Max-Planck-Institut für Plasmaphysik

Predictive fluid model for self-consistent description of inductive RF coupling in powerful negative hydrogen ion sources

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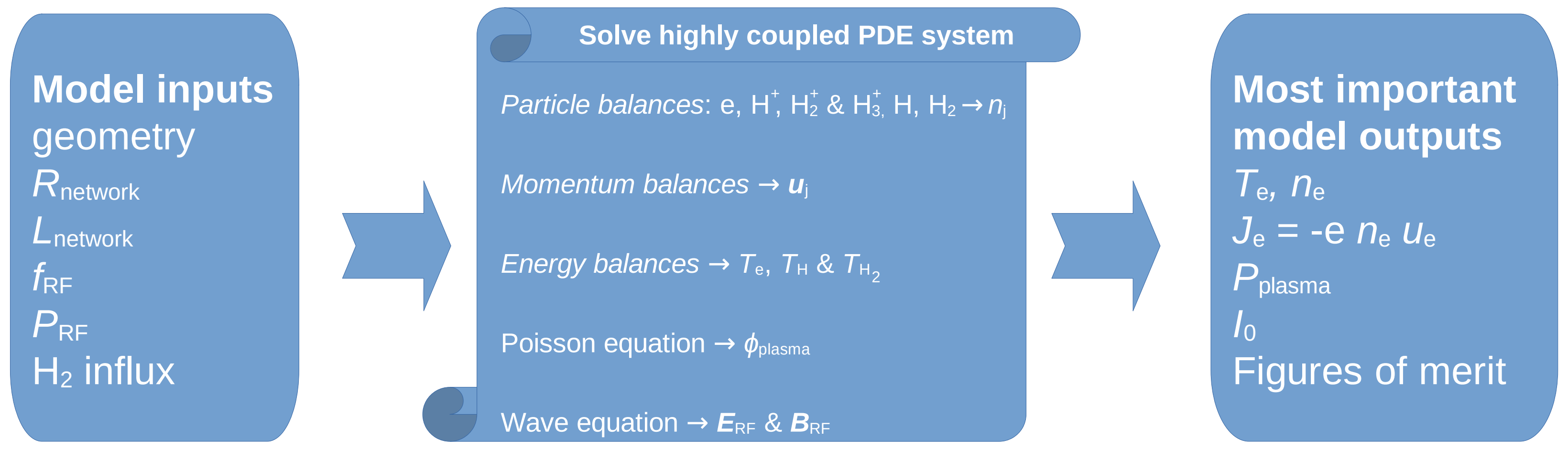
Motivation

- NNBI systems & particle accelerators use RF-driven negative H/D ion sources
- Low RF ≈ 1-2 MHz, low $p_{gas} \leq 1$ Pa, high power densities 10 Wcm^{-3}
- Low temperature H/D plasma at $T_e \approx 10$ eV & $n_e \approx 10^{18}$ m^{-3}
- RF power coupling not optimized → electric arcs → performance & reliability limited
- **Modeling approach to study self-consistent RF power coupling**
- **Validation with experimental measurements from RF ion source**

Modeling approach

EM model of the driver (3D) calculates Joule and eddy current losses in RF network components (Faraday screen & RF coil) without plasma in first step → network losses $R_{network}$ and $L_{network}$

RF power coupling fluid model (2D, cylindrically symmetric)[2]



Model inputs
geometry
$R_{network}$
$L_{network}$
f_{RF}
P_{RF}
H_2 influx

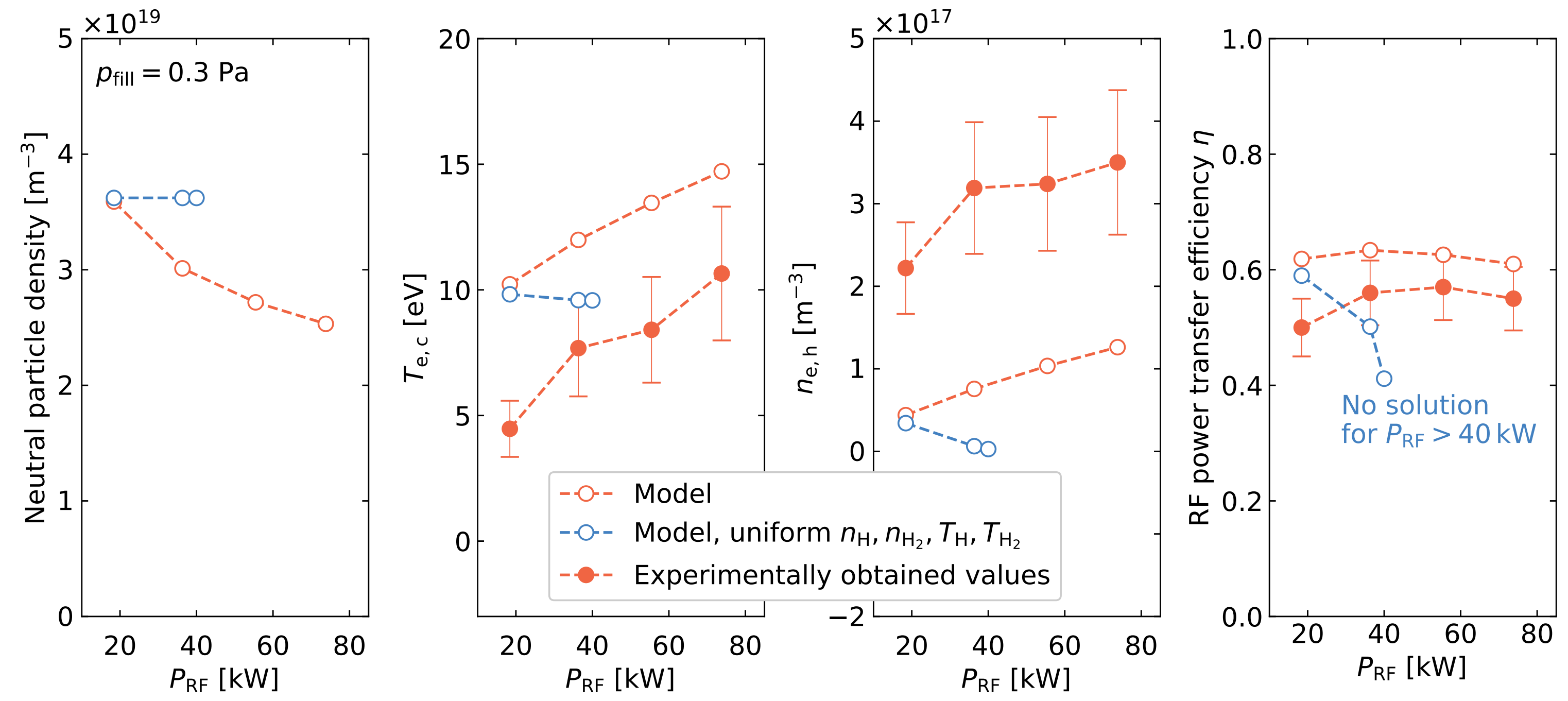
Solve highly coupled PDE system
Particle balances: e, H^+, H_2^+ & H_3^+, H, $H_2 \rightarrow n_j$
Momentum balances → $\boldsymbol{u}_j$
Energy balances → T_e, T_H & T_{H_2}
Poisson equation → ϕ_{plasma}
Wave equation → $\boldsymbol{E}_{RF}$ & $\boldsymbol{B}_{RF}$

Most important model outputs
T_e, n_e
$J_e = -e\, n_e\, u_e$
P_{plasma}
I_0
Figures of merit

➔ **Combining EM model & RF power coupling fluid model facilitates self-consistent description of the RF power coupling**

[2] D Zielke et al 2021 Plasma Sources Sci. Technol. 30 065011

Impact of neutrals description on RF power coupling

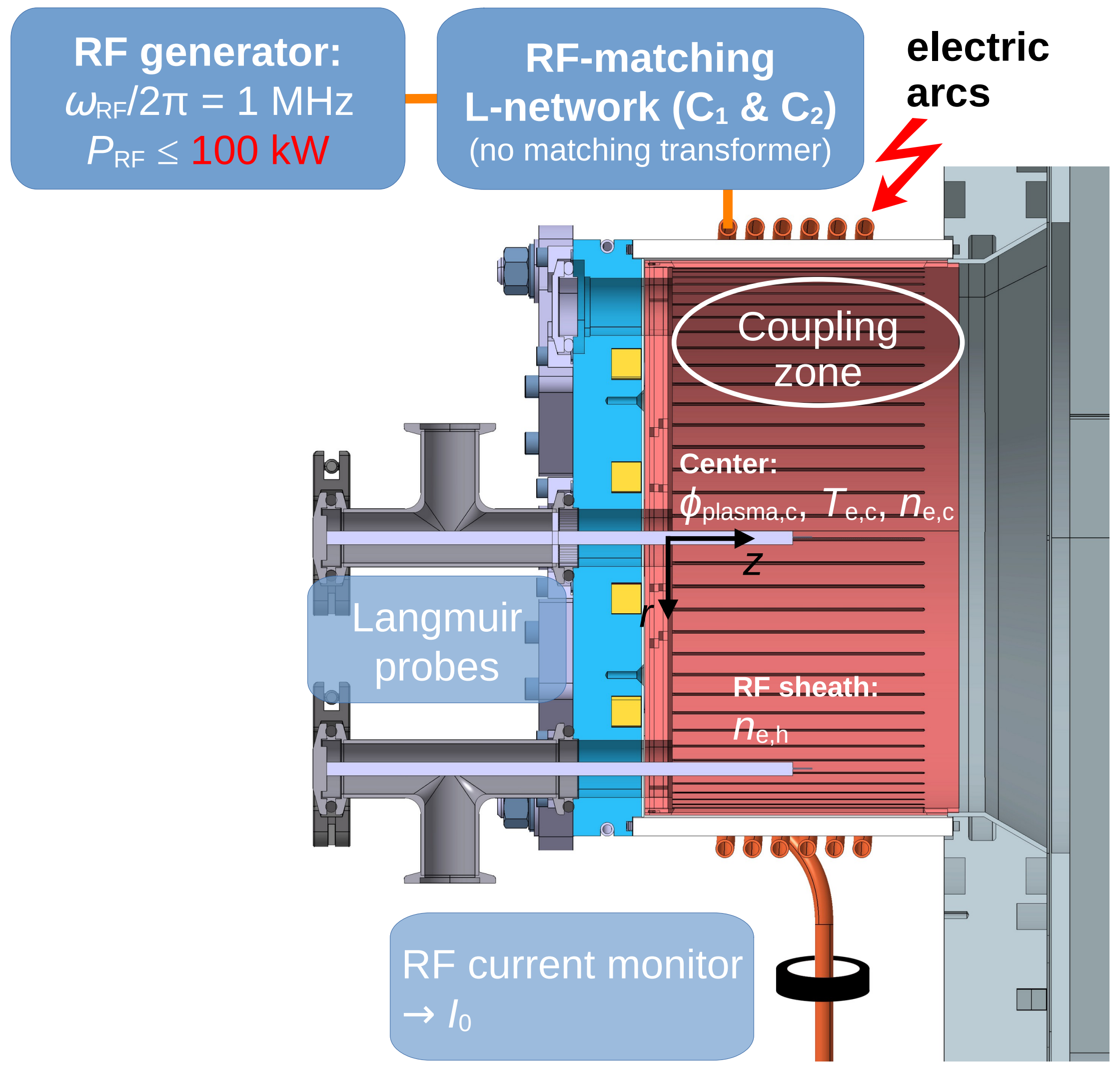


➔ **Modeled & measured trends agree well, when Navier-Stokes used for neutrals**

➔ **Modeled $T_e(P_{RF})$ ↑ ⇒ $\eta_{e,visc}$ ↑ ⇒ mitigation of plasma compression by RF current diffusion ↑ ⇒ $n_{e,s}$ ↑ ⇒ modeled η as in experiment!**

ITER prototype RF negative ion source driver at the BUG test bed for model validation[1]

[1] D Zielke et al 2021 J. Phys. D: Appl. Phys. 54 155202

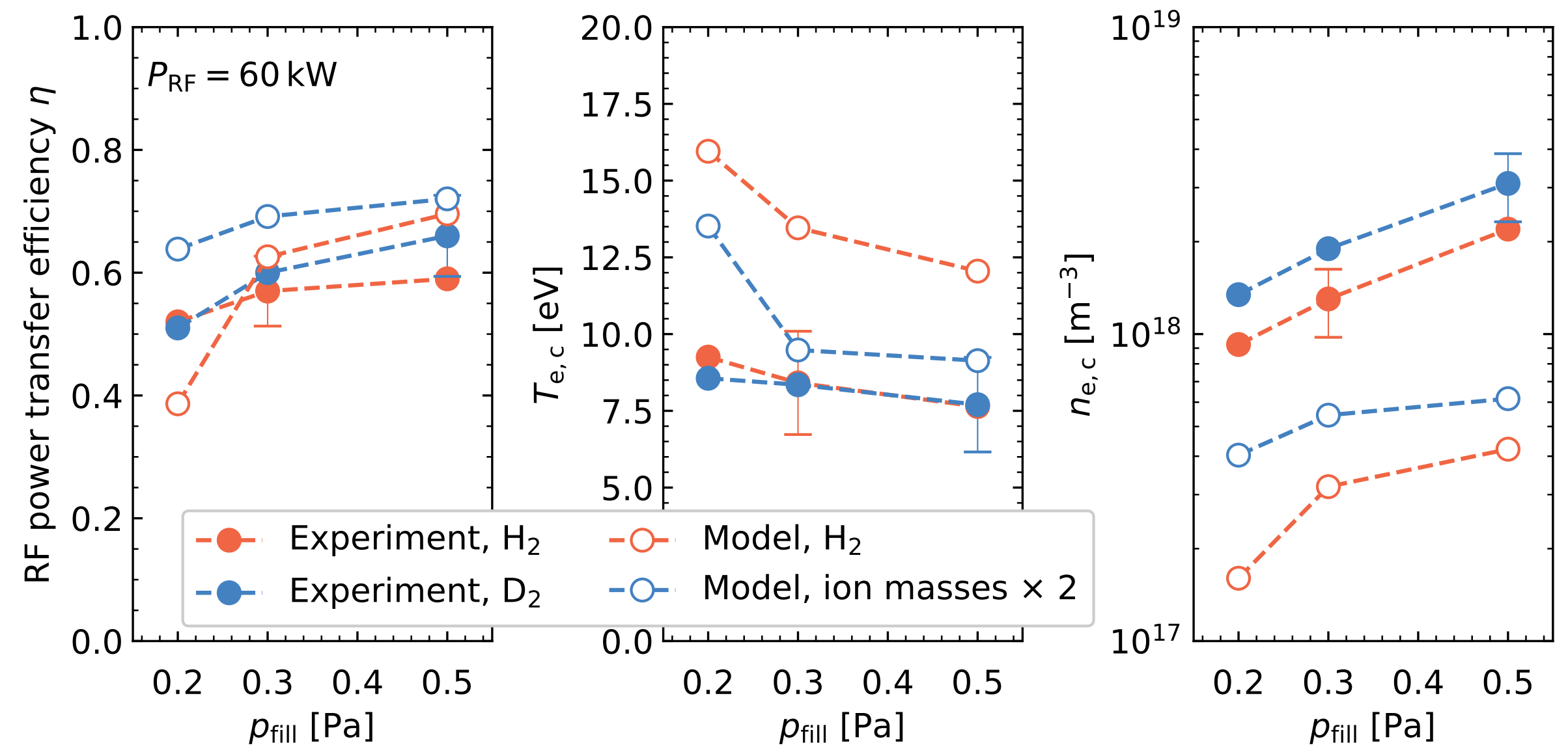


Figures of merit for RF power coupling

$$\eta = \frac{P_{plasma}}{P_{RF}} = \frac{P_{RF} - \frac{1}{2} R_{network} I_0^2}{P_{RF}}$$

$$|U_{coil}| \approx \omega_{RF} L_{network} I_0$$

Investigation of H_2 & D_2 discharges



➔ **Numerical trends scale as experimental ones**

➔ Cusp field in driver back plate not modeled → probable reason for systematic differences in modeled & measured T_e & n_e

➔ First step towards deuterium model by increased ion masses

➔ **Decreased wall losses due to larger mass explain larger plasma density & RF power transfer efficiency in D_2**

Conclusion

Validation successful → **Predictive model applicable to optimize RF power coupling** → **Talk by S. Briefi, We, 22.09., 08:00**

- Derived formulation provides correct description of the RF power coupling in RF ion sources
- Electron viscosity mitigates ponderomotive force → quantitative description of plasma compression
- Neutral depletion at low pressures captured → stable numerical solution at 0.3 Pa

Investigation of RF power coupling mechanism in RF ion sources

- RF coupling described by electron momentum & energy balance, coupled to Maxwell's equations
- Quasi steady-state values obtained from time harmonic approximation for $E_{RF,\varphi}, \boldsymbol{B}_{RF}, u_{e,\varphi}$
- Drift-diffusion electron flux (including Lorentz force) for *r*- and *z* components:

$$\mathrm{n_e}\boldsymbol{u}_\mathrm{e} = -\mu_\mathrm{e} n_\mathrm{e}(\boldsymbol{E} + \tfrac{1}{\mathrm{e}}\bar{\boldsymbol{F}}_\mathrm{L}) - \mu_\mathrm{e}\nabla n_\mathrm{e} T_\mathrm{e}, \text{ where } \bar{\boldsymbol{F}}_\mathrm{L} = -\mathrm{e}\tfrac{1}{2}\mathrm{Re}\{\tilde{u}_{\mathrm{e,RF},\varphi}\tilde{B}^*_{\mathrm{RF},z}\boldsymbol{e}_r - \tilde{u}_{\mathrm{e,RF},\varphi}\tilde{B}^*_{\mathrm{RF},r}\boldsymbol{e}_z\}$$

- Plasma compressed by RF Lorentz force: ponderomotive effect
- RF current diffusion introduced by electron viscosity decreases RF current density

$$\mathrm{i}\omega_\mathrm{RF} m_\mathrm{e}\tilde{u}_{\mathrm{e,RF},\varphi} = -\mathrm{e}\tilde{E}_{\mathrm{RF},\varphi} - \sum_\mathrm{n} m_\mathrm{e}\nu_\mathrm{e,n}\tilde{u}_{\mathrm{e,RF},\varphi} - \frac{1}{n_\mathrm{e}}[\nabla\cdot\underline{\underline{\boldsymbol{\pi}}}_\mathrm{e}]_\varphi - \mathrm{e}(u_{\mathrm{e},z}\tilde{B}_{\mathrm{RF},r} - u_{\mathrm{e},r}\tilde{B}_{\mathrm{RF},z})$$

$$[\nabla\cdot\underline{\underline{\boldsymbol{\pi}}}_\mathrm{e}]_\varphi = -m_\mathrm{e} n_\mathrm{e}\eta_\mathrm{e,visc}(\nabla^2\tilde{u}_{\mathrm{e},\varphi} - \frac{\tilde{u}_{\mathrm{e},\varphi}}{r^2})$$

- Used **local approximation** for the viscosity $\eta_\mathrm{e,visc} = \frac{2}{3}\frac{\mathrm{e}T_\mathrm{e}}{m_\mathrm{e}X_\mathrm{e,n}n_\mathrm{n}}$ in agreement with the observed local skin effect regime

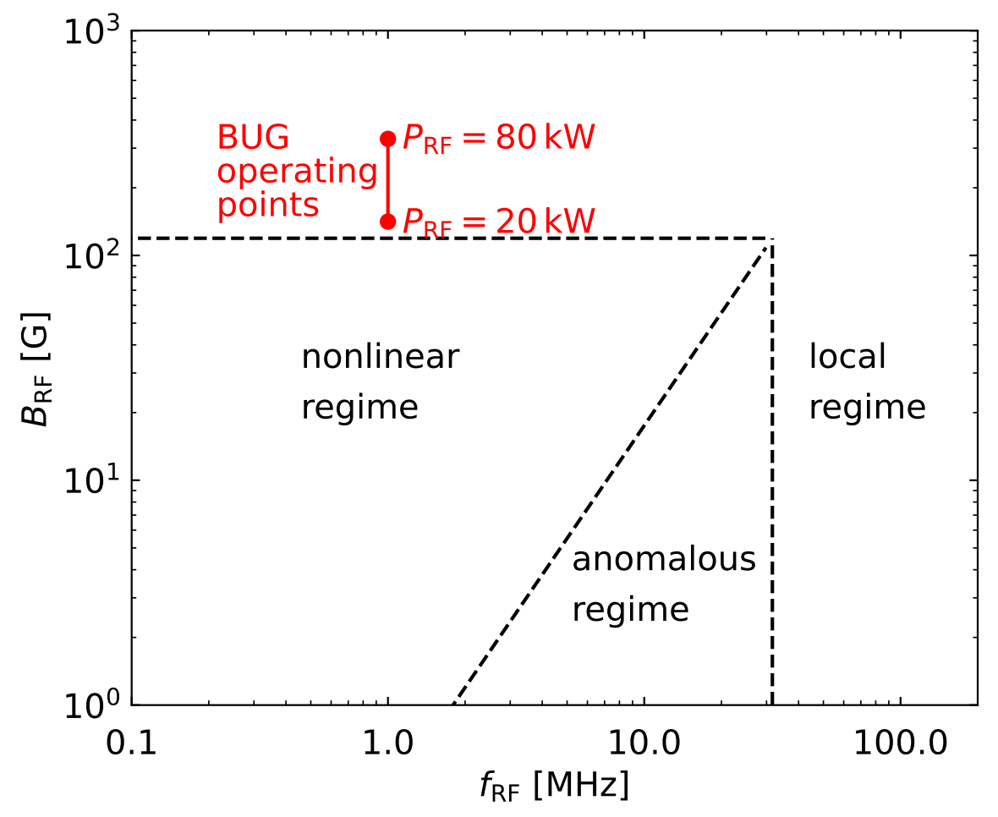
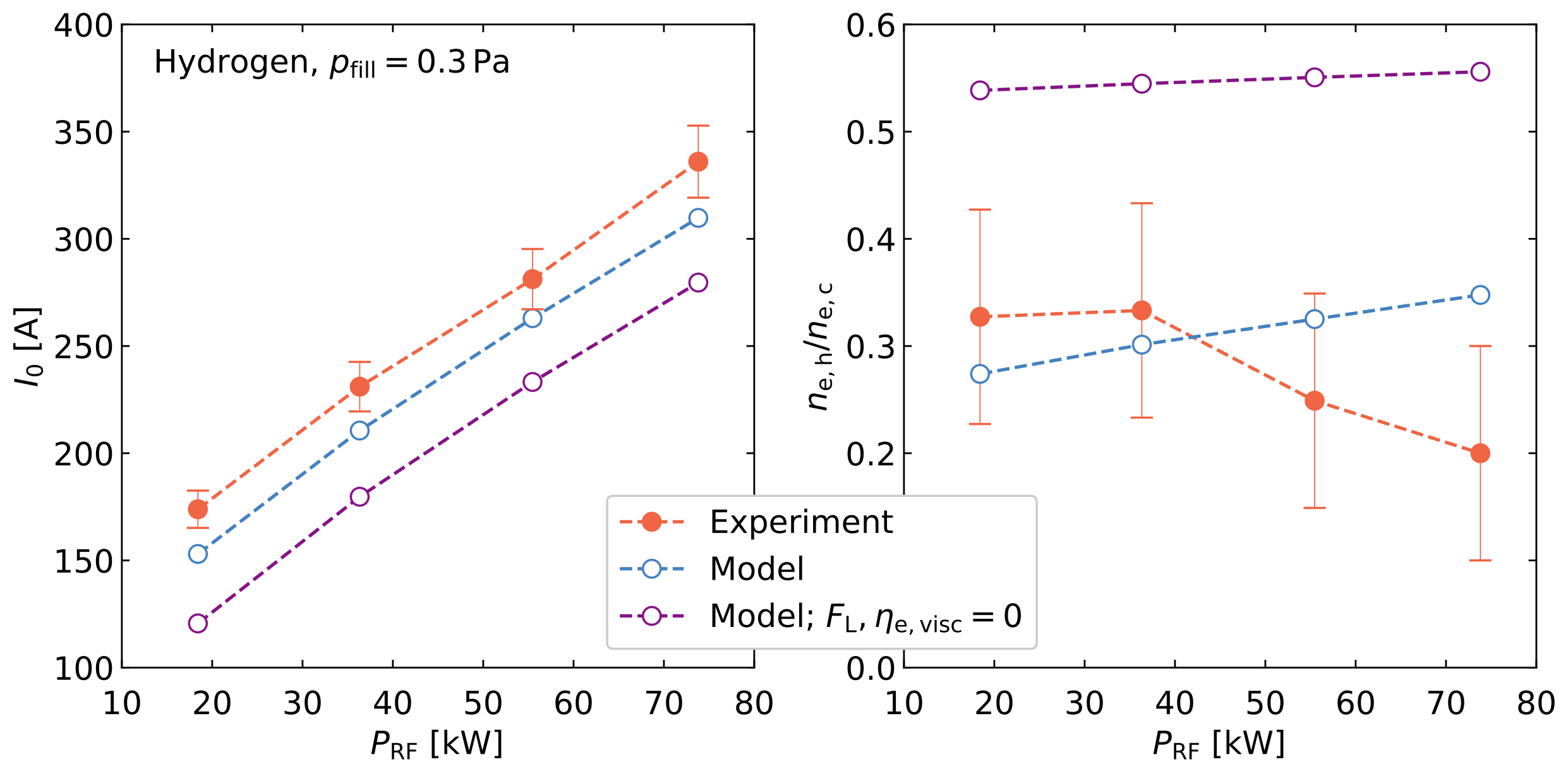


Figure adapted from Froese et al 2009 Physics of Plasmas 16, 080704

- Numerically obtained electrical & plasma parameters **in good agreement** with experimentally obtained ones **only if the Lorentz force & viscosity are retained**



➔ **RF Lorentz force & viscosity essential for steady state numerical solution within the error bars of the experimental measurements**

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