Implementation of the Spherical Tokamak MEDUSA-CR: Stage 1


Plasma Laboratory for Fusion Energy and Applications
Costa Rica Institute of Technology
Cartago, Costa Rica
The low aspect ratio spherical tokamak (ST) MEDUSA (Madison EDUcation Small Aspect ratio tokamak) was operational in the 1990s in the University of Wisconsin-Madison, USA (Oct 94-Dec 96?).

MEDUSA-CR CAD model

Material Stainless steel 304L
6x CF port 13”
11 x CF port 6”
11x CF port 4-5/8”
Coils inside of the vacuum vessel.
MEDUSA-CR Dimensions

DIMENSIONS IN MILLIMETERS
MEDUSA-CR Vacuum Vessel Dimensions

Scale 1:10
HFS: $B_T = 0.90T_{(typical)}$
1.5T_{(max)}

$B_T = 0.18T_{(typical)}$
0.30T_{(max)}
# MEDUSA-CR main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius</td>
<td>0.09 m – 0.14 m</td>
</tr>
<tr>
<td>Minor Radius</td>
<td>0.04 m – 0.10 m</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>1.5 (1.35 min)</td>
</tr>
<tr>
<td>Plasma Current</td>
<td>20 kA (40 kA max)</td>
</tr>
<tr>
<td>Toroidal Field</td>
<td>0.3 T (0.5 T max)</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>1 ms (3 ms max)</td>
</tr>
<tr>
<td>OH Flux Swing</td>
<td>10 mV – s (single swing)</td>
</tr>
<tr>
<td>Plasma Vertical Elongation</td>
<td>1.2</td>
</tr>
<tr>
<td>Toroidal Field</td>
<td>41 kJ</td>
</tr>
<tr>
<td>Ohmic Heating</td>
<td>116 kJ</td>
</tr>
<tr>
<td>Vertical Field</td>
<td>17 kJ</td>
</tr>
<tr>
<td>P(base)</td>
<td>$5 \times 10^{-8}$ torr</td>
</tr>
<tr>
<td>$T_e (0)$</td>
<td>$&lt; 140$ eV</td>
</tr>
<tr>
<td>$n_e (0)$</td>
<td>$&lt; 2 \times 10^{20}$ m$^{-3}$</td>
</tr>
</tbody>
</table>
Control and data acquisition for will be performed by desktop computers coupled with interface electronics as shown below.

We have also developed a graphical Human Machine Interface for control and visualization of all processes using LabView

MEDUSA-CR PXI-NI for Control System

PXI (PCI eXtensions for Instrumentation)
- Industrial standard
- Robust
- High synchronization
- Modular: Chassis with several PXIe-6358 cards

- 16 simultaneous channels, analogical differential input
  1.25 MS/s/ch
  16 bits resolution with a range of +/- 10 V

- 4 channel of analogical outputs
  3.33 MS/s
  16 bits resolution with range of +/- 10 V
  48 lines of digital I/O of them: 32 channels with up 10 MHz hardware-timed

- 4 counter/timers with 32-bits for PWR, encoder, frequency, event counting applications, etc.

- Analog and Digital-triggering and timing with NI-STC3 technology

- Support for Windows 7/Vista/XP/2000
The load of the power supply are describe below

<table>
<thead>
<tr>
<th>Coil</th>
<th>Maximum current</th>
<th>Inductance</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal field</td>
<td>10 kA</td>
<td>2.9x10^-4 H</td>
<td>29 mΩ</td>
</tr>
<tr>
<td>Ohmic induction set</td>
<td>16 kA</td>
<td>9.7x10^-5 H</td>
<td>35 mΩ</td>
</tr>
<tr>
<td>Vertical equilibrium</td>
<td>1 kA</td>
<td>1.8x10^-4 H</td>
<td>15 mΩ</td>
</tr>
<tr>
<td>Error field correction</td>
<td>less than 100 A</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
MEDUSA-CR Power Supplies

Charge system of capacitors and isolation of the discharge network

<table>
<thead>
<tr>
<th>Coil</th>
<th>Voltage</th>
<th>Capacitance</th>
<th>Number of capacitors</th>
<th>Number of banks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic (OH)</td>
<td>350V</td>
<td>12F</td>
<td>1200</td>
<td>12</td>
</tr>
<tr>
<td>Toroidal Field(TF)</td>
<td>350V</td>
<td>9F</td>
<td>900</td>
<td>18</td>
</tr>
</tbody>
</table>
MEDUSA-CR Power Supplies

Capacitor bank

Current control system of the coils

Coils of Tokamak and current form

Power Feedthroughs??

Looking for
MEDUSA-CR Vacuum pumping system

- Minimum pump pressure: $10^{-10}$ Torr
- 1 mechanical pump ($10^{-4}$ Torr), and 1 turbo-molecular pump ($10^{-10}$ Torr)
- Additional equipment: RS485 communication, vacuum convectron, ion gauge sensors and RGA (Residual Gas Analyzers)
MEDUSA-CR Gas injection system

Gas injection system

<table>
<thead>
<tr>
<th>Specification table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
</tr>
<tr>
<td>Needle valve</td>
</tr>
<tr>
<td>Meetering valve</td>
</tr>
<tr>
<td>Mini Plug</td>
</tr>
<tr>
<td>Piezoelectric valve</td>
</tr>
<tr>
<td>Manometer</td>
</tr>
<tr>
<td>Pressure gauge</td>
</tr>
</tbody>
</table>
**MEDUSA-CR Diagnostics**

**DAY ONE**

**Magnetic**: Rogowski Coils and Plasma Current \((I_p)\)

**Electric**: Validation of all Existing 12 flux loops : 2 for Loop Voltage \((V_r)\)

**Monitors for Gas Detection**: RGA (residual Gas Analyser)

**Monitors for Radiation Detection**: \(\text{H}\alpha, I_{\text{HXR}}, \text{C-III} \approx 48\text{eV}, \text{O-VI} \approx 138\text{eV}\)

**MEDIUM TERM**

**Interferometer**: Line Integrated Density, Michelson Scheme, 1mm \((n_c=9\times10^{20}\text{m}^{-3})\)

**Magnetic**: Flux Loops for Tokamak 2.0 and FIESTA Equilibrium Reconstruction codes

Horizontal and Vertical Position Control

Validate the existing 14 Mirnov Coils \((\theta)\) and expand to \(\phi\) direction

Magnetic Probe Array (Hall Probe) for Equilibrium Reconstruction

**Triple Langmuir Probe**: 4-PIN scheme, 4mm inter pin space \(\Omega=0.5\text{mm}, 2\text{mm length}, \text{with rotating axis, i.e., a similar design of the one used at TCABR (e.g. C. Ribeiro, APS 2010)}\)
MEDUSA-CR external magnetics

1 Rogoswski Coil (Ip)
14 Flux loops
14 Mirnov coils

Positions of MEDUSA external magnetics
The existing computer facilities are:

**SOFTWARE**
- FIESTA code installed locally
- EFIT code installed locally
- COMSOL Multiphysics, Solid Works and Inventor Autodesk Softwares

**HARDWARE**
- Hardware available at the National Laboratory of Advanced Computing in Costa Rica.
- Specialized and up-to-date hardware, efficient applications and trained personnel to take advantage of all that technology
One of the attractive features of MEDUSA is the glass vessel because this leads instant field penetration for any external coils.

The major topics for the scientific programme are:

- Comparative studies of equilibrium and stability between natural divertor D and bean-shaped ST plasmas [3].
- Study of an ergodic magnetic limiter [3,4,5].
- Alfvén wave heating and current drive.
- Transport.

References:
Ergodic limiter

D-shape with low or highly triangularity and the novel bean-shaped ST equilibrium can be created via external inboard poloidal field coils.
Simulations using FIESTA code

- **FIESTA** is a forward equilibrium solver developed by Geoffrey Cunningham from CCFE. The code was written in Matlab.

- The popular EFIT code is currently being installed locally for more precise/real simulations of Medusa-CR confinement behavior.
Simulations using FIESTA code
MEDUSA in Costa Rica

MEDUSA-CR (Dec 2014) as it is at Instituto Tecnológico de Costa Rica, Cartago, Costa Rica
3) Alfvén wave heating

No plasma shield is needed

We will adopt the folded antenna design with a return strap radius far from the plasma for optimizing the power deposition

Antenna positioned between two consecutive toroidal field coils

Use a single module external to the vessel

This unique scheme may clarify, once for all, whether sputtering and hydrogen release from the antenna/vessel play any role in the density rise observed in the previous experiments, where the antenna was an in-vessel system.

Preliminary design of the folded Alfvén Wave antenna coupled to MEDUSA-CR device
Publications and Conference Contributions MEDUSA-CR

CONFERENCE CONTRIBUTIONS


PEER-REVIEWED ARTICLES