Modelling current and pressure evolution in Gauss Fusion stellarator power plant

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Introduction. In a fusion power plant, the preferred choice for heating the plasma is electron cyclotron resonance heating (ECRH). However, in existing experiments, purely ECRH-heated plasmas show poor coupling between electrons and ions, and therefore it is important to develop a self-consistent and predictive tool that simulates, in a stellarator, the plasma equilibrium and profiles evolution between start-up and fusion self-heating phases. In this work, simulations of the current and pressure evolution during ECRH ramp-up are presented. The considered magnetic equilibrium is that of GIGA, a stellarator power plant currently being developed by Gauss Fusion GmbH. The current-diffusion simulations are performed with the THRIFT code which evolves the total toroidal current in time and has been recently integrated with the neoclassical codes DKES+PENTA which compute the bootstrap current. Current diffusion simulations of GIGA show that the inductive current will take about 1 hour to fully diffuse away. During this transient phase, the time-variations of the edge iota are small and should produce little displacement of the divertor strikelines – an essential requirement for the operation of an island-divertor.

Self-consistent current evolution in a stellarator. Due to the finite plasma resistivity $\eta_{\parallel}$, the net toroidal current I in a stellarator does not instantaneously match the non-inductive current $I_{NI} = I_{BS} + I_{ECCD}$. Instead, $I(t) = I_{NI}(t) + I_i(t)$, where I_i is the inductive current which has a decay time of $\tau_{L/R} \sim a^2 \log(8R_0/a)/\eta_{\parallel}$. The toroidal current evolves as [1]:

$$\frac{\partial I(r,t)}{\partial t} = \frac{S_{11}}{\Phi_a^2}\frac{\partial}{\partial r}\left[\eta_{\parallel} V'\left(\frac{\langle B^2\rangle}{\mu_0}\partial_r I + p' I - \frac{\Phi_a}{\mu_0}\langle J_{NI} B\rangle\right)\right] \qquad (1)$$

S_{11} is the susceptance which only depends on the magnetic field, Φ_a is the toroidal flux at the LCFS and p is pressure. As illustrated in Figure 1, the self-consistent evolution of the total current requires coupling with an MHD equilibrium code (that solves for B given I and p), a neoclassical code that provides the bootstrap current, and a code/model for the externally driven current.

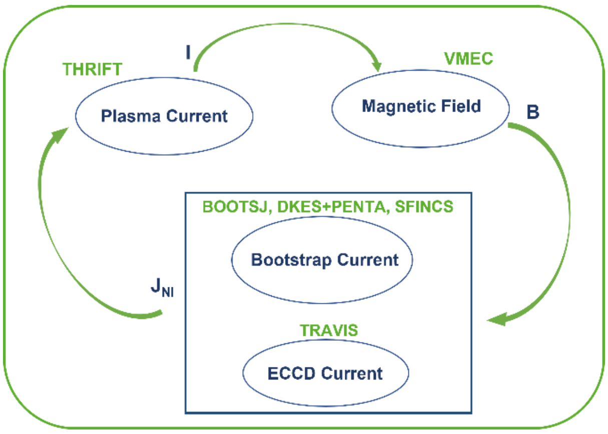

Figure 1. Self-consistent current evolution

THRIFT is a code part of the STELLOPT package which solves Eq. (1) in a self-consistent way. It has been recently modernized and verified, and comparison against W7-X discharges were made [2]. The comparison revealed that the code was able to predict the time scale for current decay in W7-X discharges, but not the magnitude of the total current. The discrepancy was attributed to the modelling of the bootstrap current with the BOOTSJ code, which makes use of a semi-analytical model only valid in the collisionless limit. In the present work, we overcome that issue by integrating the neoclassical codes DKES+PENTA in THRIFT. While DKES solves the 3D drift-kinetic equation and computes mono-energetic diffusion coefficients [3], PENTA corrects these coefficients to account for momentum conservation and parallel flows [4,5]. This is a relatively fast and accurate way of computing J_{BS}. Besides, PENTA not only provides J_{BS} and $\eta_{\|}$, which are needed to solve Eq. (1), but also the ambipolar radial electric field and the neoclassical fluxes, which can be used to assess other properties of the plasma such as transport and fast particle confinement.

GIGA equilibrium and time-dependent profiles along the Cordey Path. We consider the magnetic equilibrium of GIGA, a stellarator power plant currently being developed by Gauss Fusion GmbH to produce 1GWe by 2040s. The equilibrium is a result of a multi-stage optimization that started with the W7-X high-iota magnetic configuration harmonics as defined in [6]. GIGA has 4 field periods, major radius R_0=20.0m, aspect ratio R_0/a = 10 and a vacuum magnetic field B_0=6T. The Poincaré cross sections at different toroidal angles are shown in Figure 2.

Pressure evolution can be added to THRIFT via coupling with a transport solver. In the present work, however, we do not solve the transport equations, but instead assume a 6th order polynomial for density and a linear profile for temperature, as motivated by experimental observations:

$$n_e(\rho, t) = n_0(t)\left[f_{edge} + \left(1 - f_{edge}\right)(1 - \rho^6)\right]$$

$$T_{e,i}(\rho, t) = T_0(t)\left[f_{edge} + \left(1 - f_{edge}\right)(1 - \rho)\right]$$

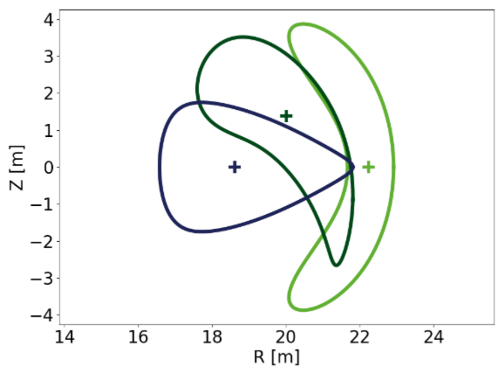

Figure 2. GIGA cross sections

The time-dependent values on axis, $n_0(t)$ and $T_0(t)$, are emulated assuming a transport time-scale of 1s for energy and 5s for density. We consider a plasma with equal deuterium and tritium densities, 5% of helium ash, 1% of protium and 0.01% of tungsten. We set f_{edge}=0.01 and consider that all species have the same temperature. Starting from a low-density, low-temperature state, plasma reaches a high-density operational regime by moving along the Cordey Path, indicated with a black dashed line in the POPCON plot shown in Figure 3.

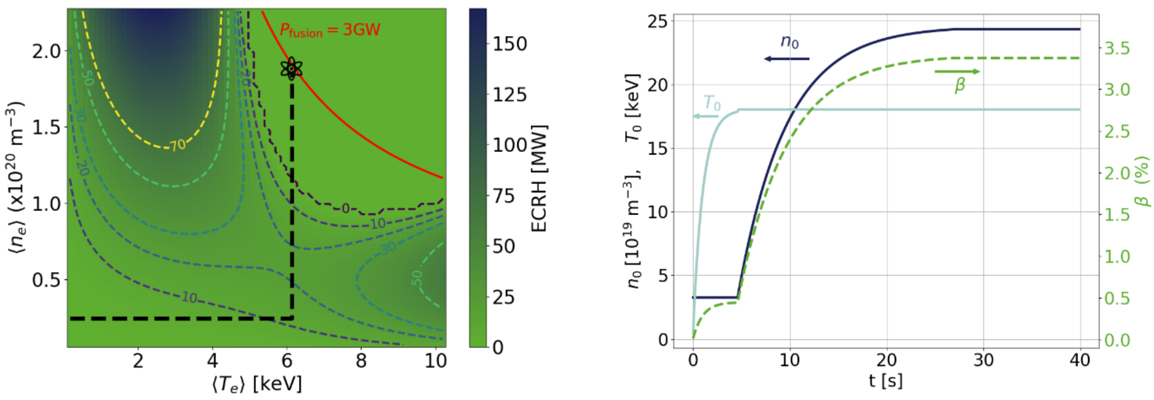

Figure 3. (Left) POPCON plot with simplified Cordey Path in dashed black line. (Right) Density, temperature and total beta time evolution. Plasma starts from a low-density, low-temperature state until it reaches 3GW of fusion power (1GWe)

Current diffusion. Current-diffusion simulations of GIGA using THRIFT show that the inductive current will take about 1 hour to diffuse away (Figure 4, left). Although during this transient phase the rotational transform profile changes, the variations of iota on the edge are small (Figure 4, right), therefore allowing for a 4/4 island divertor to be safely used. In the core, however, iota crosses 4/5 in the transient phase, which can be harmful if no actuator acts to revert the appearance of an island. This suggests that further optimization of the equilibrium might still be needed.

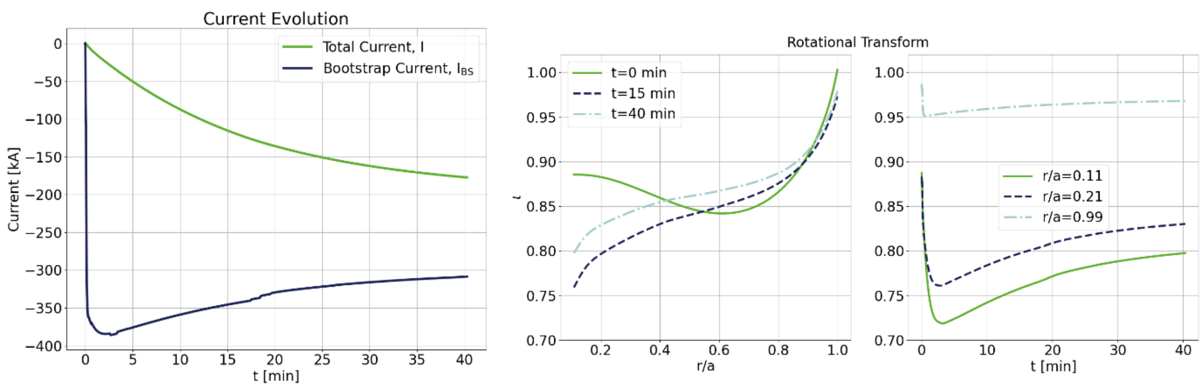

Figure 4. (Left) THRIFT evolution of total and bootstrap current in GIGA power plant. (Middle) Rotational transform profile at t=0;3;28 min. (Right) Time evolution of rot. transform at selected radial positions

Comparison DKES+PENTA with SFINCS. Neoclassical codes that solve the 4D drift-kinetic equation exempt the calculation of mono-energetic coefficients. However, they are computationally expensive and integrating them in THRIFT would highly compromise the time to solution. We show that the results of DKES+PENTA compare well with one of these codes, SFINCS [7], at both low and high collisionalities. We consider a case where $\nu^*(r)$ varies between $[10^{-2}, 10^{0}]$ and another case where $\nu^*(r)$ is in the range $[10^{0}, 10^{2}]$. Not only the bootstrap current compares well in both cases (see Figure 4), but also the ambipolar radial electric field is essentially the same, with both codes predicting an ion root. The particle and heat neoclassical fluxes also compare well (not shown here).

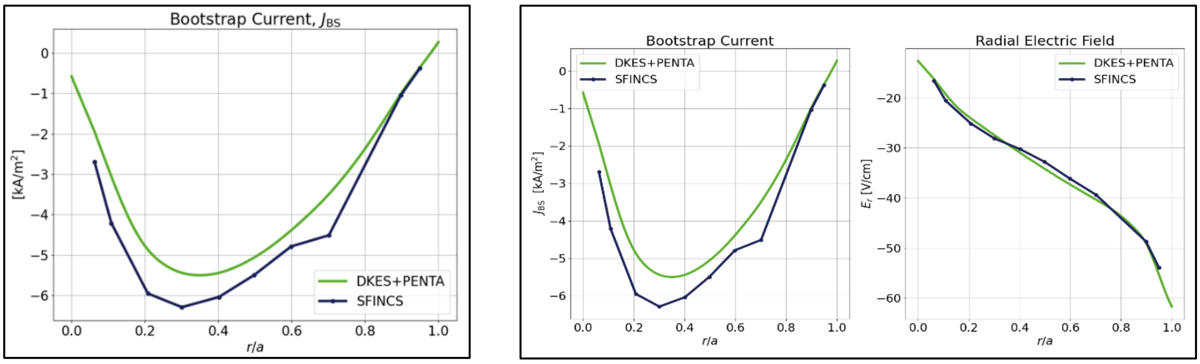

Figure 5. Comparison between DKES+PENTA and SFINCS at (left) high and (right) low collisionality.

Overall, the good agreement between DKES+PENTA and the more sophisticated model employed by SFINCS gives us confidence in the results of THRIFT when using DKES+PENTA. The fact that these compare well should not be, however, of big surprise. In [7] it is shown that when the ambipolar electric field is far from the resonance E_r^{res}=r*iota*B*c_s/R, the approximations employed by DKES are valid. For ion temperatures ranging from 20eV to 20keV, E_r^{res} >180 V/cm. For all r/a>0.1, this value is twice the maximum absolute value of E_r in GIGA (Figure 4 right). Finally, we note that without PENTA corrections, the bootstrap current given by DKES would be one order of magnitude different, no matter the collisionality, thus showing that momentum corrections are important even when ν^* is small.

Conclusions. The self-consistent evolution of the total current in a stellarator power plant is important to verify that (1) the rotational transform in the core does not cross undesirable low-order rationals in the transient phase; and (2) that the time variations of iota on the edge are compatible with the good functioning of an island divertor. By integrating the neoclassical codes DKES+PENTA into the current diffusion simulation code THRIFT, we have verified that the second condition is clearly met by GIGA, where a 4/4 island divertor can be safely placed in the edge. In the core, however, iota crosses 4/5, suggesting that further optimization of the equilibrium might still be required.

References

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