First MHD equilibrium characterization and electromagnetic waves interaction on hydrogen plasma in the SCR-1 Stellarator

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Introduction

The stellarator of Costa Rica 1 (SCR-1) is a two period small size modular stellarator with a major radius of 247.7 mm and a minor plasma radius of 39.95 mm which has started first plasma operation on June 29th , 2016 . The SCR-1 has 12 modular coils which produce a magnetic field strength at the center of 43.8 mT. ECRH systems injecting microwaves at 2.45 GHz are installed in SCR-1, with a maximum input power of 5 kW. The design, construction and implementation of SCR-1 have proved the feasibility of manufacturing a low cost stellarator that is equipped with a large amount of ports, automatized systems and diagnostics [1] .

MHD Equilibrium

The free boundaries of MHD equilibrium calculations for SCR-1 stellarator were obtained with the three-dimensional Variational Moments Equilibrium Code (VMEC). The vacuum magnetic flux surfaces were obtained by the BS-SOLCTRA code [2] and compared with the results of VMEC and POINCARE code [3]. VMEC does not show the magnetic islands due to the conservation of the energy that assumes nested flux surfaces, as it is shown in figure 1.a [4]. BS-SOLCTRA code can reproduce similar surfaces to POINCARE code where there are error fields with some different contours as is shown in figures 1.b and 1.c.

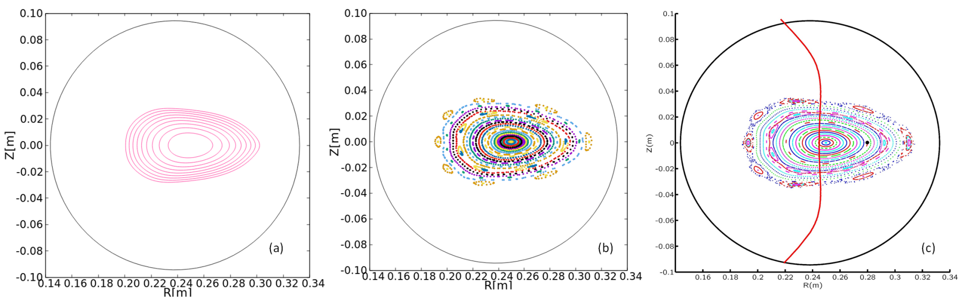

Figure 1: *Vacuum magnetic flux surfaces at the toroidal position of* 0° *obtained by (a) VMEC, (b)POINCARE and (c) BS-SOLCTRA*

The iota profile for 0° toroidal degrees is shown in figure 2.a. The rotational transform decreases towards the low field side and produces that the outer surface is more curve than in the inner surfaces. The depth of the magnetic well is shown in figure 2.b. It is a magnetic well located near to the center of the plasma and a magnetic hill when the radius decreases. Negative and low values for the magnetic well might be indicators of a possible appearance of increased plasma edge fluctuations, as it is reported for TJ-II stellarator [5].

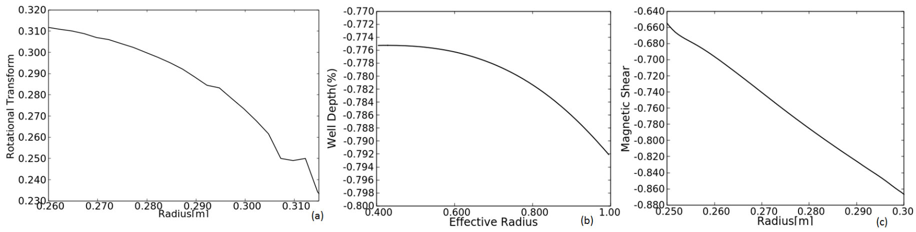

Figure 2: *(a) Rotational transform, (b) magnetic well and (c) magnetic shear profile for the SCR-1 stellarator*

The magnetic shear profile is shown in figures 2.c. Negative values of the magnetic shear indicate a reduction in drift waves instabilities [6]. The negative magnetic well and magnetic shear is related with more curved and smaller magnetic flux surfaces [5].

Microwave Heating Scenarios

Simulations of microwave heating scenarios have been performed in order to understand the relation between the injected electromagnetic waves in the SCR-1 plasma and the power deposition. The IPF-FDMC code is useful in this case because the density length scale $\nabla n_e/n_e \sim 0.1\,\mathrm{cm}$ is small compared with the wavelength of the incident wave (12.45 cm) (2.45 GHz) and therefore the WKB method is not appropriate for this low-temperature plasma [7]. The full wave code IPF-FDMC allows to evaluate the conversion to Electron Bernstein waves which would be absorbed at the electron cyclotron resonant frequencies [8]. Electron Bernstein waves propagate with no restriction for electron cut-off density. The conversion process studied is the O-X-B process: an O mode wave injected at a incident angle is converted to an X mode wave close to the O mode cutoff and then coupled to Bernstein wave in the vicinity of the Upper Hybrid Resonance [9]. This code takes as input parameters the plasma density as shown in figure 3 and vacuum magnetic field at one toroidal position. Microwaves are injected into the vacuum vessel at a toroidal position of 30°.

The figure 4.a shows a microwave scenario that does not consider the geometry of the vacuum vessel. The incident angle of the electromagnetic wave is 55° in the poloidal direction. The optimum angle was roughly estimated with the WKB theory. The variations along the radial coordinate at the $z = 0$ position of the amplitude of the electric field are presented in the figure

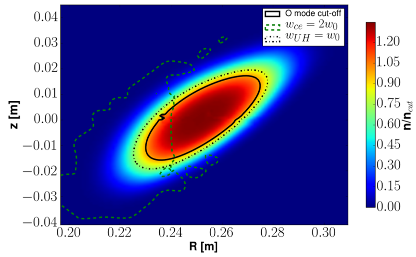

Figure 3: *Electron density contour map for the toroidal position of* 30°

4.b. It indicates an UHR layer present in the SCR-1 plasma and a possible conversion O – X because the magnitude of the amplitude of the electric field changes near to the UHR layer [7]. It is mandatory in order to affirm the existence of electron Bernstein waves to obtain an experimental deposition profile to localize where the microwave power is deposited [9] and to determine the effects of collisional damping of the SCR-1 plasma to understand its propagation.

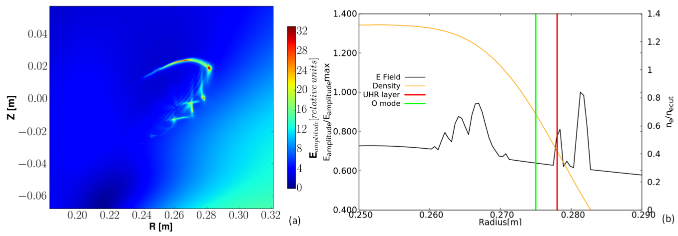

Figure 4: *(a) Full wave simulation at the toroidal position* 30° *after 40 period of oscillations (b) Variations of the electric field at the injected microwave for the plasma*

Magnetic Mapping Experiment

A magnetic mapping has been carried out in order to check the magnetic confinement. This process allows to find closed magnetic vacuum surfaces with the magnetic islands. The figure 5.a shows the set: an e-gun emits an electron beam that follows the magnetic field line and impacts a fluorescent target with zinc oxide. The experimental setup and design of the egun is shown in the figure 5.b and 5.c : an electrically heated tungsten filament excites electrons which are accelerated by an electrical potential difference [10].

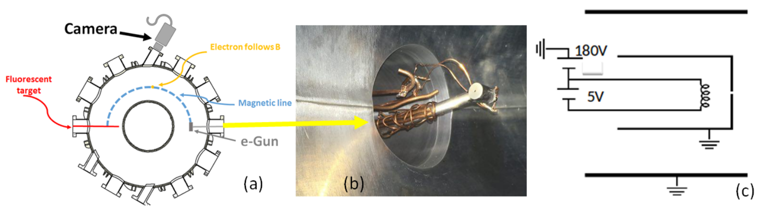

Figure 5: *(a) Experimental scheme of the magnetic mapping experiment of the SCR-1 stellarator, (b) e-gun installed at SCR-1 stellarator vacuum vessel and (c) electrical system of the e-gun*

The exit of the electrons is via a small hole in the cup with a diameter larger than the Larmor radius at the given magnetic field. A photographic camera was installed for taking photos with an exposure time of 5 seconds. Three kind of targets are used: an oscillating rod, a mesh and "cuchillo de mantequilla" which is combination of the first two ones. Figure 6.a and 6.b show the experimental vacuum magnetic flux surface measurements compared with BS-SOLCTRA results. Both surfaces matched.

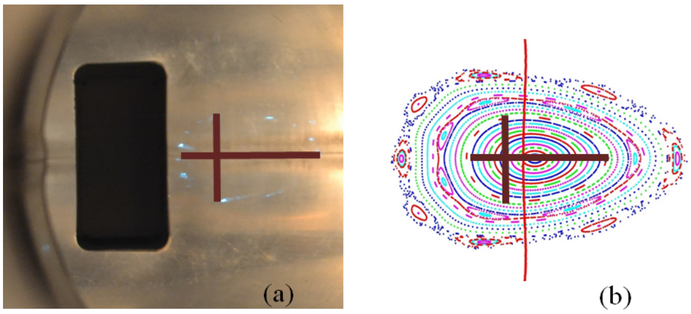

Figure 6: *Comparison between (a) the experimental results and (b) simulations with BS-SOLCTRA code*

Conclusions

Important results are obtained from experimental campagins and computational simulations for the SCR-1 stellarator: the MHD equillibrium calculations shows that the SCR-1 plasma is a low beta plasma with a negative magnetic shear and shows the formation of magnetics islands in the outter vacuum magnetic flux surfaces. Microwave heating scenarios without taken into account the vacuum vessel proves the existence of UHR layer with O-X conversion of >3% (preliminary results) at the toroidal position of 30°. The magnetic mapping experiment confirms the correct positioning of the modular coils in SCR-1.

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