Status of SST-1 Project and Fusion Research in India

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Plan of Talk

• Fusion Research In India
  – ADITYA Tokamak
  – SINP Tokamak

• SST-1 tokamak
  – Objectives
  – Parameters
  – Description of Sub-systems & Fabrication Status
## Indian Tokamaks

<table>
<thead>
<tr>
<th>ADITYA</th>
<th>SINP Tokamak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius $R_0$</td>
<td>0.75 m</td>
</tr>
<tr>
<td>Minor Radius $a$</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Toroidal Field $B_T$</td>
<td>1.50 T</td>
</tr>
<tr>
<td>Plasma Current $I_p$</td>
<td>250 kA</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>250 ms</td>
</tr>
<tr>
<td>Plasma Cross-section</td>
<td>Circular</td>
</tr>
<tr>
<td>Configuration</td>
<td>Poloidal Limiters</td>
</tr>
<tr>
<td>Coils Type (TF &amp; PF)</td>
<td>Copper Water cooled</td>
</tr>
<tr>
<td>Current Drive &amp; Heating</td>
<td>Ohmic Transformer (Air Core)</td>
</tr>
<tr>
<td>Vacuum vessel</td>
<td>Vessel with Electrical break</td>
</tr>
<tr>
<td>Design &amp; Fabrication</td>
<td>Indigenous</td>
</tr>
<tr>
<td>Installation</td>
<td>1989</td>
</tr>
</tbody>
</table>
• Regular operations with transformer-Converter power system. 80-100 kA; 100 ms plasma discharges at 8.0 kG field are being studied. Standard Diagnostics have been developed and deployed.

• Magnetic fluctuations have been studied using Single value decomposition technique.

• Edge fluctuations and turbulence in density and potential have been investigated.

  • Pdf are found to be non-Gaussian; turbulence exhibits intermittency
  • Low frequency (< 50 kHz) contribute to convective particle transport
  • Turbulence exhibits complex, chaotic spatial and temporal variation.

• Coherent structures have been obtained in potential fluctuations using conditional averaging techniques. The dynamics of the structures suggest mechanism of “bursty” transport of edge plasma.

• Coupling coefficients and coherencies have been obtained using Wavelet analysis to study the power transfer due to linear, mixed and quadratic coupling.
Upgradation:

- A 20-40 MHz 200 kW ICRH system has been added.
- A 28 GHz 200kW Gyratron based ECRH system is commissioned.
- Additional Diagnostics have been implemented:
  - Thompson Scattering system
  - Spectroscopy (GIM, 10-600nm; NIM, 100-300 nm; VIS 300-800 nm)
  - Electron Cyclotron Emission measurement
  - Soft X-ray Camera
SINP Tokamak

Two Operational Regimes:

• Normal q regime; \( q_{\text{edge}} > 3 \)
• Low q regime; \( 0 < q_{\text{edge}} < 2 \)

Experiments in low q regime:

• Accessibility condition for VLQ and ULQ regimes
• Anomalous Ion heating in VLQ discharges
• Edge Biasing experiments in VLQ discharges
• Runaway Electrons in startup phase of VLQ discharges
• Variation in Up-down asymmetry with edge safety factor
Experiments in normal q regime:

- Drift wave like instability in Tokamak core region.
- Anomalous current penetration
- Temperature fluctuation induced anomalous transport
- Origin of inversion of up-down potential asymmetry
- Observation of ringing toroidal current explainable by Helicity conservations
- Observation of Runaway Electrons by ECE

Proposed to add LHCD on the tokamak in near future.
**OBJECTIVES:**

- Maintaining shaped, double/single null plasmas with non-inductive Current drive & auxiliary heating
- Steady state operation with controlled particle and power exhaust
- Advanced Tokmak Configurations with bootstrap current
- Learning new Technologies relevant to steady state tokamak operation:
  - Superconducting Magnets
  - Large scale Cryogenic system (He and LN2)
  - High Power RF Systems
  - Energetic Neutral Particle Beams
  - High heat flux handling

3-D Cut View of SST-1
SST1 MACHINE PARAMETERS

- **MAJOR RADIUS**: 1.1M
- **MINOR RADIUS**: 0.2 M
- **ELONGATION**: 1.7-2
- **TRIANGULARITY**: 0.4-0.7
- **TOROIDAL FIELD**: 3T
- **PLASMA CURRENT**: 220 kA.
- **ASPECT RATIO**: 5.2
- **SAFETY FACTOR**: 3
- **AVERAGE DENSITY**: $1 \times 10^{13} \text{cm}^{-3}$
- **AVERAGE TEMP.**: 1.5 keV
- **PLASMA SPECIES**: HYDROGEN
- **PULSE LENGTH**: 1000s
- **CONFIGURATION**: DOUBLE NULL
- **:**: POLOIDAL DIVERTER
- **HEATING & CURRENT DRIVE:**
  - **LOWER HYBRID**: 1.0 MW
  - **NEUTRAL BEAM**: 0.8 MW
  - **ICRH**: 1.0 MW
  - **TOTAL INPUT POWER**: 1.0 MW
  - **FUELLING**: GAS PUFFING

3-D Cut View of SST-1
SST-1 MAGNET SYSTEM

Requirements:
- Confinement, Shaping and Equilibrium Fields
- Ohmic Flux Storage
- Feed-Back Control

Superconducting Magnets:
- Toroidal Field (TF) Coils: 16 Nos.
- Poloidal Field (PF) Coils: 9 Nos.

Copper Magnets (Water Cooled):
- Ohmic Transformer (TR) Coils: 7 Nos.
- Position Control Coils (in-Vessel): 2 Nos.
### Conductor Characteristics

**Conductor type:** CICC.

**Outer Dimensions:** 14.8 × 14.8 mm².

**No. of Strands:** 135.

**Cabling Pattern:** 3⁺3⁺3⁺5.

**Last stage wrapped (half overlap) with 25 mm thick SS304 tape.**

**Twist Pitches:**
- I stage: 40 mm
- II stage: 75 mm
- III stage: 130 mm
- IV stage: 290 mm

**Conduit Material:** SS 304L.

**Conduit thickness:** 1.5 mm.

**Void Fraction:** 36%.

**Ic @ 5T, 4.5K:** 36 kA.

**Iop @ 5T, 4.5K:** 10 kA.

### Strand Characteristics

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>NbTi in Cu</td>
</tr>
<tr>
<td>Strand Diameter</td>
<td>0.86 mm</td>
</tr>
<tr>
<td>Filament Dia.</td>
<td>10 µm</td>
</tr>
<tr>
<td>Filaments per strand</td>
<td>1272</td>
</tr>
<tr>
<td>Cu : NbTi</td>
<td>5 : 1</td>
</tr>
<tr>
<td>Cu RRR</td>
<td>100</td>
</tr>
<tr>
<td>Ic @ 4.5K; 5T</td>
<td>232 A</td>
</tr>
<tr>
<td>Index ‘n’</td>
<td>45</td>
</tr>
<tr>
<td>Hysteresis Losses</td>
<td>33.5 mJ cm⁻³</td>
</tr>
</tbody>
</table>

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**Conductor for SST-1 Superconducting Magnets**
SST-1 TOROIDAL FIELD COILS

**PARAMETERS OF TF COILS:**
- Total No. of Coils: 16
- Turns per Coil: 108
- 6 Double Pancakes with 9 turns per pancake
- Current per turn (3T Field at Plasma Center): 10 kA
- Maximum Field at Conductor: 5.1 T
- Maximum Field Ripple: 0.35%
- Total Inductance (16 Coils in series): 1.12H
- Total Stored Energy: 56MJ
- Dump Time Constant: 12 s
- Peak Dump Voltage: ± 600V

**TF COIL Winding Pack:**
- Modified D-Shape
- Base Conductor: NbTI based CICC
- 6 # of Double pancakes
- Cross-section: 194x144 mm²
**SST-1 Poloidal Field Coils**

**Design Drivers:**
- Support single & double null equilibria with wide range of Triangularity (0.4-0.7), Elongations (1.7-1.9), $l_i$ (0.75-1.4), $\rho$ (0.01-0.85) & slot divertor configuration
- Limiter operation during Plasma current ramp up

**Parameters of PF Coils**

<table>
<thead>
<tr>
<th>Coil type</th>
<th># coils</th>
<th>Coil Radius (m)</th>
<th>Vertical Location (m)</th>
<th>Winding Cross-section (mm$^2$)</th>
<th># turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF1</td>
<td>1</td>
<td>0.45</td>
<td>0.0</td>
<td>71x320</td>
<td>80</td>
</tr>
<tr>
<td>PF2</td>
<td>2</td>
<td>0.45</td>
<td>0.43</td>
<td>71x163</td>
<td>40</td>
</tr>
<tr>
<td>PF3</td>
<td>2</td>
<td>0.50</td>
<td>0.93</td>
<td>136x380</td>
<td>192</td>
</tr>
<tr>
<td>PF4</td>
<td>2</td>
<td>1.72</td>
<td>1.03</td>
<td>85x136</td>
<td>40</td>
</tr>
<tr>
<td>PF5</td>
<td>2</td>
<td>2.01</td>
<td>0.65</td>
<td>85x136</td>
<td>40</td>
</tr>
<tr>
<td>PF6</td>
<td>2</td>
<td>1.35</td>
<td>0.35</td>
<td>100x100</td>
<td>16</td>
</tr>
</tbody>
</table>
**SST-1 OHMIC TRANSFORMER**

**Design Drivers:**
- Stress limited maximum flux storage
- Matching to existing power supply
- Plasma Break down and initial plasma current ramp up

**Characteristics:**
- Water cooled copper coils
- Stored Flux: 1.4 Vs @ 20 kA per turn
- Maximum Field in plasma Volume: 18 G

<table>
<thead>
<tr>
<th>Coils</th>
<th>#</th>
<th>Radius (m)</th>
<th>Turns (#)</th>
<th>X-section (mm²)</th>
<th>Center (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR1</td>
<td>1</td>
<td>0.20</td>
<td>672</td>
<td>120?260 0</td>
<td>0.00</td>
</tr>
<tr>
<td>TR2</td>
<td>2</td>
<td>0.49</td>
<td>40</td>
<td>195 ? 95</td>
<td>1.40</td>
</tr>
<tr>
<td>TR3</td>
<td>2</td>
<td>2.42</td>
<td>3</td>
<td>58 ? 23</td>
<td>0.73</td>
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</tbody>
</table>
Fabrication of Magnetic Field Coils
Manufacturing of Magnetic Field Coils
### SST1 Vacuum Vessel & Cryostat

#### Vacuum Vessel parameters
- **VESSEL MAJOR RADIUS**: 1.285 m
- **VERTICAL SEMI AXIS**: 0.81 m
- **RADIAL SEMI AXIS**: 0.53 m
- **POLOIDAL LENGTH**: 4.4 m
- **NO. OF MODULES**: 16
- **NO. OF TOP PORTS**: 16
- **NO. OF BOTTOM PORTS**: 16
- **NO. OF RADIAL PORTS**: 16
- **TOTAL SURFACE AREA**: 75 m²
- **TOTAL VOLUME**: 16 m³
- **TOTAL WEIGHT**: 4100 kg
- **MATERIAL**: SS 304L
- **VACUUM**: \(10^{-8}\) mbar

#### Cryostat parameters:
- **Vertical Height**: 2.6 m
- **Outer Diameter**: 4.4 m
- **Inner Diameter**: 0.355 m
- **Wall Thickness**: 10 mm
- **Total Surface Area**: 59 m²
- **Total Volume**: 39 m³
- **Total Weight**: 4520 kg
- **Material**: SS 304L
- **No. of Modules**: 8
Fabrication of SST1 Vacuum vessel and Cryostat
NORMAL PUMPING OF VACUUM VESSEL:
- Out gassing gas load = 1 x 10(-4) mbar l/s
- Design base pressure = 1 x 10(-8) mbar
- Required pumping speed = 10,000 l/s
- 2# TMP each (5000 l/s)
- 2# of Cryopumps (10,000 l/s)

DIVERTOR PUMPING OF SST-1 TOKAMAK:
- Particle exhaust requirement = 22 mbar l/s at 1x10(-3) mbar
- Required pumping speed = 22000 l/s for hydrogen
- Design value of pumping speed = 44600 l/s for hydrogen
- 16 # TMP (5000 l/s) ; on top and bottom ports

CRYOSTAT PUMPING:
- Out gassing gas load = 5 x 10(-2) mbarl/s at 300 K
- Design base pressure = 1 x 10(-5) mbar
- Required pumping speed = 5,000 l/s
- 2# TMP (5000 l/s) on Cryostat ports
Plasma Facing Components of SST-1

Design Drivers:

- Steady state heat and particle removal
- 1 MW power Input
- Surface temperature ? 1000 °C
- Baking up to 350 °C
- Electromagnetic forces during VDE, disruptions and halo currents
- Modularity

- Isostatically pressed, low ash content, Graphite
- Tiles mechanically attached to High strength copper alloy (CuZr & Cu CrZr) backplate;
- Cooling tubes (SS304) embedded in & brazed to the back plates.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>3.7 GHz.</td>
</tr>
<tr>
<td>Power (2 klystrons each of 500 kW CW)</td>
<td>1 MW</td>
</tr>
<tr>
<td>Antenna type</td>
<td>Grill</td>
</tr>
<tr>
<td># of subwaveguides</td>
<td>32 x 2 rows</td>
</tr>
<tr>
<td>Periodicity (with 2mm thick septa)</td>
<td>9 mm</td>
</tr>
<tr>
<td>Subwaveguide opening</td>
<td>76 x 7 mm²</td>
</tr>
<tr>
<td>Design $N_{\parallel}$ (at 90° phasing)</td>
<td>2.25</td>
</tr>
<tr>
<td>$N_{\parallel}$ variation (from 40° to 60° phasing)</td>
<td>1.0 - 4.0</td>
</tr>
<tr>
<td>Klystron input power</td>
<td>10 Watt</td>
</tr>
</tbody>
</table>

**SST-1 LHCD SYSTEM**

![SST-1 LHCD SYSTEM](image)

**PLAN VIEW OF LHCD SYSTEM**

![Plan View](image)

**KLYSTRON 2103D WITH DIRECTIONAL COUPLER**

![Klystron 2103D](image)
SST1 ICRH System

PARAMETERS
Frequency Range : 22.8 - 92 MHz
Power : 1.5 MW
No. of Antenna : 4 #
Duration : 1000 sec
Tx-Line system : 9" water cooled
Coupling efficiency : 80 – 92

45.6 MHz for 2 $n_e$ heating at 1.5 T
91.2 MHz for 2 $n_e$ heating at 3.0 T
22.8 MHz for D-Minority heating at 3.0 T
24.3 MHz for Ion-Ion Hybrid resonance at 3.0 T

Two generators of 1.5 MW each to cover the frequency range
SST1 ECRH SYSTEM

Objectives:
- Pre-Ionisation & Plasma start up
- Electron Cyclotron Heating to assist Current drive during LHCD

Main Parameters
- Gyratron Frequency : 82.6 GHz
- Output Power : 200 kW CW
- Output Mode : HE-11
- Operating TF Field :
  - Fundamental : 3 T
  - 2nd Harmonic : 1.5 T
- Exit dimensions of Waveguide : 63.5 mm
Objectives:
For SST-1:
  • Heating and Current Drive
  • Fuelling
  • Momentum Injection
On Test Stand:
  • Long Pulse Operation
  • Data Base Generation

Parameters:
Injection          Co-Tangential
Species            H/D (He on Test stand)
Beam Voltage        20 - 80 kV
Beam Power          0.3 - 1.7 MW
Ion Source          Multipole Bucket Type
Beam Divergence     < 1
Number of Beam Line 1
Number of Sources   1
Duti Factor         1000s on 5000s off
Pumping             Cryo-condensation pumps @3.8K
NBI SYSTEM

Chevron Baffle for Cryo-pump
Heat Loads & Cooling Requirements:

- Steady State Heat Loads : 180 W
- Energy input to SCMS : 125 kJ
- Current leads : 150 l/hr

Features of He Plant

- Fully automated refrigerator/liquefier
  - 400 W for SCMS + 250 W for Cold Circulation Pump
  - 200 l/h Liquefaction for Current leads
- Equivalent nominal power 1350 W@4.5K
- 2500 l capacity Master Control Dewar
- Cold Circulation Pump with Heat exchangers
  - 300 g/s flow of SHe through SCMS:
  - 4.5K, 4.0 bar(a) Inlet to SCMS; <5.0K, > 3.0 bar(a) at outlet to SCMS
INTEGRATED FLOW DISTRIBUTION & CONTROL SYSTEM

IFDCS links the He Plant to SCMS

- Supercritical He flow through TF coils, PF coils, TF casings & Cold Bus Duct
- Liquid Helium Supply to Current leads . Provision for SHe supply to test chamber
LN$_2$ & Gas Management System

LN$_2$ Requirements (1.5 bara; 79K):
- Radiation Shield : 350 l/h – 1450 l/h
- CLB, Cryo-transfer lines: 95 l/h
- Liquid Helium Plant : 110 l/h
- On-line Purifier : 110 l/h
- NBI system : 225 l/h – 400 l/h

LN$_2$ Storage & Distribution:
- 3# tanks 35 m$^3$ each (105 m$^3$ Total)
- Max operating pressure 2.75 bar g
- Max Discharge rate 2000 l/h
- Main Transfer Lines (250 m)
- Phase separator/ Sub-cooler Dewar
- LN2 Distribution and Return lines
- N2 Gas vent lines

High pressure storage system:
- 2# of 25 m$^3$ SS tanks at 150 bar

Medium Pressure storage system:
- 4# of 68 m$^3$ tanks at 14 bar.

Gas Recovery system:
- 2# of 40 Nm$^3$ gas bags
- 1 g/s recovery compressor @150 bar
- Purifier
Foundation and support structure
TF Coil Assembly Mock Up
Thanks for your kind attention