HIGH INTENSITY NEGATIVE ION BEAM NEUTRALIZATION
Universidad Autonoma de Sinaloa

- Universidad Autonoma de Sinaloa (UAS)
  - Facultad de ciencias Físico matemáticas

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

- The detectors group 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
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 it 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 \( \rho \) radius “a” and current \( I \).

The magnetic field creates an opposite force to the electric field

\[ F = q(E \frac{v}{c} E) \]

\[ = q(E^2 E) = q \frac{E}{2} \]

\[ E_r = \frac{r}{2} \]

\[ J = \frac{I}{a^2} \]

\[ B = \frac{0Jr}{2} = \frac{0Ir}{2} \]

\[ = \frac{E_r}{c} \]

\[ = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]

<table>
<thead>
<tr>
<th>Energy</th>
<th>( \gamma ) (protons)</th>
<th>( \gamma ) (electrons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45Kev</td>
<td>1.00004</td>
<td>1.088</td>
</tr>
<tr>
<td>50 Mev</td>
<td>1.05328</td>
<td>98.084</td>
</tr>
<tr>
<td>160 MeV</td>
<td>1.17052</td>
<td>314.112</td>
</tr>
<tr>
<td>1 Gev</td>
<td>2.06574</td>
<td>1957.145</td>
</tr>
<tr>
<td>1 TeV</td>
<td>1066.7889</td>
<td>1956952.375</td>
</tr>
</tbody>
</table>
Beam potential

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

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

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

\[
\frac{d^2 r}{d z^2} + k_0^2 r + \frac{e^2}{r^3} - \frac{K_0}{r} = 0
\]

50 KeV proton beam
Source and beam extraction

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

A plasma or discharge chamber

Material input

Power to create a plasma / discharge

An extraction system

A hole to let the ions out!

The beam energy is calculated by the difference of potential

\[ E = q(V_{source} - V_{ground}) \]

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

Child–Langmuir law
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:

$$
e_{total, geometric} = \frac{\text{Area}}{\pi}$$

$$= \frac{r}{2c} \sqrt{\frac{kT}{m}} \mu T^{1/2} \frac{L \mu}{y}$$

10/19/2017
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

\[ p + X \rightarrow p + X^+ + e \quad \text{ and } \quad p + H_2 \rightarrow p + H_2^+ + e \]
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.

\[ p + X \rightarrow p + X^+ + e \]
\[ p + H_2 \rightarrow p + H_2^+ + e \]
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 it is necessary to use advanced codes to simulate this effect.
Residual gas and beam interaction

It is not a 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 for H-beam by interactions with the residual gas.
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 things 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° dipoles
Do not overcomplicate

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

Beam passing through one of 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.

Electrons (yellow) are extracted along with negative ions (red).
Linac4 Test stand

The system includes:
- 1 XSolenoid
  - Beam focusing
  - Matching
- 2 XSteerers
  - 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 measurements in both planes $X(Y), X_p(Y_p)$
• 0.5mm resolution in $X$
• 1mrad in $X_p$
• Time resolution $6 \times 10^{-6}$ 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

Simulations

Secondary particles are included

Source

High voltage clear secondary particles

Solenoid  Faraday Cup  Emittance meter
Beam transport first solution

**Beam potential**

\[ \nabla^2 \phi = 0 \]

Calculate trajectories and Beam Charge Density \( \rho_B \)

\[ \nabla^2 \phi = \rho / \varepsilon \]

Converge

No
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

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

<table>
<thead>
<tr>
<th>Emittance (mm.mrad (norm))</th>
<th>Simulation</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>0.55</td>
<td></td>
</tr>
</tbody>
</table>
Measurements

Evolution on time of the beam size in the emittance meter position with different pressures in the beam pipe.
A new routine has been created to carry the SCC using secondary ions.
We include the secondary particles created by the gas collision by using a montecarlo generator.

This generator takes into account the mean free path of the $H^-$.

The beam was tracked during time steps equal to the emittance meter resolution in time; $6 \times 10^{-6}$ s.

The input beam was generated also Ibsimu.
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 \sim 0

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

The emittance reported is after 70 us

Emittance vs time
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

Trapped Secondary ions

Number of ions (A.U) normalized vs Time (μs)
The secondary particles are accumulated in the beam center driving to a hollow space charge distribution.
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

Time 5 μs

Time 55 μs

Time 105 μs

Time 155 μs

10/19/2017
Simulations vs Measurements

The evolution in time show a good match

Beam profile evolution in \( x-z \)

Beam size evolution in time

10/19/2017
Space Charge compensation using $\text{H}_2$

- Pressure $1.2 \times 10^{-6}$ mbar
- Current 35 mA

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Simulation Plot" /></td>
<td><img src="image2" alt="Measurements Plot" /></td>
</tr>
<tr>
<td><img src="image3" alt="Simulation Plot" /></td>
<td><img src="image4" alt="Measurements Plot" /></td>
</tr>
<tr>
<td><img src="image5" alt="Simulation Plot" /></td>
<td><img src="image6" alt="Measurements Plot" /></td>
</tr>
</tbody>
</table>
Compensation using different gases

- $H_2$, $N_2$, and $Kr$
- Several pressures were used

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$</td>
<td></td>
</tr>
<tr>
<td>$N_2$</td>
<td></td>
</tr>
<tr>
<td>$Kr$</td>
<td></td>
</tr>
</tbody>
</table>
Results for 5 \times 10^{-7} \text{ 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.

- 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

**Distribution x,y source z=0**

Total Current = -30 mA

**Phase space Horizonal Emittance meter**

**Phase Space Vertical Emittance Meter**
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
• 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
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.

It 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!!
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