Electron emission modeling in ionisation gauges for magnetic confinement fusion

IPP

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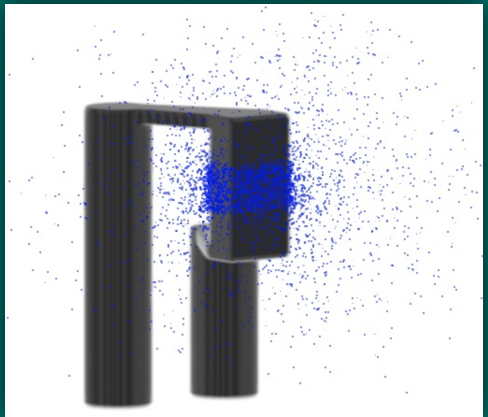

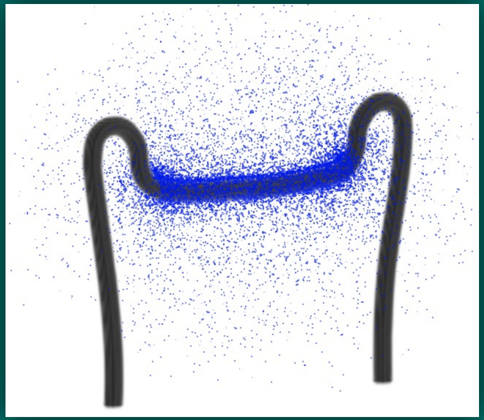

EUROfusion

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Federal Ministry of Research, Technology and Space

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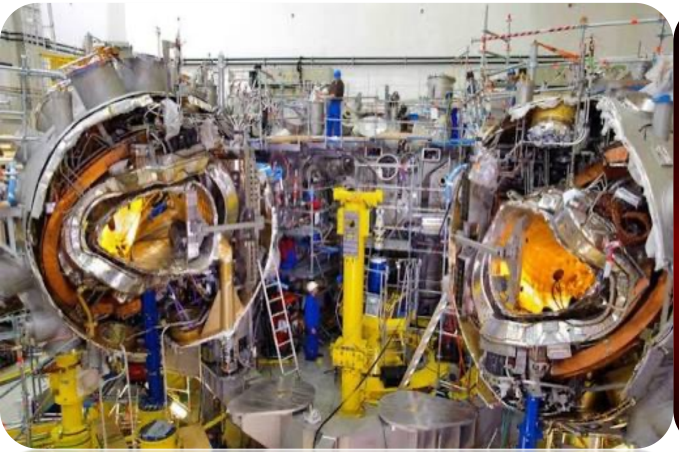
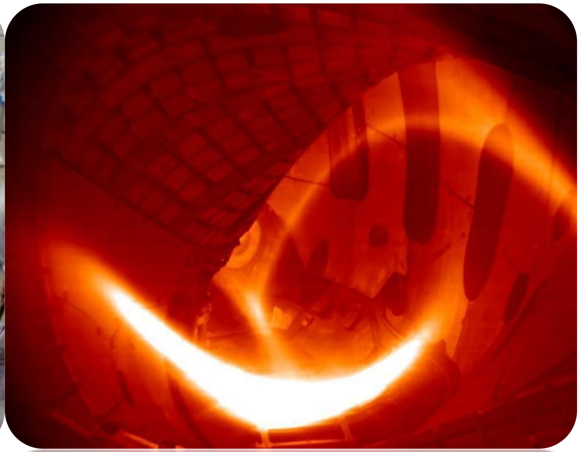
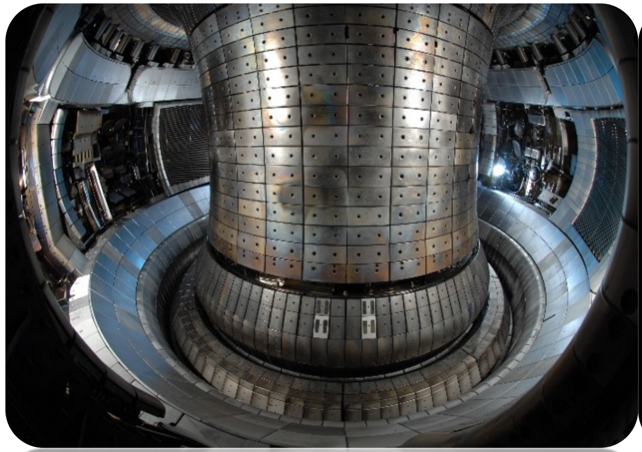
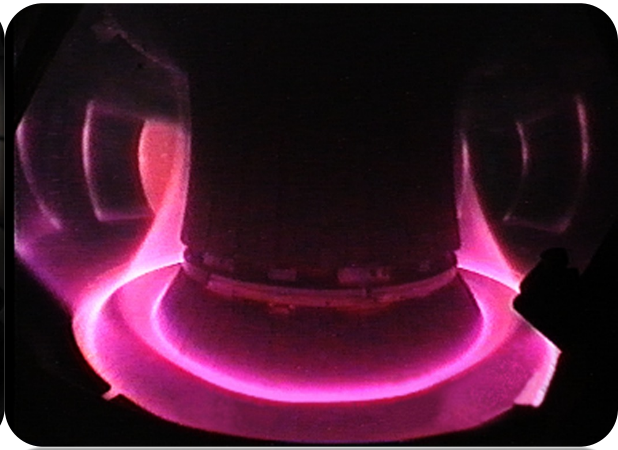
Magnetic confinement fusion research at IPP

Wendelstein 7-X Stellarator (Greifswald)

- Operating since 2015
- Plasma volume ~ 30m³
- Magnetic field 3T (on axis)

ASDEX Upgrade Tokamak (Garching)

- Operating since 1991
- Plasma volume ~ 13m³
- Magnetic field 2.5T (on axis)

In vessel pressure measurements

In vessel pressure for **real-time plasma control**.

Conditions close to the plasma, behind first wall:

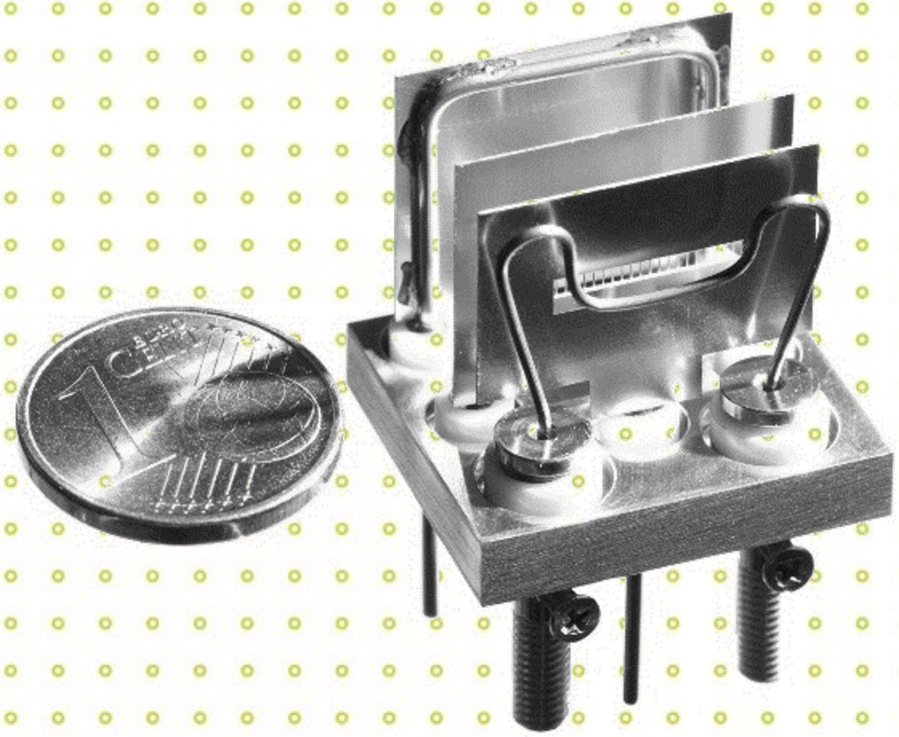
- **Pressure range** from 10^{-4} – 30Pa
- **Time resolution** < 1ms
- **Magnetic field** 1 – 8T (tested range)
- **Neutron flux / radiation** 10^{2} – 10^{5}Gy/h (ITER)
- **Temperature** up to 700K (ITER)

→ **Not possible with Pirani, Baratron and cold cathode gauges**

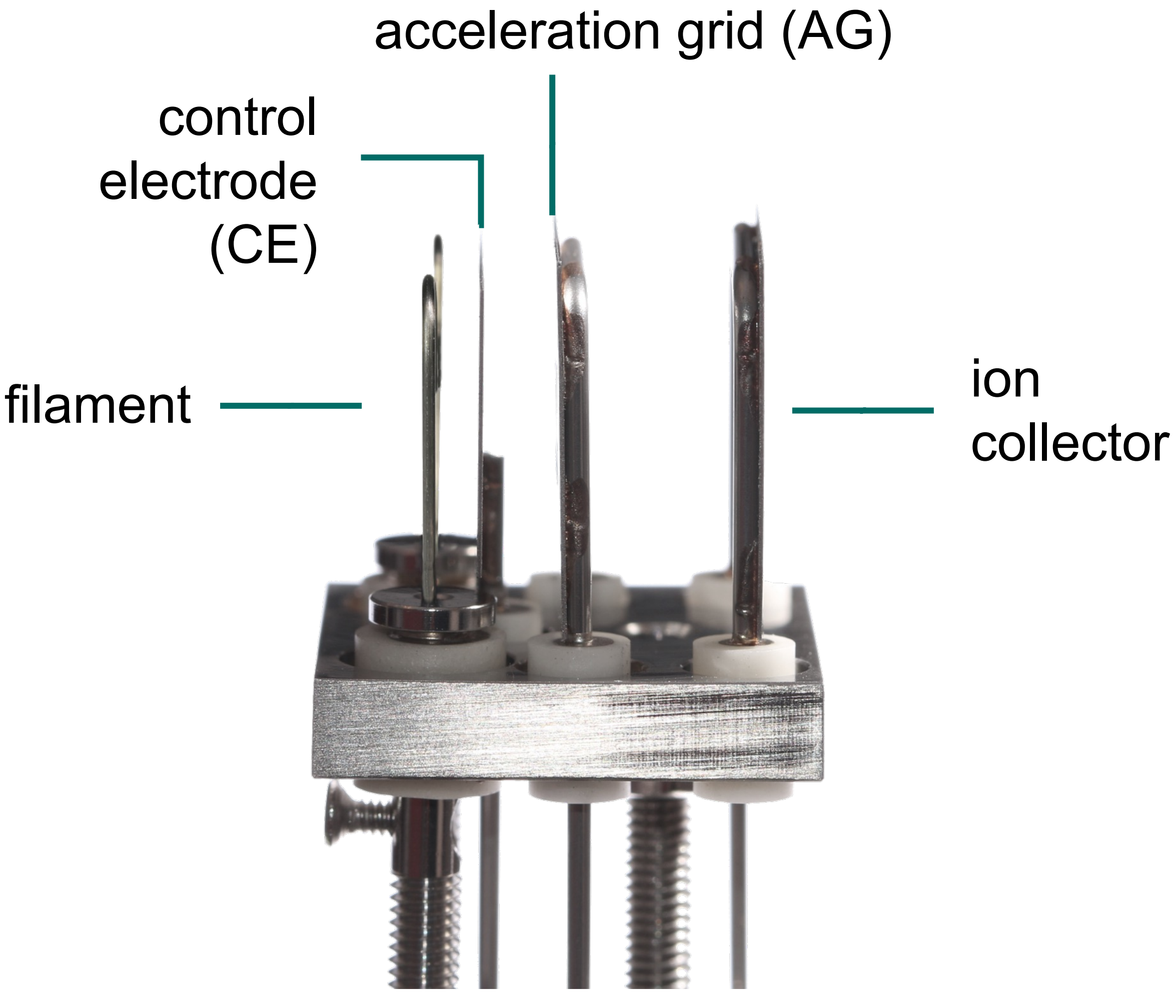
→ still used for machine safety and calibration

„ASDEX"-type pressure gauge

Functionality:

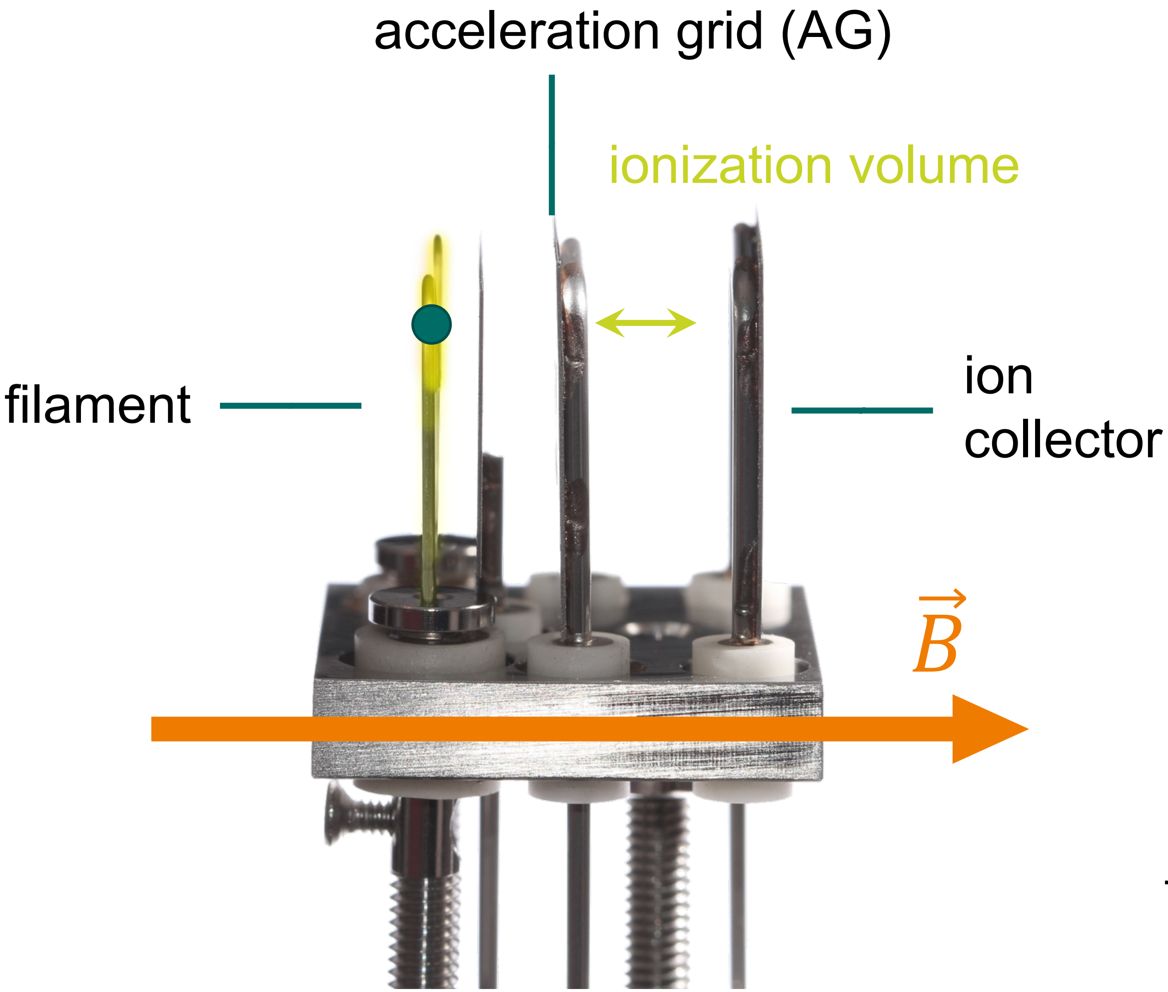


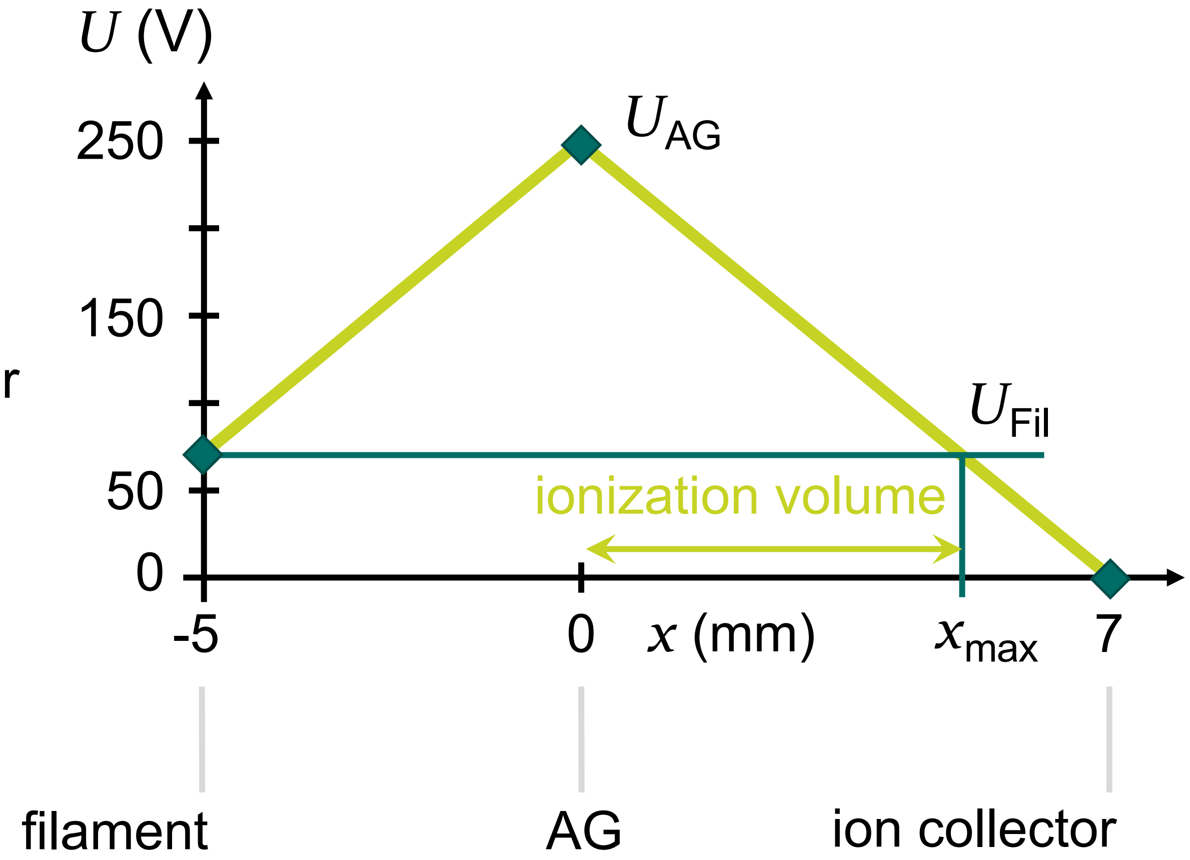
ASDEX gauge – hardware



hot cathode ionization gauge

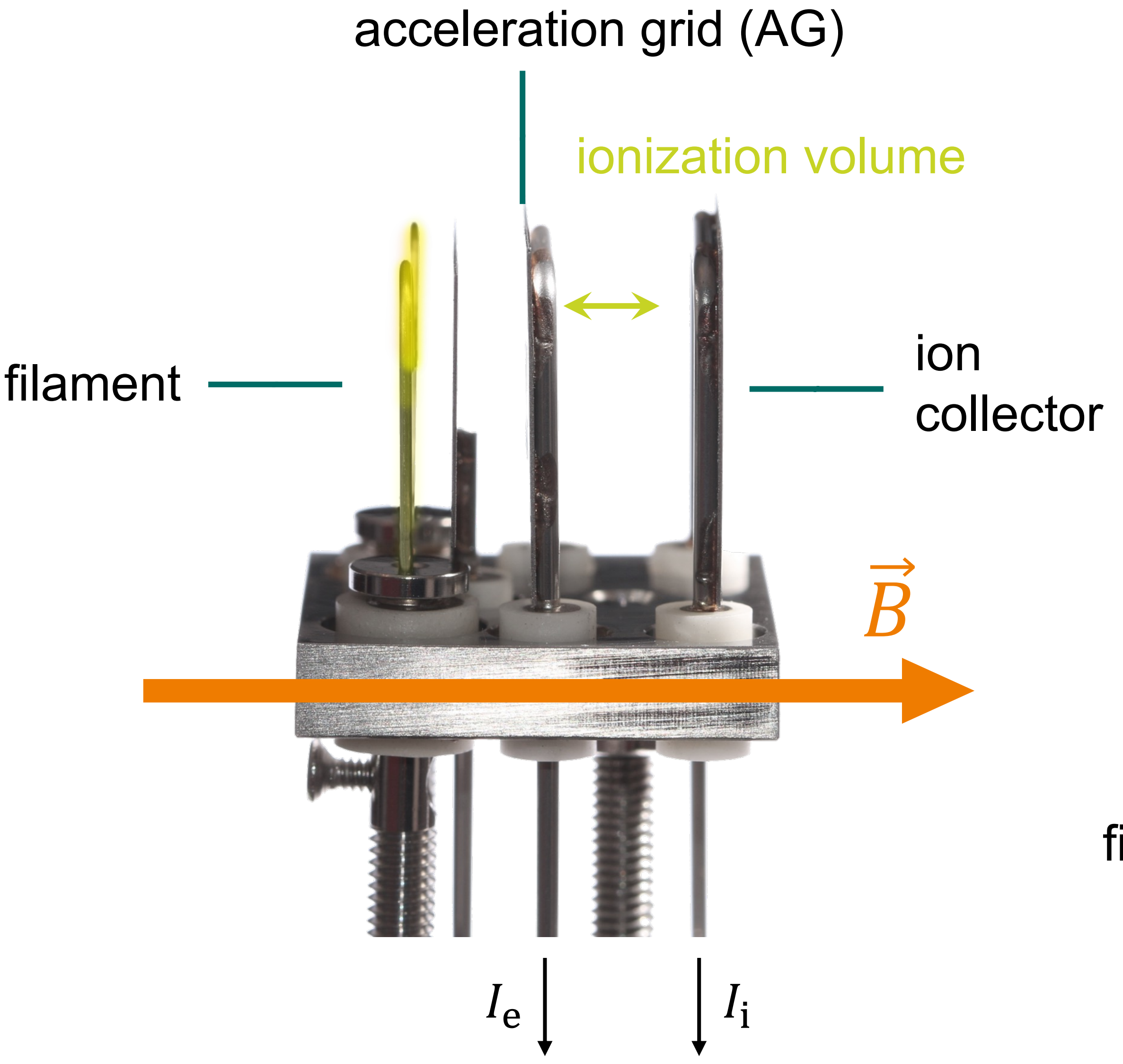
ASDEX gauge - potentials

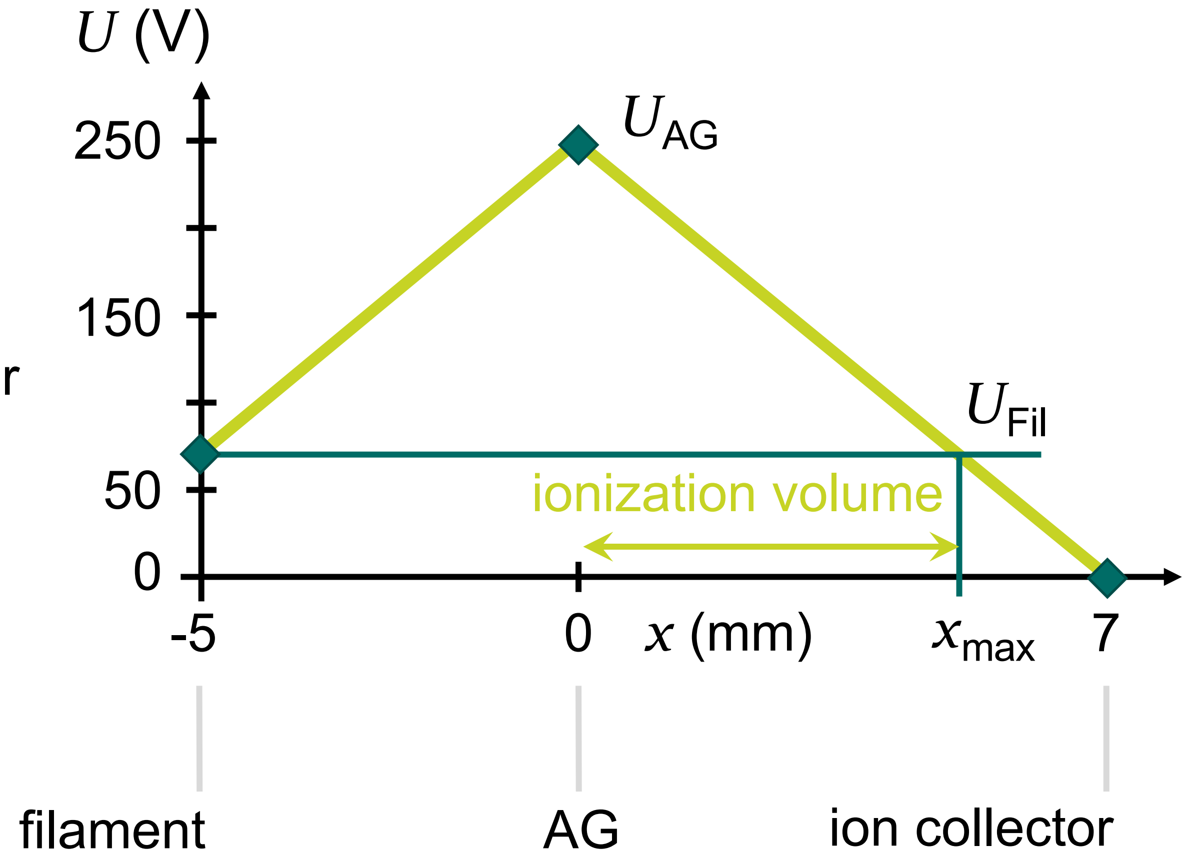




Based on: Haas, G. & Bosch, H.-S. *Vacuum* **51**, 39–46 (1998)

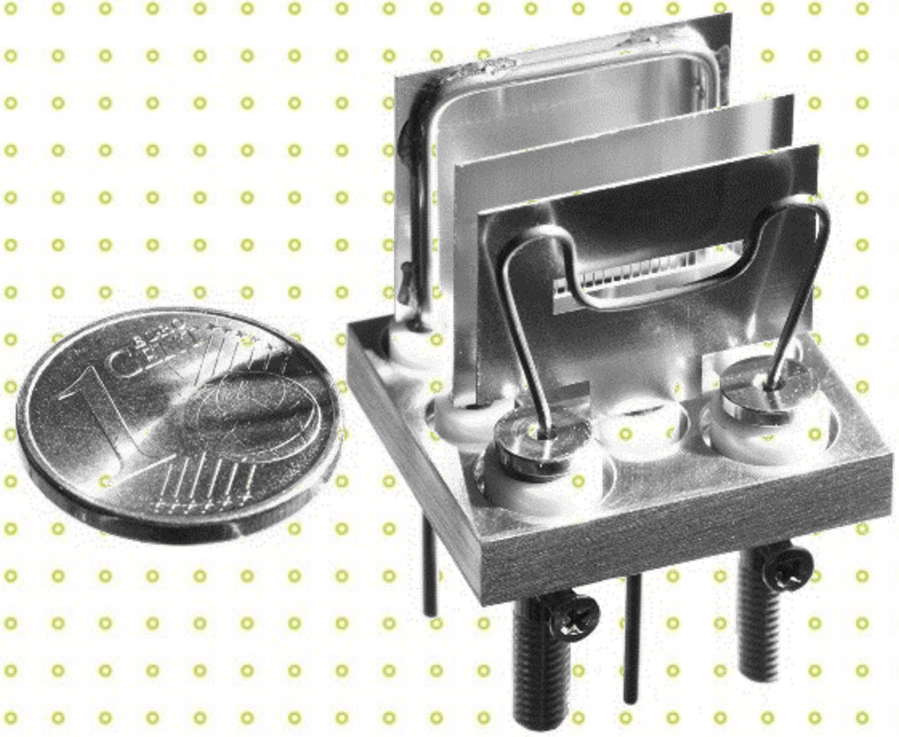
ASDEX gauge - output





Based on: Haas, G. & Bosch, H.-S. *Vacuum* **51**, 39–46 (1998)

Modeling:



Overview

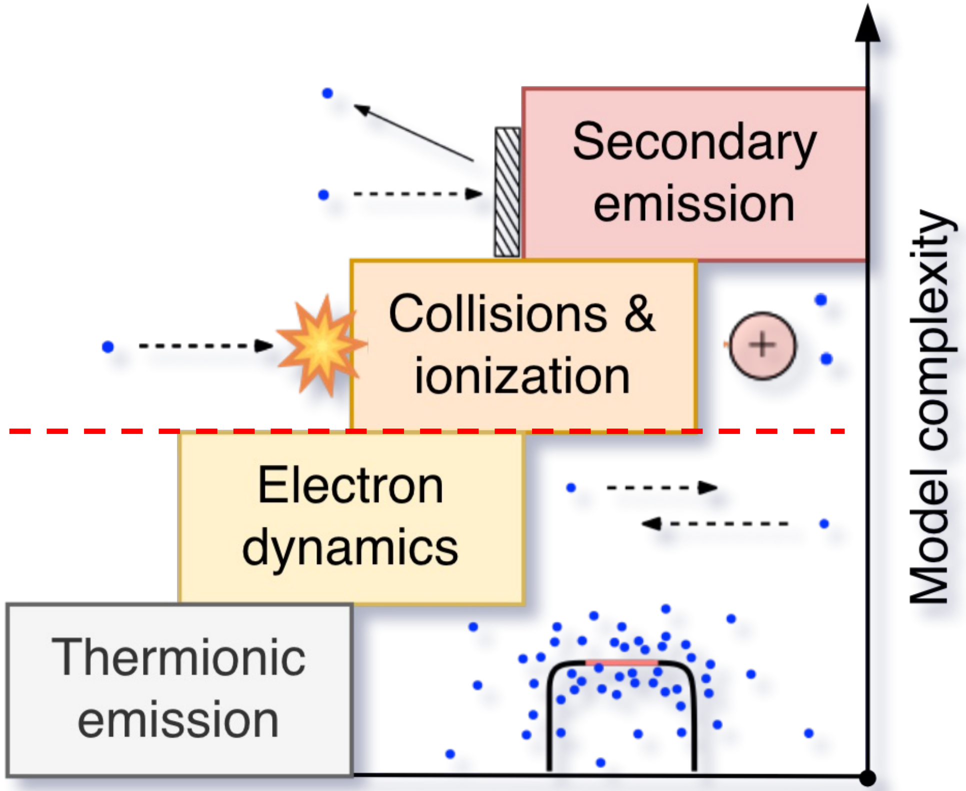
Design optimization and "synthetic diagnostic":

- Performance prediction and improvement
- Parameter sweeps and automation
- Extrapolation beyond lab capabilities

Characteristic plasma physics:

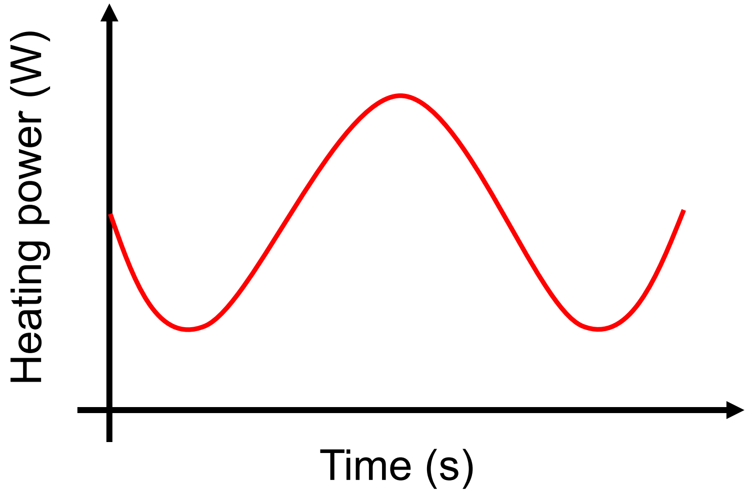
- Access to "invisible" quantities
- Isolated effects and Laboratory verification

Focusing on colissionless electrons (for now)



Thermionic emission & electron dynamics

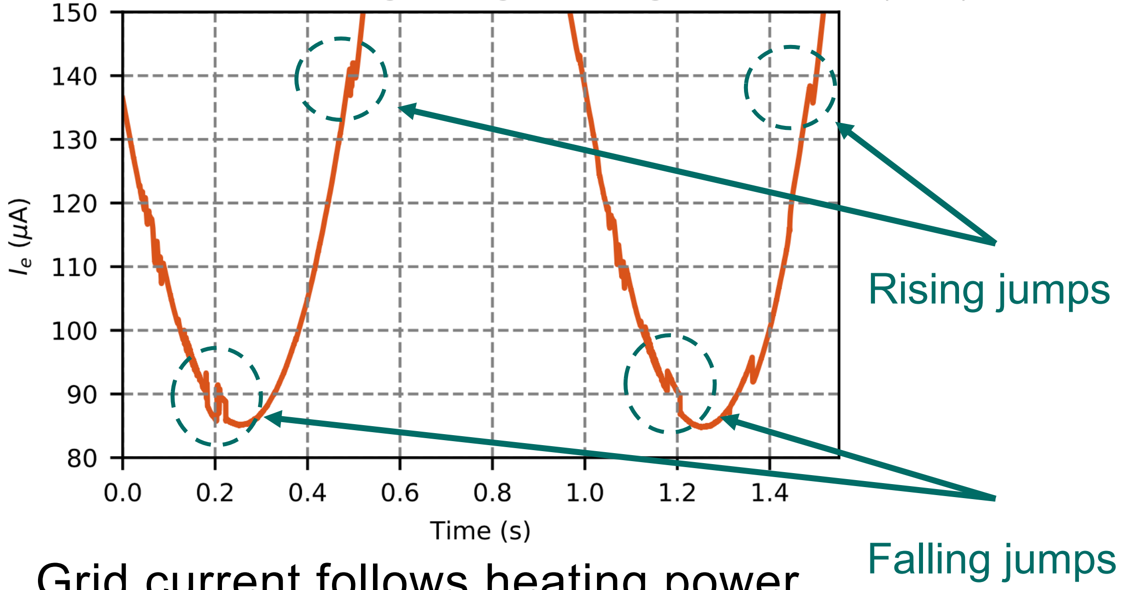
Input:



- No gas background = **no ions**
- Sinusoidal variation in filament heating

Experimental observation:

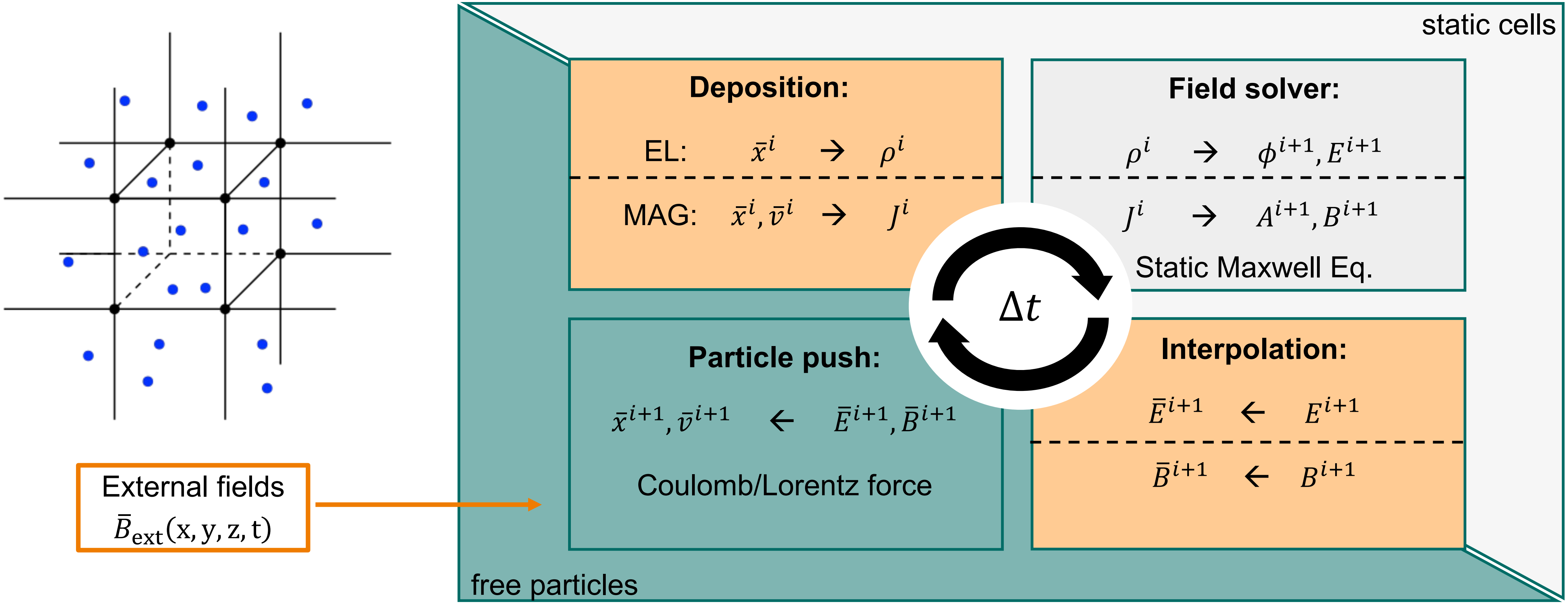
A. C. Castillo et al.. *Fusion Engineering and Design*, Volume **181** (2022)



- Grid current follows heating power
- **Reproducible, hysteretic jumps**

→ State transitions/perturbations in the electron population

“Electromagnetostatic” Particle-In-Cell method



Used codes

Geometry generation:

Gmsh [1]

- Generating complex geometries in 3D

PIC simulation:

[2]

- Massively parallelized with openMP/MPI
- Scalable on CPU and GPU clusters

Postprocessing:

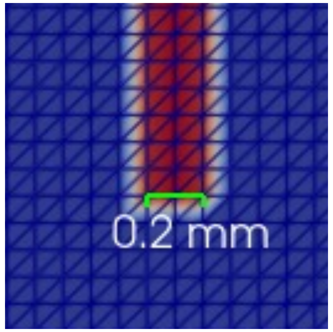
- Matplotlib for standard 2D plots
- Paraview for 3D and particle visualization

[1] C. Geuzaine and J.-F. Remacle, ***Gmsh:** a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities*, International Journal for Numerical Methods in Engineering, Volume 79 (2009)
[2] J.-L. Vay et al., **WarpX:** An advanced Particle-In-Cell code. DOI:10.5281/zenodo.4571577, https://blast-warpx.github.io (2018)

This research used the open-source particle-in-cell code WarpX. Primary WarpX contributors are with LBNL, LLNL, CEA-LIDYL, SLAC, DESY, CERN, Helion Energy, TAE Technologies, and Realta Fusion. We acknowledge all WarpX contributors.

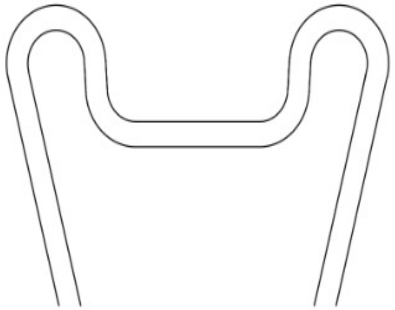
The electron model

1. General constraints

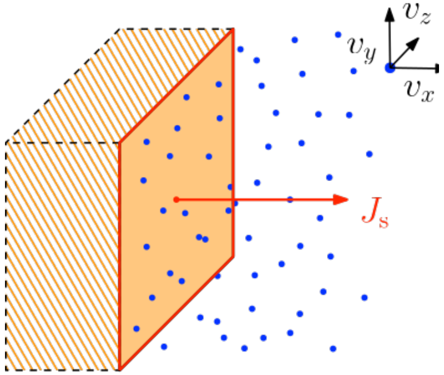


$\Delta t, \Delta x$

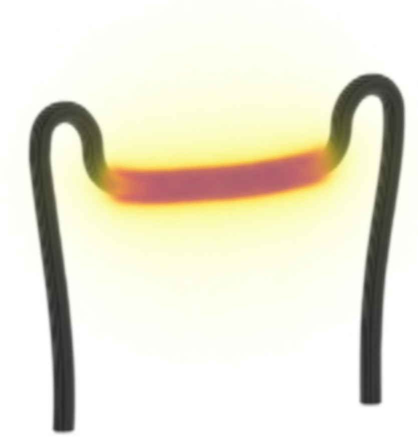
2. Emitter types



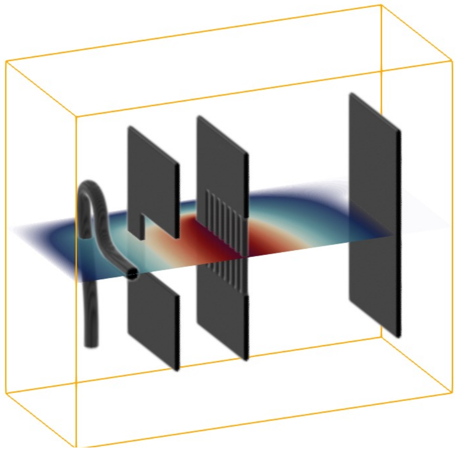
3. Source flux



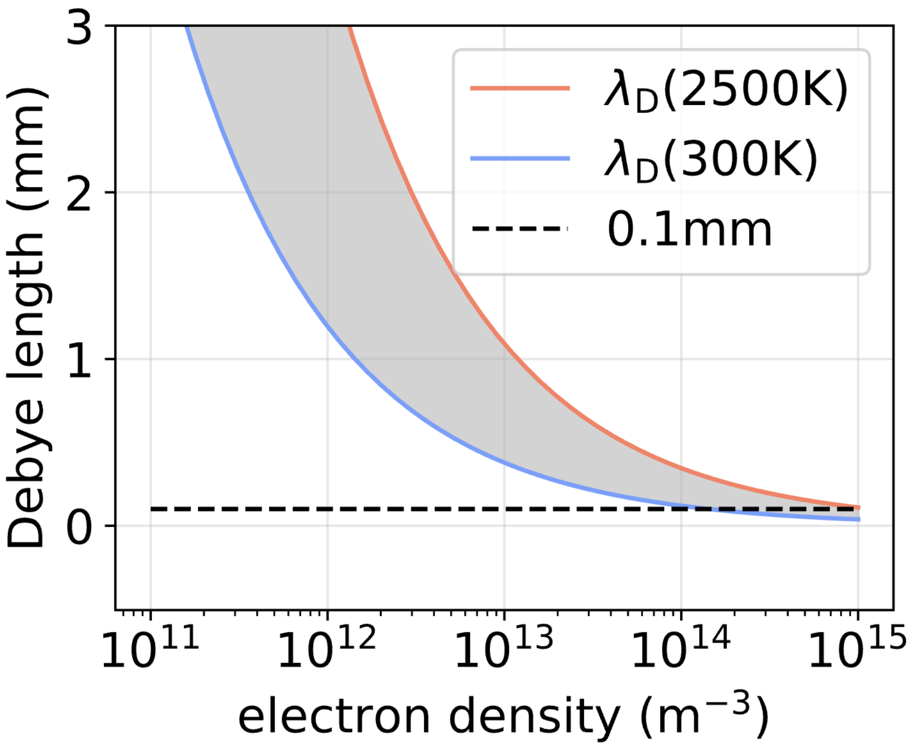
4. Source distributions

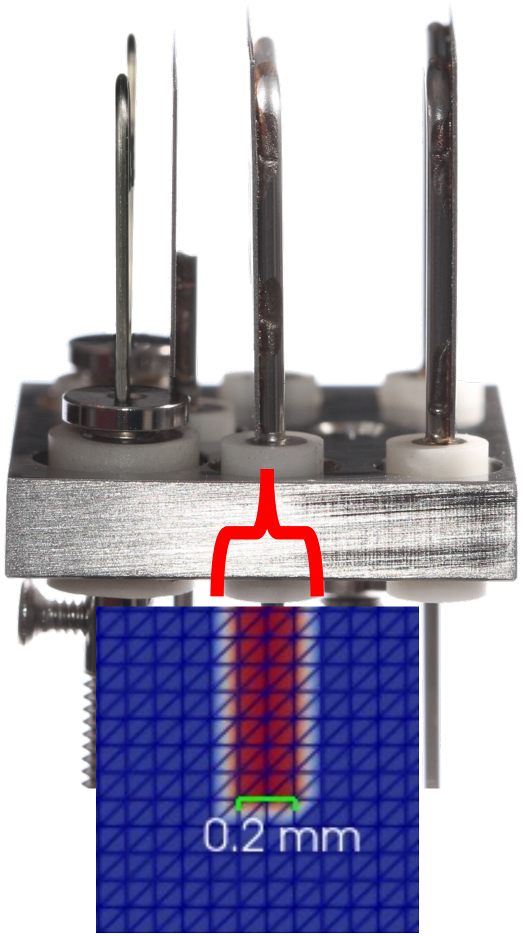


5. Boundaries



1. General constraints





1. Debye and geometric:

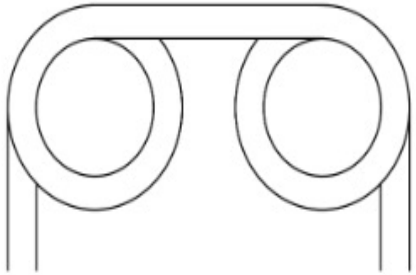
$$\Delta x \approx \mathcal{O}(10^{-4}\mathrm{m})$$

2. Maximum particle velocity:

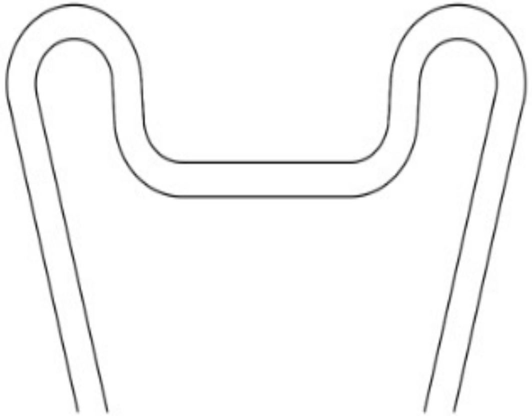
$$v_{\max} \approx \sqrt{\frac{2\, q_e\, U_{\max}}{m_e}} + 4\, v_{th}$$

$$\Delta t \approx \mathcal{O}(10^{-12} s)$$

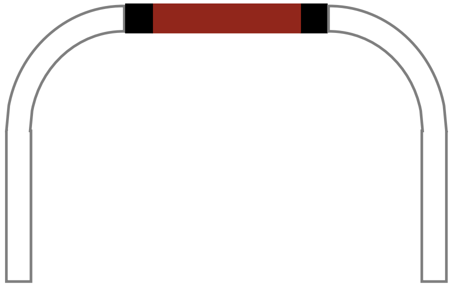
2. Emitter types



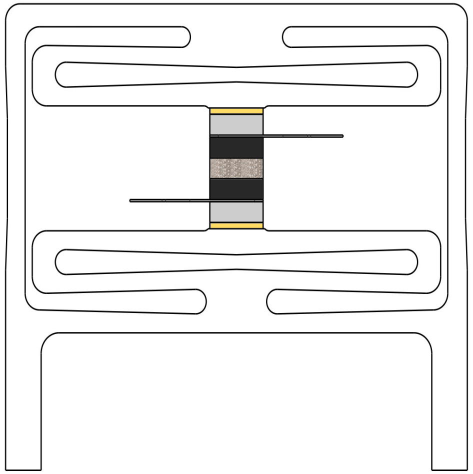
Spiral design



Meander design



LaB_6



ZrC

Actively heated emitters

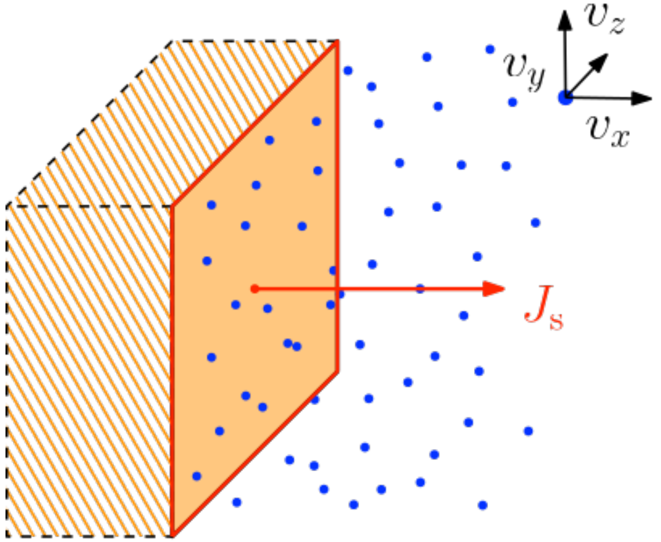
Passively heated emitters

* Filament diameters not to scale

3. Source flux

Using the **Richardson-Dushman** law:

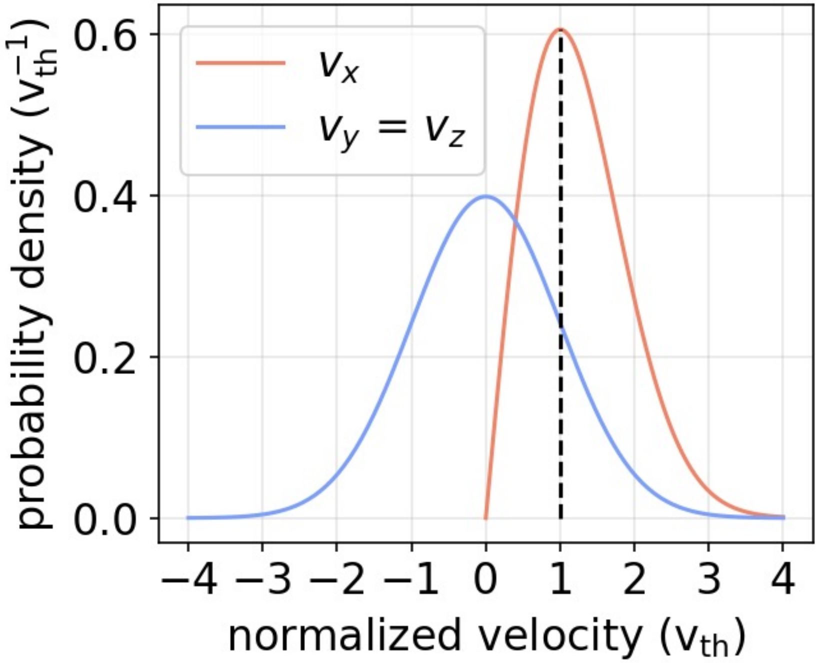
$$J_s = A_G\, T^2 \exp\left(-\frac{W_f}{k_B T}\right)\, C(T)\,, \qquad \sqrt{\frac{q_e^3 E}{4\pi\varepsilon_0}} \approx \text{const.}$$



And the most probable **thermal velocity**:

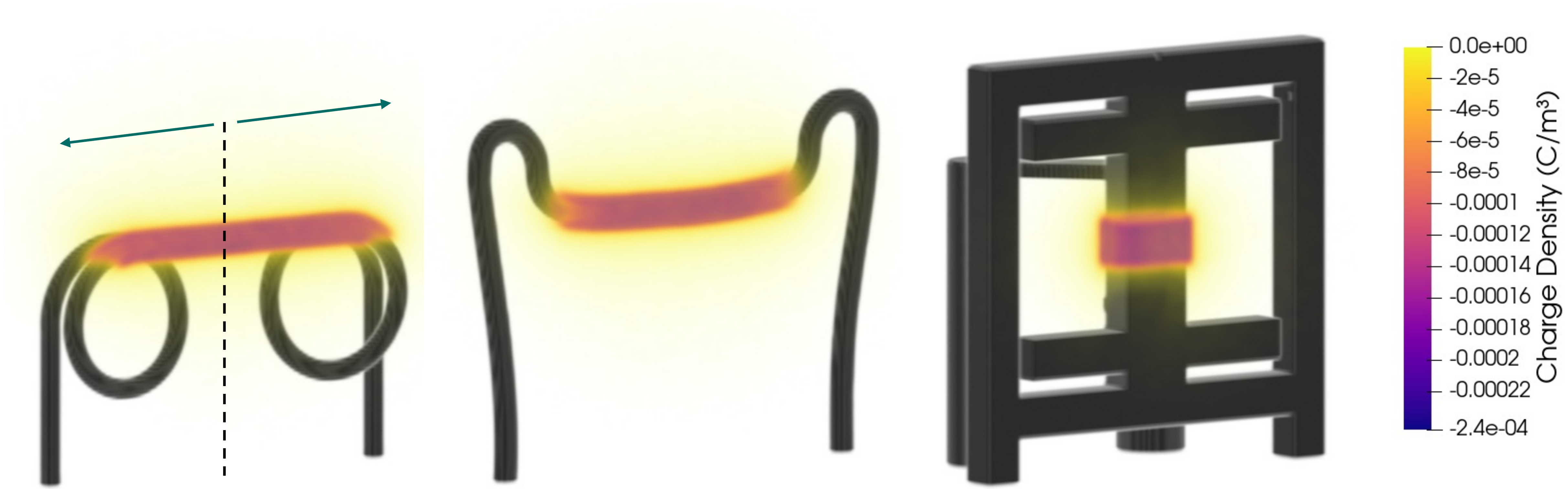
$$v_{th} = \sqrt{\frac{k_B\, T}{m_e}}$$

Cutoff at $\pm 4 v_{th}$ (99.38% of velocity dist.)



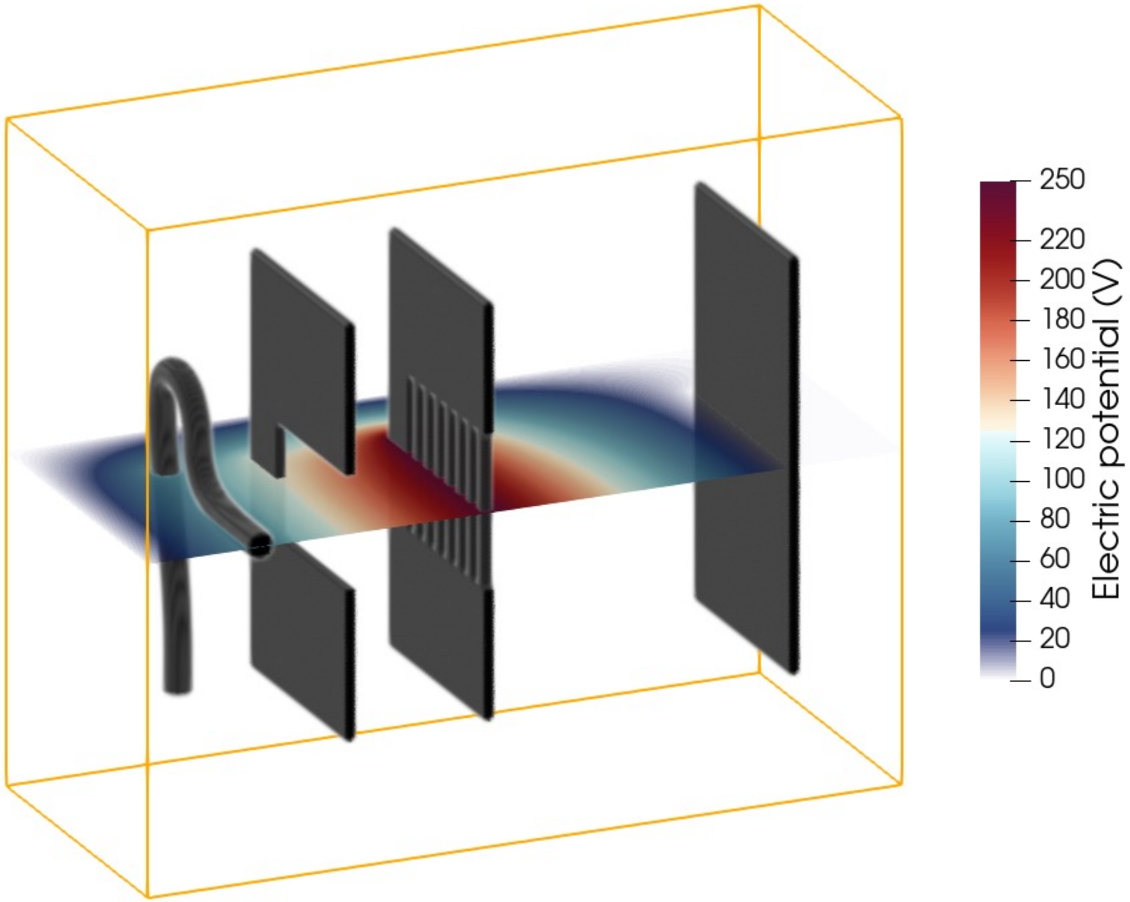
Birdsall, C.-K. & Bridges, W.-B.
Electron Dynamics (1966)

4. Source distribution



- Spatial non-uniform source flux
- Partial surfaces

5. Boundary conditions



Electrostatics:

- **Fixed potentials** as Dirichlet conditions:

$$\phi\big|_{\partial\Omega} = U$$

Particles:

- **Absorbing boundaries** (perfect conductor)

$$I\big|_{\partial\Omega} = \frac{\mathrm{d}Q}{\mathrm{d}t}\bigg|_{\partial\Omega}$$

Mirror plane:

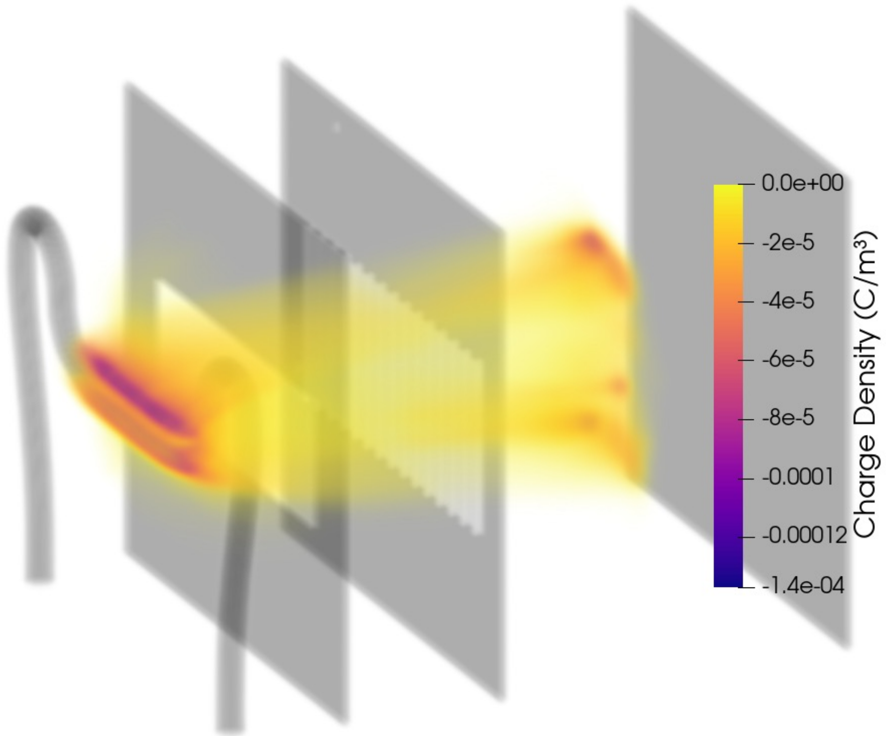
- **Neumann potential**
- **Inversion of normal particle velocity**

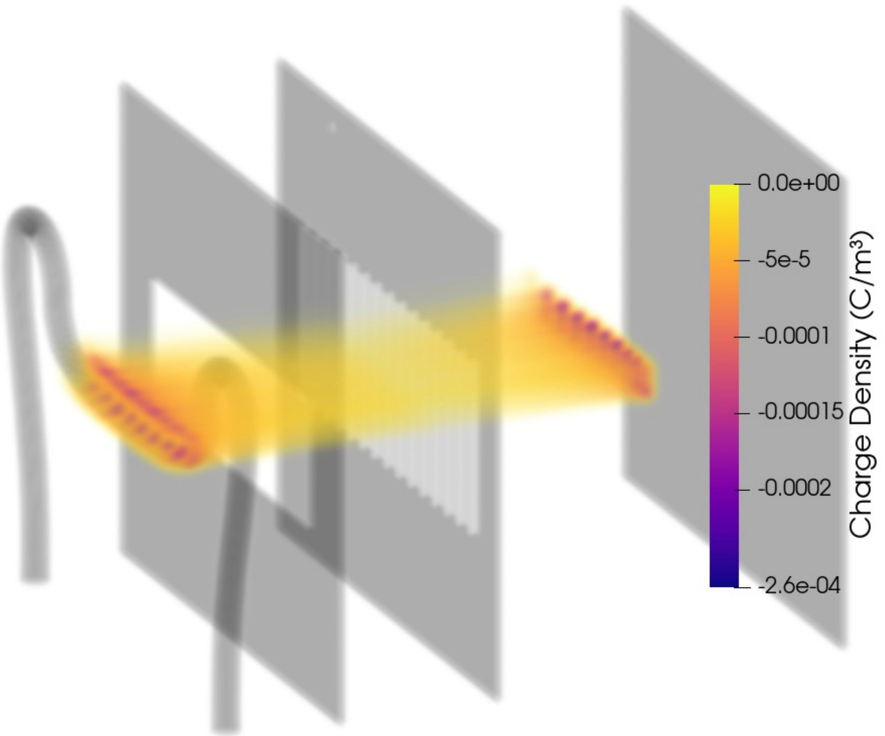
First results – magnetic field influence

$\vec{B}$

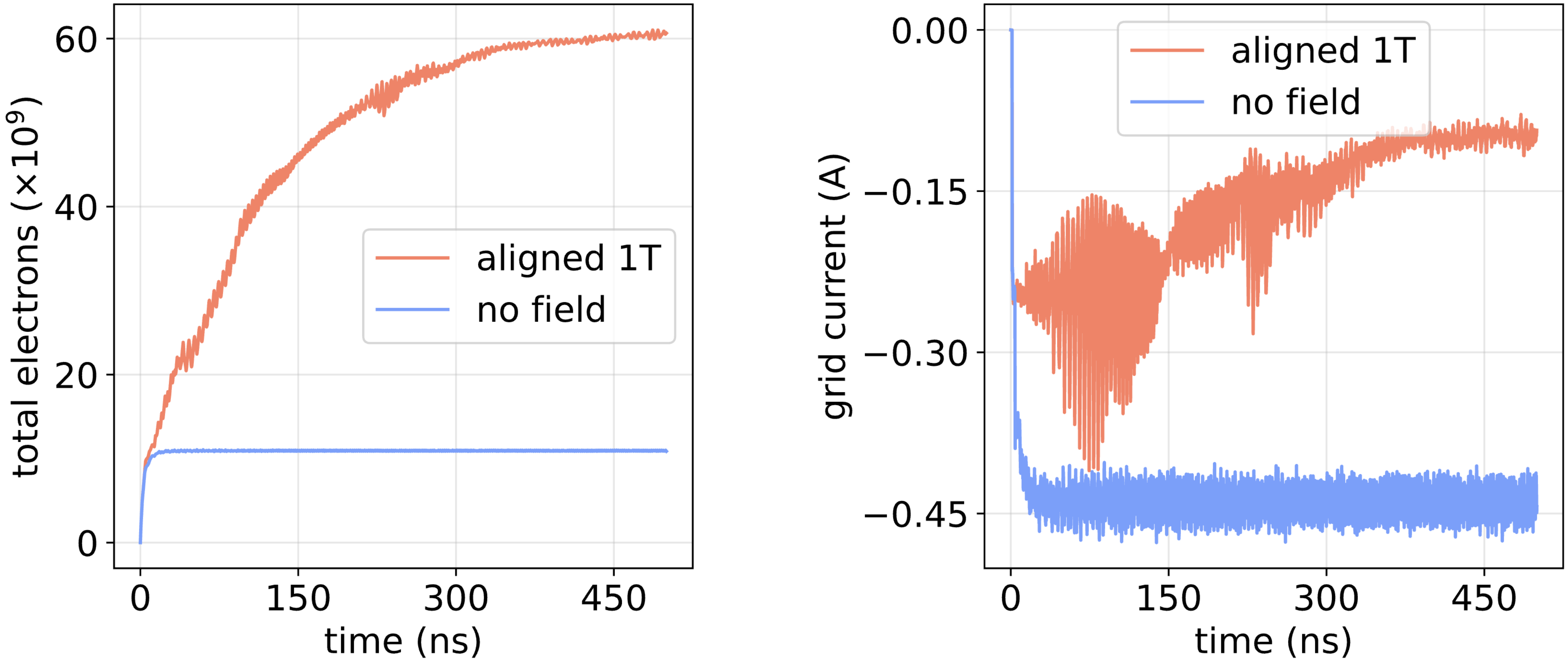
no magnetic field

perfectly aligned field of 1T





First results – electron trapping and current oscillations



Conclusion

Space-charge formation:

- The gauge geometry traps electrons, even for relatively weak background fields at the ends of the oscillation volume.
- Electron densities continue to grow for more **>100 electron oscillation cycles**, reaching higher peak values than initially expected.

“Steady-state” oscillations & current instability:

- When is the true steady state reached - **μs or ms timescales**? How does this depend on the **B-field magnitude and gauge parameters/emitters**?
- What is the driving mechanism behind the observed oscillations?

→ **Further analysis and follow-up studies of source transients are planned.**

For more information and/or questions: **alexander.glock@ipp.mpg.de**