Sources of halo and beam losses in a high intensity hadron linac

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Sources of emittance growth, halo or losses

- Bad design
- Mismatch
- Emittance exchange
- Interactions with residual gas
  - Scattering on Residual gas
  - Charge exchange
  - Space-charge compensation
- Magnetic stripping
- Linac errors

Bad design

Some basic rules have to be respected for a good linac

- Keep the phase advance per lattice lower than 90°.
  Resonance with structure + envelope instability
  Large Halo formation

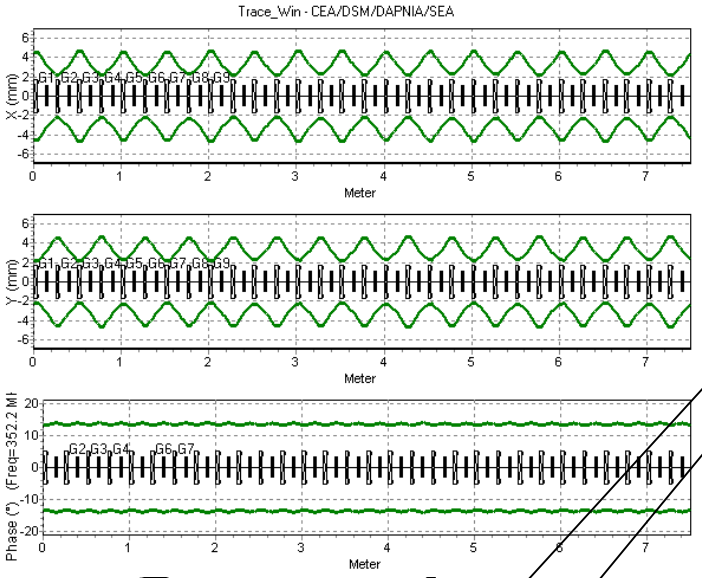
- Keep continuous the phase advance per meter at transitions.
  Change of beam equilibrium in space-charge
  Small emittance growth + current dependent matching

- Keep as much as possible the same lattice scheme.
  Change of beam equilibrium in space-charge
  Small emittance growth + current dependent matching

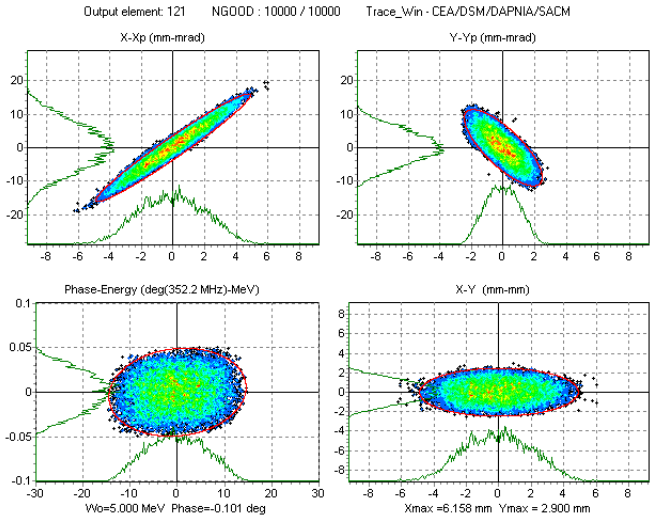
RMS match the beam at transitions.

Avoid crossing of longitudinal and transverse phase advance curves.

Good design

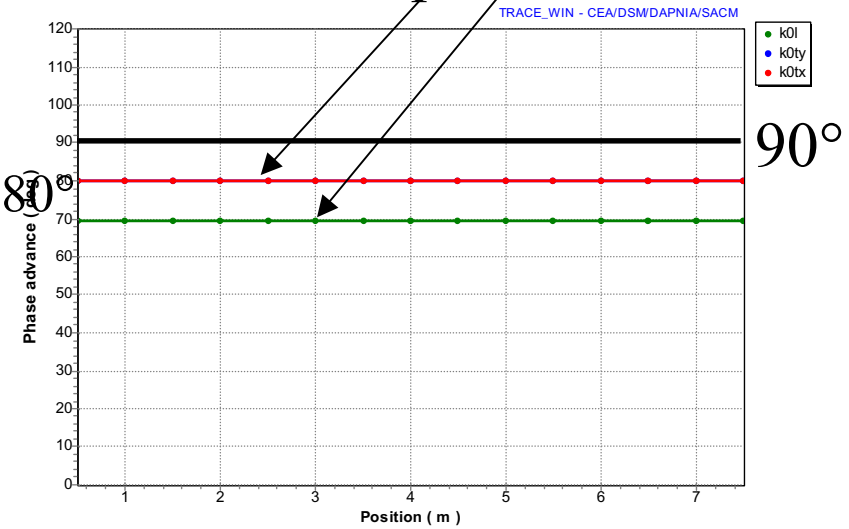


- FODO channel
- 0.5-0.6 tune depression
- WB matched input distribution
- 80° trans phase adv.
- 70° long phase adv.



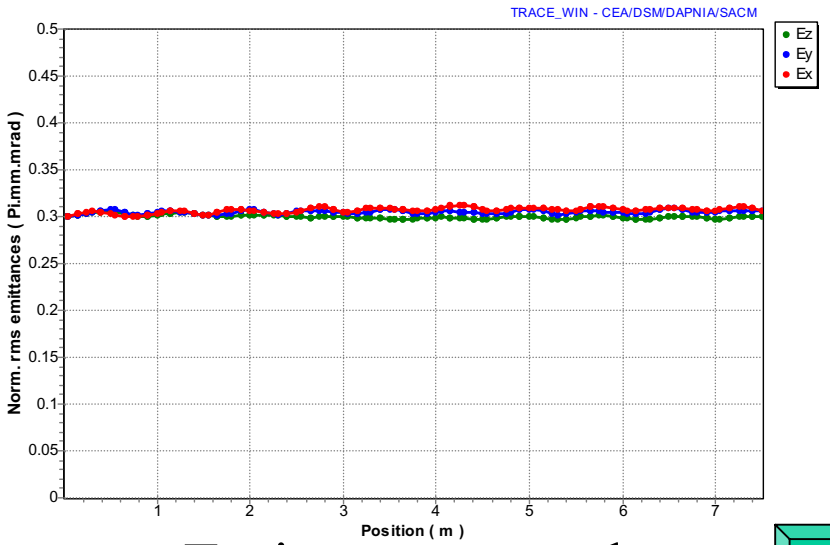
Beam envelopes

Output phase-space distrib.



90°

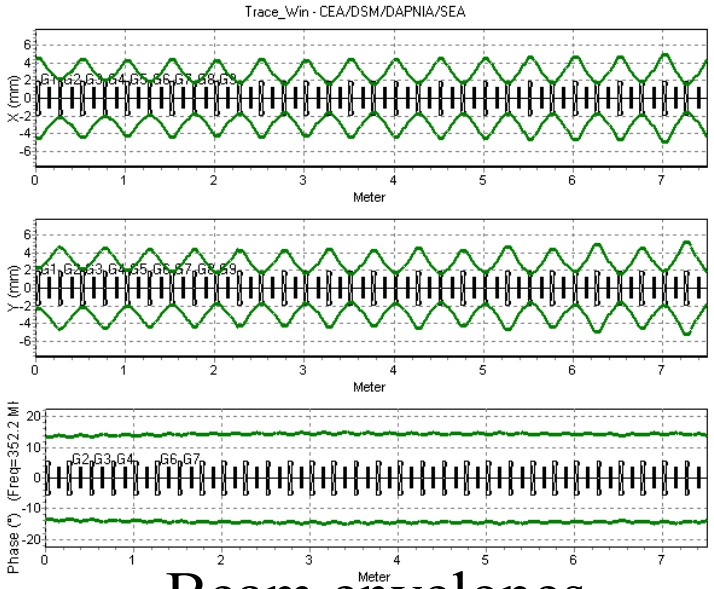
80°



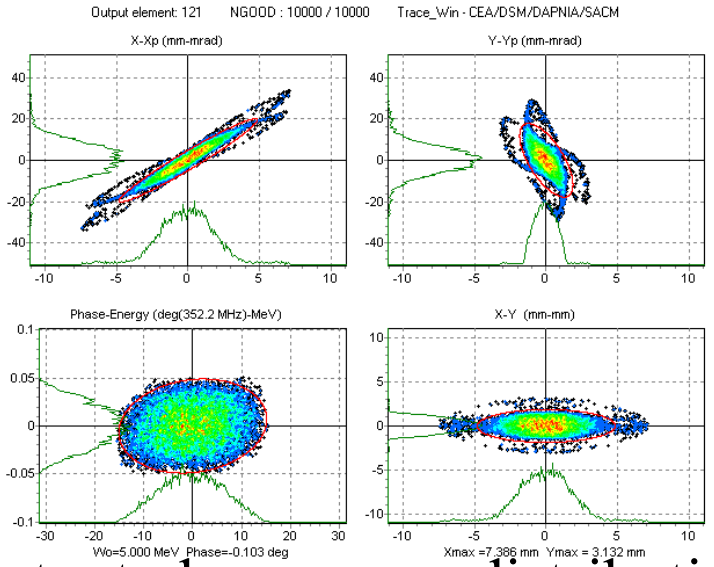
Phase advance

Emittance growth

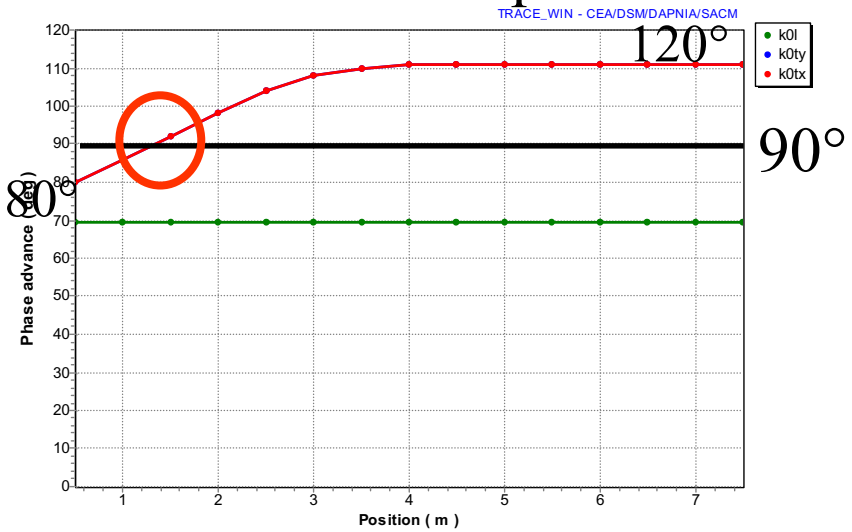
Phase advance higher than 90°



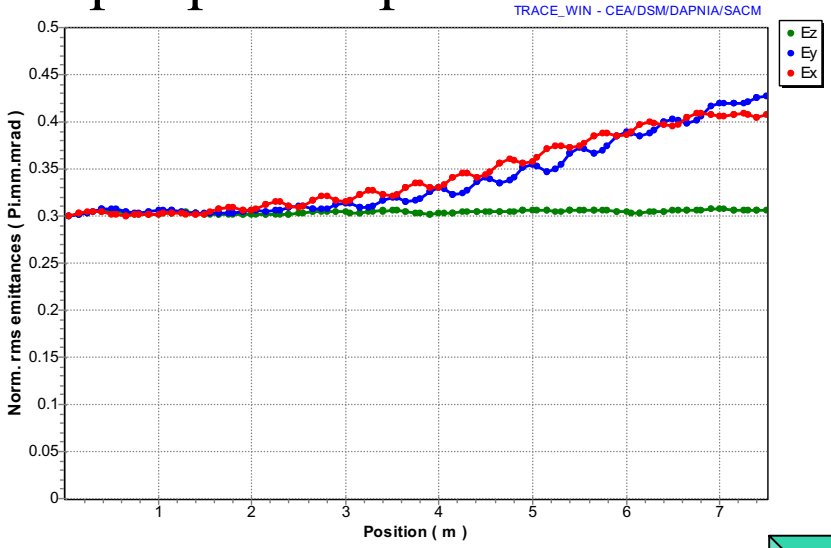
Beam envelopes



Output phase-space distribution



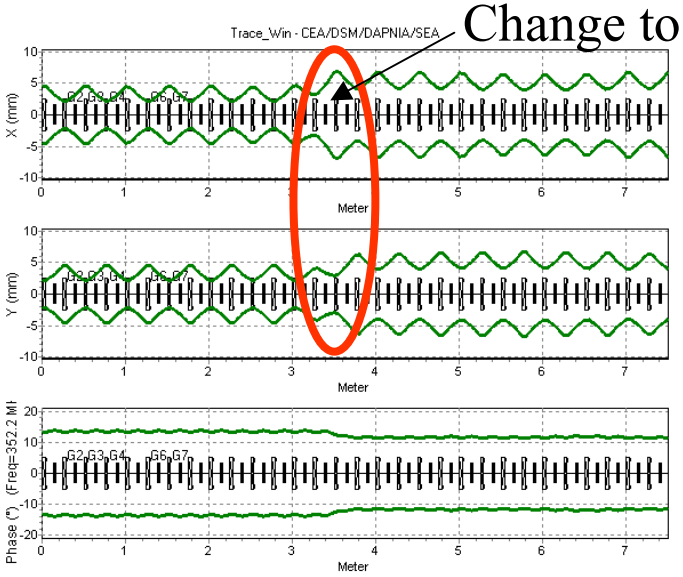
Phase advance



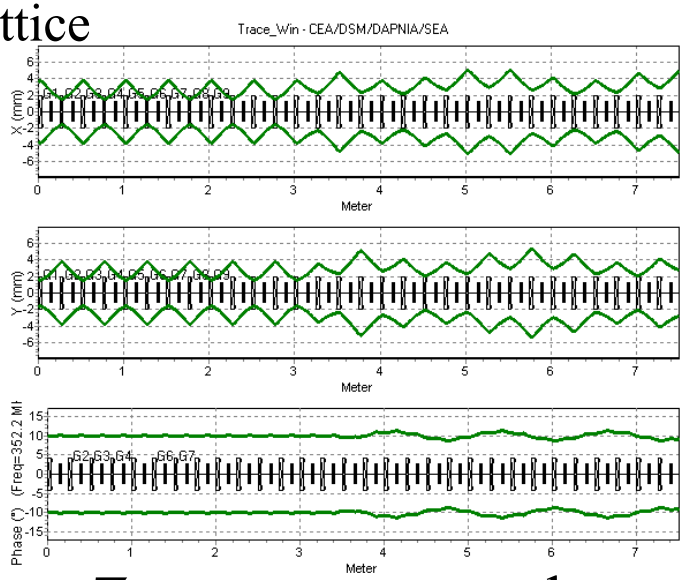
Emittance growth

Phase advance not continuous at transition

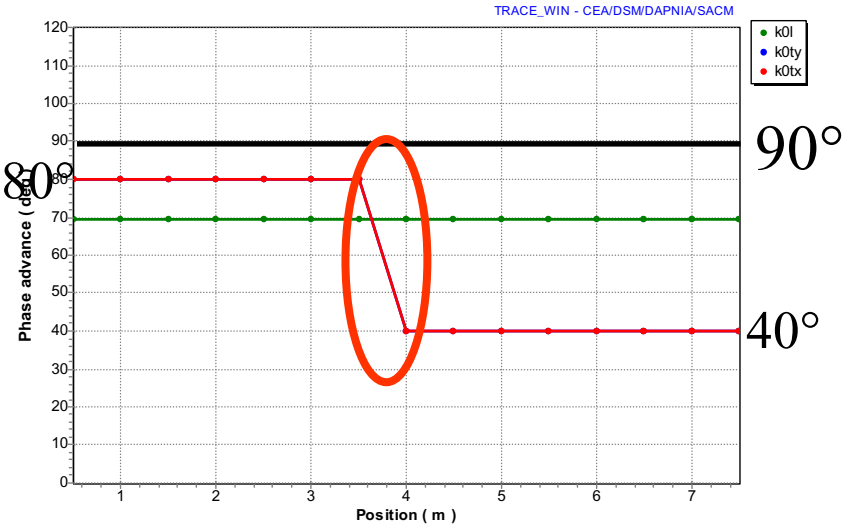
Change to doublet lattice



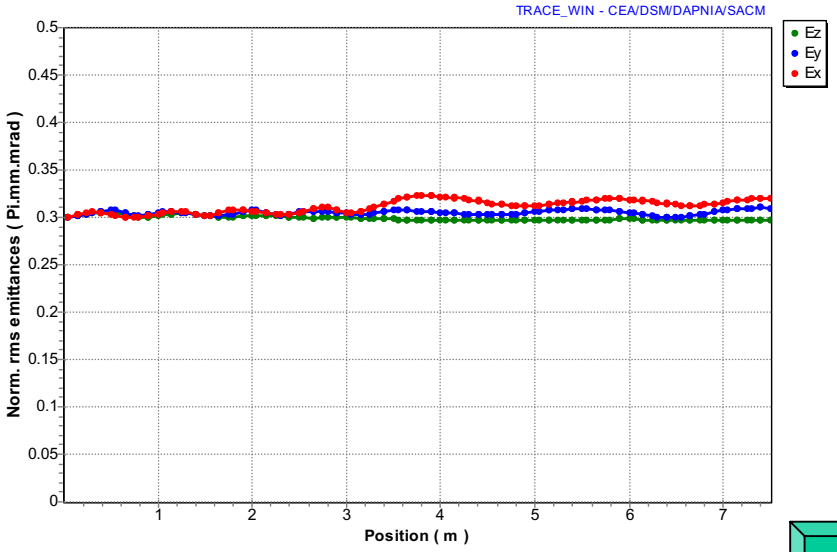
Beam envelopes



Zero current envelopes

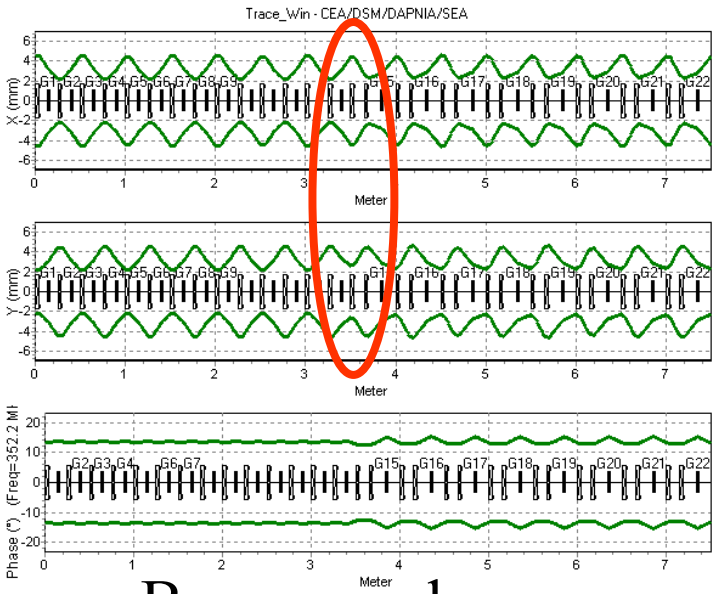


Phase advance

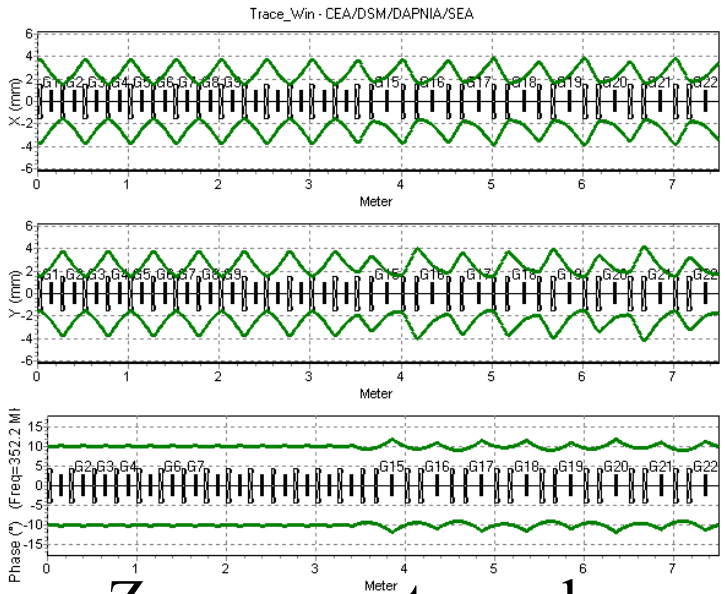


Emittance growth

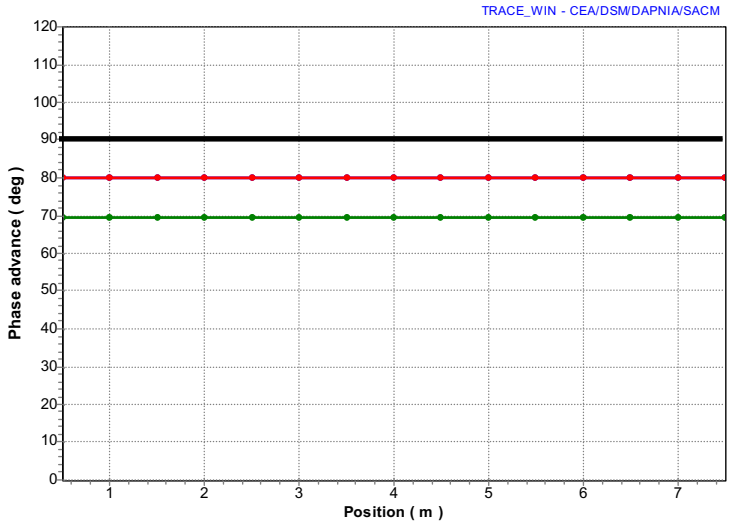
Change of focusing lattice



Beam envelopes

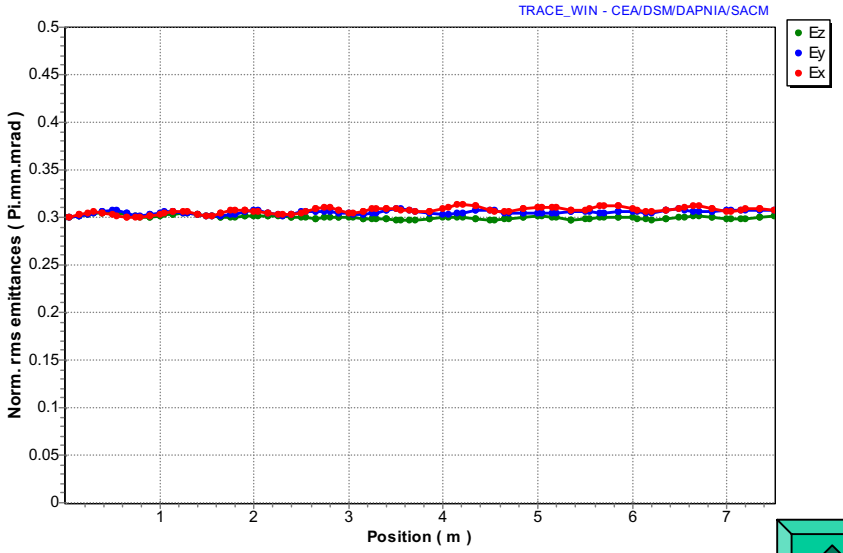


Zero current envelopes



90°

Phase advance



Emittance growth

Nicolas Pichoff, HB 2002

Mismatch

Two phenomena :

- Filamentation
- Resonnance with mismatch modes
- Experimental measurements at Saclay

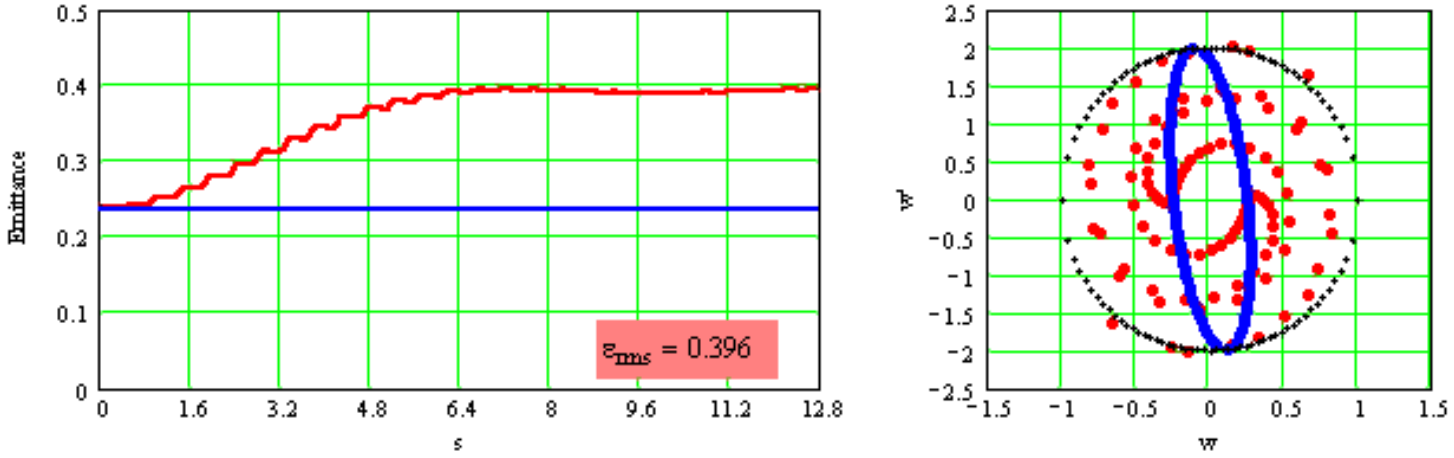
Mismatch-Filamentation

Non linear force : Particles do not oscillate with the same period

Space-charge : The largest the amplitude, the faster the oscillation.

Time scale : $Z \approx \frac{1}{2 \cdot (1-\eta)} \cdot Z_0$ Z_0, the zero current period

Extension : Mismatch parameter *M*



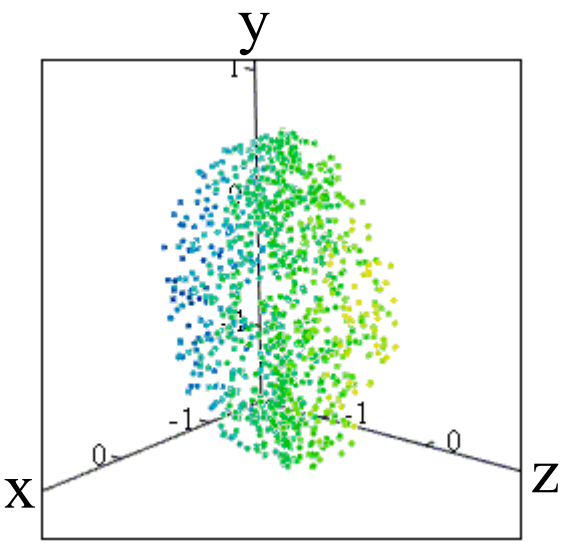
Linear force Non-linear force (space-charge)

Mismatched modes

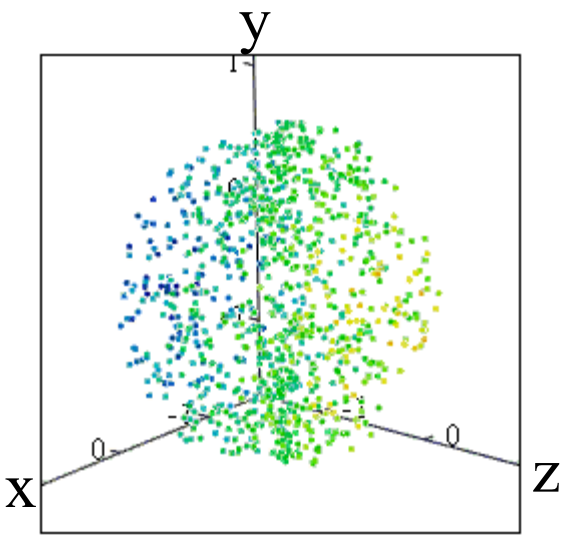
Matched beam : Beam core oscillation with same period as external focusing

Mimatched bunched beam : Beam core oscillation with 3 other frequencies.

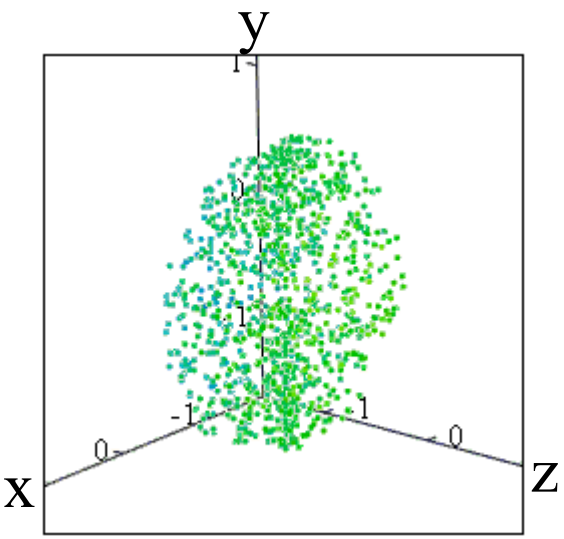
$\Rightarrow$ ***the mismatch modes***



Quadrupole mode



High frequency
breathing mode



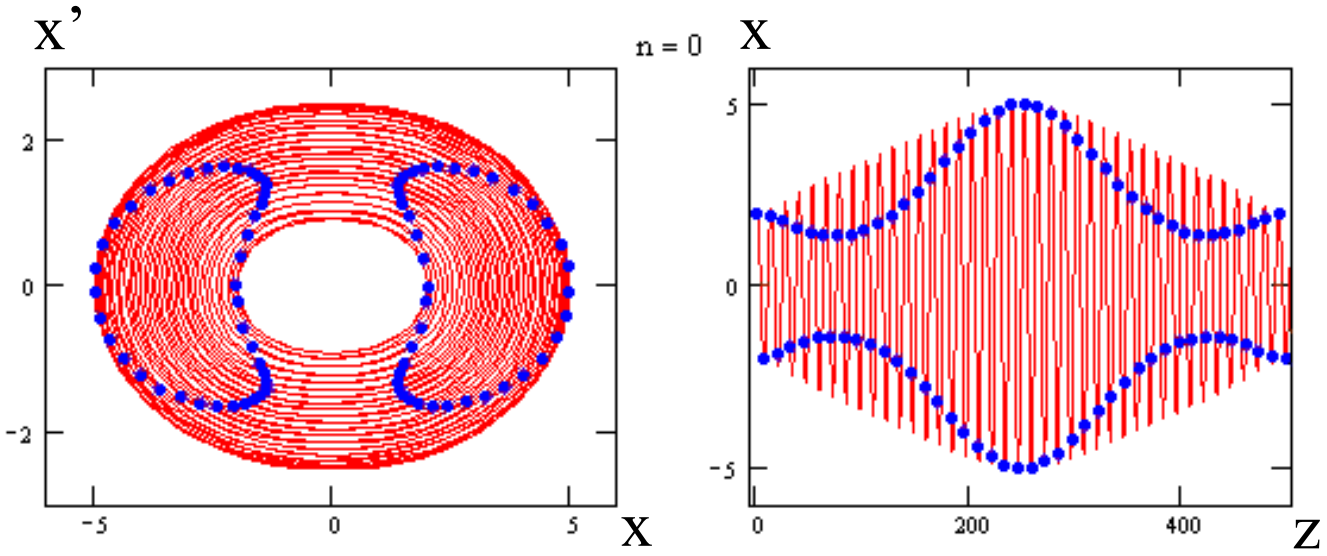
Low frequency
breathing mode

Resonance

Particules oscillating with a period Z_p that is a multiple of a mismatch mode Z_m.

$\Rightarrow$ **Modulation of amplitude**

Exemple : Mismatch: M=30%; Depress tune: η=70%; Z_p/Z_m=1.92



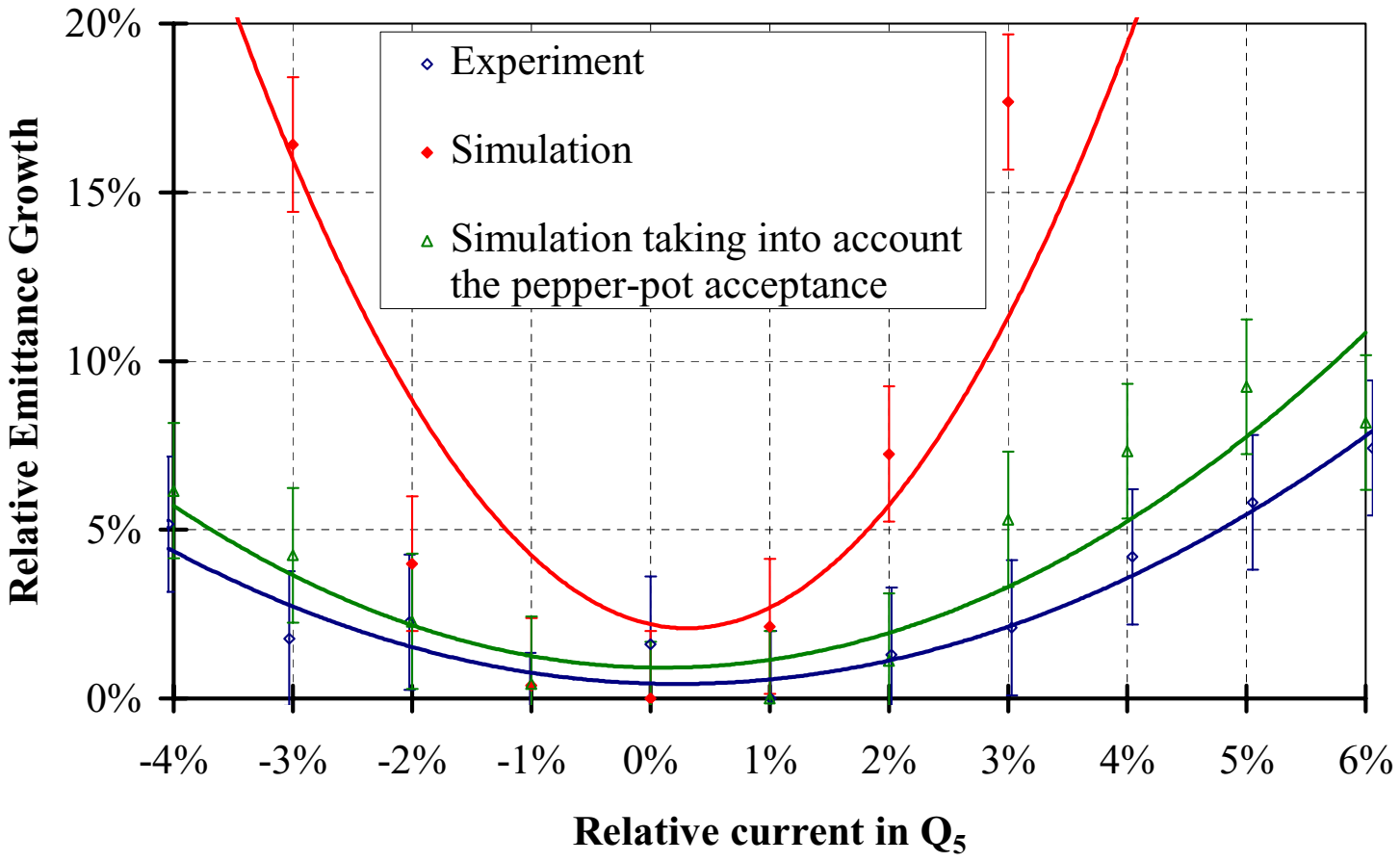
Particle trajectory Poincaré section

Time scale : Z = A few Z_0 Z_0, the zero current period

Extension : Much high than the mismatch parameter >> M

Experimental measurement at Saclay

Measurement of space charge-dynamics effects in a FODO channel,
N. Pichoff et al., EPAC98

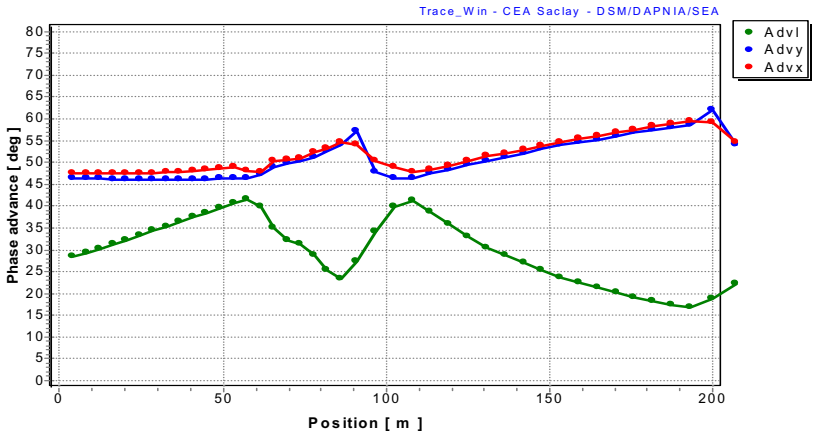


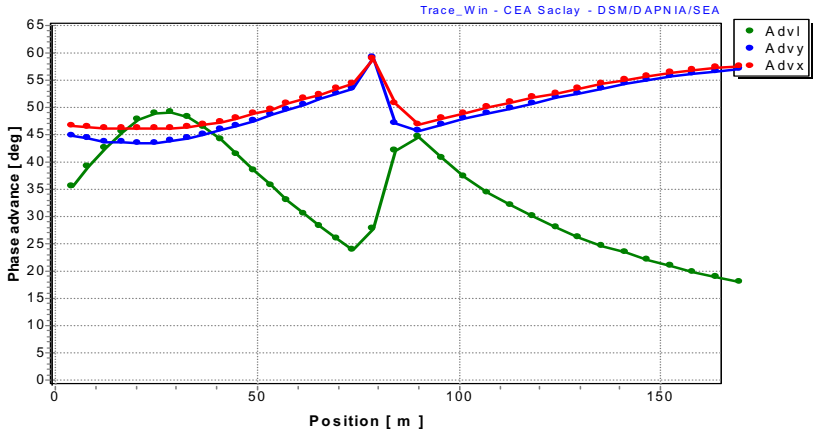
And now at LANL.

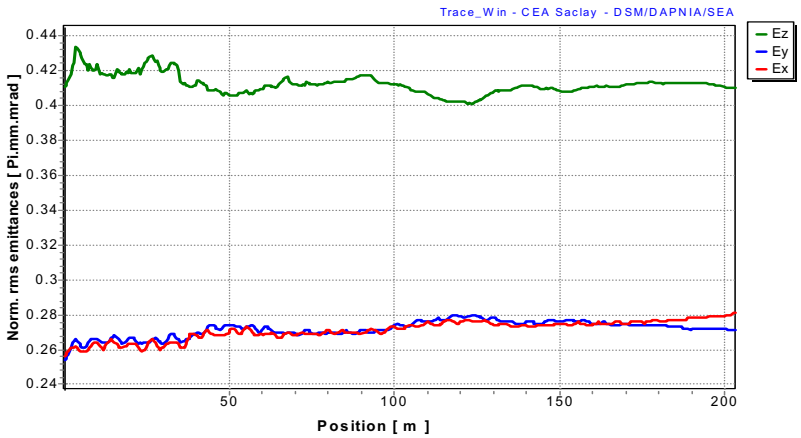
Emittance exchange

- What is the problem ?
- Is the external focusing force involved ?
- Is it really dangerous ?
- Is it coming from intrabeam-scattering ?
- What is the basic physics of the phenomenon ?
- How to avoid or minimise it ?

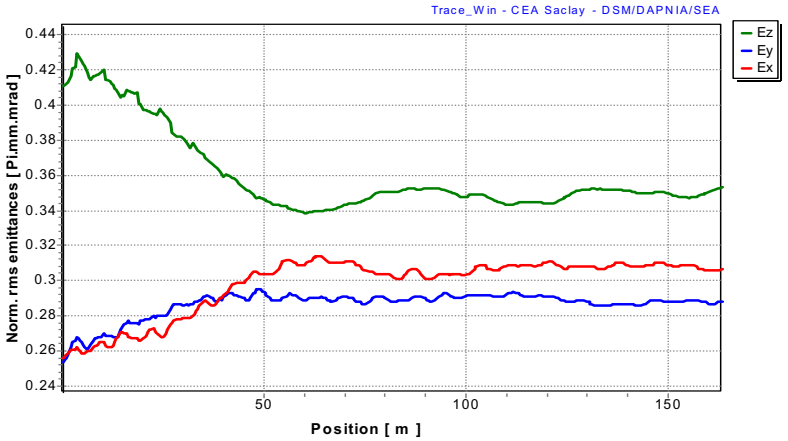
Emittance exchange : Problem?







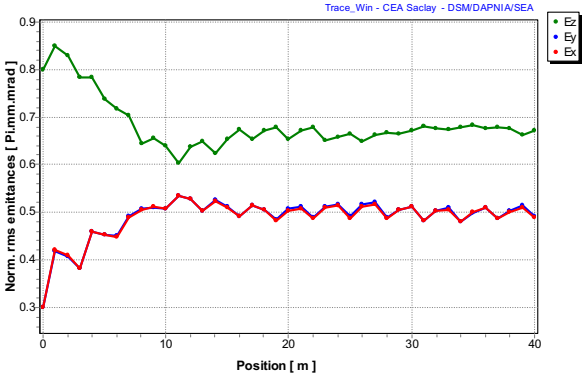
No phase advance crossing



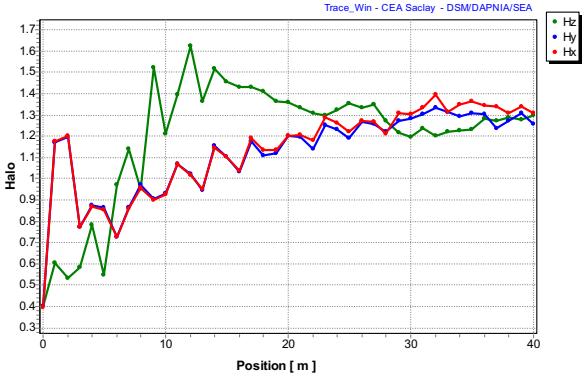
Phase advance crossing

Emittance exchange : External focusing?

Continuous channel

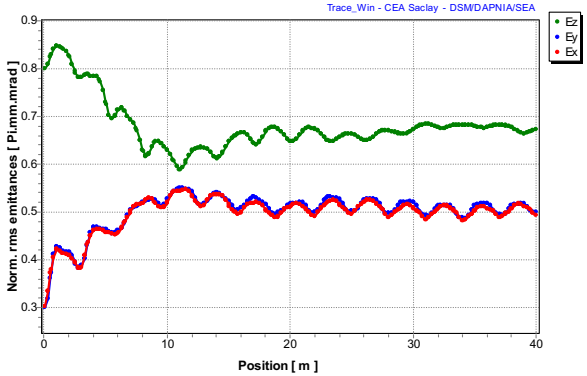


Rms emittance

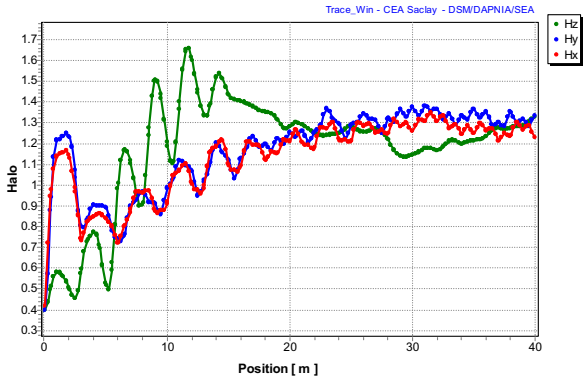


Halo parameter

FODO channel

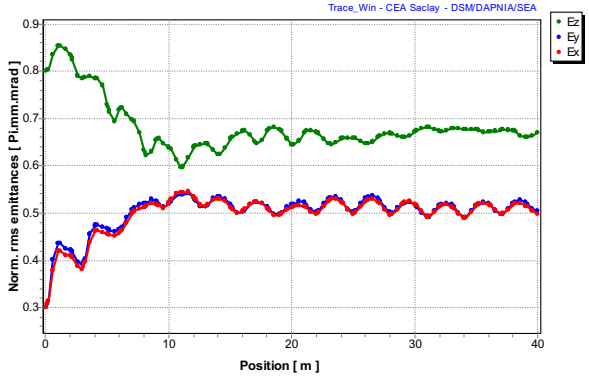


Rms emittance

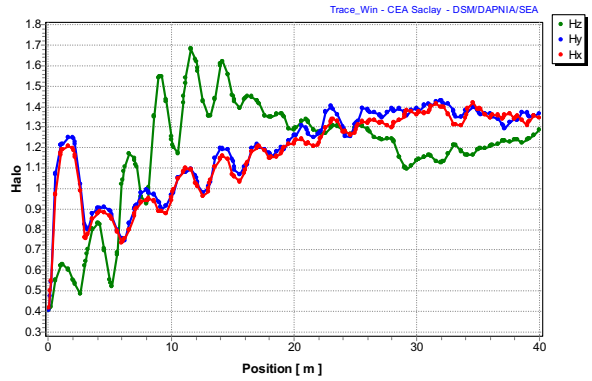


Halo parameter

Doublet channel



Rms emittance



Halo parameter

⇒ Can be studied in a continuous focusing channel

Emittance exchange : Dangerous?

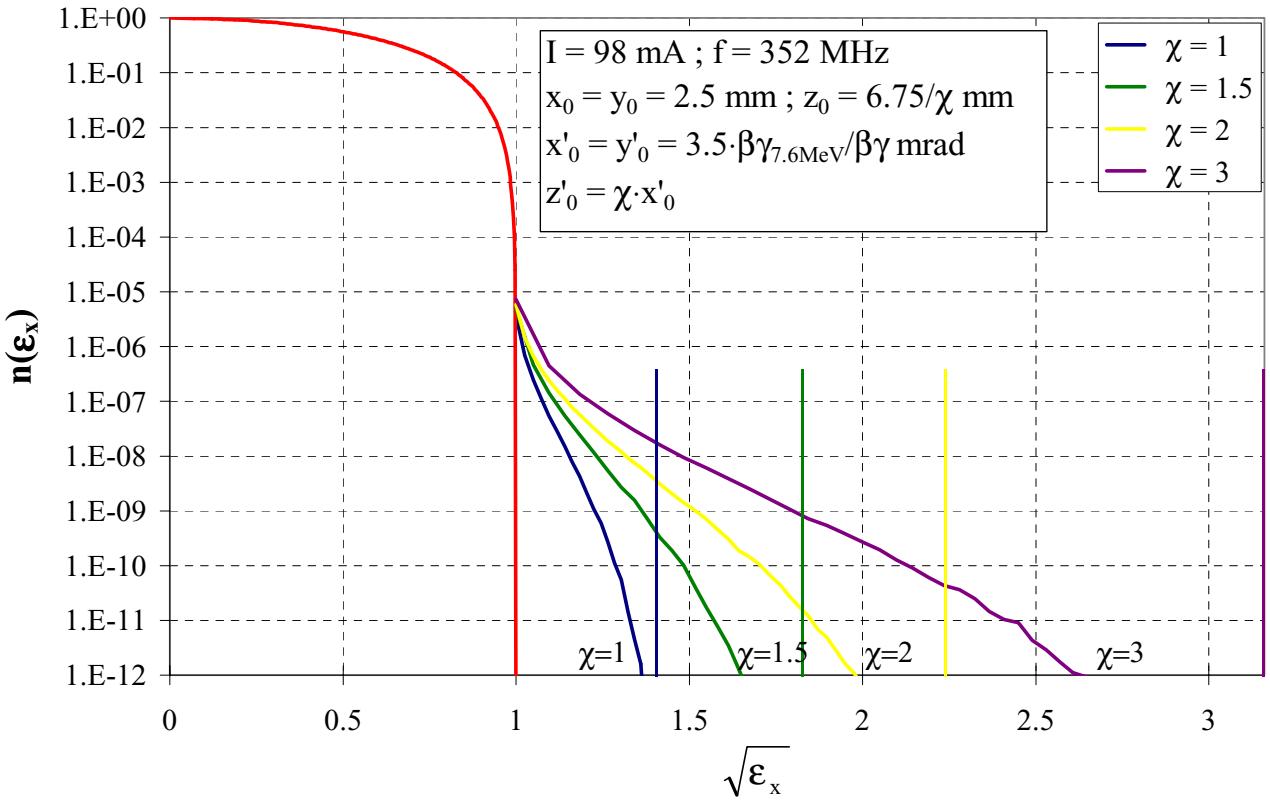
- Because of space-charge, the matching depends on the beam emittance :
$\Rightarrow$ If there is emittance exchange, what happens to the matching ?

- Through the coupling resonance, particles with large energy in one direction can get large energy in the other direction :
$\Rightarrow$ Halo transfer

- Do the coupling resonances amplify the effect of mismatch on emittance growth and halo formation ?

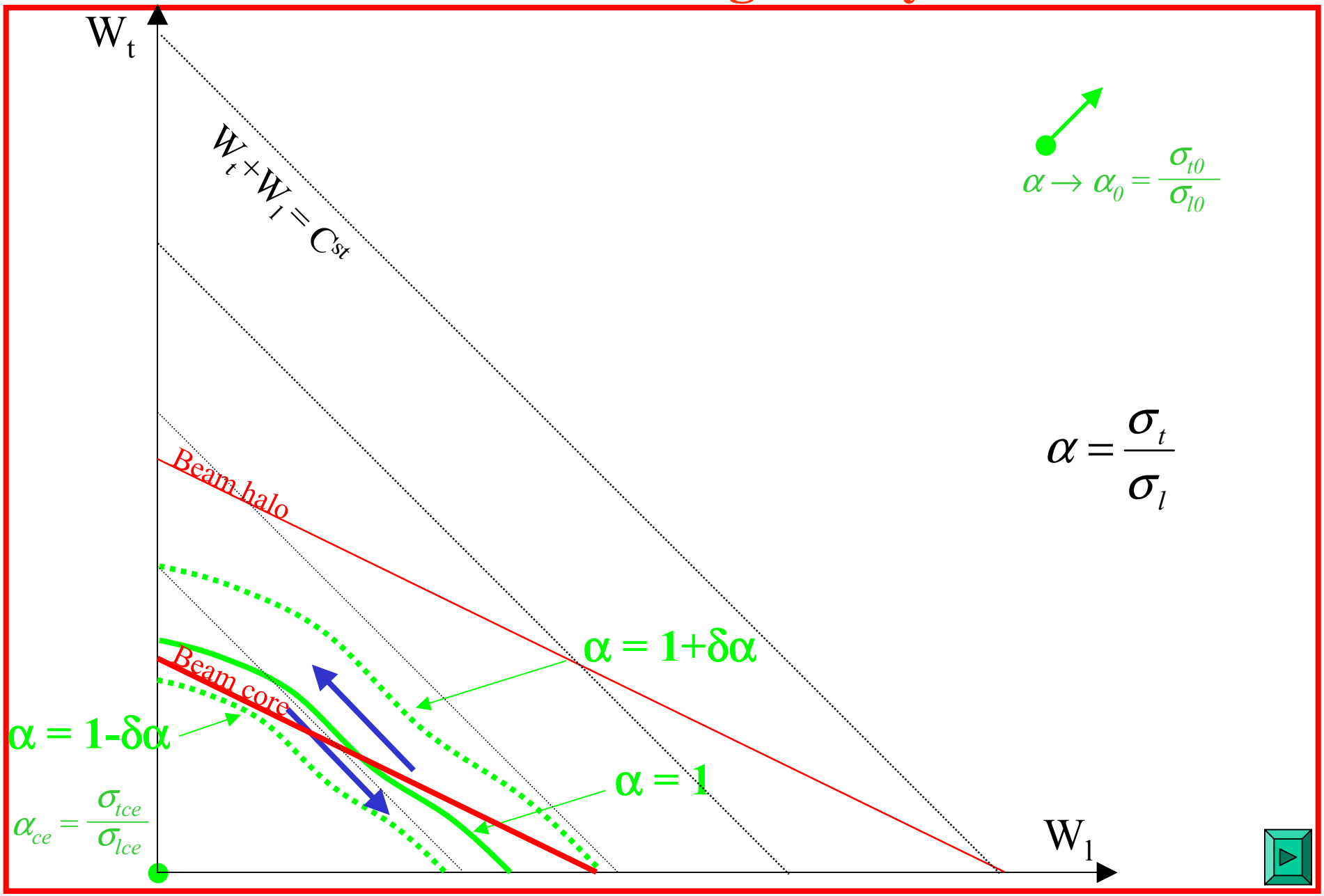
Emittance exchange : Intrabeam scattering ?

- This phenomenon is observed whatever the space-charge routine, the number of particles, of lattices in the mesh.
- A dedicate code can evaluate the tail from this effect.



Tail induced by intrabeam scattering at typical linac end

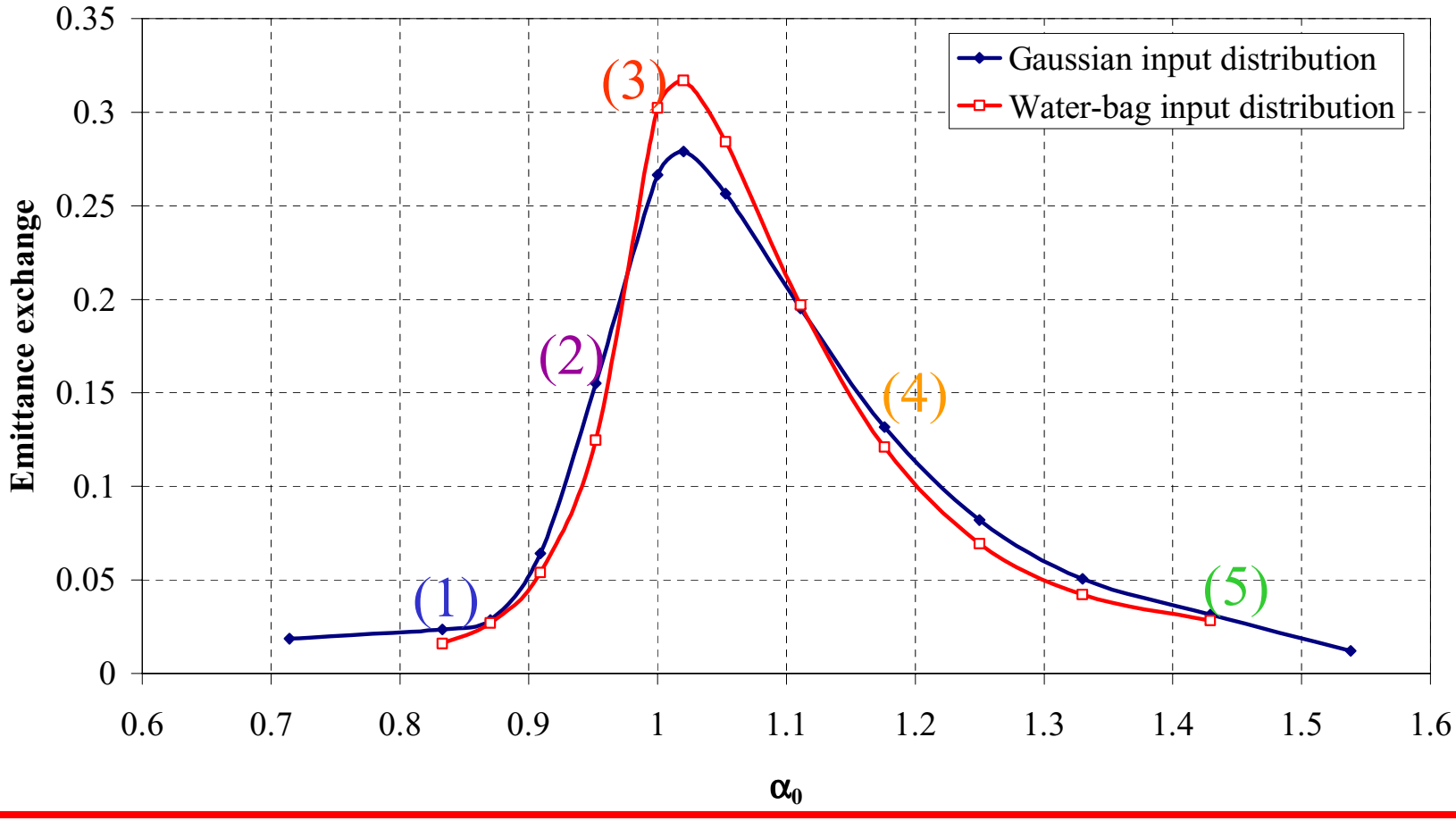
Emittance exchange : Physics?



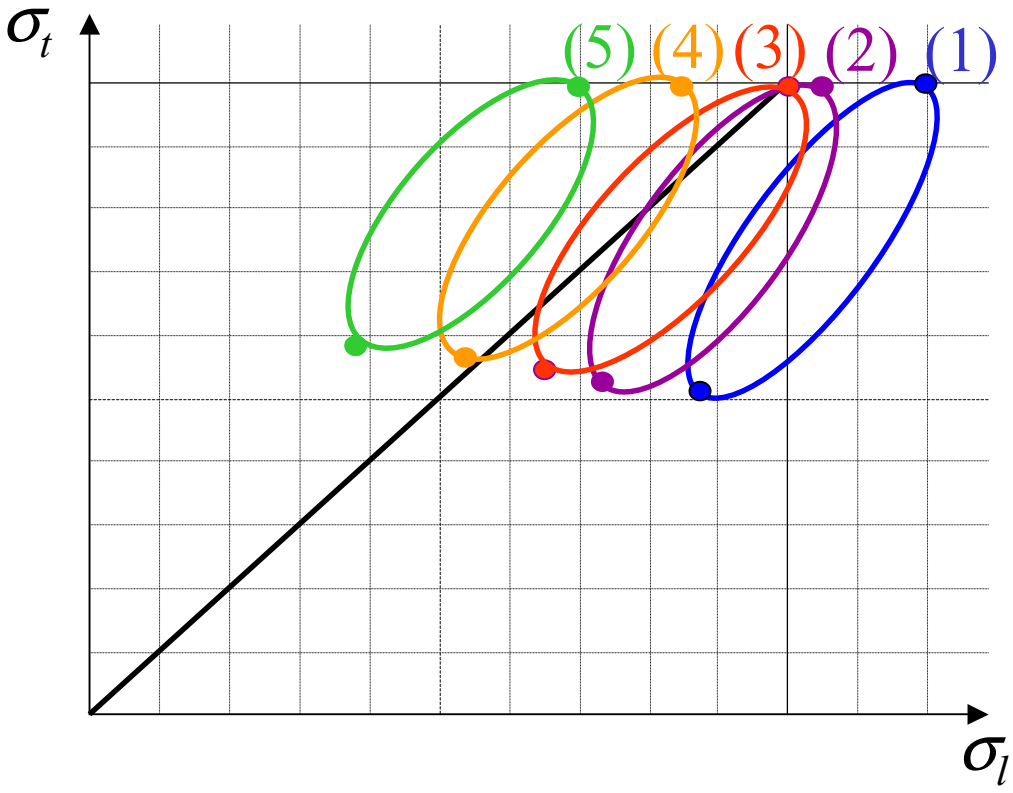
Emittance exchange : Physics? (2)

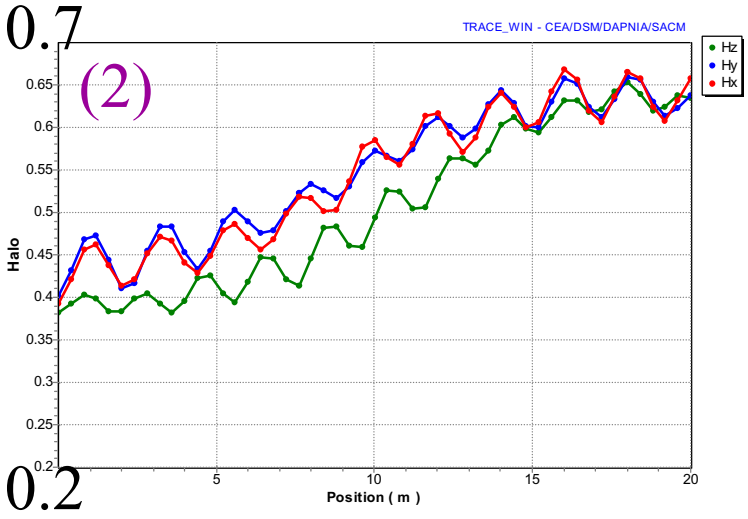
Emittance exchange : $\dfrac{\Delta\varepsilon_l - 2\cdot\Delta\varepsilon_t}{\varepsilon_{l0} + 2\cdot\varepsilon_{t0}}$

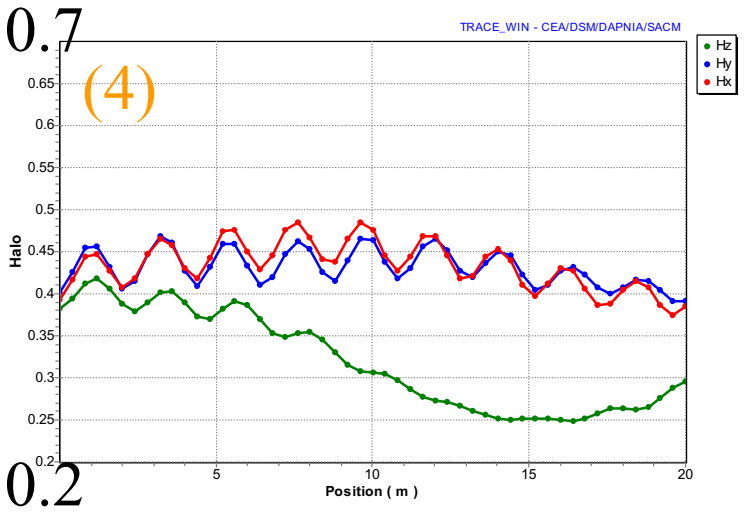
$\dfrac{\varepsilon_{l0}}{\varepsilon_{t0}} = 2 \quad \sigma_{t0} = 1 \quad For\ \sigma_{l0} = 1,\ \eta_t$=0.53, η_l=0.68.



Emittance exchange : Physics? (3)







Halo parameter

Emittance exchange : Minimise, avoid?

- Find a working point with 1 not in $[\alpha_0=\sigma_{t0}/\sigma_{l0};\ \alpha_{ce}]$.
  - Some « mismatch instabilities » have been observed for $\alpha_0 <1$,
  - For more security take 1 not in $[\sigma_t/\sigma_{l0};\ \sigma_{t0}/\sigma_l]$.

- Be equipartionned is preferable as it should reduce the effect, but it will not avoid halo exchange from one direction to the other one.

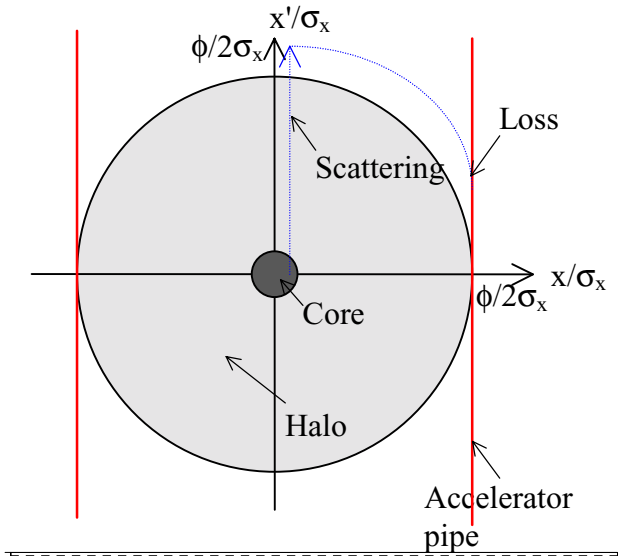
Interaction with residual gas

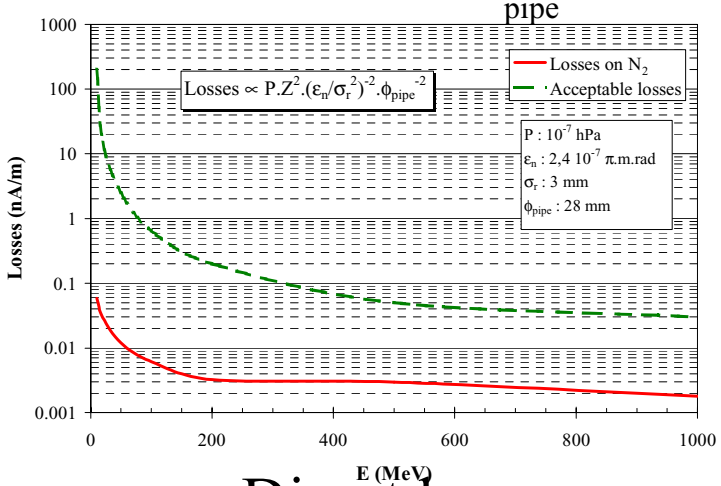
This effect can have a large influence as it is generally not taken into account by simulation codes

- Elastic scattering
- Charge exchange
- Space-charge compensation

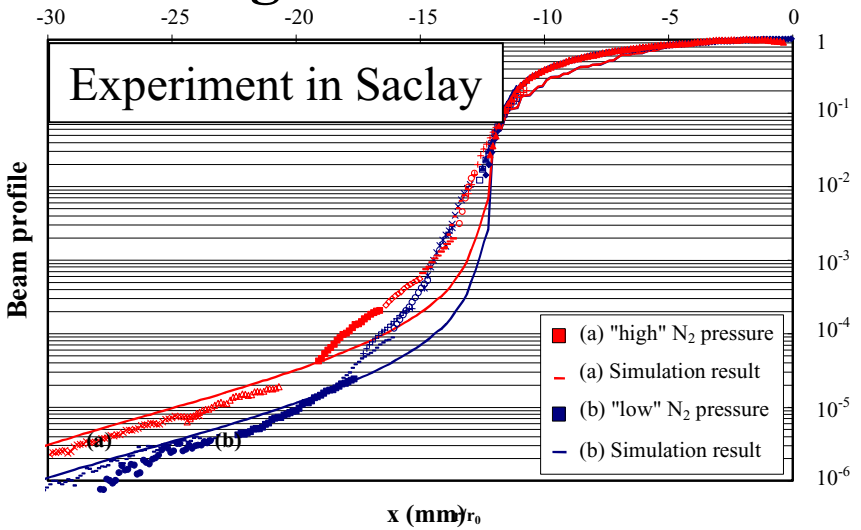
Elastic scattering on residual gas

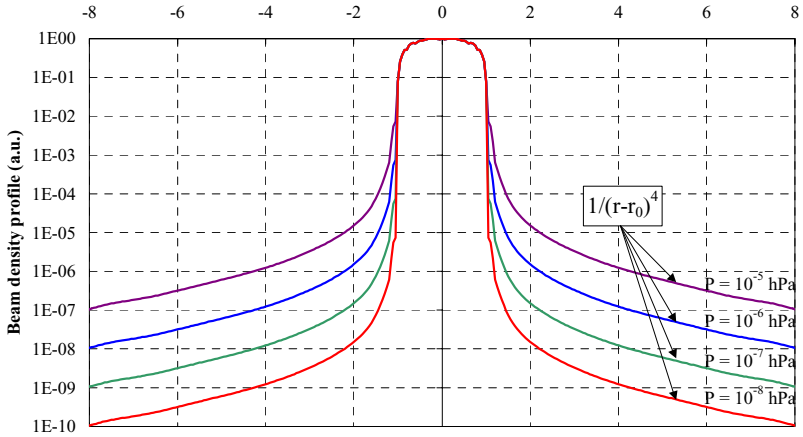
Transverse momentum can be given to a particle through a collision on one molecule of the residual gas





Direct losses

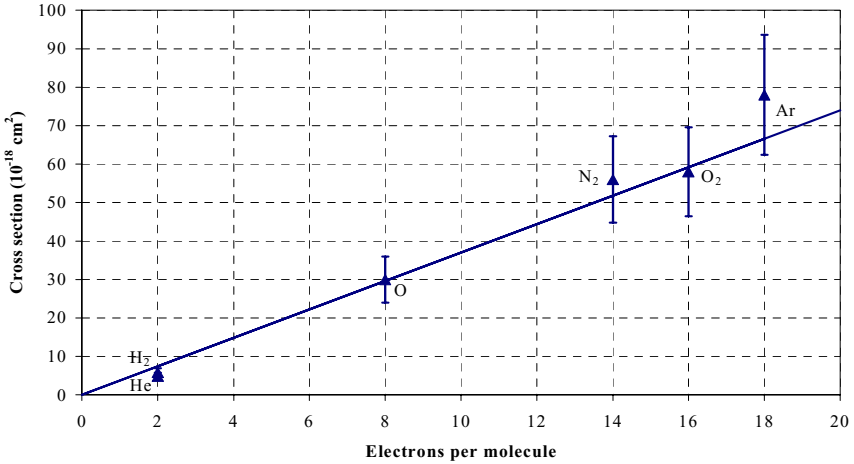




Beam tails and halo

Charge exchange with residual gas

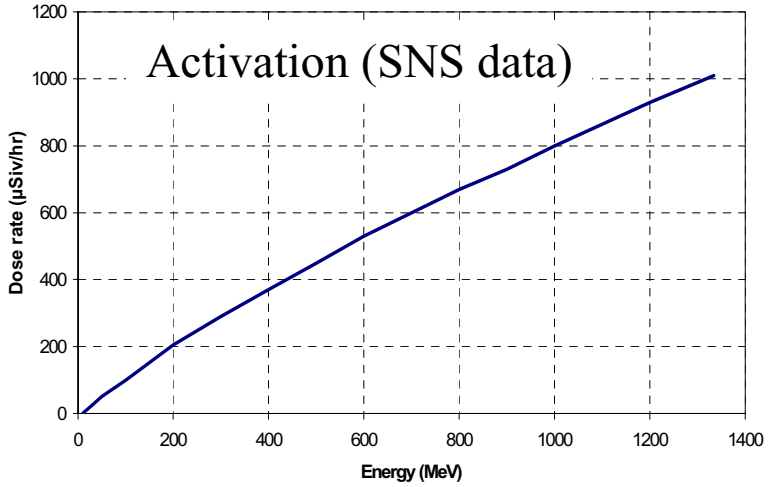
Some beam particles can be neutralised by an electron exchange with the residual gas

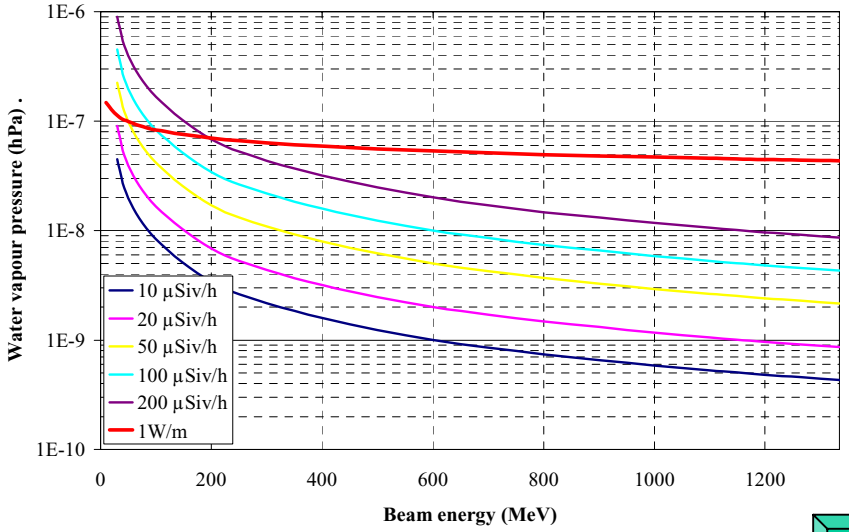


Cross section of H^- stripping at 10 MeV

$$\sigma = 2.1 \cdot 10^{-20} \cdot E^{-3/4}$$

σ the cross section in m^2,
E the particle energy in MeV

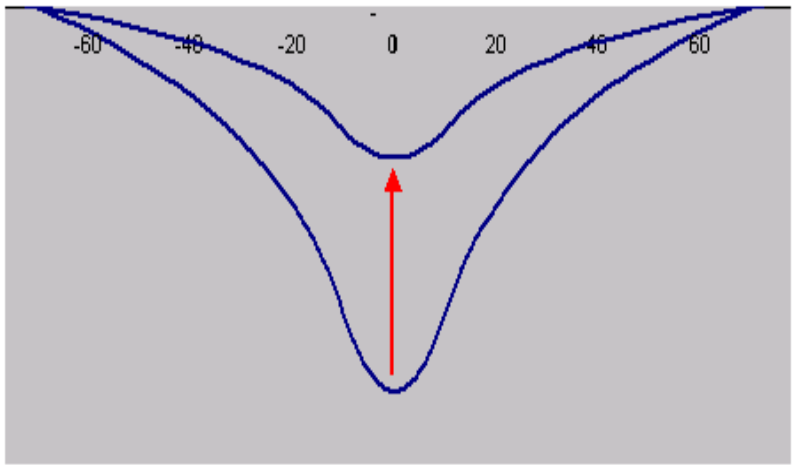




H_2O maximum pressure

Space-charge compensation

- The charge density produces a potential well in a beam, defocusing its particle.
- The beam ionises the residual gas, creating ions and electrons
- Species with opposite charge are trapped in the well, the others are expulsed
- The potential well is filled
- The space-charge force is changed with time
- The matching conditions are changed with time



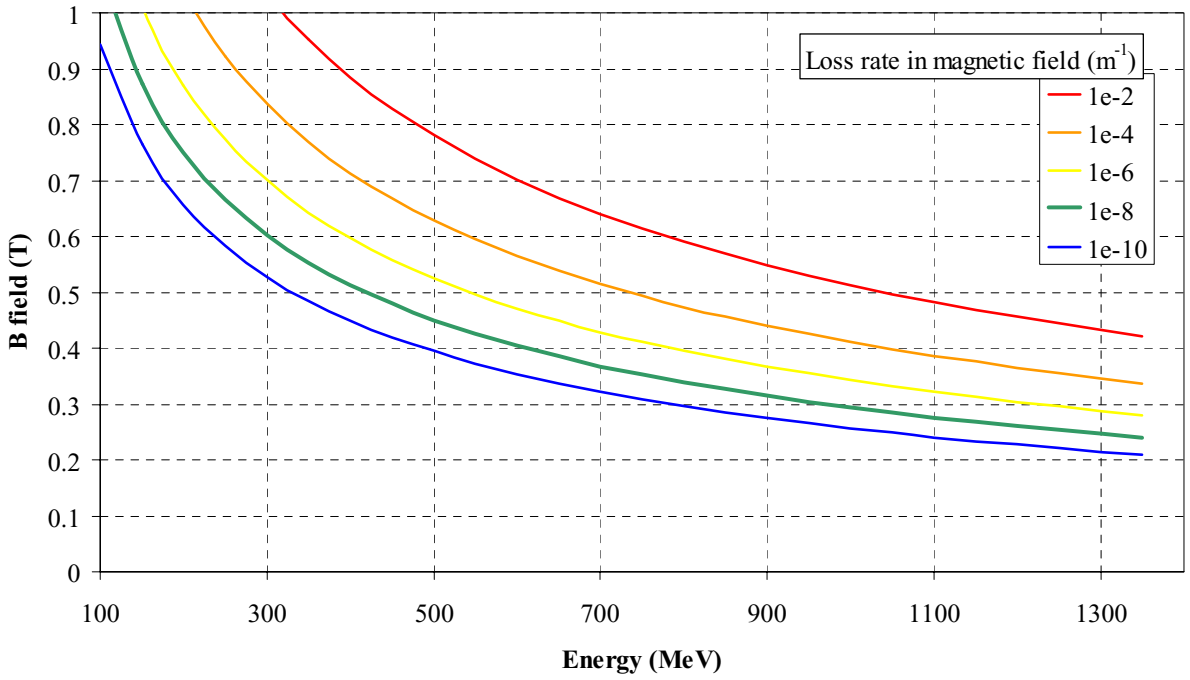
Pulse front end is mismatched

Magnetic stripping of H^-

A magnetic field can tear an electron from a H^- ion.

The probability ***P***, per meter, to strip a H^- in a magnetic field ***B*** is:

$$P_{m^{-1}} = 9.53 \cdot 10^5 \cdot B_T \cdot \exp\left(-\frac{16.4}{\beta\gamma \cdot B_T}\right)$$



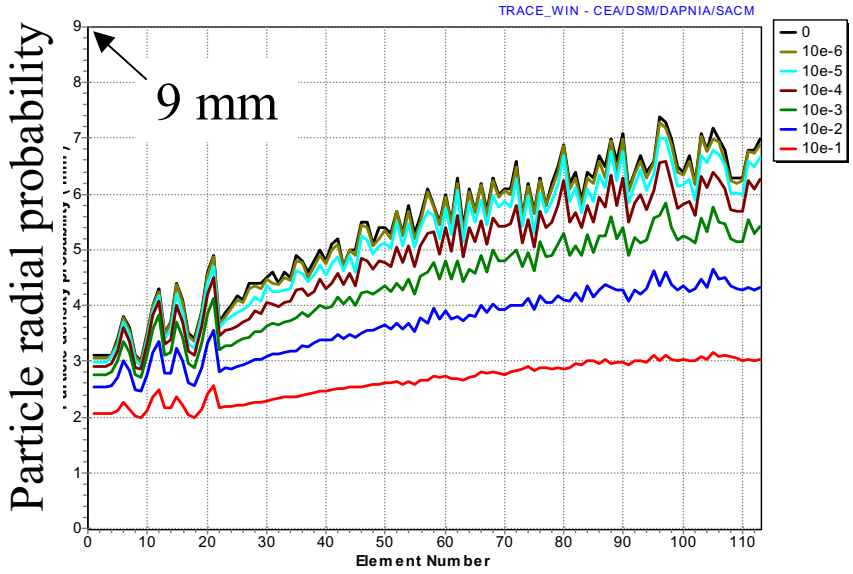
Magnetic field at a given loss rate level as a function of the beam energy

Linac errors

The linac errors have an influence on beam centre of gravity displacement, mismatching and non linear forces.

Static errors : can be measured and corrected

Dynamic error : cannot be corrected



Longitudinal position

Statistical treatment :

n_l linacs of n_p particles

$\Rightarrow$ Calculus of a probability of presence