SELF-CONSISTENT SIMULATIONS OF ICRH WITH THE BACKGROUND EQUILIBRIUM IN TOKAMAKS AND STELLARATORS

TECHNICAL NOTE

W. A. COOPER,[a]* M. JUCKER,[b] and J. P. GRAVES[a]

[a]*Association Euratom-Confédération Suisse, Centre de Recherches en Physique des Plasmas Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*
[b]*Princeton University, Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey 08540-6649*

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The SCENIC code package has been developed to integrate self-consistently an anisotropic pressure magnetohydrodynamic equilibrium state with power absorption from ion cyclotron resonance heating and with a guiding center particle distribution function for the energetic particles generated in three-dimensional geometry. The main novelty constitutes the inclusion of the background equilibrium state in the iterative procedure, an approach that has not been previously addressed. Applications to tokamaks and stellarators demonstrate viability of the model considered.

KEYWORDS: *stellarator, tokamak, integrated modeling*

Note: Some figures in this technical note may be in color only in the electronic version.

The SCENIC integrated code package[1] determines self-consistent ion cyclotron resonance heating (ICRH) simulations involving the equilibrium state, the heat deposition due to the ICRH waves, and the hot ion distribution function. Three-dimensional (3-D) tokamak and stellarator magnetohydrodynamic (MHD) equilibrium states with imposed nested magnetic flux surfaces are computed with the ANIMEC code,[2] an anisotropic pressure variant of the 3-D VMEC code.[3] The wave propagation and absorption in an ANIMEC background equilibrium is calculated with the LEMan code.[4] The hot particle guiding center drift orbits are followed with the VENUS code.[5] A radio-frequency–particle interaction operator is implemented in the VENUS code to provide Monte Carlo kicks to particles that cross the resonant layer.[6,7] Fits to the moments of the resulting distribution function are approximated with a special bi-Maxwellian distribution function. The anisotropic pressure model in the ANIMEC code adopts the same bi-Maxwellian for the determination of the MHD equilibrium and the dielectric tensor in the wave code LEMan. Iterative computations of the MHD equilibrium state, the ICRH wave absorption by a minority species at the ion-ion hybrid layer, and the energetic particle distribution function are undertaken until a converged solution is achieved. A schematic diagram of the interactions between the three computational tools encompassed in SCENIC is described in Fig. 1 for the interactive evaluation of self-consistent solutions between the anisotropic pressure equilibrium state, the absorption of ICRH waves, and the fast particle distribution function. Typically, all previous calculations have only considered back-and-forth interactions of the ICRH waves with the distribution function, ignoring the impact on the background equilibrium.[6–10] Applications to the JET tokamak[11] and a quasi-axisymmetric stellarator[12] demonstrate the validity of this approach.

The generation of self-consistent ICRH solutions in JET involved minority heating of a 1% concentration of helium-3 ions in a deuterium plasma with a central

*E-mail: wilfred.cooper@epfl.ch

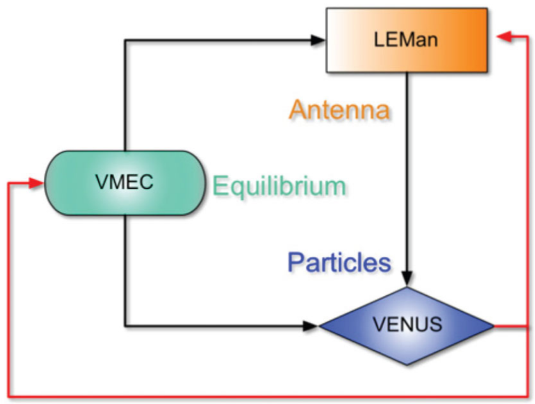

Fig. 1. Schematic diagram of the iteration procedure between the anisotropic pressure equilibrium solver VMEC/ANIMEC, the wave field solver LEMan, and the guiding center particle code VENUS.

electron temperature of 3.5 keV and a central electron density of 3.4×10^{19} m^{-3}. In Fig. 2, the mean energy of the minority helium-3 ions is plotted as a function of time (normalized to the slowing-down time $t_{\_s}$) for cases with only a single iteration, as well as with 2, 8, and 16 iterations. Converged solutions for the mean hot particle energy are reached in about 2.5 slowing-down times. Between two and eight iterations are required to obtain acceptably converged results. A similar application to a two-field quasi-axisymmetric stellarator[13,14] scaled to a JET-sized plasma with a magnetic field on axis of $B_0 = 2.57$ T; central electron density and temperature of 3×10^{19} m^{-3} and 3 keV, respectively; and plasma volume of 37.3 m^3 in a deuterium plasma with a 1% helium-3 minority concentration is explored.

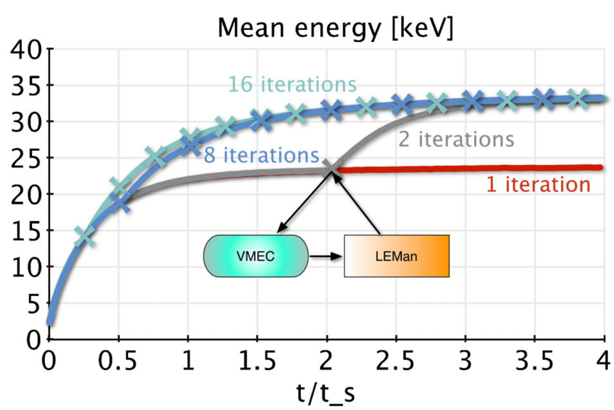

Fig. 2. The mean fast particle energy in JET after 1, 2, 8, and 16 iterations between the anisotopic VMEC/ANIMEC equilibrium, the ICRH wave absorption (LEMan), and the guiding center particle orbit minority ion distribution function (VENUS). The slowing-down time is denoted by $t_{\_s}$.

The toroidal current varies between 1 and 4.5 kA, depending on the input ICRH power, but this only weakly affects the rotational transform. The number of marker particles in the VENUS simulations was 4×10^6. High field side deposition calculations converged in 2.7 slowing-down times applying 16 iterations lasting 25 ms each with 6-MW input power. The localized deposition of ICRH power on the high field side causes the fast particle contribution to the perpendicular pressure to concentrate in this region of the plasma (the pressure ceases to remain a flux surface quantity) and depresses slightly the magnitude of the equilibrium magnetic field strength around the resonant layer. The heating efficiency of low field side ICRH deposition is poor. The hot particle perpendicular pressure obtained from the VENUS guiding center particle code on a number of toroidal cross sections is displayed in Fig. 3.

Strong 3-D plasma effects that are of particular interest in tokamaks arise from helical cores associated, in particular, with high-β hybrid operation. In the future, it will be important to simulate ICRH heating scenarios in such a challenging environment. Fixed and free boundary computations of such hybrid-like tokamak scenarios lead to bifurcated equilibrium states, as obtained with ANIMEC, even when the plasma boundary is axisymmetric. One solution corresponds to the standard axisymmetric branch. The second branch displays a 3-D helical

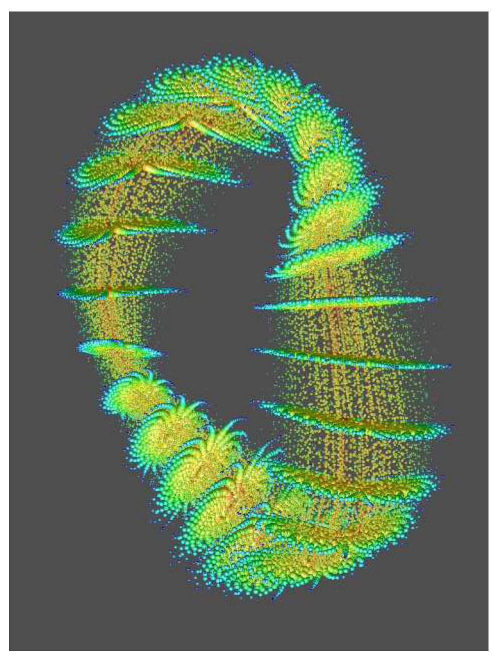

Fig. 3. The fast particle perpendicular pressure in a two-field period quasi-axisymmetric stellarator configuration in real space calculated from the corresponding moment of the hot helium-3 ion distribution function component obtained with the VENUS code[5] for a case with high field side ICRH deposition.

core similar to a saturated ideal internal $m/n = 1/1$ kink mode. This 3-D bifurcation represents a viable model for snakes observed in tokamaks.[15] The spectrum of Boozer coordinate[16] modes broadens significantly at the interface between the 3-D helical core and the axisymmetric mantle. This complicates the study of physical phenomena, such as orbit analysis and ICRH deposition with codes like LEMan and VENUS (which are based on a Boozer coordinate description), as the effort can become computationally very expensive.

In summary, the main novelties of the SCENIC package[1] are (a) self-consistent inclusion of the anisotropic pressure equilibrium state fitted with a fast particle bi-Maxwellian distribution function in the iterative solution and (b) the model allows for 3-D geometry applications, hence, tokamaks with 3-D helical cores (i.e., snakes, long-lived modes, etc.), as well as applications to general stellarator configurations as illustrated in Fig. 3 in the investigation of ICRH in a quasi-axisymmetric stellarator device.

Detailed descriptions of self-consistent simulations of ICRH in tokamaks and stellarators summarized here can be found in Refs. 1, 11, and 12.

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