HIGH INTENSITY NEGATIVE ION BEAM NEUTRALIZATION

JEFFERSON LAB ACCELERATOR SEMINAR

19/10/2017

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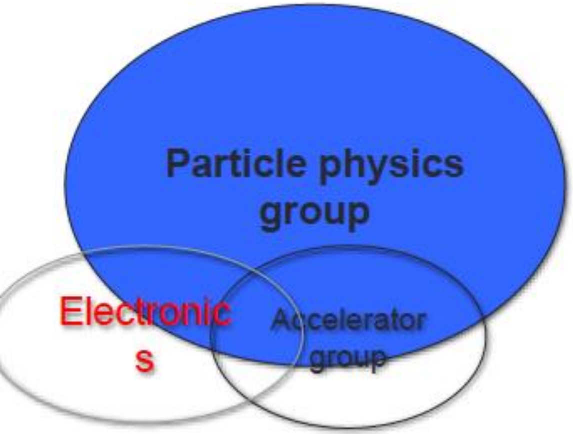
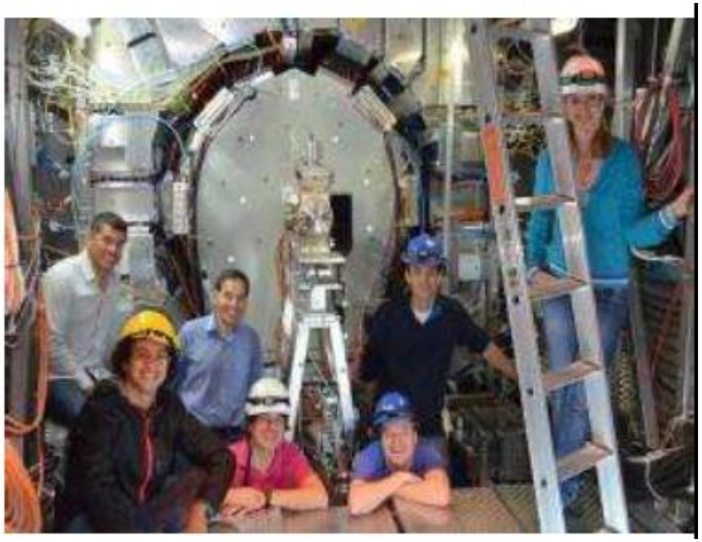


Creation of detectors for several laboratories
- Alice project CERN
- BELLE II JAPAN

The detectors group it has active collaboration With several universities in Mexico and international institutes



Two years ago a new group dedicated to accelerator physics has been created

- Source and extraction
- system design
- Beam Simulation
- Outgoing collaborations with different Mexican institutes

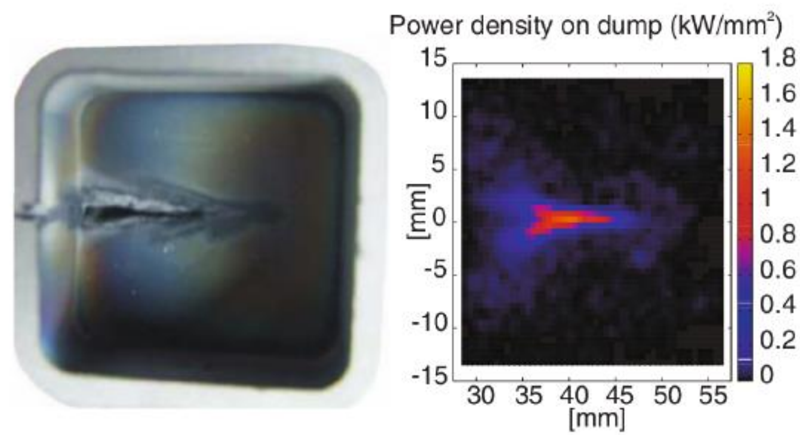
UAS-CERN COLLABORATION

- The collaboration with CERN is concerning two of the LHC Linacs

- Linac4 in the Source department
- Linac3 in beam dynamics and realistic simulations of Heavy ion beam transport

Beam commissioning and simulations

Life makes more sense when the measurements agree with the simulations!
Is also better when is not too late..

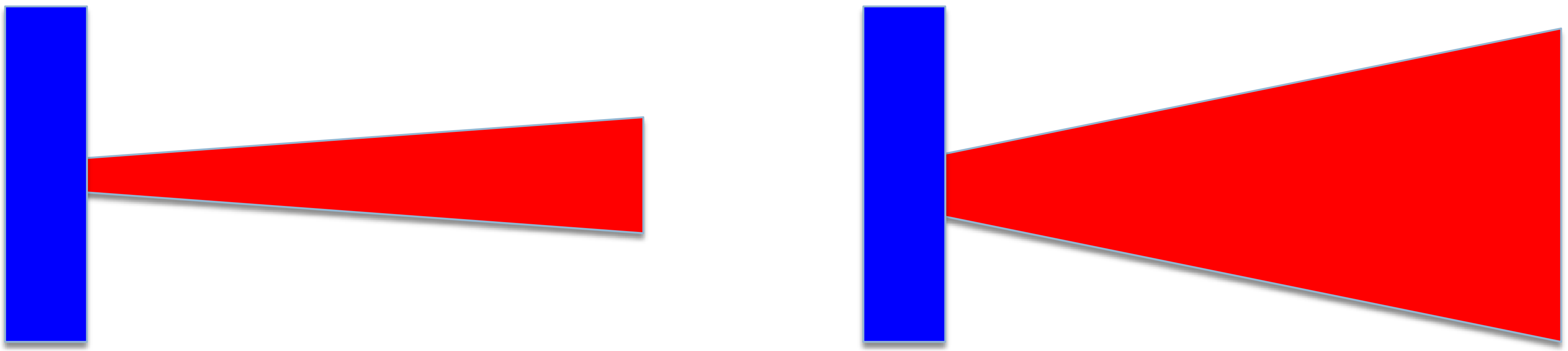


What did you expect?
What did you get?

Damage dump by electron beam(left), simulations (Right)

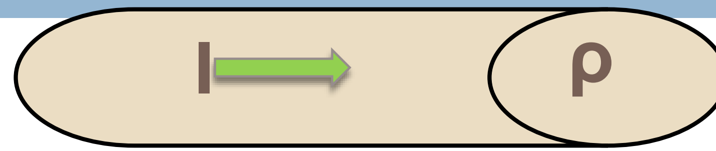
Space charge effect

- When the beam is created charged particles are forced to be together
- Space charge effect play an important role in the low energy beam dynamics
- It can limits the ion transport



Beam Space charge

$$F = q(E + v \times B)$$



Consider a longitudinally cylindrical beam with constant charge density ρ radius “a” and current I.
The magnetic field creates an opposite force to the electric field

$$E_r = \frac{\rho r}{2\varepsilon_0} \qquad J = \frac{I}{\pi a^2} \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$B_\theta = \frac{\mu_0 J r}{2} = \frac{\mu_0 I r}{2\pi a^2} = \frac{\beta E_r}{c}$$

$$F = q\left(E - \frac{v\beta E}{c}\right)$$

$$= q(E - \beta^2 E) = q\frac{E}{\gamma^2}$$

Energy	γ (protons)	γ (electrons)
45Kev	1.00004	1.088
50 Mev	1.05328	98.084
160 MeV	1.17052	314.112
1 Gev	2.06574	1957.145
1 TeV	1066.7889	1956952.375

Beam potential

For $j(R) = 0$

$$\phi(r) = \frac{I}{4\pi\varepsilon_0 c\beta}\left[1 + 2\ln(\frac{R}{a}) - \frac{r}{a}\right]$$ r<a

$$\phi(r) = \frac{I}{4\pi\varepsilon_0 c\beta}\left[\ln(\frac{R}{r})\right]$$ a<r<R

The longitudinal difference for the beam potential can be also important.

Envelope equation(Hill's equation)

The envelope of a cylindrically symmetric beam transported along the z-axis can be described by the differential equation:
If the space charge is too intense it can limit the beam transport to solve this is possible to have 3 approaches:

1) Increase the focusing strength
2) Increase the beam pipe radius.
3) Use **space charge compensation**

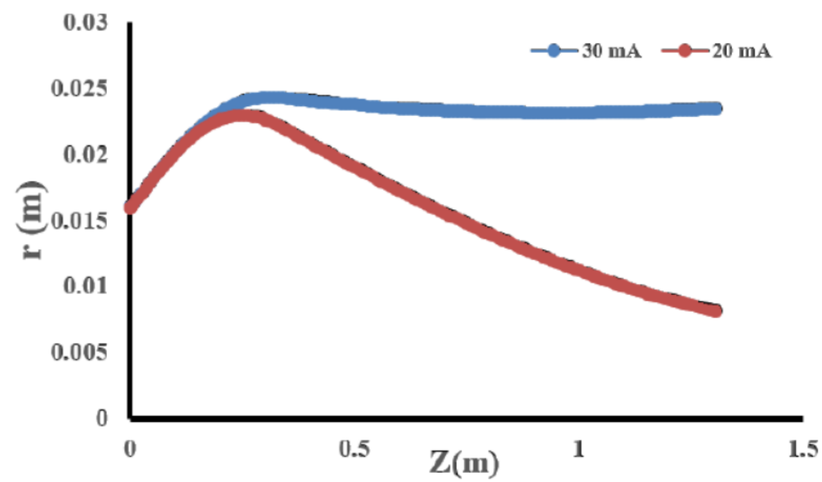
$$K_0 = \frac{I}{2\pi\varepsilon_0 m_0 c^3 \beta^3 \gamma^3 a^2}$$

Magnet

Space charge term

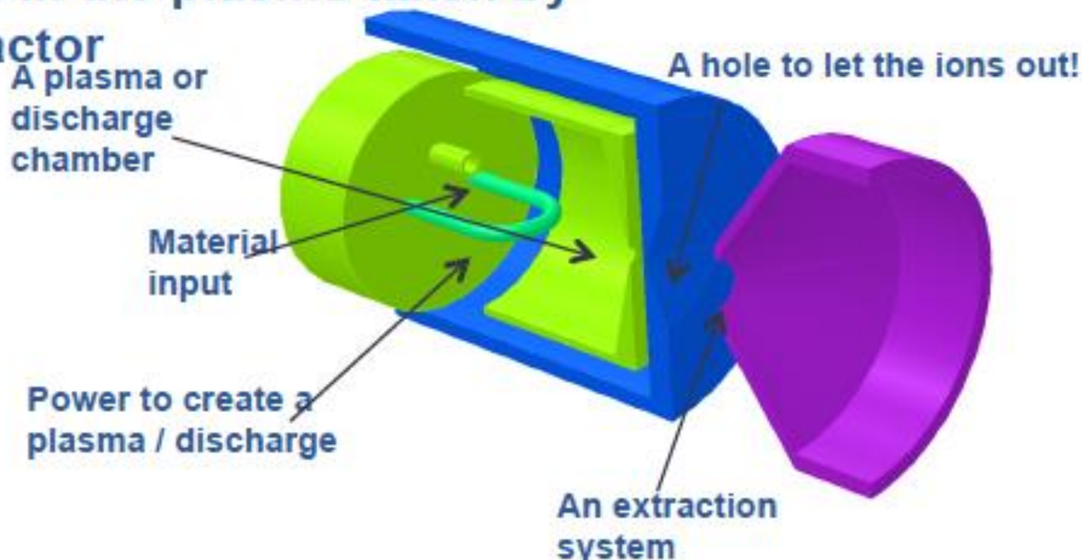
$$\frac{d^2 r}{dz^2} + k_0^2 r + \frac{\epsilon^2}{r^3} - \frac{K_0}{r} = 0$$

50 KeV proton beam



Source and beam extraction

The beam is formed by the particles in the plasma taken by the extractor

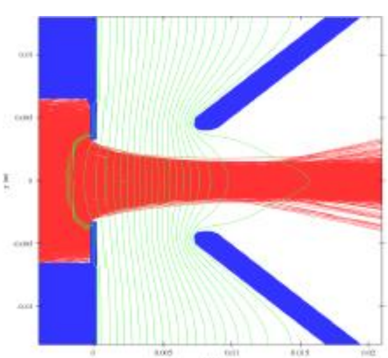


$$j = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{V^{3/2}}{d^2}$$

Child–Langmuir law

Ground Extractor

Plasma



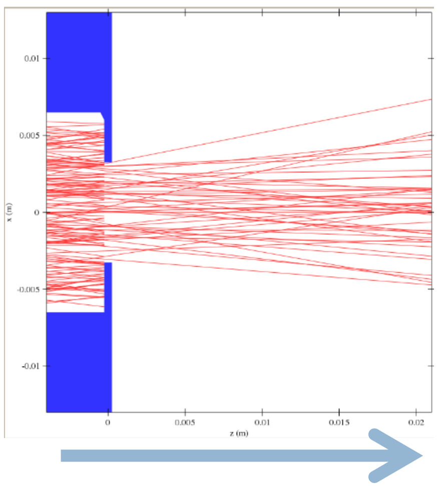
Potential lines(green)
Electrodes (blue)
Ions (Red)

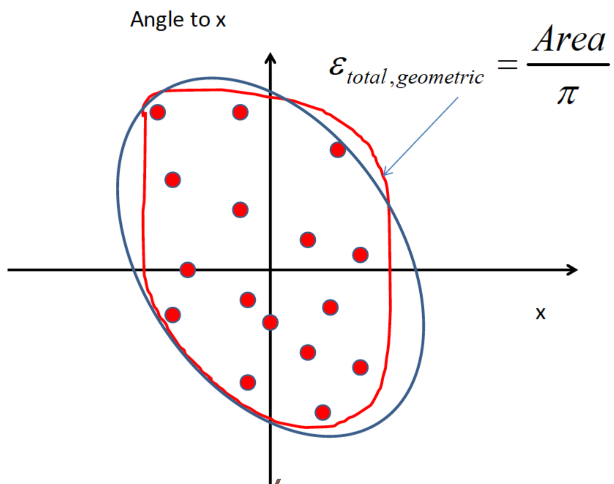
The beam energy is calculated by the diference of potential

$$E = q(V_{source} - V_{ground})$$

Emittance

- The region in phase space that the particles in a beam occupy is called the beam emittance

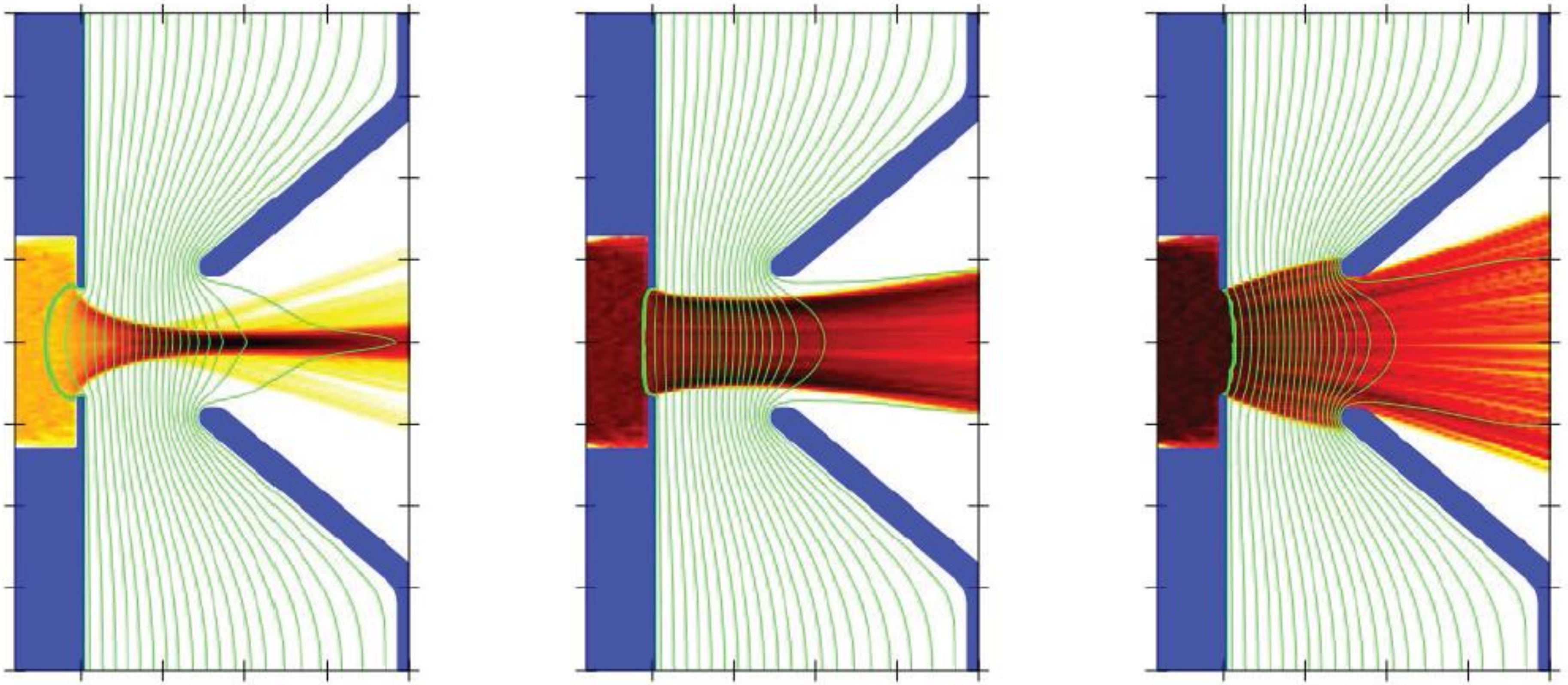




- Mm.mrad? mrad from p_x/p_z
- The goal in every accelerator is to have the lower beam emittance achievable

$$e = \frac{r}{2c}\sqrt{\frac{kT}{m}} \mu\, T^{1/2} \qquad L \mu \frac{1}{e_y}$$

Scape charge effect in the extractor



Current too Low:
Over focus

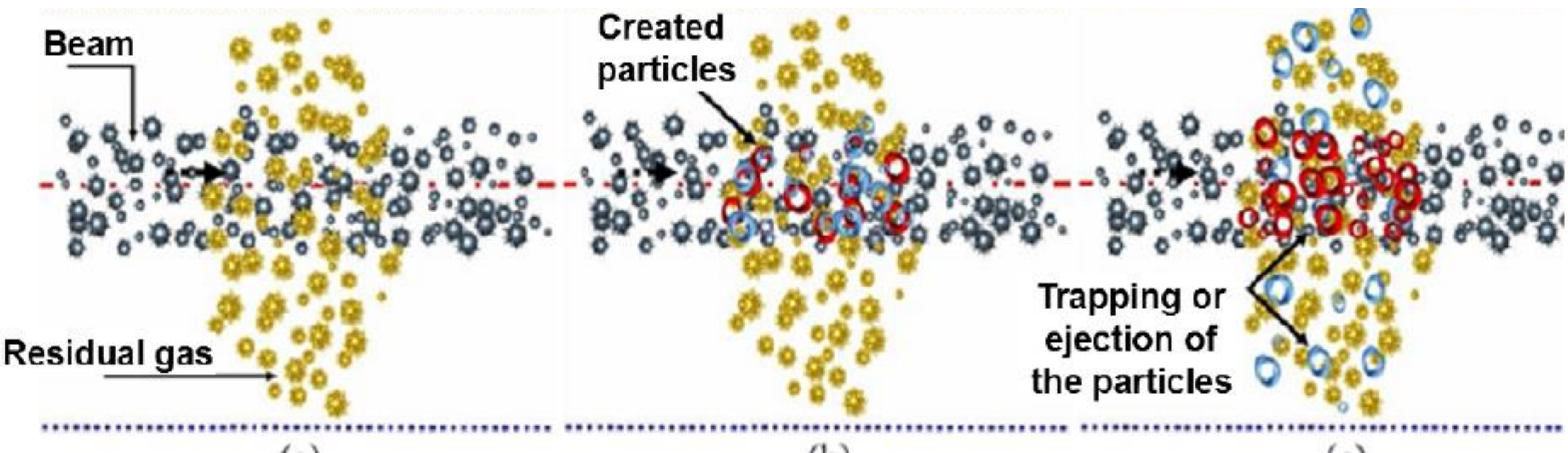
Matched conditions:
Parallel beam

Current too High:
Beam losses
Divergent beam

Neutralization (Space charge compensation)

- **The vacuum is not perfect inside the beam pipe**
- **The beam ionizes residual gas atoms**
- **The ionized particles from opposite charge are trapped by the beam potential and same charge particles are expelled to the walls**

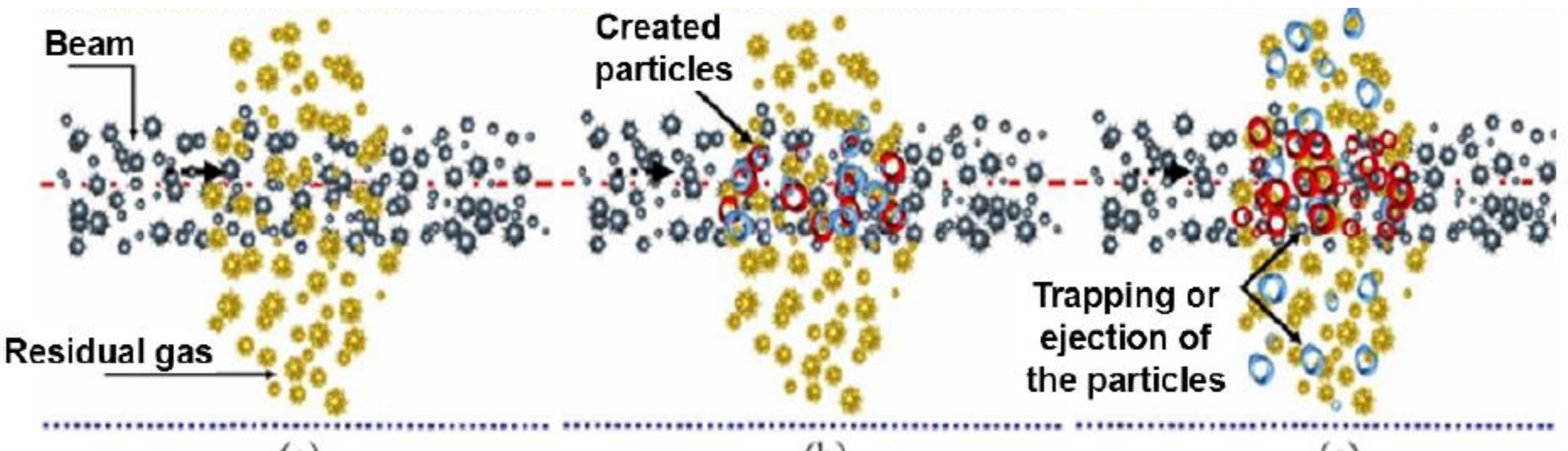
$$p + X \rightarrow p + X^{+} + e \qquad p + H_2 \rightarrow p + H_2^{+} + e$$



Neutralization

- The H- beam get neutralized with residual gas
- The positive ions are trapped by the beam
- Is possible to create a neutral beam
- Now the accelerator community is really interested in the beam an residual gas interaction.

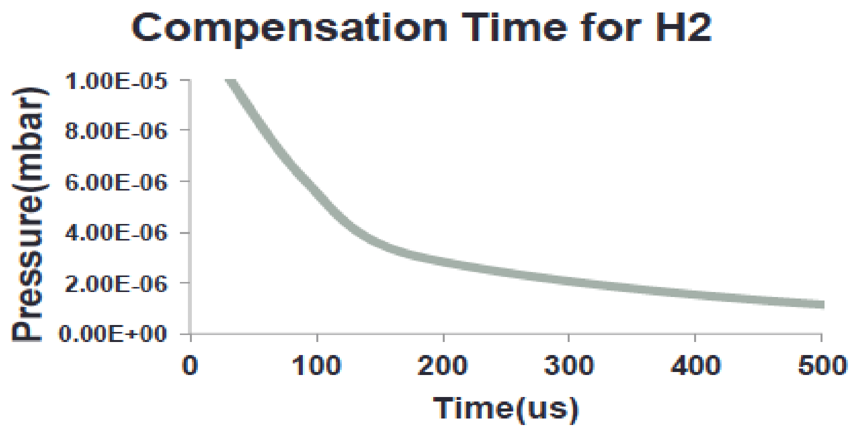
$$p + X \rightarrow p + X^{+} + e \qquad p + H_2 \rightarrow p + H_2^{+} + e$$

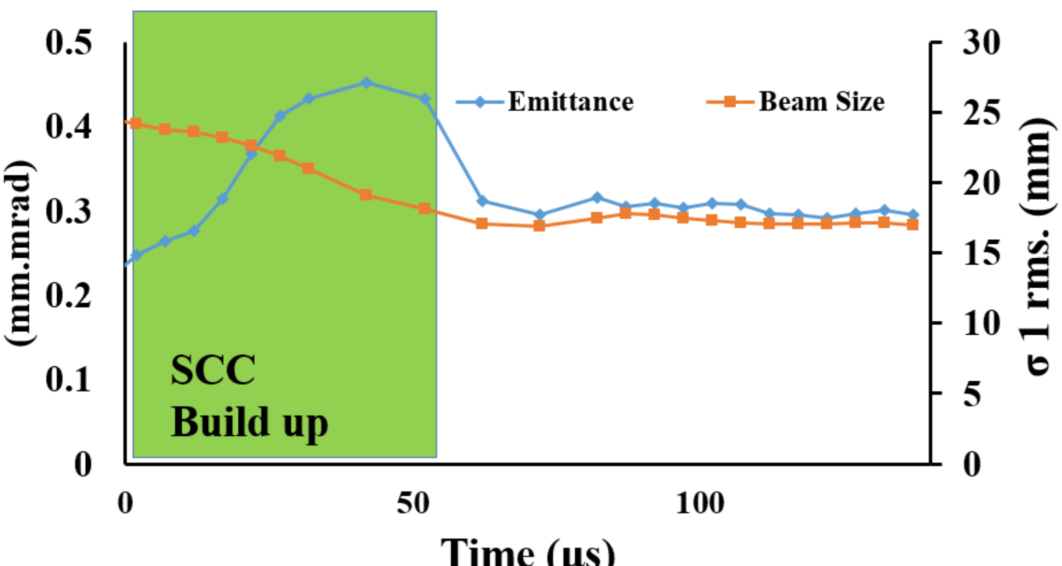


Neutralization time

The space charge compensation is time dependent

$$\tau = \frac{1}{v_b \sigma(E) n_{H2}}$$





The beam properties are not constant in time and is necessary to use advanced codes to simulate this effect.

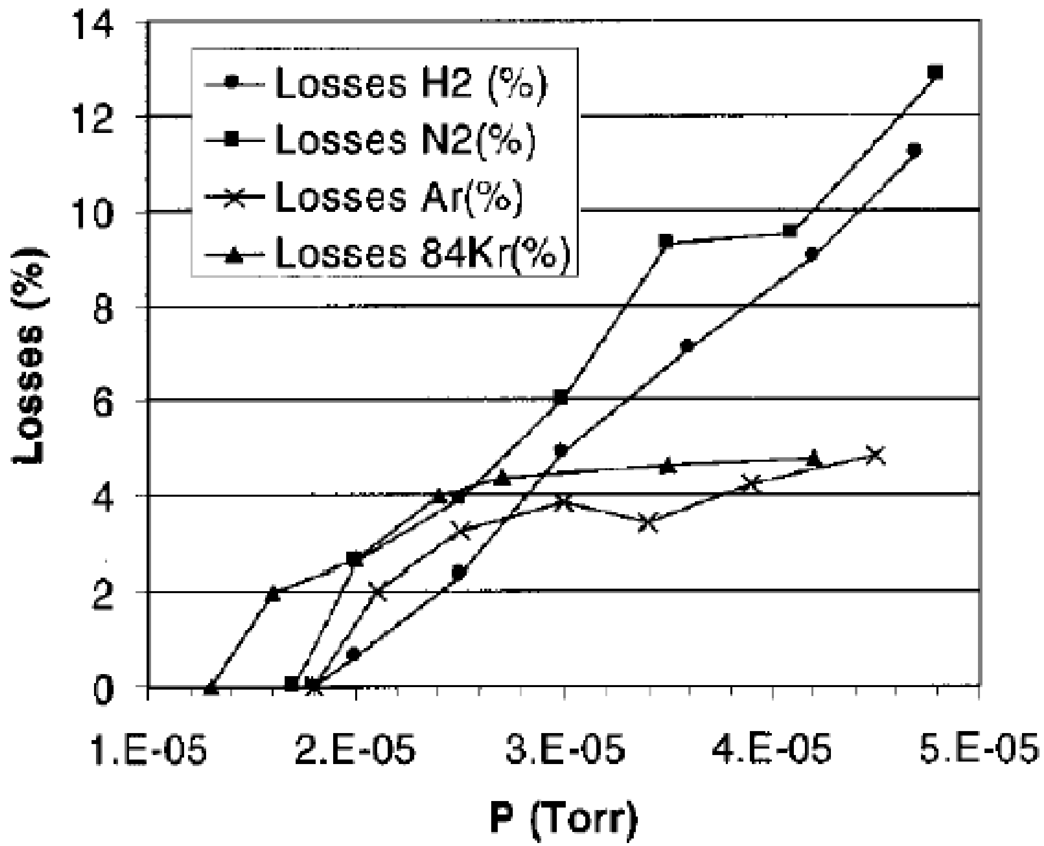
Residual gas and beam interaction

Is not good idea to add too much gas pressure to the system

Mean free path

$$\lambda = \frac{1}{n\sigma_i(E)}$$

n neutral gas density



Beam losses fot H- beam by interactions with the residual gas

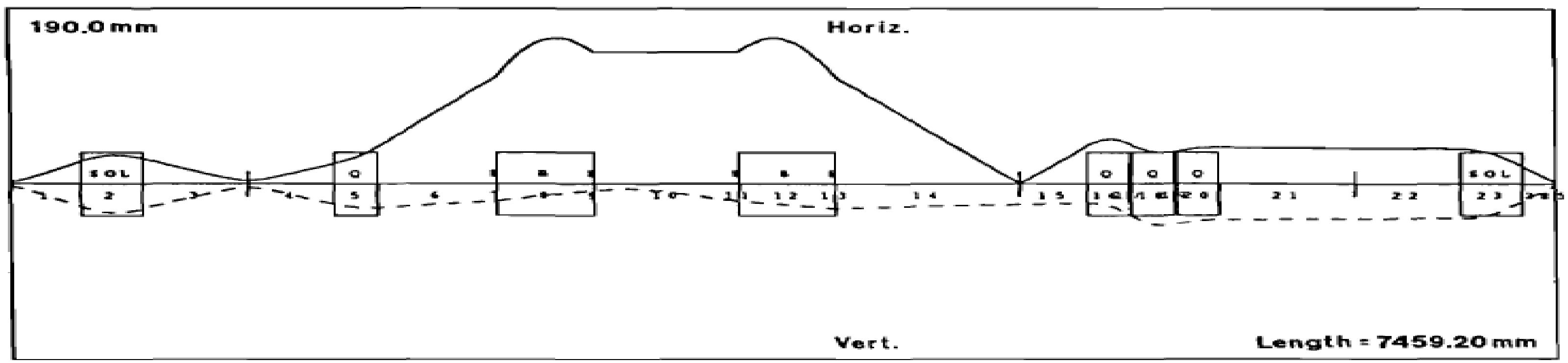
Beam Dynamics for LINAC Design

- TRACE 3-D and MAD-X are "Design Codes" to set the main constrains using Beam envelopes.
- Particle Codes as PATH Manager – multiparticle code used if space Charge is a Major Consideration in the Design of a Code
  - Is also possible to include 2-D and 3-D field maps to get more accurate results.
  - To include more physics other codes (PIC and EM) as WARP and Ibsimu is necessary

These codes usually are not “ User friendly“

Do not overcomplicate

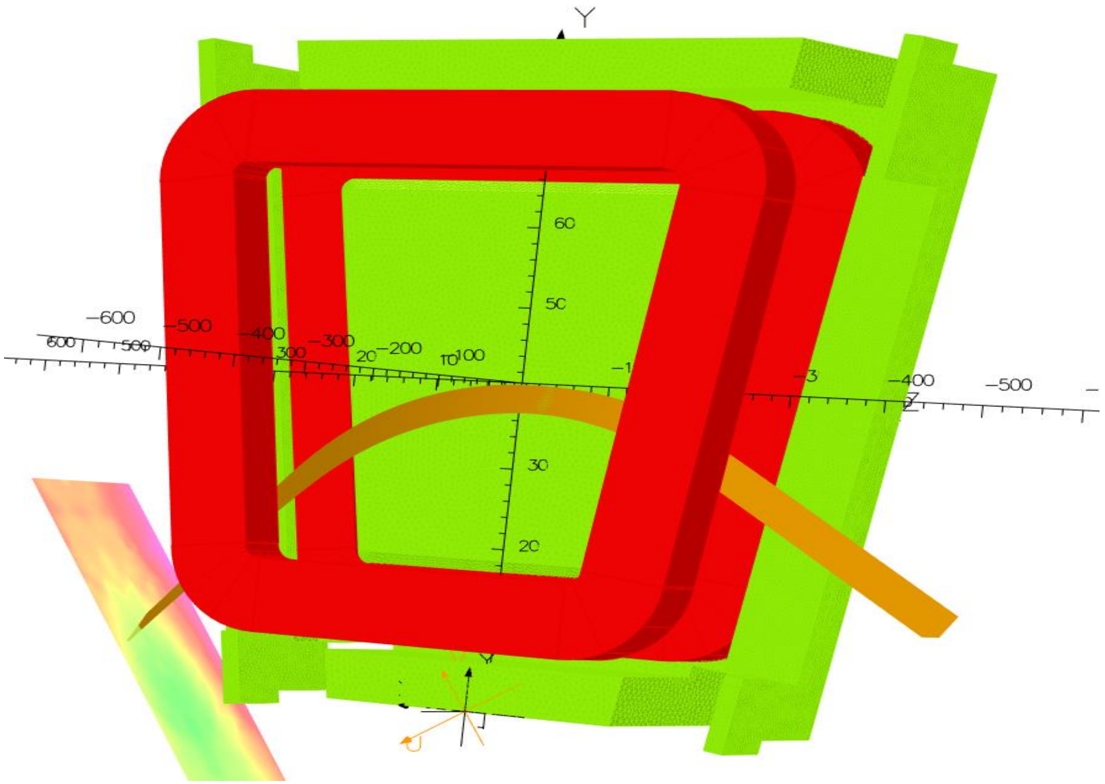
- Simulations are here to help, no to make the tings more difficult.



Envelope Matrix simulation of the linac3 beam line
Simulations does not match measurements..
We decide to do a more complicate simulation for the two 75^0 dipoles

Do not overcomplicate

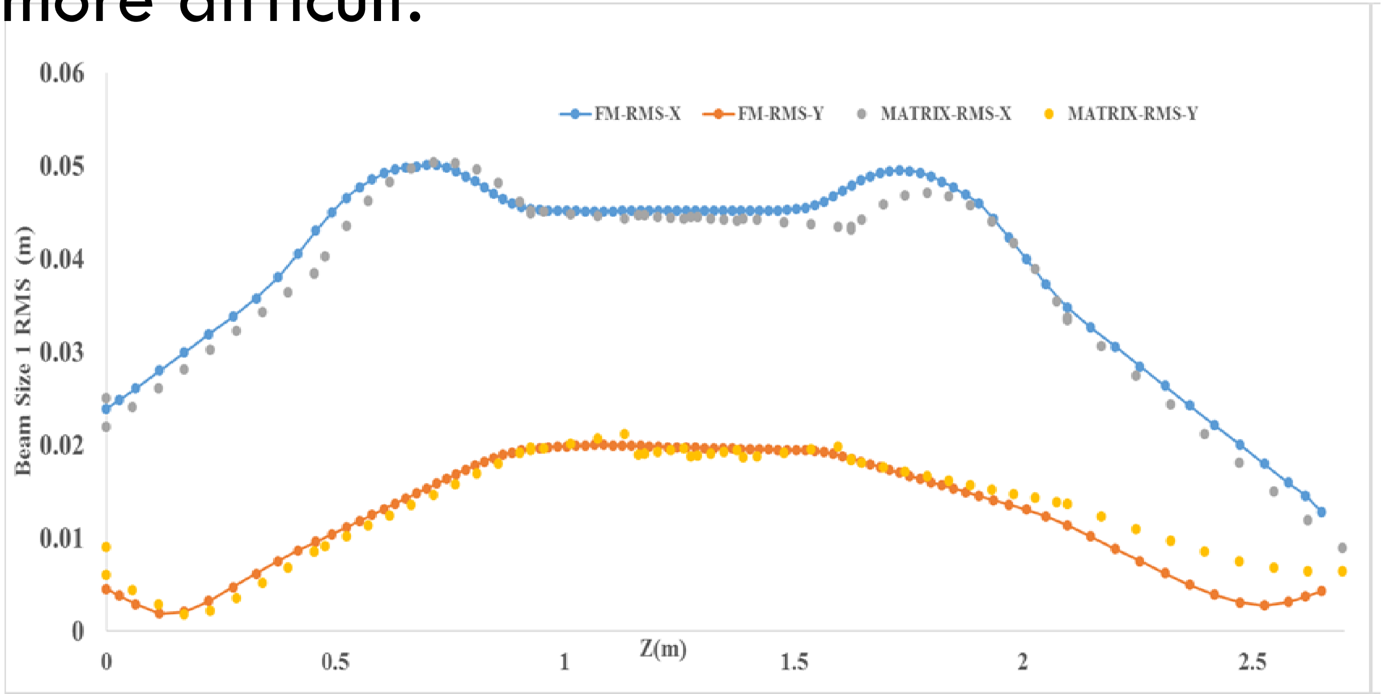
- Simulations are here to help, no to make the things more difficult.



Beam passing through one the dipoles

Do not overcomplicate

- Simulations are here to help, no to make the things more difficult.

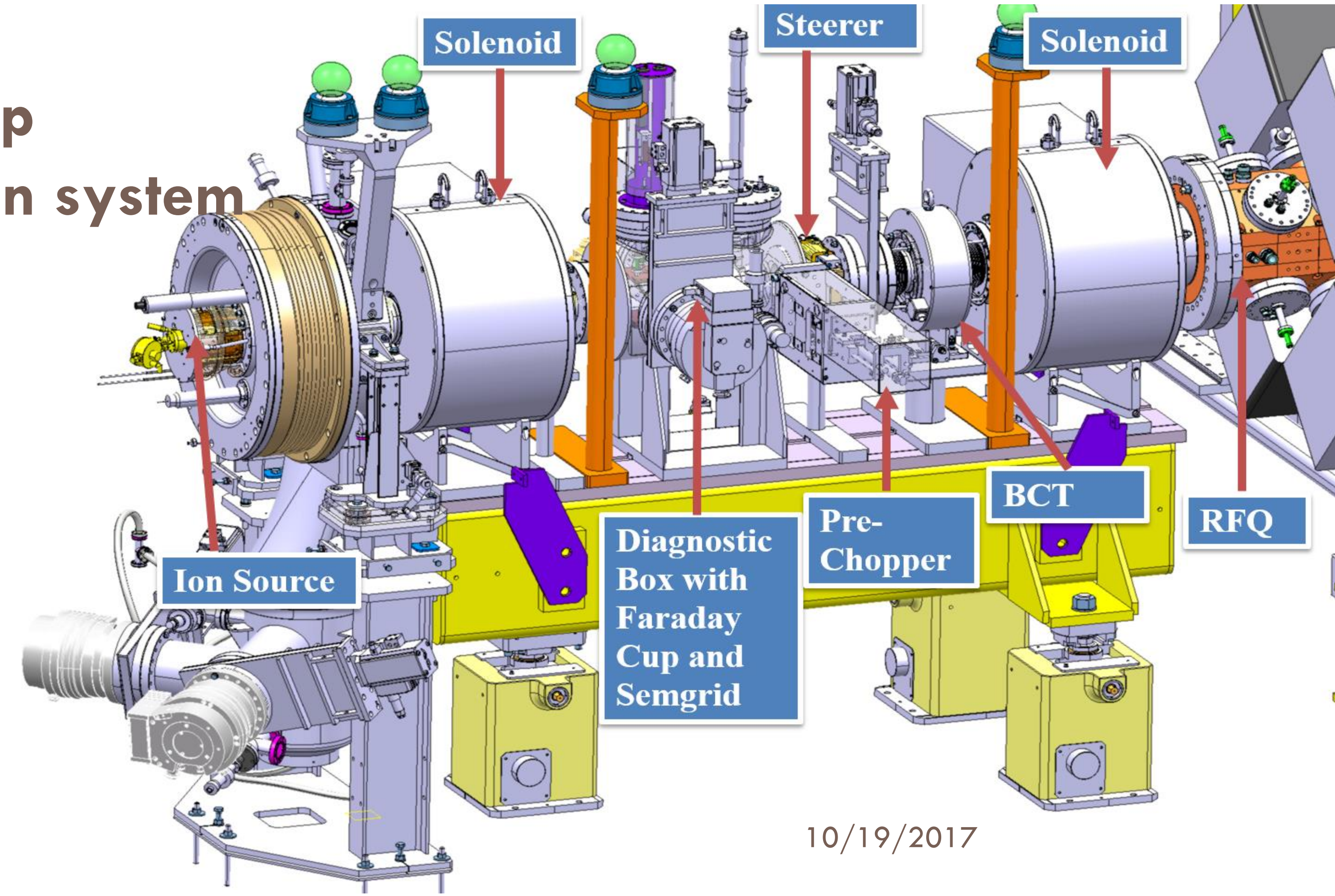


Comparison between the matrix code and the 3-D simulations including space charge

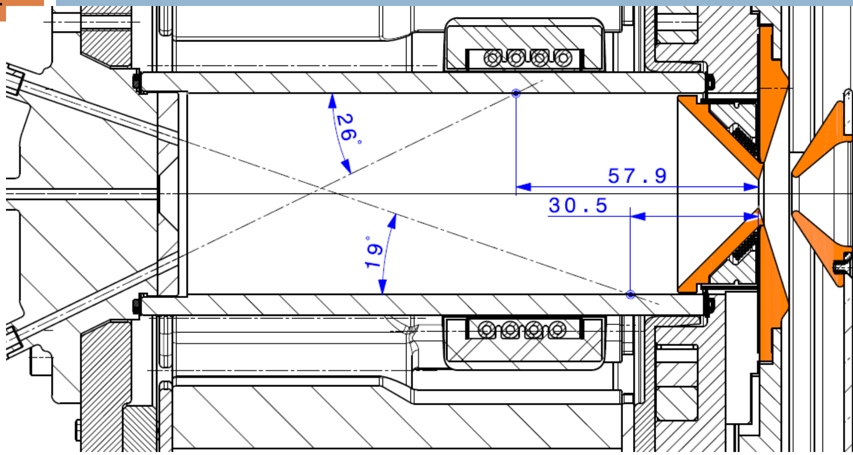
- Sometimes there is not other option….

Linac4 Low energy beam transport

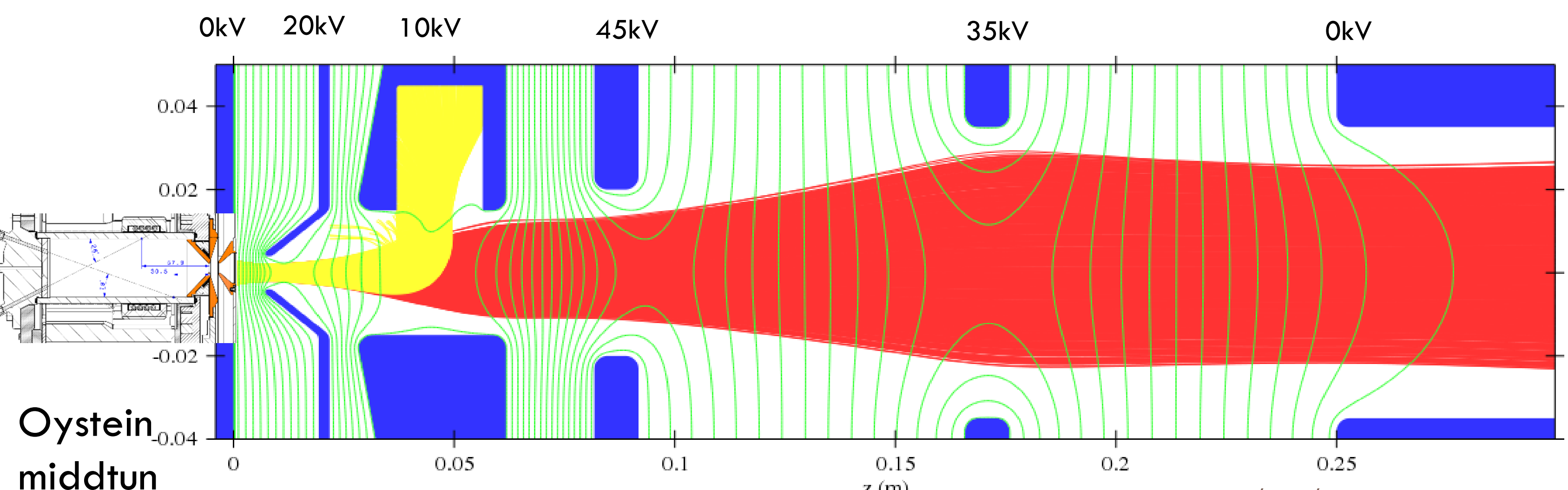
- Source
- Multi step extraction system
- LEBT
- RFQ



Linac4 Ion Source and extraction system



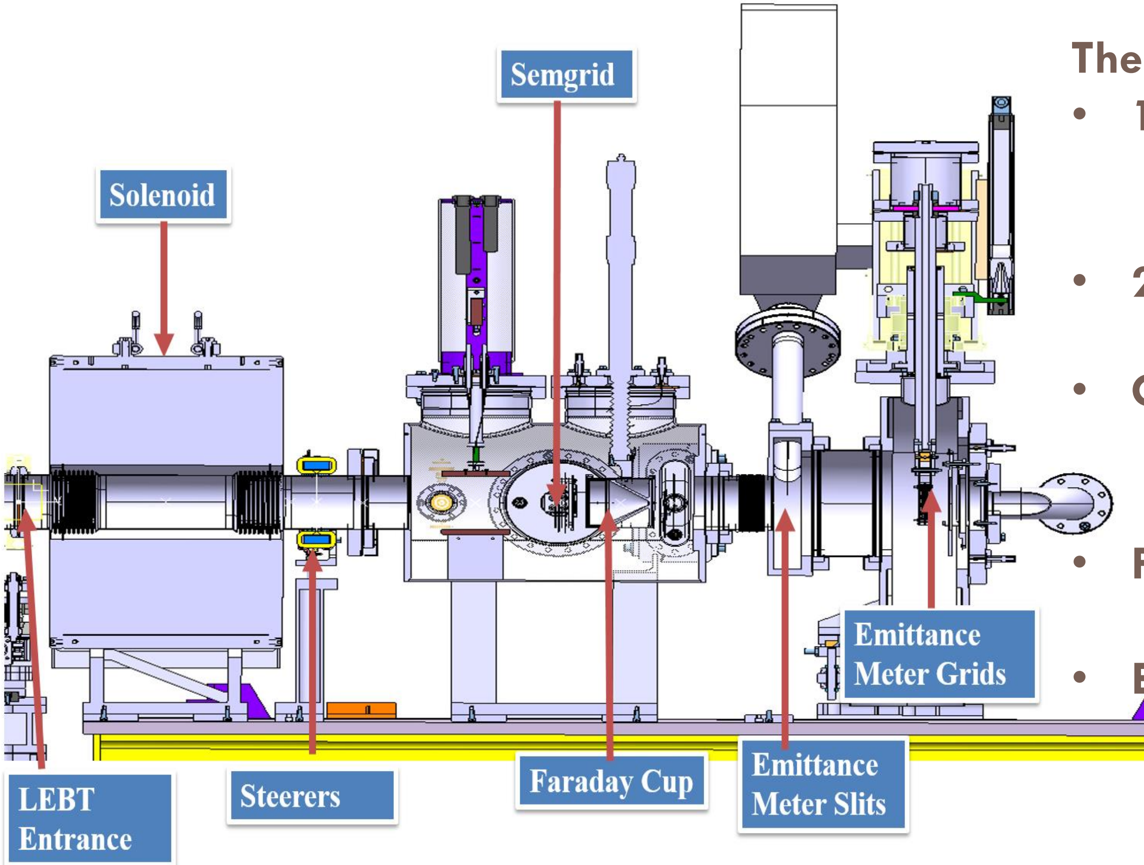
- Plasma is created using 2MHz RF in a solenoid coil.
- The H- is produce in the plasma volume and surfaces
- A surface near the extraction is coated with cesium, evaporated from an oven at the back of the source.
- The plasma ions strike the cesium surface and H- are emitted.



Oystein middtun

- Electrons (yellow) are extracted along with negative ions (red).

Linac4 Test stand

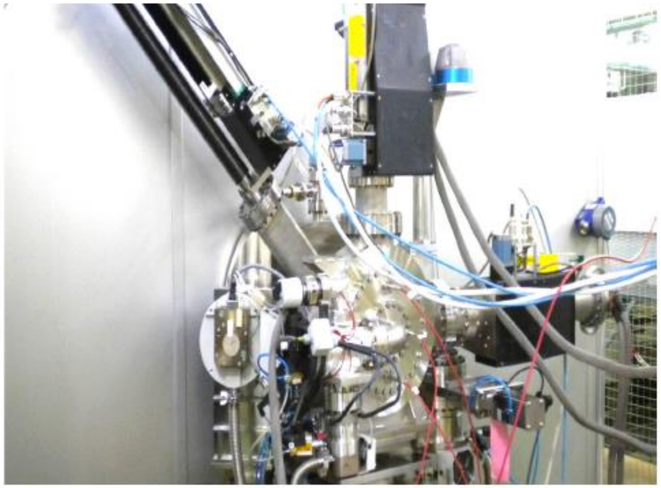


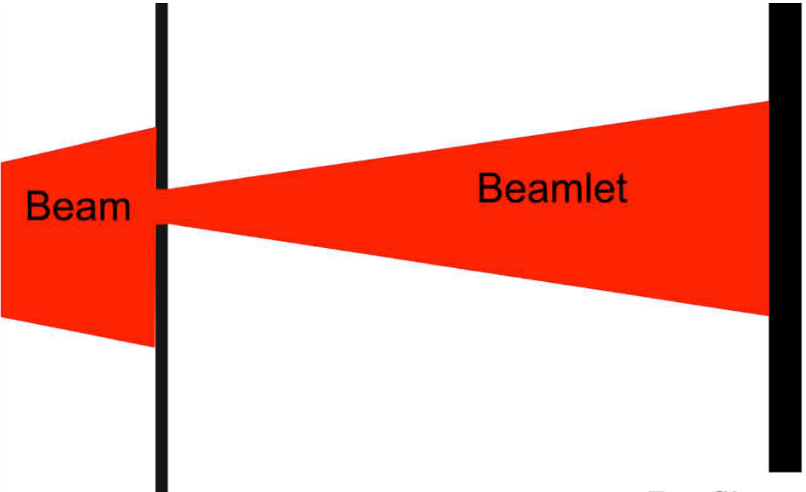
The system include:

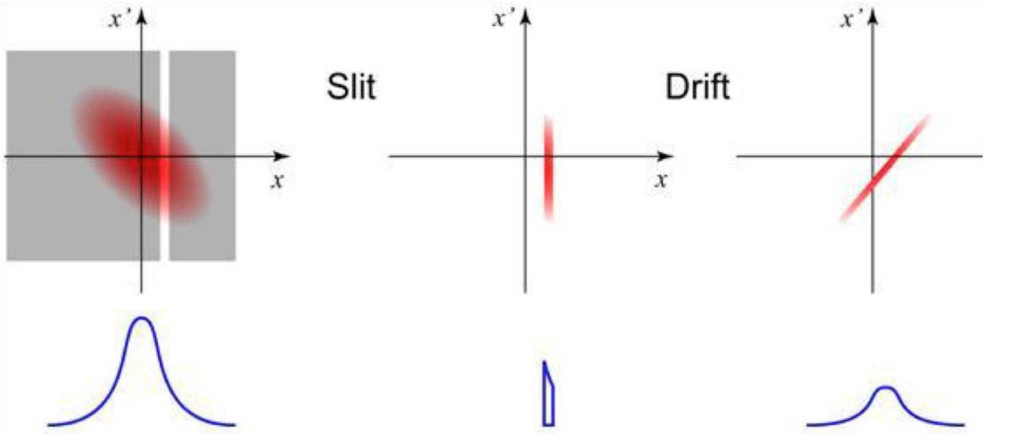
- 1XSolenoid
  - Beam focusing
  - Matching
- 2XSteerers
  - Correct beam center alignment
- Gas Injection
  - Controlling space charge compensation degree
- Faraday Cup
  - Beam current measurement
- Emittance meter
  - Phase space measurements

Emittance meter

- Phase space measuremnts in both planes $X(Y), X_P(Y_P)$
- 0.5mm resolution in X
- 1mrad in X_P
- Time resolution $6X10^{-6}$ s

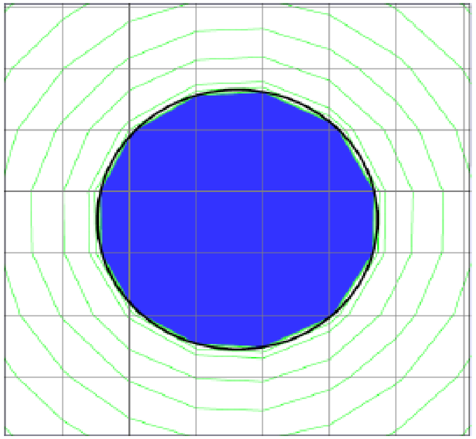




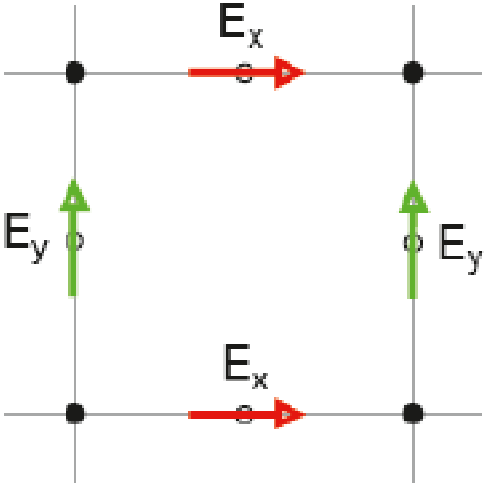


3-D Simulations

- The Code Ion Beam Simulator (IBsimu)
- • Libraries in C++
- • It has been used to design extraction systems in
- several experiments including Linac4



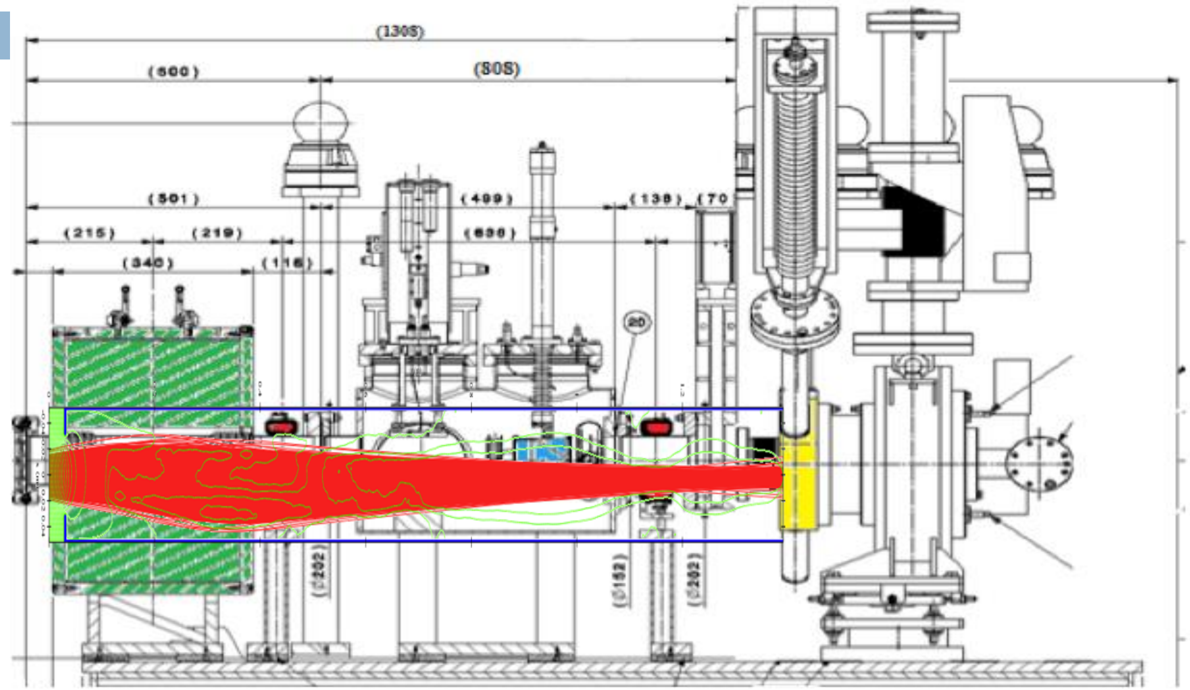
Electric potential (Green line)
Solids (blue)



1) T. Kalvas, et. al., "IBSimu: A three-dimensional simulation software for charged particle optics", Rev. Sci. Instrum. 81, 02B703, (2010).

Simulations

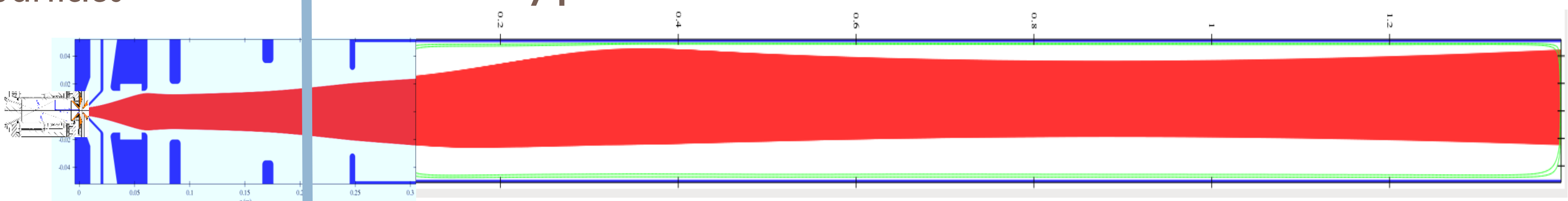
Source



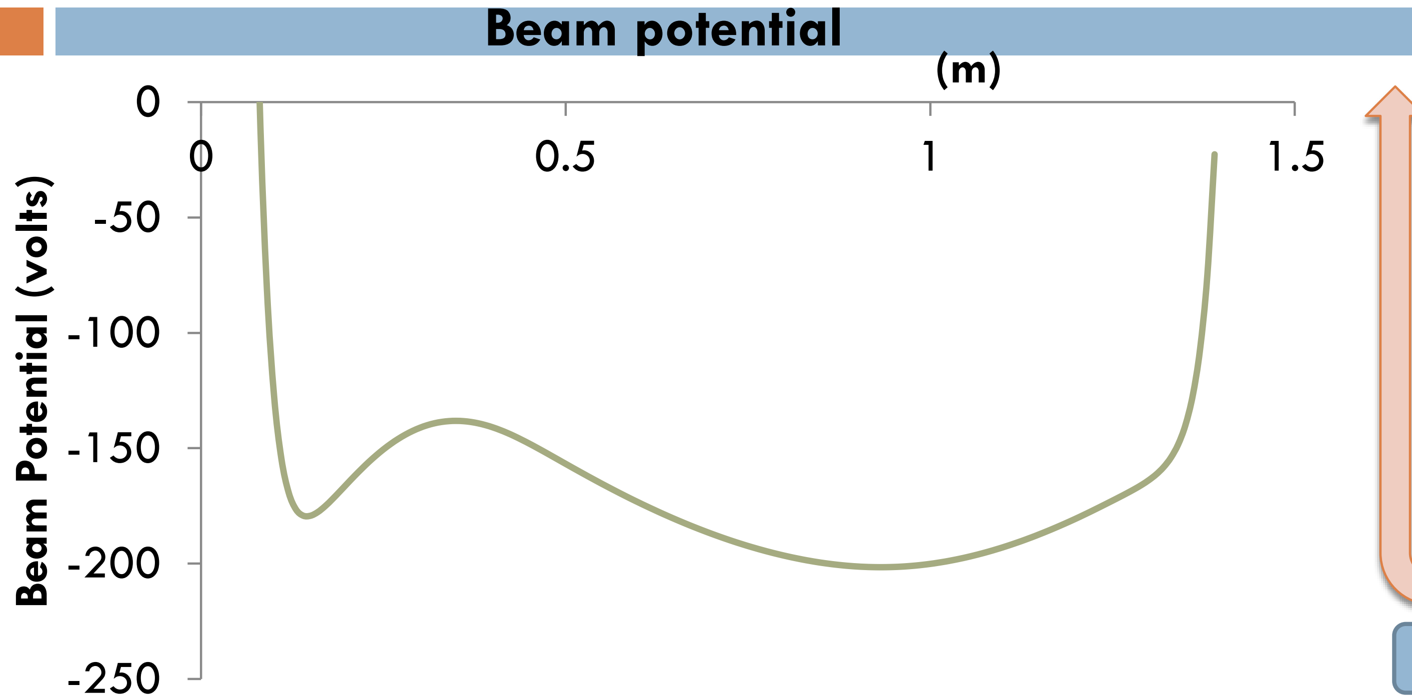
High voltage clear secondary particles

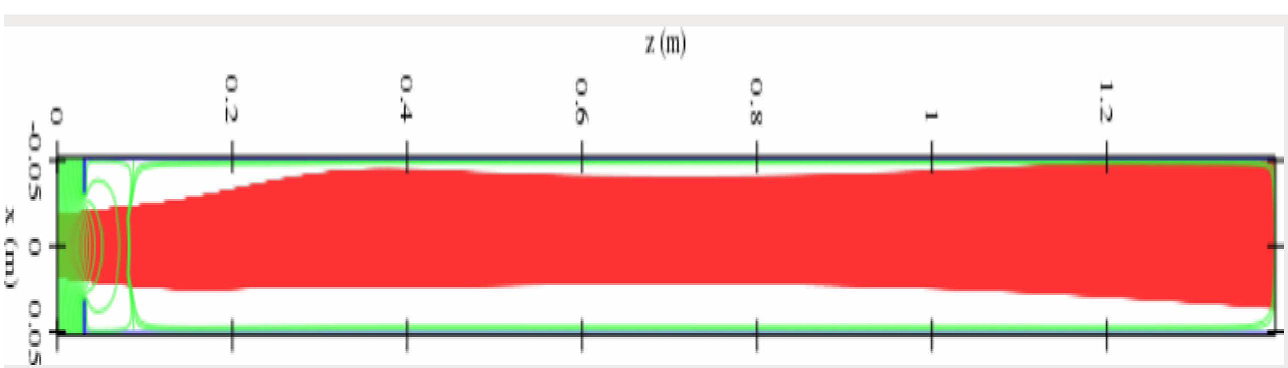
Solenoid Faraday Cup Emittance meter

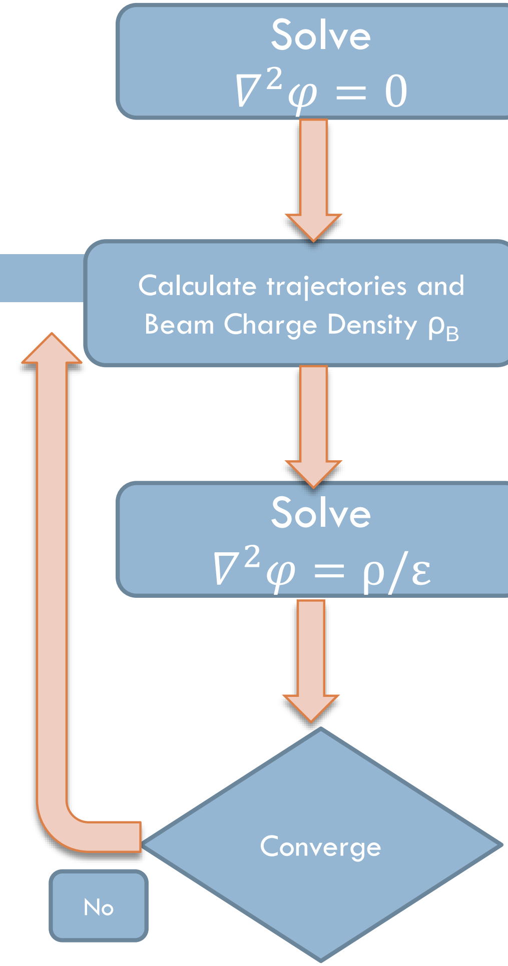
Secondary particles are included



Beam transport first solution

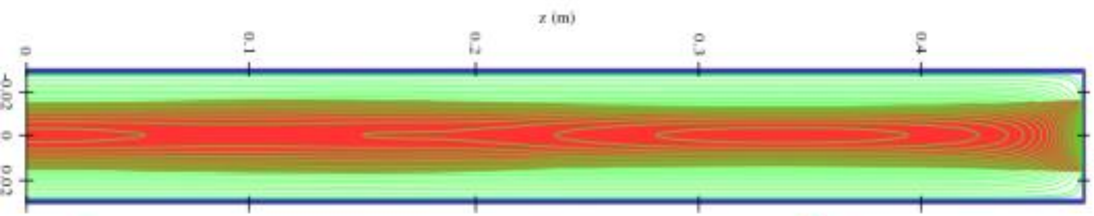


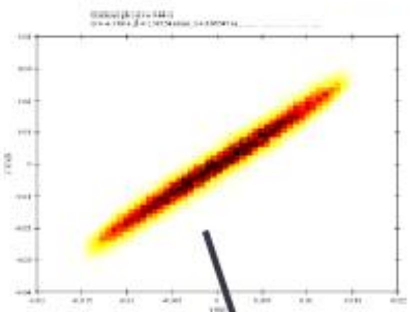




Classic neutralization simulation

Ions(Red)

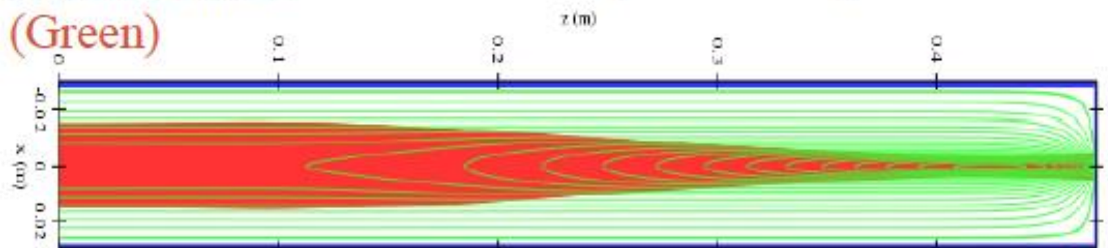


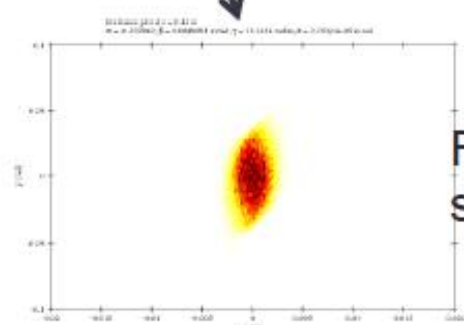


Beam Direction

Potential lines (Green)

20% space charge

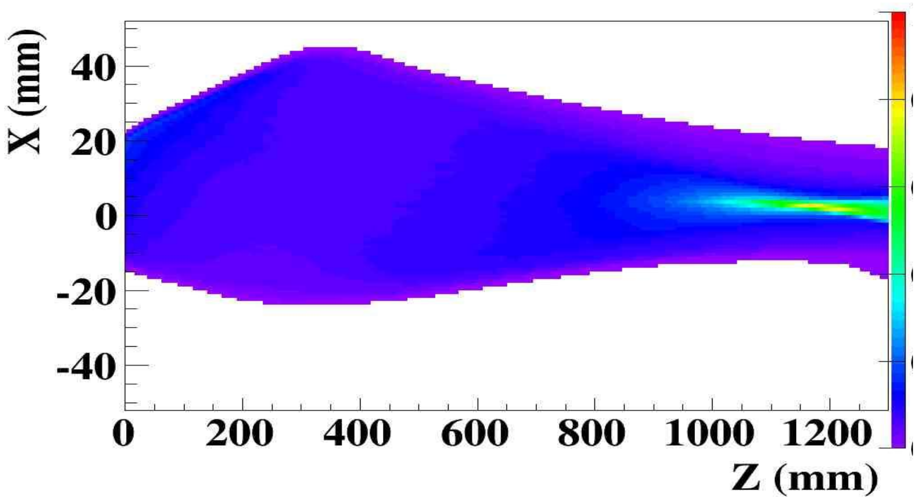




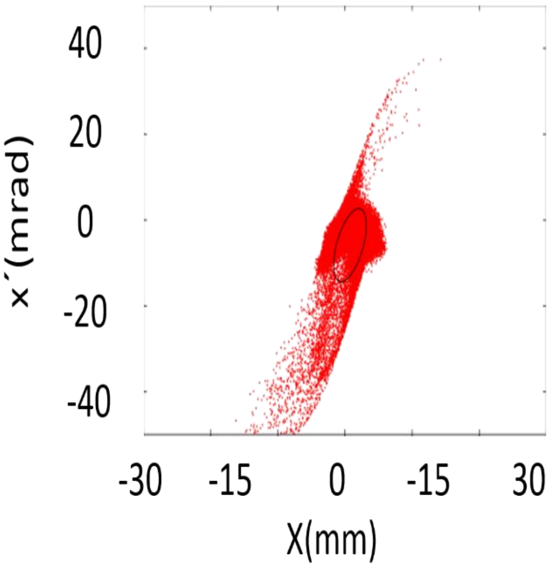
Frozen model simulations

Space Charge compensation using Frozen model

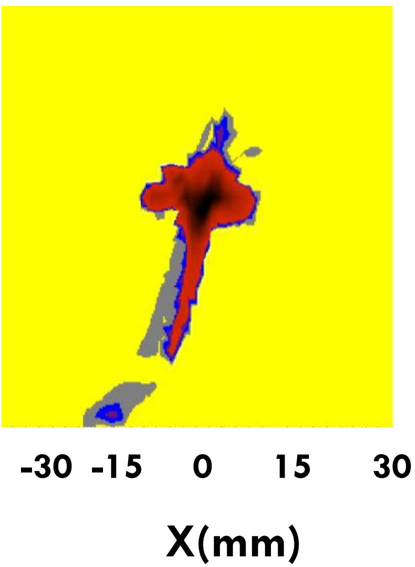
- Beam Current 35 mA



Simulation



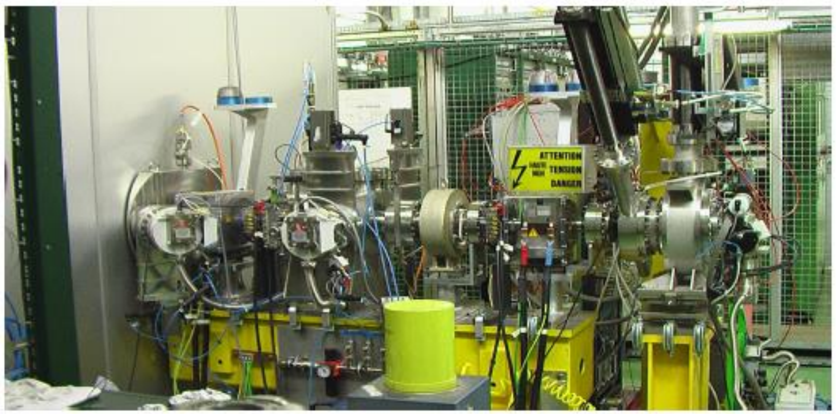
Measurements

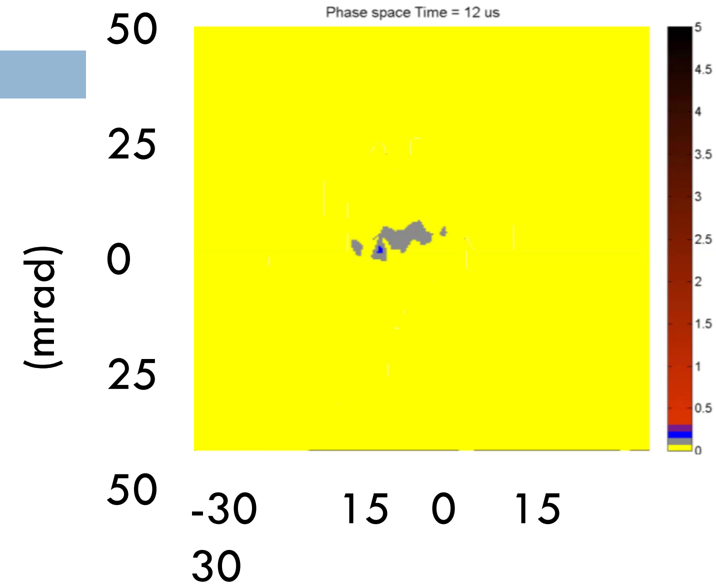


Emittance mm.mrad (norm) : 0.29 0.55

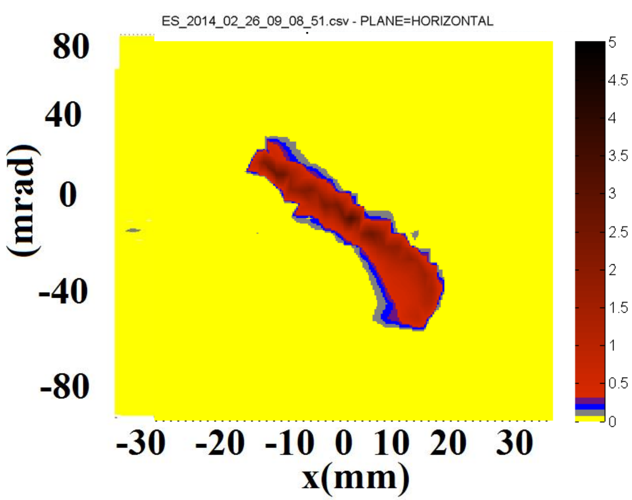
The absolute value of the emittance is almost 200% bigger in measurements

Measurements

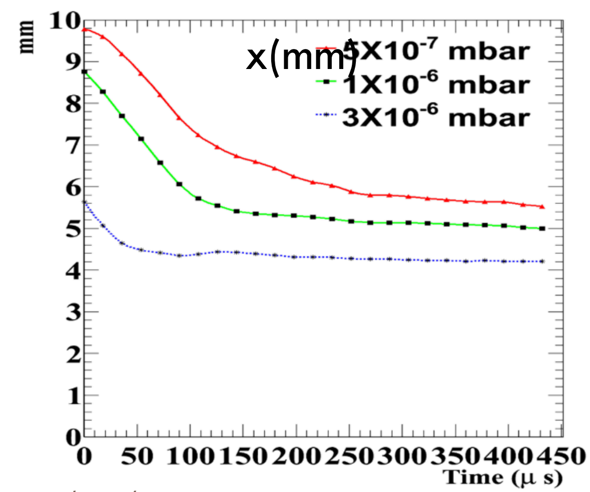




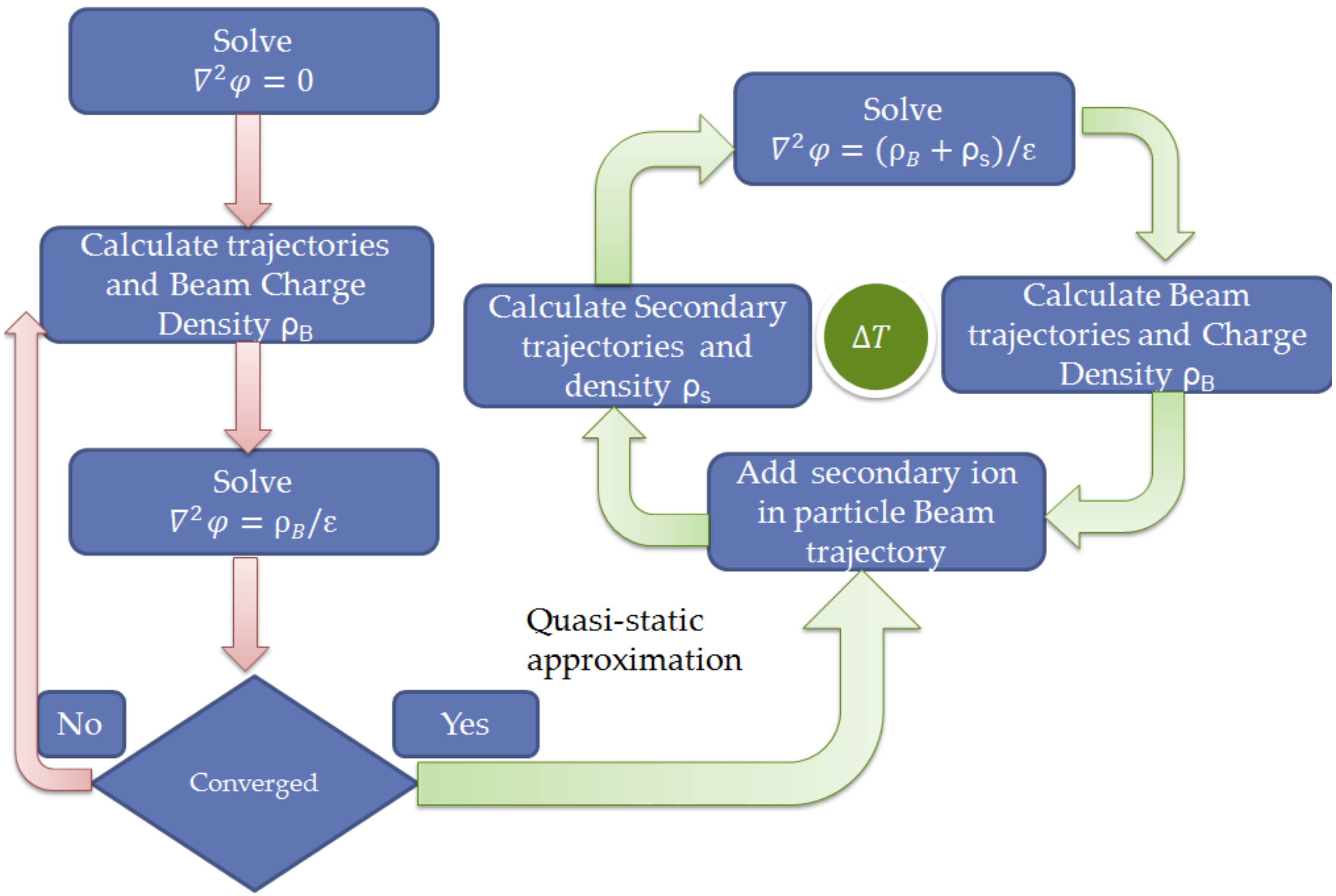
Phase space plot



Evolution on time of the beam size in the emittance meter position With different pressures in the beam pipe



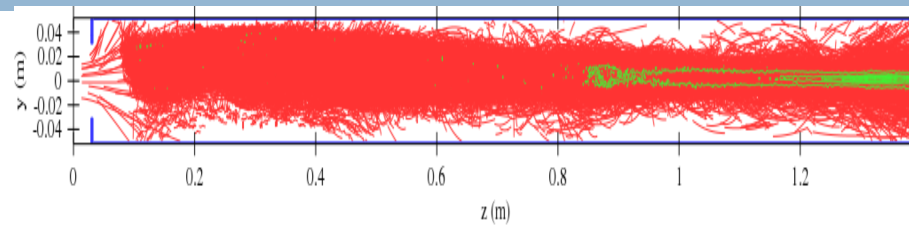
SCC simulation



A new routine has been created to carry the SCC using secondary ions

Scc simulationwith secondary particles

- **We include the secondary particles created by the gas collision by using a montercarlo generator.**
- **This generator take into account the mean free path of the H^-**
- **The beam was tracked during time steps equal to the emittance meter resolution in time; $6x10^{-6}$ s**
- **The input beam was generated also Ibsimu**



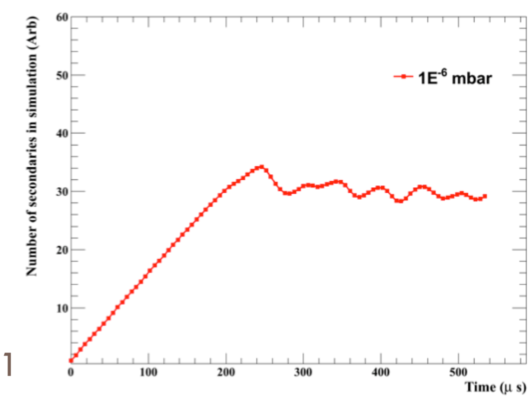
Secondary particles in the System

$$\sigma(E) = 2.5 \times 10^{-20} m^2$$

$$L = \frac{1}{\sigma(E) n_{H2}}$$

Pressure $1x10^{-6}$ mbar

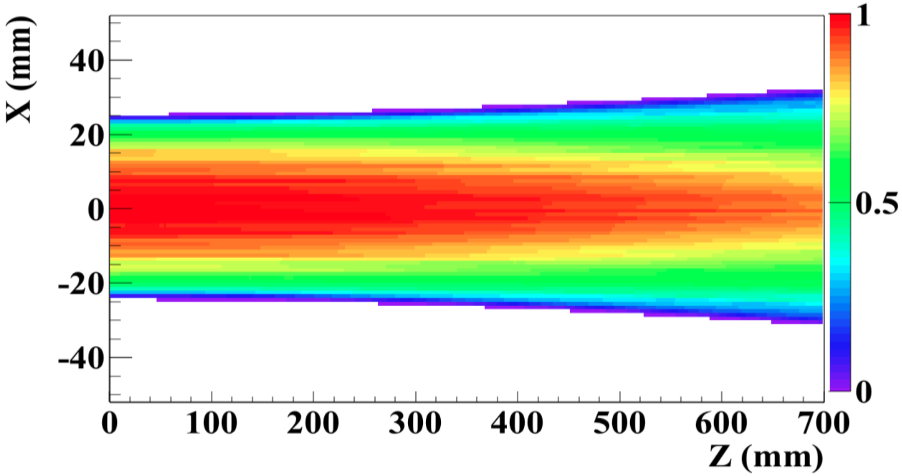
Secondary particles trapped in the bam

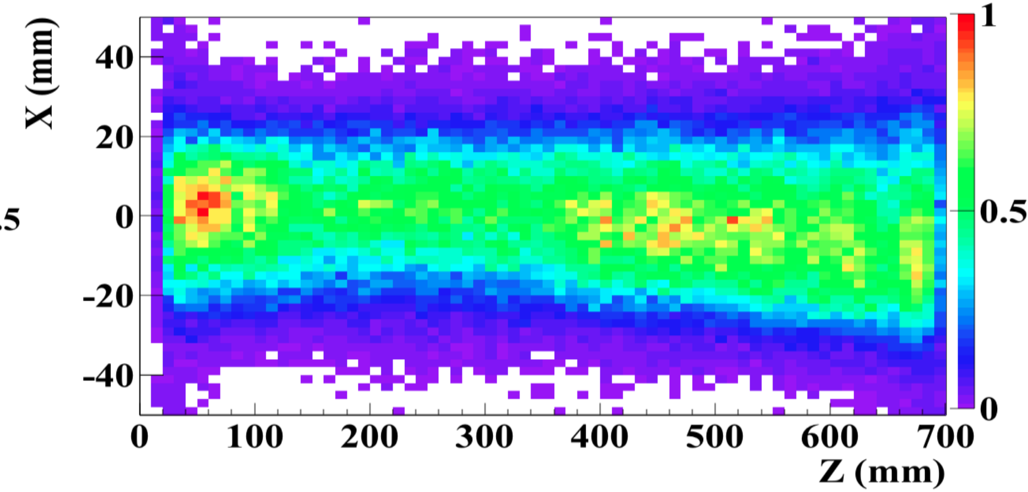


Drift simulation

100 V

0 V



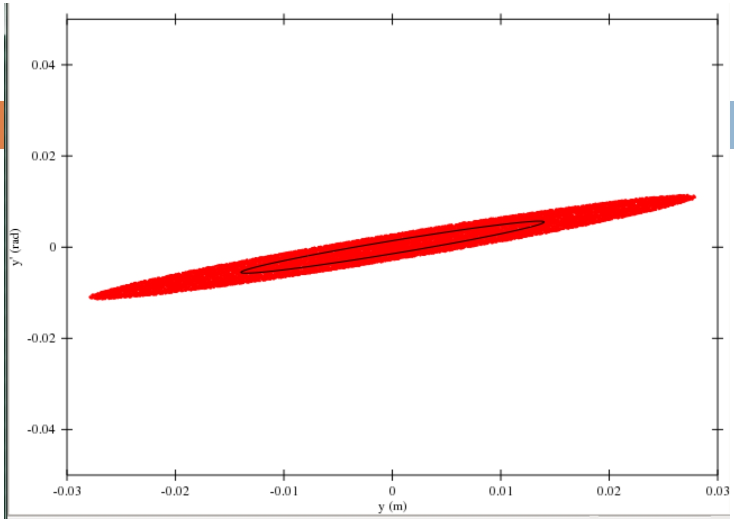


To separate the LEBT and Source effects we simulate a drift to simplify the problem
The solenoid is not necessary to transport the beam at the end of the system

Gaussian Beam
Emittance 0.2 mm.mrad (norm)
Energy 45 Kev
Beta = 8
Alpha=10
30 ma

Residual gas pressure ~2e-6 mbar

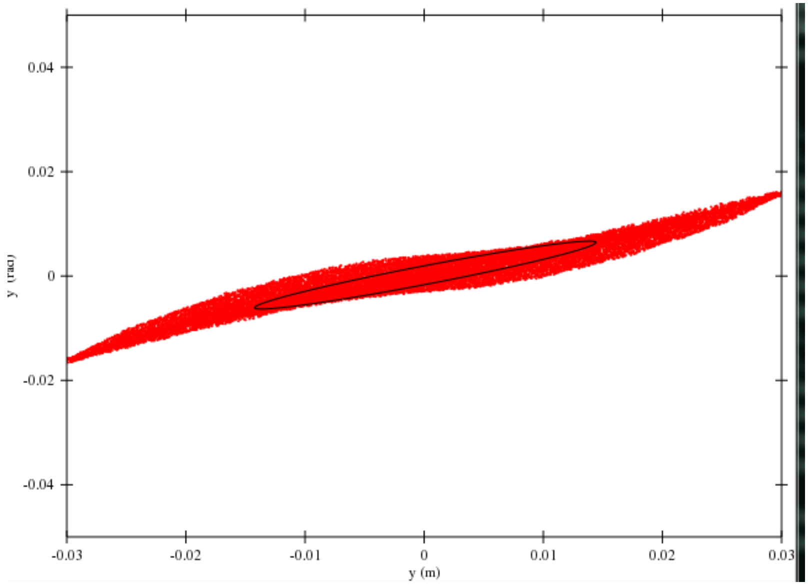
Drift results : Solenoid off



Frozen space charge 80% compensation

Emittance 0.20005 mm.mrad

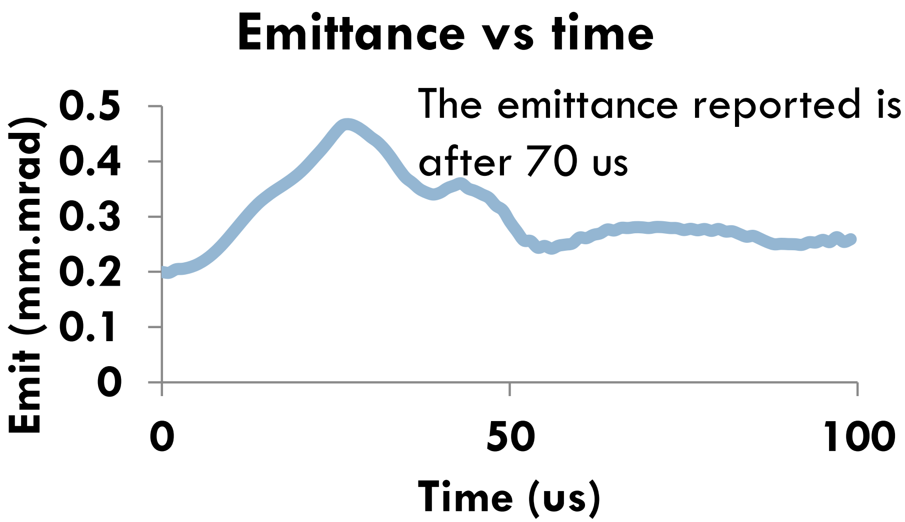
Emittance growth ~0



Secondary particles in simulation

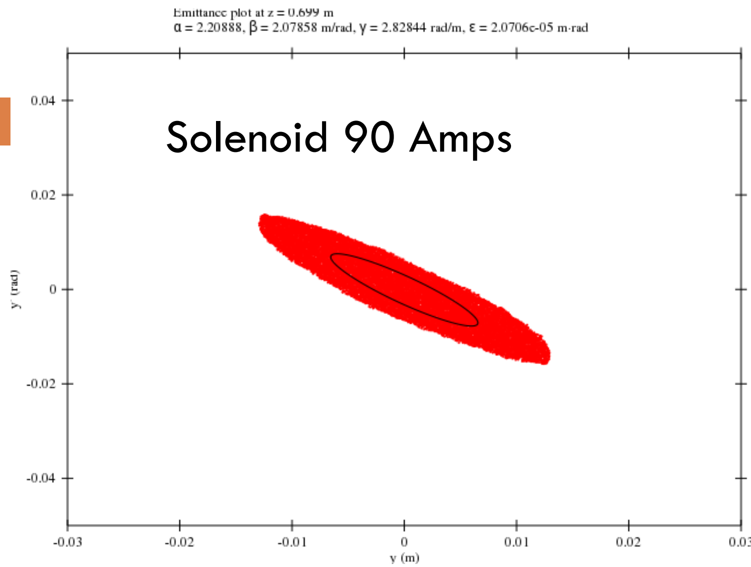
Emittance 0.26 mm.mrad

Emittance growth 28%

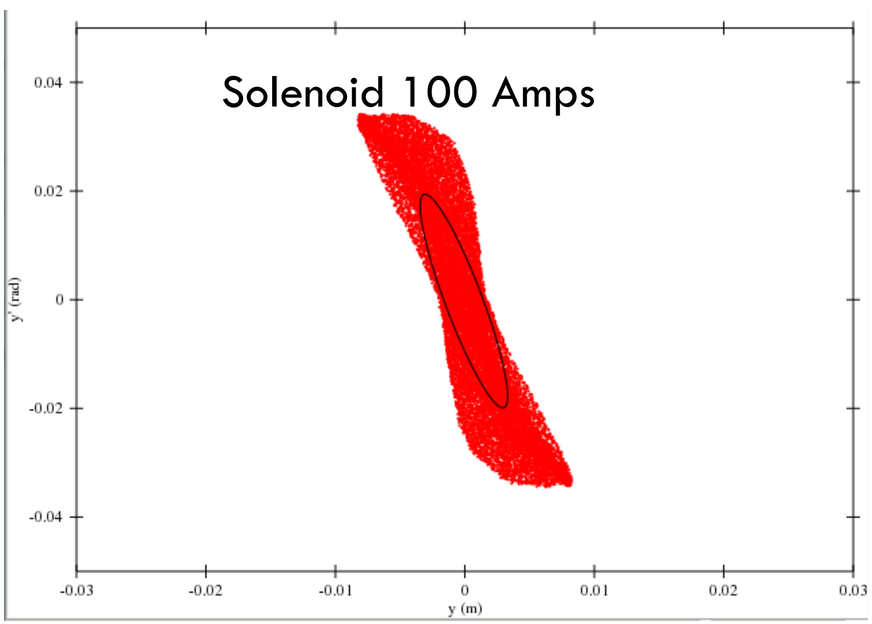


The emittance reported is after 70 us

Results : Solenoid on



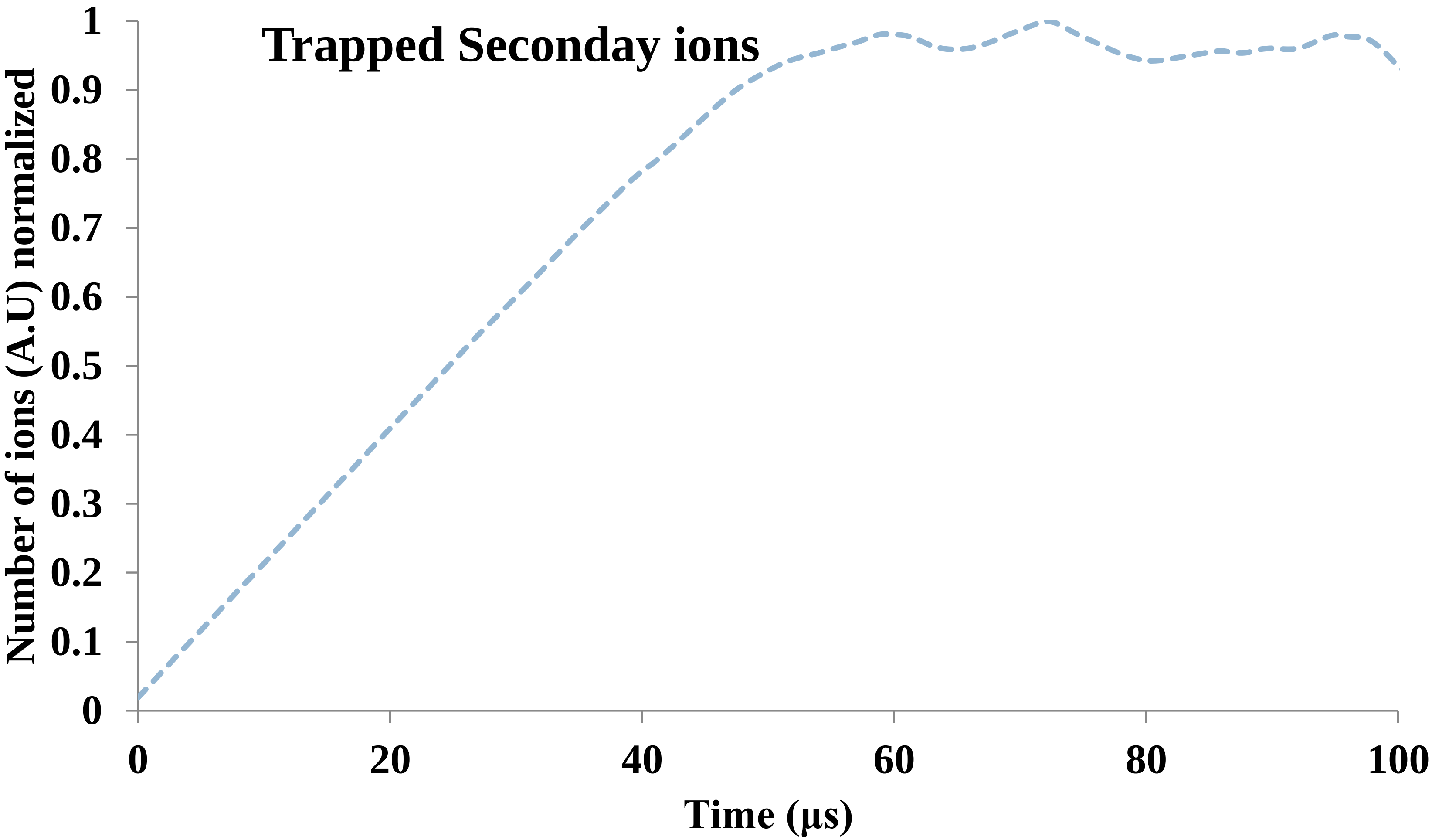
Frozen space charge 80% compensation
Emittance 0.207 mm.mrad
Emittance growth of 3%



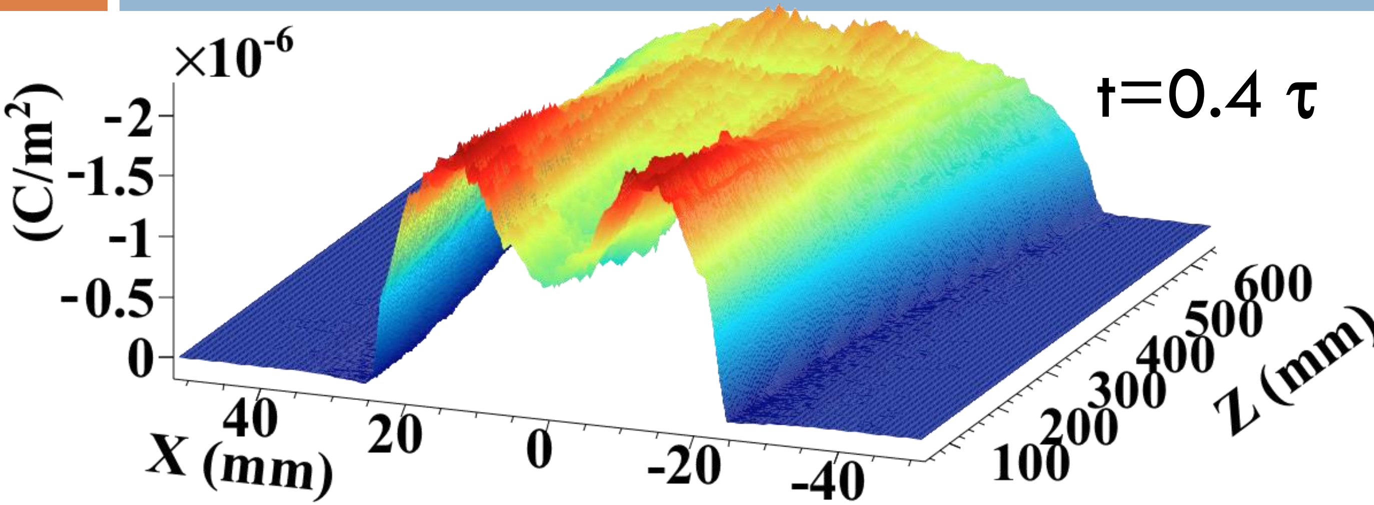
Secondary particles in simulation
Emittance 0.30 mm.mrad

Emittance growth of 50%!

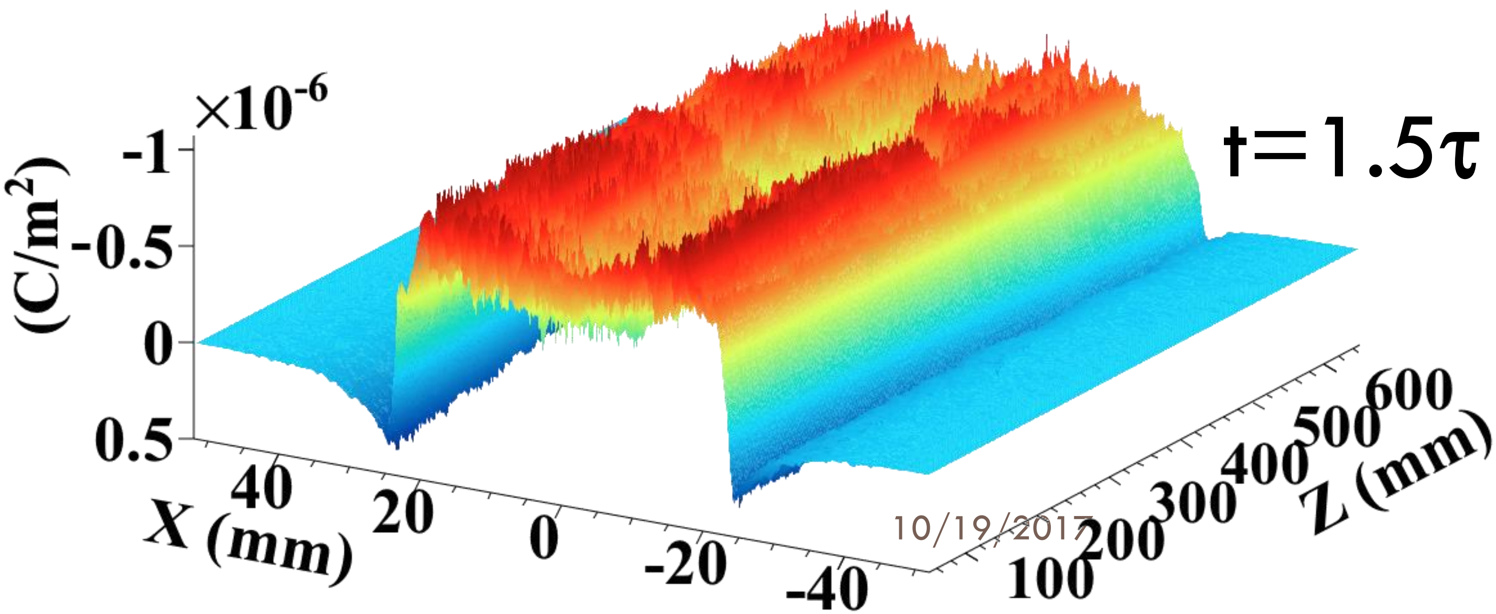
Secondary Ions in the system



Space charge evolution

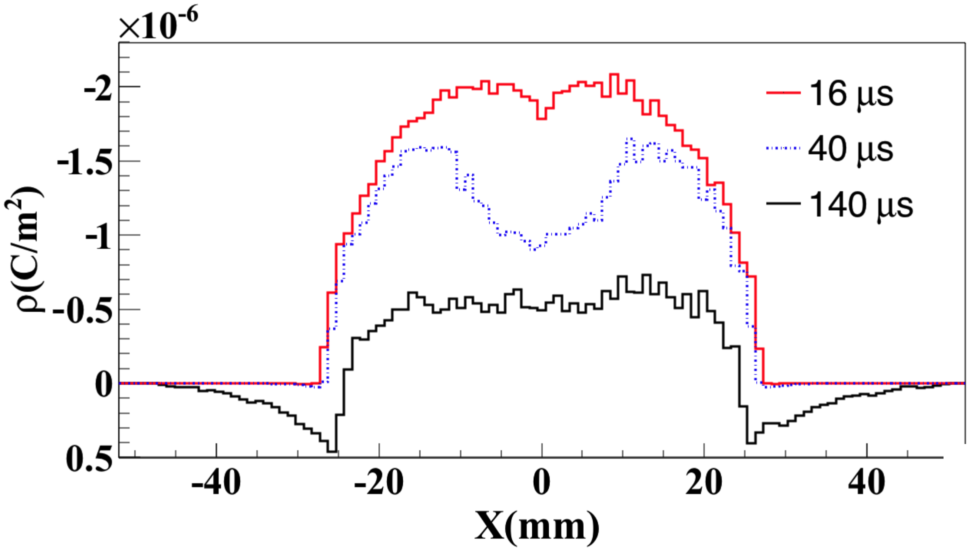


The secondary particles are accumulated in the beam center driving to a hollow space charge distribution

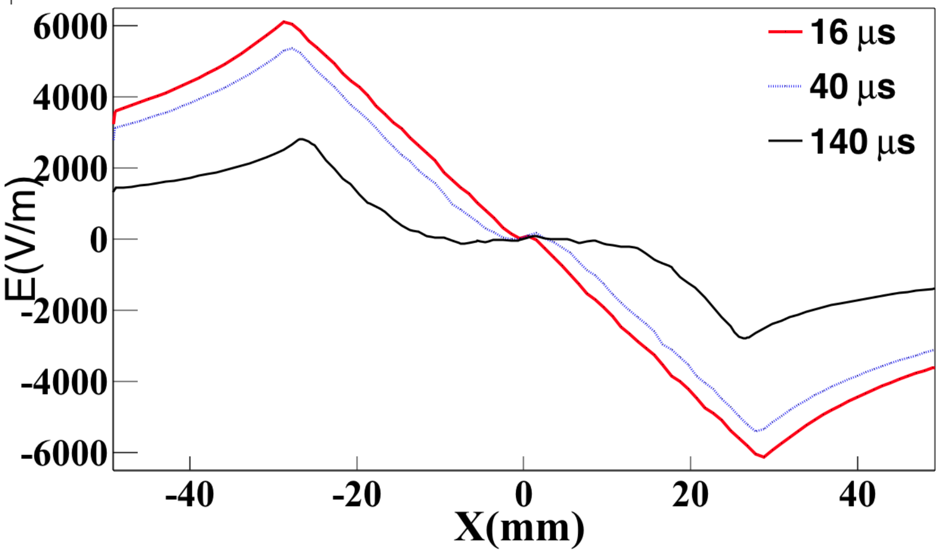


Space charge and electric field

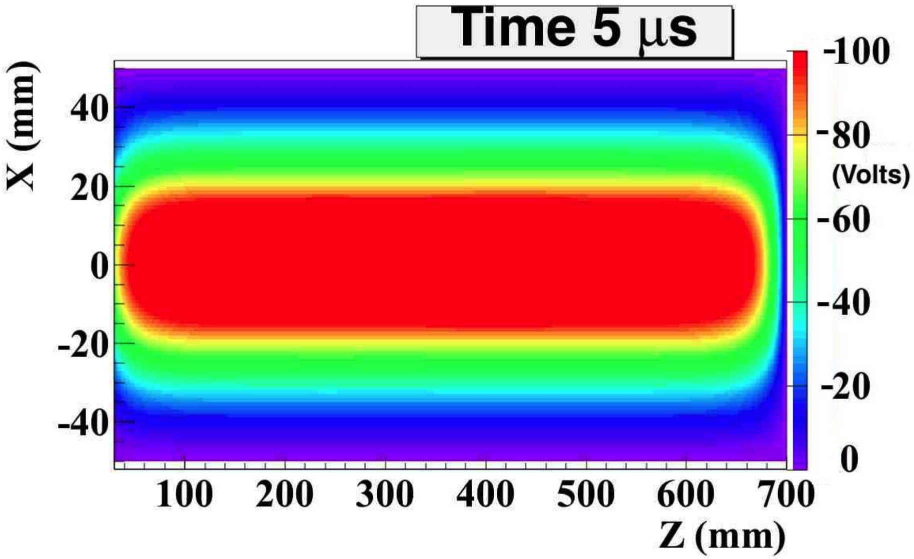
The space charge map is redistributed all around the beam volume

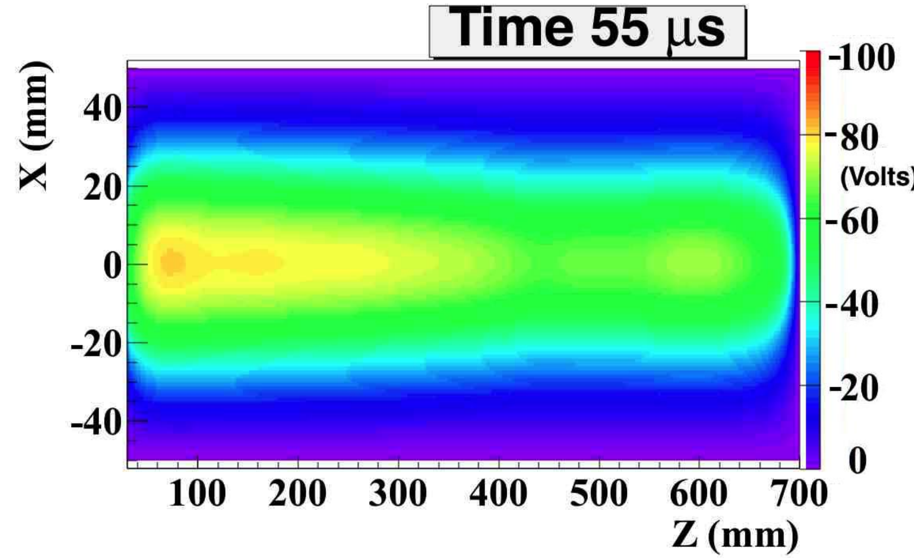


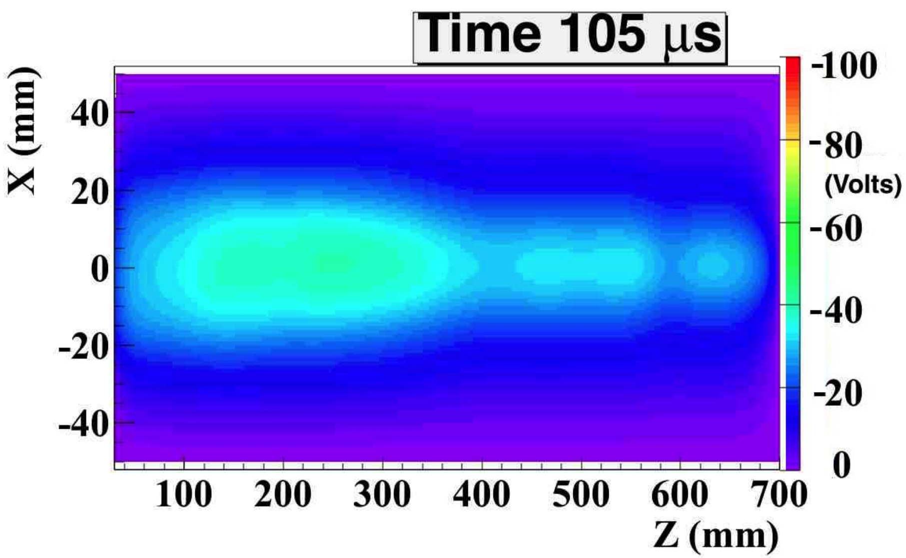
The SCC decrease the electric field but the resulting field is less linear than the field produced in the frozen model

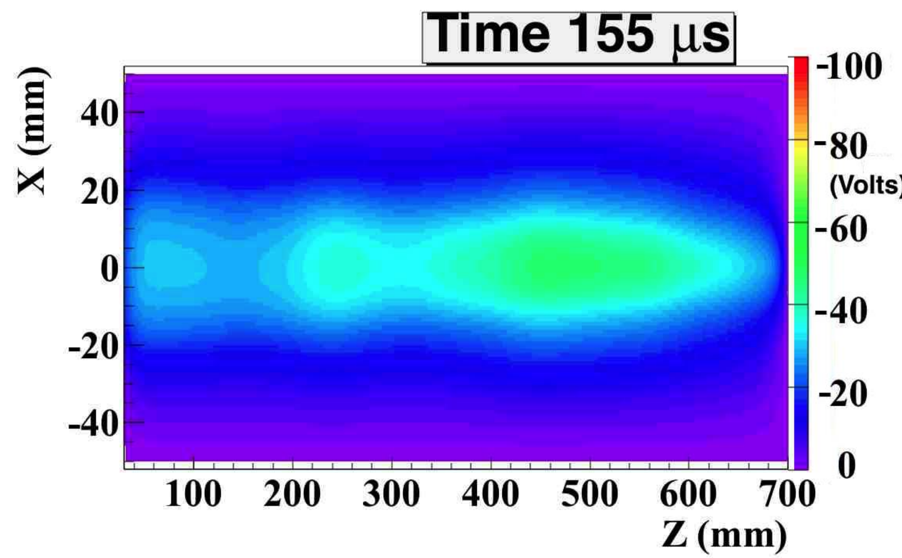


Electric potential



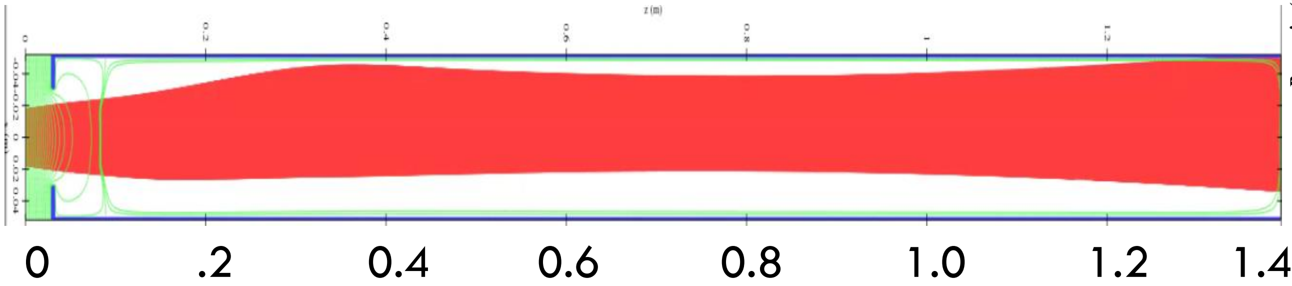


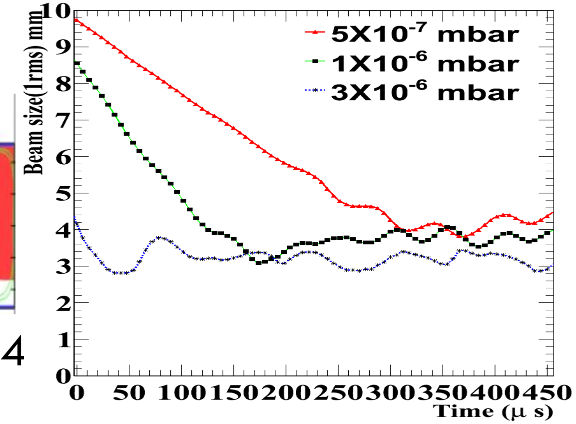




Simulations vs Measurements

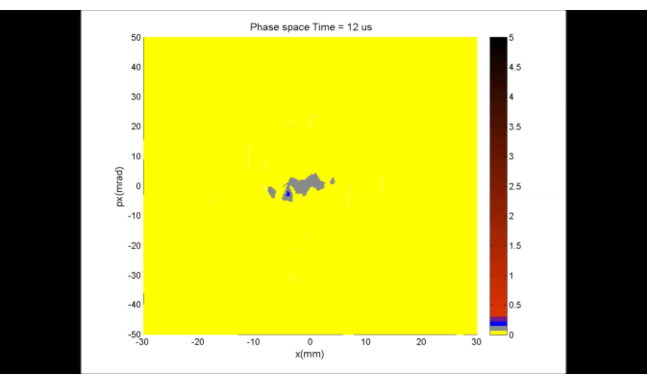
Beam profile evolution in x-z

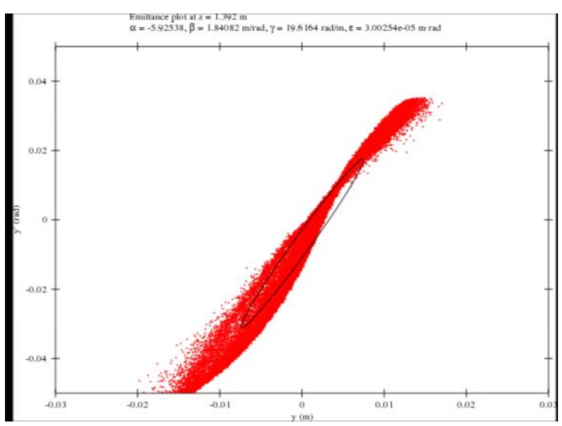


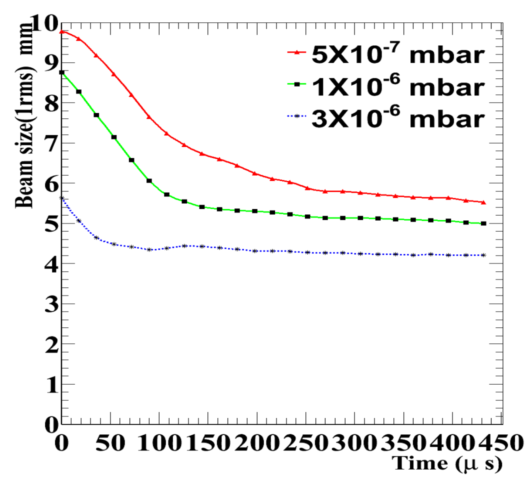


Beam size evolution in time

The evolution in time show a good match



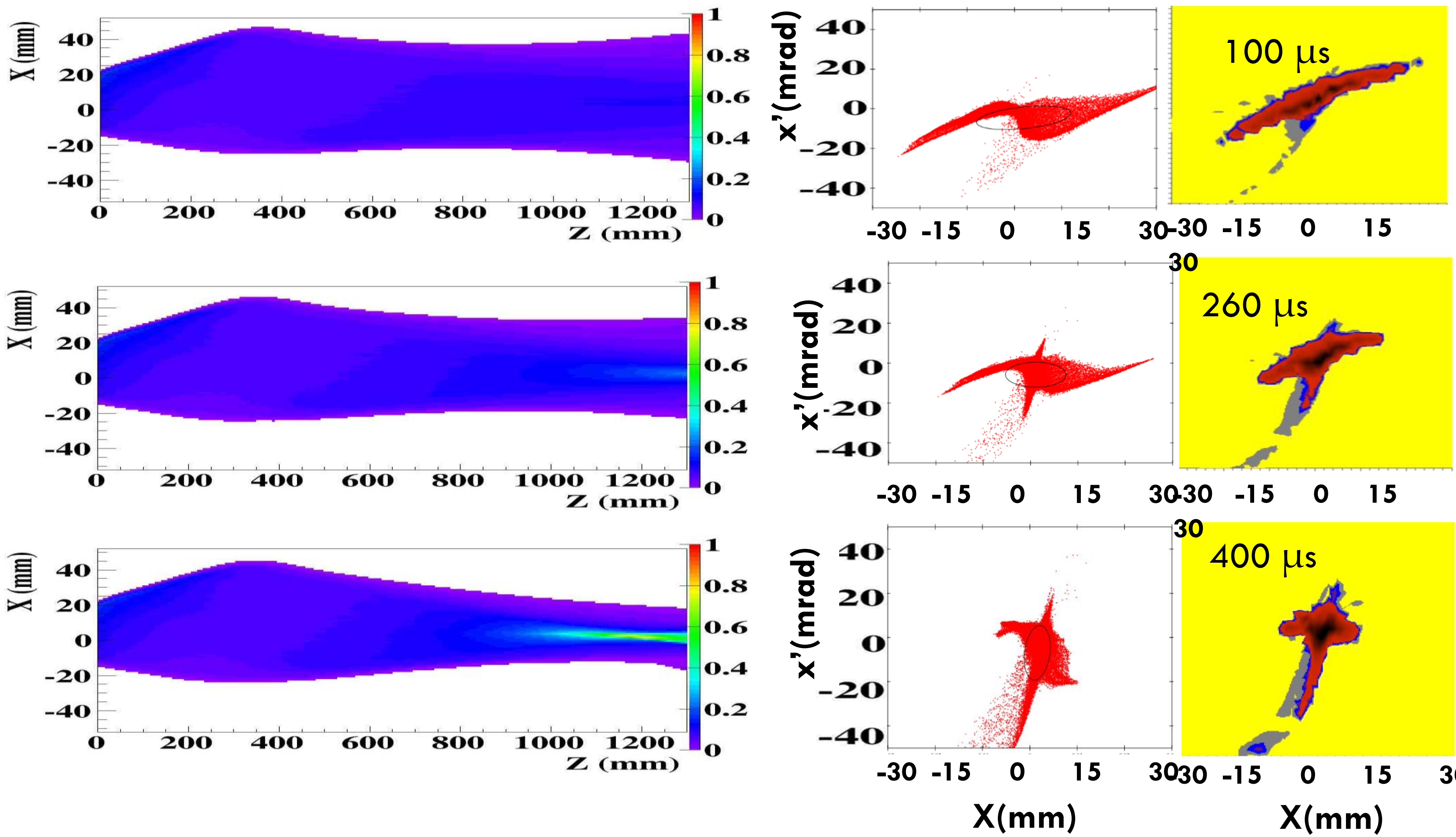




Space Charge compensation using H_2

- Pressure $1.2X10^{-6}$ mbar
- Current 35 mA

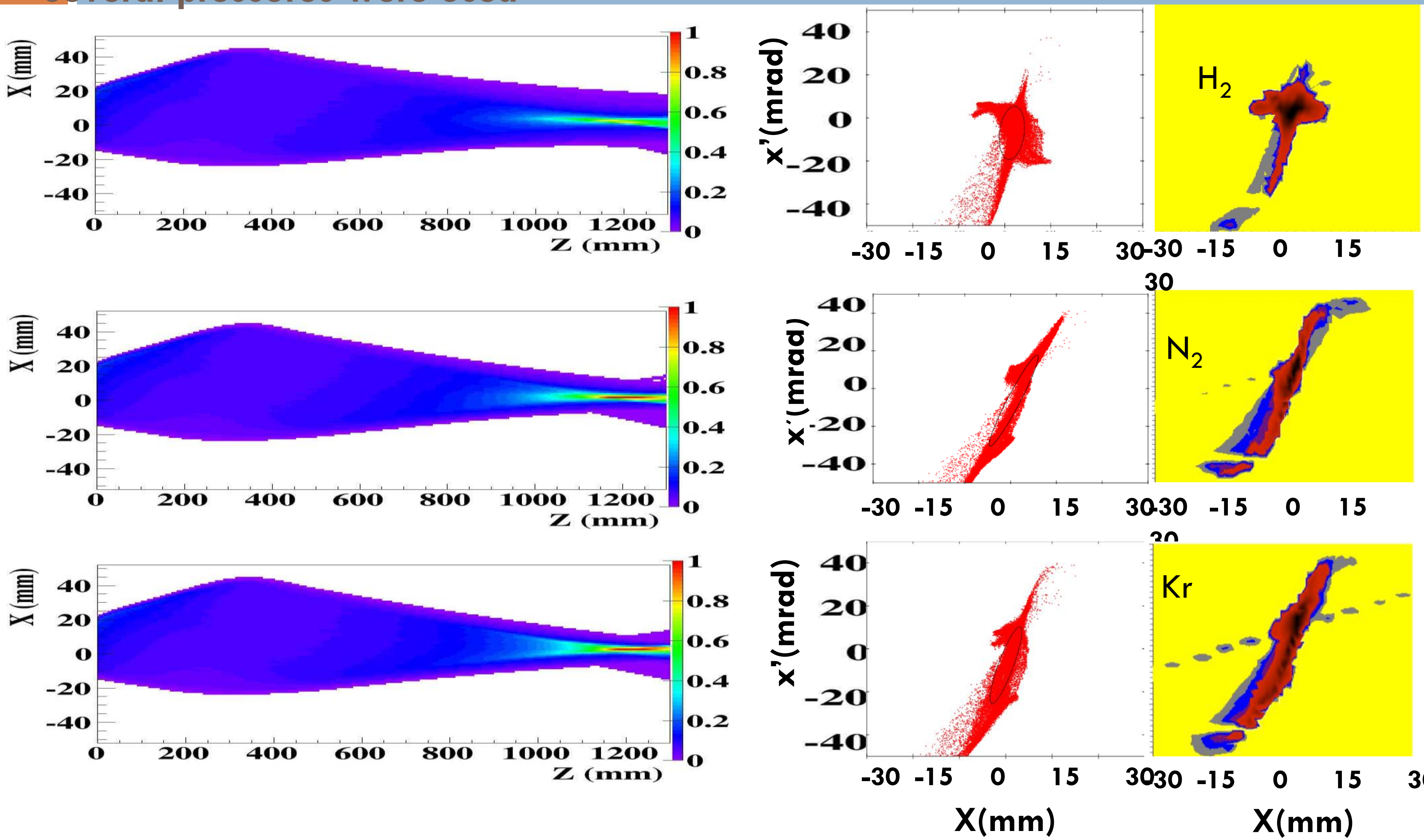
Simulation Measurements



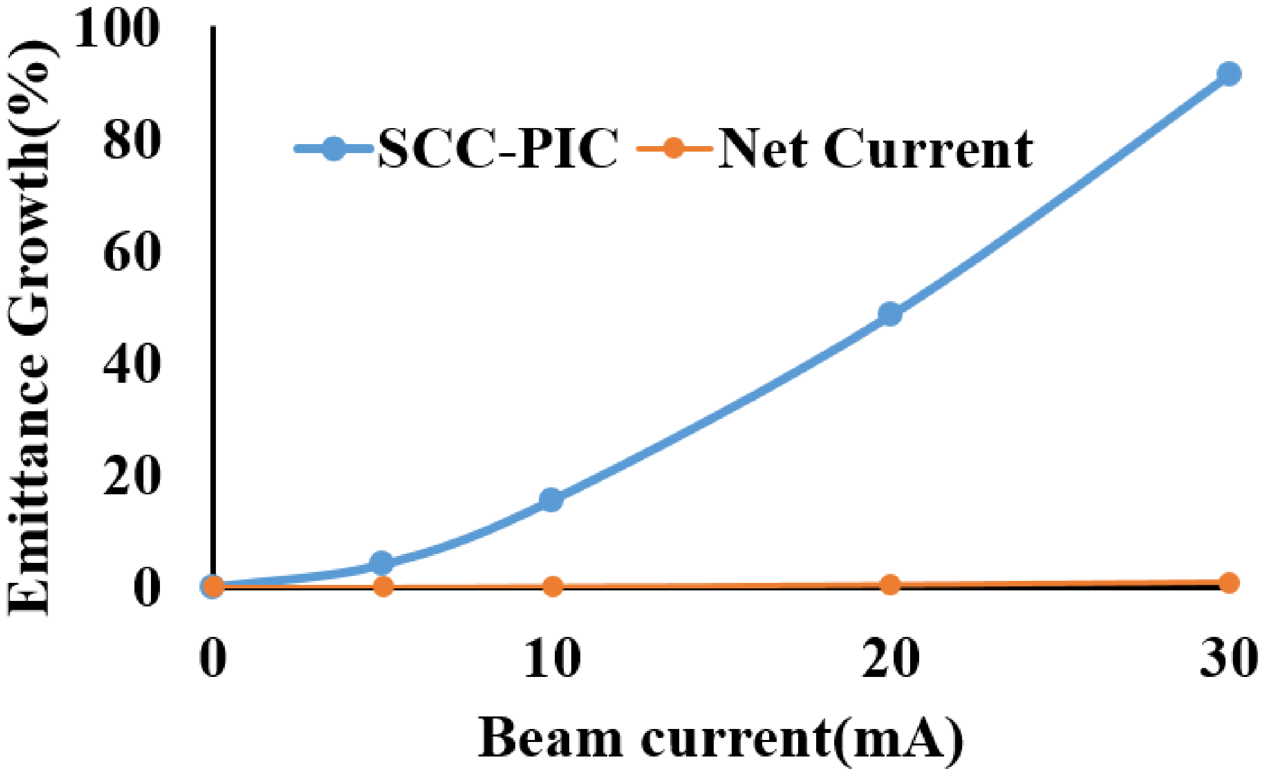
Compensation using different gases

- H_2 N_2 and Kr
- Several pressures were used

Simulation Measurements

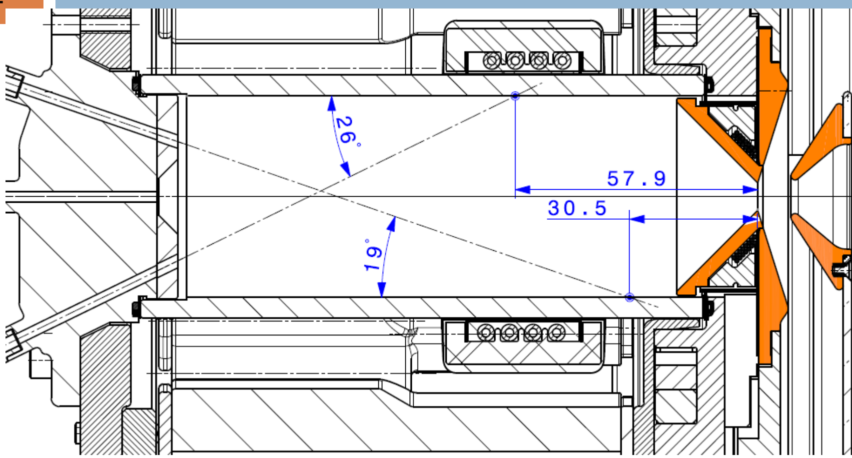


Emittance growth due neutralization

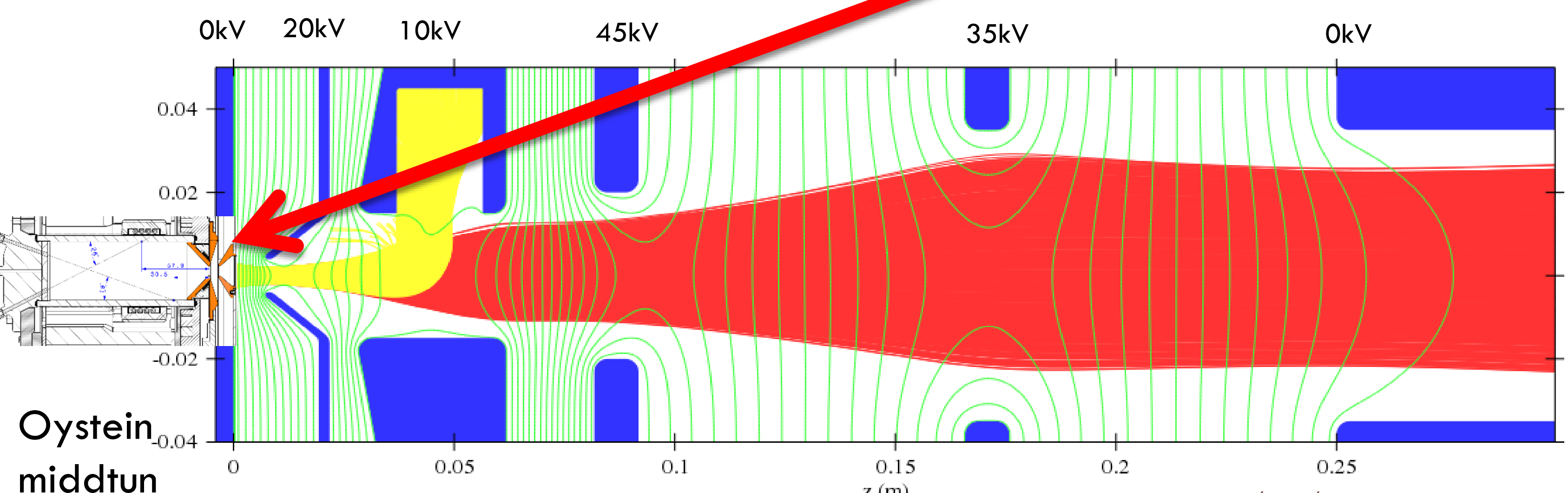


Results dor 5X10^{-7} mbar, the Emittance can be improved by increase the pressure but the beam losses increase

Going back to the source…



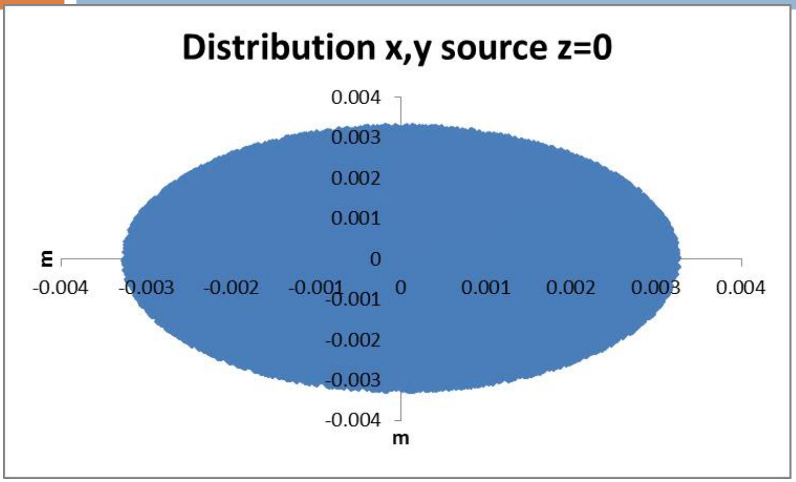
- Tracking back the ions we can comback to the plasma chamber and see where the halo particles are created



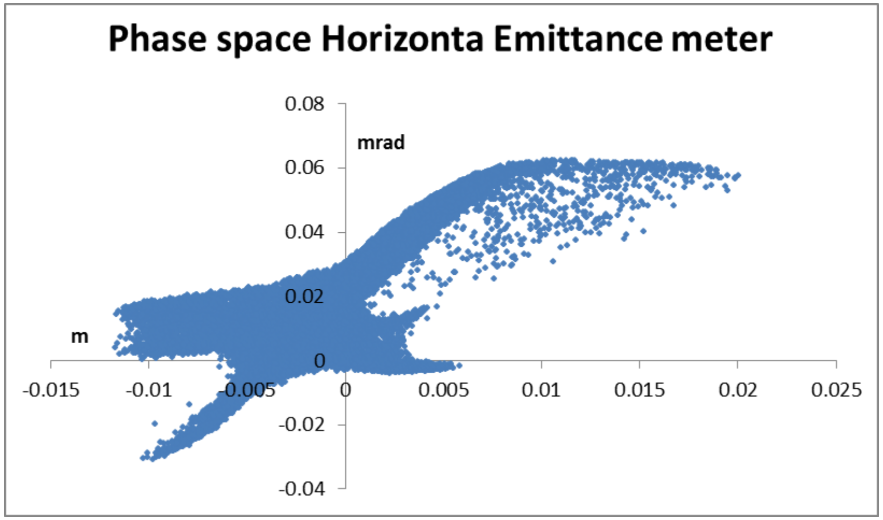
Oystein middtun

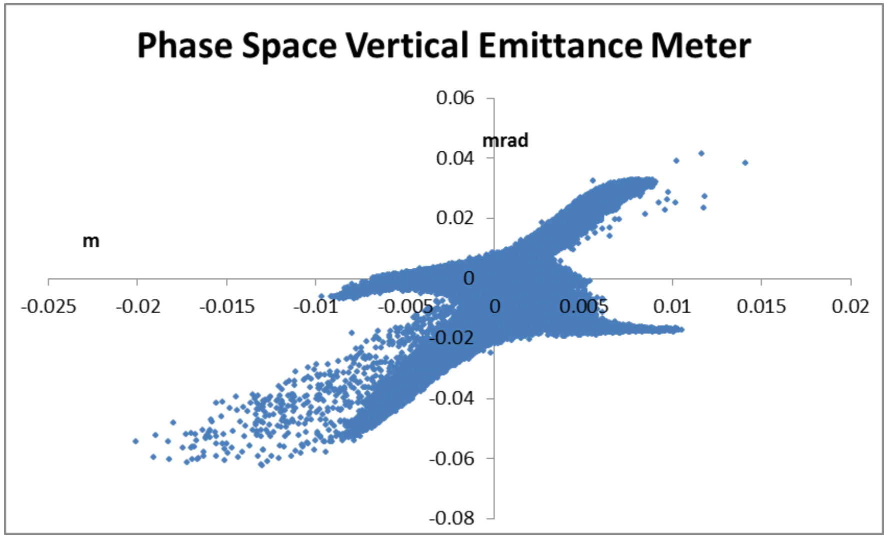
- Electrons (yellow) are extracted along with negative ions (red).

Distribution particles xy in the plasma aperture z=0 and phase space in emittance meter relation

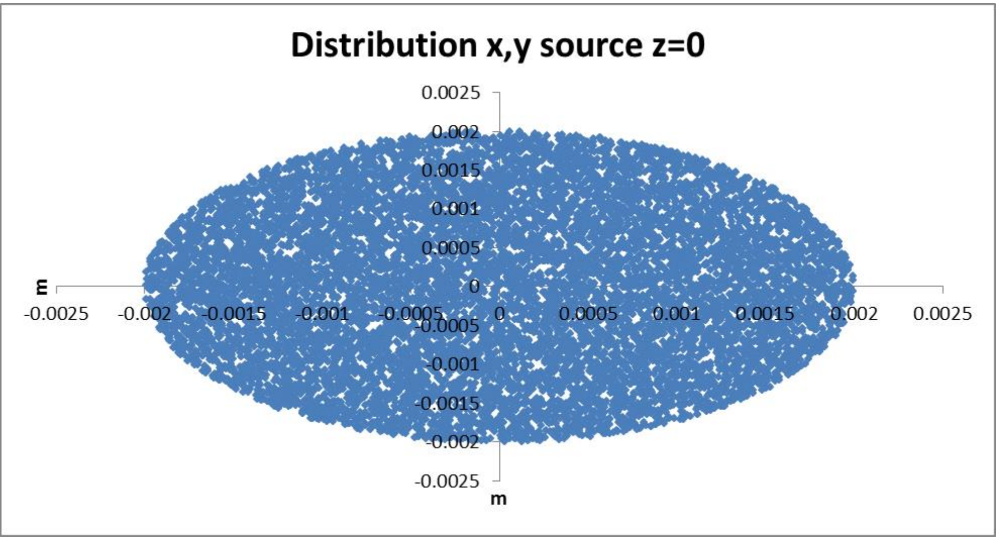


Total Current =-30 mA

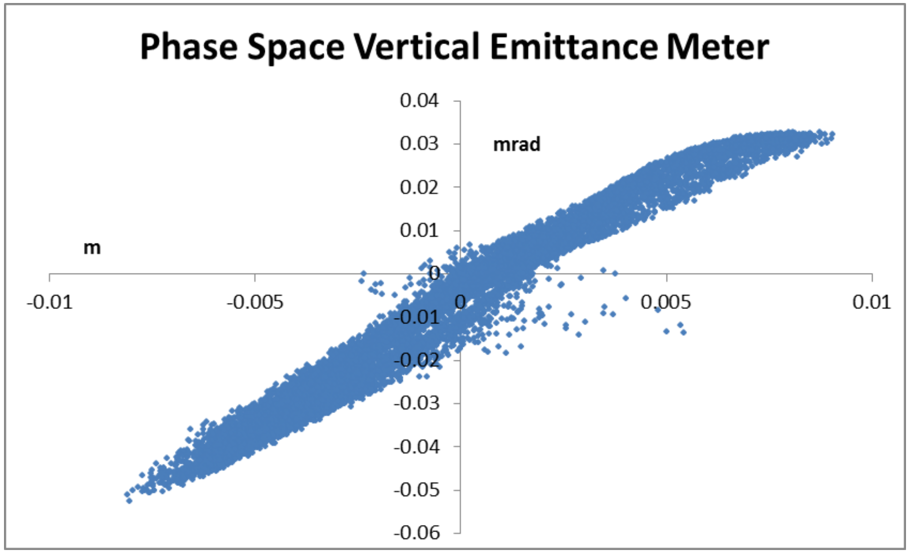


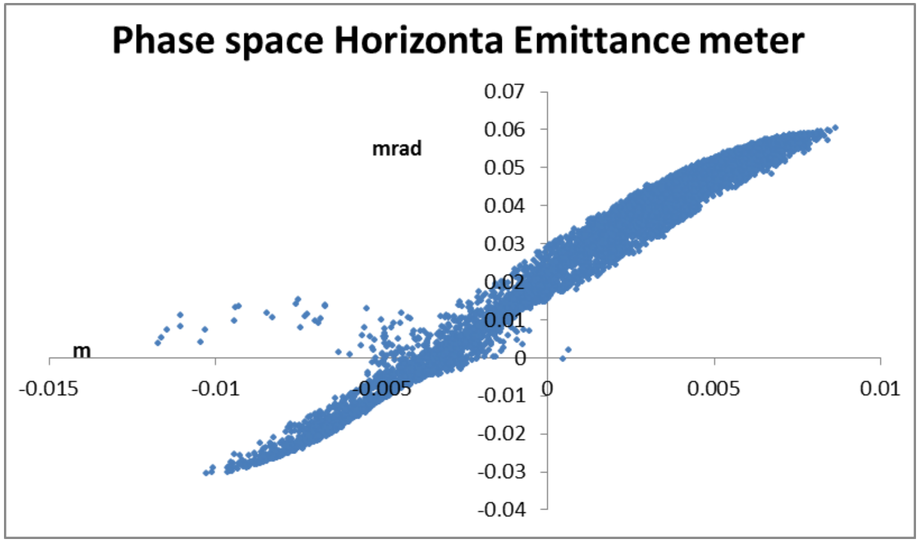


we cut all the particles with radius bigger that 2mm in the plasma aperture and almost all the second beam dissapear.



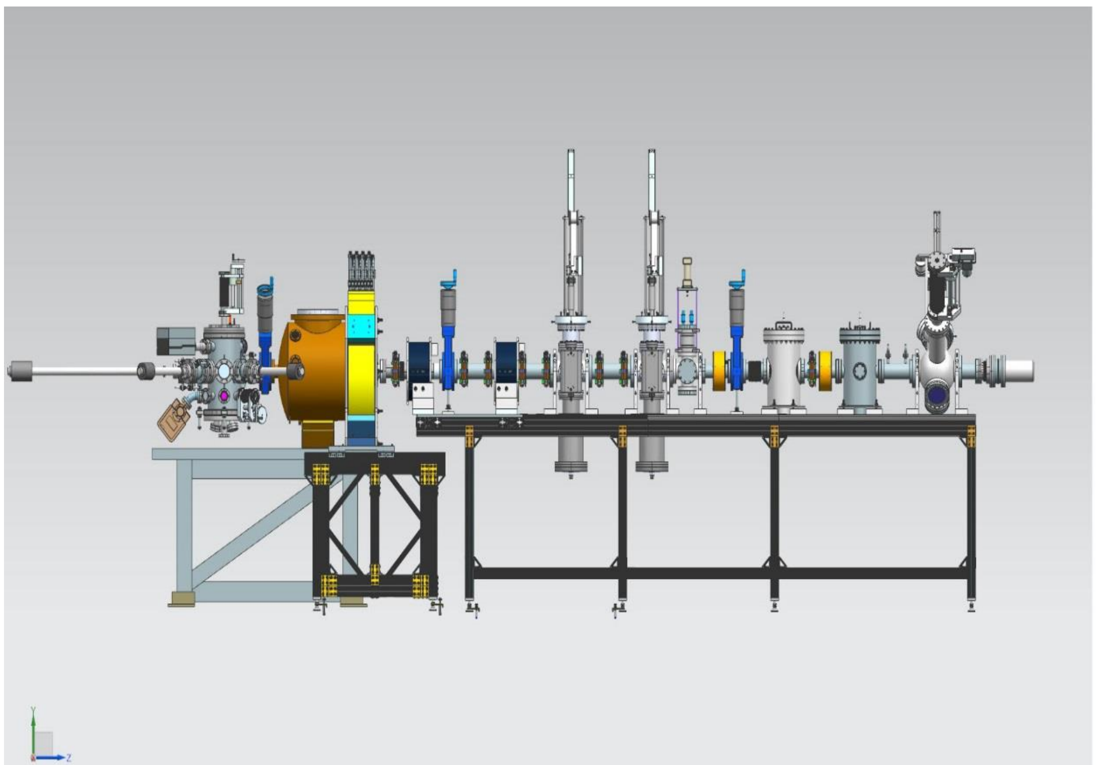
Total current =-11 mA
The cut beam is just proportional to the cut area



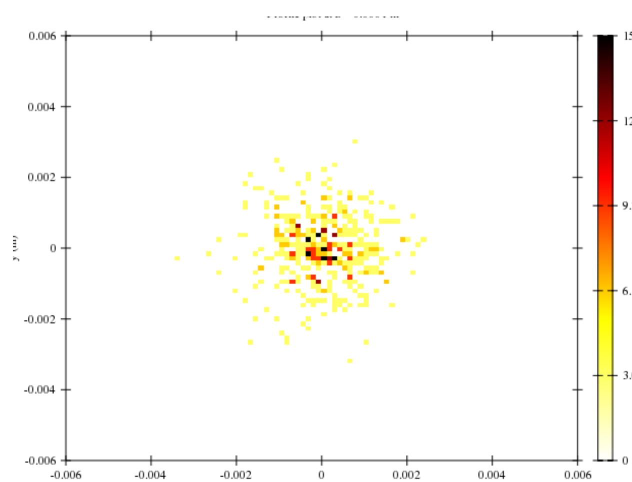


JLAB GTS

- Work in progress…..



- Try to explain the cathode lifetime.
- Why the first solenoid enhance the lifetime?
- Predict the beam emittance depending of the emitter position in the cathode



Positive Ion back-bombardment

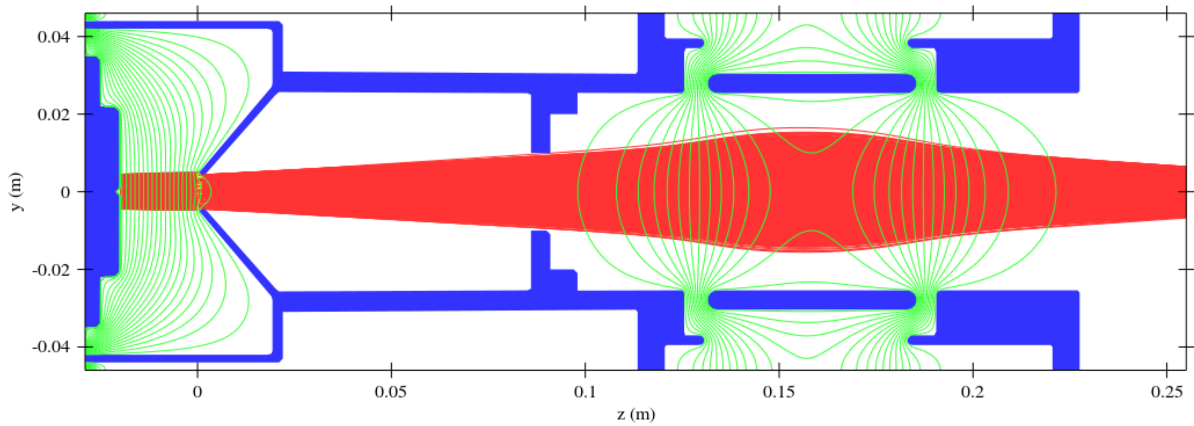
conclusions

- Beam commissioning can be less painful if there is simulations to “make more clear” the results.
- Local variations in the density of secondary ions can lead to plasma like waves that can propagate in the longitudinal direction accelerating the secondary ions.
- Is more and more important to take into account the beam interaction with the residual gas(neutralization, electron cloud, gamma production by secondaries, etc.).

- GRACIAS!!

ININ Ion Source

- There are two ion Linacs at Instituto Nacional de Investigaciones Nucleares
- A profound research need to be done to increase the beam intensity in the source and improve the extend of its research.



Ion source 3-D Simulation with beam intensity at 50 nA