DOUBLE-NULL DIVERTOR DESIGN FOR JT–60SU, A 10 MAMP CLASS LONG PULSE TOKAMAK

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OUTLINE

A conceptual design of the divertor configuration for a next generation long pulse, double-null, high triangularity tokamak is presented. As a specific example, the projected performance characteristics of the JT–60SU device during its D-D operation phase were used.

1) Discussion of Advantages of Symmetric Double Null Design

2) Overview of Plasma characteristics, Equilibrium Shape & Baffle Shapes

3) Estimated Heat Flux and Thermal Design of Divertor PFCs

4) Estimated Mechanical Stress from Halo Currents and Vessel Bake out

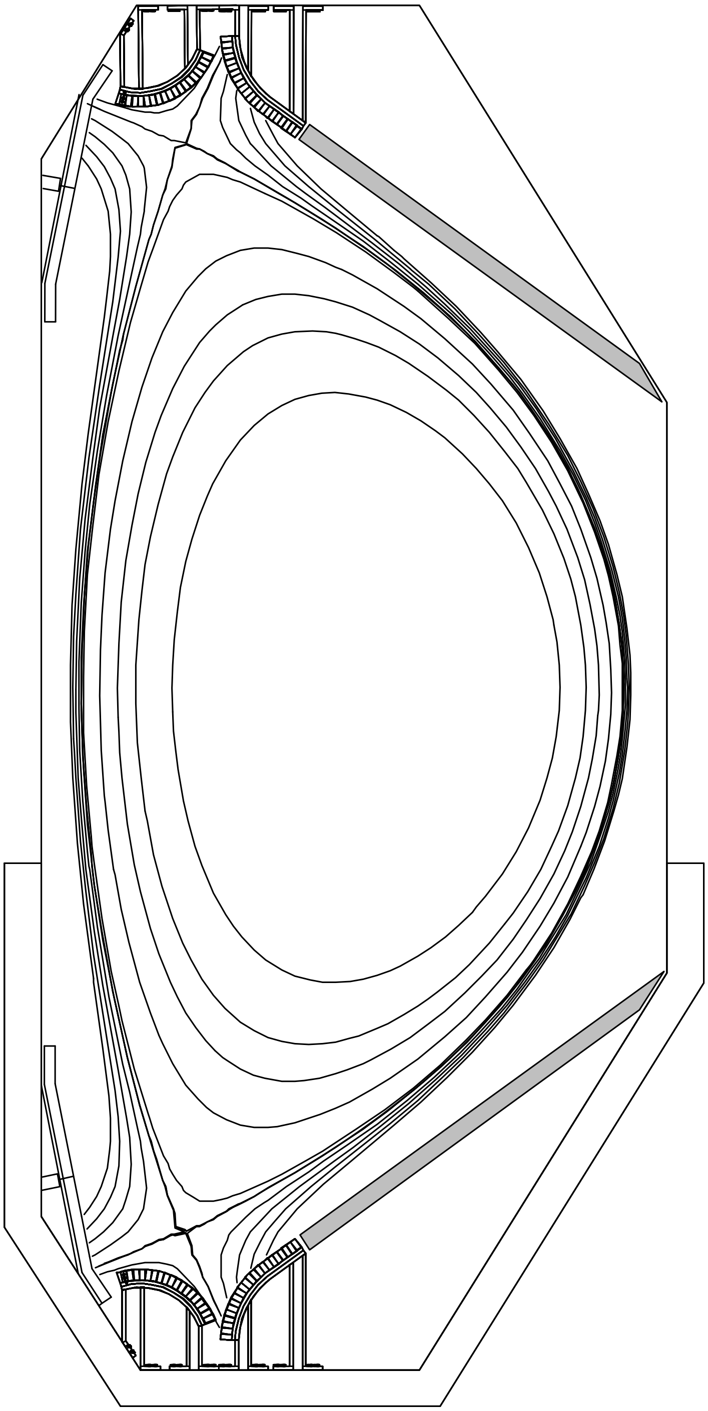
5) Discussion of Particle Pumping.

6) Summary

Symmetric Double Null Shape Has Performance Advantages

- **Demonstrated <u>higher performance</u> in Double Null (DN) compared to similar single–null configurations in DIII-D.**
- **DN shape can have <u>high triangularity</u>, both upper and lower.**
- **Higher triangularity allows <u>higher β</u> plasmas through increased plasma current for the same edge safety factor, q_{95}.**
- **This higher performance can result not only in higher equivalent fusion power, but also in <u>higher bootstrap</u> current fractions.**
- **A <u>reduction of the peak heat</u> load at the outer strike points is achievable in balanced DN.**
- **<u>Loss of vertical control</u> during disruptions is <u>minimized</u> when operating at the neutral point and a symmetric DN assures operation at the neutral point.**

JT-60SU Double Null Divertor Conceptual Design



Symmetric Design Recommended:

- Vertical Displacement Events can go up or down
- Small upward magnetic imbalance results in dominance of the upper divertor, in both heat and particle flux
- For a balanced double null, particle control best with symmetric pumping
- Designed for lower or upper single null operation

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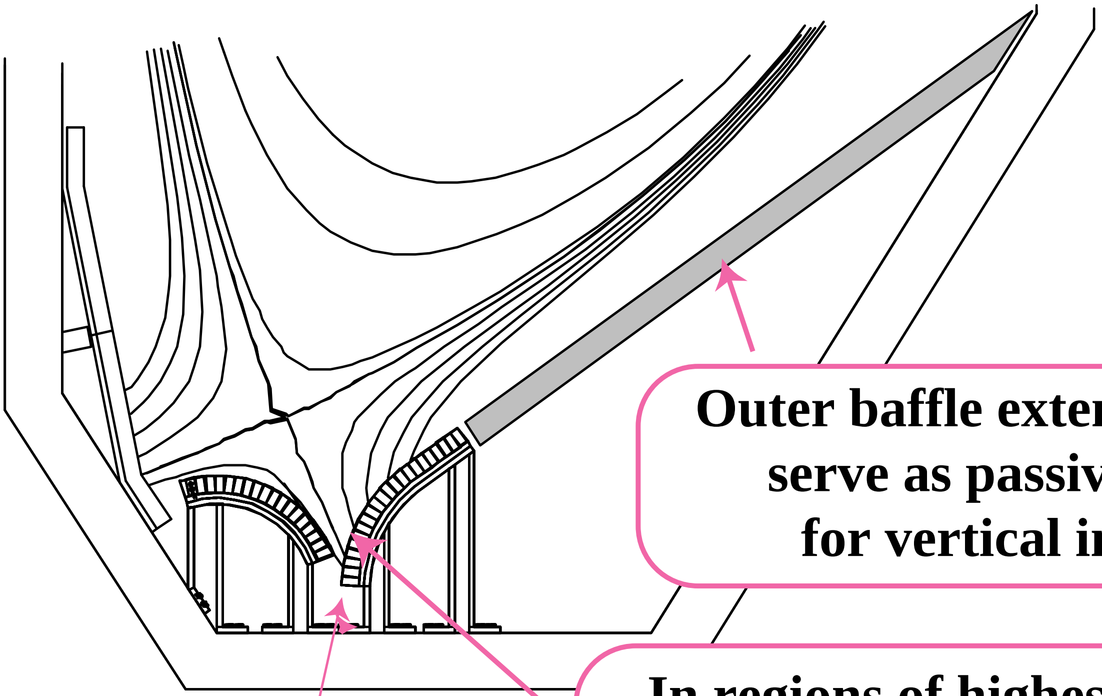
Baffles shaped to reduce peak heat flux and provide good neutral gas pumping



Outer baffle extension may also serve as passive stabilizer for vertical instabilities

In regions of highest heat flux small angle between baffle and flux surface is achieved

Pumping gaps large compared to gaps between baffles

- Baffles shaped to flux surfaces from the EFIT equilibrium reconstruction code

- Each baffle is segmented toroidally into forty five 8° sections for removal through midplane ports

EFIT Equilibrium used to define Divertor Flux Surfaces

I_p = 10 MA

B_t = 6.25 T

β_t = 1.62%

β_n = 1.45

β_p = 0.75

l_i = 1.04

δ = 0.63

κ = 2.01

a = 1.494 m

R_m = 5.168 m

q_{95} = 3.8

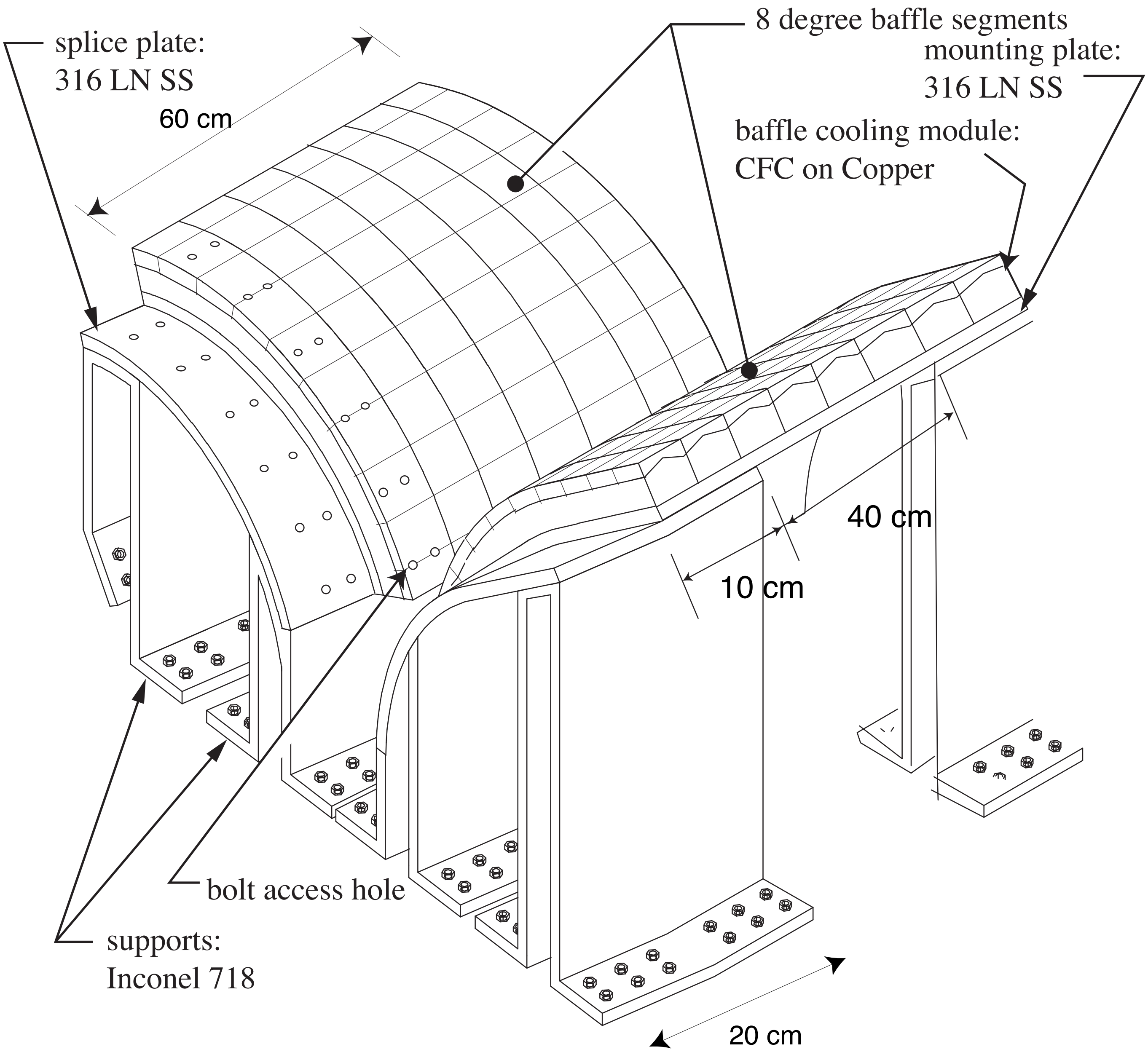
W_{dia} = 200 MJ

Equilibria at start and end of flat top flux states are essentially identical.

PF Coil and Plasma Parameters for IM and SOF & EOB Fiducial States

	Design Allowables	Initial Magnetization	EFIT SOF:	EFIT EOF:
Boundary Flux		70.4 Vs	8.9 Vs	-20.6 Vs
Center Flux		70.4 Vs	51.0 Vs	21.4 Vs
Coil Current (MA-t)				
PF1	6.72	0.2899	-3.0548	-3.2490
PF2	4.0	0.5799	-4.1864	-4.2388
PF3	7.84	6.1572	9.1397	6.2448
PF4 (CS)	20.2	18.4657	0.3516	-6.8260
PF5 (CS)	20.2	16.5245	-12.5272	-19.7693
PF6 (CS)	20.2	16.5284	-12.4447	-19.6517
PF7 (CS)	20.2	18.4547	0.2405	-6.9388
PF8	8.96	6.1556	9.1791	6.2450
PF9	4.8	0.5808	-4.1952	-4.2246
PF10	7.8	0.2900	-3.0586	-3.2709

3D Schematic of one segment of the private flux and outer baffles with twin vertical support struts



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Heat Flux Reduction Using Geometry

$$Q_{div,0} = \frac{P_{input}(1-f_{rad})\, f_{outboard/total}\, f_{gradB/total}\,(1-f_{pfr})\sin(\alpha)}{2\pi R_s\, f_{exp}\,\lambda_p\left(1+\dfrac{f_{exp}\,\lambda_p}{R_s}\right)}$$

PARAMETERS OF SINGLE-NULL AND DOUBLE-NULL CASES

	Single Null	Double Null
λ_p (m)	0.01	0.01
R_S — inboard (m)	3.5	3.5
R_S — outboard (m)	4.3	4.3
α (m) — inboard	85°	85°
α (m) — outboard	45°	45°
$f_{inboard/total}$	0.33	0.17
$f_{outboard/total}$	0.67	0.83
f_{exp}	7	7
f_{pfr}	0.1	0.1
$f_{gradB/total}$ — lower	1.0	0.6
$f_{gradB/total}$ — upper	—	0.4

Peak Heat Flux at Inner & Outer Strike Points As a Function of Core Plasma Radiated Power

		Single-Null		Double-Null	
frad	Prad	Q0 inner	Q0 outer	Q0 inner	Q0 outer
	MW	MW/m^2	MW/m^2	MW/m^2	MW/m^2
.00	0	15.6	18.0	4.8 (3.2)	13.4 (9.0)
.25	20	11.7	13.5	3.6 (2.4)	10.0 (6.8)
.50	40	7.8	9.0	2.4 (1.6)	6.7 (4.5)
.75	60	3.9	4.5	1.2 (0.8)	3.4 (2.3)
1.0	80	0.0	0.0	0.0 (0.0)	0.0 (0.0)

The single null peak heat flux in the outer divertor at 50% radiated power fraction, i.e. 9 MW/m^2, is chosen as the design criterion.

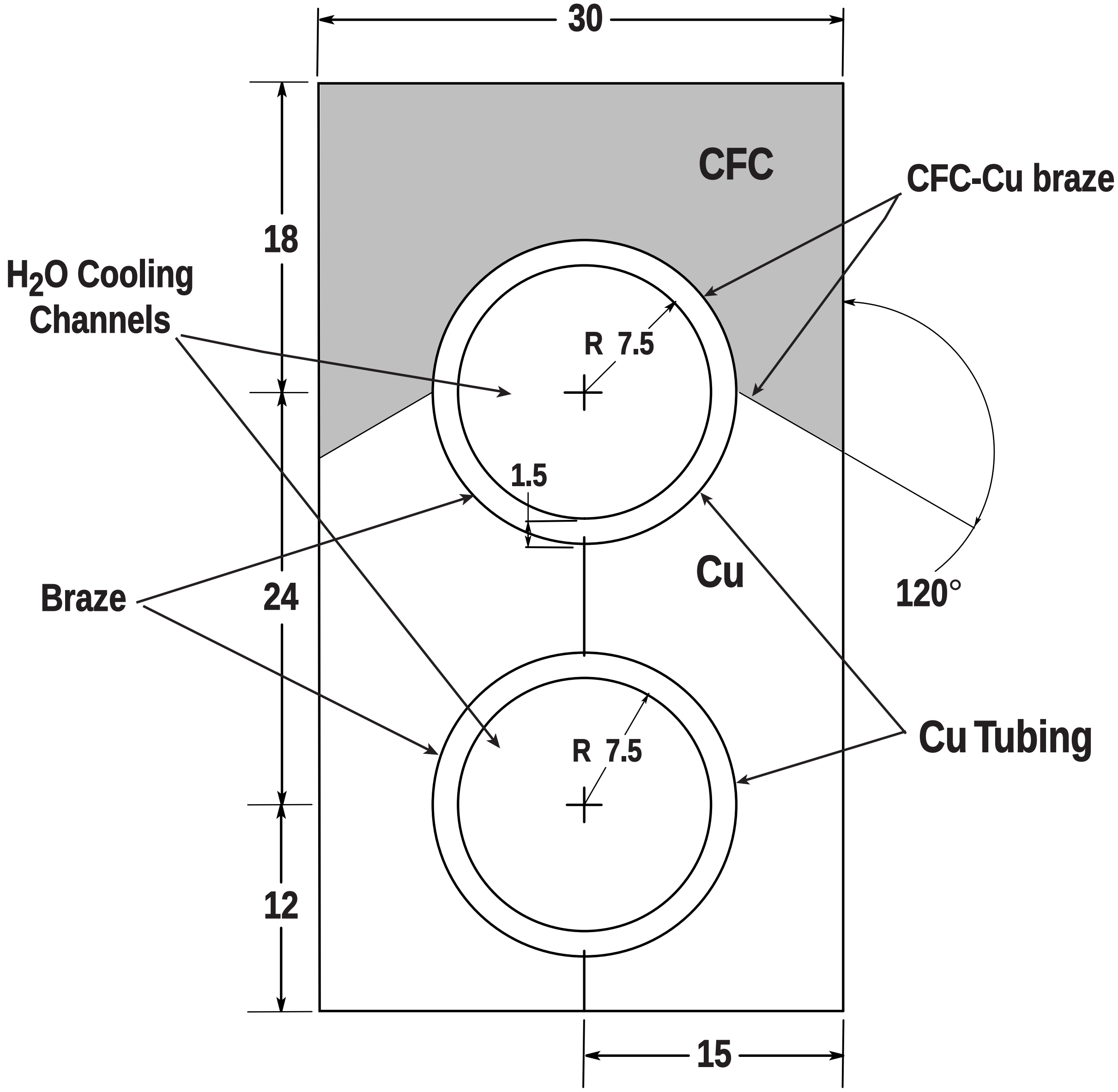
Strike Point Motion May Result in Excess Peak Heat Flux

- If the strike point locations are not well controlled and are allowed to “wander,” excessive heating of regions of the vessel not properly “armored” may occur.

- For example, the outer strike point may move onto the top of the lower private flux baffle. When this happens, the baffle receives considerable power, ≈14 MW/m^2.

- If the outer strike point moves away from its standard slot location and farther up onto the outboard baffle, local heating can again be relatively high as the angle α approaches 90 deg. In this case, the peak heat flux could be ≈12 MW/m^2 where $frad = 0.5$ and power input is 80 MW.

CROSS SECTION OF THE ACTIVELY COOLED TILES FOR THE JT–60SU DIVERTOR PLATES (mm)



Twist tape (twist ratio 2:1) in cooling channels to increase heat transfer

Cooling Water Flow Velocity Requirement Reasonable

- Finite element thermal analysis used to determine the peak cooling tube heat flux to be about 20% greater than the plasma facing surface heat flux.

Thermal Properties of the Carbon Fiber Composite

Temperature (°C)	**Thermal Conductivity (|| to Plasma-Facing Side) (W/cm-C)**	**Thermal Conductivity (⊥ to Plasma-Facing Side) (W/cm-C)**
0	0.35	5.7
500	0.2	3
1000	0.15	2.5

- All cooling modules connected in parallel

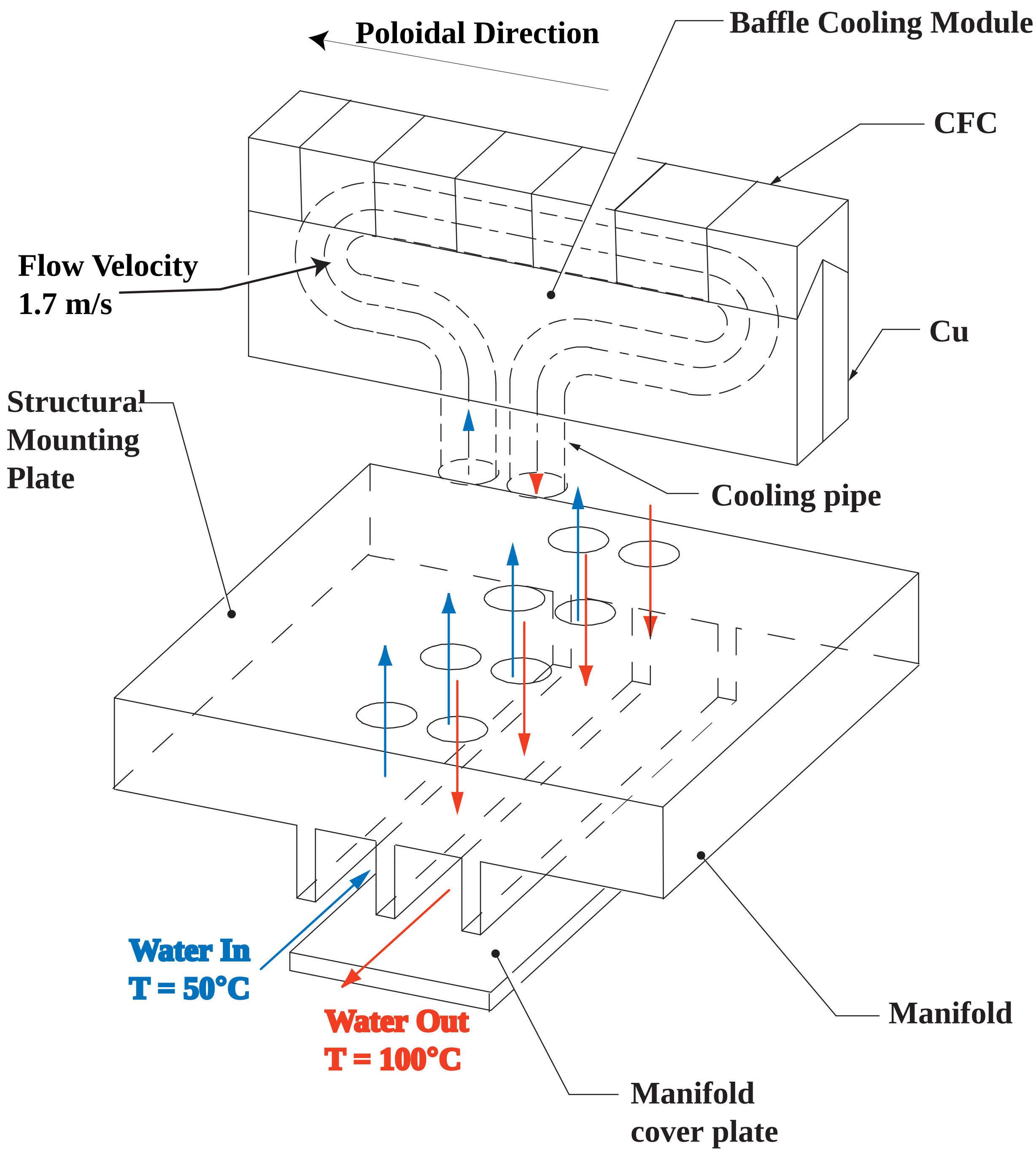
- Safety factor of 2, i.e. for 9 MW/m^2 at plasma facing surface the heat flux at cooling tube surface is 21.5 MW/m^2

- Flow velocity of 1.7 m/s is required, T_{in} 50°C, T_{out} 100°C

Flow and Power For Series/Parallel Connections

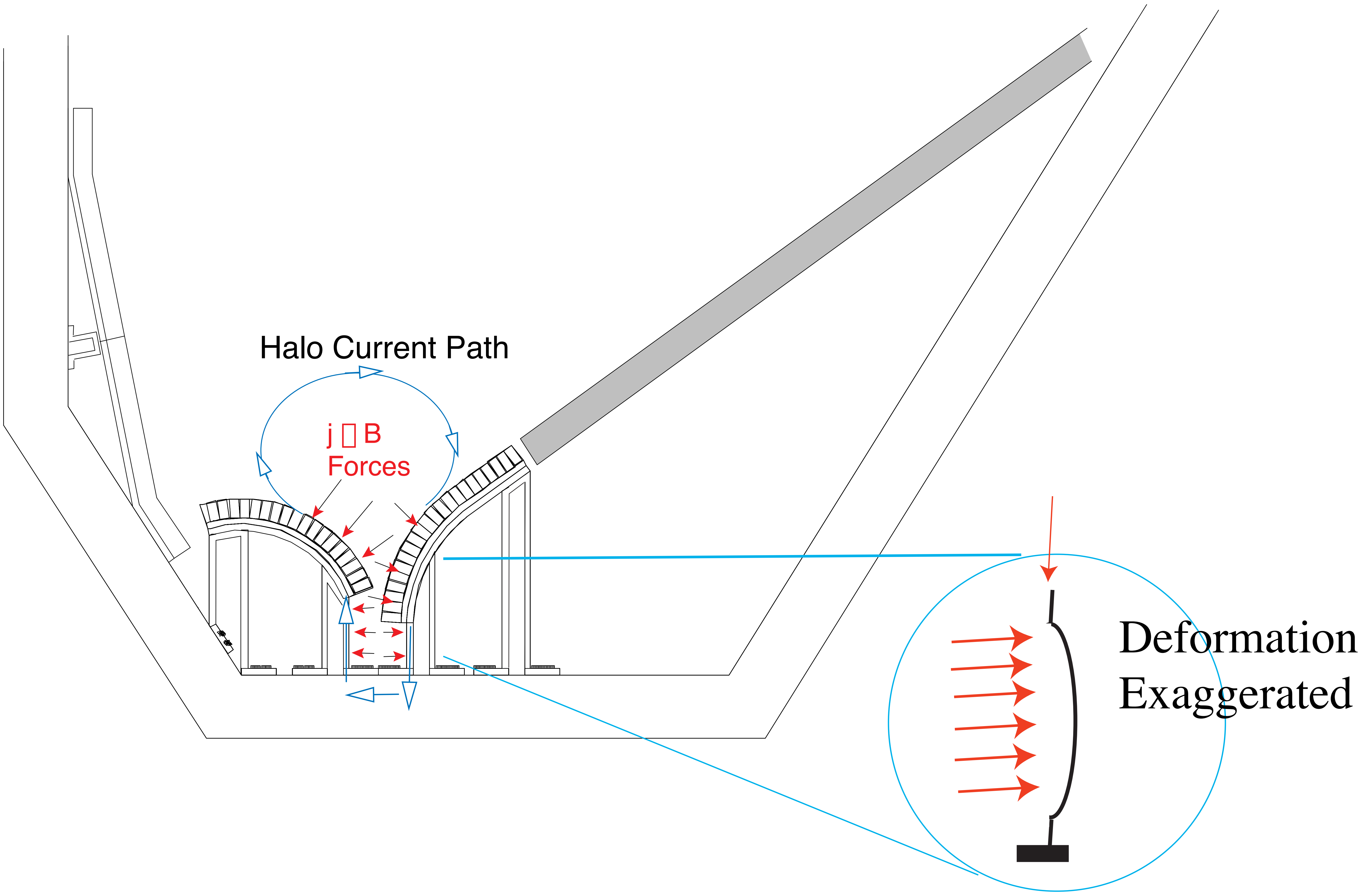
Number of Channels Connected in Series	Flow Velocity (m/s)	Flow in 45 Modules (l/s)	Pumping Power For Outer Divertor (W)
None	1.7	266	2240
2	2.2	172	3650
4	2.8	110	6080
12	4.8	63	23290

3D Schematic of Cooling Water Flow Path



Vertical displacement events cause poloidal halo currents

- Poloidal halo currents and the toroidal field produce j × B forces on divertor components
- 4.7 MAmp halo currents with 2:1 toroidal peaking factor predicted

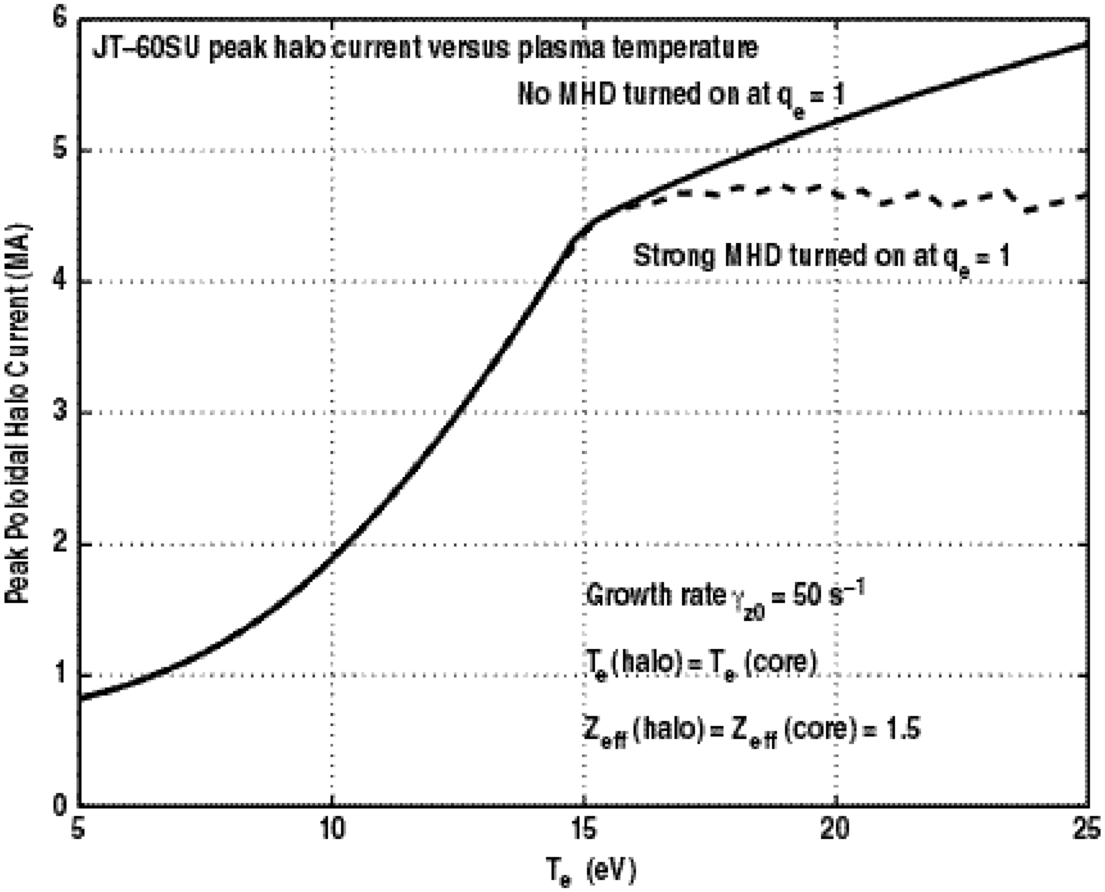


GA Halo Current Model

VDE Drives Halo Current By:

- Poloidal Field Induction
- Toroidal Field Induction
- Plasma Motion toward the Divertor Surfaces.

Benchmarked Against DIII-D,
Alcator C-Mod, JT-60U and Jet Data



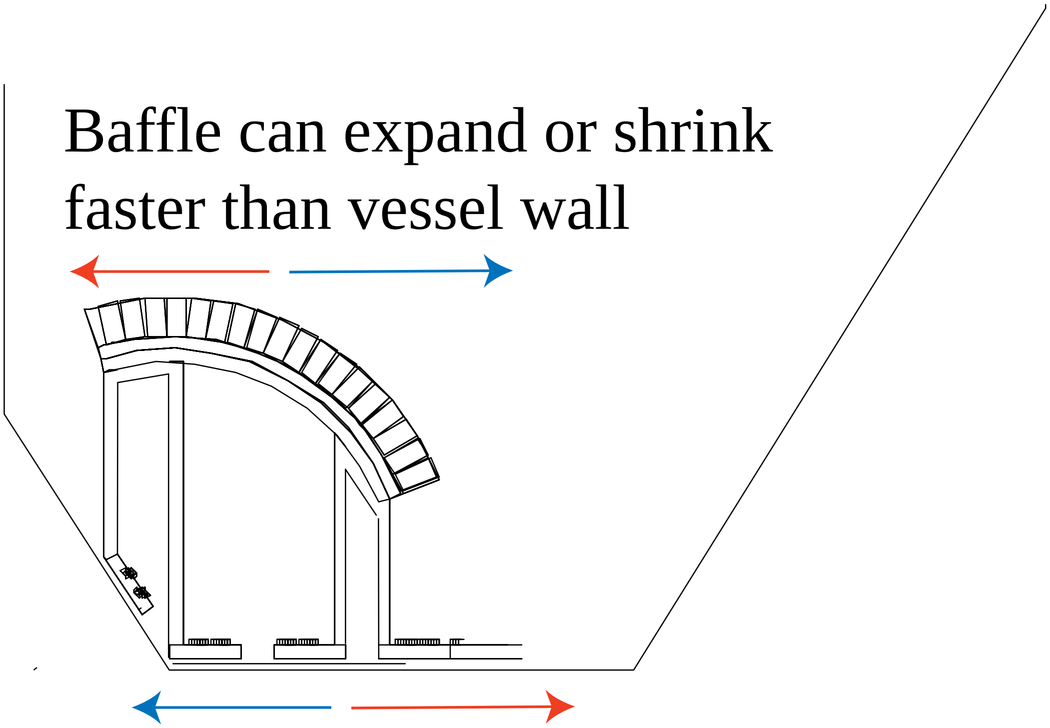
Post Thermal Quench Electron Temperature

Stress in support beams during vessel bakeout

- Vessel heated to 350°C for vacuum conditioning

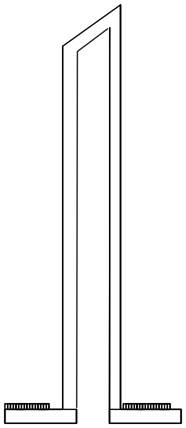
- Assume a temperature difference of 100°C can exist between vessel and baffle

- A radial growth differential of 0.7 cm is produced for 316 Stainless Steel



Baffle can expand or shrink faster than vessel wall

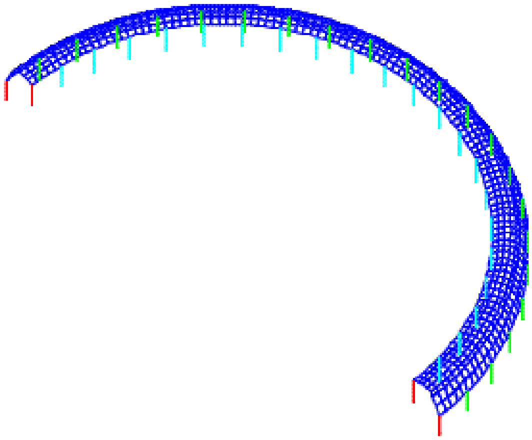
Twin Support Beams Needed For Stiffness and Flexibility



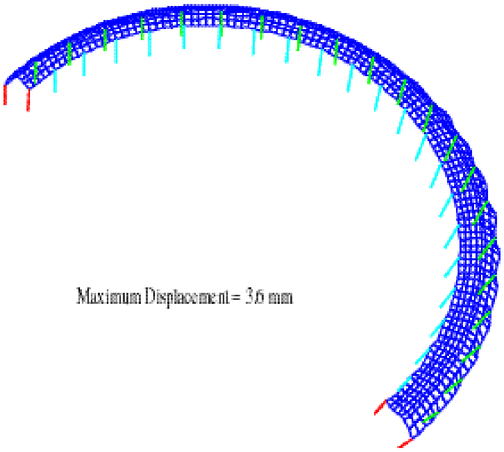
- Close proximity allows halo current to split between beams

- Each beam flexible enough to relax under thermal expansion stresses

Finite element model indicates acceptable stresses for both halo current and thermal expansion forces



Structural model of the private baffle with flexible plate supports



Deformed shape of divertor due to halo current loads

Calculated Peak Stresses

Condition	Location	Material	Peak Stress	Allowable
			MPa	MPa
Halo Current	Private Baffle	316 LN Stainless	223	241
Halo Current	Support Beam	Inconel 718	818	1035
Thermal Expansion	Private Baffle	316 LN Stainless	272	327 (@ 400°C)
Thermal Expansion	Support Beam	Inconel 718	614	1035 (@ 400°C)

Gas Throughput Most Stressful during Active Flow (“Puff and Pump”) for Impurity Radiation Control

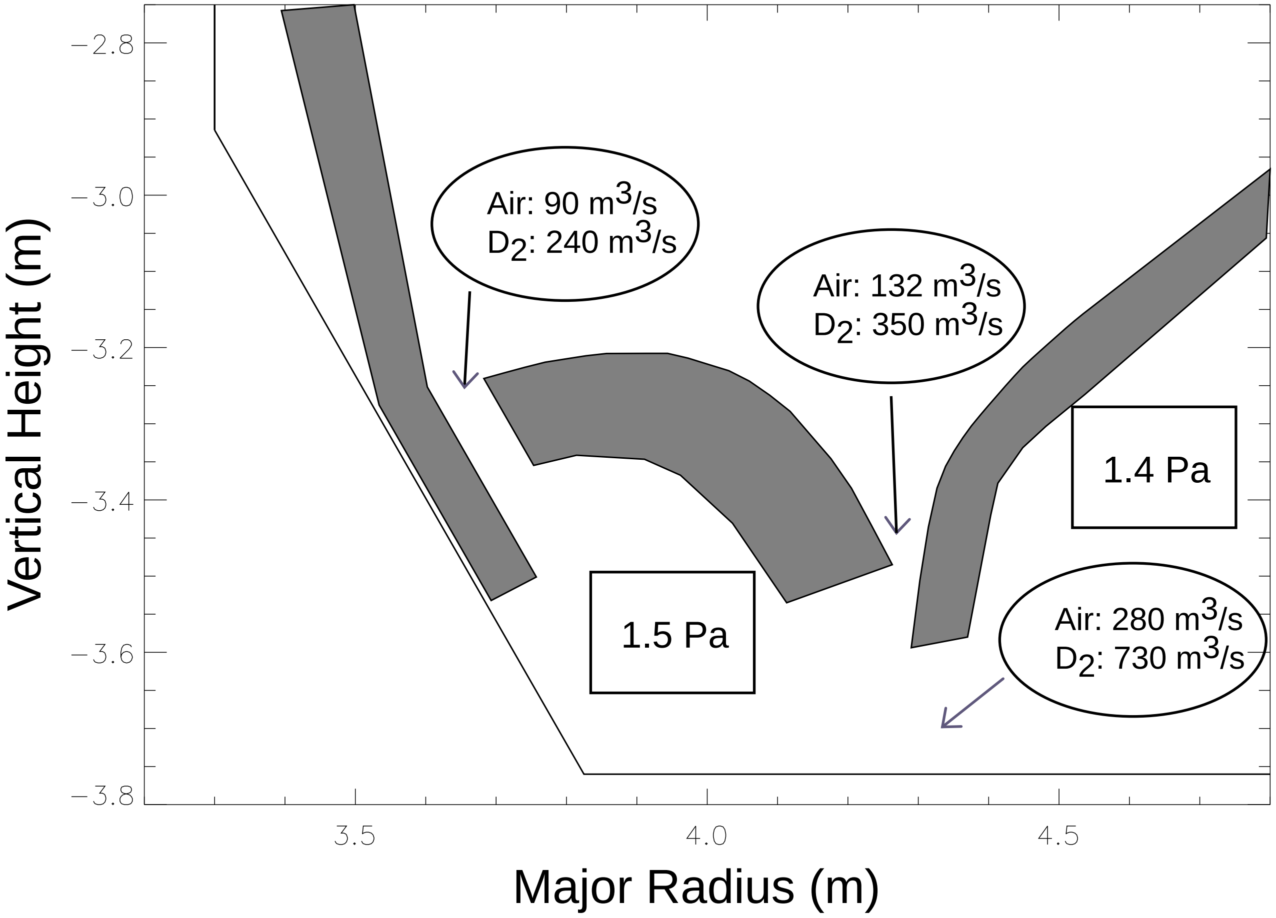
- Active control of plasma flow on DIII-D has been shown to enhance divertor radiation.

- Scaling from DIII-D results, assuming constant SOL width, yields a total throughput requirement of 50 Pa m^3/s of D_2.

- Conductance of divertor gaps estimated from Monte Carlo corrections to the simple aperture conductance formula.

- Gas pressure under baffles shown to be acceptable, about 1.5 Pa, under these strongly flowing conditions.

JT-60SU Divertor Gas Conductance and Baffle Pressures



Summary

- A conceptual design for a double null divertor for highly triangular, elongated plasmas in JT-60SU is presented. The design is suitable for the D-D operation phase.

- The design is contoured to flux surfaces to reduce the peak surface heat flux and to provide particle pumping.

- The thermal design is capable of single null operation in either divertor at full auxiliary heating power, assuming a modest 50% radiated power fraction.

- Structural support is designed to withstand the rather large forces predicted from a model of halo currents during vertical displacement events. It also has sufficient flexibility to withstand differential thermal expansion during vessel bakeout.

- This conceptual design is sufficiently robust to justify a continuation of detailed design.
  Strike Point Control with _ and l_i variations
  Detailed Mechanical Design
  Inner Baffle Design
  Remote Maintenance Considerations
  Diagnostic Access
  …