

Structural Analysis of Inner Passive Stabilizer of Steady State super conducting Tokamak-1 (SST-1) for Electromagnetic and thermal loads using ANSYS

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For achieving fusion energy as the viable global energy source, the events of launching projects to develop advanced fusion devices are on their way in almost all countries. It is advance in developing technology. Tokamak is a Russian acronym concerned with the toroidal confined magnetic device for producing and confining plasma. Steady State Super Conducting Tokamak-1 (SST-1) is being developed at the Institute for Plasma Research, Gandhinagar, India. The machine will be operating with Hydrogen plasma for a steady state operation of 1000 seconds pulse with the help of superconducting electromagnets and related technologies.

Tokamak means Toroidal chamber with magnetic coil. The Tokamak is the most successful device developed to attain conditions for fusion. Plasma and its parameters have listed here. Major plasma facing components are: (i) Inner Passive Stabilizer (IPS) (ii) Outer Passive Stabilizer (iii) Divertor (iv) Baffles

As a part of our paper, we have done Analysis of only Inner Passive Stabilizer (IPS). Detailed study on the Structural analysis for thermal and electromagnetic loads at transient conditions for the Inner passive stabilizer components needs to be carried out using ANSYS. Modeling of IPS, material of IPS, material for support structure of IPS, its properties, and Ansys analysis of IPS, calculation for Induced current, Magnetic force, Deflection and Stresses have been carried out.

Two different methodologies adopted for analysis are Coupled Field analysis and Symmetric Boundary Condition. In the first method, steps involved are: (i) Modeling and meshing of the assembly. (ii) Loading & boundary conditions be applied on the assembly. (iii) Electromagnetic forces obtained due to the above loading in Transient condition are to be transferred on to the structural analysis for the calculation of stresses. In second method, for the analysis of IPS during baking operation only one sector assembled model of IPS is taken and the solution is obtained by applying symmetric boundary condition at all cut portion and the result for this condition is same as that of full model.

Keywords: SST-1 Tokamak, plasma and plasma facing components, Inner passive stabilizer, Analysis of IPS with result tables using ANSYS.

Introduction

Fusion energy is the most useful and intense source of energy in the universe. With the hydrogen bomb, fusion energy was released in an uncontrolled form. At that time scientists thought about the possibility of a controlled thermonuclear reactor as an energy-producing unit. Since continuous research and development exit for fusion reactor relevant technology. At the same time magnetic plasma was introduced on the Tokamak concept. Various research was done and many designs for the Tokamak were prepared.

What is Tokamak?

The word Tokamak is an acronym for the four Russian words toroidal 'Naya kamera magnitnoi katushki'. It means Toroidal chamber with magnetic coil. The Tokamak is the most successful device developed to attain conditions for fusion. It is a toroidal device (shaped like a car tire) in which a vacuum vessel contains a plasma ring confined by twisting magnetic fields. Tokamak contains two types of coils: Poloidal field coil and Toroidal field coil. Fig. 1 shows the Magnetic confinement system of Tokamak.

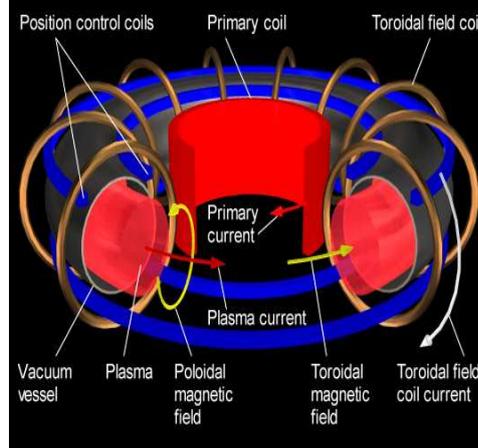
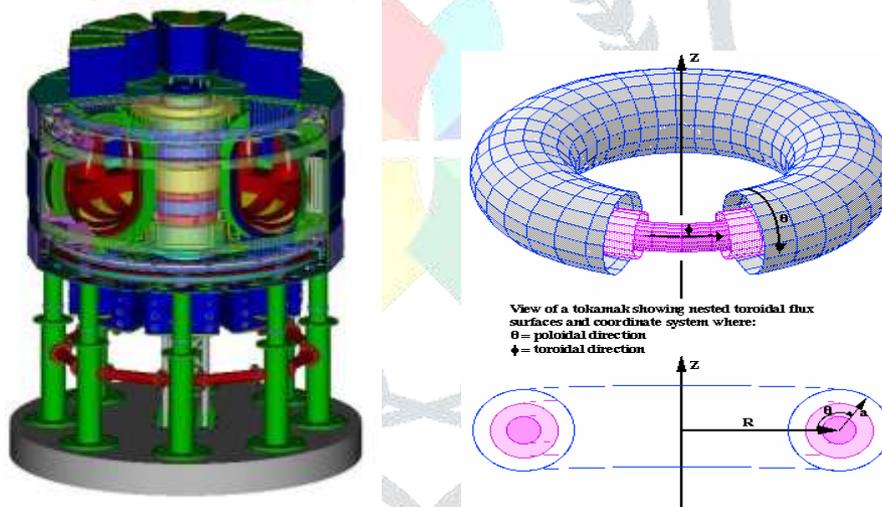


Fig. 1 Magnetic confinement system of Tokamak

The transient electric current circulates in the Poloidal field coil that induces a current in the plasma ring. That heats the plasma and produces the Poloidal magnetic field. When electric currents circulate in the toroidal field coil it generates the toroidal magnetic field. The currents circulating in the position control coils generate auxiliary magnetic field components. It is used to modify the Poloidal field, equilibrating the plasma ring and controlling its position.

Steady State Superconducting Tokamak (SST-1)

A steady state super conducting Tokamak SST-1 is under design and fabrication at the Institute for Plasma Research (IPR), Bhat, Gandhinagar. The objectives of SST-1 include studying the physics of the plasma processes in Tokamak under steady state conditions and learning technologies related to the steady state operation of the Tokamak. The SST-1 Tokamak is a large aspect ratio Tokamak. It can run double null diverted plasmas with significant elongation and triangularity.



Plasma Parameters for SST-1

Plasma major radius	1.1m
Plasma minor radius	0.20 m
Elongation	1.7-1.9
Triangularity	0.35-0.6
Internal Inductance	0.75-1.40
Poloidal cross-section area	0.19 m ²
Centroid of Poloidal cross-section area	1.10 m
Perimeter of Poloidal cross-section area	1.75 m
Volume of plasma core region	1.25 m ³
Surface area of plasma core region	11.77 m ²
Typical energy confinement time	10 ms
Typical particle confinement time	20-40 ms
Toroidal magnetic field	3 T
Total input power	1 MW
Plasma current	220 KA; (max.330 KA)
Plasma cross-section	D-shaped
Gas used	Hydrogen
Divertor	Poloidal
Plasma pulse width	1000

Considerations during Analysis

1. For the electromagnetic load calculation, the condition of disruption of Plasma is taken and these electromagnetic loads the structural analysis on IPS are performed. Plasma is disrupted from 220 KA to 0 KA at different time steps.
2. For the structural analysis of the IPS support structure analysis for the condition of Baking is considered.

Methodologies adopted for Analysis

Following two methodologies adopted for analysis.

1. Coupled Field analysis:

A coupled field analysis is an analysis that considers the interaction (coupling) between two or more disciplines. Steps involved are: (i) Modeling and meshing of the assembly. (ii) Loading & boundary conditions be applied on the assembly. (iii) Electromagnetic forces obtained due to the above loading in Transient condition are to be transferred on to the structural analysis for the calculation of stresses.

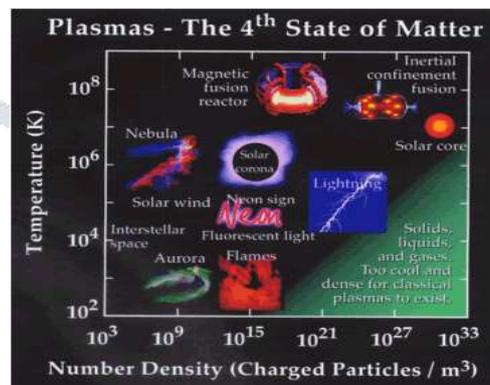


Fig. 2 State of Plasma

2. Symmetric Boundary Condition:

For the analysis of IPS during baking operation only one sector assembled model of IPS is taken and the solution is obtained by applying symmetric boundary condition at all cut portions and the result for this condition is same as that of full model.

Plasma:

Plasma is the most common form of matter. In 1879, Sir William Crooke's, an English physicist, identified a fourth state of matter. It was PLASMA. Plasma temperatures and densities range from relatively cool and less dense to very hot and dense. Plasma consists of a collection of free-moving electrons and ions-atoms that have lost electrons. Energy is needed to strip electrons from atoms to make plasma. Plasma is a "fourth state of matter" because of their unique physical properties, distinct from solids, liquids, and gases. When plasma is fully ionized it is composed in ions and electrons. Plasma has two characteristic properties: (1) Electric charge density of the two species is so large that any substantial separation would lead to a very large restoring force (2) A ability to carry a current as result of a relative drift between the ions and electrons. Plasmas are estimated to constitute more than 99% of the visible universe.

Plasma Facing Components:

Major plasma facing components: (i) Inner Passive Stabilizer (IPS) (ii) Outer Passive Stabilizer (iii) Divertor (iv) Baffles

Passive Stabilizer:

The Tokamak shaped plasma column is inherently unstable to vertical displacements because of negative equilibrium index. There are requirements to stabilize this motion. For that active and passive elements are used. The vertical stabilization of elongated plasma imposes severe requirements on the system. It is usually not possible to do this with an active coil system alone. Because of that excessive peak power is required. Consequently, stability using passive coils has been under evaluation. The desired role of passive structure is to reduce the vertical stability growth rate. It makes active control feasible. The general approach is to allow the rapid plasma displacement to generate eddy currents in passive elements and produce an associated induced magnetic field, which will reduce the rate of displacement. The active coil can then control the plasma motion on a longer time scale.

This imposes two basic requirements on the passive stabilization system:

1. Its location and geometry must provide an induced field of sufficient magnitude.

2. The induced field must be applied for sufficient time.

A passive stabilization system forms an electrically conducting loop around the toroidal plasma. The elongated plasma in Tokamak is generally unstable to vertically shift away from its equilibrium position. Any such vertical movement of plasma induces stabilizing currents in the saddle loop formed by this component. Since, functioning of this component is totally based on induced currents. No external electric power supplied to it.

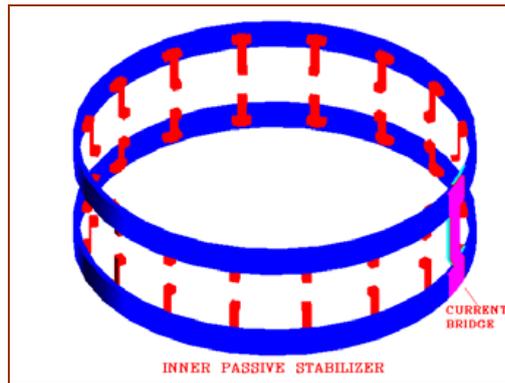


Fig. 3 Inner passive stabilizer

The passive stabilizer assembly consists of inner and outer passive stabilizer. There is pair of inner and outer passive stabilizers placed symmetrically up and down. As our part of paper, we have included only Inner Passive Stabilizer (IPS) (refer Fig. 3) to calculate the electromagnetic loads and for structural analysis. IPS consists of a pair of vertical legs insulated from each other. Mechanically the top and bottom rings are connected across the mid plane with this current bridge. This whole assembly is supported to inner vacuum vessel wall. As a design criterion the time constant of the stabilizer plate should be 3 milliseconds. Since the Inner passive stabilizer is the first wall component to be maintained in vacuum.

Support Structure requirements for Inner Passive Stabilizer (IPS):

The passive stabilization coil needs to be supported against the following:

- (i) The weight of IP S coil is 300 kg. So, the support structure should be able to handle this weight.
- (ii) There will be $J \times B$ forces on the stabilizer and the vertical connecting legs during normal operation.
- (iii) Large forces are expected on the system due to eddy currents and halo currents during startup, disruption and VDE.

As mentioned earlier, the hoop forces on the stabilizer will not need any external support structure. The thickness and dimension should be able to withstand the force. Ultra high vacuum insulation material SS-304L can be used as support structure. On the inboard side there is virtually no space for nut - bolt mechanism for supports. Once the modules have been pushed into the grooves it is bolted from top and bottom. This type of support structure is expected to take care of the forces on IPS.

Material for IPS:

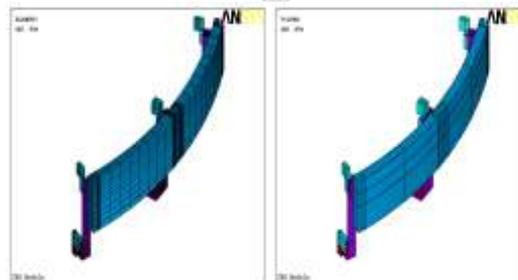


Fig. 4 3D modeling of support structure

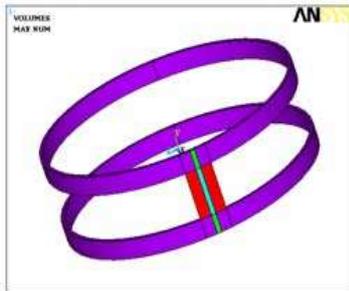
Parts	Cross- sectional Area (m ²)	Material
IPS (Up & Down)	0.003	CuZr
IPS-Shunt	0.003	Inconel 625
IPS-Leg	0.00183	CuZr

Properties of Material:

Material	Resistivity	Permeability	E (Gpa)	v	α (m/m ⁰ c)	Yield Strength (MPa)
CuZr	2.87E-08	1	118	0.311	15.8E-06	440
Inconel 625	1.12E-08	1	200	0.278	13.1E-06	490

Modeling of IPS:

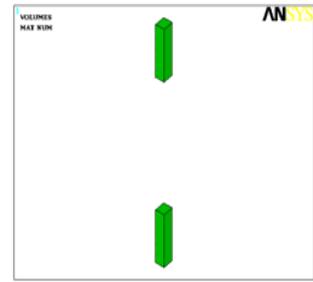
With current bridge



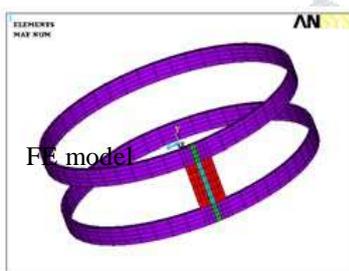
IPS- leg



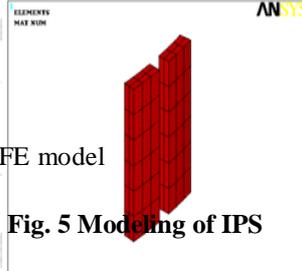
IPS Shunt



Solid Model



Solid Model



Solid Model

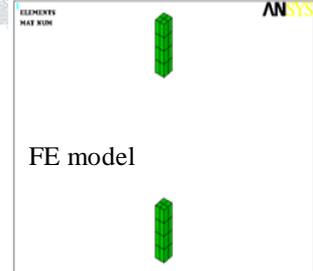


Fig. 5 Modeling of IPS

Assembly of the IPS with the support structure:

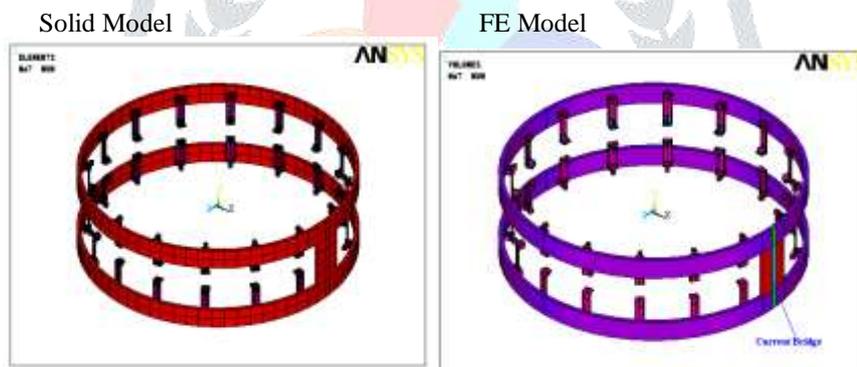
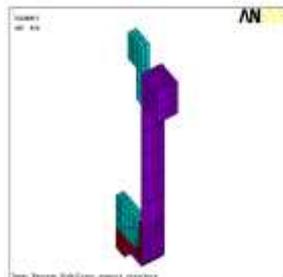


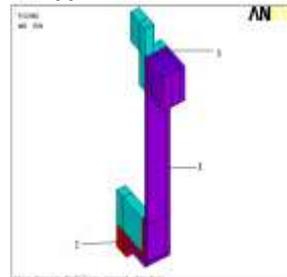
Fig. 6 Assembly of IPS with support structure

There are 16 supports each on Top as well as bottom modules. Total No. of elements = 288.

Sector Model for IPS



Support Structure for IPS



Material for Support structure for IPS:

Part	Material	
Sport Plate	Inconel X-750	The support structure for IPS is a simple form of cantilever beam that can bend to allow radial expansion. There is a total of 16 such identical supports each for the top and bottom IPS rings.
Insulator	Alumina	
Spacer Plate	Inconel X-750	
Support Bracket	Inconel X-750	
Reinforcing bar	Inconel X-750	
Splice plate	Inconel X-750	

Properties:

Material	E (GPa)	α (m/m ^{0c})	ν	Yield Strength (MPa)
Inconel X-750	208	12.1 E-06	0.304	635
Alumina	370	6.9 E-06	0.220	2100

Disruption details of Plasma Current at different time points:

Time (sec)	0.028	0.0298	0.0313	0.0333	0.0351	0.0399
Plasma current (KA)	220	205	90.7	3.01	0.071	0.00117

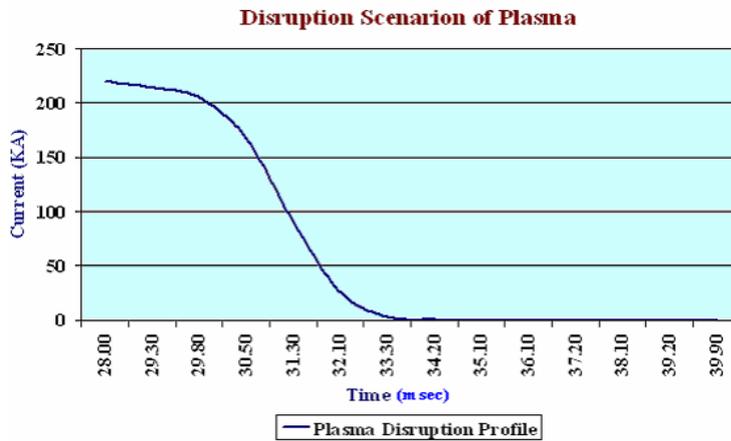


Fig. 7 Plasma disruption profile

Due to the disruption of Plasma from 220 KA to 0 KA in different time step will result in Induced current and Induced Magnetic force on IPS module and due to this there will be deflection and stress in the modules. At each time we will calculate the values of Induced Current, Magnetic force, Deflection and Stress induced.

Induced current in IPS at different time step:

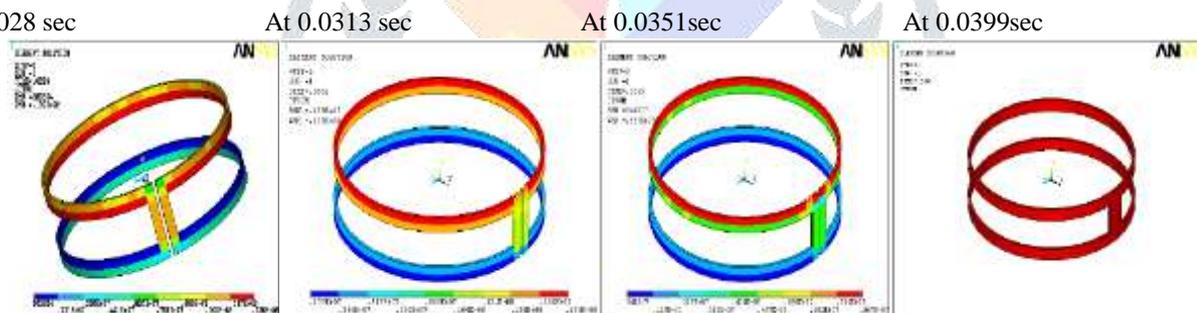


Fig. 8 Time based induced current in IPS

Details of Induced current in IPS:

Time (sec)	0.028	0.0298	0.0313	0.0333	0.0351	0.0399
IPS-Top	0.00	2.02	19.31	42.65	45.96	33.13
IPS-Bottom	0.00	0.36	3.45	6.47	8.95	9.38

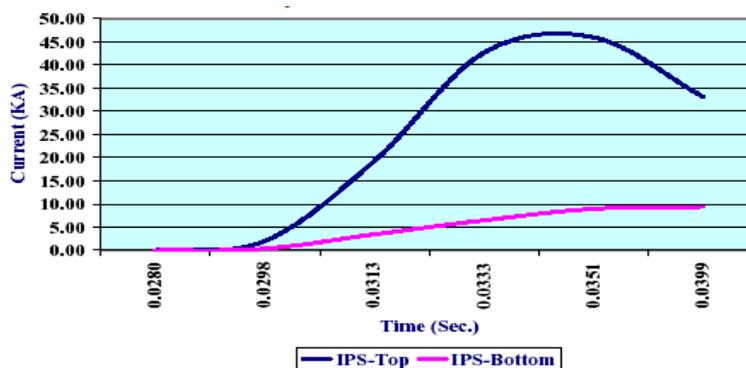
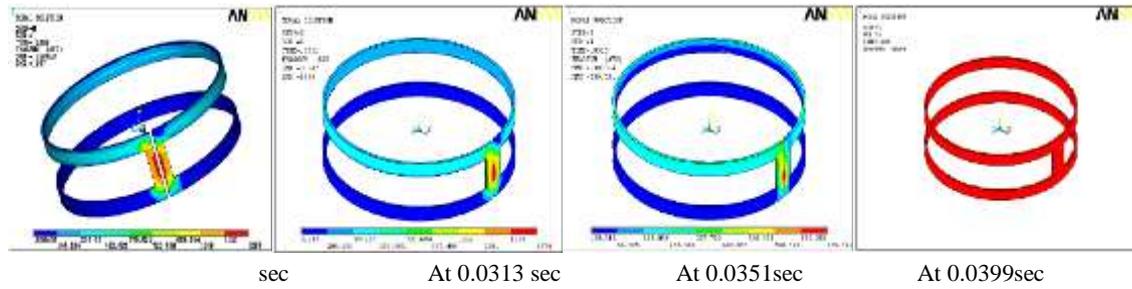


Fig. 9 Induced current profile in IPS

Induced current obtained by ANSYS satisfied with the Filament Methodology. Maximum current in IPS (Top) is 45.96 KA and IPS (Bottom) is 9.38 KA.

Magnetic forces in the IPS at different time step:



At 0.028

Fig. 10 Time based magnetic forces in IPS

Sr. No.	Time (Sec)	Magnetic force in IPS	
		F _{mag} Sum in Newton	
		IPS Top	IPS Bottom
1	0.028	00	00
2	0.0298	7790	1360
3	0.0313	71970	12830
4	0.0333	144910	25090
5	0.0351	143990	31630
6	0.0399	92940	29910

Profile of Disruption Induced Magnetic Force in IPS:

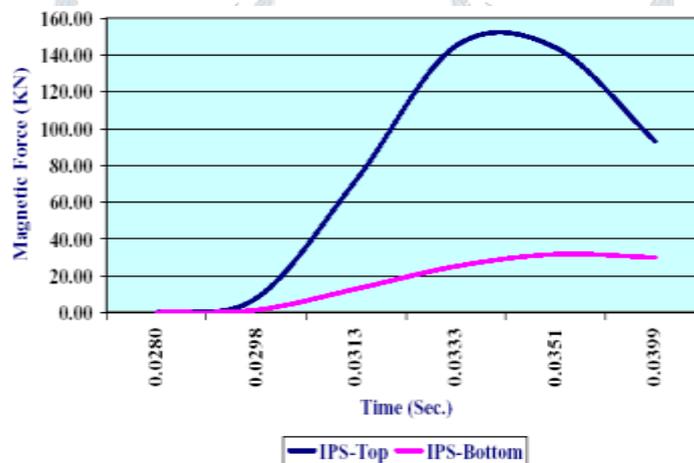


Fig. 11 Disruption Induced Magnetic Force profile in IPS

Maximum value of the magnetic force for IPS top is 144.91 KN at time step of 0.0351 sec and for IPS bottom maximum force is 31.63 KN at time step of 0.0351 sec.

Deflection in the IPS:

Sr. No.	Time (Sec)	Deflection (meters)			
		IPS Top	IPS Bottom	IPS Module	Current Bridge
1	0.028	00	00	00	00
2	0.0298	0.117×10^{-4}	0.769×10^{-5}	0.117×10^{-4}	0.787×10^{-5}
3	0.0313	0.110×10^{-3}	0.730×10^{-4}	0.110×10^{-3}	0.752×10^{-4}
4	0.0333	0.239×10^{-3}	0.188×10^{-3}	0.239×10^{-3}	0.188×10^{-3}
5	0.0351	0.276×10^{-3}	0.259×10^{-3}	0.276×10^{-3}	0.251×10^{-3}
6	0.0399	0.271×10^{-3}	0.277×10^{-3}	0.271×10^{-3}	0.257×10^{-3}

Stresses in IPS Module:

Sr. No.	Time (Sec)	Stress (Newton/meter ²)			
		IPS Top	IPS Bottom	IPS Module	Current Bridge
1	0.028	00	00	00	00
2	0.0298	0.465×10^6	0.166×10^6	0.108×10^7	0.330×10^6
3	0.0313	0.431×10^7	0.109×10^7	0.992×10^7	0.314×10^7
4	0.0333	0.101×10^8	0.415×10^7	0.112×10^8	0.739×10^7
5	0.0351	0.377×10^7	0.907×10^8	0.143×10^8	0.932×10^7
6	0.0399	0.853×10^7	0.402×10^7	0.402×10^7	0.118×10^8

Results of stresses show that IPS icons withstand the electromagnetic loads, the stress obtained is below the allowable limit.

Conclusion:

Electromagnetic and Structural analysis has been carried out successfully using ANSYS software for Inner Passive Stabilizer during disruption of Plasma. During the ramping down of the current during disruption of Plasma the induced current obtained in IPS (Top and Bottom) satisfies the methodology adopted at IPR, Gandhinagar. The stress obtained at different time steps due to the electromagnetic loads are well below the allowable limit for IPS. During the baking analysis of the PFC's the stresses will be on the support structure as they are flexible and allow the plate for full expansion. The stress obtained can also be reduced as there are some assumptions considered while doing this analysis.

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