Mexican Particle Accelerator School 2015

SPACE CHARGE COMPENSATION (NEUTRALIZATION)

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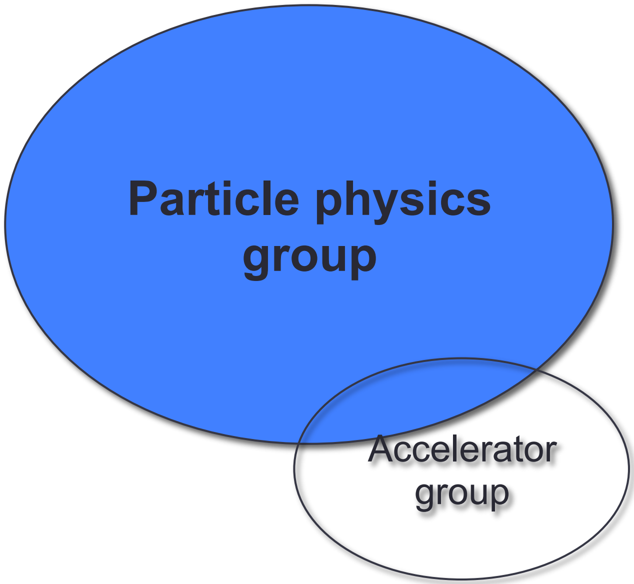
Bibliography

- **CERN Accelerator School** http://cas.web.cern.ch
- **USPAS** **http://uspas.fnal.gov**
- **Indico CERN**
- **Joint Accelerator Conferences Website** **http://jacow.org**
- **CERN DOCUMENT SERVER (THESIS)**

Facultad de ciencias Físico matemáticas



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

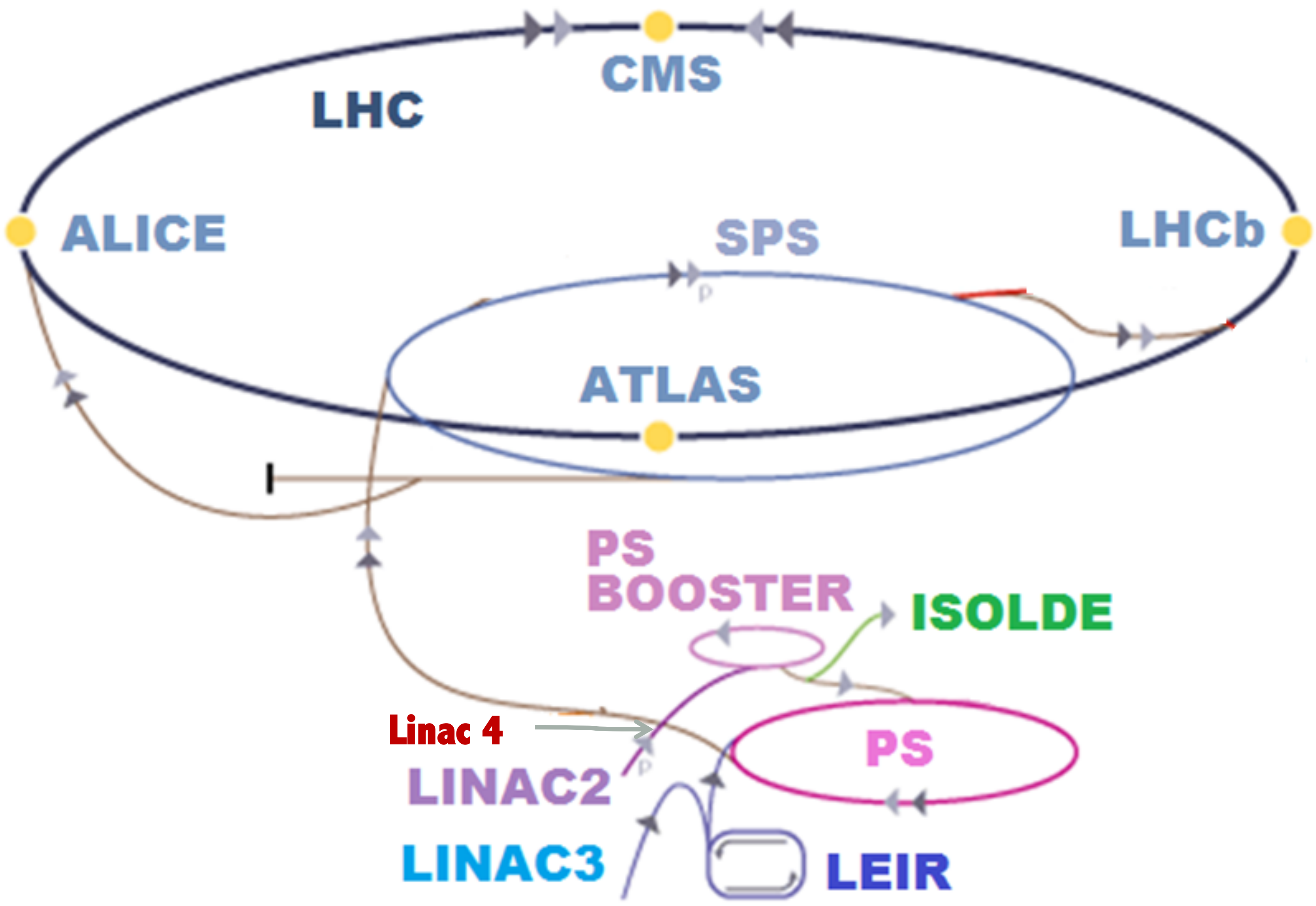
The detectors group it has active collaboration With several universities in Mexico and international institutes

A new group dedicated to accelerator physics has been created

We start a collaboration with CERN at the Linac4 Project

Richard Scrivens

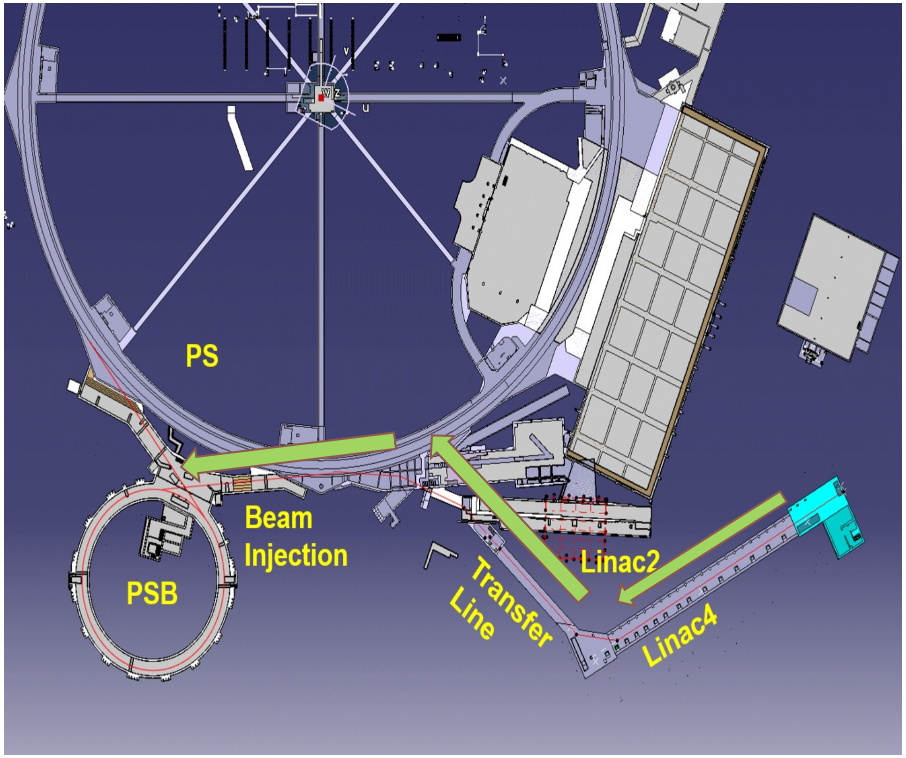
Cern Accelerator complex

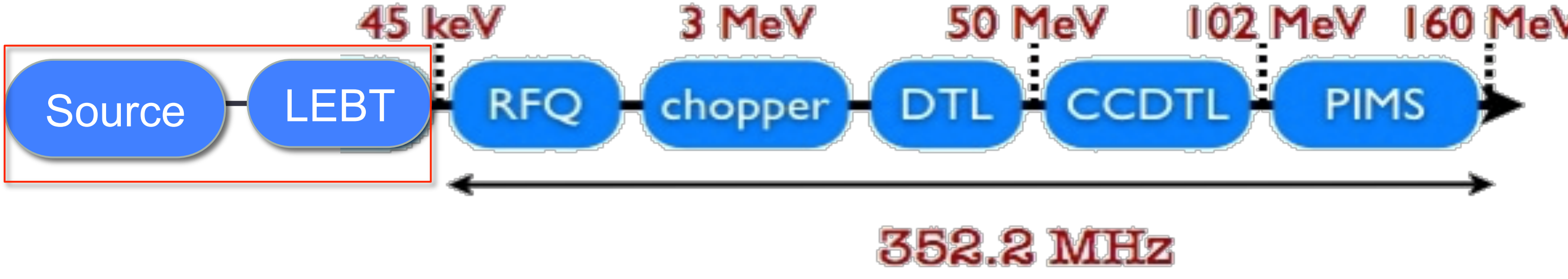


Linac 4

- **H$^-$ Beam**
- **160 Mev**
- **Lower Emittance than Linac2**

	Linac 4	Linac 2
Ions	H-	P
Energy	160 MeV	50 MeV
Emittance	0.4 mm mrad	1 mm mrad
Frequency	352.2 MHz	202.56 MHz
Beam Current	40 mA	170 mA.
Pulse Lenght	400 us	100 us





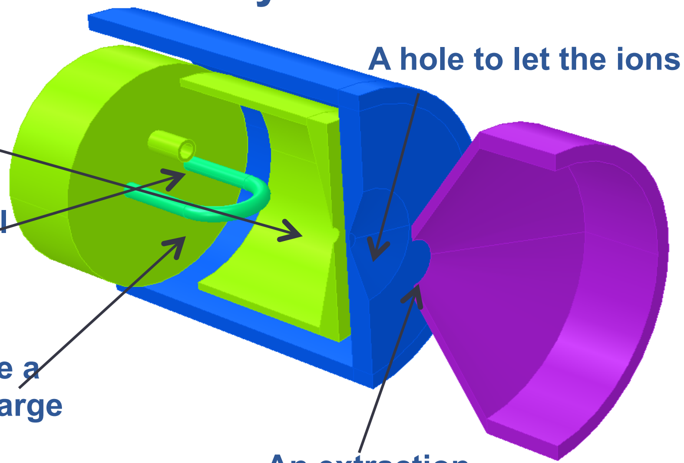
Source and Beam Extraction

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

A plasma or discharge chamber

Material input

Power to create a plasma / discharge



A hole to let the ions out!

An extraction system

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

Child–Langmuir law

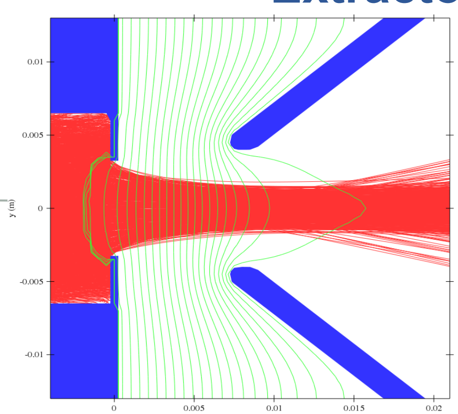
The beam energy is calculated by the diference of potentia

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

Plasma extraction potential (meniscus)

Ground **Extracto**

Plasma

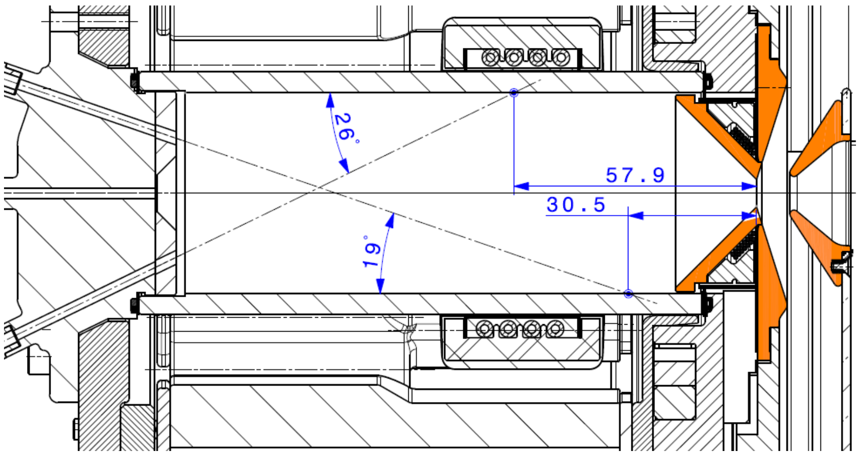


Potential lines(green)
Electrodes (blue)

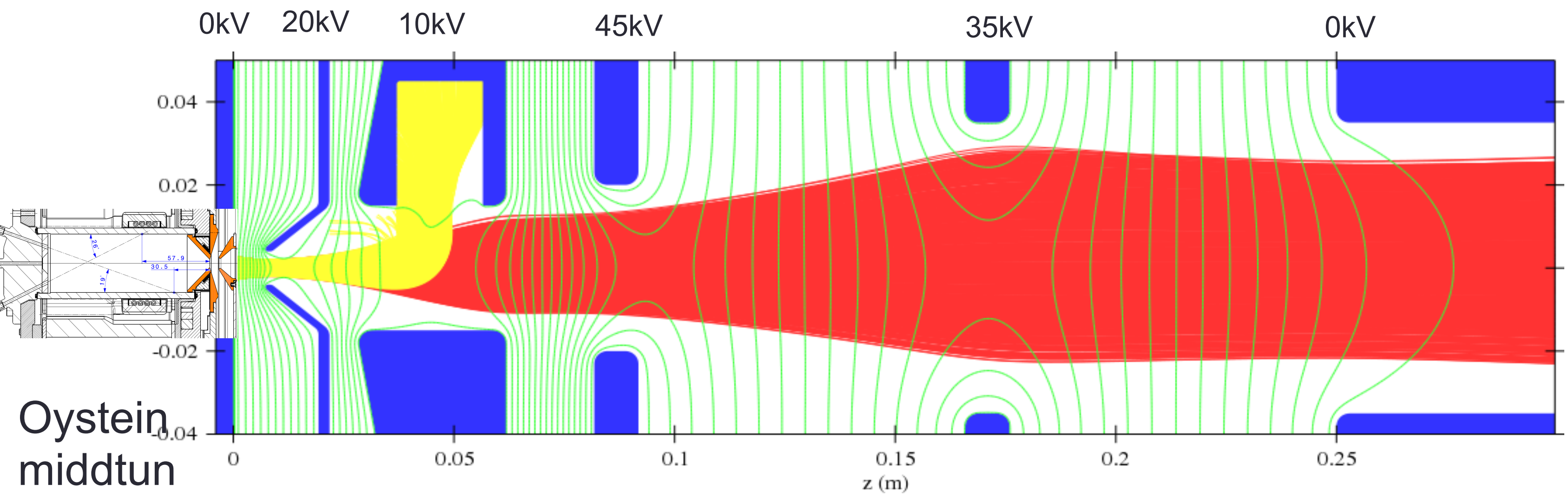
Ion Beam

Ions (Red)

Linac4 Ion Source and extraction system

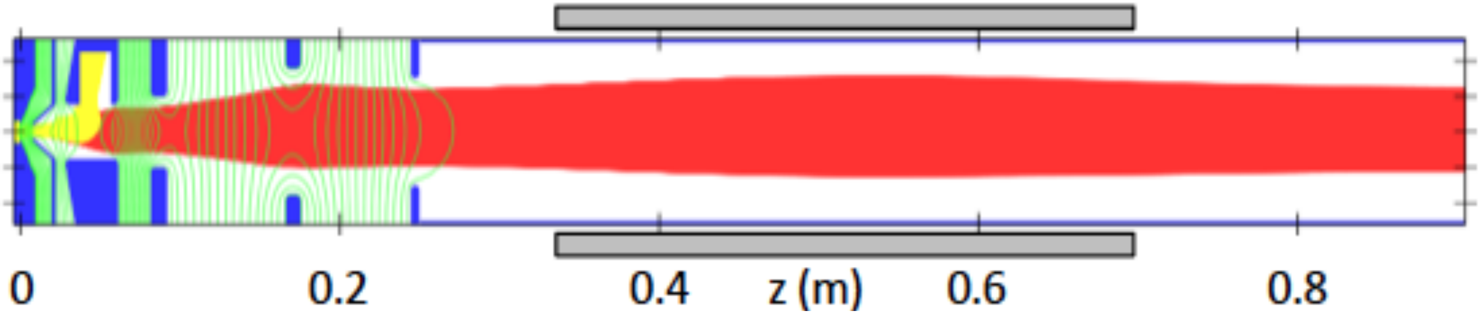


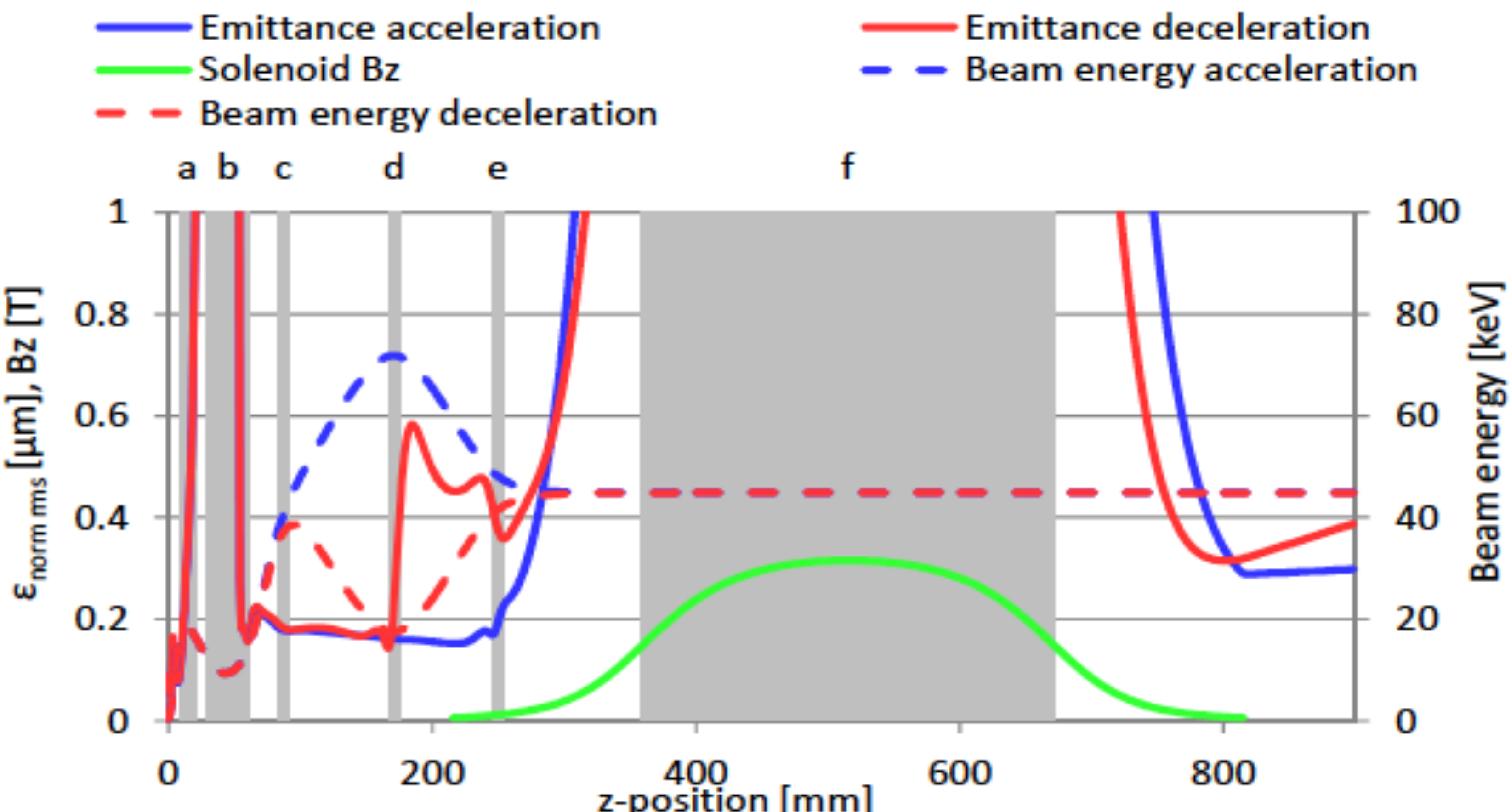
- Plasma is created using 2MHz RF in a solenoid coil.
- The H- is produce in the plasma volume and surfaces
- A surface near the extraction is coated with cesium, evaporated from an oven at the back of the source.
- The plasma ions strike the cesium surface and H- are emitted.



Oystein middtun

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

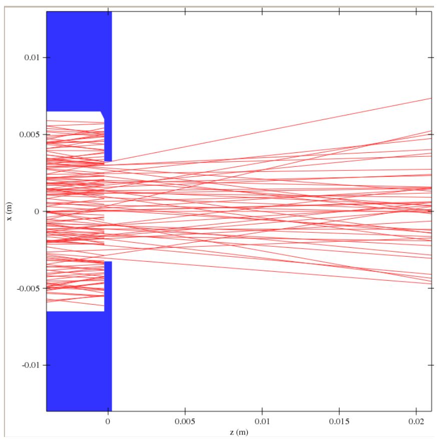


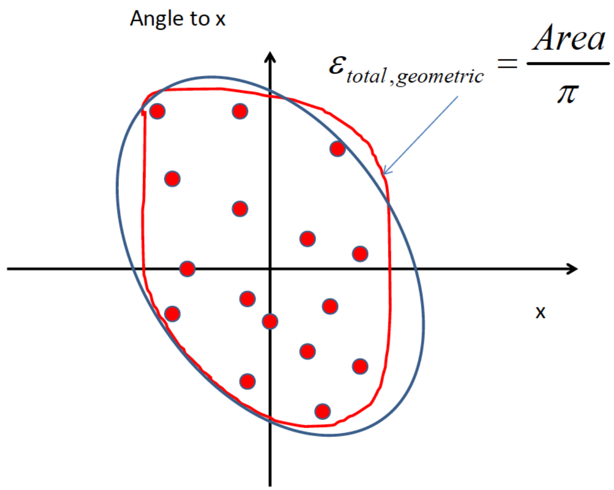


Oystein middtun thesis pictures

Emittance

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

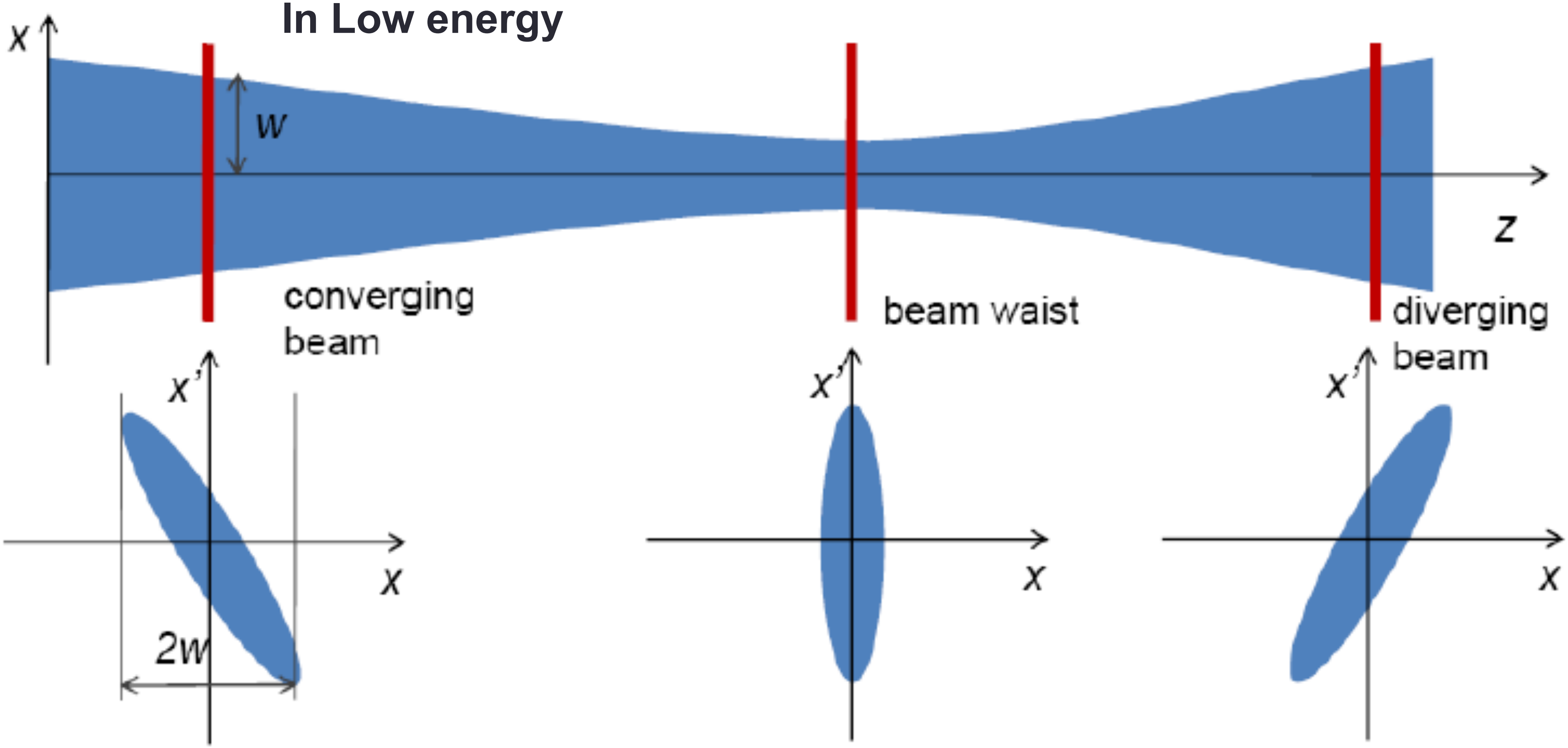




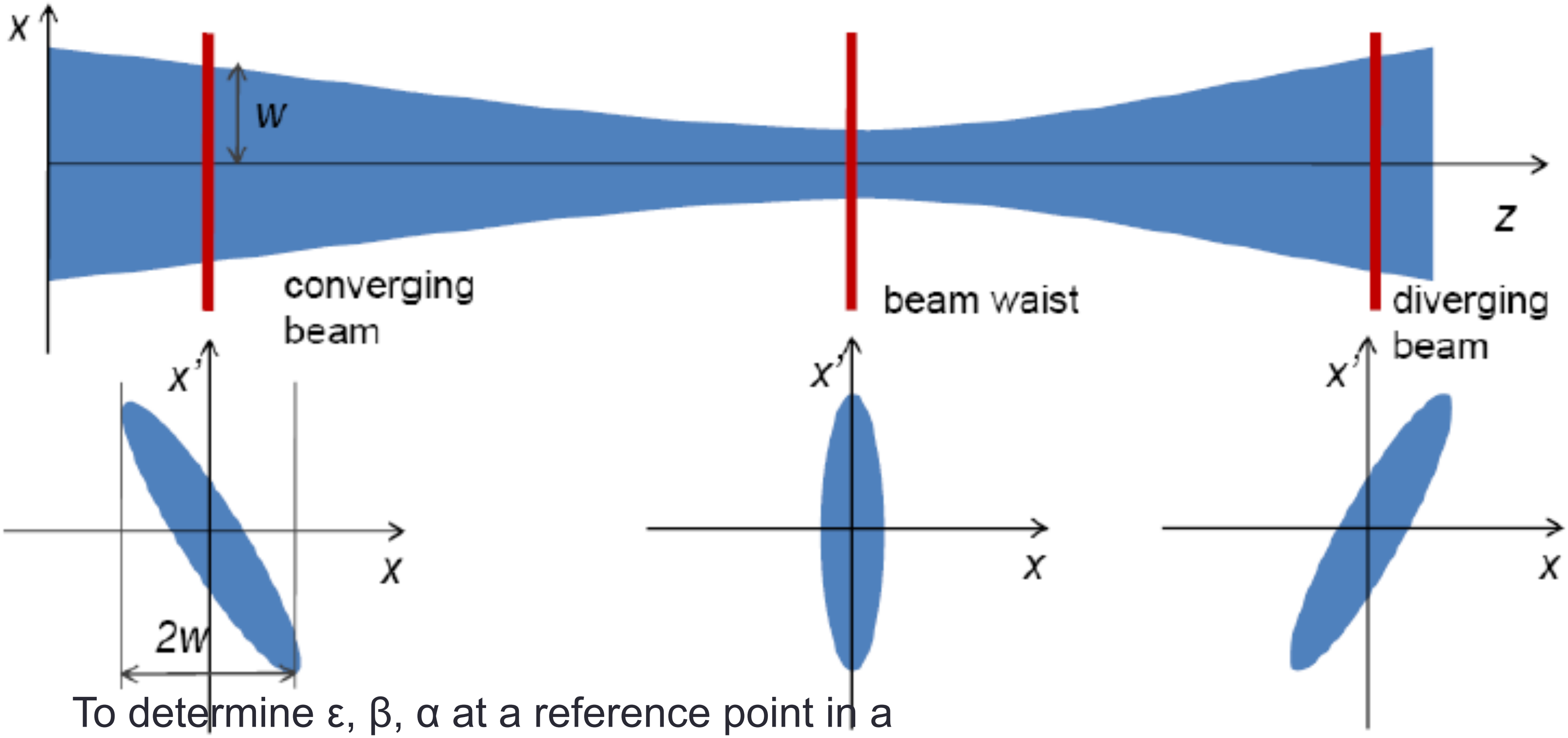
- Mm.mrad? mrad from p_x/p_z
- In Linacs the number of magnets neccesary to keep the beam inside the pipe is proportional to the emittance

$$\varepsilon = \frac{r}{2c}\sqrt{\frac{kT}{m}} \propto T^{1/2}$$

How do you measure phase space?



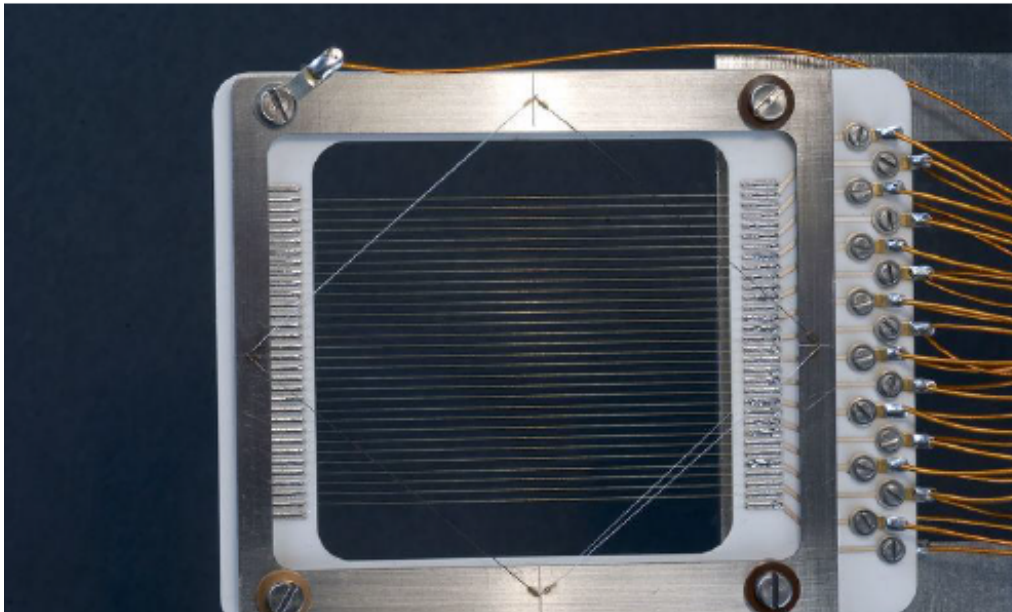
How do you measure phase space?



To determine ε, β, α at a reference point in a beamline one needs
at least three σ measurements with different transfer matrices between the reference point and the *w* measurements location.

$$\sigma = \sqrt{\beta\varepsilon}$$

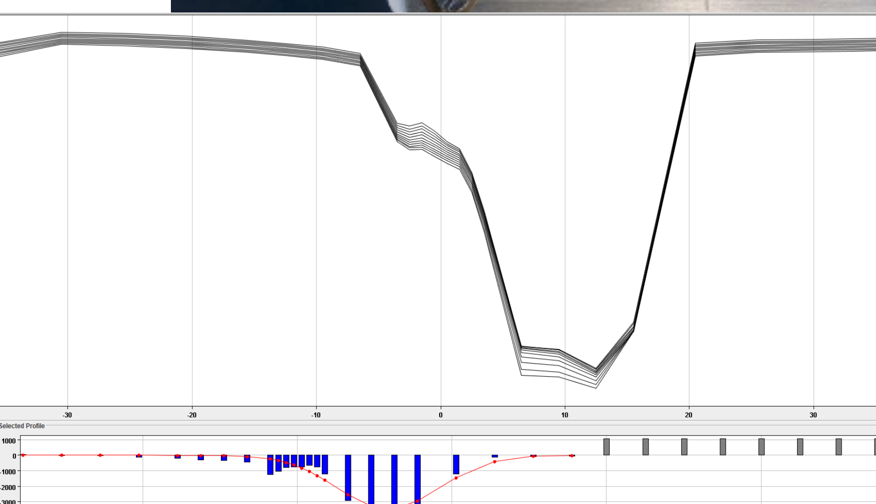
Secondary Emission Grid

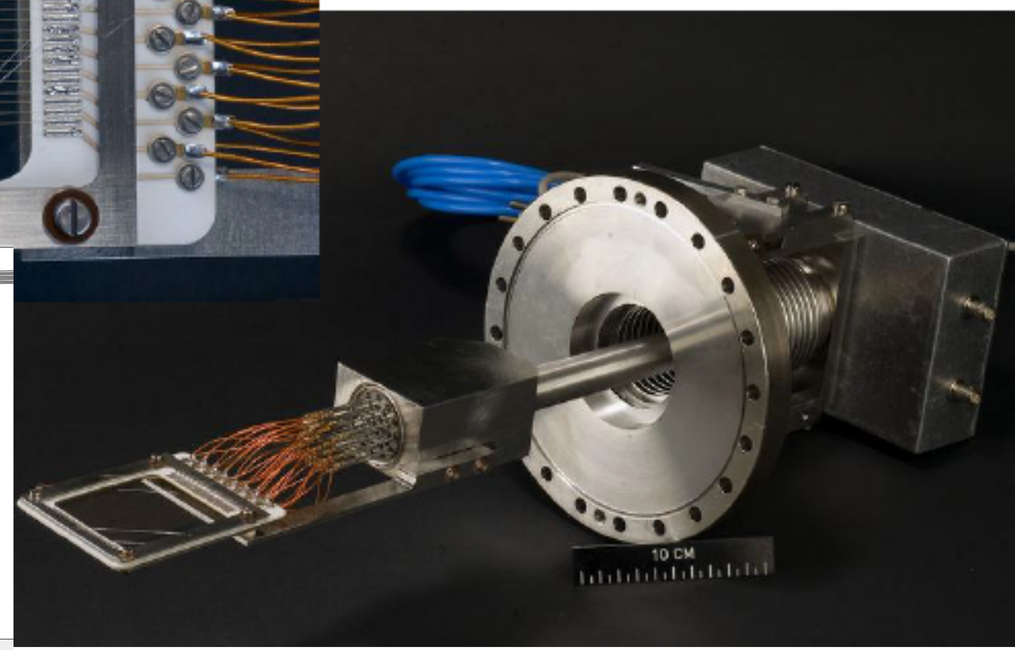


R=200 microns

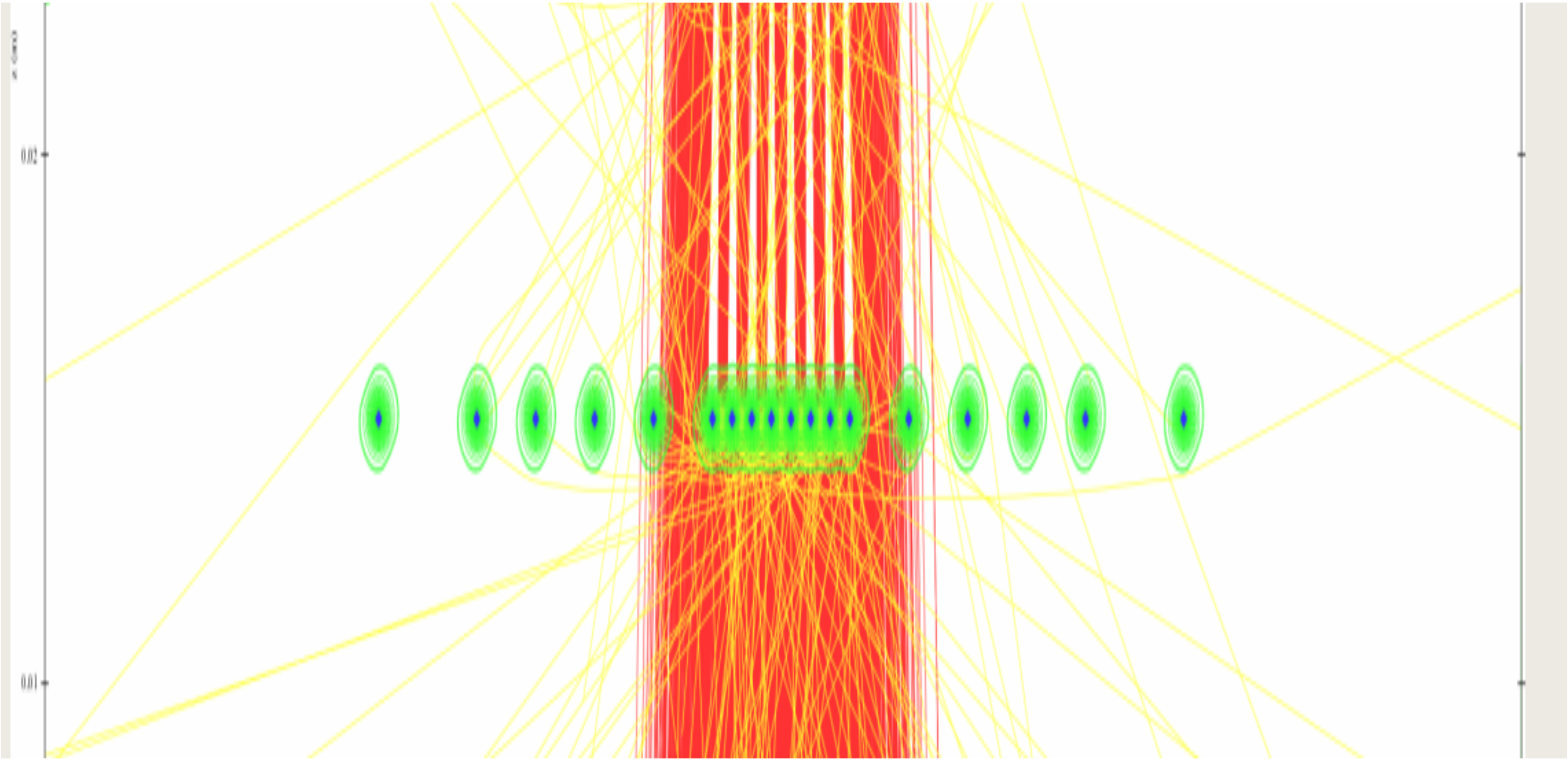
Beam Size

$$\sigma = \sqrt{\beta \varepsilon}$$



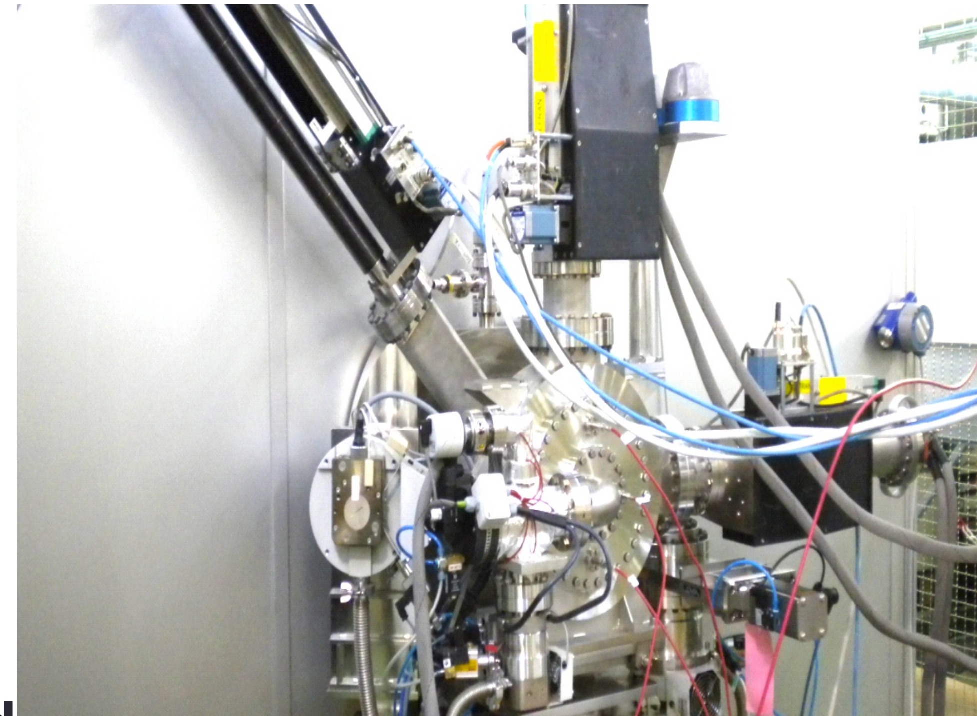


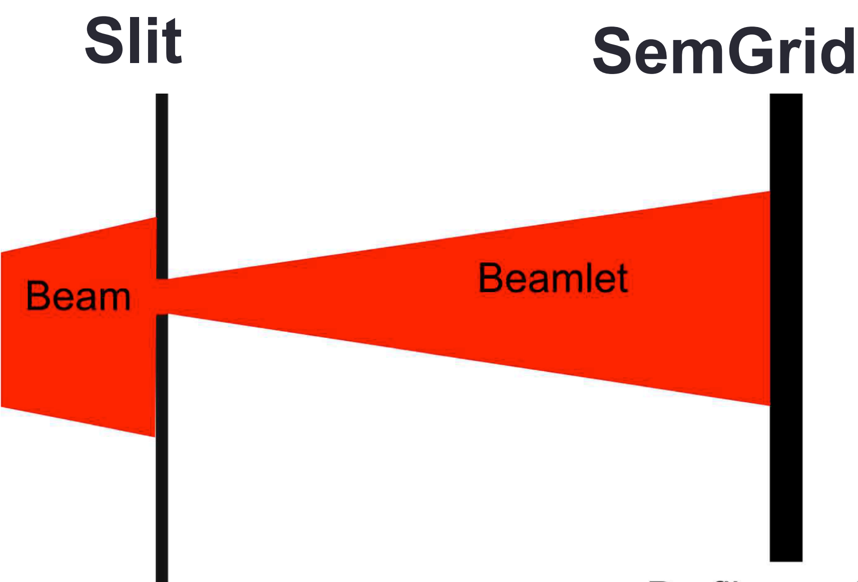
Simulation of the Semgrid wires

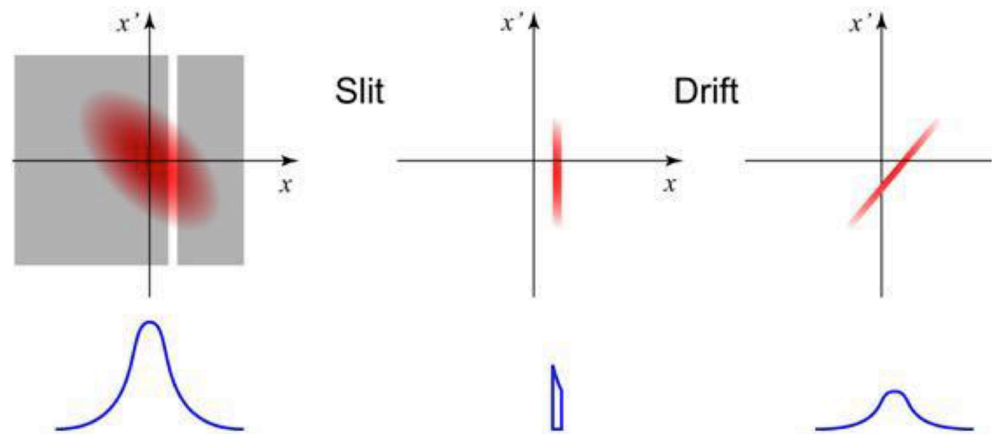


Emittance meter

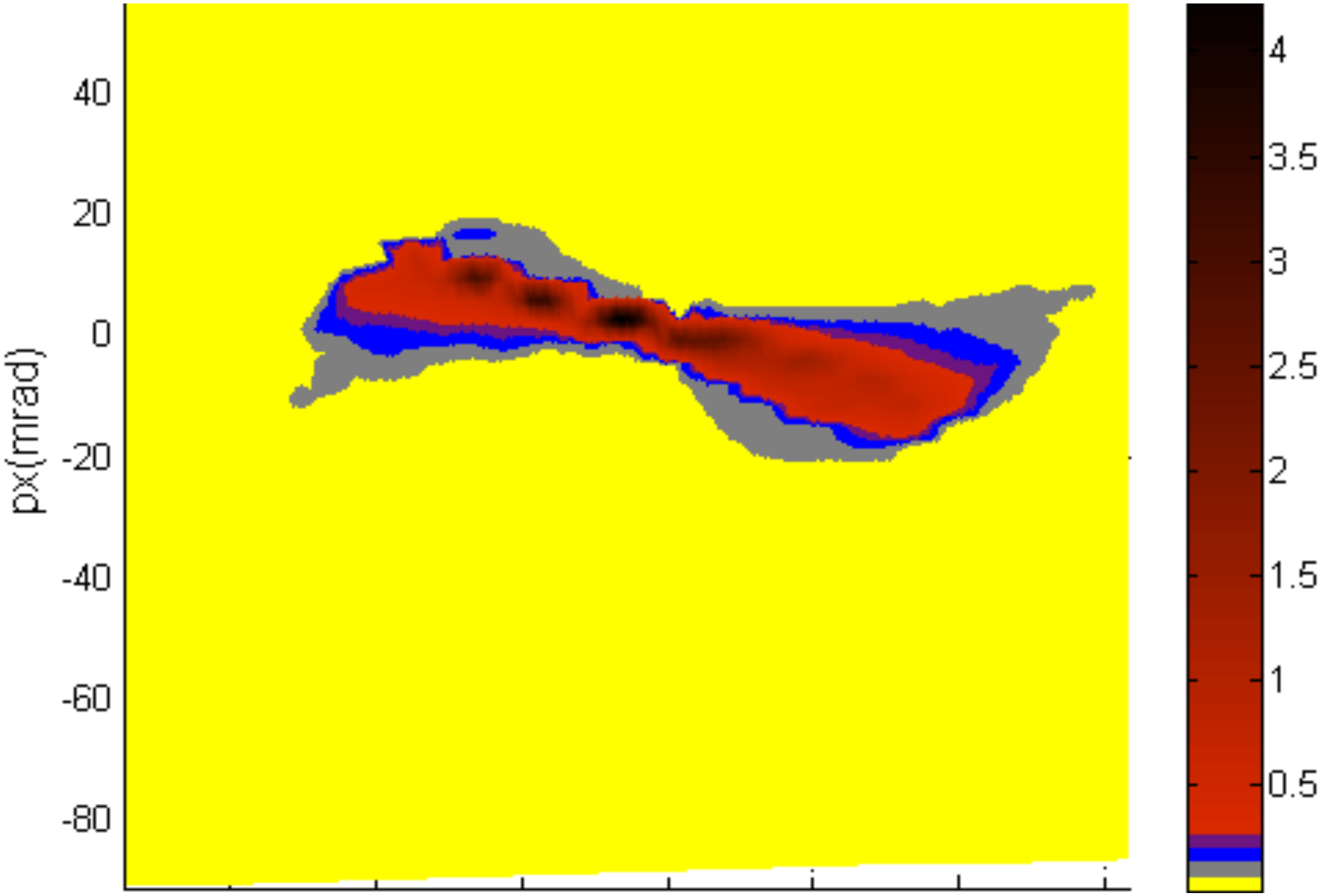
- Phase space measurements in both planes X(Y),X’(Y’)
- 0.5mm resolution in X
- 1mrad in X’
- Time resolution 6X10^{-6} s





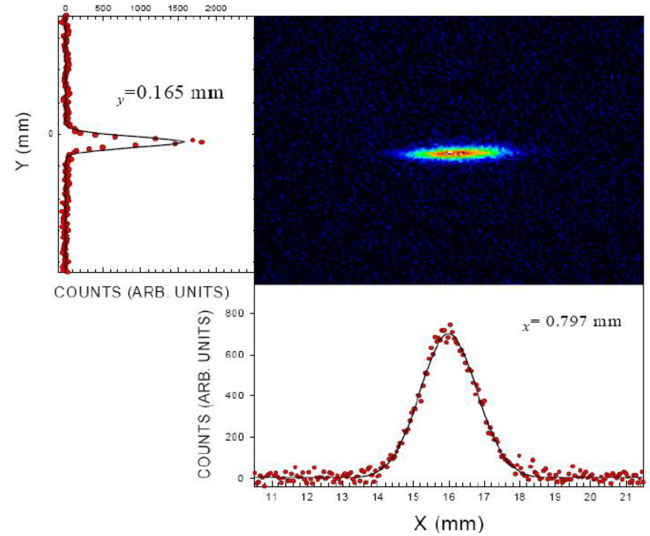


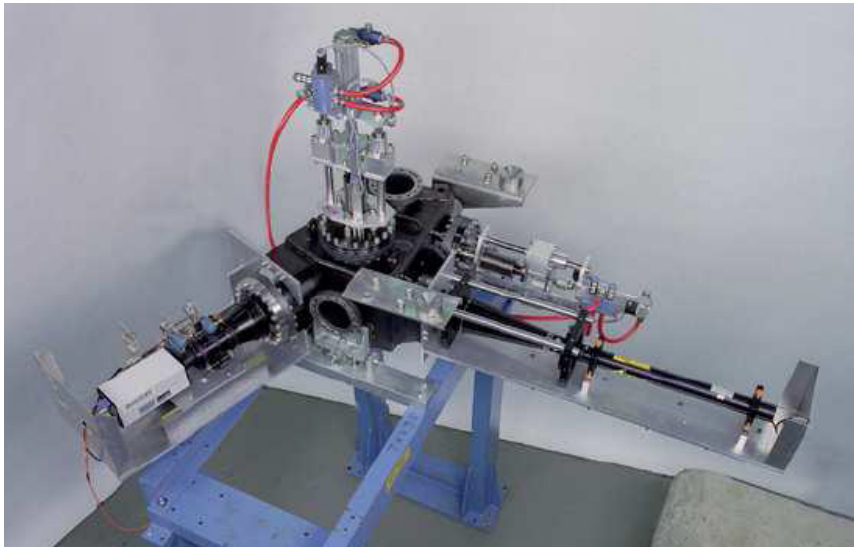
Emittance meter



Emittance meters

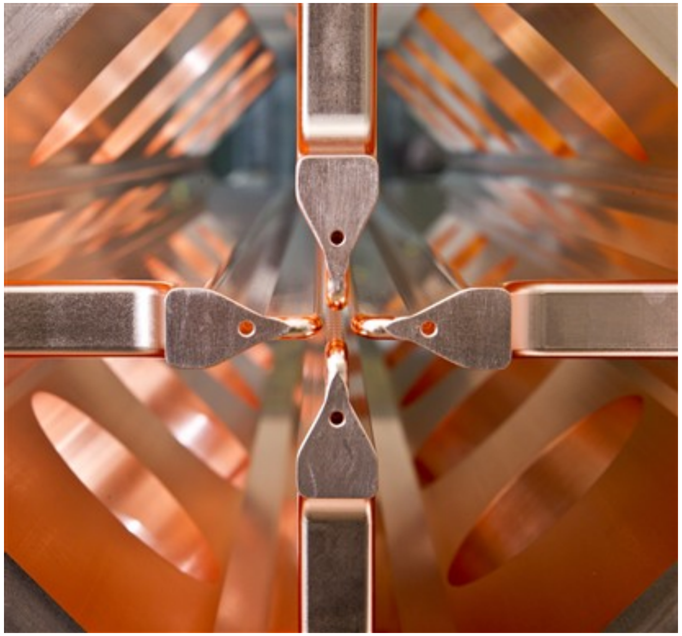
- Synchrotron radiation
- Screen mechanism
- Pepperpot
- Filamentation





Accelerator acceptance

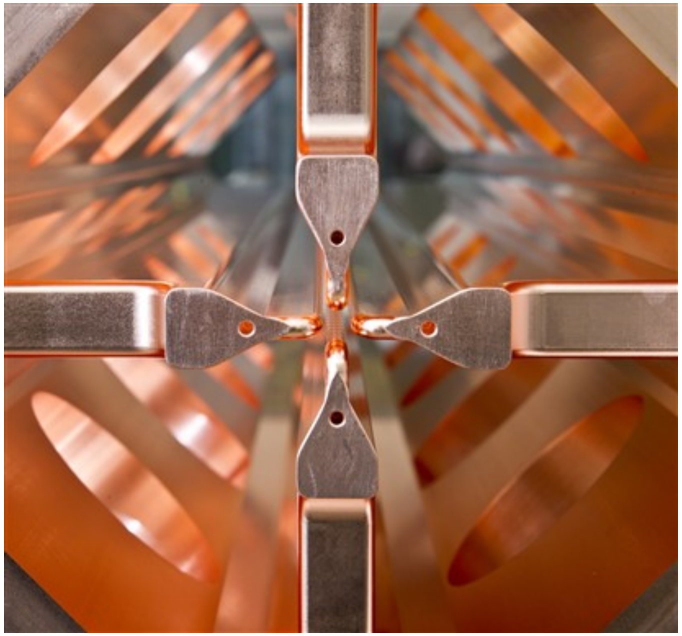
If the beam doesn't have specific properties the accelerator device can not take the beam



Which parameters are necessary?

Accelerator acceptance

If the beam doesn't have specific properties the accelerator device can not take the beam



Which parameters are necessary?

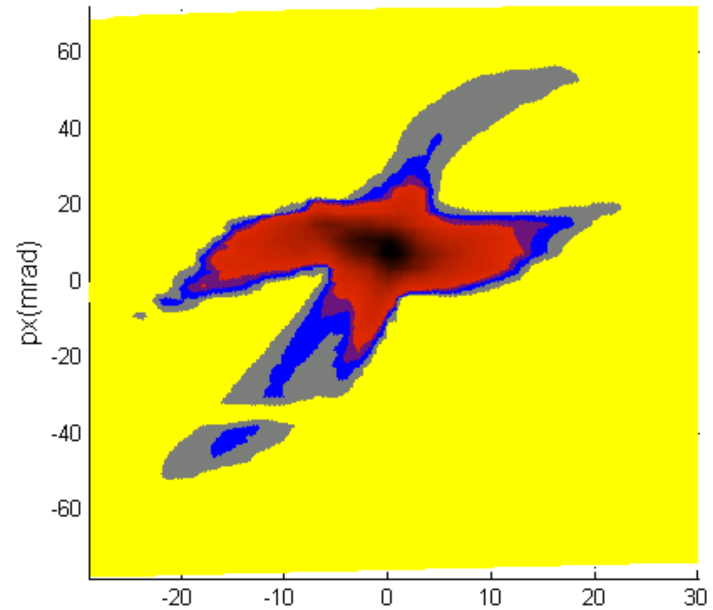
- Emittance
- Size
- Angle
- Energy

Accelerator acceptance

If the beam doesn't have specific properties the accelerator device can not take the beam

Which parameters are necessary?

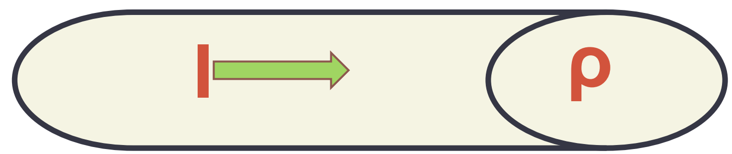
- Emittance
- Size
- Angle
- Energy



Try to focus this monster!!

Beam Space charge

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



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

$$E_r = \frac{\rho r}{2\varepsilon_0}$$

$$J = \frac{I}{\pi a^2}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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

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

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

$$= q\frac{\rho r}{\varepsilon_0 \gamma^2}$$

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

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

r<a

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

a<r<R

R is the beam pipe radius

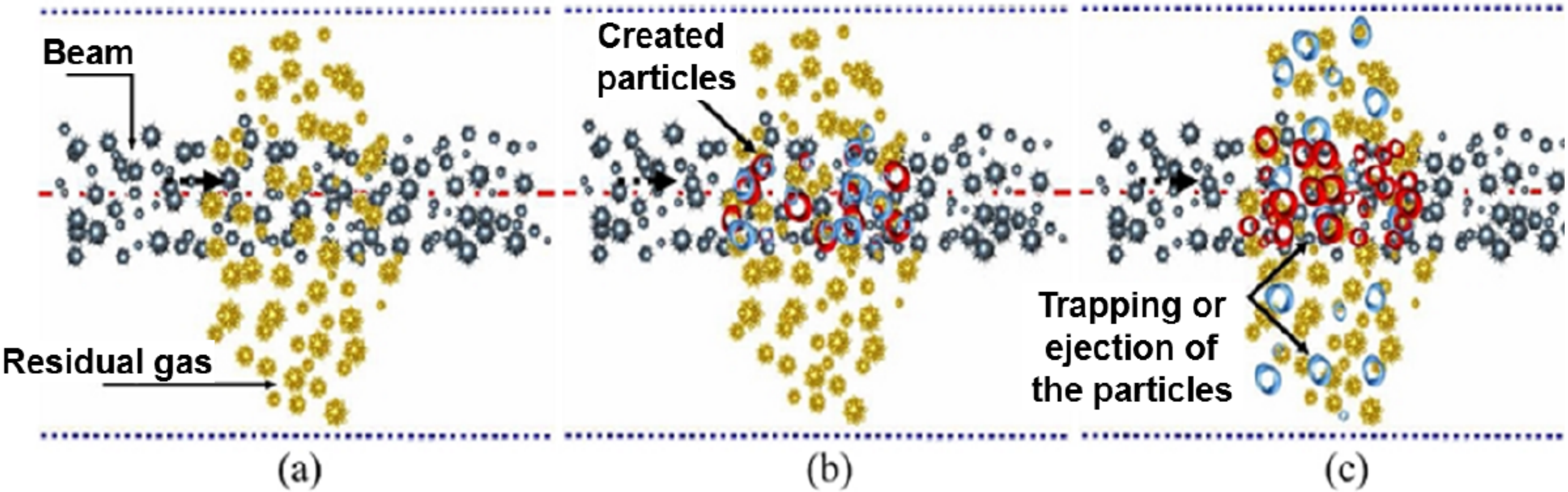
Residual gas and beam interaction

- Now the interaction between the beam and the residual gas is a important topic
- Plasma lenses, electron cloud, Beam instabilities,
- Is necessary to understand the dynamics

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

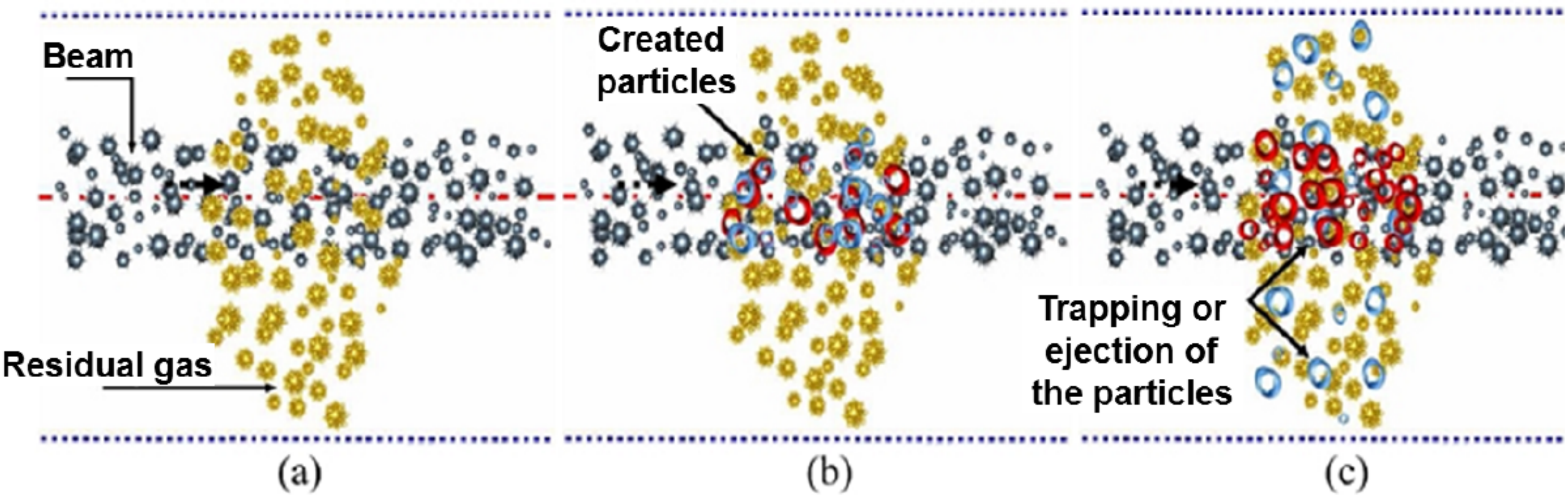
$$p + X \rightarrow p + X^{+} + e \qquad p + H_2 \rightarrow p + H_2^{+} + e$$



Space charge compensation

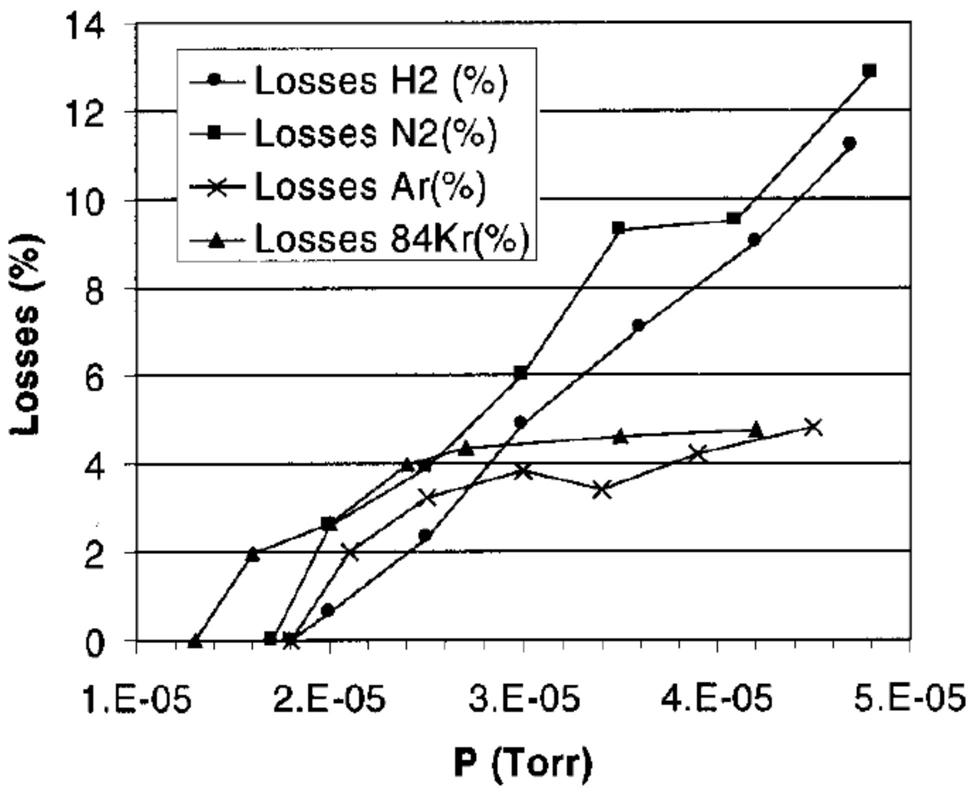
- The H^- beam get neutralized with residual gas
- The positive ions are trapped by the beam
- Is possible to create a neutral beam

$$H^- + H_2 \rightarrow H^0 + H_2^+ + 2e$$



Residual gas and beam interaction

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

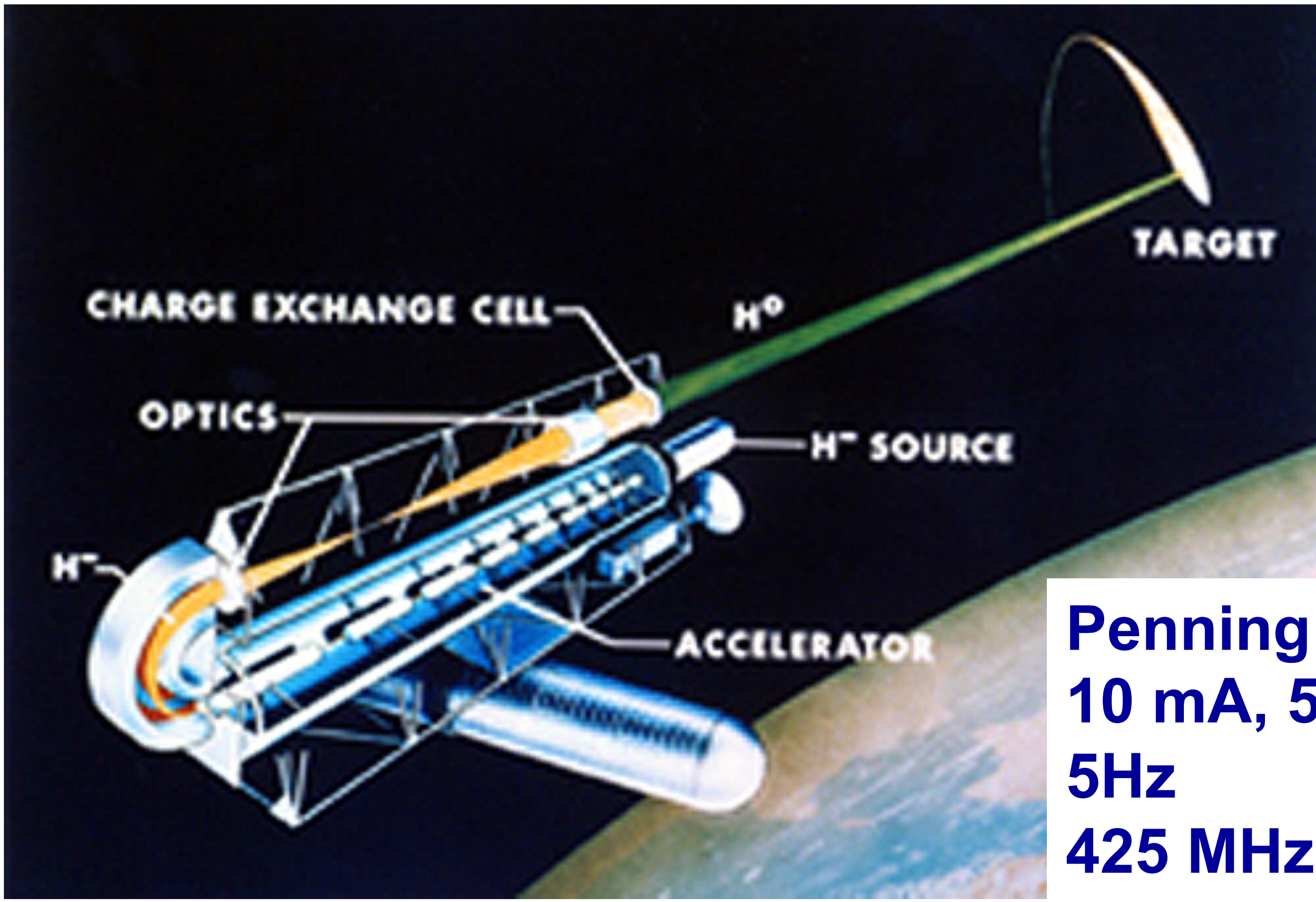


Mean free path

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

n is the residual gas density

Defense application:
Beam Experiment Aboard Rocket (BEAR) successfully operated a neutral beam particle accelerator in space



Neutalisation stops spac
charge to target, and
avoids deflection by eart
magnetic field, and som
counter measures.

Penning source
10 mA, 50 µs pulses at 5Hz
425 MHz 1 MeV RFQ
Gas-cell neutralizer

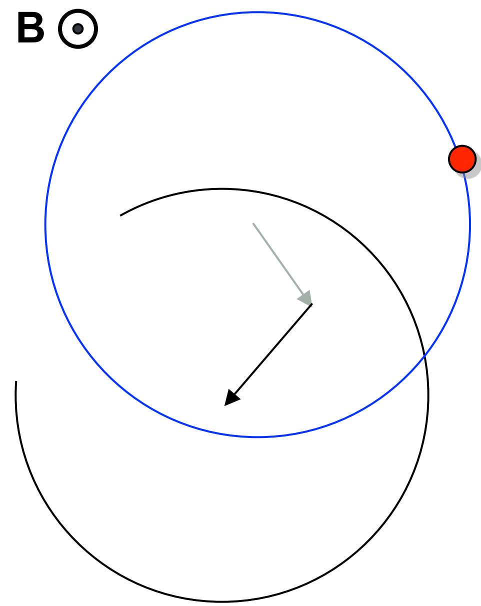
Space charge compensation

$$F = q(E - \beta^2 E) = q\frac{\rho r}{\varepsilon_0 \gamma^2} \qquad \eta(z,t) = (1 - \frac{\phi(z,t)}{\phi_{NC}(z)})$$

Magnetic field enhance this effect

The beam collect so many particles that the local beam density is affected

$$\rho = \rho_{beam} - \rho_{secondary}$$



$\rho_1(t)$ $\rho_2(t)$ ρ

Drift | Magnets | Acceleration

Envelope equation(Hill's equation)

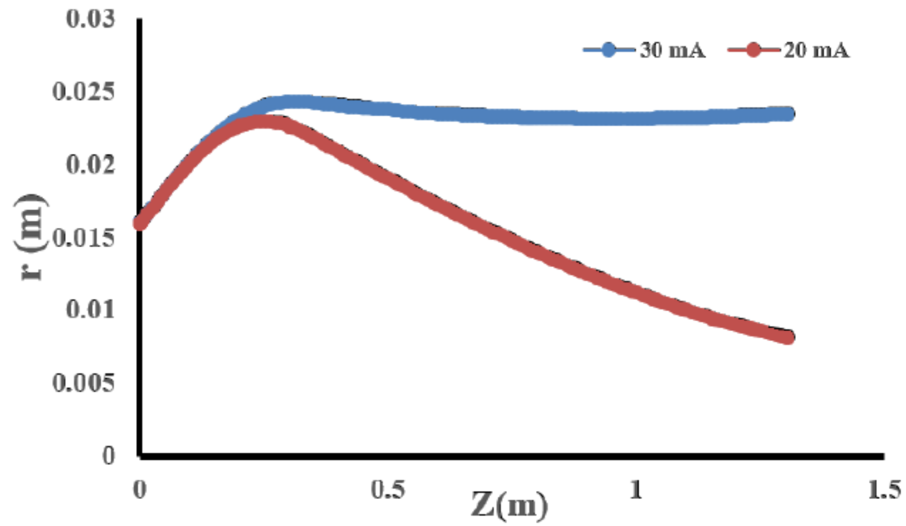
- The envelope of a cylindrically symmetric beam (r) transported along the z-axis can be described by the differential equation:

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

Magnet

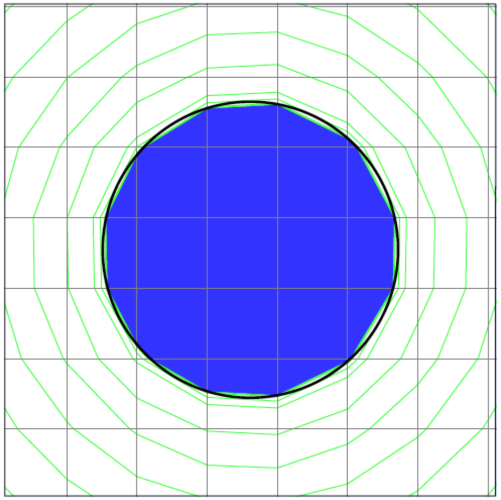
Space charge term

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

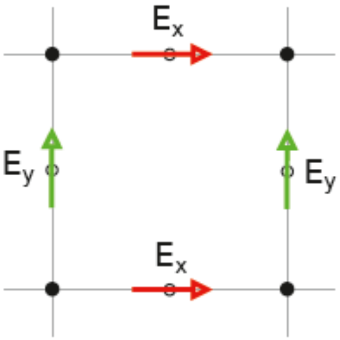


Simulations

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

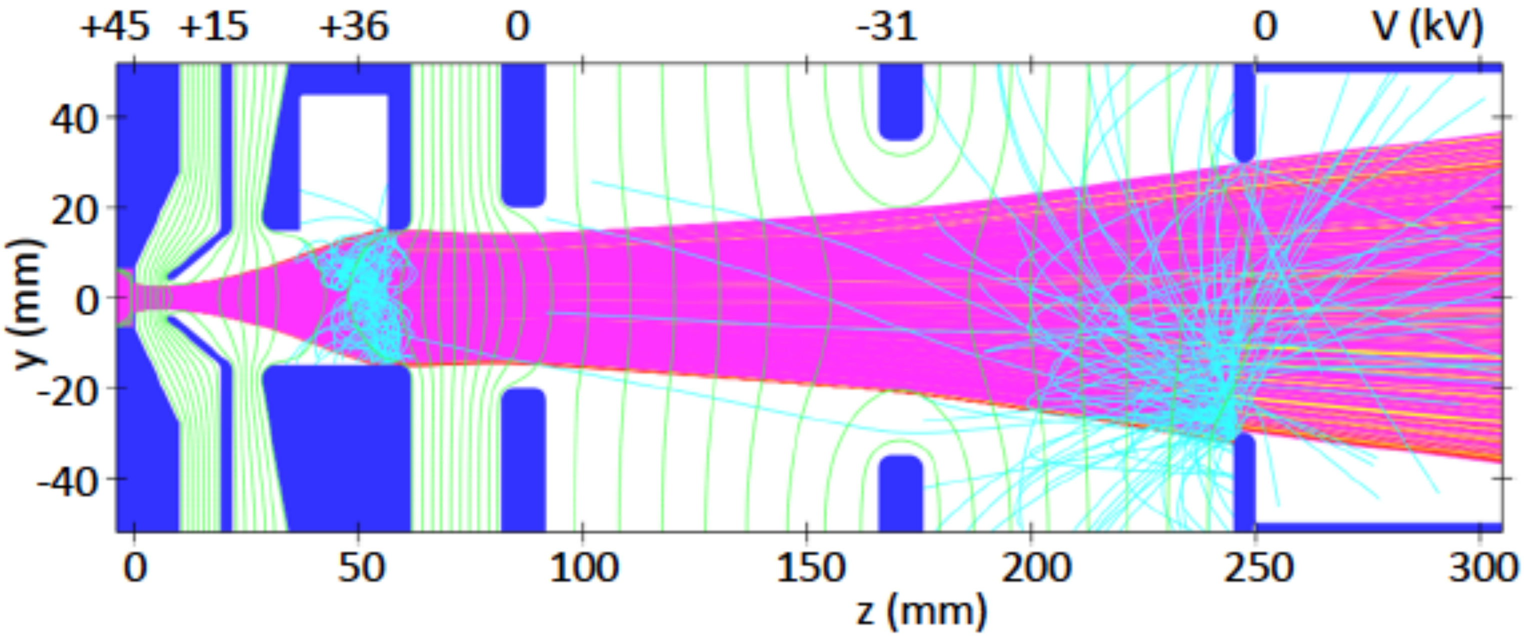


Electric potential (Green line)
Solids (blue)



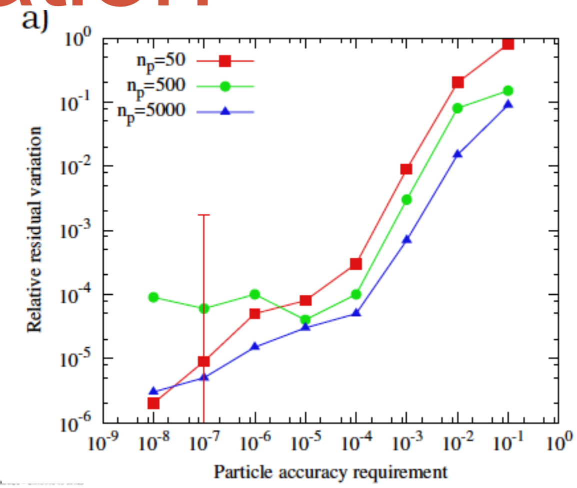
1) T. Kalvas, et. al., *"IBSimu: A three-dimensional simulation software for charged particle optics"*, Rev. Sci. Instrum. 81, 02B703, (2010).

Secondary electrons simulation



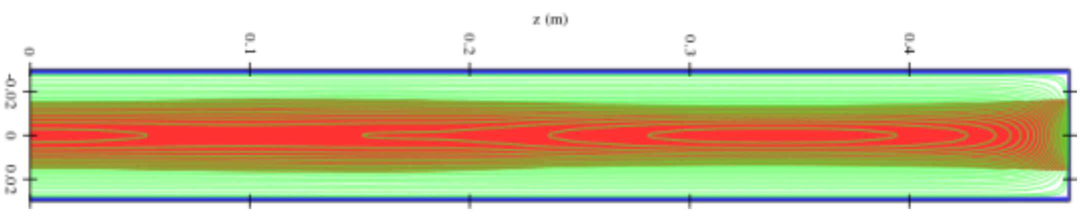
Oystein middtun thesis pictures

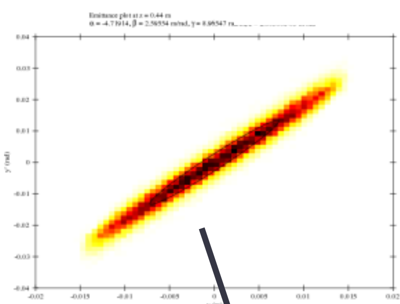
Space charge compensation



Full space charge beam transport

Ions(Red)

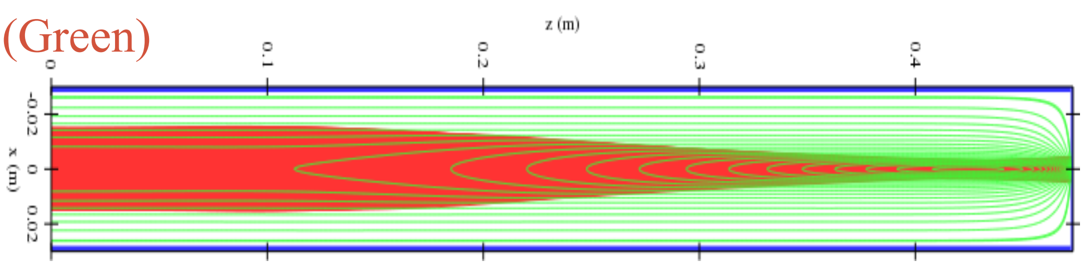


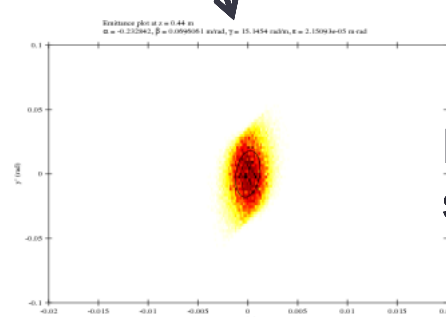


Beam Direction

Potential lines (Green)

20% space charge

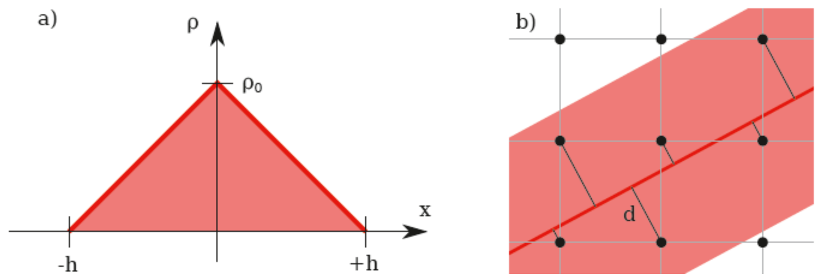


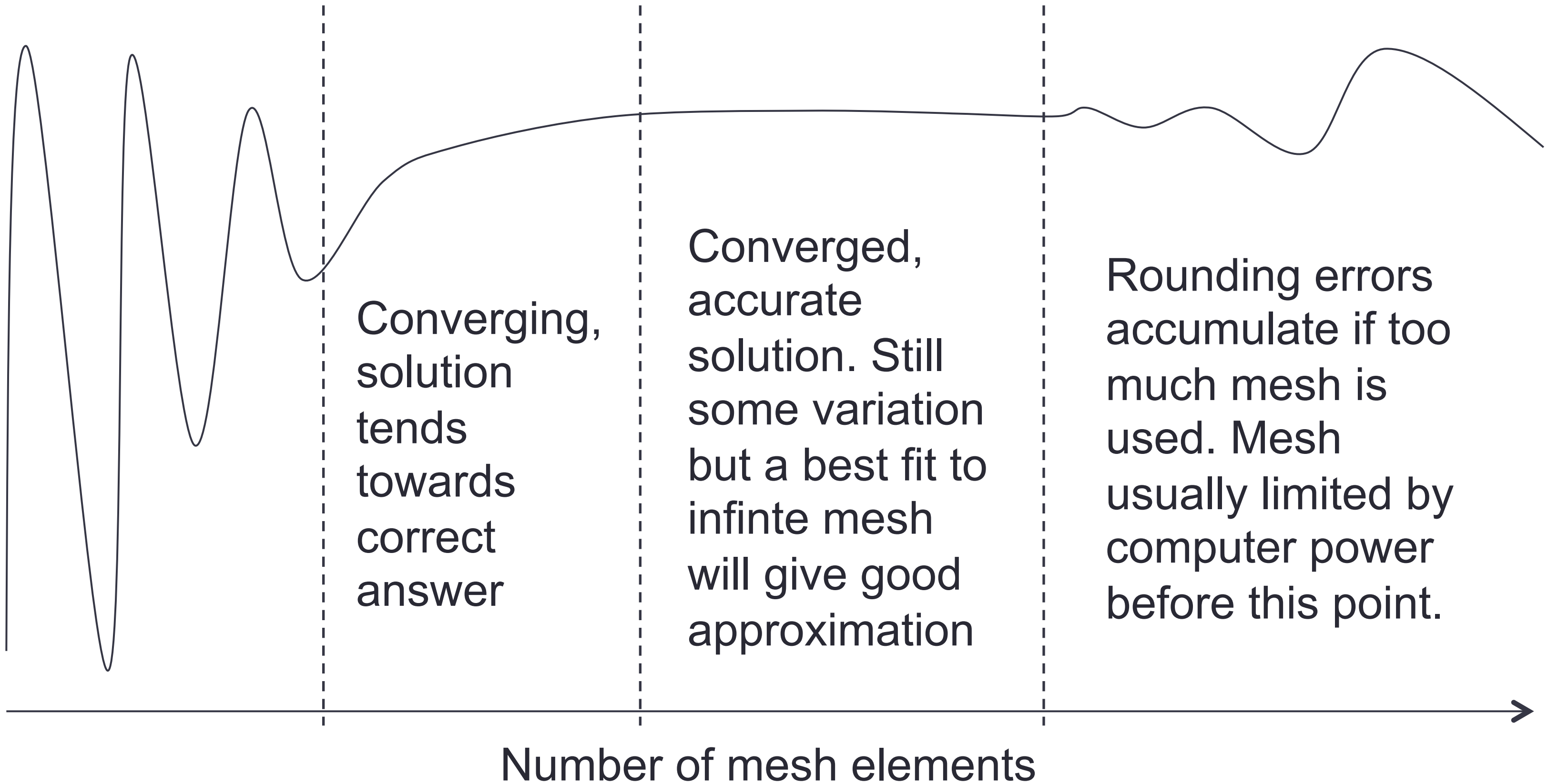


Frozen model simulations

Mesh Stability

Not enough mesh,
solution unstable

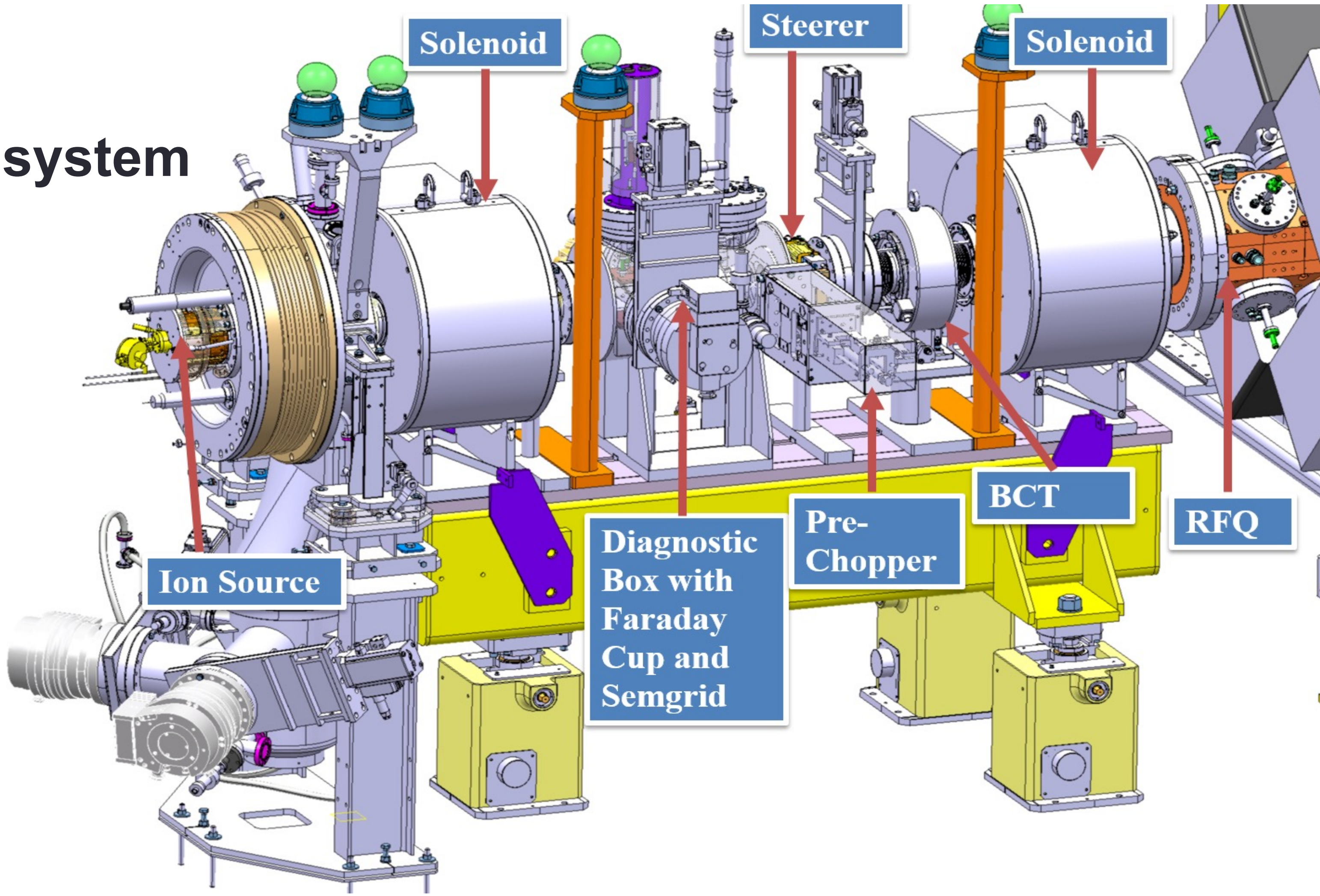




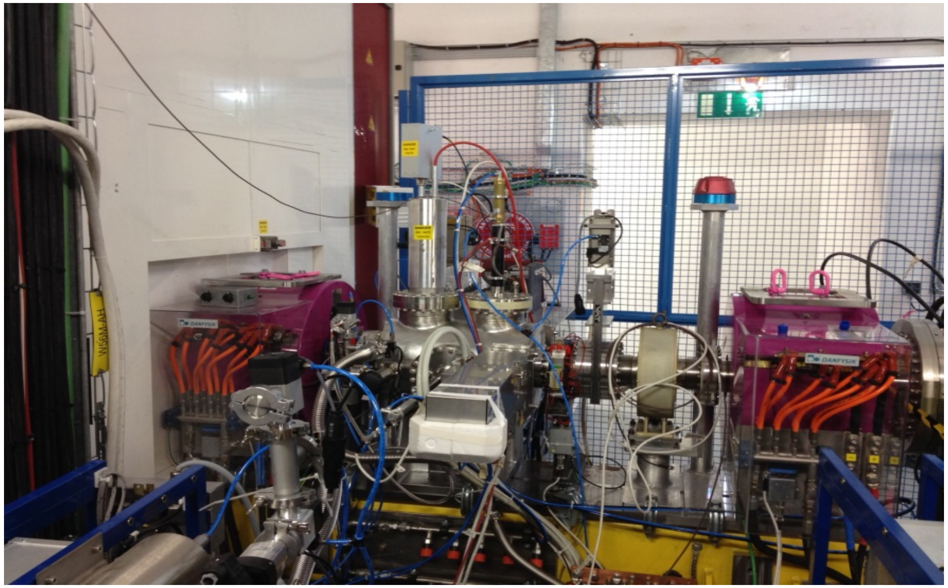
*from G. Burt, Lancaster University.

Linac4 Low energy beam

- Source
- Multi step extraction system
- LEBT
- RFQ

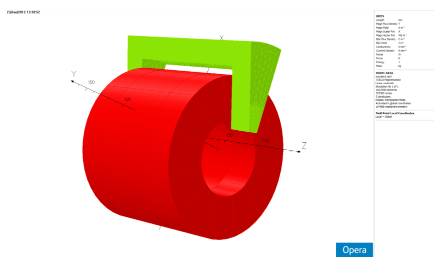


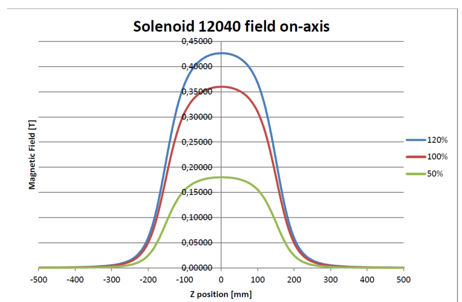
Linac4 LEBT elements



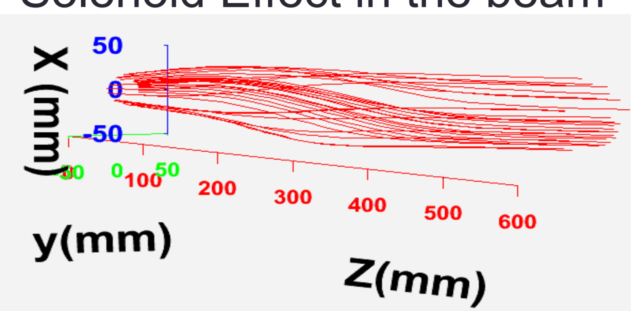
The system include:

- 2XSolenoid
  - Beam focusing
  - Matching
- 4XSteerers
  - Correct beam center alignment
- Gas Injection
  - Controlling space charge compensation degree
- Faraday Cup
  - Beam current measurement
- The beam is unbunched in this stage.
-



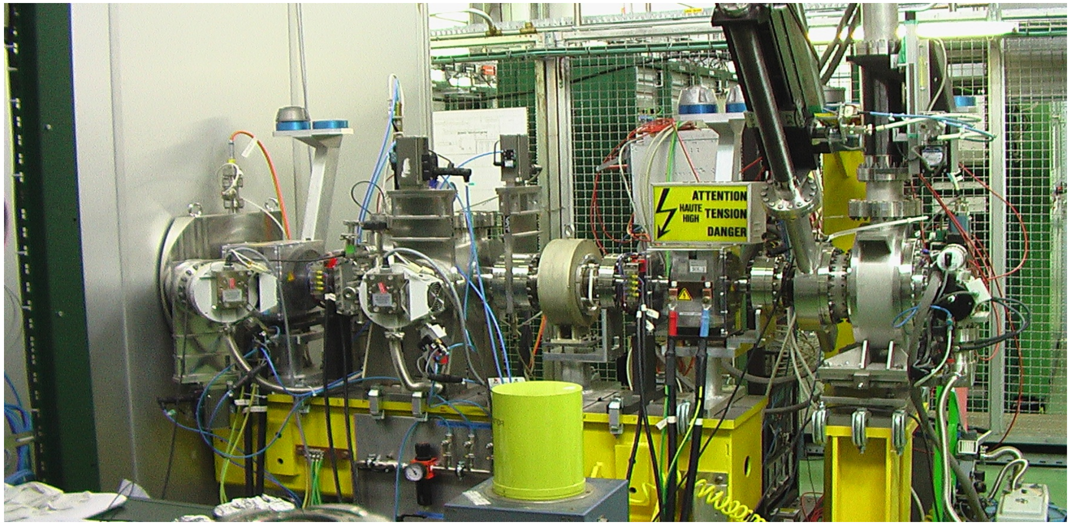


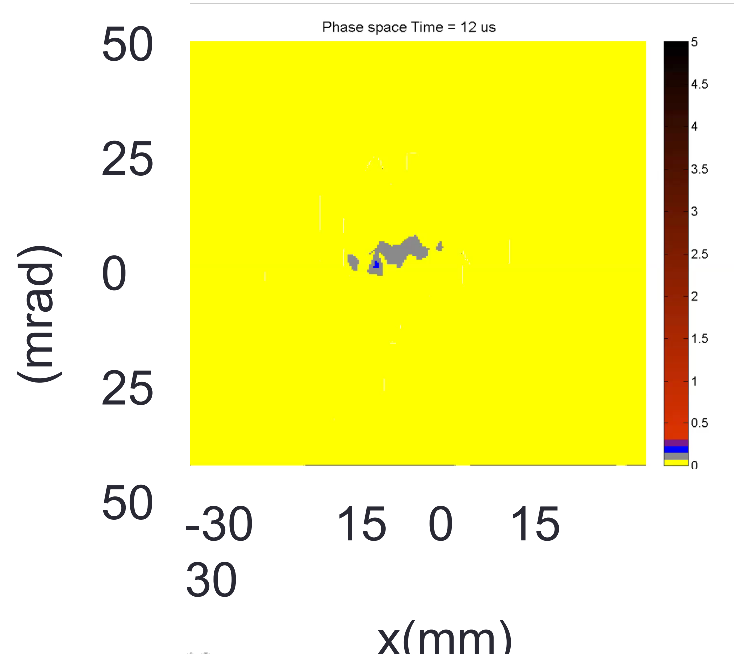
Solenoid Effect in the beam



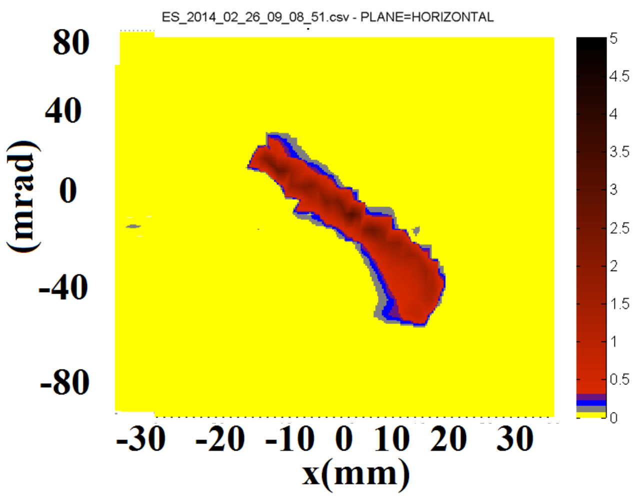
Ions (red)
Conductors (blue)

Measurements

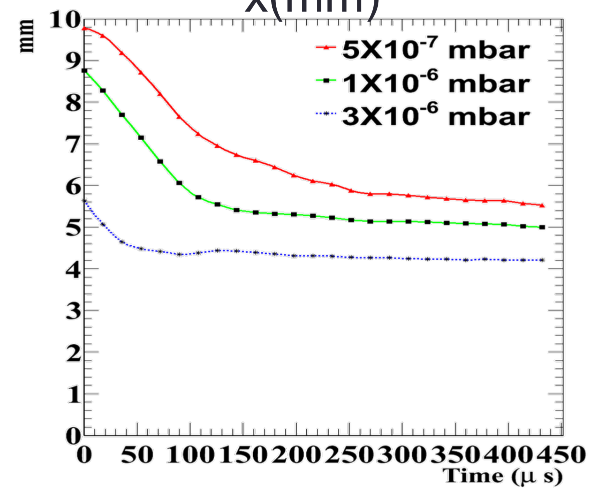




Phase space plot



The time evolution of the beam size in the emittance meter position With different pressures in the beam pipe

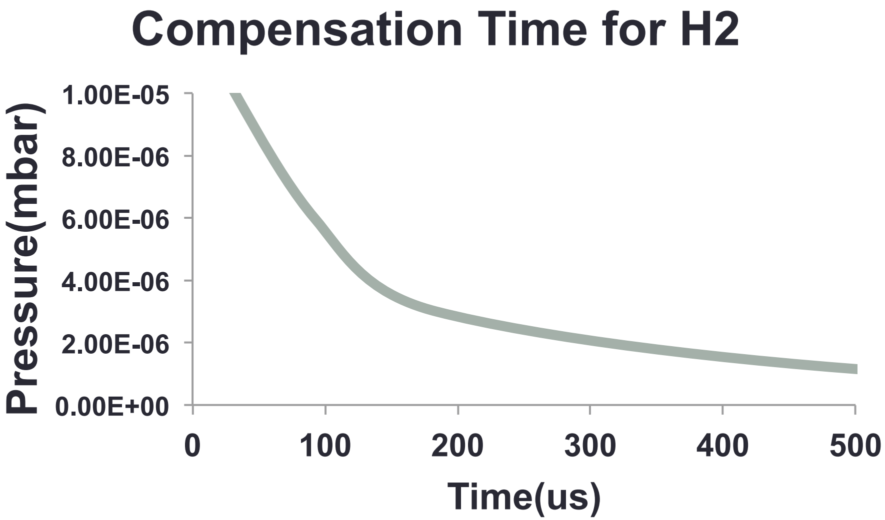


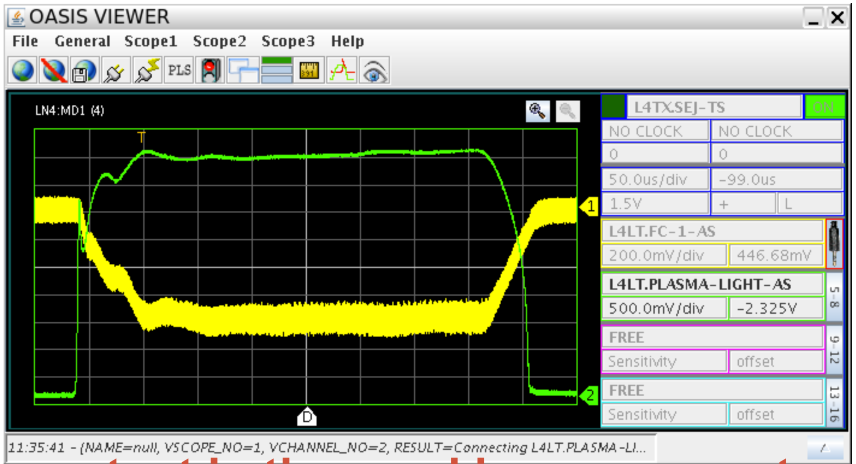
Compensation time

- **The space charge compensation is time dependent**

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

- **Beam pulse 500 µs**

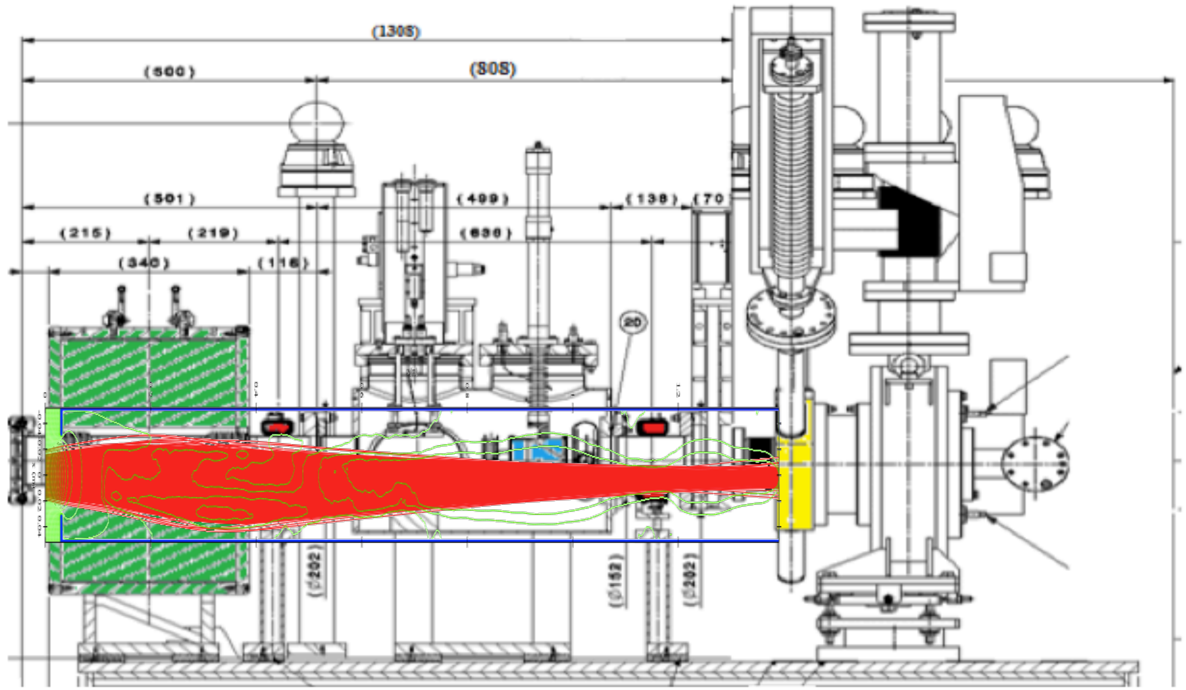




The beam properties are not constant in time and is necessary to use advanced codes to simulate this effect.

Test stand simulations

Source

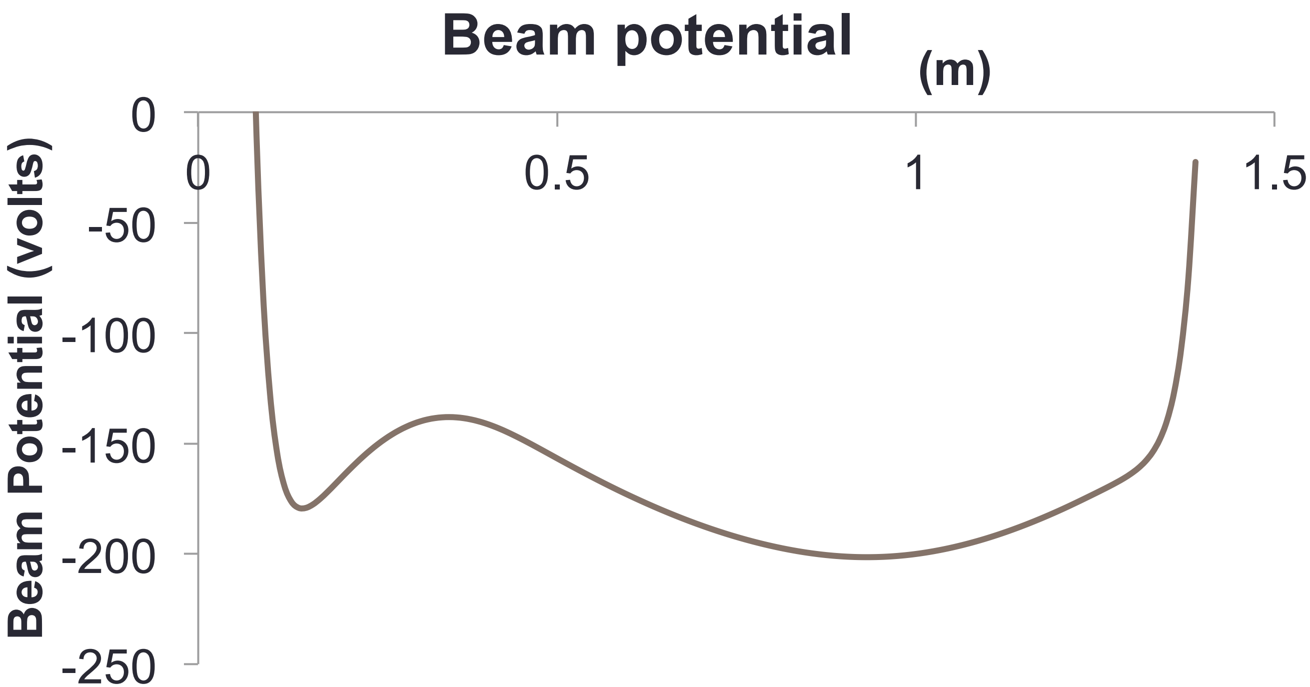


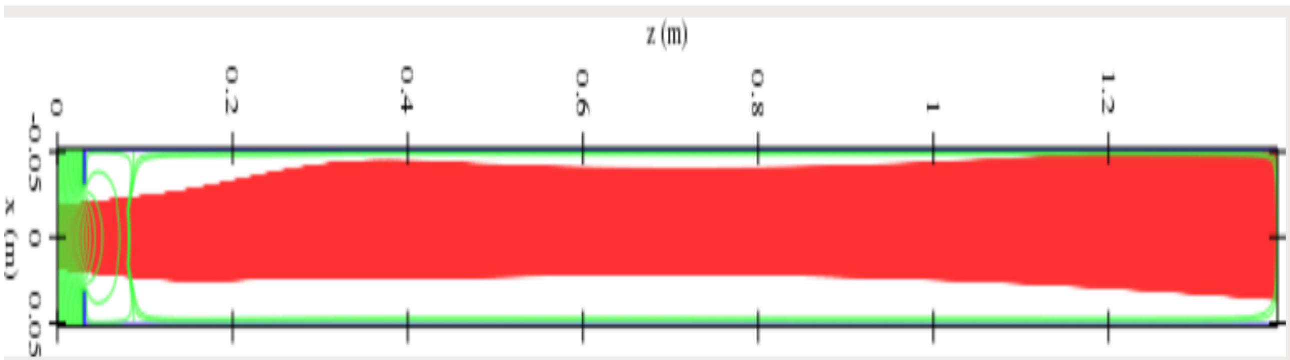
High voltage clear secondary particles

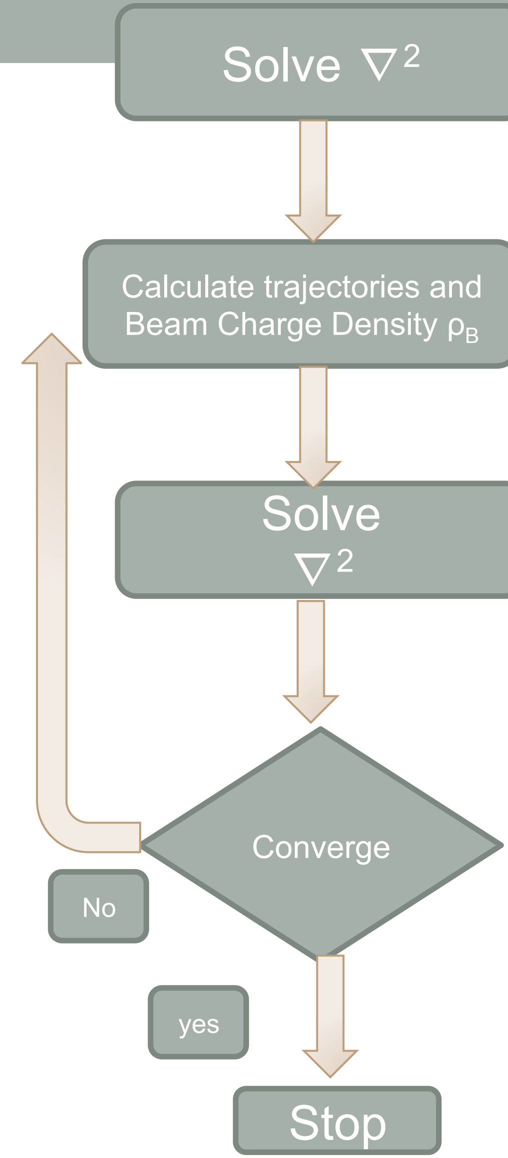
Solenoid Faraday Cup Emittance meter

Secondary particles included

Beam transport First solution



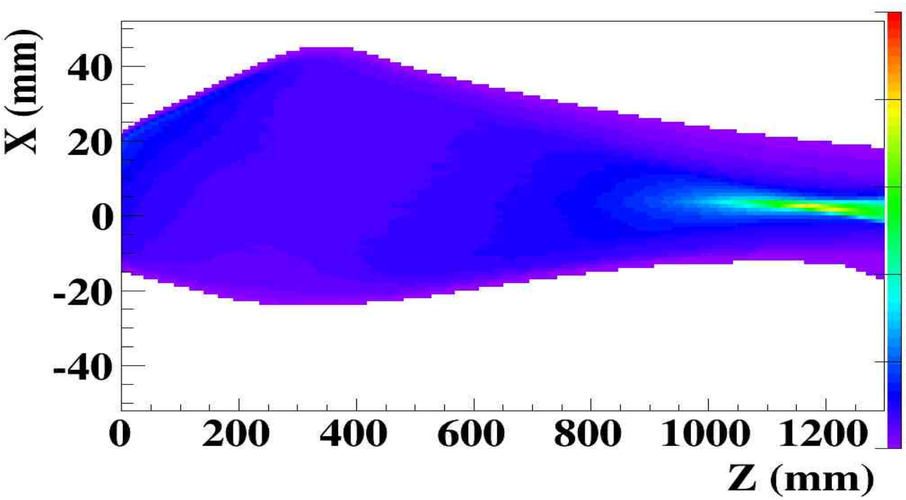




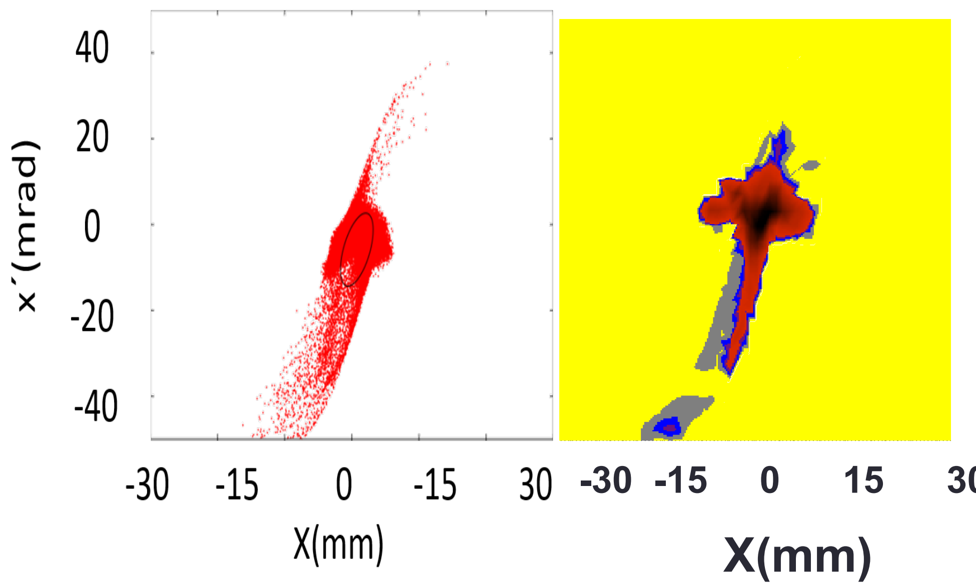
Travel and Ibsimu were used

Space Charge compensation using Frozen model

- Beam Current 35 mA



Simulation   Measurements

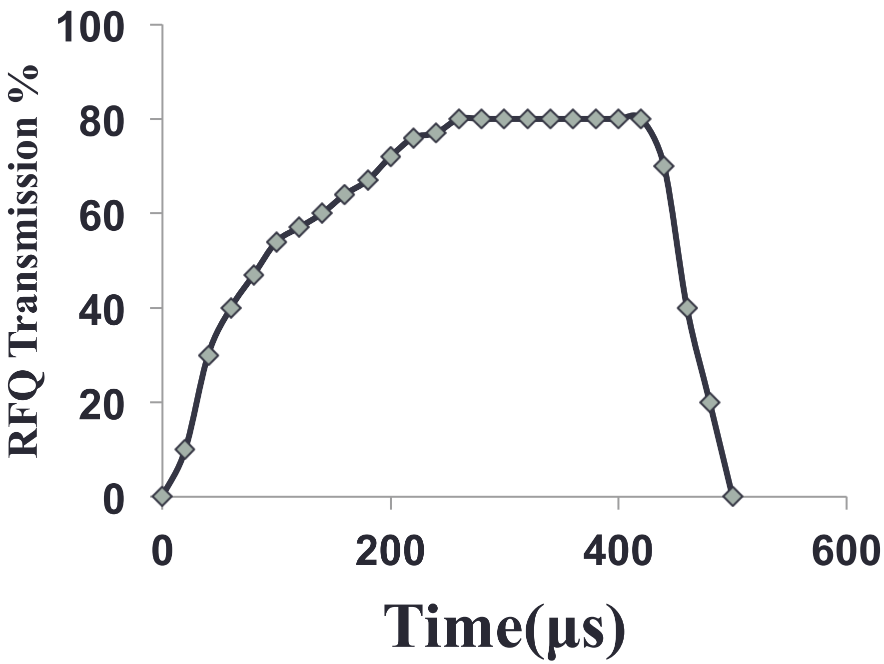


Emittance mm.mrad 1 rms (norm) :   0.29   0.55

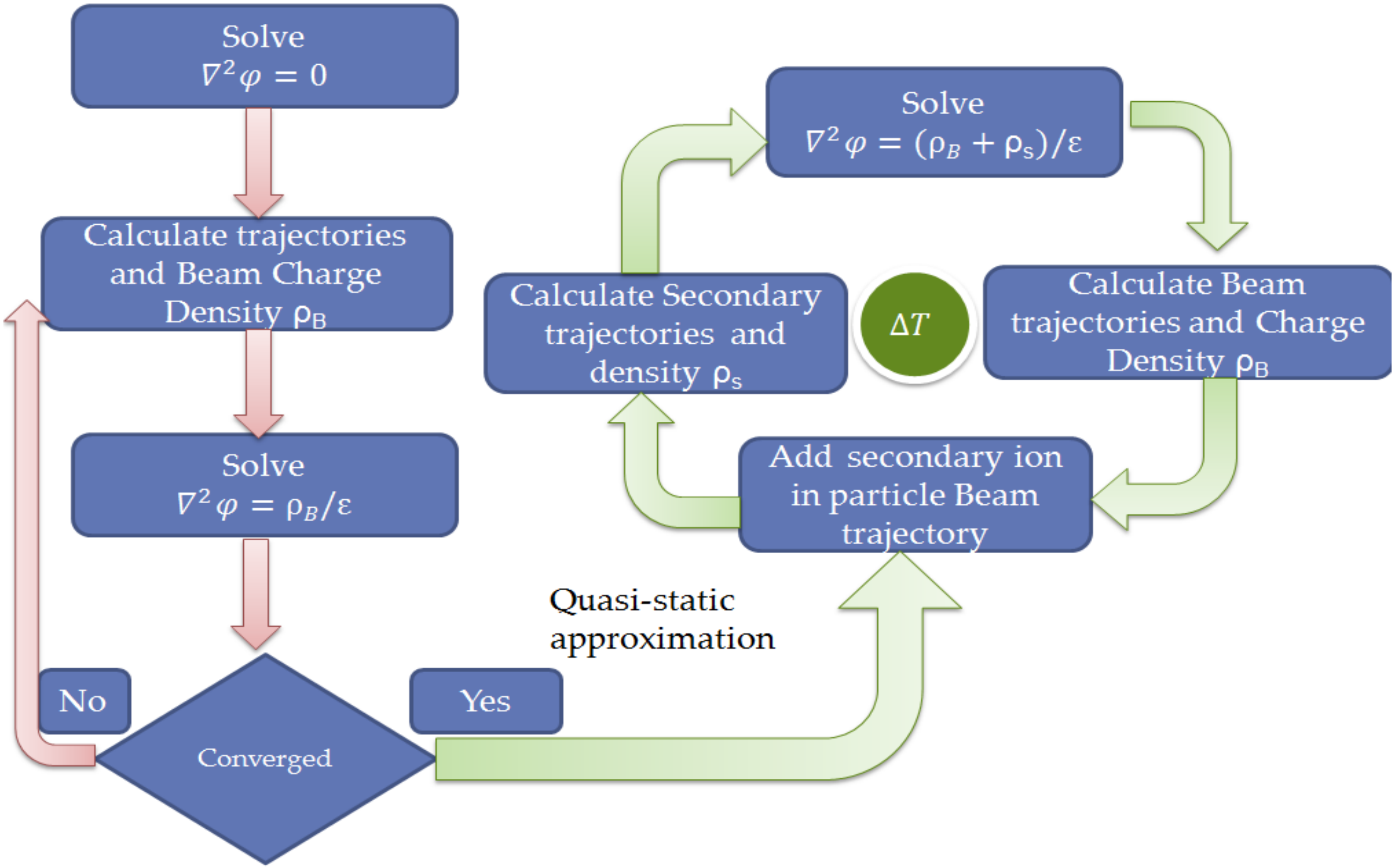
The absolute value of the emittance is 200% bigger in measurements

Problem to solve

- The beam parameters cannot be taken like constant in time due the SCC
- Is necessary to include the secondary particles in the simulation to predict and understand the beam behaviour before and after the SCC build-up to identify the emittance growth mechanisms

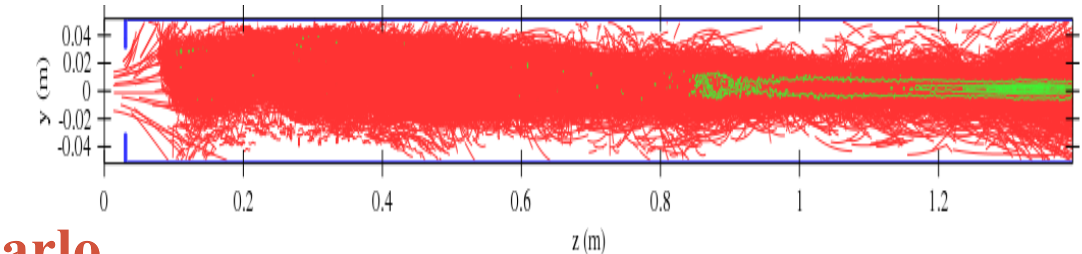


SCC simulation



Scc simulations with 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 in IBSimu**

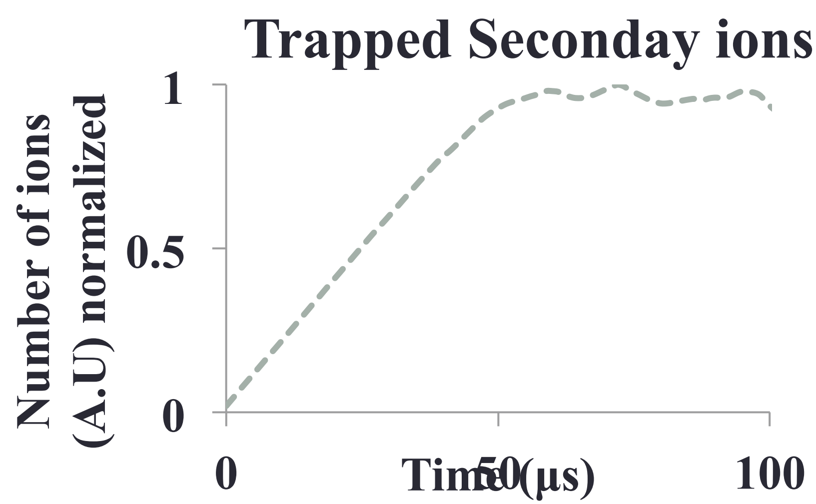


Secondary particles in the System

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

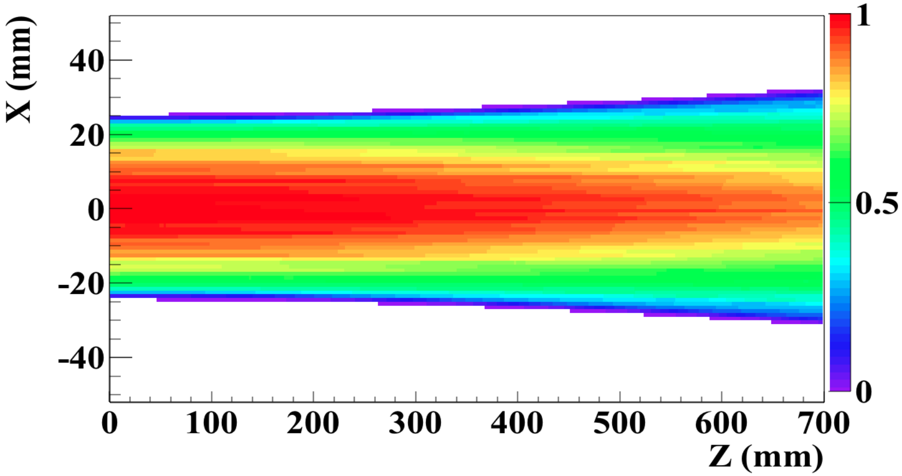
$$L = \frac{1}{\sigma(E) n_{H2}}$$

Pressure $1x10^{-6}$ mbar

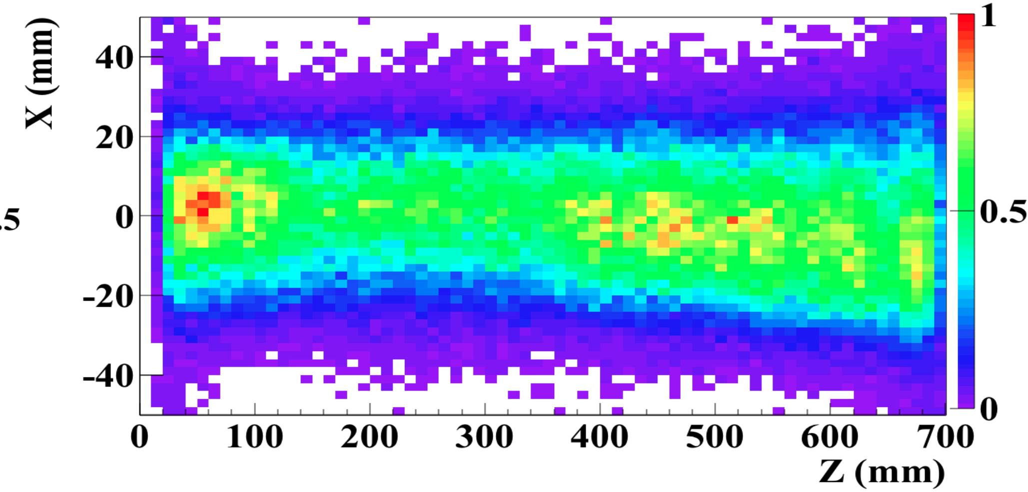


Drift simulation

100 V



0 V

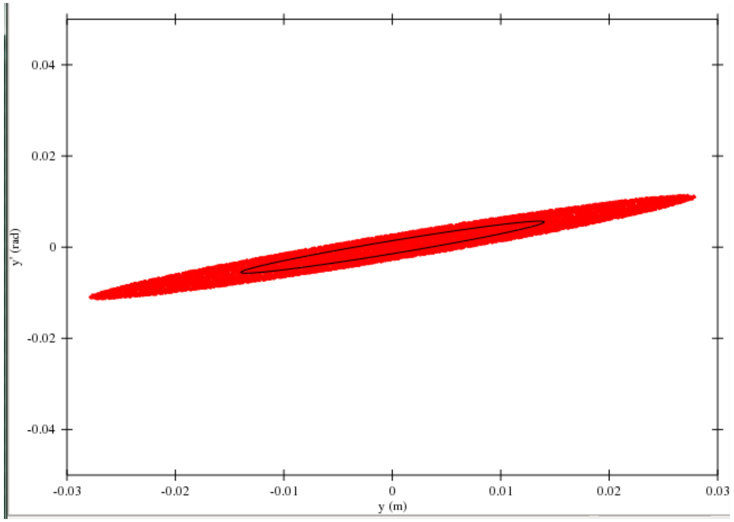


To separate the LEBT and Source effects we simulate a drift to simplify the problem
The solenoid is not necessary to transport the beam at the end of the system

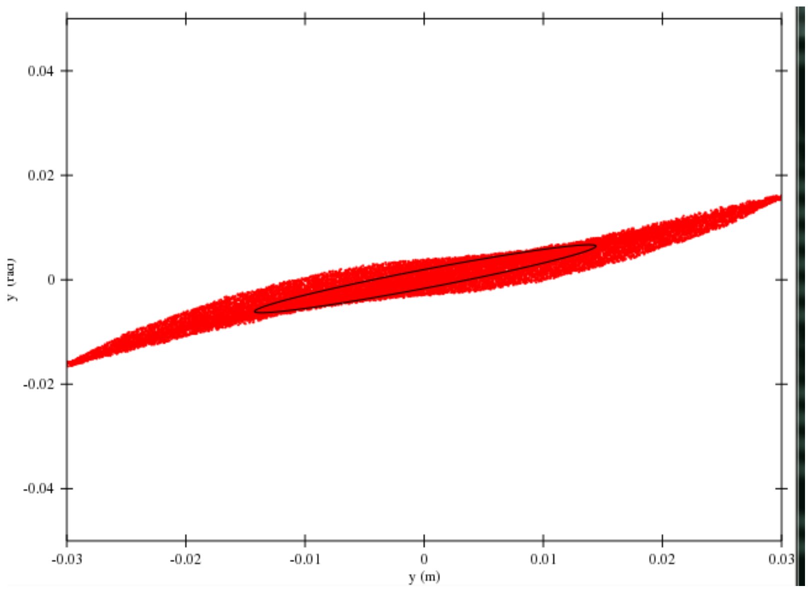
Gaussian Beam
Emittance 0.2 mm.mrad (norm)
Energy 45 Kev
Beta = 8
Alpha=10
30 ma

Residual gas pressure ~2e-6 mbar

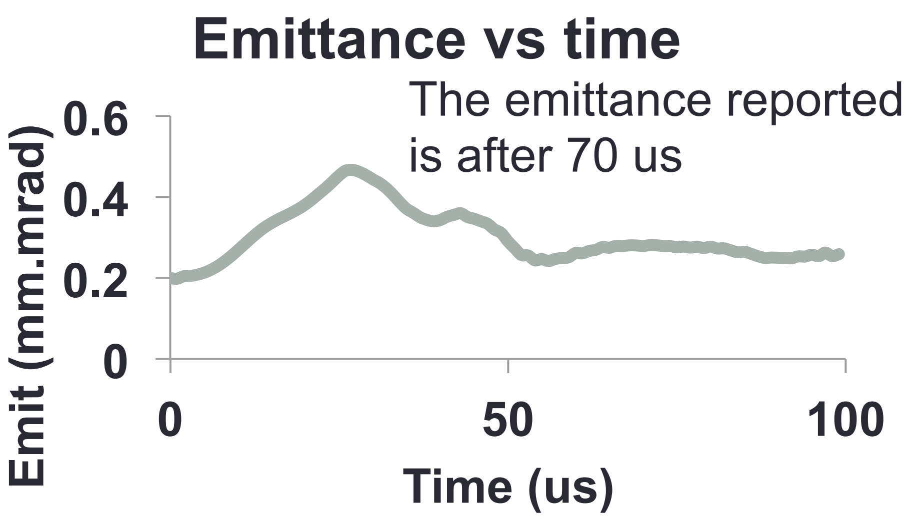
Drift results



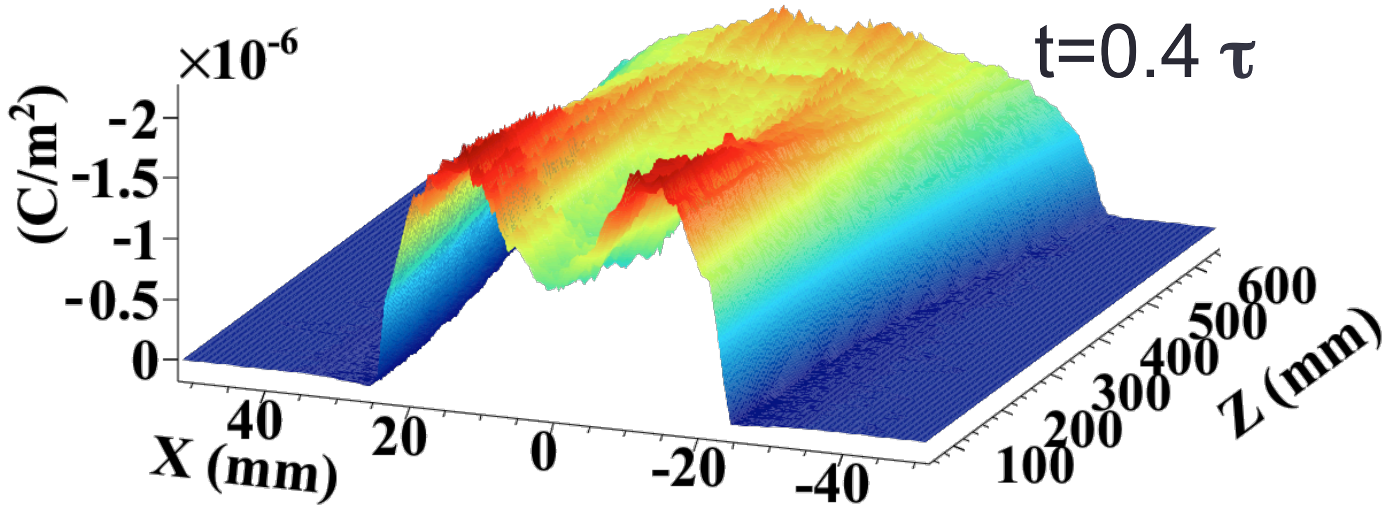
Frozen space charge 80% compensation
Emittance 0.20005 mm.mrad
Emittance growth ~0



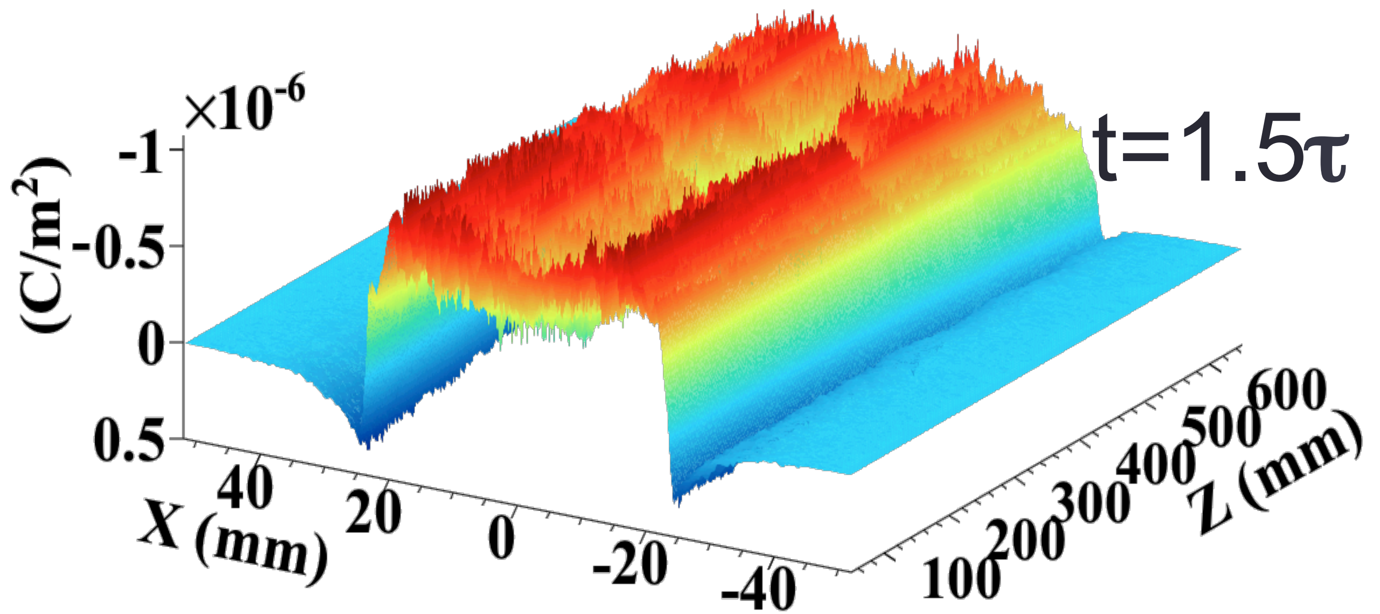
Secondary particles in simulation
Emittance 0.26 mm.mrad
Emittance growth 28%



Space charge evolution

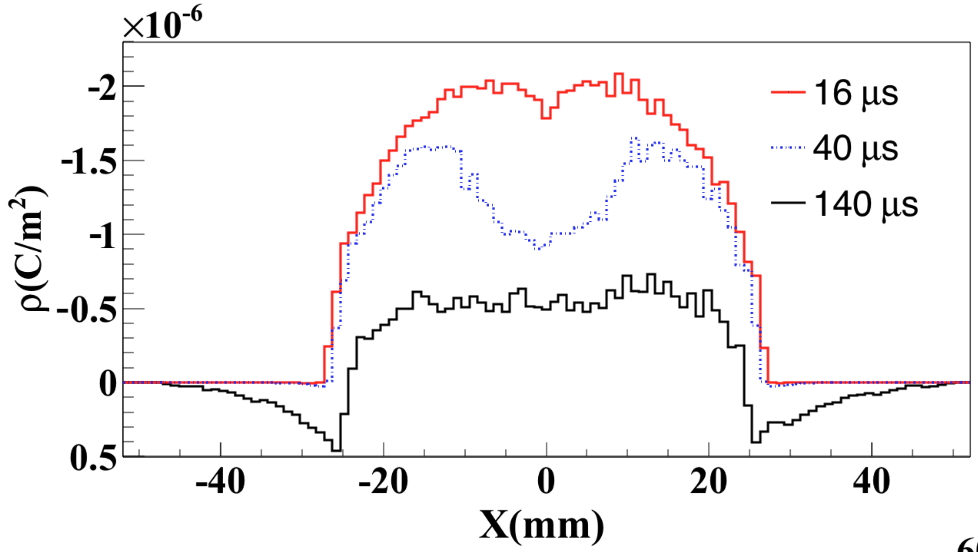


The secondary particles are accumulated in the beam center driving to a hollow space charge distribution



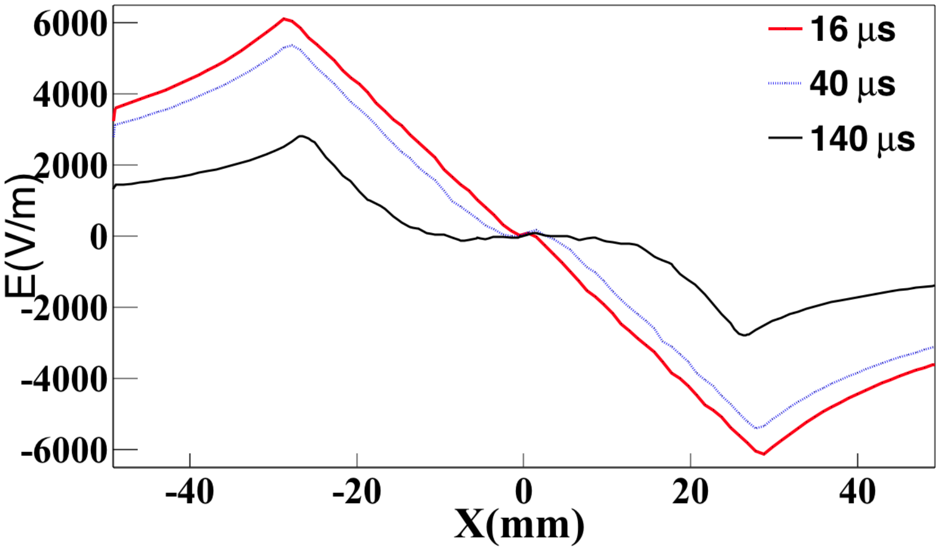
There is overcompensation in the beam edges
The distribution is more homogeneous

Space charge and electric field

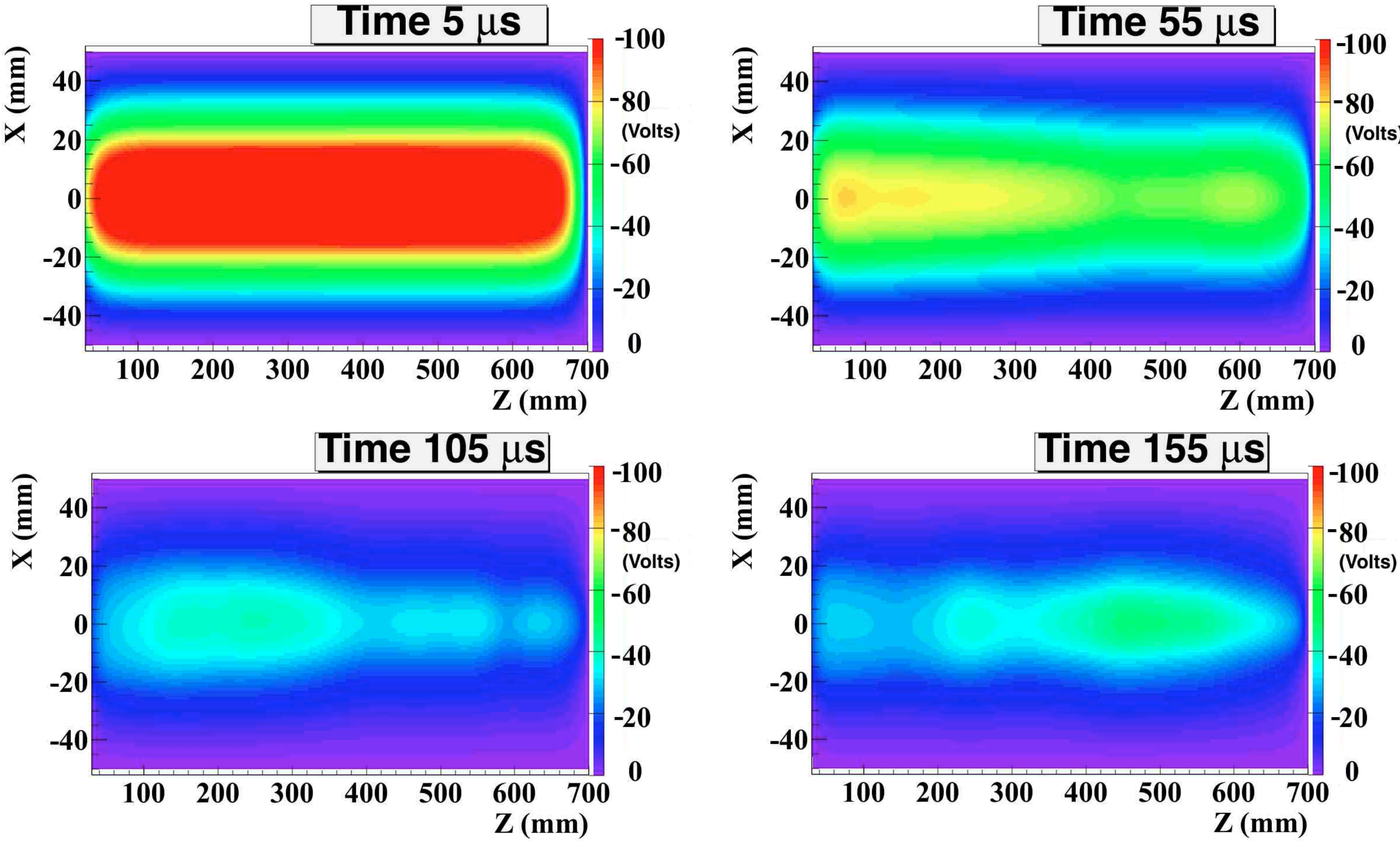


The space charge map is redistributed all around the beam volume

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

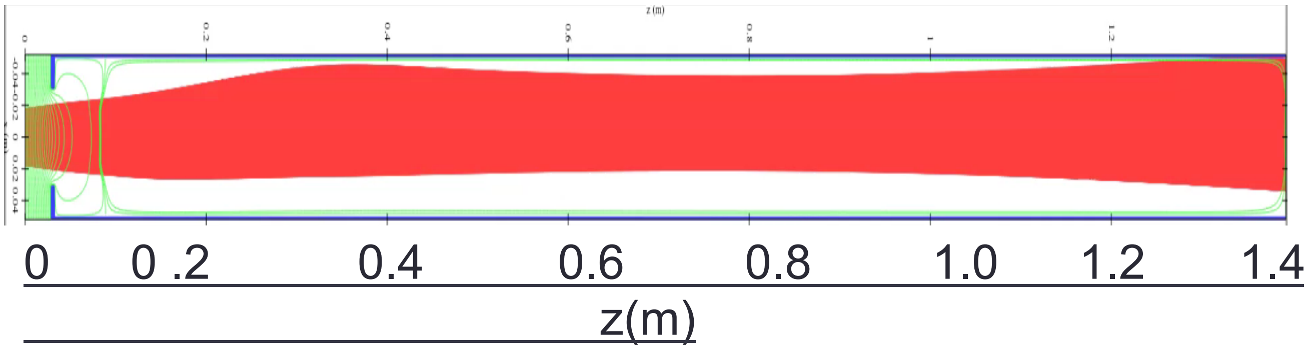


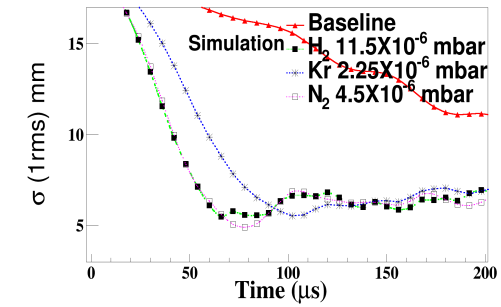
Electric potential evolution



Simulations vs Measurements

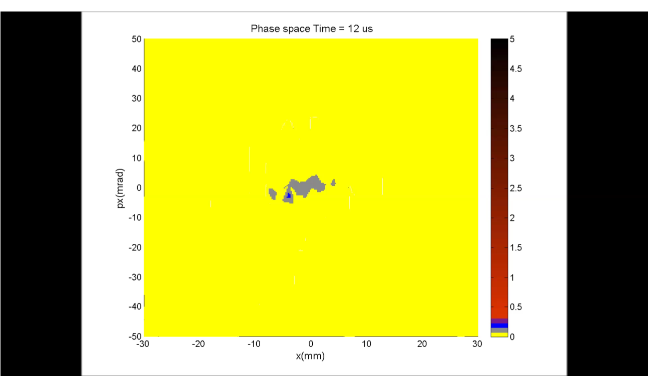
Beam profile evolution in x-z

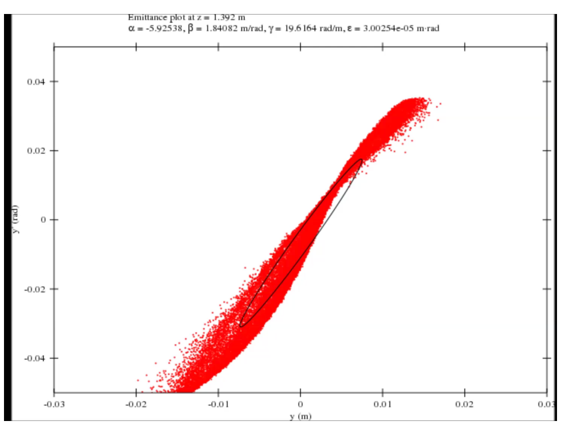


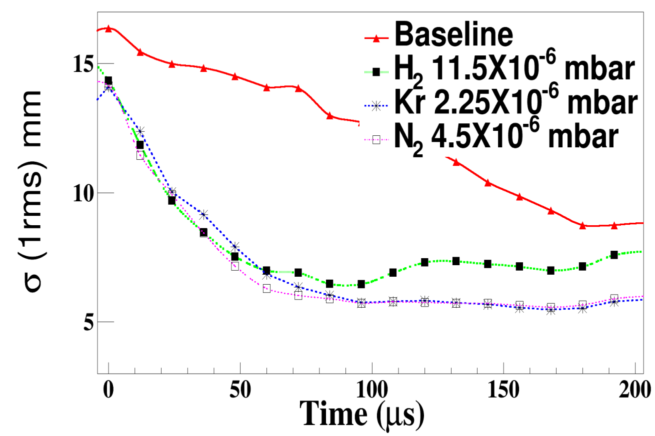


Beam size evolution in time

The evolution in time shows a good agreement

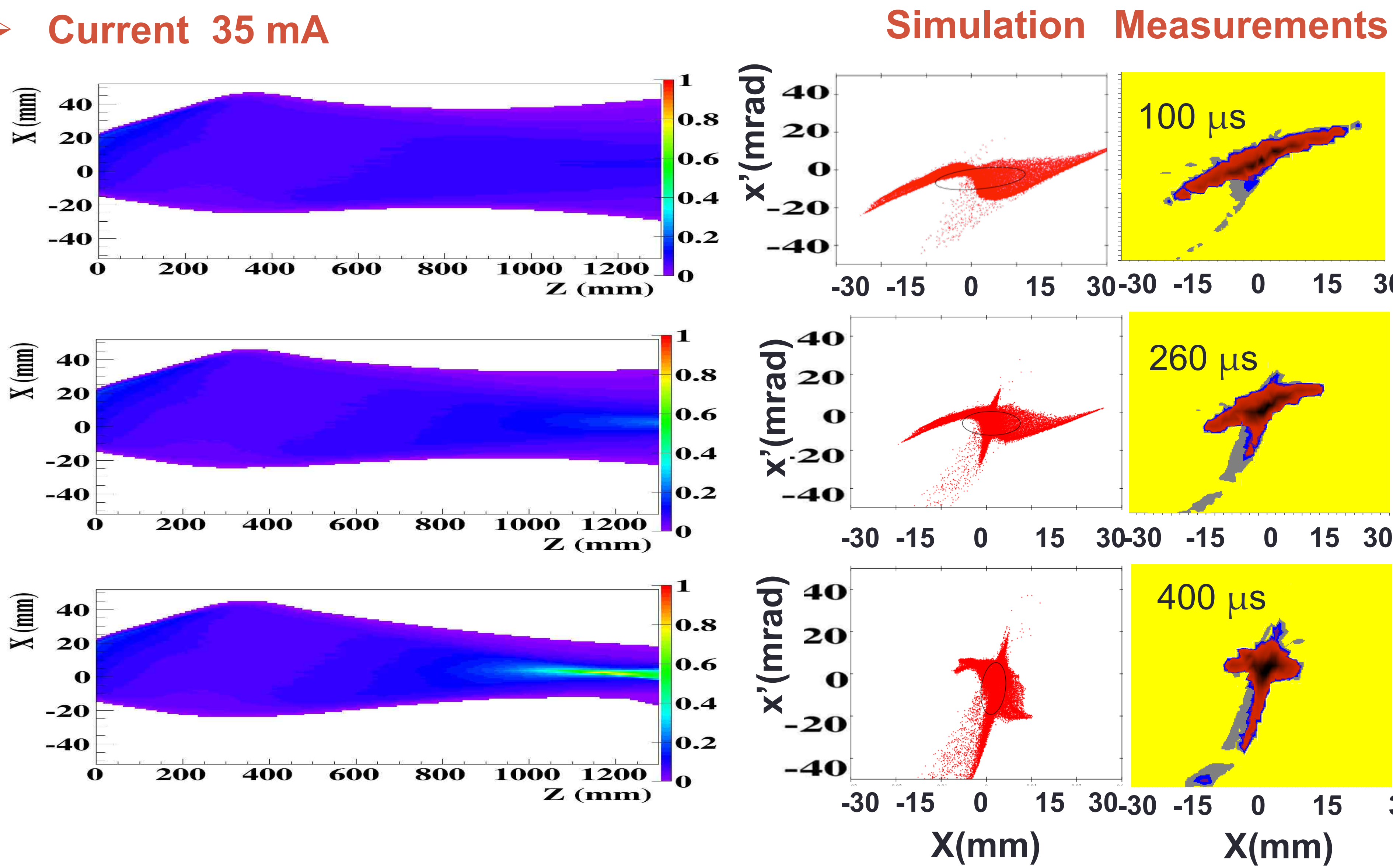






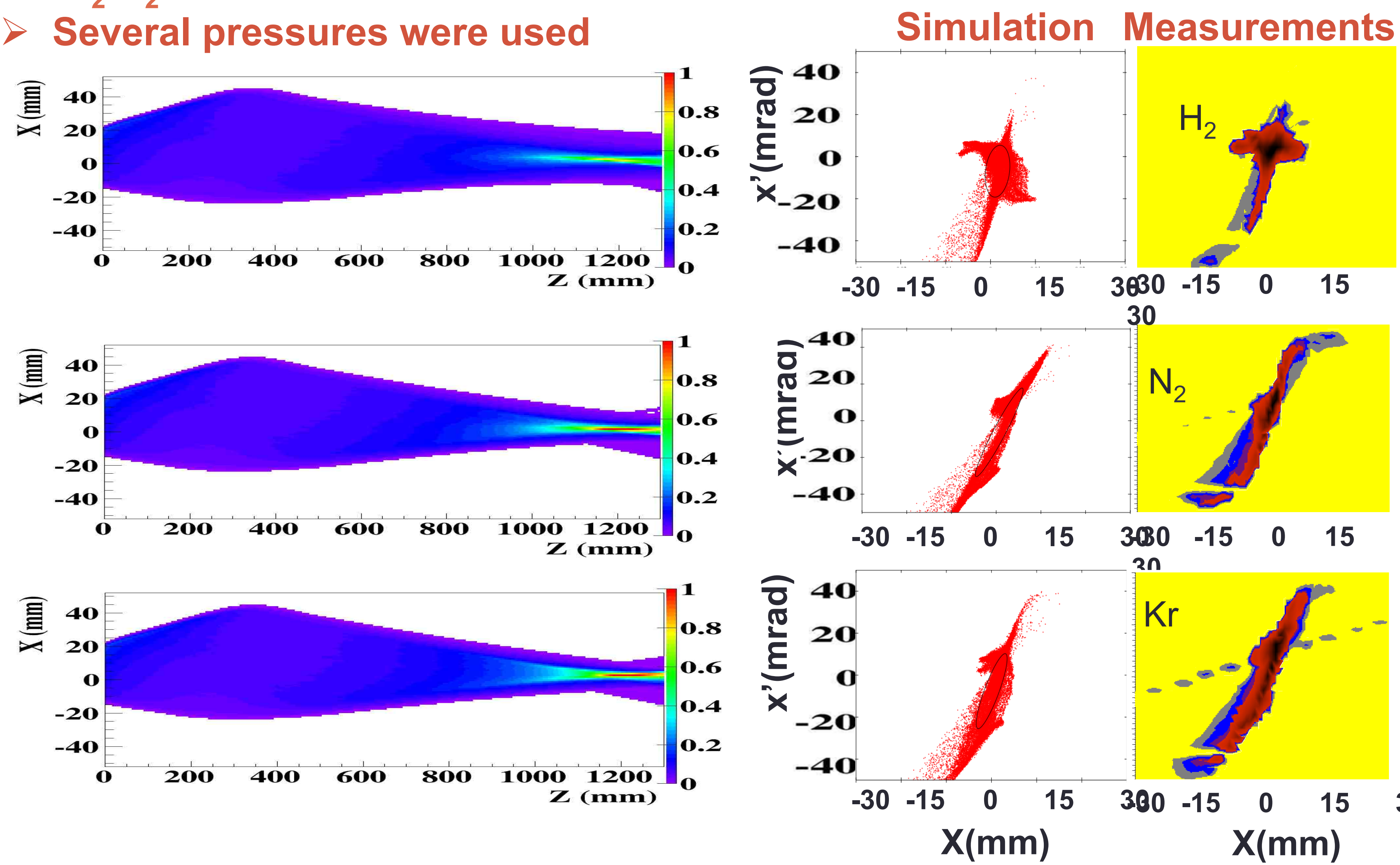
Space Charge compensation using H_2

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

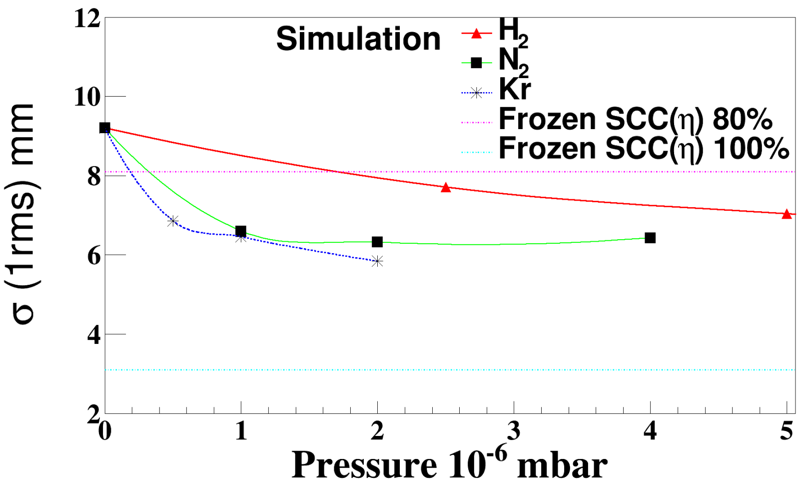


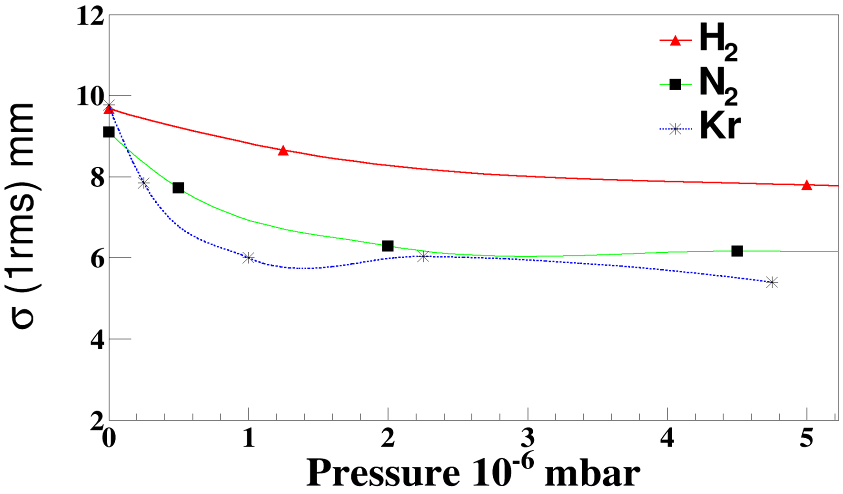
Compensation using different gases

- H_2 N_2 and Kr
- Several pressures were used

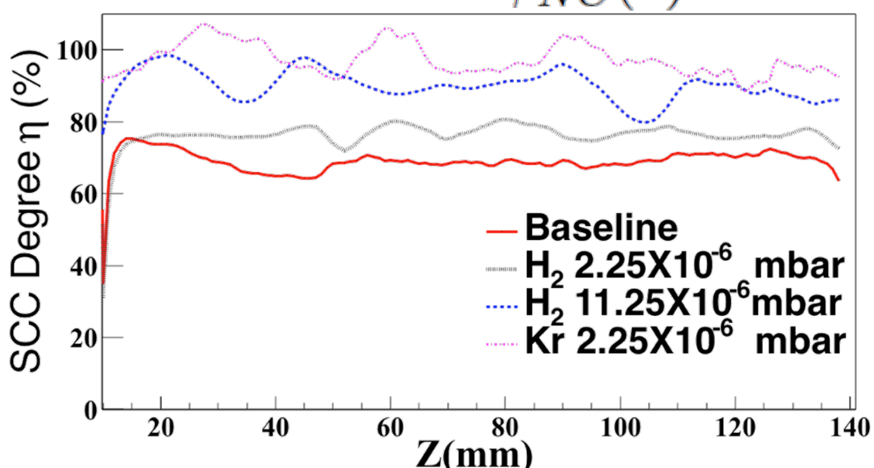


Beam size and Compensation Degree





$$\eta(z,t) = (1 - \frac{\phi(z,t)}{\phi_{NC}(z)})$$



The final beam size and Scc degree depends of the gas pressure and gas type

Conclusions

The new method to simulate the space charge compensation using secondary particles works.

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.

The results agree with the measurements like not other code available today.

Some improvements has been made to the extraction system thanks to the results of the simulation

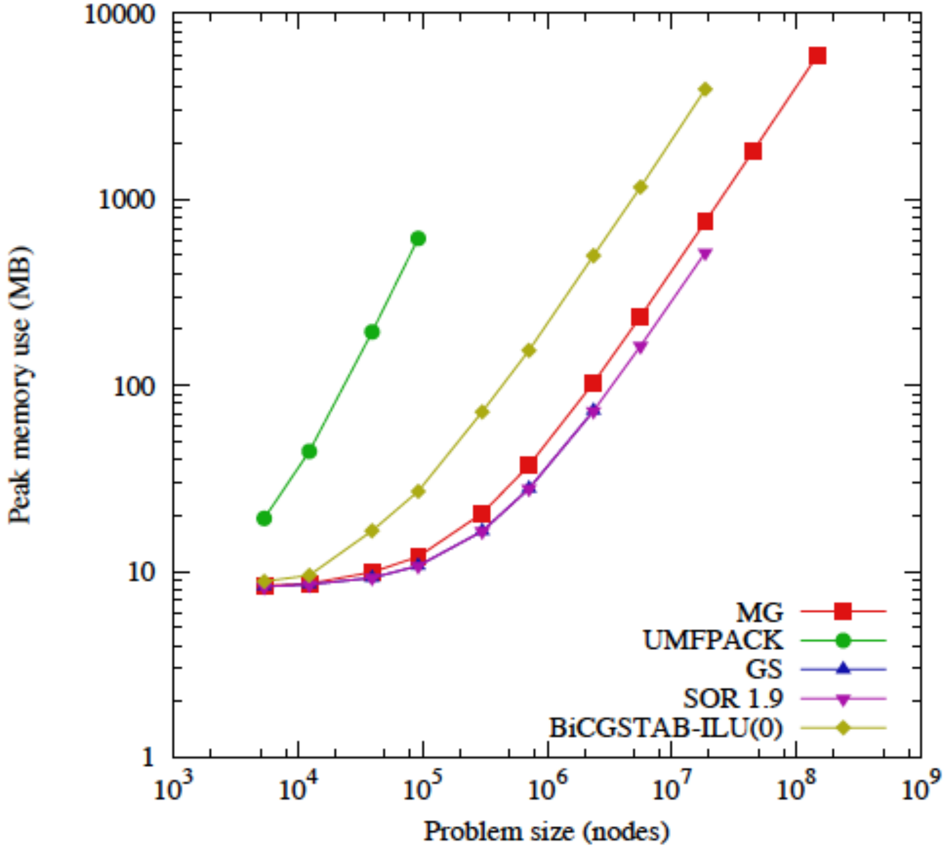
The matching parameters can be predicted in a really accurate way taking in to account the time dependence

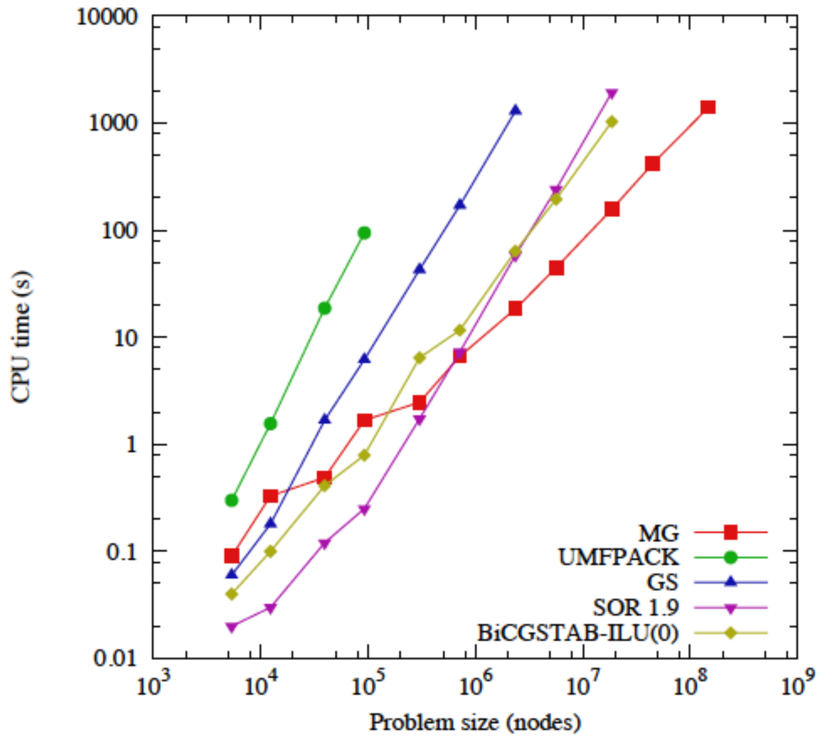
There are 3 papers and 2 international conference posters using this work

Thank you!

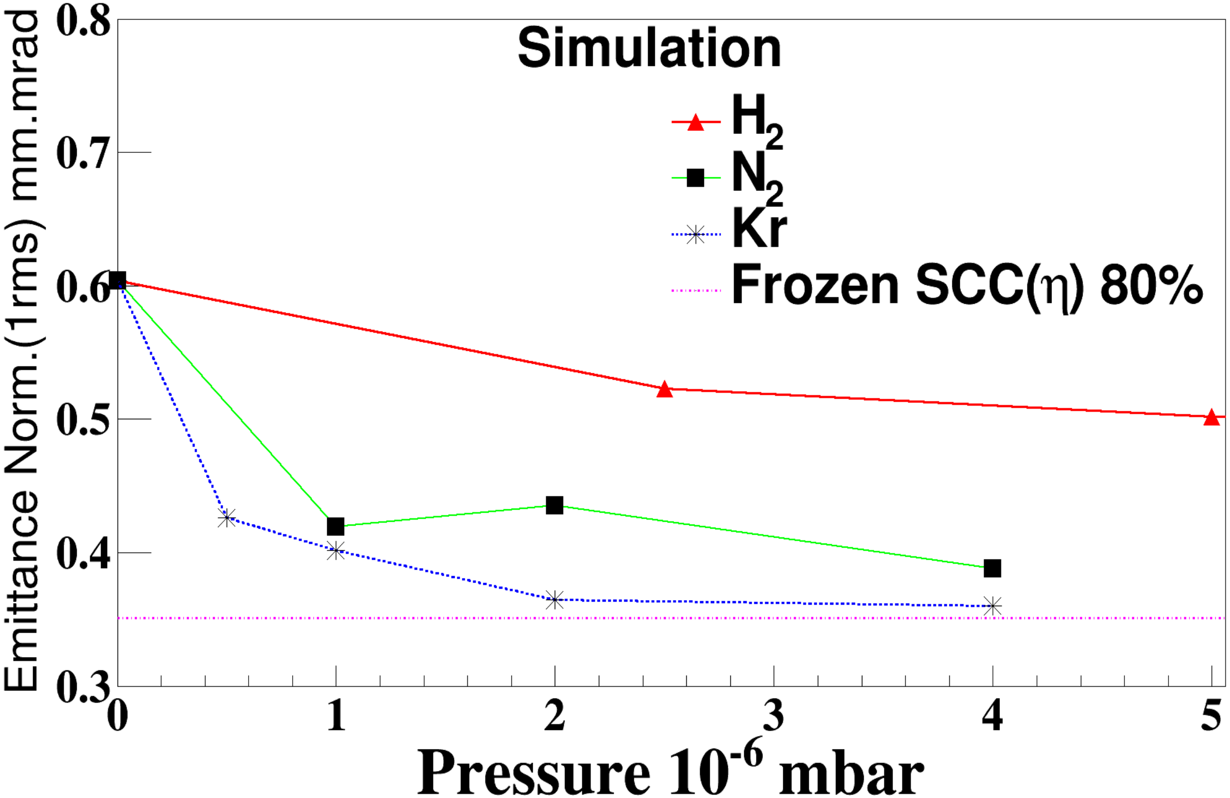
Acknowledgement

Richard Scrivens
Ildefonso León
Santos Jesús Castillo
Guillermo Contreras
CONACYT
And the Linac4 collaboration


Peak memory use (MB)
10000
1000
100
10
1
10^3 10^4 10^5 10^6 10^7 10^8 10^9
Problem size (nodes)
MG
UMFPACK
GS
SOR 1.9
BiCGSTAB-ILU(0)


CPU time (s)
10000
1000
100
10
1
0.1
0.01
10^3 10^4 10^5 10^6 10^7 10^8 10^9
Problem size (nodes)
MG
UMFPACK
GS
SOR 1.9
BiCGSTAB-ILU(0)

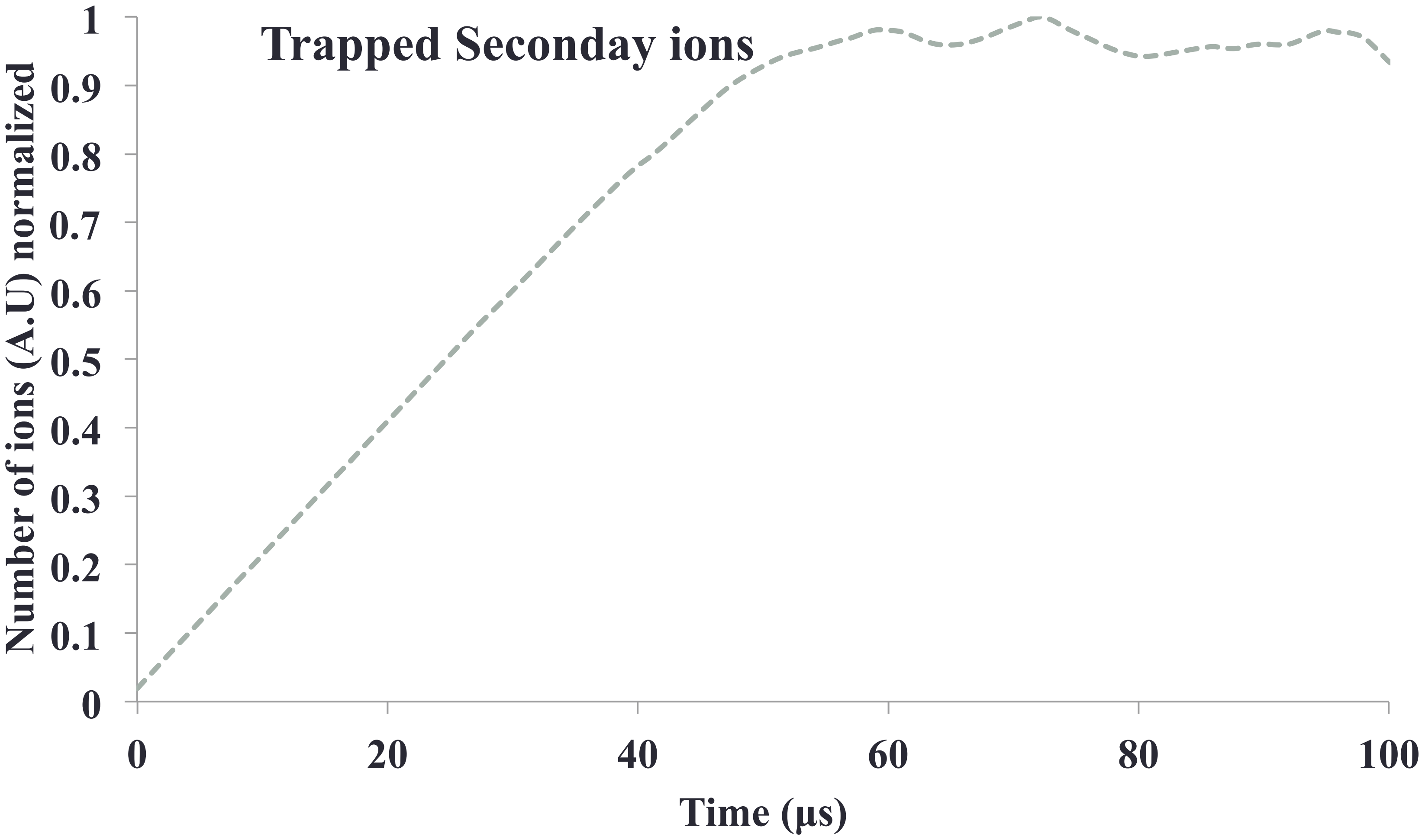
Stabilization time



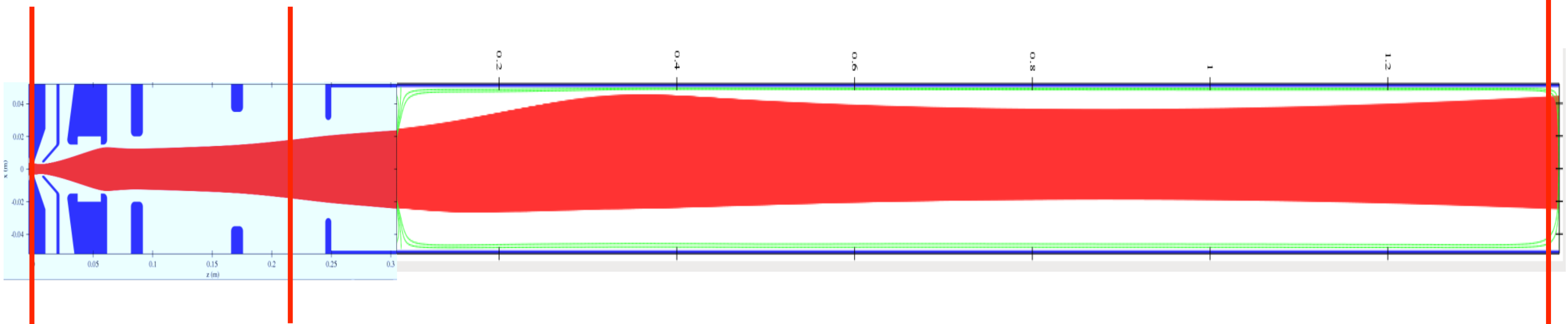
$$\sigma(t) = \sigma_0 e^{-t/\tau}$$

Measured beam size decay time of the partial pressures for H_2, Kr and N_2. The dot line shows the desired stabilization time of 25 μs.

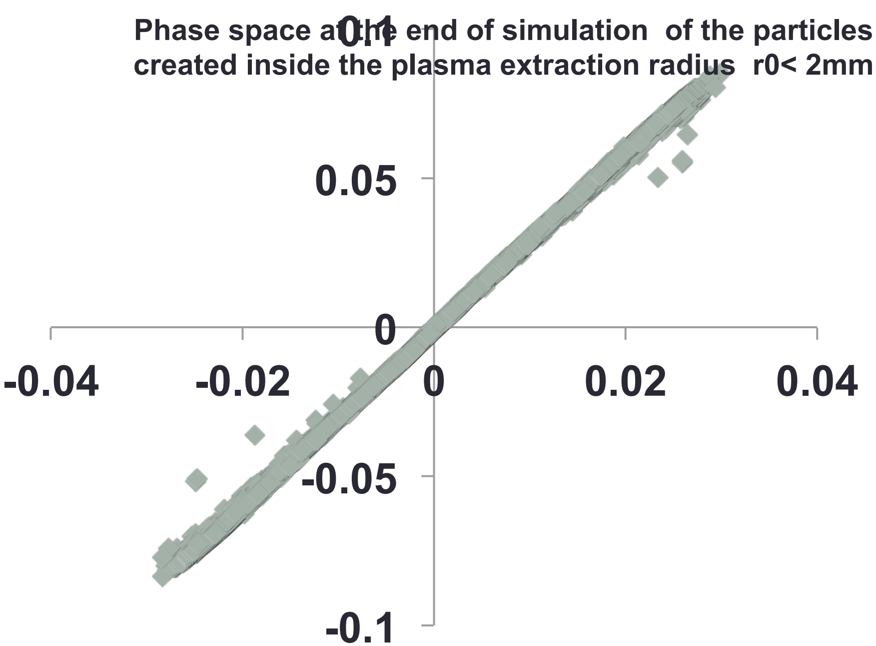
Secondary Ions in the system

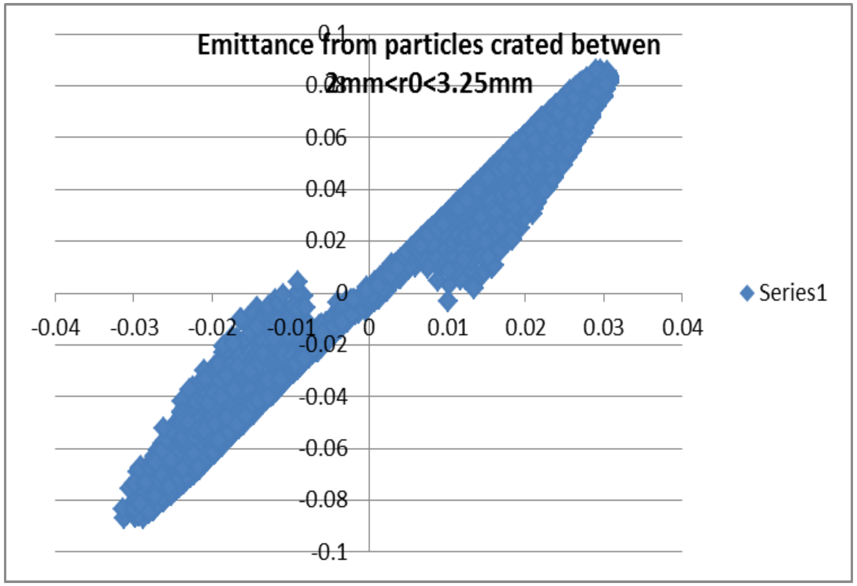


Tracking back the particles to the Source aperture

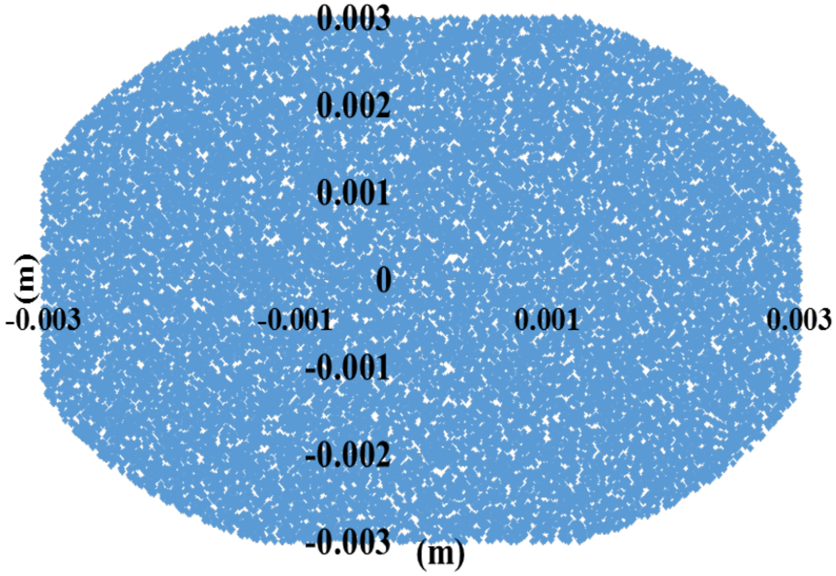


1)Tag the particles in the ion source
2) Use the tag to compare the particles that manage to arrive to the emittance meter

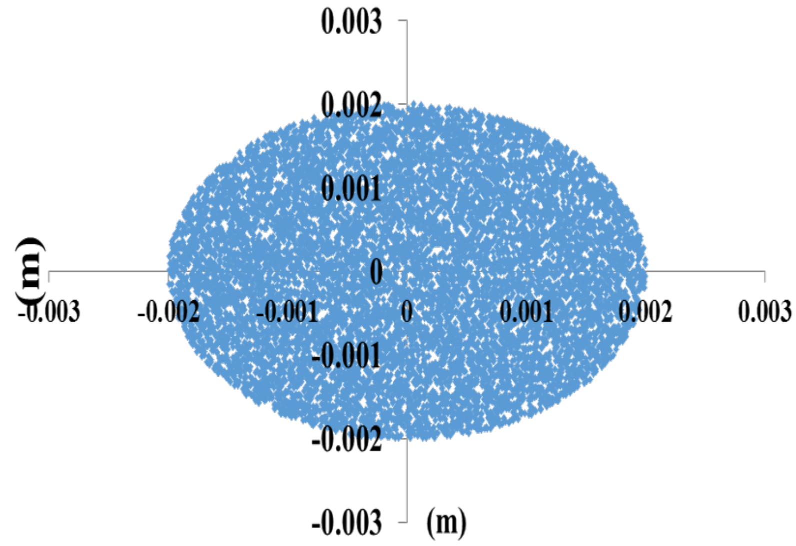




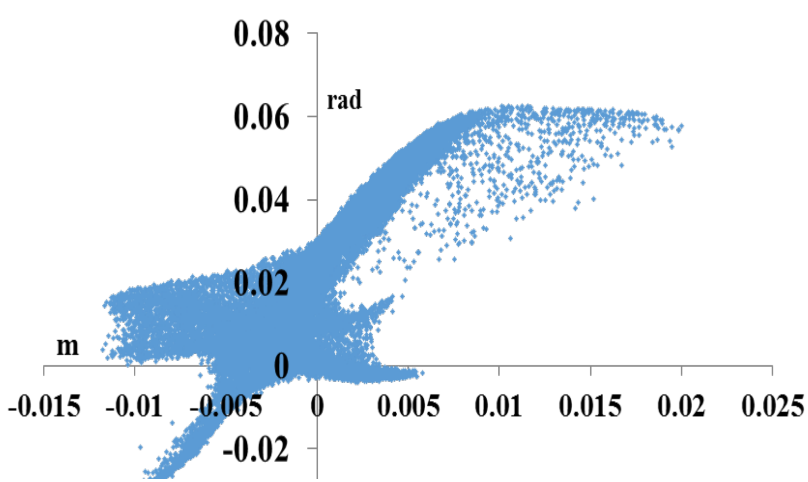
Real space ion source hole



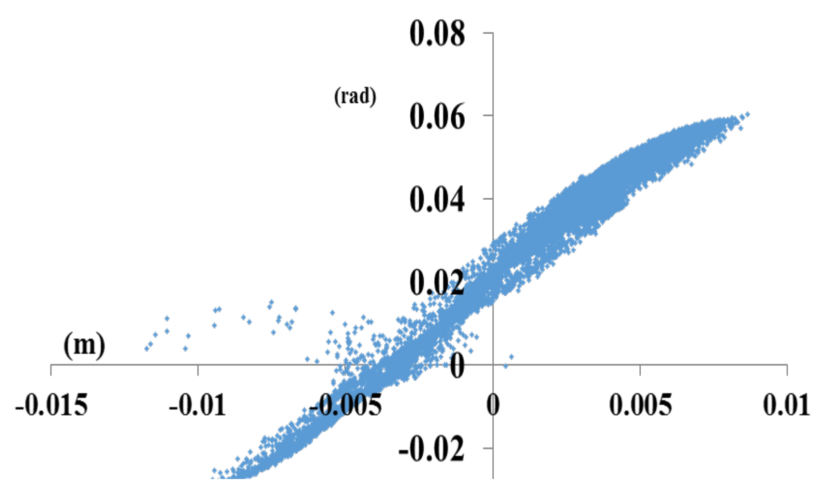
Real space ion source hole



Phase Space Emittance Meter



Cut Phase space Emittance meter



Publications

Space charge compensation in the Linac4 low energy beam transport line with negative hydrogen ions

Cristhian A. Valerio-Lizarraga[1,2)], Jean-Baptiste Lallement [1],Ildefonso Leon-Monzon[3], Jacques Lettry[1], Øystein Midttun[1,4)] and Richard Scrivens[1]

Rev. Sci. Instrum. 85, 02A505 (2014)

Linac4 low energy beam measurements with negative hydrogen ions

R. Scrivens[1],, G. Bellodi[1], O. Crettiez1, V. Dimov1, D. Gerard1, E. Granemann Souza1, R. Guida1, J. Hansen1, J.-B. Lallement1, J. Lettry1, A. Lombardi1, Ø. Midttun1, C. Pasquino1, U. Raich1, B. Riffaud1, F. Roncarolo1, C. A. Valerio-Lizarraga[1,2], J. Wallner1, M. Yarmohammadi Satri1 and T. Zickler1

Rev. Sci. Instrum. 85, 02A729 (2014)

Optimization of the beam extraction systems for the Linac4 H^- ion source

D. A. Fink[1], J. Lettry[1], Ø. Midttun[1], R. Scrivens[1], D. Steyaert1 and C. A. Valerio-Lizarraga[1,2]

Negative Ion Beam Space charge Compensation by Residual Gas

Cristhian A. Valerio-Lizarraga[1,2],Ildefonso Leon-Monzon[3] Richard Scrivens[1]

Phys. Rev. ST Accel. Beams (**2015)**

Weighted statistics for unevenly spaced SEM-grids on Linac4 line.

E. Granemann Souza[1],C.A.Valerio-Lizarraga[1,2),] A. Lombardi[1]

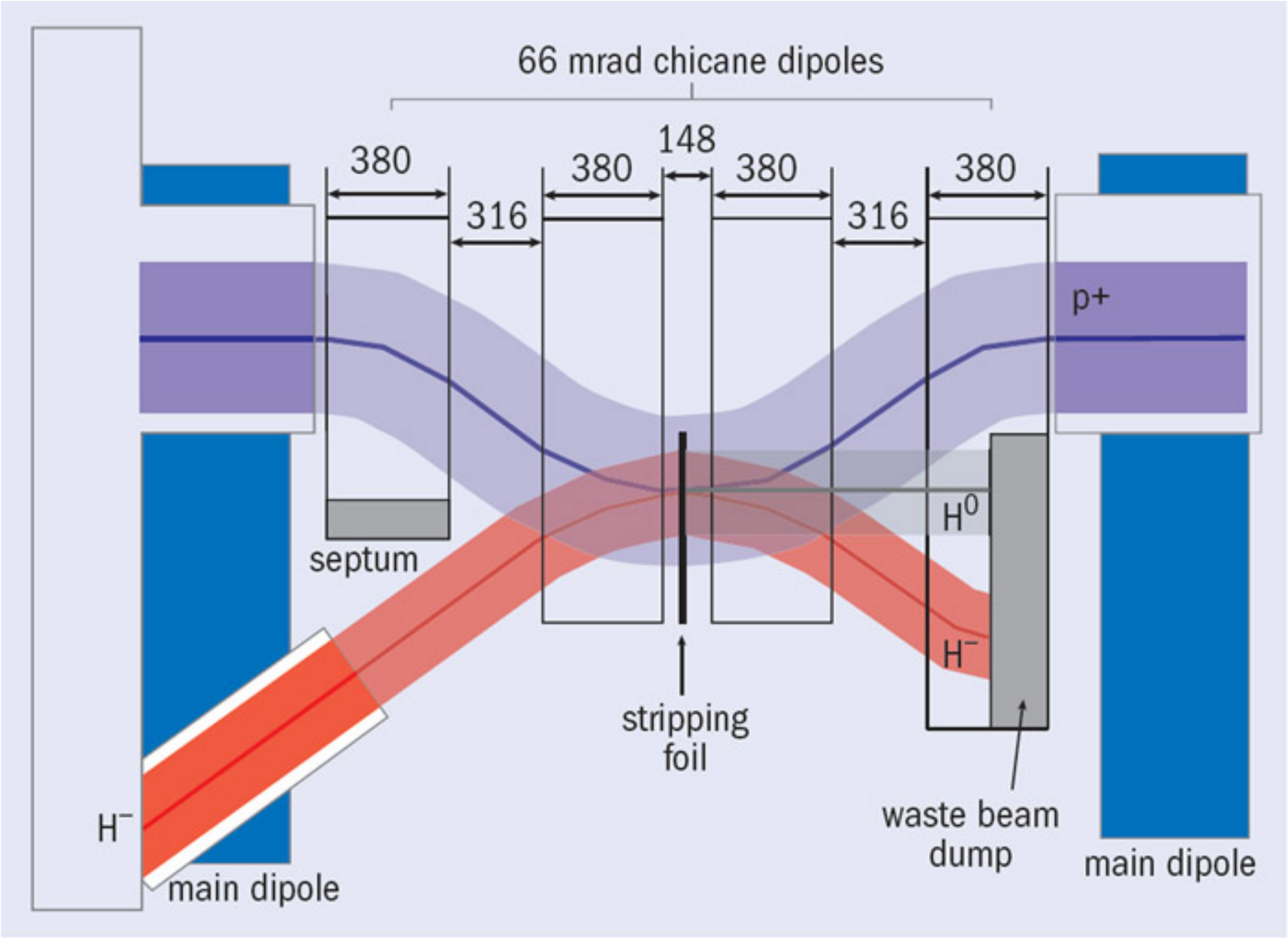
CERN-ACC-NOTE-2013-0034

1CERN, Geneva, Switzerland
2Departamento de Investigación en Física, Universidad de Sonora, Hermosillo, Mexico
3Facultad de Ciencias Fisico-Matematicas, Universidad Autónoma de Sinaloa,Culiacan
4University of Oslo, Oslo, Norway

Why H$^-$?

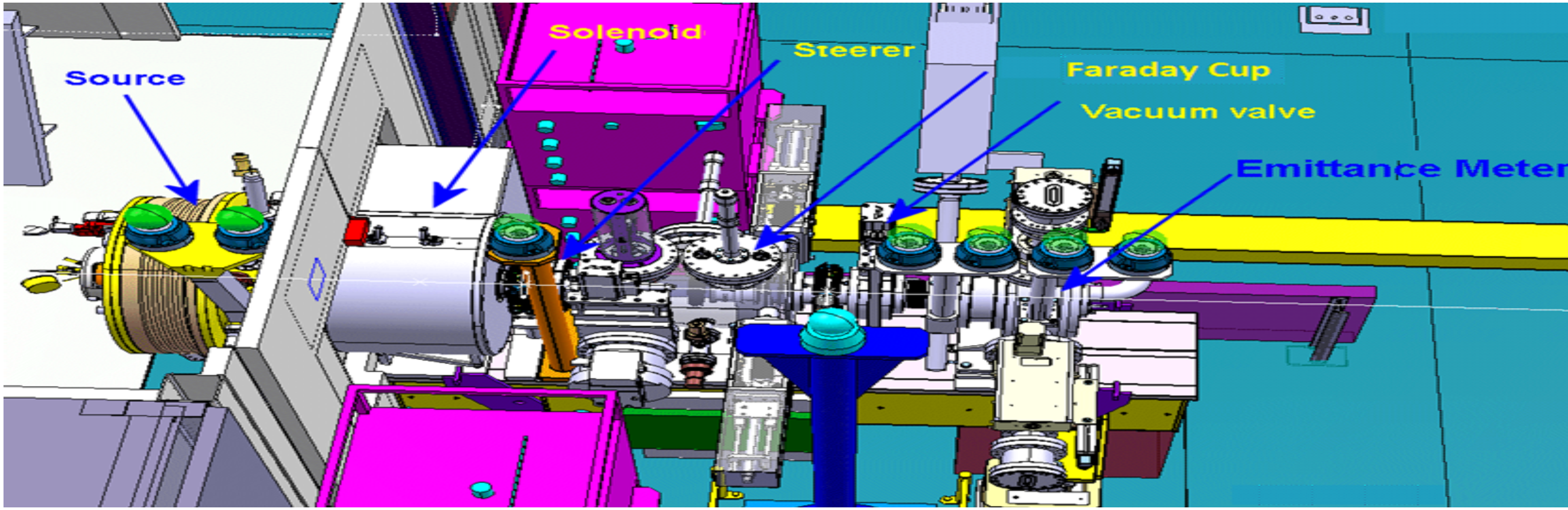
- Because the Space charge repulsion is easier to insert a negative beam inside a positive beam
- In therory the efficiency will be 99% in transform the H$^-$ in to protons

Schematic of H$^-$ injection into a circular machine.



[1] CERN Courier, Sep 2012.

Linac4 Test stand



- 45 keV
- Unbunched Beam
- Secondary Ions Trapped in beam

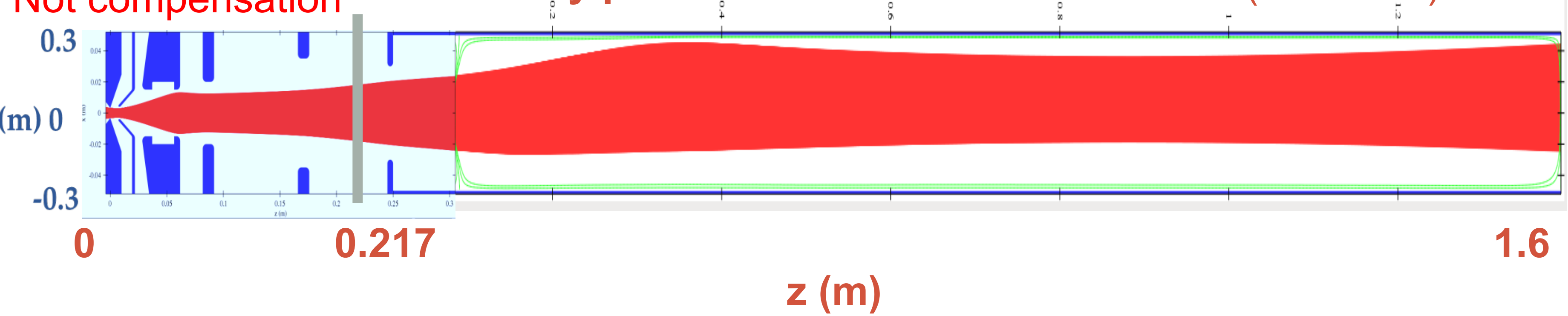
- Measurement of beam phase space
- Injection of H2, N2, Kr gases
- Comparison to simulation

High voltage clear secondary particles

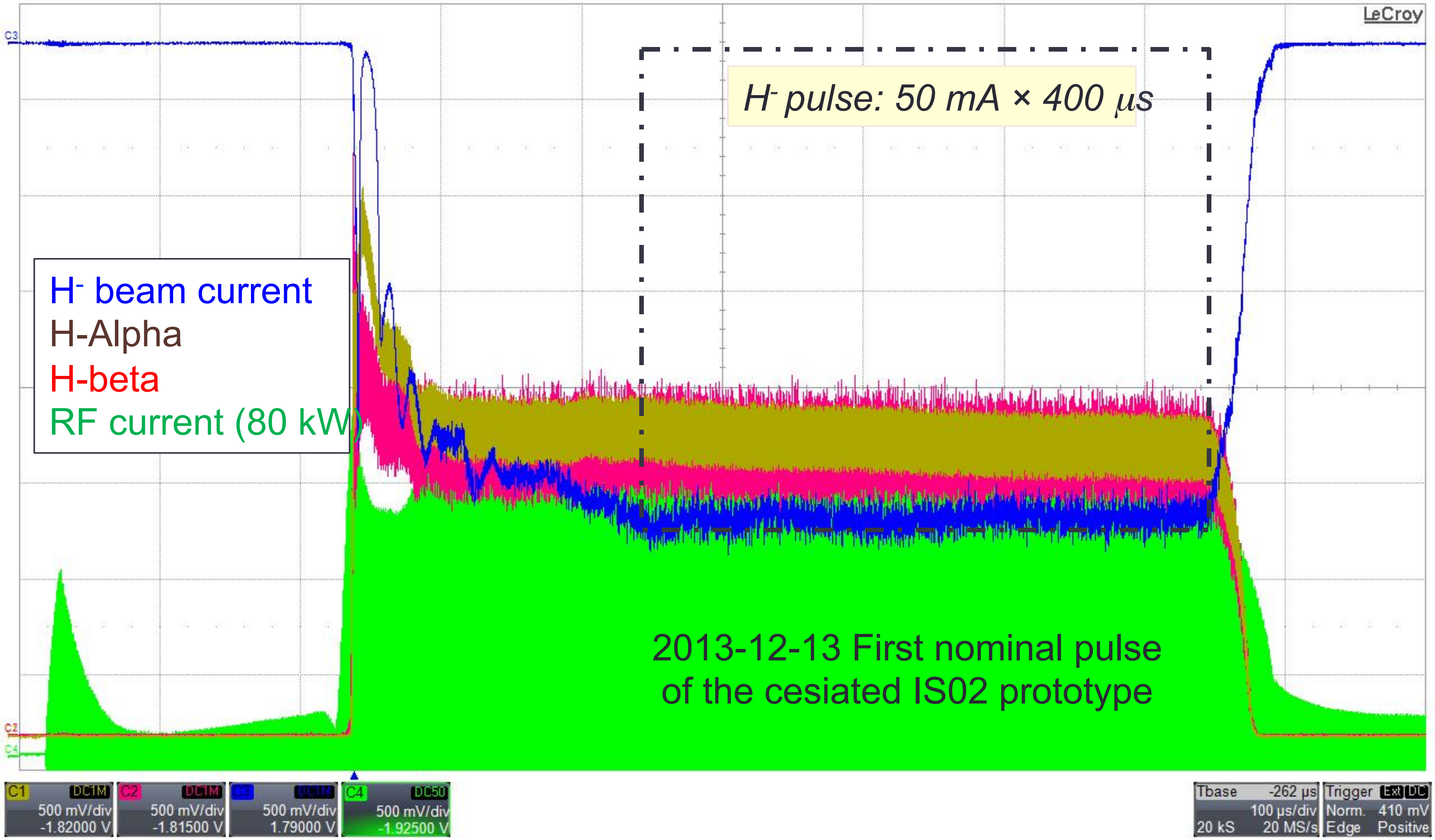
Not compensation

Secondary particles included

Red (H^- Beam)



Linac4 Ion sources status



Still 157 MeV to go…

3 MeV commissioning in the tunnel starting in 2 weeks

- Time resolved measurement of chopping on the ns scale
- Spectrometry / Time Of Flight
- Matching to DTL and 3^{rd} buncher cavity

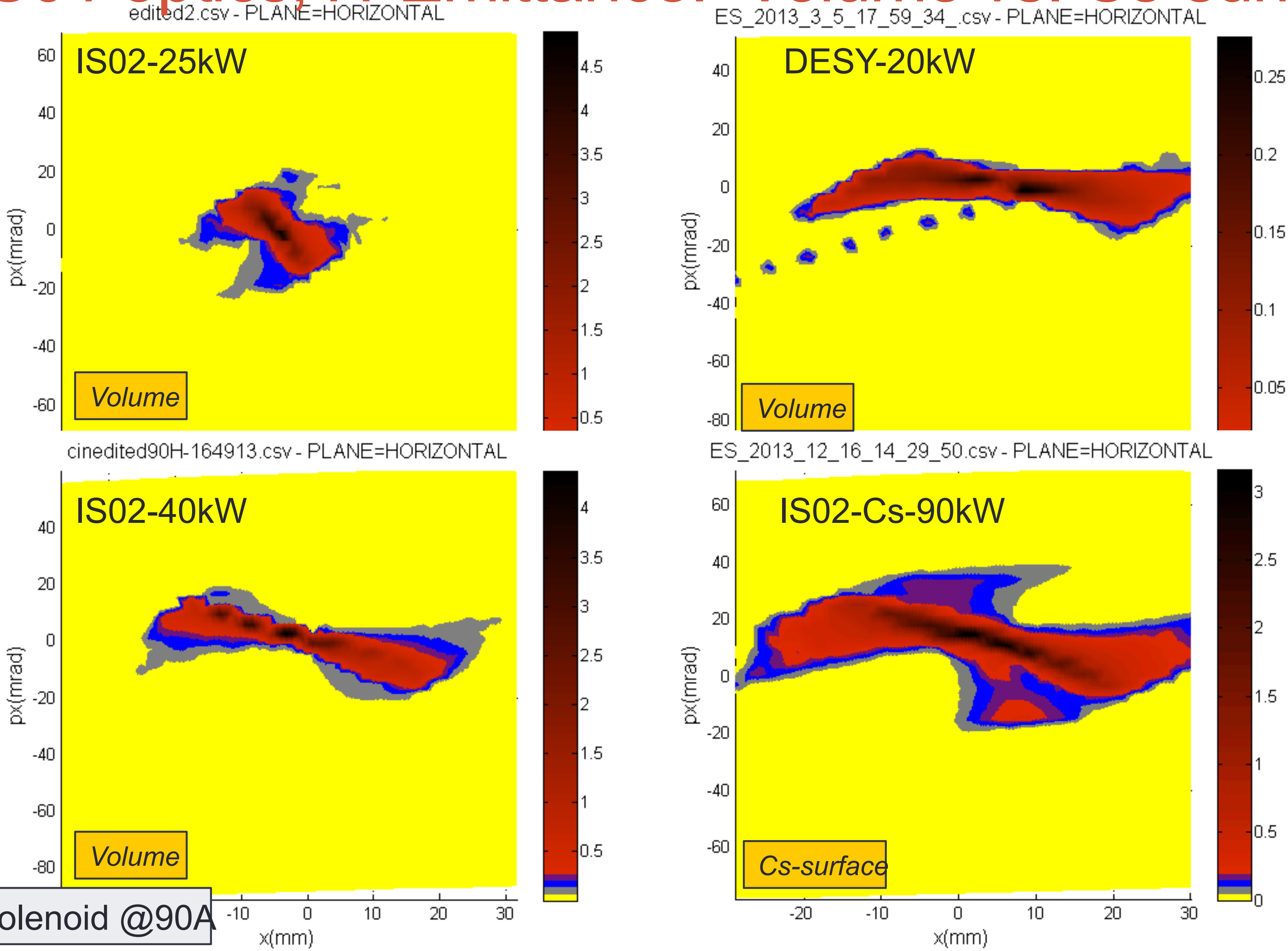
Beam commissioning interlaced with installation period until end 2015

~~Connection to PSB foreseen in 2017-18~~

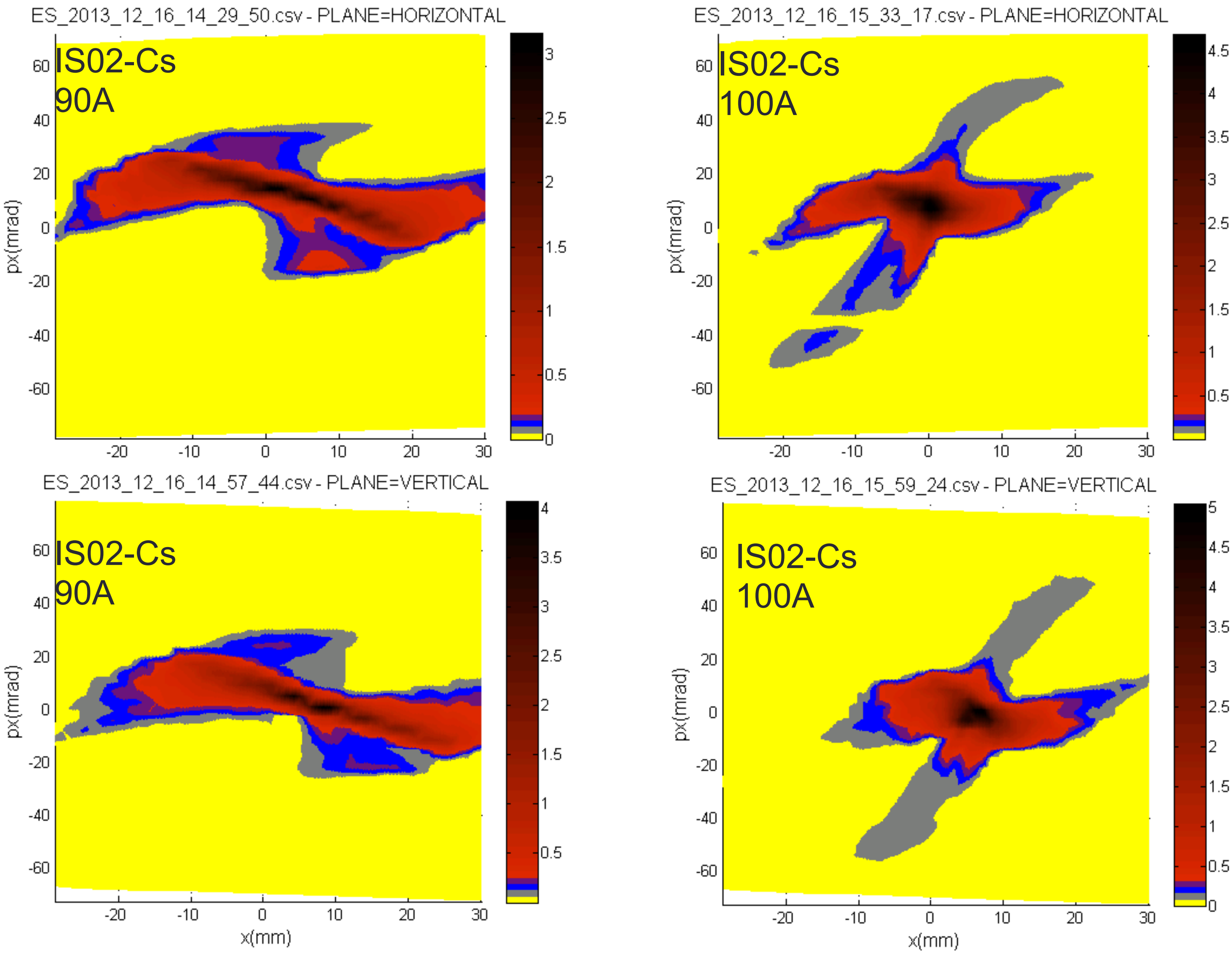
Still a long …

… but quite straight way

IS01 optics, H- Emittance: Volume vs. Cs-surf

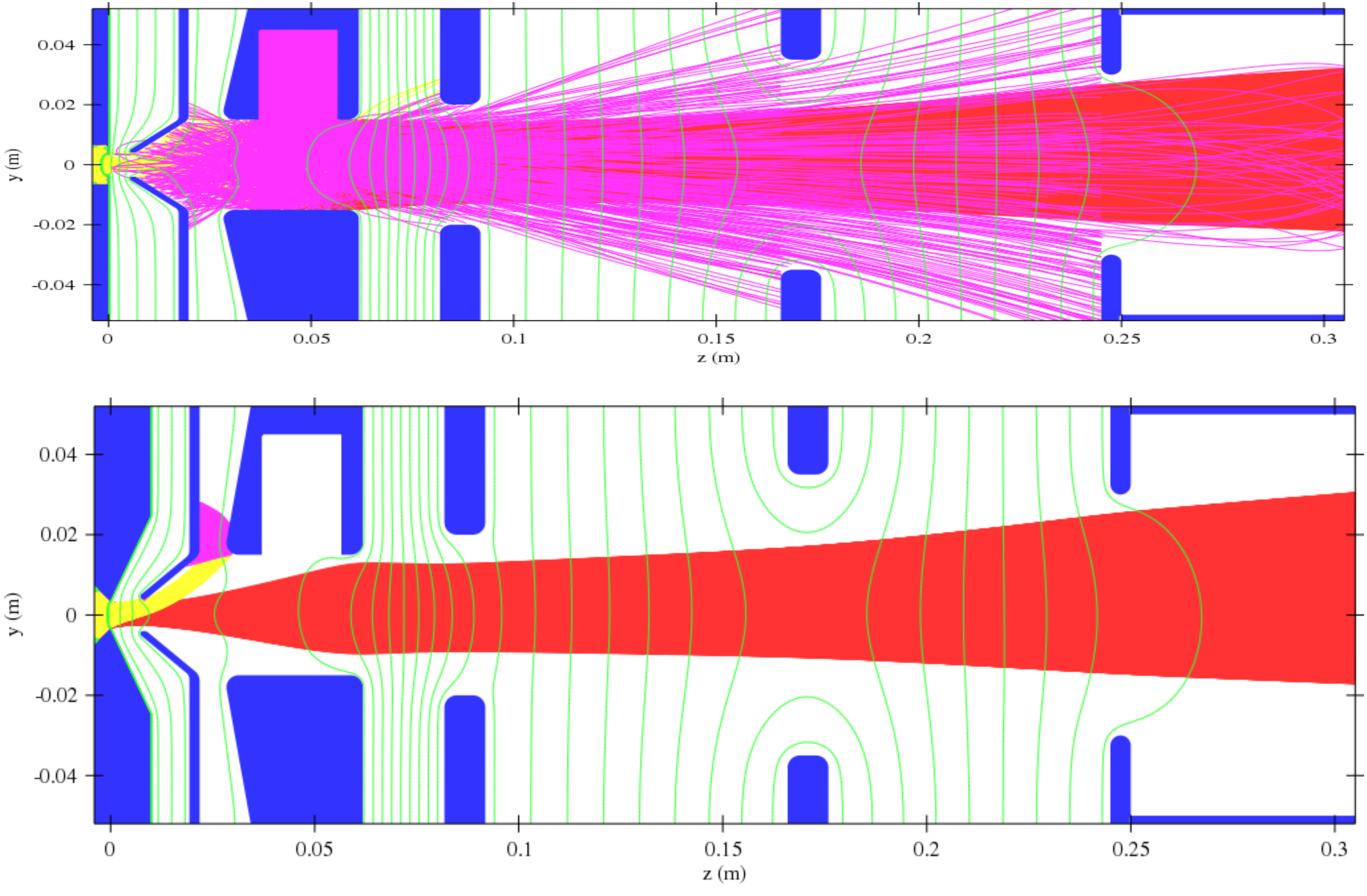


solenoid @90A


ES_2013_12_16_14_29_50.csv - PLANE=HORIZONTAL
IS02-Cs
90A
ES_2013_12_16_15_33_17.csv - PLANE=HORIZONTAL
IS02-Cs
100A
ES_2013_12_16_14_57_44.csv - PLANE=VERTICAL
IS02-Cs
90A
ES_2013_12_16_15_59_24.csv - PLANE=VERTICAL
IS02-Cs
100A
px(mrad)
x(mm)

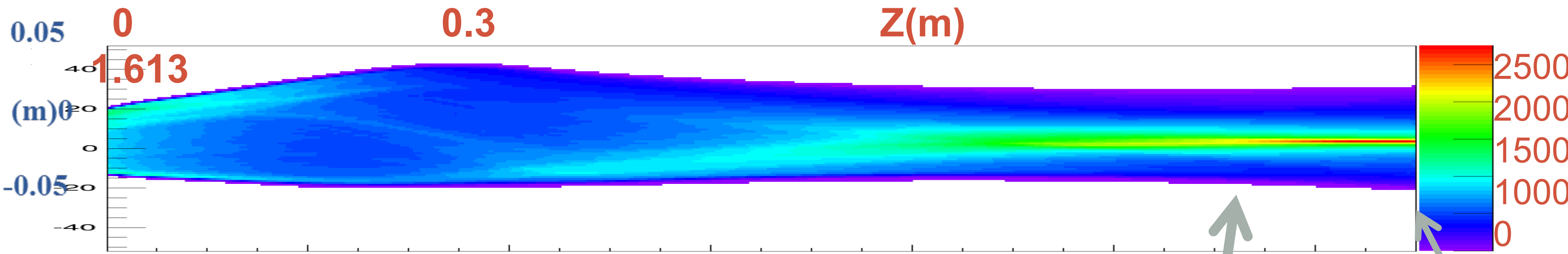
The new extraction system

Beam DUMP



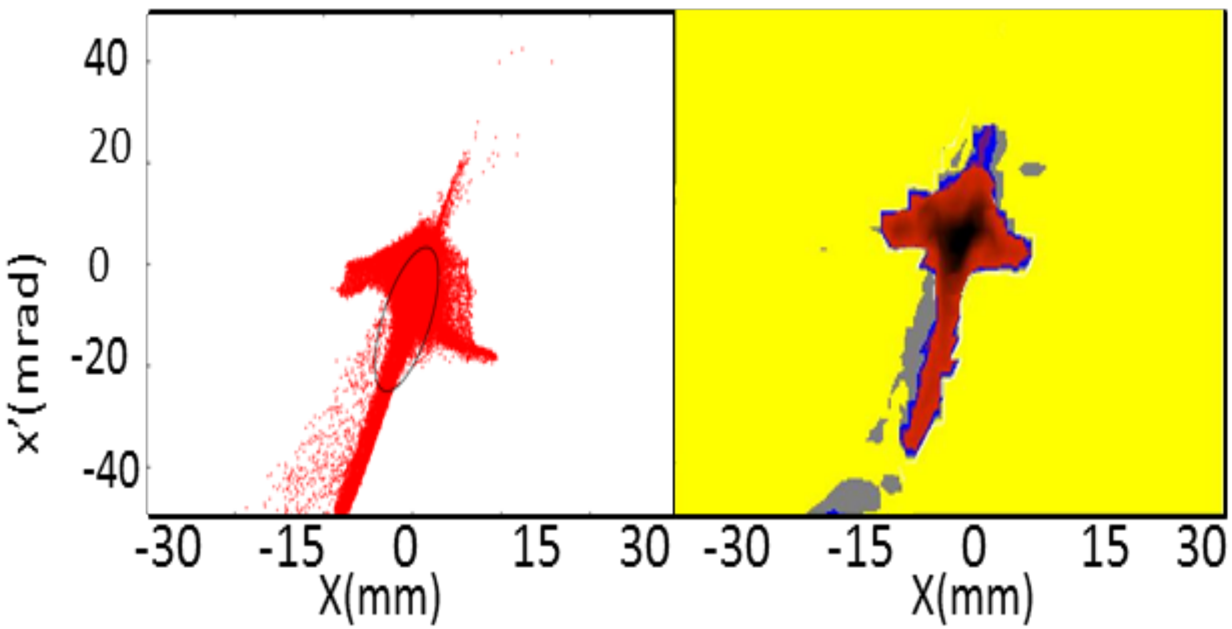
Simulations and measurements

Beam Density along LEBT



Measurement position

Measurements **Simulations**



The second component is generated in the beam waist

Dump surface damage