ACASC-Asian ICMC 2023
Shanghai, China
29 October-1 November 2023

Current Activities in the Field of Applied Superconductivity & Cryogenics in India

T S Datta

Indian Institute of Technology. Kharagpur
India

Email : tsdatta59@gmail.com

This talk is dedicated to ISRO for the recent success of Landing on South Pole of Moon

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

Outline of my Lectures

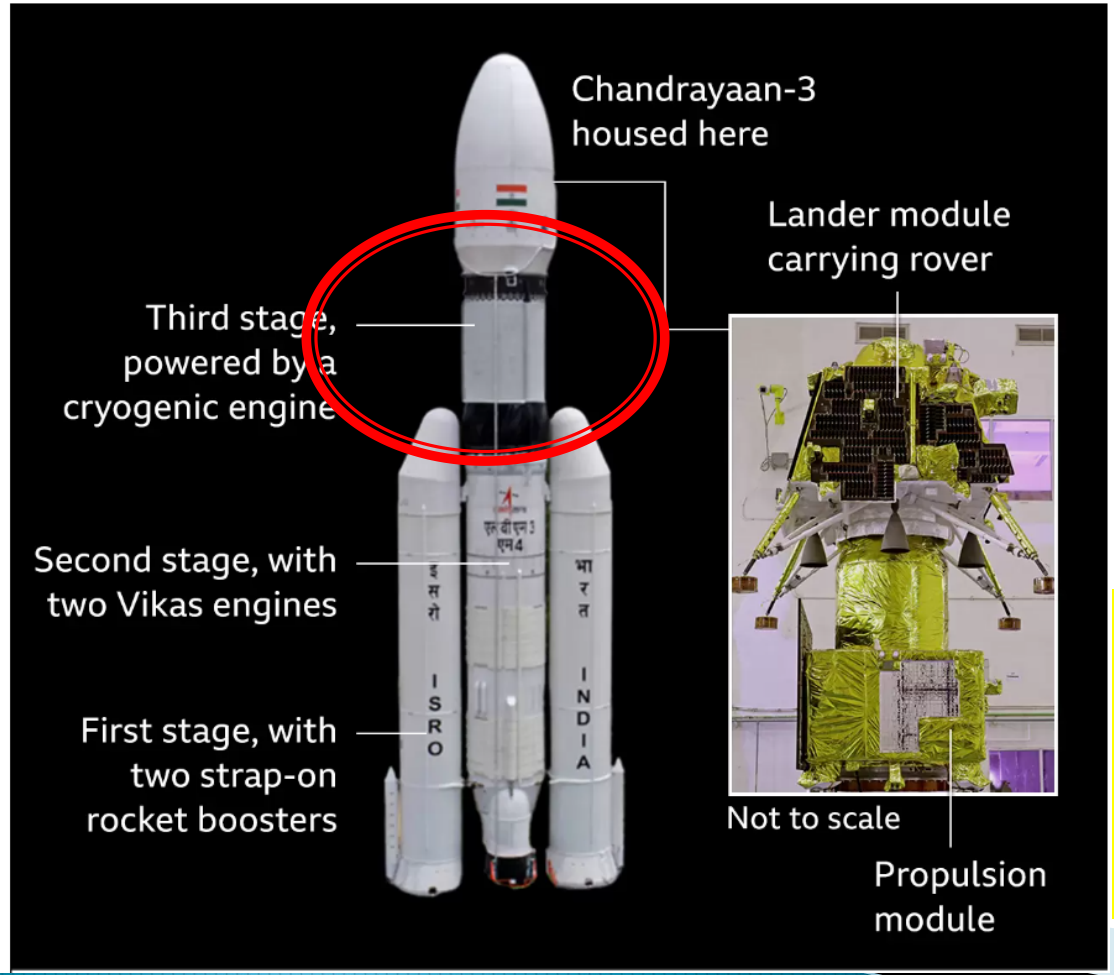
1. **Recent Achievement on Major Programme in the field of Applied Superconductivity and Cryogenics :**
    - A. **Chandrayaan -3 by Space**
    - B. **Indigenous MRI Development**

2. **On going activities**
    - A. **Accelerator with RF Cavity**
    - B. **Superconducting Tokamak**

3. **R & D on HTS for Power Application and Quantum Computing**

Historical Scientific Event for India (August 23, 2023) on Successful Landing of VIkram on the South Pole of Moon

The LVM3 launch rocket and Chandrayaan-3



More than 1 Billion People from India watched this important event

India on July 14, 2023 successfully Launched Lunar Mission Chandrayaan-3 by powerful rocket LVM with CE- 20 Cryo Engine on upper stage

Indigenous Cryogenic Upper Stage CE25 is integrated with LVM 3

Three Stage (Solid, Liquid & Cryogenic) Launch Vehicle with Cryo Engine

Fuel : Liquid Hydrogen (20 K) & Liquid Oxygen (90 K)
Fuel Mass : 27 Tons
Thrust : 180- 200 kN

ISRO Cryogenic Engine CE 20

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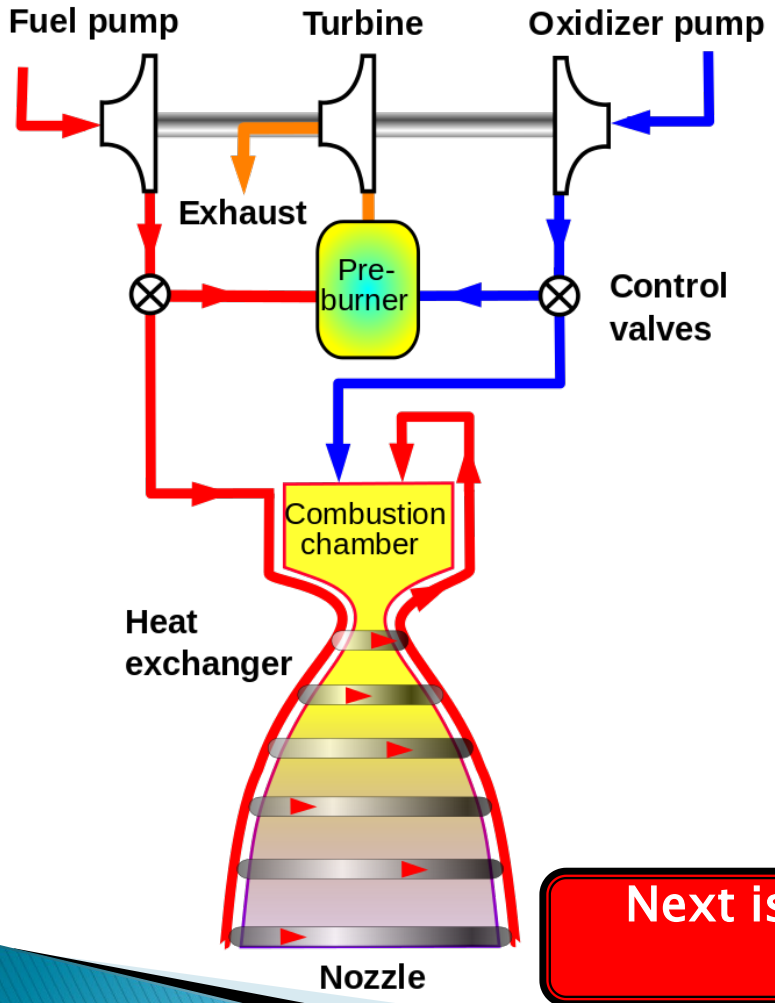
CE 20 is the first Indian cryogenic engine to feature a Gas Generator Cycle. The high thrust cryogenic engine is one of the most powerful upper stage cryogenic engines in the world.



Gas-generator rocket cycle. Some of the fuel and oxidizer is burned separately to power the pumps and then discarded. Most gas-generator engines use the fuel for nozzle cooling.

POWERFUL ENGINE CE 20 WITH THURST 200 kN , Fuel (H_2+O_2 : 27 Tons)

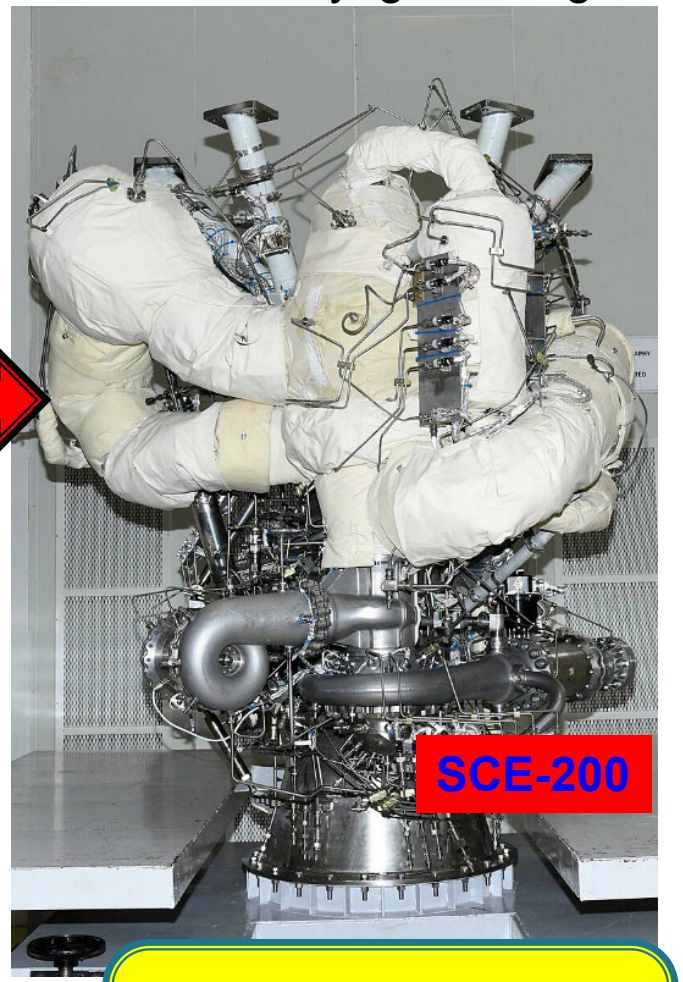
Next is Semi Cryogenic Engine with Liquid Oxygen and Kerosene

Evolution of Cryogenic Engine by Indian Space

Fuel : LH2+ LO2
Fuel Mass : 12 Tons
Duration : 720 Sec
Thrust : 75 kN

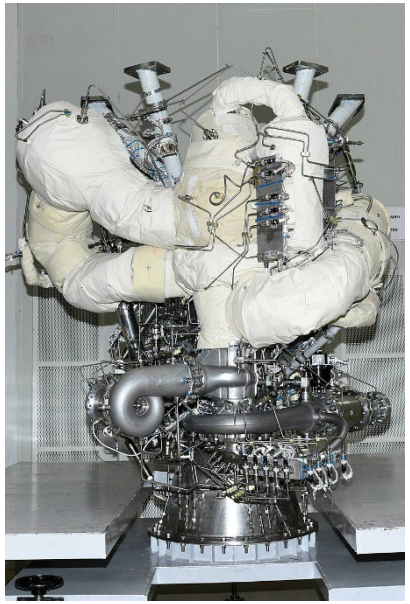
Fuel : LH2 + LO2
Fuel Mass : 27 Tons
Duration :
Thrust : 180- 200 kN

Semi Cryogenic Engine



Fuel : Kerosene + LO2
Fuel Mass :
Thrust : 2000 kN

On July 1, 2023, ISRO conducted the first hot test on an intermediate configuration of the Semi-cryogenic Engine (SCE-200) , at ISRO Propulsion Complex (IPRC), Mahendragiri, Tamil Nadu.



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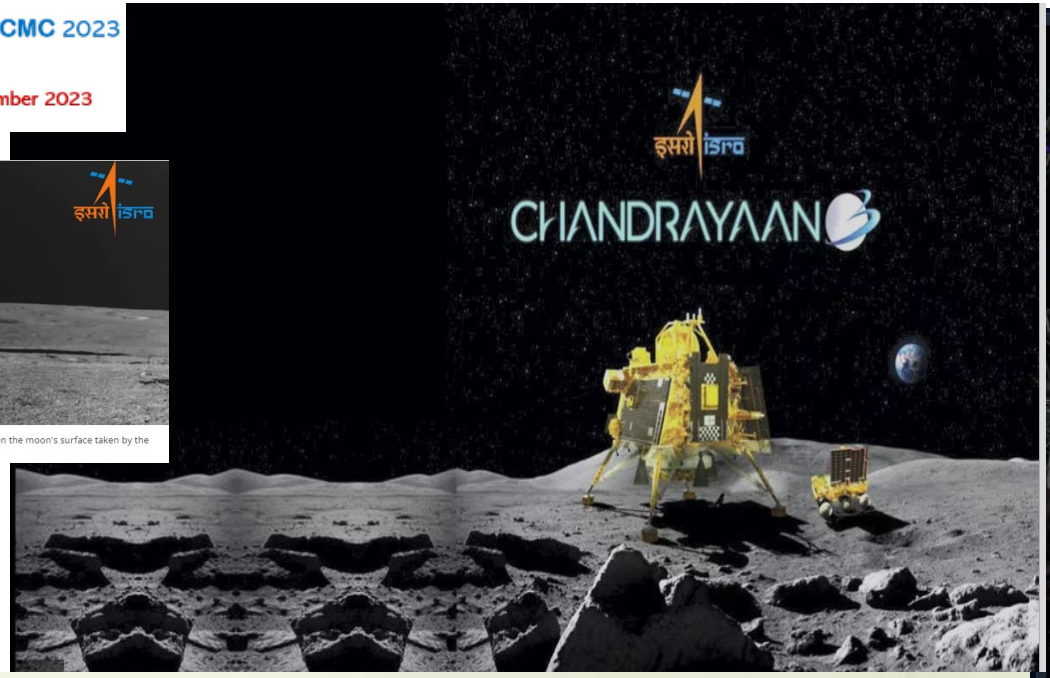
The first image of the Chandrayaan 3 mission's Vikram lunar lander on the moon's surface taken by the mission's Pragyan rover. (Image credit: ISRO)



The GSLV Mk III booster at Satish Dhawan Space Centre, Andhra Pradesh, India. Photo Credit: ISRO

INDIAN CRYOGENIC COMMUNITY ARE PROUD WITH ISRO ACHIEVMENT

Before Moving to Indigenous Development of MRI in India , would like to brief on Ongoing activities/ Status on which was reported earlier conference in Okinawa

Superconducting Accelerator / Tokamak Programme

We have International Collaboration in this field

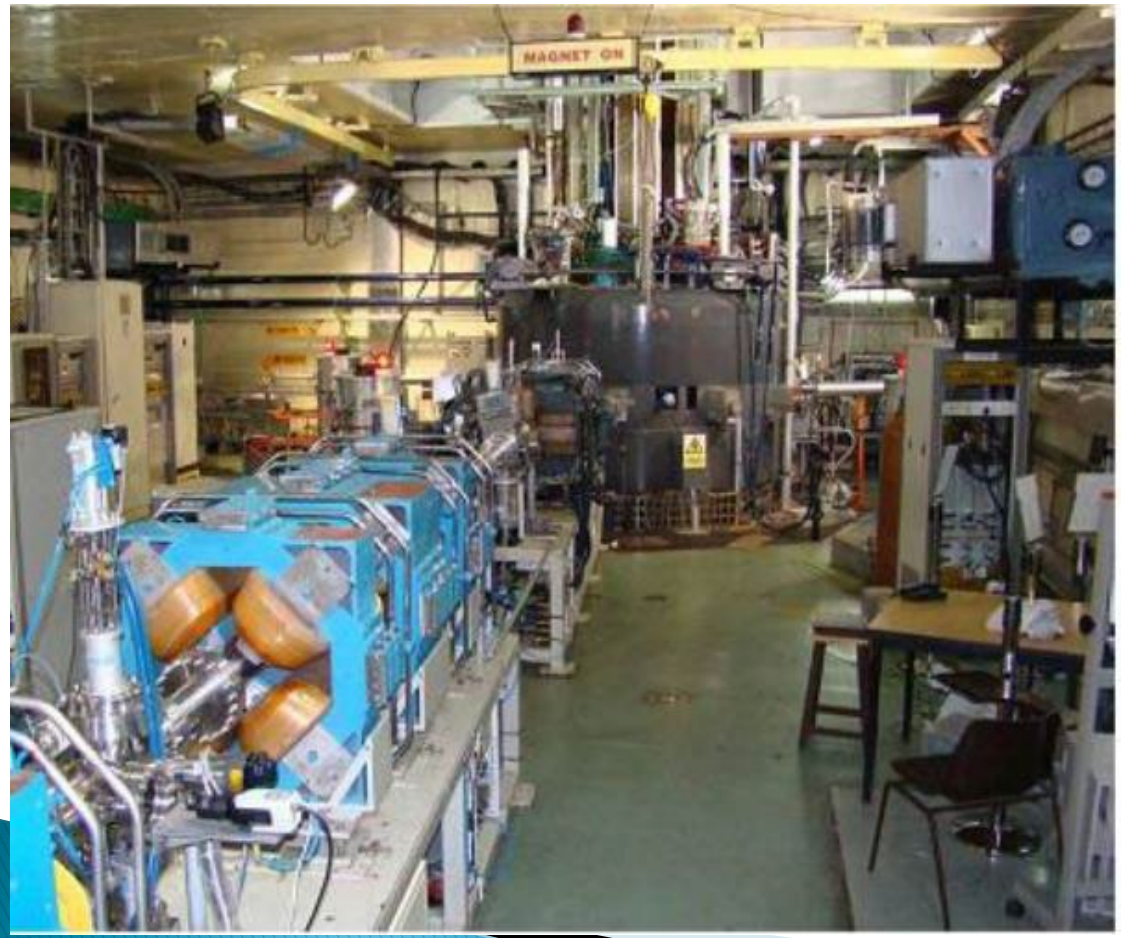
1. FERMI LAB- DAE Institutes on Proton Accelerator Programme/ Spallation Neutron Source
2. VECC. KOLKATA & TRIUMP . CANADA on RIB Facility
3. FAIR PROJECT at GERMANY and DST : In Kind Contribution

RF SUPERCONDUCTING CAVITY / CRYO MODULE / Helium Refrigerator Development

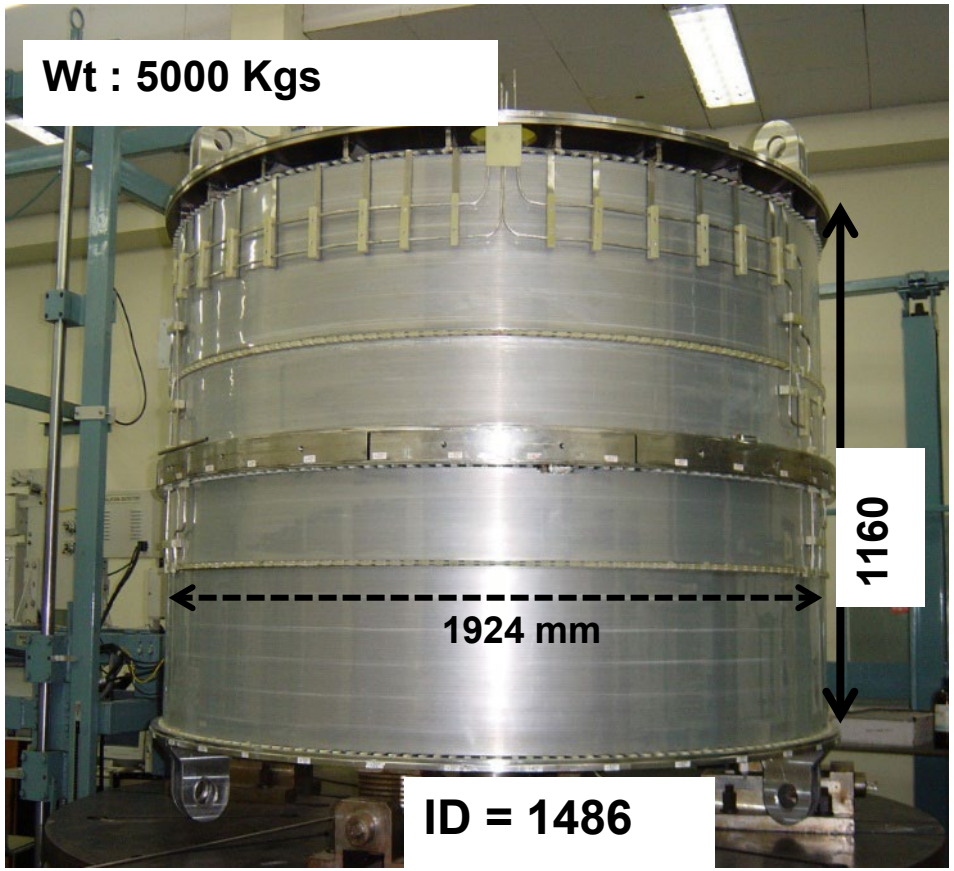
1. ITER, France : In-kind Contribution on **CRYOLINE / CRYO DISTRIBUTION BOXES / CRYOSTAT**

First Major Accelerator Programme in India with Superconductivity

The superconducting cyclotron (K- 500) with a large superconducting solenoid (5 Tesla) was constructed to enhance the energy of 80 MeV/A for lighter ions and 5-10 MeV/A for heavier ions



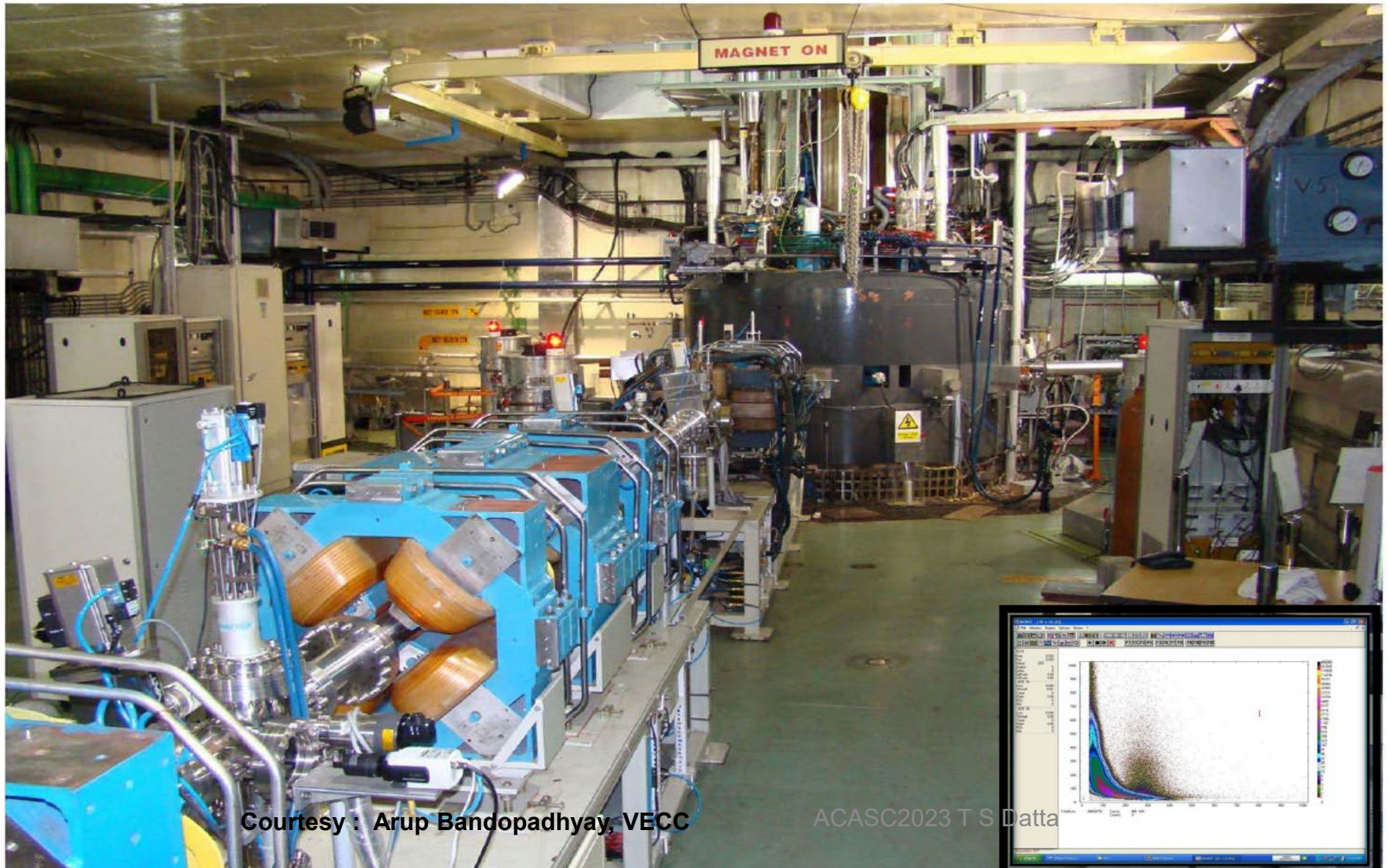
Courtesy : Arup Bandy[illegible]ev, VECC



Beam Extraction difficulty : Shifting of Magnet Axis. Dismantled and Finally Commissioned

Superconducting cyclotron in operation at VECC from 2022

Initially, the internal beam could be accelerated up to the extraction radius, but could not be extracted due to imperfection of ~ 50 Gauss of 1st harmonic magnetic field (B1) at the extraction region prohibiting the beam's extraction. Whole Cryostat was realigned

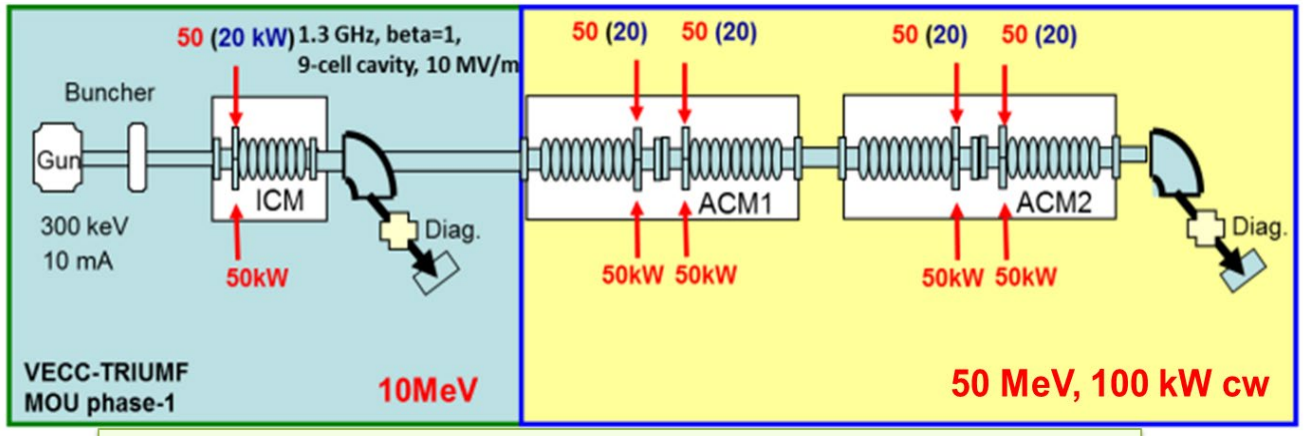


Courtesy : Arup Bandopadhyay, VECC

Ion beam extracted

Ion	q	T(MeV)
Ne	6	360.0
Ne	6	386.2
Ne	6	436.0
O	5	309.0
O	5	330.6
N	4	252.0
N	4	270.3

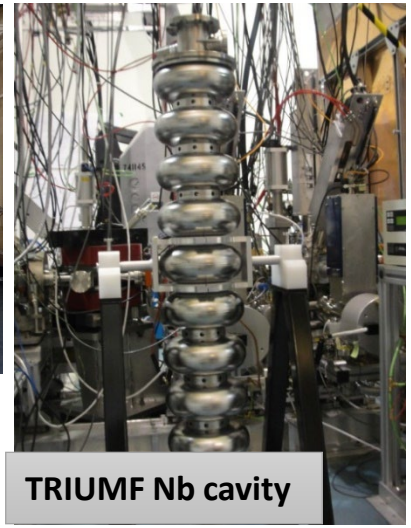
SUPER-CONDUCTING ELECTRON LINAC (E-LINAC FACILITY) AT KOLKATA



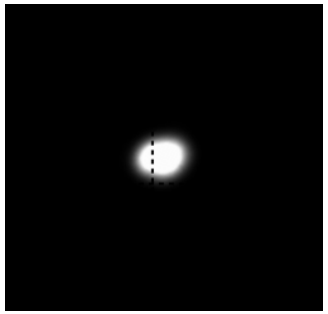
SC electron LINAC for production of RIBs using photofission route
Acc. Grad ~ 10 MV/m

Injector Cryo Module at VECC

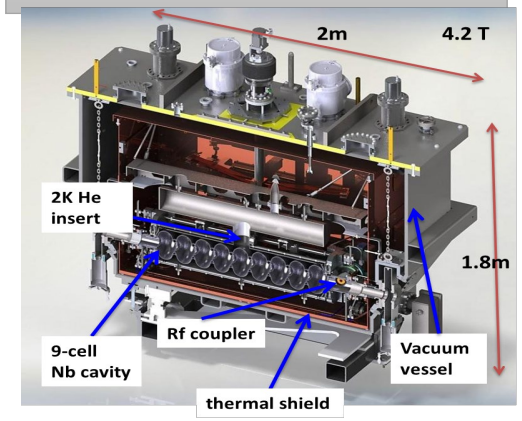
Liq. Helium plant installed at VECC Kolkata



TRIUMF Nb cavity



Beam successfully accelerated to 10.6 MeV using one nine cell cavity



VECC Kolkata & TIRUMF Canada Collaboration

Courtesy : Vaishali Nayek. VECC

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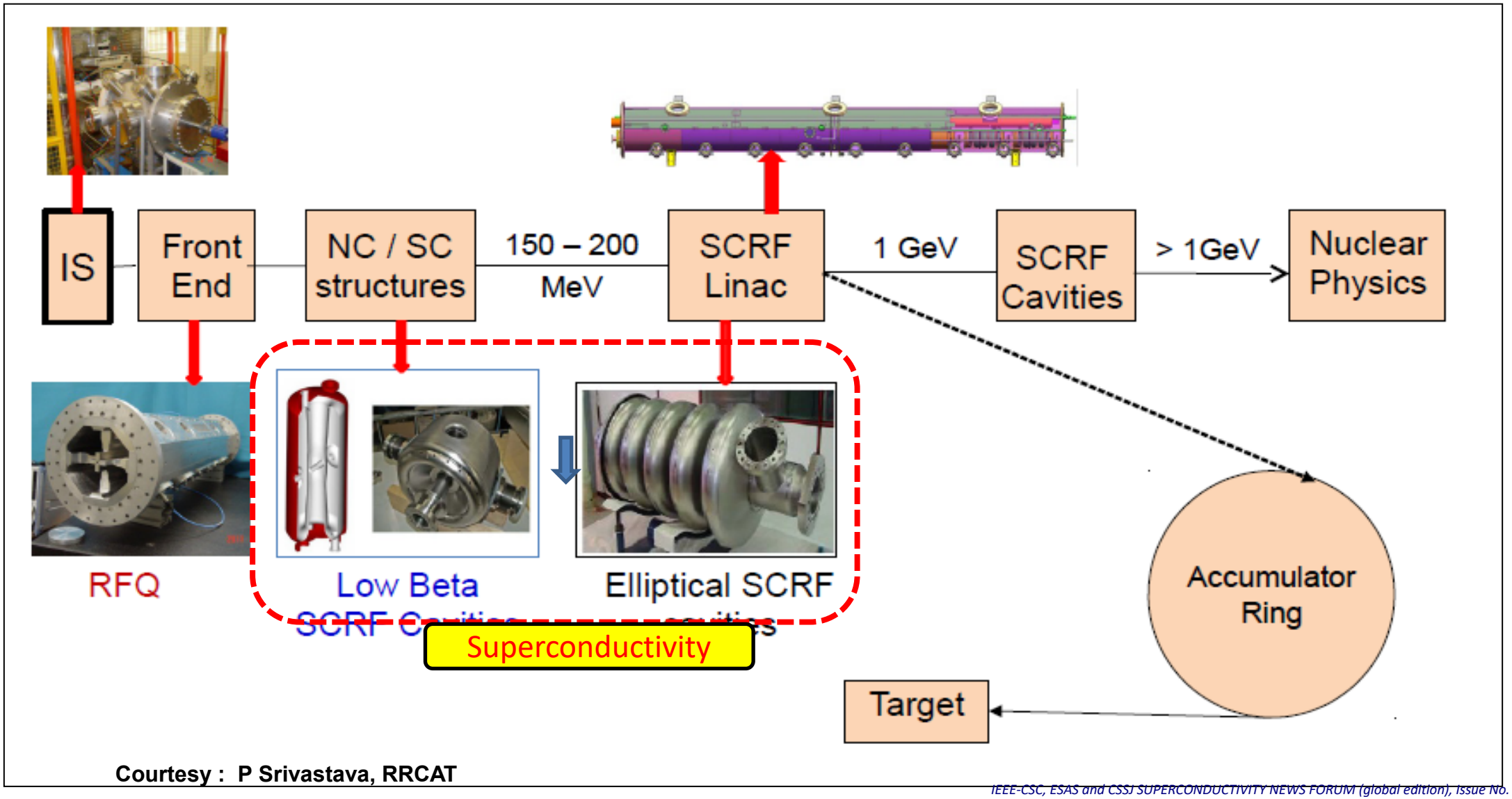
High Energy Proton LINAC Based Spallation Neutron Source (RRCAT)

Collaboration between Fermi Lab & Indian Institutes

Ongoing/ Future



Courtesy : P Srivastava, RRCAT

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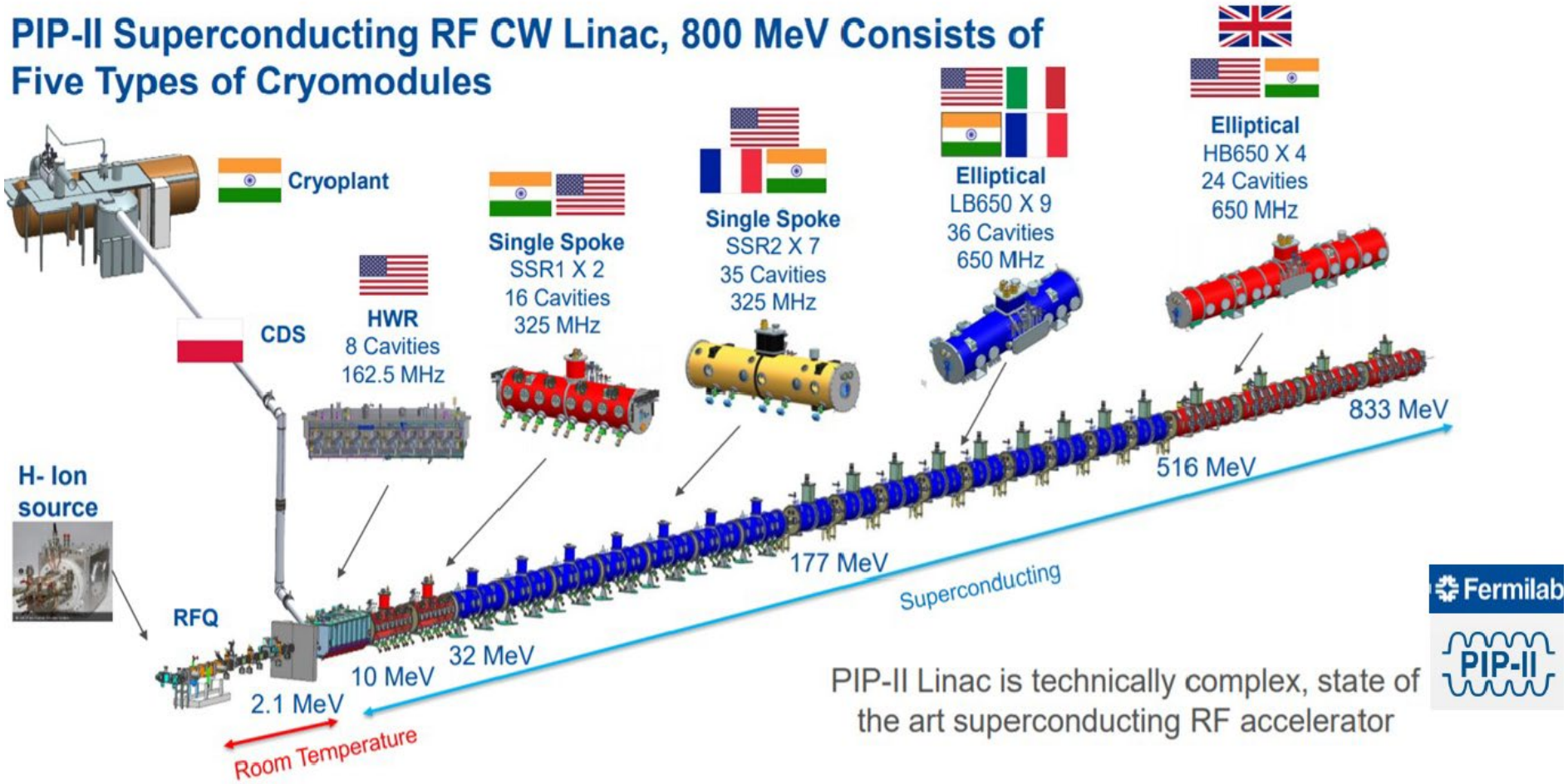
Collaboration on RF Cavity and Cryomodule with RRCAT/BARC & Fermi Lab, USA

SRF activities related to PIP-II



PIP-II is the world's highest energy and power CW proton linac, and the U.S. first accelerator project to be built with major international contributions

Courtesy : P Srivastava, RRCAT

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Ongoing RF Cavity Testing and Cryomodule Development at RRCAT

Status of HB 650 MHz Superconducting cavity development , Infrastructure and Testing under IIFC Collaboration at RRCAT

RRCAT efforts to the R&D phase under the Indian Institutions-Fermilab Collaboration for the PIP-II project:

(i) beta=0.92, 650 MHz (HB 650) five-cell bulk niobium SCRF cavities.

(ii) Horizontal Test Stand (HTS) cryostats,

(iii) 40 kW, 650 MHz solid state RF amplifiers,

- processing and HPR upgraded. Crossed the bar and reached 21.4MV/m first time, and after re-HPR reached to 29MV/m qualifying at 19MV/m for Q. Dressing/jacketing of one cavity successful at RRCAT and second at Fermilab with joint participation.
- Vertical Test Stand, VTS at RRCAT is operational and in regular use. Installation and commissioning of HTS done with unity coupler @1.98K. AES 10 cavity installed.
- RRCAT will soon be reaching to a complete cycle of SCRF cavity development after completing HTS test with high power coupler.


Forming of half cell


RF measurements

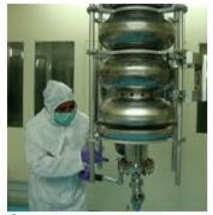

EB Welding (15kW)


Electro-polishing


Cavity Tuning


Vacuum Annealing


High pressure rinsing


Clean room Assy.

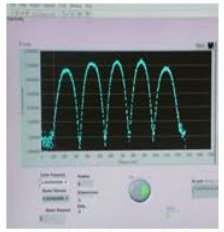

HB 650 MHz cavities


VTS testing at RRCAT


Helium Vessel


Tuner Assembly


Dressing in Glove box at RRCAT


Field flatness 92%


dressed cavity with tuner and coupler in HTS


HTS Facility


40kW 650MHz RF


LLRF and RFPI for HTS

Courtesy : P Srivastava, RRCAT

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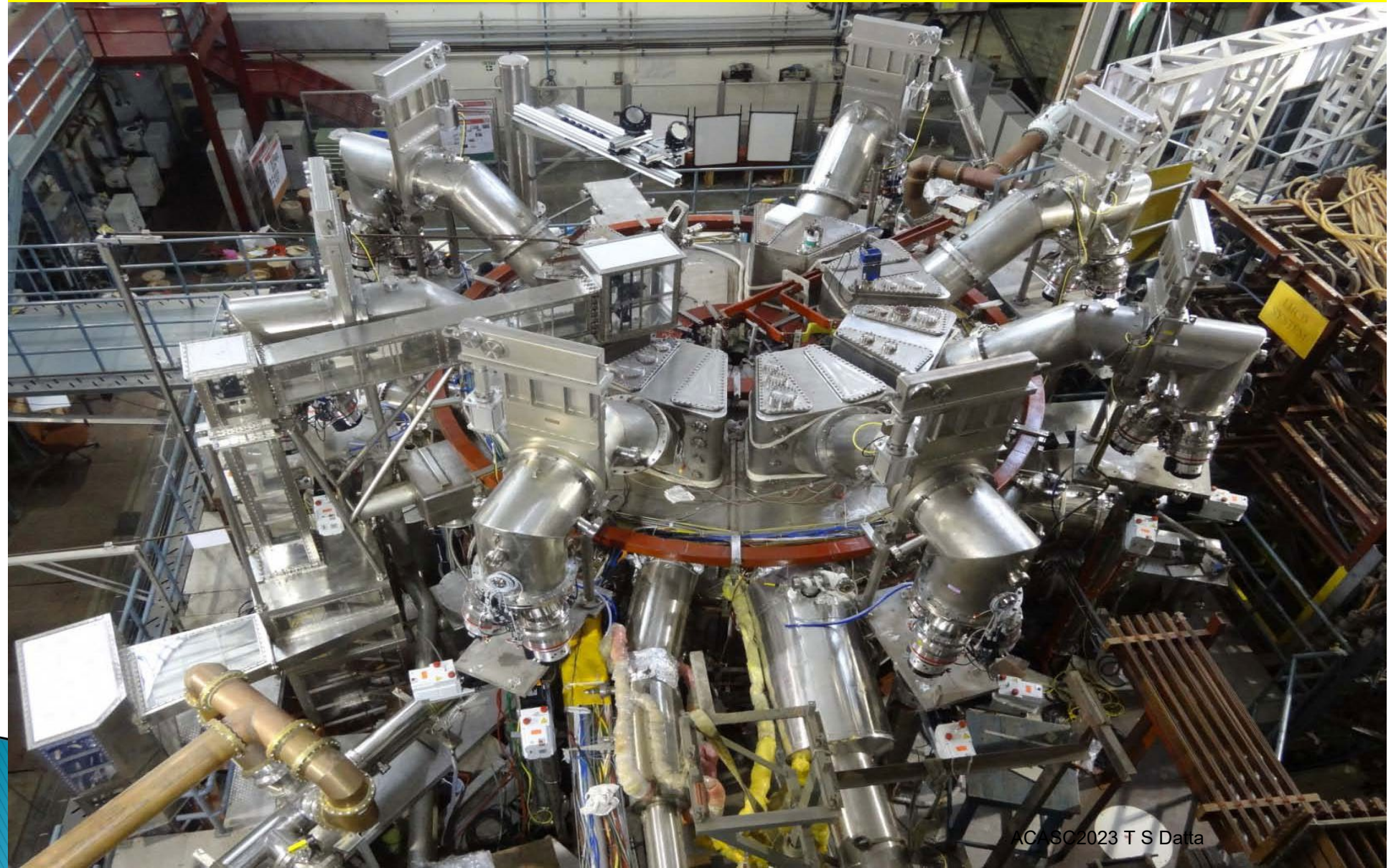
Steady State Superconducting Tokamak (SST-1) developed at Institute for Plasma Research, Gandhinagar



SST-1 Tokamak(1/1)

Machine Parameters

- Major Radius 1.10 m
- Minor Radius 0.20 - 0.25 m

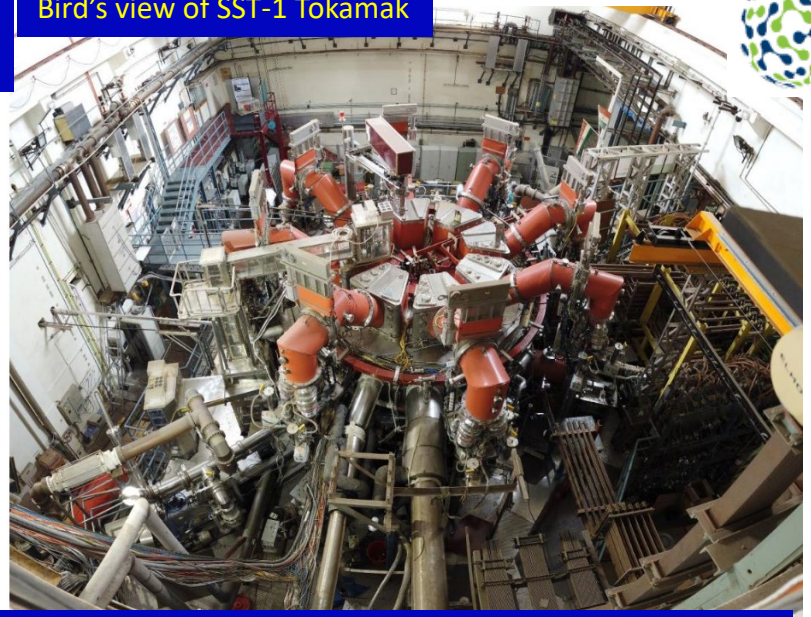
Auxiliary system

- 1.3 kW @ 4.5 K Helium cryogenic System
- ECRH Pre-ionization, LHCD and ICRH heating and current drive system

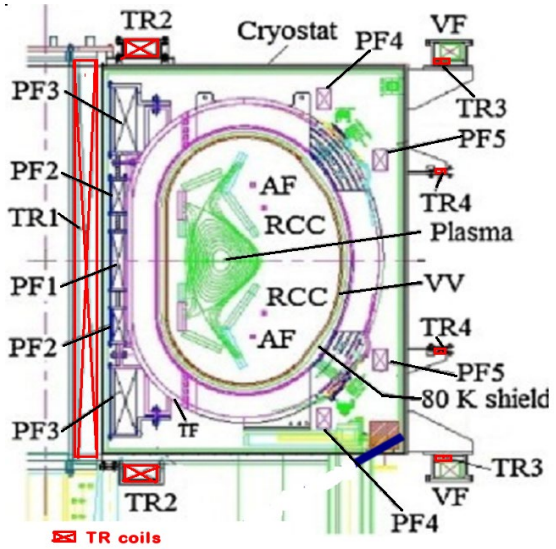
Parameters: Planned & Achieved

Parameters	Design value		Achieved (Maximum)
	Phase-I	Phase-2	Recent Experiments
Toroidal Field (T)	1.5	3	1.5 (tested @2.7)
Plasma Current (kA)	110	220	~100
Plasma Duration (ms)	100	1000	650
Plasma configuration	Circular	Transition from Circular to shaped	Circular
Plasma temperature (eV)	250	1000	250

Bird's view of SST-1 Tokamak



Cross-sectional view of SST-1 showing location of various Copper and Superconducting coils



Curtesy : Dr Upendra. IPR

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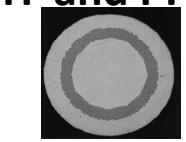
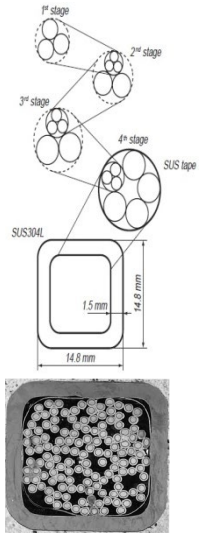
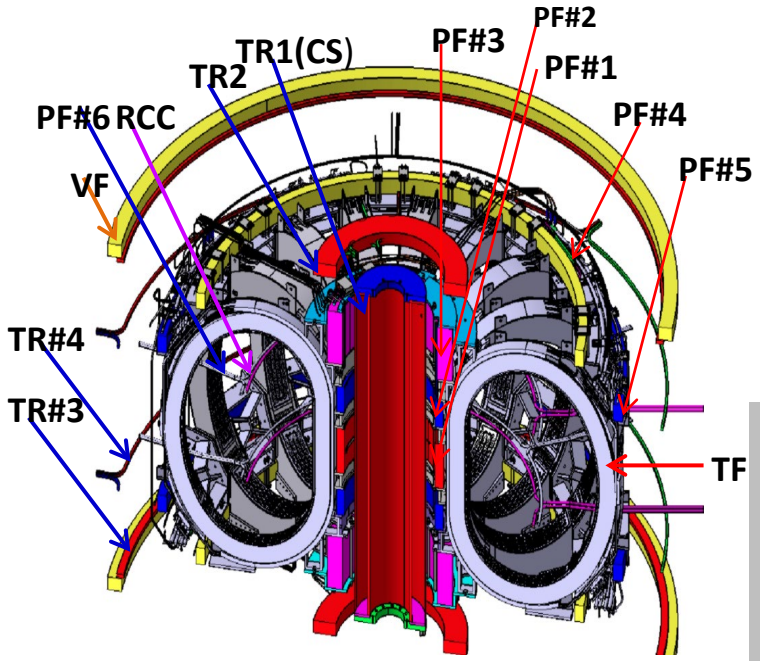
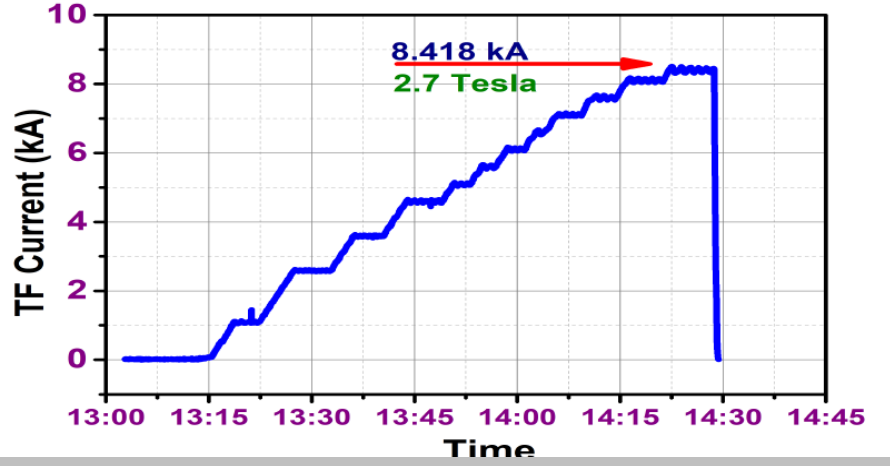
SST-1 Superconducting magnets Operational update(1/2)

TF and PF NbTi CICC









- TF coils operated up to 2.7 T@8.4 kA (90 % of the design value)
- TF coils are being routinely operating at 1.5 -1.6 T for plasma experiments

Current status of SST-1 : operational. Next campaign in SST-1 : November 2023.

Issue with One PF Coil : Large Hydraulic Loss / Pressure Drop and Higher Cryogenic Load : Bypassed at 25 K

In parallel, the thermal hydraulic and higher heat load aspects of PF coils have been worked out for SST-1 upgradation.

Curtesy : Dr Upendra. IPR

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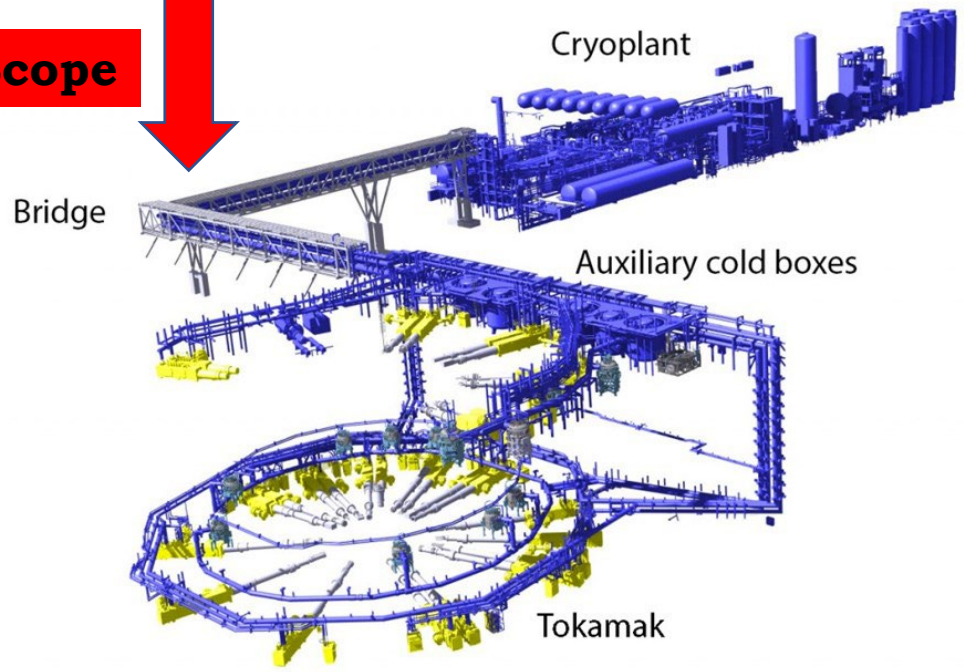
Cryolines and Cryodistribution System for ITER

75 kW at 4.5 K
1MW at 80 K

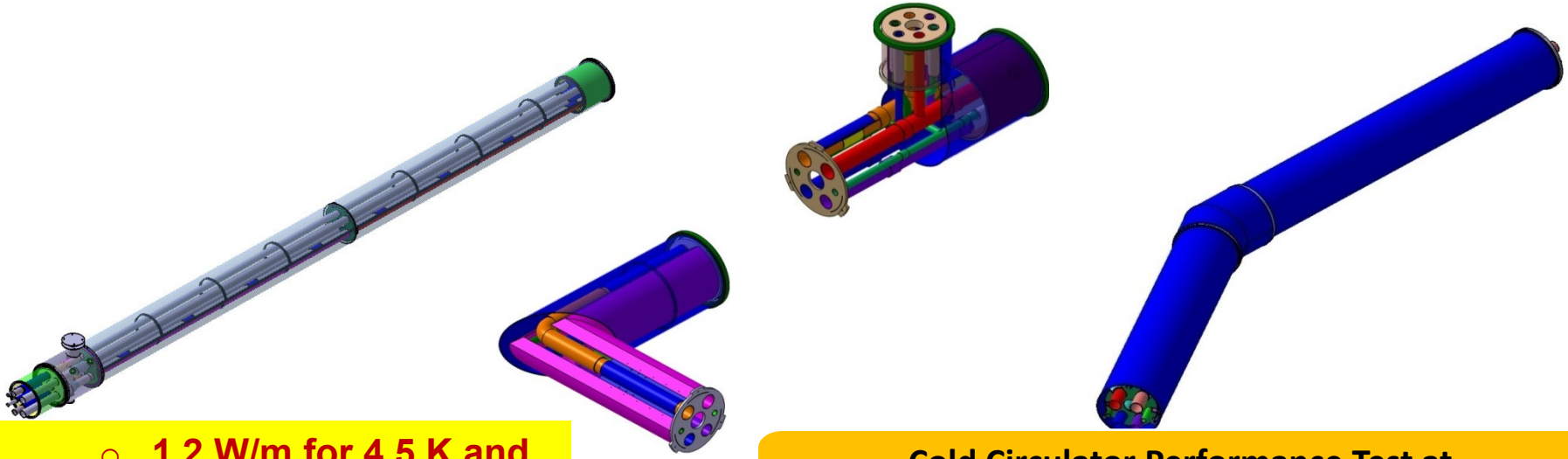
Indian Scope



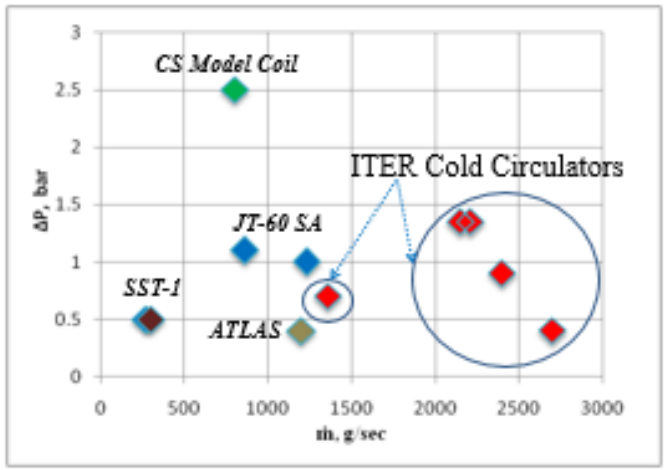
- **Cryogenic Users are;**
  - **Superconducting magnets with forced flow supercritical helium at 4 K level**
  - **Cryostat and thermal shields with forced flow of He at 80 K**
  - **Cryosorption pumps with supercritical He at 4 K level**

Indian scope : **4 km long cryolines , 7 km long warm lines, 7 cryo-distribution boxes**

Typical Segments of Cryolines



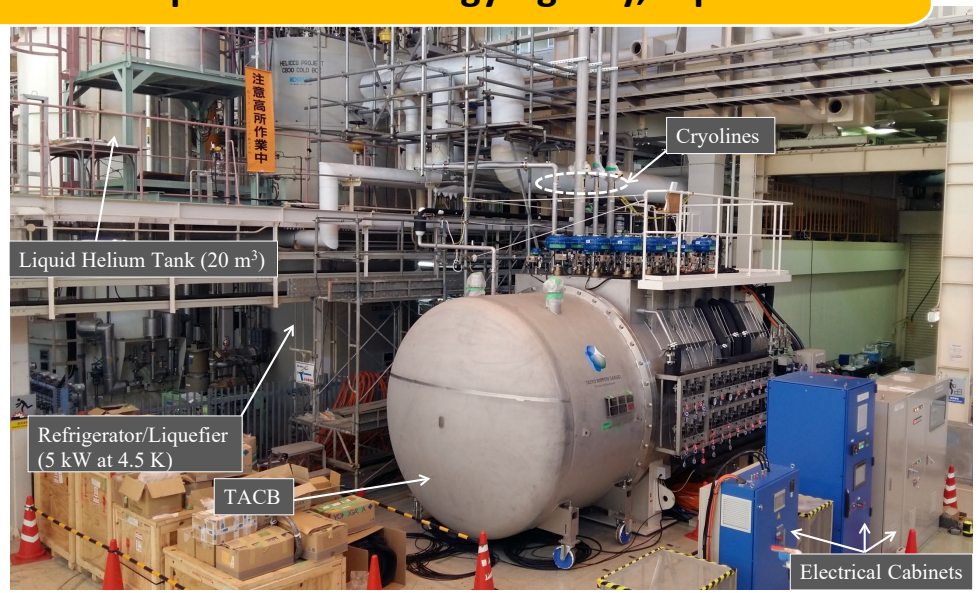
- 1.2 W/m for 4.5 K and
- 4.2 W/m for 80 K lines



kg/s at 4.3k

IHI, Japan

Cold Circulator Performance Test at Japan Atomic Energy Agency, Japan



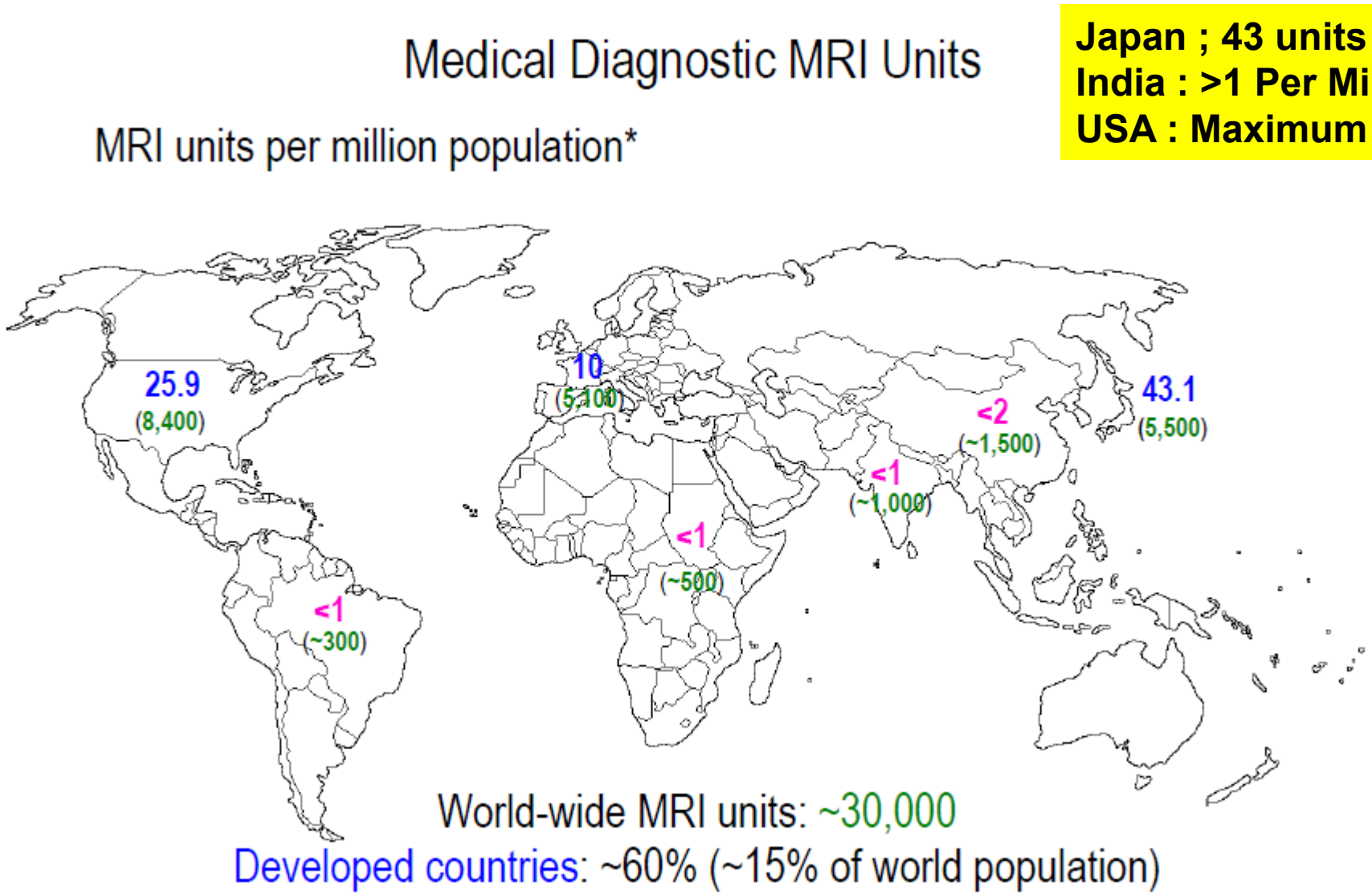
Multi **Multi- process Cryoline under manufacturing at M/S INOXCVA. India**

Cryolines and Warm Lines manufactured by INOX CVA under Installation at ITER, France

Final Shipment of Cryo-line flagged off by the Dignitaries at M/s INOXCVA on July 2021

THIS DATA MOTIVATES US and GOVT to DEVELOP MRI IN INDIA

Japan ; 43 units per Million
India : >1 Per Million
USA : Maximum Number



Good Market In India and China Together in Coming Years

Curtsey : Yuki Iwasa

MRI INITIATIVE IN INDIA (PRESENT)

Collaborative R & D Project
Initiated by
Ministry of Electronics and Information Technology

Objective : To Design, Develop and Test an Indigenous 1.5 Tesla MRI System for Medical Imaging

Collaborative Institutes

1. SAMEER, Mumbai
2. IUAC, New Delhi
3. CDAC, Trivandrum
4. CDAC- Kolkata
5. Dayanand Sagar Institutions, Bangalore

I was Principle Investigator (Magnet & Cryostat) till 2019 at IUAC.
After that Dr. Soumen Kar is leading .

Superconducting MRI Mission: Commitment

Critical Features of MRI Magnet

- **Field Strength** — ~ 1.5T
- **Field Homogeneity** — Spatial: < 10ppm peak-to-peak @50 cm FOV
- **Field Stability** — Temporal: 0.1ppm/hr
- **Magnet Stability** — Stable Operation in Ever-cooled Mode

Cryostat heat load
Must be less than 1.0 W @4.2 K

Active Shielding

Safety

5 Gauss in 4m X 2.5m Elliptical Space

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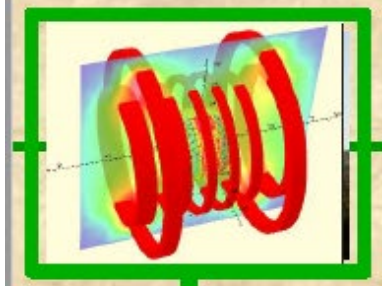


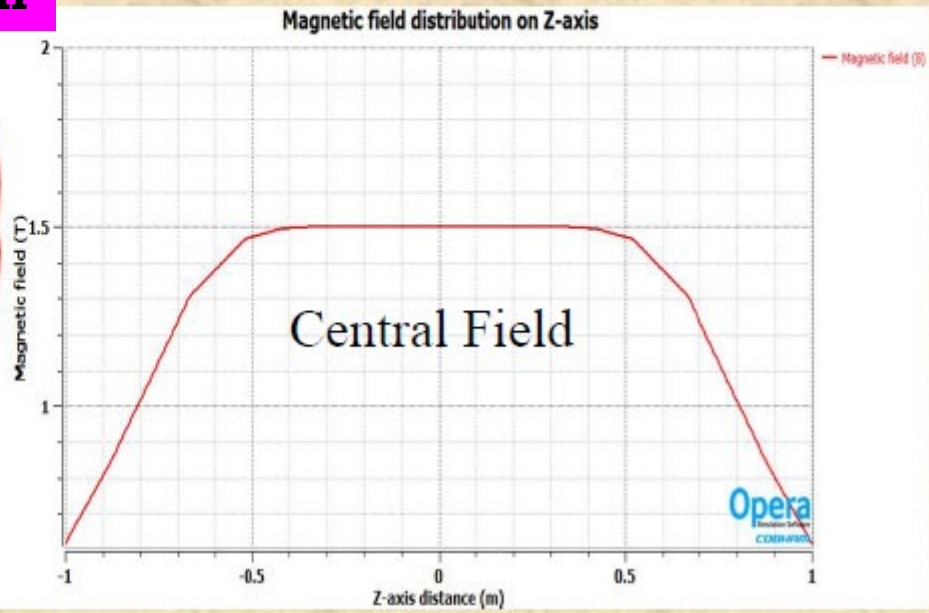
1.5 T MRI Magnet

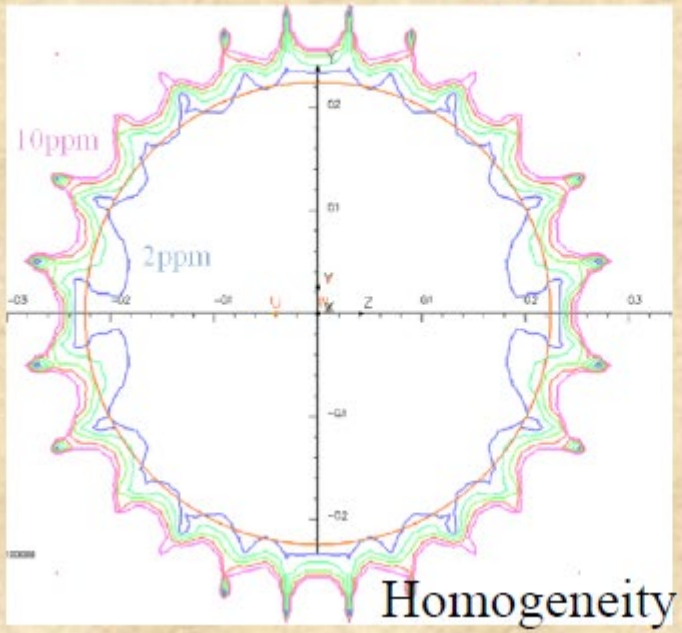
Magnet Parameters	
5G safety region	4m x 2.6
Inner diameter	1.01 m
Outer diameter	1.7 m
Length	1.4 m
Total number of turns	12924
Superconductor volume	0.1922 m^3
Ampere- length	23.3 E+6 A-m
Ampere- Turn	5.99 E+6
Radial force (max)	87.25 MN
Axial force (max)	543.51 kN
Hoop stress (max)	70.7 MPa
Axial stress (max)	2.82 MPa
Total Inductance	42.34 H
Stored Energy	4.4 MJ

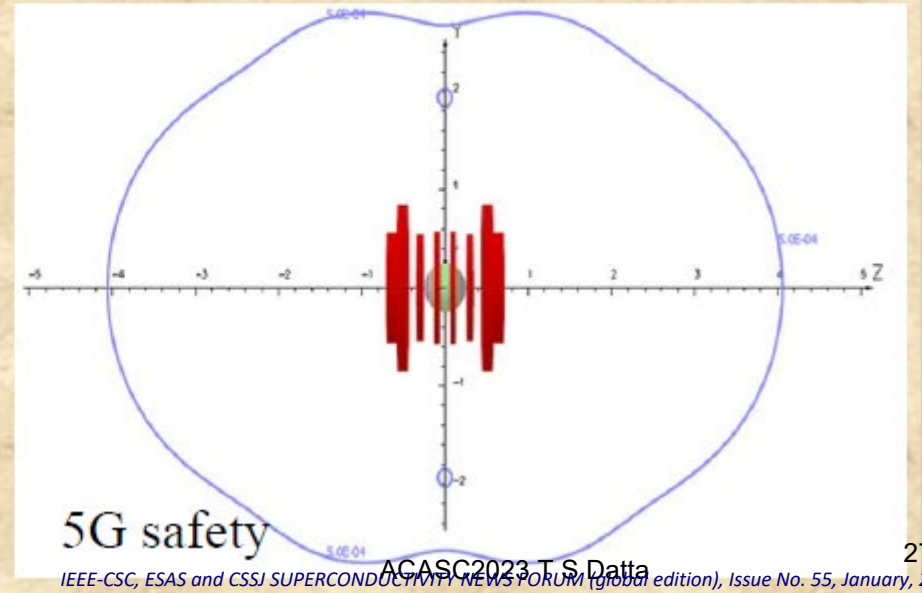
MRI@IUAC

1.5 T MRI Magnet

6 Main Magnet Coil + 2 Shield Coil







MRI@IUAC

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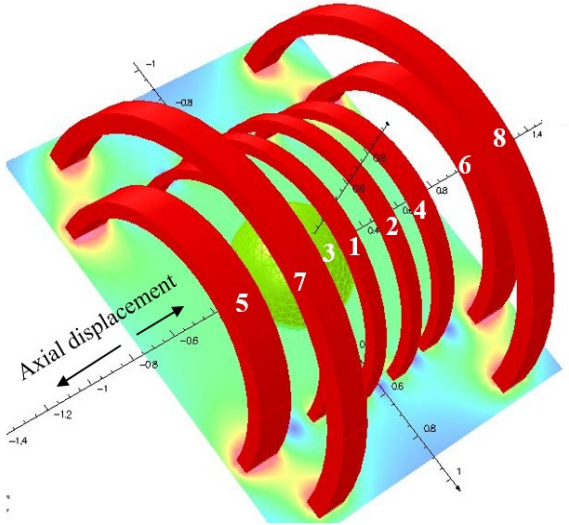
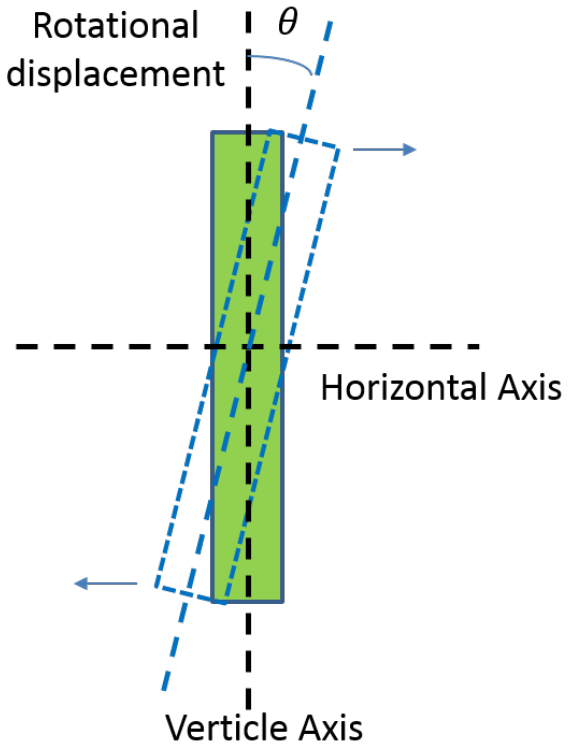
1.5T MRI magnet: In-homogeneity

Deviation in Axial Placement of coil ~ 0.1mm



Homogeneity ~200-500ppm

Deviation in Angular placement of coil ~ 0.1 degree



Homogeneity ~500-800ppm

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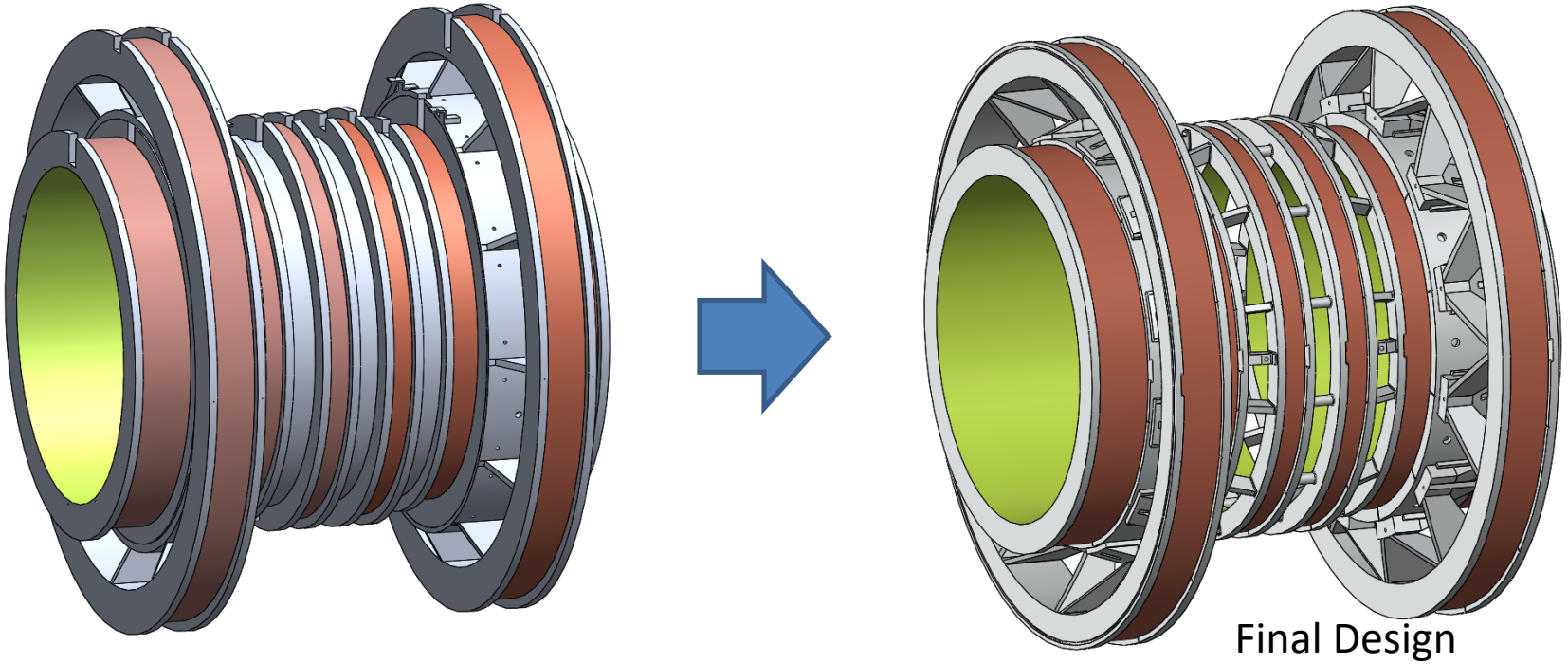
Bobbin Design Optimisation



Final Design

Final configuration of Bobbin after 8 design iterations:

- **Minimizing Fabrication complexity**
- **Minimizing Integration complexity**
- **Minimizing Mechanical stresses**
- **Weight optimisation**

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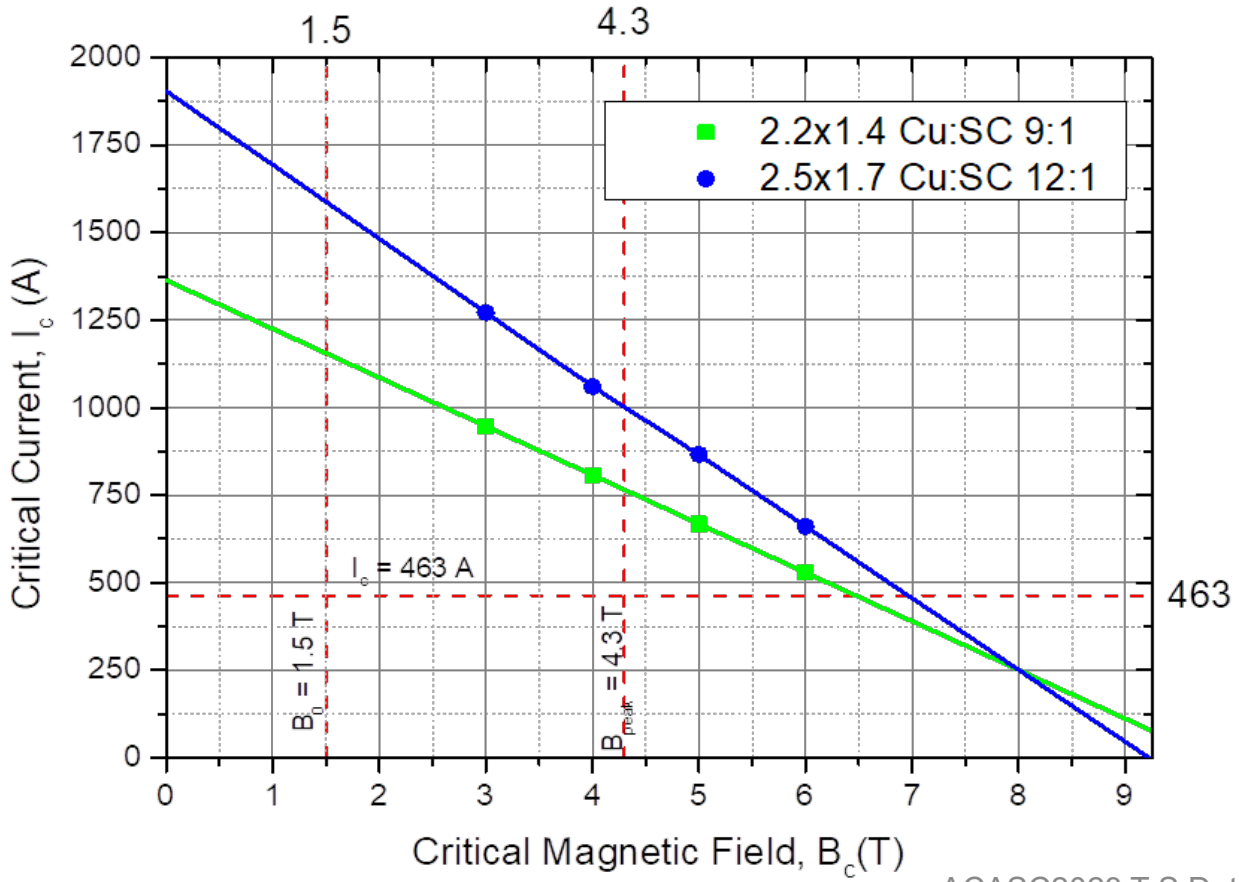
SC Wire in Channel for Our MRI

2.2 x1.4 Cu : Sc : :9:1
2.5 x1.7 Cu: Sc :: 12:1
From LUVERTA



Total conductor length
Primary 6 Coils – 30.87
Shield Coils - 17.94

Total (km) 48.81
Operating Current : 463 A

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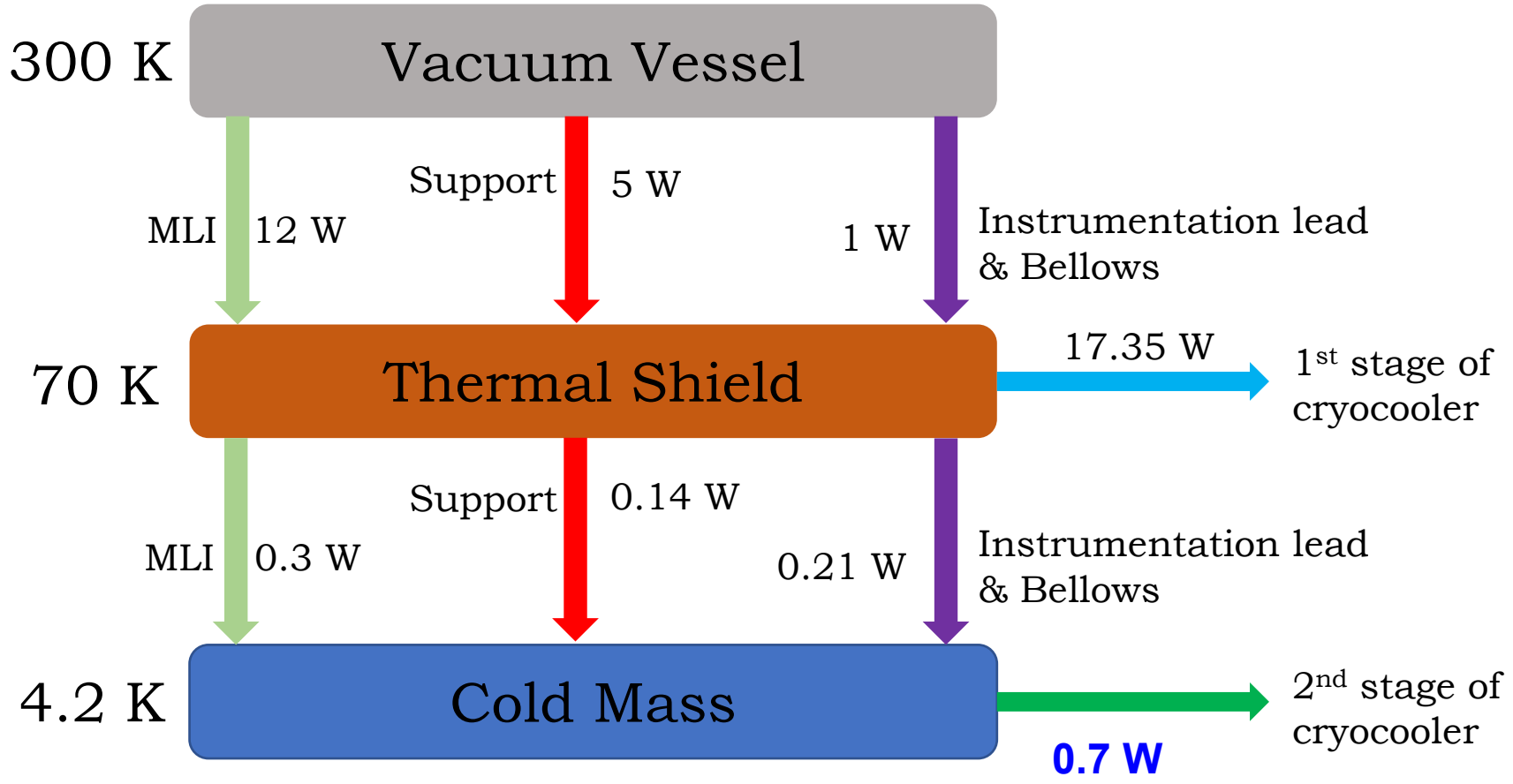
Heat Load for MRI Cryostat

One Cryocooler of 1.25 W at 4.2 K and 40 W at 45 K will be used



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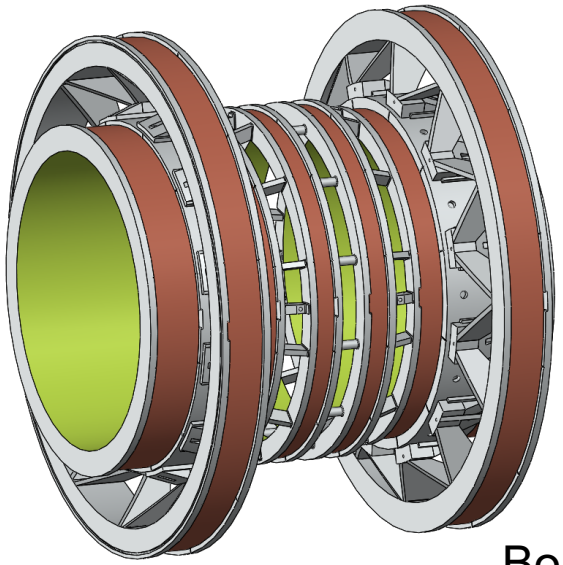
MRI DEVELOPMENT AT DIFFERENT STAGE at IUAC. Delhi



Bobbin

Total conductor length
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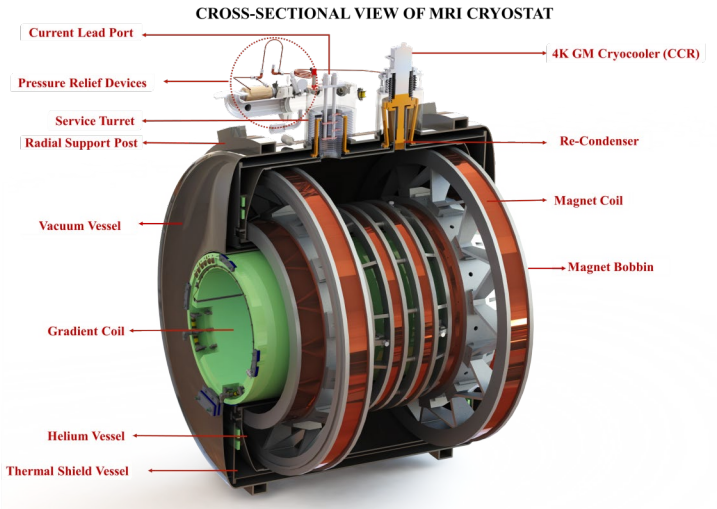
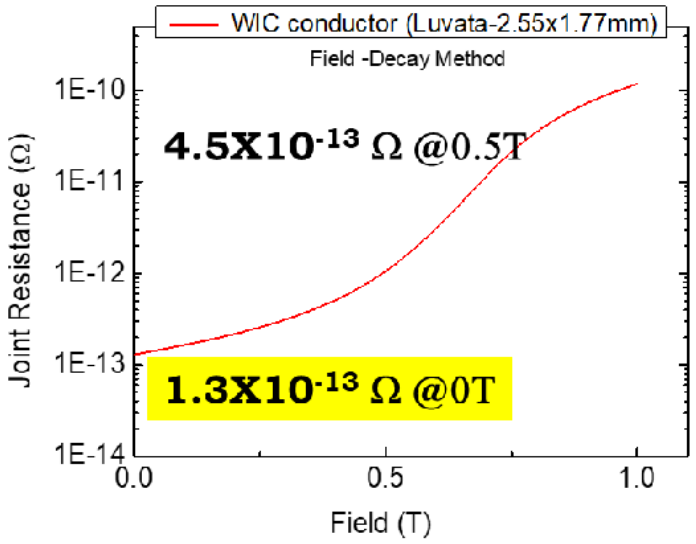


Cryostat

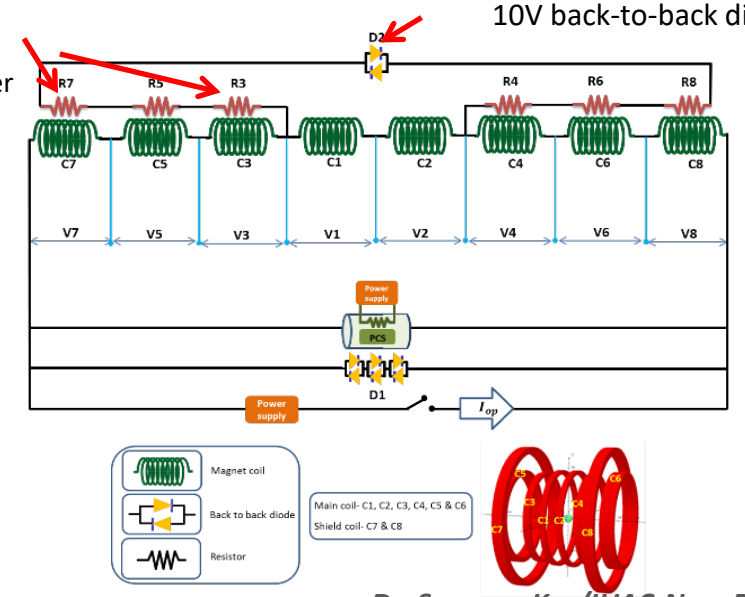


Joint Resistance

Quench Protection

100 Ω
Quench
back heater

10V back-to-back diode



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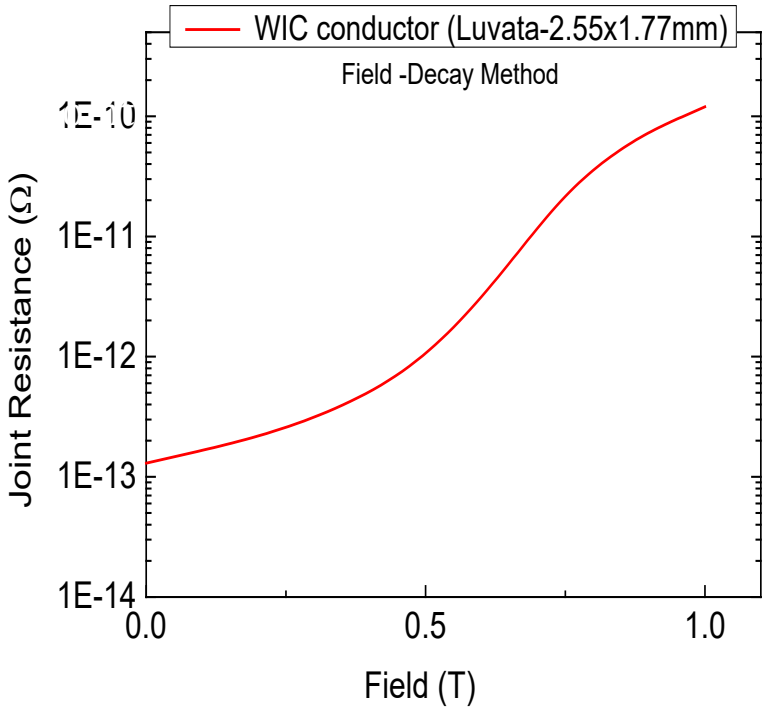
Superconducting Joint Development

- Development of Superconducting Joint (less than pico- ohm) and characterization
- Development of of 1kA Superconducting switch or persistent current switch (PCS)
- Development 4K-test rig for measurement of Sc-Joint up to 550A
- Development 4K-test rigs for characterization of superconducting Switch



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Tin-diffusion protocol/ superconducting soldering protocol/ Ultrasonic soldering process { between two round Cu-NbTi conductors or between CuNi-NbTi conductor

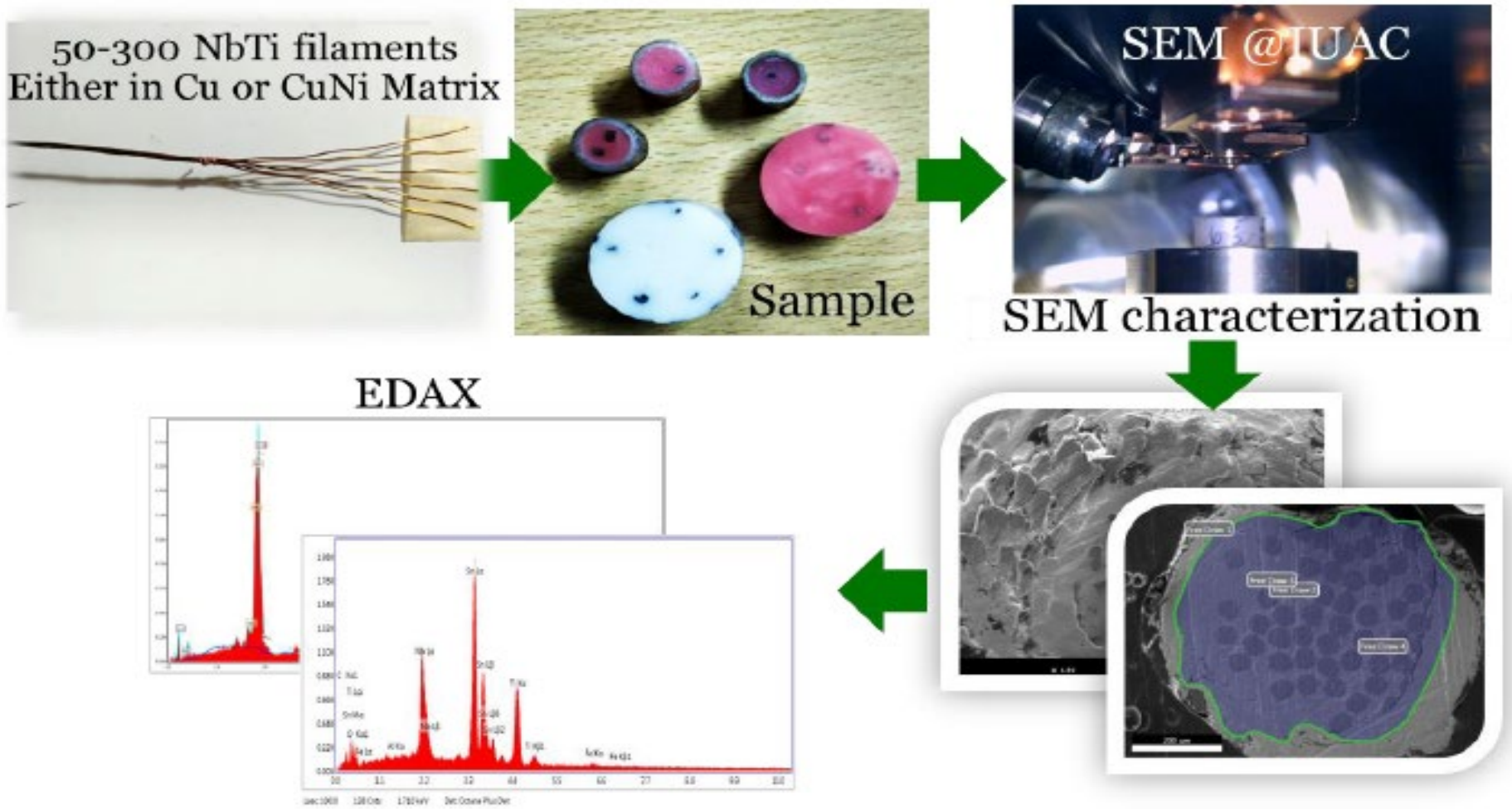

Figure 3: The flow chart of the superconducting joint characterization process using SEM/EDAX.

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Quench Protection

Detailed information of material properties and coil geometry is necessary, so the quench simulation of the 1.5T MRI magnet can be possible using OPERA-Quench code.

- ✓ Maximum (peak) temperature in magnet and peak temperature in each coil.
- ✓ Transient thermal 3D map of each/all coil.
- ✓ Voltage across each coil.
- ✓ Current decay in each coil.
- ✓ Eddy current generation during quench (coupled analysis of Quench and Electra/Tempo); (in magnet coil, bobbin and thermal shield/vacuum jacket).
- ✓ Stress generation during quench (coupled analysis of Quench and Stress Solver); (in magnet coil, bobbin and LHe vessel/support structure).

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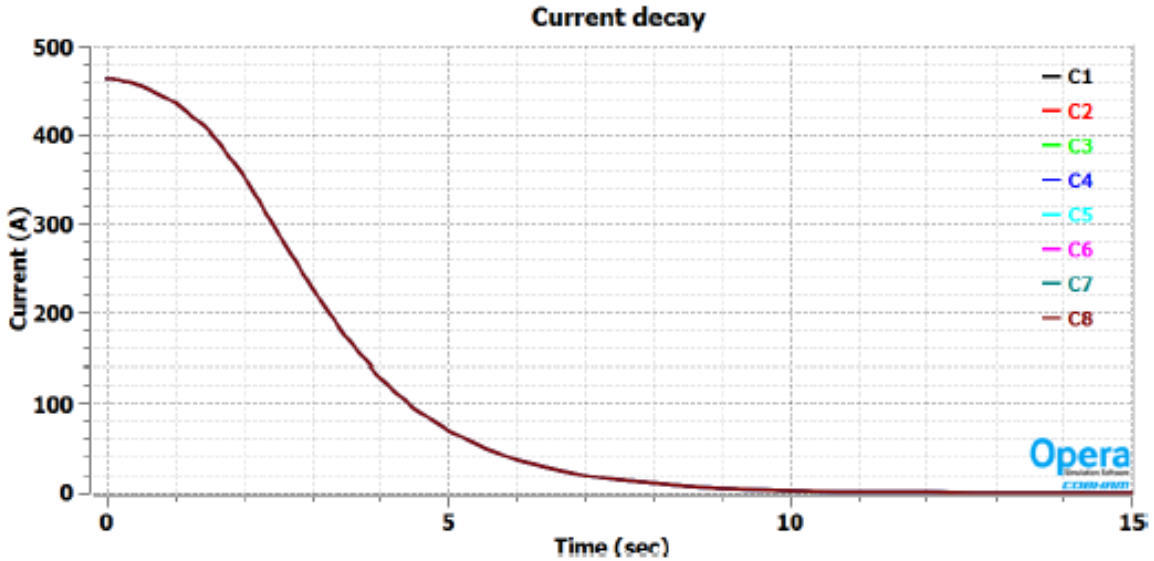


Figure 59 Post-quench current decay profile of the 1.5T MRI magnet.

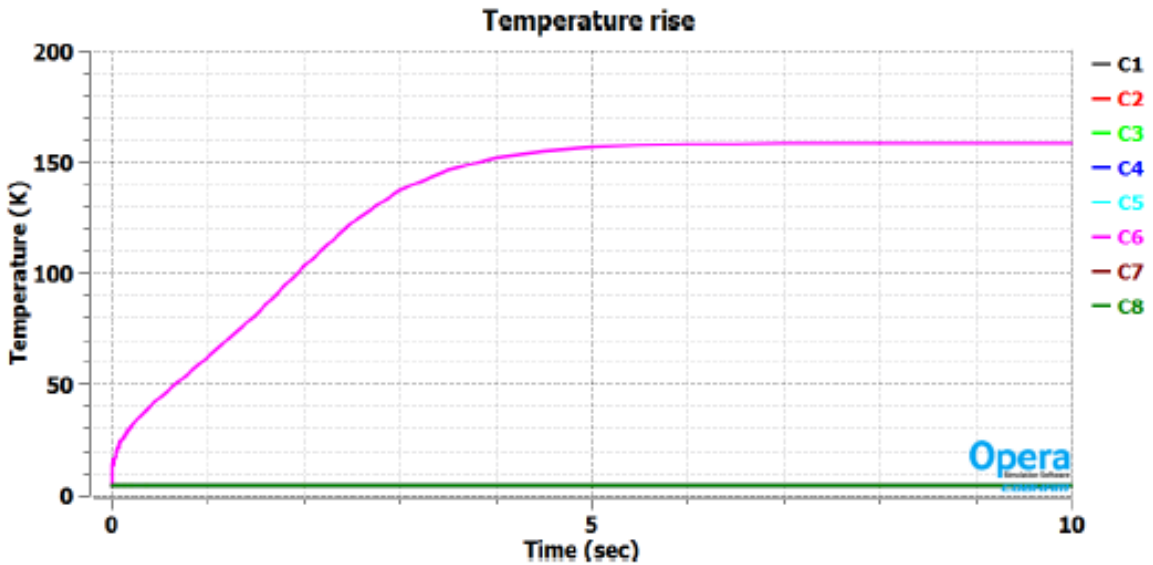


Figure 60 Post-quench temperature growth of the hot-spot the on coil-6 of the 1.5T MRI magnet.

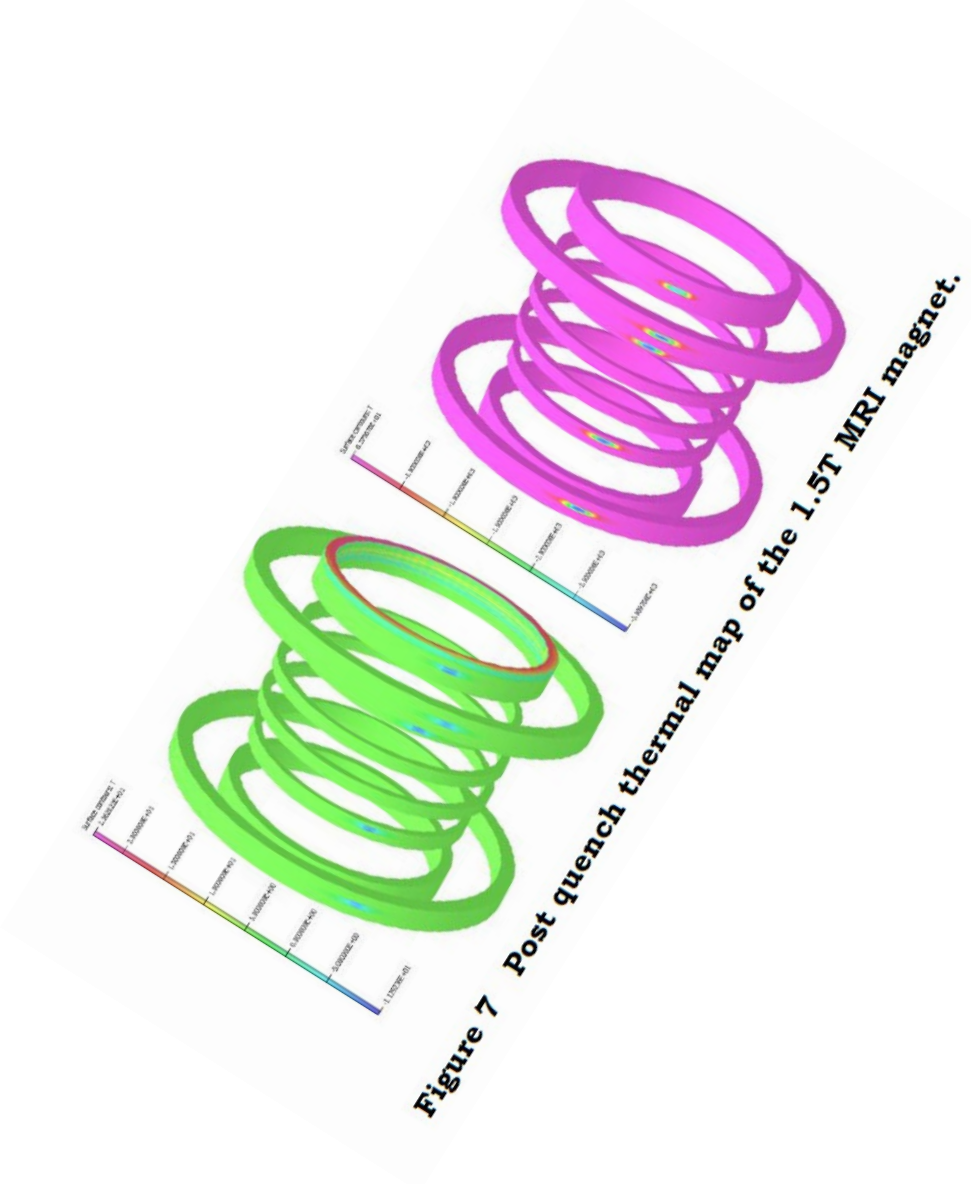
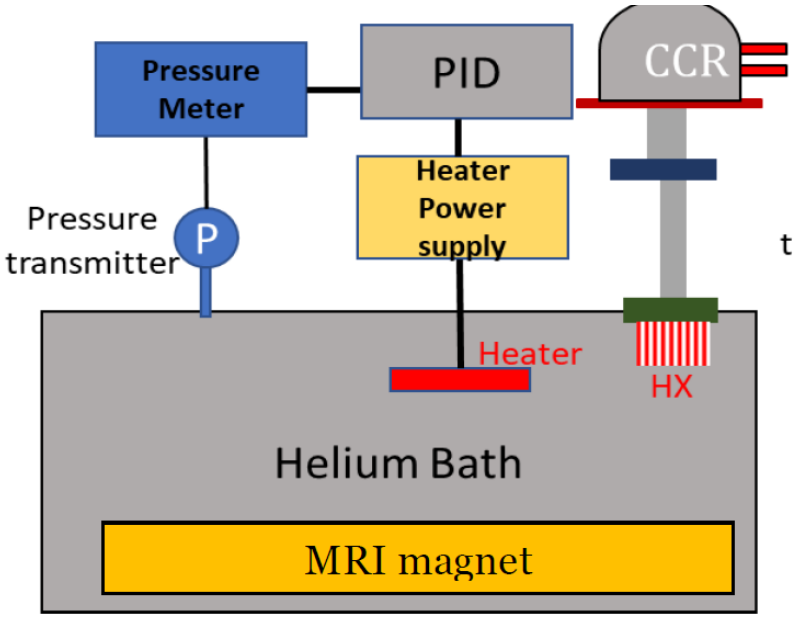
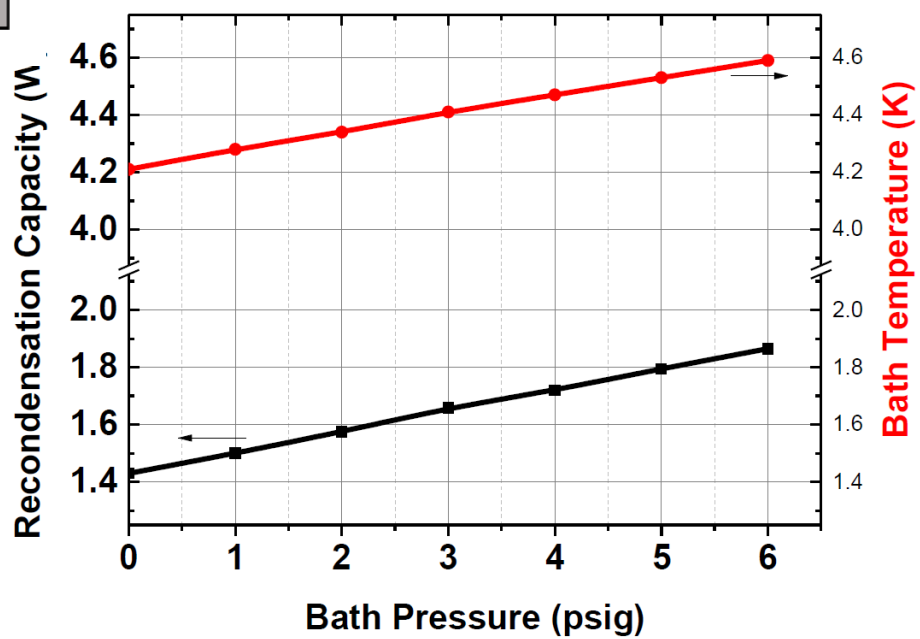


Figure 7 Post quench thermal map of the 1.5T MRI magnet.

PRESSURE STABILIZATION WITH CRYOCOOLER AND HEATER





Inter-University Accelerator centre

Thermal cycling at the Factory

Magnet testing at IUAC

Achieved Parameters

Description	Target	Achieved	Comments
Central Field	1.5T	1.5T in the First Energization	Very rare for a New magnet Even big companies take 2-3 chances
Homogeneity in Un-shimmed magnet (shimmed magnet)	< 2000 ppm in 45 cm (10ppm)	615 ppm in 45 cm (un-shimmed magnet) (Will be done after commissioning)	- Good for a first magnet (can be achieved by passive shimming)
5G Stray field	5m (axial) x 3 m (radial)	3.5m (axial) x 2.5m radial)	Within USFDA limit
Field Stability	< 0.1ppm /hr	< 0.04- 0.07 ppm/hr After 10 hrs	- Need more tests
Training Quenches	3-5 quenches for a new design 1-1.5 Quenches in production level	Zero Quenches during Training 1 (Induced Quench)	It is probably the First MRI Magnet with Dry winding having No training quenches

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Recent Picture (August 2023)
While Testing of MRI Magnet

There are minor issues (Particularly on Persistent Switch , which will be addressed and Corrected

There is a parallel MRI Development by Private Industry with partial Support from Government

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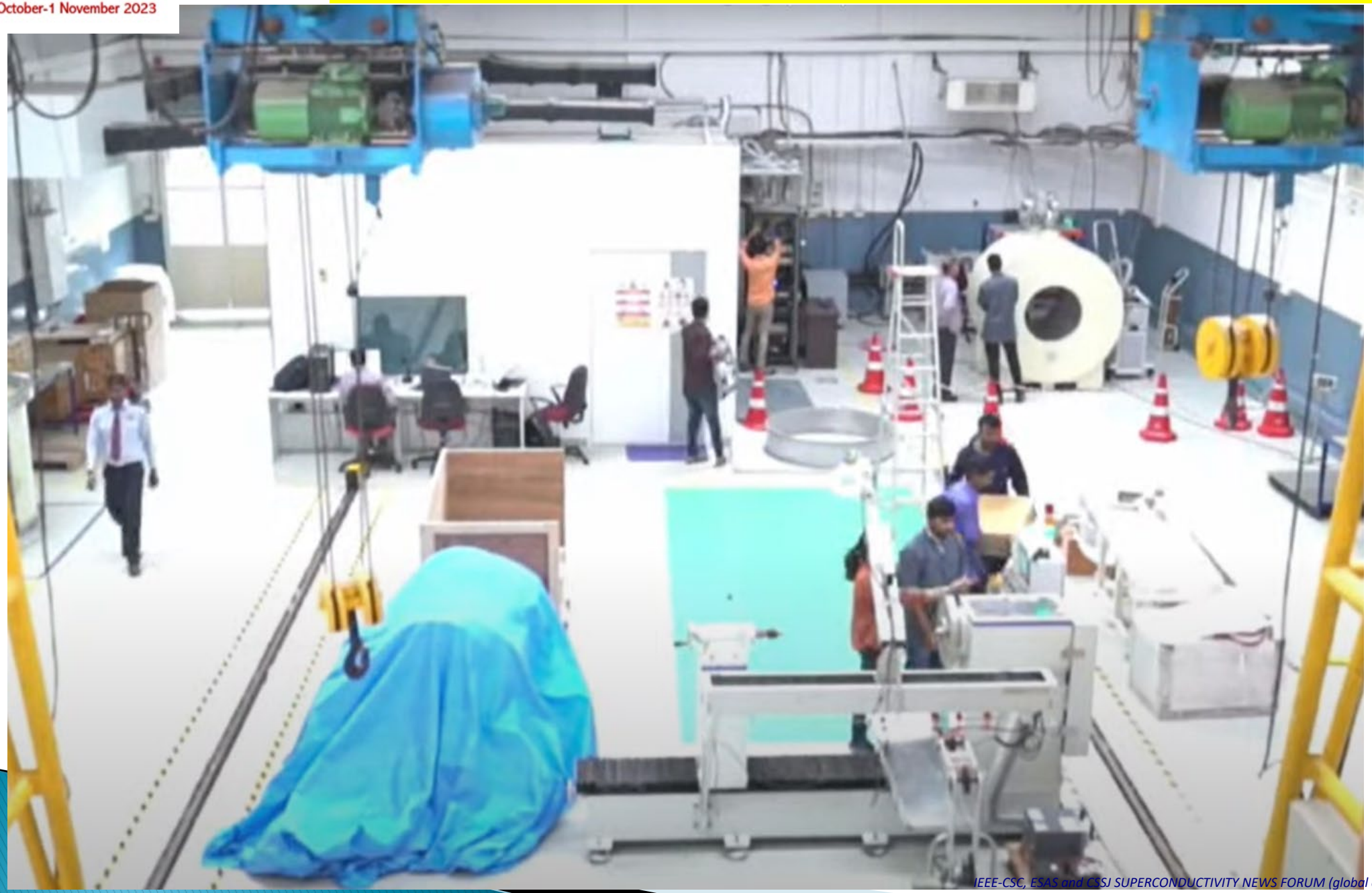
Next Generation MRI (1.5 Tesla) by M/s Voxelgrids. Bangalore. India

- Light Weight (2 Tons),
- Ultrafast Scanning (Parallel Data Collection)
- Dry MRI (Cryocooler) . No Liquid Helium : Precooling by Liquid Nitrogen
- Bobbin : Aluminium Alloy
- Most Important : Cheap

MRI Manufacturing Site at Bangalore. India



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Received Commercial Licence from Ministry in July, 2023

No Major National Project on HTS for Power Application

Not able to defend high cost of HTS to our funding agency

Small Scale Development with HTS

1. **Superconducting Cable/ SMES / MRI Magnet at IIT Kharagpur**
   (There will be few talks by my Colleague Prof Abhay Gour)

   We also Established a bilateral Collaboration with Kyushu University on Coil development

2. **Superconducting Motors by BHEL**

3. **HTS Magnet at VECC. Kolkata and IPR. Gandhinagar**

Summary

- Significant achievement on Indigenous MRI Development. Encouragement from Government under the banner Make in India. Expecting Commercial Indian MRI in Market Shortly

- Indian Space Research Organization is doing good on Cryogenic Engine Development for ambitious programme on Chandrayaan, Gaganayaan

- Accelerator & Fusion Programme by Department of Atomic Energy dominates along with Space Cryogenics & It will continue in Future

- Superconductivity (HTS & Cryo Cooler) for Power Application is yet to take the momentum in India unlike Japan, China and Korea. Small scale activity is on

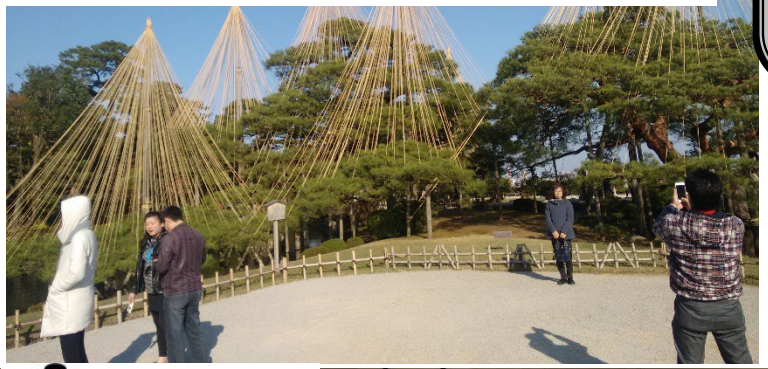
- Quantum Computing and Dilution Refrigerator and Hydrogen as Fuel : Recent Liberal funding from Government

ACKNOWLEDGEMENT TO CONTRIBUTORS

- Scientist/Engineer from ISRO
- Dr. Vaishali (VECC. Kolkata)
- Dr Arup Bandyopadhyay (VECC. Kolkata
- Mr. Upendra Prasad (IPR, Gandhinagar)
- Mr. P. Srivastava (RRCAT, Indore)
- Dr. Soumen Kar (IUAC. Delhi)
- Mr. Nitin D Shah (ITER- INDIA)
- M/s. Voxelgrids, Bangalore

ACASC-Asian ICMC 2023

Shanghai, China
29 October-1 November 2023



I will Cherish the First/Second Asian ICMC Conference in Kanazawa/ Okinawa in 2016 and 2019

Thank You

Joint Conference
10th ACASC
2nd Asian-ICMC
CSSJ

1st Asian ICMC-CSSJ 50

Wonderful Evening