Secondary electron effects in low energy ion beams

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Measured secondary electron effects

"Satellites" in emittance measurements

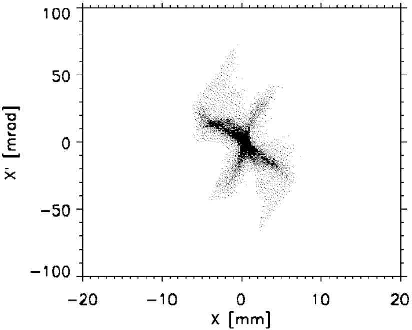


Figure: 10 keV, 2.5 mA He^+ beam transported through a 2-solenoid LEBT with compensation electrodes[1]

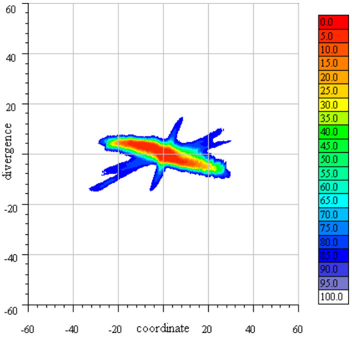


Figure: 95 keV, 98 mA proton beam measured at CEA/Saclay[2]

[1] Peter Groß. "Untersuchungen zum Emittanzwachstum intensiver Ionenstrahlen bei teilweise Kompensation der Raumladung". PhD thesis. Goethe Universität Frankfurt am Main, 2000

Measured secondary electron effects

Beam potential

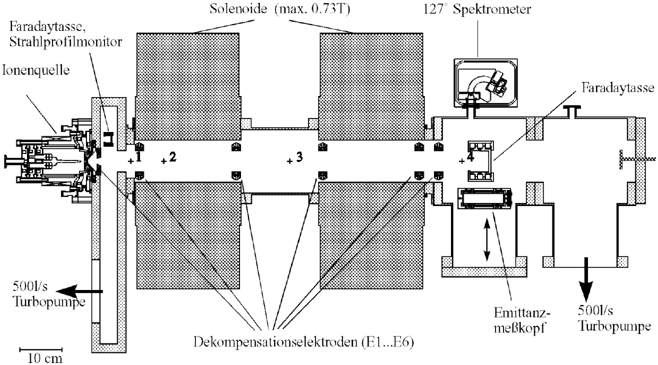


Figure: Setup used by P. Groß to measure space charge compensation[1]

[1] Peter Groß. "Untersuchungen zum Emittanzwachstum intensiver Ionenstrahlen bei teilweise Kompensation der Raumladung". PhD thesis. Goethe Universität Frankfurt am Main, 2000

Measured secondary electron effects

Beam potential

Energy distribution of residual gas ions

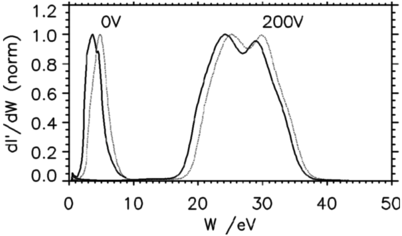


Figure: Spectrum between the solenoids with partially compensated and decompensated beam[1]

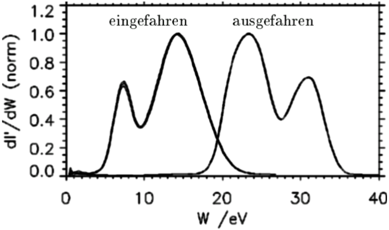


Figure: Spectrum with emittance scanner inserted and retracted[1]

[1] Peter Groß. "Untersuchungen zum Emittanzwachstum intensiver Ionenstrahlen bei teilweise Kompensation der Raumladung". PhD thesis. Goethe Universität Frankfurt am Main, 2000

Sources of secondary electrons

Impact of lost particles

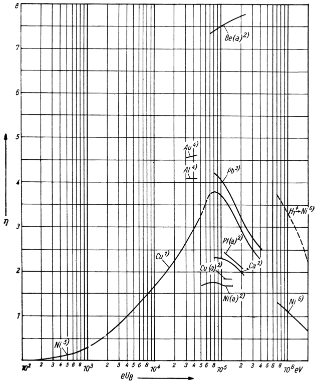


Figure: SEY for protons[3]

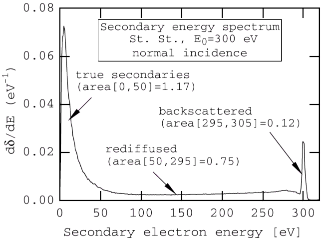


Figure: SEY for electrons [4]

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

[3] Manfred von Ardenne. *Tabellen zu Angewandten Physik Band 1*. VEB Deutscher Verlag der Wissenschaften, 1973

[4] MA Furman and MTF Pivi. "Probabilistic model for the simulation of secondary electron emission". In: *Phys. Rev. ST Accel. Beams* 5.124404 (2002), pp. 124404–1

Sources of secondary electrons

Ionisation of residual gas

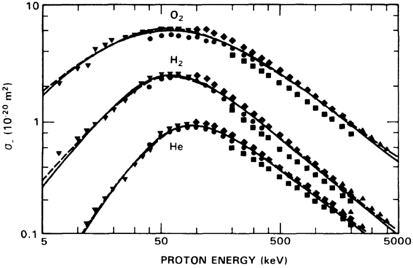


Figure: Electron production cross section for protons on different residual gas ions [5]

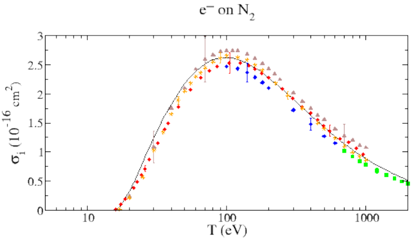


Figure: Electron impact ionisation cross section for N_2 [4]

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

A lot of open questions...

"Einige Erweiterungen, z. B. die Einbeziehung der Restgasionen in die Simulation, sind zwar schon vorgezeichnet und harren „lediglich" der Realisierung, das gravierendste Problem, die Beschreibung des kompensierten Strahles in Anwesenheit von magnetischen Feldern, erfordert jedoch noch weitergehende theroretische und experimentelle Untersuchungen."

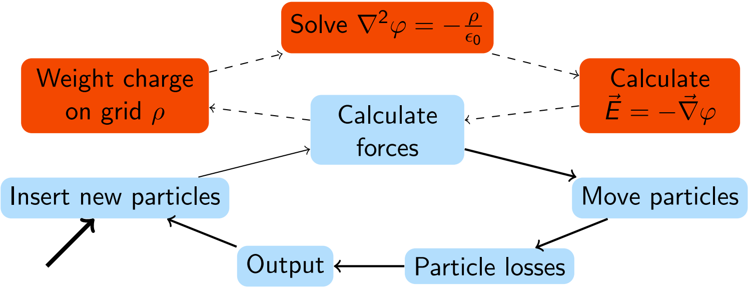
Dissertation P. Groß, 2000

The Particle-in-Cell code "Bender"

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 code "Bender"

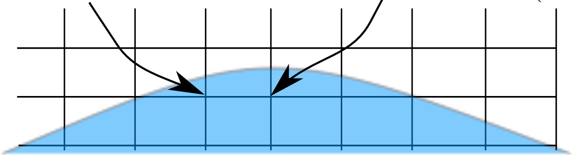
Approximation of geometry on the grid

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

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

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

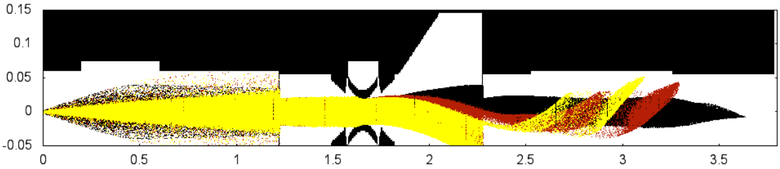
$$E_z(x, z) = \frac{\partial\varphi}{\partial z}\Big|_{(x-h_x^-, z)} + \frac{\partial^2\varphi}{\partial z \partial x}\Big|_{(x-h_x^-, z)} h_x^-$$



The Particle-in-Cell code “Bender”

Currently implemented features

- Gebunchte und kontinuierliche Strahlen
- Multi-Species
    -



Simulation difficulties

Limits on time step:

- $\frac{\Delta p}{p} \ll 1 \longrightarrow \Delta t \ll \frac{\sqrt{2mW}}{q|\vec{E}|}$, 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 $\Delta t \ll \frac{2}{\omega}$, 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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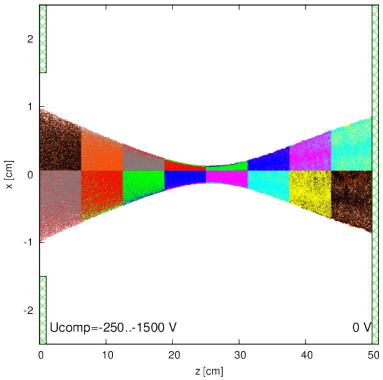
Ionisation of residual gas

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

Simulation of a beam drift with repeller electrode



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

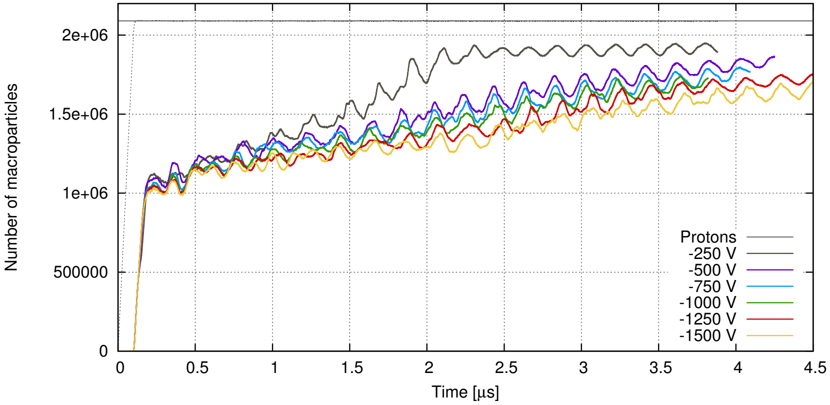
One electron per proton
$W_e^{start} = 1\,\mathrm{eV}$

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

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

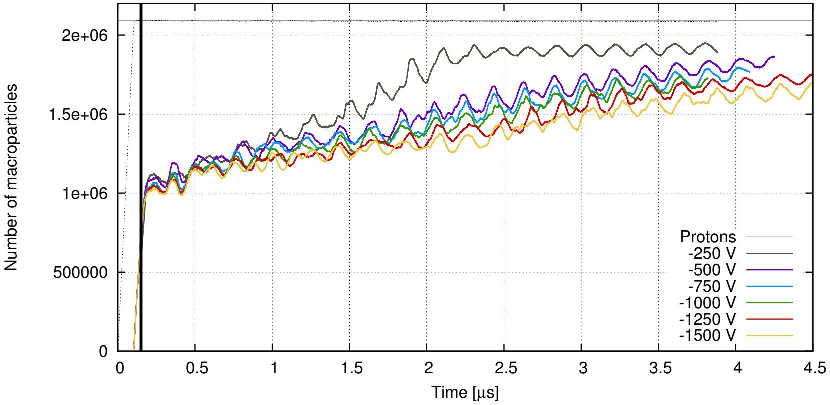
Simulation of a beam drift with

Rise times for different voltages



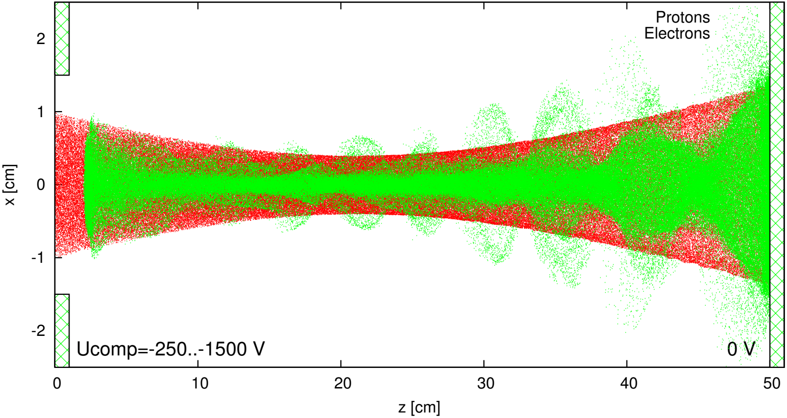
Simulation of a beam drift with compensation lens

Rise times for different voltages



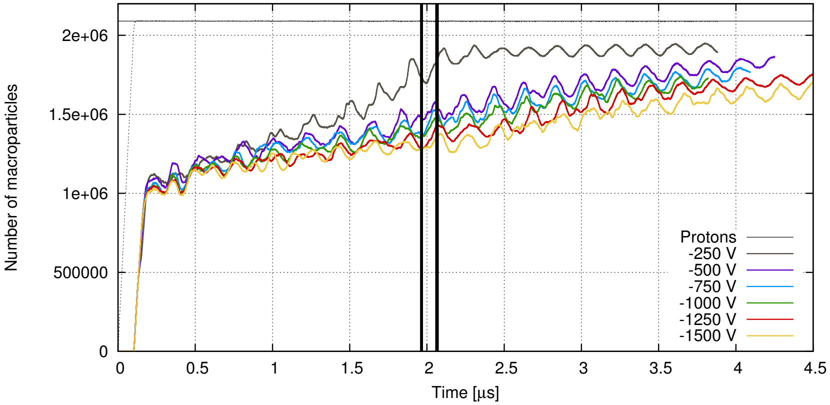
Simulation of a beam drift with repeller electrode

Proton hitting the wall

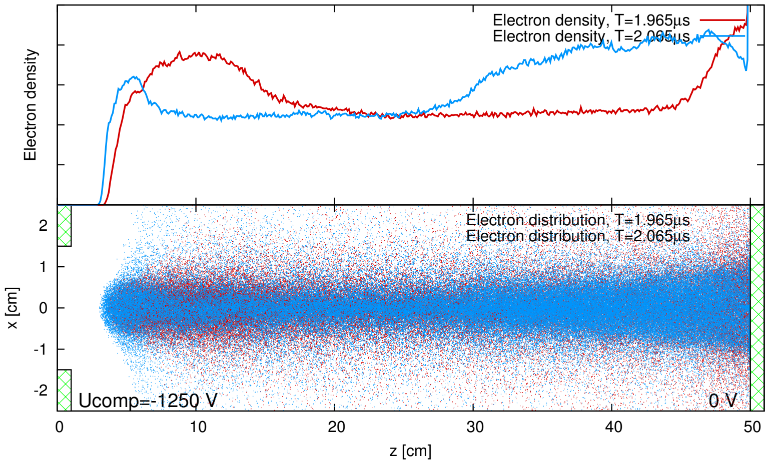


Simulation of a beam drift with repeller electrode

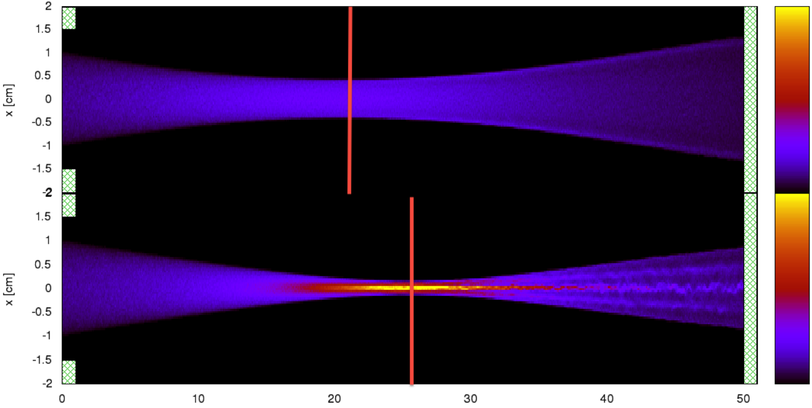
Rise times for different voltages



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
- 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 [2] for electron ↔ wall interaction
  - Interaction between electrons, ions ↔ residual gas – dynamics of the residual gas?
- Space charge compensation in beam line components
- 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