Fast Ion Instability Study in the CLIC Main Linac

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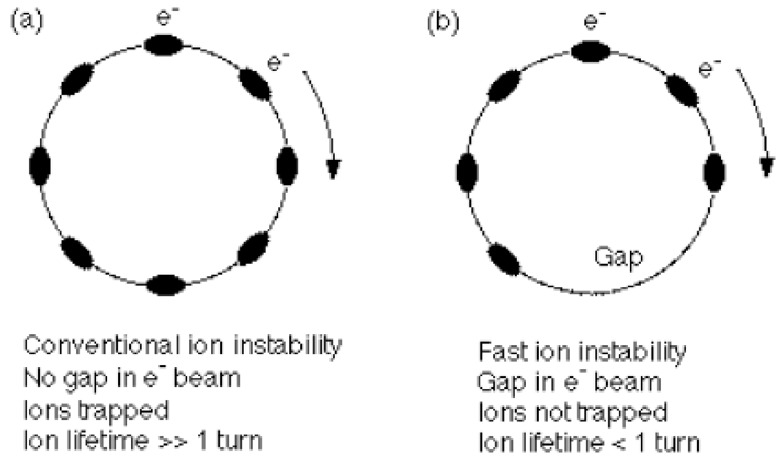
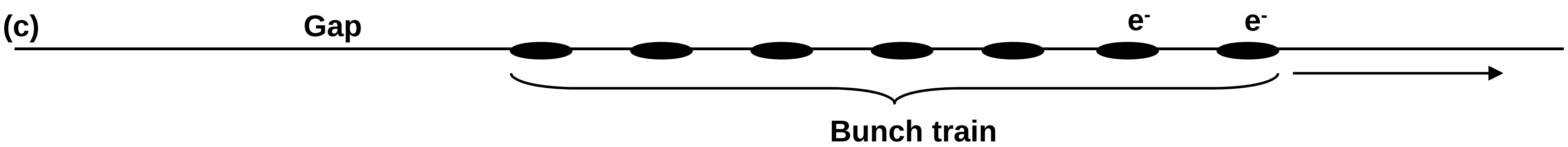
- General introduction to the physics of the fast ion instability
- ***Fastion*** code used to model fast ion instability problems in lines
  - Short Description of the code
  - Input and outputs
- Simulations of the CLIC main linac
- conclusions and outlook



Illustrative pictures taken from A. Chao's notes on the Fast Ion Instability



Ion instability in a circular electron machine

→ Each passing bunch **ionizes the residual gas**

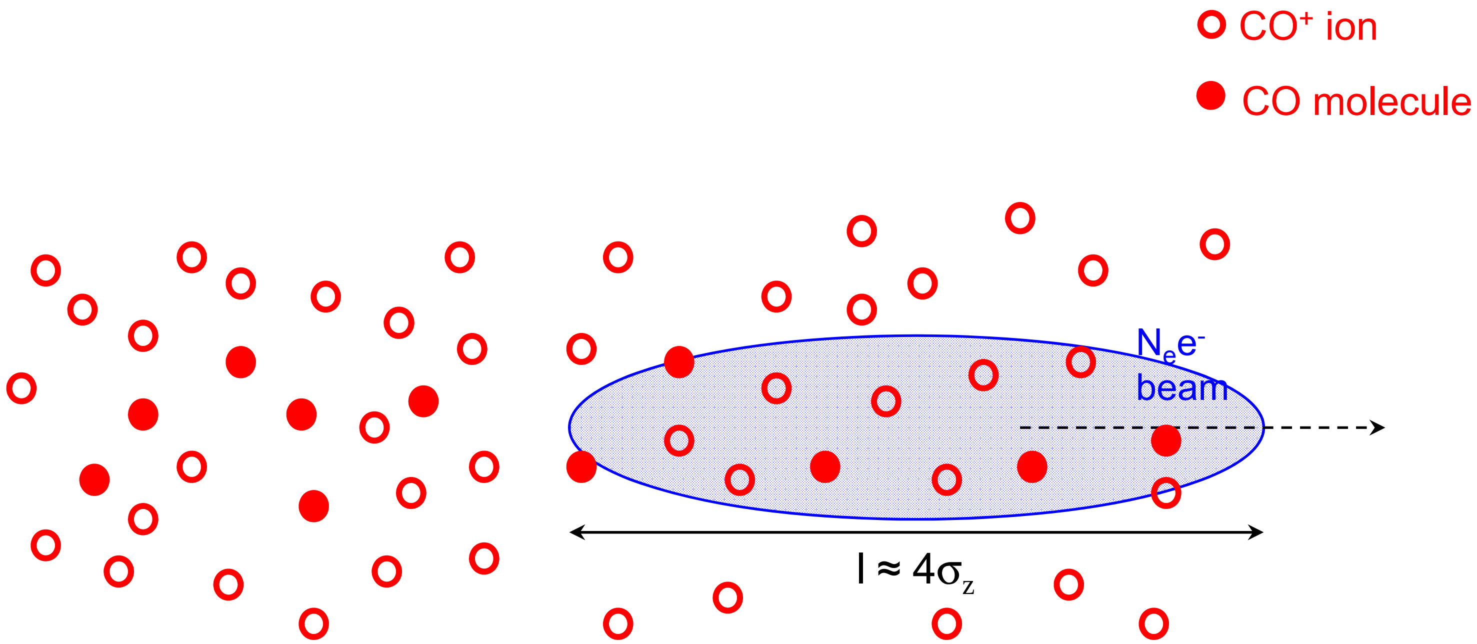
→ Ions produced by a bunch move slowly and can **be trapped around the beam** because they are focused by the following bunches

→ They can affect the motion of

- the full train, if the bunches fill uniformly the machine and the ions survive in the machine (**conventional ion instability**, case (a))

- only the tail of the train if there is a long enough gap to clean up the ions (case (b), **fast ion instability**). This type of instability can also occur in a linac (case (c))

Example of beam ionization process

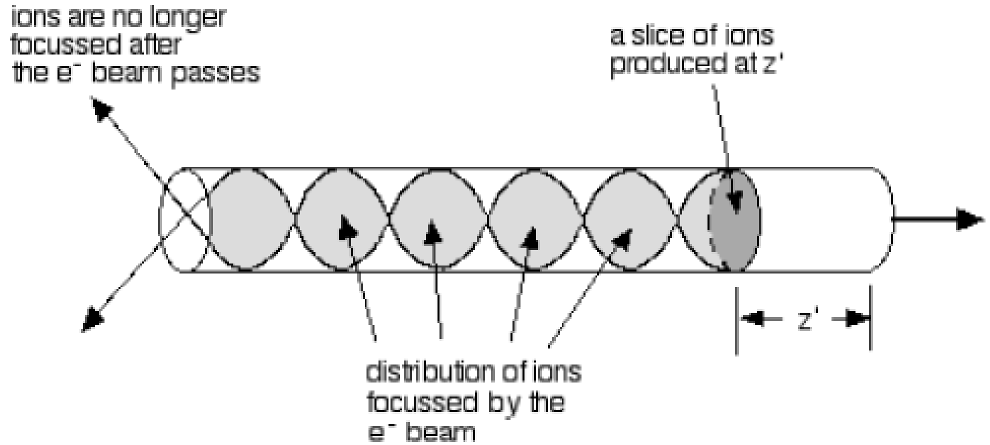


The number of ions created per unit length (λ) depends on the partial pressure of the residual gas component (P), the cross section of the ionization process (Σ), the number of electrons per bunch (N)

$$\lambda = \frac{\Sigma N P N_A}{RT}$$

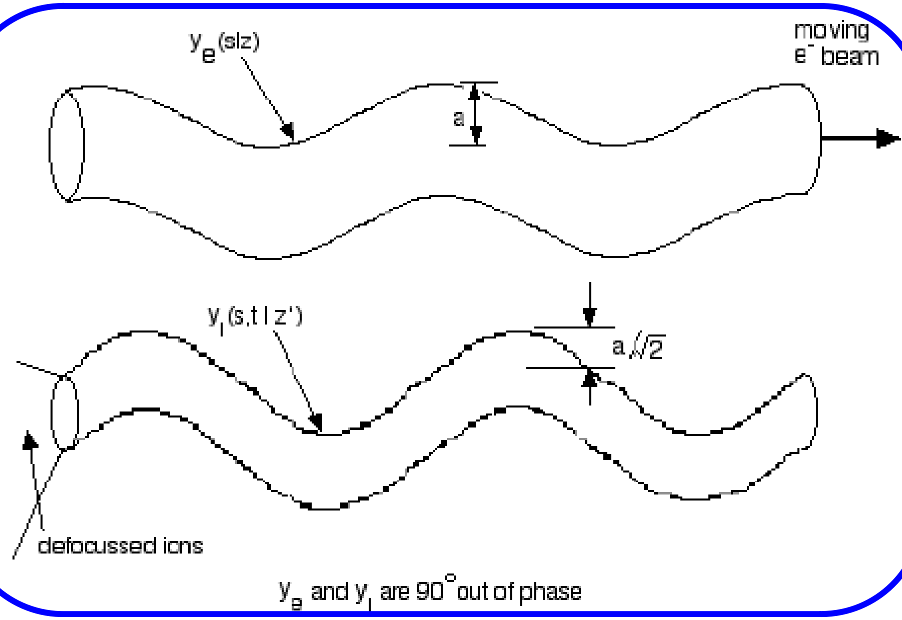
For ex. CLIC $\lambda \approx$ 25 ions/m

The ions can be focused by the electric field of the following bunches and they accumulate in the vicinity of the beam (trapping condition)



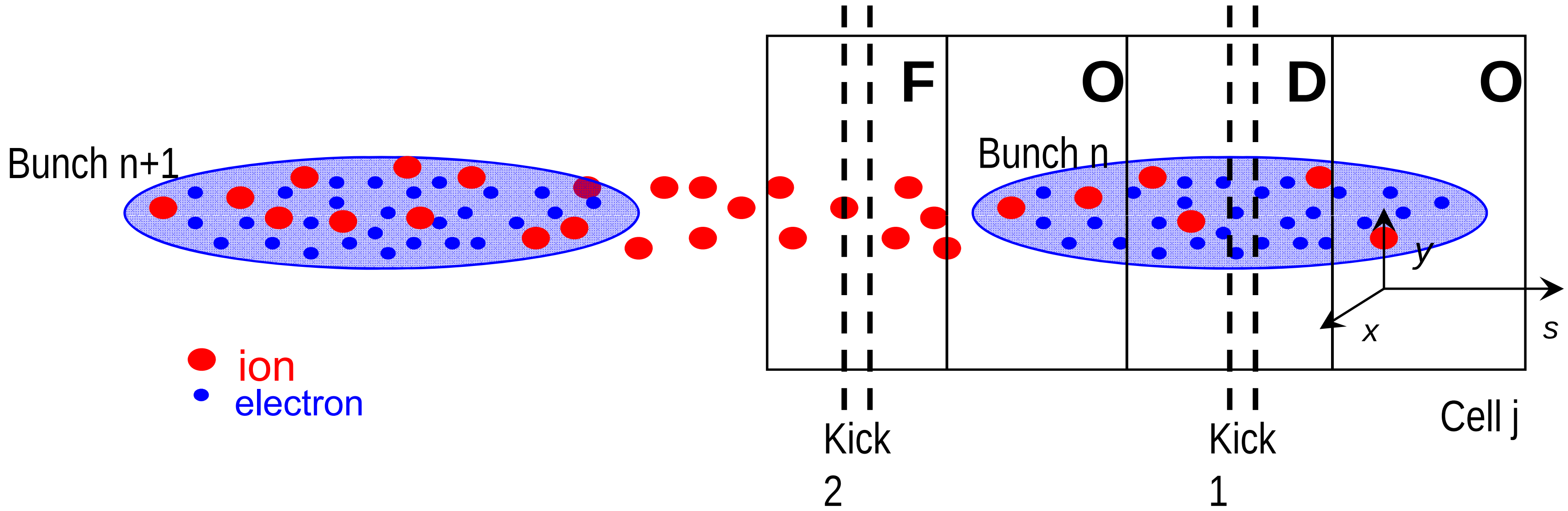
The ion cloud can affect the motion of the bunches and an unstable ion-electron coupled motion can be excited

Two-stream instability



FASTION (I)

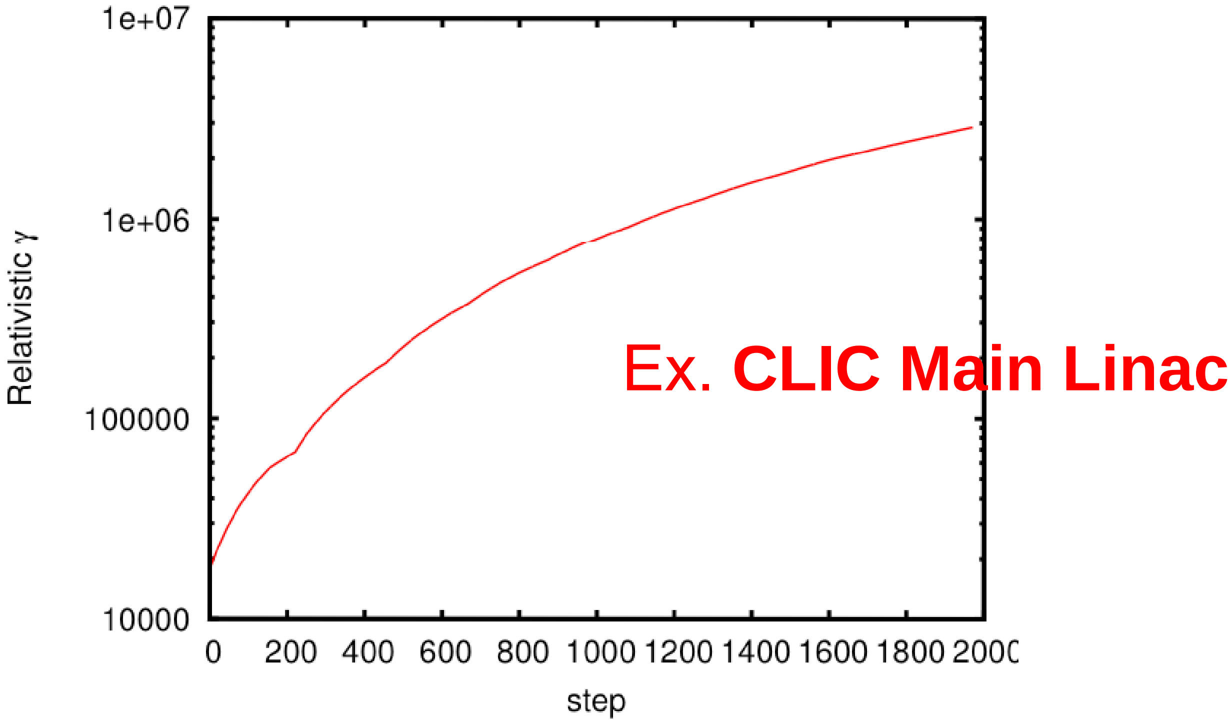
- **Multi-bunch** code, ions and electrons modeled as macro-particles
- Ions of an **arbitrary number of species** are created at each bunch passage and propagated through the train
- Line can be:
  - ✓ A simple **sequence of FODO cells**, with two kicks per FODO cell
  - ✓ Described through an **output *PLACET* Twiss file**
  - ✓ Described through an **output *MAD-X* Twiss file**
- **Electromagnetic interaction**: the ions are kicked by the passing bunches and the bunch macro-particles feel the effect of the ion field



FASTION (II)

Acceleration along the line can be taken into account

- Initial and final energy are given through the standard input file and **a simple linear model of acceleration** is applied
- The ***PLACET* Twiss file** gives the energy at all the specified ***s*** locations along the line
- The coordinates of the transverse phase space shrink like $\gamma^{1/2}$



FASTION (III) → Input file

⇒ **All the necessary parameters are passed through a simple ascii input file (N_{el}, N_{ion}, N_{bunch} to be specified in the source)**

Number_of_ion_species: 2
Partial_pressures_[nTorr]: 1. 1.
Atomic_masses: 28. 18.
Ionization_cross_sections_[MBarn]: 2. 2.
Number_of_electrons_per_bunch: 3.7e+9
Bunch_spacing_[ns]: 500.e-3
Normalized_horizontal_emittance_(rms_value)_[nm]: 660.
Normalized_vertical_emittance_(rms_value)_[nm]: 10. Bunch_length_(rms_value)_[ns]:
0.12e-3 Initial_relativistic_gamma: 17610.15
Final_relativistic_gamma: 17610.15 Number_of_FODOs:
500 FODO_Length_[m]: 40.
Phase_advance_per_cell_[degrees]: 70.

CO (or N_2) and H_2O

Possible change during acceleration

The bunches can be accelerated through the line

FASTION (IV) → Output files

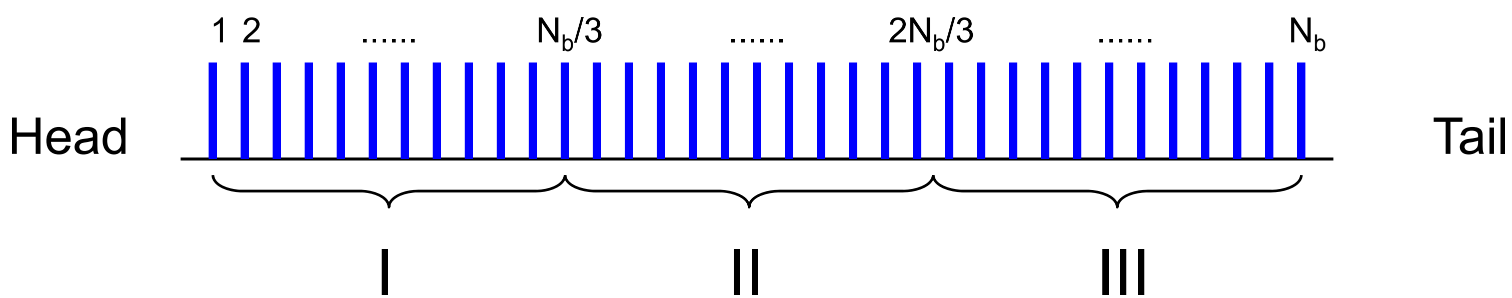
⇒ **The code transports the bunch train through the line, generates the ions at each interaction and propagates them**

✓ **Ion distributions** in x and y are stored at an arbitrary time step (for instance, at the beginning)

✓ The **phase space coordinates of 4 sample ions** are stored at the same time step as above

✓ Snap-shots of the **bunch by bunch centroids and emittances** are saved at each time step

✓ Time evolution of the **beam centroids and emittances** (averaged over one third of the train) are stored



Application to CLIC Main Linac

⇒ **We have carried out simulations of fast ion instability usingthe lattice file from PLACET (Daniel) and the following parameters**

⇒ Beam energy from 9 GeV to 1.5 TeV over a length of 20 km.

⇒ Residual gas pressure from 10 to 50 nTorr for each species. Only two species of ions have been considered (CO and H_2O)

⇒ Bunch population is 4 x 10^9

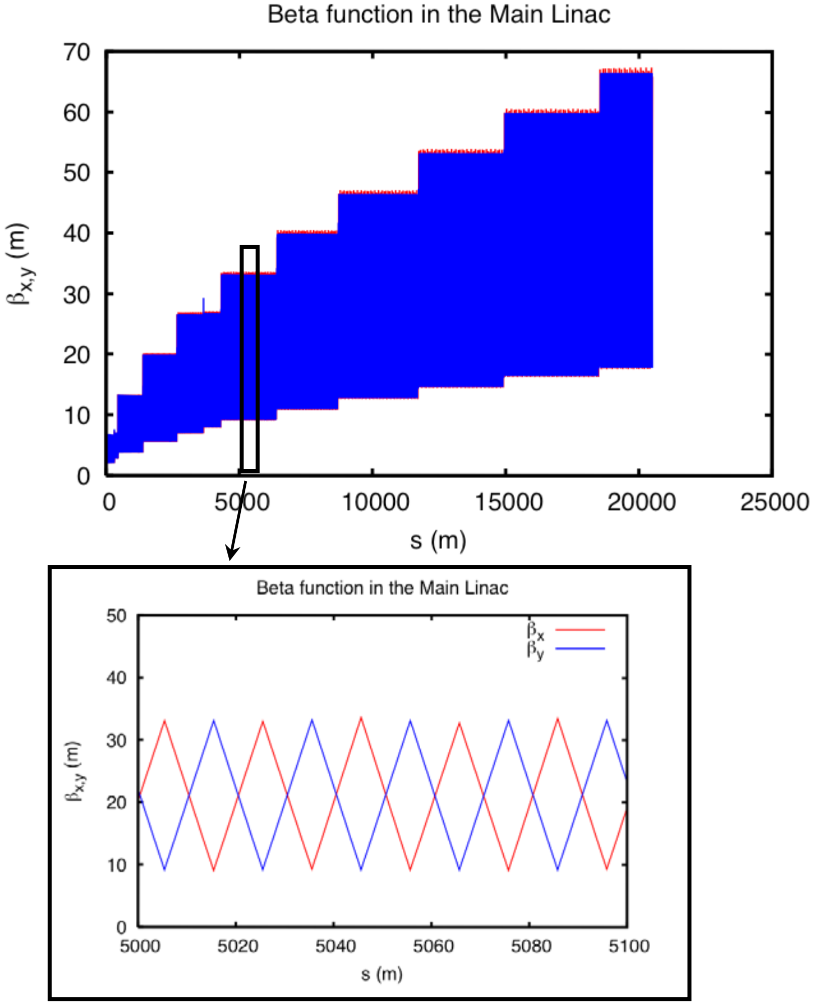
⇒ Bunch spacing is 500 ps

⇒ Number of bunches (N_b) is 312

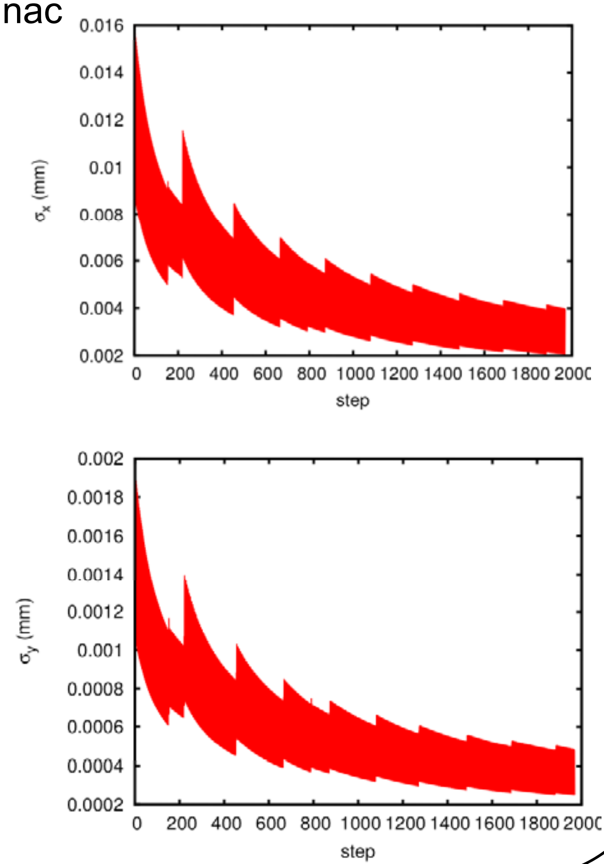
⇒ Normalized emittances are 680,10 nm

Application to CLIC Main Linac (II)

Through the twiss.dat file, both beta functions and beam energy at different locations in the main linac are passed to the FASTION code and used for tracking with the generated ions.

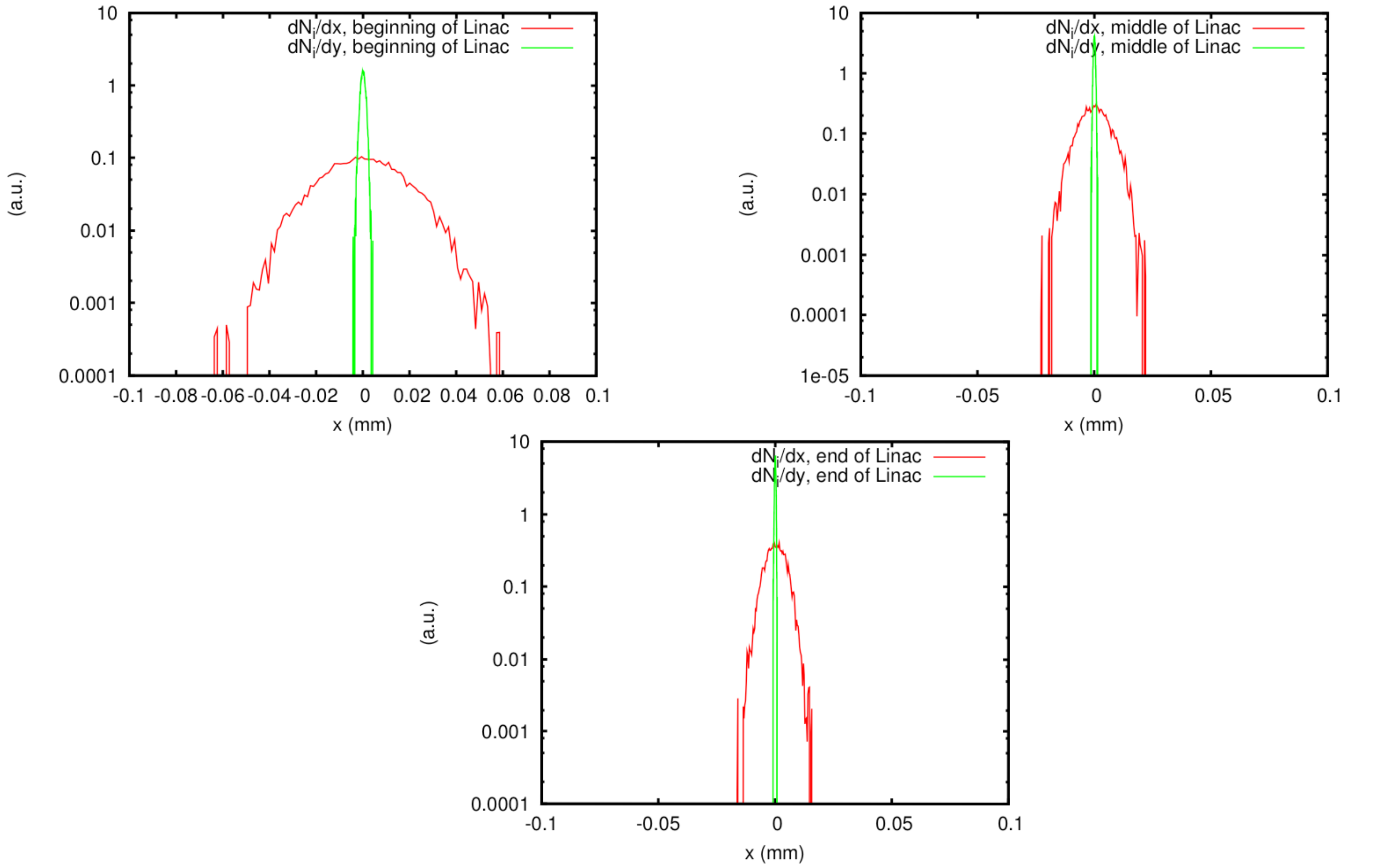


Decreasing beam sizes along the Linac



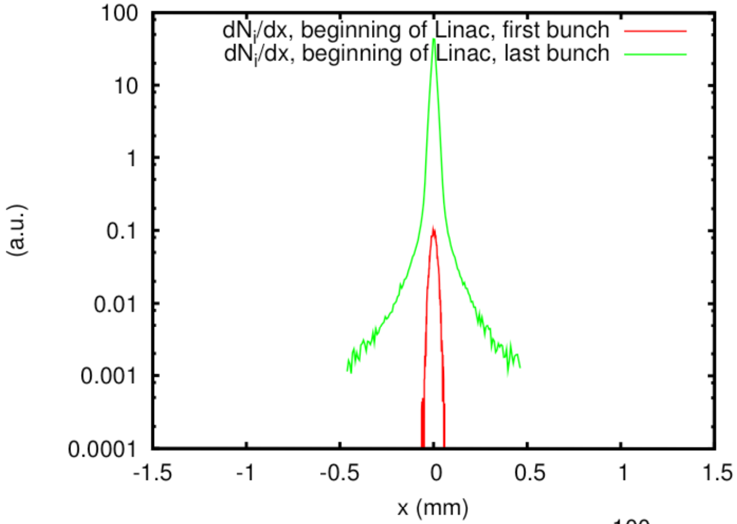
Application to CLIC Main Linac (III)

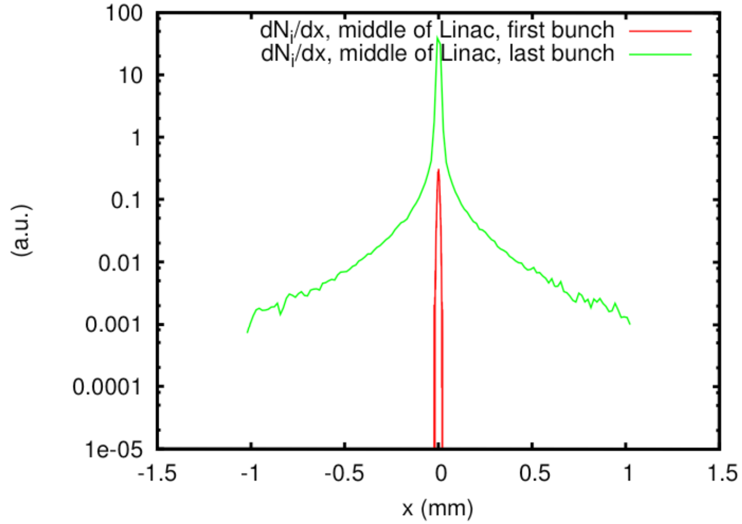
As ions are produced by residual gas ionization, the distribution of ions as generated at the first bunch passage follows the beam sizes along

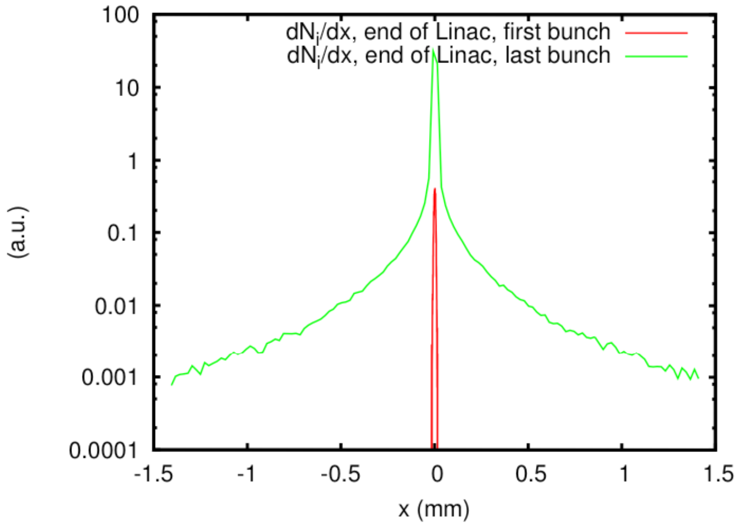


Application to CLIC Main Linac (IV)

Loss of trapping along the Linac shown by the extension of the tails of the ion distribution at the first and the last bunch passage at three different locations

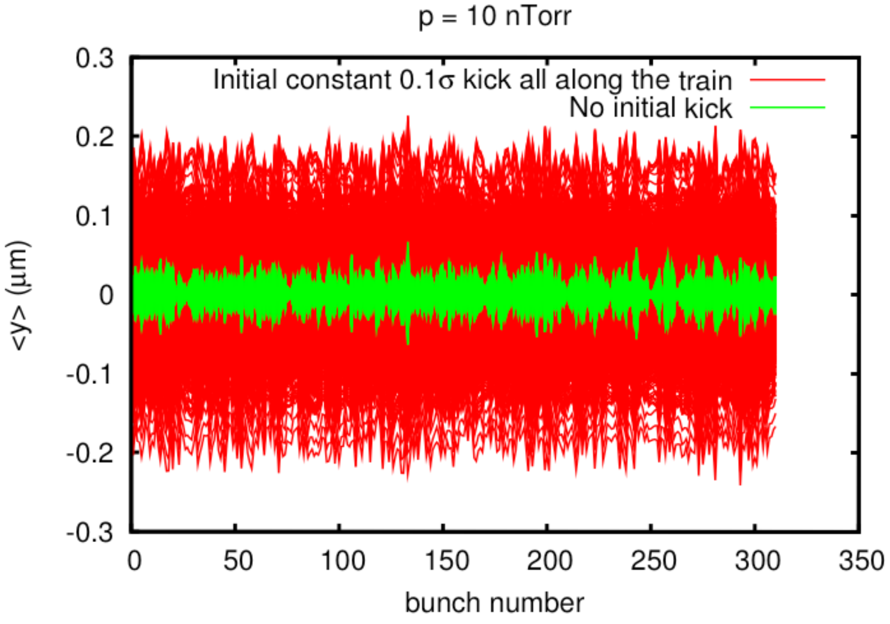


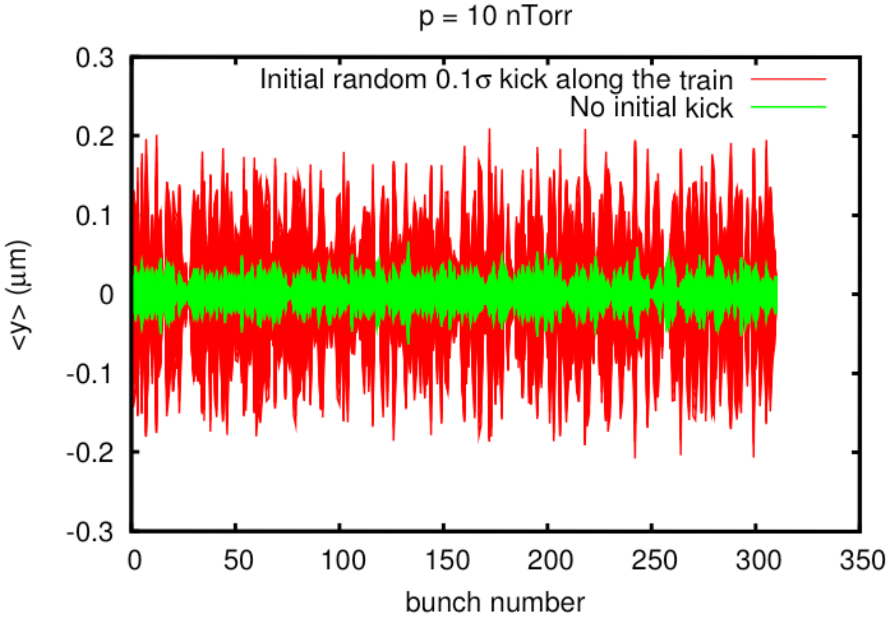




Application to CLIC Main Linac (V)

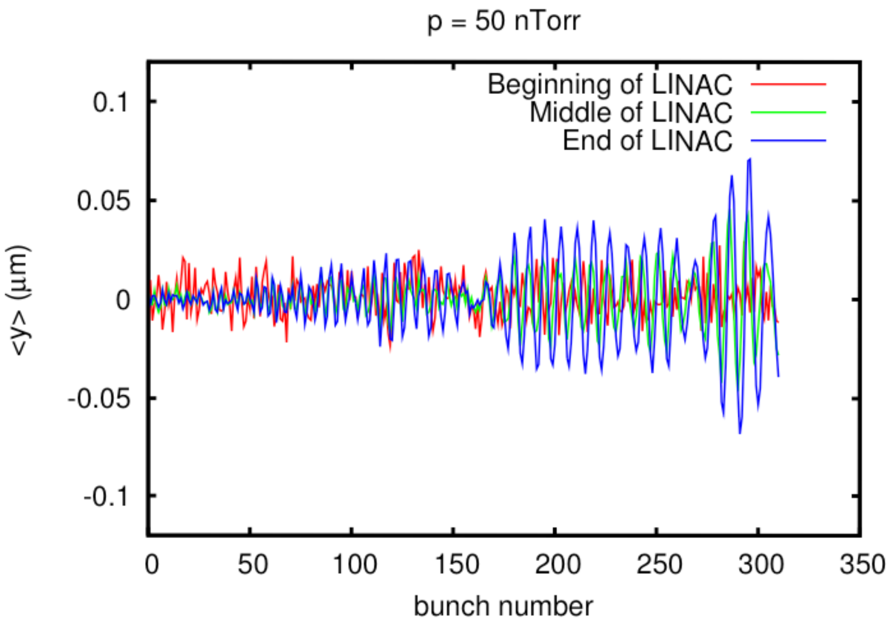
The beam is stable with a vacuum pressure of 10nTorr, even giving initial offsets of 0.1xσ_0 to the different bunches (constant along the train or randomly distributed)

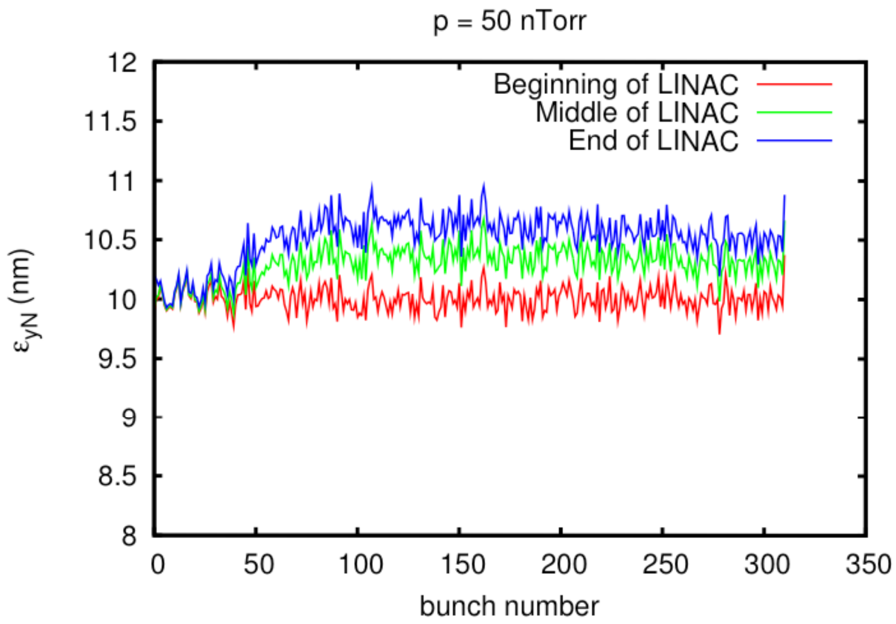




Application to CLIC Main Linac (VI)

The beam is unstable with a vacuum pressure of 50nTorr, and both a coherent centroid motion and a small incoherent emittance growth appear along the line





Conclusions and outlook

- The code ***FASTION*** has been applied to study the fast ion instability in the CLIC Main Linac.
  - Detailed lattice from PLACET
  - Effect of acceleration included
  - Evident loss of trapping along the Linac (stabilizing)
- Simulations show that:
  - The beam is stable with P=10 nTorr (no amplitude growth observed)
  - The threshold of instability lies between 10 and 50 nTorr
- The present model still does not include
  - The effect of the rf fields on the ions (expected not to be critical)
  - The effect of field ionization. This may become very important in the late stages of the ML and could significantly alter this picture
- A model of field ionization is currently under development to be included in FASTION