First Results of the Stellarator of Costa Rica 1 (SCR-1)

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Abstract This work presents the results of the VMEC simulation and full-wave simulations using the IPF-FDMC code to develop different electron waves Bernstein heating scenarios. And the main reason is to present the first plasma shots made on the Stellarator of Costa Rica 1.

1. Introduction

Since 2009, the Instituto Tecnológico de Costa Rica started a research project on stellarators which aims at designing, constructing and implementing the first device of this technology in Latin America. SCR-1 is a small-size, modular stellarator (R_o=0.238 m, <a>=0.059 m, R_o/a>4.4, expected plasma volume ≈ 0.016 m^3, 10 mm thickness 6061-T6 aluminum vacuum vessel) [1]. The magnetic field strength at the center is around 43.8 mT which will be produced by 12 copper modular coils with 4.6 kA-turn each. This field is EC resonant at R_o with a 2.45 GHz as 2nd harmonic, from 2 kW and 3kW magnetrons. SCR-1 was redesigned from UST_1 stellarator [2].

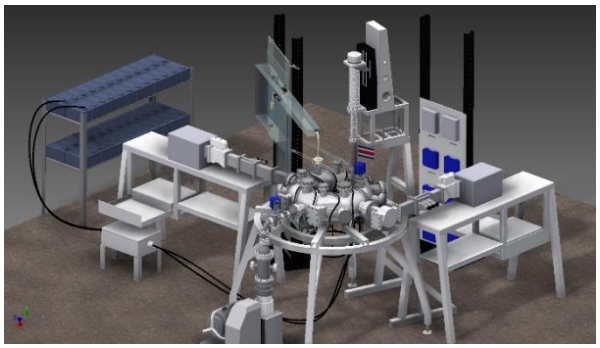

Figure 1. 3D model of the Stellarator of Costa Rica 1 with all the subsystems.

The SCR-1 has several subsystems as shown in figure 1: vacuum system (1), coils system (2), high electric current system (3), EC heating system (4), gas injection system (5), control and acquisition system (6) and diagnostics (7).

2. Subsystems

2.1.Vacuum system

In the vacuum system [1] to start the experiment, it is mandatory to reach at least $2x10^{-6}$ torr. This is a requirement to manage the injection system and it is the base to start. Figure 2 shows the shape of the vacuum reach curve before starting the experiment. It is important to mention that this curve is reached after validating the vacuum chamber.

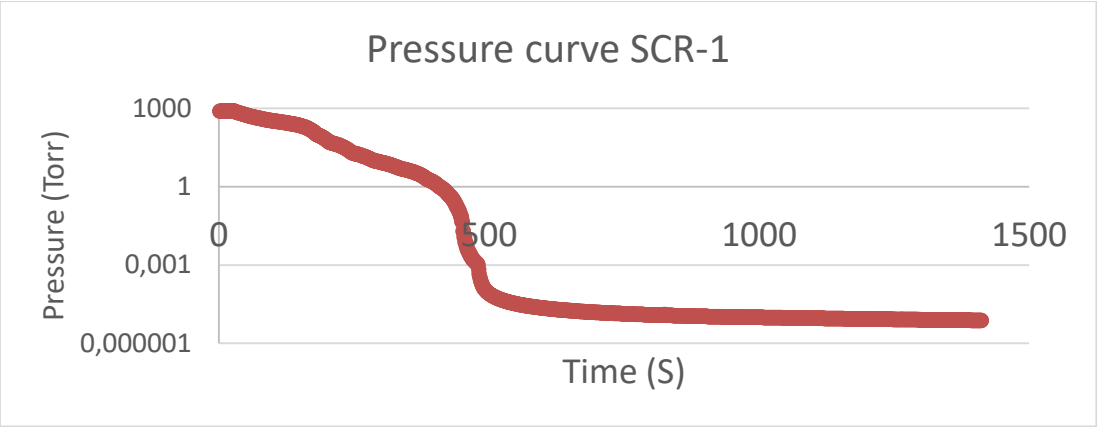

Figure 2. Pressure curve of the vacuum chamber SCR-1.

2.2.Coils system

The main parameter to control in this system is the temperature, by any means it should reach 100°C because the heat shrink tubing use on the wire can degrade and can damage the chamber and the coils. To avoid that, it is used a thermocouple on 3 different coils (0, 4 y 8). In the experiment, the temperature reached after 4,5 seconds was 70°C and to be ready again for a shot it is necessary to wait until the temperature was below 30°C.

2.3.High electric current system

For the first shot, it was used an alternative regulator (figure 3), which is much simpler. This device consists of a resistor made of stainless steel 304L with a diameter of ¾ inches and a length of 1350mm. The main regulator [1] was not working. The current curve with this new regulator is shown in figure 4. It can be seen a current drop throw time because the resistor changed with the heat. In this first shot, this is not relevant due to the fact that the resonant surface is always inside the vacuum chamber. In fact, it is mandatory to use a constant current regulator, as explained before.

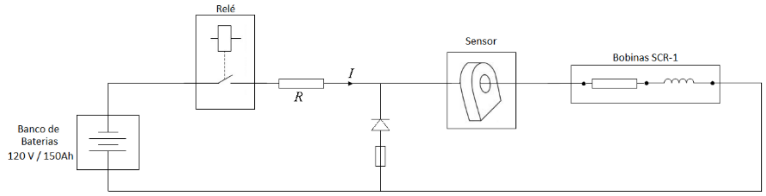

Figure 3. Alternative regulator for the SCR-1[6]

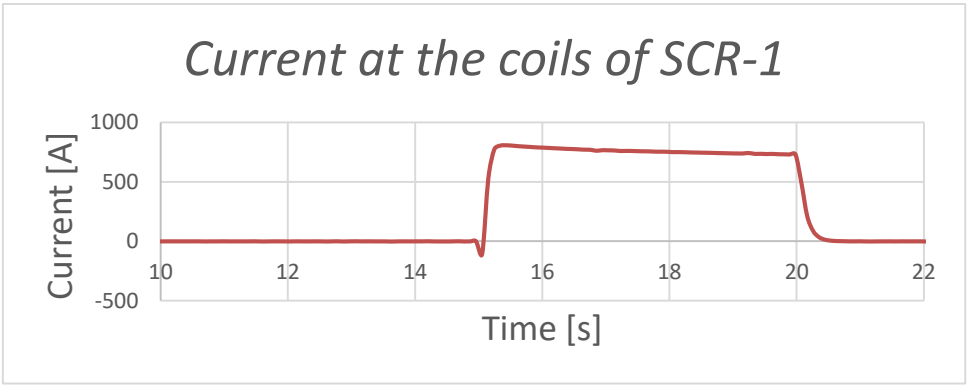

Figure4. Current curve on coils of the SCR-1

2.4.EC heating system

For the first shot, all the power of the system (5kW) was not used. In fact only one magnetron of 2kW was utilized. This decision was due to a safety reason: to go step by step until it reached the maximum power. As in figure 5, the power that is absorbed by the plasma is around 1000 watts during the shot, but there are a lot of power reflected. This is something that we are still researching to determine what is happening.

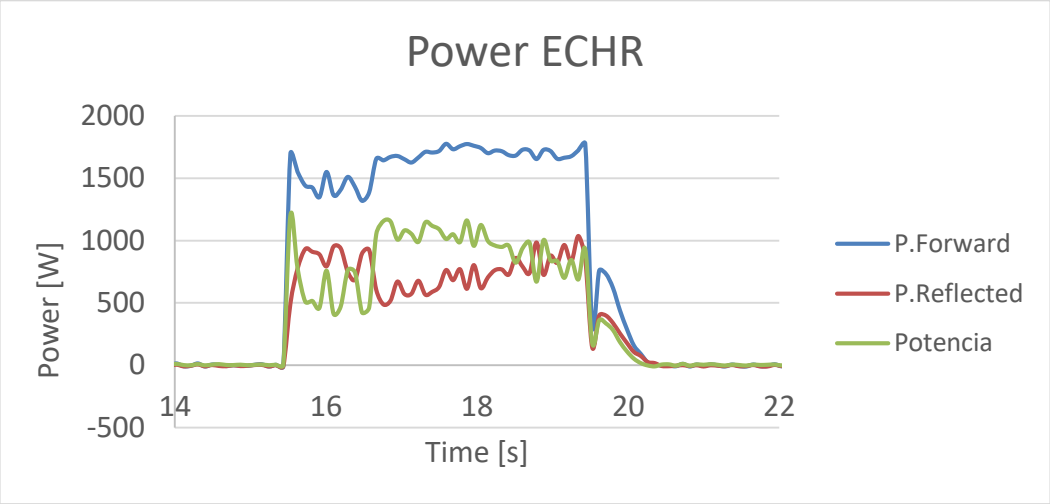

Figure 5. Power of the ECHR

2.5.Gas injection system

For the first shot, 2 sccm were injected to reach a pressure of $1x10^{-4}$ torr to $3x10^{-4}$. For this parameter there is not a curve due to the fact that at the moment of the shot the ion gauge used turn itself off. This was because it measured an over pressure, caused by the plasma that we generated and its functioning. The way to determine the pressure of work was using the cut of density.

2.6.Control and acquisition system

The main task of the control system is to coordinate the signals of figure 6. It is mandatory that the execution of these signals stay as close as possible to the signals shown in the figure 6. Besides that, it is in charge of starting the vacuum system and the sequence to follow which is necessary reach $2x10^{-5}$ Torr. Also, it was ran a security system that turns off everything if some parameter is out of the limits; for example, if the current it's under 700 A.

For the first plasma shot the times set were as follows: TG1 : 8000 ms, TG2: 4000 ms, TC: 5000 ms, TE1: 500 ms, TE2: 4500 ms and TD: 2500 ms. The time of the shot is TE2, the rest of the times were for waiting until all the subsystems are on stationary regime.

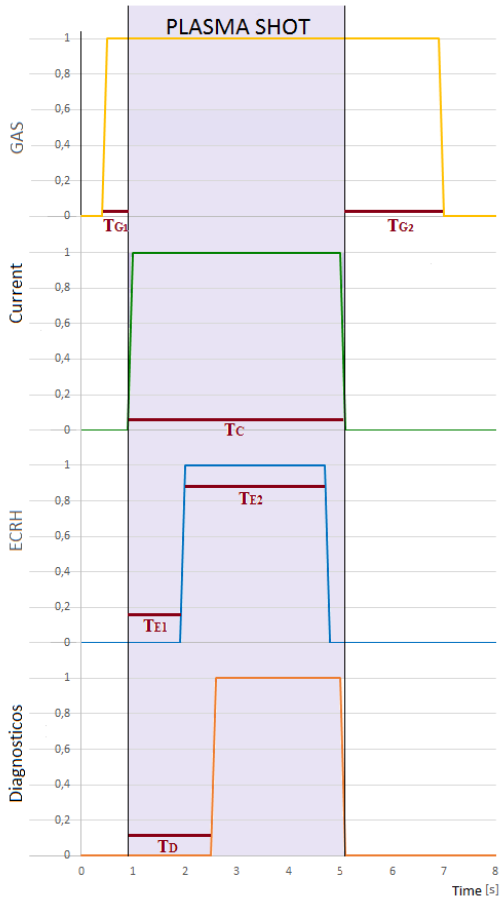

Figure 6. Main signals of the control system Dìwö[6]

3. Test

3.1. Magnetic mapping

To achieve this goal, it was necessary to design all the components for the experiment. The method of transparent fluorescent screen [4] was selected. This method has the advantage that it does not require movement parts. As a result, that was easy to implement. The parts are: E-Gun, a mesh with ZnO:Zn phosphor and it needed to be in vacuum at least $1x10^{-5}$ Torr.

The E-Gun on figure 7 is made of stainless steel 304. Its mayor diameter is 9 mm and the hole for the electrons is 1 mm. It uses a filament of a 2W bulb from Christmas lights. It is highly recommended not to use aluminum or plastic materials with higher power bulbs. The electric diagram is shown on figure 7.

The mesh is made of stainless steel 304. The cover in the edge with aluminum paper helps to avoid scratches on the vacuum chamber. To see the electrons hit the mesh, it is used a ZnO:Zn phosphor. It is important to mention that it is mandatory that the ZnO:Zn phosphor came doped with zinc. If it wasn't like that, it wouldn't work. The way to deploy the ZnO:Zn phosphor to the mesh is using acetone: it was mixed together and applied to the mesh. The mesh was at phi 0° on the vacuum chamber, and the E-Gun was on phi 180° as in figure 8.

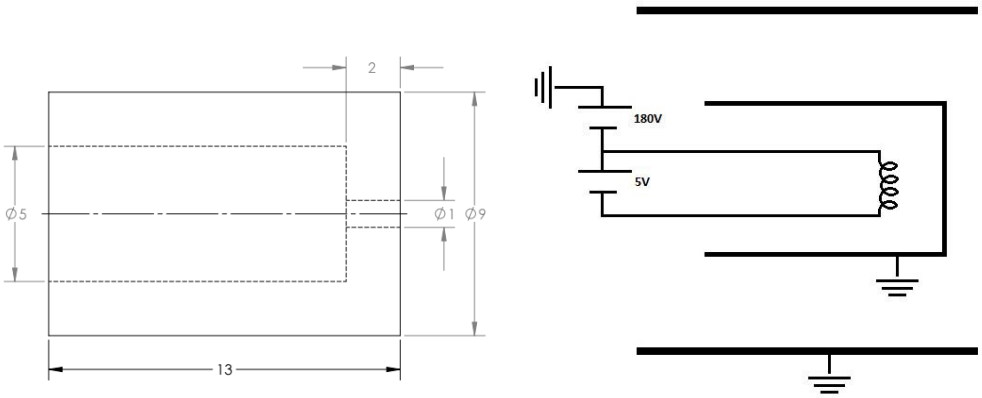

Figure 7. Mechanical and electric diagram of the E-Gun

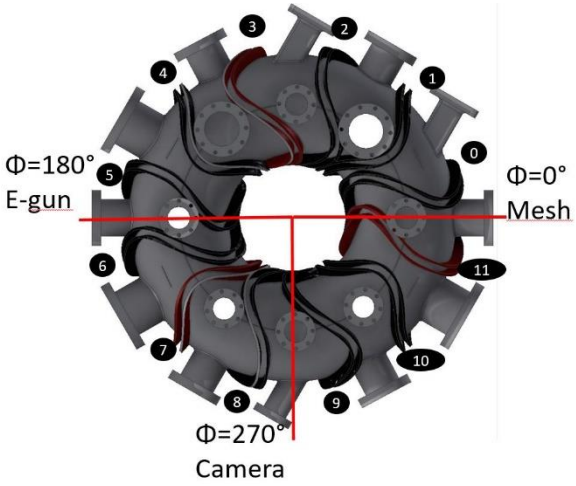

Figure 8. Position of the experiment

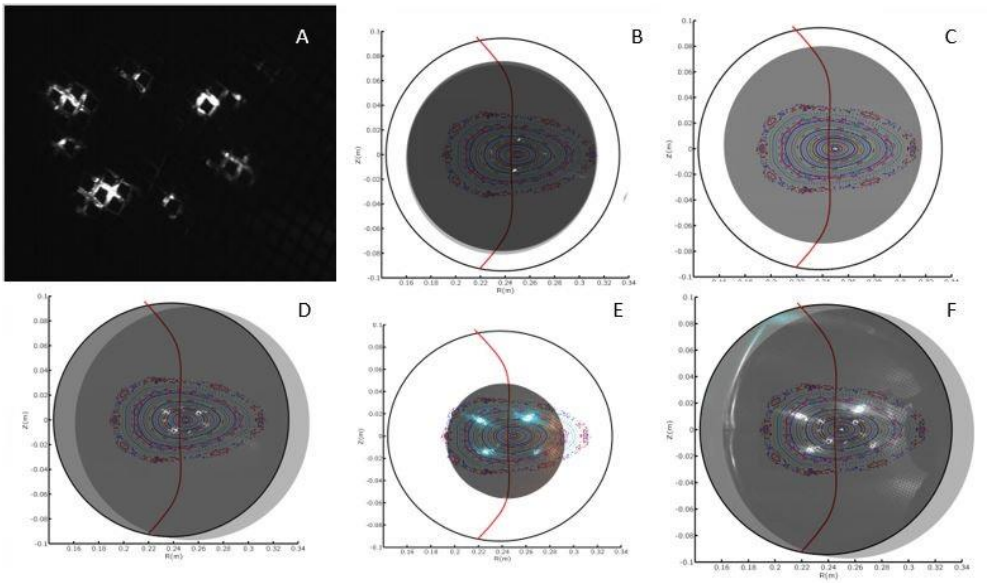

Figure 9. A) show the points where the electrons hit on the mesh using a high speed camera. B) superposition of one of the lines of the magnetic field. C) magnetic axis measured and compere. D) points of A compere with the Poncare diagram. E) Outer surface measure. F) image composed by B, C, D and E.

As it can be appreciated on figure 9, the magnetic field is working well. All the magnetic surfaces are in the right place including the magnetic axis. This means that the manufactureing procedure [5][1] of the coils is good and it can be replicated for future stellarators.

It is imperative to test these results using other methods like oscillation road [3] and elliptical wire [4]. These results are going to be shown in future research.

3.2.Plasma Shot

Using all the parameters on section 2, the results of the plasma are on figure 10. With a duration of 4.5 seconds, the Stellerator of Costa Rica 1 works for the first time doing a plasma shot.

Figure 10. Sequence of the first plasma shot of the Stellerator of Costa Rica 1.

Using the iHR550 optical spectrometer to measure the temperature of this plasma, the wave form in figure 11 was obtained. However, this curve alone can't be analyzed because there is not enough data. This is an ongoing issue at this moment.

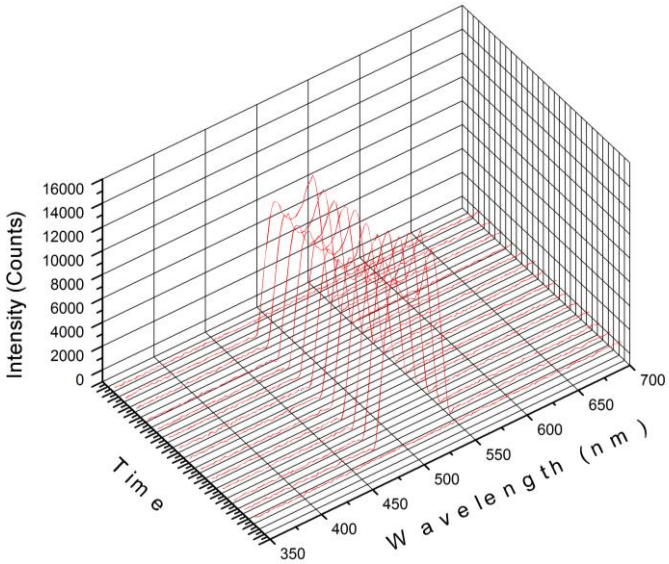

Figure 11. Spectrum of the plasma shot betwen 475-495nm

The temperature reached at the SCR-1 using Langmuir probe is around of 14eV, and the density Ne is $7.5x10^{15}m^{-3}$. Figure 12 shows where the probe is on the plasma, and one of the curves obtained.

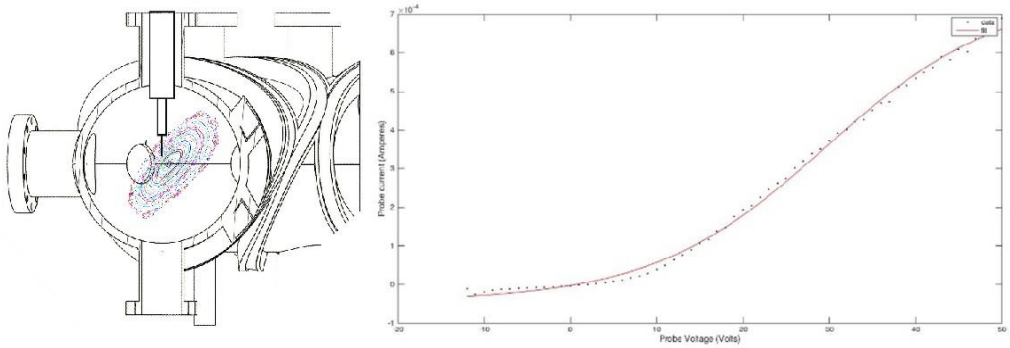

Figure 12. Langmuir probe on the plasma, and curve obtained.

3.2. Simulation with VMEC code

VMEC is a code that allows solving the configuration on MHD equilibrium. For the case of the SCR-1, Free Boundary mode was used with the toroidal and poloidal magnetic field without errors in this field. With this simulation it is possible to validate our Poincare diagram. Figure 13 A shows the magnetic flux surface on phi 0°, and in B, the rotational transform profile is presented. On this simulation it is only considered nested flux surfaces. Figure 14 it shows Last magnetic flux surface on 3 dimension produced on VMEC.

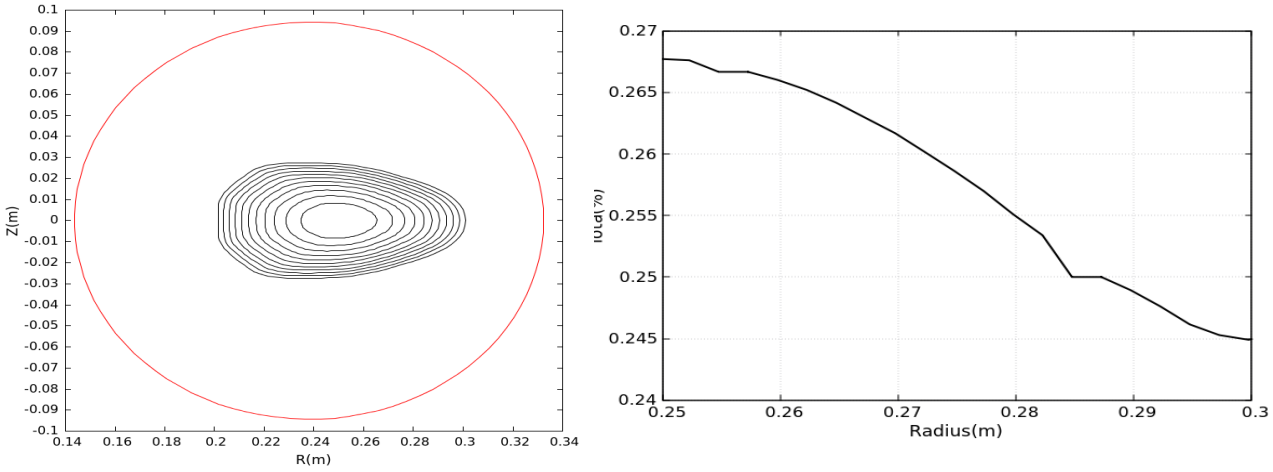

Figure 13. A) magnetic flux surface on phi 0°. B) rotational transform profile on phi 0°

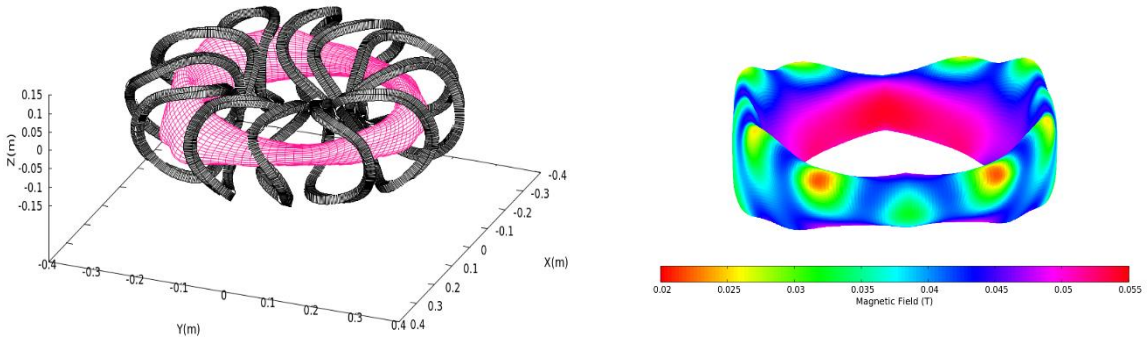

Figure 14. Last magnetic flux surface on 3 dimension produced on VMEC.

3.3.Simulation IPF-FDMC

Using the results of the VMEC code, in figure 14 A, there is a contour map of radial and horizontal position showing the density cut of the plasma (the ratio between the density and the plasma cut-off density). Also, it shows the frequency cut (cut-off frequency of the O wave)(it is showing the O mode cut-off frequency layer). In addition, the figure shows the heat frequency and the upper-hybrid resonance layer. Figure 14 B shows a simulation of the full wave code IPF-FDMC developed by A. Köhn [7]. An O-wave was emitted with an incident angle of 43° with respect to the toroidal direction, from small antenna aperture. Using the values of the electric(magnetic) field and the magnetic(electron density), it is obtained the change of the electric field of the electromagnetic wave on the region of the plasma. As it may be seen, there is a power dissipation due to conversion to O mode to X mode and, later a conversion to electrostatics Bernstein waves. It is also possible to calculate the absorption and conversion percentage. In further studies, we will try to include the vacuum vessel walls and different antenna geometries.

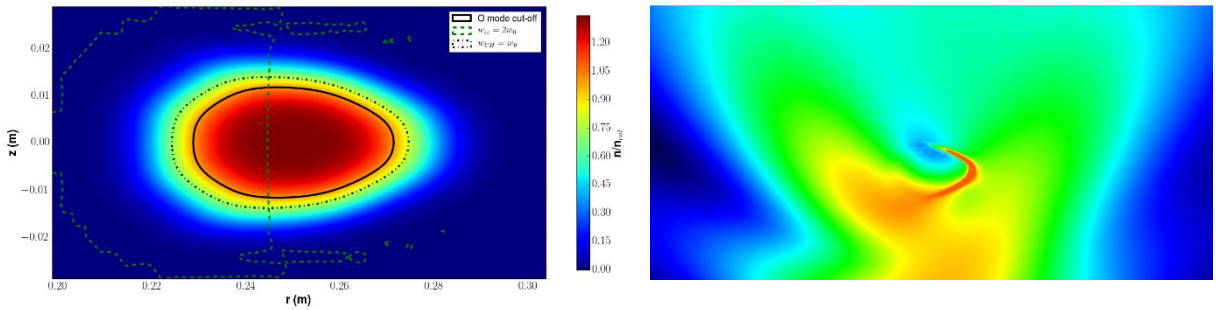

Figure 15. A) base for the simulation of the IPF-FDMC. B) Simulation of the IPF-FDMC

4. Conclusion

The manufacturing process used to make the Stellerator of Costa Rica 1 is valid, making this a very good way to do a small modular stellerator. Using less than a half of the power to heat the plasma we got a great temperature.

5. Outgoing.

Research should be continued with another method to do the magnetic mapping, for example using the oscillation road. It is necessary to measure the temperature of the plasma using the optical spectrometer fixing the issue that we have. New research should measure the temperature using other diagnostics. And it is mandatory to start increasing the power of the ECRH to reach 5kW.

References

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