Expanding ASTRA: A unified framework for tokamak and stellarator transport modelling

F. Solfronk*[1,2], E. Fable[1], E. Buglione-Ceresa[1], G. Tardini[1], M. Zanini[3], S. Kwak[3], H. Zohm[1], and the W7-X Team[4]
[1]Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
[2]Ludwig-Maximilians-Universität München, 80539 München, Germany
[3]Max-Planck-Institut für Plasmaphysik, 17491 Greifswald, Germany
[4]see the author list of O. Grulke *et al* 2026 *Nucl. Fusion* **66** 116003

INTRODUCTION / MOTIVATION

Fenix flight simulator [1]:

- Simulates entire discharges using ASTRA transport solver [2,3] to model the plasma and a simulated control system in the framework of PCSSP (Plasma Control System Simulation Platform) [4]

→ Development of the first stellarator flight simulator

- Reduced models and current diffusion equation in ASTRA were initially derived for tokamaks

Extension of ASTRA8 code to stellarator physics:

- Implementation of a generic current diffusion equation [5]
- Coupling to a 3D equilibrium solver [5,6]
- Calculation of neoclassical transport and bootstrap current in 3D geometry [7]

UPGRADING ASTRA8 FOR STELLARATORS [5,6,7]

Upgraded current diffusion equation [5]:

$$\left.\frac{\partial\Psi}{\partial t}\right|_{\rho} = \frac{2\pi B_0\rho}{\sigma_{\parallel}\mu_0}\left(S_{21}\iota + S_{22}\right)^2 \frac{\partial}{\partial\rho}\left[\frac{1}{S_{21}\iota + S_{22}}\left(\frac{S_{11}}{2\pi B_0\rho}\frac{\partial\Psi}{\partial\rho} + S_{12}\right)\right] - \frac{V'}{2\pi\rho\sigma_{\parallel}}\left(j_{BS} + j_{CD}\right)$$

→ Valid for both stellarators and tokamaks (S_{12} and S_{21} are only nonzero for nonaxisymmetric devices)

→ Ψ is the poloidal magnetic flux, $\iota \equiv \partial\Psi/\partial\Phi$ is the rotational transform

→ S_{ij} are 3D geometrical factors as defined in [5]

- Robin boundary condition based on external circuit equation:

$$\begin{aligned} U_{\text{ext}} &= U_{\text{pl}}(\rho_{\text{B}}) + \frac{d}{dt}\left(L_{\text{ext}} I_{\text{tor}}\right) \\ \Leftrightarrow \quad \Psi(\rho_{\text{B}}) + L_{\text{ext}} \frac{S_{11}(\rho_{\text{B}})}{\mu_0} \left.\frac{\partial\Psi}{\partial\rho}\right|_{\rho_{\text{B}}} &= \Psi_{\text{ext}} + \frac{2\pi B_0 \rho_{\text{B}}}{\mu_0} L_{\text{ext}} S_{11}(\rho_{\text{B}})\,\iota_{\text{vac}}(\rho_{\text{B}}) \end{aligned}$$

Furthermore:

- Coupling to the **3D equilibrium solver VMEC** [8] to ensure a self-consistent evolution of the equilibrium [5,6]
- Coupling to **DKES** [9] via look-up tables to enable the calculation of **neoclassical transport coefficients** and the **bootstrap current**, and the evolution of the **radial electric field** [7]

VALIDATION AGAINST A W7-X DISCHARGE

- Simulation of W7-X discharge 20171206.036
- n_e and T_e profiles are taken from the experiment
- ECCD current density calculated using TRAVIS [10]

Two cases:

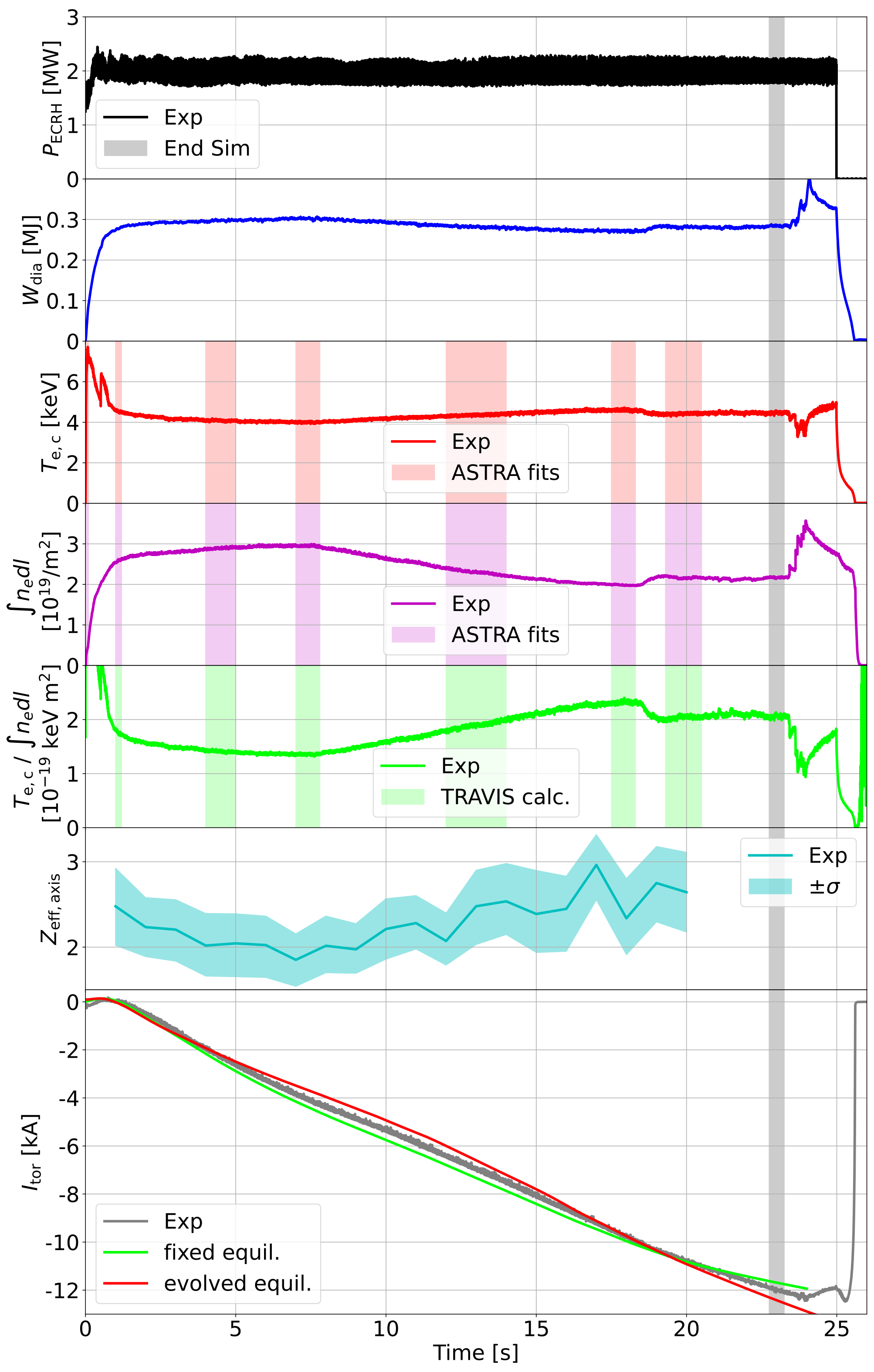
1. As in [5]: fixed equilibrium; $\sigma_{\parallel}$ calculated using the expression from [11]; bootstrap current approximated using a parabolic profile with a total current of 2.5 kA

2. Evolved equilibrium; $\sigma_{\parallel}$ and bootstrap current calculated as in [7]

→ In both cases, the simulated total toroidal current matches the experimental evolution

→ Remaining deviations can easily be explained by error bars in n_e, T_e, and Z_{eff} profiles

→ Difference between the case with fixed equilibrium and the case with self-consistent equilibrium evolution can be observed, but the overall behaviour of the current evolution remains unchanged



SUMMARY / OUTLOOK

- Validation of the generic current diffusion equation with self-consistent calculation of the equilibrium [6], and computation of parallel conductivity and bootstrap current for stellarators [7]

→ Evolution of the total toroidal current matches the experiment

- Investigation of the dynamic response of stellarator current profiles to modulated current drive

→ Local and global current evolution occur on different timescales

→ Self-consistent evolution of the equilibrium transforms the linear response of oscillatory current drive into a nonlinear dynamical evolution, generating additional frequency components through feedback between current diffusion and equilibrium evolution

NONLINEAR CURRENT RESPONSE

Oscillatory ECCD:

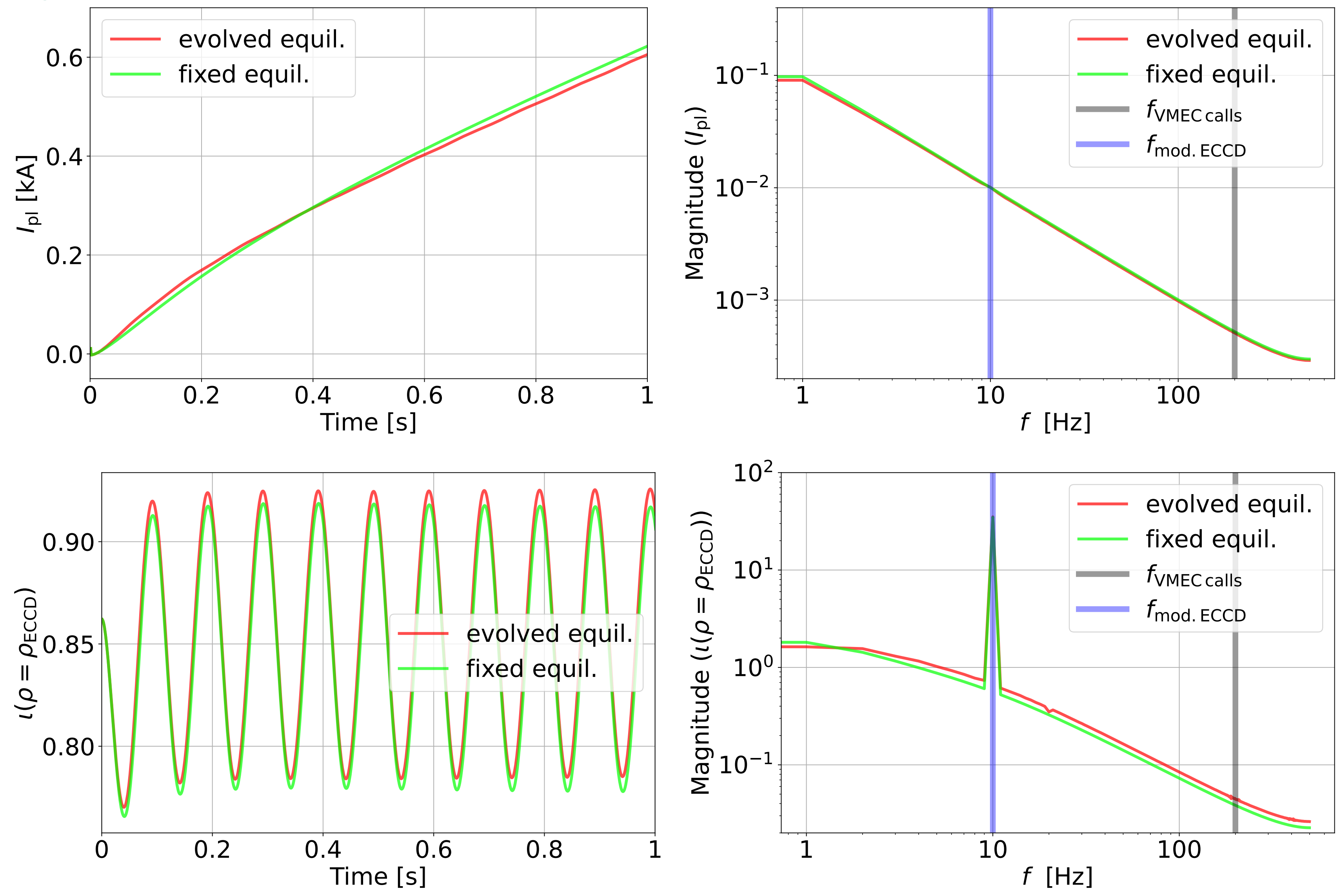
- T_e, n_e, and Z_{eff} taken from W7-X discharge 20171206.036 at 7.8 s
- Calculation of bootstrap current using DKES coupling described in [7]
- ECCD:

$$j_{\text{ECCD}}(t) = \sin\left(\frac{2\pi}{T}t\right) j_{\text{ECCD,t=7.8\,s}}$$

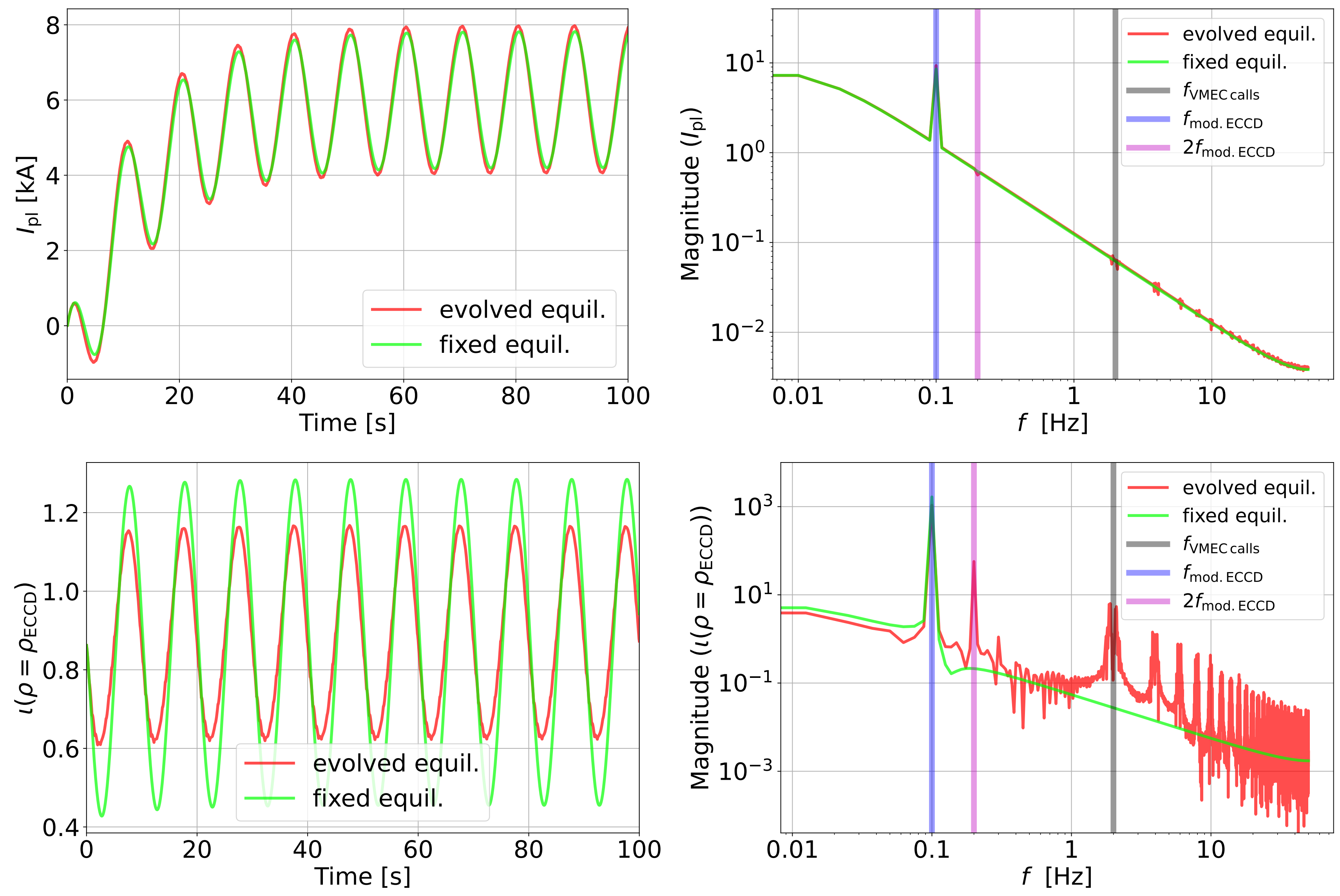
Comparison:

1. Low vs. high frequency (T_1 = 0.1 s; T_2 = 10 s)
2. Fixed vs. self-consistently evolved equilibrium

High frequency case (T = 0.1 s):



Low frequency case (T = 10 s):



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*Corresponding author: fabian.solfronk@ipp.mpg.de

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