Fast Ion Instability Study

G. Rumolo and D. Schulte

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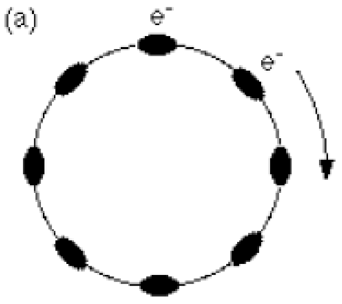
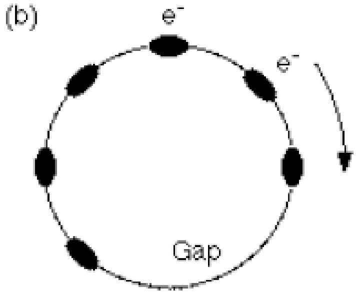
- General introduction to the physics of the fast ion instability
- ***Fastion*** code used to model fast ion instability problems in transport lines
  - Description of the code
  - Input and outputs of the code
- Applications to the CLIC transport line and main linac
- conclusions and outlook

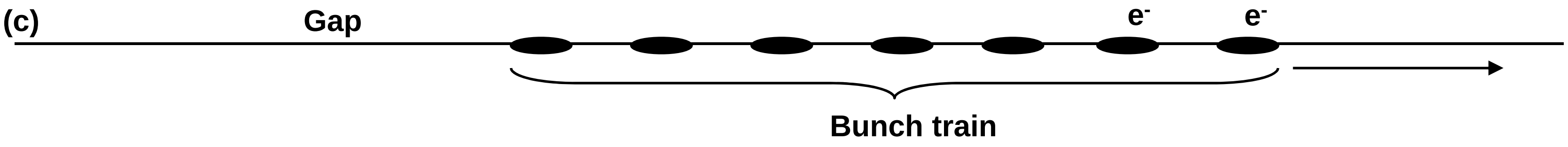


Conventional ion instability
No gap in e^- beam
Ions trapped
Ion lifetime >> 1 turn



Fast ion instability
Gap in e^- beam
Ions not trapped
Ion lifetime < 1 turn

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



Ion instability in a circular electron machine

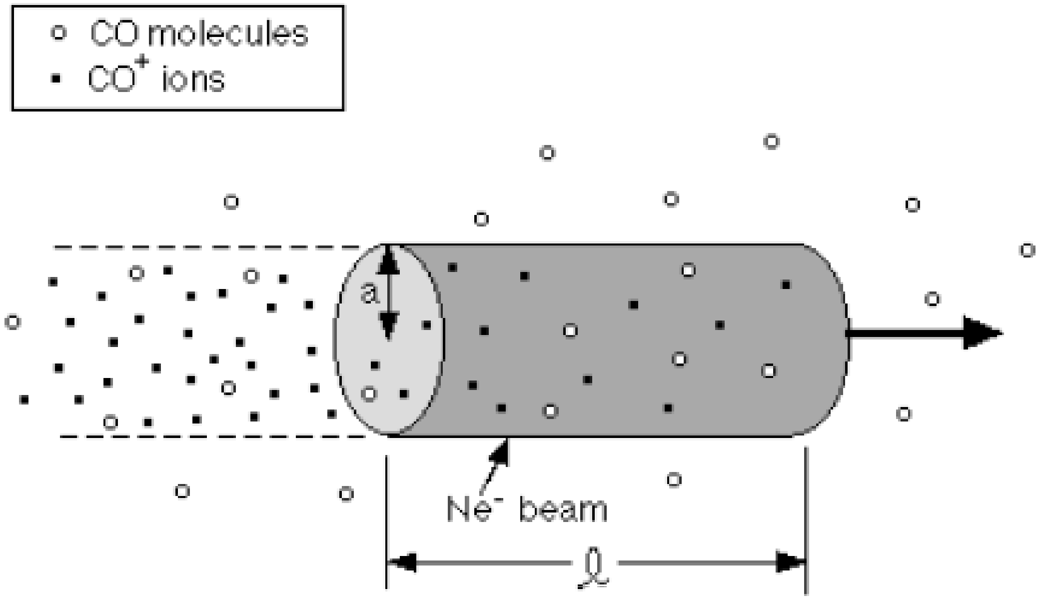
→ Each passing bunch **ionizes the residual gas**

→ 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

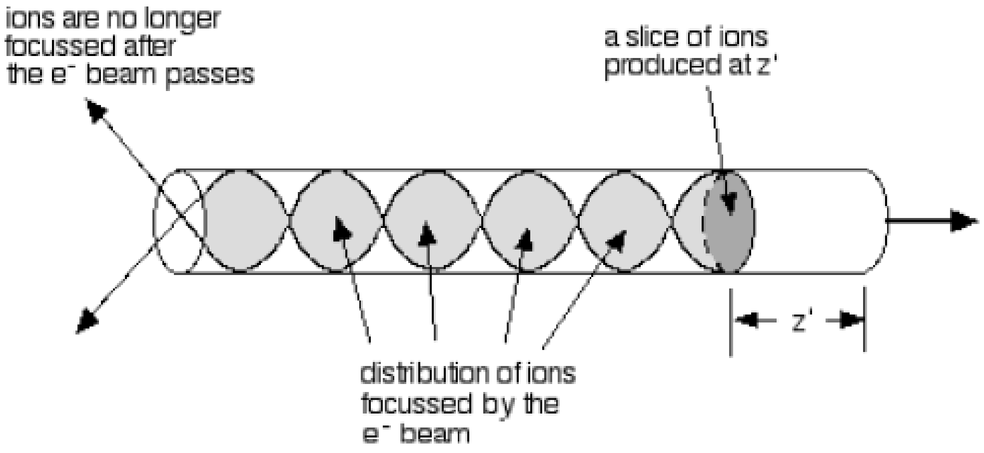


The number of ions created per unit length (λ) depends on the partial pressure of the residual gas component (P), the cross section of the ionization process (Σ), the number of electrons per bunch (N)

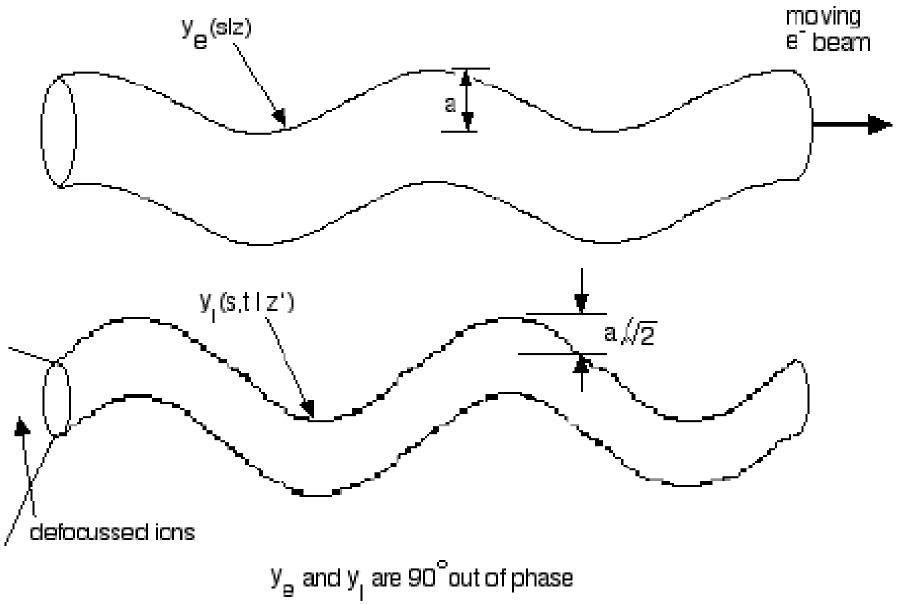
$$\lambda = \frac{\Sigma N P N_A}{RT}$$

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 (they are released after the train passage)



The ion cloud can affect the motion of the following bunches, so that a **coherent instability can be driven** (correlated coupled motion of the ion and the electron beam)



Resumé of some simplified formulae (I)

- They can be trapped in the beam (F. Zimmermann et al.)

$$4f_i \leq \frac{c}{L_{sep}}$$

- The ion frequency is given by

$$f_i = \frac{c}{\pi}\sqrt{\frac{Q_i N r_e \frac{m}{M}}{3\sigma_y(\sigma_x+\sigma_y)L_{sep}}}$$

- Linear rise time for noise is

$$\frac{1}{\tau_c} = \frac{4}{\sqrt{27}}\left(\frac{N r_e}{\sigma_y(\sigma_x+\sigma_y)}\right)^{\frac{3}{2}}\sqrt{\frac{m}{M}}\sqrt{L_{sep}}\frac{p\sigma_{ion}}{kT}\frac{\beta_y c n^2}{\gamma}$$

- If ions are trapped they increase beam noise at some frequency as

$$\frac{1}{\tau_e} = \frac{1}{\tau_c}\frac{c}{\sqrt{32}\pi L_{sep} n a f_i}$$

Resumé of some simplified formulae (II)

- We rewrite for a round beam

$$\frac{1}{\tau_e} = \frac{p\sigma_{ion}}{kT}\frac{Nnr_ec}{\sqrt{18}(\sqrt{\epsilon_x\epsilon_y}+\epsilon_y)a}\frac{1}{\sqrt{Q}}$$

- For a flat beam

$$\frac{1}{\tau_e} = \frac{p\sigma_{ion}}{kT}\frac{Nnr_ec}{\sqrt{18}\sqrt{\epsilon_x\epsilon_y}a}\frac{1}{\sqrt{Q}}$$

⇒ If ions are trapped, the growth depends on the optics via a

- only possibility is to excite different noise frequencies

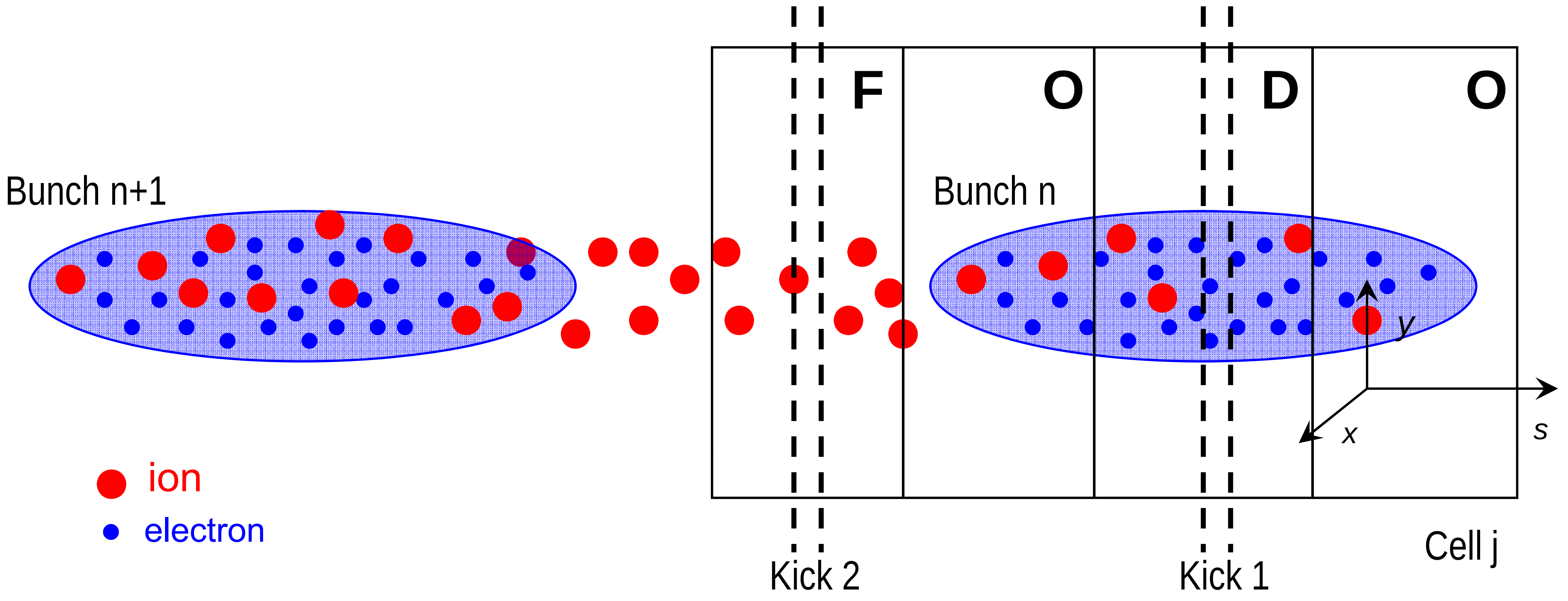
Using these formulae and some quick estimations, we can expect:

→ ~100 e-folding times in the ML for 10 nTorr

→ ~17 e-folding times in the TL for 1 nTorr

To study the fast ion instability in a transport line, we have developed ***FASTION***

- Multi-bunch code, ions and electrons are macro-particles
- Ions of an arbitrary number of species are created at each bunch passage and propagated through the train
- Line is made of a sequence of FODO cells, two kicks per FODO cell. Acceleration along the line can be included in a simplified manner.
- Electromagnetic interaction: the ions are kicked by the passing bunches and the bunch macro-particles feel the effect of the ion field



Required input file

⇒All the essential parameters are passed through a simple 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

They might change during the acceleration

The bunches can be accelerated through the line

Output files

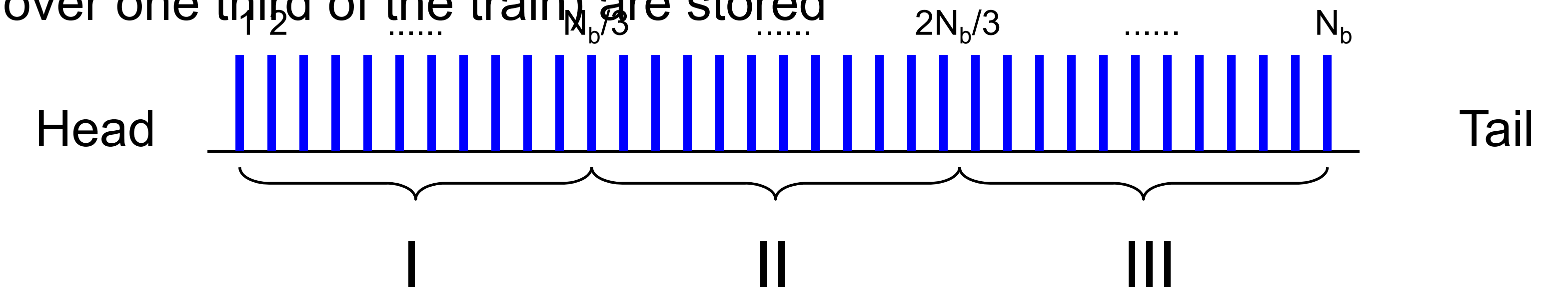
⇒ The code transports the bunch train through the line, generates the ions at each interaction and propagates them

✓ **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 Transport Line and Main Linac

⇒ We have carried out simulations of fast ion instability using the following parameters

⇒ Beam energy is 9 GeV in the TL and it is made to gradually increase from 9 GeV to 1.5 TeV in the ML. Length is 20 km.

⇒ Residual gas pressure is 1 nTorr for each species (also 10 nTorr considered for the ML). Only two species of ions have been considered (CO and H_2O)

⇒ Bunch population is 4×10^9 (3.7×10^9)

⇒ Bunch spacing is 667 ps (500)

⇒ Number of bunches (N_b) is 300 (270)

⇒ Normalized emittances are 680,10 nm (660,10)

Application to CLIC Transport Line

⇒ The ion distribution in the x direction as it develops while the N bunches are going through the interaction point

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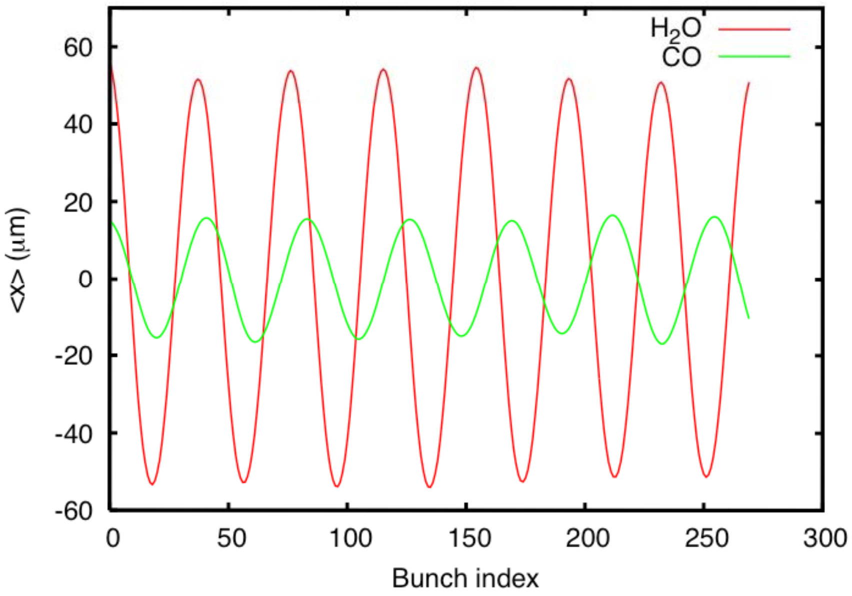
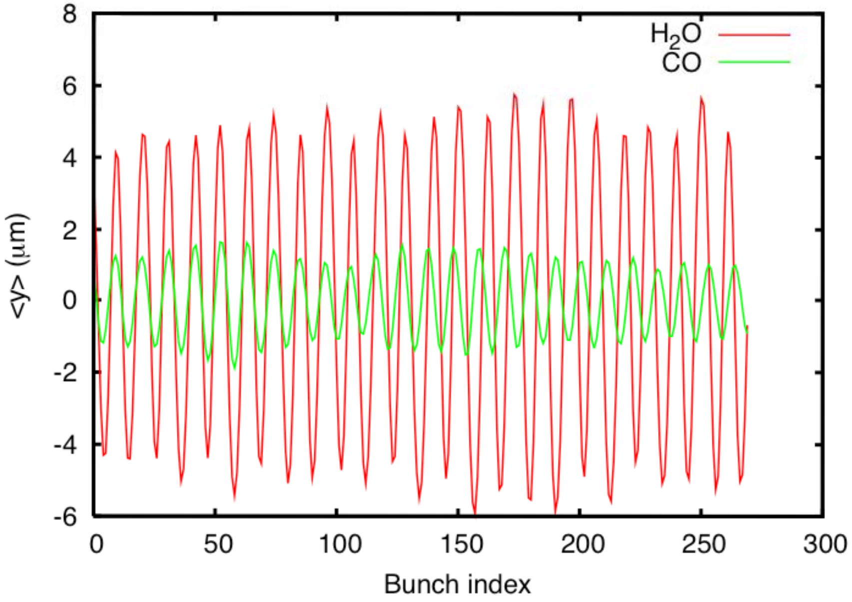
benötigt.

Application to CLIC Transport Line

⟹ **The motion of two sample ions (of two different species) show that they are trapped around the beam**





Application to CLIC Transport Line

$\Longrightarrow$ **A coherent instability in the vertical plane develops along the line**

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Application to CLIC Transport Line

⇒ **The instability in the vertical plane also causes emittance growth**

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Application to CLIC Transport Line

⇒ Using the new parameters for bunch population and spacing, there is still an instability that develops in the line

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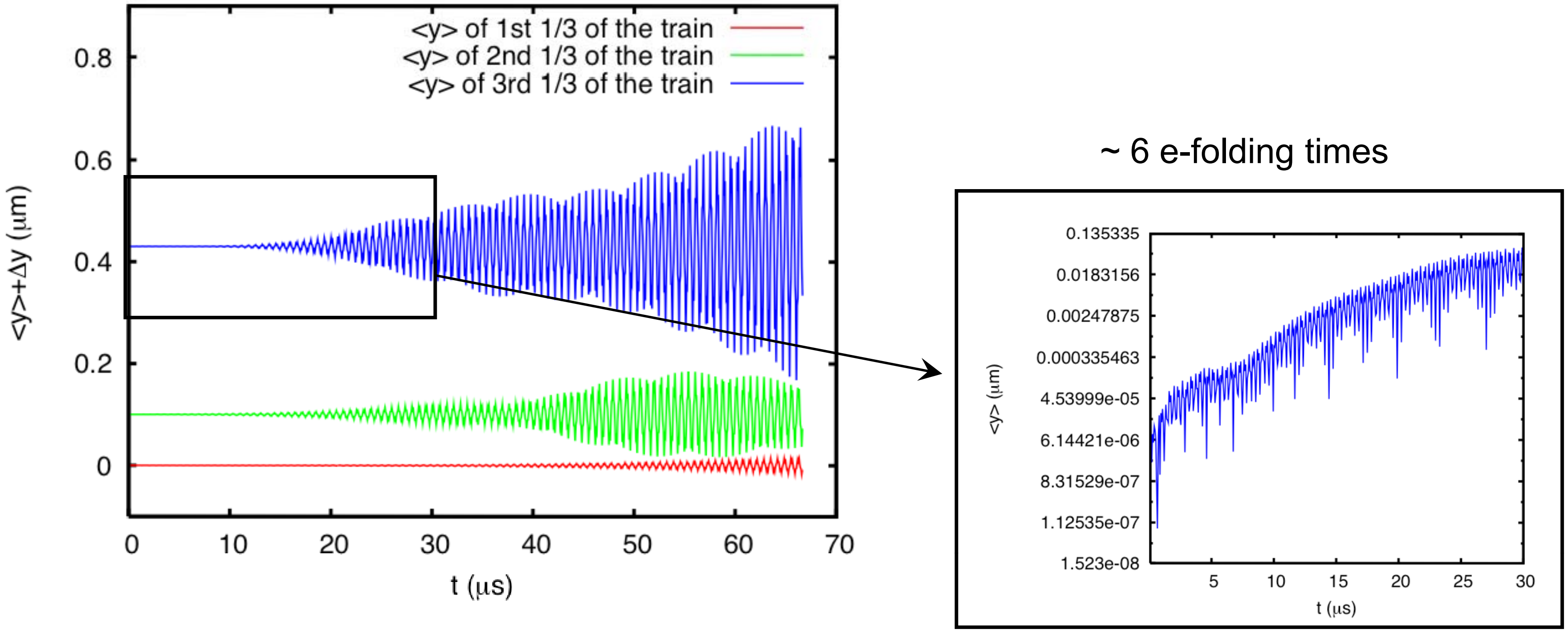
Application to CLIC Transport Line

⟹ **If we look at the time evolution of the instability at the head, middle and tail of the batch, we clearly see a strong growing coherent signal mainly affecting the last part of the train**



~ 6 e-folding times

Application to CLIC Main Linac

⇒ **In the ML there seems to be no instability if the gas pressure is 1 nTorr. But with 10 nTorr a very fast instability develops also along the ML**

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Application to CLIC Main Linac

⇒ ... with very fast emittance growth along the train!

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Conclusions and outlook

- A new code, ***FASTION***, has been developed to study numerically the fast ion instability of a bunch train along a transport line
  - It models the generation of ions and their interaction with a train of bunches going down a transport line
  - It can deal with an arbitrary number of different types of ions
  - It can include beam acceleration along the line
- The code has been applied to study possible **ion effects in the CLIC Transport Line and Main Linac**
  - 1 nTorr is enough to have a fast instability in the TL
  - The threshold of instability lies between 1 and 10 nTorr in the ML
- In the future several significant improvements are foreseen
  - Include the effect of external electric and magnetic fields on the ion motion
  - Include the effect of field ionization, which becomes very important in the last stages of the ML
  - Eventually, integrate the FASTION code as a **PLACET module**