Vacuum specifications in Linacs

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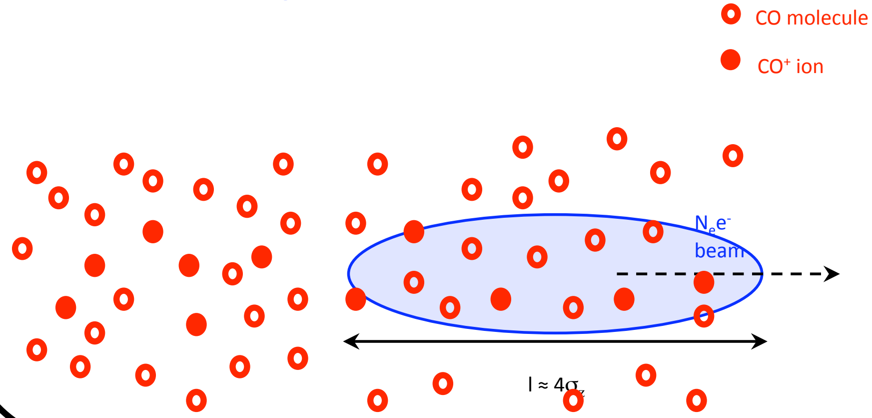
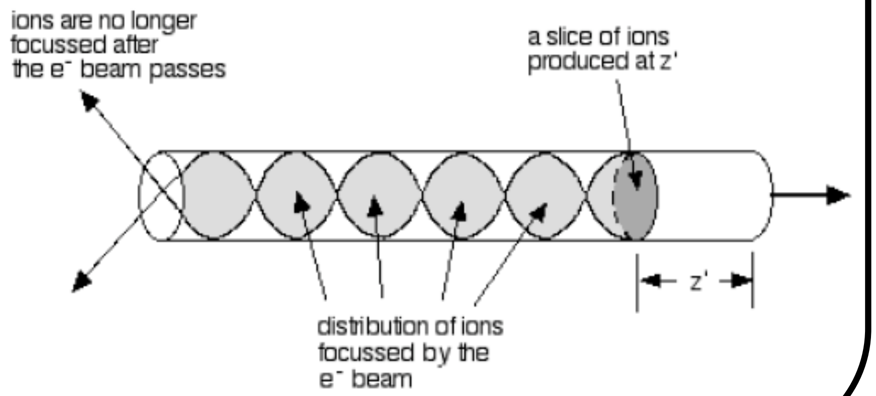
- Fast Ion Instability in Linacs and the simulation code FASTION
- The case of the CLIC Main Linac
  - Initial model
  - Field Ionization
- Outlook:
  - Improvement of the field ionization model
  - Study of the drive beam decelerator (FASTION module for PLACET)
- Summary

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

Ions: residual gas ionization



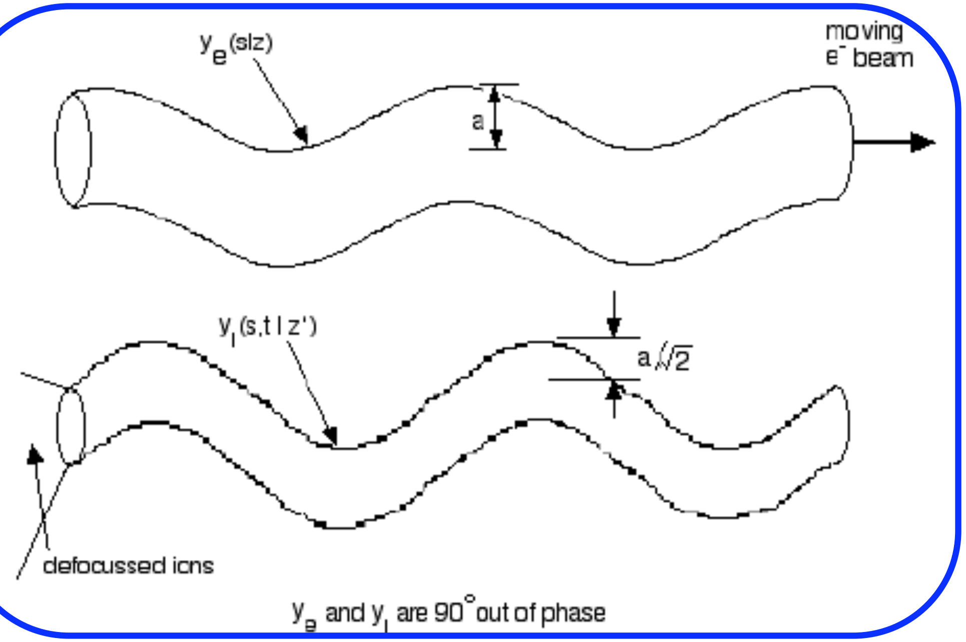


The ion cloud can affect the motion of the bunches

1) Tune shift along the bunch train

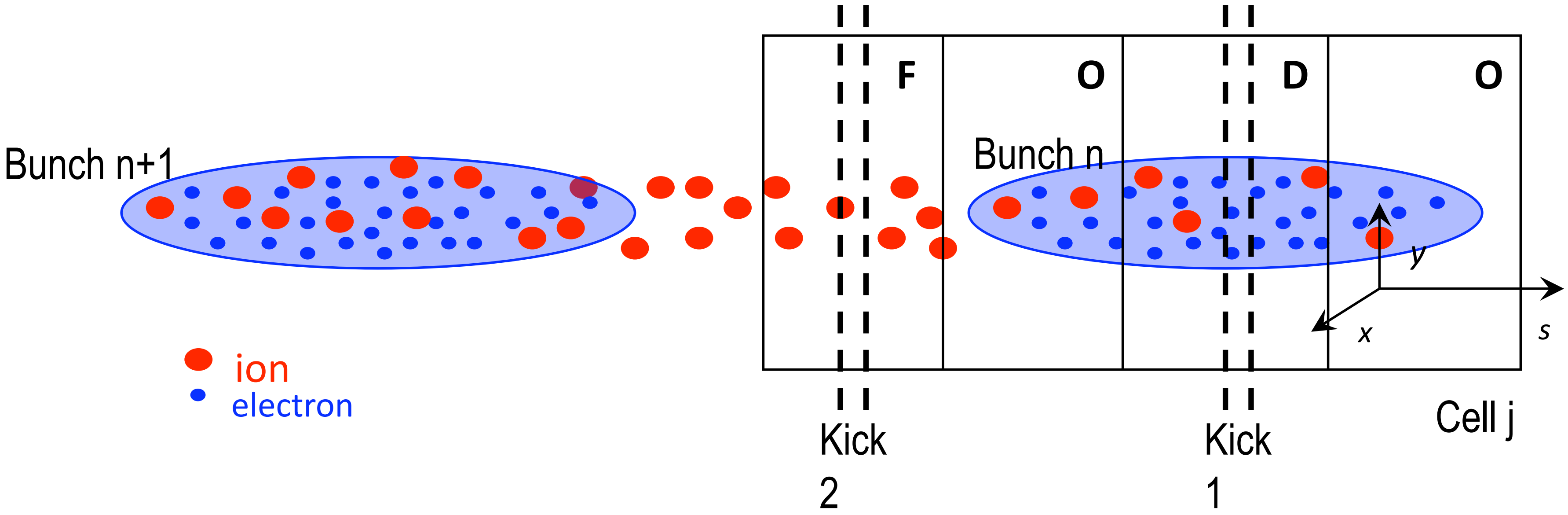
2) An unstable ion-electron coupled motion can be excited

Two-stream instability



FASTION (I)

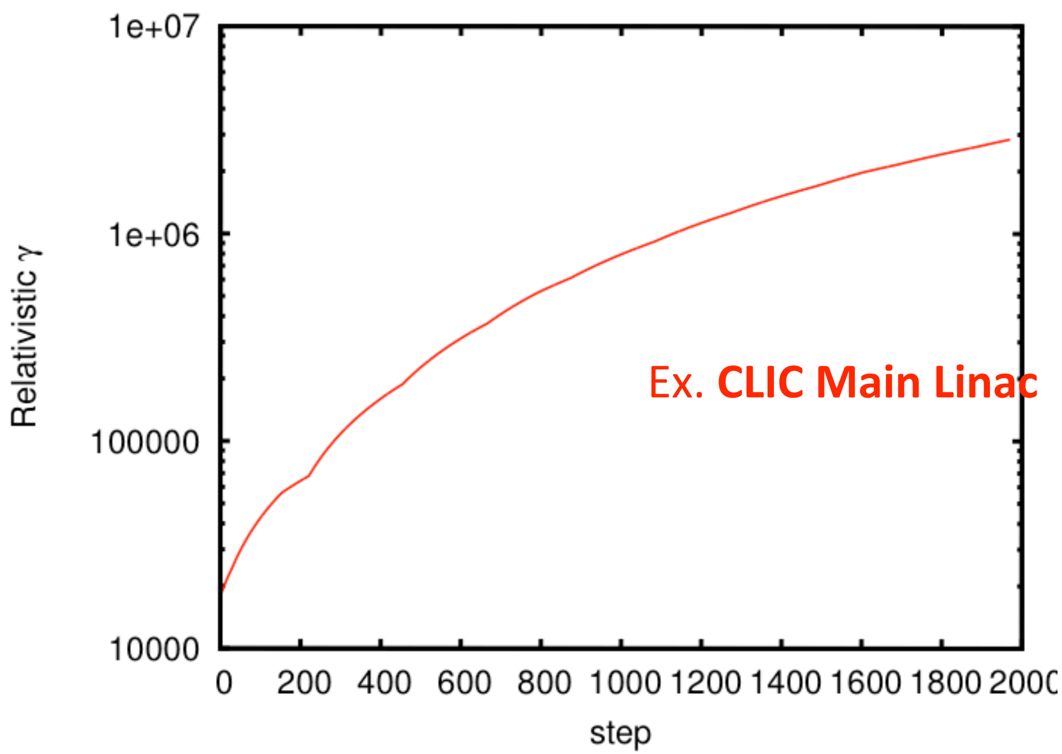
- **Multi-bunch** code, ions and electrons modeled as macro-particles
- Ions of an **arbitrary number of species** are created at each bunch passage and propagated through the train
- Line can be:
  - ✓ A simple **sequence of FODO cells**, with two kicks per FODO cell
  - ✓ Described through an **output *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)

Beam energy change along the line can be taken into account

- Initial and final energy are given through the standard input file and **a simple linear model** 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 are scaled 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.	CO and H_2O
Atomic_masses:	28. 18.	
Ionization_cross_sections_[MBarn]:	2. 2.	
Number_of_electrons_per_bunch:	4.0e+9	
Bunch_spacing_[ns]:	500.e-3	
Normalized_horizontal_emittance_(rms_value)_[nm]:	680.	
Normalized_vertical_emittance_(rms_value)_[nm]:	10.	
Bunch_length_(rms_value)_[ns]:	0.12e-3	
Load_external_lattice_file:	1	The lattice can be loaded from external file or is a sequence of FODOs
Number_of_FODOs:	500	
FODO_Length_[m]:	40.	
Phase_advance_per_cell_[degrees]:	70.	

Application to CLIC Main Linac

⇒ **We have carried out simulations of fast ion instability using the lattice file from PLACET and the following parameters**

Table 1: Parameters used in our study: the main linac

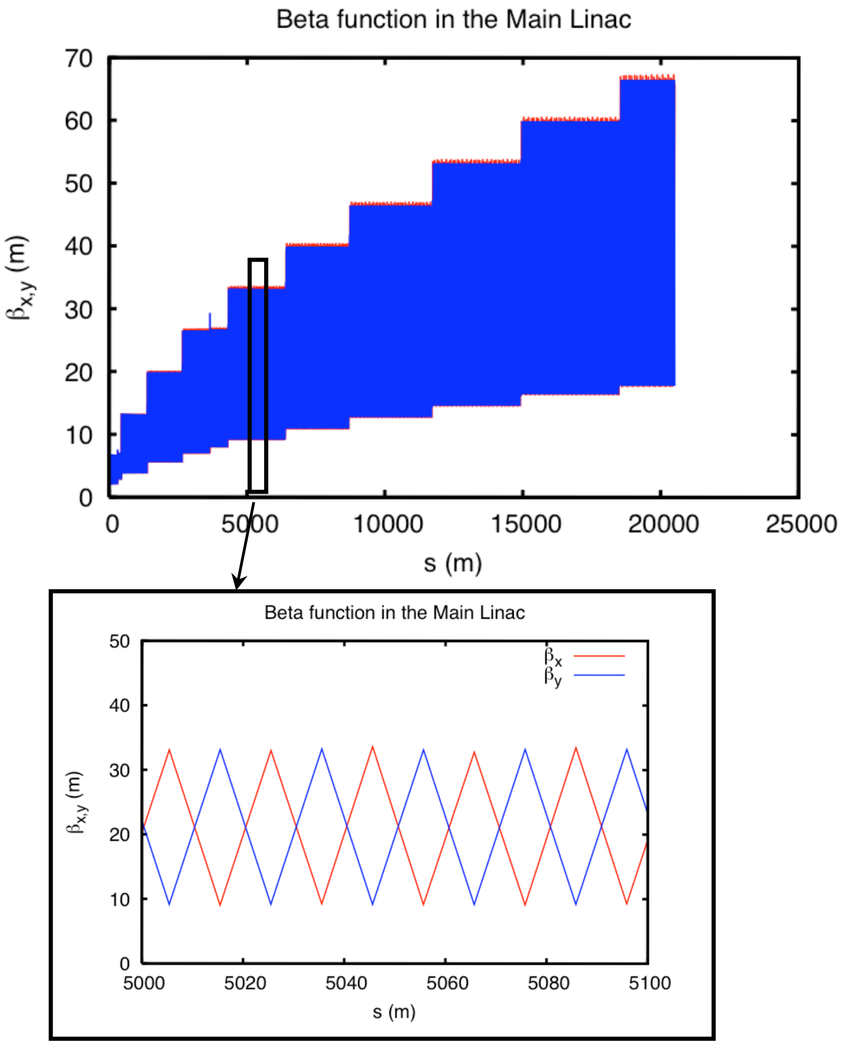
Energy	p_0 (GeV)	9 to 1500
Norm. transv. emitt.	$\epsilon_{x,y}$ (nm)	680, 10
Bunch length	σ_z (ps)	0.15
Bunch spacing	ΔT_b (ns)	0.5
Bunch population	N	4×10^9
Number of bunches	N_b	311
Gas pressure	$P_{H_2O,CO}$ (nTorr)	10 to 50
Ioniz. cross sect.	$\sigma_{H_2O,CO}$ (MBarn)	2, 2
Threshold E	E_{max} (GV/m)	5, 10, 100
Length	L (km)	20.5

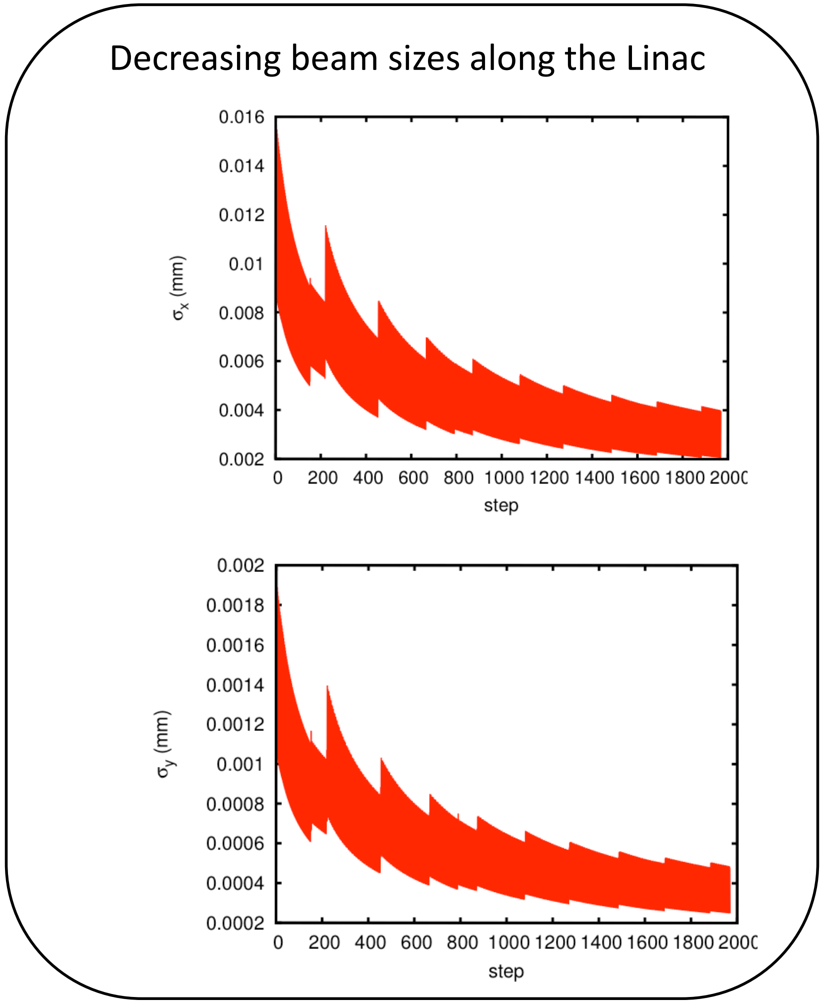
⇒ **In the initial model, ions were only generated through scattering ionization**

$$\frac{dN_{ion}}{ds} = kN_b \sum_n \sigma_n^{ion} P_n$$

Application to CLIC Main Linac (II)

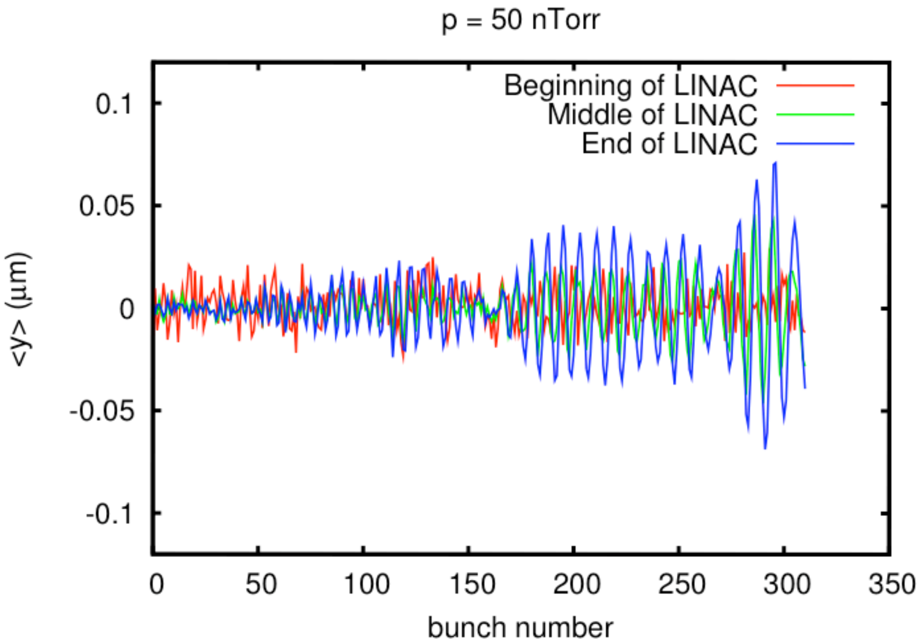
Through the twiss.dat file, both beta functions and beam energy at different locations in the main linac are passed to the FASTION code and used for tracking with the generated ions.

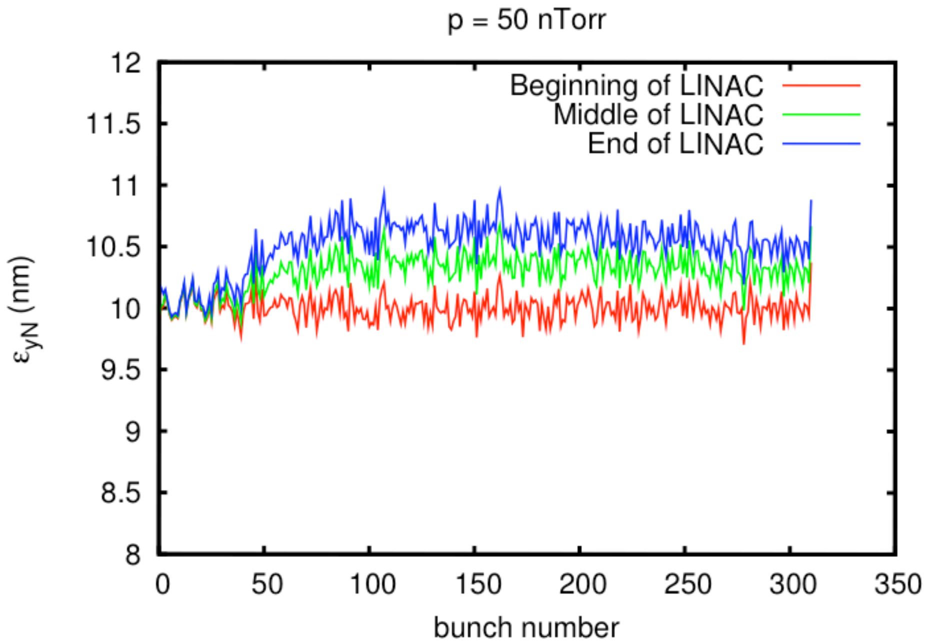




Application to CLIC Main Linac (III)

The outcome of the simulation is that the beam is found to become unstable with vacuum pressures above 50nTorr
⇒ Both a coherent centroid motion and a small incoherent emittance growth appear along the line





Application to CLIC Main Linac (IV)

⇒ **However, when the beam becomes very small, field ionization can become important.... First model implemented:**

⇒ The beam sizes in the Main Linac decrease to minimum values of about 2 μm in H and 0.2 μm in V toward the end of the linac. The peak electric field can easily become larger than a critical value (tens, hundreds of GV/m)

⇒ When the field exceeds the critical value, the full volume occupied by the beam is assumed to be ionized in our simplified model.

⇒ The second (and all successive) bunches will only be able to ionize the molecules that diffuse in the volume swept by the bunch during the time between two bunch passages

⇒ At each step of the Linac, FASTION runs a scan on $E_{x,y}$(x,y) varying (x,y) and stops if it finds a point in which the electric field is larger than a set threshold value (e.g., 10 GV/m).

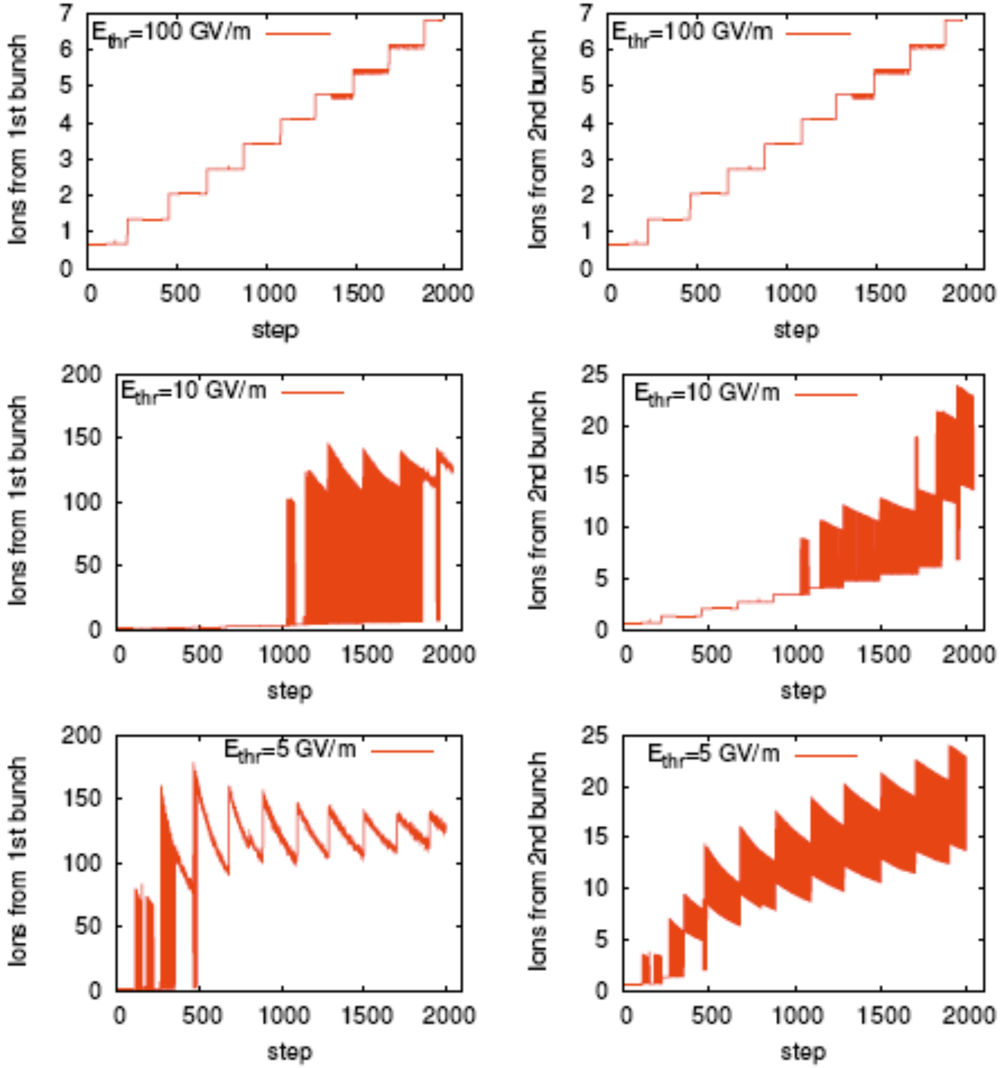
⇒ Ions keep being generated in the area of the bunch cross section, but their charges are re-calculated according to the generation from field ionization (i.e., full ionization of the volume swept by the bunch for the first bunch and ionization of all the residual gas molecules diffusing into the ionized volume in the interbunch gap for all the following bunches of the train.

Application to CLIC Main Linac (V)

⇒ **Simulated ionization rates**

Ionization rates plotted along the Linac for three different values of E-threshold for field ionization. First bunch ionization in the left plots, second bunch ionization in the right plots.

Scattering ionization rates increase because Δs increases along the Main Linac

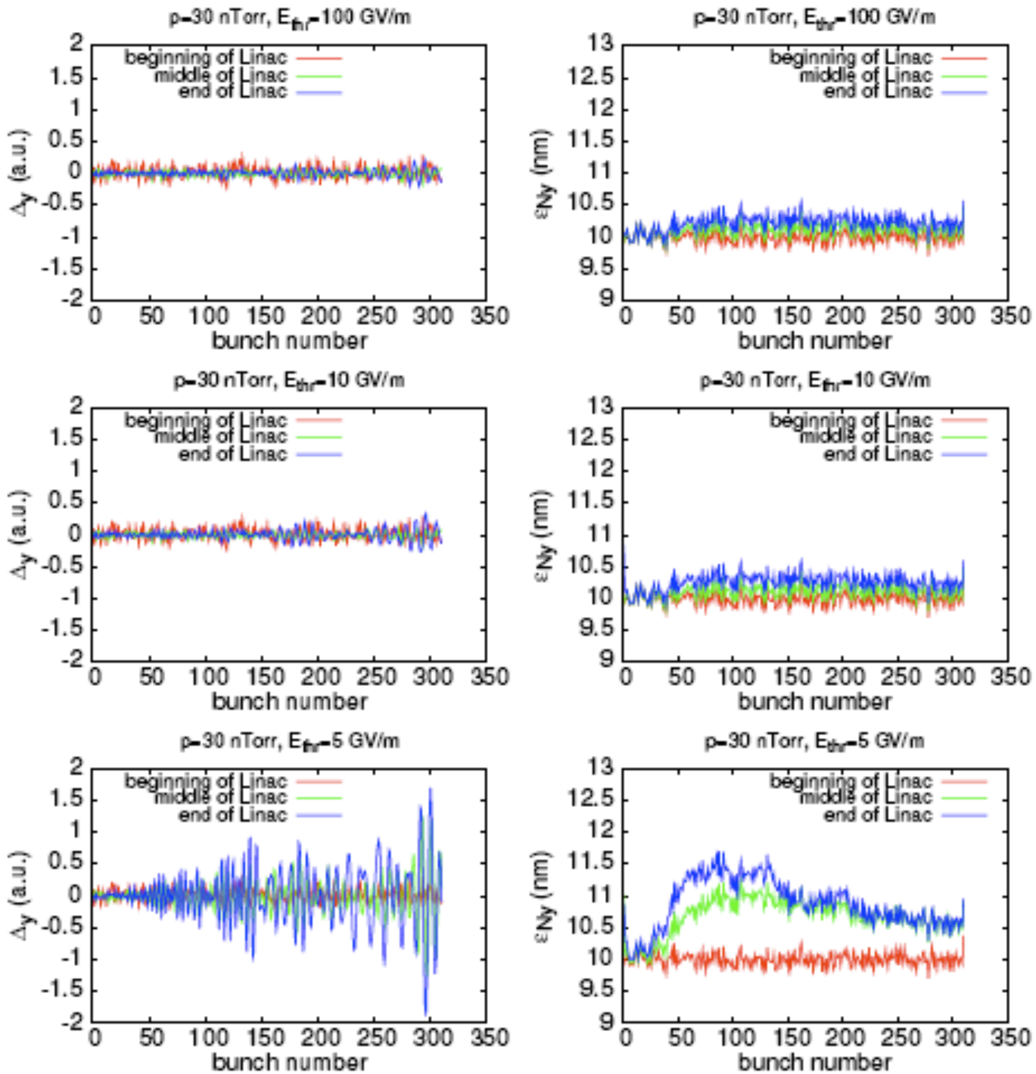


Application to CLIC Main Linac (VI)

⇒ **Instability**

Beam becomes unstable with p=30 nTorr only when the threshold electric field for field ionization is set to 5 GV/m, however the effect starts to become visible for 10 GV/m

The impact of field ionization is probably less important when it occurs in regions where the ion trapping is weaker.



Future work (I)

⇒ **What we should improve in the present model of field ionization....**

⇒ Specify the **threshold value of the critical electric field** in a more realistic way

⇒ When the beam becomes smaller, the number of ions produced by field ionization decreases because the volume swept by the beam decreases. In reality, **the ionized volume should be determined by the region in which the electric field gets higher than the threshold value**, therefore

- could be transversely larger than the beam cross section, as it is defined by σ_x than by σ_y
- should not decrease with the beam becoming smaller if the beam charge does not change

⇒ Ions produced by second and subsequent bunches depend **on the number of molecules that diffuse into the region swept by the beam during the time between two bunch passages**. A more realistic distribution could be assumed, instead of a uniform distribution.

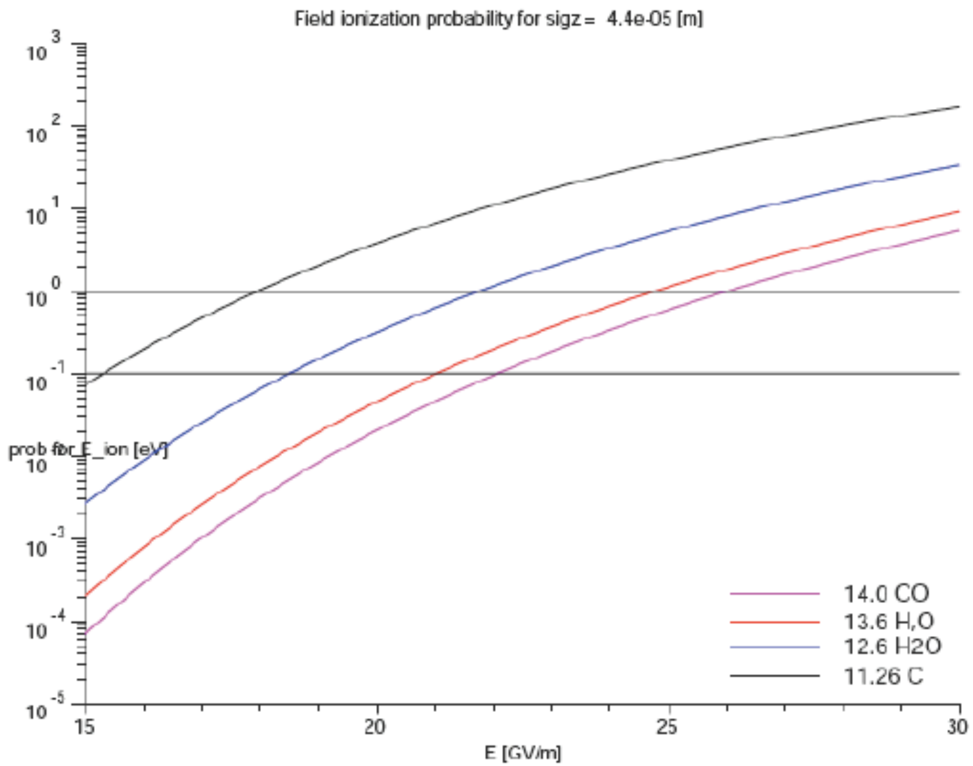
Future work (II)

⇒ **Critical electric field**

Ionisation probability for one bunch

Ref : D.L. Bruhwiler, Phys. Plasma, Vol 10, p2022, 2003

$$p_{\text{bunch}} = \frac{2\sigma_z}{c} \times p(\xi, E) = 7.3\,10^{-14} \times p(\xi, E)$$

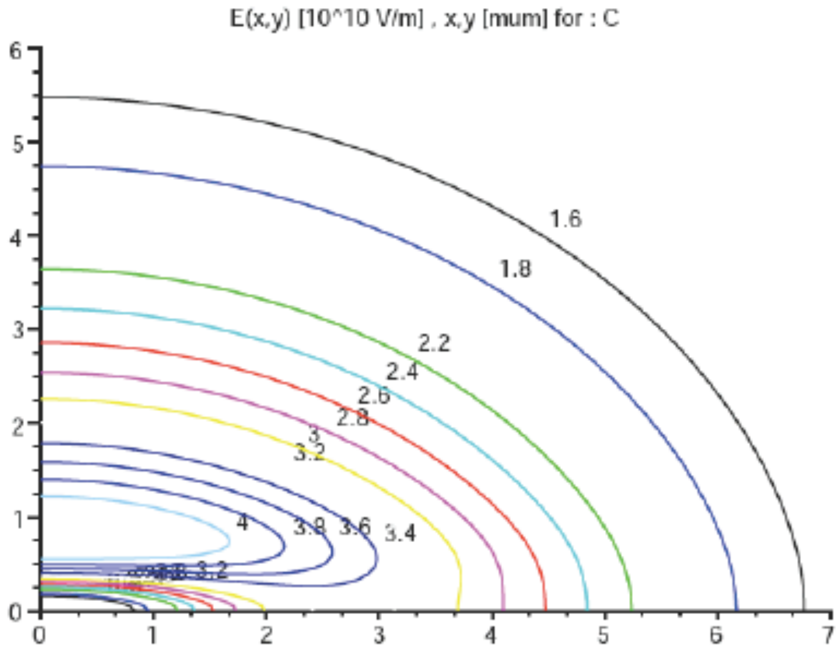


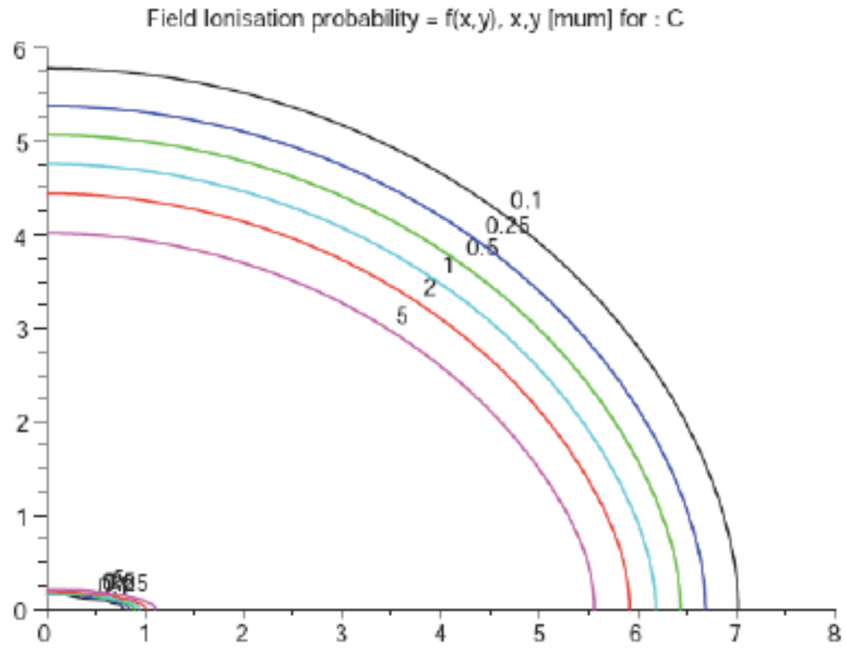
Future work (III)

⇒ **Critical electric field**

Field and probability maps

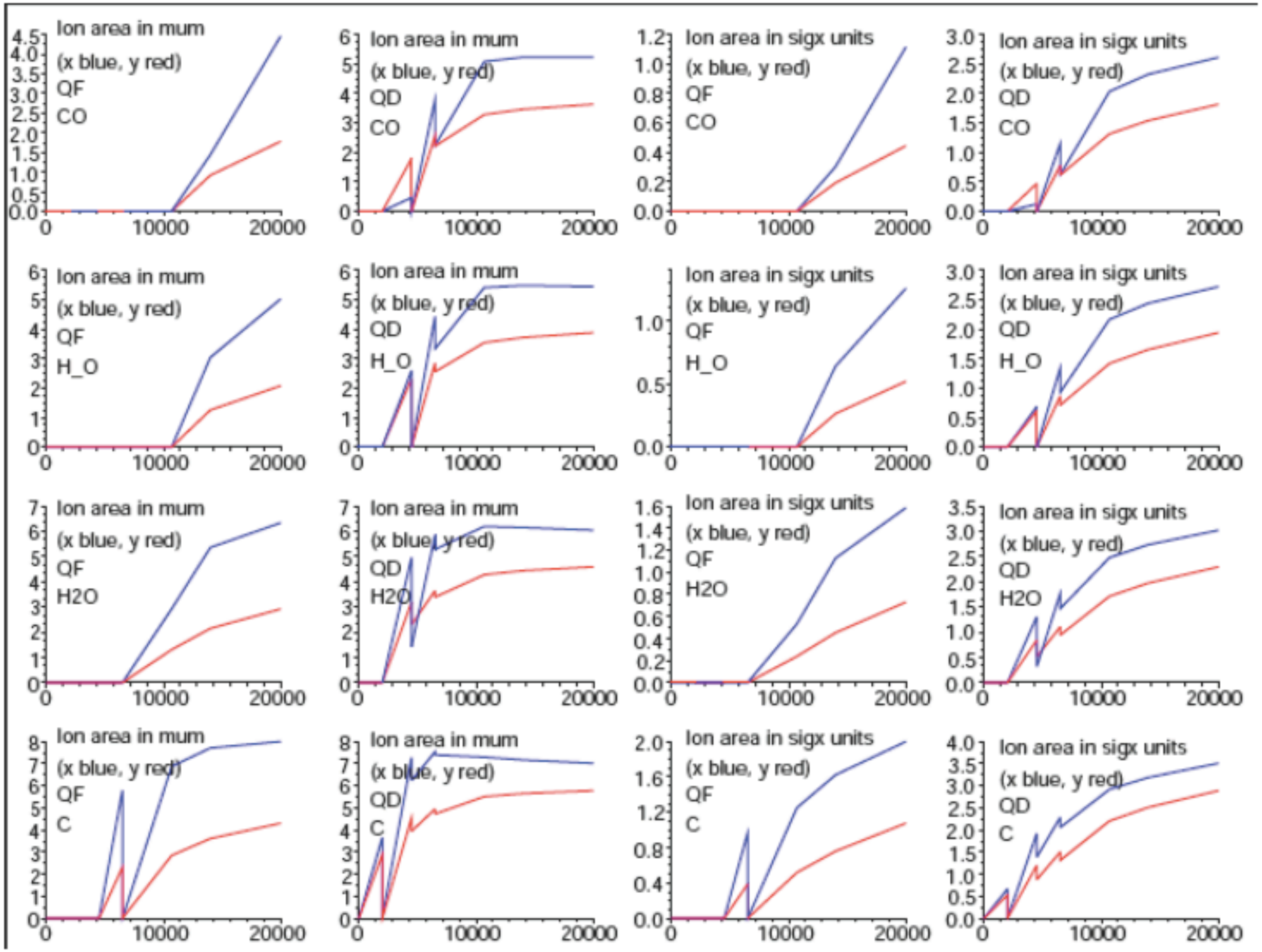
Here : $\sigma_x = 2\ \mu \quad \sigma_y = 0.4\ \mu$





Future work (IV)

Fully ionised area along the ML for p=0.1



Future work (V)

⇒ Steps of Jean-Bernard's recipe for future simulations......

- Averaging QF & QD:
  - Fully ionised in ellipse a = 7 mum , b = 4 mum
  - Simplify to rectangle of equal perimeter : Δx = 5.6 mum, Δy = 3.2 mum
  - In the longitudinal range s = [4 km, 20 km]
- Gas density $\rho_0 = \rho$ (1nTorr) = 3.5 10^{13} mol/m^3
  - 1st bunch ionises n1 = $\pi ab\rho_0$ = 3.1 10^3 mol/m
- Refill between 2 bunches (δt = 0.15m/c = 5 10^{-10} s)
  - δn = 105 mol go in ion. area with $\langle \delta r_{in} \rangle = 10^{-7}$ m
  - → origin at the edge of the rectangle is OK
- Total refill (last bunch) :
  - $n_{300} = n_1 + 312\delta n$ = 3.28 10^4 ion/m (note : n_{312}/n = 11.6 'refill')
  - Speed spectrum : close to thermal spectrum but only v<0 (pointing inside)

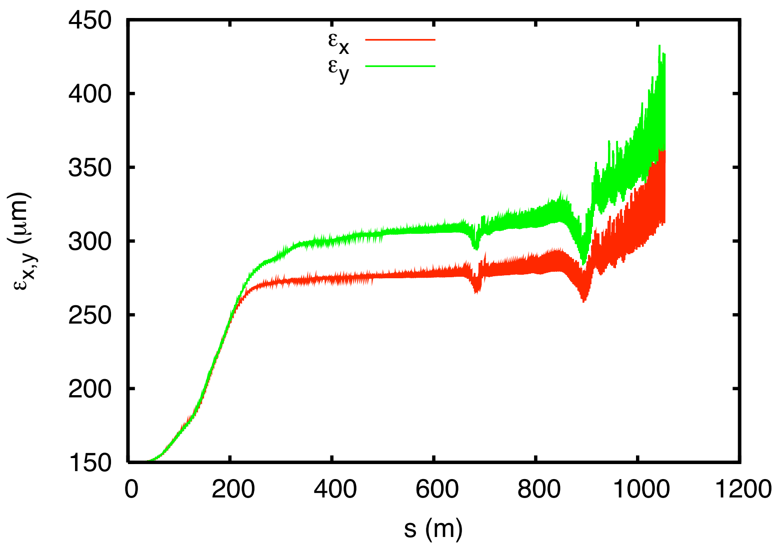
Future work (VI)

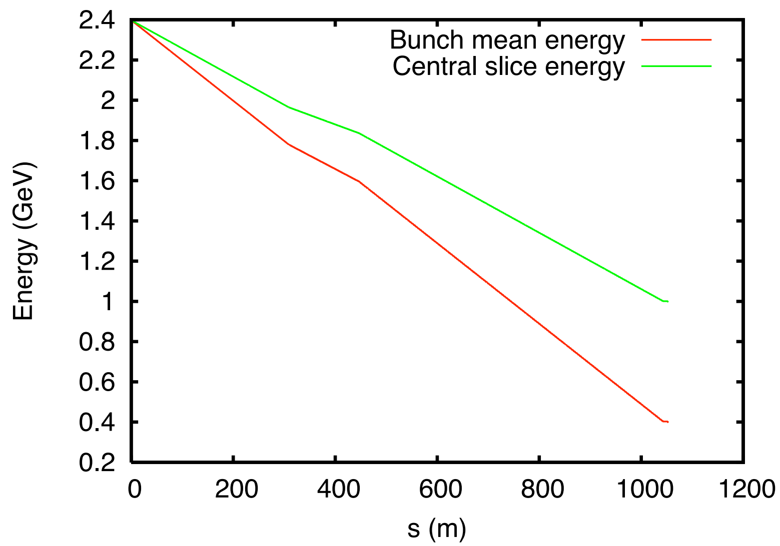
⇒ **Study of the fast ion instability for the drive beam.** Some new ingredients come into play

✓ as the beam is decelerated, its emittance grows (additional input file emit.dat, but lack of self-consistency)

✓ during deceleration a large energy spread is generated across the bunch (seen for instance in the difference between the energy of the central slice and the bunch energy averaged over the whole bunch)

✓ for correct tracking, we believe the best option is to include FASTION into PLACET as an independent module (B. Dalena)





Summary

- The fast ion instability was studied for the CLIC Main Linac using the **FASTION** code (previously developed for the transfer line)
- Including only scattering ionization in the model, the required pressure in the Main Linac is **10 nTorr**
- Extending the model to include field ionization did not change dramatically this picture, as long as full ionization from a peak electric field of 10 GV/m is applied only to the volume swept by the beam
- However, a **more accurate calculation** shows that:
  - Critical electric fields for which the field ionization probability becomes 0.1 (i.e. it takes ten bunches to ionize the full volume) are around 20 GV/m
  - The ionized area is much larger than the beam cross section
  - Field ionization affects a large fraction of the Linac
  - The new model needs to be implemented into FASTION following a simplified conservative recipe. **As a result, the vacuum tolerance could then become much lower than presently specified !!**
- For the study of the fast ion instability in the drive beam decelerator, **implementation of a FASTION module into PLACET** is necessary