SCR-1: Design and Construction of a Small Modular Stellarator for Magnetic Confinement of Plasma.

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Abstract. This paper describes briefly the design and construction of a small modular stellarator for magnetic confinement of plasma, called Stellarator of Costa Rica 1, or SCR-1; developed by the Plasma Physics Group of the Instituto Tecnológico de Costa Rica, PlasmaTEC. The SCR-1 is based on the small Spanish stellarator UST_1, created by the engineer Vicente Queral.

The SCR-1 will employ stainless steel torus-shaped vacuum vessel with a major radius of 460.33 mm and a cross section radius of 110.25mm. A typical SCR-1 plasma will have an average radius 42.2 mm and a volume of 8 liters (0.01 m3), and an aspect ratio of 5.7.

The magnetic resonant field will be 0.0878 T, and a period of 2 (m=2) with a rotational transform of 0.3. The magnetic field will be provided by 12 modular coils, with 8 turns each, with an electrical current of 8704 A per coil (1088 A per turn of each coil). This current will be fed by a bank of cell batteries. The plasma will be heated by ECRH with magnetrons of a total power of 5kW, in the first harmonic at 2.45GHz. The expected electron temperature and density are 15 eV and 10 17 m-3 respectively with an estimated confinement time of 7.30 x 10 -4 ms. The initial diagnostics on the SCR-1 will consist of a Langmuir probe, a heterodyne microwave interferometer, and a field mapping system.

The first plasma of the SCR-1 is expected at the end of 2011.

1. Introduction and motivation

The world as we know it depends on energy, in particular electrical power. The electrical power that we consume in commerce and industry is largely generated using resources such as coal and gas that pollute the environment, are non-renewable and are being depleted [1]. To reduce the negative impact of electricity generation and ensure the long term supply of energy, there is a strong motivation to develop a safe, clean, efficient and renewable energy source: nuclear fusion is a potential candidate for achieving these aims may fulfils these requirements [1].

Some of the main obstacles in fusion research are the large budgets and facilities required to research the typical plasmas used to achieve fusion. Despite this, between 2005 and 2007, a small
Stellerator (UST_1) was designed, built and operated by just one person: the Spanish engineer Vicente M. Queral, on a budget of under $4000; proving that low-cost techniques to build accurate-acceptable quality stellarators are possible [2].

The low volume of research on small size magnetic confinement devices and the need to contribute to the world’s energy solution research motivated the Plasma Physics Group of the Instituto Tecnológico de Costa Rica (ITCR), PlasmaTEC, to build on the achievement of Queral and design a new upgraded and improved model based on the UST_1: the Stellarator of Costa Rica 1 (SCR-1). This model will be, so far, one the few small stellarators ready to diagnose some of the main parameters of the plasma.

2. The SCR-1 Project

2.1. Structure and areas of the SCR-1 Project

The SCR-1 Project is run mainly by undergraduate students from a range of engineering degrees under the supervision of experts and professionals. The structure of the project involves about 25 engineering and physics undergraduate students, mainly from the ITCR, 1 graduated physics and 4 supervisor engineers, all of them under the leadership of two plasma physics and nuclear fusion doctors. This kind research structure had never been presented before in Costa Rica.

The project is divided into the following areas: Coil Systems and Layer Materials, Vacuum Systems, Magnetic Fields, Power Supply Systems, Heating, Diagnostics, Simulation, Safety, Data Acquisition and Control Systems, and finally, the Administrative, Technical, and General Supervising areas. Each area represents a part or system of the SCR-1 and it is constituted by at least 3 students, except for the Supervising areas, which are logistical areas managed by the graduated engineers and the doctors. A diagram of the SCR-1 Project structure is show in Figure 1.

![Figure 1. Diagram of the SCR-1 Project structure](image)

A description of each part or area of the SCR-1 will be described, including its characteristics and parameters. At the end, the expected plasma parameters will be mentioned too. Before starting, it is important to mention that the SCR-1 Project is on design and construction phase at this time, so some parameters may change in the future.

2.1.1. Vacuum Systems. This area is responsible for designing the vacuum vessel, as well as selecting the equipment for reaching the desired vacuum. As vessel, is has been designed and selected a torus-shaped vacuum chamber, with major radius of 238 mm and a cross section radius of 80 mm (this is shown on Figure 2). The vessel will have 14 ports available for different applications, as seen
The chamber design has more ports than the actual diagnostics and probes require, which is good because that will let PlasmaTEC incorporate more components if needed.

The vessel material will be austenitic 304L grade stainless steel, with an approximated thickness of 3 mm; these parameters depend on the commercial availability of the material and its price.

The minimum pressure that the vacuum pump can reach is $10^{-9}$ Torr, and the expected pressure in the vacuum vessel will be $10^{-6}$ Torr.

![Figure 2. SCR-1 vacuum vessel dimension drawing.](image)

![Figure 3. SCR-1 vacuum vessel with labeled ports](image)

2.1.2. Coil Systems and Layer Materials. The SCR-1 will have 12 modular copper coils, with 8 turns each one. The electrical current passing through each coil will be 8704 A approximately, this means, 1088 A per turn. This area is in charge of positioning the coils, that is why they are currently investigating on materials that can be set over the vacuum vessel and mechanized the grooves to place the coils. The first option, as shown in Figure 4, is to set a layer of plaster over the vacuum chamber and mechanized the grooves with a special machining device that is being designed and built, in order to obtain the complex coil geometries required. This special machining device will have the flexibility to allow for alternative coil shapes to be implemented in future magnetic confinement devices.

The Coils Systems and Layer Materials area is also in charge of assemble and test the field mapping system.

2.1.3. Power Supplies Systems. The electrical supply system will consist of an array of 82 lead-acid electrochemical cells (battery bank); each cell will have a nominal voltage of 2V and an electrical
storage capacity of 200 Ah. Due to the electrical requirements of the SCR-1, these cell characteristics are necessary to ensure the functioning of stellarator during a plasma discharge. The battery bank will have a final voltage of 164V and will be able to deliver a current of 1088A at least during one duty cycle of the stellarator. It is estimated that each cycle will last for about 4s; however, the battery bank capacity will allow us to increase the length of the cycle.

The system will also use a variable load connected between the bank and coils system in order to maintain a constant current flow during each work cycle, dissipate excess power, counteract the changes in wire resistance due to temperature and automate the delivery of current pulse.

A drawing of the battery bank is presented in Figure 5.

Figure 4. Device mechanizing the coil grooves into the layer material (plaster) of the vacuum vessel.  
Figure 5. Representation of the battery bank: an array of 82 lead-acid cells.

2.1.4. Heating. The plasma in the SCR-1 will be heated with electron cyclotron resonance heating (ECRH), through 2 magnetrons of 2.5kW each (5 kW total), at 2.45 GHz in the first harmonic. These were chosen due to commercial availability of magnetrons with this frequency, plus other calculation made in order to have the best heating possible, with the simplest systems (this reduces costs).

2.1.5. Diagnostics Systems. As mention, this stellarator will be able to diagnose plasma when it will be ready. The diagnostics consist of a Langmuir Probe (Figure 6) and a Heterodyne Microwave Interferometer, especially design for the current application: a small stellarator. It is important to mention that the interferometer was developed along with a computer program to receive the data of the lineal density of the plasma (Figure 7). Both diagnostics were design by 2 PlasmaTEC engineering students with the collaboration of the Laboratorio Nacional de Fusión, in Madrid, Spain.

Also a field mapping system will be installed using an e-gun and a CCD camera, in order to superposition the frames taken by the camera and compare the experimental field lines with the ones simulated; this will validate that the calculations made for the SCR-1 are correct.

2.1.6. Magnetic Fields. The magnetic resonant field for the Stellarator of Costa Rica 1 will be 0.0878 T, and a period of 2 (m = 2) with a rotational transform $\iota = 0.3$.

2.1.7. Simulations and Modeling. A JAVA code named SimPIMF was developed by V. 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 [2]. In Figure 8 are presented some vacuum magnetic surfaces on 3 different toroidal angles obtained on Poincaré simulations for UST_1, which also work for SCR-1.

This area work together with Magnetic Fields area and they both are currently developing new codes for simulations, in order to predict some plasma behaviour and implement modifications if needed into the current design of the SCR-1.
2.1.8. Data Acquisition and Control Systems. The responsibility of this group is to automate all possible systems of the SCR-1, in order to accurately launch the plasma shooting sequence. They are also in charge of any data acquisition in the project. The actual work of this group will start just after the SCR-1 is built, but right now the area also supervises the rest of the areas before buying any equipment, with the intention of recommend products that contribute with the automation of the SCR-1.

2.1.9. Safety. This is consider the most important and respected area of the project, because its main purpose is aim to achieve the goals of the project according to any necessary aspect that guarantees the safety of the people and the equipment, as well as the correct development of the operations. They must establish a protection and risk reduction system that relate from the development and operation of each stage of the SCR-1; and also, they must have knowledge on technical aspects of the SCR-1 and human issues.

2.1.10. Plasma parameters: The following are the expected plasma parameters and other characteristics.

- Minor plasma radius: 42.2 mm
- Electron temperature: 15 eV
- Electron density: $10^{17}$ m$^{-3}$
- Estimated confinement time: $7.30 \times 10^{-4}$ ms
- Volume: 8 liters (0.01 m$^3$)
The first SCR-1 plasma is expected at the end of 2011. Finally, Figure 9 describes a computer image of the SCR-1 shown in layers.

Figure 9. Computer image of the SCR-1 shown in layers

3. Final comments
It is important to emphasize that the experience of designing and building of this small stellarator provides important opportunities for students, especially for undergraduates, to develop the skills required for future research by working on real research; engaging with the real engineering problems involved and finding their solutions; and contributes to the hands-on experience that is required before graduating. It is also very significant for PlasmaTEC to work on the design and construction of the first stellarator of Latin American; we hope that this can bring more research opportunities to our countries.

We also hope that the SCR-1 inspires more universities to develop similar devices, like this one, that can work well for didactical purposes.

We appreciate any kind of help, comment or suggestion. Please contact us if any question. Further information about the SCR-1 and other PlasmaTEC projects are available at http://www.tec.cr/sitios/Vicerrectoria/vie/investigacion/plasma/Paginas/default.aspx

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