Conceptual Design of Vacuum Chamber for Testing of High Heat Flux Components using Electron beam as a Source

M.S.Khan

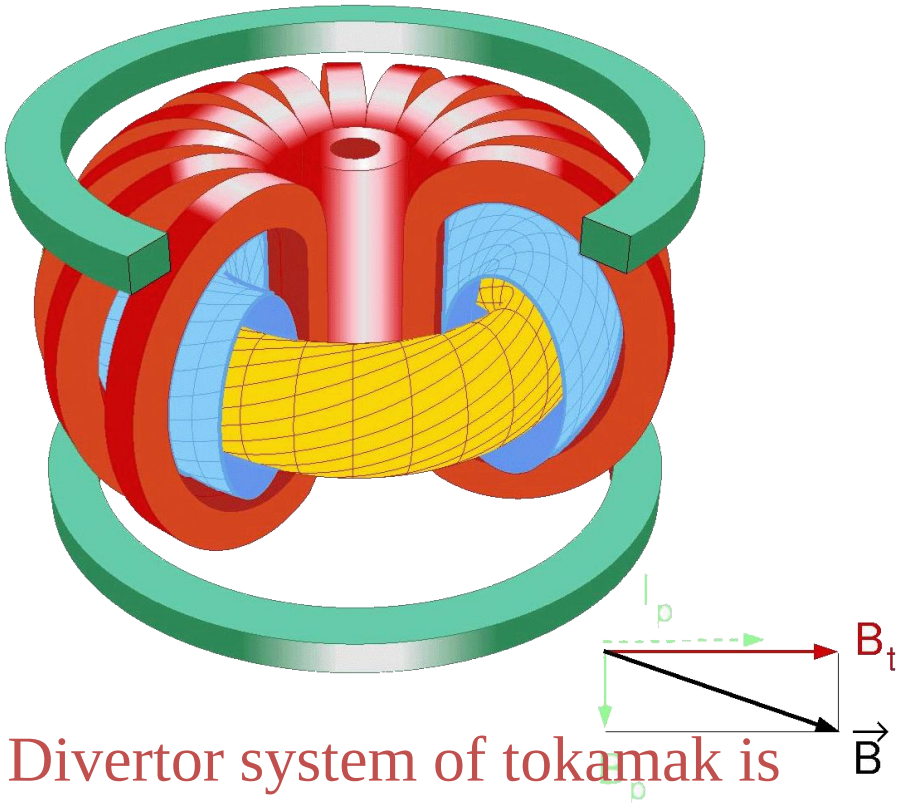
Prototype Divertors Division

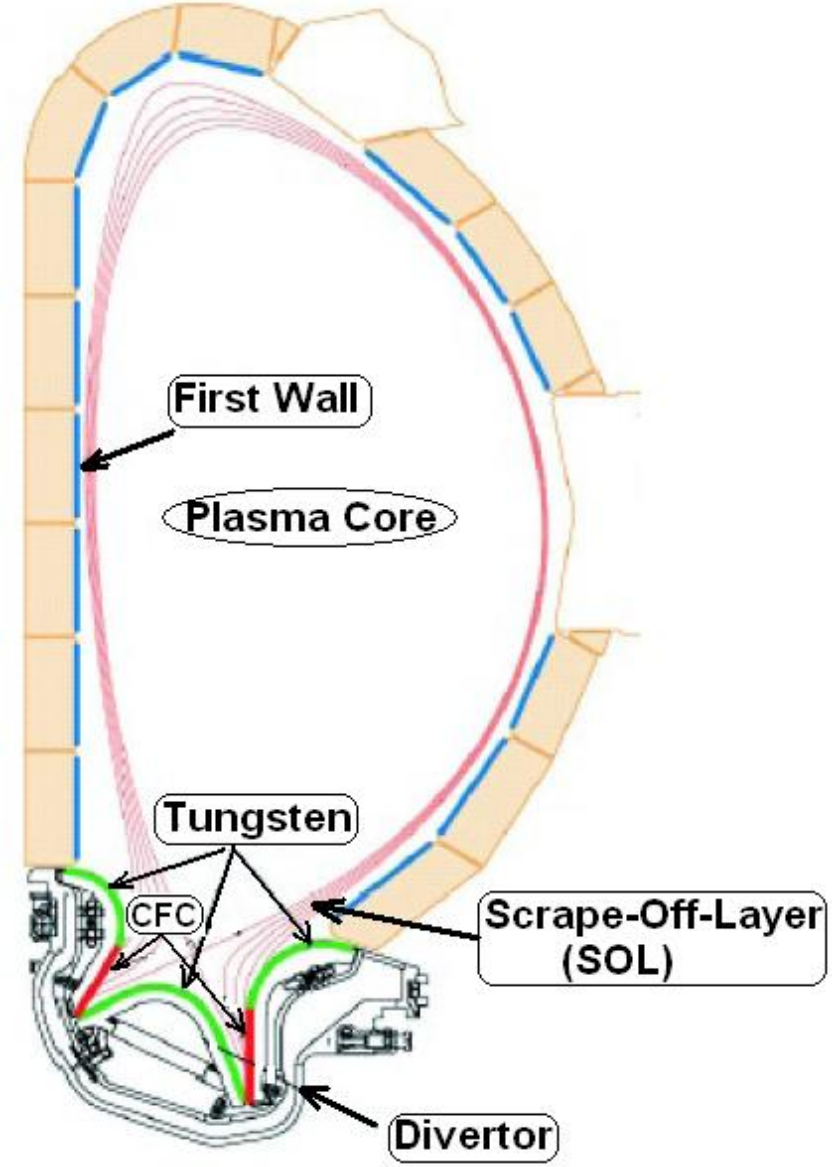
Institute for Plasma Research

Bhat, Gandhinagar -382428

Contents

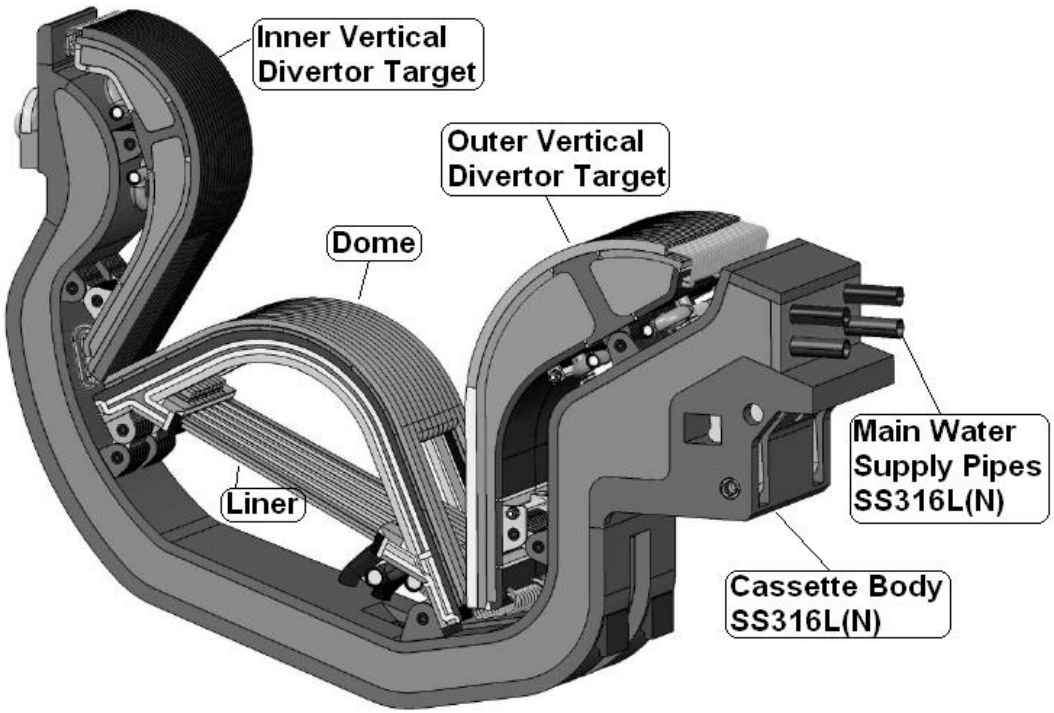
Divertor System of Tokamak





Divertor system of tokamak is responsible for safe extraction of heat and particles escaping out of plasma core region.

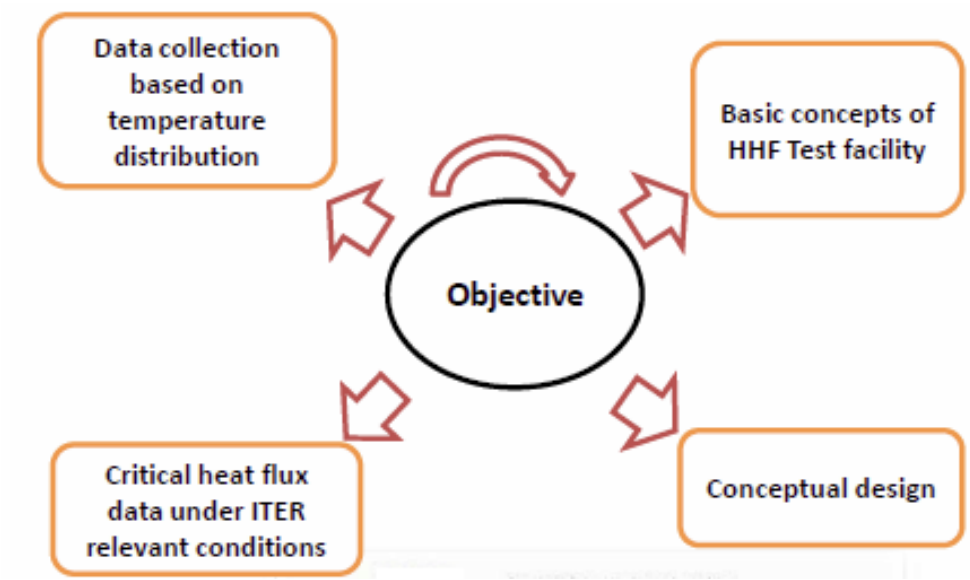
Parts of divertor system

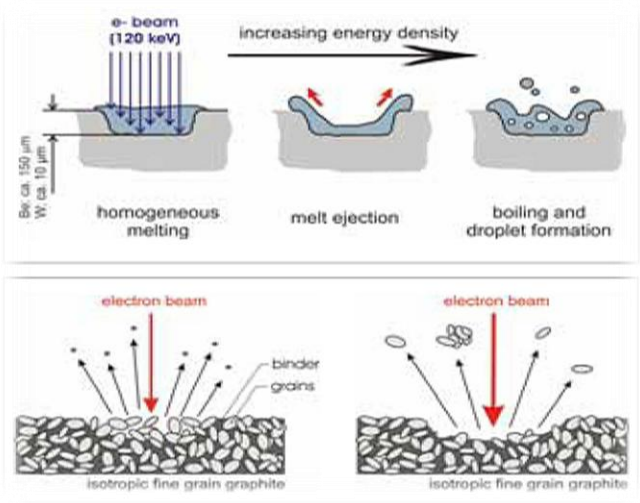


Divertor Cassette of ITER

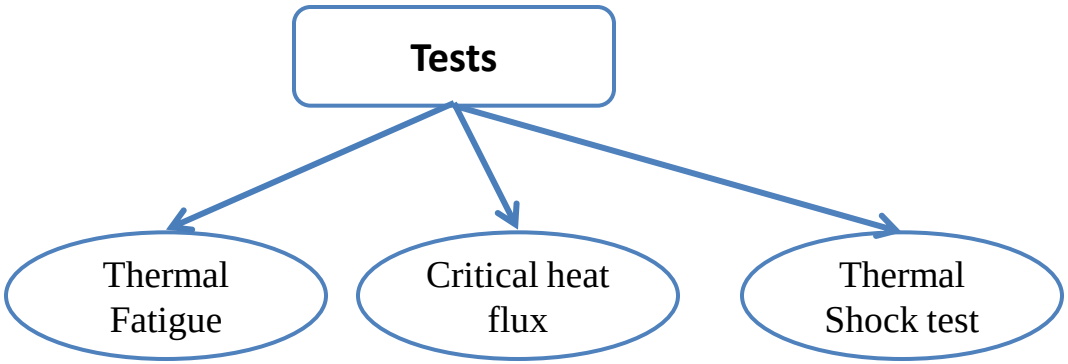
Reference: Engineering of Plasma-Facing Components – Mario Merola, PFMC-11 (Oct-2006), Griefswald, Germany

Introduction





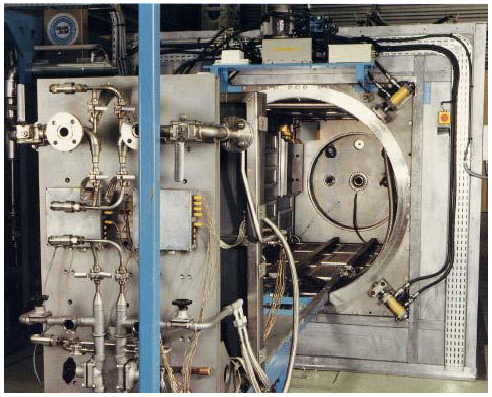
Metals (top) and graphite (bottom)under intense thermal loads in an electron beam device [1]



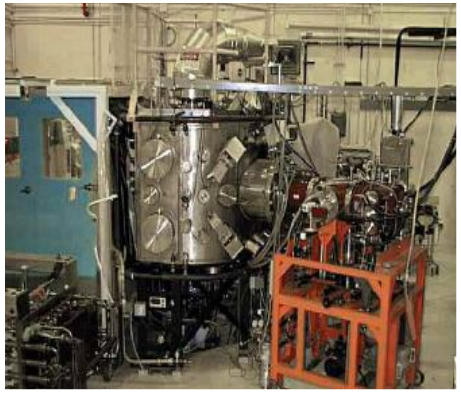
Facilities Worldwide

FACILITIES	JUDITH 2	JEBIS	TSEFEY	FE 200	EB 1200	PBEF	GLADIS	INDIA
Max voltage (KV)	30-60	100	30	200	40	50	50	45
Max power (KW)	200	400	60	200	1200	1500	2200	200
Max heated area (m^2)	0.25	0.18	0.25	1.0	0.27	0.1	0.3	0.16
Particle type	e^-	e^-	e^-	e^-	e^-	H^+, He^+	H^+	e^-
Power density (GWm^{-2})	10	2	0.2	60	10	0.06	0.05	1.2
Institute ITER partner	FZJ EU	JAEA JA	Efermov RF	CEA EU	SNLA US	JAEA JA	IPP EU	IPR, INDIA
Beam spot	scanned beam Ø ~5mm	Beam sweeping Ø ~ 1-2mm	Scanned beam Ø=20mm	Scanned beam Ø=2-3mm	Scanned beam Ø=2-12mm	Two ion sources 0.75MW Ø=150 mm	Two ion sources 1.1 MW Ø =70 mm	scanned beam Ø ~15mm

JUDITH 2



FE 200



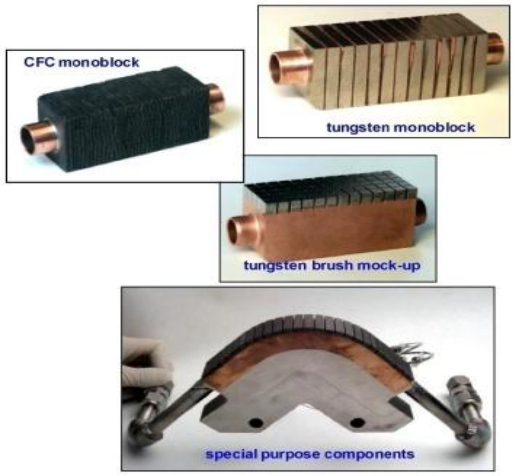
EB 1200

GLADIS

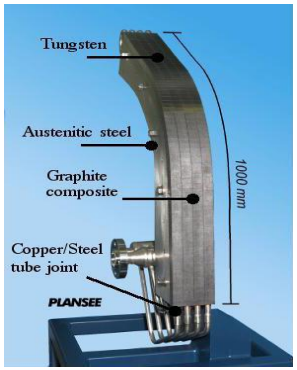
Ref: []

Features of Vacuum chamber

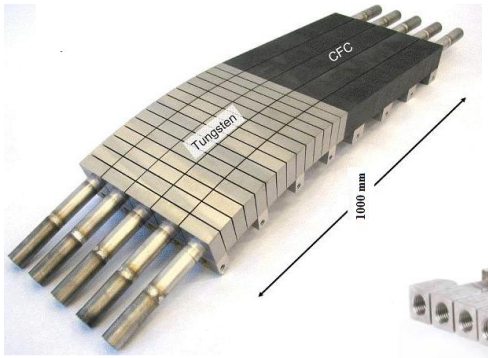
- To study the thermal response of high heat flux components using electron beam as a heat source of power 200 KW and with different diagnostic devices

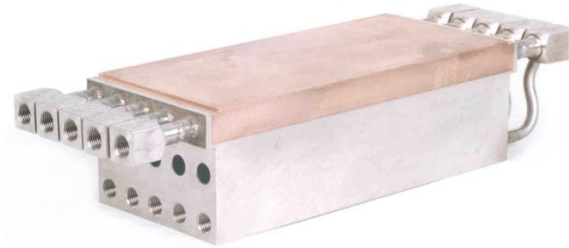


Medium scale divertor module



Vertical target full scale prototype





Divertor mockups	Dimensions (mm)
Small scale	50X30X30
Medium scale	400x50x200
Full scale	1600x300x300

HPHTWCS to test mock –ups

Maximum inlet pressure	60 bar
Maximum pressure drop expected in the test mock -up	~2 bar
Expected pressure range operated at inlet	5 bar – 60 bar
Adjustable Inlet Temperature	RT -150°C
Maximum expected temperature rise across test mock-up	~ 10°C
Maximum volumetric flow rate required	300 LPM
Pipe size (ID) of test mock –up	5 mm – 10 mm

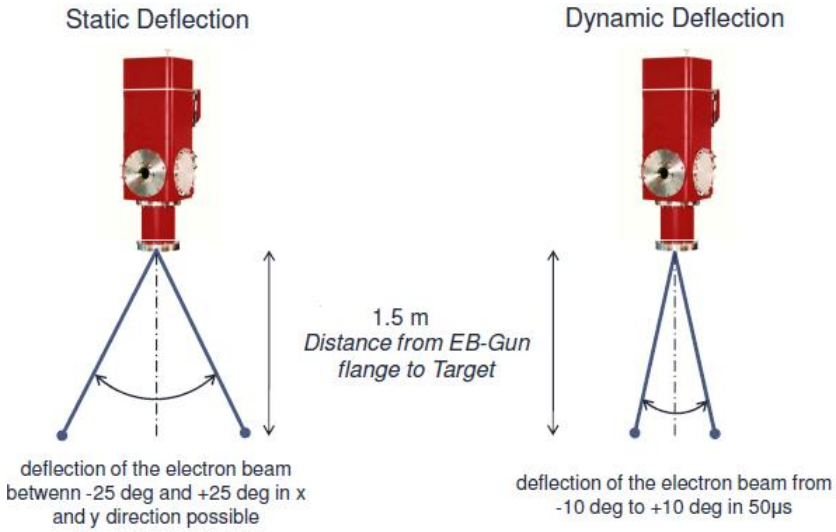
Thermal loads to plasma facing components

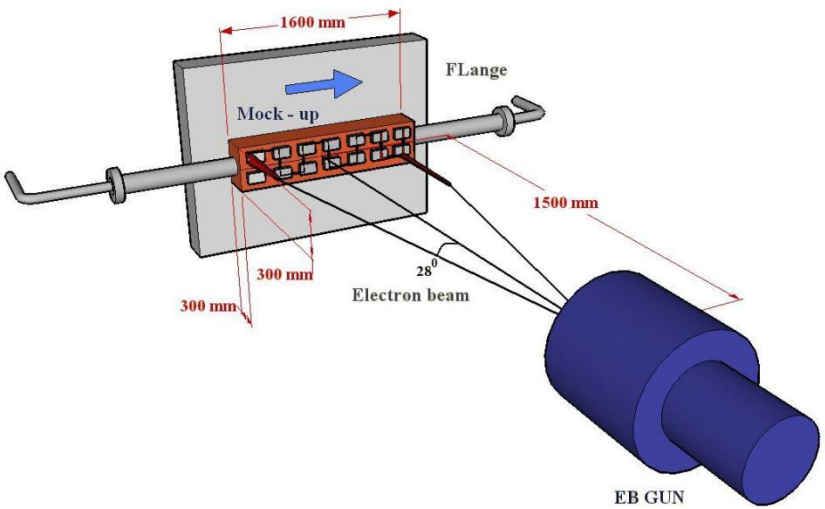
Normal Operation
5 ... 20 MWm^{-2} 500 s $n \geq 1000$

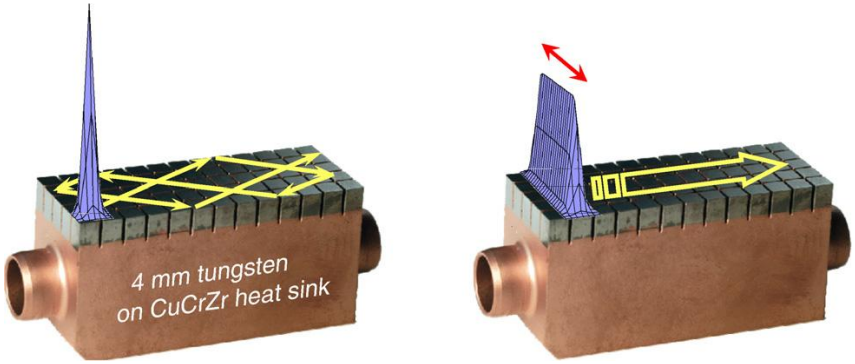
Vertical Displacement Events (VDE)
60 MJm^{-2} 0.1 ... 0.3 s $n \approx 10$

Plasma Disruptions
Several 10 MJm^{-2} 1 ... 5 ms $n = 200$

Edge Localized Modes (Type I ELMs)
1.0 MJm^{-2} 0.5 ms $f = 1$ Hz

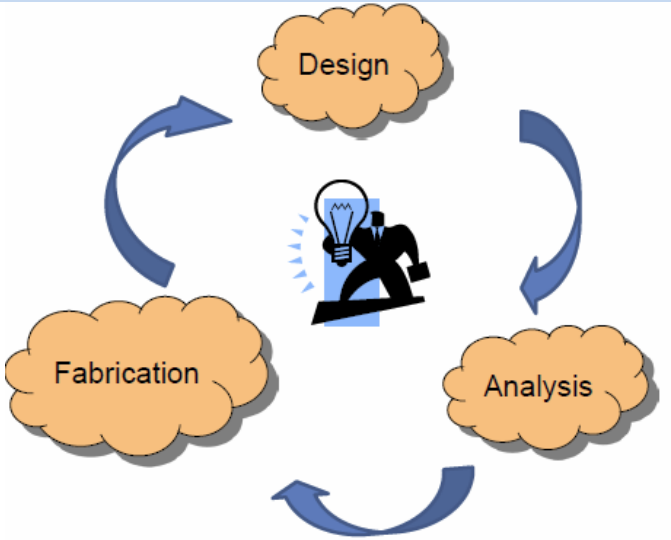




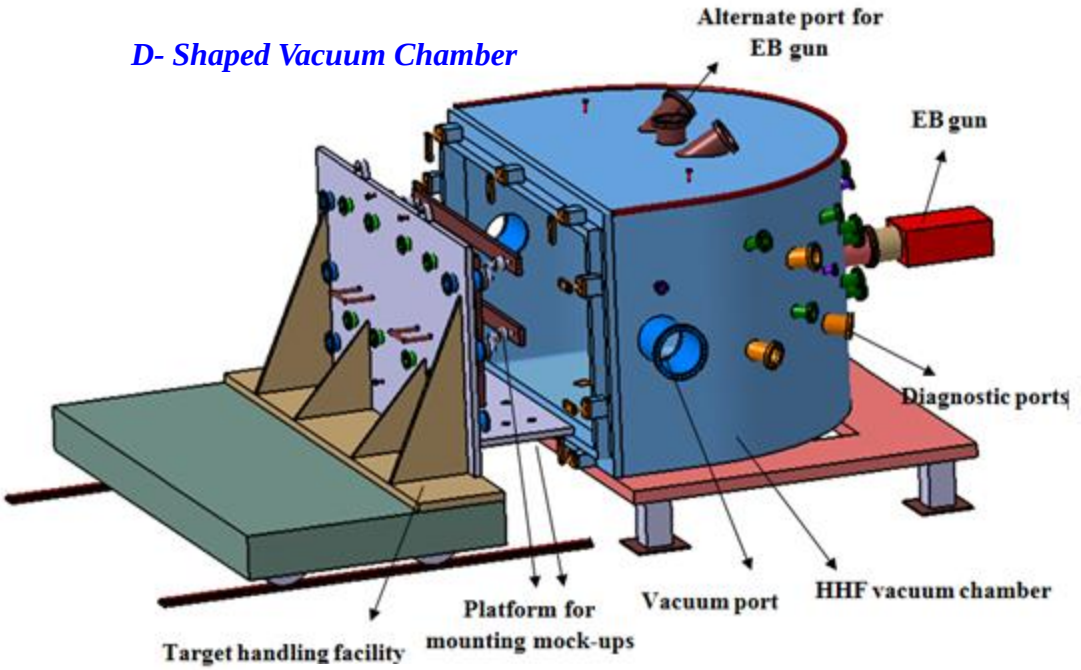


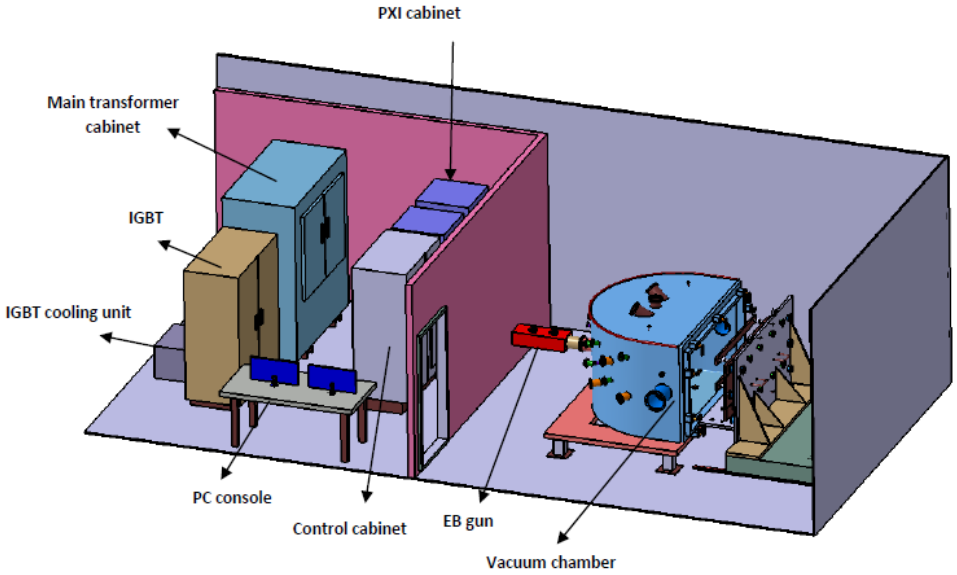
Electron beam scanning during thermal fatigue tests (left) and transient thermal loads (right) [ref(2)]

Development of Conceptual Design

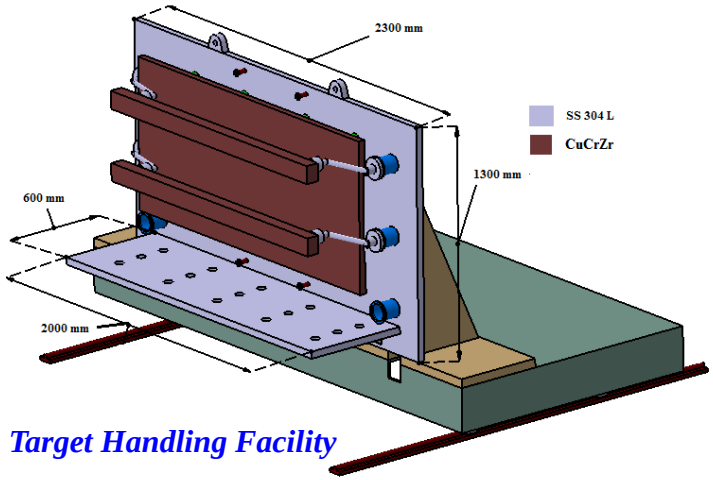


D- Shaped Vacuum Chamber





Proposed HHF test facility at IPR



Target Handling Facility

HHF test facility Technical Specifications

D-shaped Double wall vacuum chamber	
Operating Parameters	
Vacuum inside the chamber	10^{-3} mbar to 10^{-6} mbar
Maximum temperature inside the chamber due to radiation	350°C
Materials tested inside the chamber	
Mock-ups	Tungsten, CFC blocks with CuCrZr as heat sink
Materials used for chamber	
D-shaped vacuum chamber	SS 304L
Beam dumps	CuCrZr alloy
Support stand, railing systems, collar	Mild steel
X – ray shielding	Lead
Vacuum pumping system	Turbo molecular pump, Cryopump

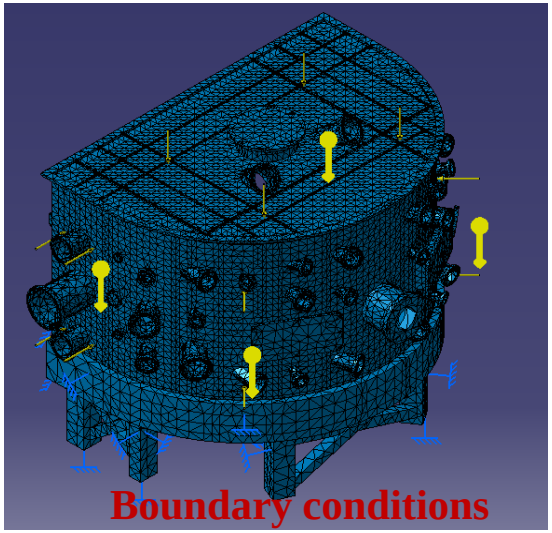
ELECTRON BEAM SYSTEM	
Maximum beam power	200 KW
Maximum accelerating voltage	45 kV
Maximum deflection angle (superimposed static and dynamic)	+/- 25^0
Maximum dynamic deflection angle for 1 KHZ	+/- 10^0
Minimum spot diameter (at a distance of 1 m & max beam power & 45 KV)	~ 15 mm
Mode of operation	Steady state/ pulsed mode

Diagnostic devices	
IR camera	15^0 C to 3000^0 C
Optical Pyrometers (2)	One color 600 – 1400^0 C Two color 1000 – 3500^0 C
Thermocouples (5 – 10)	Type K, 0.5 mm diameter
CCD camera (2)	Visual monitoring
Bore Scope (3)	In situ surface observations
Water calorimetry (1)	Platinum resistance temperature device (RTD)

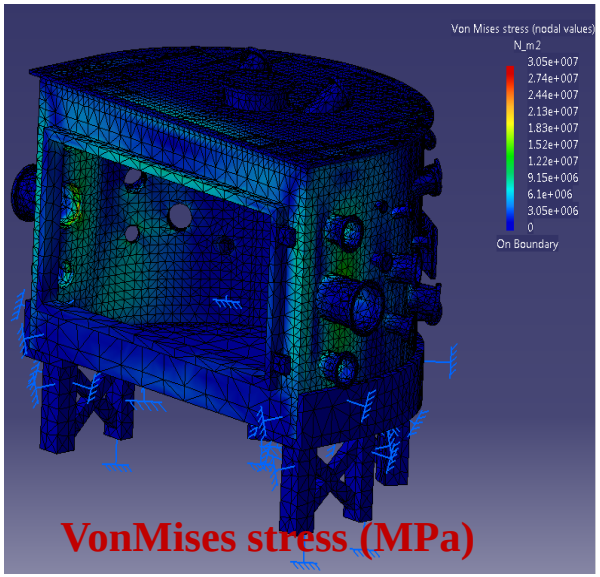
Design Procedure for Cylindrical Shell

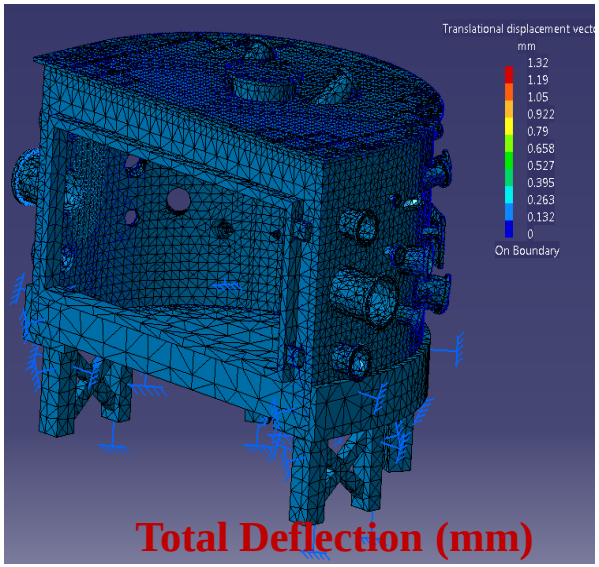
S.No	Parameter	Unit	Value
Design of shell thickness for external pressure as per UG-28 (C) – ASME Section VIII Div 1			
1	External pressure	Pe (Bar/PSI)	1.013/14.7
2	Temperature	T(^{o}C)	27
3	Material for construction ▪ Shell plates, flanges, blanks: ASTM/ASME SA 240 Grade SS 304L ▪ Collar for the rectangular front plate: forged plate F304L ▪ Reinforcing bars (channel) made from plates of ASTM/ASME SA 240 Grade SS 304L or SA 182 F304L ▪ Column: MS channels of IS2062		
4	1st assumed thickness (due to external pressure)	ta (mm)	8
5	Unsupported length	L (mm)	1500
6	Outside diameter	Do (mm)	2400
7	Allowable pressure Pa = 4B/(3(Do/t)), where t = ta	Pa(PSI)	52.44, Safe
8	Provided thickness	tp (mm)	12
Design of Flat head (Non circular cross section) – as per appendix 13 – ASME Section VIII Div 1			
9	Thickness $t = d\sqrt{\frac{ZCP}{S \cdot e}}$ Where t = Minimum required thickness for head d = Diameter of circular heads e = Joint efficiency, S= code allowable stress, P = design pressure C= attachment factor = 0.33, Z = factor =1.77	t (mm)	Top plate: 20 Bottom plate: 20 Front plate: 20

Static FE analysis



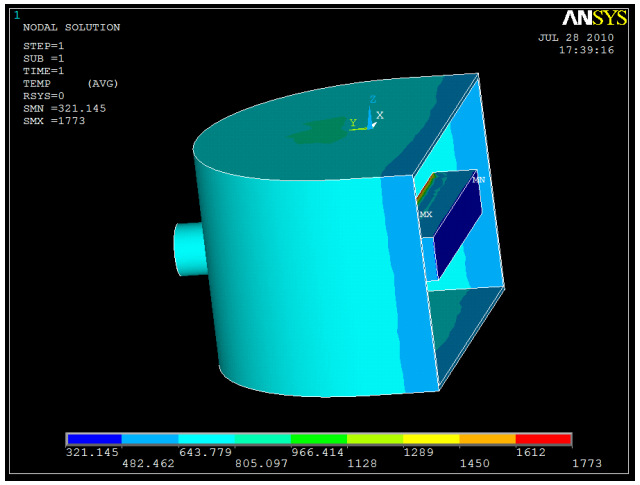
Structural analysis: CATIA V5 R12 Generative Structural Analysis tool	
Material	SS 304L for chamber and mild steel for the stand
Element type	Solid 185 having three (3) degrees of freedom Tetrahedron
Boundary conditions	▪ External surface load: pressure $1x10^5$ Pa ▪ Gravity load ▪ Lower key points for support columns as a fix point
Vector sum deflection	1.3 mm
Von Mises stress Max	30.05 MPa, within the yield strength of the material and is safe



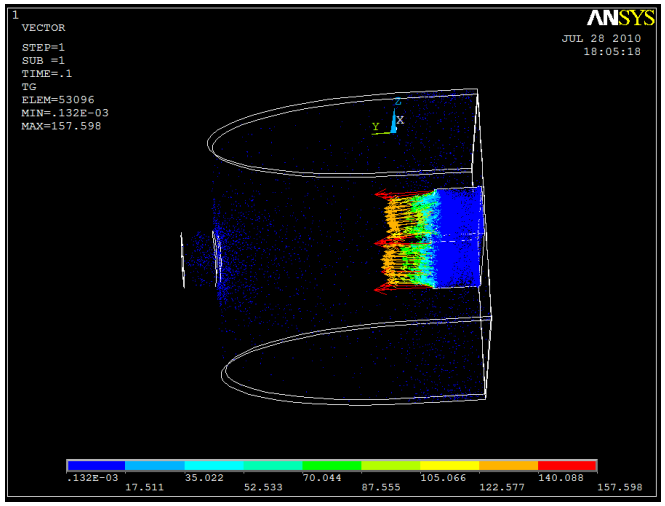


Radiation Analysis

Radiation analysis: ANSYS 12	
Method	AUX 12 radiation matrix generator method
Element type	Solid Tet 10 node 87, Shell 57 with temperature as a one degree of freedom
Radiation surface	PFC and VV
Boundary conditions	▪ Temperature on the surface of PFC 1773 K ▪ Space temperature: 300 K
Maximum surface temperature	643.7 K



Contour plot of nodal temperature



Vector plot representing thermal gradient

Vacuum Pump Calculations

Assumptions

Pressure: 10^{-6} Torr
Pumping gas: air
Vacuum pump: Turbo Pump and Cryo Pump
No. of pumps: 2
Pumping speed: 2000 litre/sec, 3000 lt/s

Pumping Speed

$$\frac{1}{S} = \frac{1}{S_p} + \frac{1}{C}$$

Free mean path (air)

$$\lambda = \frac{5 \times 10^{-3}}{P}$$

Conductance elbow

$$C = 3.81\sqrt{\frac{T}{M}}\frac{D^3}{(L_1 + L_2)}$$

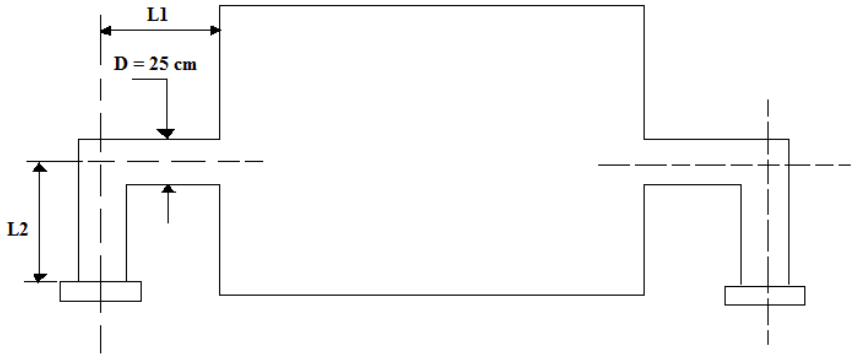
Total gas load

$$Q_g = Q_L + Q_D + Q_P$$

Where $Q_D = q_D S$

Time required for lowering the pressure in the chamber from P_i (initial) to P is given by

$$t = \left(\frac{V}{S_t}\right)\left[1+\left(\frac{S_t}{C}\right)\right]\ln\frac{P_i - \left[1+\left(\frac{S_p}{C}\right)\right]P_0 - \left[1+\left(\frac{P_0}{P_p}\right)\right]P_u}{P - \left[1+\left(\frac{S_p}{C}\right)\right]P_0 - \left[1+\left(\frac{P_0}{P_p}\right)\right]P_u}$$



Notations

- S_t =Theoretical pumping speed of pump, litre/sec
- S_p = Real pumping speed, litre/sec
- S = Pumping speed
- P_i = Initial pressure inside chamber, Torr
- P_o = Lowest pressure of pump, Torr
- P = Ultimate pressure, Torr
- P_u = Ultimate pressure due to gas load, Torr
- C = Conductance, litre/sec
- V = Volume of chamber, litre

- The total effective specific speed S_{eff} = 3500 lt/sec
- The ultimate pressure in the chamber Pu = 6.884 x 10^{-7} Torr
- Total out gassing rate Q_D = 1.094 x10^{-3} Torr litre/sec
- Time required is t = 68 min (approx)

Conclusions

A conceptual design approach of setting up HHF test facility at IPR has been discussed and high lighted the features of the vacuum chamber with the design calculations. Theoretical calculations were done to support the conceptual design and FEA structural analysis was carried out to identify the deflections and observed to be in the safe limit. Through radiation analysis, the surface temperature inside the chamber is determined which gives an outline for the cooling of the chamber.

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Continued….

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Thank you!