IN-VESSEL INSPECTION SYSTEM: DESIGN PROGRESS OF HIGH VACUUM AND TEMPERATURE COMPATIBLE REMOTE HANDLING FOR FUSION PURPOSES

MANOAHSTEPHEN M.[1, a], KRISHAN KUMAR GOTEWAL[1], PRAMIT DUTTA[1], NAVEEN RASTOGI[1], RAVI RANJAN KUMAR[1], JIGNESH CHAUHAN[1]
[1]Institute for Plasma Research (IPR),
Gandhinagar, 382428 Gujarat, India
[a]Email: manoah@ipr.res.in

Abstract

The plasma facing components (PFCs) in a tokamak are subjected to high heat flux and high temperature during plasma operation, which causes erosion of the first wall. There is also hot spot formation on the PFC due to physical phenomenon like thermal electron emission. In addition to fore-mentioned phenomenon, the events such as Edge Localized Mode (ELM), vertical displacement event (VDE) are serious concern for the fatigue damage of the PFCs. Therefore, health monitoring of the PFCs is an essential requirement in any tokamak, which is met by periodic inspection of the PFCs. The periodic inspection can be performed during the tokamak shutdown period or during plasma operation. The latter is most desirable as it allows quick and frequent in-service inspection of the PFCs between the plasma shots without breaking the vacuum.

The work presented in this paper covers the conceptual design of In-Vessel Inspection System (IVIS) and storage chamber to carry out in-service visual inspection of SST-1 like tokamak under vacuum in between the plasma shots. The designed IVIS manipulator is ~2m long with 04- Degrees of Freedom (DOF), comprising of three rotary joints and one linear motion for deployment within the tokamak. The manipulator is designed to handle a cantilevered payload of ~1kg with a positional accuracy of <2mm. IVIS is initially stowed in a 4m long Ultra-High Vacuum (UHV) storage chamber isolated from the VV by an UHV gate valve. During (one quarter i.e. + 90°) viewing, the gate valve will open so that IVIS can be deployed inside the VV, complete the viewing procedure and return back to its initial position outside the VV. Issues like choices of the structural materials to minimize the out-gassing under vacuum and high temperature during conditioning are discussed with feasible solutions. Improvements to enhance IVIS operation under temperature and vacuum conditions for SST-1 like machine are reviewed. Results for theoretical calculations, kinematic and structural integrity analyses are presented in detail along with ways to optimize the design.

1. INTRODUCTION

The In-Vessel Inspection System (IVIS) allows for in-vessel inspection of plasma-facing components to look for possible damage caused during plasma operations at temperature (~100ºC) and without breaking the vacuum (~1x10^-7 mbar). The IVIS unit comprises a viewing/metrology probe or camera mounted on a deployment arm inserted into the SST-1 scale plasma chamber through the equatorial port. Whilst not in operation IVIS unit shall be housed within a vacuum storage chamber mounted at the vacuum vessel port extension. The IVIS has radial navigation for guiding the IVIS from its storage unit to its in-vessel positions.

K. Ioki, et al. [1] have presented the importance, preliminary definitions and conceptual designs of in-service inspection and instrumentation for the safe operation of the ITER vacuum vessel. L. Gargiulo, P. Bayetti, V. Bruno, et al. [2] and Y. Perrot, L. Gargiulo, M. Houry, et al. [3]have presented the importance of long reach multi-link robot equipped with various diagnostics for mini-invasive and closed inspection of Tore-Supra vessel under UHV conditions and hazardous nuclear environment. Shi S S, Song Y T, Cheng Y, et al.[4], [5] have presented the conceptual design progress for EAST articulated maintenance arm (EAMA) and cask system to stow EAMA for the purpose of remote inspection and simple maintenance operations in EAST vacuum vessel during physical experiments without breaking the ultra-high vacuum condition. ManoahStephen M., et al.[6] have presented the conceptual design and structural reinforcements of sub-components of ITER Multi-Purpose Deployer (MPD) to verify the structural integrity of the MPD system, and to provide reaction forces to the interfacing systems such as vacuum vessel and cask based on static structural, modal and frequency response spectrum analyses (various seismic events) performed.

This paper presents in a first part the IVIS system, with its conceptual design, the kinematics of the robot and the selection of relevant technologies for operations at temperature (~100ºC) and without breaking the UHV (~1x10^-7 mbar). Section 05 about the structural optimization and reinforcement of machine elements and results for the design of IVIS taking gravity loads due to self-weight and payload into consideration. An iterative methodology for analyses and design updates was used to improve the structural behavior of the realistic conceptual design of the equipment that fit the requirements of inspection operation inside the SST-1 toroidal chamber.

2. KINEMATIC ASSESSMENT OF IVIS

The main scope of this R&D program is to conduct the feasibility study for the design of an in-vessel remote handling inspection using a long reach, limited payload carrier (~1 kg) that penetrates the SST-1 like toroidal chamber through the equatorial port. This device is dedicated to close inspection of the plasma facing components (PFCs). The architecture of IVIS manipulator is chosen keeping in mind high mobility in a constrained design envelope. Kinematic assessment as shown in Fig. 1 refers to arriving at the structural configuration of the system that can meet the required functional specification as shown in Table 1.

TABLE 1. FUNCTIONAL SPECIFICATIONS OF IVIS.

Parameter	Value
Payload	1 kg (Camera)
Maximum toroidal reach	±90° (~ 2m)
Ambient Conditions	Vacuum -10^{-7} mbar Baking Temperature (VV) – ~100°C Magnetic Field – 10 Gauss
Port Configuration	Equatorial
Control System	Robust Control System with VR Interface

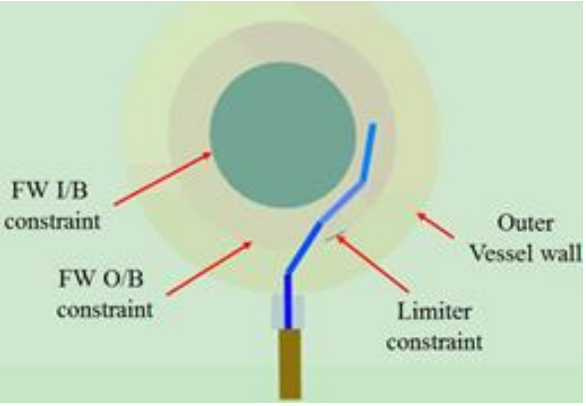

FIG. 1. Kinematic assessment of IVIS

The IVIS is expected to enter the SST-1 machine from an equatorial port with available cross-section of 600mm x 380 mm and poloidal opening of 322 mm between the outer passive stabilisers as shown in Fig. 2 and traverse inside the vessel ±90° toroidally. The number of links, their lengths, and their strokes have been determined by performing kinematic simulations in virtual reality model. Based on the kinematic VR simulation, it was found that a total of 03 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 SST-1 machine. The required actuation torque for the farthest joint is ~ 15Nm, which is estimated based on the inertial load of the links and actuator components, and payload with an overload factor of 1.5. Table 2 gives the details of length, mass and joint range of each IVIS links.

TABLE 2. LENGTH, MASS AND JOINT RANGE OF IVIS

Body	Link00	Link01	Link02	Link03
Length (mm)	293	425	402	431
Mass (kg)	14.33	4.54	4.07	4.07
Joint Range	~ 4 m	±90°	±90°	±90°

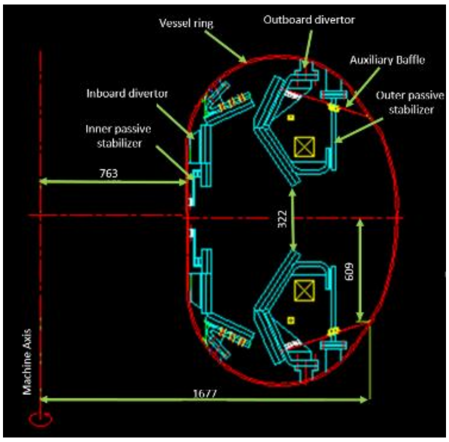

FIG. 2. Section view of SST-1 Vessel

3. CONCEPTUAL DESIGN OF IVIS AND STORAGE VACUUM CHAMBER

As shown in Fig. 3, In-Vessel Inspection System (IVIS) mainly consists of one link, known as deployer, which provides linear motion, 03- DOF robot arm, articulated links which provide rotary motion and storage vacuum chamber with several condition maintaining systems. IVIS can handle cantilevered payload of ~1kg with a positional accuracy of <2mm. IVIS is ~2m long system which is initially stowed in a 4m long UHV storage chamber isolated from the VV by an ISO 500 UHV gate valve. During one quarter (i.e. ±90°) viewing, the gate valve will open so that the RH equipment can be deployed inside the VV, complete the viewing procedure and return back to its initial position outside the VV. To check the viewing capacity of the system within the machine while following safe distance from the vessel wall, a VR simulation was also performed see Fig.04.

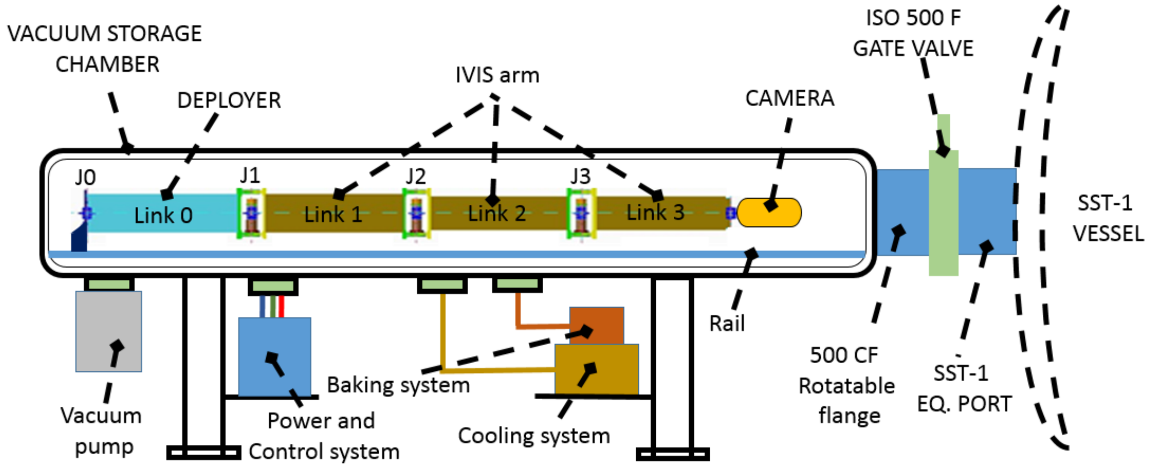

FIG. 3. Overall systematic of IVIS System

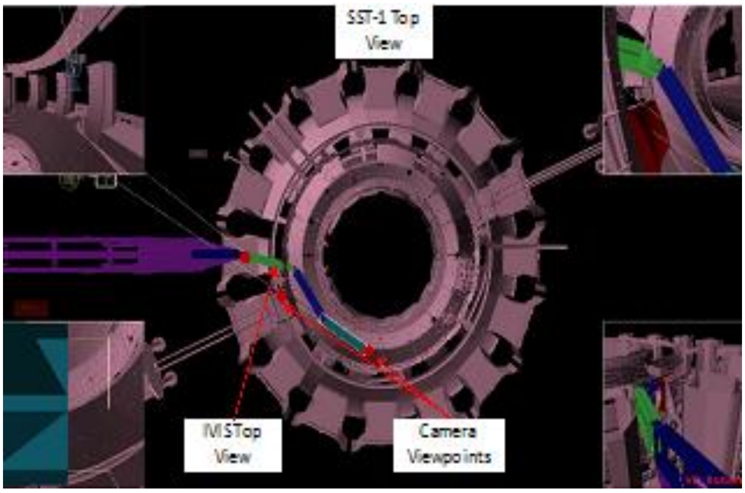

FIG. 4. Virtual IVIS model deployed inside SST-1 VV

The storage vacuum chamber is about 4 m in length and 2.5 m in height, mostly made of SS 304L. Main body structure consists of rectangular vessel with stiffeners, supports, UHV gate valves, vacuum end flanges, linear guide rail, etc. as shown in Fig. 04. The sealed storage chamber is a single walled stiffened boxed structure with numerous holes. Several standard flanges (DN300, DN250, DN150, DN100, DN63 and DN40) are connected around the vessel as the interfaces for turbo molecular pumping (TMP), wiring, positioning and observation. Linear guide rails are mounted on the base plate of the chamber, in order to guarantee the straightness and positioning accuracy of guide rail. The IVIS storage vacuum chamber comprises of a vacuum sealing flange, which mates directly with the vacuum vessel port flange, and includes vacuum tight feed-through for IVIS systems controls and positioning. Table 3 gives details of the parameters used to arrive at the joint torque requirements. Torque requirement at each joint is tabulated in Table 4.

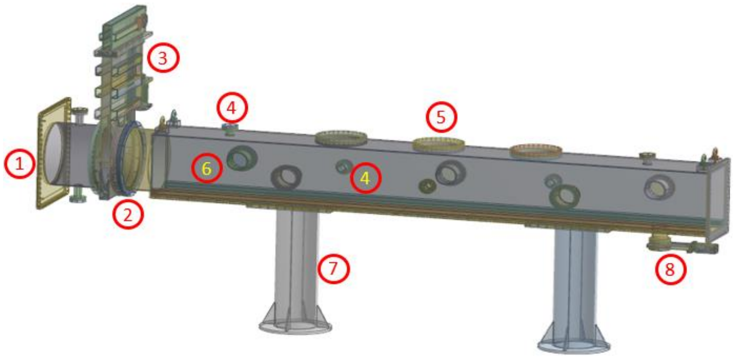

FIG. 4. Vacuum storage chamber to stow the IVIS arm, sub-components nomenclature: 1) Rectangular flange for interface with SST-1 radial equatorial port, 2) 500 CF Rotatable flange, 3) ISO 500 F Gate Valve 4) 63 CF port for mounting diagnostic accessories, 5) 300 CF Maintenance port, 6) 150 CF port for mounting diagnostic accessories, 7) Vacuum Storage Chamber Support and 8) 250 CF Gate Valve interface with TMP and backing pump.

The components in the robotic manipulators can be divided into four groups:

- Structural components, namely the parts that are supporting the forces.
- Actuation components responsible for the movement of the robotic manipulator such as motors and their transmissions devices.
- Sensing components, for information feedback to the robot control and the supervision system.
- Information processing units and information transfer components.

TABLE 3. PARAMETERS REQUIRED FOR JOINT TORQUE ESTIMATION

Parameters	Value	Logic/Reasoning
Payload Weight (kg)	1	Camera assembly weight
Payload length (m)	0.1	Camera assembly length
Alpha (rad/sec^2)	0.02	Standard angular acceleration
TCP linear speed (m/s)	0.01	Standard linear speed for slow robotic systems
Standard Earth Gravity (m/s^2)	9.81	
Coefficient of friction	0.2	Based on selection of bearing components
Bearing Inner Diameter (m)	0.02	Min. length based on typical motor shaft diameter
Vertical Distance b/w bearing (m)	0.25	*Based on motor specifications*
Motor + Gear Box Weight (kg)	1	Based on motor specifications

To calculate the total torque requirement of each joint, the following are used:

- I*alpha is the torque load on each joint due to inertia of the systems in front of the joint
- Friction Torque is the torque load on each joint due to the bearing friction force
- Total Torque = Friction Torque + I*alpha
- Net Torque = Total torque * overload factor (1.5)

TABLE 4. TOTAL TORQUE REQUIREMENT AT EACH JOINT OF IVIS

Joint	Moment on Joint	Force	Friction Torque	Total Torque	Overload factor	Net Torque on Motor
J03	168.2 Nm	672.6 N	4.0 Nm	4.1 Nm	1.5	6.2 Nm
J02	300.4 Nm	1201.5 N	7.2 Nm	7.4 Nm	1.5	11.1 Nm
J01	431.3 Nm	1725.2 N	10.3 Nm	10.7 Nm	1.5	15.4 Nm

The DH parameters of the IVIS arm is given in Table 5.

TABLE 5. DH PARAMETERS OF IVIS ARM.

Joint	Joint Type	α_i(Deg.)	a_i(m)	d_i(m)	θ_i(Deg.)
J0	Prismatic	90	0	$variable$	0
J1	Revolute	0	0.7	0	$variable$
J2	Revolute	0	0.7	0	$variable$
J3	Revolute	0	0.7	0	$variable$

The transformation matrix linking the end-effector of IVIS to the base of the linear guide is given by (1).

$$T_5^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Once the system has reached the desired toroidal location at a macro level, visual servoing will correctly align the end effector along a tile or in-vessel component. The D-H parameters for the IVIS robotic arm are used to develop a C++ class. This class is used to define the robot and initiate it for simulation. The class can be further used to implement with the actual hardware setup.

4. VACUUM AND TEMPERATURE SELECTED TECHNOLOGIES

A feasibility assessment of suitable technologies to operate the IVIS under the SST-1 like conditions of vacuum and temperature was performed. Robotics components should sustain ~100ºC during VV inspection and UHV (~1x10-7 mbar) for its conditioning prior to entering the VV. Limits on out-gassing inside the VV impose serious constraints for the design (e.g. on material, on joints design, actuators and cables). This assessment was carried out through close collaboration and knowledge sharing involving Vacuum Engineering Services Division. First design of lubricant free joints is based on incorporation of MoS_2 bushes instead of bearings in IVIS joints. The COTS availability (actuators, reducers and bearings) to match the performances compatible with high temperature, ultra-high vacuum requirements and to overcome pollution issues of the tokamak environment. The rotation axes are always in the horizontal plane. This configuration limits the torque required from the yaw actuator due to the absence of gravitational torques. DC off-the-shelf motors and their standard attached gear-boxes both hardened to the required high temperature operation and vacuum conditions are selected. At this step it has been identified the need for developments of specific new technologies in particular for bearings, viewing systems and electronics.

5. STRUCTURAL ANS THERMAL ANALYSES OF IVIS

The software used for CAD design was CATIA V5. Moreover, a parametric simulation approach using ANSYS Workbench has been adopted to arrive at the final cross section of the manipulator links structure to withstand the gravity effects and payload. Final cross sectional dimensions of the scoping studies is tabulated in Table 6.

TABLE 6. CROSS-SECTION OUTPUT OF SCOPING STUDIES.

Link number	Width x Depth (mm x mm)	Thickness (mm)	Length (mm)	Material
Link 0	90 x 200	5	640	SS 304L
Link 1	90 x 200	5	580	AL 6061-T6
Link 2	80 x 180	5	580	AL 6061-T6
Link 3	80 x 180	5	580	AL 6061-T6

The 2D surface geometry of the joints (~ 4kg) were imported to ANSYS workbench, links were modeled as beams which were assigned geometric section and actuator masses (~1kg) were defined as point mass on the link geometry at the time of FEM analyses and dead weight analysis with a payload of 1kg was carried out to check the structural integrity.

To guarantee the safety of cask structure design, finite element (FE) calculations have been finished for important stress parts including cask shell. The storage vacuum chamber has a huge inner vacuum space while the thickness of shell is 8 mm, vacuum condition for inner space, 0.1 MPa pressure on the outer shell, peak stress is 6 MPa; dead weight of the vessel components, vacuum components, robot mass and actuator mass impose gravity load of ~1.2tons on rail guides and support structure.

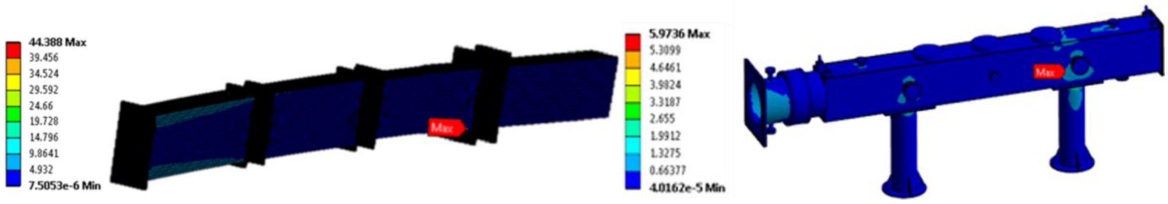

FIG. 6. Distribution of stress intensity on (A) IVIS arm and (B) Storage vacuum chamber

Vacuum load, robot dead weight and payload: The IVIS is subjected to 0.1 MPa pressure on the outer shell due to vacuum condition when stowed in the storage cask and while inspecting the SST-1 vacuum chamber. Dead weight of robot mass, actuator components mass and payload impose gravity load of ~ 45 kg. The analysis has shown that the maximum stress intensity of 44 MPa appears near the connecting area between lugs and link bodies. The maximum displacement at the distal end of the structure is <2mm. The distribution of the stress intensity on IVIS structure and storage vacuum chamber are shown in Fig. 6.

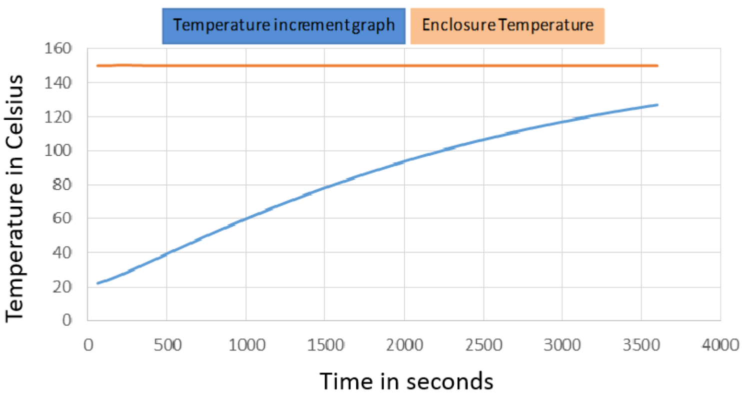

FIG. 7 In-vessel operation time of IVIS arm

Radiation analysis was performed with initial temperature of IVIS system at 22ºC, enclosure temperature at 150 ºC and emissivity as 0.8 to check the in-vessel inspection time of the IVIS arm to match the performances compatible with high temperature, ultra-high vacuum requirements of the actuator, gearbox and bearing components. During (one quarter i.e. ± 90º) viewing, the IVIS arm will traverse half of the toroidal (circumferential) span of the VV, complete the viewing procedure and return back to its initial position outside the VV. Total time of viewing cycle is 2000 seconds as shown in Fig. 7.

6. IVIS JOINT PROTOTYPING

The fabricated prototype joint assembly is shown in Fig. 8. In the present design a lug separation distance of ~200mm, is considered with a total bending moment of ~1kN-m at joint axis. The material selection is as provided in Table 7. Two different ideas for revolute joint, a) bushing arrangement and b) bearing arrangement have been implemented to study the frictional functionality and required actuation torque in vacuum conditions. The coefficient of friction between bushing and pin as 0.3 and maximum calculated required actuation torque ~

19 N-m (in bushing concept). In order to reduce the friction between two contacting surfaces MoS_2 dry lubricant (molybdenum disulfide) has been used. This can be improved by using the bearing concept.

FIG. 8. IVIS Joint Prototype

TABLE 7. MATERIAL SELECTED FOR JOINT COMPONENTS.

Component	Material
Lug	SS304L
Flange	Aluminium 6061-T6
Bushing	Aluminium Bronze
Bearing	Stainless Steel

7. SUMMARY

In this paper, the detailed conceptual design of In-Vessel Inspection System (IVIS) and Vacuum Storage chamber to carry out in-service visual inspection of SST-1 tokamak under vacuum in between the plasma shots has been discussed. The architecture of IVIS manipulator is chosen keeping in mind high mobility in a constrained design envelope.

Based on the kinematic VR simulation, it was found that a total of 03 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 SST-1 machine. The manipulator is designed to handle a cantilevered payload of ~1kg with a positional accuracy of <2mm. IVIS is initially stowed in a 4m long Ultra-High Vacuum (UHV) storage chamber isolated from the VV by an UHV gate valve.

Limits on out-gassing inside the VV impose serious constraints for the design (e.g. on material, on joints design, actuators and cables). This assessment was carried out through close collaboration and knowledge sharing involving Vacuum Engineering Services Division, IPR. First design of lubricant free joints is based on incorporation of MoS2 bushes instead of bearings in IVIS joints. The COTS availability (actuators, reducers and bearings) to match the performances compatible with high temperature, ultra-high vacuum requirements and to overcome pollution issues of the tokamak environment. Improvements to enhance IVIS operation under temperature and vacuum conditions for SST-1 like machine were reviewed. Theoretical calculations, kinematic assessments and structural integrity analyses were carried out in detail to optimize the design.

In future the endurance tests in vacuum and temperature will be implemented to evaluate the overall performances of one module integrated with solid lubrication bearings, motors and electronics. Endurance test will also be performed on Integrated IVIS arm to do functional tests in normal and tokomak condition. According to the testing results, several beneficial optimizations may be considered for the whole IVIS arm, which will be available for the experiments in middle of next year as planned.

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