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In-Vessel Inspection System: Development and Testing activities of high vacuum and temperature technologies for Fusion Remote Handling

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Abbreviation

Abbreviation	Explanation
RH	Remote Handling
IVIS	In-Vessel Inspection System
SST-1	Steady State Superconducting Tokamak
RTD	Resistance Temperature Detector
DOF	Degrees of Freedom
PFCs	Plasma Facing Components
UHV	Ultra-High Vacuum
VDE	Vertical Displacement Events
VV	Vacuum Vessel
FEA	Finite Element Analysis
SS	Stainless Steel
Al	Aluminium
SVC	Storage Vacuum Chamber
D-H	Denavit-Hartenberg
TCP	Tool Centre Point
RHRTD	Remote Handling and Robotics Technology Development Division
VR	Virtual Reality
AIA	Articulated Inspection Arm
JET	Joint European Torus

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Outline

- Introduction
- Challenges in Fusion RH
- Objectives and Requirements
- Design Approach
- Design and Development activities
  - Kinematic assessment
  - Structural integrity
  - Radiation analysis
  - Modal analysis
  - Storage Vacuum Chamber specifications
  - In-Vessel Inspection System specifications
  - Viewing System specifications
  - Fabrication activities
  - VR based control system
- Testing and Validation
  - Joint testing
  - Component testing
  - Integrated testing
  - Operational Demonstration
- Conclusion and Summary.

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Introduction

- A fusion device needs maintenance to be operational
- The severe working conditions causes wear out of the first wall
- Some first wall protection material like beryllium are hazardous for human
- The high neutron energy causes vessel activation and forbids human access in vessel due to high irradiation levels
- The use of tritium imposes severe contamination control and protections

The only way to perform the maintenance of a fusion facility employing hazardous and irradiated materials, is to use remote handling and remote inspection tools.

Challenges in Fusion RH

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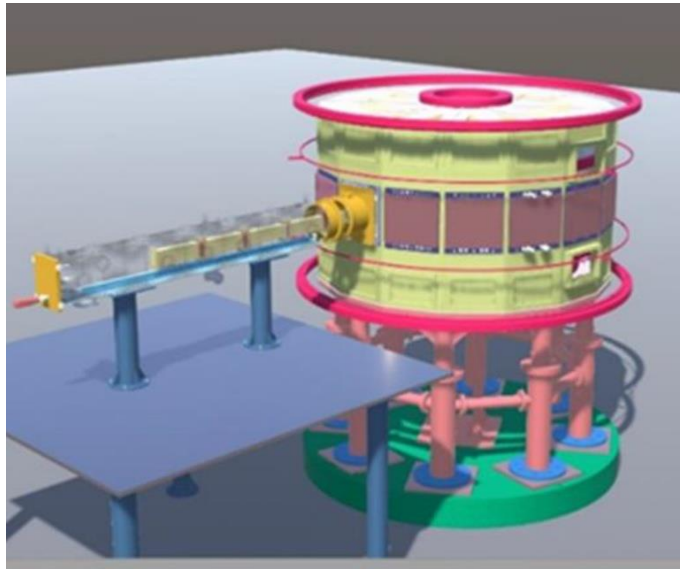
Physical challenges

- ❑ Complex working environment
- ❑ Large and heavy components
- ❑ Limited access through narrow ports
- ❑ Long maintenance and inspection time
- ❑ In-service viewing and inspection

Environmental challenges

- ❑ Ultra High Vacuum
- ❑ High Temperature
- ❑ Activation
- ❑ Contamination (e.g. Beryllium/ CFC Tungsten dust, etc.)

IVIS mounted in SST-1 tokamak port



Objective and Requirements

- Design and develop a RH in-service system for visual **inspection of SST-1 scale PFCs** under **high vacuum and high temperature** in between the plasma shots.
- The **size (link & joints) and reach of the IVIS** are based on the **constraints of** VV port openings and surrounding interfaces.
- **Cantilevered lightweight design.**
- Design of sub-components & accessories for **operational stability in high temperature and vacuum**.
- The system **should not pollute the background UHV condition in the fusion device**.
- **VR based monitoring and remote control.**

FUNCTIONAL SPECIFICATIONS OF IVIS

Parameter	Value
Payload	~1 kg (Camera)
Maximum toroidal reach	±90° (~ 2m)
Ambient Conditions	Vacuum -10^{-8} mbar Baking Temperature (VV) – ~100°C Residual Magnetic Field
Port Configuration	Equatorial
Control System	Robust Control System with VR Interface

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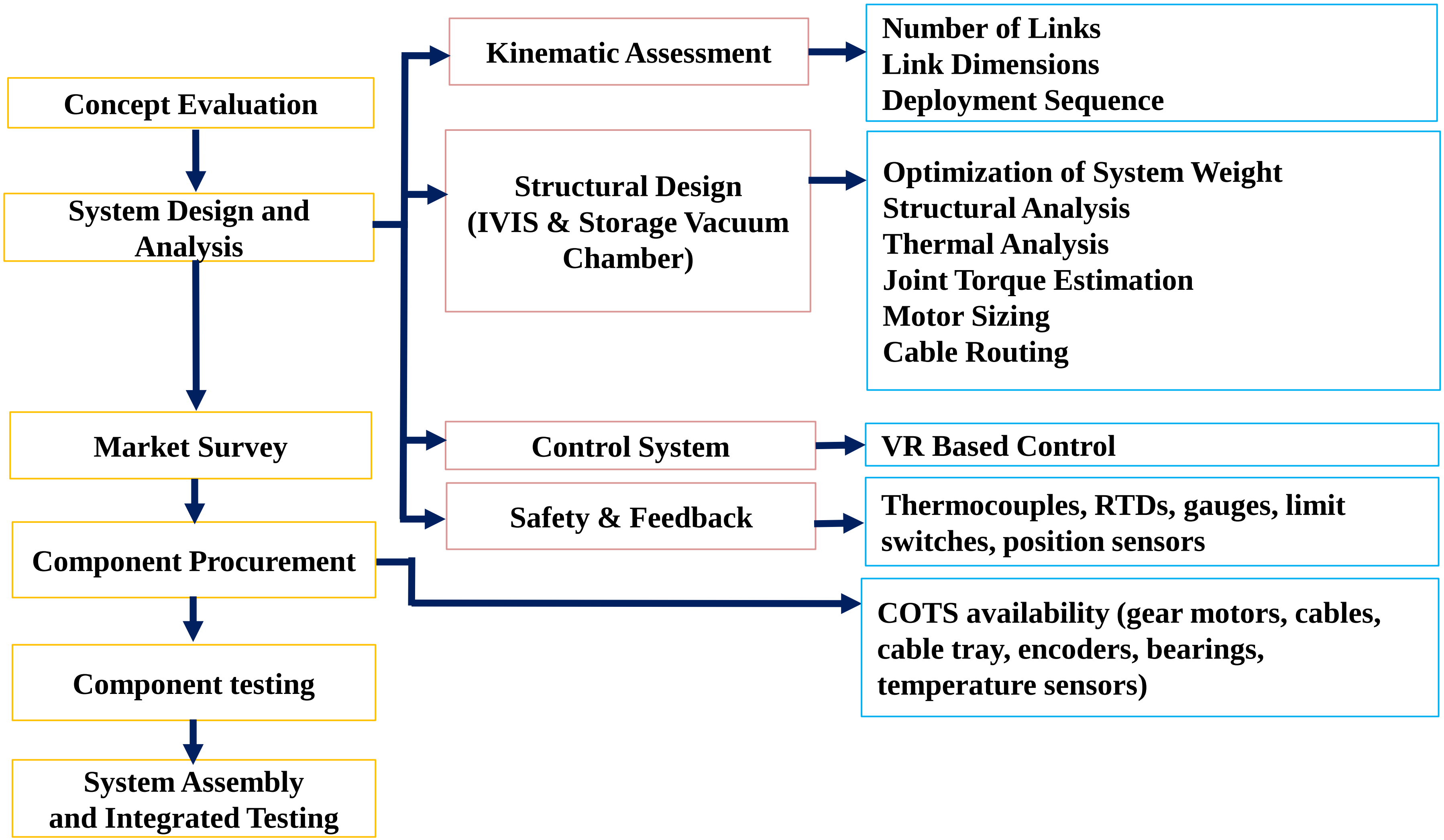
Design approach for IVIS System

Constraints: Tokamak Geometry, ultra high vacuum, high temperature and clash avoidance with sub-systems, non-pollutant



Design Activity
Kinematic Assessment

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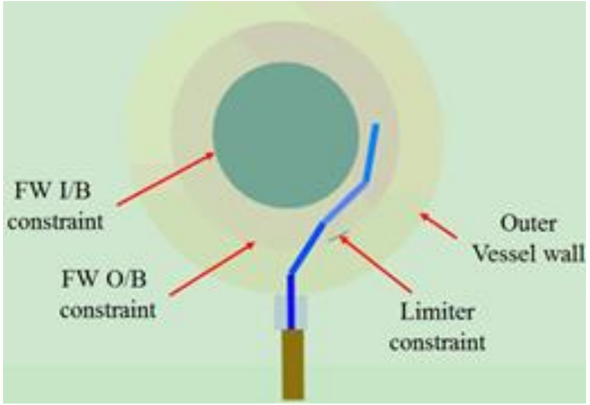
Kinematic study includes the following

- A **maximum reach simulation** for finding the **least possible links** that can be used to reach 90^o within the vacuum vessel.
- Based on the **minimum possible links** and **link lengths**, a simple CAD model is developed.
- Both **steel** and **aluminum** are considered for this arm.

Results of Kinematic Study

- Minimum number of links and link lengths for 90^o deployment with SST-1 scale port and in-vessel constraints
- Optimized Design solution

Kinematic assessment of IVIS



Design Activity
Kinematic Assessment

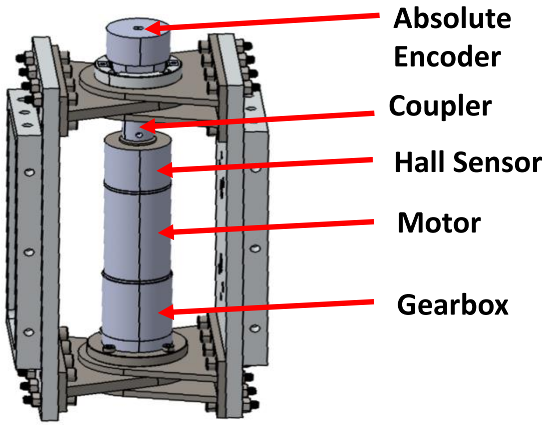
- Based on the **kinematic VR simulation**, **04 rotary links** with maximum **link lengths of 0.7m** (joint to joint) and **01 fixed link** is required for maximum **toroidal reach** of 90° inside the machine.

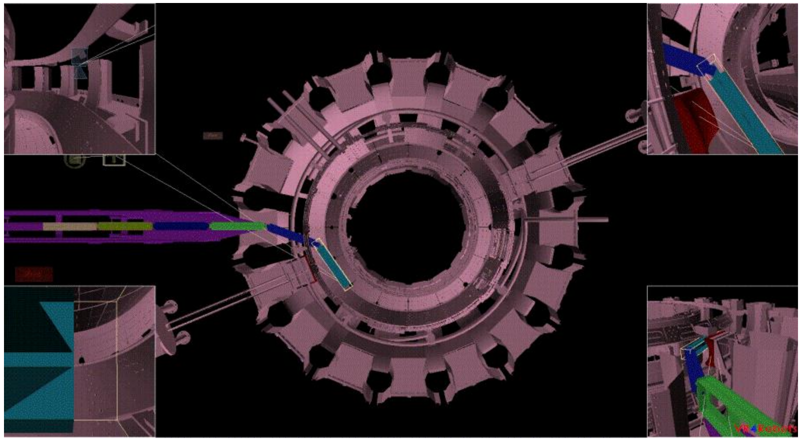
- The required **actuation torque** for the farthest joint is ~ 15Nm, which is estimated based on the **inertial load** of the **links**, **actuator components**, and **payload**.

- To **check the viewing capacity** of IVIS within the machine **while following safe distance** from the vessel wall, a VR simulation was also performed. This simulation asserts the claim of number of links and maximum link lengths.

LENGTH, MASS AND JOINT RANGE OF IVIS LINKS

Body	Link00	Link01	Link02	Link03
Length (mm)	293	425	402	431
Mass (kg)	14.33	4.54	4.07	4.07
Joint Range	~ 3 m	±70°	±70°	±70°





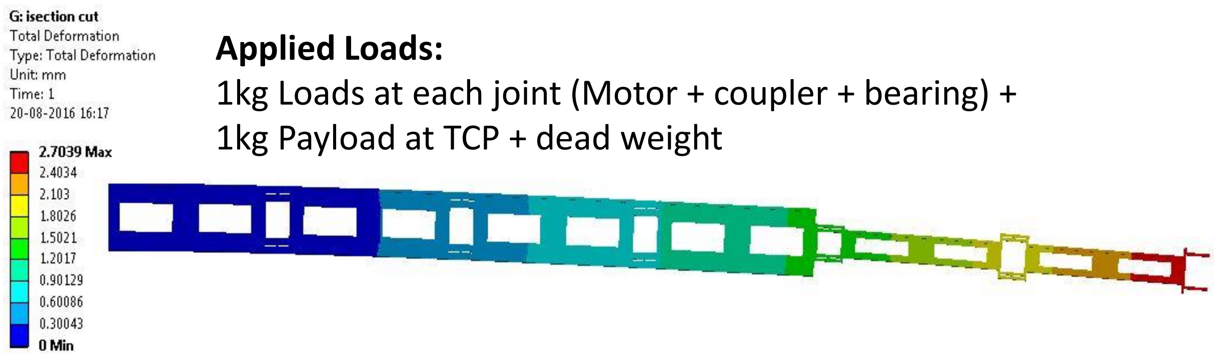
Virtual IVIS model deployed inside SST-1 VV

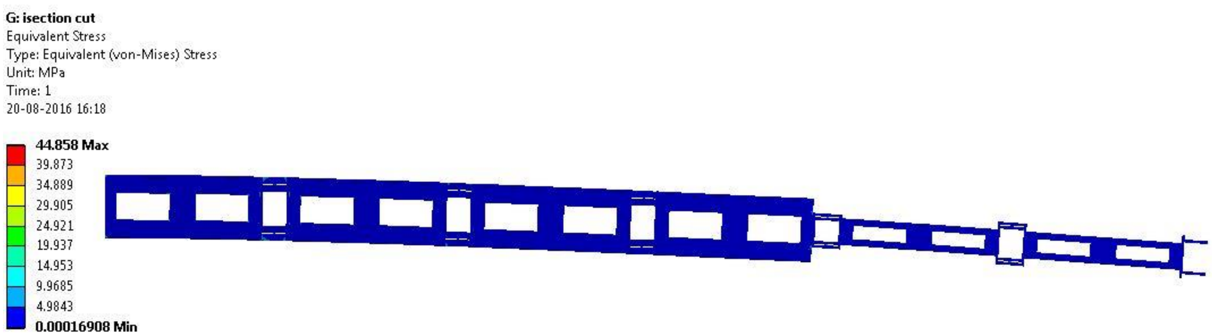
Design Activity

Parametric optimized design - dimensional details

- A parametric simulation approach was utilized to arrive at the final cross section of the manipulator links structure to withstand the gravity effects and payload.

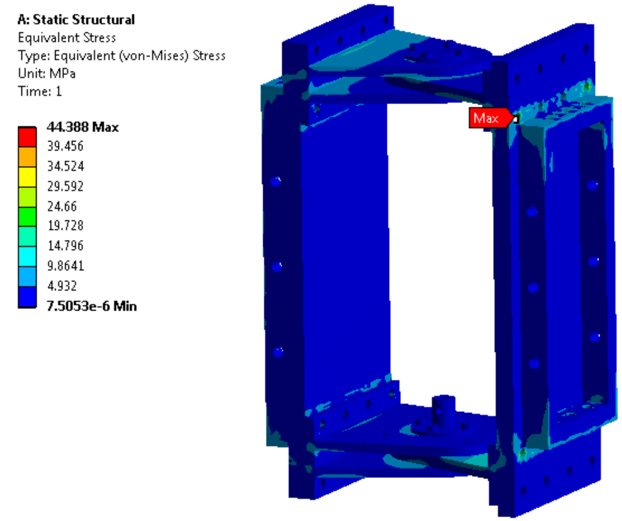
Applied Loads:
1kg Loads at each joint (Motor + coupler + bearing) +
1kg Payload at TCP + dead weight





Conclusion:
Maximum deflection with all aluminum bodies with is <3mm
Maximum stress is 44.858 (eq. stress) << (2/3) of yield stress.

Max. Eq. Stress Plot on Lug Joint



- Final cross sectional dimensions of the scoping studies is tabulated

CROSS-SECTION OUTPUT OF SCOPING STUDIES

Body	Link00	Link01	Link02	Link03
Width x Depth (mm)	90 x 200	90 x 200	80 x 180	80 x 180
Thickness (mm)	5	5	5	5
Length (mm)	640	580	580	580
Material	SS304	Al 6061-T6	Al 6061-T6	Al 6061-T6

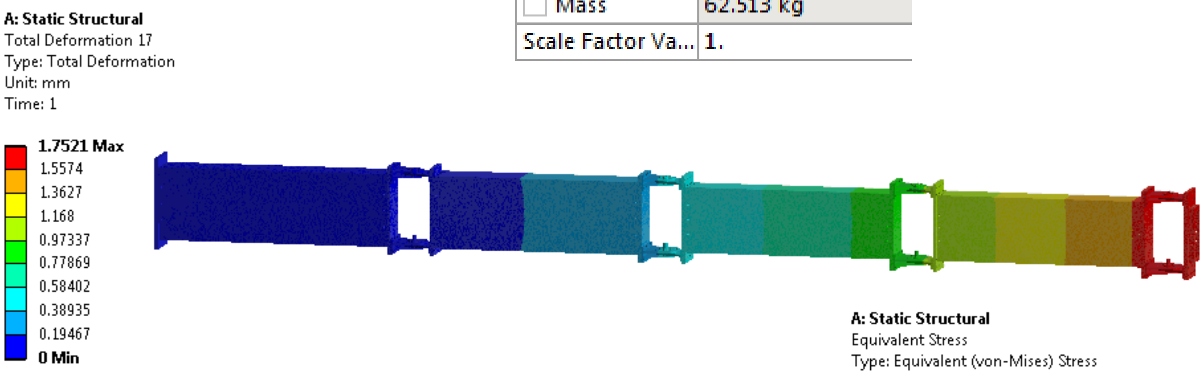
Design Activity

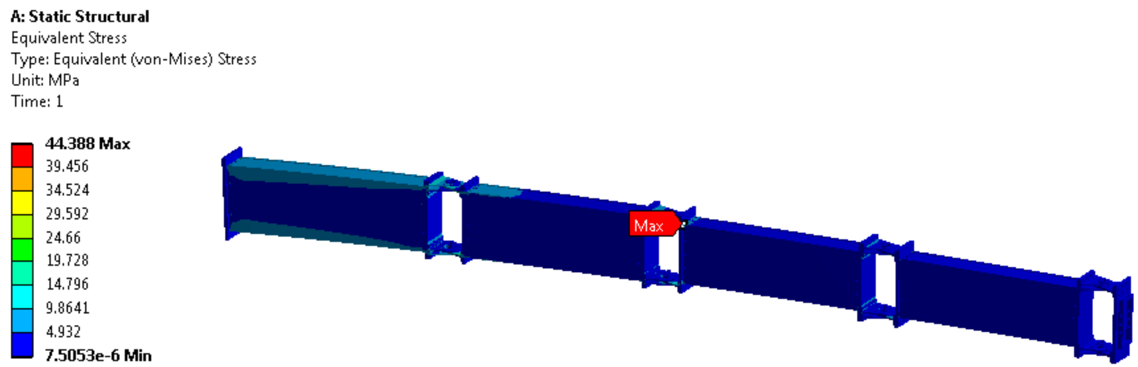
Parametric optimized design - dimensional details

Applied Loads:

1kg Loads at each joint (Motor + coupler + bearing) + 1kg Payload at TCP + dead weight

Properties	
Volume	1.3878e+007 mm³
Mass	62.513 kg
Scale Factor Va...	1.





Results Summary:

Maximum deflection with all aluminum bodies with is <3mm

Maximum stress is 44.388 (Eq. stress) << (2/3) of Yield stress.

Design Activity

Thermal Analysis

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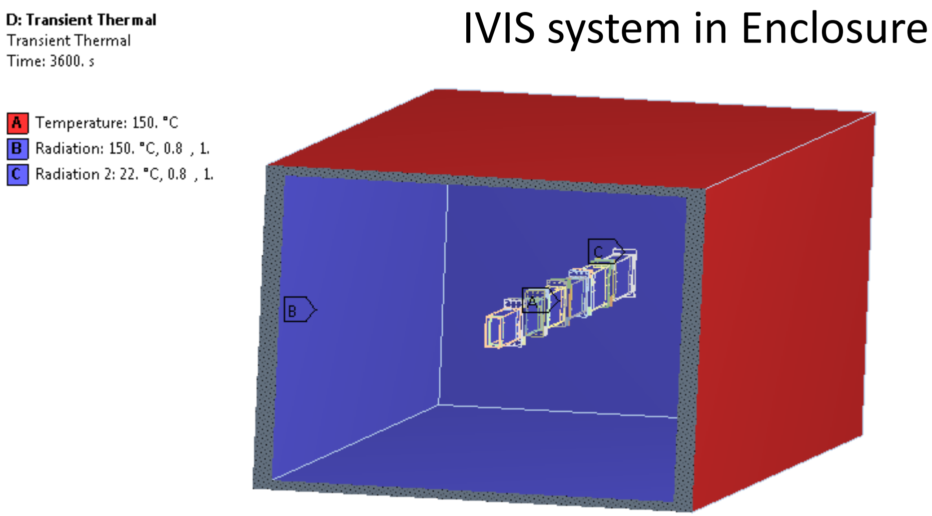
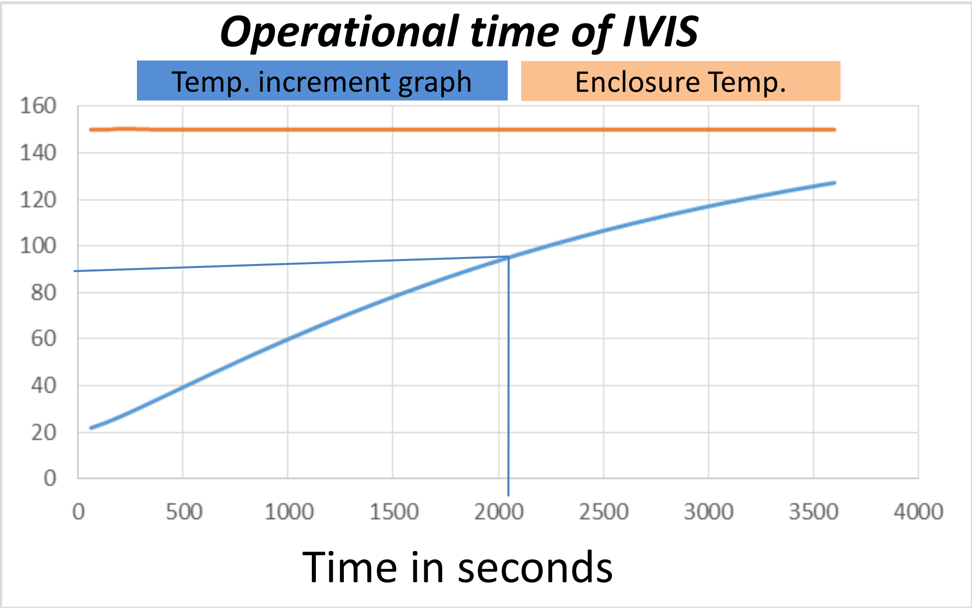




Radiation analysis was performed with initial temperature of IVIS system at 22°C, enclosure temperature at 150°C and emissivity as 0.8 to check the in-vessel inspection time of the IVIS arm to match the performances compatible with high temperature and UHV.

Results Summary:

Total time for one viewing cycle of IVIS is 2000 seconds.

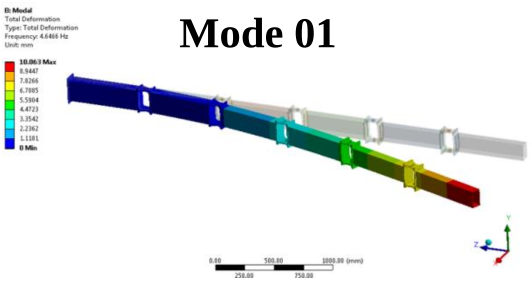
Design Activity

Modal Analysis

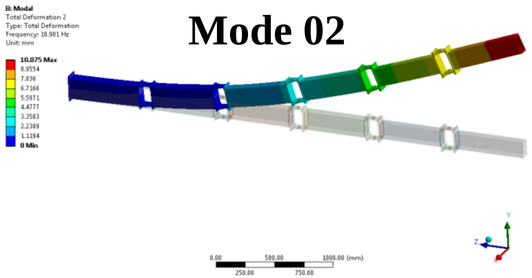
FREQUENCY AND PARTICIPATION FACTOR ESTIMATES

MODE SHAPES

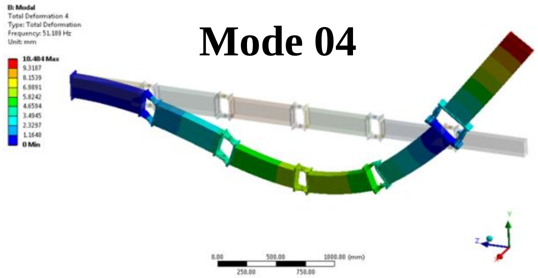
Mode 01



Mode 02



Mode 04



***** PARTICIPATION FACTOR CALCULATION ***** X DIRECTION

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	CUMULATIVE MASS FRACTION	RATIO EFF.MASS TO TOTAL MASS
1	4.64662	0.21521	0.16308	1.000000	0.265954E-01	0.613395	0.432349
2	10.9807	0.91069E-01	0.32198E-05	0.000020	0.103669E-10	0.613395	0.168530E-09
3	24.3829	0.41012E-01	-0.97625E-01	0.598626	0.953055E-02	0.833208	0.154934
4	51.1891	0.19535E-01	-0.17253E-04	0.000106	0.297650E-09	0.833208	0.483877E-08
5	60.9395	0.16410E-01	0.66922E-01	0.410359	0.447850E-02	0.936500	0.728051E-01
6	109.487	0.91335E-02	-0.52471E-01	0.321748	0.275321E-02	1.00000	0.447577E-01
sum					0.433576E-01		0.704846

***** PARTICIPATION FACTOR CALCULATION ***** Y DIRECTION

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	CUMULATIVE MASS FRACTION	RATIO EFF.MASS TO TOTAL MASS
1	4.64662	0.21521	-0.33364E-05	0.000020	0.111315E-10	0.295069E-09	0.180960E-09
2	10.9807	0.91069E-01	0.16435	1.000000	0.270105E-01	0.715985	0.439099
3	24.3829	0.41012E-01	0.53193E-05	0.000032	0.282947E-10	0.715985	0.459975E-09
4	51.1891	0.19535E-01	-0.10351	0.629823	0.107145E-01	1.00000	0.174181
5	60.9395	0.16410E-01	-0.18902E-04	0.000115	0.357283E-09	1.00000	0.580819E-08
6	109.487	0.91335E-02	0.12737E-04	0.000077	0.162219E-09	1.00000	0.263713E-08
sum					0.377250E-01		0.613280

***** PARTICIPATION FACTOR CALCULATION ***** Z DIRECTION

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	CUMULATIVE MASS FRACTION	RATIO EFF.MASS TO TOTAL MASS
1	4.64662	0.21521	0.52690E-06	0.000685	0.277618E-12	0.425997E-06	0.451312E-11
2	10.9807	0.91069E-01	-0.76901E-03	1.000000	0.591375E-06	0.907448	0.961373E-05
3	24.3829	0.41012E-01	0.23056E-05	0.002998	0.531596E-11	0.907456	0.864192E-10
4	51.1891	0.19535E-01	-0.24550E-03	0.319246	0.602718E-07	0.999941	0.979812E-06
5	60.9395	0.16410E-01	0.36838E-06	0.000479	0.135704E-12	0.999941	0.220608E-11
6	109.487	0.91335E-02	0.61828E-05	0.008040	0.382266E-10	1.00000	0.621433E-09
sum					0.651691E-06		0.105943E-04

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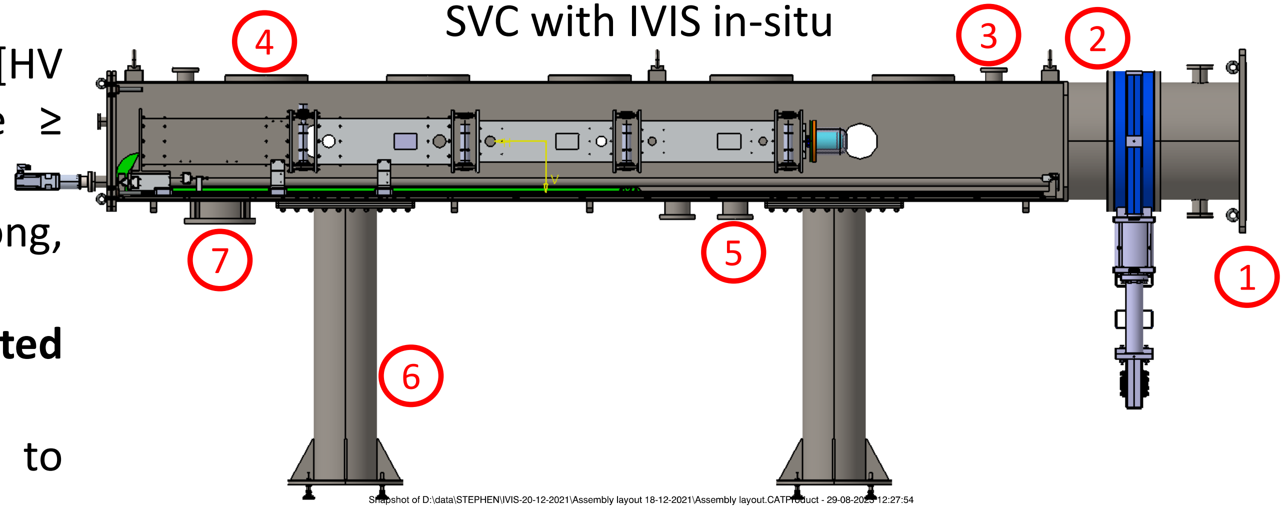
Design and Development

Storage Vacuum Chamber (SVC)

- **Conditioning** and **stowing** the IVIS [HV < 8x10^{-8} mbar and temperature ≥ 90°C]
- **Stainless steel enclosure** [5m long, 1.5m height, ~2 tons]
- Two **electrically** & **thermally insulated** support frames
- **Quick connection/disconnection** to the vessel on dedicated port
- ISO 500 F UHV **gate valve system** to **isolate SVC and vacuum vessel**
- Bottom mounted **linear guide rails** - to **maintain the straightness** and positioning **accuracy during translation**.
- SVC consists of **vacuum sealing flange** for **interface with VV port flange**, and includes vacuum tight electrical feed-through for IVIS cabling inside the UHV environment.

SVC with IVIS in-situ



Vacuum storage chamber to stow the IVIS arm, sub-components nomenclature: 1) Rectangular flange for interface with SST-1 radial equatorial port, 2) 500 CF Rotatable flange, 3) 63 CF port for mounting diagnostic accessories, 4) 300 CF Maintenance port, 5) 150 CF port for mounting actuator control & sensors, 6) Storage Vacuum Chamber Support, 7) 250 CF Gate Valve interface with TMP and backing pump

Design and Development

In-Vessel Inspection System (IVIS)

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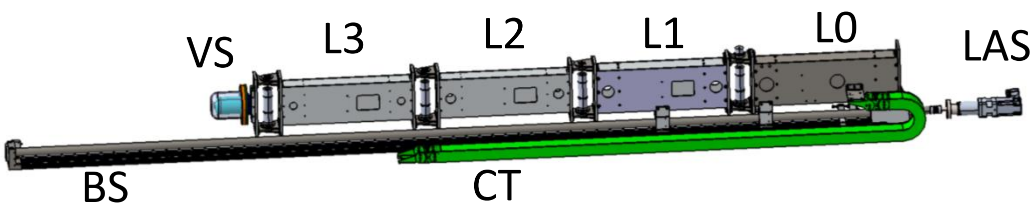
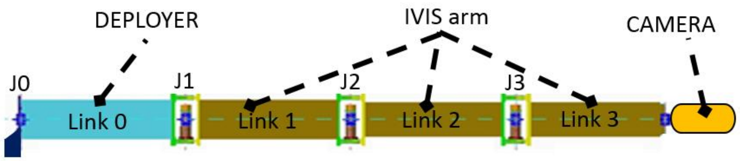
- **In-Service inspection** inside tokamak vacuum vessel
- **5-DOF articulated system** with up to **~1kg** camera **payload** at **03m** maximum **reach**
- **Working environment**: **UHV** – 8x10^{-8} mbar, **Vessel Temperature: ~ 100°C**
- Joint Axes: **04 Revolute joints** and **01 translation stage**
- **Virtual Reality based control** and **monitoring remotely** over large distances using a high speed network
- **Position Repeatability: ±2 mm** for 3m reach



L0 – Link 00, L1 – Link 01, L2 – Link 02, L3 – Link 03, VS – Viewing System, BS – Ball Screw, CT – Cable Tray, LAS – Linear Actuation System



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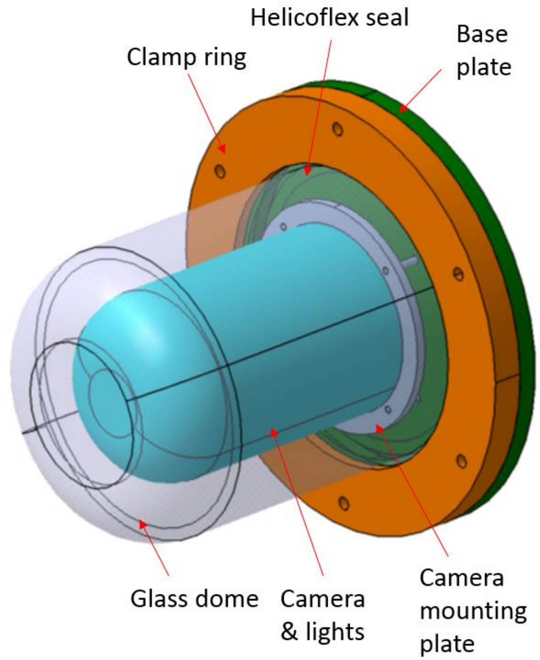
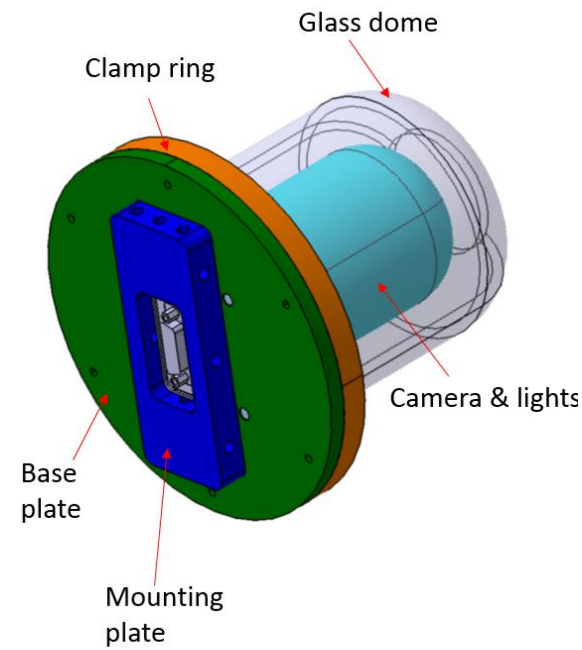
Design and Development

Viewing System

- **UHV compatible** viewing system
- Optical camera **protected** inside **borosilicate glass dome**
- Zoom lens and **02 degree of freedom** (pan and ±90° tilt) **remote controlled**
- ±70° **actuated yaw joint**
- **Operation temperature** for the camera is 70° C
- **UHV compatible** SUB – D weldable **connector feedthroughs**

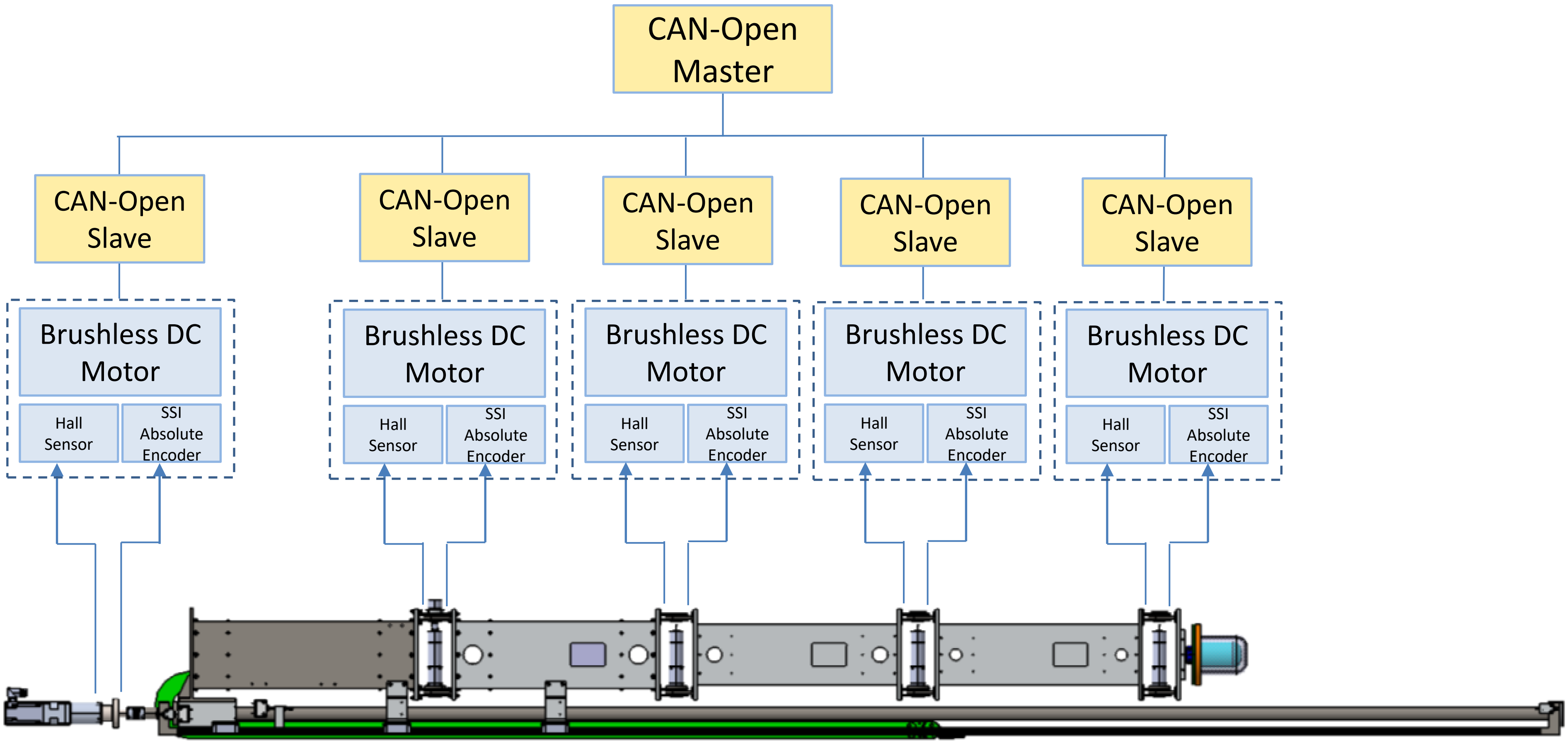
UHV compatible Viewing System





Control System

- Built on CAN-Open network architecture and include high precision servo drives with position feedback from hall sensors at motors and absolute encoders at joints.
- For system safety, various sensors & actuators such as RTDs, thermocouples, limit switches, position sensors have been mounted inside the IVIS system



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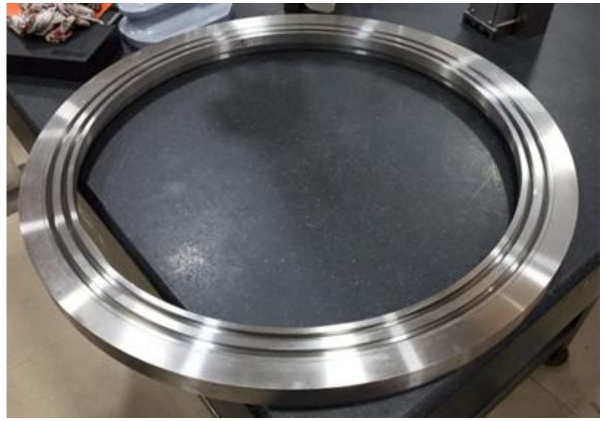
Fabrication Activity

Sub-Components

IVIS Flanges

500 CF rotatable flange



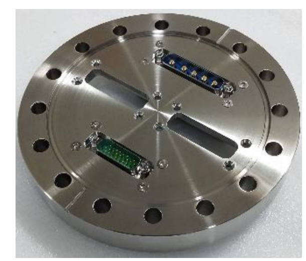
Cable tray

IVIS Link

Ball Screw (04 meters)

IVIS Male and Female Lugs

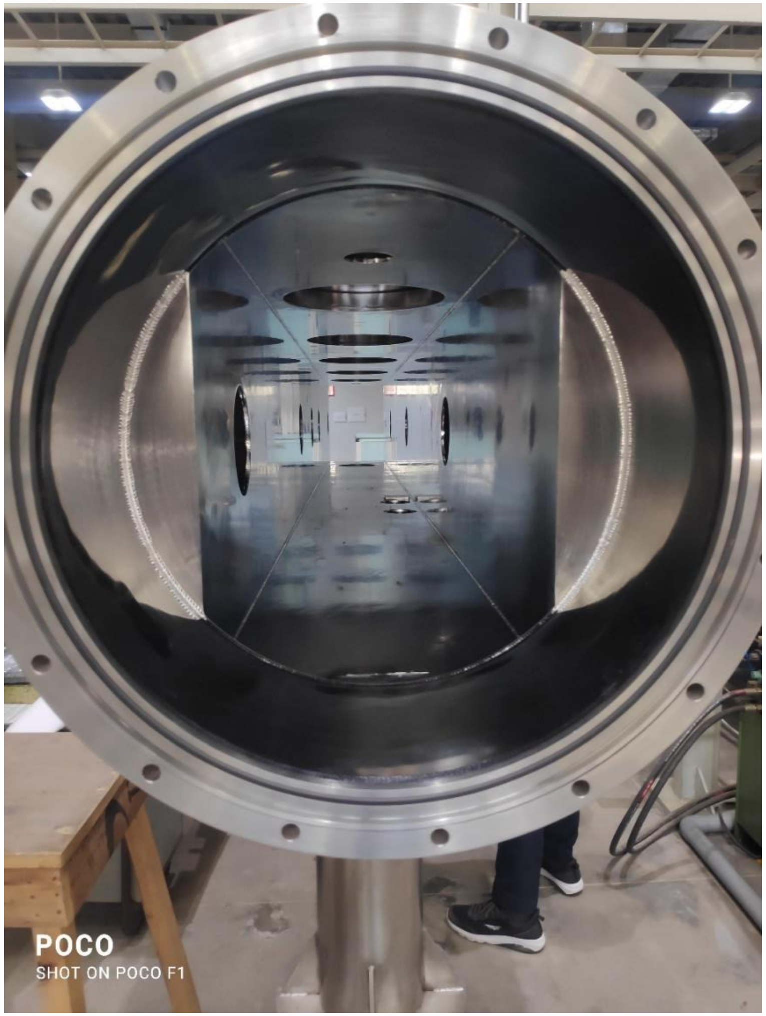
IVIS Electrical Feedthroughs



Fabrication Activity

Sub-Components

Thorough Cleaning and preparation of SVC for integration of IVIS arm



~ 5 m SS SVC

Internal View of SVC

Fabrication and Assembly Activity

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Sub-Components

04 m SS Ball Screw assembly

04 m IVIS am

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Joint Testing

IVIS Joint Prototype

Vacuum Set-up for testing of UHV compatible IVIS joint

MATERIAL SELECTED FOR JOINT COMPONENTS

Name of the Component	Material
Lug	SS304L
Flange	Aluminium 6061-T6
Bushing	Aluminium Bronze
Bearing outer race	Stainless Steel

Components Testing

All components which were integrated with IVIS system was subjected to outgassing measurement to qualify the vacuum non-pollutant criteria and the outgassing measurement values are tabulated.

Components and its outgassing rate

Sr. #	Components	Surface Area (cm^2)	Outgassing Rate (mbar.litre/sec/cm^2)
1	UHV compatible BLDC motors with integrated gearbox	245	6.35×10^{-9}
2	UHV compatible Absolute Encoders	55	8.52×10^{-7}
3	UHV compatible kapton insulated cable	100 meters	1.48×10^{-9} mbar.litre/sec/m
4	Storage Vacuum Chamber material SS304	109800	4.69×10^{-10}
5	IVIS link material Al6061	60000	5.24×10^{-10}

Hybrid bearings

BLDC Motor

Absolute Encoder

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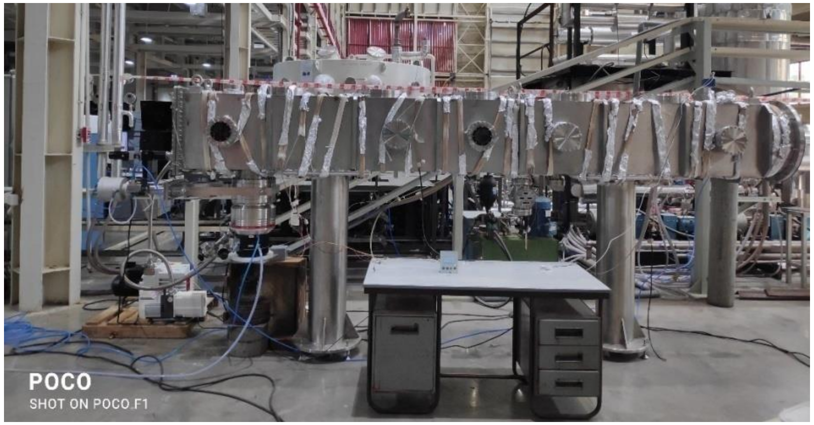
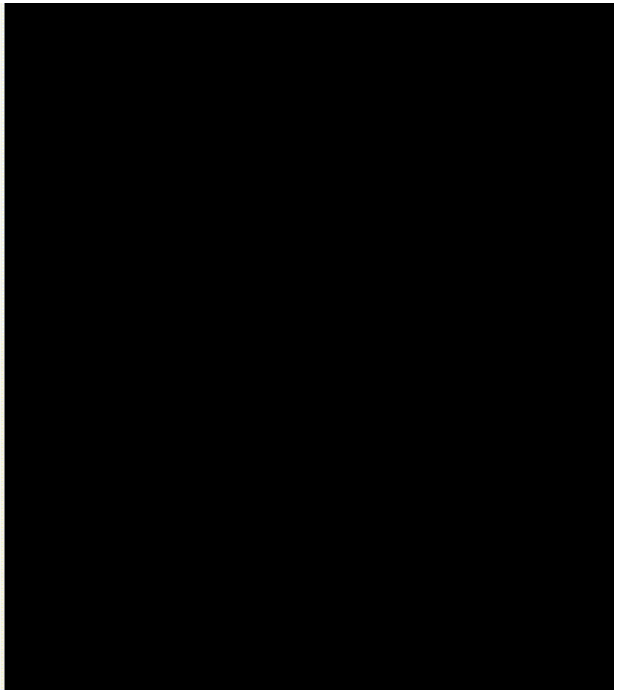
Integrated System & Operational Testing

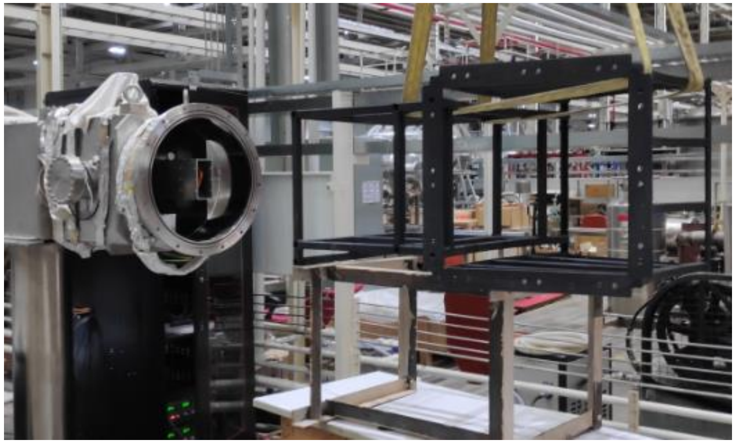


Evacuation of Storage Vacuum Chamber (SVC) with in-situ IVIS) arm with vacuum and baking arrangement

IVIS deployed to maximum reach in atmosphere



Operational Demonstration



IVIS deployed to maximum reach in atmosphere inside kinematic testing frame

Conclusion and Summary

- 5-DOF (04 Revolute joints and 01 translation stage) cantilevered articulated system with up to ~1kg camera payload at ~03 m maximum reach – developed and functionality demonstrated.
- IVIS system working environment: HV – $8x10^{-8}$ mbar, high temperature - ~ 90°C – developed, validated and functionality demonstrated.
- Position Repeatability – ±2 mm for maximum reach – achieved.
- Remote Control and monitoring using Virtual Reality based control system over a high speed network – achieved.

THANK YOU FOR THE ATTENTION
ANY QUESTIONS