Re-commissioning of the Spherical Tokamak MEDUSA in Costa Rica

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Abstract. The low aspect ratio spherical tokamak (ST) MEDUSA (Madison EDUcation Small Aspect ratio tokamak) is currently being re-commissioned in Costa Rica and was donation to Costa Rica Institute of Tecnology by University of Wisconsin-Madison, USA. The major characteristics of this device are: plasma major radius $R_o < 0.14$ m, plasma minor radius a < 0.10 m, plasma vertical elongation 1.2, toroidal field at the geometric center of the vessel $B_T < 0.5$ T, plasma current $I_p < 40$ kA, $n_e(0) < 2 \times 10^{20}\ m^{-3}$, central electron temperature $T_e(0) < 140$ eV, discharge duration is < 3 ms, top and bottom rail limiters, natural divertor D-shaped ohmic plasmas). In addition to training, the major objective of renamed device MEDUSA-CR is to address relevant physics for spherical and conventional tokamaks, taking advantage of the insulating vessel which allows plasma real time response to applied external electrical or magnetic fields.

The major topics for the scientific programme are 1) Comparative studies of equilibrium and stability between natural divertor D and bean-shaped ST plasmas; 2) Study of an ergodic magnetic limiter; 3) Alfvén wave heating and current drive and; 4) Transport. Advances in some of these topics will be presented in this work, in addition to the technical tasks of machine re-commissioning involving the re-design of energy, gas injection, vacuum system and control systems.

1. Introduction

Small magnetic confined plasmas devices are essential for guiding large machines in several tasks which are fusion relevant [1].

In addition to the physics and engineering addressed (and some in a total a proof-of-principle basis), they can also act as a bench test devices for reducing the cost-risk/benefit ratio of in large devices making unfeasible several developments otherwise due to the increase budged tighten experienced by many Institutions all of the world, caused by budged-cuts and increasing commitments with the international joint projects such as ITER. Therefore, small devices are more important than ever. In this context, small spherical tokamaks are no exception and can guide either large conventional as well as spherical tokamaks. Recommissiong the spherical tokamak MEDUSA in Costa Rica (see FIG.1) allows this device to play such role, in additional be become the first new fusion experiment to be in operation in the entirely Latin America for more than a decade.

MEDUSA-CR, will play vital role for training new generation of scientists posing also huge challenging for to the local scarce experts of these scientific communities and theirs institutions in many tasks from supervision, creation of job opportunities, and to the ability of maintain continuity of their fusion researching programmes.

MEDUSA-CR will also help the SCR-1 stellarator commission and training and will pave the way for having a medium size device leading Costa Rica to keep tracking and effectively contribute to the world effort in fusion research as one of the leaders in the field in Latin America.

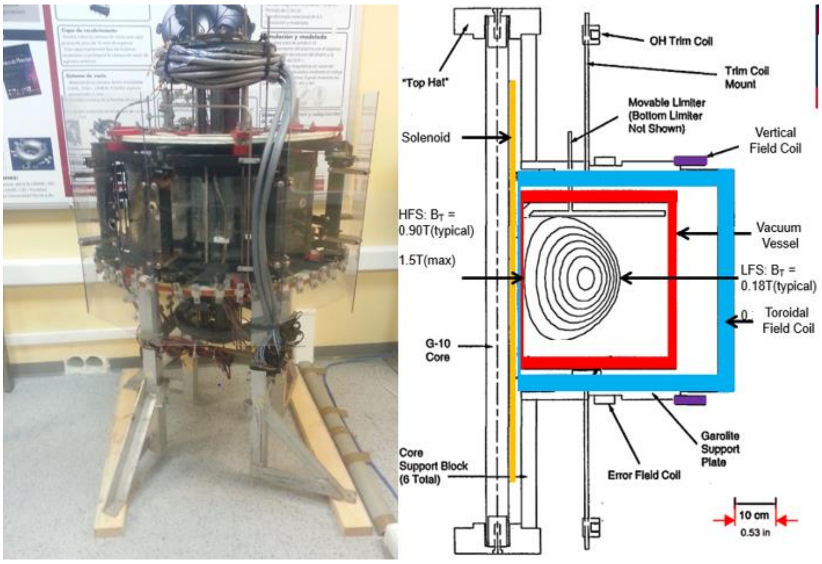

FIG. 1. Spherical Tokamak MEDUSA-CR.

This paper describes the preliminary scientific programme in Re-commissioning of the Spherical Tokamak MEDUSA in Costa Rica (Section 2), progress on Re-commissioning (Section 3) and finally the conclusions (Section 4).

2. Preliminary scientific programme

MEDUSA-CR´s proposed research involves several parallel tasks on machine recommissiong and operation, diagnostics and additional systems development, and computer modelling.

The preliminary scientific programme is based on these tasks (mainly in the last two) and it is intended to clarify several issues in relevant physics for the conventional and mainly for the spherical tokamaks, notably about topics as heating and current drive via Alfvén wave injection and possible operation of spherical tokamaks with natural divertor configuration with ergodic magnetic limiter [2]. ECR for preionization aiming reliable breakdown and ohmic flux saving and possibly for heating is also expected. All these tasks are synergetic with edge diagnostics development aiming to study the anomalous transport under those scenarios.

To conduct such research tasks, strong liaison with international plasma physics communities is expected. Activities on plasma & engineering modelling are expected to be developed in parallel with the experimental programme by using the existing good computer facilities and computer codes such as EFIT (recently acquired) and FIESTA code/ASTRA (already available) for plasma simulation and transport studies, respectively.

2.1.Machine recommissiong

To start up the spherical tokamak we will do the following activities:

- Design and implementation of a Power Supplies Units and Control. This system is expected to deliver maximum toroidal field of 0.5 T and maximum plasma current around 30 kA with a time discharge of 5 ms (3 ms flat-top). These were the maximum expected design values form these device [3]. Some unities are already being re-designed here [4,5,6].

- Design and implementation of a Control and Data-Acquisition System. A schematic view of the potential system is shown in Refs.[4,5,6].
- Design and implementation of a Plasma Control System. Initially, it is expected a real time control for plasma position (vertical and horizontal) and in the future for extension and for maintaining the plasma current constant with a pre-programmed scheme with feedback. Potential collaboration with ISTOK team (Portugal) has been preliminarily agreed since this team has a highly established expertise in several technical issues such as this and fortunately is also part of CRP-IAEA [7].
- Design and implementation of a Vacuum and Gas Feeding System. This is expected to lead to low vacuum base pressure as lower as ~10^{-8}mbar with very low gas impurities in the chamber and gas feeding system monitored by RGA (Residual Gas Analyser) and measured by fast pressure gauges (e.g. capacitance and ion gauge types). All the information should be digitally recorded locally in a dedicated computer and automatically backed up into the major data store system.
- Design of external power system to deliver the energy (machine energy system), electrical load and personal protections (radiation shielding, dosimeter monitors, first aid courses), earth tests (building, machine, diagnostics, data acquisition).

2.2.Diagnostics

They are shown in FIG.2 [4,5,6]. Basically they are divided in two types: "day one", i.e. the ones needed at the very beginning of operation and "medium term", that is, those intended to be added in the subsequent months. The one of the first group are expected to be designed, calibrated, and bench tested (if possible), during the machine recommisioning task. The others are expected the have direct impact in the scientific programme such as the multi-function triple probe which unique and compact design is expect to address the issues of anomalous transport as well as a potential new input for equilibrium.

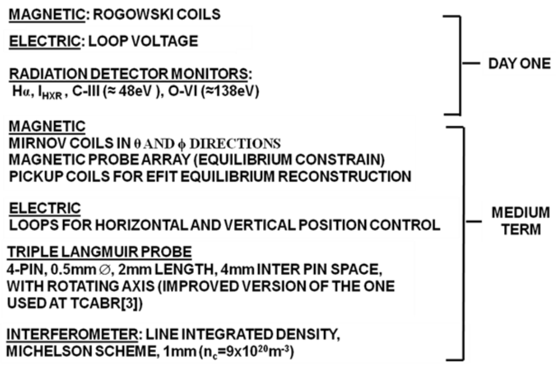

FIG. 2. Diagnostics for MEDUSA-CR.

2.3.Additional Systems

It is expected to implement the following additional systems:

Alfvén Wave (AW) Heating and Current Drive (CD)

Alfvén Wave heating and current drive in magnetic confined plasma relays on mode conversion of fast waves to kinetic Alfvén waves (KAWs) and their subsequent deposition via combined kinetic and collisional effects, and it has been already analyzed for spherical tokamaks [8].

AW scheme is very attractive because the RF system is cheap due to the range of launching frequencies below de ion-cyclotron range (few MHz). AW-CD is also highly relevant particularly for spherical tokamaks given the inherent lack of space of the solenoid for driving substantial plasma current. Here we propose a unique proof-of-principle experiment using AW antennas composed by just a single module posted externally to the glass vessel [9]. This unique feature allows to resolve, once for all, the role of sputtering and hydrogen release from the antenna and vessel present in all previous experiments, where the antennas have always been placed internally to the vessel. Potential collaboration with SUNSIT spherical tokamak team (China) is agreed either in the antenna design and simulations [10], taking advance of their expertise: they are currently testing their own AW system their device [11].

Ergodic Limiter

Ergodic limiter is a system composed by external coils in order to produced resonant magnetic perturbations highly localized at the plasma edge in order to control plasma-wall interactions.

It was initially proposed as a resonant helical limiter [12] via helical coils wounded toroidally to a tokamak vessel but later adopted (and used ever since) in a more simple configuration, composed by a single strap-coil placed poloidally in cross section in a fixed toroidal position, aiming to create an magnetic limiter with an ergodic behavior [13]. It has been so far restricted to the conventional tokamaks without divertor (natural divertor) configuration.

More recently, a simple alternative for setting up an edge ergodic field was successful tested in TEXTOR in which the axisymmetric field is broken via external perturbations produced by an inner coil with tilted circular loops, placed between the plasma and the vessel [14]. We will study this scheme first but with the difference that in MEDUSA-CR those coils are external to the vessel placed in the gap between the solenoid and vessel. For modelling such limiter, simulations via Poincaré maps will be conducted using the EFIT code or 3-D MAPTOR code [15]. Preliminary results on this has been already published [2].

Electron Cyclotron Resonance (ECR) for Preionization and Heating

ECR is a classical way for heating magnetized plasma. It relies on the absorption via resonance between the local magnetic field with the electron cyclotron waves and the final absorption occurs at upper hybrid resonance due the local plasma density [16]. The waves are launched from an external horn antenna connected to a high power (ten of kWs) microwave source. ECR has also been used as a high effective preionization in tokamaks [17], also saving considerable ohmic flux which is essential mainly for the spherical tokamaks.

Ideally, an ECR system in MEDUSA-CR should have 8.4 GHz frequency for having the electron cyclotron resonance right at the major radius of 0.12 m, using a typical toroidal field of 0.3 T. ECR in MEDUSA is intended preliminary for effective preionization, but also possibly for heating, depending on the source we can acquire (pulse length, frequency, and power). A simulation ray code for wave absorption is also expected to be acquired.

For comparison, we aim also to simulate an ergodic limiter using the strap-coil design in an inherent more complex poloidal geometry dictated by MEDUSA-CR square cross-section.

Studies on plasma wall-interaction using mainly the refine triple-probe described earlier will lead to address several interesting physics issues such as the power load, changes on the local anomalous transport, and the potential of the natural divertor configurations for the spherical tokamaks, as a way to overcome the intolerable divertor power load predicted by scaling in any tokamaks (conventional or spherical).

2.4.Computer Modelling

Activities on plasma & engineering modelling are expected to be developed in parallel with the experimental programme by using the existing good computer facilities. Initially, two codes will be used, and described as follows.

EFIT (Equilibrium FIT code)

EFIT code [19] is a computer code developed to translate measurements from plasma diagnostics into useful information like plasma geometry, stored energy, and current profiles. It became a standard equilibrium code for reconstruction for conventional (e.g. DIII-D) and spherical (e.g. START, MAST, NSTX) tokamaks, and it has been constantly updated and customized. We already acquired EFIT code from DIII-D [20]. EFIT code is being currently recompiled. To use EFIT, we have received training by the PPPL and we are establishing a colaboration with them for Re-commissioning of MEDUSA-CR in Costa Rica.

At this stage, it is expected to simulated simple equilibria giving external coil currents and giving plasma current. In a medium term, after the machine being in operation, this expected to reconstruct the plasma equilibrium in scenarios using the conventional constrains from dedicated external poloidal flux loops and magnetic coils and compared to those reconstructions via a unique and additional input constrain which is the edge radial profile of the measured magnetic pitch angle. This input will be inferred from the same triple probe described above, using the magnetic shadowing effect in two tips of this diagnostic, deliberately oriented for this propose [9].

FIESTA code

FIESTA is a simulation code created in MATLAB by Geoffrey Cunningham from Culham Centre for Fusion Energy. The FIESTA code simulates equilibrium scenarios for Tokamak-like structures.

FIESTA is basically a forward equilibrium solver expanded into a toolbox for dealing with equilibrium related problems. The code works solving the Grad-Shafranov Equation together with Green’s function within an object orientated programing which calls two mayor structures: the fiesta_configuration and the fiesta_equilibrium. The fiesta_configuration contains the Tokamak particular structure, such as coils and limiters plus the mesh grid used for the simulation. The fiesta_equilibrium deals the iterative solving for equilibrium. The coils object is arranged into a hierarchy of coils, filaments and circuits leading to the final Medusa magnetic configuration.

3. Progress on Re-commissioning

To date we have preliminary results in the following:

- Design and implementation of a Vacuum and Gas Feeding System;
- Computer Modelling using FIESTA code.

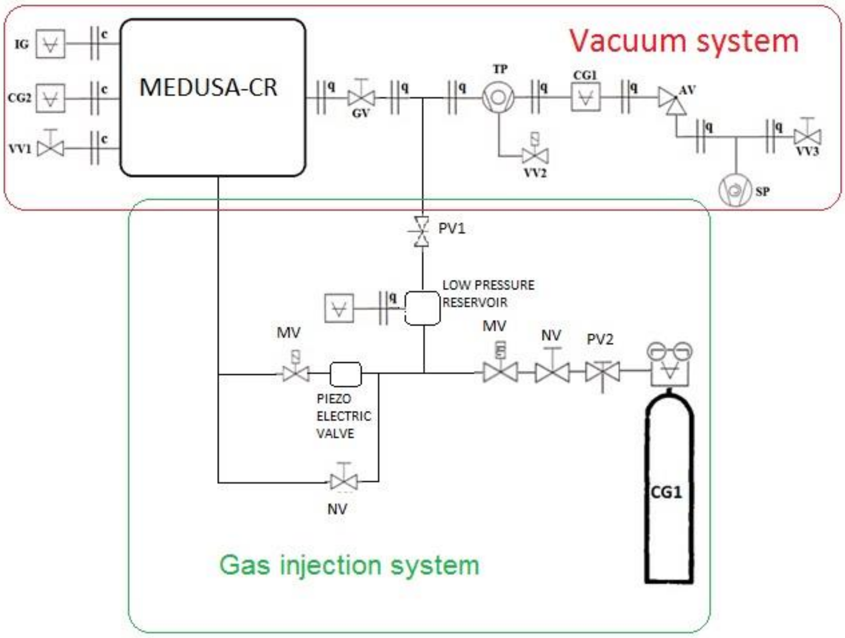

FIG. 3. Vacuum system and gas injection system of the MEDUSA-CR.

3.1.Design and implementation of a Vacuum and Gas Feeding System

The vacuum and gas feeding system were redesigned as shown in FIG. 3. To date both systems are being implemented for the first tests. On the re-commissioning of the Tokamak Medusa-CR it is important to mention that is going to use an Edwards EXT/DX TIC Controlled Pumping Station. To measure the pressure, we used a convection enhanced Pirani gauge and two hot filament (Ion) gauge distributed across the vacuum vessel, as is show on FIG.3.

To achieve the gas injection, use a system with a low pressure reservoir, which will be at vacuum before inject gas to it. When it is at vacuum, will be filled with gas to a certain pressure and the gas tank will be closed. Then using a Piezoelectric Gas Flow Valve Model PEV-1 will be injected the gas to the vacuum chamber. The main reason to use this valve is the fast response to change the state. FIG.3 shows the gas injection system.

3.2.Computer Modelling using FIESTA code

In FIG.4 the MEDUSA-CR parameters variation with the radial coordinate are presented. The numerical value of the current for the central rod in these simulations was about 0.227 MA; an external magnetic field of 0.261 T and a safety factor of 3.34. The corresponding 3D last magnetic closed surfaced is presented in FIG.5a for the axis symmetrical equilibrium in MEDUSA-CR. D-shape with low or highly triangularity and the novel bean-shaped ST equilibrium can be created via external inboard poloidal field coils. The axisymmetric field is broken via external perturbations produced by an inner coil with tilted circular loops, placed in the gap between the solenoid and the vessel. This design is similar to that used in TEXTOR, but in MEDUSA-CR device those coils are placed externally to the vessel. Notice the beam shaped cross section obtained with the simulation of a central solenoid called ergodic limiter shown in the FIG.5b. The ergodic limiter creates a beam shape cross section presenting a well-defined plasma confinement. Preliminary simulation on this configuration has been recently published [21].

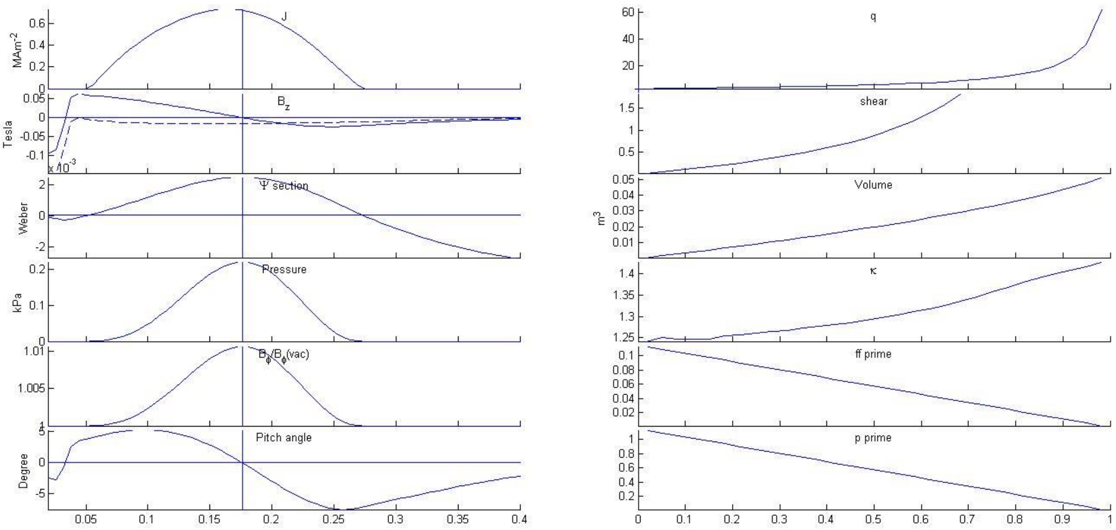

FIG. 4. MEDUSA-CR parameters as function of the radius.

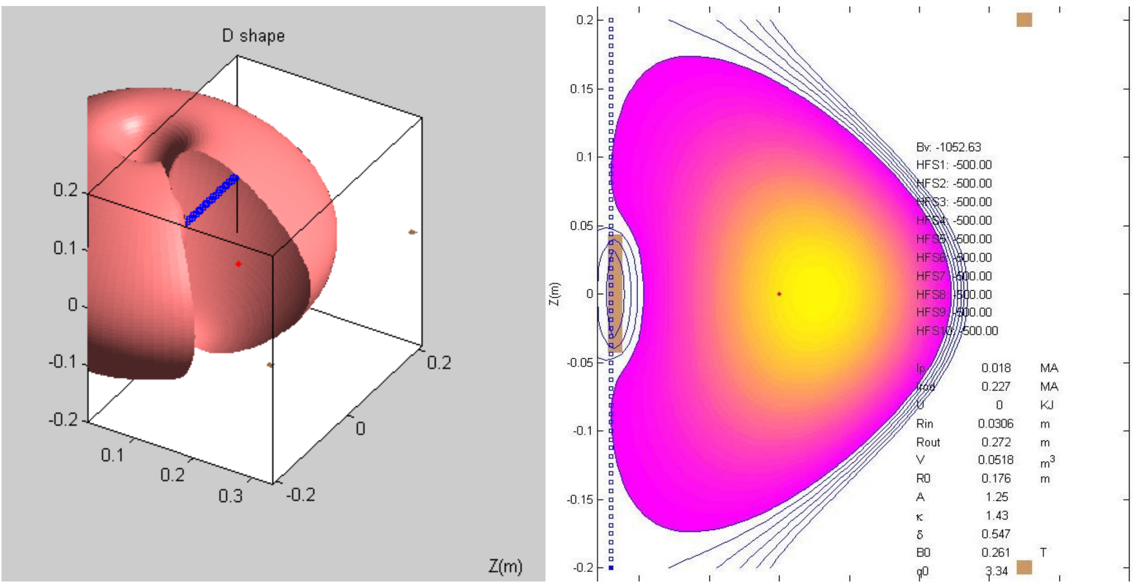

FIG. 5. (a) 3D last magnetic closed surfaced, (b) Beam shaped cross section; of MEDUSA-CR.

4. Conclusions

The spherical tokamak (ST) MEDUSA-CR is currently being re-commissioned in Costa Rica. We have defined a work plan for the machine recommissiong which seeks design and implementation of the systems power supplies units and control, control and data-acquisition system, plasma control system, vacuum and gas feeding system, and external power system to deliver the energy. Also we have defined the diagnostics to be used in MEDUSA-CR, as well as additional systems that will be investigated and implemented as Alfvén Wave (AW) Heating and Current Drive (CD), Ergodic Limiter, Electron Cyclotron Resonance (ECR) for preionization and heating. Preliminary results using FIESTA code indicate the main parameters of ST MEDUSA-CR.

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