Constructing a small modular stellarator in Latin America

2015 J. Phys.: Conf. Ser. 591 012016

(http://iopscience.iop.org/1742-6596/591/1/012016)

Constructing a small modular stellarator in Latin America

V.I. Vargas, J. Mora, J. Asenjo, E. Zamora, C. Otárola, L. Barillas, J. Carvajal-Godínez, J. González-Gómez, C. Soto-Soto and C. Piedras
Plasma Laboratory for Fusion Energy and Applications, Cartago, Costa Rica
Instituto Tecnológico de Costa Rica, Cartago, Costa Rica

E-mail: ivanvargasblanco@gmail.com.

Abstract. This paper aims at briefly describing the design and construction issues of the stellarator of Costa Rica 1 (SCR-1). The SCR-1 is a small modular stellarator for magnetic confinement of plasma developed by the Plasma Laboratory for Fusion Energy and Applications of the Instituto Tecnológico de Costa Rica (ITCR). SCR-1 will be a 2-field period small modular stellarator with an aspect ratio > 4.4; low shear configuration with core and edge rotational transform equal to 0.32 and 0.28; it will hold plasma in a 6061-T6 aluminum torus shaped vacuum vessel with an minor plasma radius 54.11 mm, a volume of 13.76 liters (0.01 m^3), and major radius R = 238 mm. Plasma will be confined in the volume by on axis magnetic field 43.8 mT generated by 12 modular coils with 6 turns each, carrying a current of 767.8 A per turn providing a total toroidal field (TF) current of 4.6 kA-turn per coil. The coils will be supplied by a bank of cell batteries of 120 V. Typical length of the plasma pulse will be between 4 s to 10 s. The SCR-1 plasmas will be heated by ECH second harmonic at 2.45 GHz with a plasma density cut-off value of 7.45×10^{16} m^{-3}. Two magnetrons with a maximum output power of 2 kW and 3 kW will be used.

Keywords. Magnetic confinement; Stellarator; low shear configuration; small modular stellarator

1. Introduction

Stellarators are toroidal devices where the required rotational transform of the magnetic field lines (needed to confine the plasma) is generated by external field coils and not via an induced net toroidal plasma current as in Tokamaks. This confinement scheme has the advantages that, in principle, steady-state plasma operation is possible and the machine does not have to brace itself against the strong impulses generated by short pulses of high current, such as the halo-currents generated by plasma disruptions in Tokamaks. At the cost of the increased complexity in toroidal asymmetry, the properties of the Stellarator's magnetic geometry can be tailored to suit reactor needs. Research focusing on the plasma confinement properties of different Stellarator fields and their suitability for reactor sized devices is an area of ongoing research.

In a toroidal device, the magnetic field lines need to be helically twisted in order to prevent polarization of the plasma due to the opposite vertical directions of ions and electrons curvature and gradient drifts that would otherwise prevent confinement [1]. In a Stellarator the net toroidal current that is required to be carried the plasma is zero and the confining magnetic field is generated solely by external field coils. This requires some of the coils to helically revolve around the plasma.

The goal of Stellarator research —as well as tokamak research— is to prove that the concept is suitable for a fusion reactor. Thus it is necessary to determine the magnetic field structure that can confine a plasma at sufficiently high density, n, and temperature, T, with sufficiently long energy confinement time τ_E, in order to meet the Lawson criterion [2]. Large Stellarator experiments have been developed to explore the attractiveness of the concept: for example, ATF in Oak Ridge, USA (R = 2.1 m); CHS (R = 1.0 m), LHD (R = 3.9 m) and CHS-qa (R = 1.5 m) in Tokio, Japan; Heliotron E (R = 2.2 m) and Heliotron J (R = 1.2 m) in Kyoto, Japan; TJ-II (R = 1.5 m) in Spain, W7-AS (R = 2.0 m) and W7-X (R= 5.5 m) in Germany, HSX (R = 1.2 m) and QPS (R = 0.9 m) in USA.
Recently, there has been an interest on developing small low cost Stellarators (major radius less than 0.9 m). A small Stellarator (R=119 mm) called Ultra Small Torus (UST_1) [3] was designed, built and operated by the Spanish engineer Vicente M. Queral on a budget of under $4000, demonstrating for the first time that low-cost techniques can be used to build small, functioning Stellarators.
UST_1 is a 2-field period modular Stellarator with an aspect ratio ≈ 6, formed by 12 partially optimized modular coils. Each coil is formed by 6 turns of flexible copper conductor wound in a groove machined in a circular toroidal plaster frame by a specially designed toroidal milling machine. Electron cyclotron frequency heating (ECH) at the second harmonic (B_0 = 46 mT) heats the plasma using a 0.8 kW, 2.45GHz commercial magnetron. Typical length of the plasma pulse is 2 s. Toroidal field (TF) current per coil is 2.3 kA-turn. Also the plasma volume is 1.1 liters, major radius R = 119.2 mm, average minor radius a ≈ 21 mm. Low shear configuration with core and edge rotational transform equal to 0.32 and 0.28, optimized to occupy a narrow range just below 1/3 in order to avoid high-order rationals and large magnetic islands. Additionally, UST_1 was optimized for other important plasma parameters, such as large plasma size, deep magnetic well, low ripple, and low variance of the minima of |B|. Optimization is modest because the coils are constrained to lie on a circular torus [3]. Plasma parameters for this small device deduced from ISS04v1 [4] with B_0 = 0.1 T, enhancement factor = 0.1, and P_{ECH} = 400 W are very modest, on the order of $T_e \sim 2$ eV, $n_e \sim 2\times10^{17}$ m^{-3}, and $\tau_E \sim 0.2$ µs, with $\beta \sim 0$ [3].
This paper presents the design of a small modular Stellarator that uses the same magnetic configuration as the UST_1. Stellarator of Costa Rica 1 (SCR-1) is built to a scale twice the size of UST_1 in length dimensions, stronger magnetic field (0.0438 T), increased heating power (5 kW), and has an minor plasma radius (54.11 mm), plasma volume of 13.76 liters (0.01 m^3), estimated electron temperature (13 eV) and electron density (5×10^{16} m^{-3}).

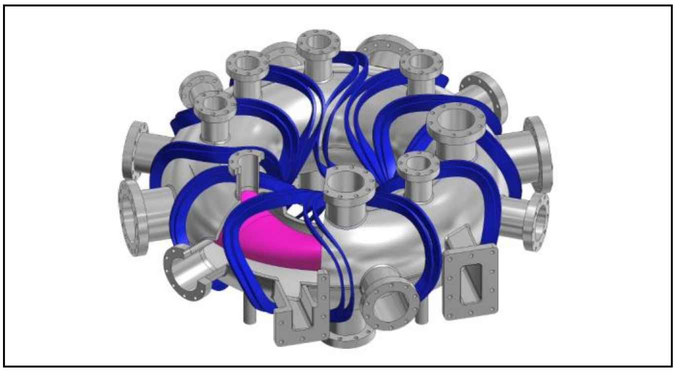

Figure 1. SCR-1 vacuum vessel drawing.

The main objectives of SCR-1 are to improve the engineering of the UST_1 device, focus on training human resources, identifying of problems related to the design and construction of small modular stellarators and also investigate the plasma physics in a small modular stellarator (R = 238 mm).
This article is organized as follows. The system description is described in detail in section 2, where each part of the SCR-1 will be presented, including its characteristics and parameters, and a description of engineering approach taken and problems overcome by the authors during the designing of the device,

and their solutions. Expected plasma parameters are also presented. Conclusions are summarized in section 3.

2. System description

2.1. Organization of the SCR-1 Project (Heading 2)
The structure of the project involves about 4 engineering and physics undergraduate students, mainly from the ITCR, 3 supervisor engineers, under the supervision of two PhDs in plasma physic and nuclear fusion.
The project is divided into the following areas: Coil Systems and Layer Materials, Vacuum Systems, Power Supply Systems, Heating System, Diagnostics, Safety, Data Acquisition and Control Systems, the area of Magnetic Fields, Simulation and Modeling; and finally, the Administrative, Technical, and General Supervising areas.

2.2. Vacuum Systems
The torus-shaped vacuum vessel of the SCR-1 will be made of 6061-T6 aluminum. Although using austenitic 304L grade stainless steel was analyzed, it was discarded because of the difficulty to manufacture parts according to the device dimensions and the vacuum vessel price is higher.

Figure 2. Stages of the vacuum vessel construction.

The vacuum vessel of 10 mm thickness will have a volume of 0.0434 m^3, with an external radius of 364.1 mm, internal radius of 112.1 mm and major radius R = 238.1 mm. Since the vacuum vessel must

support a minimum pressure of 10^{-6} Torr (10^{-6} mbar), it will be used 6061-T6 aluminum in TIG welding Process.
The vessel will have 24 conflat ports with diametric dimensions of 6" CF, 4-1/2" CF, 3-3/8" CF and two rectangular shaped; available for different applications, as seen in Fig. 1 and Fig. 2.
The vacuum vessel design includes more ports than required by diagnostics, in order to support the future incorporation of more components if required.
For the construction of the torus shape two aluminum parts were melted subsequently they were polished on the inside by using a multi-axis CNC machine. Once the above was completed, the pieces were welded using the TIG welding process as shown in Figs. 2. Finally they were performed external polishing and liquid penetrant and porosity tests were done. CF Ports were also machined of aluminum as shown Fig 2. It has decided to use the same design the aluminum CF port of the vacuum vessel for a Cusp Confinement Plasma call MPDX (Madison Plasma Dynamo Experiment) from the University of Wisconsin, Madison [5].
The main vacuum system component is the vacuum pumps group, which is composed by one mechanical pump able to reach 10^{-4} Torr, and one turbo-molecular pump that can then achieve a further reduction in pressure to 10^{-10} Torr. An automated pump system was chosen, integrating the controllers of both pumps. This group has additional equipment such as RS485 communication, vacuum convectron, ion gauge sensors and RGA (Residual Gas Analyzers) for possible gas leak issues.

2.3. Coil Systems
The magnetic field that confines the plasma will be produced by 12 modular (irregularly shaped, non-planar) copper coils. Modular coils (see Fig. 1) in principle allow the best possible confinement of the plasma to be achieved. The geometry of the coils was obtained by engineer Vicente Queral [3], and has been optimized as discussed in section 1.
Each modular coil will have 6 turns, made of AWG#4 wire, and a current of 767.8 A per turn providing a total toroidal field (TF) current of 4.6 kA-turn per coil. It is not possible to add more turns due to the geometric constraints of the coils and vessel. Heat transfer simulation results from the modular coils are shown in Fig 3. The thermal behavior of copper wire by electrical current pass in the modular coil was simulated using COMSOL Multiphysics software and other methods. Temperature, resistance, voltage and power calculations as a function of time were performed for the electrical circuit under different wire configurations per modular coil to select the power supply taking into account the available budget. The wire configurations of 1, 2 and 4 turns per coil were discarded due to the high price of the power supply (USD > 50 k $). Also the wire configurations of 8 and 12 turns were also discarded because the clashes occurring between close coils when the height per coil increased. Finally it was decided 6 turns per coil (green color in the Fig. 3 and Fig. 4)
Active cooling systems were considered as a possible solution for the temperature rise of the coils but discarded due to the constraints imposed by the available space and complex geometry of the coils, though remain a possibility for future upgrades. Instead, temperature rises are limited to acceptable levels by increasing the number of turns, lowering the required current to maintain the same magnetic field strength; and increasing the cross section of the wire, thus lowering the resistance of the wire.
Having this in mind, authors realized that most of the difficulty of the coil system relies on the mechanical issues and not electrical. The number of extra turns and increased coil width is constrained by the available space for coils. A test bed model of one of the grooves was created and coils were wound exploring different AWG wire calibers, insulations and configurations of the turns, in order to gauge the ability of various coil configurations to be successfully implemented during the building of SCR-1. Once an optimal configuration based on these requirements was determined, the parameters of this configuration were applied to all coils on the Stellarator using a CAD program to check that the coils did not overlap, and calculations were performed to corroborate the temperature rise of the coils during the pulse are within acceptable levels. The results are shown in Figs. 3 y 4, where the current coils configuration provides 767.8 A.

For positioning of the coils in the vacuum vessel a CNC machine that generated little grooves in the vacuum vessel was used (see Fig. 2). A specialized automated machining device has been designed to cut the grooves into an acrylic material coating the torus in a pattern corresponding to the coil shapes [6], however, it was discarded because the supplier who constructed the vacuum vessel also has manufactured the coil guides using 3D printer and then casting technique. Subsequently the coil guides were welded to the vacuum vessel as shown in Fig. 2.

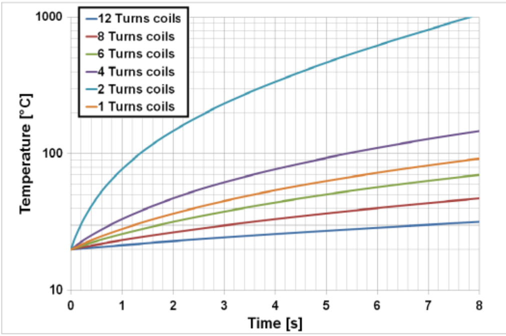

Figure 3. Temperature comparison between different coils configurations.

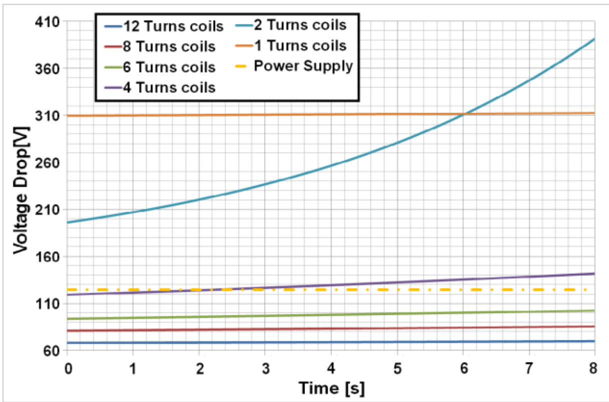

Figure 4. Voltage-Drop vs time for the battery bank of the SCR-1.

Before operation of the SCR-1, a magnetic field mapping system will be assembled to verify that the coils have been positioned correctly. This mapping system will consist of a movable thin rod impregnated with a substance (probably barium oxide or phosphor P15 or P24) that produces a fluorescent luminescence when electrons propelled by an e-gun hit with the rod. These impacts will be filmed by a CCD camera at approximately 1/10 – 1/30 frames per second; the number of frames per second chosen must be the same number of the frequency of the oscillation of the rod. Finally, the images will be superimposed to generate a final image of the vacuum magnetic surfaces, which will be compared to those calculated theoretically. This magnetic field mapping methodology was originally applied to UST_1 [3].

2.4. Power Supplies systems

The electrical supply system consist of an array of 60 lead-acid electrochemical cells (battery bank); each cell will have a nominal voltage of 2 V and an electrical storage capacity of 150 Ah. The battery bank will have a voltage of 120 V and is capable to deliver a current of at least the required 767.8 A during one duty cycle of the SCR-1; as mentioned previously the duty cycle of SCR-1 is mainly limited by the ohmic heating experienced by the coils during operation (Fig. 3). The temperature rise leads to a rise in the coil resistance (Fig. 4), in order to maintain constant current over the estimated 4 to 10 seconds of a SCR-1 pulse, the system will use a switching current controller between the battery bank and coils system in order to allow the voltage across the coils to rise as the coils resistance increases [7]. The electrical current and electrical circuit for the SCR-1 is shown in Fig 5.

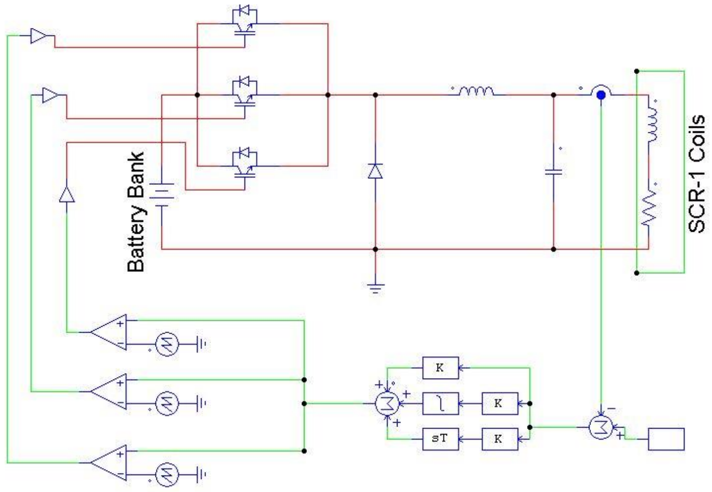

Figure 5. Electrical circuit for the SCR-1.

2.5. Heating Systems

The SCR-1 plasmas will be heated by ECH 2nd harmonic at 2.45 GHz with a plasma density cut-off value of 7.45×10^{16} m^{-3}. Two magnetrons with a maximum output power of 2 kW and 3 kW will be used, located in symmetrical positions. The heating system was specifically designed to meet the requirements of the characteristics of this small stellarator [8], with a focus on the efficiency of the energy transfer from the electromagnetic wave (EM) to the plasma bulk and reducing the reflection coefficient through impedance coupling, as well as safety and ease of measurement. Because the SCR-1 is much smaller than those commonly operated by other laboratories, the main engineering considerations have been: shot time, electron cyclotron frequency (2.45GHz) at a specific magnetic strength for the main heating frequency, and power consumption for the current supply affordable by the funding agency (ITCR).

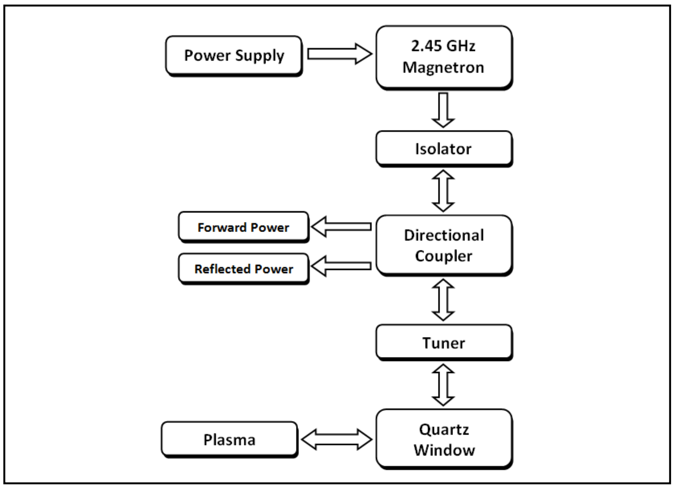

Figure 6. Simple block diagram of the Heating System of the SCR-1.

In terms of heating frequency, the wide selection and lower cost of components at 2.45GHz has defined several parameters of design such as the magnetron frequency and waveguide selection. In addition continuous wave (CW) magnetrons can be used and heating problems will not arise because of the short duration of shots (4 s to 10 s). Using the parameters discussed in previous sections, quantities such as skin depth, plasma density and others can be used to estimate the coupling of the plasma and heating power through selection of a tuner to match the impedance and avoid strong reflections, thus achieving maximum energy transfer and safety (see Fig. 6).

2.6. Heating Systems

The diagnostics consist of a Langmuir Probe, an iHR550 optical spectrometer and a Heterodyne Microwave Interferometer, specially designed for the requirements of this small scale stellarator design. A versatile remotely controlled reciprocating Langmuir probe presented in Fig. 7 (located in vertical position) has been developed for the SCR-1. The main components of the system are two removable heads, containing the measurement four tips each one, and a displacement system that enables the probe to be displaced in vacuum. Diagrams of tips and Langmuir Probe system especially designed for the SCR-1 is shown in Fig. 7.

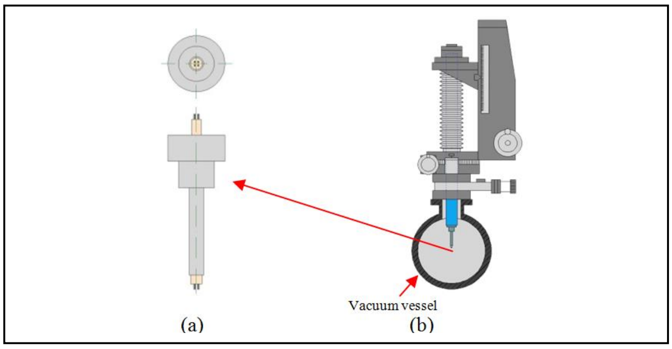

Figure 7. Diagrams of: (a) Close-up of the Langmuir probe tip. (b) Langmuir Probe system especially designed for the SCR-1.

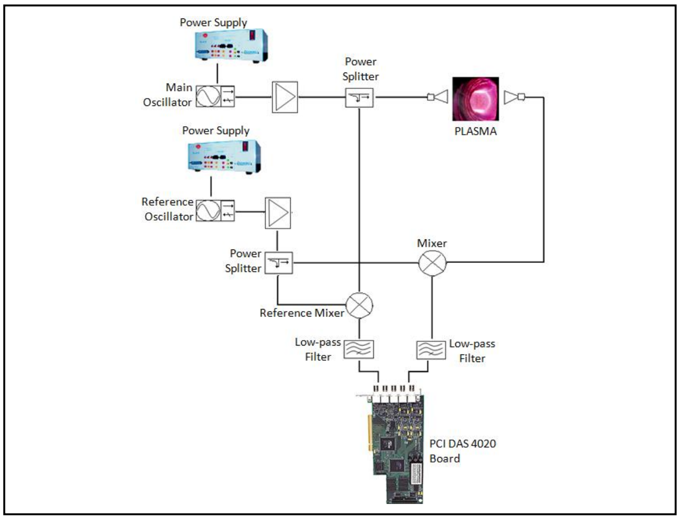

Figure 8. Diagram of the components of the Heterodyne Microwave Interferometer.

The probe heads that supports the Langmuir probes is easily removable. It consists of two boron nitride heads and an array of four tungsten tips per head. The probe will allow to investigate the local plasma density, temperature, plasma potential, and their fluctuations.

The Microwave Interferometer diagnostic is located vertical. The probing beam has a frequency of 28 GHz, corresponding to a wavelength of λ = 10.71 mm. The line-integrated electron density is deduced from the cumulative phase change of the probing beam and the theoretical length of the intersection of the probing beam with the plasma (obtained from the magnetic geometry in vacuum). It is important to state that the interferometer was developed along with a computer program to receive the data of the linear density of the plasma. Fig. 8 shows a diagram of the components of the interferometer.

2.7. Simulations, Modeling and Magnetic field calculations

A JAVA code named SimPIMF was developed by the creator of the UST_1, engineer Vicente Queral, to calculate three-dimensional (3D) magnetic fields. Later, the code evolved, and was able to calculate/simulate by field line tracing: Poincaré plots, rotational transform and magnetic well profile, plasma size, orbit simulation with drifts, particle losses, other 'plasma' parameters, minimum distance between coils, and optimization of such parameters by iterative generation of parametric 3D coils [3].

To obtain calculations of the SCR-1 magnetic structure and corroborate the UST_1 results, a computer code in MatLab was developed to estimate the 3D magnetic field, magnetic surfaces, rotational transform profile and magnetic well. Also particle tracking results and Poincaré maps were obtained using the COMSOL Multiphysics software. In Fig. 9 vacuum magnetic surfaces are presented on cero toroidal angle obtained on Poincaré simulations by MatLab code for SCR-1.

The magnetic resonant field for the SCR-1 will be 0.0438 T, and a period of 2 (m = 2) with a flat rotational transform profile with ι = 0.3.

The magnetic field simulation has been approached by two different methods. In the first approach, the magnetic field is calculated using a Biot Savart solver implemented in JAVA and MatLab codes. The second approach on magnetic field simulation was done through a reduced model of the 12 modular coils set also using one turn per coil of the SCR-1 using the Magnetic and Electric Field module of COMSOL Multiphysics software. Using MatLab code and COMSOL Multiphysics software were obtained calculations of magnetic surfaces and where ECH resonance surface is located (Fig. 11) [9].

Journal of Physics: Conference Series **591** (2015) 012016 doi:10.1088/1742-6596/591/1/012016

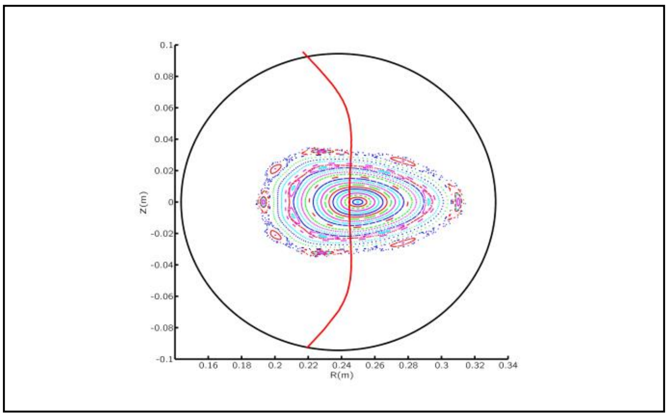

Figure 9. Magnetic surfaces at Φ = 0º.

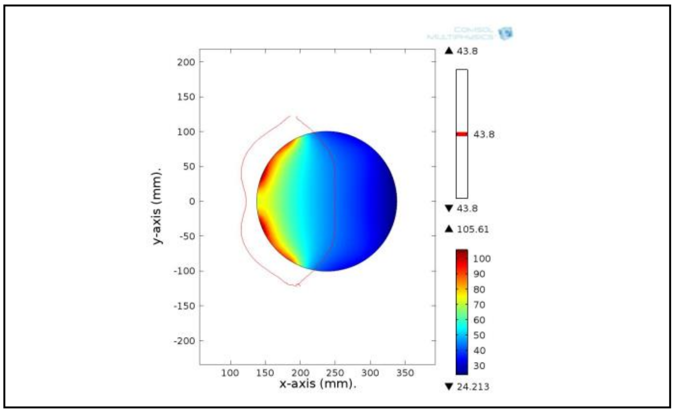

Figure 10. Contour map of magnetic field at Φ = 0º for I=4607 A.

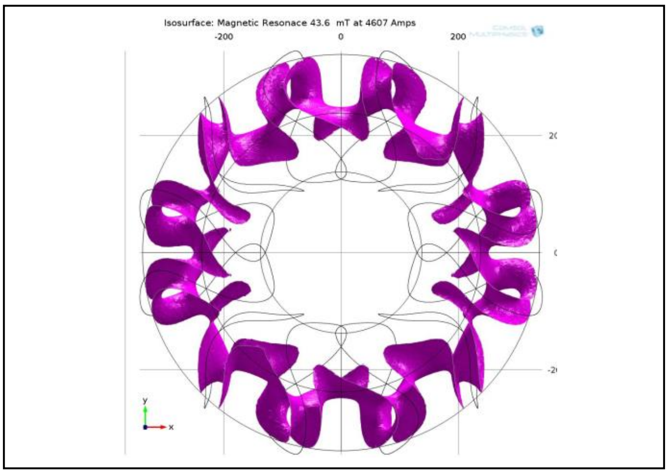

Figure 11. Resonant surface (2.45 GHz) for I=4607 A.

The magnetic field and the magnetic surfaces are important to define the best ECH heating system and diagnostics locations. Also, the magnetic surfaces and the rotational transform are both needed to evaluate the confinement of the device.

2.8. Data Acquisition and Control Systems

Currently, an application has been developed to generate and diagnose plasma using uniquely one click button. In order to make it possible it has been achieved primarily the identification and control of three threads associated with the plasma generation, which are: vacuum generation in the vessel, the automatic gas injection and heating system. For the gas injection process, a proportional – integrative - derivative (PID) compensator, for automatic control theory, was design using dynamic equations and physics of the system. The role of this compensator is to regulate the gas flow automatically to achieve a reference pressure within and specified time with a smooth behavior; this could be made by sending commands with the new set point, calculated by the compensator at every sampling time, to the Power Source and Readout device for the Mass Flow Controller.

2.9. Safety

Its main purpose is to achieve the goals of the project in a manner that guarantees the safety of the people and the equipment, as well as the correct development of the operations. The level of protection must be established as well as a risk reduction system on the development and operation of each stage of the SCR-1; coordinators in this aspect have knowledge on technical aspects of the SCR-1 and human issues. With this purpose a safety plan was developed and protocols are defined for the operation of stellarator

2.10. Plasma parameters

The following are the expected plasma parameters and other characteristics.

- Minor plasma radius: 54.11 mm.
- Electron temperature: 13 eV.
- Electron density: 5×10^{16} m^{-3}.
- Estimated confinement time: 5.70×10^{-4} ms (of ISS04 [10])
- Volume: 13.76 liters (0.01 m3).
- Aspect ratio: >4.4

The first SCR-1 plasma is expected to half of 2015.

3. Conclusions

The experience of designing and building this small Stellarator provides important opportunities for students, especially undergraduates, to develop the skills required for future opportunities in the field of experimental plasma physics and magnetic confinement fusion by working on professional research; engaging with the real engineering problems involved and finding their solutions; and contributing to the hands-on experience that is required before graduating.

As the future first Stellarator of Latin American, it is also very significant for the Plasma Physics Group from Instituto Tecnológico de Costa Rica (PlasmaTEC) to work on the design and construction of SCR-1; hoping that this can bring more plasma research opportunities to Latin American countries.

It is also hoped that the SCR-1 inspires more universities to develop similar devices that can work well for didactical purposes as well as achieving its main objective: contribute to the engineering and physics of small Stellarators [11,12,13].

Any kind of help, comment or suggestion is appreciated. Please contact us if any question.

4. Acknowledgment
The authors would like to thank the engineer Vicente Queral, CIEMAT and the Laboratorio Nacional de Fusión, in Madrid, Spain; for the support provided throughout this project.

5. References
[1] R.R. Weynants, "Fusion machines," Transactions of Fusion Science and Technology, Vol.49, pp. 36–42, February 2006
[2] E. Rebhan, and G. V. Oost, "Thermonuclear burn criteria for D-T plasmas," Transactions of Fusion Science and Technology, Vol.49, pp. 16–26, February 2006
[3] V. Queral, "UST_1 a small low cost stellarator," Stellarator News, Issue 118, pp. 1–6, December 2008. (references)
[4] H. Yamada, "Characterization of energy confinement in net-current free plasmas using the extended International Stellarator," Nucl. Fusion, Vol.45, pp. 1684–0000, May 2005
[5] M.M. Clark, A. Eckhart, K. Flanagan, J. Milhone, A. Rasmus, I. Reese, J.P. Wallace, D. Weisberg and C.B. Forest, "Fabrication of a Vacuum Vessel for a Cusp Confinement Plasma using Cast Al," Abs. Proc. 54th APS-DPP Meeting, Providence, US, November 2012
[6] L. Barillas, V.I. Vargas, et. al., An Engineering Approach to the Design and Construction of a Small Modular Stellarator for Magnetic Confinement of Plasma: SCR-1, in Proceedings of the19th International Conference on Nuclear Engineering, May 16-19, 2011, Chiba, Japan
[7] J. Mora. "Diseño del soporte y el control de corriente de las bobinas del Stellarator de Costa Rica 1. Informe de Proyecto de Graduación para optar por el título de Ingeniero en Mecatrónica con el grado académico de Licenciatura". Instituto Tecnológico de Costa Rica. Cartago, Noviembre de 2014, unpublished.
[8] H. Trimiño, V.I. Vargas, S. Tallents, L. Rivas, D. Chacon, J. Chacon, S. Fatjo, J. Jimenez, L.F. Villegas, J.Mora, J. Asenjo, J.M. Carranza, F. Cerdas, L. Barillas, J.I. Monge, J.Morera, H. Peraza, C. Rojas, G. Sánchez, M. Sandoval, J. Umaña, R. Gutiérrez, G. Solano. Design of an ECH system for a small modular stellarator, in Proceedings of the 38th International Conference on Plasma Science and 24th Symposium on Fusion Engineering, June 26-30, 2011, Chicago, Illinois, USA
[9] V.I.Vargas, J. Asenjo, A. Sura, S. García, F. Cerdas, D. Chacón, J. Chacón, S. Fatjó, J. Jiménez, and L. Rivas, Proc. 14th Latin American Workshop on Plasma Phys., Mar del Plata, Argentina, 2011
[10] Yamada H. et al., Nucl. Fusion 45, 1684 (2005).
[11] D.A. Hartmann, "Stellarators," Transactions of Fusion Science and Technology, Vol.49, pp. 43–55, February 2006.
[12] Stellarator News 2004-92.
[13] A. H. Boozer, "What is a stellarator?," Physics of Plasmas, Vol.5, pp. 1647–1655, May 1998.