Secondary electron effects in low energy ion beams

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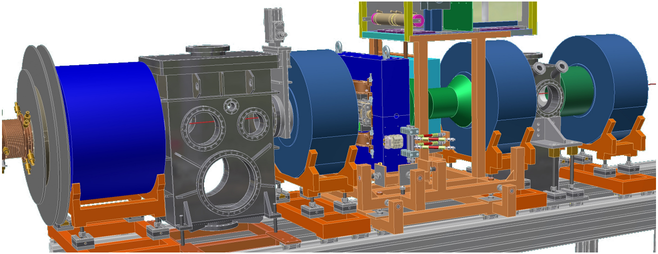
Overview

Introduction to low energy beam transport

- Matches the beam from the ion source into the first accelerator
- Prepares beam for injection into first accelerator (strong focussing required)
- Separation of unwanted beam fractions
- Can imprint time structure on the beam



Introduction to low energy beam transport

Design choices

Challenges for high intensity beams:

- Combat space charge forces
- Avoiding high beam losses and emittance increase

Introduction to low energy beam transport

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Electrostatic LEBT

- Use of electrostatic lenses for focussing
- Limited by high voltage discharges
- Full space charge force

Introduction to low energy beam transport

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LEBT using solenoids

- Radial symmetric focussing
- Secondary electrons can accumulate in the beam potential – compensation of space charge

Introduction to low energy beam transport

Sources of secondary electrons: impact of lost particles

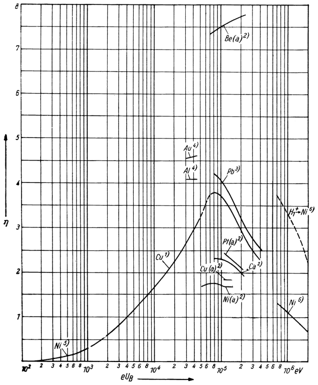


Figure: SEY for protons [3]

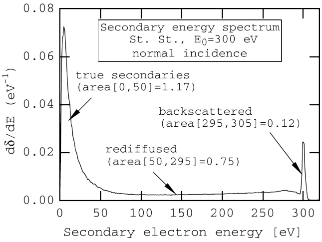


Figure: SEY for electrons [4]

- Depends on surface treatment
- Data for electrons available, for ions hard to find

Introduction to low energy beam transport

Sources of secondary electrons: ionisation of residual gas

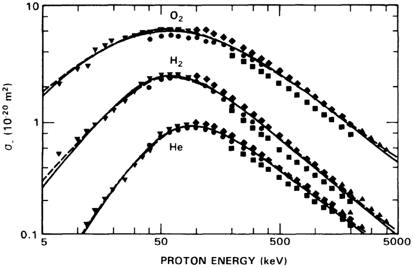


Figure: Electron production cross section for protons on different residual gas ions [5]

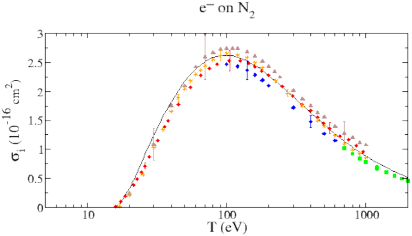


Figure: Electron impact ionisation cross section for N_2[6]

Maximum on $\mathrm{N_2}$: $\sigma_p\left(50\mathrm{keV}\right) = 5.96\,\mathrm{\mathring{A}}^2$, $\sigma_e\left(100\mathrm{eV}\right) = 2.62\,\mathrm{\mathring{A}}^2$

Measured secondary electron effects

Beam potential

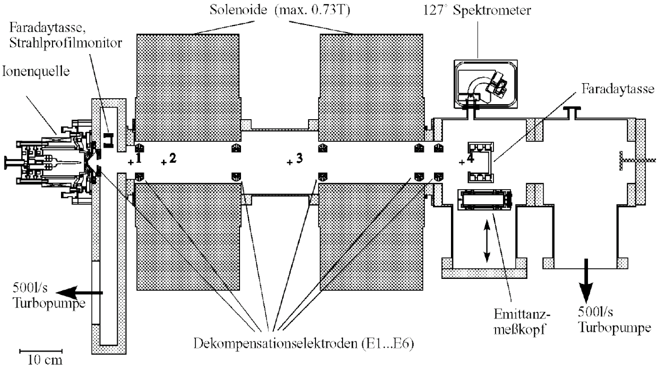


Figure: Setup used by P. Groß to measure space charge compensation [7]

Measured secondary electron effects

Beam potential

Energy distribution of residual gas ions

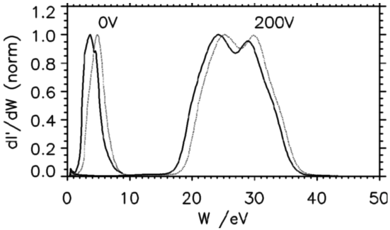


Figure: Spectrum between the solenoids with partially compensated and decompensated beam [7]

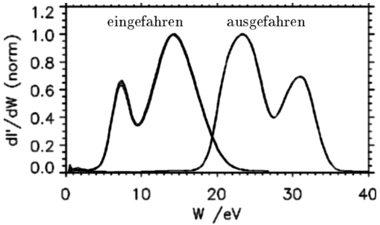


Figure: Spectrum with emittance scanner inserted and retracted [7]

Measured secondary electron effects

Beam deflection

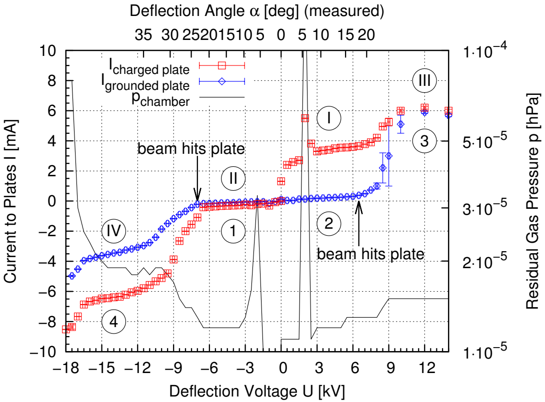
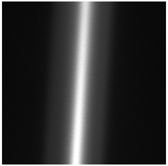
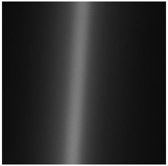


Figure: Measurements on a deflected He^+ beam at the HTL beam line[1]



"-" 0 V



"+" 0 V

Measured secondary electron effects

Longitudinal variation of the beam potential

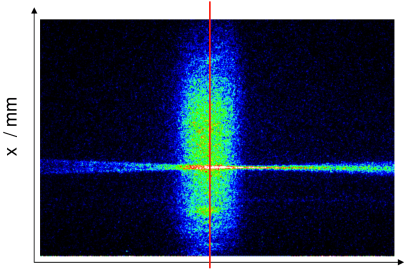


Figure: Spektrum of a focussed ion beam. Photo taken through borsilicate vacuum window [2]

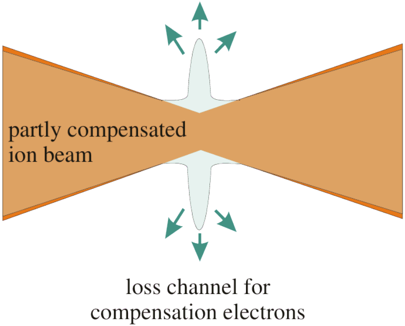


Figure: Possible explanation: electrons are attracted by the high beam potential in the focus and can escape radially [2]

Measured secondary electron effects

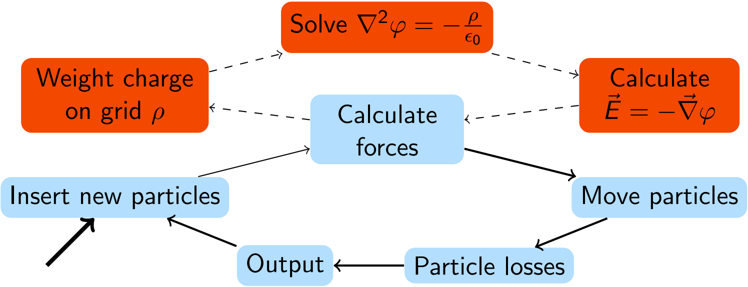
A lot of open questions...

- On what does the degree of compensation depend?
- What is the distribution of the generated secondary electrons in the beam potential?
- Influence on the distribution of the beam particles?
- Is there an equilibrium state? Does thermalization take place?
- What are the build-up times?
- How does all of this depend on the production mechanism?
- Are there regions where one of the mechanisms dominates?
- Are there states which behave collectively?

The particle-in-cell method

Valid approximations for low-energy beams:

- Non-relativistic: $\beta < 0.1, \gamma \approx 1$
- Electrostatic: self-magnetic field $B_{Beam} \approx B_{Earth}$
- Grouping of particles to macroparticles – "phase space sampling"



The particle-in-cell method

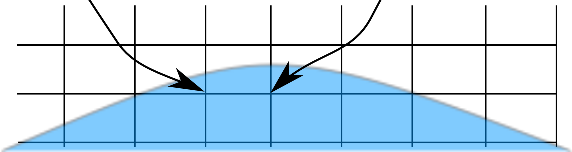
Approximation of geometry on the grid

Finite difference discretization of the second derivatives with different stencil distances h_+, h_-:

$$\frac{\mathrm{d}^2\varphi}{\mathrm{d}x^2}(x) = \frac{2}{h_- h}\varphi(x - h_-) + \frac{2}{h_+ h}\varphi(x + h_+) - \varphi(x) + \mathcal{O}(h^2)$$

$$E_z(x,z) = \frac{\partial\varphi}{\partial z}\Big|_{(x-h_x^-,z)} + \frac{\partial^2\varphi}{\partial z^2}\Big|_{(x-h_x^-,z)} h_x^-$$

$$E_z(x,z) = \frac{\partial\varphi}{\partial z}\Big|_{(x-h_x^-,z)} + \frac{\partial^2\varphi}{\partial z \partial x}\Big|_{(x-h_x^-,z)} h_x^-$$



Simulation difficulties

Limits on time step:

- $\frac{\Delta p}{p} \ll 1 \longrightarrow \Delta t \ll \frac{\sqrt{2mW_{beam}}}{q|\vec{E}|}$, i.e. $\approx 480\,\mathrm{ps}$ for $10\mathrm{eV}\ \mathrm{e}^-$ in $200\,\mathrm{mA}, 120\,\mathrm{keV}$ proton beam
- Cyclotron frequency: $\omega = \frac{qB}{m}$, stable numeric integration (velocity verlet algorithm) requires $\Delta t < \frac{2}{\omega}$, i.e. $\approx 23\,\mathrm{ps}$ in $B = 500\,\mathrm{mT}$

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Electron production on walls

- $\eta > 1$ in relevant energy range: high number of particles
- Limited data on secondary emission yield available

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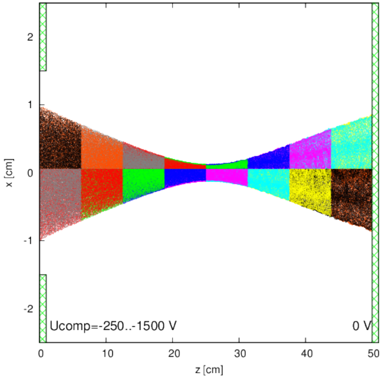
Ionisation of residual gas

- Mean time between collisions ($p = 10^{-7}\,\mathrm{mbar}$, $W_b = 50\,\mathrm{keV}$): 2.2 s
- Influence on residual gas pressure?

Simulation of a beam drift with repeller electrode



$\Delta T = 50\,\mathrm{ps},\ T = 5\,\mu\mathrm{s}.$

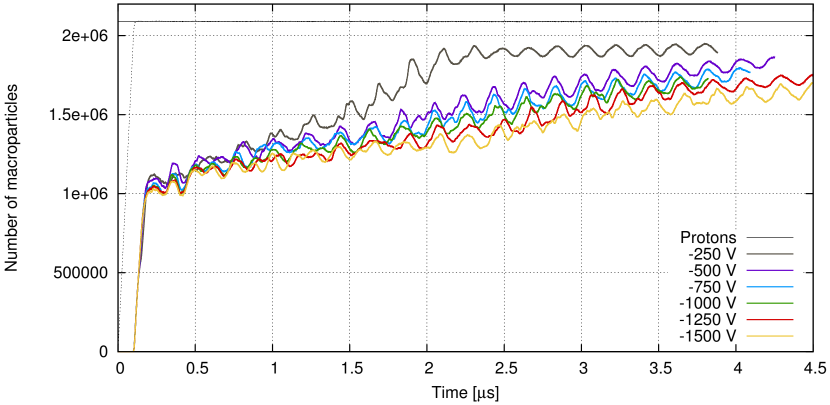
One electron per proton
$W_e^{start} = 1\,\mathrm{eV}$

$I_b = 100\,\mathrm{mA}$
$W_b = 120\,\mathrm{keV}$
$\varphi_b^{max} = 1090\,V$
$U_{comp} = -250\ldots-1500\,V$

32 CPUs on CSC "Fuchs"
Lattice $80 \times 80 \times 400$,
$h = 1.25\,\mathrm{mm}$
1.9 million dofs
1000 new particles per step,
3.7 million in flight

Simulation of a beam drift with

Rise times for different voltages



Simulation of a beam drift with repeller electrode

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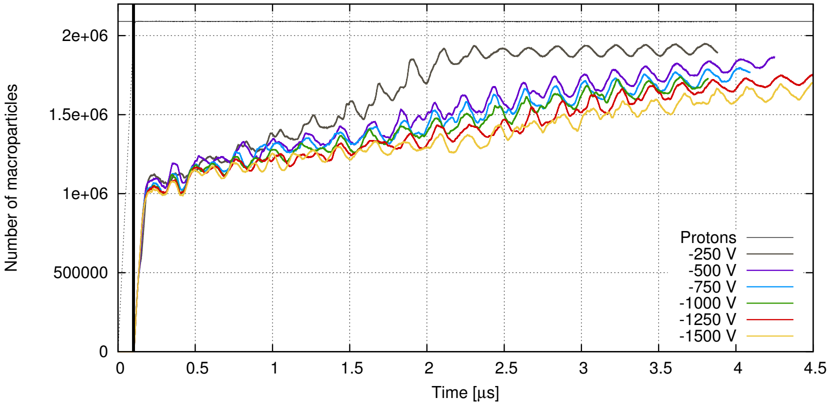
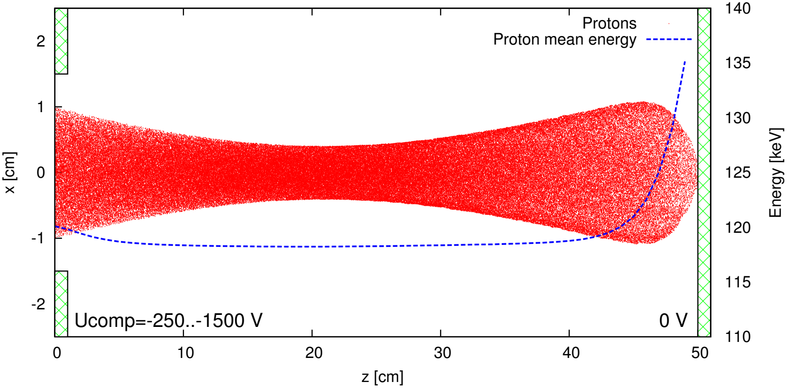


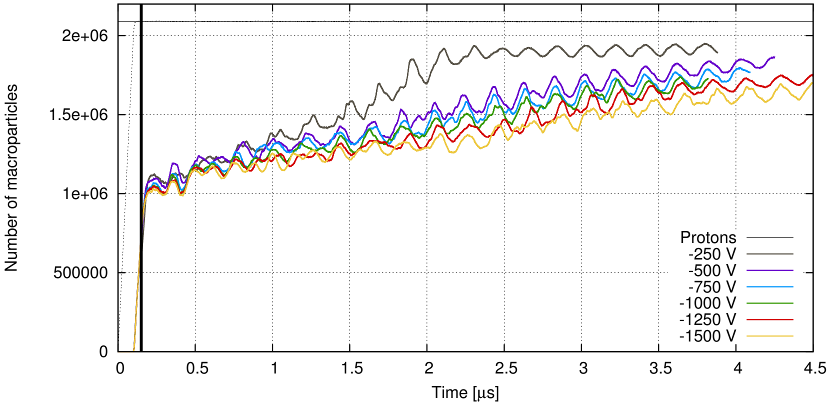
Simulation of a beam drift with repeller electrode

Proton beam at start



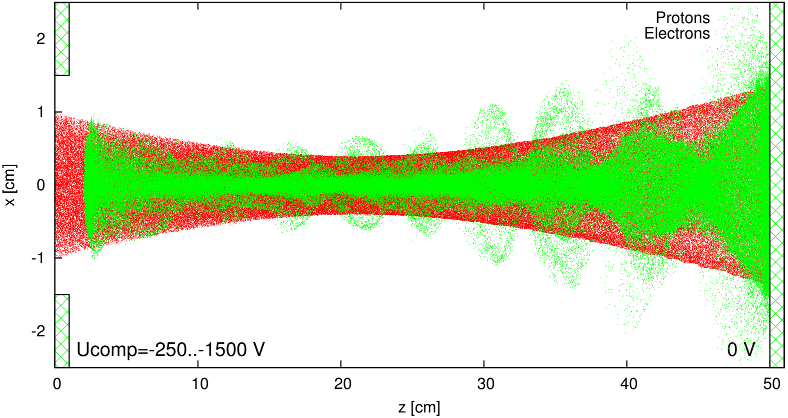
Simulation of a beam drift with compensation lens

Rise times for different voltages



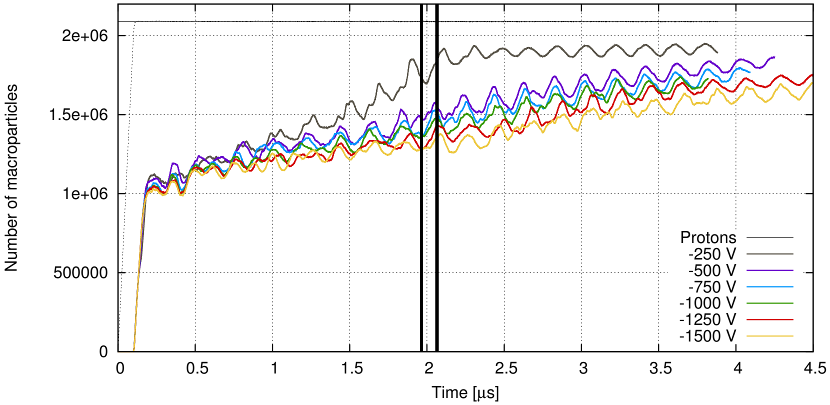
Simulation of a beam drift with repeller electrode

Proton hitting the wall

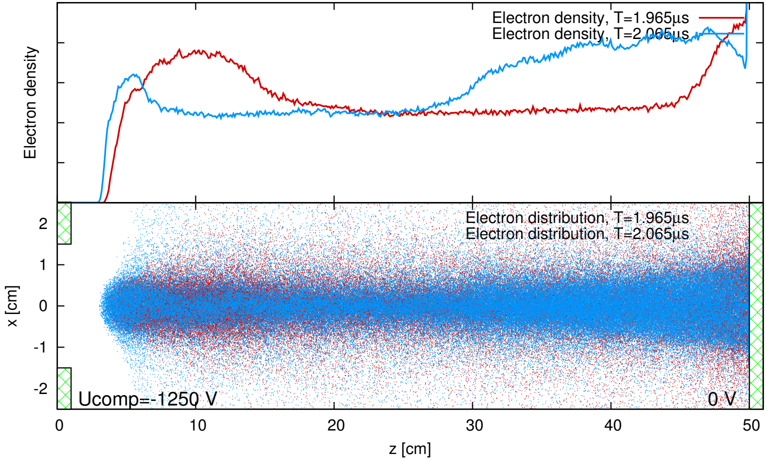


Simulation of a beam drift with repeller electrode

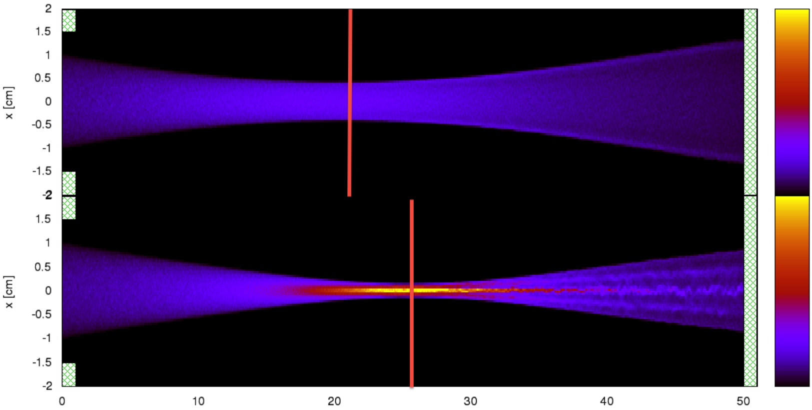
Rise times for different voltages



Electron column oscillation



Influence on the proton beam



Conclusion and outlook

- Secondary electrons have an effect on beam dynamics in the low energy section of an accelerator
- The Particle-in-cell method can be used to study these effects

- Systematic studies of the dependance of the equilibrium state and the rise time on the production rates
- Space charge compensation in beam line components
- Realistic models for electron production
  - Measurement of the SEY for different materials for different beam energies at the HTL test stand – inclusion in the PIC code
  - Include model from Furman and Pivi [4] for electron ↔ wall interaction
  - Interaction between electrons, ions ↔ residual gas – dynamics of the residual gas?
- Simulation of real systems and comparison with measurements
  - FRANZ LEBT and E$\times B$ chopper – compensation of a pulsed proton beam
  - Gabor lenses – focussing using a confined electron plasma

Thank you for your attention!

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