

Engineering approaches to the simulation and optimization of radio-frequency ion thrusters: from Particle-in-Cell to global models and model verification

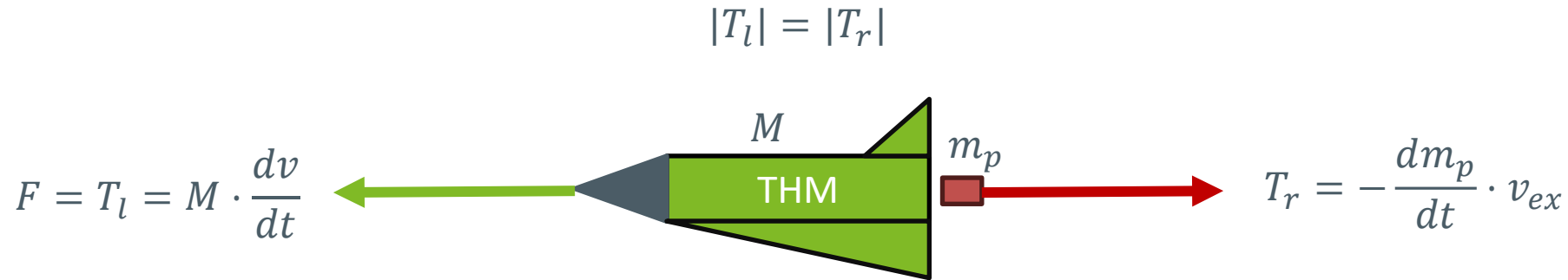
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Space Electronics Workgroup

Gießen, 12.05.2026

Classic Rocket Equation / Tsiolkovsky Equation



$$M(t) = m_d + m_p(t) \rightarrow \frac{dM}{dt} = \frac{dm_p}{dt}$$

$$dv = -v_{ex} \cdot \frac{dM}{M}$$

$$v_{final} - v_{init} = \Delta v = v_{ex} \cdot \ln\left(\frac{m_d + m_p}{m_d}\right)$$

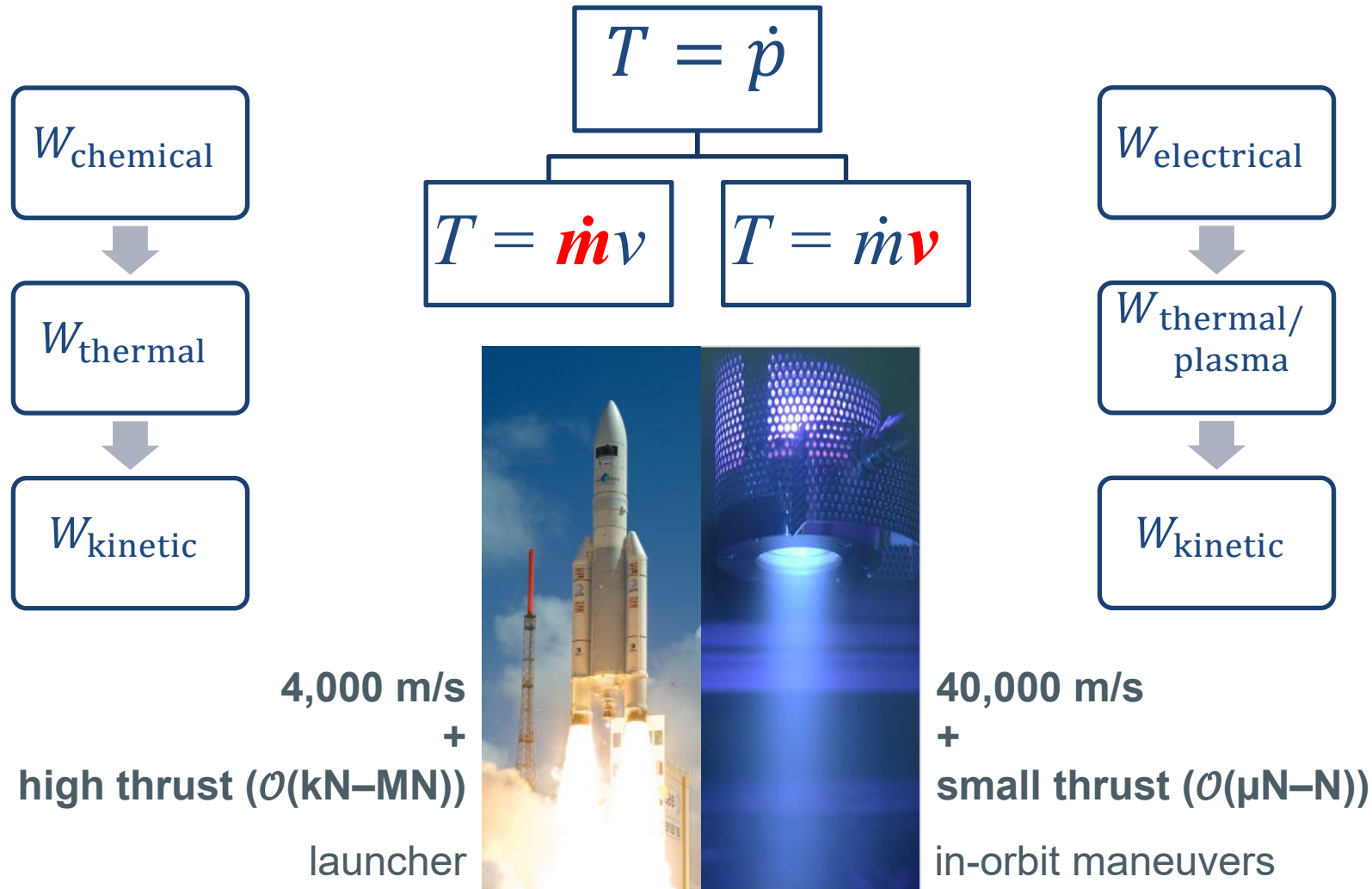
Δv : change of velocity due to acceleration

v_{ex} : exit velocity of propellant

m_d : fixed mass

m_p : propellant mass

Types of Thrusters



Example of cost reduction using electric propulsion

Satellite displacement	Δv (m s ⁻¹ per year)
Drag compensation (500 km)	30
Attitude control	2–6
Station keeping in GEO	50
Orbit transfer	Δv (km s ⁻¹)
Earth—LEO	9,7
LEO—GEO	4,3
LEO—Moon	5,9
LEO—L1	3,7
LEO—L2	3,4
LEO—Mars	4,3
Interplanetary journeys	Δv (km s ⁻¹)
Nearby planets	5–8
Far-off planets	10–15
100–1000 au	100
10 000 au	1000
Interstellar medium	30 000

$m_d = 1.000$ kg (payload)

Chemical Propulsion (CP)

$v_{ex} \cong 4$ km/s $\rightarrow m_p \cong 1.930$ kg

Electric Propulsion (EP)

$v_{ex} \cong 30$ km/s $\rightarrow m_p \cong 166$ kg

Launch cost/kg

- Falcon 9: \$2.270
 - ~\$8 Mio. (CP) | ~\$3 Mio. (EP)
- Ariane 5: \$9.167
 - ~\$27 Mio. (CP) | ~\$11 Mio. (EP)

Cost reduction approx. 60 %

Electric propulsion systems are more mass efficient than chemical thrusters but has lower absolute thrust.

$$\Delta v = v_{ex} \cdot \ln \left(\frac{m_d + m_p}{m_d} \right)$$

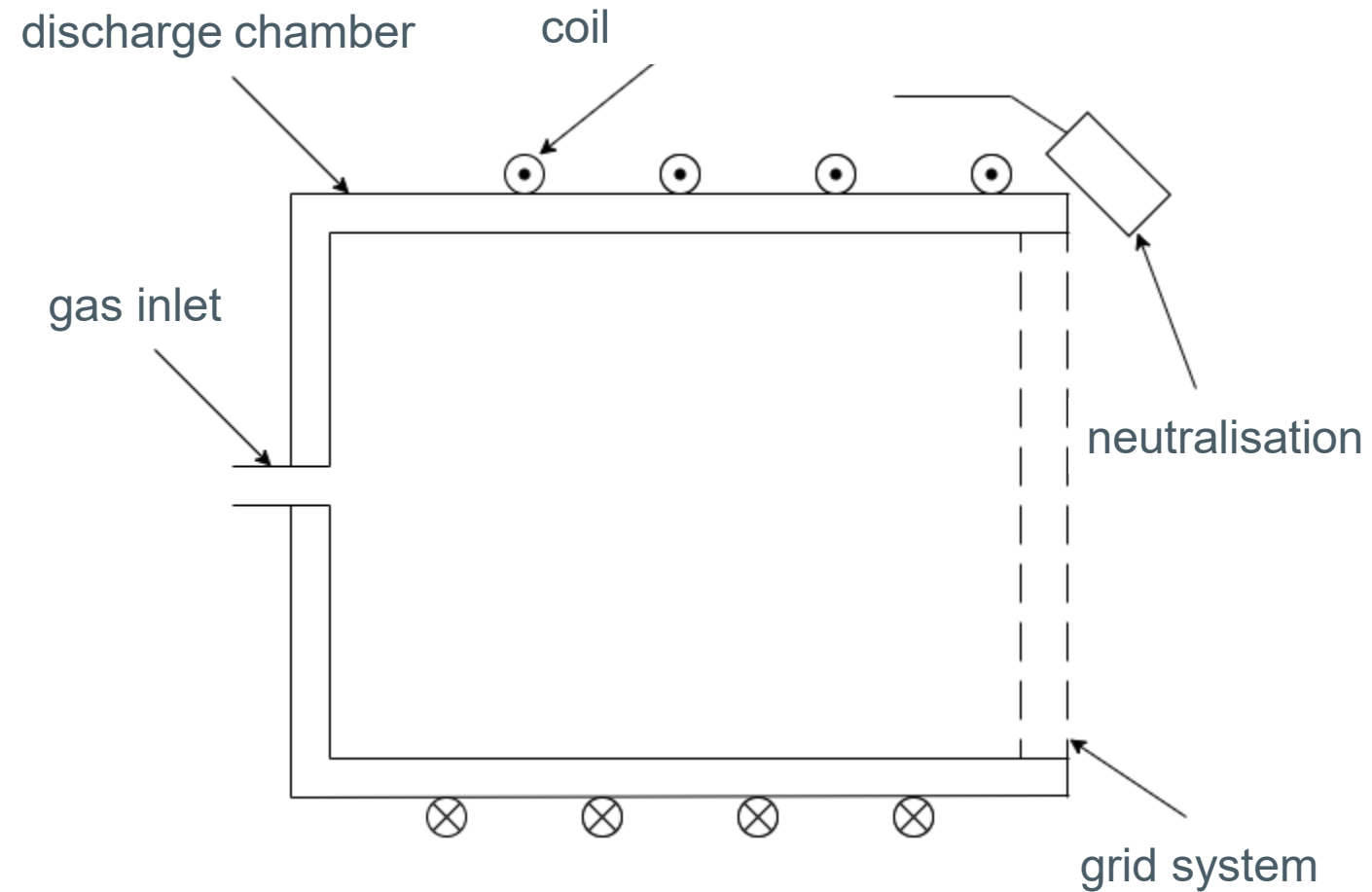
EP typically used:

- orbit raising
- deep space missions
- station keeping

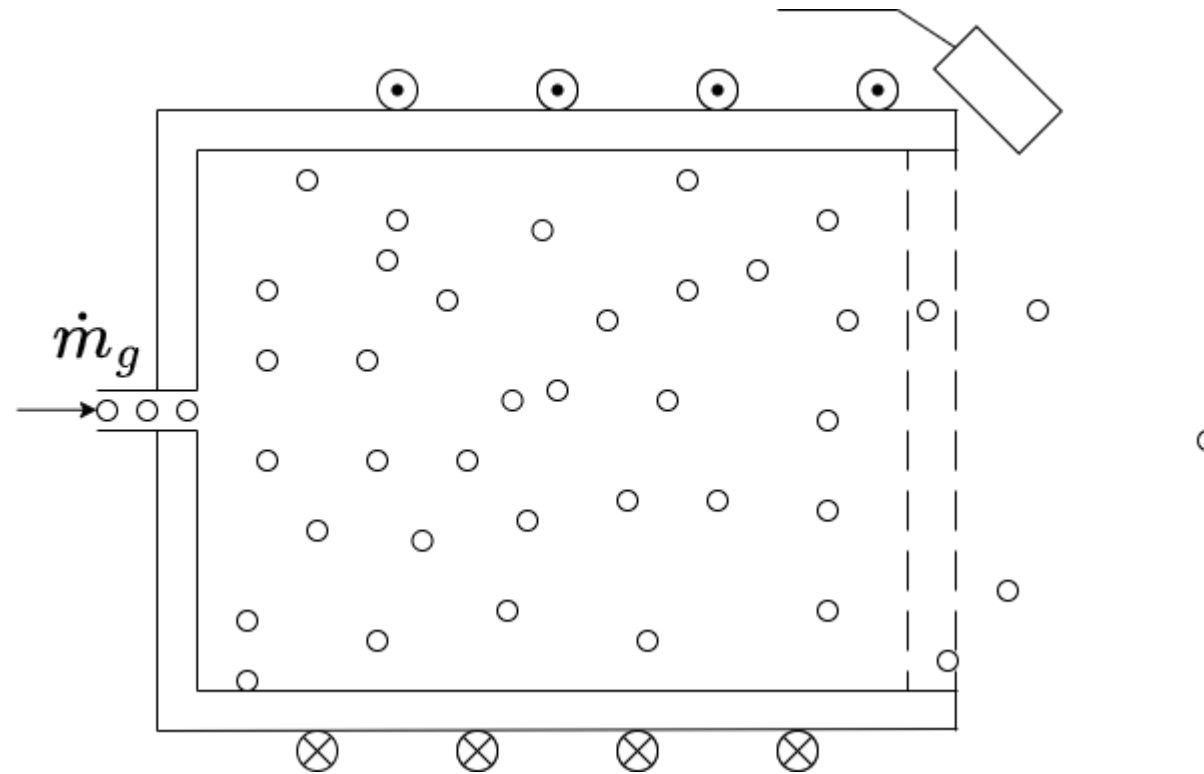
Categories of EP systems:

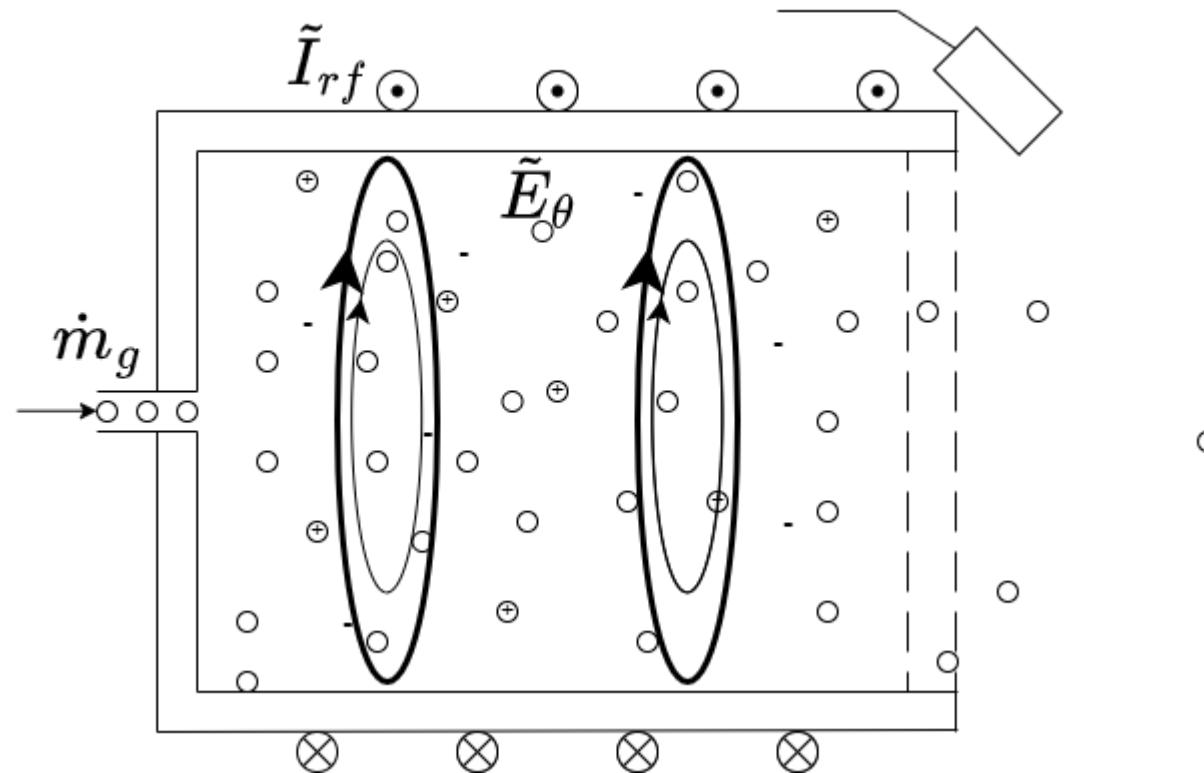
- electro thermal: Resisto Jet (RJ)
- electro static: **Radiofrequency Ion Thruster (RIT)**
- electro magnetic: Hall Thruster (HET)

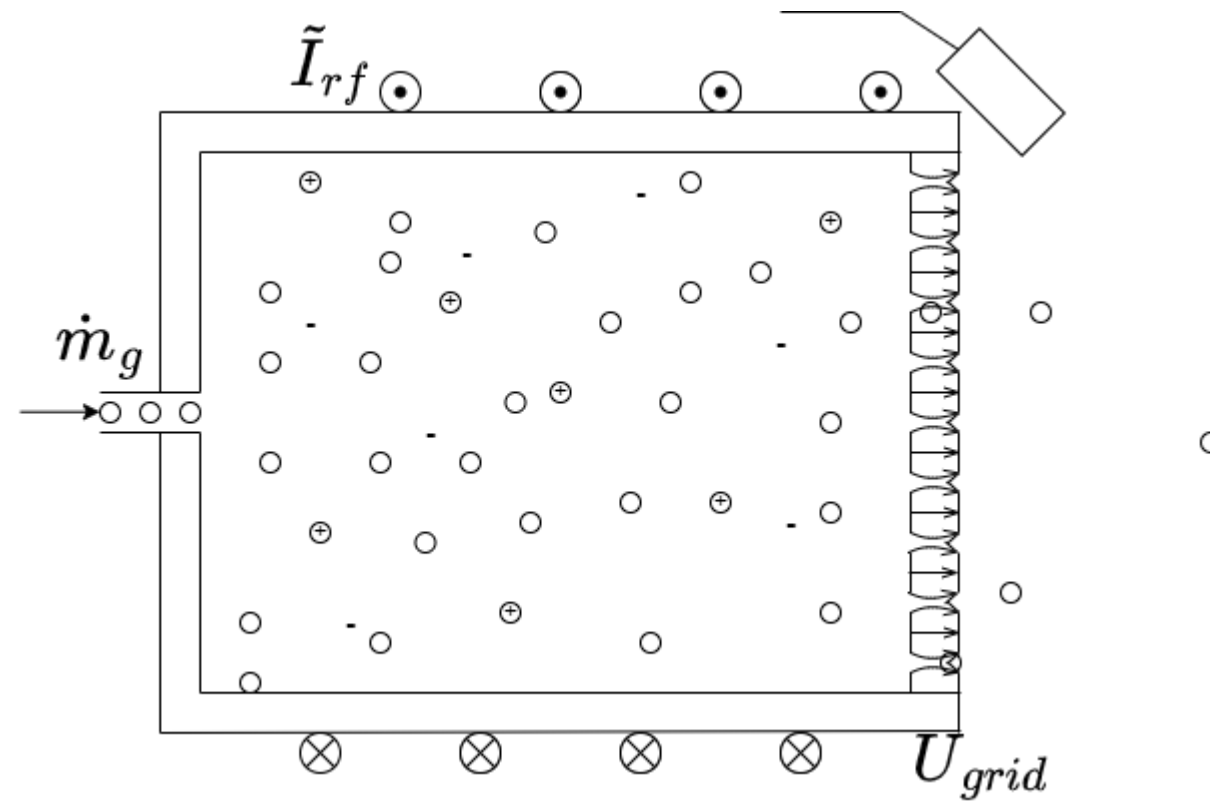
Radiofrequency ion thruster

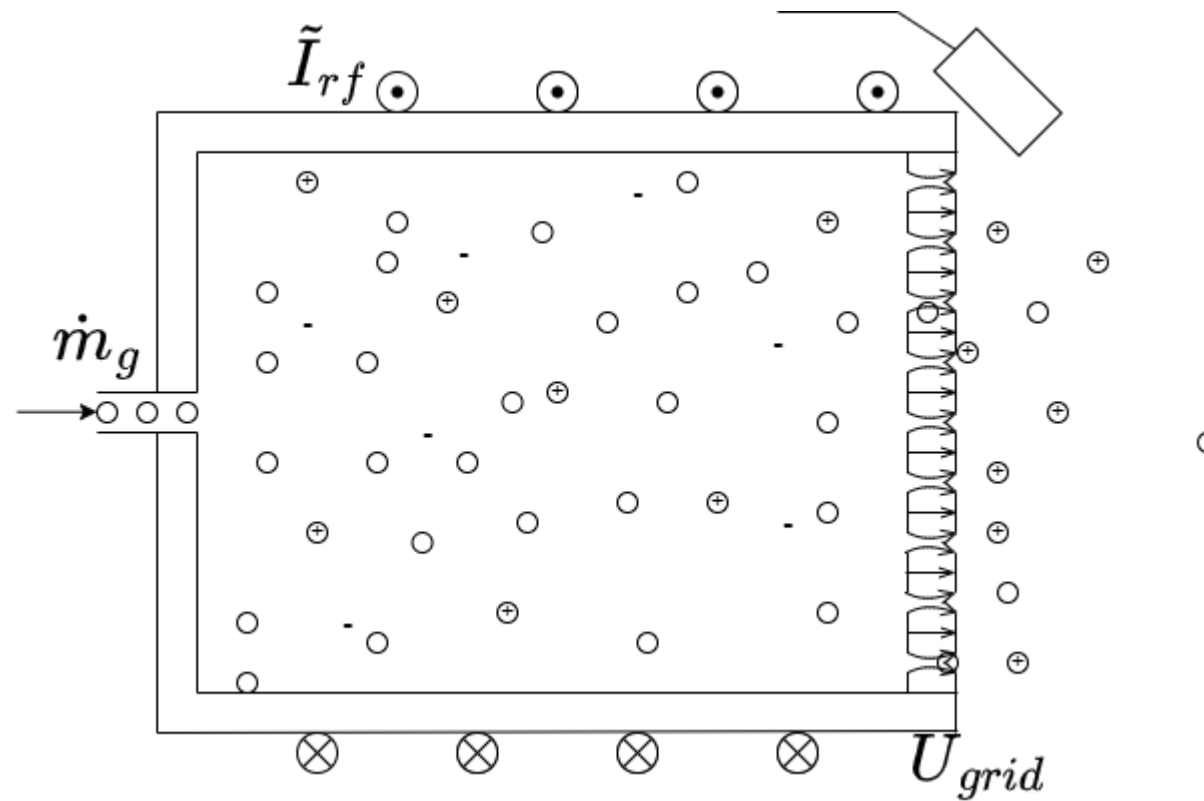


Radiofrequency ion thruster

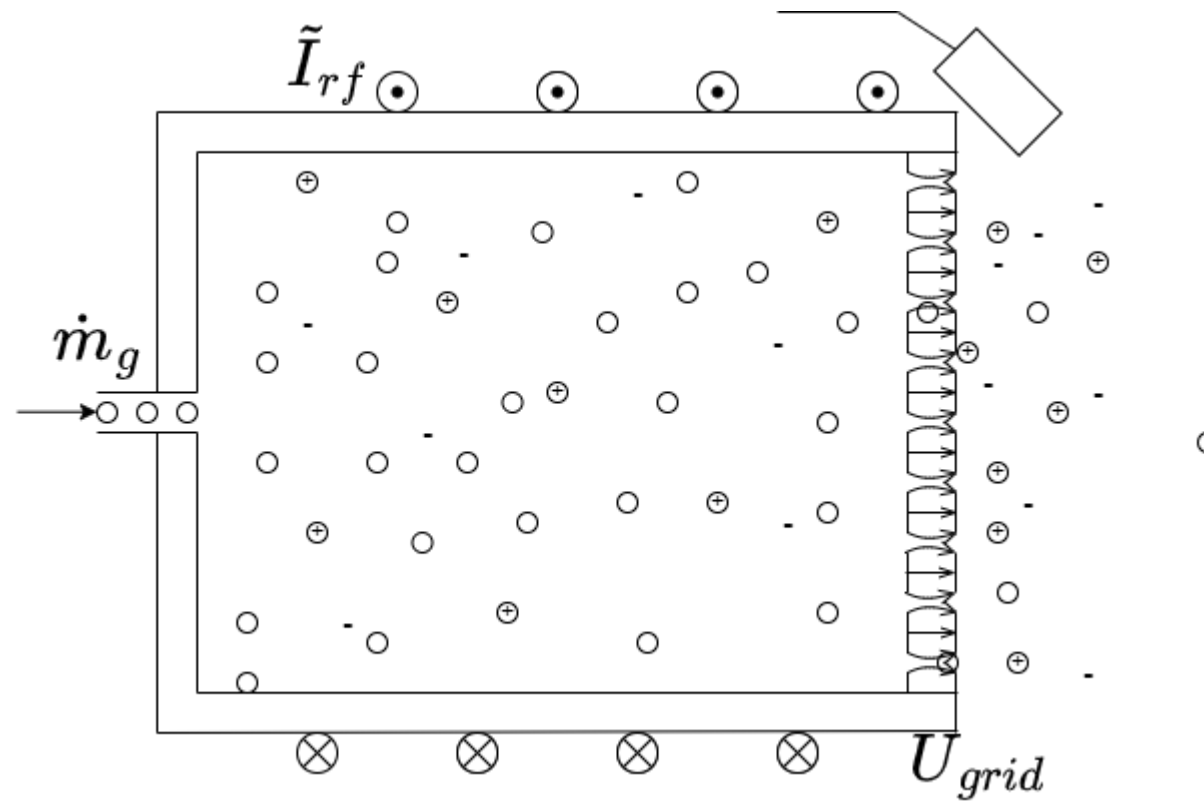




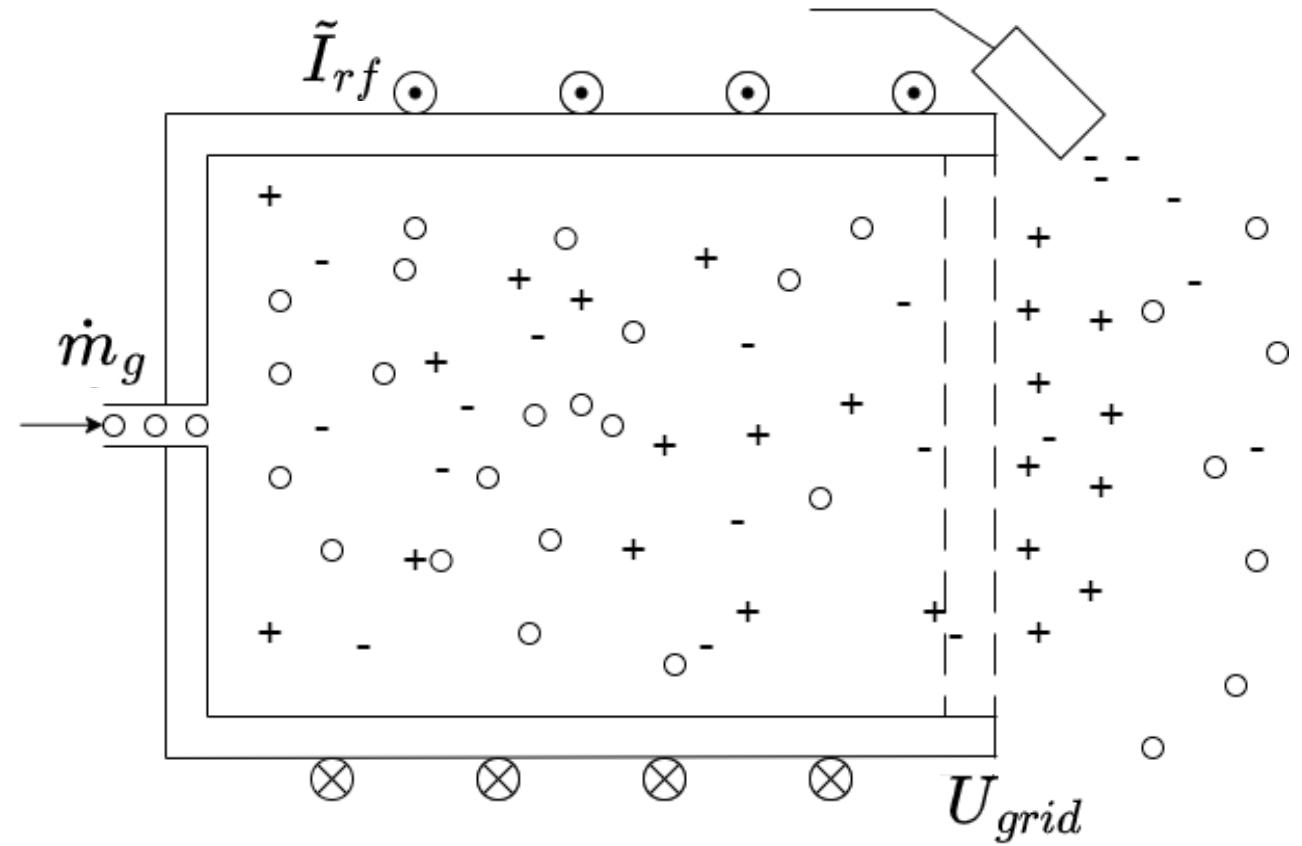
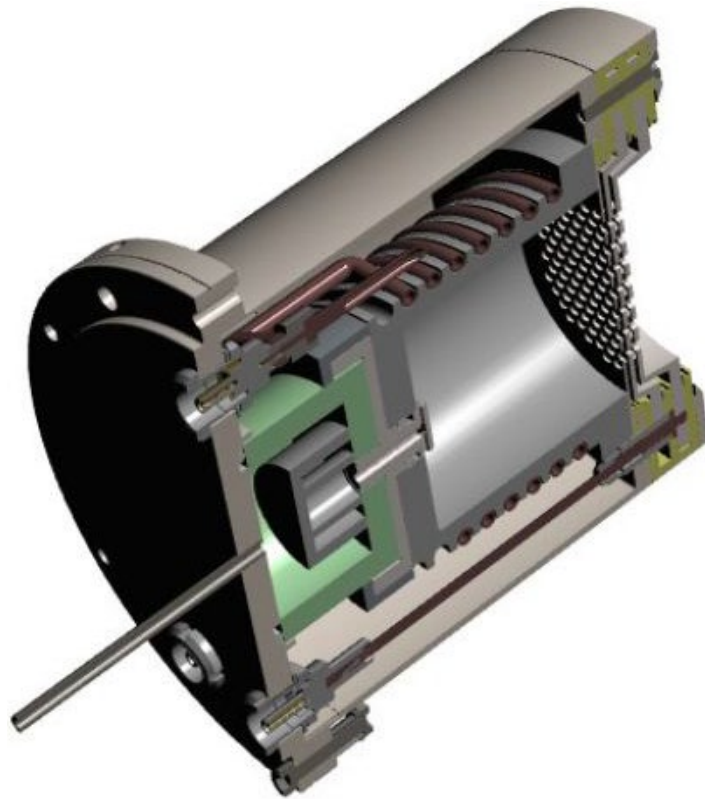


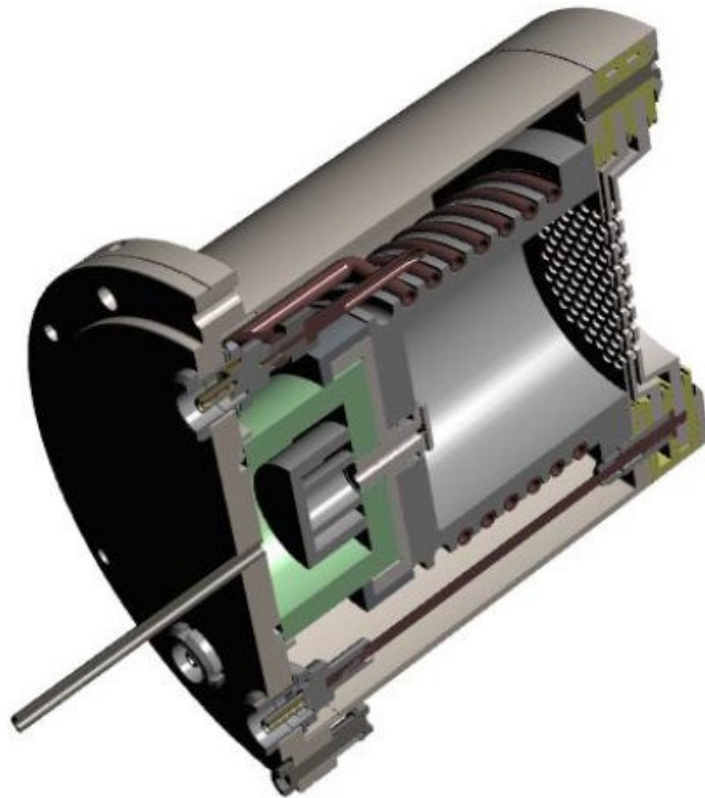


Radiofrequency ion thruster



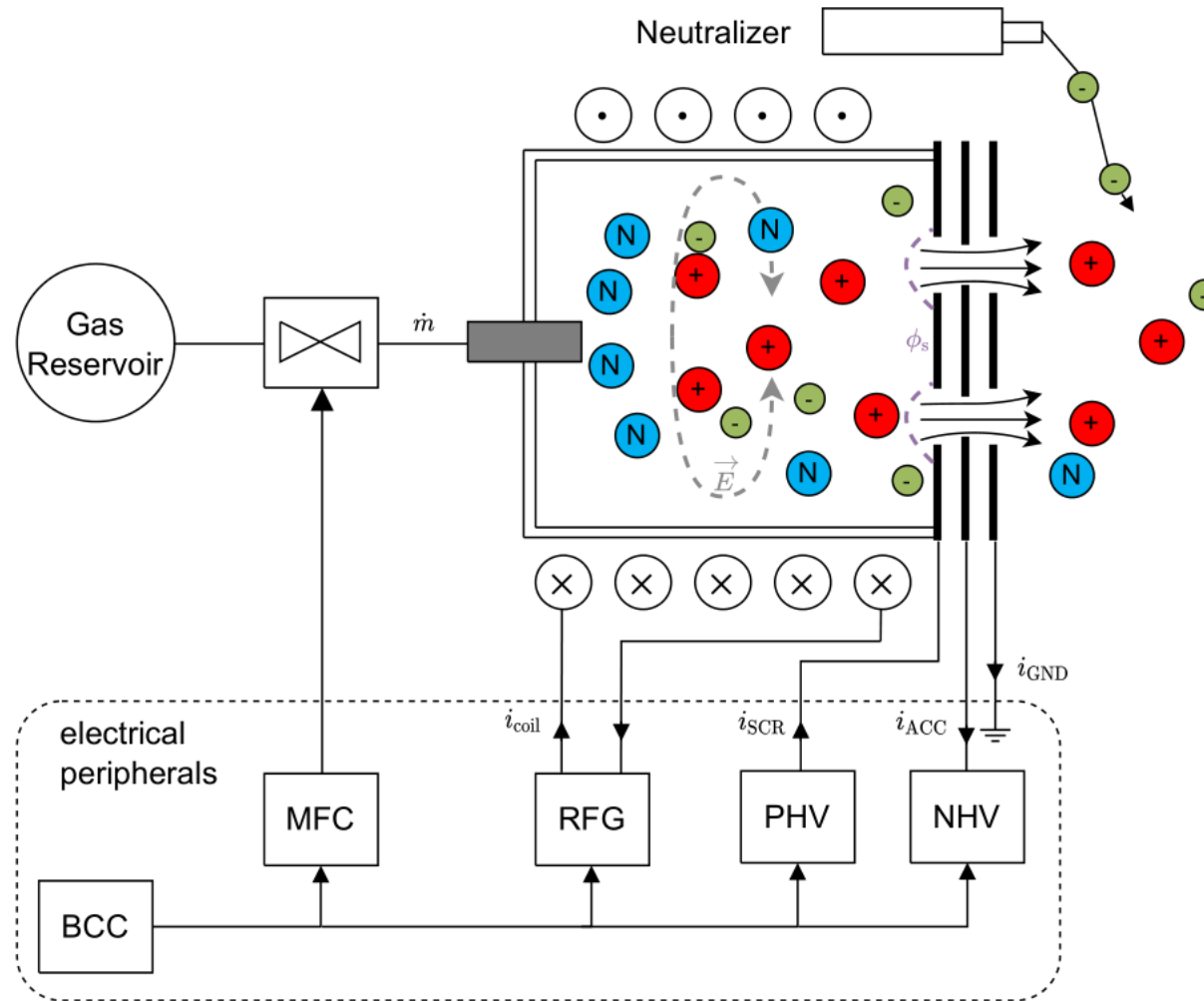
Radiofrequency ion thruster (RIT)



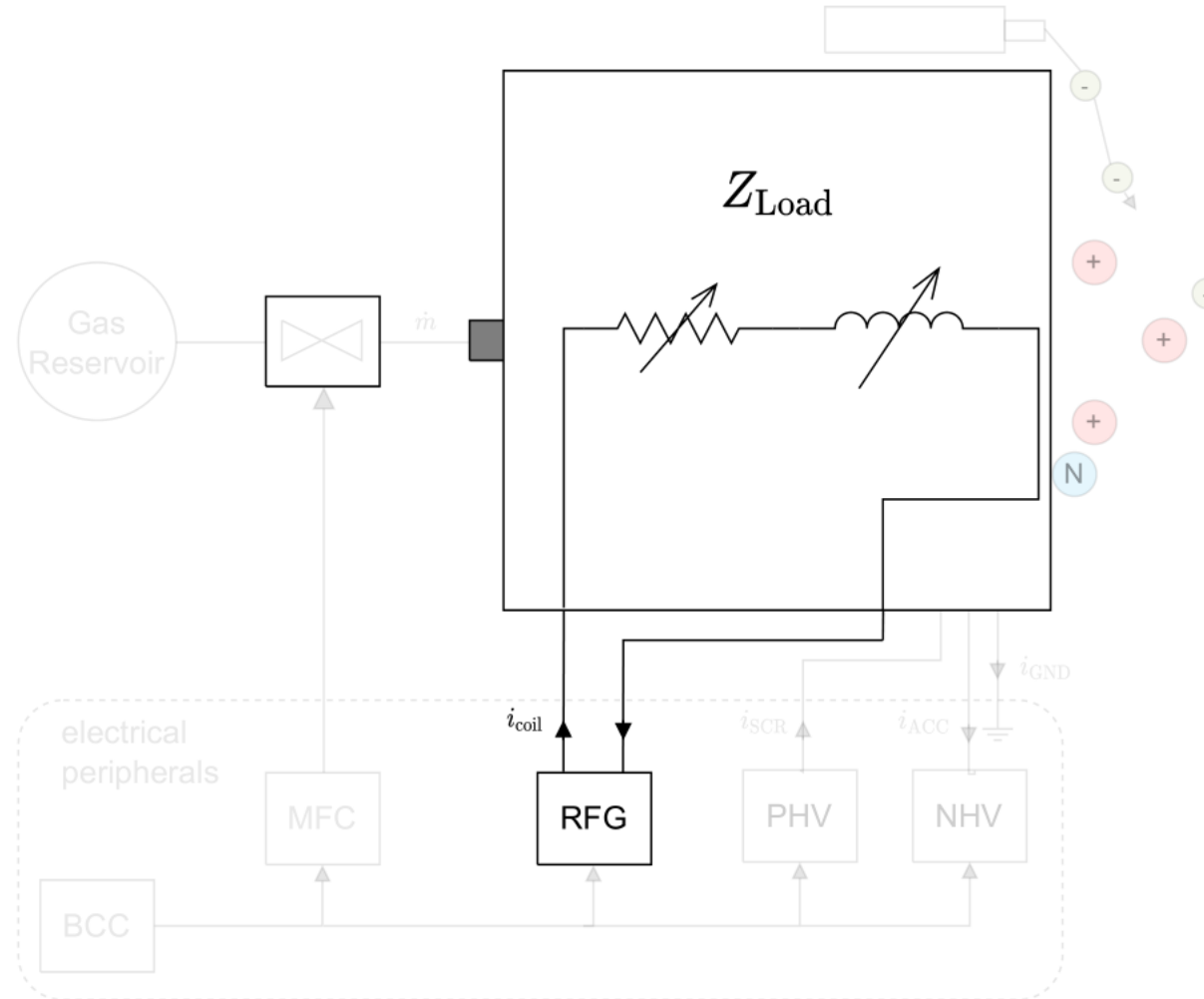


property	typical value
Radius r	6 cm
Length l	7 cm
current frequency f	1 – 13.56 MHz
Power applied to coil	~ 200 W
Propellant type	Xe (Ar) / iodine
mass flow Q_0/m_g	1-15 sccm

Why modeling?



Why modeling?



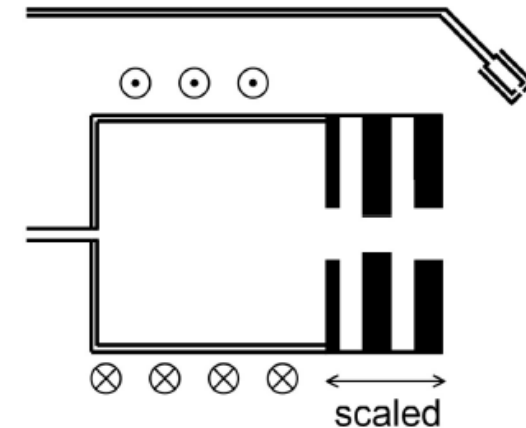
Simulation Objectives

Modelling and simulation of a radio-frequency ion engine (RIT) for an 'engineering tool'

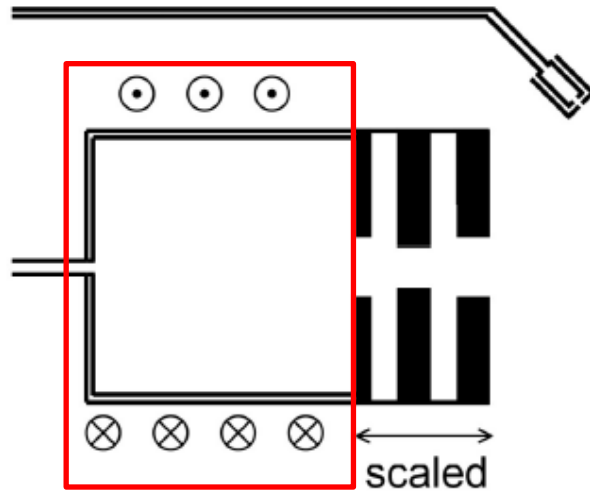


Requirements for the engineering tool

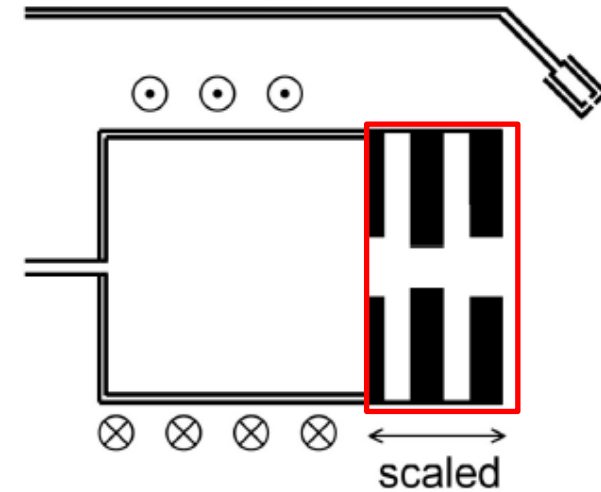
- short calculation time for each operating point (maximum of a few minutes)
- be correct
- specification of the numerical uncertainties in the results
- one simulation program
- ease of use



Modelled thruster components

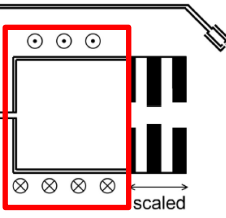


Simulation of plasma inside the discharge chamber



acceleration grid

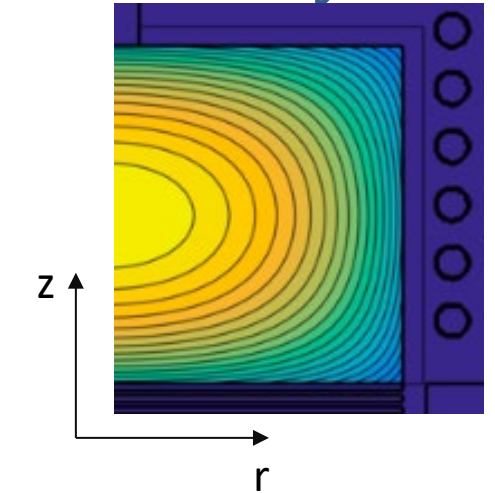
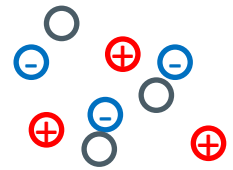
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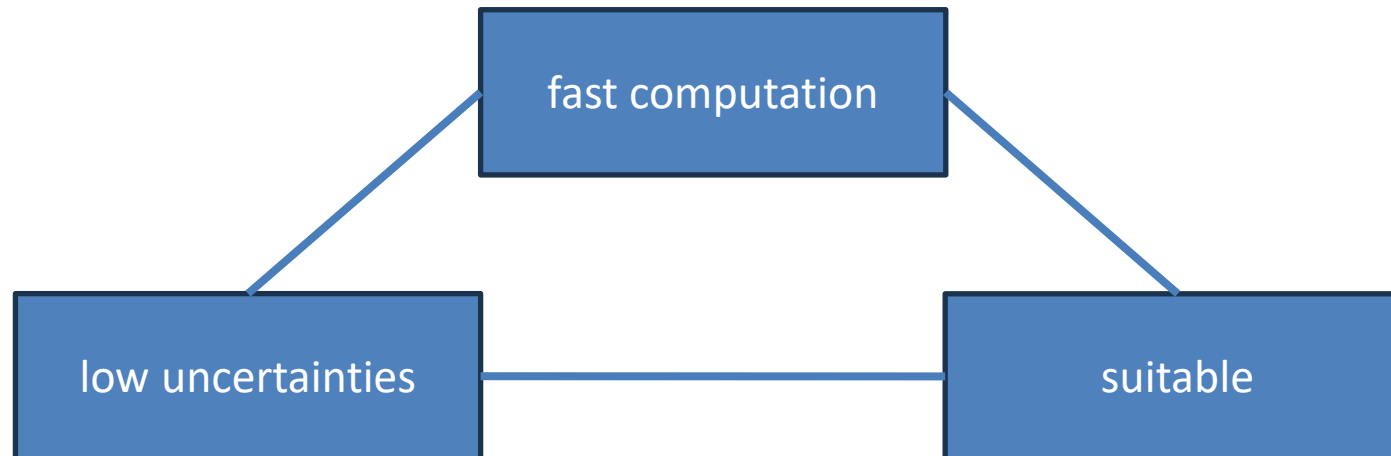
classification of plasma models:

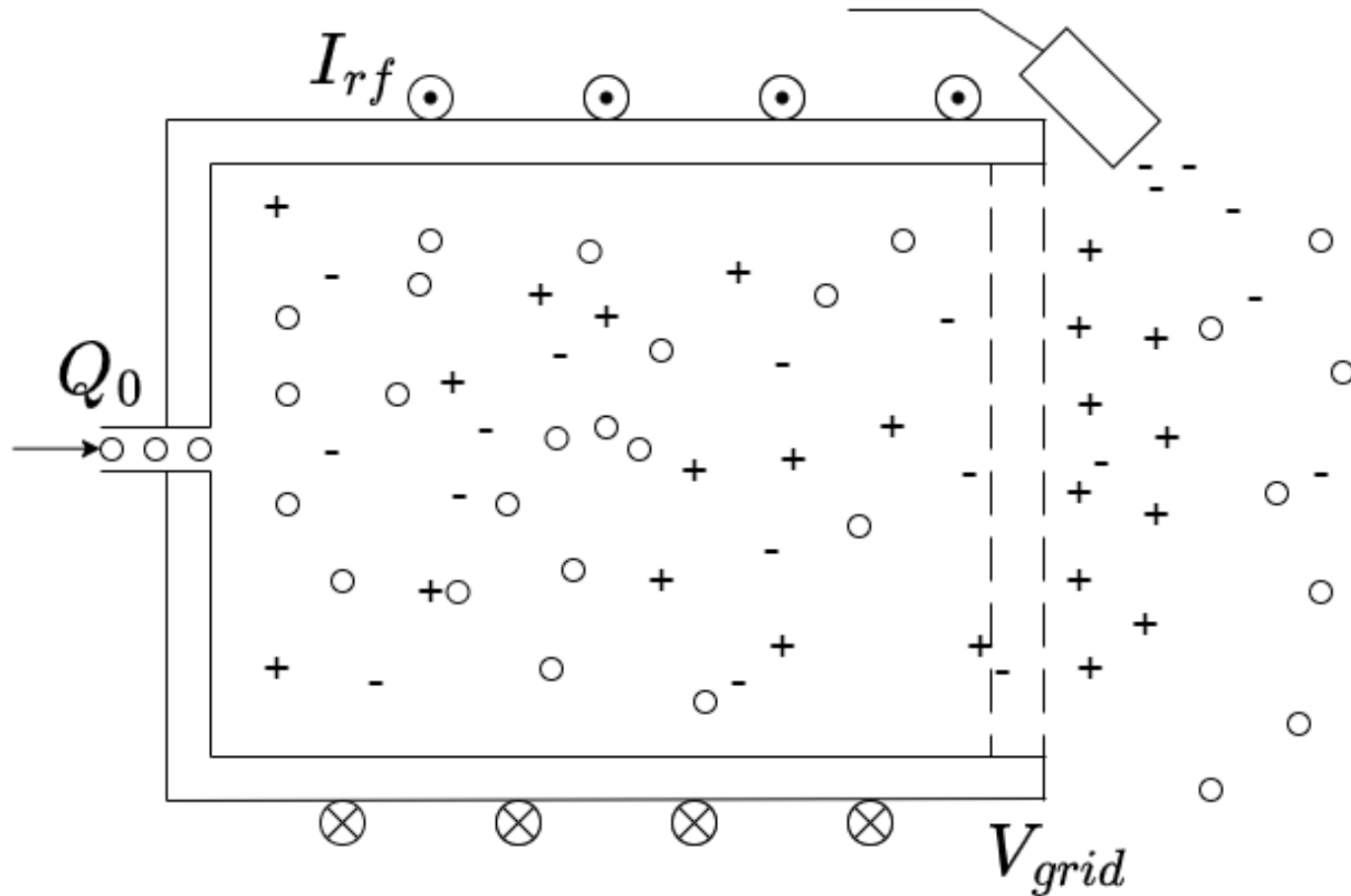
Particle based models

global models/
volume-averaged models



choose 2:





Balance equation

neutral gas particles

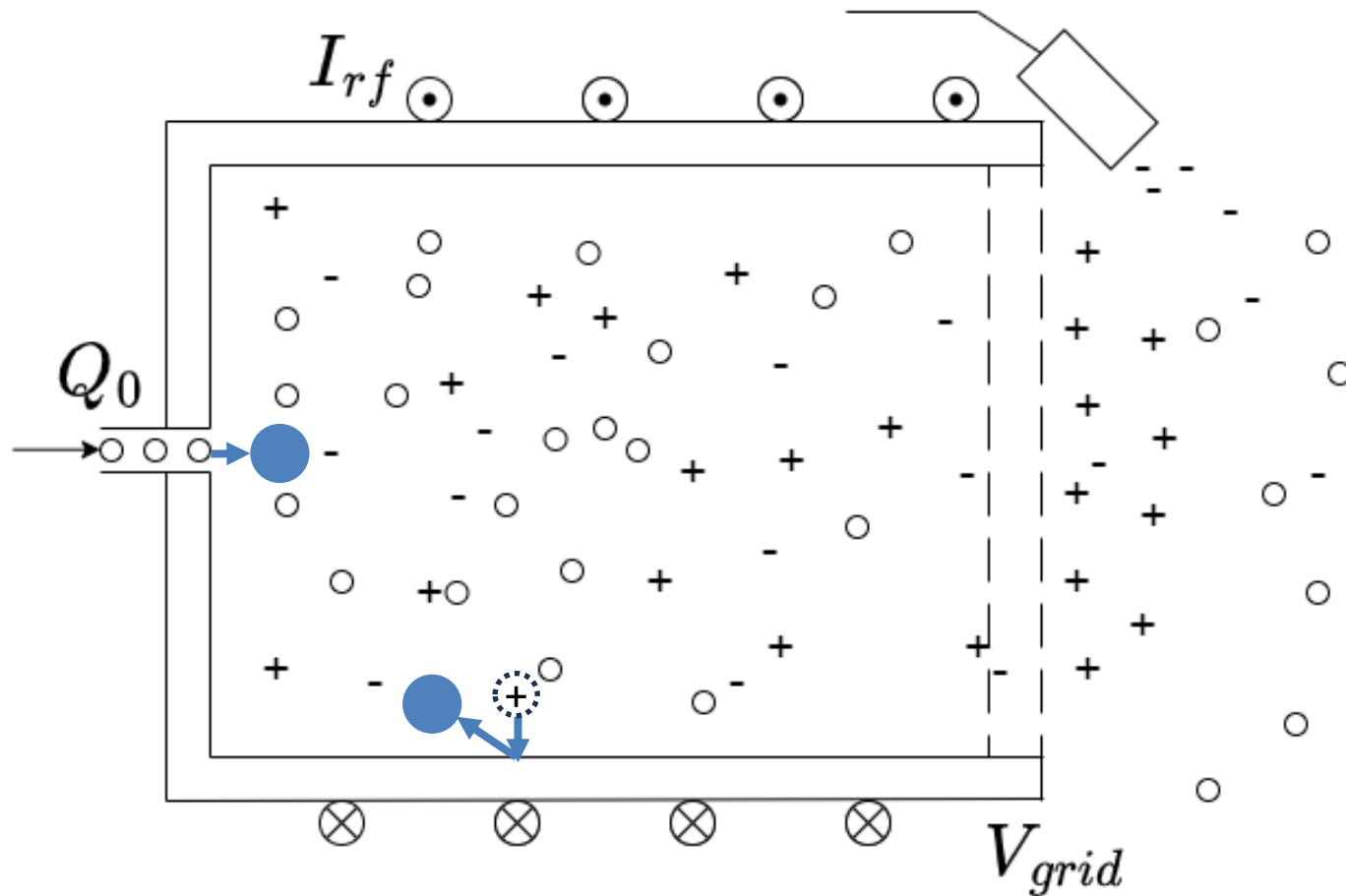
$$0 = C_{ng} - L_{ng}$$

$$0 = P_{g,abs} - P_{g,loss}$$

charged particles

$$0 = C_I - L_I$$

$$0 = P_{e,abs} - P_{e,loss}$$



Balance equation

neutral gas particles

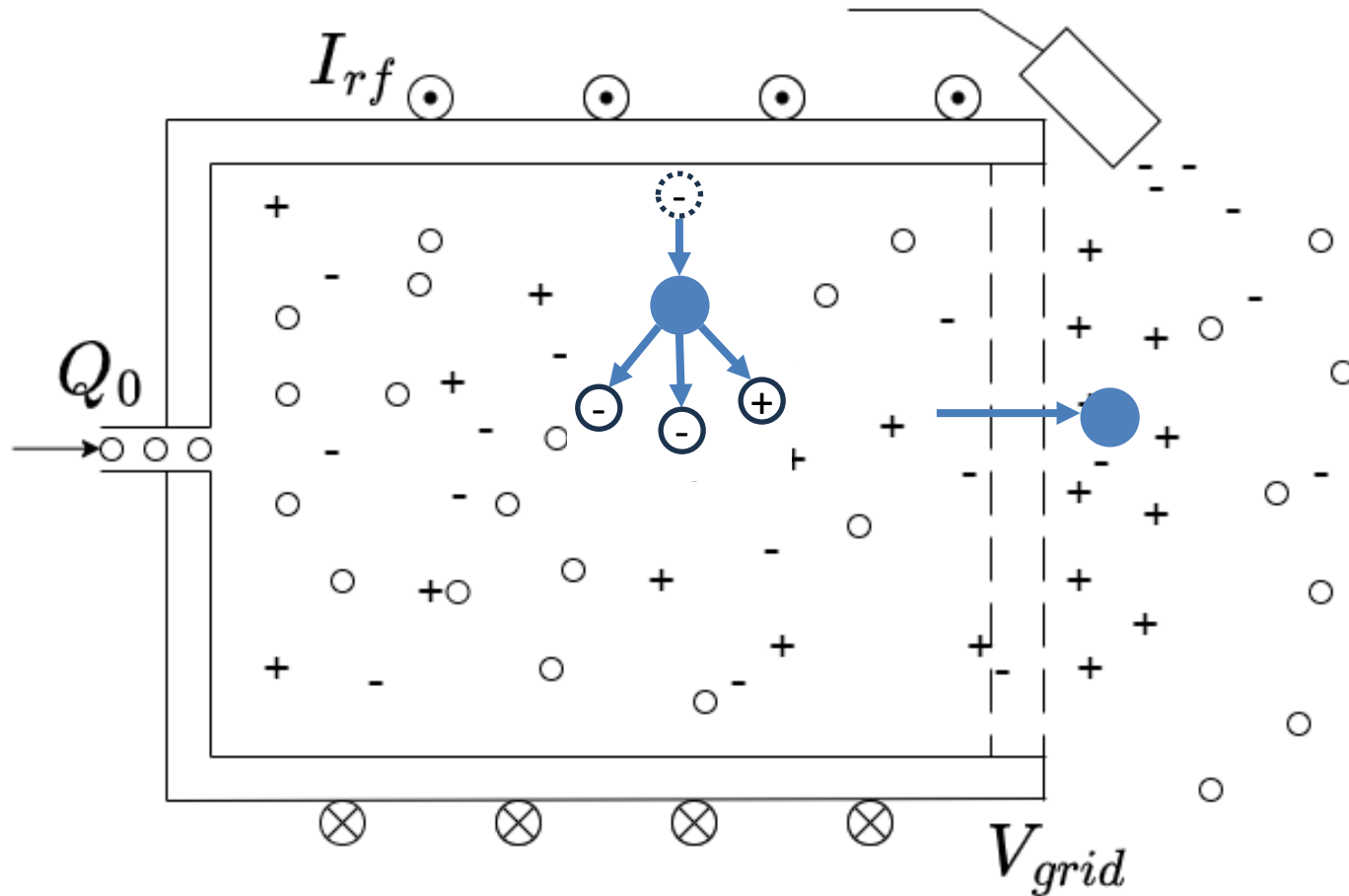
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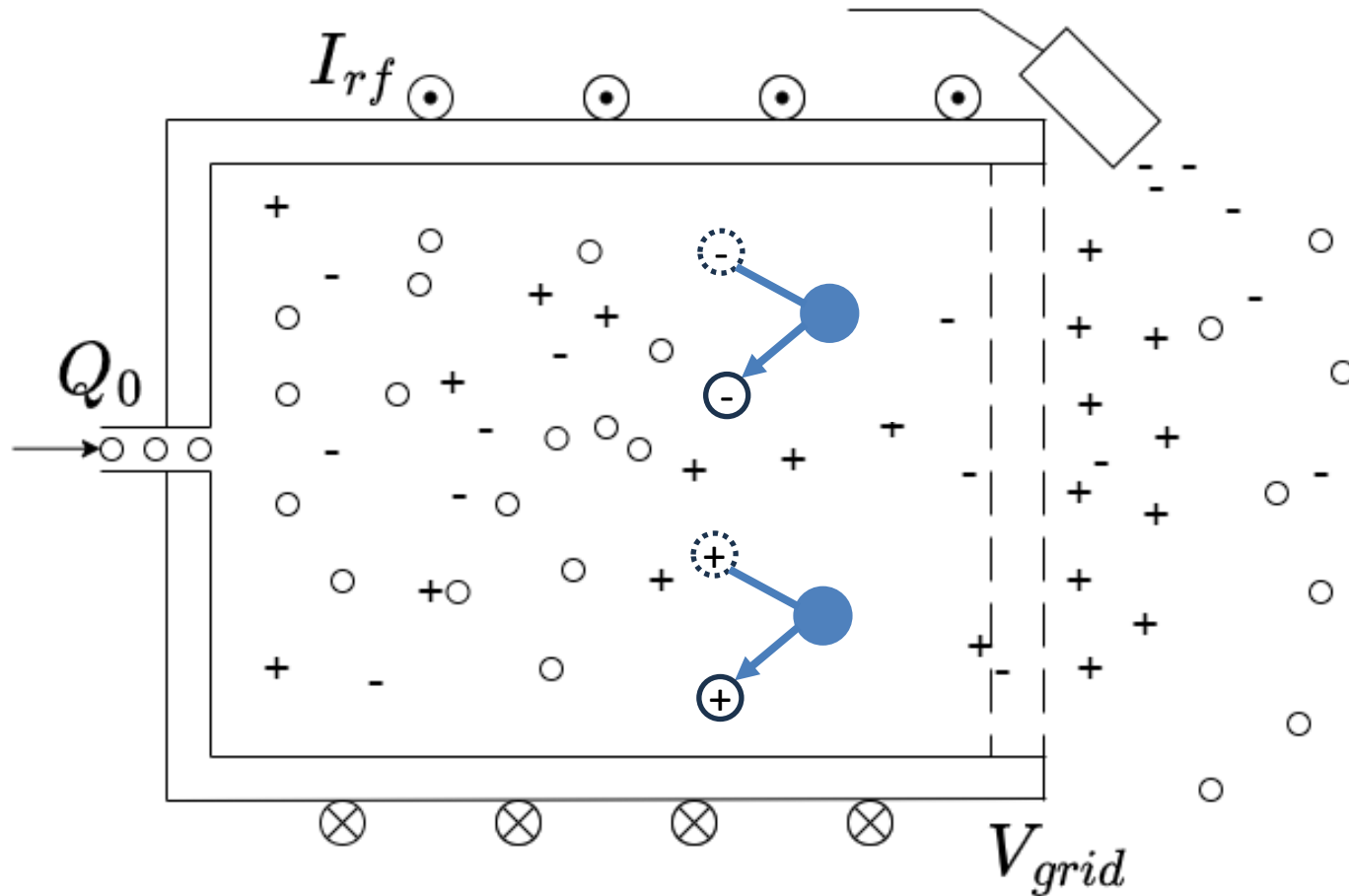
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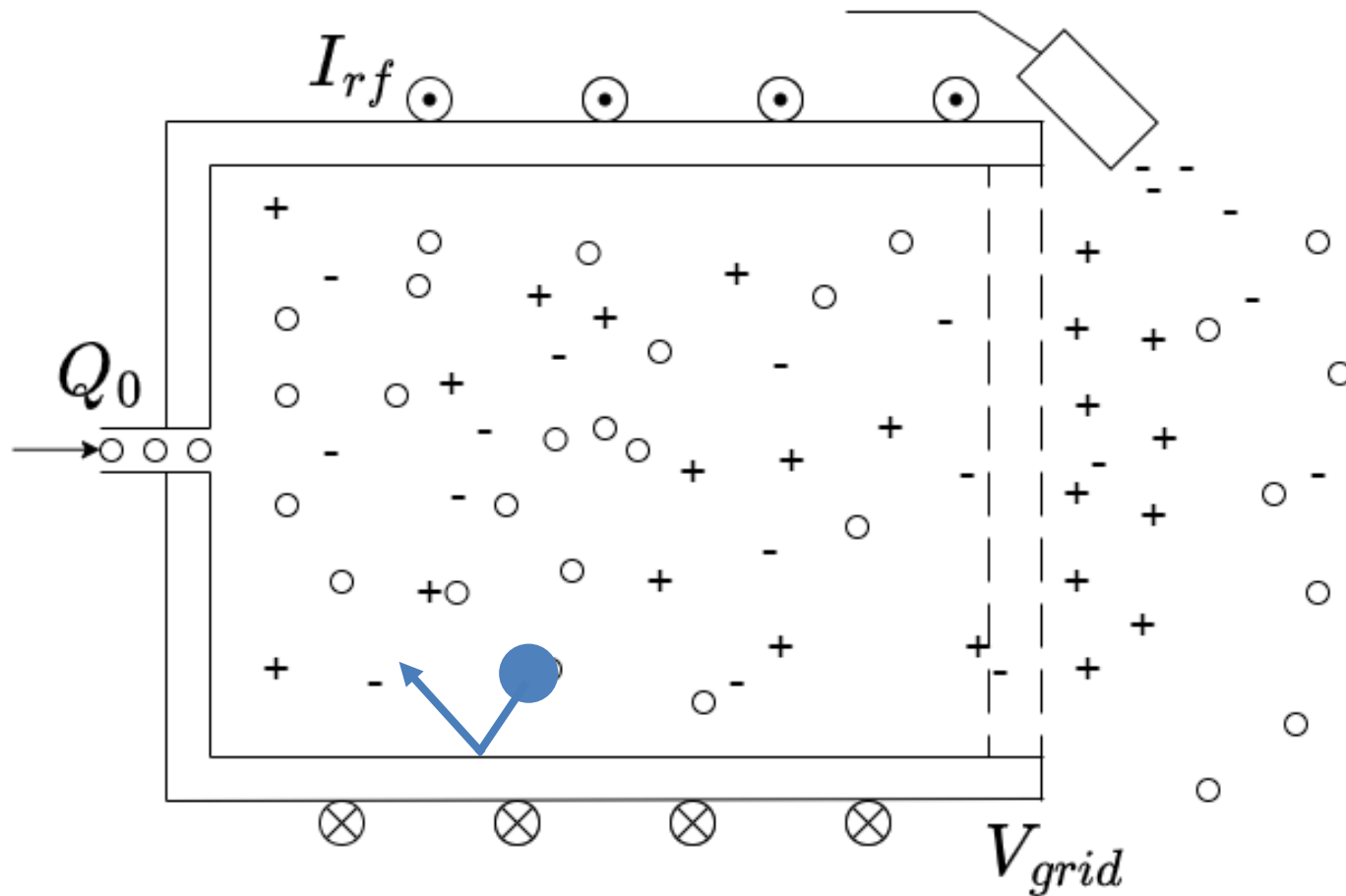
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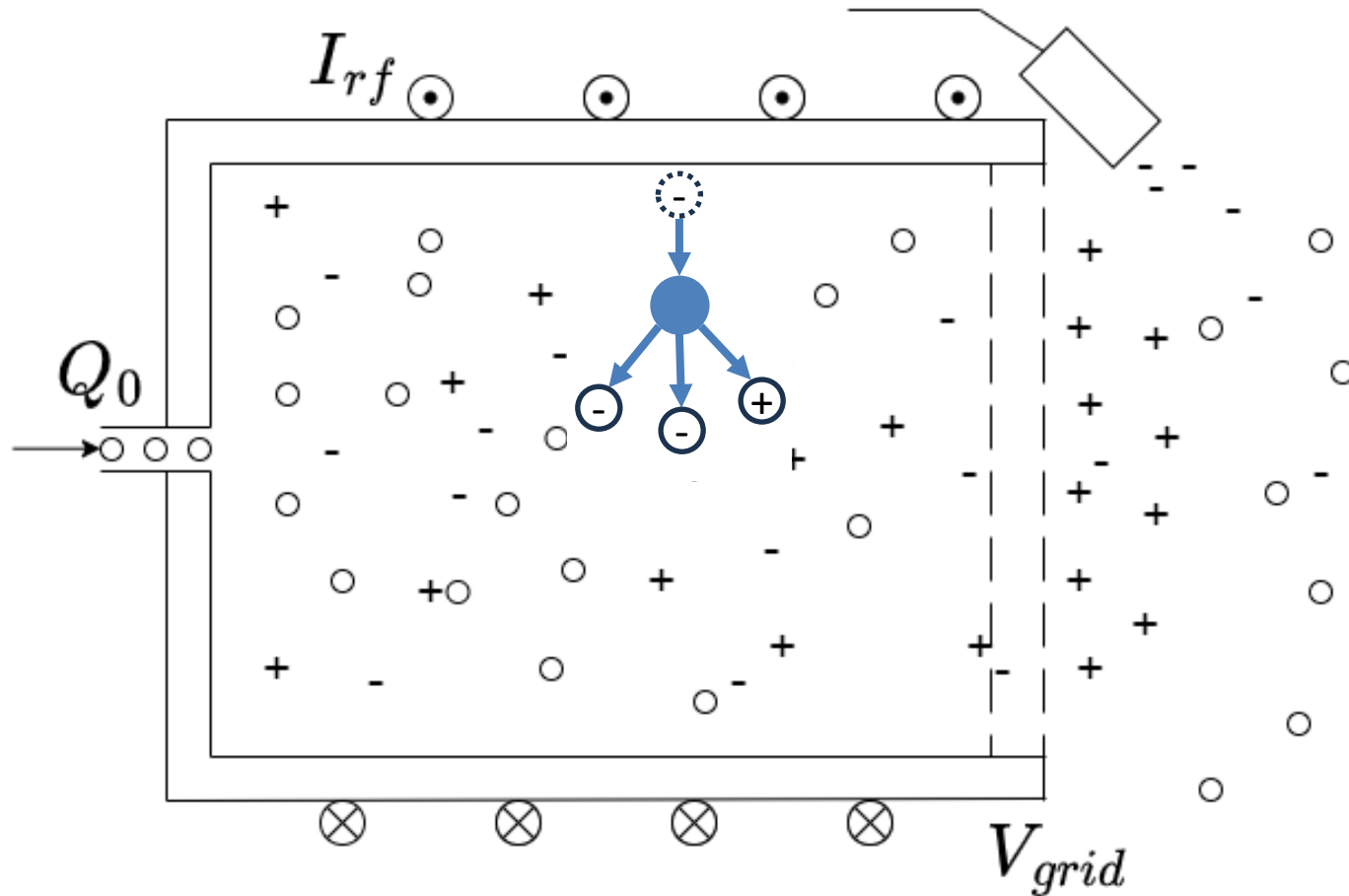
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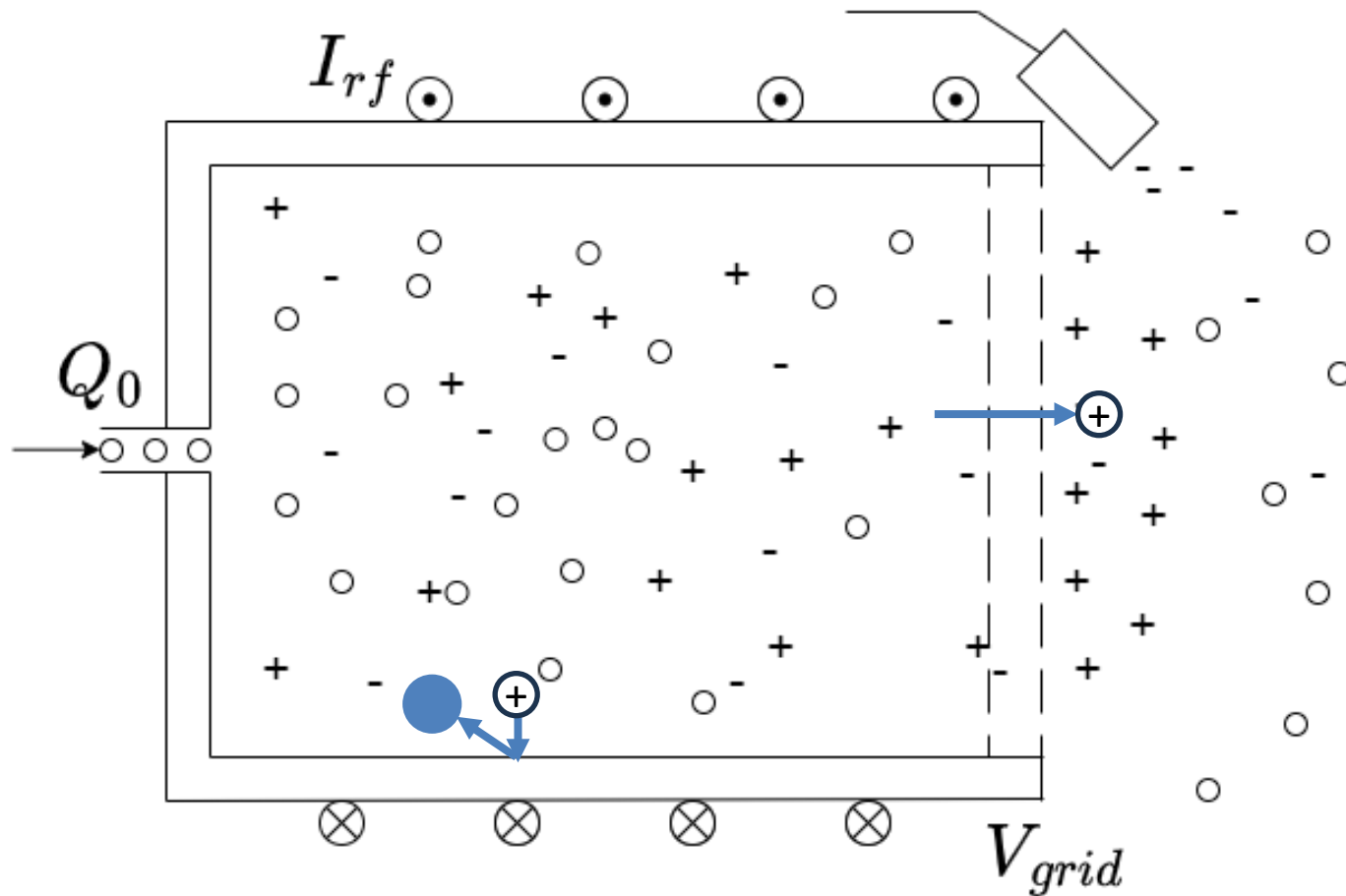
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Balance equation

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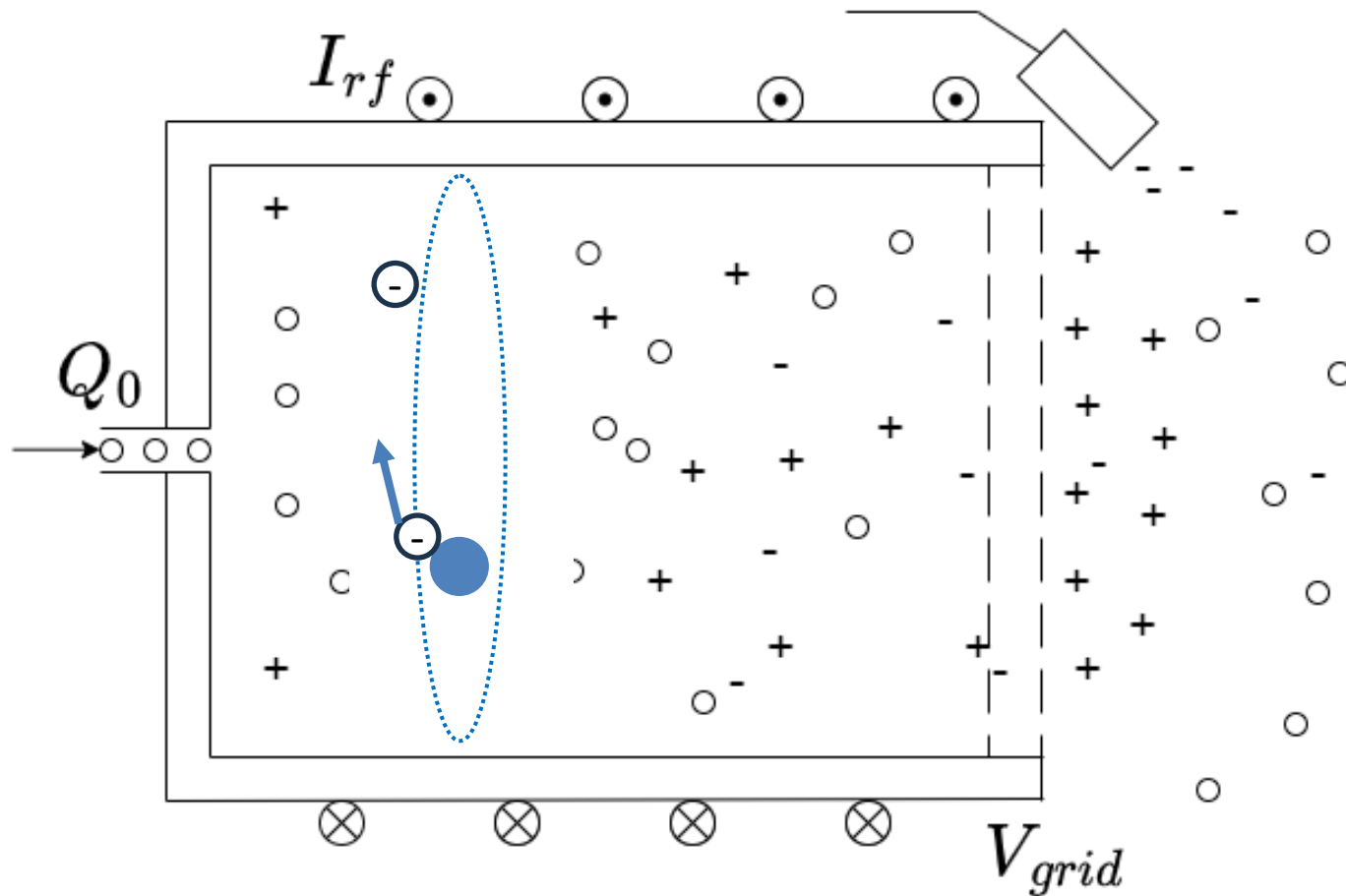
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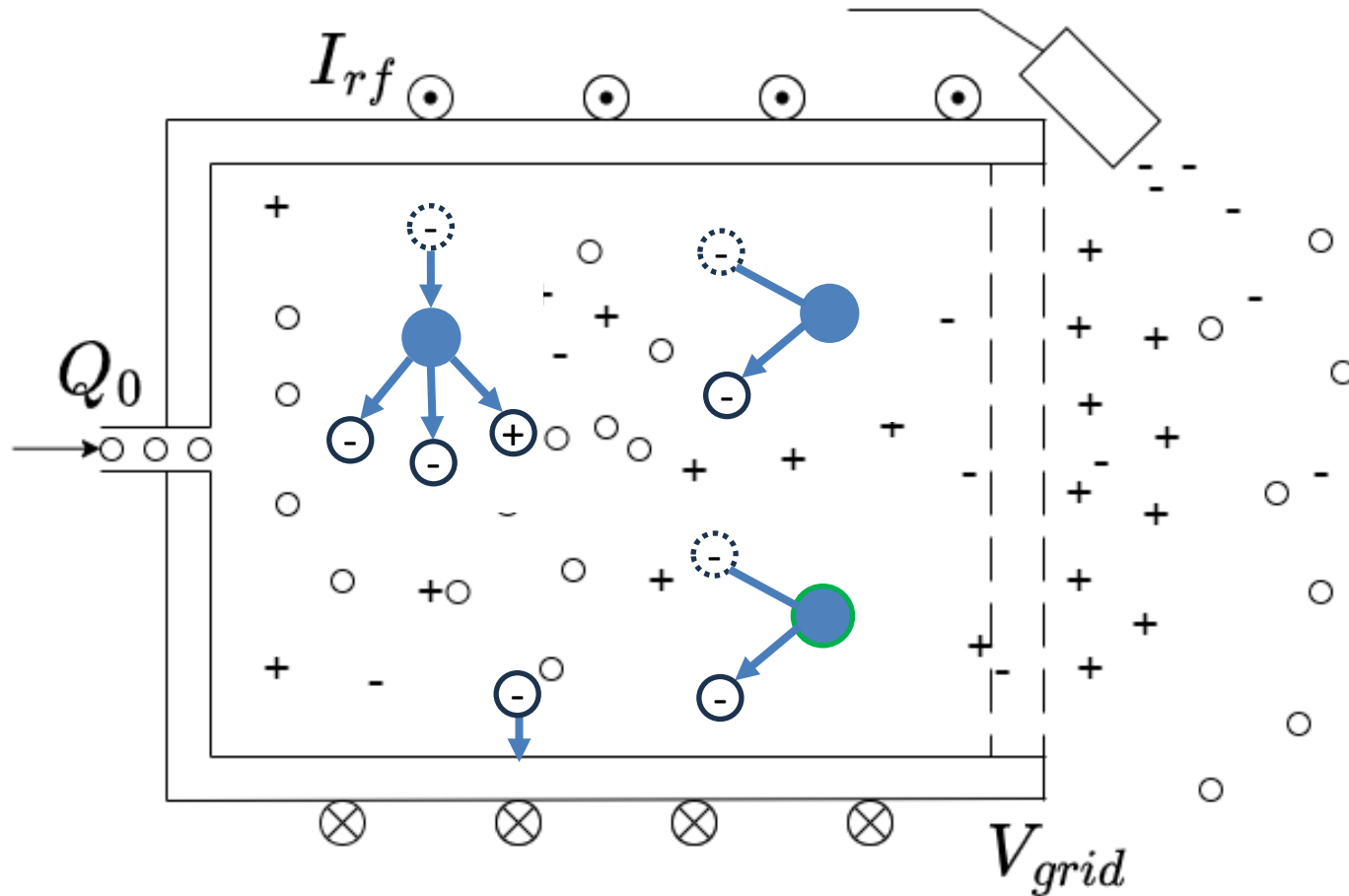
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Balance equation

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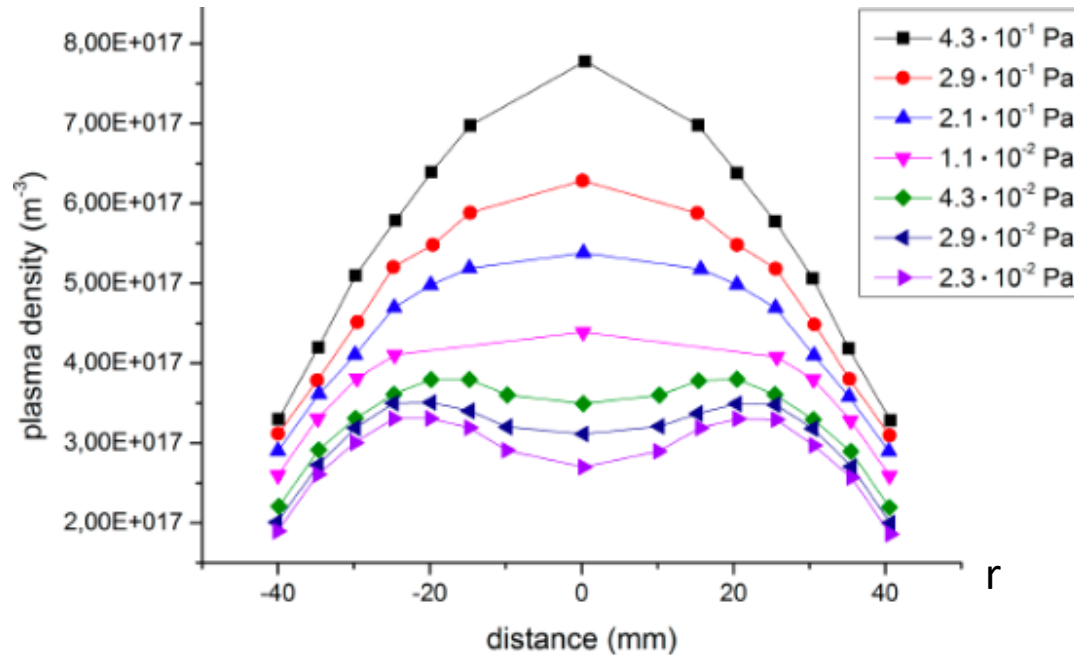
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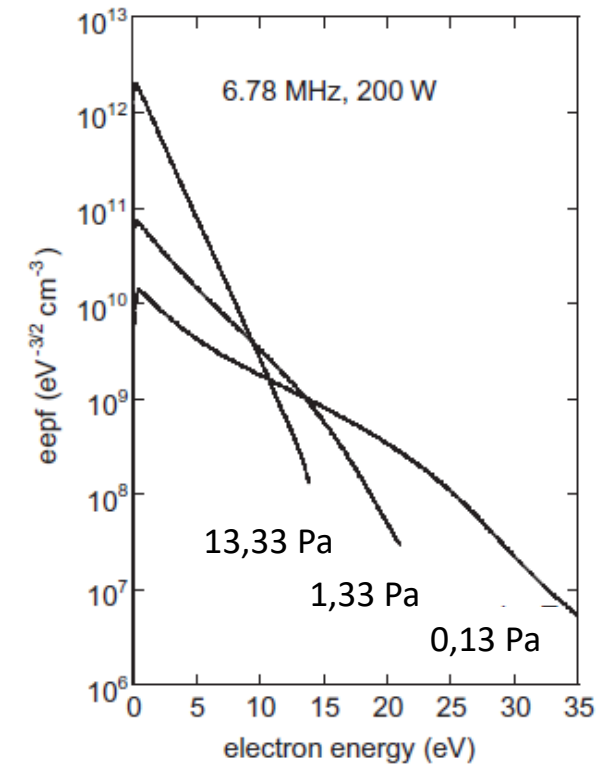
Assumptions in volume averaged models

Two key assumptions are required for the calculation of the volume-weighted model:

plasma potential



Electron energy distribution function



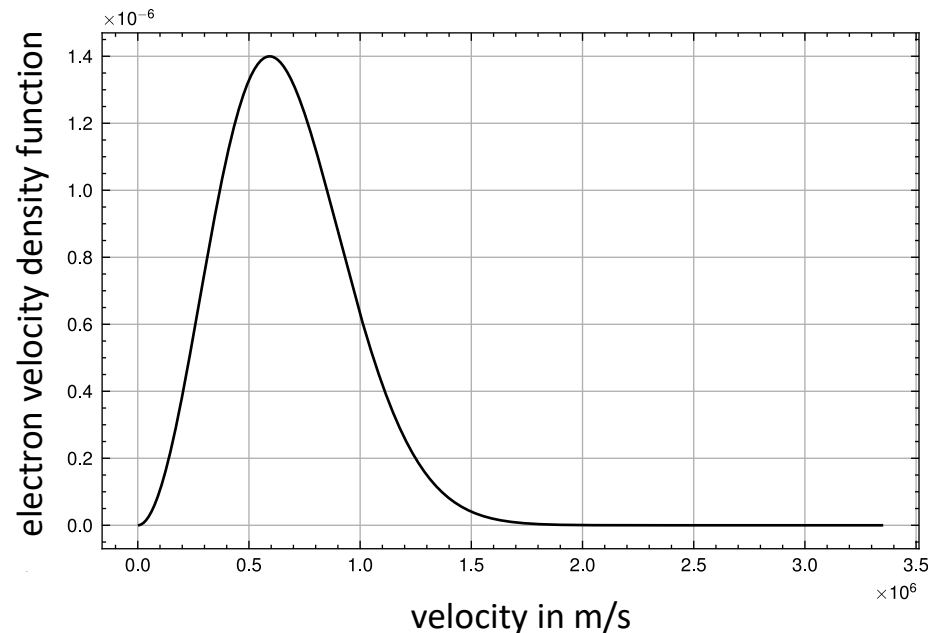
M.Schäfer: Plasmadiagnostik und Energiebilanzuntersuchung an dem HR-Ionentriebwerk RIT 10 (1971)

V A Godyak, R B Piejak and B M Alexandrovich; Electron energy distribution function measurements and plasma parameters in inductively coupled argon plasma, 2002

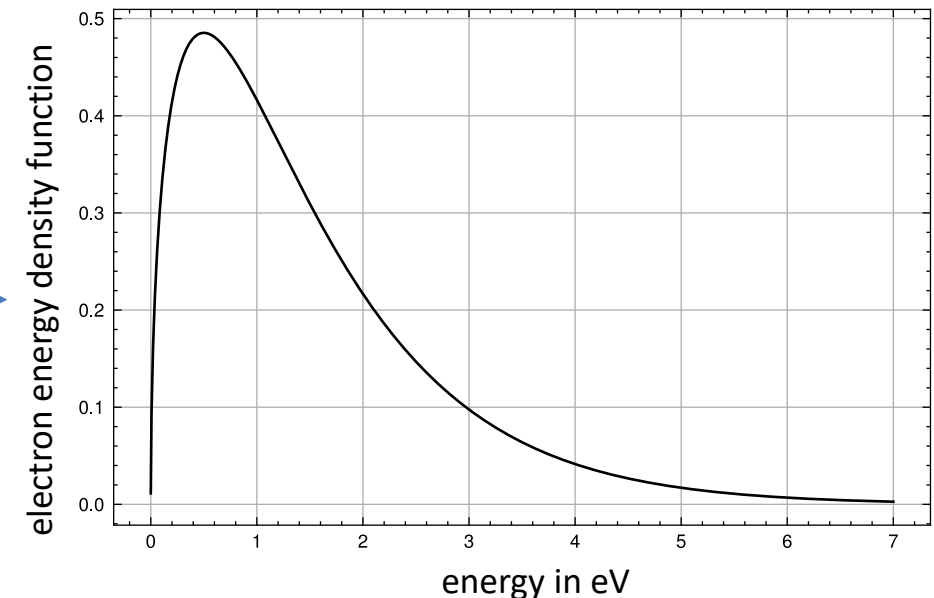
Electron Energy Distribution Function (EEDF)

A distribution function determines how a physical property (velocity, energy, momentum) is distributed within a collection of particles

In plasma physics, the velocity or energy distribution function of the electrons is required to calculate processes within the plasma



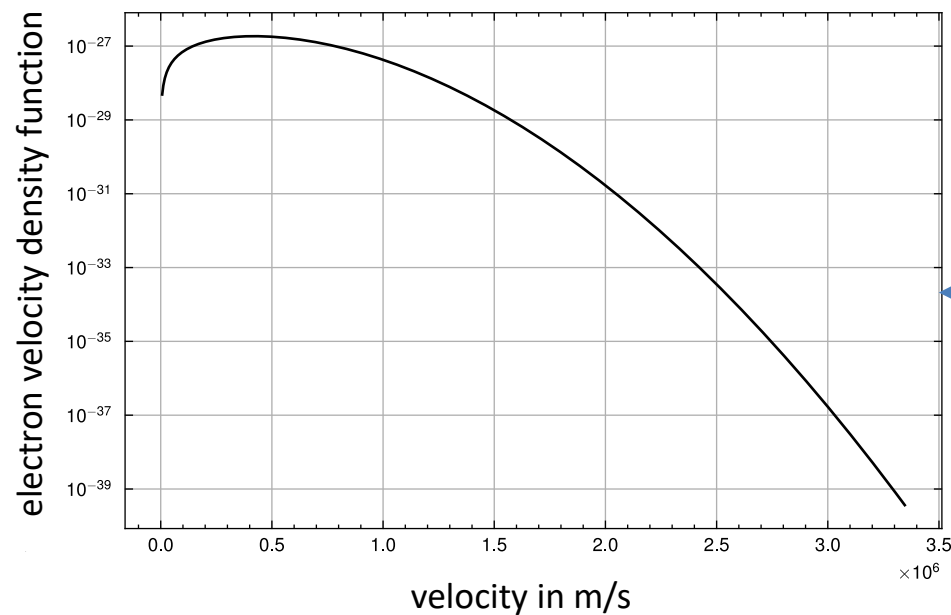
interchangable 



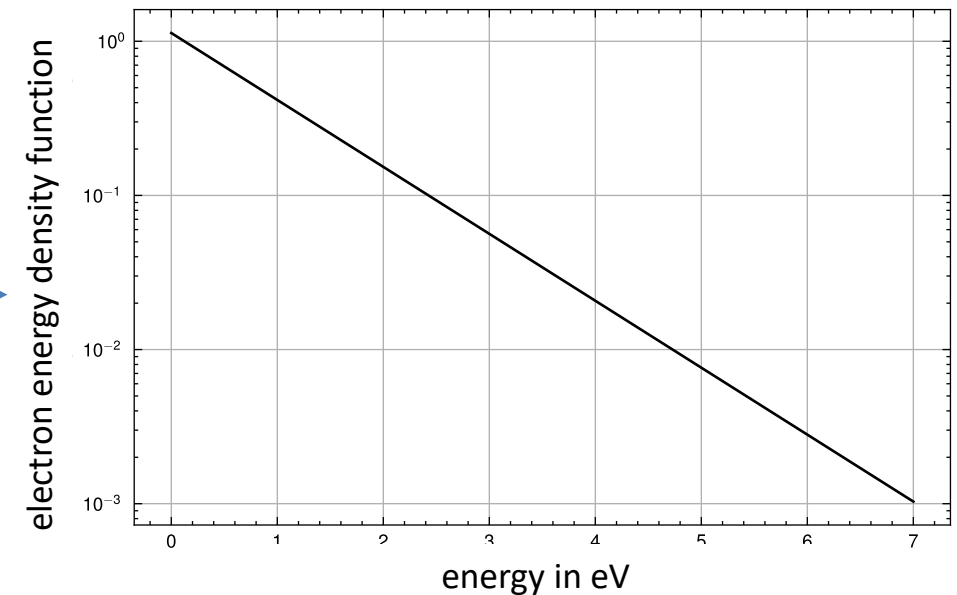
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interchangable



$$f(\varepsilon) = c_1 \varepsilon^{1/2} \exp(-c_2 \varepsilon^x)$$

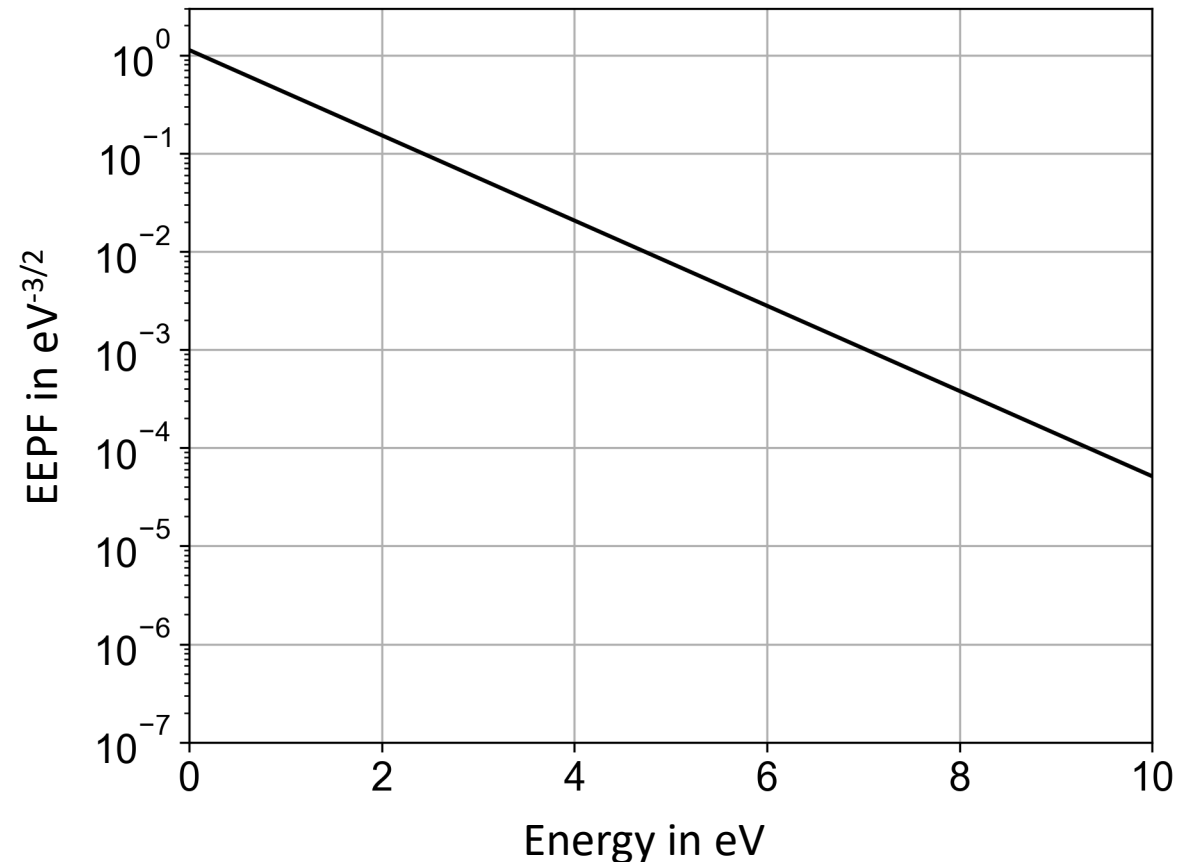
Adjustment of c_1, c_2 :

1) Same temperature:

$$\langle \varepsilon \rangle = \frac{3}{2} k_b T_{eff}$$

2) Same normalisation

Shape of EEPF



$$f(\varepsilon) = c_1 \varepsilon^{1/2} \exp(-c_2 \varepsilon^x)$$

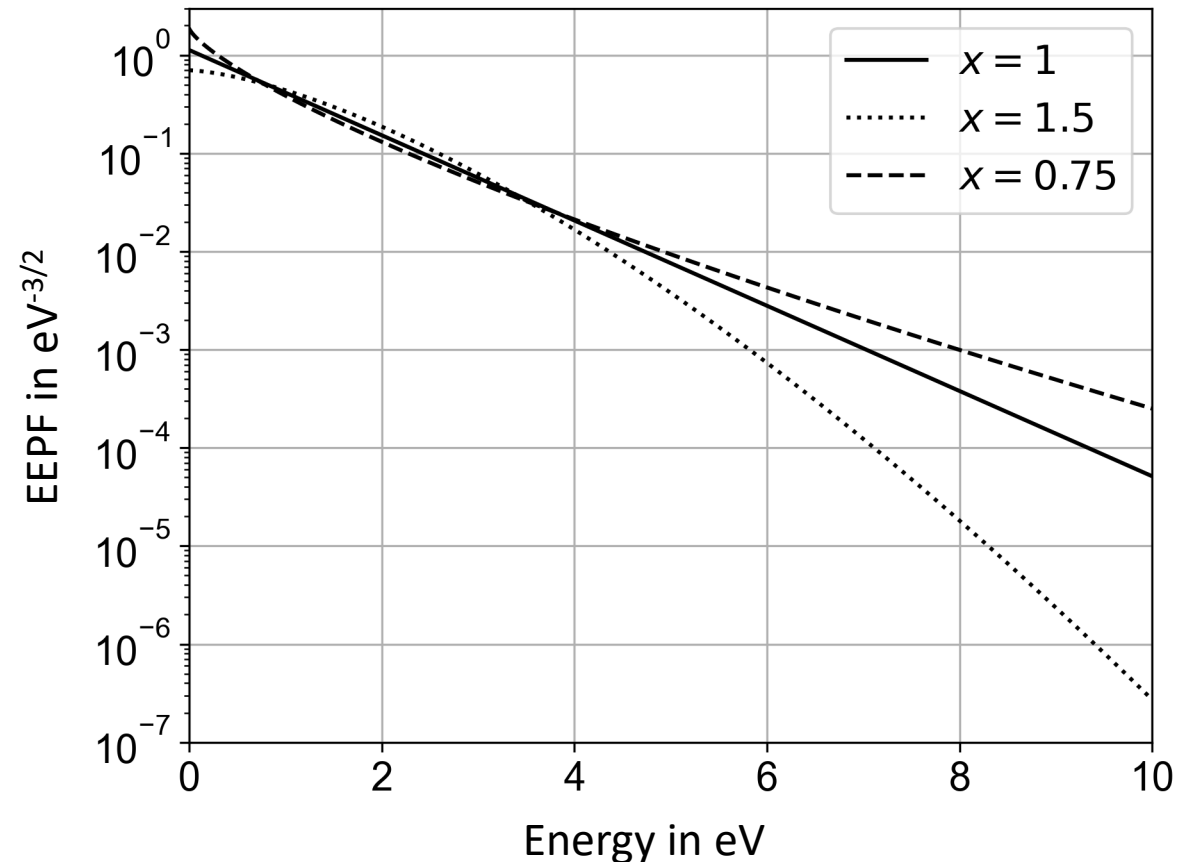
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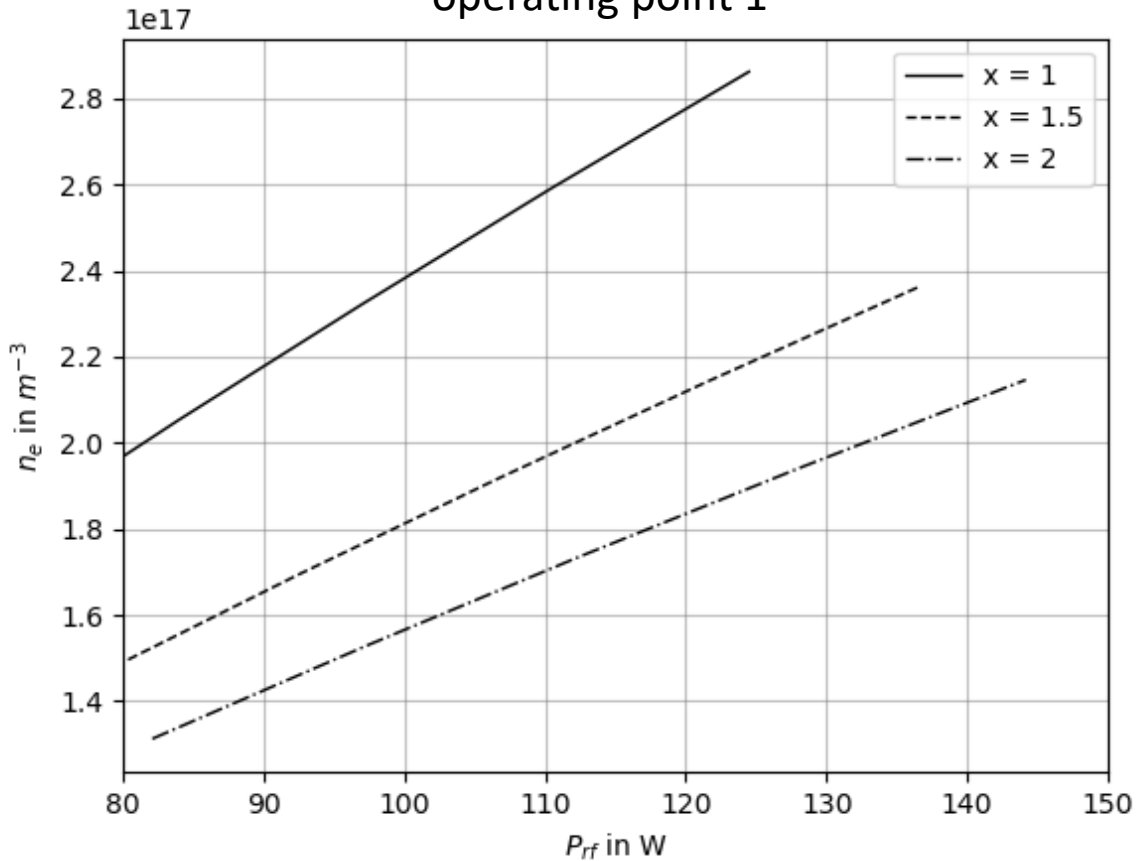
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Shape of EEPF

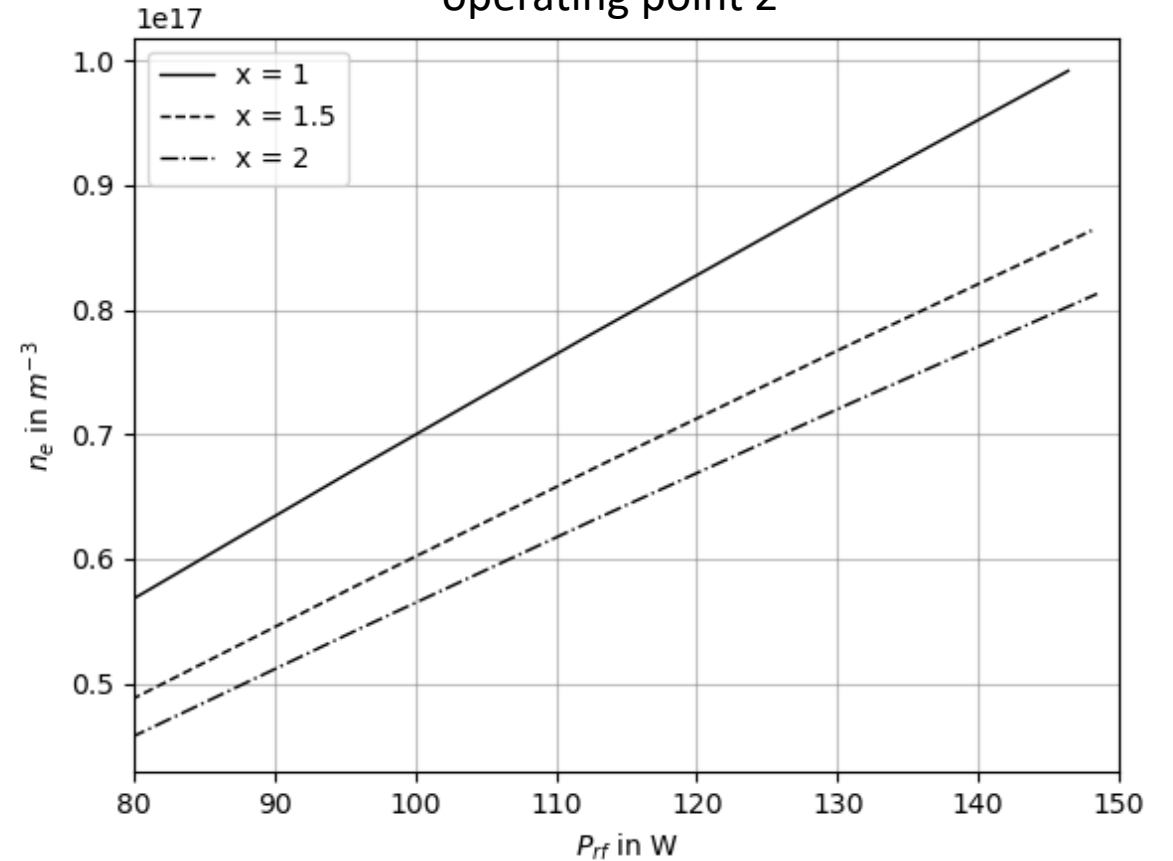


Volume averaged plasma density

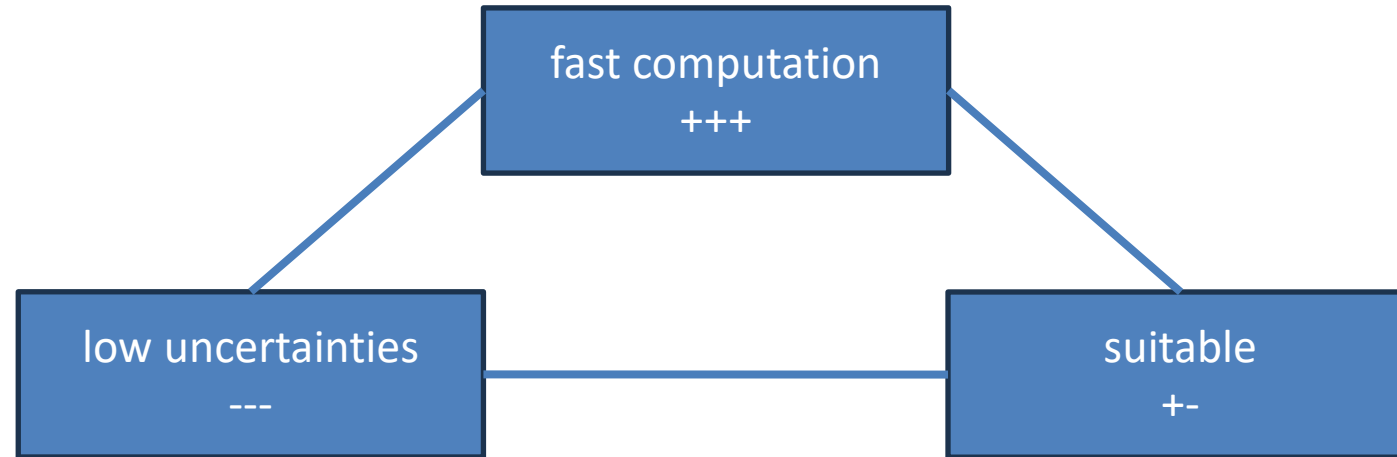
operating point 1



operating point 2

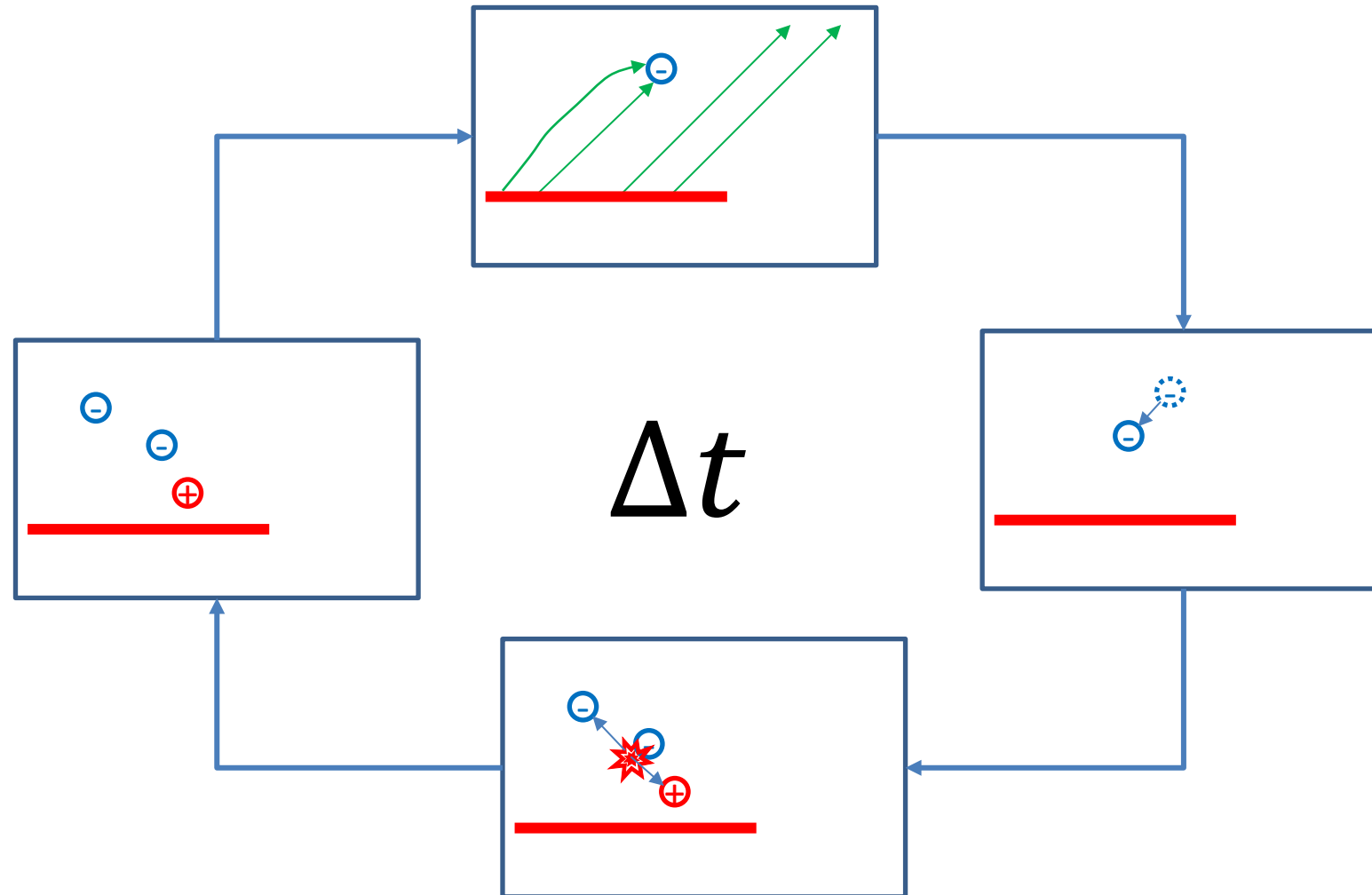


Conclusion: Plasma parameters are highly sensitive to the electron energy distribution function!

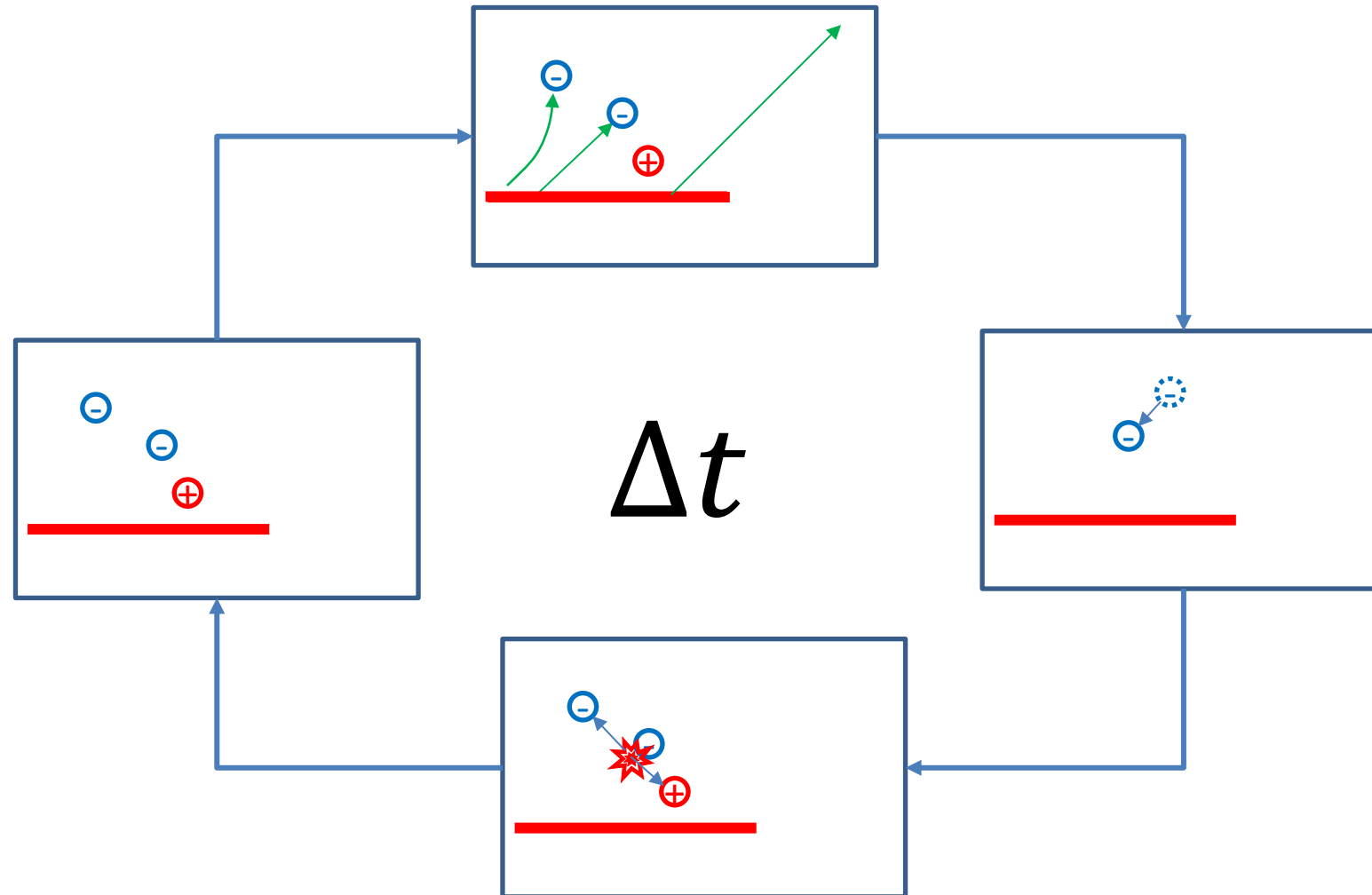


Problem: Assumptions about preconditions: Shape of EEDF?

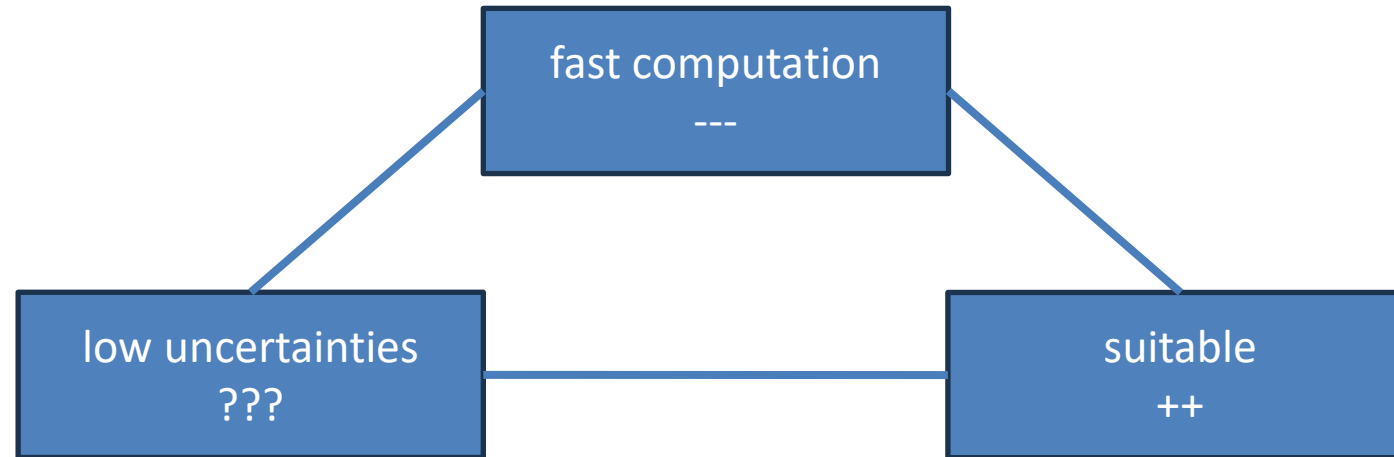
Remedy: Particle-in-Cell simulation



Remedy: Particle-in-Cell simulation



Problems with Particle-in-Cell-Models...



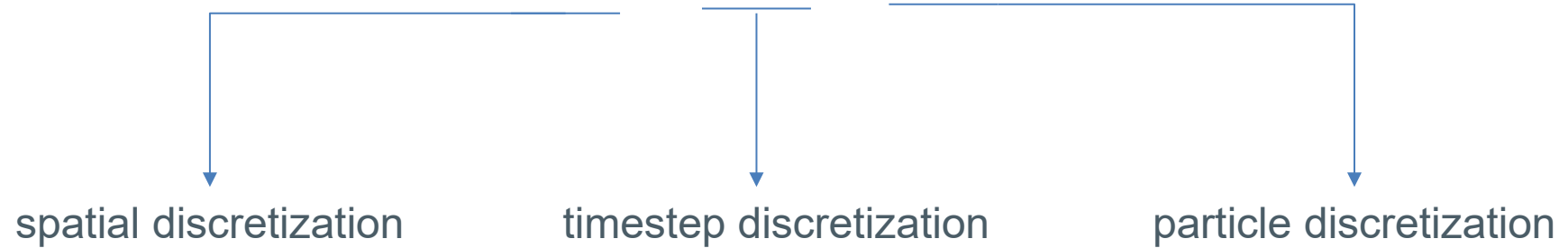
Computation depends on number of considered dimensions, simplifications, etc... (weeks, years, lifetimes)

Model is suitable for many applications

Uncertainties depend on discretisation parameters → not investigated



$$h^p = \left(\frac{\Delta x}{\Delta x_0} \right)^\alpha = \left(\frac{\Delta t}{\Delta t_0} \right)^\beta = \left(\frac{w}{w_0} \right)^\gamma$$



Terminology:

- Verification:

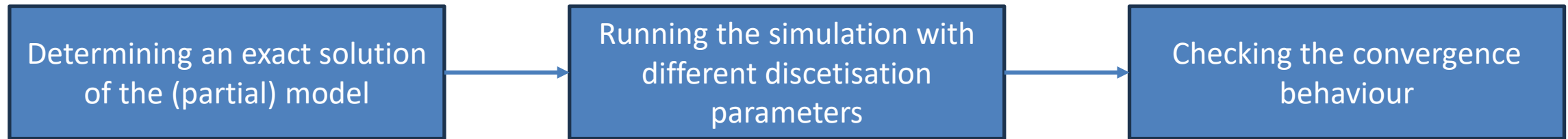
- **Code Verification:**

Does the code solve the model correctly?

- **Solution Verification:**

How large are the numerical uncertainties to the specific solution to my model?

- Validation: Does the model match the experimental observations?



However:

- Not always is an suitable exact solution possible (stochastic effects, complexity, mathematically, ...)

Example: Code Verification

Goal: Code Verification of calculation of Poisson equation

$$\nabla^2 \Phi(x) = -\frac{\rho(x)}{\epsilon_0}$$

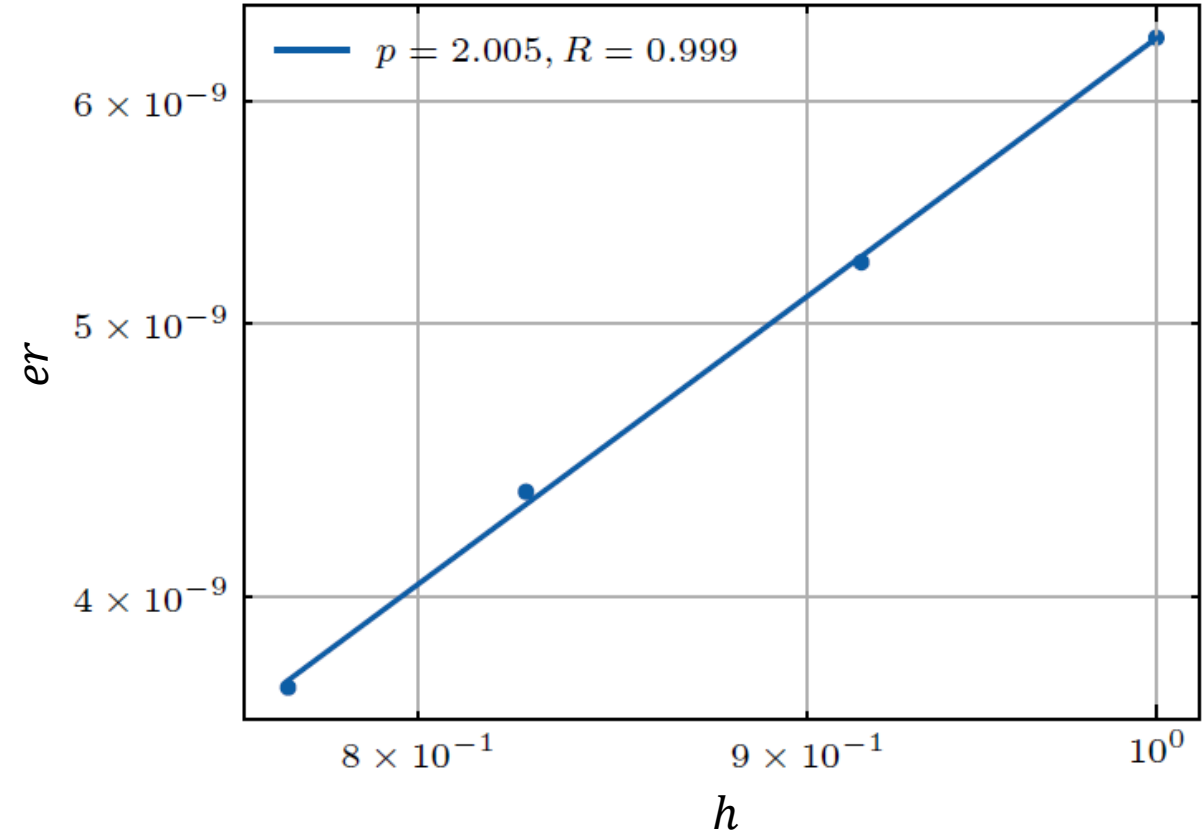
Used Method: Finite-Difference-Method (2nd order)

$$\nabla^2 \Phi(x) = \frac{d^2 \Phi(x)}{dx^2} \approx \frac{\Phi(x-h) - 2\Phi(x) + \Phi(x+h)}{h^2}$$

Error Calculation: Calculation of $\Phi(x)$ with different h :

$$er = \frac{\|\Phi_{sim} - \Phi_{theo}\|_2}{\|\Phi_{theo}\|_2}$$

Check expected convergence rate



Conclusion

Electric propulsion is more mass-efficient than chemical propulsion.

Radiofrequency ion thruster parameters depend on the physical dimensions and operating conditions.

Optimizing RITs using numerical models is not yet sufficiently feasible.

Many engineering questions still need to be addressed:

→ Verification and Validation

Thank you very much for your attention!

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