XV MEXICAN WORKSHOP ON PARTICLES AND FIELDS

RING INJECTORS LUMINOSITY LIMITS: SPACE CHARGE

Dr. Cristhian Alfonso Valerio Lizárraga
Facultad de ciencias Físico matemáticas
Universidad Autónoma de Sinaloa
Mazatlán, México.

Beam parameters

The luminosity is a famous parameter in detectors …

$$L_{del} = t < L > barn^{-1}$$

$$N_{event} = BR\sigma L_{del}$$

$$L = \frac{N_b^2 k_b \gamma f}{4\pi\beta^* \varepsilon_n} F$$

N_b Number of particles per bunch
K_b Number of bunches per beam
β^* Beta function
γ Relativistic factor
ε_n Normalized emittance
BR Branching Ratio
f collision frequency

LHC Luminosity from 10^{33} to 10^{34} cm^{-2} s^{-1}
Tevatron Max Luminosity 10^{32} cm^{-2} s^{-1}

Beam parameters

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There is a group in Guanajuato working in this parameter

Two Mexicans working here

- A good luminosity is the difference between wait 1 o 10 years!

LHC Luminosity from 10^{33} to 10^{34} cm^{-2} s^{-1}
Tevatron Max Luminosity 10^{32} cm^{-2} s^{-1}

Electron cloud issues in the LHC

Humberto Maury – Universidad de Guanajuato
Gerardo Guillermo - CINVESTAV

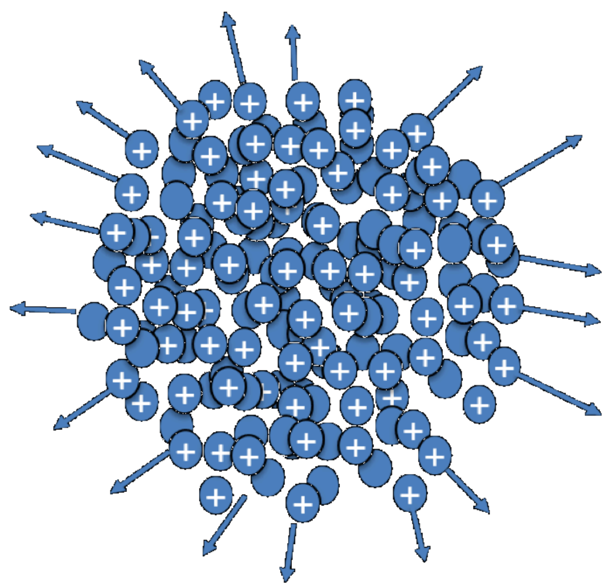
- Electron cloud: a set of electrons created inside the LHC vacuum chamber by *ionization of the residual gas* or by photoemission due to *beam-induced synchrotron radiation*. It can affect the **accelerator performance** and or **degraded beam quality**.
- Effects:
  - pressure increase by several orders of magnitude.
  - Beam instabilities
  - Additional heat load to the cryogenic system.

$$L = \frac{N_b^2 k_b \gamma f}{4\pi\beta^* \varepsilon_n} F$$

Space charge

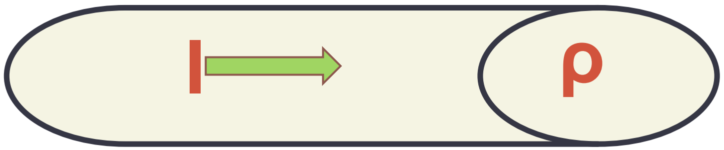
- Coulomb´s force separate the same charge particles from each other
- High intensity beams suffer from instabilities due severe space charge problems

$$L = \frac{N_b^2 k_b \gamma f}{4\pi\beta^* \varepsilon_n} F \qquad I = \frac{qeN_b}{t}$$



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

$$E_r = \frac{\rho r}{2\varepsilon_0} \qquad J = \frac{I}{\pi a^2}$$

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

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

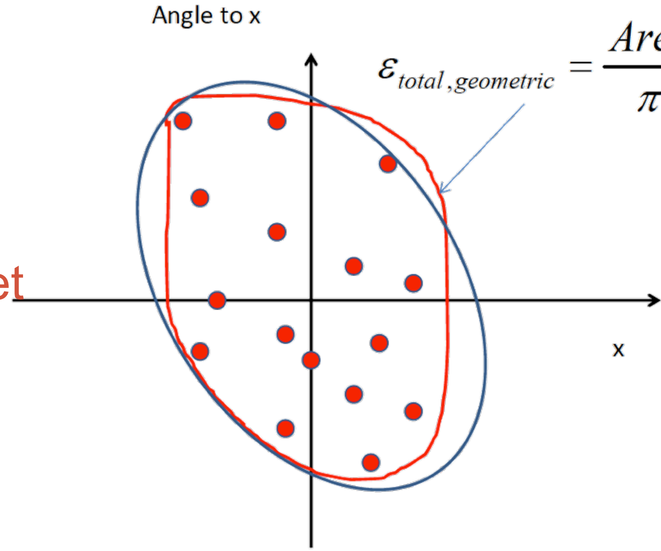
$$= q(E - \beta^2 E) = q\frac{E}{\gamma^2}$$

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

Emittance

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

The emittance always get worse(only by losing particles can get better)



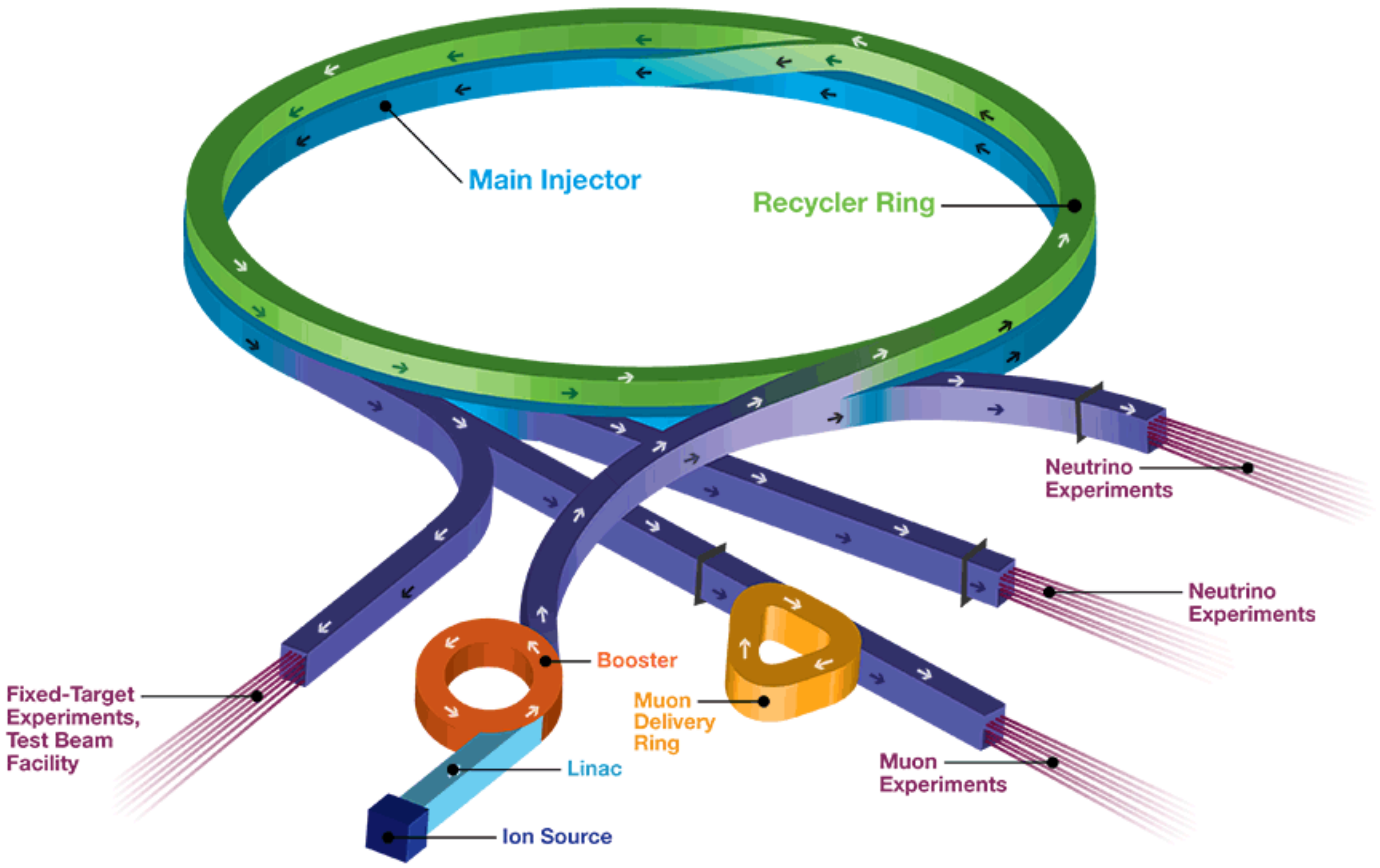
$$\varepsilon_{total,geometric} = \frac{Area}{\pi}$$

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

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

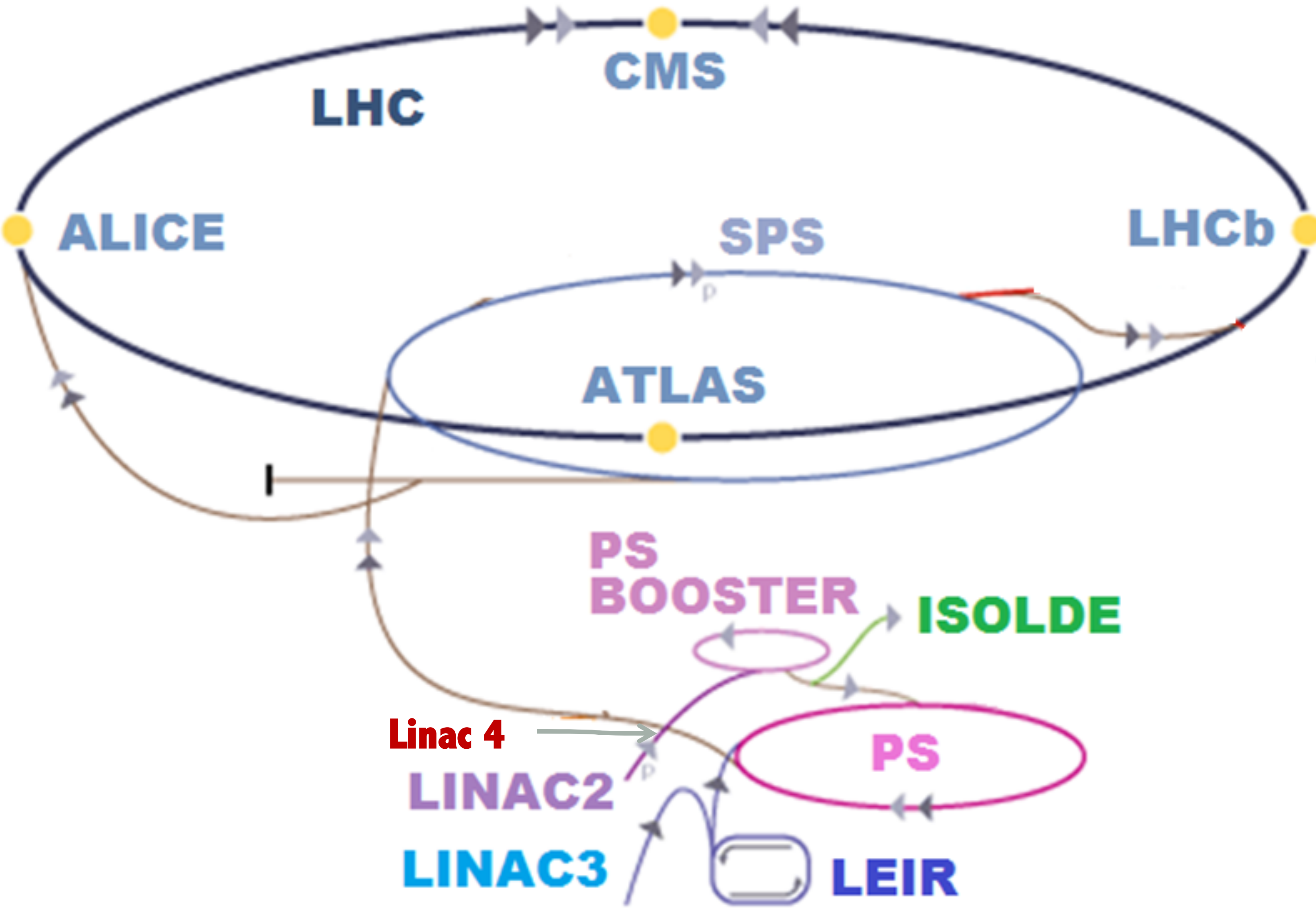
$$Brighness \propto \frac{1}{\varepsilon_y \varepsilon_x}$$

Fermilab Accelerator Complex



[1] http://www.fnal.gov/

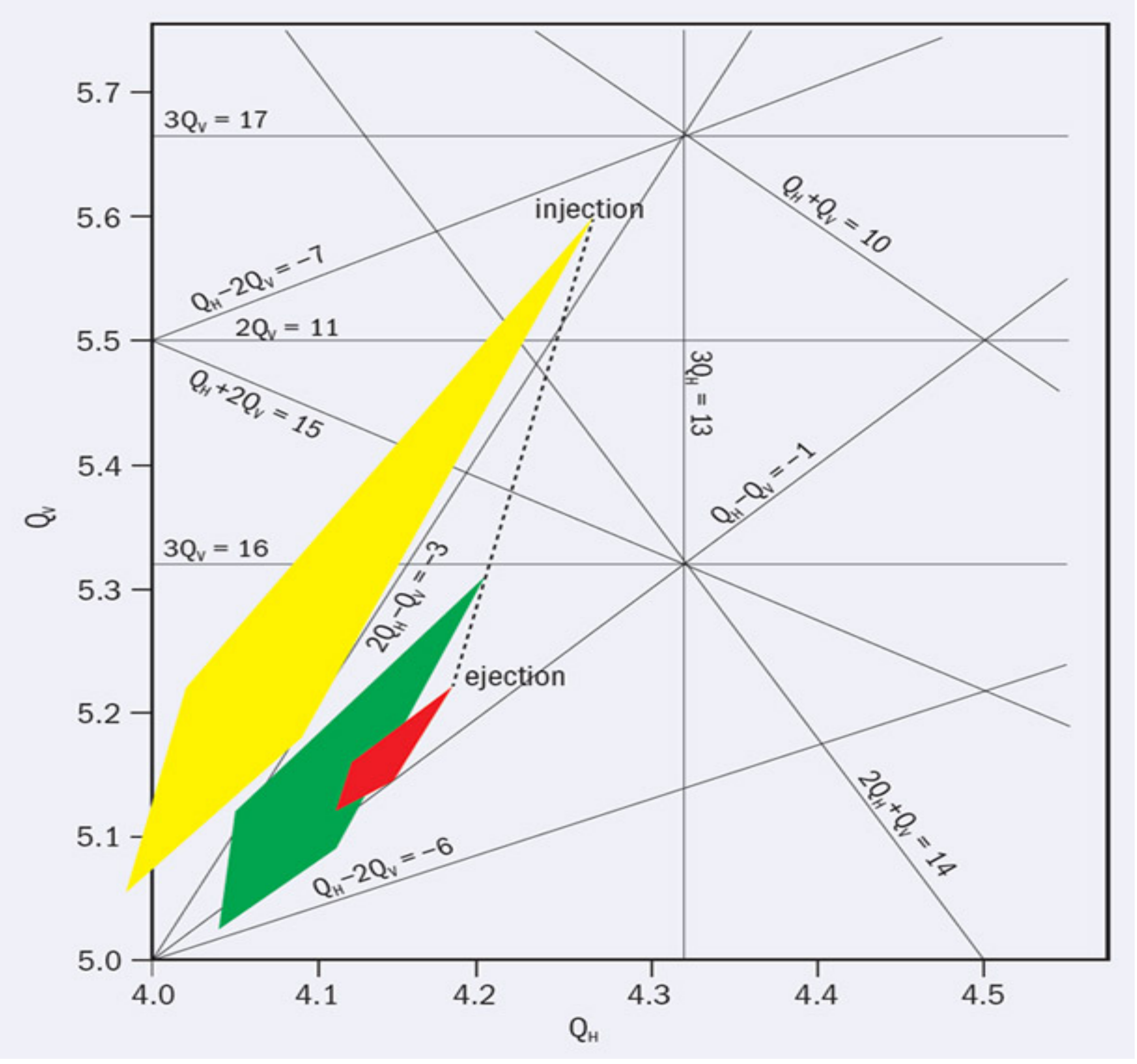
Cern Accelerator complex



Why we need Linacs before the Rings?

- The space charge limits the beam intensity inside the ring

$$\Delta Q \propto \frac{N_b}{\varepsilon_n \beta \gamma^2}$$



[1] CERN Courier, Sep 2012.

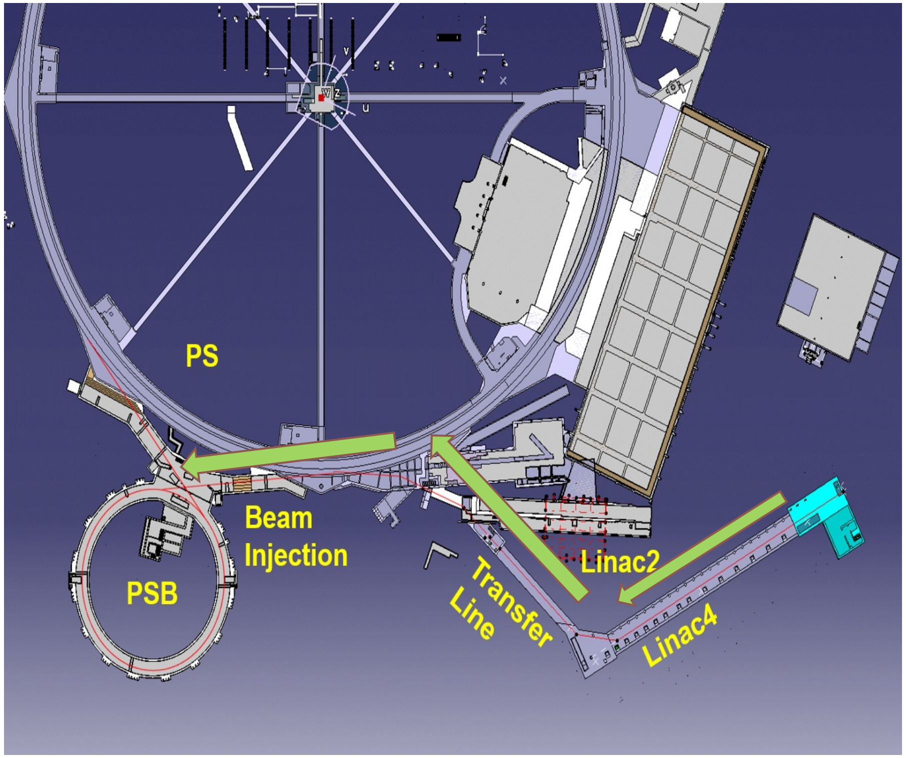
PS BOOSTER Tune shift using Linac2.

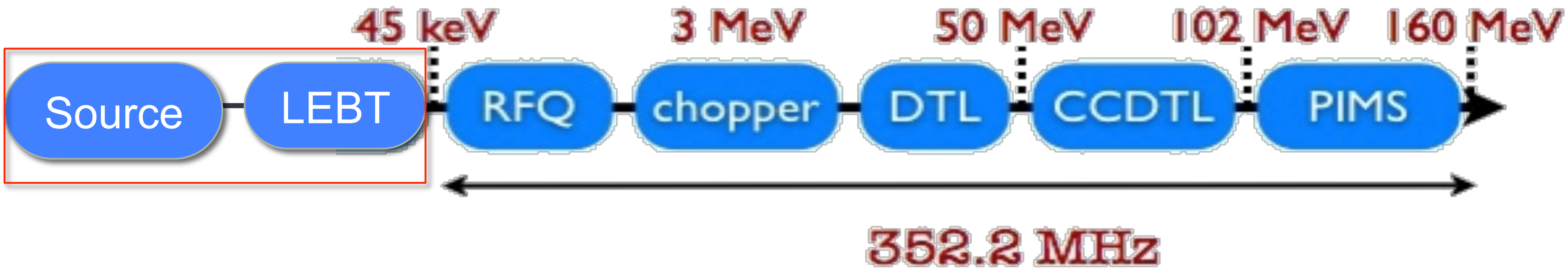
Linac 4 vs Linac2

$$\Delta Q \propto \frac{N_b}{\varepsilon_n \beta\gamma^2}$$

- 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

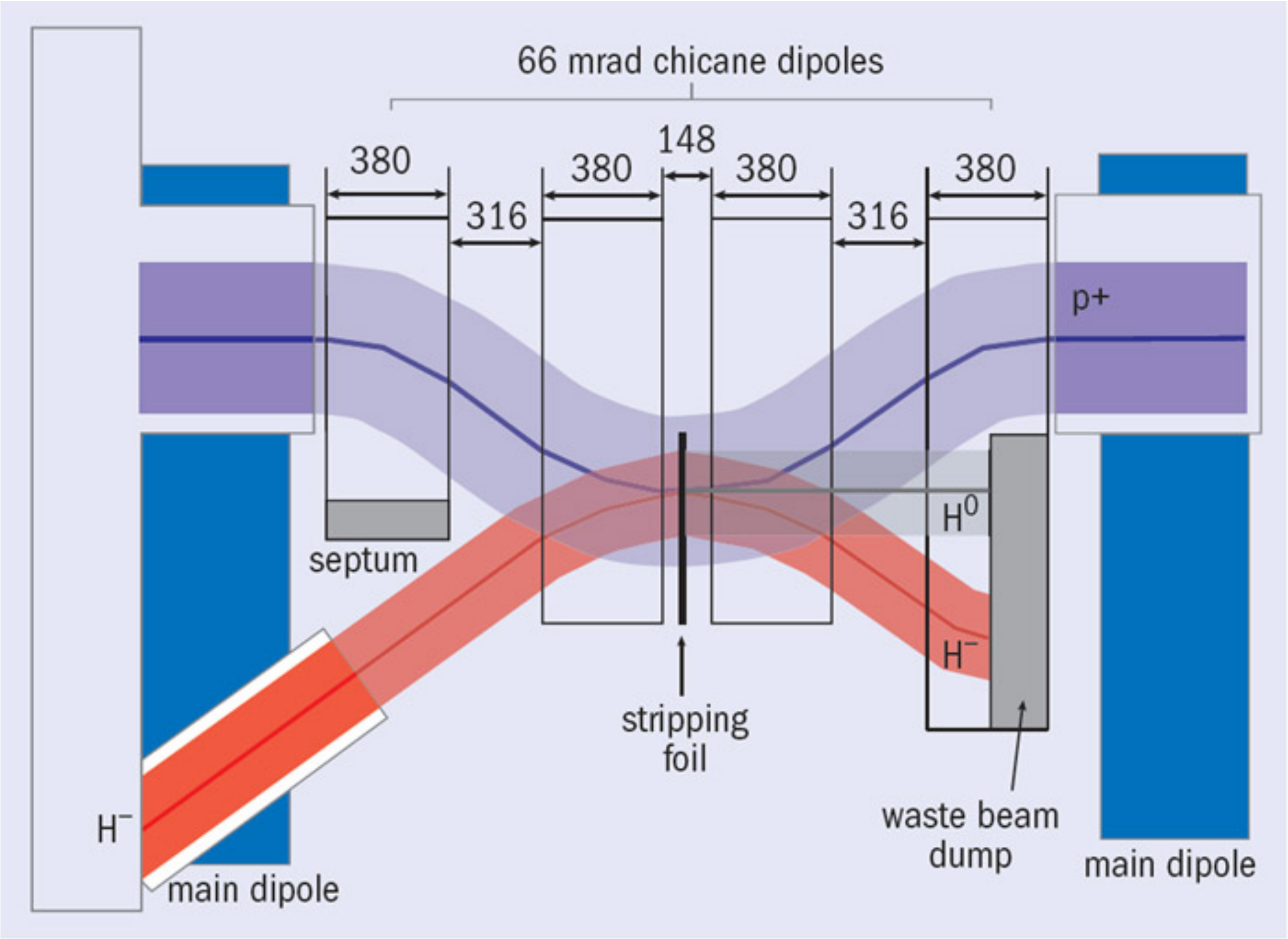




Why H^-?

- 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.

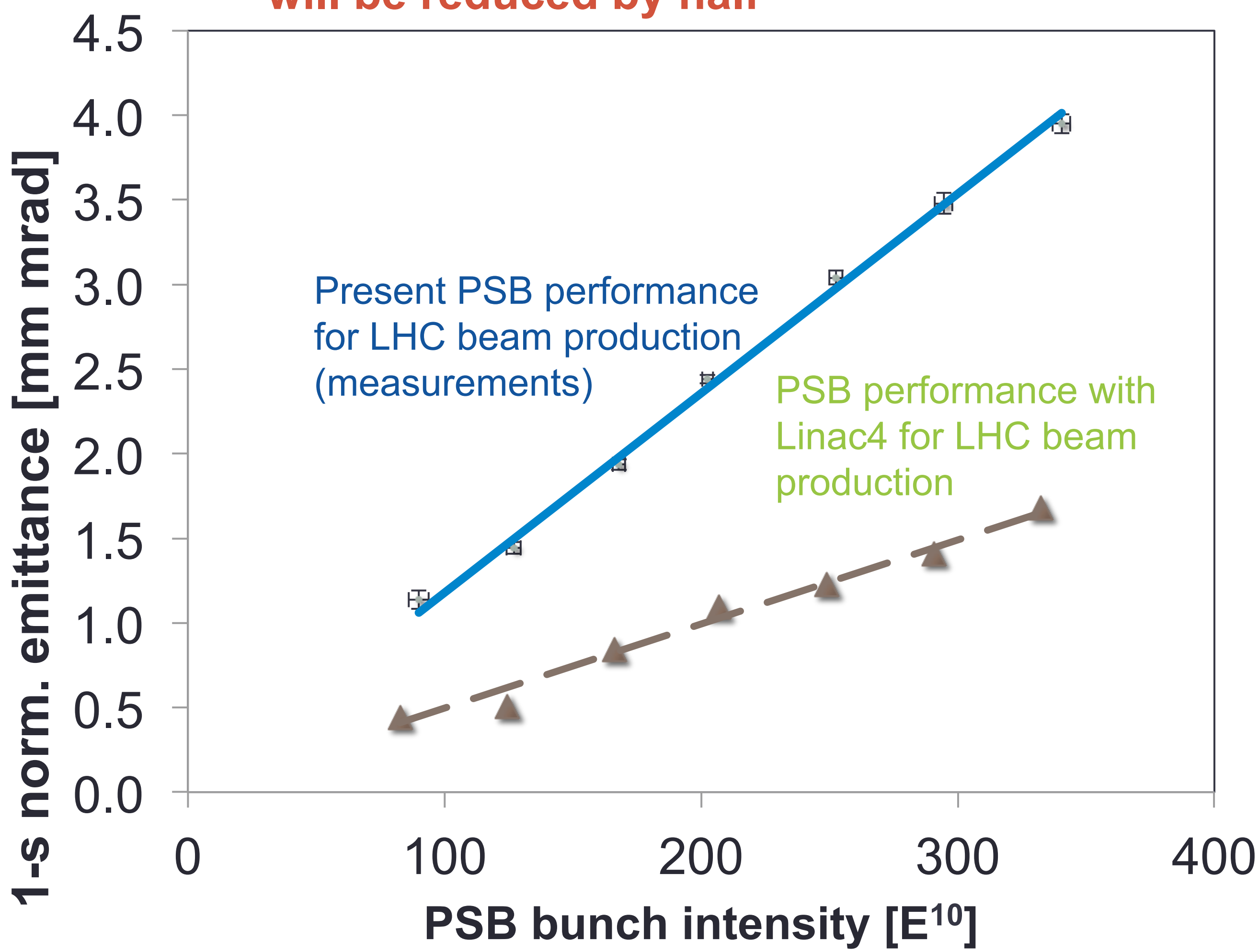


[1] CERN Courier, Sep 2012.

PSB Emittance

By inject H- the emittance after the injection will be reduced by half

- **LHC beams Brightness out of the PSB are mainly determined by space charge during the injection process**



G. Romulo Space charge meeting CERN, 19 March, 2015

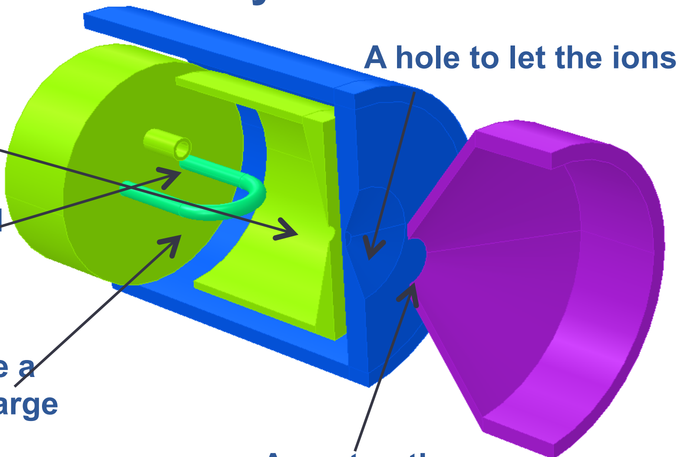
Where the particles are created?

- The maximum N_b will be at the beam source output
- After been created the value C will be almost constant
- As we get closer to the ion source more physics need to be included in simulations to predict results

$$C \propto \frac{N_b}{\varepsilon_n}$$

Source and Beam Extraction

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



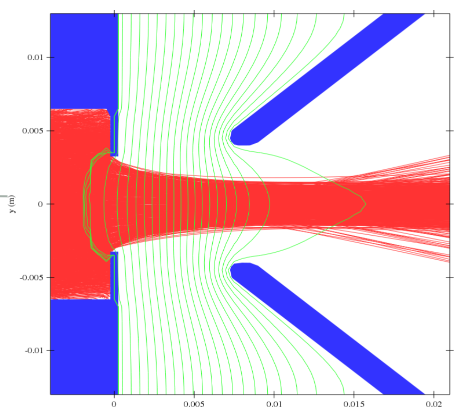
$$j = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m}}\frac{V^{3/2}}{d^2}$$

Child–Langmuir law

The beam energy is calculated by the diference of potentia

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

Plasma extraction potential (meniscus)

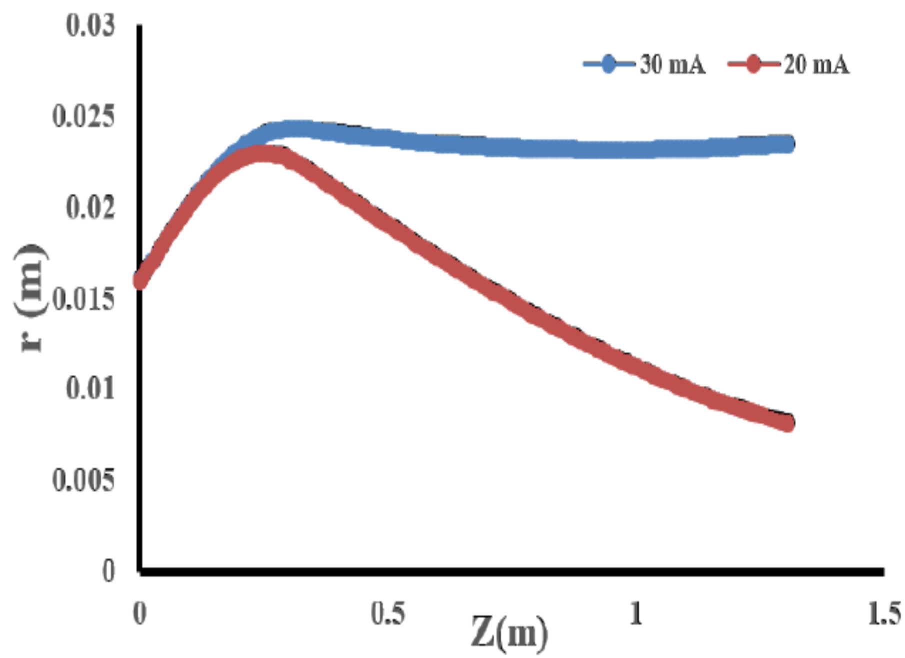


Potential lines(green)
Electrodes (blue)
Ions (Red)

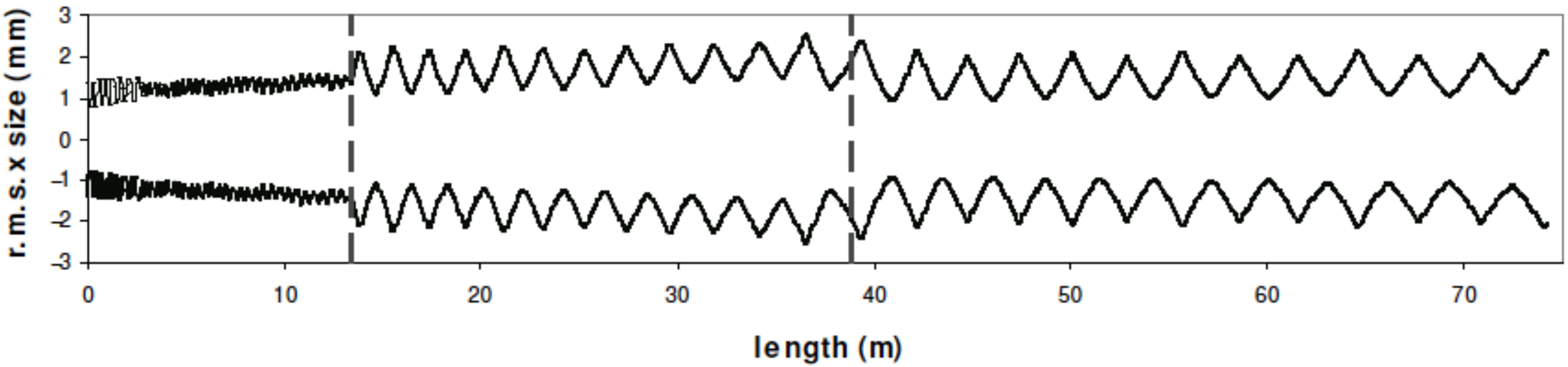
Beam transport under Space charge

- The envelope of a cylindrically symmetric beam (r) transported along the z-axis can be described by the differential equation:
  - k_o is the focusing strength
  - K_0 is the space charge term

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



Beam transport simulations

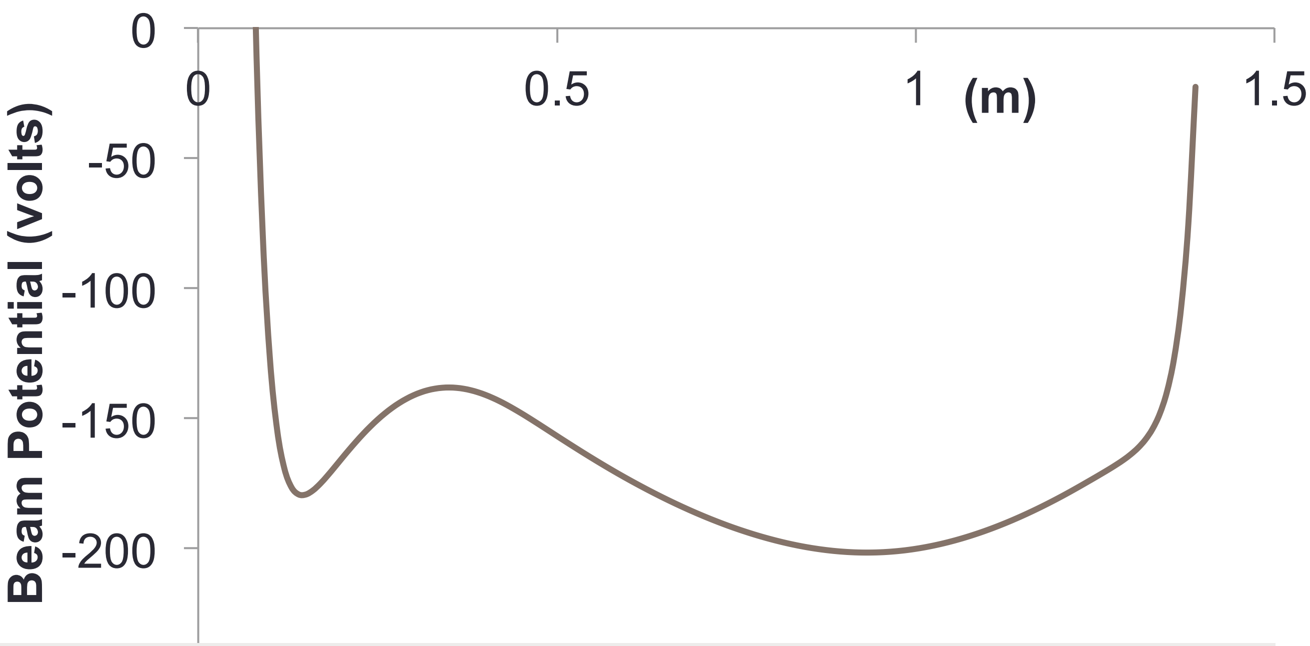


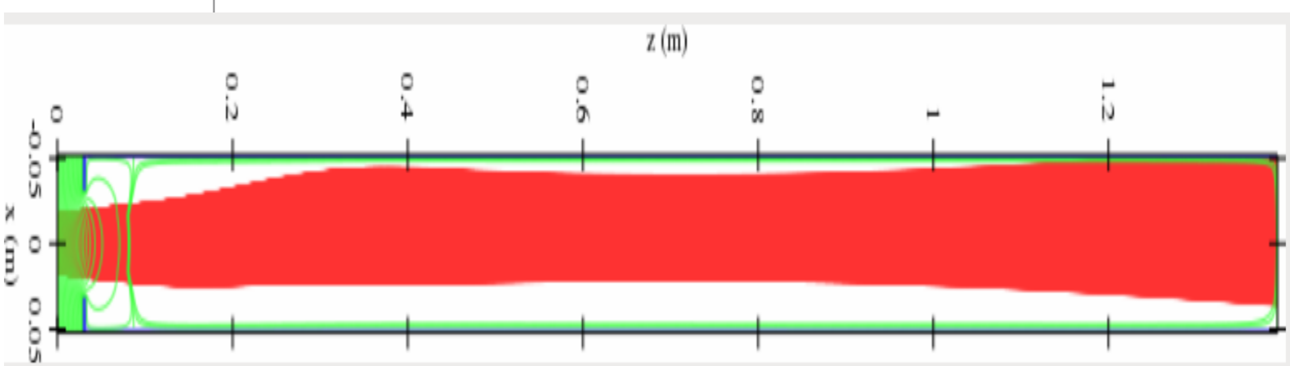
- **Envelope code where a set of matrix represent the magnets in the accelerator**

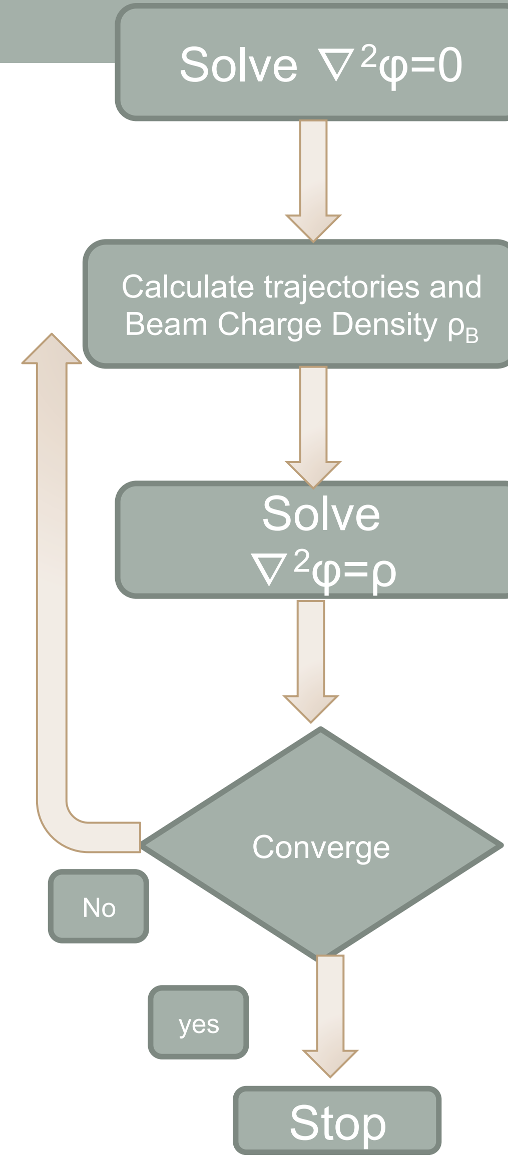
$$X = RY = R(n)\ldots R(2)R(1)Y$$

- **They are really fast(to obtain the solution it takes a few seconds), and can cover all the accelerator chain in a normal computer without problem**

Ray tracing codes







- **Is more accurate but the simulation time and resource consumption is higher**

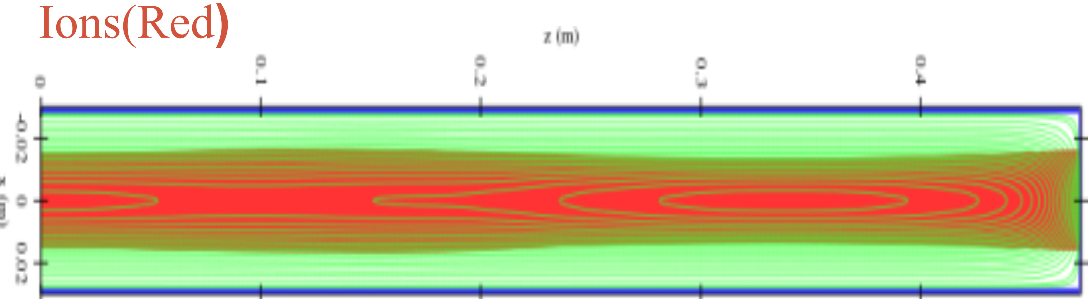
Space charge compensation

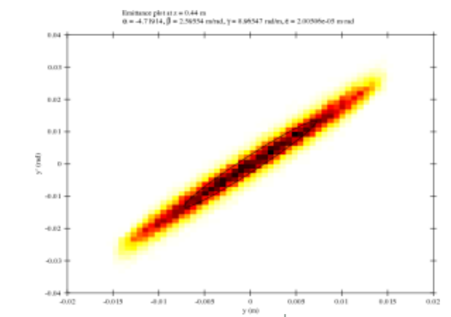
- **The vacuum is not perfect inside the beam pipe**
- **Range of pressure from $5x10^{-7}$ mbar $1x10^{-5}$ mbar**
- **The beam ionizes residual gas atoms**
- **The ionized particles from opposite charge are trapped by the beam potential and same charge particles are expelled to the walls**

Full space charge beam transport

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

Ions(Red)

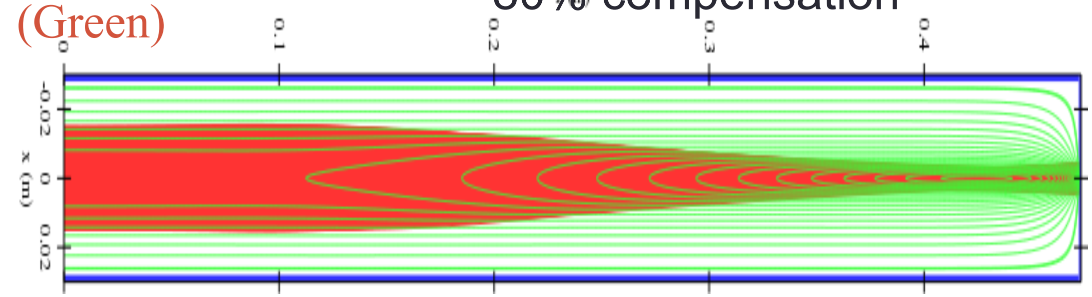


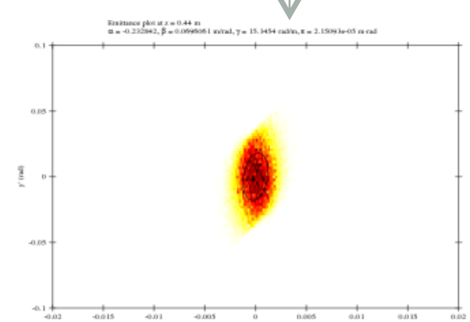


Beam Direction

Potential lines (Green)

80% compensation



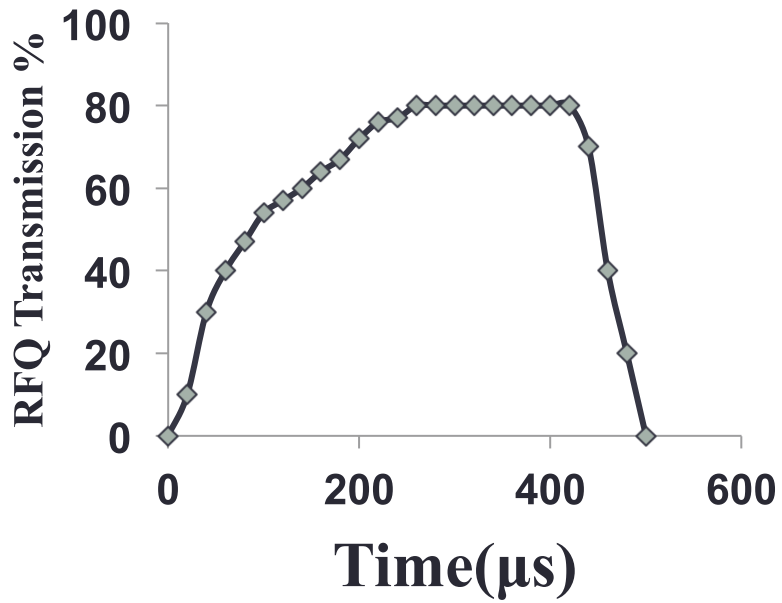


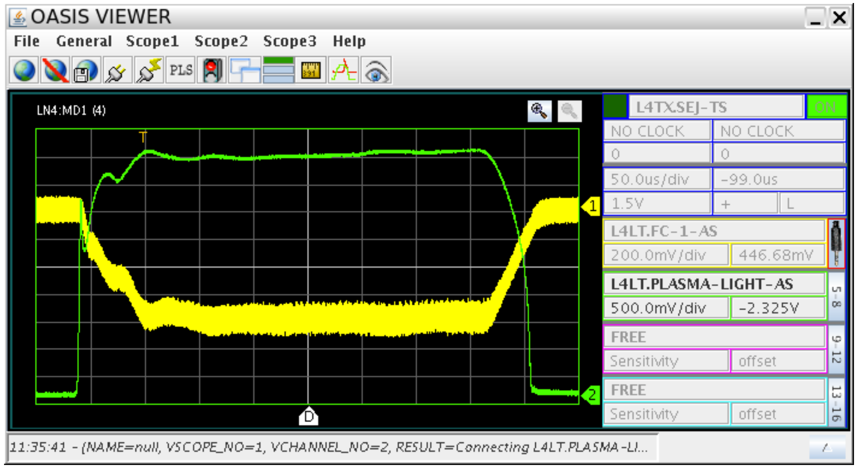
Compensation time

- The space charge compensation is time dependent

$$\tau = \frac{1}{v_b(\sigma_{H2}(E)n_{H2} + \sigma_x(E)n_x)}$$

- Beam pulse 500 µs
- Baseline 1x10^{-6} mbar

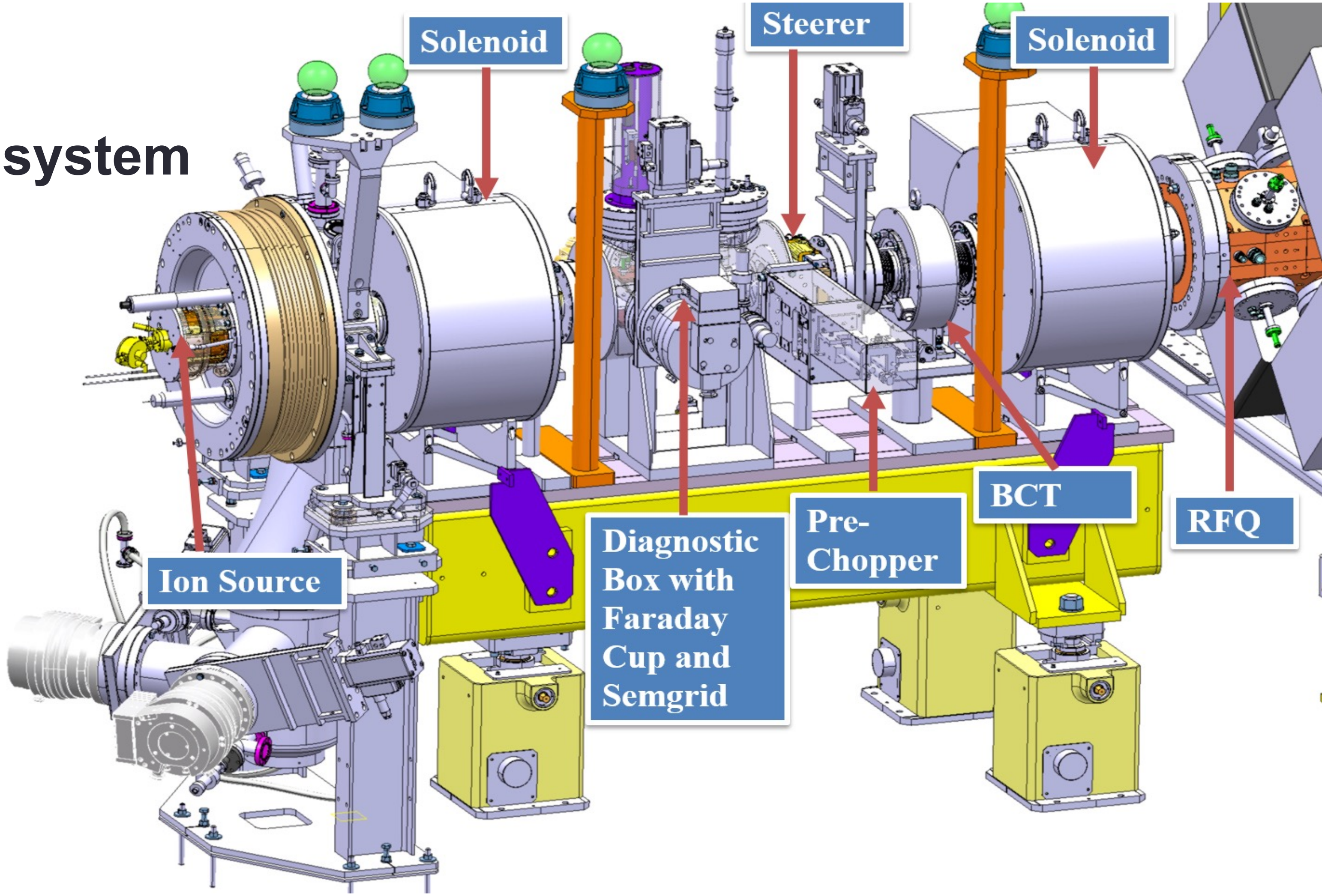




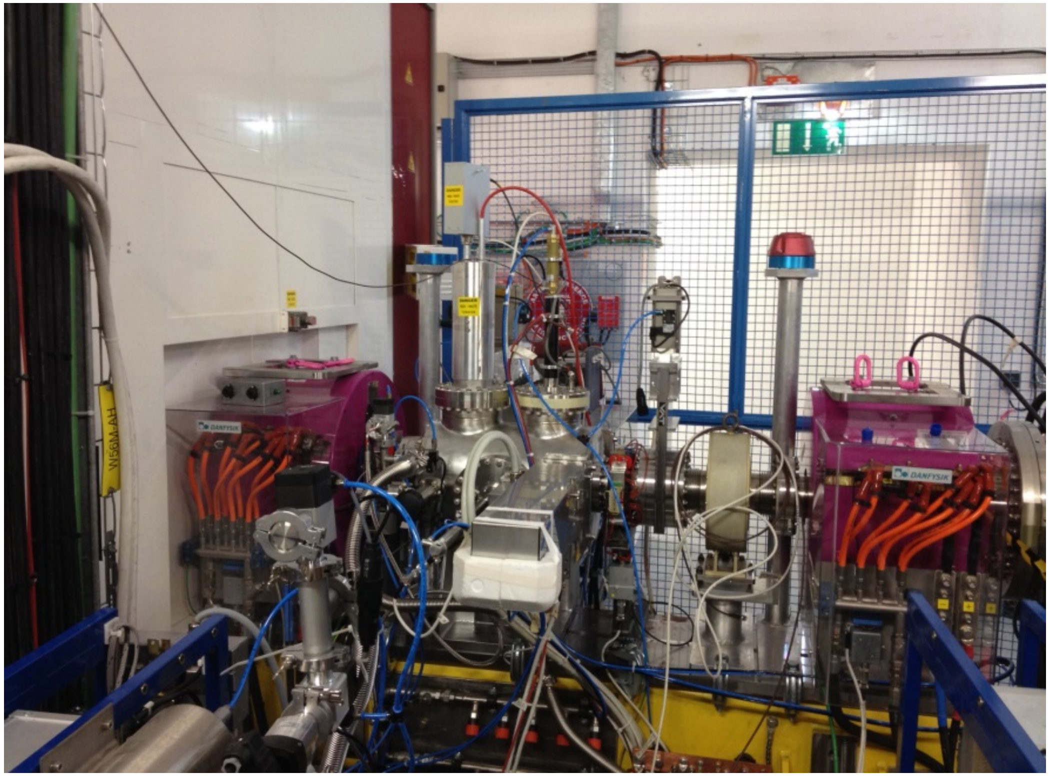
The beam properties are not constant in time and is necessary to use advanced codes to simulate this effect.

Linac4 Low energy beam Transport (LEBT)

- Source
- Multi step extraction system
- LEBT
- RFQ



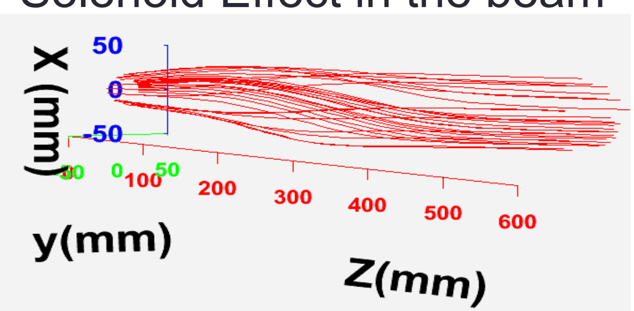
Linac4 LEBT elements



The system include:

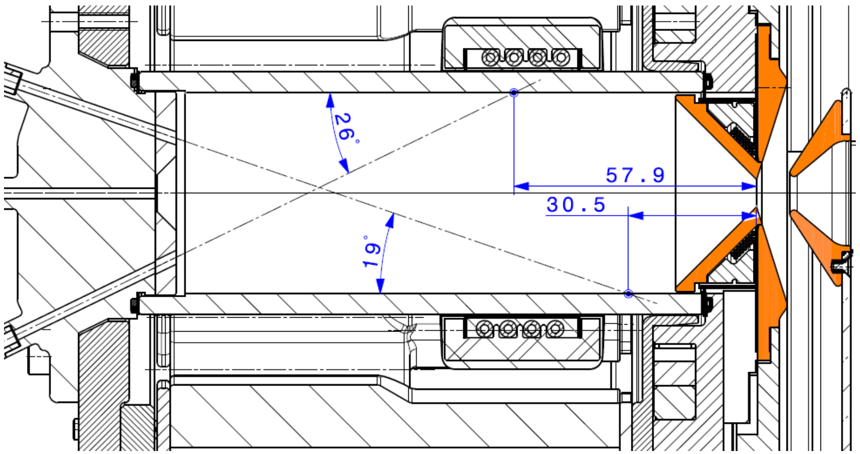
- 2XSolenoid
  - Beam focusing
  - Matching
- 4XSteerers
  - Correct beam center alignment
- Gas Injection
  - Controlling space charge compensation degree
- Faraday Cup
  - Beam current measurement
- The beam is unbunched in this stage.
-

Solenoid Effect in the beam

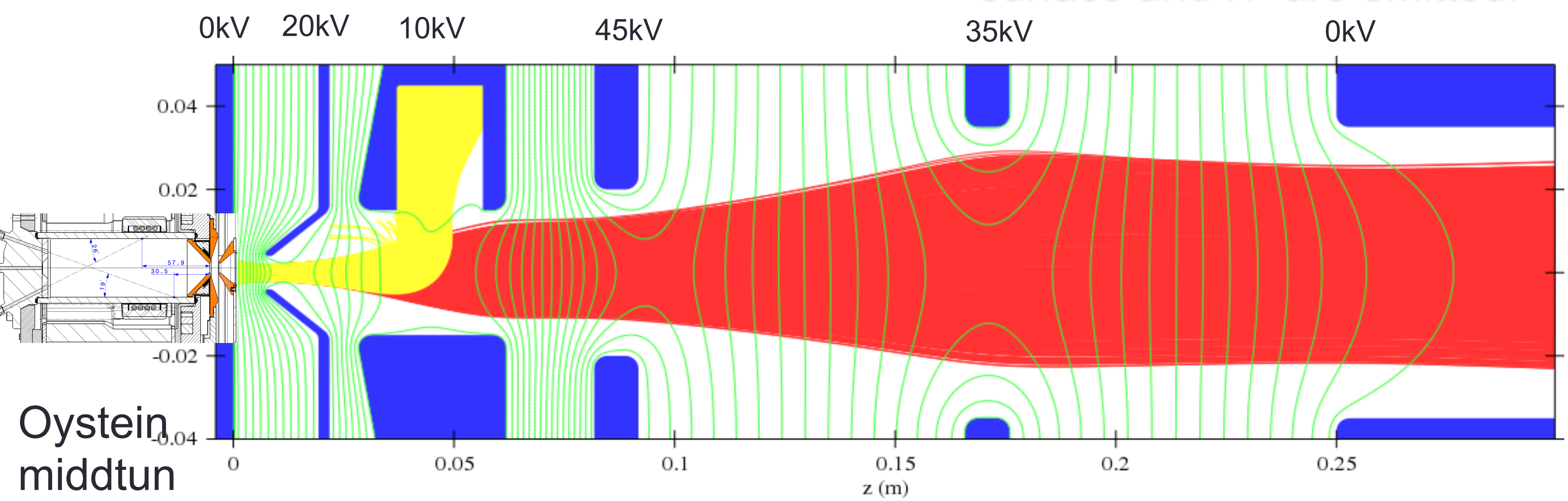


Ions (red)
Conductors (blue)

Linac4 Ion Source and extraction system



- Plasma is created using 2MHz RF in a solenoid coil.
- The H- is produced 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.



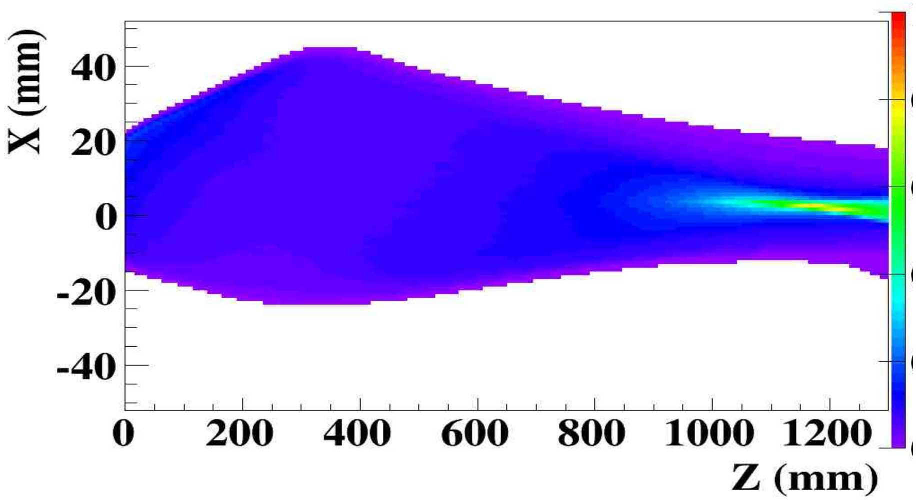
Oystein middtun

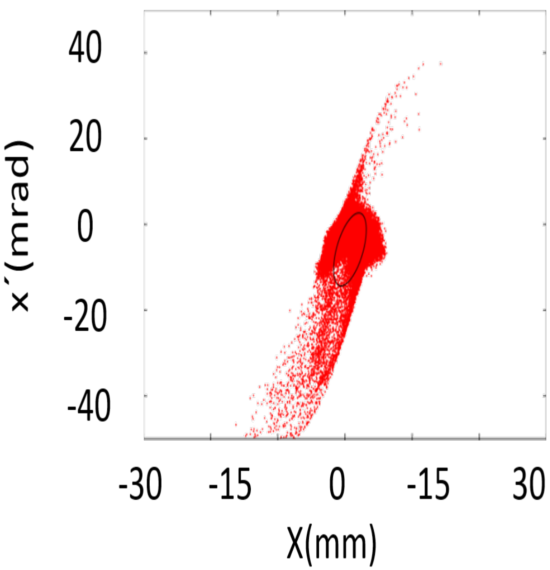
- Electrons (yellow) are extracted along with negative ions (red).

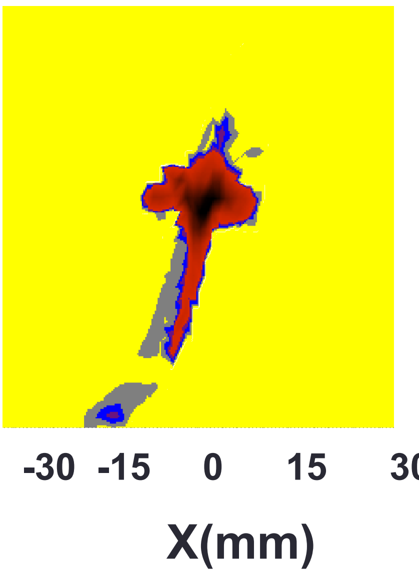
Linac4 source simulation using Ray tracing code

- Beam Current 35 mA

Simulation   Measurements



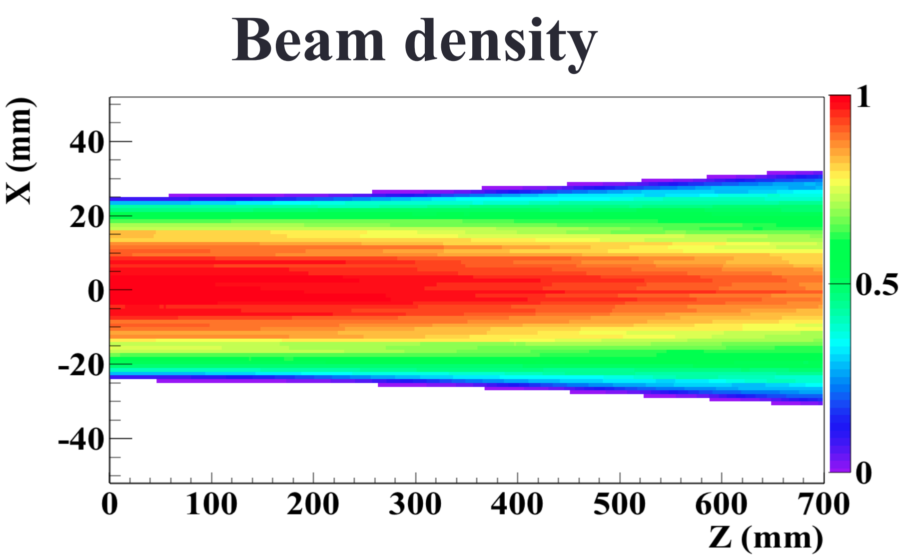


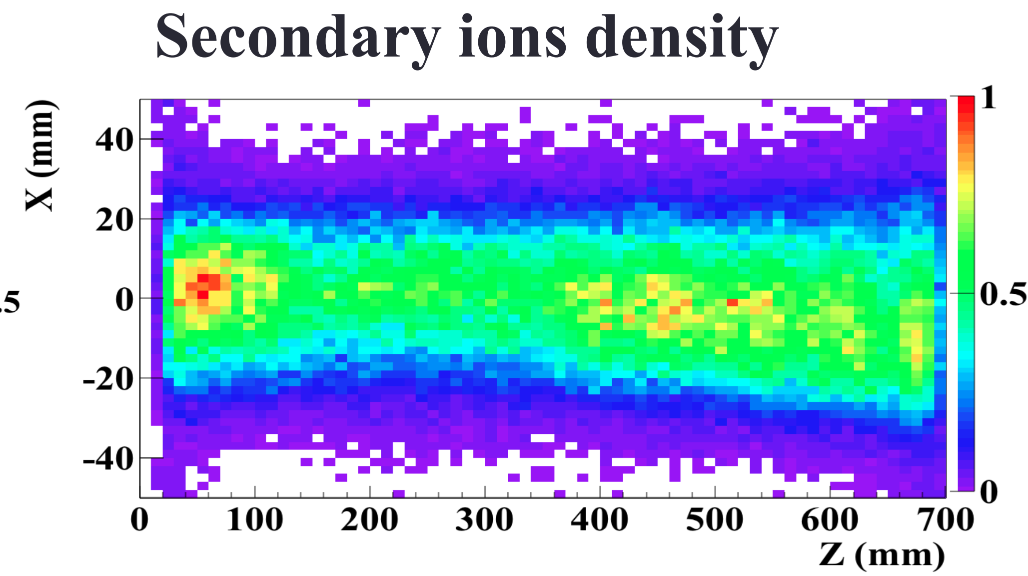


Emittance mm.mrad 1 rms (norm) :   0.29   0.55

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

Particle in Cell codes (PIC)



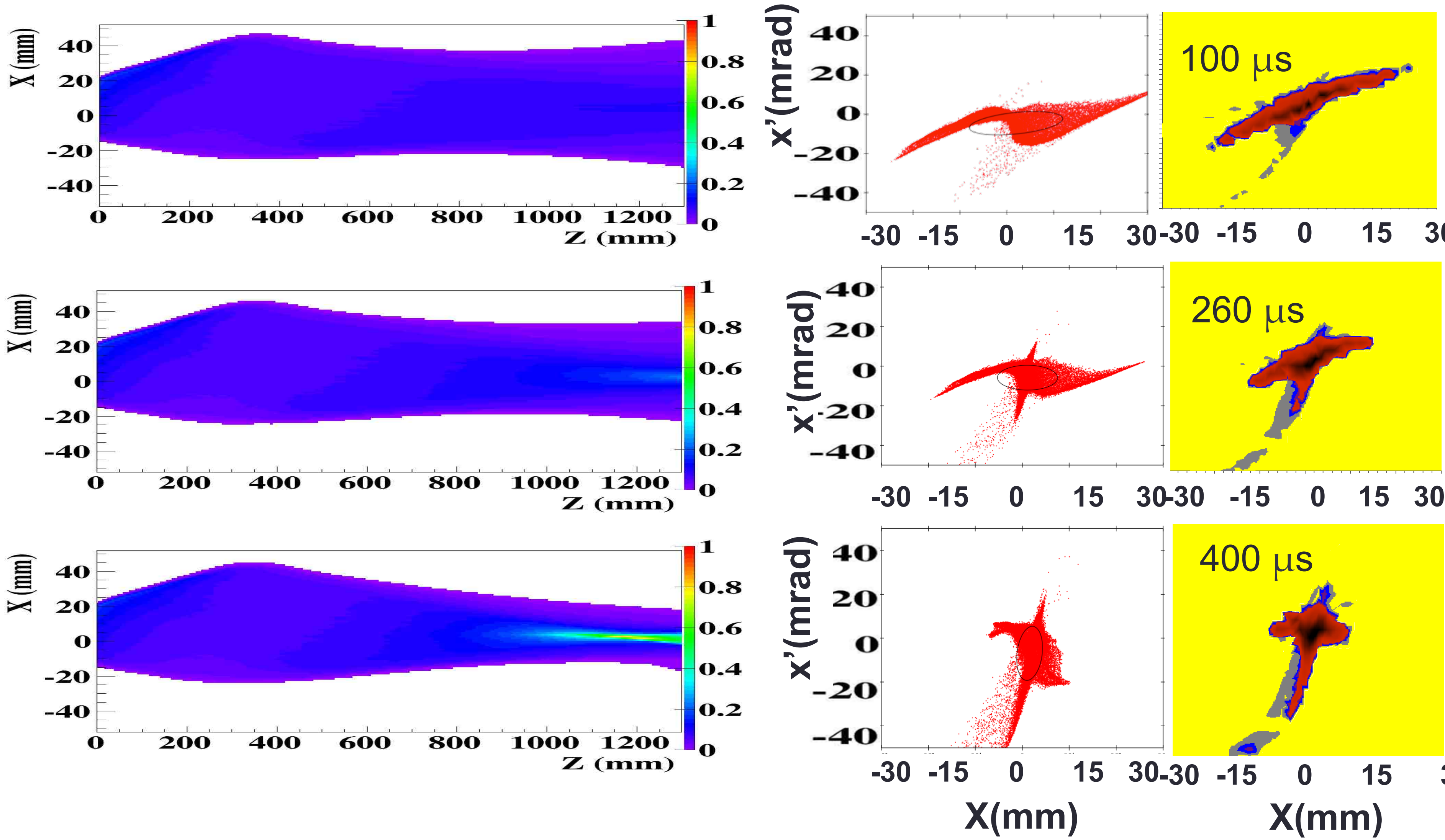


- The interaction between the beam and the residual gas inside the vacuum pipe generates secondary ions
- The secondary ions play a major role in the beam transport
- To simulate 1 meter the simulation time goes from 1 day to 3 months

Space Charge compensation using H_2

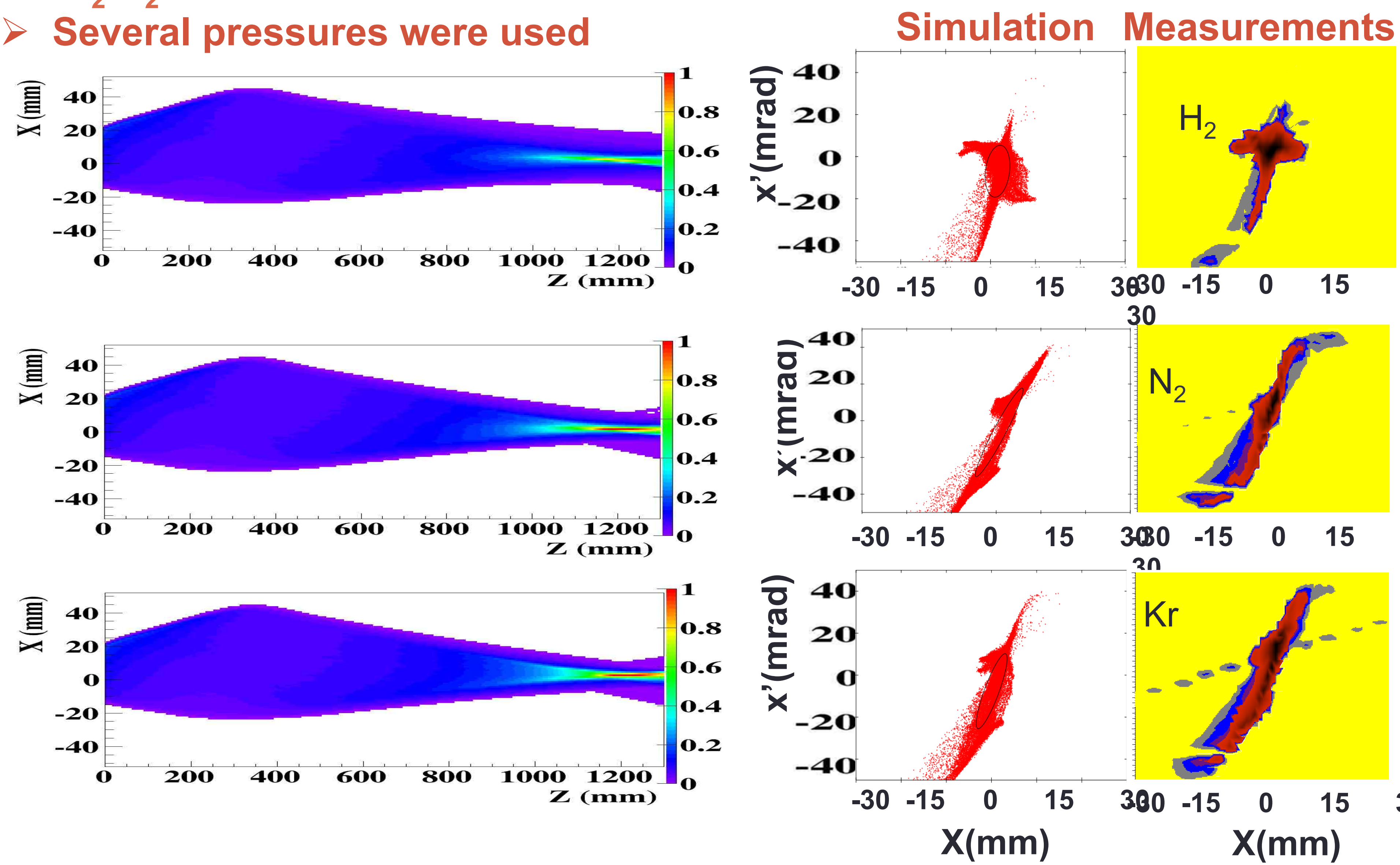
- Pressure $1.2X10^{-6}$ mbar
- Current 35 mA

Simulation **Measurements**



Compensation using different gases

- H_2 N_2 and Kr
- Several pressures were used



Summary

The beam space charge in the injectors is one of the biggest challenge to reach a higher luminosity in beam colliders

At CERN, Linac4 is under construction to mitigate this problem and duplicate the Luminosity.

The goal of produce 80 mA in the Linac4 source continue to be a problem

A new method to take into account secondary ions created by the beam has been developed

The simulation results from the Linac4 beam source agree with the measurements like not other code available today.

Some improvements has been made to the beam source at linac4 thanks to the results of the simulations

Thank you!

Disfruten la playa

Acknowledgement
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