Improvements in global modeling of gridded ion thrusters

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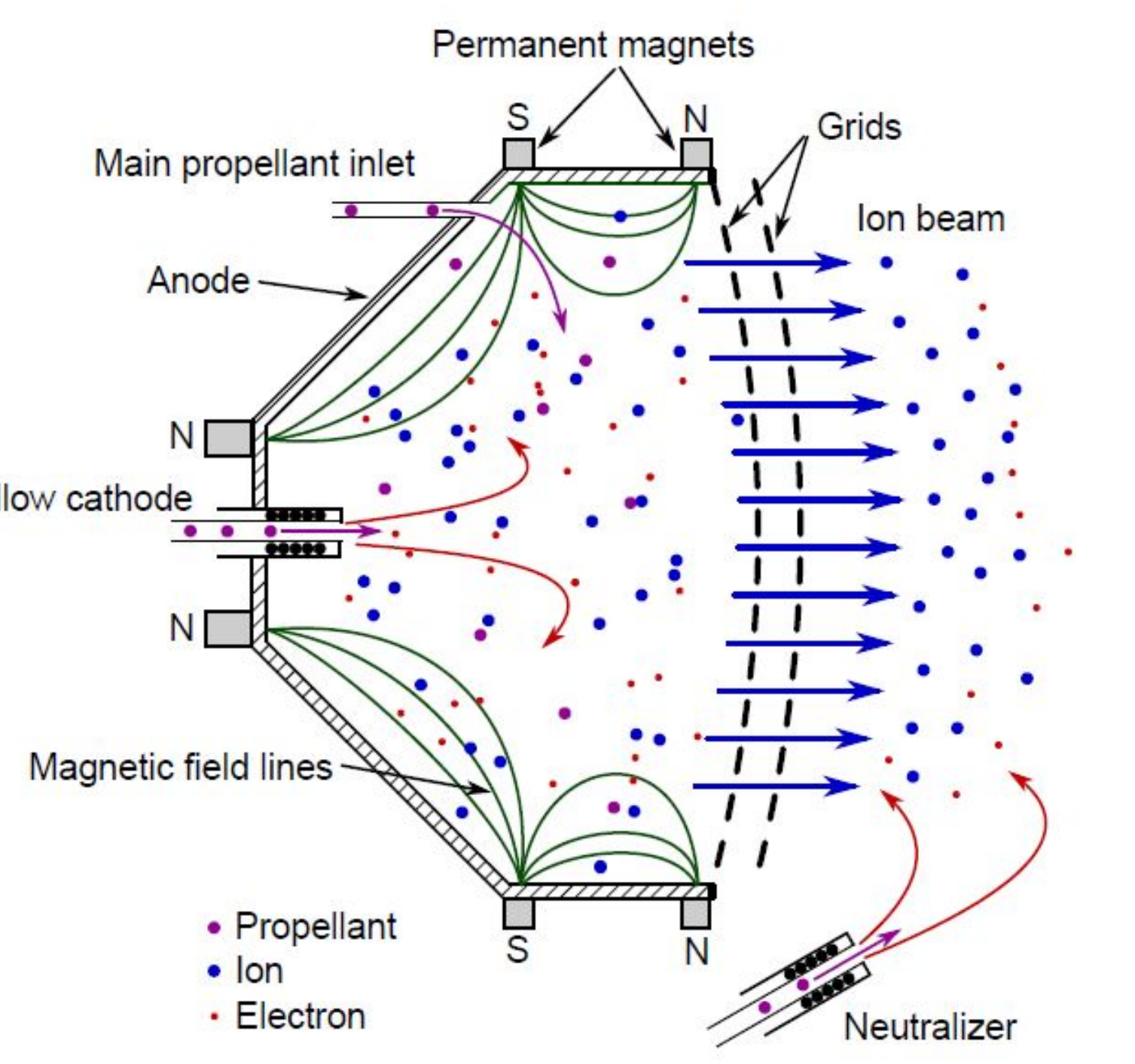
Abstract

PEGASES is an ion-ion thruster concept developed at LPP for over ten years. The neutralization of the plume by alternate negative and positive ion extraction leads to a thruster design where no external neutralizer is required anymore. First 0D fluid models - or global models - of plasma thrusters were developed for DC ion thrusters operated with Xenon [1]. The model was extended to RF gridded thrusters including more complex molecular iodine chemistry [2]. Recently, neutral gas heating by ion acceleration in the sheath was added to the model, which has a very large influence on the neutral power balance.

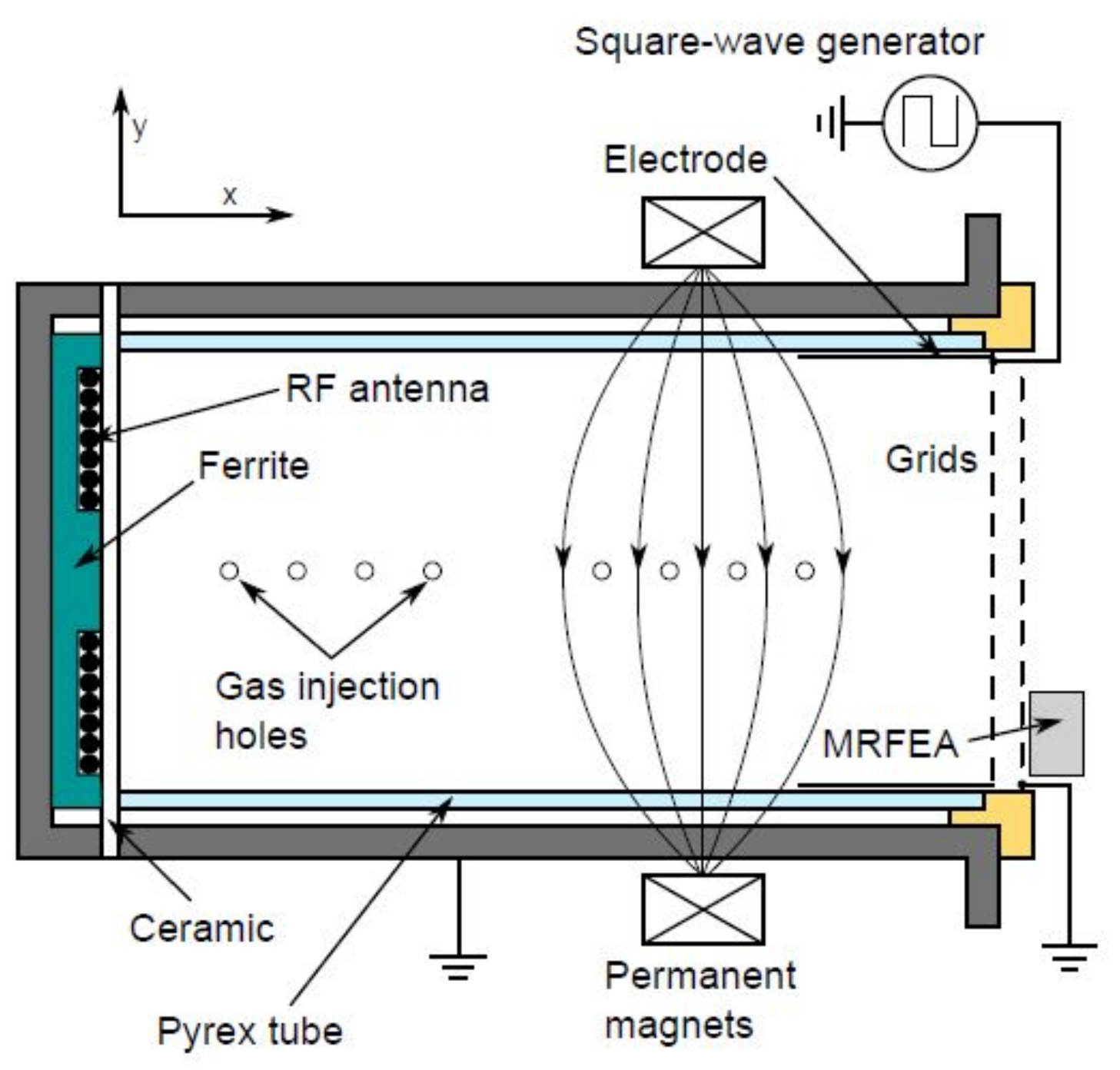
Following the description of collisionless heating in inductively coupled RF plasma provided in [3], stochastic heating was also taken into account both through an effective collision frequency, and a heating term in the electron power balance. Refining the global model leads to a better predictability of the thruster efficiency. Both numerical PIC simulations and experiments are in progress to validate the analyses that were conducted here.

[1] P. Chabert, J. Arancibia Monreal, J. Bredin, L. Popelier, and A. Aanesland. Physics of Plasma, July 2012.
[2] P. Grondein, T. Lafleur, P. Chabert, and A. Aanesland. Physics of Plasmas, 2016.
[3] M. A. Lieberman and A. J. Lichtenberg. Principles of Plasma Discharges and Materials Processing. Wiley, second edition edition, 2005.

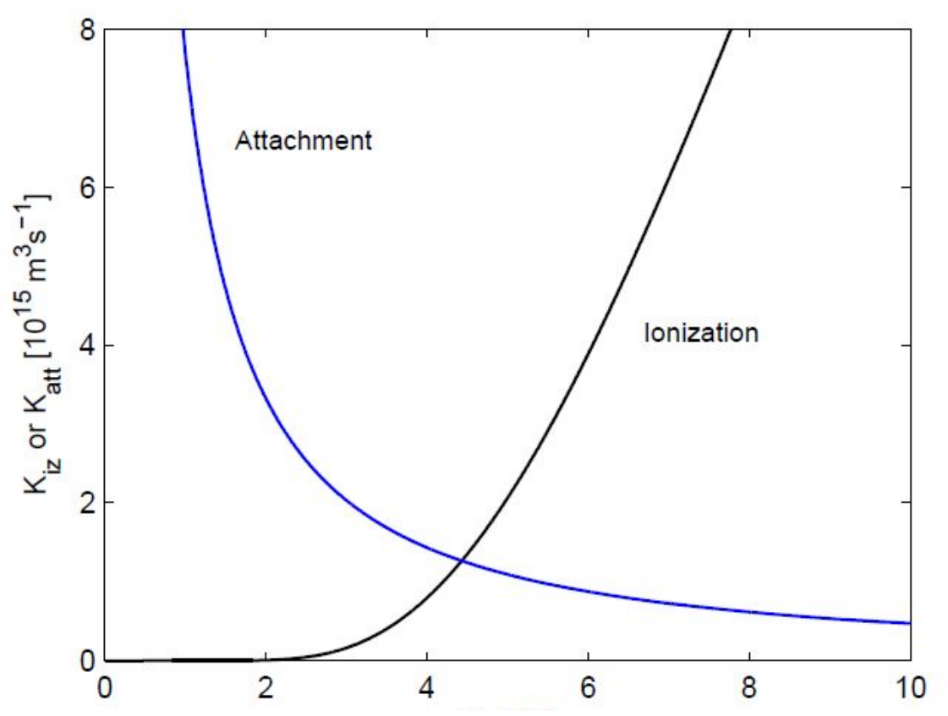
From conventional gridded thrusters...

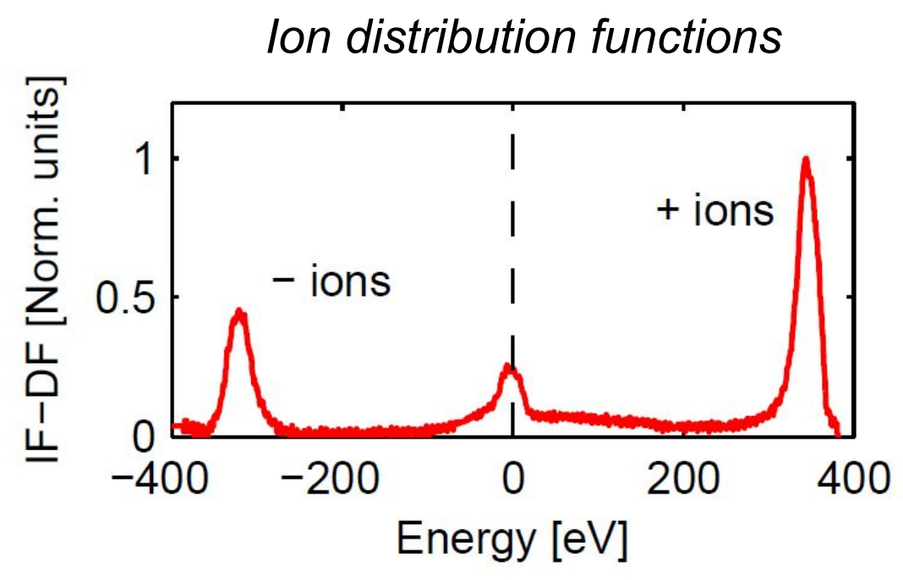


...to the PEGASES thruster

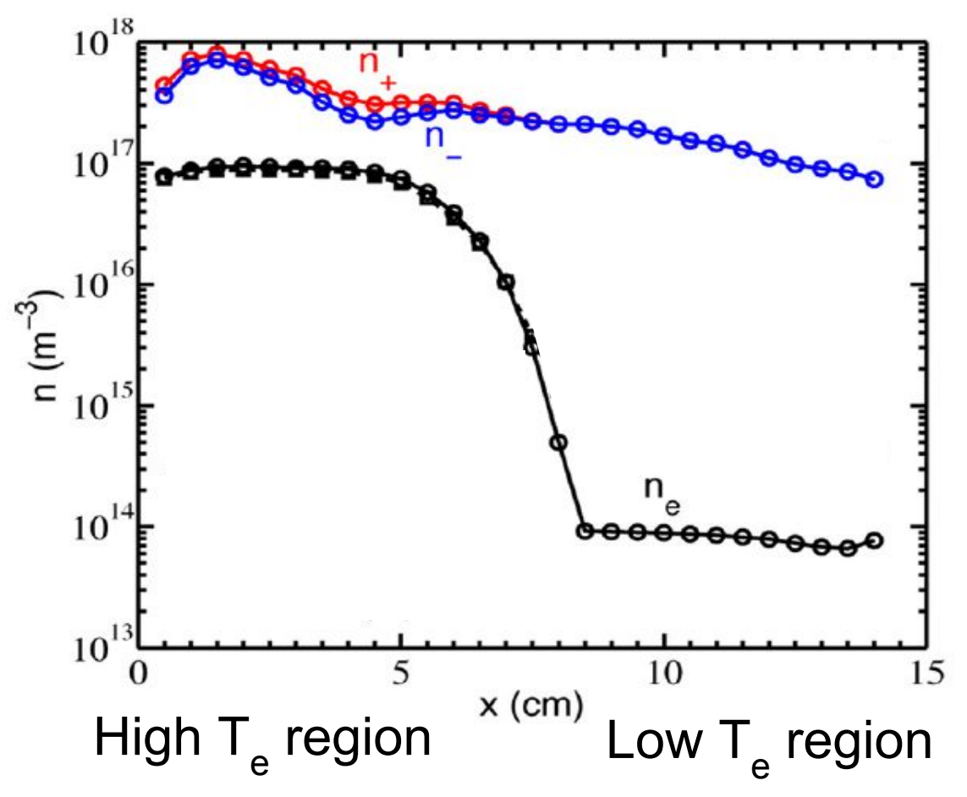


- Conventional gridded thrusters use a DC voltage on the grids, and need to reinject electrons into the exhaust plume to prevent charge buildup on the spacecraft.
- PEGASES uses electronegative gases to produce positive and negative ions.
- An RF voltage is applied to the acceleration grids, and both positive and negative ions are alternately extracted and accelerated.
- The beam packets mix downstream allowing neutralization to occur without needing an electron-emitting neutralizer.





- The **magnetic filter** enhances electron confinement and causes a drop in electron temperature downstream.
  - Attachment increases and ionization decreases in the magnetic filter
- **Electronegativity up to 1000** was reached experimentally.

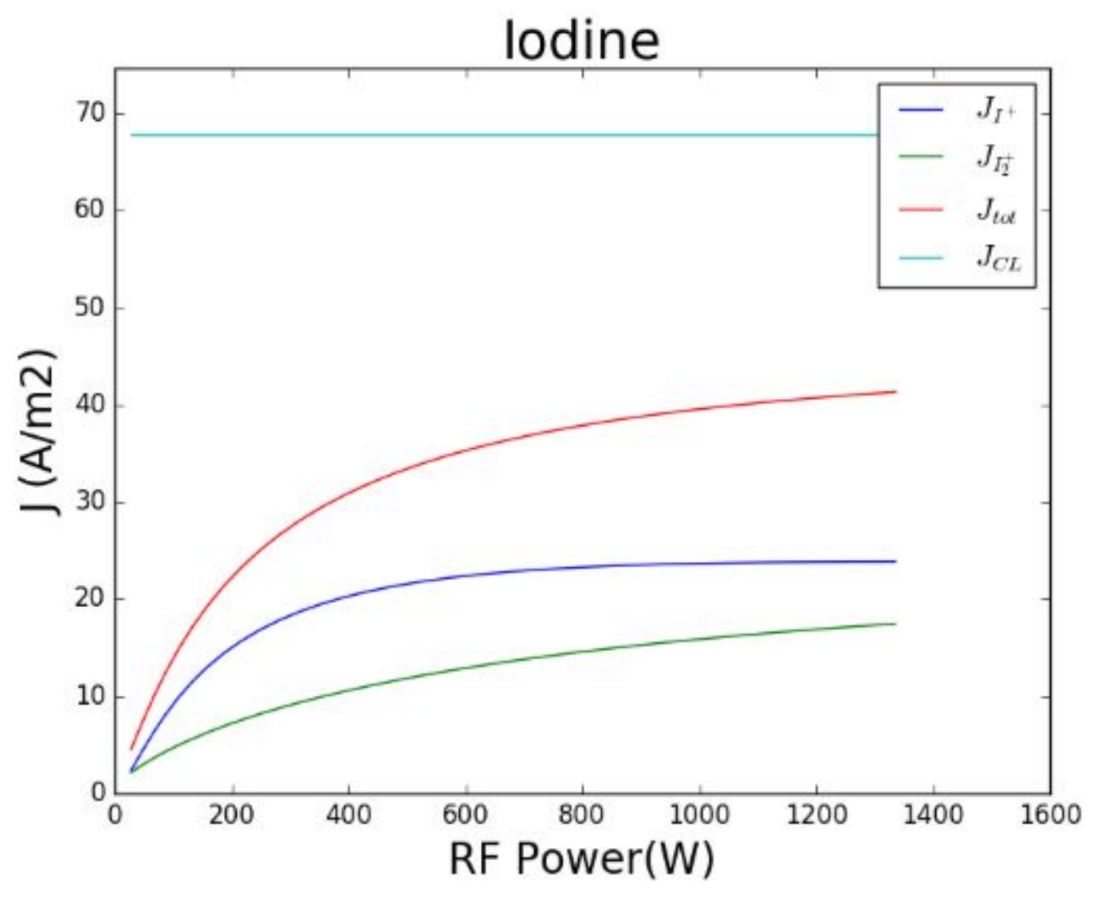


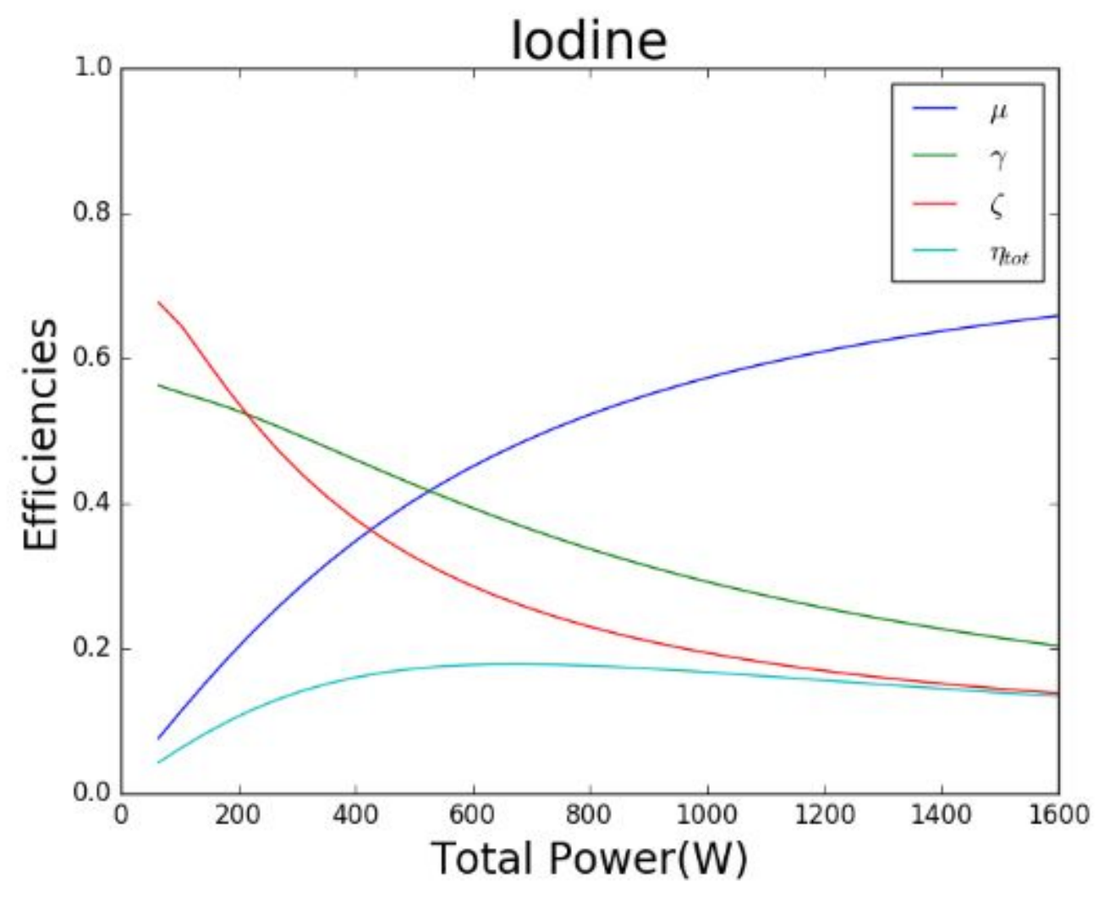
Global model

Mean parameters of the plasma and global thruster performances are estimated by fast numerical solver.

- Particle balance for each species
- Gas heating
- Electron power balance

Reaction	Process
$e^- + I \longrightarrow e^- + I^*$	Excitation of I
$e^- + I_2 \longrightarrow e^- + I_2$	Elastic collision of I_2
$e^- + I \longrightarrow e^- + I$	Elastic collision of I
$e^- + I_2 \longrightarrow I^- + I$	Dissociative attachment
$e^- + I_2 \longrightarrow I^+ + I + 2e^-$	Dissociative ionization
$e^- + I \longrightarrow I^+ + 2e^-$	Ionization of I
$e^- + I_2 \longrightarrow I_2^+ + 2e^-$	Ionization of I_2
$e^- + I_2 \longrightarrow 2I + e^-$	Dissociation
$I^- + I_2^+ \longrightarrow I + I_2$	Charge exchange
$I^- + I^+ \longrightarrow 2I$	Ion recombination
$2I \longrightarrow I_2$	Surface recombination





A kinetic model was developed to simulate the ***iodine chemistry****, including RF power injection, power loss to the walls, and grid extraction.*

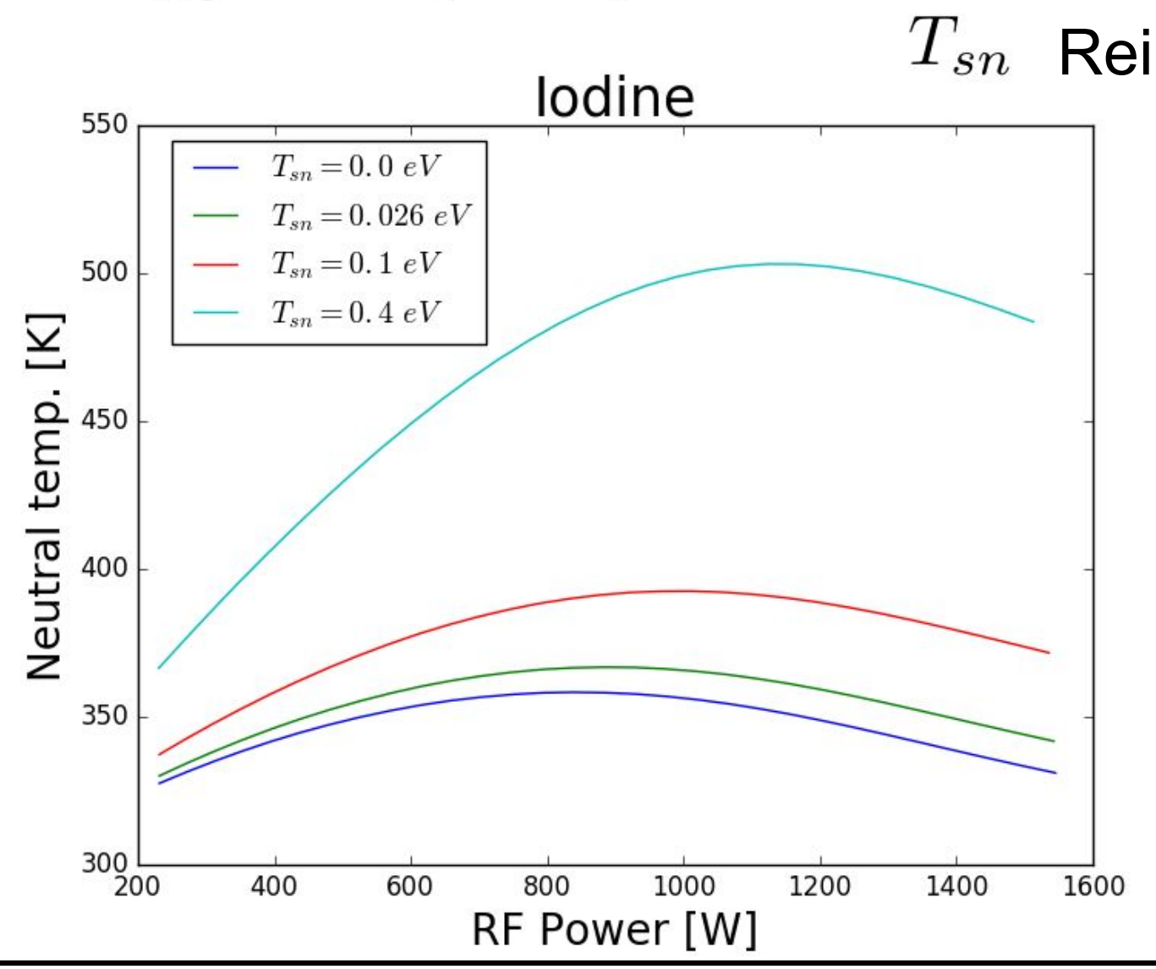
Neutral gas heating by ion acceleration in the sheath

Power balance equation for neutrals

$$\frac{d}{dt}\left(\frac{3}{2}(n_I+n_{I_2})eT_g\right) = 3m_e e(T_e-T_g)n_e\left(\frac{n_{I_2}}{m_{I_2}}+\frac{n_I}{m_I}\right)K_{el}$$
$$+\frac{1}{4}n_e\left(n_{I_2}m_{I_2}u_{BI_2}^2K_{in_{I_2}}+n_Im_Iu_{BI}^2K_{in_I}\right)-\kappa\left(\frac{T_g-T_{g0}}{\Lambda_0}\right)\frac{A}{V}$$
$$+\boxed{eT_{sn}\left(n_{I_2^+}u_{BI_2}+n_{I^+}u_{BI}\right)\frac{A_{eff_p}}{V}}$$

$A_{eff_p}=\pi R^2(2-\beta_i)h_L+2\pi RLh_R$ Effective surface for I / I_2 production by I^+ / I_2^+ losses

T_{sn} Reinjected neutral temperature after ion collision to the walls



- Small fraction of the ion energy gained in the sheath contributes to gas heating
- Both constant reinjection temperature approach and accommodation coefficient approach are investigated
- Experiments are planned to determine T_{sn} in an iodine plasma with more accuracy using Two-Photon Absorption Laser-Induced Fluorescence (TALIF) methods.

Stochastic heating in an inductively-coupled plasma

- Transverse electric field gradient in the skin depth of an inductive discharge
- RF perturbation of the electron velocity distribution function at small space scales induces collisionless heating
- Induced surface power flux depends on the skin depth δ:

$$\overline{S}_{stoc}=\frac{mn_e}{\overline{v}_e}\left(\frac{e\tilde{E}_0\delta}{m}\right)^2\mathcal{I}(\alpha)$$

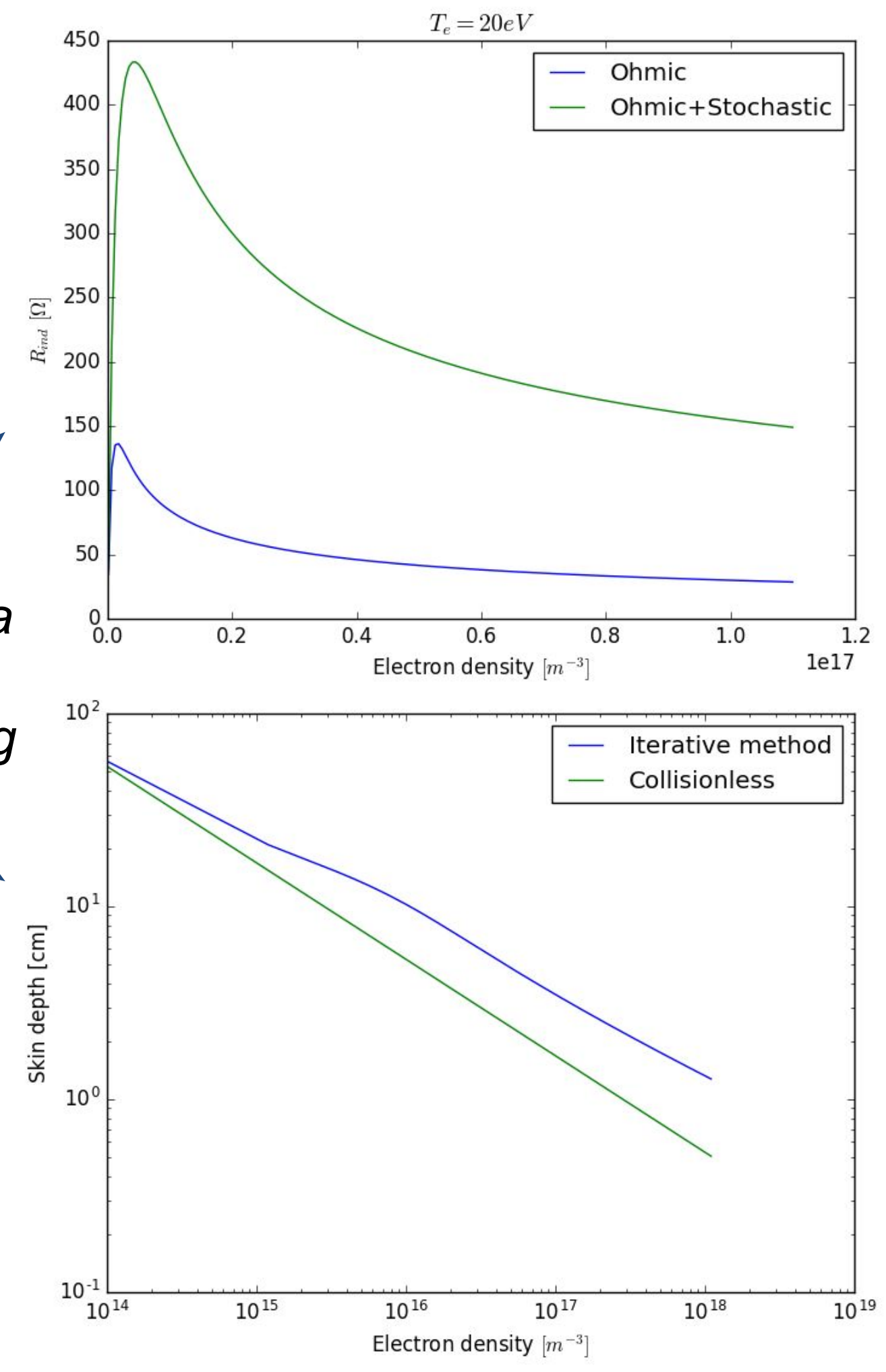
- Equivalent collision frequency

$$\nu_{stoc}\approx\frac{C_e(\alpha)\overline{v_e}}{4\delta}$$

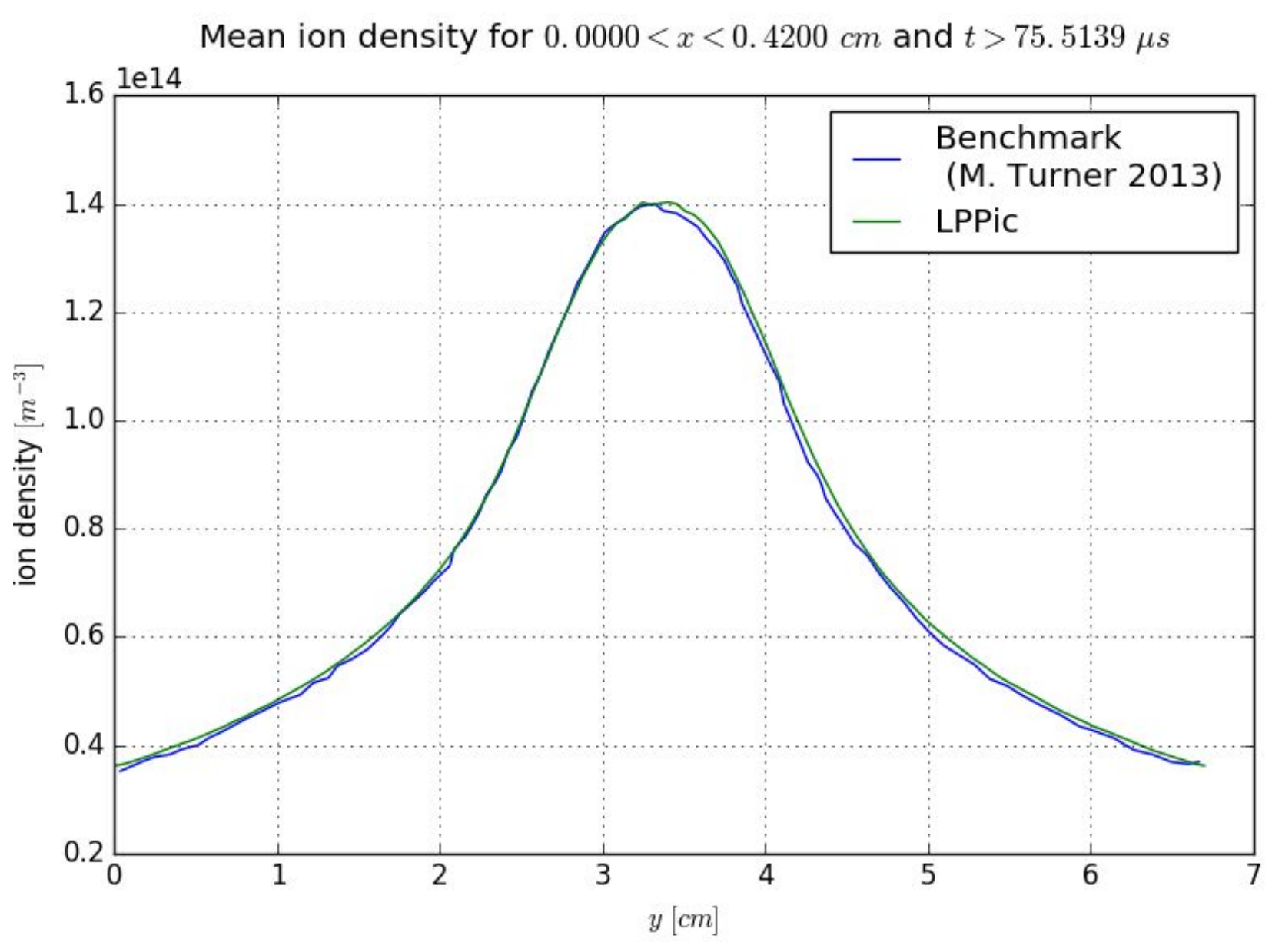
- The skin depth accounting for collisionless heating was calculated iteratively
- Plasma resistance rises by a factor 3 due to stochastic heating

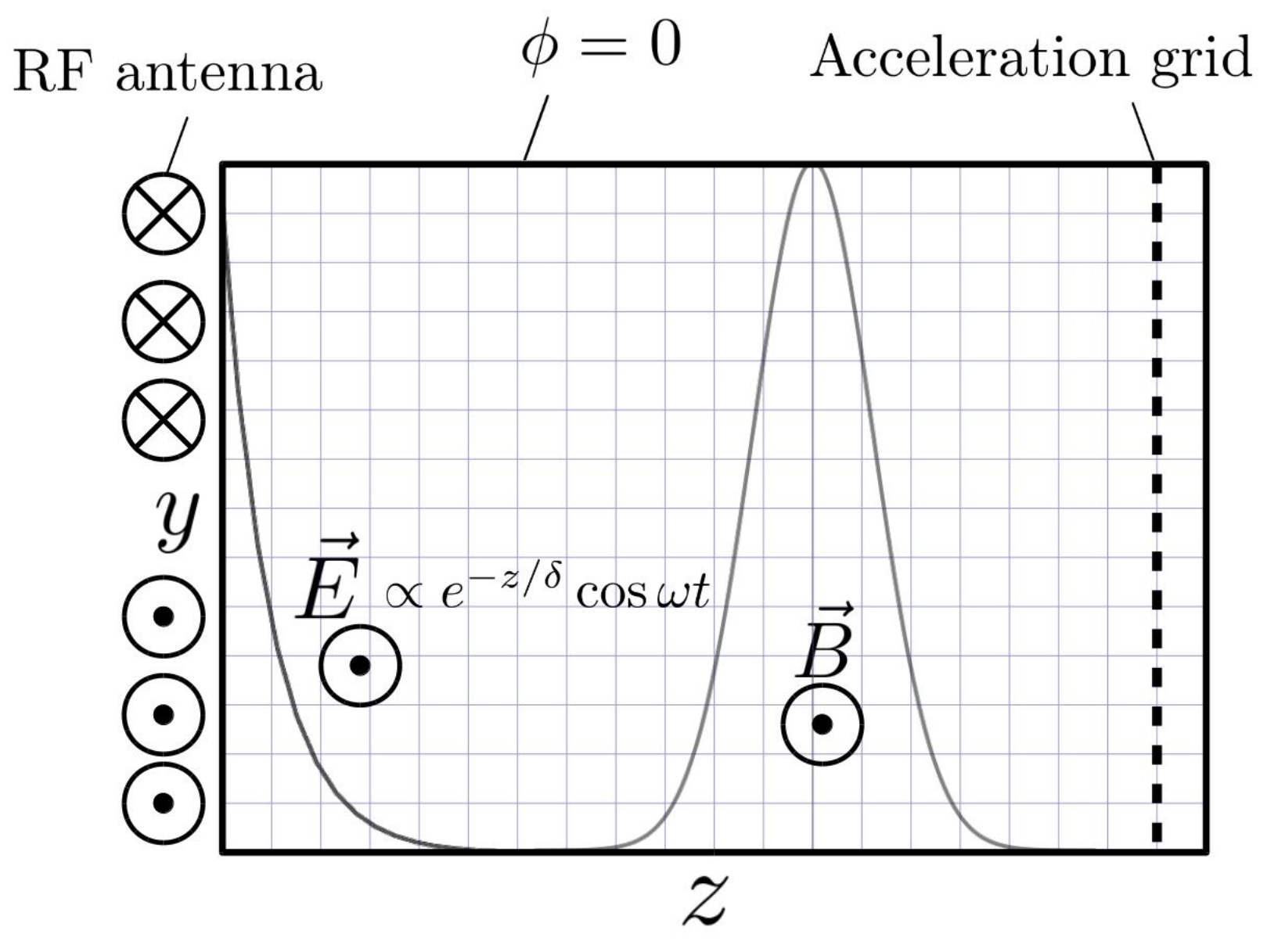
Neutral gas density	n_g	1.0×10^{19}	m^{-3}
RF frequency	ω	13.56	MHz

Estimated plasma response to stochastic heating



2D PIC simulations



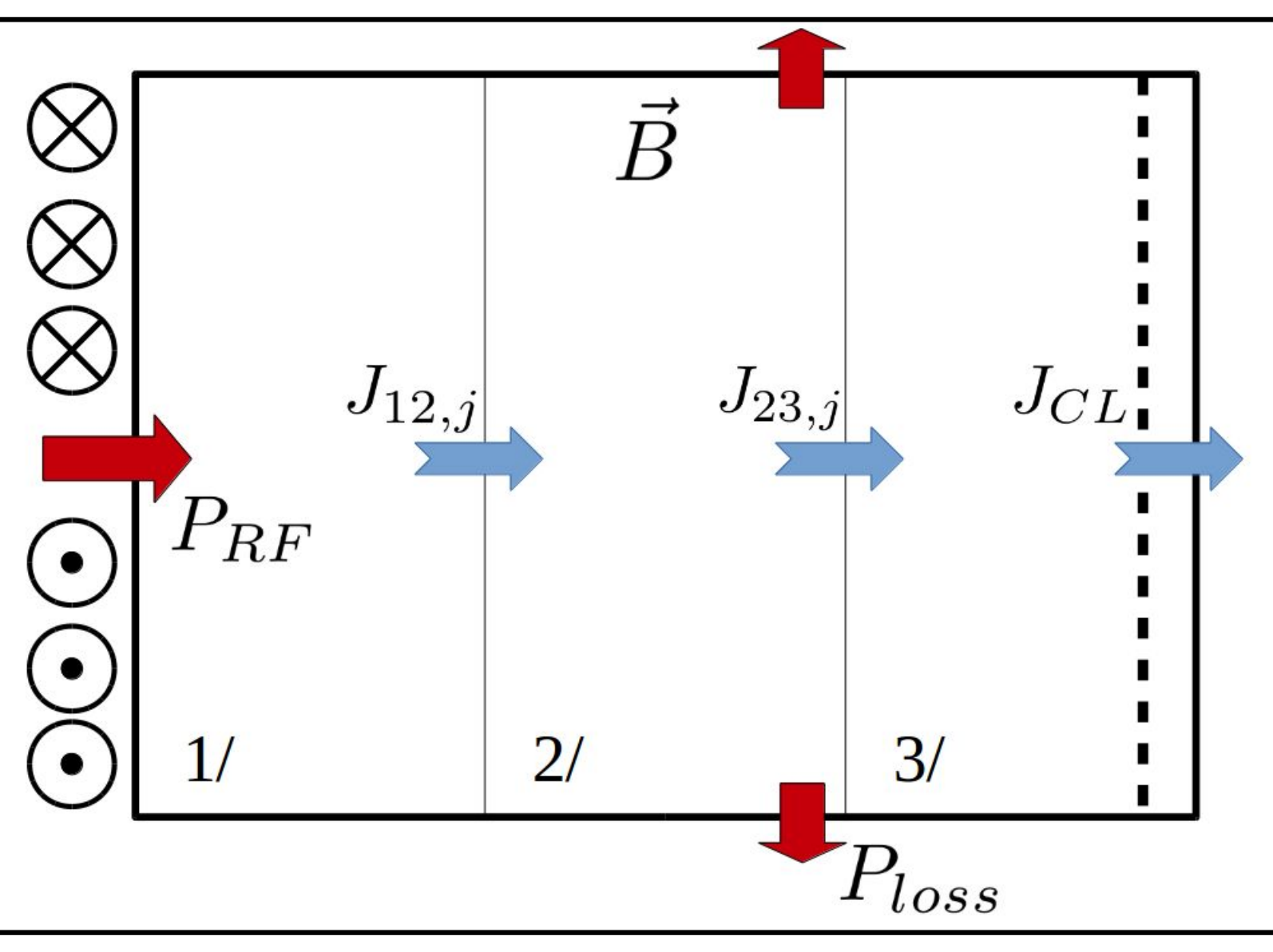


- **2D PIC code modified** to run with any noble gas type propellant (Xe, He, Ar, Kr, I electropositive)
  - 1D capacitively coupled discharge benchmark validated
- After validation by the global model, simplified iodine chemistry will be implemented in the code.
- Magnetic barrier of PEGASES can be simulated with argon and iodine, for which many experiments were conducted.
- Complex geometry of acceleration grid will be implemented in the future

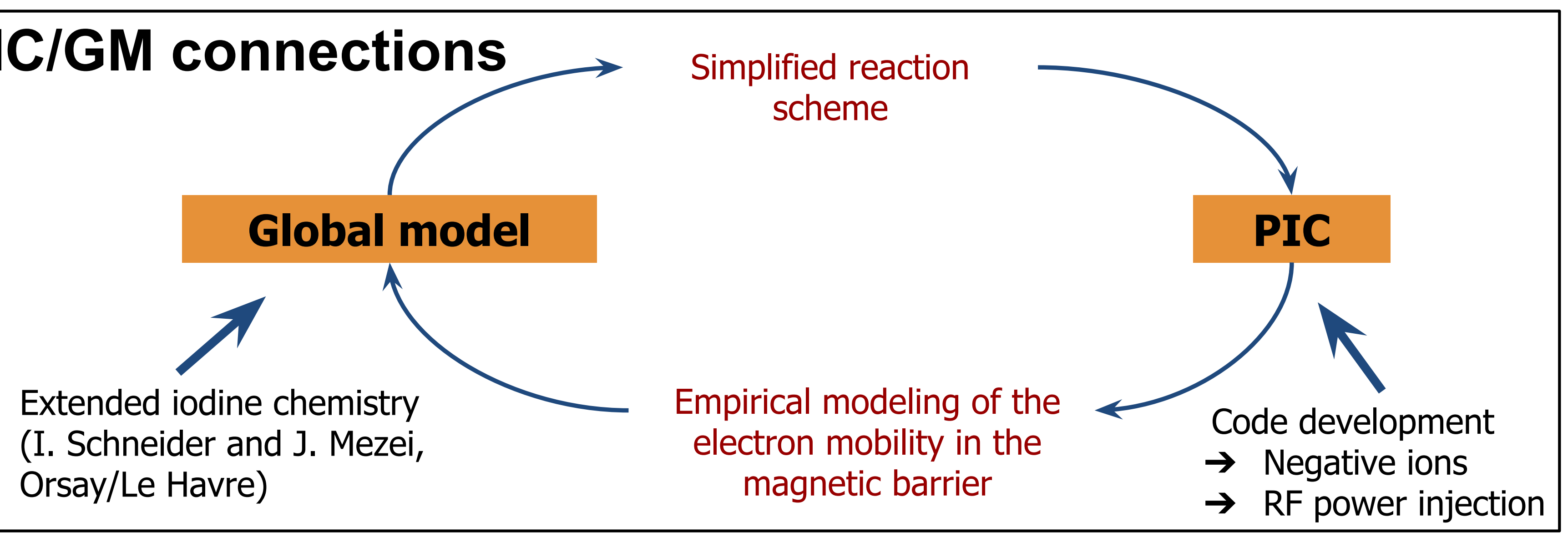
Future magnetised global model

Improvement of the global model to take into account electron confinement by the magnetic field.

- 3 regions:
  - RF heating
  - Electron attachment
  - Downstream extraction and acceleration
- Thermal fluxes connect the 3 regions together
- A longer effective distance for electrons in region 2/ is implemented to account for an increased confinement time.



PIC/GM connections



Simplified reaction scheme

Global model

PIC

Extended iodine chemistry (I. Schneider and J. Mezei, Orsay/Le Havre)

Empirical modeling of the electron mobility in the magnetic barrier

Code development
➔ Negative ions
➔ RF power injection