Status of SST-1 Project and Fusion Research in India

Yogesh C. Saxena

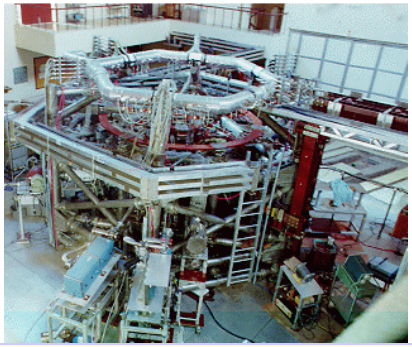
Institute for Plasma Research

Gandhinagar, INDIA

Plan of Talk

- Fusion Research In India
  - ADITYA Tokamak
  - SINP Tokamak
- SST-1 tokamak
  - Objectives
  - Parameters
  - Description of Sub-systems & Fabrication Status

Indian Tokamaks



		ADITYA	SINP Tokamak
Major Radius	R_0	0.75 m	0.30 m
Minor Radius	a	0.25 m	0.075 m
Toroidal Field	B_T	1.50 T	2.00 T
Plasma Current	I_p	250 kA	75 kA
Pulse Duration	?	250 ms	20-30 ms
Plasma Cross-section		Circular	Circular
Configuration		Poloidal Limiters	Poloidal Limiters
Coils Type (TF & PF)		Copper Water cooled	Copper
Current Drive & Heating		Ohmic Transformer (Air Core)	Ohmic transformer (Iron Core)
Vacuum vessel		Vessel with Electrical break	Conducting Shell
Design & Fabrication		Indigenous	M/S Toshiba, Japan
Installation		1989	1987

ADITYA TOKAMAK

- 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 flutuations 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 Wavlet analysis to study the power transfer due to linear,mixed and quadratic coupling.

ADITYA TOKAMAK

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:
    - Thomsom 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 ; $q_{egde} > 3$
- Low q regime; $0 < q_{egde} < 2$

Experiments in low q regime:

- Accessibility condition for VLQ and ULQ regimes
- Anomalous Ion heating in VLQ discharges
- Edge Biasing experiemts in VLQ dicharges
- Runaway Electrons in startup phase of VLQ discharges
- Variation in Up-down asymmetry with edge safety factor

SINP Tokamak

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 assymetry
- Observation of ringing toridal current exlinable by Helicity conservations
- Observation of Runaway Electrons by ECE

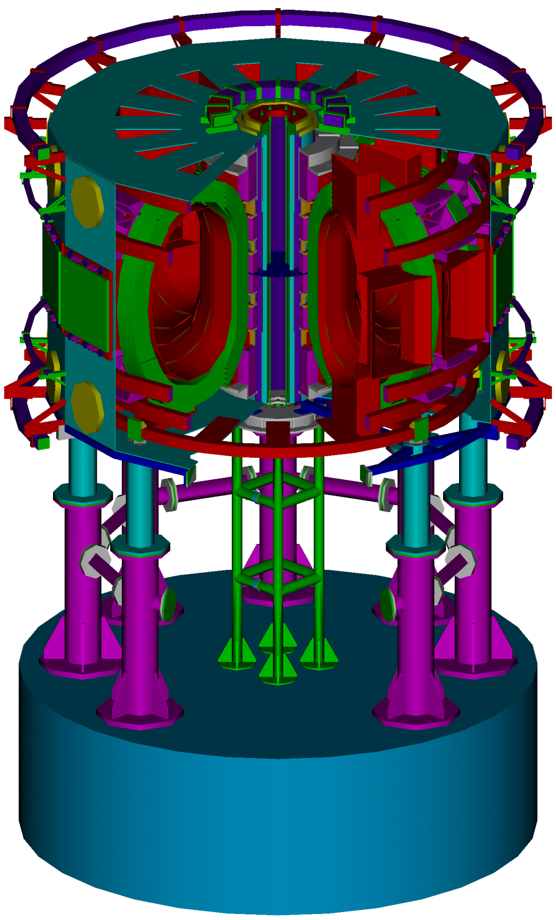
Proposed to add LHCD on the tokamak in near future.

SST-1

STEADY STATE SUPERCONDUCTIG TOKAMAK

OBJECTIVES:

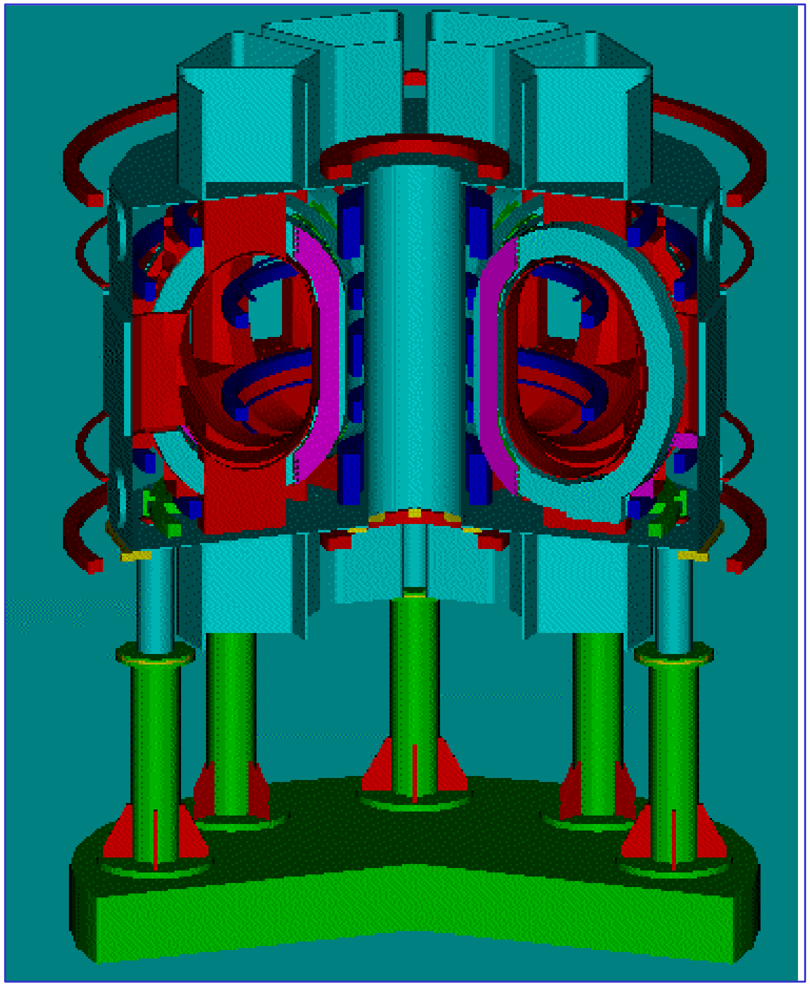
- Maintaining shaped, double/single null plasmas with non- inductive Current drive & auxiliary heating
- Steady state operation with controlled particle and power exhaust
- Advanced Tokmak Configurations with bootstrap current
- Learning new Technologies relevant to steady state tokamak operation:
    - 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 : $1X\ 10^{13} cm^{-3}$
- 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:

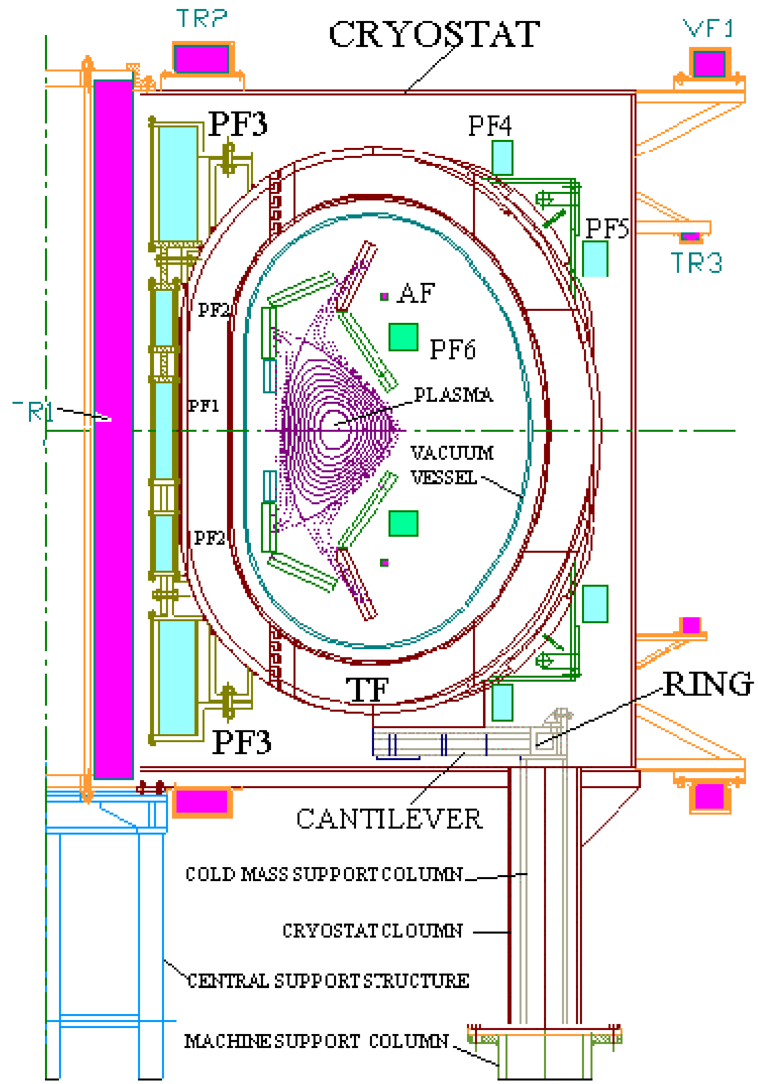
- Confinement, Shaping and Equilibrium Fields
- Ohmic Flux Storage
- Feed-Back Control

Supercondcting Magnets:

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

Copper Magnets (Water Cooled) :

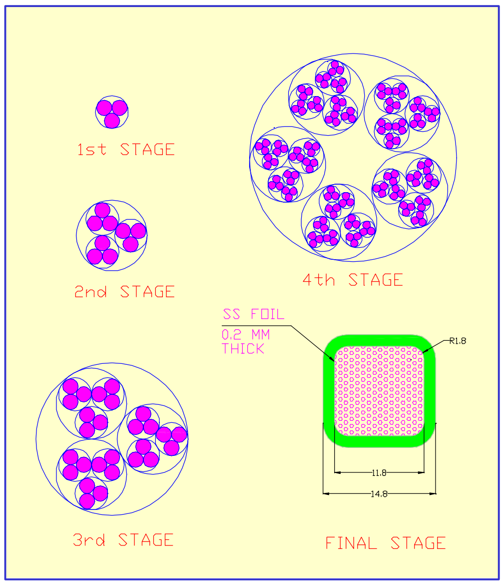
- Ohmic Transformer (TR) Coils : 7 Nos.
- Poloidal Field (PF) Coils (in-Vessel): 2 Nos.
- Position Control Coils (in-Vessel) : 2 Nos.

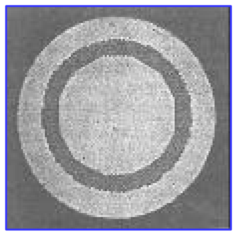


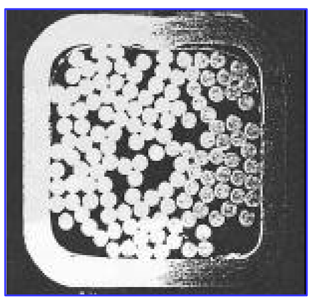
Conductor for SST-1 Superconducting Magnets

Strand Characterstics

Material	: NbTi in Cu
Strand Diameter	: 0.86 mm
Filament Dia.	: 10 µm
Filaments per strand	: 1272
Cu : NbTi	: : 5 : 1
Cu RRR	: 100
I_c@4.5K; 5T	: 232A
Index ‘n’	: 45
Hysterisis Losses	: 33.5 mJ cm^{-3}







Conductor Characteristics

Conductor type	: CICC.
Outer Dimensions	: 14.8× 14.8 $mm^{2.}$
No. of Strands	: 135.
Cabling Pattern	: 3? 3? 3? 5.

Last stage wrapped (half overlap) with 25 ? m thick SS304 tape.

Twist Pitches:

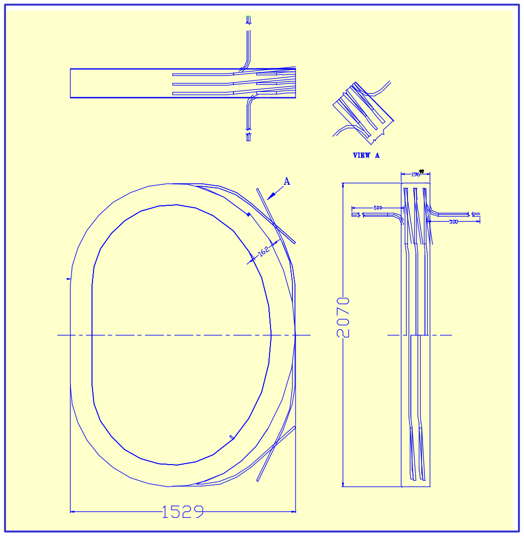
– I stage : 40 mm
– II stage : 75 mm
– III stage: 130 mm
– IV stage: 290 mm

Conduit Material	: SS 304L.
Conduit thickness	: 1.5 mm.
Void Fraction	: ? 36 %.
I_c @ 5T, 4.5K	: 36 kA.
I_{op} @ 5T, 4.5K	: 10 kA.

SST-1 TOROIDAL FIELD COILS

TF COIL Winding Pack:

- Modified D-Shape
- Base Conductor: NbTI based CICC
- 6 # of Double pancakes
- Cross-section : 194x144 mm^2



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

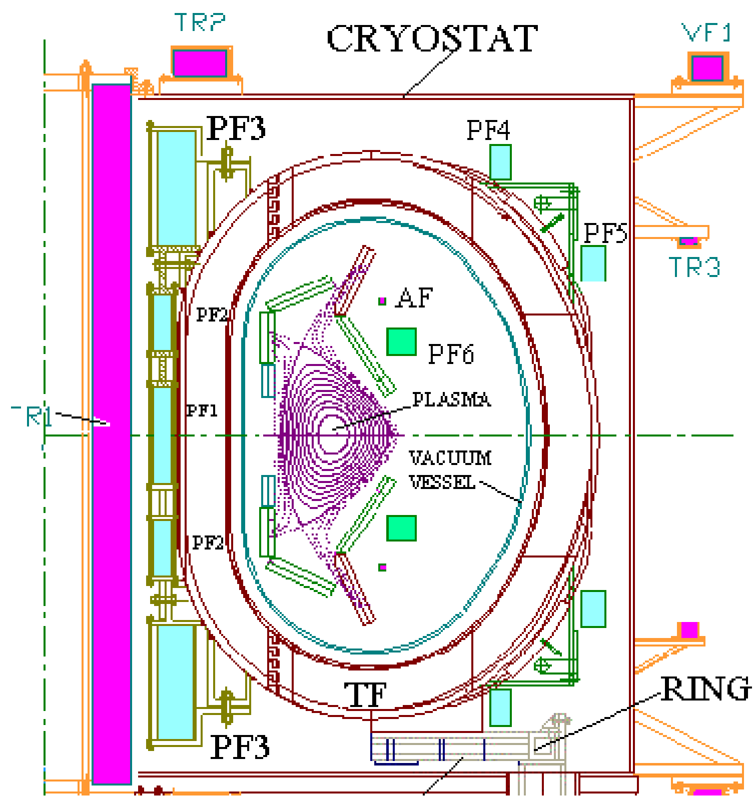
SST-1 Poloidal Field Coils

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), ?$_p$ (0.01-0.85) & slot divertor configuration
- Limiter operation during Plasma current ramp up

Parameters of PF Coils

Coil type	# coils	Coil Radius (m)	Vertical Location (m)	Winding Cross-section (mm^2)	# turns
PF1	1	0.45	0.0	71x320	80
PF2	2	0.45	?0.43	71x163	40
PF3	2	0.50	?0.93	136x380	192
PF4	2	1.72	?1.03	85x136	40
PF5	2	2.01	?0.65	85x136	40
PF6	2	1.35	?0.35	100x100	16



SST-1 OHMIC TRANSFORMER

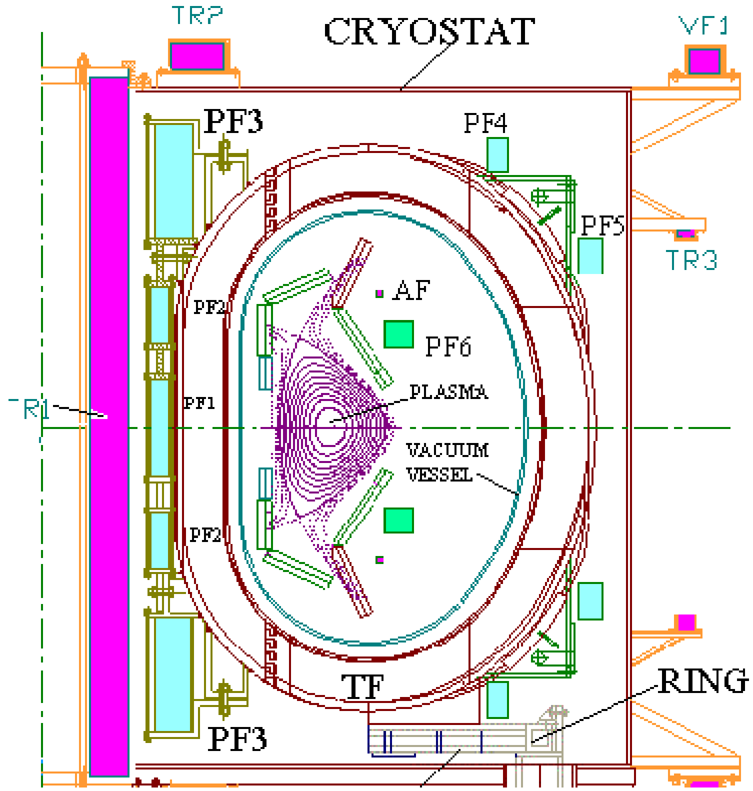
Design Drivers:

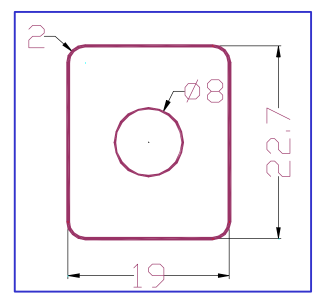
- Stress limited maximum flux storage
- Matching to existing power supply
- Plasma Break down and initial plasma current ramp up

Characteristics:

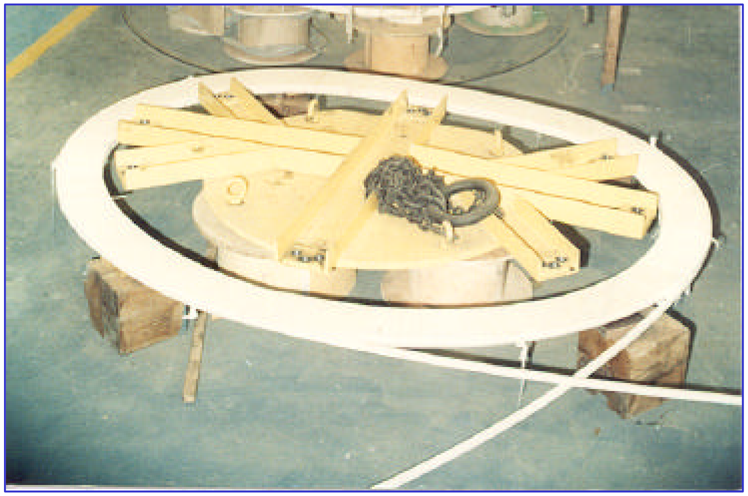
- Water cooled copper coils
- Stored Flux : 1.4 Vs @ 20 kA per turn
- Maximum Field in plasma Volume : 18 G

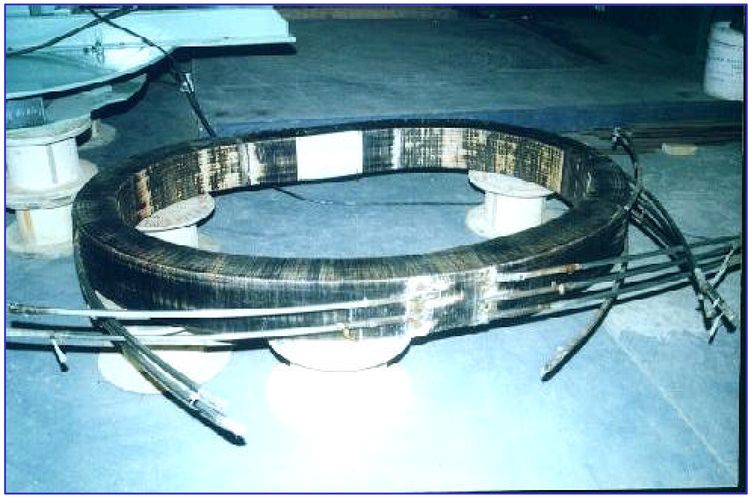
Coils	#	Radius (m)	Turns (#)	X-section (mm^2)	Center (m)
TR1	1	0.20	672	120?260 0	0.00
TR2	2	0.49	40	195 ? 95	⁇ 1.40
TR3	2	2.42	3	58 ? 23	⁇0.73

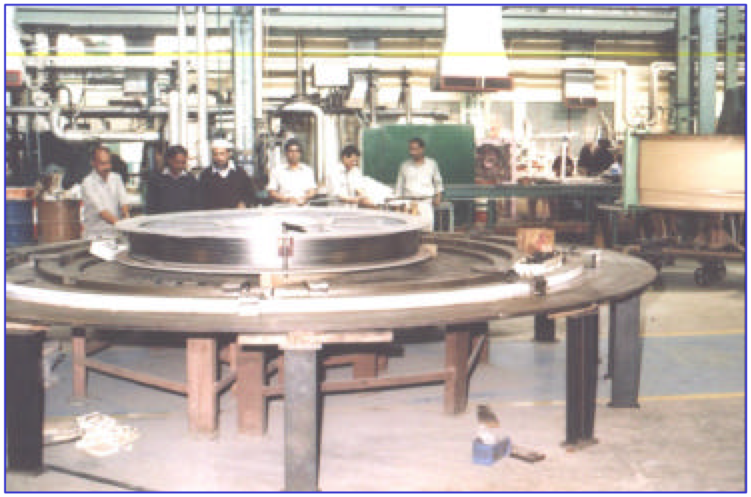




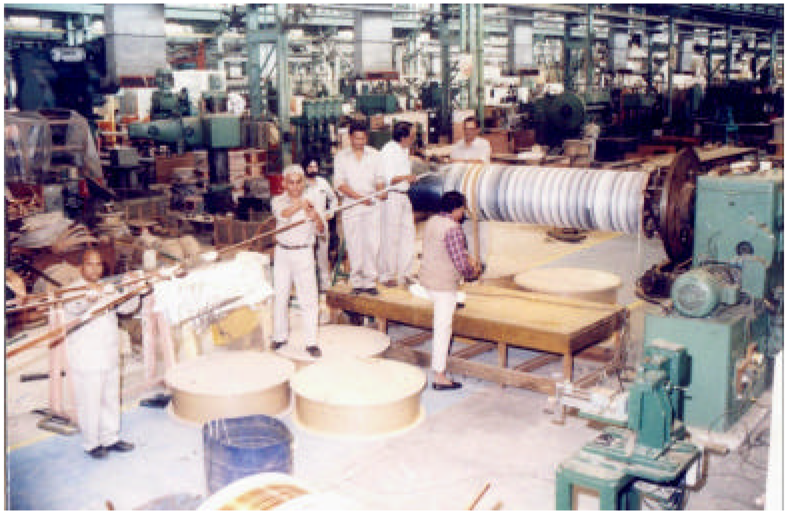
Fabrication of Magnetic Field Coils







Manufacturing of Magnetic Field Coils



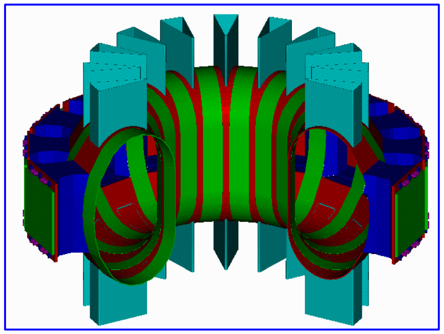
SST1 Vacuum Vessel & Cryostat

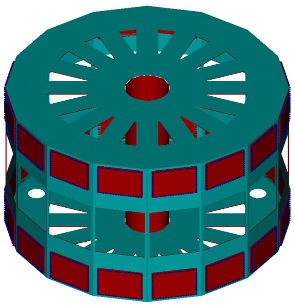
Vacuum Vessel parameters

- VESSEL MAJOR RADIUS : 1.285 m
- VERTICAL SEMI AXIS : 0.81m
- 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 m^2
- TOTAL VOLUME : 16 m^3
- TOTAL WEIGHT : 4100 kg
- MATERIAL : SS 304L
- VACUUM : 10^{-8} mbar

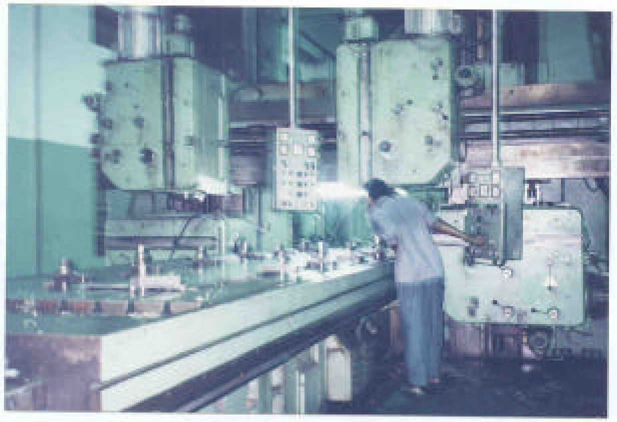
Cryostat parameters:

Vertical Height	: 2.6 m
Outer Diameter	: 4.4 m
Inner Diameter	: 0.355 m
Wall Thickness	: 10 mm
Total Surface Area	: 59 m^2
Total Volume	: 39 m^3
Total Weight	: 4520 kg
Material	: SS 304L
No.of Modules	: 8





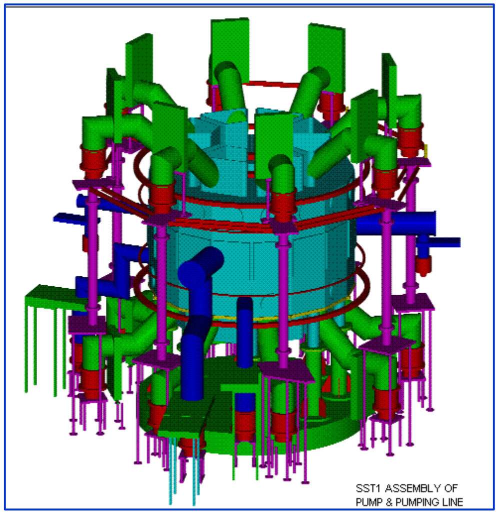
Fabrication of SST1 Vacuum vessel and Cryostat



PUMPING SYSTEM FOR SST-1 TOKAMAK

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 1×10(-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:

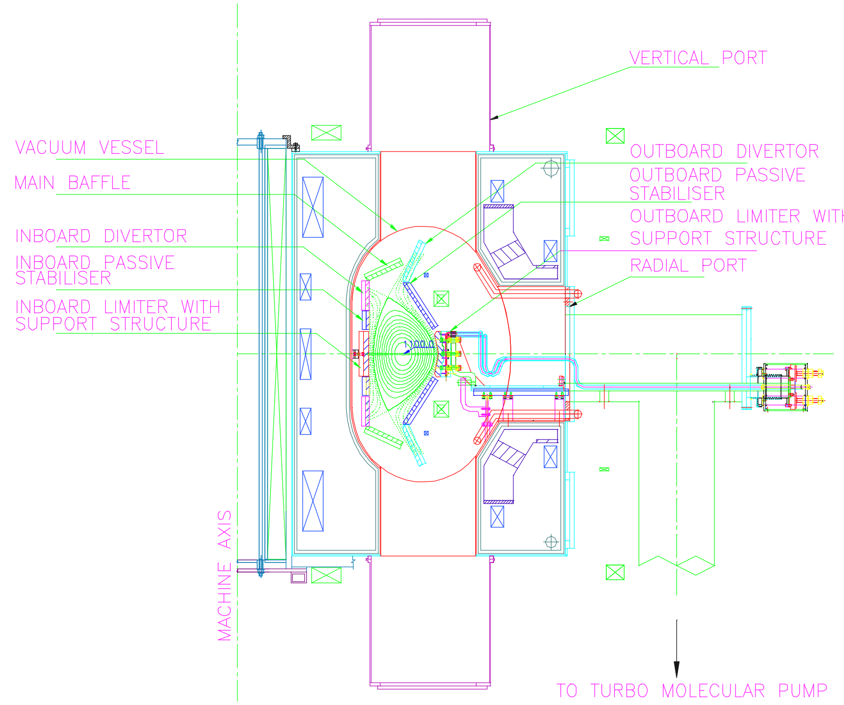
- Out gassing gas load ? 5 x 10(-2) mbarl/s at 300 K
- Design base pressure ? 1 x 10(-5) mbar
- Required pumping speed ? 5,000 l/s
- 2# TMP (5000 l/s) on Cryostat ports

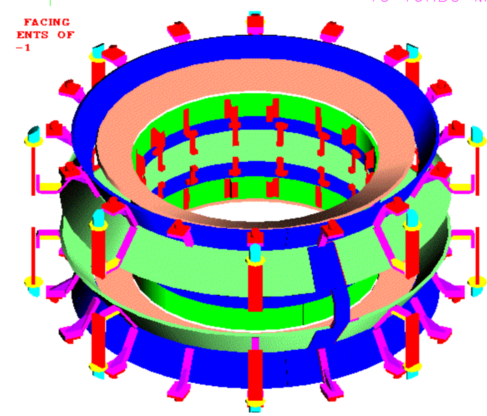
Plasma Facing Components of SST-1

Design Drivers:

- Steady state heat and particle removal
- 1 MW power Input
- Surface temperature ? 1000 ^{0}C
- Baking up to 350 ^{0}C
- Electromagnetic forcesss during VDE, disruptions and halo currents
- Modularity

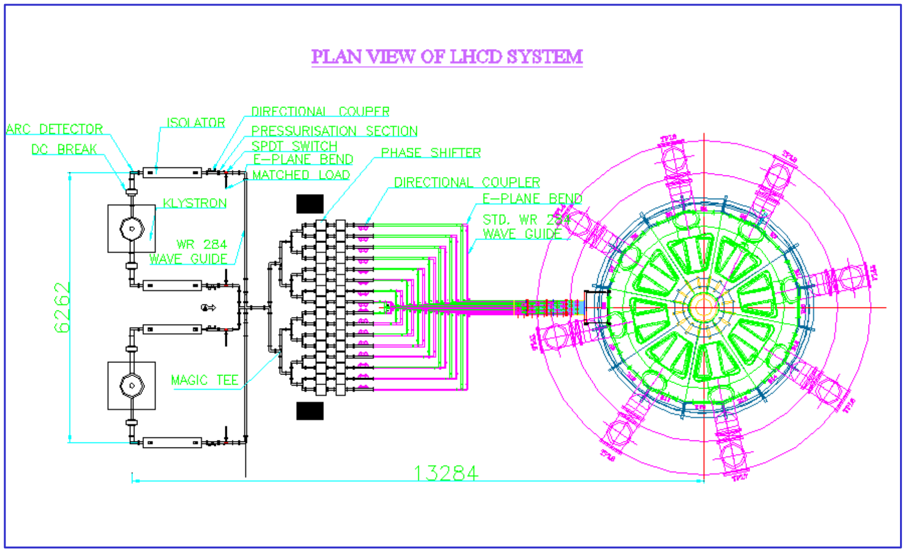
- Isostatically pressed, low ash content,Graphite
- Tiles mechanically attached to High strength copper alloy (CuZr & Cu CrZr) backplate;
- Cooling tubes (SS304) embedded in & brazed to the back plates.





SST-1 LHCD SYSTEM

Frequency	: *3.7 GHz.*
Power (2 klystrons each of 500 kW CW)	: *1 MW*
Antenna type	: *Grill*
# of subwaveguides	: *32 x 2rows*
Periodicity (with 2mm thick septa)	: *9 mm*
Subwaveguide opening	: *76 x7 mm^2*
Design N_{II} (at 90^o phasing)	: *2.25*
N_{II} variation (from 40^o to 60^o phasing)	: *1.0 - 4.0*
Klystron input power	: *10Watt*



KLSTRON 2103D
WITH DIRECTIONAL COUPLER

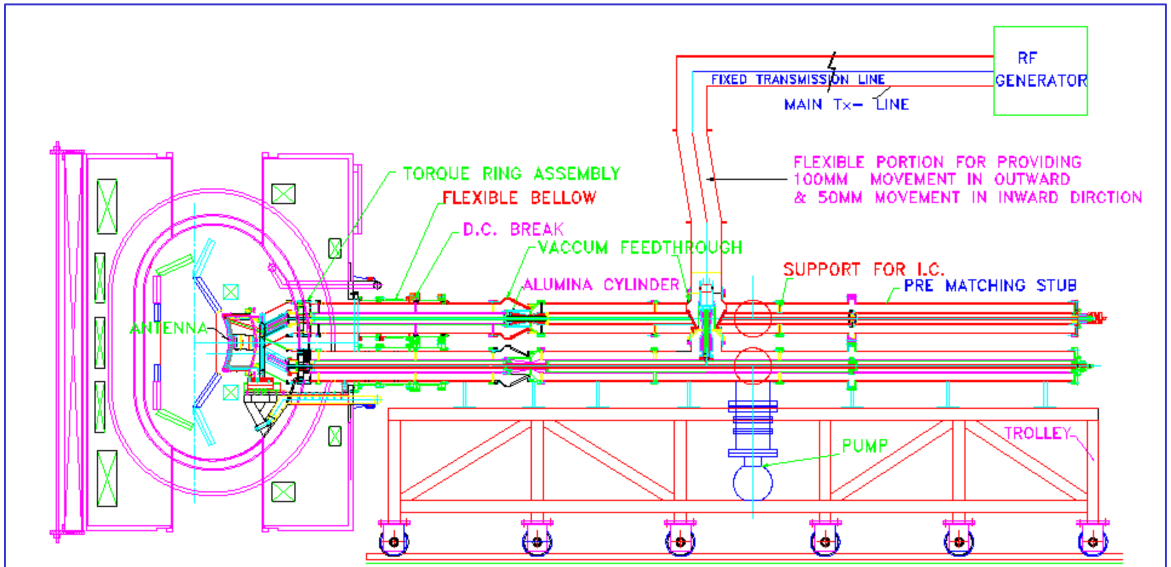
SST1 ICRH System

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 ? $_{ce}$ heating at 1.5 T
91.2 MHz for 2 ? $_{ce}$ 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



ELEVATION VIEW OF ICRH ANTENNA MOUNTED IN RADIAL PORT

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

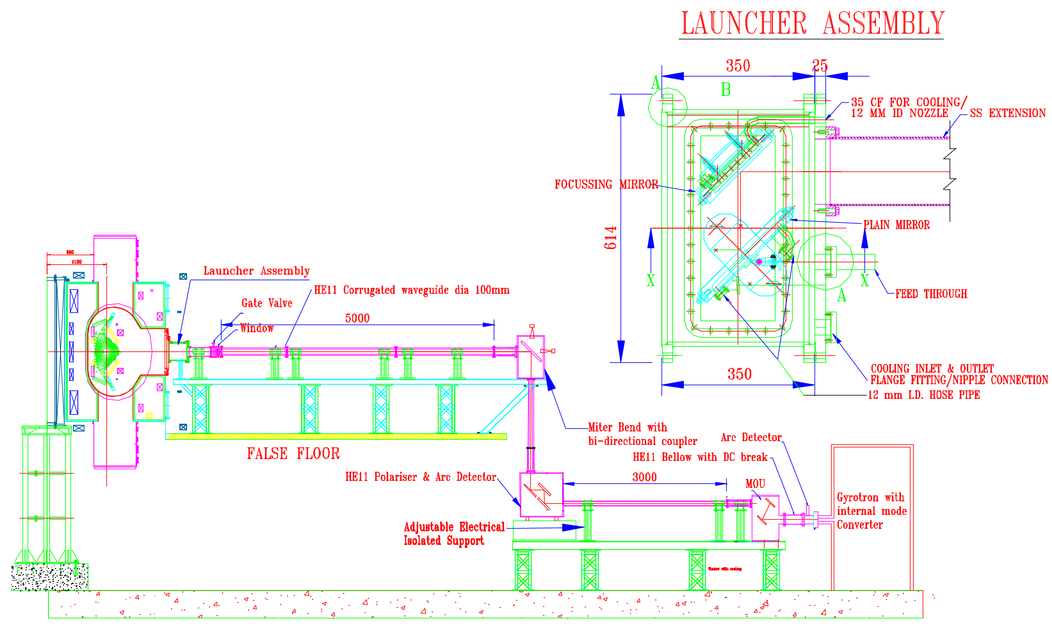
• Output Mode : HE-11

• Operating TF Field :

  • Fundamental : 3 T

  • 2nd Harmonic : 1.5 T

• Exit dimensions of Waveguide : 63.5 mm



NEUTRAL BEAM INJECTION SYSTEM

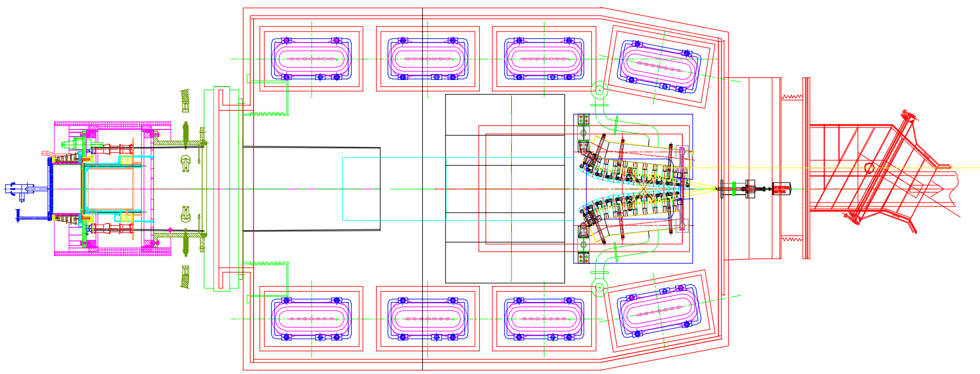
Objectives:

For SST-1:

- **Heating and Current Drive**
- **Fuelling**
- **Momentum Injection**

On Test Stand:

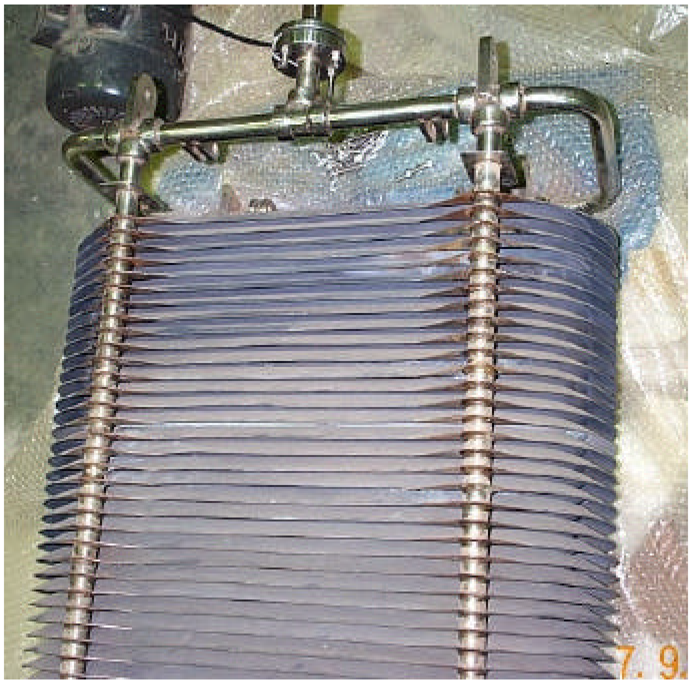
- **Long Pulse Operation**
- **Data Base Generation**



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

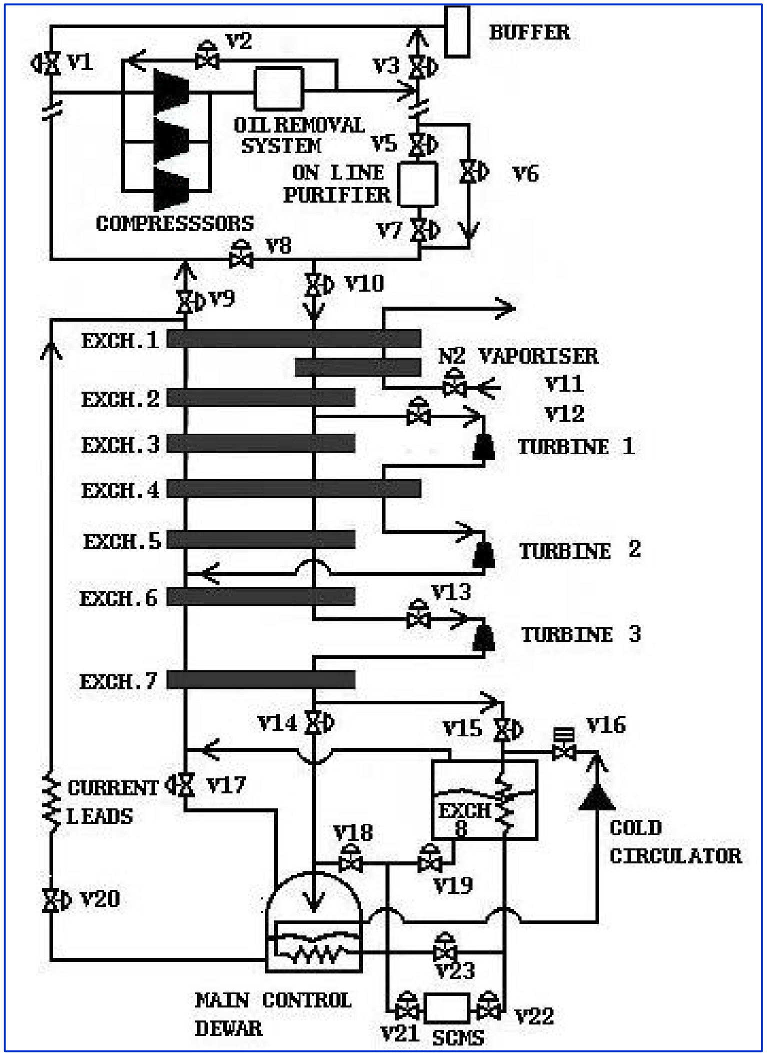
Helium Cryogenic System

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

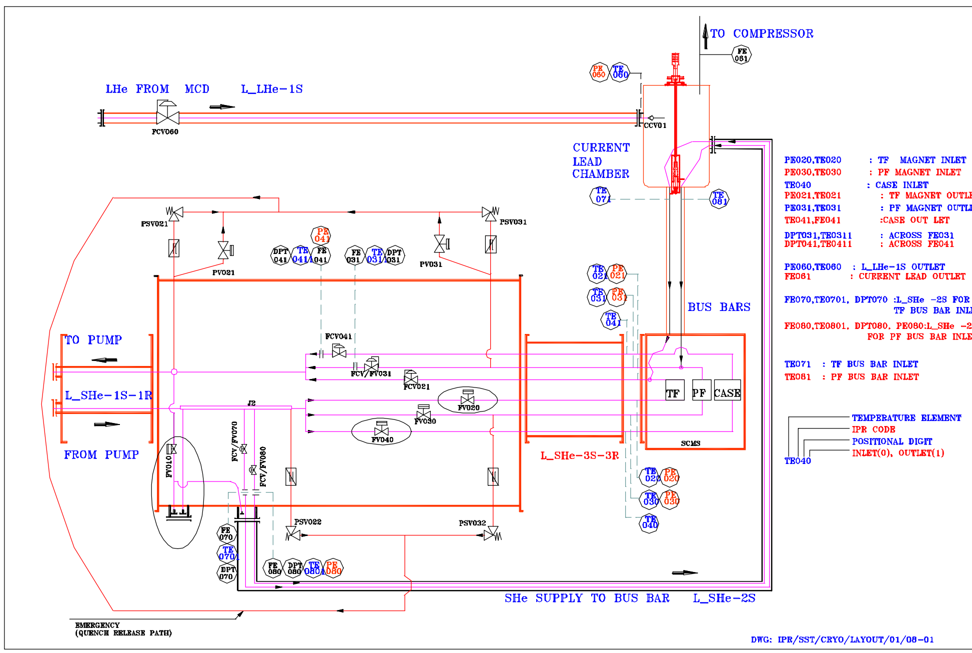


Erection of Helium Plant

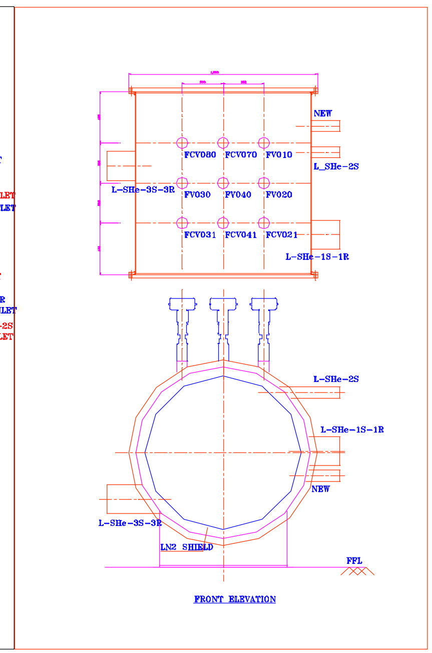
INTEGRATED FLOW DISTRIBUTION & CONTROL SYSTEM

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



IFDCS PID



Valve Box Schematics

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 & Dostribution:

- 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

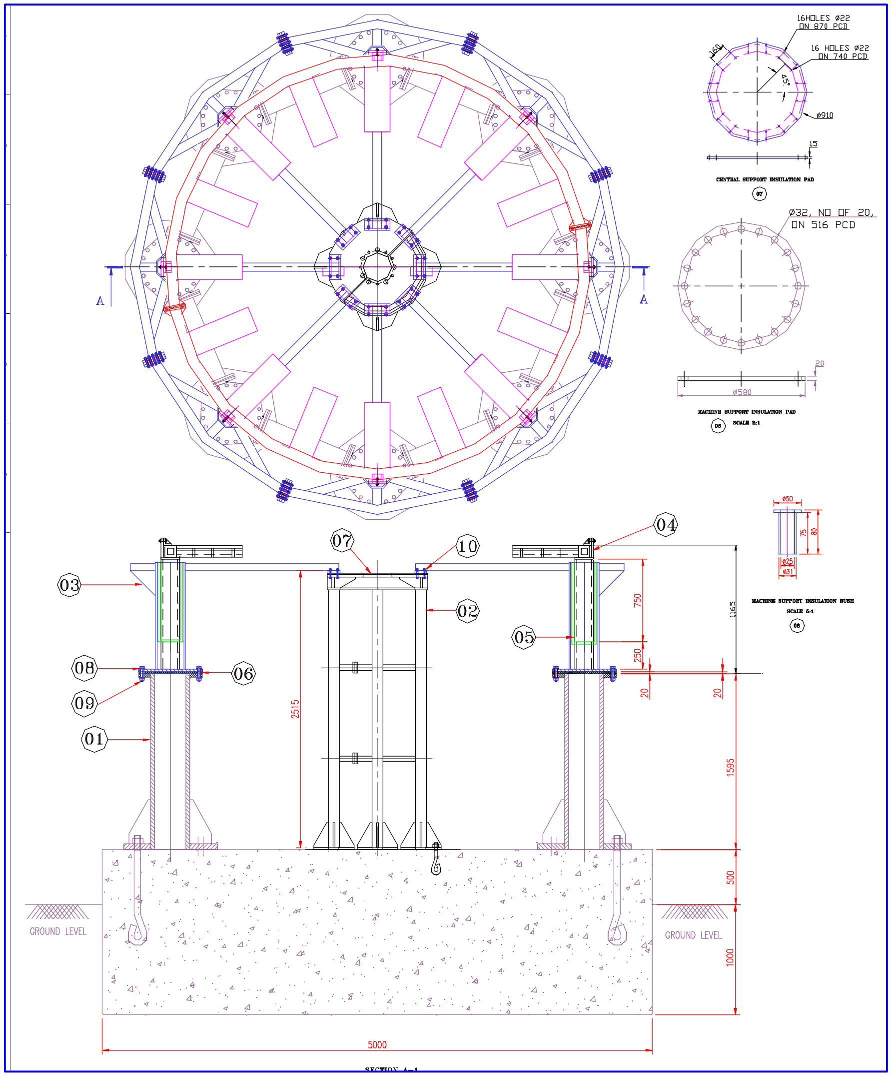
Medium Pressure storage system:

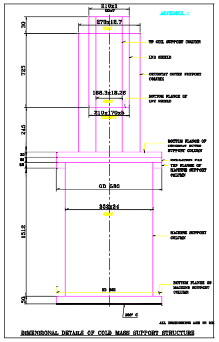
- 4# of 68 m^3 tanks at 14 bar.

Gas Recovery system:

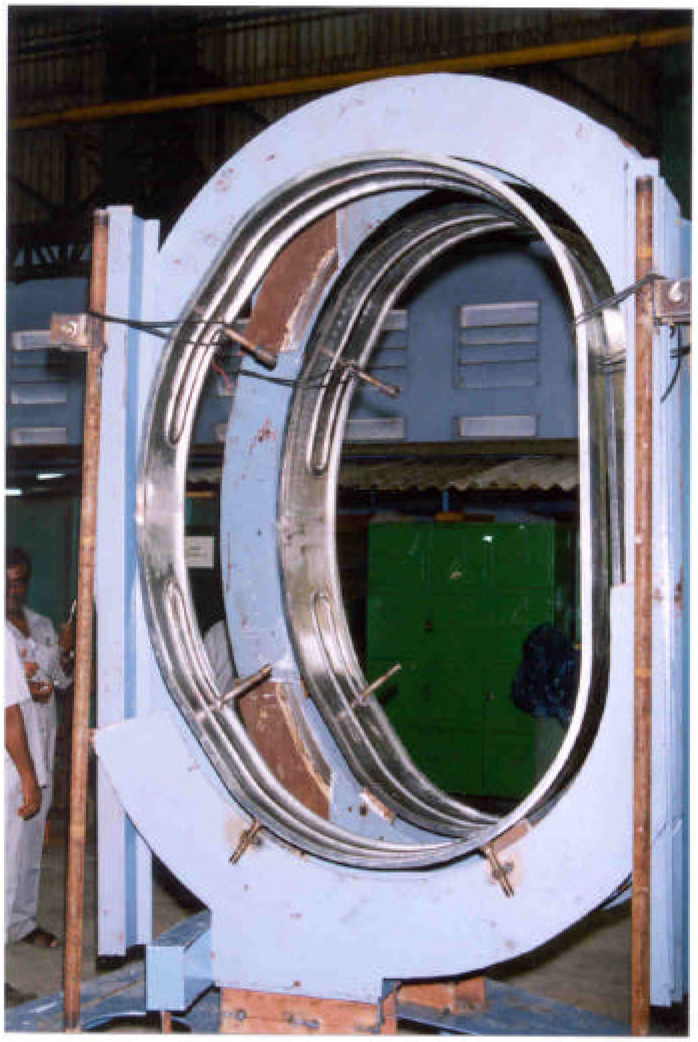
- 2# of 40 Nm^3 gas bags
- 1 g/s recopvery compressor @150 bar
- Purifier

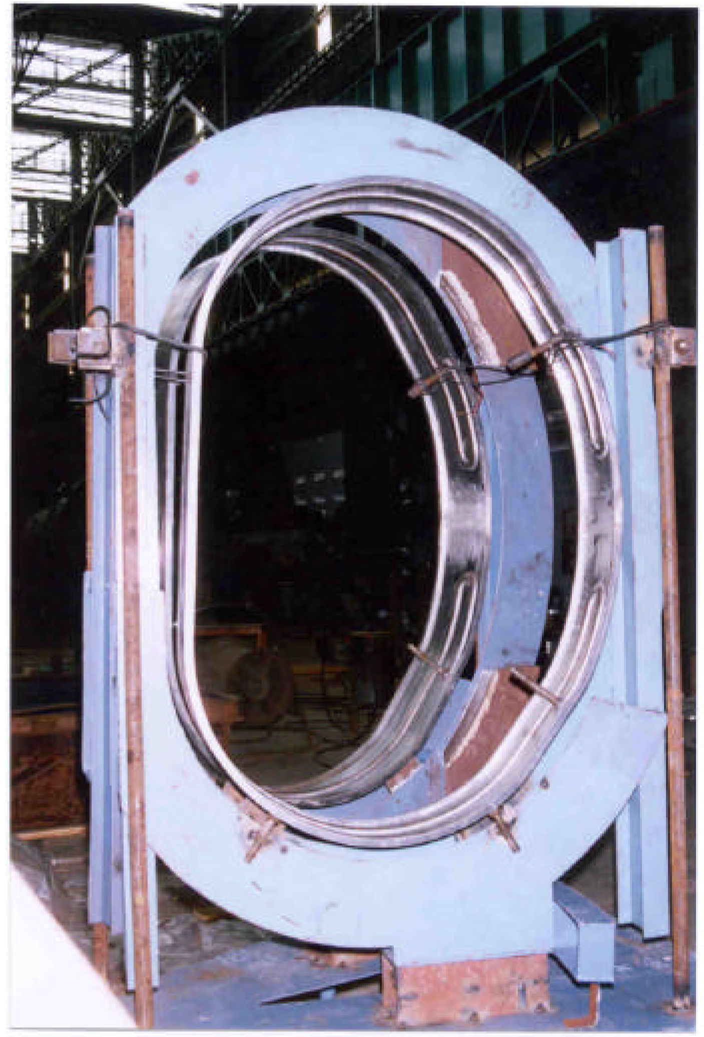
Foundation and support structure



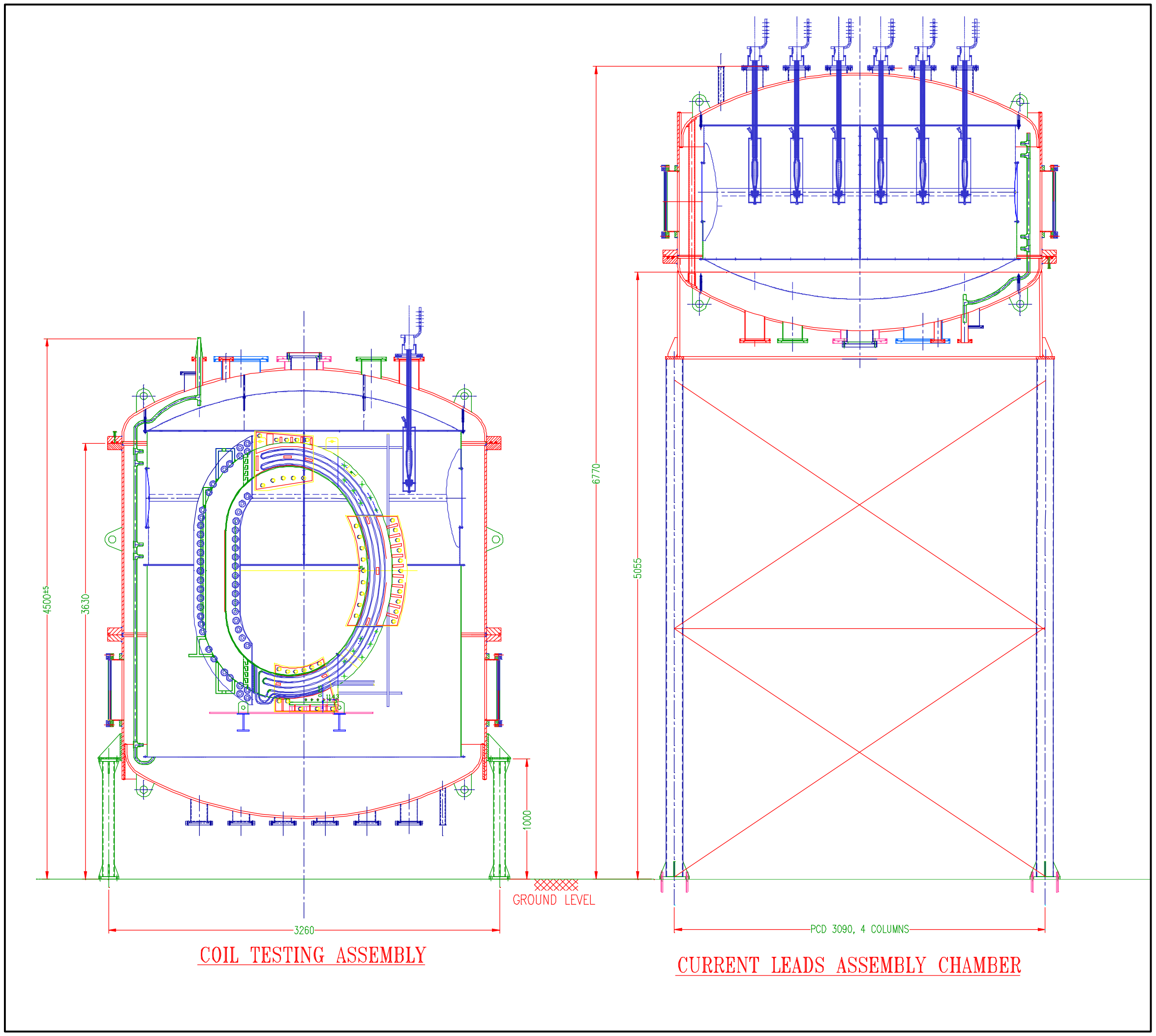


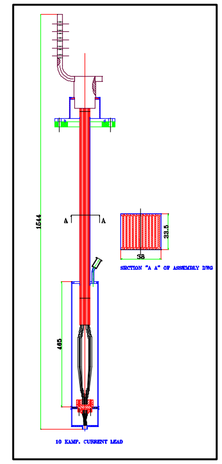
TF Coil Assemly Mock Up



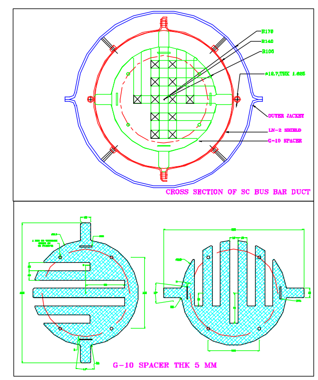


TF Coil Vessel Sector Assemly Mock Up





Current Lead



Bus Duct

Thanks for your kind attention