Progress on small modular stellarator SCR-1

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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. Small stellarators present clear advantages related to total cost of the project which allows with a relatively low investment train human resources and contribute to the physics and engineering of such devices within the fusion scientific community.

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 of > 4.4; a 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 of 54.11 mm; a volume of 13.76 liters (0.01 m^3); and, major radius of R = 238 mm. Plasma will be confined in the volume by an axis magnetic field of 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.

Engineering aspects

The stellarator vacuum vessel along with its coil support, coils and ports were completely constructed in Costa Rica by the Instituto Costarricense de Electricidad (ICE), after hiring their services. All ancillary components and peripherical systems were chosen according to design criterion and they were bought new. Additional stellarator support structures for the peripherical systems (ECH system, Gas Injection System) and the diagnostics were constructed in Costa Rica using 304LN austenitic steel with relative magnetic permeability below 1.01.

The engineering phase, previous to the construction of SCR-1, was divided in the following steps [2]: Predesign, Design, Design review, Detailed design within the manufacturing contracts.

Vacuum Vessel

SCR-1 vacuum vessel was manufactured with two 6061-T6 aluminum cylindrical building blocks. 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 because it increased greatly project costs. Internal surface was polished and it was obtained a R_a=0.3. It was finally obtained a vacuum vessel with 10 mm thickness and a volume of 0.0418 m^3, an external radius of 364.1 mm, an internal radius of the central circle of 112.1 mm, a major radius of R = 238.1 mm, and the internal radius of the vacuum vessel is 94.42 mm.

Each CF port was mechanized according to design dimensions. The vacuum vessel has 24 conflat ports: three of the ports are CF of 6", 10 are CF of 4-5/8", and 9 are CF of 3-3/8". Two rectangular ports, internal dimensions of 90 mm x 40 mm, were added to accommodate future needs. It was decided to use, for all ports, the same CF aluminum design of the vacuum vessel with Cusp Confinement Plasma called MPDX (Madison Plasma Dynamo Experiment) from the University of Wisconsin, Madison. The welding process was certified by manufacturer to AWS welder and it was used a standard procedure as AWS A5.3 and AWS A5.10, which specify aluminum welding procedure.

Modular field coils

a) **Coil support system**

In the predesign, design, and design review phases, different ideas on how to place the coils above the vacuum vessel, methods as the one indicated on [1], were considered. Finally in the detailed design phase, it was decided to use coil support or guides that were welded to the vacuum vessel and with the specific shape of each; which should leave a channel in which a conductor wire would be placed. The fabrication of coil supports and guides was done through a cast procedure. This method was chosen because it allows building pieces with the exact shape. Now, to create the casting molds a 3D printer, Dimension DST1200ES, was used. It has a print volume of 254 x 254 x 305 mm and a print precision of 0.254 mm, which is more than acceptable for the creation of the supports because the defined tolerance in the design phase for this process was +/- 2 mm. Once supports were ready with the 3D printer, the casting mold was created and the cast started. The following step was to place the supports in the vacuum vessel, but first it was necessary to mark accurately where the supports were to be welded. It was decided to use a CNC milling machine with a ball mill (to allow to always making contact with the tangency point) to create a channel of 0.2 mm with the coil shape reflected on the vacuum vessel for the welder to know where to place the piece and weld it.

b) Magnetic coil system

The SCR-1 magnetic field of confinement will be generated by 12 copper modular coils, whose supports and positioning were done according to the beforehand explanation. Coil geometry was obtained by engineer Vicente Queral [1], from CIEMAT, in Spain. 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.

Thermal transfer simulations were performed in modular coils [2]. The thermal behavior of copper wire by electrical current passing 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.

c) Coils connection and electric current regulator

Modular coils were connected in series with heterogeneous welding, using tin to create joints in cabling ends. This allows reducing total resistance of 12 coils to 60 mΩ by not using connectors among the coils. Once the coils were connected, they were welded to the end of an AWG #4 cable, AWG #0 copper cable, and it was returned through where the coils are connected in series to cancel magnetic fields generated by peripherical wires to the coils.

To keep a constant current during a period of time less than 10 s, in spite of ohmic heating in coil conductor cable, it was designed an electrical current controller [2].

Peripherical systems and support structure

The Peripherical systems and support structure are formed by ECRH system, gas injection system, vacuum pumping system, power supply, control system, support structure. More information about the auxiliary systems can be found at reference [2].

Status of assembly on site, test program and commissioning tests

To this date the covers, viewports, vacuum sensor, vacuum pumps, etc, have been placed. The first vacuum testing suggests pressures of 10^{-7} Torr in the toroidal vessel. ECRH systems of 2 kW and 3 kW have been tested and operated thanks to the control system indicated above. There have been hydrogen gas injection testing and an injection pattern has been determined for the first discharge. The battery bank is operating and charging; it is ready to be used in the first tests to provide power supply to the coils. Electrical current controller is being assembled and it is expected that by June 2015, it will be operational to be able to do the first plasma discharge. Once all peripherical systems finish the start up, they will undergo magnetic field mapping tests. For the second half of 2015, it is expected to have the first electron density and temperature measures using Langmuir probe and optical spectrometer.

Conclusions

A small modular stellarator has been designed and constructed and it is under the implementation phase at Instituto Tecnológico de Costa Rica (See Figure 1b). To this date the aluminum vacuum vessel has surpassed the values of expected low pressures. It was implemented an innovative method to construct modular coils using 3D printer and casting Al. The peripherical systems as ECRH, gas injection, vacuum pumping system, power supply, control system and support structure are ready and operational. It is expected that in June 2015 the start up of the electrical current controller is finished and with that being able to do the first plasma discharge, besides being able to do magnetic field mapping testing.

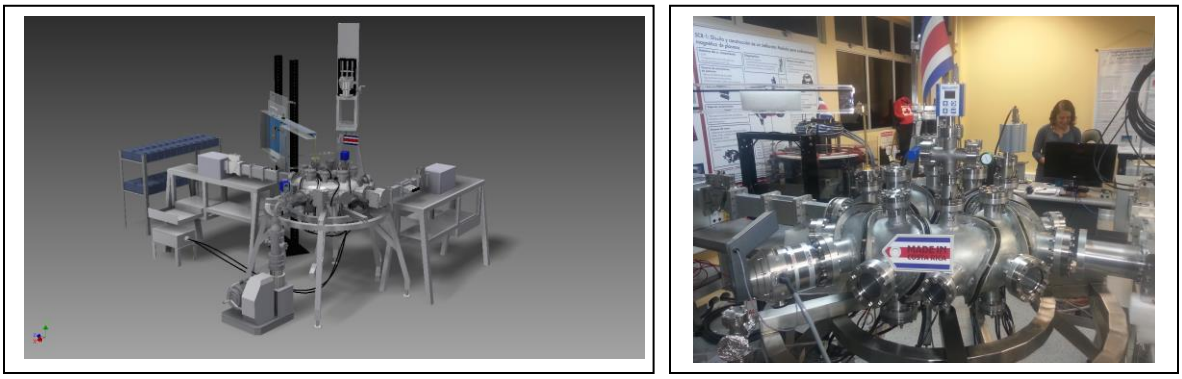

Figure 1: a) Drawing of all peripherical systems and support structures, b) Status of assembly on site of Stellarator SCR-1.

References

[1] V. Queral, "Coil fabrication of the UST_1 modular stellarator and potential enhancements," Fusion Eng. Des., vol. 88, no. 6–8, pp. 683–686, Oct. 2013.

[2] V.I. Vargas, et al. Implementation of Stellarator of Costa Rica 1 (SCR-1), in Proceedings of the 2015 IEEE 26th Symposium on Fusion Engineering (SOFE), May 31-June 4, 2015, Austin, Texas, USA.