Full-wave simulation of mode-converted electron Bernstein waves at very low magnetic field in the SCR-1 Stellarator

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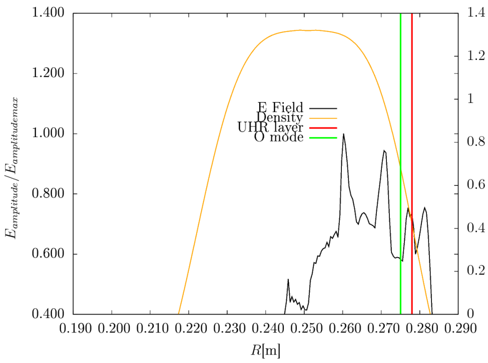
Introduction

The SCR-1 stellarator is a two periods modular stellarator (R =247.7 mm, R/a =6.2, ι_a =0.264) whose is equipped with an ECRH system which maximum input power is 5 kW and heats at second harmonic with microwaves at 2.45 GHz. The coil configuration is of 12 copper modular coils with 4.6 kA-turn each [1]. Plasma heating and magnetic field configuration are important and challenging topics for small devices due its complexity and limitations when optimizing them. This contribution provides new computational results related with single O-X pass conversion with microwave heating scenarios at very low magnetic field strength (43.8 mT at the center) performed by the IPF-FDMC full wave code. The BS-SOLCTRA (Biot-Savart Solver for Computing and Tracing magnetic fields) code also has been improved with a better visualization quality and parallel execution that turns into an easy, high-performance computing platform. Vacuum magnetic flux surfaces measurements are compared with the BS-SOLCTRA code calculations to verify the design and correct position of the coils. Preliminary measurement analysis and design of a bolometer and magnetic diagnostics are presented.

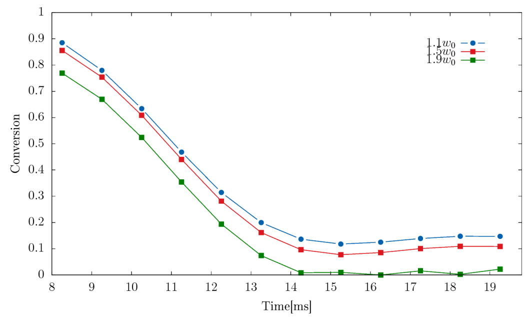
Microwave Heating Scenarios

The generation of electron Bernstein waves in SCR-1 plasma was studied through the coupling between the incident electromagnetic radiation and charged particles of the plasma. The microwave scenarios performed with the IPF-FDMC full wave code allowed to recognize the localizations along the radial coordinate at the $z = 0$ position where this coupling occurred by looking for high variations of the electric field amplitude of the incident electromagnetic radiation [2]. The IPF-FDMC full wave input parameters were obtained by VMEC equilibrium and the value of the experimental electron line-averaged density.

The analysis of different locations of the microwave full wave scenario at a toroidal angle of 330° with injected electromagnetic waves at a toroidal position of 58° is shown in subfigure 1a. It was possible to identify an upper hybrid frequency resonance because there are strong perturbations of the electric field amplitude of the incident electromagnetic radiation wave on the front of the magnetic flux surface [3]. The percentage of single pass conversion from O mode to X mode is shown in subfigure 1b. There was a decay as time progressed while radiation was propagating into the plasma due to the steady state situation not yet being reached, then it was almost constant. The percentage of conversion was between 12% and 14% for a beam size of $1.1w_o$. Besides, there was an improvement when the beam size was reduced. Experimentally corroboration must be done with a radiation deposition profile and ion density profile to calculate the ratio between ion-electron collision frequency and injected electromagnetic wave frequency. It is a fundamental parameter because it establishes whether ion-electron collisions are the dominant damping of the electron Bernstein waves[4].



(a) Amplitude oscillations of the electric field of injected microwave electromagnetic field



(b) Conversion percentage for different beam sizes

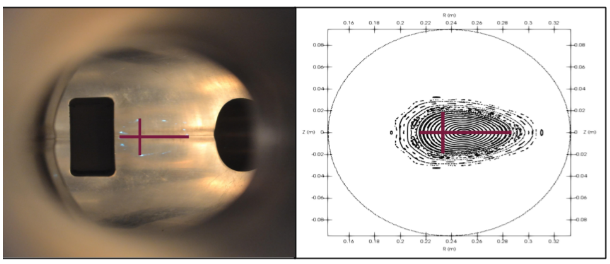
Figure 1: Results from the IPF-FDMC full wave code

The BS-SOLCTRA code

The Biot-Savart Solver for Computing and Tracing magnetic fields (BS-SOLCTRA) simulates a 3D vacuum magnetic field using Biot-Savart's Law and a simplified model of the twelve modular coils present in the SCR-1, allowing for the visualization of magnetic flux surfaces. The first serial implementation could last hours or even days tracing a few particles during a given number of simulation steps. Due to performance demands, the computationally intensive portion of the code was ported from Matlab to C++ and parallelized [5]. The computationally intensive component of BS-SOLCTRA implements a fourth order Runge-Kutta method (RK4), to trace the trajectory of each particle along the magnetic field lines. The effect of each coil upon an observation point r is estimated using Biot Savart fields of a filamentary segment [6]. Two well known parallel programming technologies, namely the Message Passing Interface library (MPI) and the Open Multi-Processing API (OpenMP), were chosen to create independent processes that can handle the subsets of particles. As part of the initial BS-SOLCTRA version, a Matlab program had been developed to find and display magnetic surfaces at specific toroidal angles using Poincaré maps. This code was not part of the parallelized components and in an effort to turn BS-SOLCTRA into a simulation-visualization infrastructure, is currently being integrated into the visualization workflow by CeNAT research group. By using the Poincaré sections determined by the Matlab code, which uses the trajectories obtained from the BS-SOLCTRA, we are generating visualizations in Paraview to better explain the behavior of confined plasma. We are currently working on porting the Matlab Poincaré code to Python to take advantage of the ease of integration with Paraview, which also can be used on parallel computer clusters. We plan to use this visualization features to study other plasma phenomena that can be extracted with the Field Line Tracing technique used by BS-SOLCTRA.

Magnetic Mapping Experiment

The magnetic mapping was performed in order to verify the correct position of the SCR-1 coils. The experimental arrangement consisted in an e-gun (an electrically heated tungsten filament emits electrons which are accelerated by an electrical potential difference) which generated an electron beam that followed the magnetic field line and impacted a fluorescent target with zinc oxide [7]. Photos were taken with an exposure time of 2.5 s. Three different targets were used. The measurements were compared with the improved version of BS-SOLCTRA in figure 2. The magnetic axis was corroborated and magnetic flux surfaces coincided with the magnetic field lines tracing.



(a) (b)

Figure 2: Comparison between (a) the experimental results and (b) simulations with BS-SOLCTRA code

Measurement of the total radiated power in SCR-1

To obtain measurements of the total radiated power of the SCR-1 plasma, an array of silicon photodiode detectors, such as absolute extreme ultraviolet devices (AXUV) will be used. According to the preliminary estimations relying on the electron temperature measurements in SCR-1 the region of major radiative loss is in the ultraviolet, so an AXUV photodiode will be useful for diagnosis because these detectors can be used to cover the photon spectral range from 0.0124 nm to 1100 nm and could be used for detection of low energy electrons and ions. The array of detectors will be designed to be placed inside SCR-1 vacuum chamber and make local radiated power measurements, then to extrapolate them to obtain the global radiated power of the SCR-1 plasma.

Measurement of the components of the plasma currents in SCR-1

A preliminary analysis for the measurement of local and global plasma currents by a basic arrangements of induction coils for the poloidal and toroidal components of the magnetic field induced by those currents in SCR-1 has been done. The first approach to measure the plasma current will consist in creating a basic arrangements of coils known as Rogowski coils. It is important to note that both systems will be placed outside of the vacuum chamber (because placing them inside carry extra problems), and they will use a coated magnetic wire or shrink tuber for isolation. The microwave heating system will be modulated to extract the plasma current from the signals in the Rogowski coils.

Conclusions

Important results are: the full wave scenario at a toroidal position of 330° with injected electromagnetic waves at a toroidal position of 58° had a conversion percentage between 12% and 14% for a beam size of $1.1w_o$. The BS-SOLCTRA code took its first steps to turn into a full-scale simulation-visualization infrastructure with the feature of a better visualization quality of magnetic flux surfaces and it was parallized to enhance performance demands. Vacuum magnetic flux surfaces measurements coincided with the BS-SOLCTRA calculations.

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