Longitudinal and transverse ion cloud dynamics in an electron ring in presence of electromagnetic fields and gaps

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Overview

What

- We want to locate ion clouds, generated by ionisation of the residual gas, in an electron storage ring

Why

- To minimize the beam dynamics degradation because of the ion cloud, a beam stability of 40 µm is needed in the interaction point (IP)

How

- By understanding the physics of the beam-ion interaction, simulating the ion dynamics and using mitigations strategies

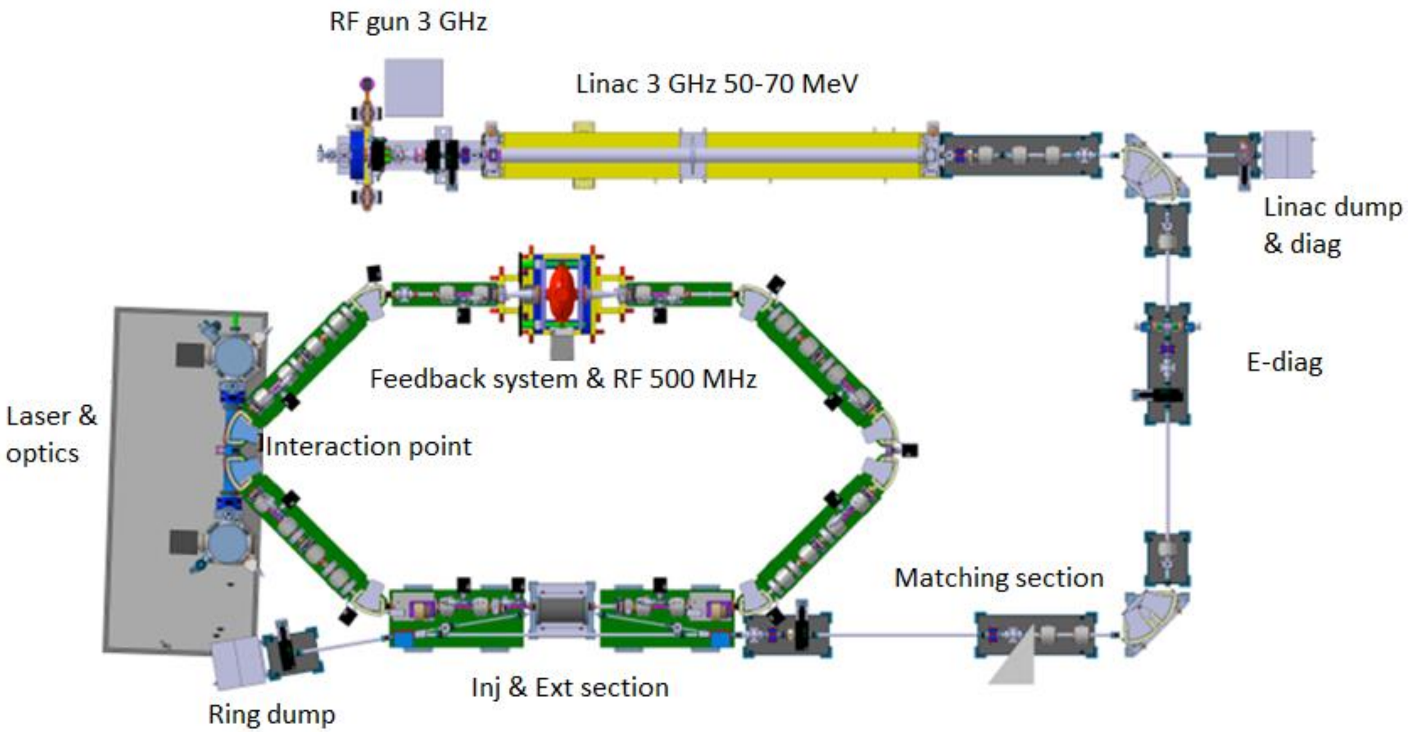
ThomX, a storage ring without damping

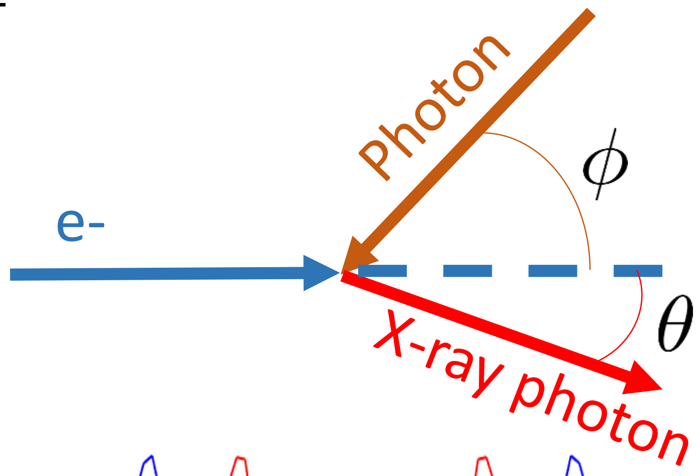
- ThomX is a Compton Backscattering Source (CBS) of X rays under construction at LAL.
- The e- bunch is stored for 20 ms then it is dumped while a new one is injected.
- Because of the short storage time and the low electron energy there is <u>no synchrotron radiation damping.</u>

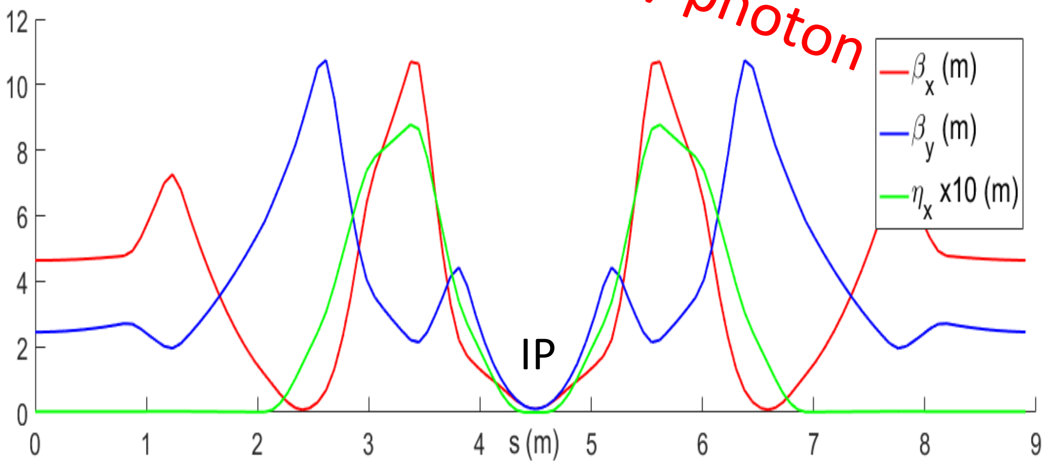
Flux $= 10^{11-13}$ X/s

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

Divergence $= 10$ mrad

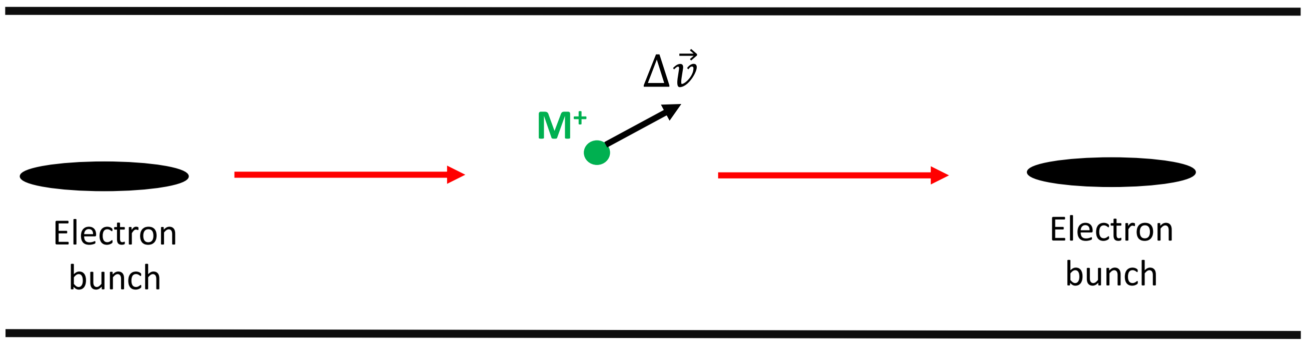






A model to describe the beam-ion interaction

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

Number of e- in a bunch

Ion position

Beam size at the ion position

$$i\Delta v_x + \Delta v_y = \frac{-NK\sqrt{\pi}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\left(w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right) - e^{-\left(\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}\right)} w\left(\frac{x\frac{\sigma_y}{\sigma_x} + iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right)\right)$$

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

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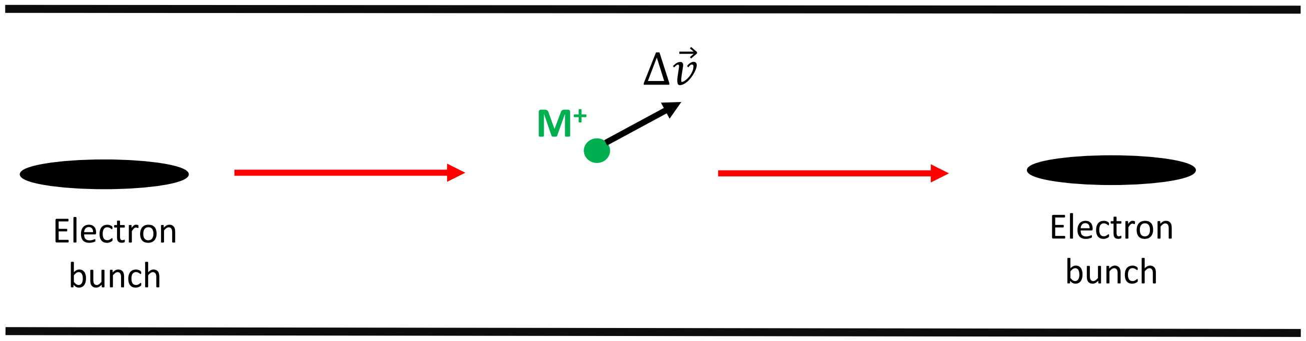


The model:

- 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

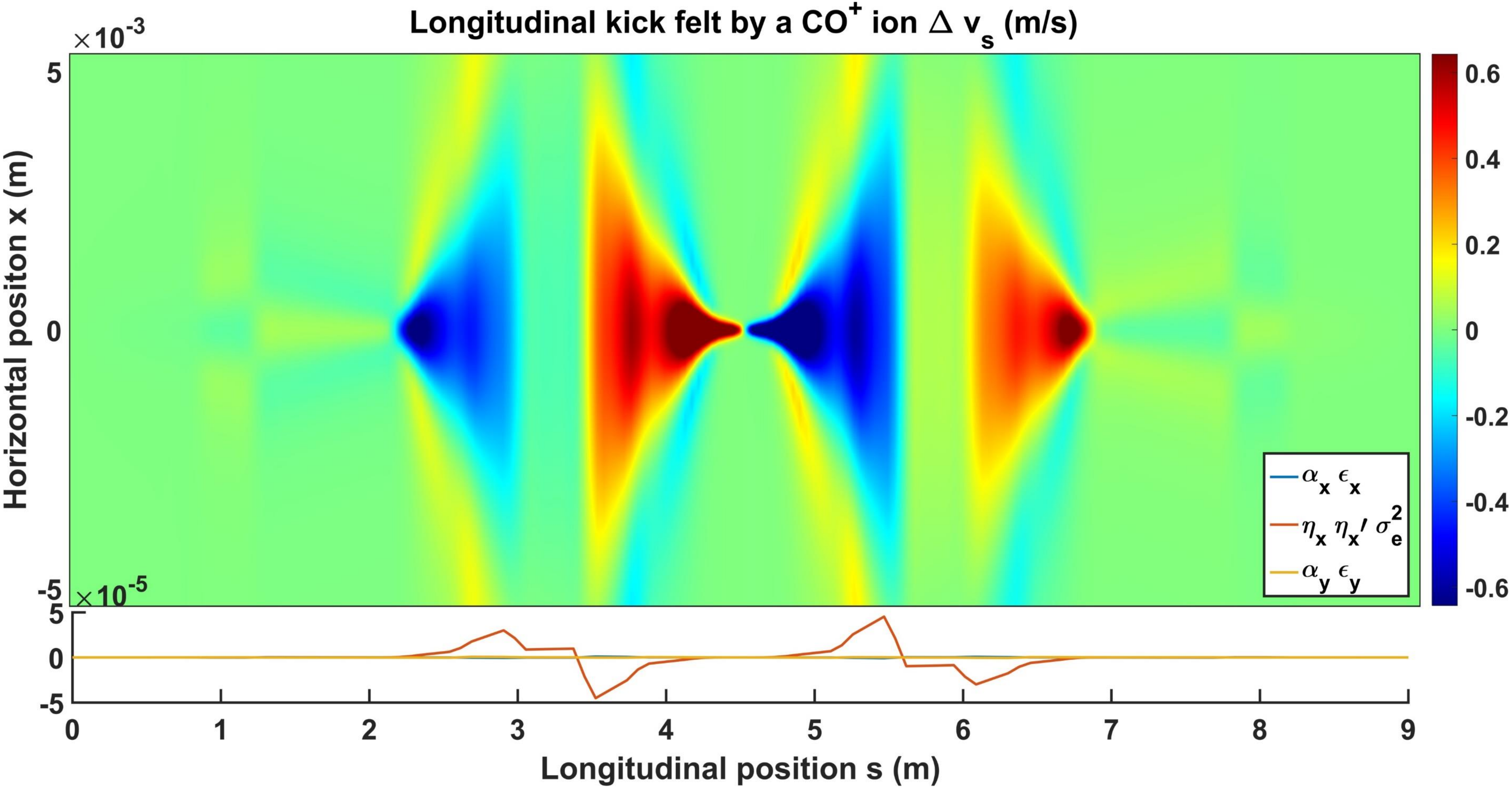
Energy spread

Dispersion function and derivative

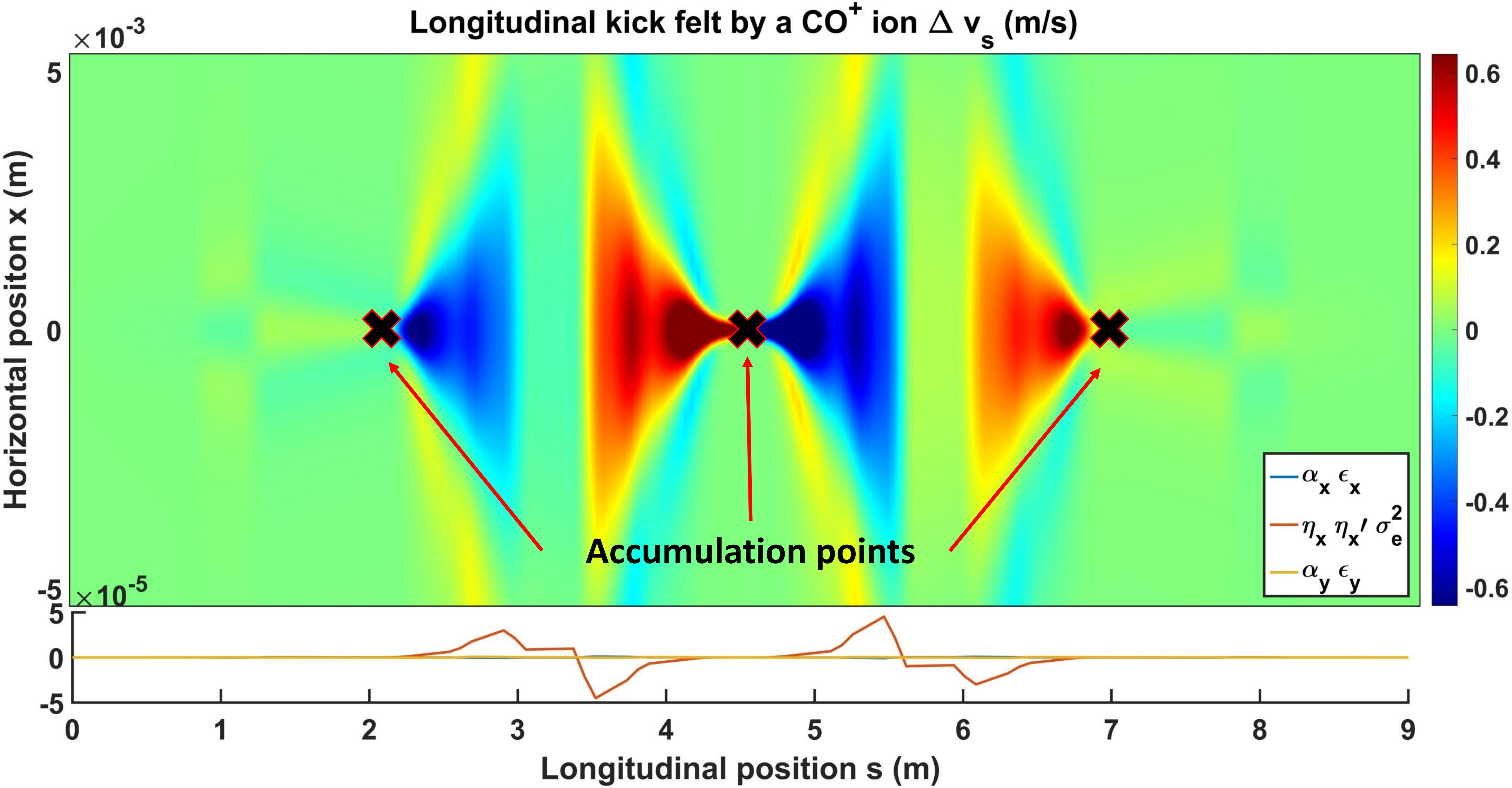
$$\Delta v_s = (-\alpha_x \epsilon_x + \eta\eta' \sigma_\epsilon^2) \frac{\partial \Delta_x}{\partial x} - \alpha_y \epsilon_y \frac{\partial \Delta_y}{\partial y}$$

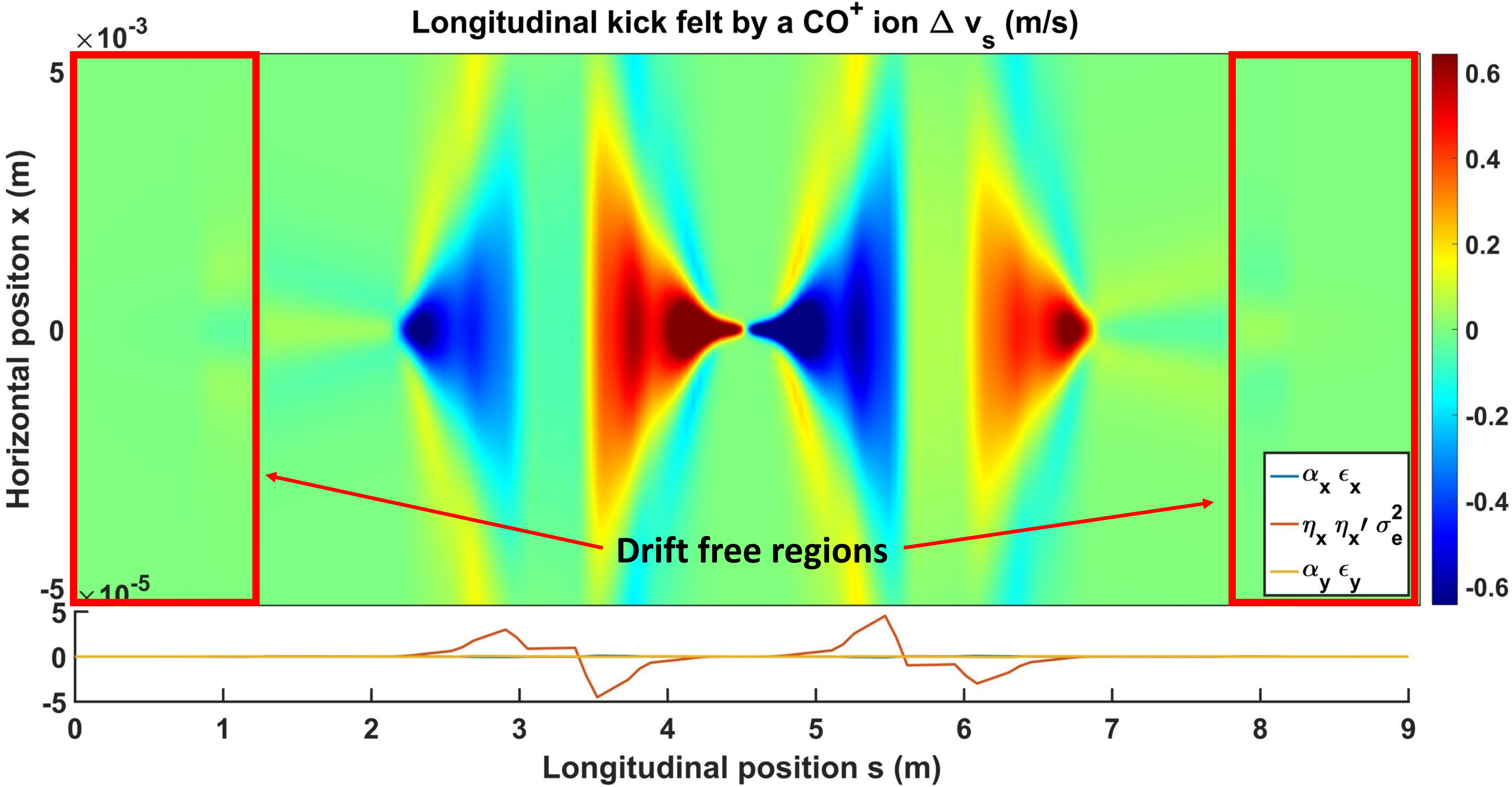
The ion dynamics are determined by the optics and the lattice design

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



Longitudinal kick felt by a CO^+ ion Δv_s (m/s)
$\times 10^{-3}$
5
0
-5
Horizontal positon x (m)
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)


Longitudinal kick felt by a CO+ ion Δ v_s (m/s)
×10^-3
5
0
-5
Horizontal positon x (m)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Accumulation points
α_x ϵ_x
η_x η_x′ σ_e^2
α_y ϵ_y
×10^-5
5
0
-5
0
1
2
3
4
5
6
7
8
9
Longitudinal position s (m)



Longitudinal kick felt by a CO+ ion Δ vs (m/s)
×10-3
5
0
-5
Horizontal positon x (m)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
αx εx
ηx ηx' σe2
αy εy
Drift free regions
×10-5
5
0
-5
0
1
2
3
4
5
6
7
8
9
Longitudinal position s (m)

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

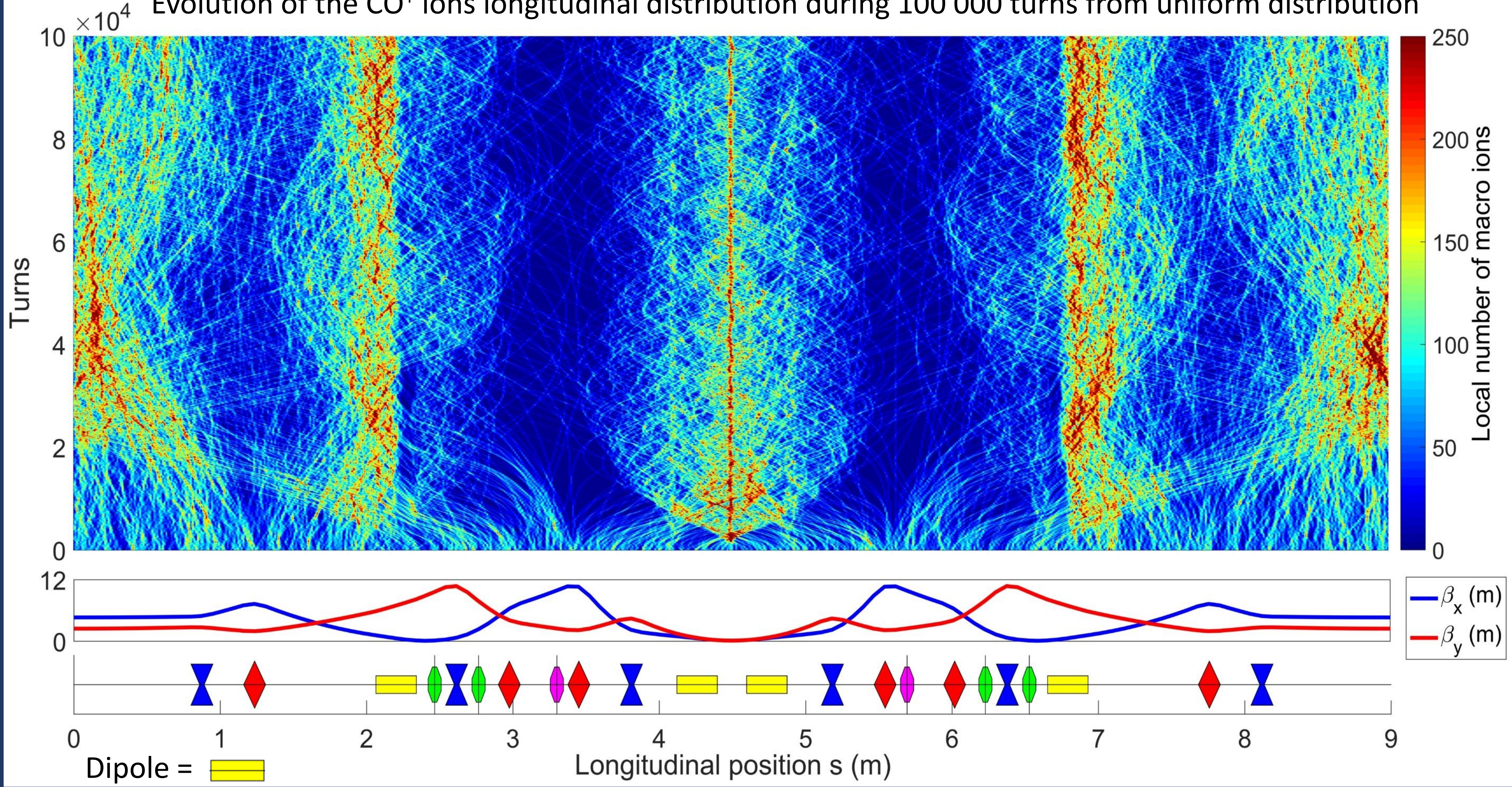
→ Tracking in magnetic elements (dipoles, quadrupoles) by solving ODE

→ Interpolation of the 3D field maps of the clearing electrodes

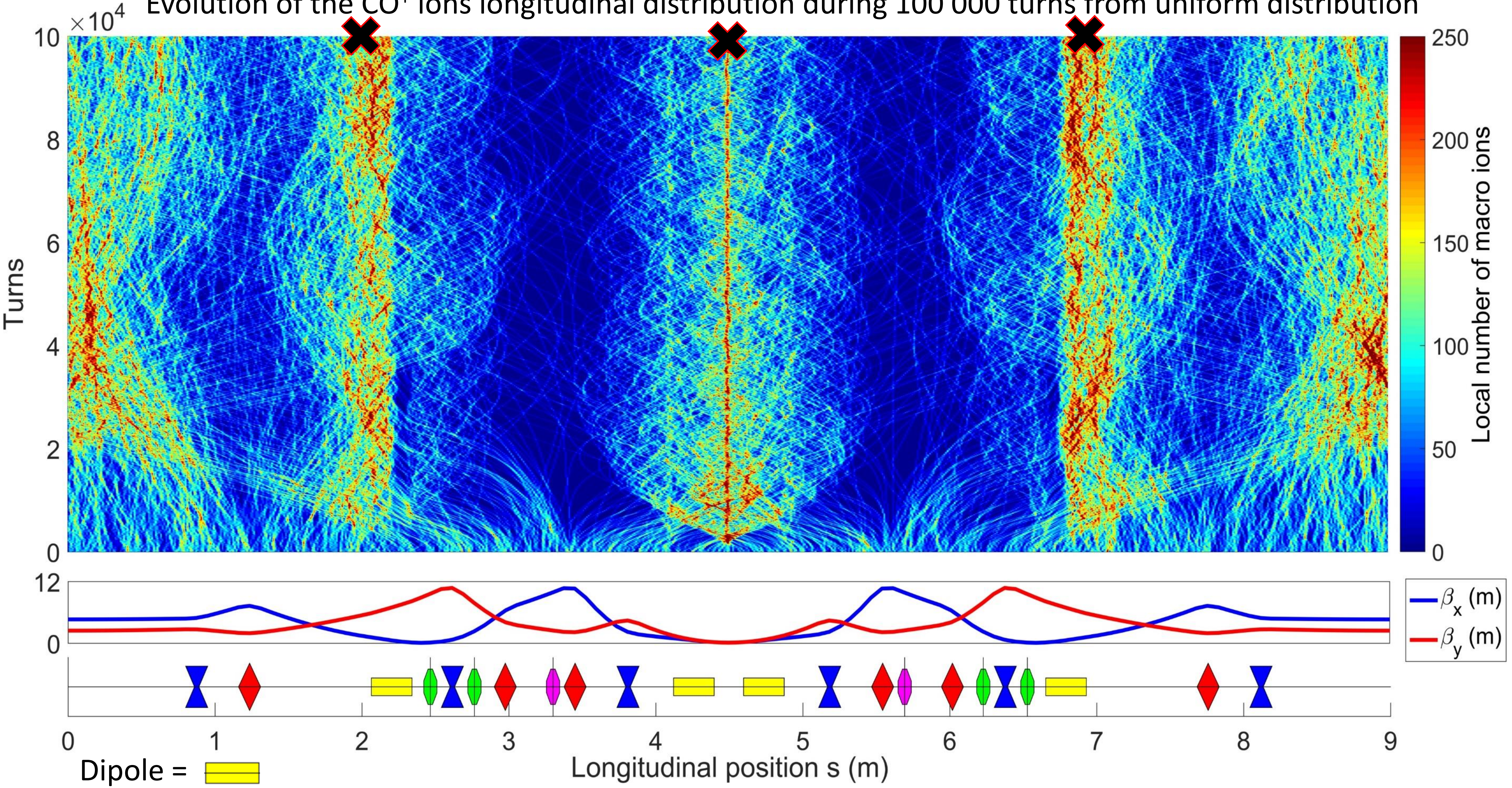
- Ion cloud collective effects (self space charge, …) → Not included in NUAGE

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.

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

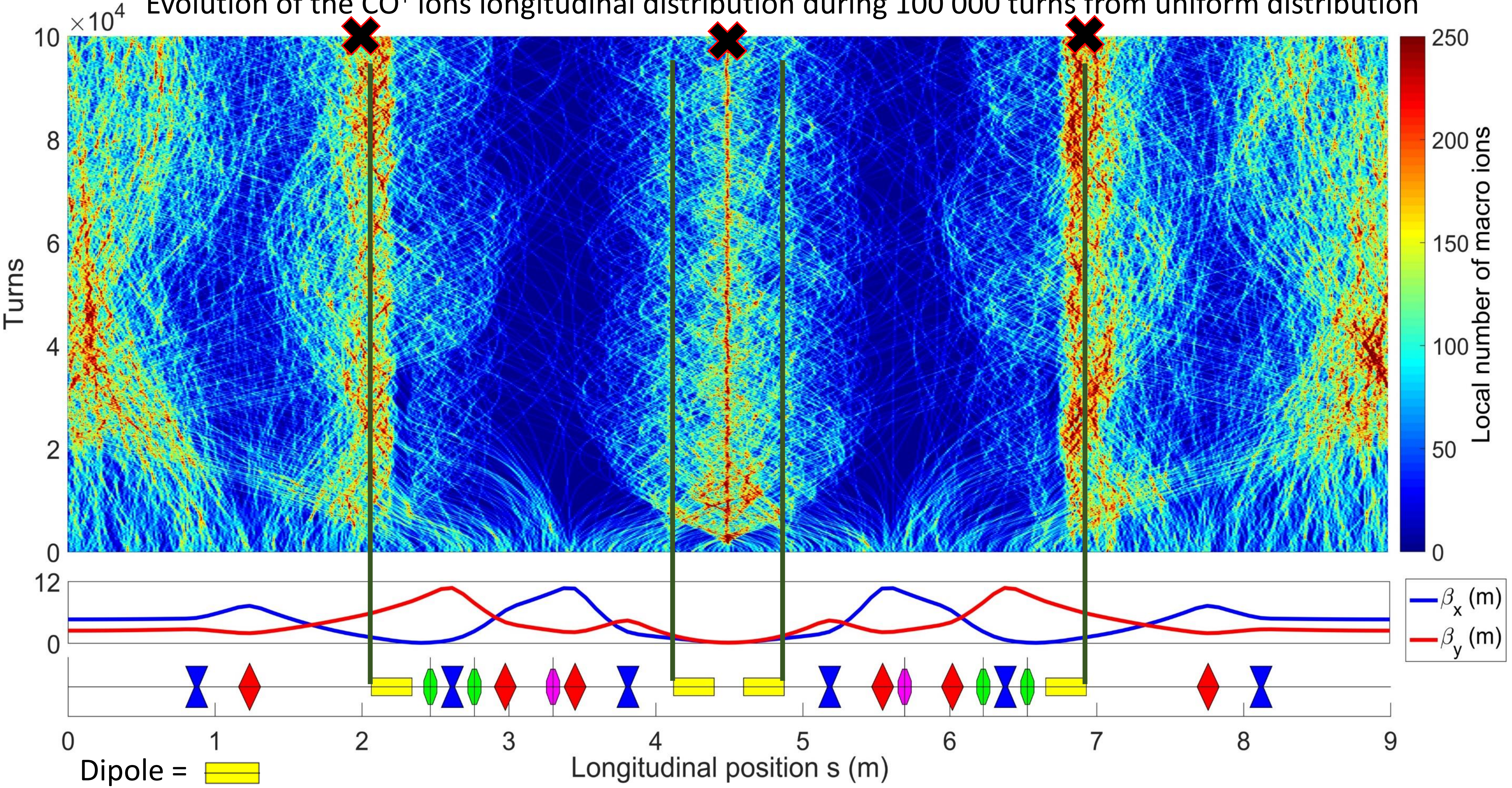


Evolution of the CO^+ ions longitudinal distribution during 100 000 turns from uniform distribution



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

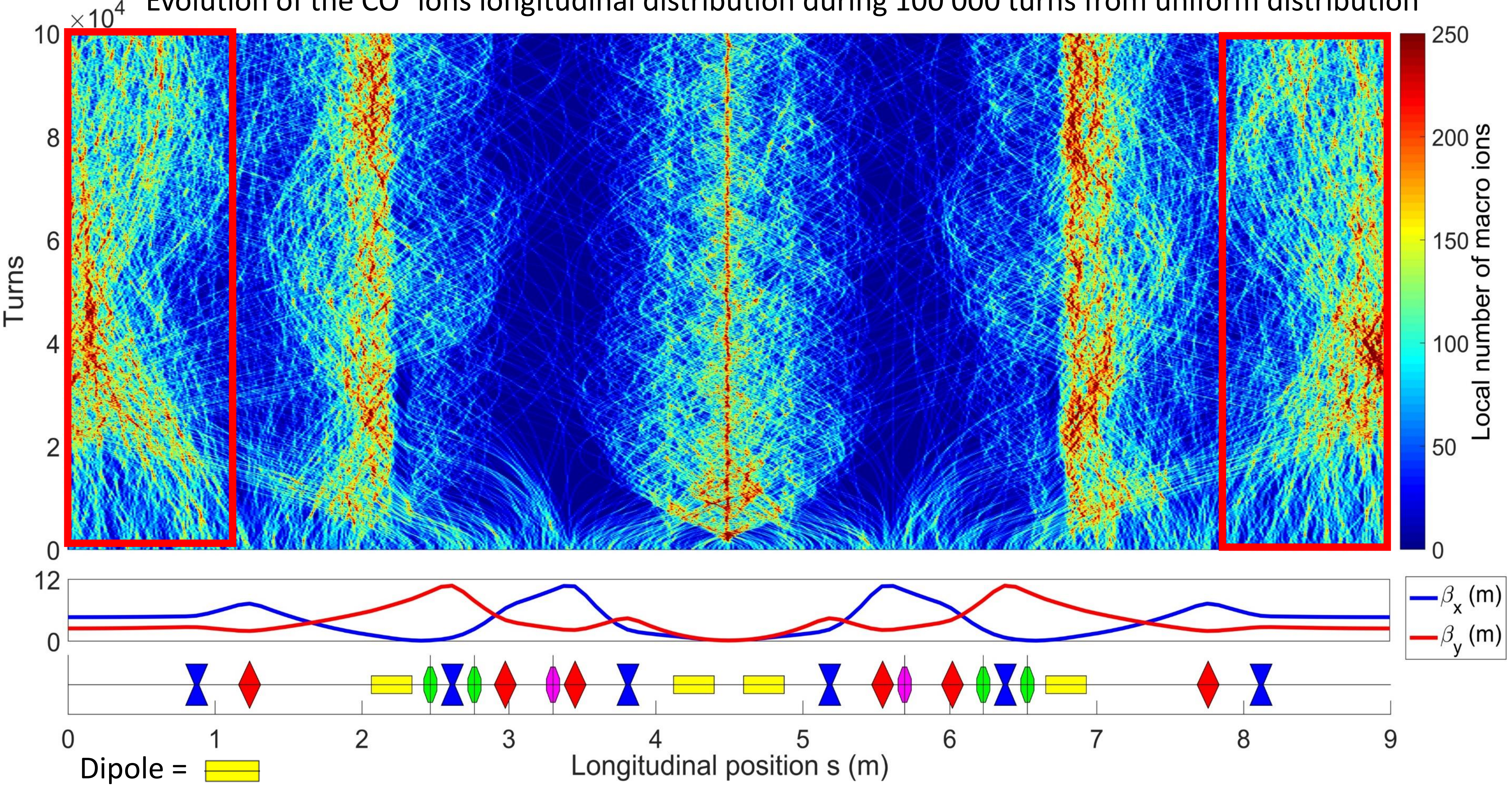
Evolution of the CO^+ ions longitudinal distribution during 100 000 turns from uniform distribution



Dipole =

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

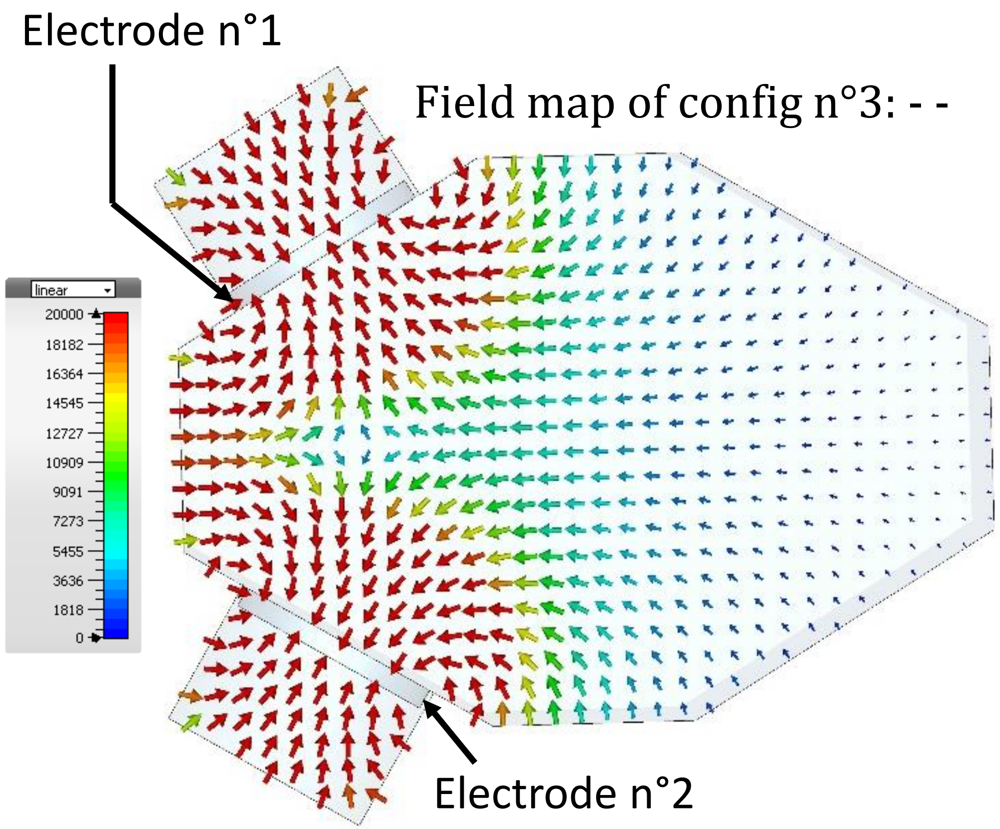
Evolution of the CO^+ ions longitudinal distribution during 100 000 turns from uniform distribution

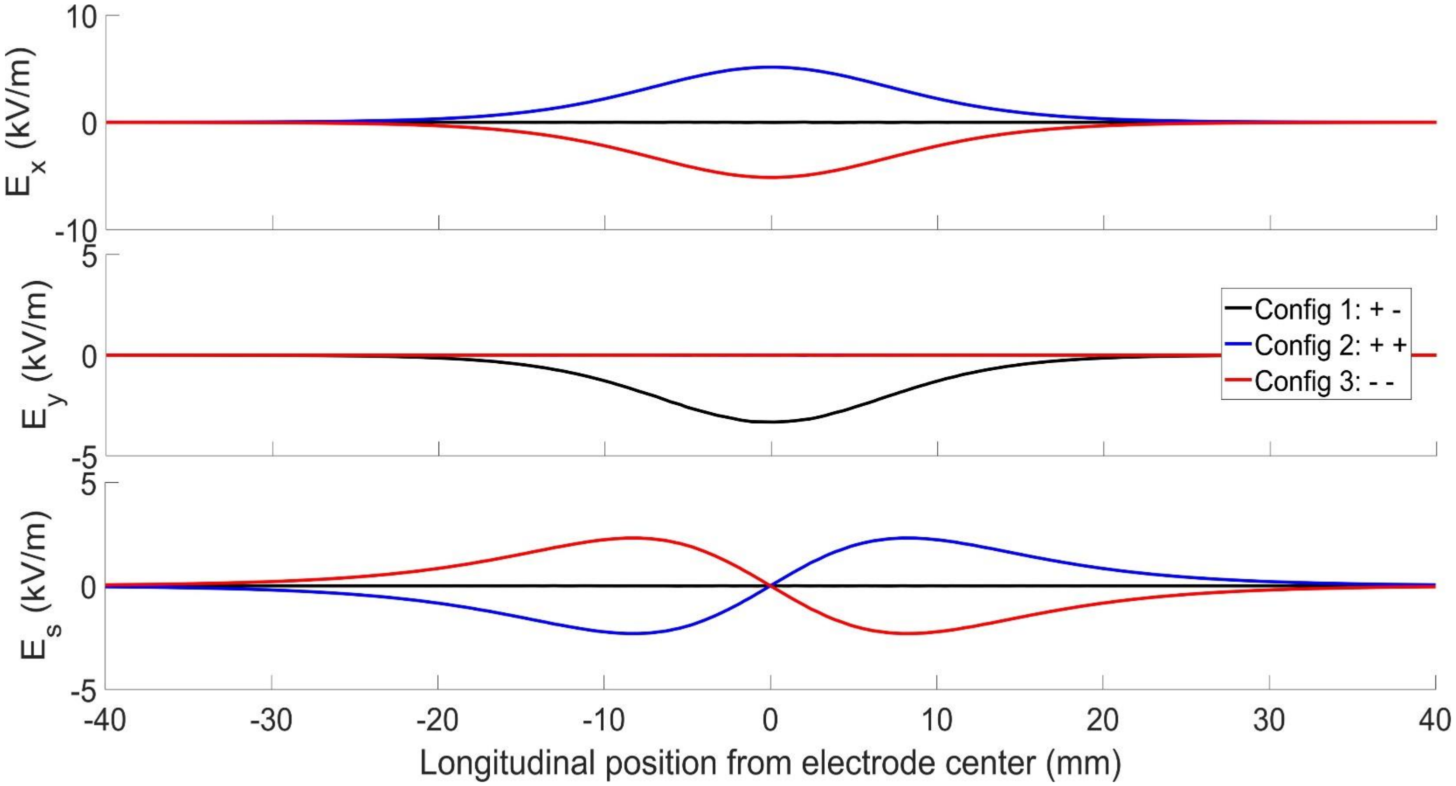


Dipole =

Clearing electrode with longitudinal field

Config n°	Electrode polarity		Effect on axis	Colour
	1	2		
1	+	-	Transverse kick $E_y < 0$	Black
2	+	+	Transverse kick $E_x > 0$ and longitudinal expulsion point	Blue
3	-	-	Transverse kick $E_x < 0$ and longitudinal accumulation point	Red



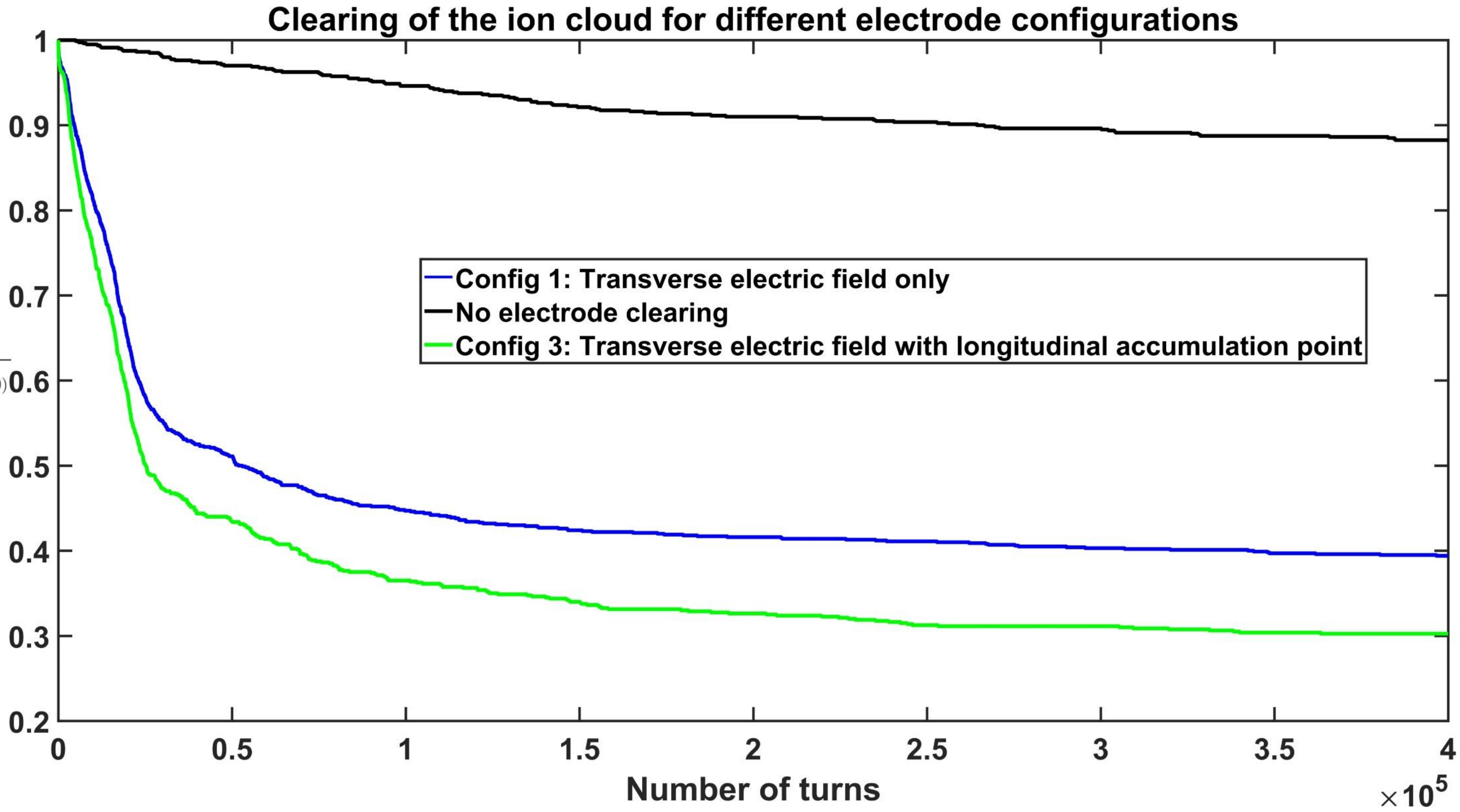


Clearing electrode with longitudinal field

The ion cloud clearing can be optimised by carefully choosing the type of clearing field and its positioning in the lattice:

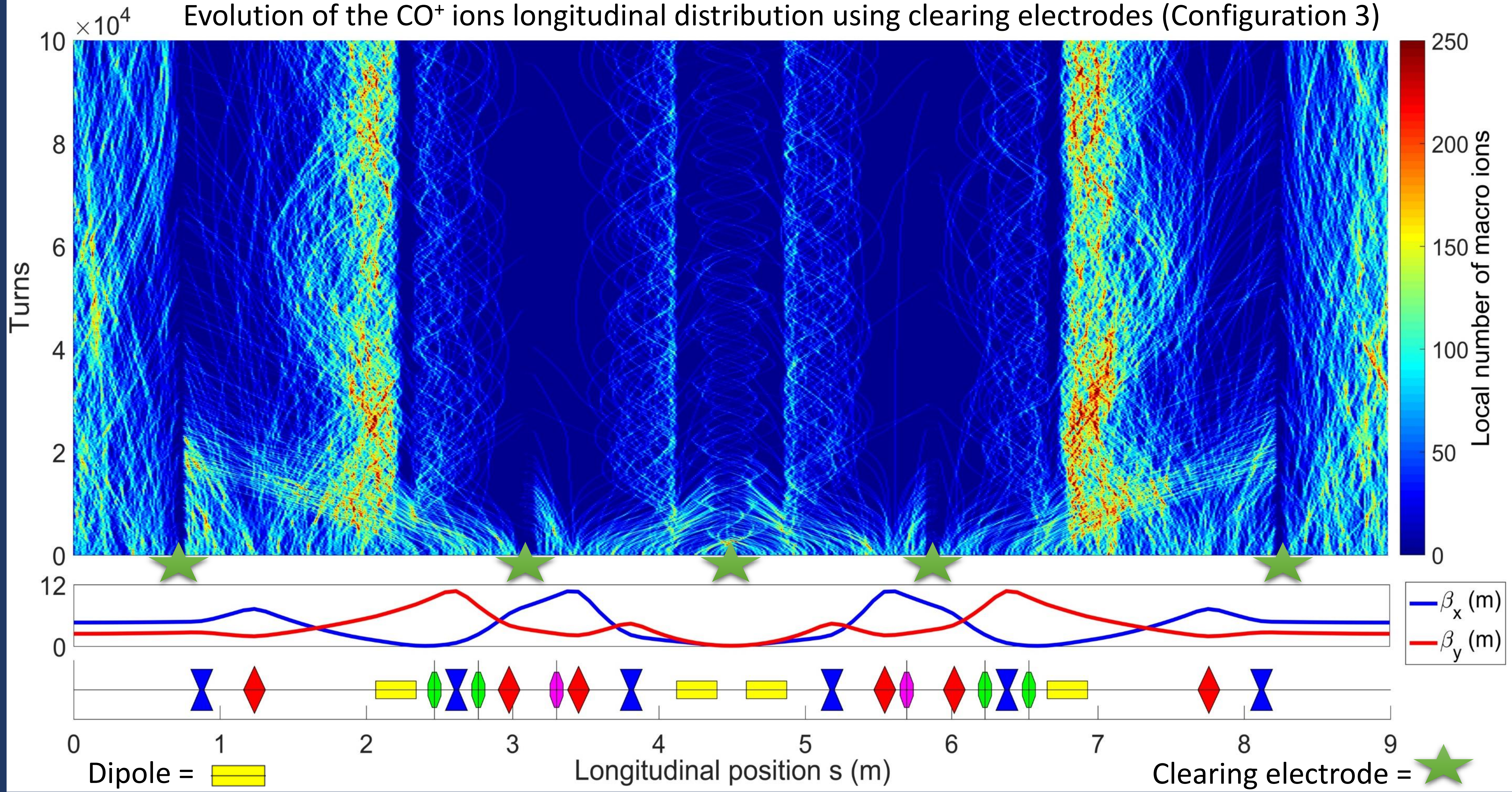
Clearing efficiency

$$\epsilon(t) = \frac{N_{ions}}{N_{ions(t=0)}}$$

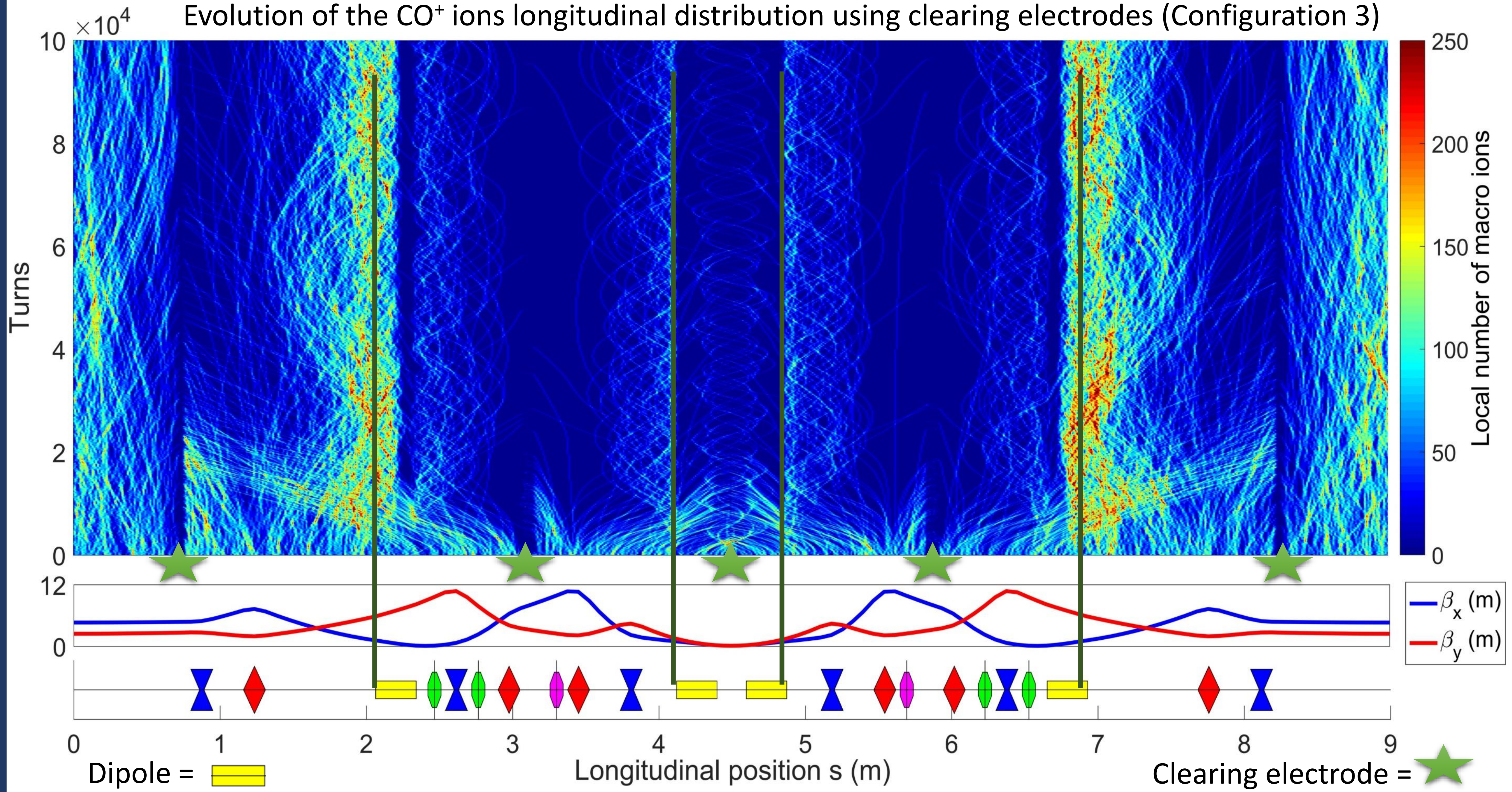


The clearing efficiency could be improved further if the electrodes are designed with this idea in mind

Evolution of the CO^+ ions longitudinal distribution using clearing electrodes (Configuration 3)

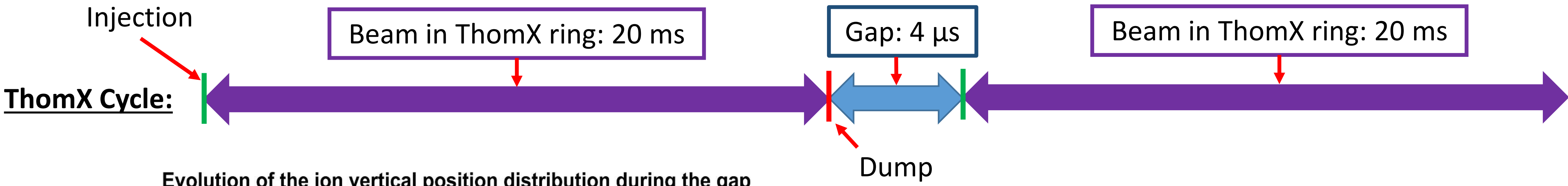


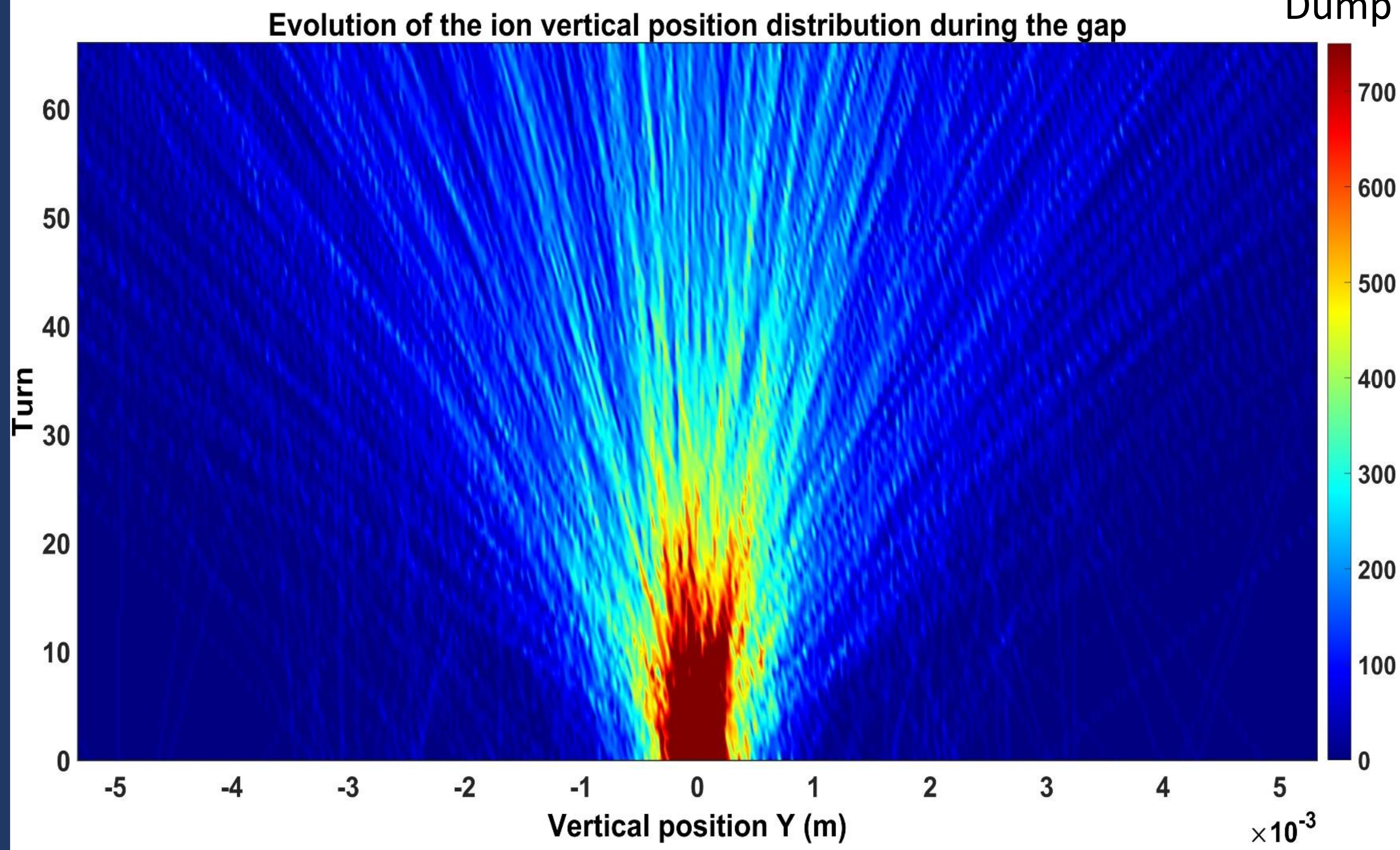
Evolution of the CO^+ ions longitudinal distribution using clearing electrodes (Configuration 3)



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

Clearing gap, mixing ion positions

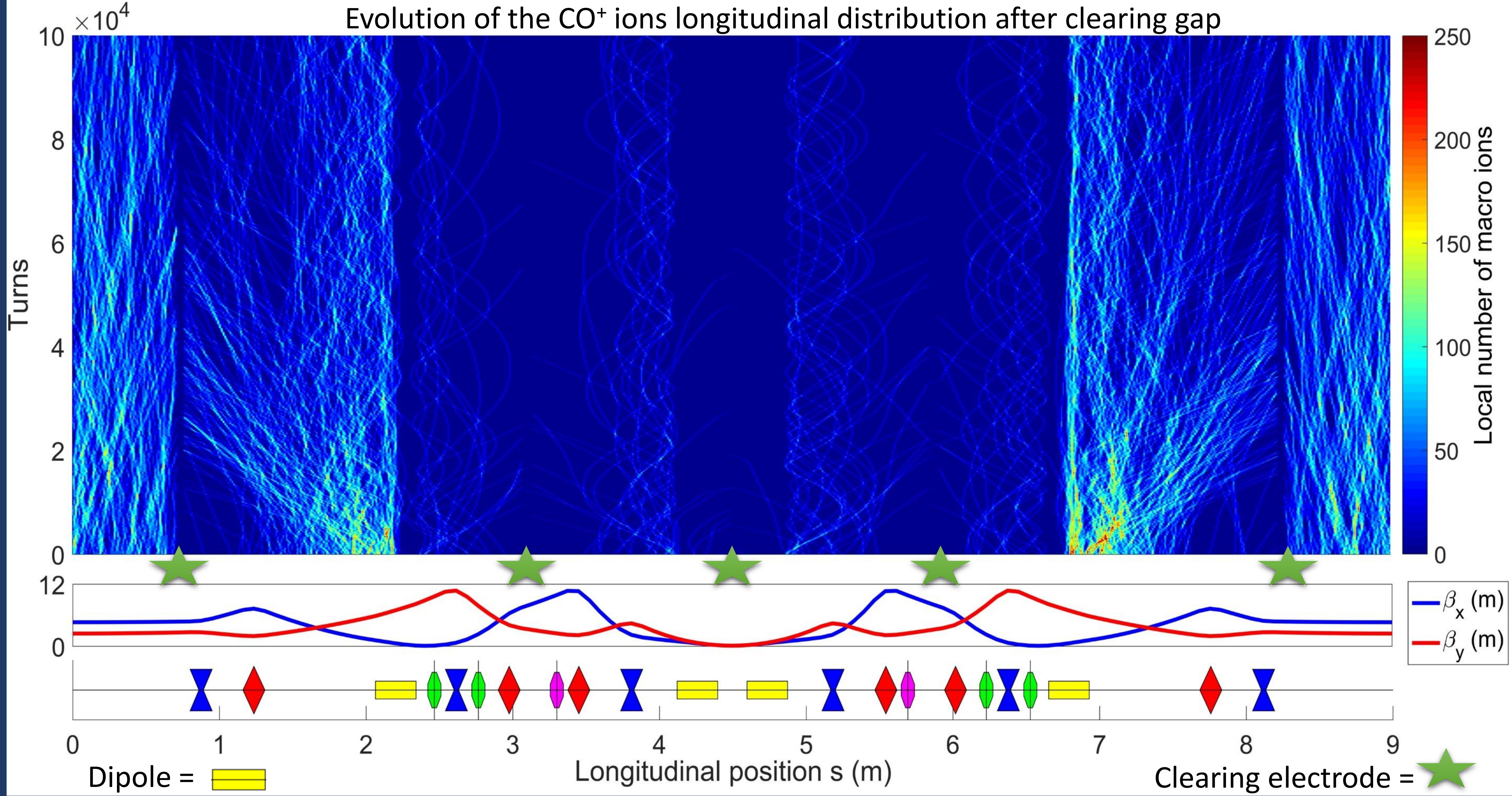




When there is no beam, ions are freed from beam potential well. The gap cleans a small part of the ions and « mix up » ion positions.

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

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



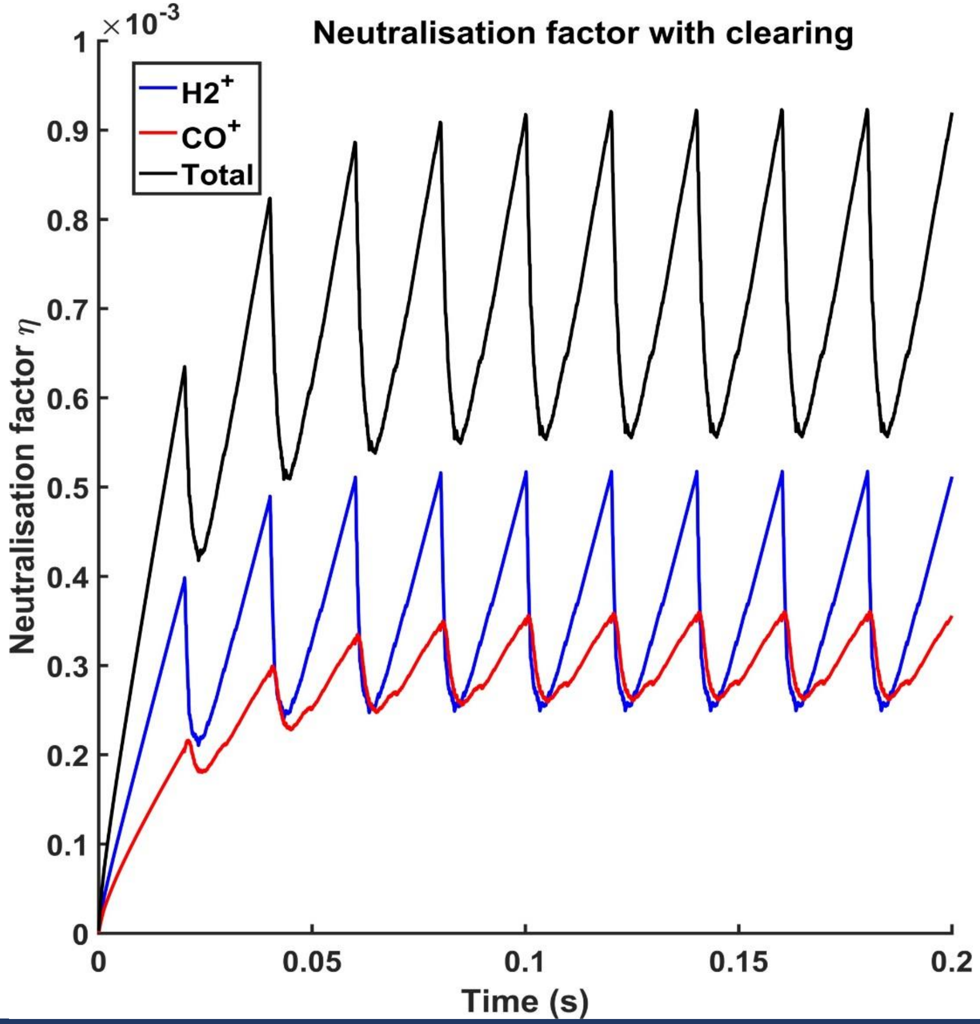
NUAGE simulation, number of macro ions at start : 39 000

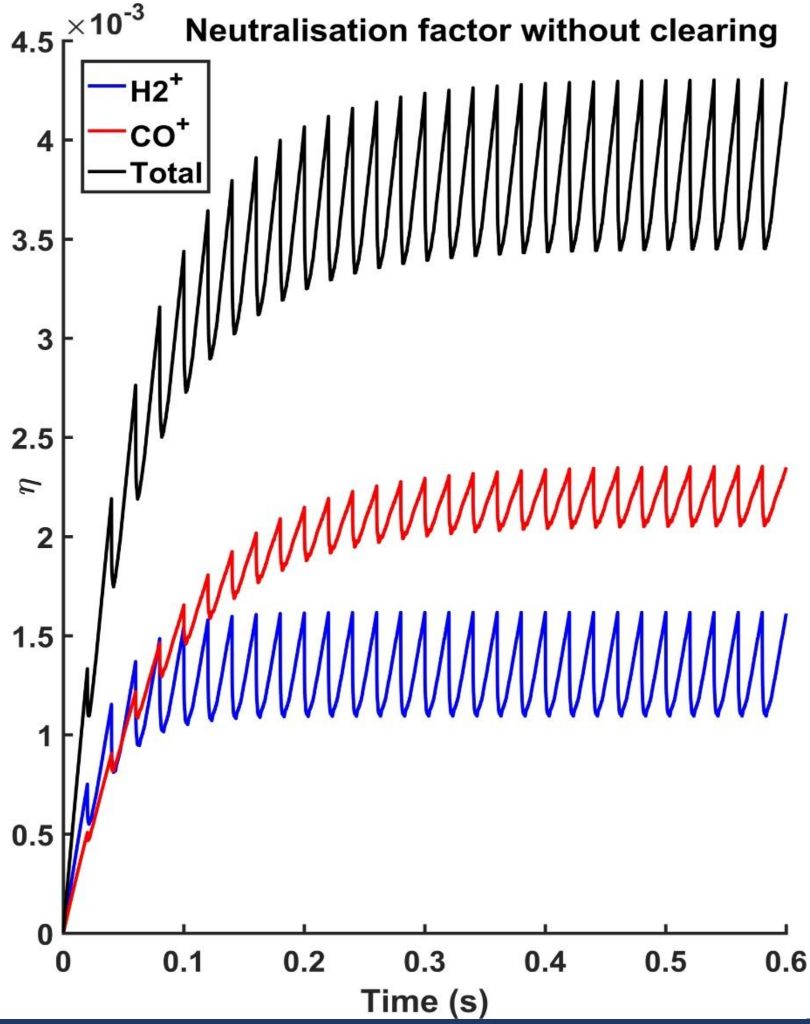
Neutralisation factor

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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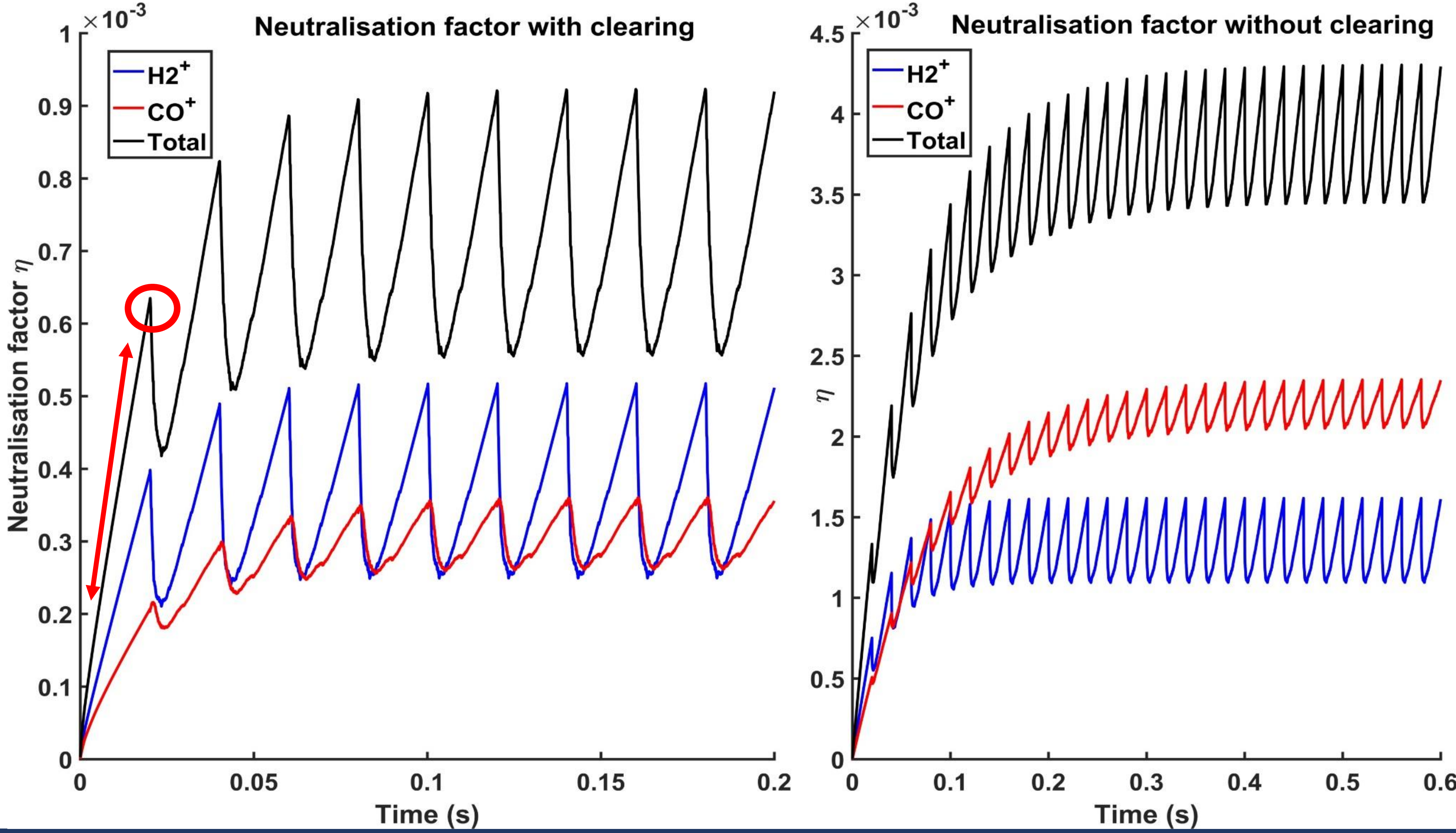


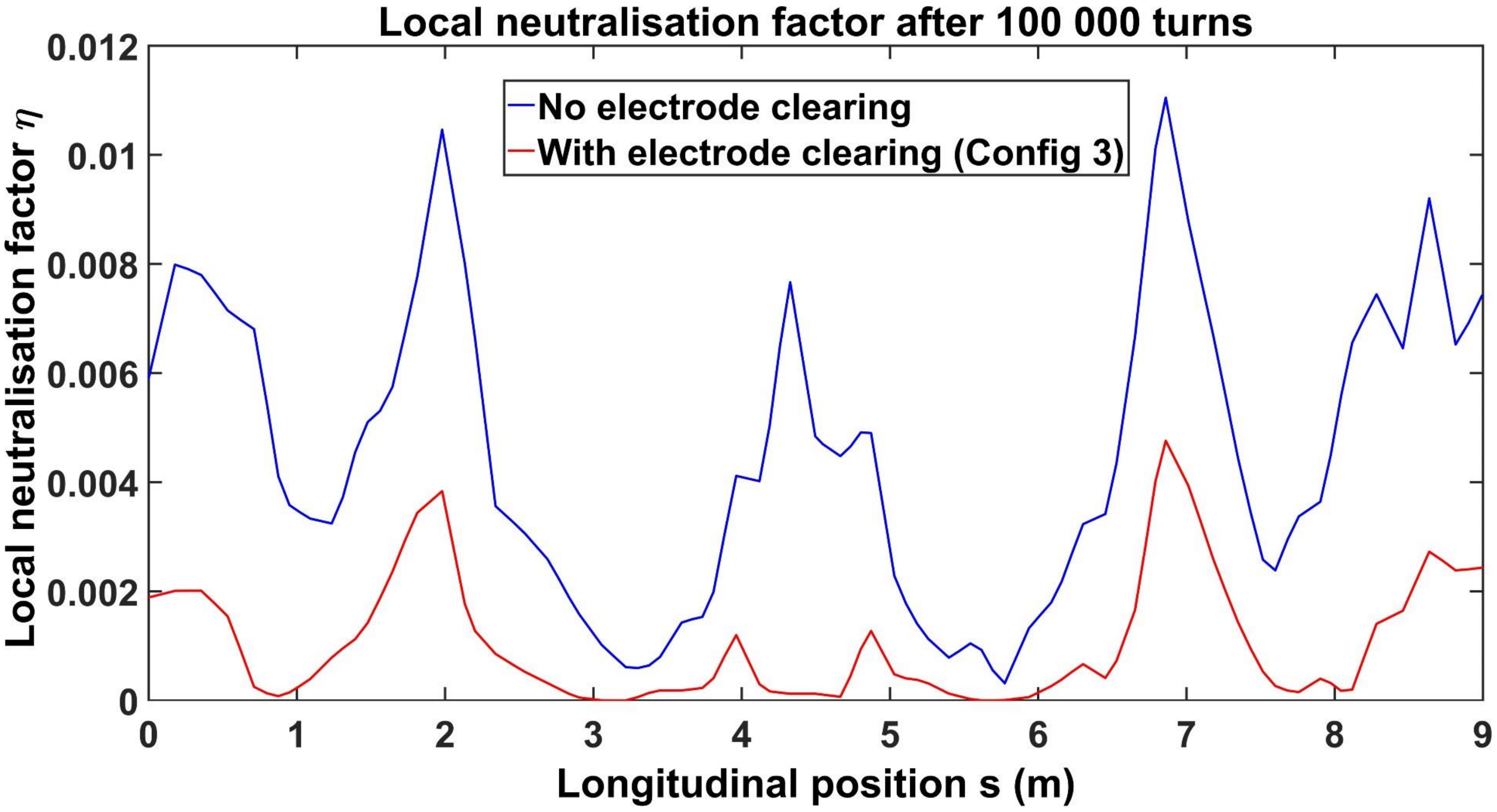
Local neutralisation factor

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:

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



[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:

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

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

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

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, …

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

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.

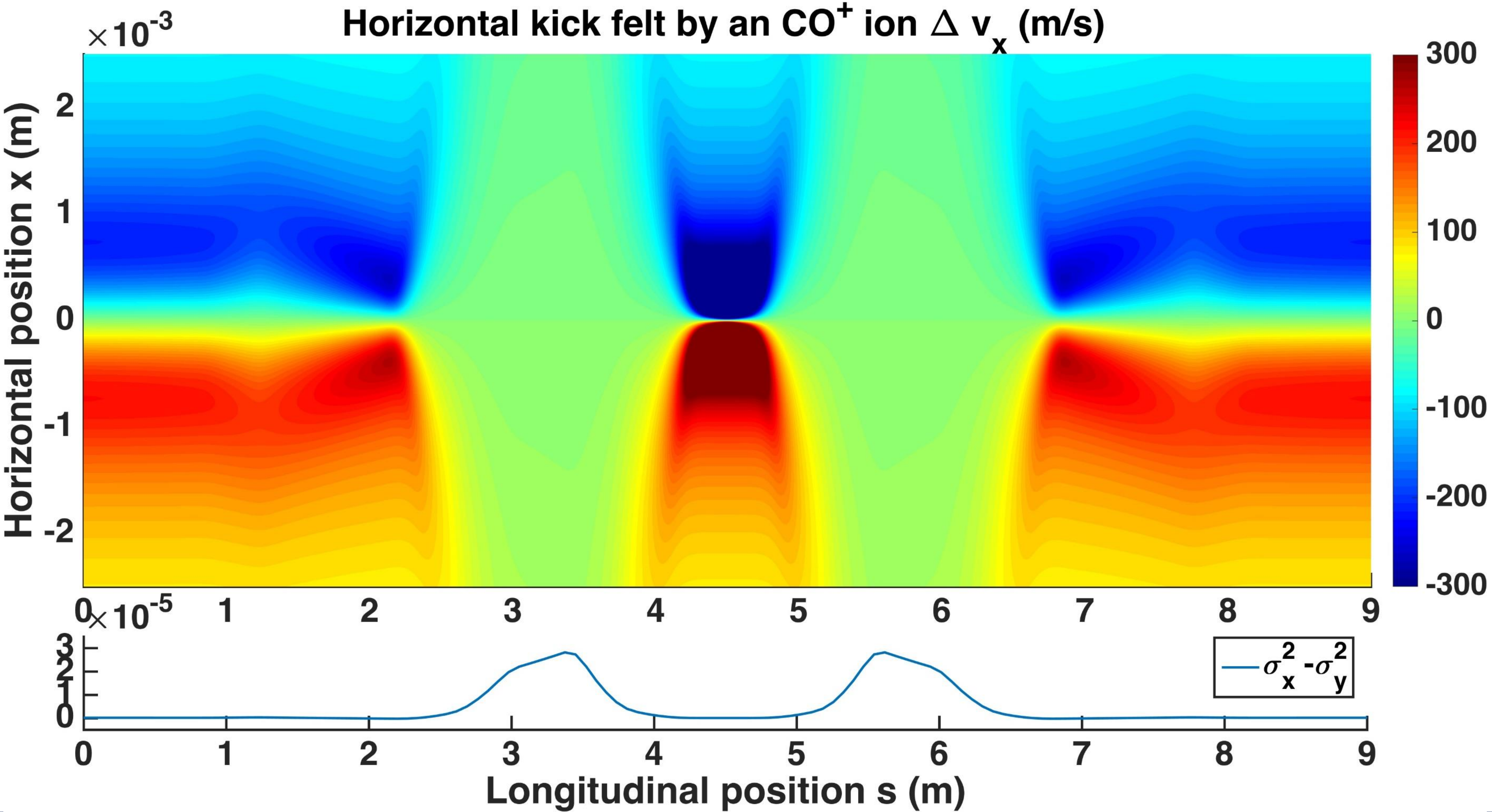
- Dipole magnets play an important role in the ion cloud dynamics.

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

- Use local values for the computation of the ion cloud induced effects in order not to minimize the effects, to be verified experimentally.

Thank you !

Backups



Horizontal kick felt by an CO+ ion Δ vx (m/s)
×10-3
Horizontal position x (m)
2
1
0
-1
-2
300
200
100
0
-100
-200
-300
0
1
2
3
4
5
6
7
8
9
×10-5
3
2
1
0
σx2 -σy2
0
1
2
3
4
5
6
7
8
9
Longitudinal position s (m)