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“In-House Development of Cryogenic Vacuum Barrier Joint of Superconducting Busbar of Fusion Machine”

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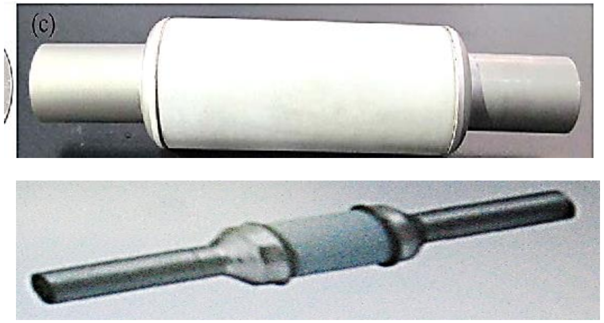
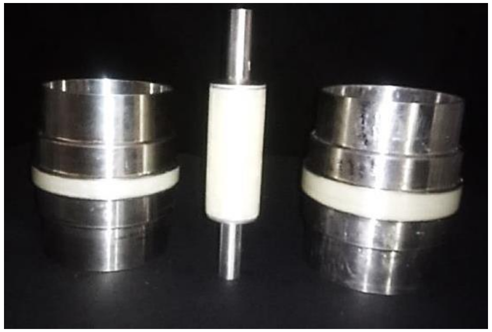
Introduction

- For fusion tokamak, these dissimilar material joints of metal Stainless steel (SS) to glass fiber or SS to ceramic are used to bifurcate the vacuum between the machine cryostat and current feeder system and provides the electrical isolation upto 2 kV DC voltage during quenching of superconducting magnets (SC).
- The dissimilar material joint used are in form of electrical insulation breaks (IB) and vacuum barriers (VB) in fusion magnets and SC bus-bar hydraulics.
- 20 numbers of VB component assembled with cable in-conduit conductors (CICC) SC busbar which carrying the electrical current upto 10 kA maximum and LHe fluid in 0-4 bar (a) pressure range.

Ceramic vacuum barrier



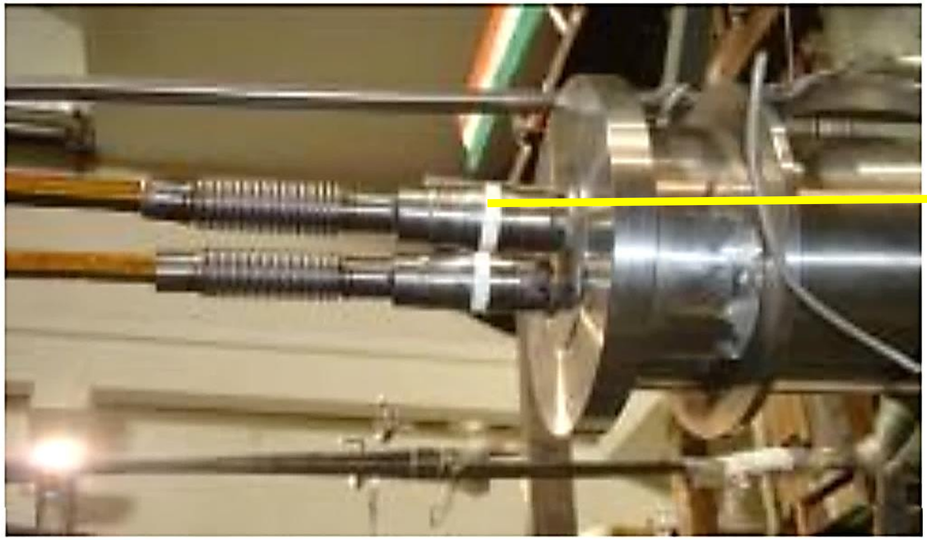
Ceramic + SS dissimilar material joint (IB)



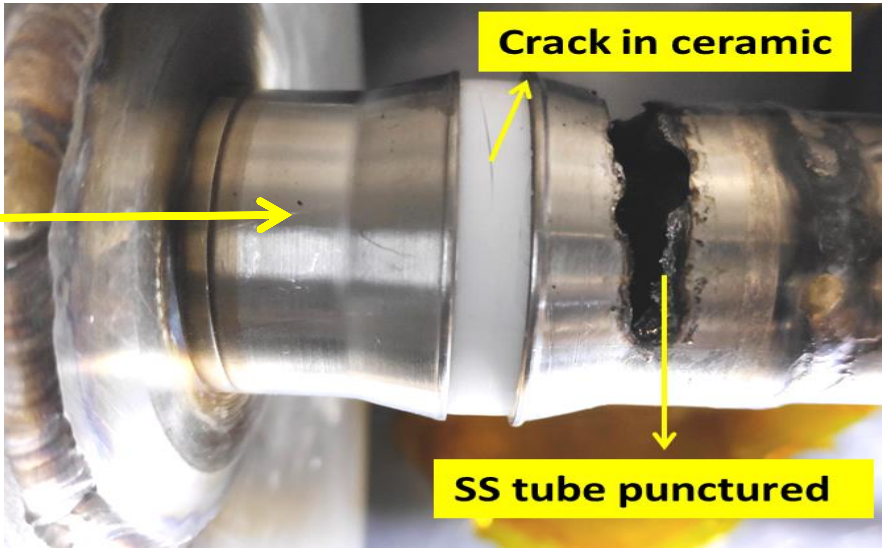
Glass fiber + SS dissimilar material joint (VB)

Motivation and Objective of the Project

- To replace the failure existing ceramic (high purity alumina) to SS metal welded VB in 10 kA SC bus bar of SST-1 machine.
- In house R & D development activity of glass fiber to SS VB for future replacement option of existing ceramic VB
- To mitigate the brittle transition failure occurrence in ceramic material after repeated thermal cycling at cryogenic temperatures.
- To reduce the high cost of imported one



CICC Vacuum Barrier in for SST-1 Tokamak



Ceramic VB failure

Technical and Operational Requirement

Technical Needs	Parameters
Material	Dissimilar materials joint of metal SS 316 + boron free S-glass fibre composites, bonding with cryogenic epoxy resin system
Two side vacuum isolation withstand capacity	$< 10^{-6}$ mbar
Temperature range cycles	300 K - 4.2 K - 300 K
Helium leak tightness at 300 K and after 5 thermal cycles at 77 K, @ 10 bar LN_2	$\leq$ 3.0×10^{-06} mbar-l/s (Pressure) $\leq$ 1.0×10^{-08} mbar-l/s (vacuum) at 300 K
Pressure withstand capacity	10 bar(g)
Electrical voltage isolation DC	2 kV
Size of conductor (at both end opening)	ID: Ø 112 mm, OD: Ø 141 mm
Installation in current feeder system	Welded at both side
Manufacturing process	Epoxy bonded joint by filament winding process to enhance the mechanical tensile and compressive strength

In-house Developments, Fabrication Technics and Design

- Vacuum barrier consists of SS 316L stubs which are separated by glass fibre tubes bonded with cryogenic epoxy.

- To eliminate the brittle failure at cryo temperature in ceramic VB, epoxy resin bonded joint was developed and fabricated.

- For bonding of dissimilar material SS and S-glass fiber composite, a two-component modified Diglycidyl ether of Bisphenol-A (DGEBA) epoxy resin developed, formulated and optimization with various hardeners, toughening agent and silane coupling agent.

- The filament winding process optimized with important parameters like mass of S-glass fiber and epoxy, fiber speed and fiber angle and torque.

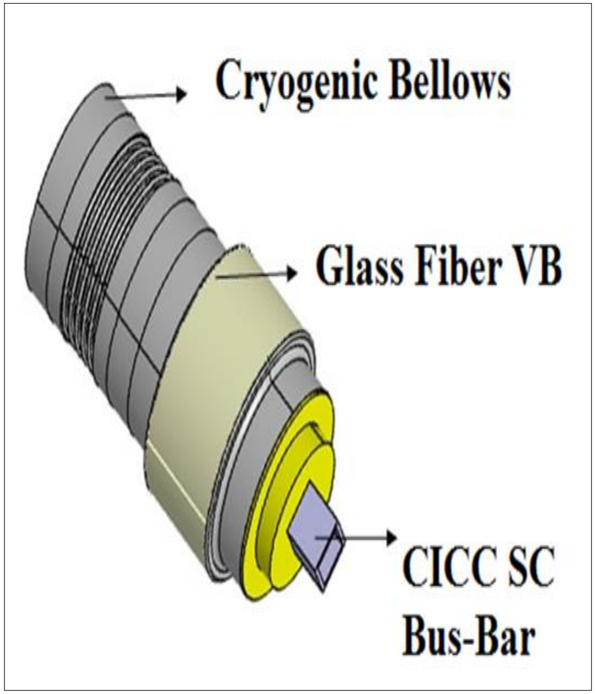
- The manufacturing process enhanced the mechanical compressive, tensile strength, and reduction in thermal radial stress in cryogenic GFRP VB.

- Pressure withstand capacity of metal conductor and insulation tubes during heat leak and pressure condition.
- Induced thermal stress during cool down from 300 K to 4.2 K, and thermal cycling
- The thermal contraction, distance between the conductors, contour geometry and sharp edge surfaces were optimized for larger VB.
- Optimized for electric field strength and breakdown phenomenon criteria, considering the Paschen discharge event occurrence to prevent the electrical incidents on VB.
- Development of cryogenic bellows that overcome the flexibility issue and helium leakages due to the high induced thermal radial stress in SC bus bar hydraulic.
- The specific contour design has enhanced the mechanical strength in compressive and tensile direction.
- Innovative step of sand blasting process (SiO_2) on SS conductors which enhances the bonding with GFRP insulation.
- QA/QC followed in each stage of fabrication

SS 316L sand blasted conductors

1st stage bonding process

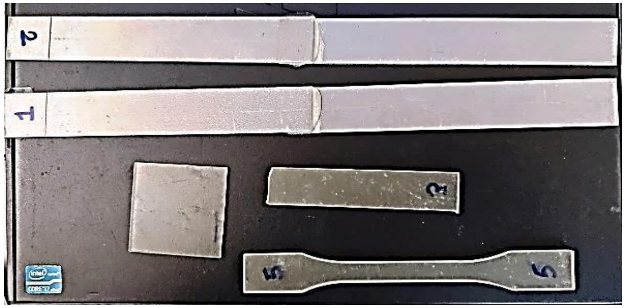
Fabrication by manual filament winding process



VB in SC bus bar

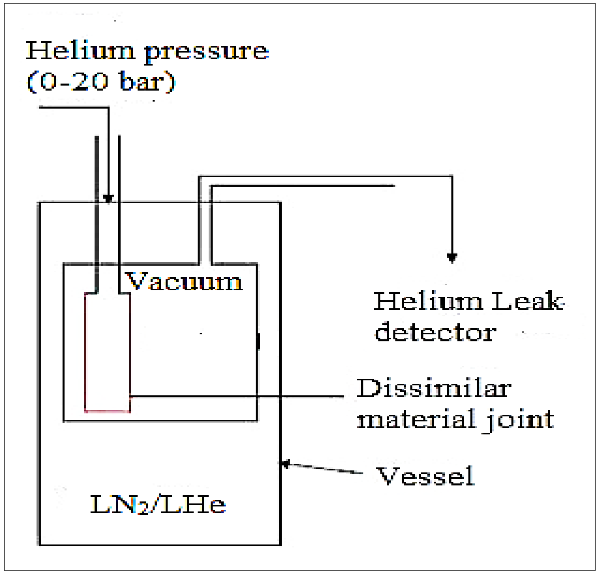
VB with cryogenic Bellows

Different Sizes Glass fiber VB



Developed epoxy resin samples

Performance Tests and Results



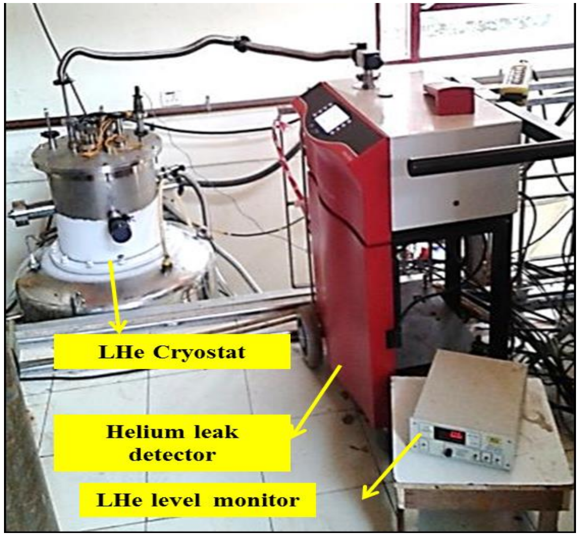
Schematic of He leak test at 77 K, 4.2 K

He leak test of VB at 300 K

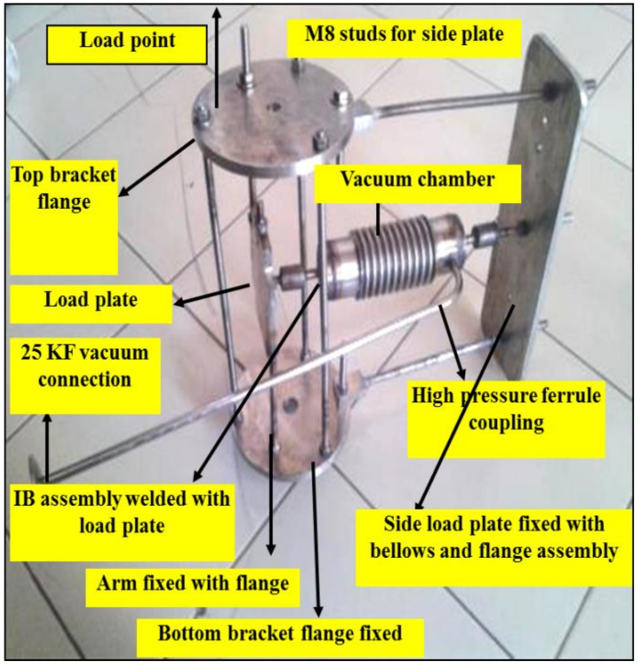
Thermal shock test at 77 K

He leak test in LN2 flow

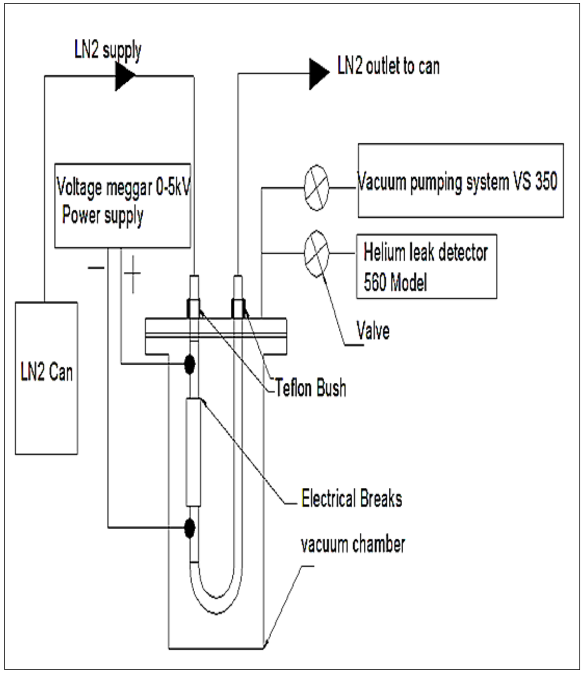
He leak test @ 10 bar LN2



He leak test @ 0-20 bar 4.2 K



Tensile, torsion and bending mechanical test set up



Schematic of Paschen test

Electric DC Meggar test at 10 kV

Tensile pulled out load test

Fractured sample of SS+ GFRP material joint

Tests Result of Glass Fiber VB

Performance Tests	**Value Obtained**	**Observations**
Two side vacuum isolation	10^{-06} mbar	
Helium leak tightness	< $2.0\text{x}10^{-06}$ mbar-l/s(Pressure) < $1.0\text{x}10^{-08}$ mbar-l/s (vacuum) At 77 K : < $2.5\text{x}10^{-06}$ mbar-l/s at 10 bar(g)pressure condition	After repeated thermal cycling from 300 K to 77 K, leakages observed > $3.0\ \text{x}10^{-4}$ mbar-l/s in ceramic VB
Pressure withstand capacity	30 bar(g)	10 bar(g) in ceramic VB
Mechanical strength (The joints were fractured at parent material region)	65 MPa at 77 K (The allowable bulk shear strength parallel to reinforced of GFRP: 30 MPa)	During mechanical testing the ceramic VB found break and brittle at 77 K
Insulation resistance, DC Leakage current, @10 kV, 77 K	254 GΩ 40.3 nA	Insulation resistance: 470 MΩ, Leakage current: 10.5 µA at 5 kV in ceramic VB
Withstand impulse high Voltage Electrical breakdown strength	Upto 1.3 kV Upto 1.7 kV @ 2.60 mA at 0.5 bar helium pressure, 80 K	Paschen test in helium pressure from 10^{-05} to 10^{-02} mbar at 77 K

Performance Tests	**Value Obtained**	**Observations**
Size of VB Different sizes of glass fiber VB fabricated : (Ø 34/41 mm ID/OD, Ø 54/58 mm ID/OD, and Ø 112/141 mm ID/OD	▪ Insulation length: 75 mm ▪ Total length: 160 mm ▪ ID: 112 mm, OD:141 mm ▪ Conductor gap: 30 mm ▪ Radial distance between CICC to VB: 45 mm	▪ Total length :58 mm ▪ ID: 32 & OD: 42 mm ▪ Conductor gap: 5 mm ▪ Radial distance between CICC to VB: 6 mm in ceramic VB
Helium leak tightness	Avg. < 5.0x10^{-09} mbar-l/s	at 0-20 bar helium pressure,4.2 K
Helium leak rate (mbar-l/s) at 300K, 77 K, @ 0-20 bar (g) in 2000 tensile and compression, 100 Nm bending and 100 Nm torsion mechanical loading condition	(i) Tensile :< 5.1x10^{-09} (ii) Bending : < 7.3 x 10^{-09} (iii) Torsion : < 7.5 x 10^{-09}	Max. load 400 Kg, Leak: >10^{-07} mbar-l/s at ~ 600 Kg (Burst test) Max load : 304 Kg Max load: 102 Kg
Neutron radiation withstand of GFRP insulation material	Neutron fluence withstand up to 1.0E+21 n/m^{2} and gamma radiation dose 0.4 MGy	Neutron irradiation experiment in 32 MWt fission reactor, IGCAR, Kalpakkam, India

Mechanical & Electrical Analysis

Mechanical Analysis (Ansys Engineering Software)

(i) Tensile stress analysis (ii) Thermal stress analysis; (iii) Tensile and compressive stress with thermal stress analysis; (iv) Tensile stress, inner pressure, and thermal stress analysis; (v) Bending moment, internal pressure, and thermal stress analysis; (vi) Torsion moment, internal pressure, and thermal stress analysis (vii) Von-Mises stress and Shear stress profile of SS and GFRP section

The boundary condition :

(a) Tensile and compressive force 2000 N in the axial direction (b) temperature from 300 K to 4.2 K (c) Inner pressure: 4 MPa (d) Bending moment: 100 Nm (e) Torsion moment of 100 Nm

Element model and mesh for stress analysis of SS metal and GFRP section

Results:

- Max. shear stress in GFRP section: (i) 13.0 MPa under load 300 K to 4.2 K (ii) 12.3 MPa under loads with 2000 N tensile force and 4 MPa inner pressure from 300 K to 4.2 K

- GFRP section in XY, YZ and ZX direction : (i) 19 MPa, 20.0 MPA & 20.8 MPa under load 100 Nm bending from 300 K to 4.2 K (ii) 22.0 MPa, 23.5 MPa and 22.5 MPa under load 100 Nm torsion moment from 300 K to 4.2 K

- Max. Von Mises stress and shear stress in SS pipe section: 183 MPa and 39 MPa

- According to shear strength of GFRP composite materials 30 MPa, design strength criterion of SS 316L materials 286 MPa, it is evident for VB for SST-1 machine that the optimized insulation structure is acceptable .

Electrical Analysis : (COMSOL Multiphysics)

- Design high voltage to ground: 2 kV
- Designed to withstand maximum voltage: > 5 kV (Max : 2 x V operational + 1 kV)
- Relative permittivity of GFRP : 3 and air and in vacuum: 1.0
- The maximum design electrical field strength of the GFRP insulation materials: not more than 4 kV/mm
- Breakdown strength of GFRP: 20-30 kV/mm (in vacuum) and ~10 kV/mm (in air), factor of safety taken : 5 times

Results

- Maximum electric field at SS metallic tubes arc : 230 V/mm and in the gap is about 500 V/mm.(Gap between high potential and ground potential)
- Electric field strength along the VB : 1.23 kV/mm which is less than safe field strength 2 kV/mm in dry air
- Maximum electric field strength on top of SS electrode : 3.1 kV/mm which is less than 4-6 kV/mm of design value.

Failures and Analysis of Ceramic and Glass Fiber VB

He leak after thermal cycle at 77 K

Ceramic VB failure

- The shorter radial distance between (i) SC CICC to ceramic VB inner surface (ii) high voltage to ground voltage could be the main cause for an electrical incident occurrence.
- The brittle transition failure observed in ceramic material during the repeated thermal cycling at 300 K to77 K & 4.2 K. Helium leakages degrades a vacuum level, which initiates a Paschen event.
- The larger size GFRP VB eliminated the chances of touching SC CICC surface to VB inner metal surface during the magnet charging which cause to electrical incident.
- The inner and outer insulation length were increased that improves the electrical breakdown strength of the VB component.

Technical Challenges and Experience

- The differential thermal contraction variation of glass fiber, epoxy resin, and metal, which induces high radial thermal residual stress in larger VB at low temperatures which is more prone to the development of cracks in the joints.
- To overcome the thermal stress and flexibility issues, cryogenic bellows were developed and assembled with VB.
- Unavailability of a high toughness epoxy resin system for bonding at cryogenic temperatures, the larger diameter (Ø 141 mm) fabrication for assembly requirement, electrical strength of 2 kV, account of induced high thermal radial stress, and ensuring helium leak tightness at 4.2 K temperature.
- Congested and limited space for welding, in-situ insulation work for installation of VB in chamber of current feeder system.
- Testing of larger sizes VB and cryogenic Bellows.

Summary & Conclusion

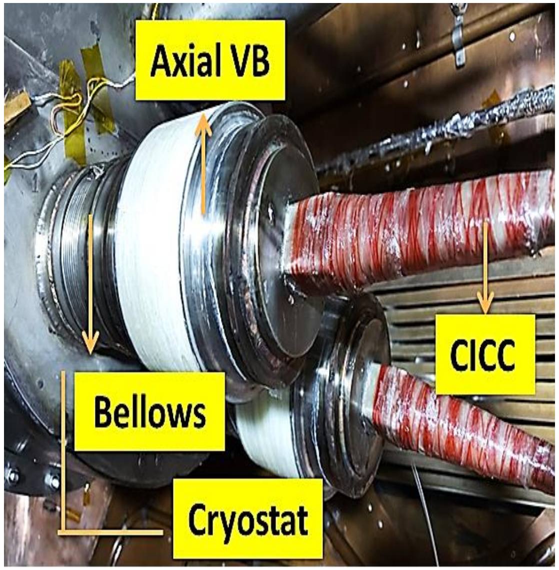
- The epoxy resin joint was fabricated in contrast to the existing metal to ceramic welded joint, which overcomes the issue of failures due to brittle transition after thermal temperature cycles as reported.
- The fractured toughness and flexibility were improved in formulated epoxy resin and the chosen filament winding process which enhances the joint strength at the cryogenic temperature.
- The developed larger size GFRP VB overcomes the electrical breakdown occurrence due to the short gap between conductors (5 mm) and radial distance between bus bars (6 mm) of ceramic VB.
- Developed dissimilar material joints in form of cryo components IB and VB have been validated and working in SST-1 machine.
- The hundreds of joints of different sizes of ½”, ¾”, 1”, and 5” were fabricated and a failure rate of 5% was noticed.
- The development fulfils the existing demand of cryo components requirement in SST-1 machine and future replacement option of installed imported items.

Future Scope and Work

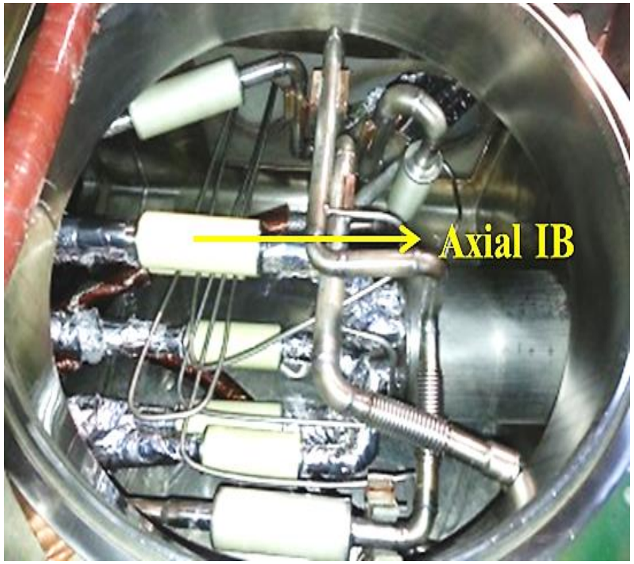
- Dissimilar material joints for space application of aluminium to SS321, similarly titanium to SS321.
- Characterization of insulation material under high neutron fluence and gamma dose of > 1.0E+22 n/m^2 and upto 10 MGy.
- Industrial application of dissimilar material joints for electrical isolation purpose.
- Epoxy based bi-metallic (SS and AL) joints could be an alternative selection or replacement of commercially available explosive, friction, splash welded joints.
- Epoxy based bi-metallic joints for heat exchanger and cryogenic services.
- S-glass fibre and similar basalt fibre glass development work
- Collaboration work and technology transfer to Industries of in-house developed technologies

Dissimilar Material Joints in Applications

In-house fabricated various sizes of dissimilar material joints



In 10 kA superconducting bus-bar current feeder



Polodial field superconducting coil magnet

10 kA current lead outlet

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Published in Fusion Engineering and Design Journal, Volume 199 (2024) 114148
ISSN: 0920-3796, Publisher: Elsevier

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