A global plasma model for linear plasma devices based on SOLPS-ITER equations

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Modelling of linear plasma devices: a simplified global approach [1]

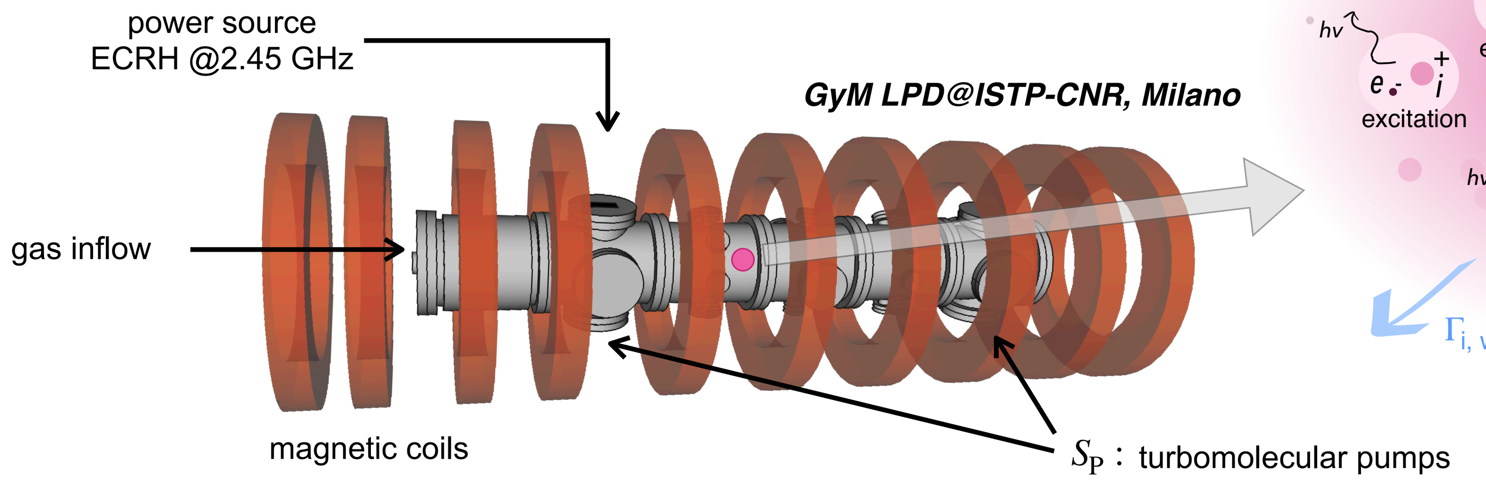
MOTIVATION:

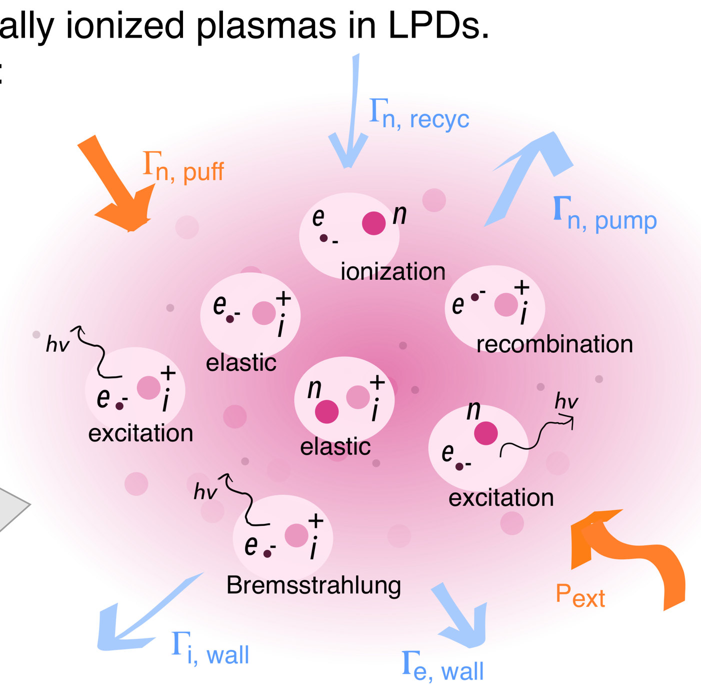
Linear plasma devices [2] represent an essential tool for **nuclear fusion research**, whereby understanding crucial aspects related to **plasma-wall interaction**, **edge plasma behavior**, including **interactions among charged and neutral particles**. In this context, simplified models are of great importance **to complement and integrate experimental and simulation results of complex systems** such as plasmas in linear machines, because they are fast and simple to employ.

PRINCIPLES OF THE GLOBAL MODEL:

Development of a space independent global model for the description of partially ionized plasmas in LPDs. Equations reduce to a system of **ordinary differential equations** (ODEs) [3]:

$$\frac{d(\dots)_p}{dt} = \sum \text{Sources}_p - \sum \text{Sinks}_p$$





Sources and sinks:

- **Atomic reactions** *(ionization, recombination, excitation, elastic…)*: atomic data from **ADAS database** [4]. A global model is particularly suitable to test the effect of different reactions included.
- **Boundary contributions** *(losses of particles and energy at the wall, recycling, pumping…)*: obtained integrating fluid equations from standard codes, e.g. **SOLPS-ITER** [5, 6]. For particle losses at the boundary:

Gauss Theorem

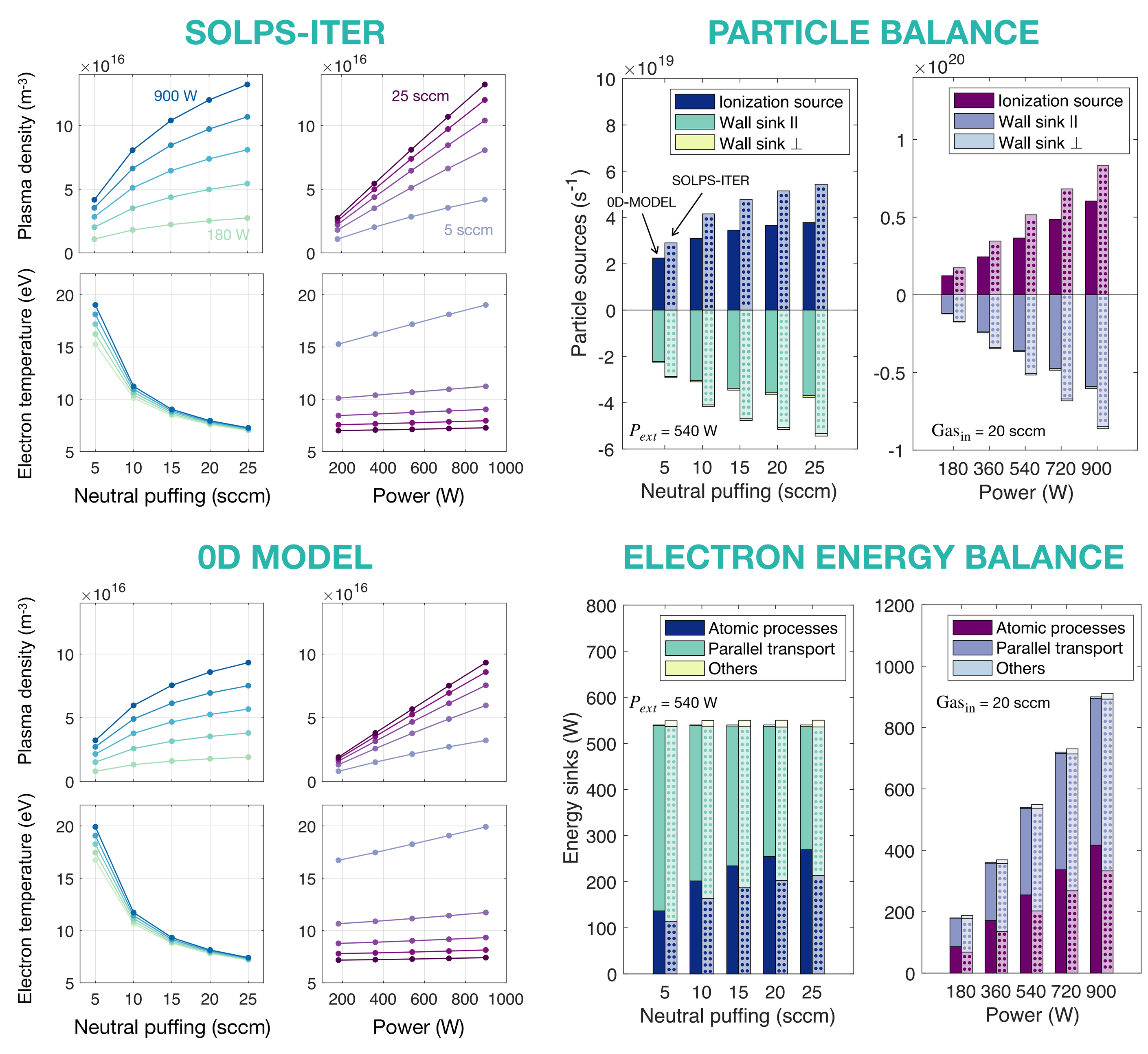
$$\Gamma_{i,\text{wall}}\, n_i = \frac{1}{\text{Vol}_i}\int_{\text{Vol}_i} \nabla\cdot(n_i \mathbf{v}_i)\,dx\,dy\,dz = \left(\frac{\alpha u_B A_T}{\text{Vol}_i} + \frac{D_\perp A_{Lat}}{\lambda_n \text{Vol}_i}\right) n_i$$

- **External sources** *(neutral puffing, electron heating…)*

First application: modelling of **pure helium plasmas** (atomic processes only, no molecules) with parameters typical of GyM linear plasma device (ISTP-CNR, Milano) [7]

$$n_i \simeq 1\times 10^{16-17}\,\text{m}^{-3} \qquad T_e \simeq 5-15\,\text{eV}$$

Comparison with SOLPS-ITER: steady-state solutions



Comparison between **SOLPS-ITER volume averaged** densities and temperature

$$\frac{\int_{\text{Vol}_p}(\dots)_p\,dV}{\int_{\text{Vol}_p} dV}$$

and results of the **global model**.

✔ *Good qualitative and quantitative agreement!*

From **particle and energy balances**:

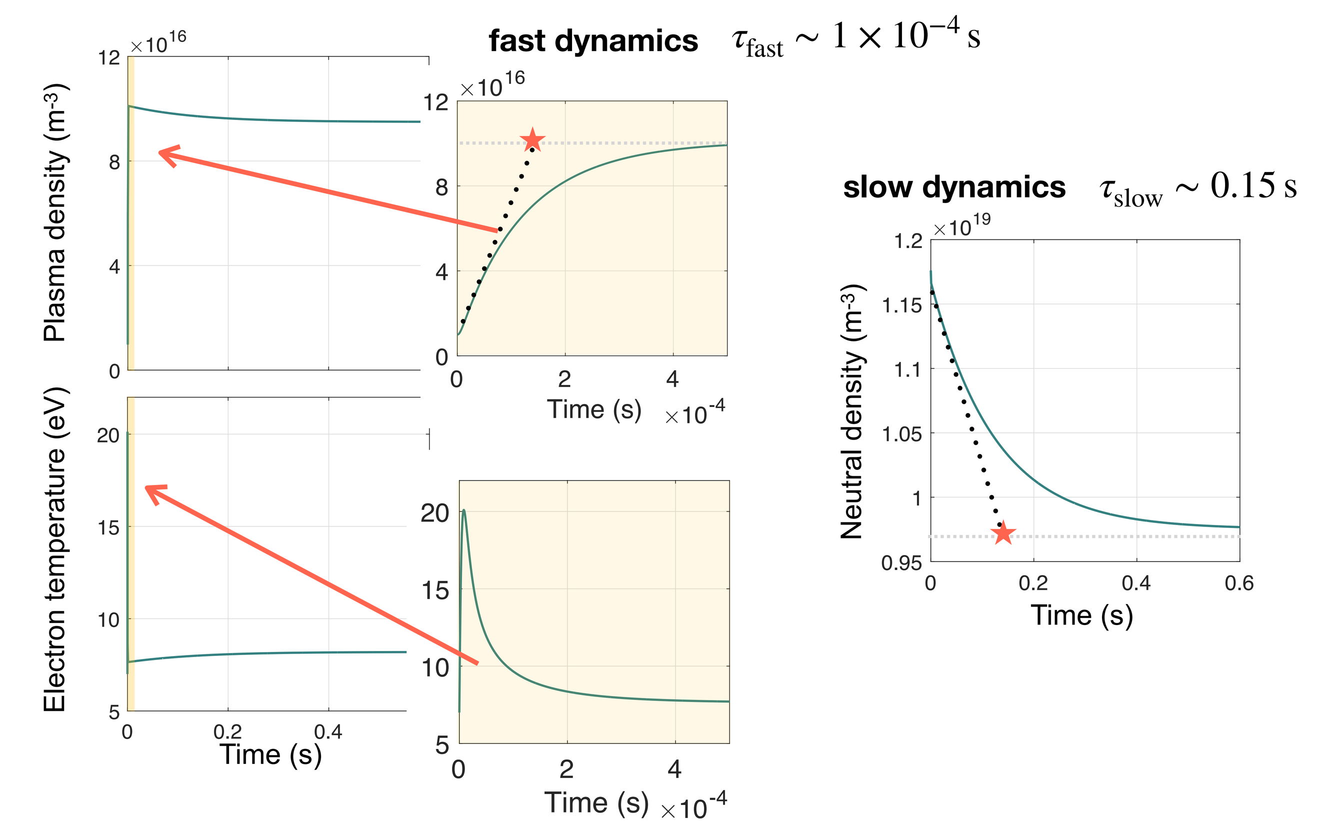
✔ *The global model includes all the relevant contributions present in SOLPS-ITER model*

✔ ***Atomic processes*** *and parallel transport are the dominant contributions!*

Time evolution

Time solution of the **global ODEs** allows to identify **two time constants**, governing the system dynamics:

- *Fast dynamics:* order of magnitude of the **plasma confinement time** $\tau_{\text{fast}} \sim \Gamma_{i,\text{wall}}^{-1} = \left(\frac{\alpha u_B A_T}{\text{Vol}_i} + \frac{D_\perp A_{lat}}{\lambda_n \text{Vol}_i}\right)^{-1}$
- *Slow dynamics:* order of magnitude of the **neutrals time constant** $\tau_{\text{slow}} \sim \Gamma_{n,\text{pump}}^{-1} = \left(\frac{S_P \times 10^3}{\text{Vol}_n}\right)^{-1}$



Analytical formulae

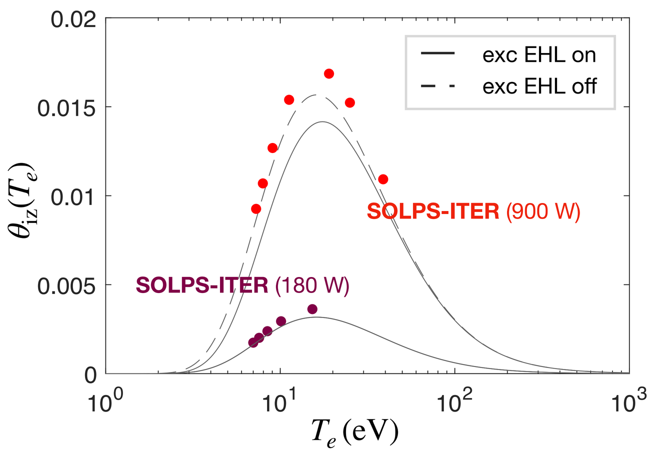
Analytical expressions for $n_i(T_e)$, $n_n(T_e)$ and the **plasma ionization degree** $\theta_{iz}(T_e)$:

$$\theta_{iz}(T_e) = \frac{n_i(T_e)}{n_i(T_e)+n_n(T_e)} = P_{\text{ext}}\left[\frac{\Gamma_{i,\text{wall}}\text{Vol}_e}{R_{iz}}\left(\Gamma_{e,\text{wall}}T_e + \left(E_{iz} + \frac{E_{n,\text{rad}}R_{n,\text{rad}}}{R_{iz}}\right)\Gamma_{i,\text{wall}}\right) + P_{\text{ext}}\right]^{-1}$$

✔ *$\theta_{iz}(T_e)$ has a maximum around the helium ionization energy $E_{iz} \simeq 25$ eV*

✔ *The maximum of $\theta_{iz}(T_e)$ is proportional to the value of external power*

✔ *Good qualitative and quantitative agreement with SOLPS-ITER simulation results*

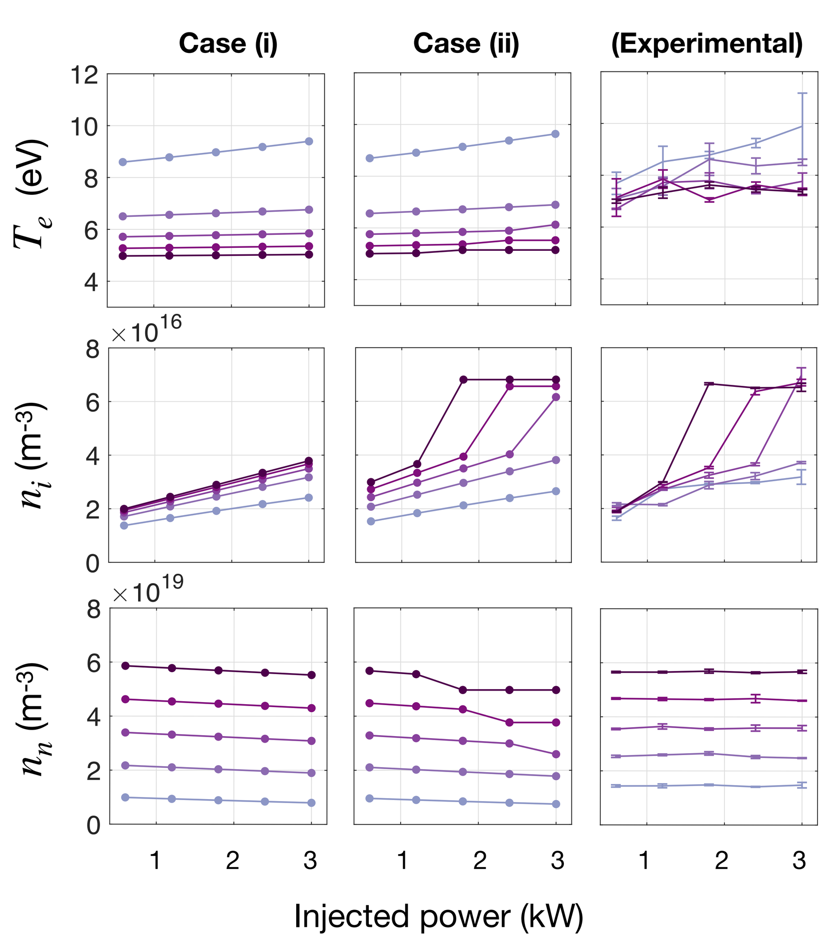


SOLPS-ITER model neglects electron-neutral excitation among the electron heat loss (EHL) mechanisms. The analytical formulae show that:

✔ *neglecting $E_{n,\text{rad}}R_{n,\text{rad}}$ results in a very good agreement with SOLPS-ITER $\theta_{iz}(T_e)$*

✔ *considering electron-neutral excitation EHL reduces the plasma density and $\theta_{iz}(T_e)$*

Comparison with experimental data



2.45 GHz microwave source heats up electron population by *electron cyclotron resonance heating* (ECRH).

$$\eta = \frac{P_{\text{ext}}}{P_{\text{injected}}}$$

Power absorbed by the electrons: **model parameter**

Power delivered by the source: **experimentally known parameter**

***η* is used as a free parameter:**

- **case(i)**: η is inversely proportional to P_{ext}
- **case(ii)**: η is inversely proportional to P_{ext} + step increase for $n_i \gtrsim 4\times10^{16}\,\text{m}^{-3}$

✔ *Good qualitative and quantitative agreement with experimental data!*

✔ *Increased η for $n_i \gtrsim 1/2\, n_{cr@2.45\,\text{GHz}}$: possible resonant mechanism turned on (O-X-B). Further studies needed!*

Conclusions and perspectives

- Development of a global 0D model for partially ionized plasmas.
- Comparison with state of the art SOLPS-ITER results showed **good agreement**.
- The global model highlighted that some atomic processes presently neglected in SOLPS-ITER (*electron-neutral and ion-neutral elastic collisions and electron-neutral excitation process*) may be relevant especially for weakly ionized plasmas, typical of LPDs.

Future works will involve:

- Extension of the model to include: **multi-species plasmas, thermal conduction** (neglected here, due to low thermal gradients in GyM)
- Coupling with **surface sputtering and erosion/evaporation models** or **numerical codes** (e.g. ERO2.0) to study plasma-wall interaction processes

References

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