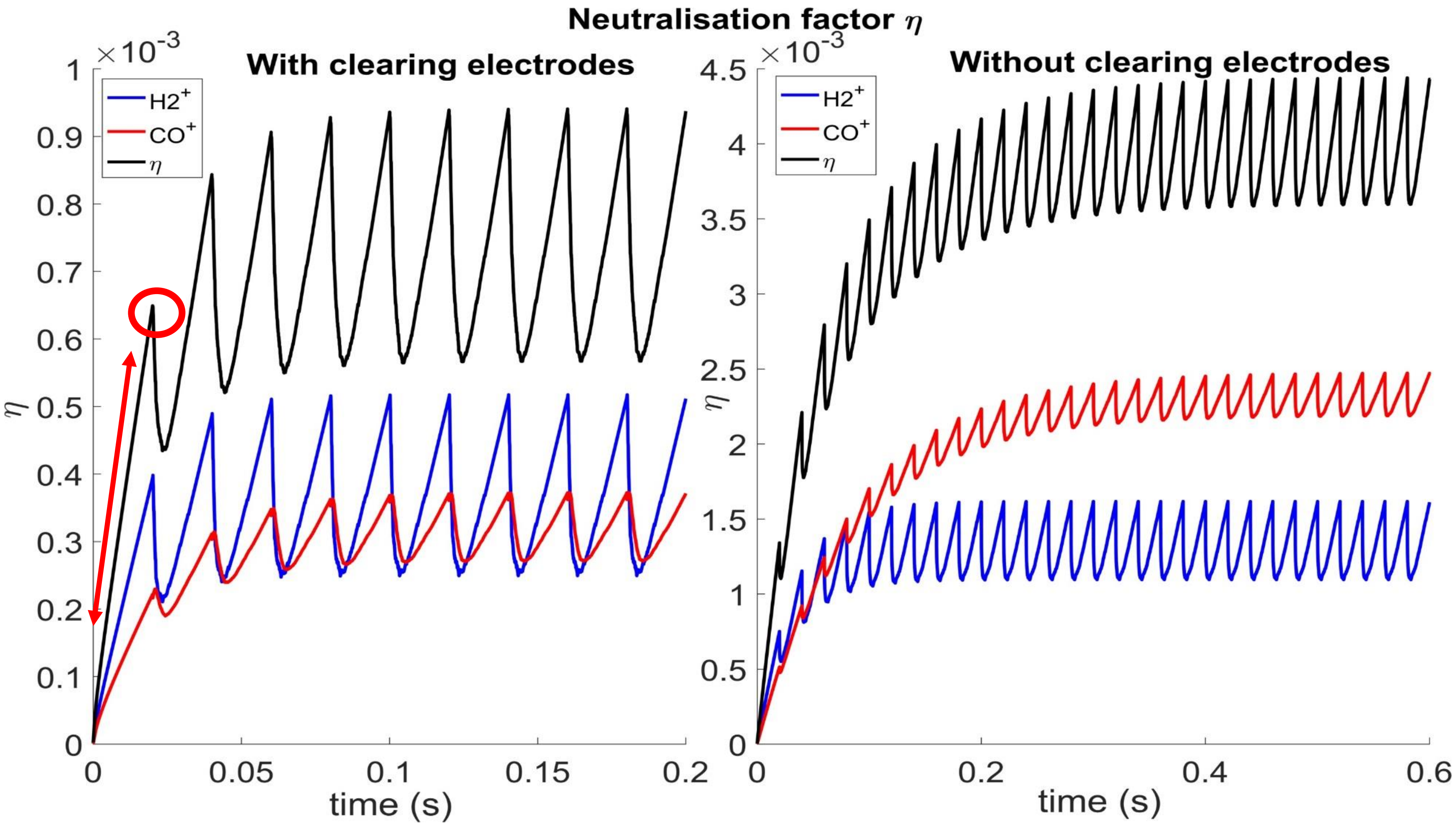


General conclusions from this study

- The longitudinal displacement of ion clouds is usually neglected but it can have an important impact. Understanding it helps to design effective mitigation strategies.

- Possibility to use clearing electrode with longitudinal electric field for more effectiveness, to be demonstrated in ThomX.

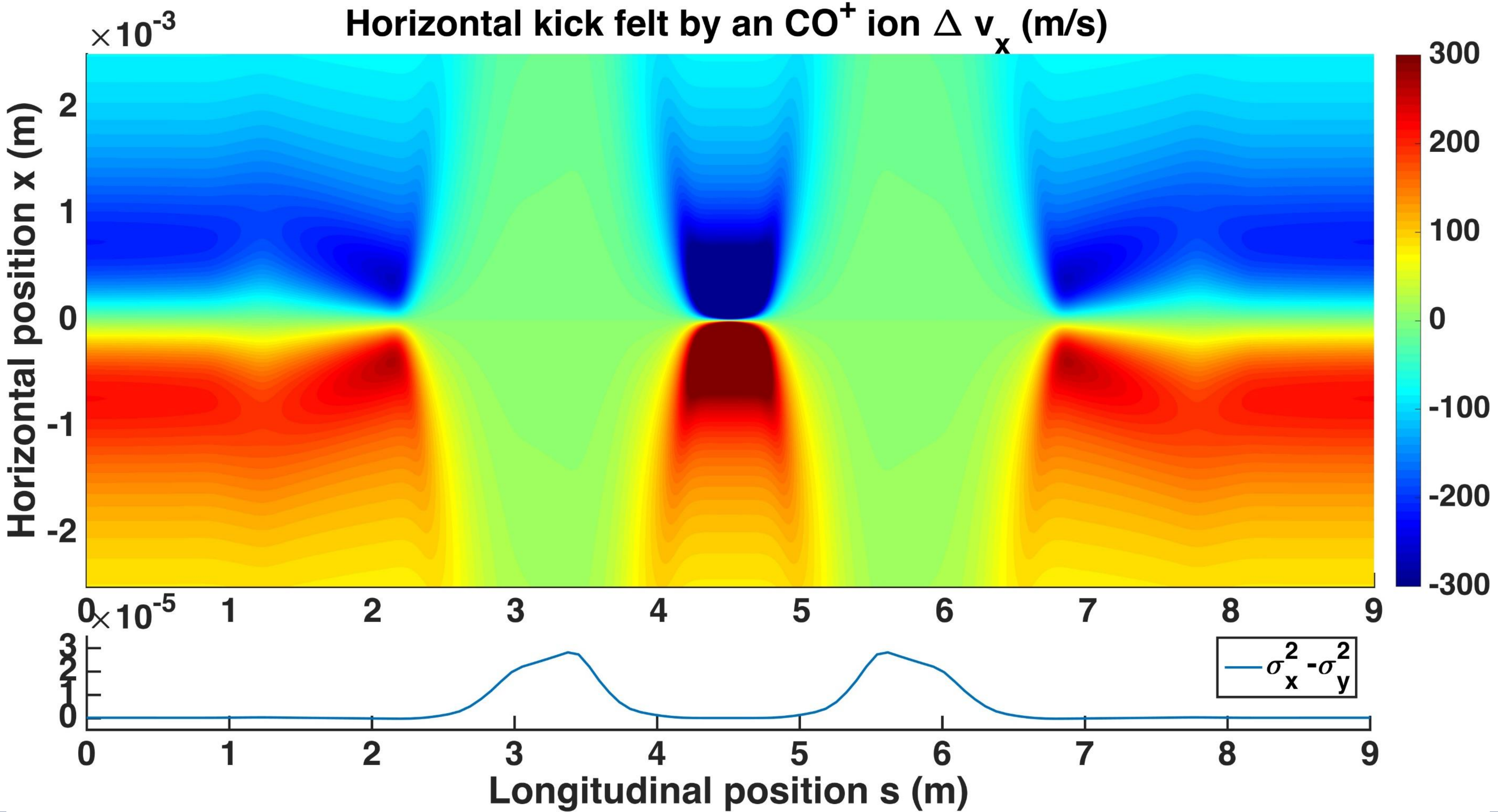
- Nearly no ion cloud effects in low emittance rings ? To be verified experimentally

- Ion cloud can still be problem for many type of accelerators: injector facilities, ERLs and compact rings.

Thank you !

Many thanks to Ryutaro Nagaoka (Soleil) and Joseph Calvey (APS) for providing the inputs needed for the simulations !

Backups


Horizontal kick felt by an CO^+ ion Δv_x (m/s)
$\times 10^{-3}$
Horizontal position x (m)
2
1
0
-1
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0
1
2
3
4
5
6
7
8
9
300
200
100
0
-100
-200
-300
$\times 10^{-5}$
3
2
1
0
$\sigma_x^2 - \sigma_y^2$
0
1
2
3
4
5
6
7
8
9
Longitudinal position s (m)

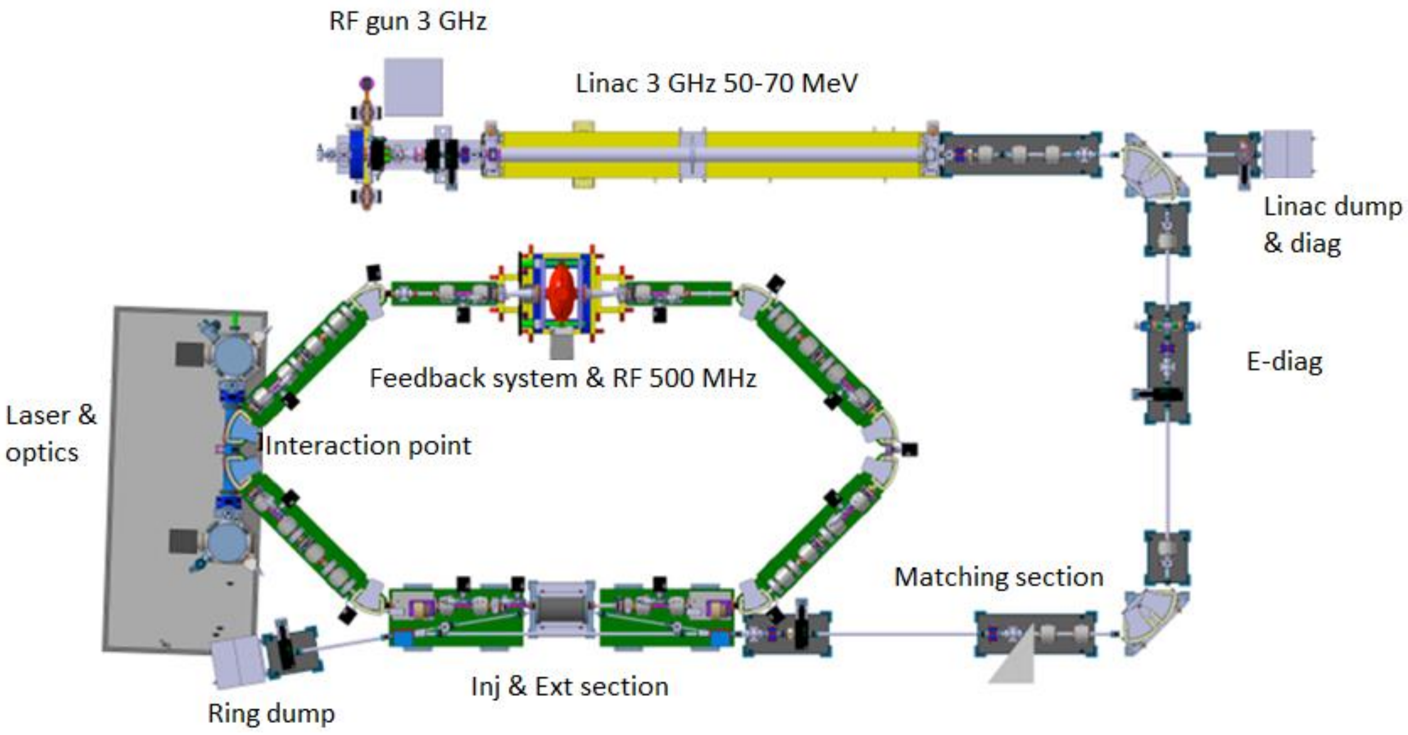
ThomX, a storage ring without damping

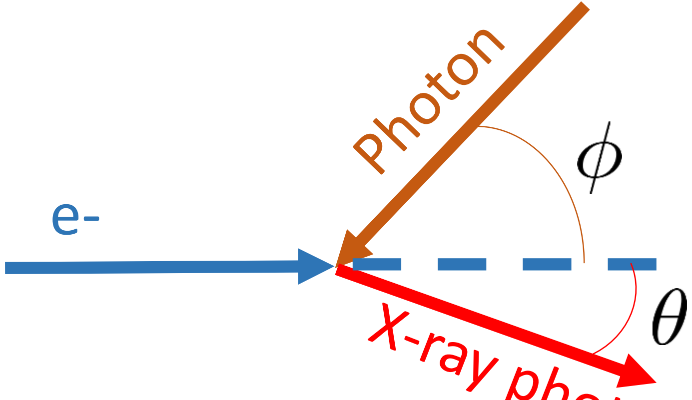
- ThomX is a Compton Backscattering Source (CBS) of X rays under construction at LAL.
- The e- bunch is stored for 20 ms then it is dumped while a new one is injected.
- Because of the short storage time and the low electron energy there is <u>no synchrotron radiation damping.</u>

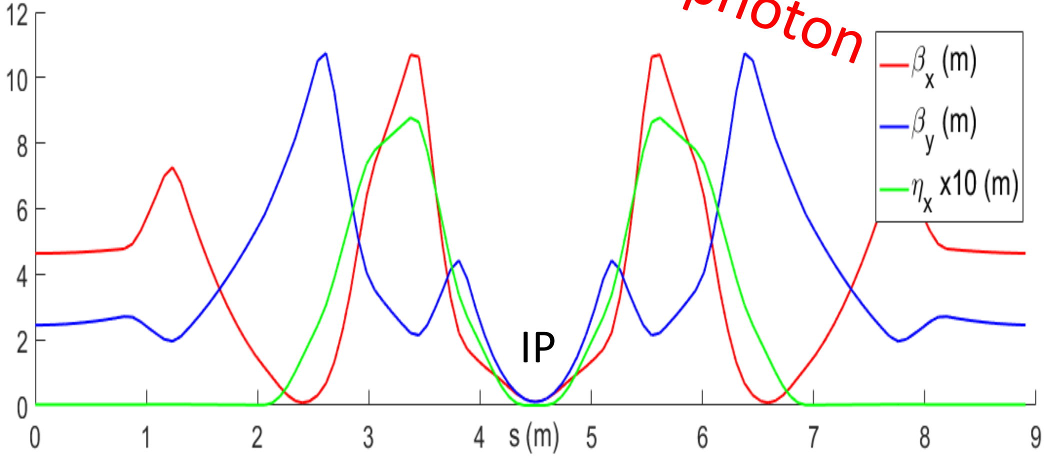
$\text{Flux} = 10^{11-13}$ X/s

$E_X^{max} = 46\text{-}90$ keV

Divergence = 10 mrad







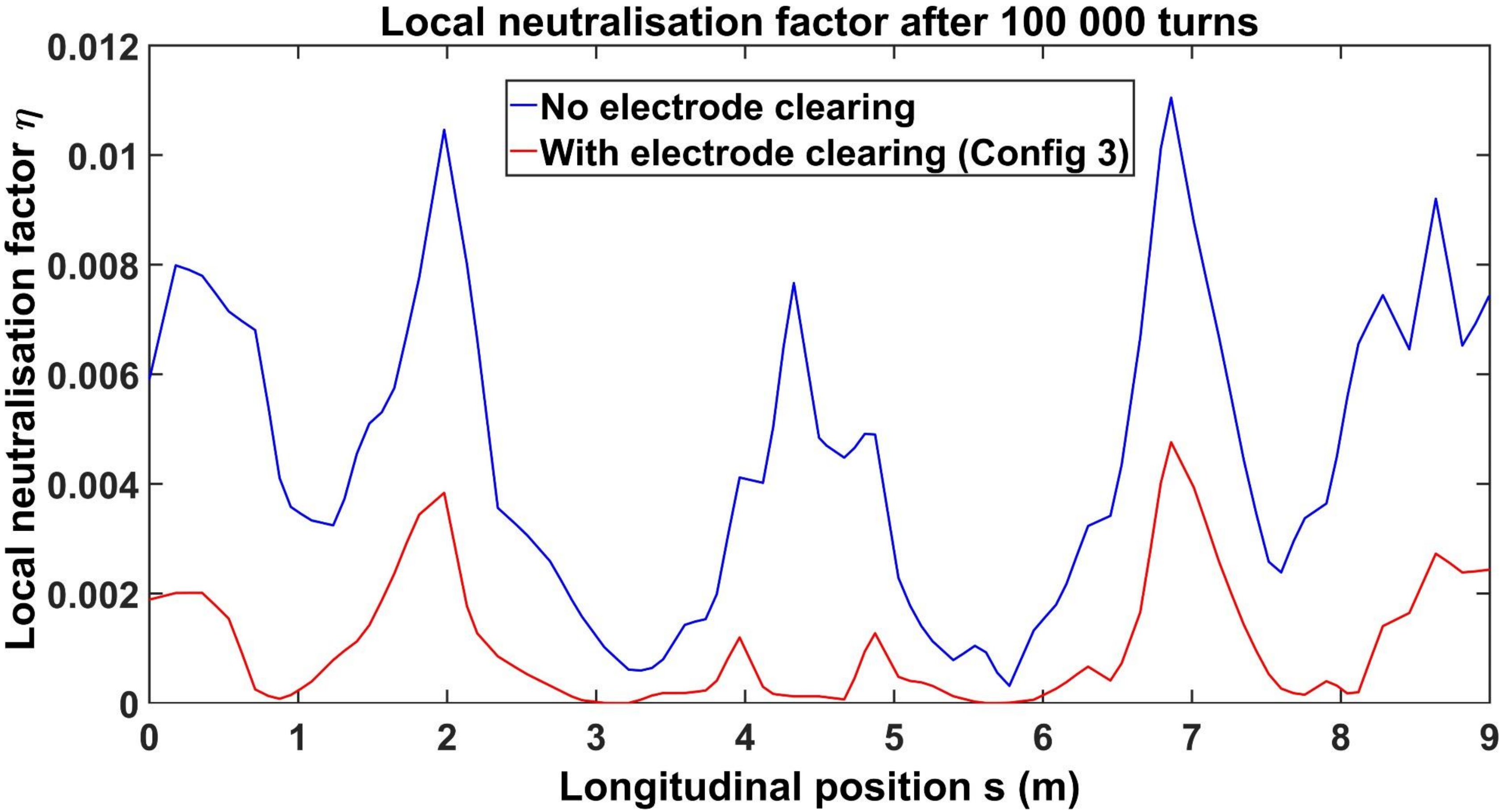
Local neutralisation factor

It is possible to define a local neutralisation factor[3] which take into account the fact that the neutralisation is not homogeneous along the ring longitudinal position:

$$\eta(s) = \frac{L}{n_e}\frac{dn_i}{ds}$$

The mean value of the local neutralisation factor gives back the usual neutralisation factor:

$$\overline{\eta(s)} = \eta$$



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[3] A, Poncet, Ion trapping, clearing, beam-ion interactions, 1999.

Induced tune shift

The tune shift induced by the ions can be computed by considering the ion force on the beam as an equivalent quadrupole. Assuming that the ion transverse distribution can be approximated[4] by a Gaussian distribution of $\sigma_i = \frac{\sigma_e}{\sqrt{2}}$, it gives:

$$\Delta Q_x = \frac{r_e n_e}{2\pi\gamma L} \int_0^L \frac{\beta_x \eta}{\sigma_{xe}\left(\sigma_{xe} + \sigma_{ye}\right)} ds$$

Usually no information about the local neutralization factor is known so mean values are used:

$$\overline{\Delta Q_x} = \frac{r_e n_e}{2\pi\gamma} \frac{\overline{\beta_x}\bar{\eta}}{\overline{\sigma_{xe}}\left(\overline{\sigma_{xe}} + \overline{\sigma_{ye}}\right)}$$

Configuration	ΔQ_x	$\overline{\Delta Q_x}$	Ratio	ΔQ_y	$\overline{\Delta Q_y}$	Ratio
No clearing	9,94 E-4	1,52 E-4	6,5	1,14 E-3	5,84 E-4	2,0
Clearing	2,24 E-4	3,23 E-5	6,9	2,78 E-4	1,24 E-4	2,2

The same type of approach is possible for other effects induced by ions like emittance growth, tune spread, pressure increase, …

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[4] L. Wang et al, Suppression of beam-ion instability in electron rings with multibunch train beam flings, PRST-AB, 2011.