VALIDATION OF BOOTSTRAP CURRENT MODELS IN LHD PLASMAS

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1. Introduction

Numerical tools to calculate the neoclassical bootstrap current in non-axisymmetric magnetic configurations use several models and approaches. The fast SPBSC code [1] is based on a quasi-analytical fluid moment approach using a monotonic approximation (connection formula) between the semi-analytical limits. A module of the 3D ideal MHD TERPSICHORE code computes the bootstrap current in the collisionless limit taking into account a wide spectrum of the magnetic field in Boozer coordinates in addition to a resonance detuning procedure [2]. The more time-consuming VENUS+δf code [3] uses guiding centre numerical orbits in Boozer coordinates calculated with the TERPSICHORE code, Monte Carlo pitch angle scattering and a δf method to compute the neoclassical bootstrap current. New correction terms of the improved collisional operator [4] which satisfy momentum, energy and particle number conservation have been implemented recently in the VENUS+δf code. Good agreement of the monoenergetic bootstrap current coefficients for various stellarator configurations (LHD, NCSX, W7X) was obtained with the DKES, VENUS+δf, NEO-MC and NEO-2 codes [5]. The SPBSC and VENUS+δf numerical predictions have been performed on experimental Large Helical Device (LHD, NIFS, Japan) configurations with different magnetic axis positions, zero electric field and simplified plasma density and temperature profiles [6].

In this paper, we use experimentally obtained plasma density and temperature profiles to compute with the SPBSC, TERPSICHORE and VENUS+δf codes the corresponding magnetohydrodynamic equilibrium states and the neoclassical bootstrap current for the LHD discharge #61863 with the magnetic axis $R_{axis} = 3.90\ m$ (Section 2) and for the LHD discharge #82582 with the magnetic axis $R_{axis} = 4.05\ m$ (Section 3). The measured LHD bootstrap current [7] (with the help of motional Stark effect) is compared with that expected from neoclassical simulations.

2. Bootstrap current in the LHD discharges #61863

Figure 1 shows the experimentally measured electron density (circles) and temperature (stars) profiles versus the normalized toroidal flux label *s* at *t=3.1 sec* of the LHD discharge #61863 with R_{axis} *=3.90 m*. The electron density has rather flat profile, while the temperature drops linearly. Motional Stark Effect measurements provide the rotational transform profile estimation and the corresponding total current of about 10 kA [7]. In this discharge, balanced neutral beam injection has been used so the beam-induced current is small. The most probable candidate as a driving mechanism of the non-inductive current can be attributed to the bootstrap current.

The flux derivative of the total current dJ_{BS}/ds in the case of the equal impact of ions and electrons (which is our simplified assumption) is obtained from the equation $J_{BS}'(s) = 2\pi a^2 <j_{||}B>/B_0$, where $<j_{||} B>$ is the ion bootstrap current density, *a* is the average minor plasma radius. The total bootstrap current is $J_{BS}= \int_0^1 J_{BS}'(s)\, ds$. The bootstrap current flux derivatives dJ_{BS}/ds as a function of the normalized flux *s* for the LHD discharge #61863 are presented in Figure 2. The SPBSC and the TERPSICHORE code results in the collisionless limit are shown as triangles and by the red solid line, respectively. Some difference is visible near the magnetic axis, where the numerically obtained equilibrium force balance is poor. Near the plasma edge, the TERPSICHORE code has found 2 resonant surfaces (2 spikes on the red curve). The integration of the dJ_{BS}/ds function gives a total bootstrap current J_{BS} of 18 kA from the TERPSICHORE code, J_{BS} of 10 kA from the SPBSC code in the collisionless regime and 27 kA from the SPBSC code using the connection formula for the given experimental conditions. The total bootstrap current J_{BS} of 10 kA, calculated with the VENUS+δf code, is shown as circles with Monte Carlo error bars of 20%, which is in a good agreement with the experimentally obtained total bootstrap current of 10 kA.

3. Bootstrap current in the LHD discharges #82582

Figure 3 shows the experimentally measured electron density (circles) and temperature (stars) profiles versus the normalized toroidal flux label *s* at *t=3.9 sec* of the LHD discharge #82582 with R_{axis} *=4.05 m*. Bootstrap current derivatives dJ_{BS}/ds as a function of the normalized flux *s* are presented in Figure 4 with triangles (calculated with the SPBSC code in the collisionless limit), with the red solid line (TERPSICHORE code, collisionless limit), with the blue dotted line (SPBSC code, the connection formula) and with circles plus error bars from the VENUS+δf code. The integration of the dJ_{BS}/ds function, obtained in the collisionless limit with the SPBSC and the TERPSICHORE codes, yields small negative total bootstrap currents J_{BS} of about -2 kA. The connection formula, implemented in the SPBSC code, gives a total bootstrap current J_{BS} of -5.5 kA. The total bootstrap current, calculated with the VENUS+δf code is equal to -8±2 kA, which corresponds to the experimentally measured total current of -14 kA within a factor of 1-2.

Summary

Different bootstrap current models, implemented into the 3D neoclassical codes SPBSC and VENUS+δf, show reasonable agreement within a factor 1-2.5 with the experimentally obtained positive total bootstrap current of 10 kA in the LHD discharges #61863 with the magnetic axis of $R_{axis} = 3.90$ m and negative total bootstrap current of -14 kA in the LHD discharge #82 863 with $R_{axis} = 4.05$ *m*. More accurate bootstrap current simulations will include in the future the electric field and inductive current effects as well as the non-equal impact of electrons and ions.

Acknowledgments

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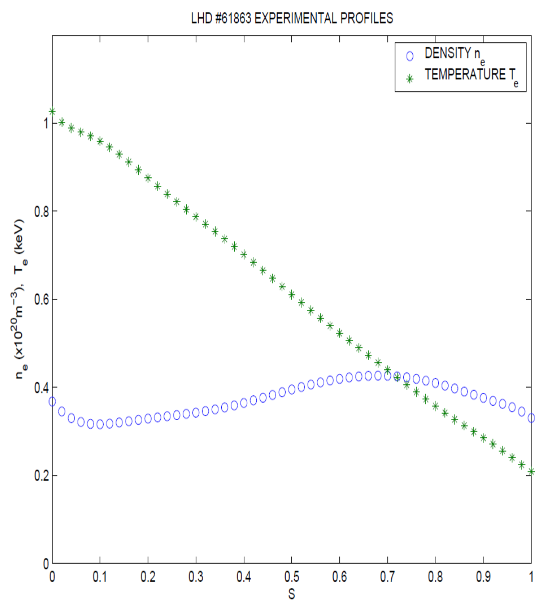

Fig.1. The electron density (circles) and the temperature (stars) versus the flux label *s* for the LHD discharge #61863 (R_{axis} =*3.90m*).

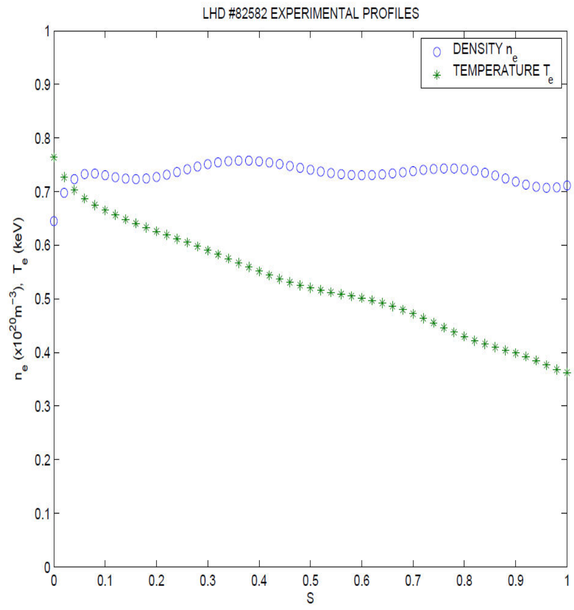

Fig.3. The electon density (circles) and the temperature (stars) versus the flux label *s* for the LHD discharge #82582 (R_{axis} =*4.05m*).

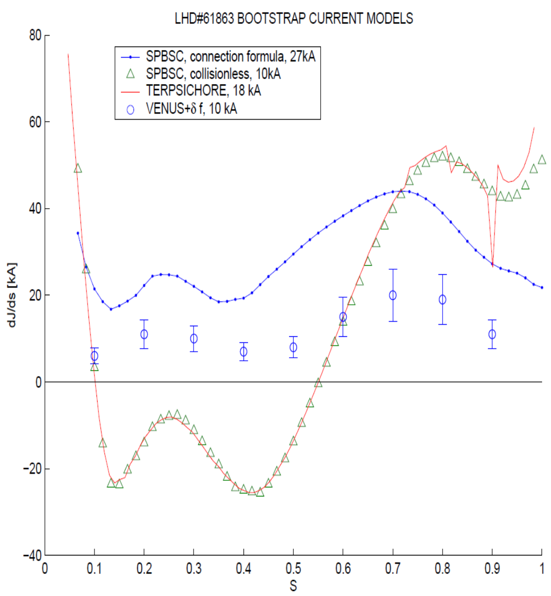

Fig.2. The LHD#61863 R_{axis} =*3.90m* bootstrap current derivative dJ_{BS}/ds versus the flux label *s* calculated with the SPBSC code in the collisionless limit (triangles), with the connection formula (blue dotted line), with the TERPSICHORE code (red solid line) and with the VENUS+δf code (circles).

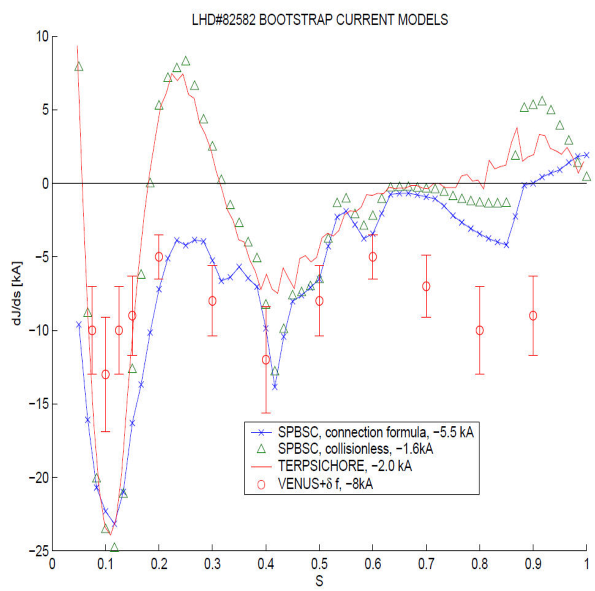

Fig.4. The LHD#82582 R_{axis} =*4.05m* bootstrap current derivative dJ_{BC}/ds versus the flux label *s* calculated with the SPBSC code in the collisionless limit (triangles), with the connection formula (blue dotted line), with the TERPSICHORE code (red solid line) and with the VENUS+δf code(circles).