IMPLEMENTATION OF THE SPHERICAL TOKAMAK MEDUSA-CR: STAGE 1

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Abstract

The low aspect ratio spherical tokamak MEDUSA-CR (Madison Education Small Aspect ratio Costa Rica) is currently being re-commissioned in Costa Rica, and the University of Wisconsin-Madison, USA donated it to the Costa Rica Institute of Technology. The major characteristics of this device are [1]: plasma major radius \( R_o < 0.14 \text{ m} \), plasma minor radius \( a < 0.10 \text{ m} \), plasma vertical elongation 1.2, toroidal field at the geometric center of the vessel \( B_T < 0.5 \text{ T} \), plasma current \( I_p < 40 \text{ kA} \), \( n_e(0) < 2 \times 10^{20} \text{ m}^{-3} \), central electron temperature \( T_e(0) < 140 \text{ eV} \), discharge duration is \( < 3 \text{ ms} \), top and bottom rail limiters, natural divertor D-shaped ohmic plasmas. This paper will show the new design of the vacuum chamber, made of stainless steel, it will also present how the design of the injection system works and it will show the upgraded system to control the current and proposes a solution to make AC discharges. Finally, it will present a transport simulation made for the spherical tokamak.

11. INTRODUCTION

MEDUSA-CR as a small magnetic confined plasma device, showed in Figure 1, plays a role for training a new generation of scientists. In addition, it can act as a bench test device for reducing the costs and risks of implementing a solution on a large-scale device. This device will take a fundamental role on the design process since small devices can configure a new experiment on a few days instead of months as the large devices, allowing scientists to test and correct the experiment or the devices that are in process of design and having a truly full test diagnostic or experiment that can be run on larger devices without going through the learning curve of the function for the diagnose or the new experiment. [2]

FIG 1. Spherical tokamak (ST) MEDUSA (Madison Education Small Aspect ratio tokamak) at Costa Rica Institute of Technology.
This paper describes the new vacuum chamber made of stainless steel that has more access ports than the previous one (section 2). It will also show the new control for the injection system. This allows the scientist to program any shape of gas injection pattern (section 3). To improve the flexibility of the device, the new design of the current control will have the possibility to make AC discharges (section 4). Finally, it will present the transport simulation made for the device (section 5).

12. VACUUM CHAMBER DESIGN

In previous works the vacuum system of ST MEDUSA-CR was designed [3]. The new vacuum system achieves $3 \times 10^{-5}$ Torr on the ST MEDUSA-CR with the original vacuum chamber, and one of the typical vacuum curves is shown in Figure 2. This parameter will be an input for the new vacuum chamber design.

![FIG 2. Pressure vs time graph obtained from ST MEDUSA-CR original glass vacuum vessel.](image)

The original vacuum chamber of ST MEDUSA-CR is made out of borosilicate (glass) whose mechanical capacities were thought to be ideal for this purpose. The wall thickness is 0.006 m, capable of holding up to 3 tons of pressure and the mayor dimension are 0.30 m height and 0.305 m radio. [1] Also, this vacuum chamber was built in 1997 and paid for its operation. It is intuited that its reliability and life cycle has been reduced in such way that it drives to the redesign, to increase its life cycle, reliability, maintenance and accessibility.

The first step taken on the redesign was to select the material to fabricate the new vacuum chamber. The final selection was made between stainless steel 304L and borosilicate. The main problem with the borosilicate was to find a manufacturer that could make it as specified. The biggest challenge with the stainless steel chamber were the Eddy currents [4] that can affect the way plasma behave, but it is easier to find a manufacturer for the chamber. With all the information taken in consideration as for advantages and disadvantages of both materials it was decided to build the vacuum chamber of stainless steel 304L. With this material it is known that the vacuum will work very well and the strength of the material will hold the pressure.

The decision of making the vacuum chamber out of stainless steel gives another problem: Eddy currents appear. The easiest way to fix this is to place the vacuum chamber outside the coils, resulting in the design show in Figure 3. But when the coils are placed back inside the vacuum chamber, the materials of the coils and supports of the coils need to work on vacuum conditions. Since this tokamak was built on 1997, it was difficult to have the datasheet of those materials, which lead to making an experiment where all the materials were put on vacuum and verifying if it was possible to reach the pressure needed.
FIG 3. New design of the vacuum chamber for ST MEDUSA-CR

The materials that will go inside of the vacuum chamber were tested inside a cylindrical vacuum chamber, which can reach pressures of $1 \times 10^{-6}$ Torr. If the vacuum can reach a pressure between $1 \times 10^{-4}$ Torr and $1 \times 10^{-6}$ Torr with a test tube of the material, and can hold it without outgassing, it will be a material that can be inside of the new vacuum chamber of the device. For this experiment, 5 different materials were selected from the: tensioning brackets, support brackets between TF coil and driver, screw coupling set for coils, base of the top hat and insulator coupling TF coil with the screws lower under the TF coil.

From all the test tubes the tensioning brackets and the base of the top hat reached a pressure higher than $1 \times 10^{-3}$ (Figures 4 and 5), meaning that these materials will not work for the application. That drove the team to build a new set of tensioning brackets changing to a material that can work on vacuum. The other 3 materials reached a pressure below of $1 \times 10^{-4}$ Torr. These conditions were hold for a period of 20 minutes without outgassing. On Figure 6 it is shown one of the pressure curves form the Screw Coupling Set for coils that reached the best pressure with a tendency to decrease.

FIG 4. Pressure vs. time curve form tensioning brackets  
FIG 5. Pressure vs. time curve form base of the top hat
The new vacuum chamber was designed with a safety factor of 8 in the weakest part. The dimensions are 1.4 m in height and an external diameter of 1.34 m. The wall thickness is 7 mm and the material is stainless steel (LS 304). The vacuum chamber has 26 Conflat ports: 6 of 13.25 inches, 10 of 10 inches and 10 of 6 inches. All these ports are distributed as shown in Figure 7. As part of the design, the vacuum chamber can be open at the middle to reach the coils inside easily.

Figure 7. Blueprints for the new design of the vacuum chamber for ST MEDUSA-CR
13. GAS INJECTION CONTROL SYSTEM

The gas injection system of ST-MEDUSA-CR is entirely designed and built in Costa Rica. [3]. The main component used to control the injection is a piezoelectric valve, which has a very fast reaction to the signals and can make fast changes in the injection of gas. The control system is based on an ATMega328 microcontroller. A microcontroller can be used with a PWM, if the duty cycle is changed properly it can have any injection pattern.

To change the pattern, it is crucial to know the time of change, meaning the time that should be opened or closed. This will give an approximation of the shape that scientists are looking for. This could be calculated on any mathematical software. For example, Figure 8 shows a pattern that is given after changing the duty cycle at the moment that is turning off.

![Figure 8: Pressure vs. time curve with a custom pattern.](image)

14. CURRENT CONTROL SYSTEM

The spherical tokamak MEDUSA-CR needs a current control system to improve flexibility and use not only one of the 4 modes to control a tokamak [5]. With this design the goal is to work on pulse mode and AC mode to be able to study materials and face control problems in a steady state in the spherical tokamak and to convert the spherical Tokamak MEDUSA CR into the first in the world to work in this mode.

The laboratory has a three-phase connection of 208V from the grid, which can give a maximum of 50A. This is why it is mandatory to use a system that stores enough energy to then perform the discharge of 100 ms. For storage a capacitor bank of 12F will be used and it will be charged with a full-wave rectifier. [3]

This capacitor bank design is made for the toroidal field coils and the ohmic field coils. In the case of vertical field coils (VF), an industrial battery bank with a voltage of 50V and 300 amp hour will be used, which will be purchased with its own battery charger since lead-acid require a system that keeps them in a floating state, when not in use.

A H-bridge is used to generate the AC signal to create a poloidal field. In this case the load of the H-bridge is modeled as an RL circuit. However, the resistance of the coil is very low, so the load of the circuit is too slow to make current changes. Therefore, a resistance is added so that the response is faster. This circuit is shown in Figure 8. In the case of the toroidal field and the vertical field, it is used a buck converter system.
The control of the H bridge is a non-linear control called Sliding Mode Control (SMC). The main reason to use this type of control is because it does not depend on the size of the controlled system. Also, it is a very simple control to implement because it only depends on a simple subtraction and a decision to make. In this particular case, the subtraction is the current that it is needed and the current measured. If the result is less than zero it will open two of the IGBTs and if it is greater than zero it will open the other two. The result of this control is shown in Figure 10. In this case, we designed a system that needed less current in order to test the control algorithm safely. And the result shown is almost square signal in AC. Also, it is important to mention that between the simulation and the experiment there is only 1% of error.
15. TRANSPORT SIMULATIONS

A forward equilibrium solver written in Matlab was employed to simulate the magnetic confinement. The code name is Fiesta, and it was originally created for MAST (Mega Ampere Spherical Tokamak in CCFE) by Geoffrey Cunningham. Fiesta solves for free-boundary (i.e. the plasma cross section shape is not forced upon solving), MHD static, zero resistivity and no electric fields conditions. Confinement parameters were obtained and compared according to two different volume cross-section geometries. On one hand there is the D geometry (typical of spherical tokamaks) and on the other hand, there is the so called “bean” (B) geometry. The latter was obtained adding an inboard set of coils (ergodic coils) placed between the solenoid and the vessel. The results are presented in the figures below.

Results for the Bean-shape plasma: poloidal beta $\beta_p=0.25$, toroidal beta $\beta_T = 0.0016$, plasma volume 0.0518 m$^3$, elongation $\kappa=1.432478$ and triangularity $\delta=0.547298$, this last two parameters are obtained with the last closed flux surface (LCFS). Whereas the results for the D-shape plasma are the poloidal beta $\beta_p=0.27$, toroidal beta $\beta_T=0.0019$, plasma volume 0.0664 m$^3$, elongation $\kappa=1.287416$ and triangularity $\delta=0.427311$.

Higher current density achieved with B geometry. The same plasma current $I_p$ (0.23 MA) was used. Current on the external coils: 0.018 MA. Higher currents resulted in de-confinement or much reduced plasma volume (this may be used to extend pulses duration). Lower radius vertical field coils are expendable. The B geometry produces higher values of triangularity and elongation; this allows to increase the safety factor and allows to work with larger plasma currents. Thus, the ergodic coils configuration shows a greater performance in enhancing equilibrium parameters.
16. **CONCLUSION**

The spherical tokamak MEDUSA-CR is being recommissioned in Costa Rica. This proves that it is a good training platform because more than 10 students are working on the design of the device. Also, a new customized vacuum chamber was designed and it is under construction. The gas injection system has a better control system which makes more flexible the research on this device. A solution to control the current in the coils and produce a magnetic field that could work on AC mode was presented. Finally, it is shown the simulation that makes the analysis on transport.

**References**