# Conceptual design of liquid metal cooled power core components for a fusion power reactor


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**and**

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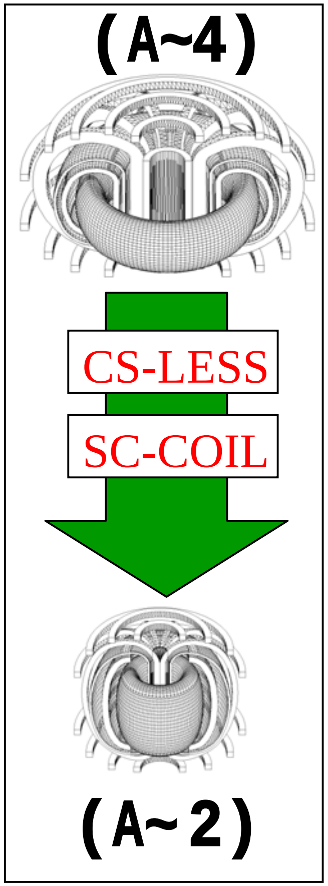
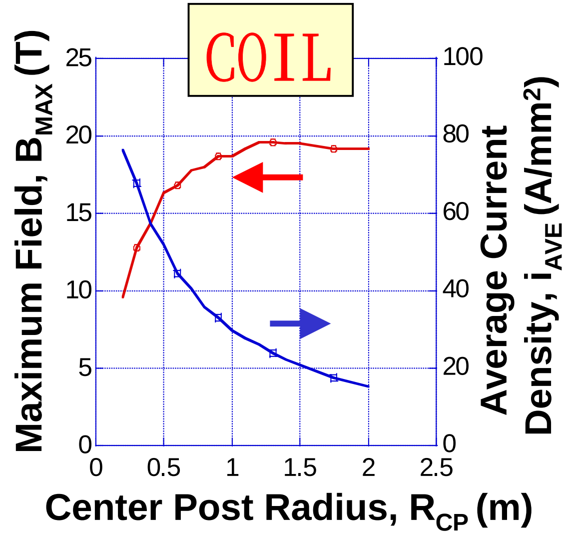
**Japan Atomic Energy Research Institute**

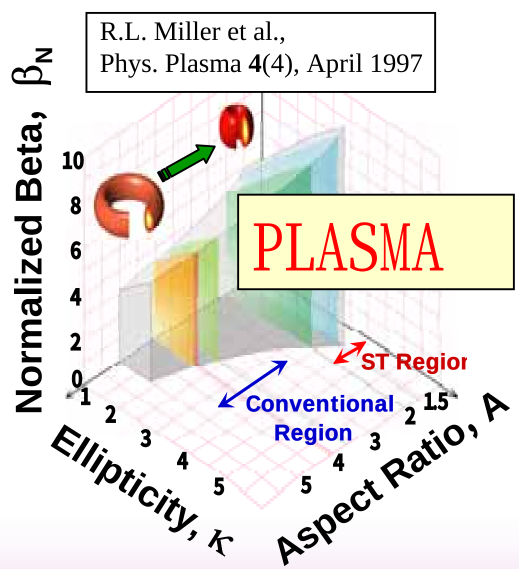

**Japan-US workshop on**
**Fusion Power Plants and Related Advanced Technologies with Participation of EU**

**Jan.11-13,2005 at Tokyo,JAPAN**

# Background of Research




**VECTOR**

**(S.Nishio 2002 IAEA)**

## Advantages:

- Light weight
- High β and B
- Small waste
- Economical aspect

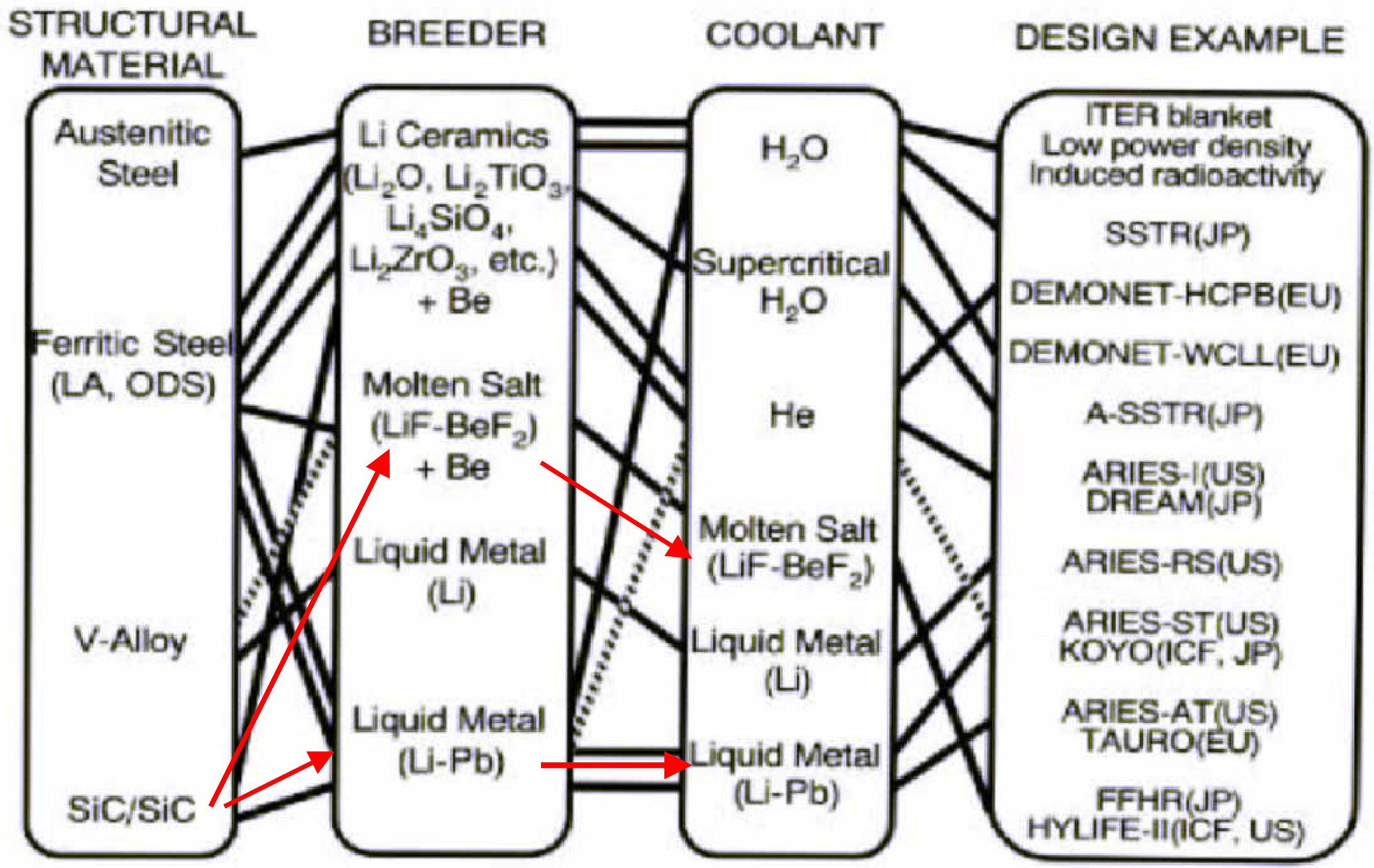
# Power core components Engineering:

0. Comparison and summary of former work on Blanket

**1. Design of Liquid metal self-cooled Blanket**

**2. Design of Plasma Facing Components**

3. Power Cycle




*How to choose*

Structure material: **SiC/SiC,V-alloy or Fe-Steel?**

Breeder ,Coolant material: **Li, LiPb or FLiBe?**

System: **Dual coolant or Self-coolant?**

## Compare of the three kinds structure materials

| | Weight Function | Fe-Steels | V-alloy | SiC |
|---|---|---|---|---|
| High temperature capability | **5** | **1** | **1** | **3** |
| Plasma disruption effect on the structure | **4** | **1** | **1** | **3** |
| Low activation | **4** | **1** | **2** | **3** |
| High heat flux capability | **3** | **2** | **3** | **2** |
| Mature development of fabrication | **3** | **3** | **3** | **1** |
| Low Economic Cost | **2** | **3** | **2** | **1** |
| High radiation damage resistance | **2** | **2** | **3** | **2** |
| Brittle fracture and Swelling behavior | **1** | **2** | **2** | **3** |
| **Total Score (Ideal score is 72)** | **Normal Distribution** | **40** | **41** | **57** |

# Comparison of the three kinds Coolant materials

| | Weight Function | Li | FLiBe | LiPb |
|---|---|---|---|---|
| Efficiency of power plant | **5** | **2** | **1** | **3** |
| Safety : reliability against leak | **4** | **1** | **2** | **3** |
| Tritum breeding and control | **3** | **1** | **2** | **3** |
| Material compatibility | **3** | **1** | **2** | **3** |
| MHD issure | **2** | **2** | **3** | **2** |
| Reactivity to oxygen | **1** | **1** | **1** | **3** |
| Total Score **(Ideal score is 54)** | **Normal Distribution** | 25 | 32 | 52 |

**LiPb :**

Simple blanket structure

Easy tritum recovery

No need to exchange

MHD probably will have significant impact on pressure drop.

**FliBe:**

**The thermal conductivity is very low, high turbulence flow is required for heat transfer**

**The viscosity is much high,  Larger channel size are required for high turbulence flow**

**Tritium breeding capability is relatively limited**

# Compare of the Dual and self cooling blanket system

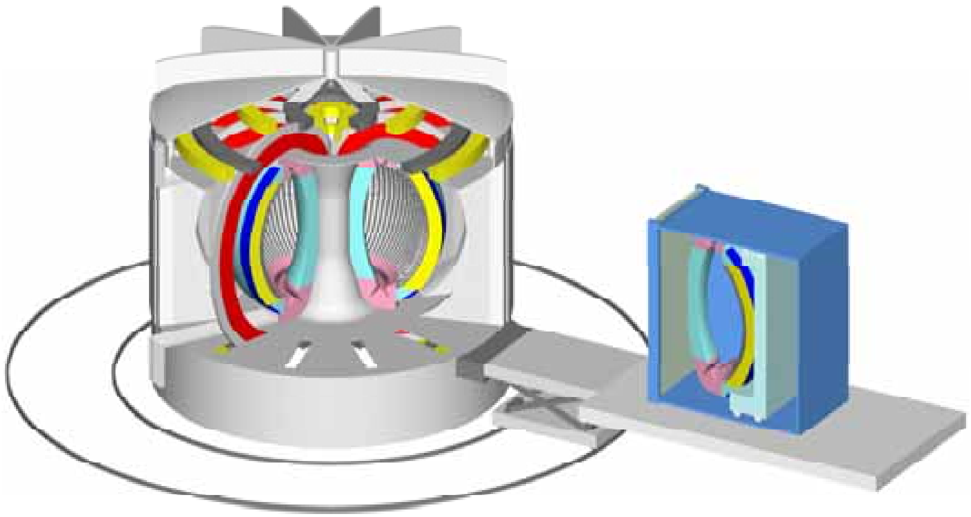
| Evaluation Item | Dual | Self-cooling |
|---|---|---|
| Simple blanket structure | Bad | Good |
| Maintenance of operation | Bad | Good |
| Ease of fabrication | Bad | Good |
| Potential net efficiency | Bad | Good |
| Probability of LOCA | Bad | Good |
| Insulator requirement for MHD | Good | Bad |
| General Score | Terrible | Excellent |

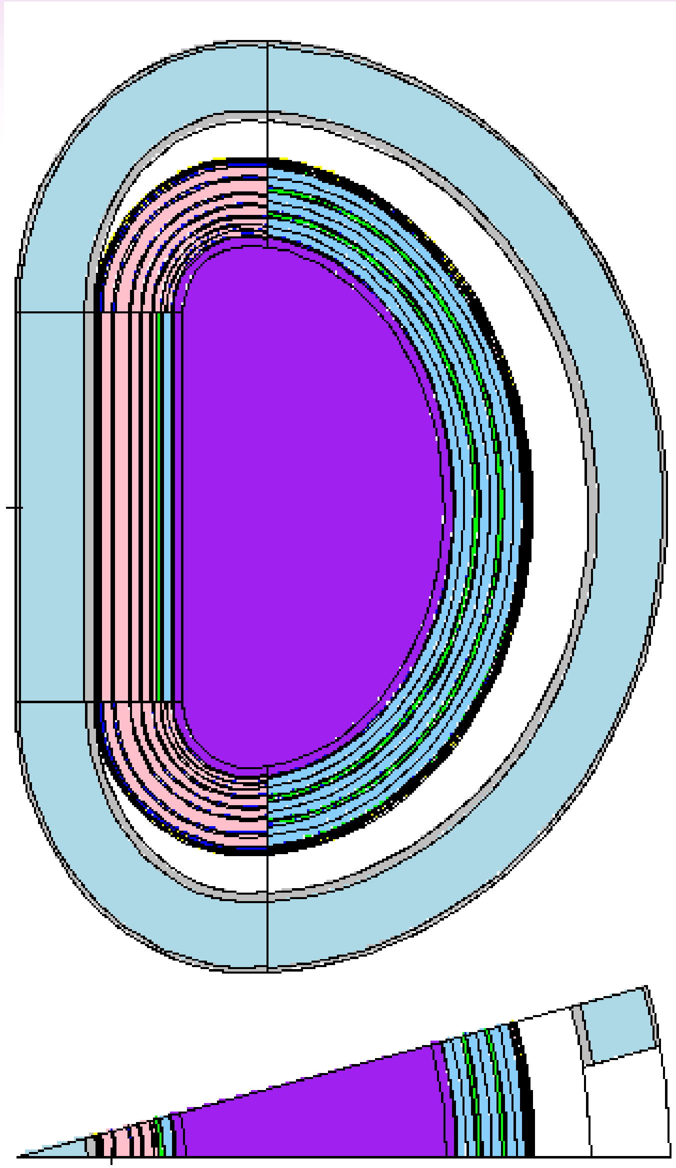
Attractive

- Structure material: SiC/SiC
- Breeder ,Coolant material: LiPb
- System: Self-cooled

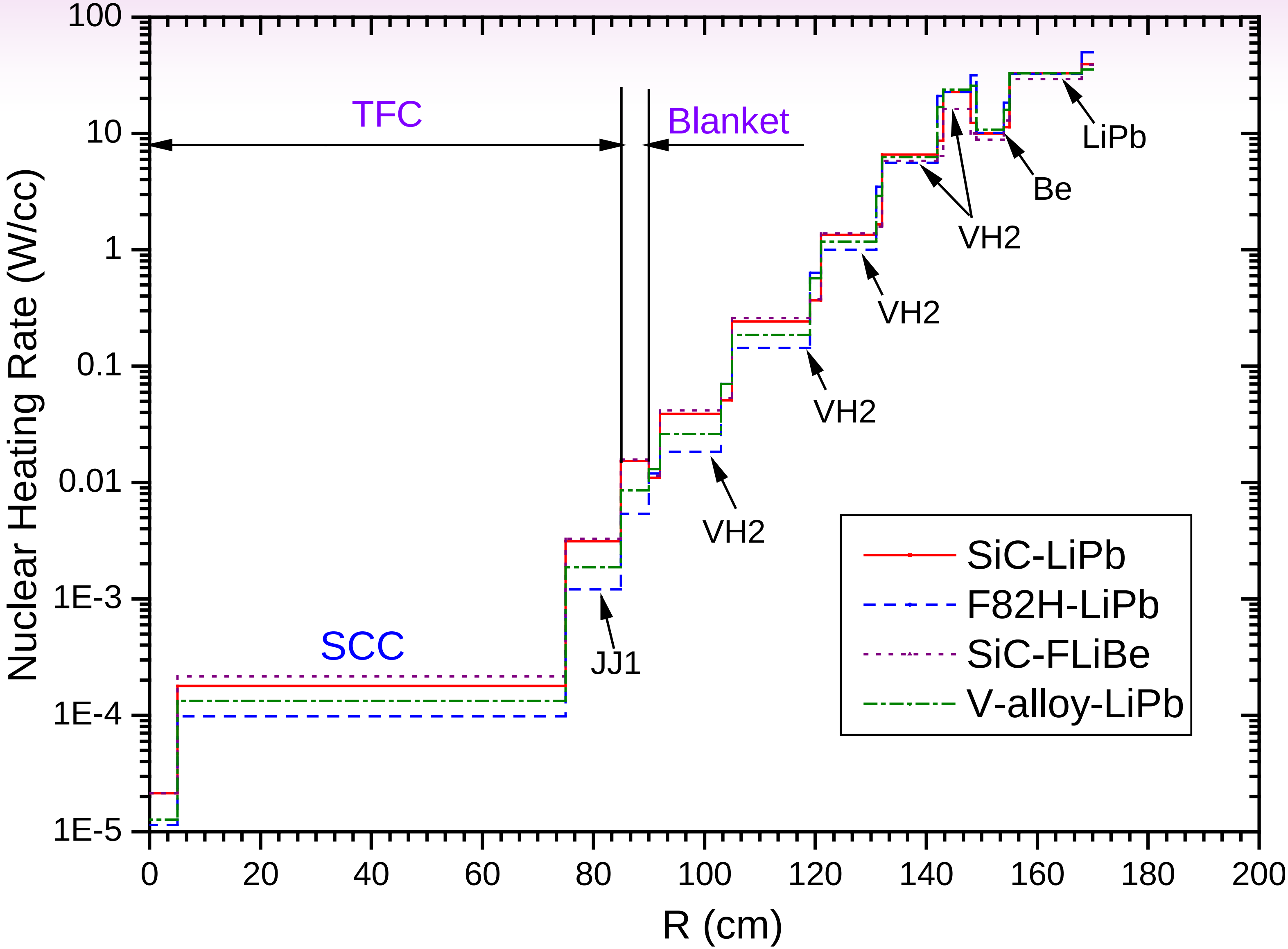
# Nuclear Analysis Model

Calculated by T.Nishitani





| | |
|---|---|
| **Plasma Major Radius :** | **$R_P$ = 3.2 m** |
| **Plasma Minor Radius :** | **$a_P$ = 1.4 m** |
| **Number of TF coils:** | **12** |
| **Vacuum Vessel:** | **SS316LN** |
| **Super conducting:** | **Bi-HTS** |
| **Fusion Power :** | **$P_F$ = 2.5 GW** |



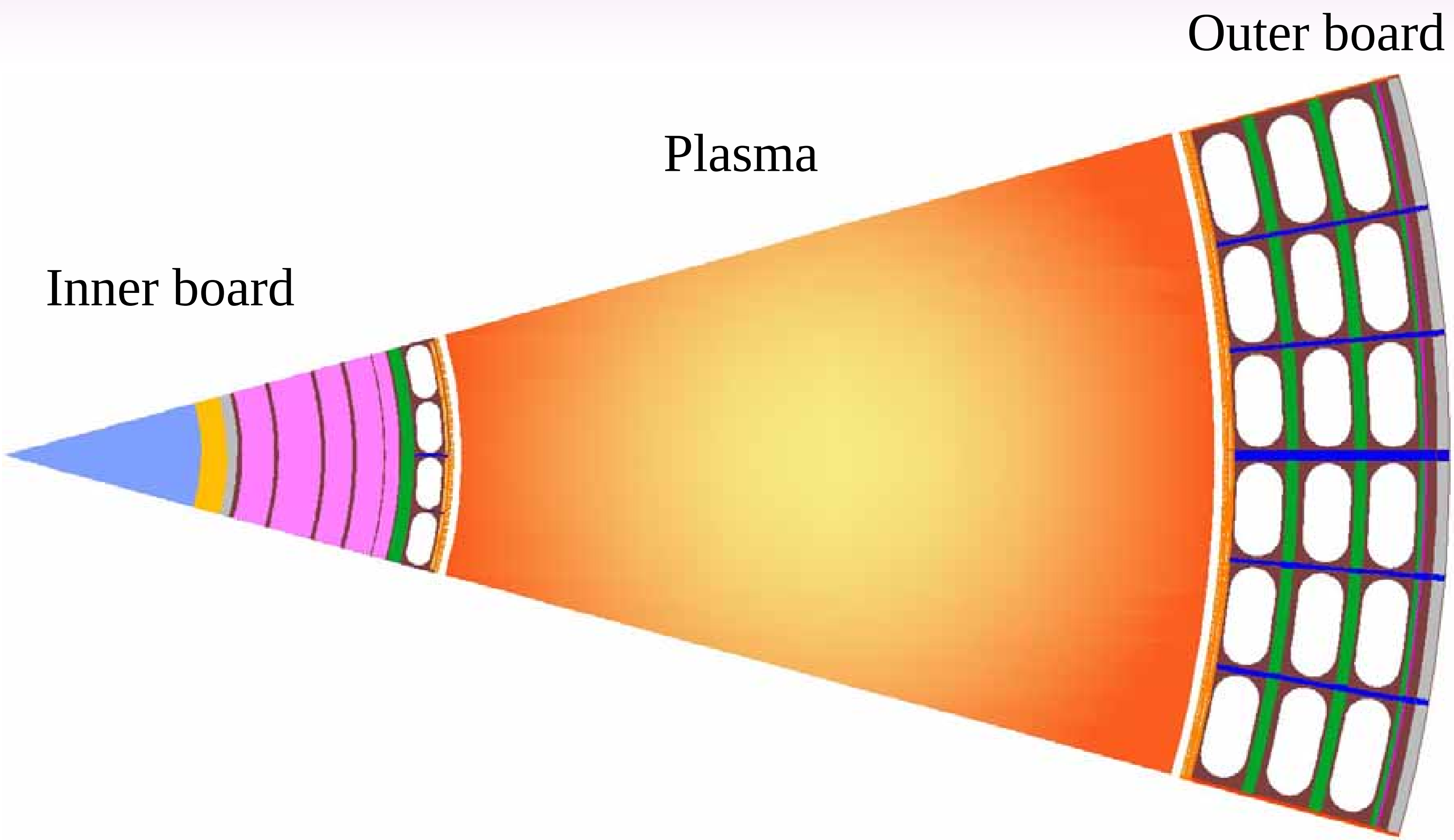

## Distribution of Nuclear Heating Rate

# Nuclear heating Analysis results (inner board)

| | case1 | case2 | case3 | case4 |
|---|---|---|---|---|
| **Structure material** | V-Alloy | SiC | SiC | F82H |
| **Breeding 、Multiply and Coolant** | LiPb | LiPb | FLiBe | LiPb |
| **Maximum Nuclear Heating Rate (W/cc)** | **35.4** | **39.4** | **38.9** | **49.9** |

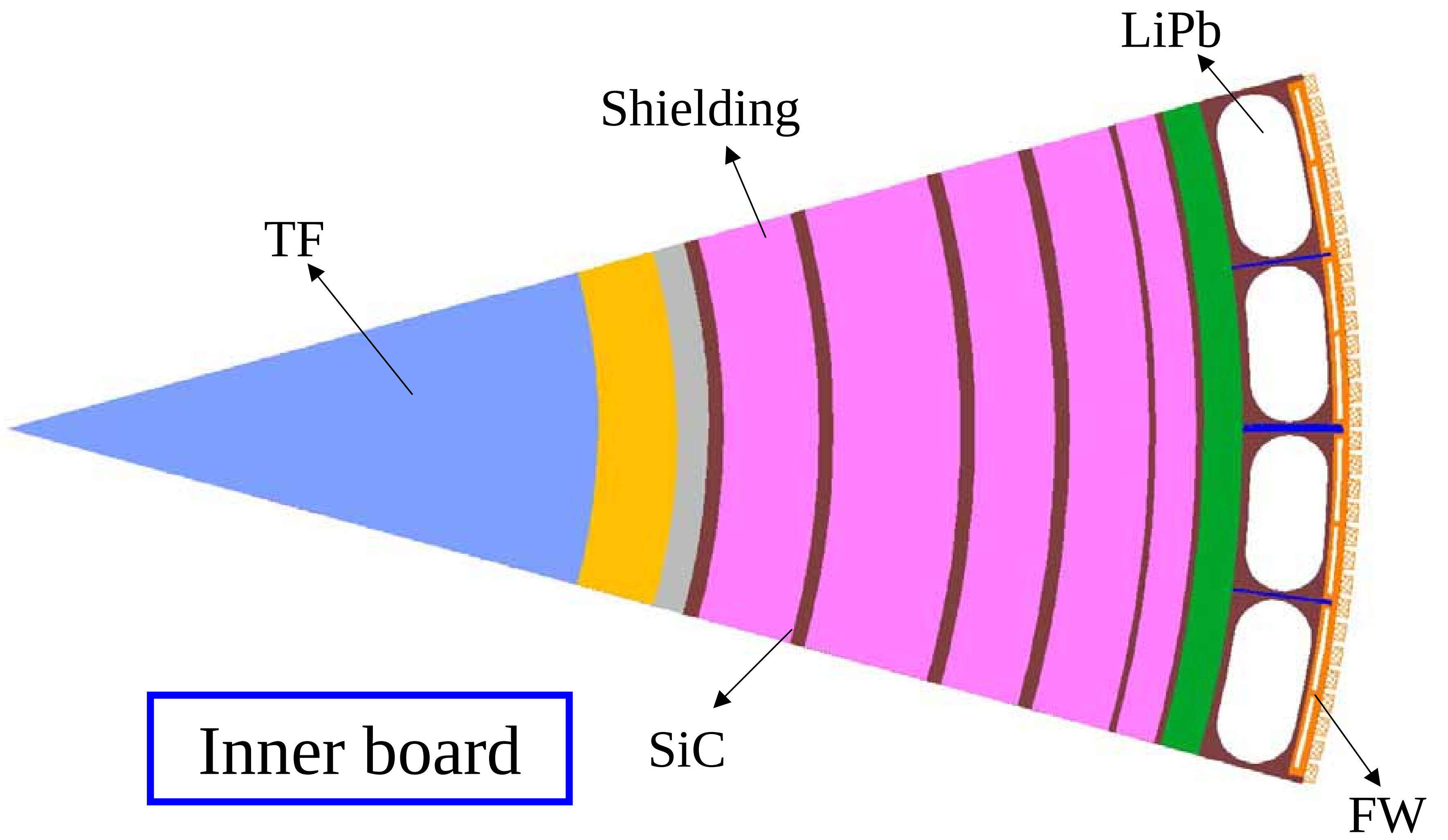
**1.Maximum nuclear heating on the First wall and LiPb: > 35 W/cc.**

**2. Maximum nuclear heating on the HTS TF coils: ≪1e-3W/cc.**



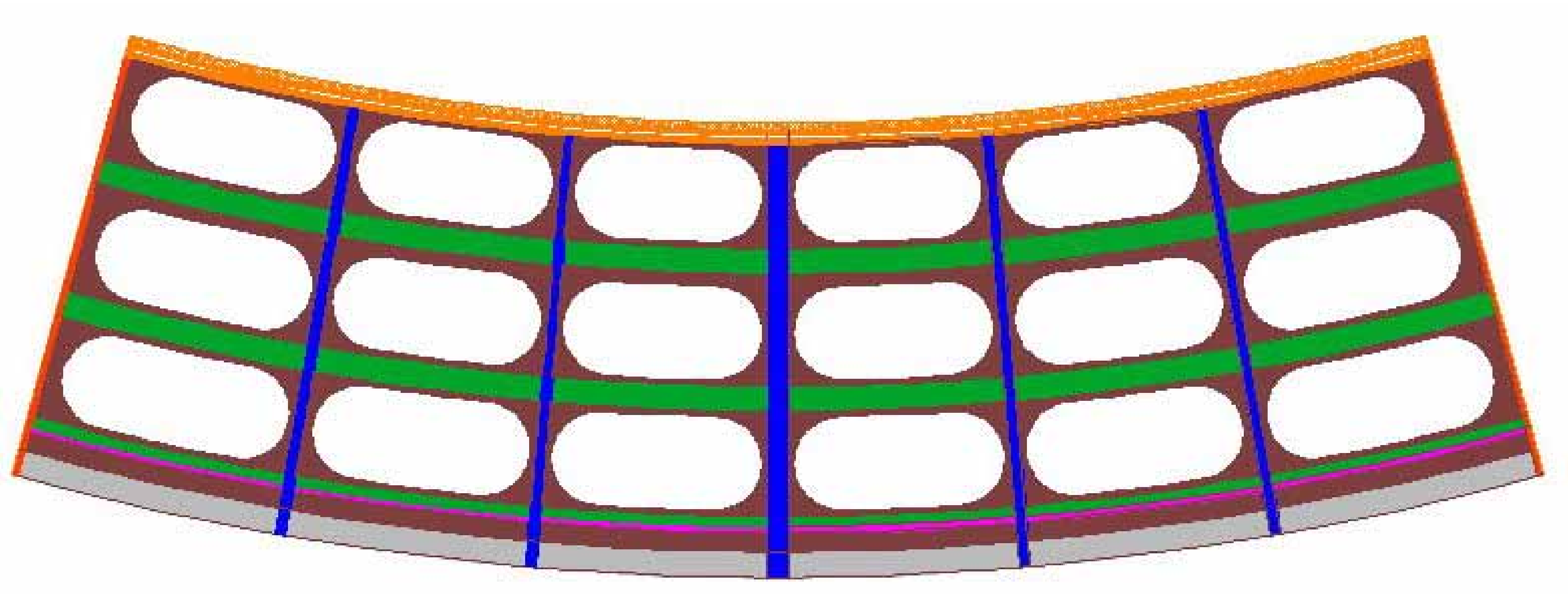

Cross section of the Low aspect ratio tokamak

# Concept Design Structure of IB for Low Aspect Ratio Tokamak

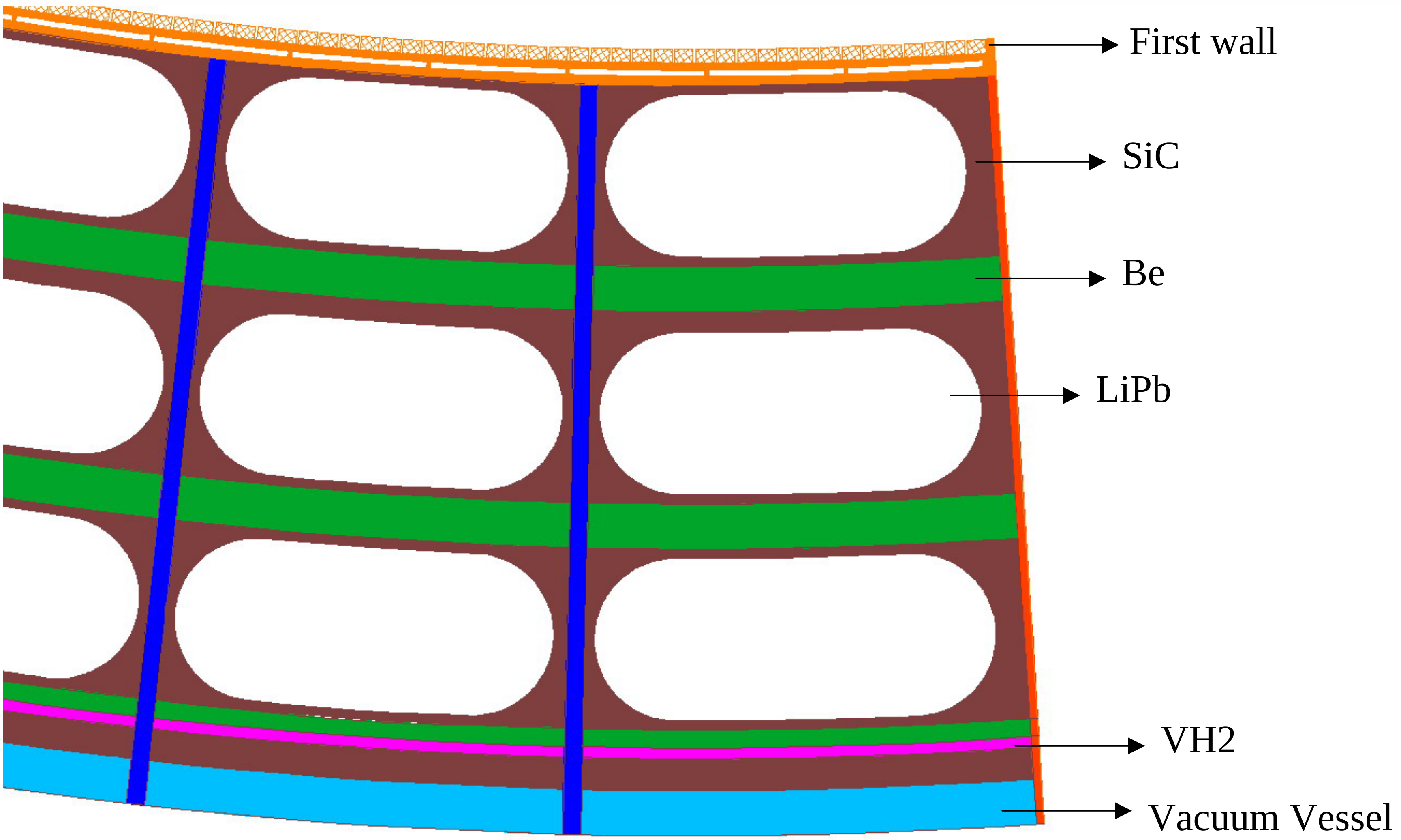



Inner board

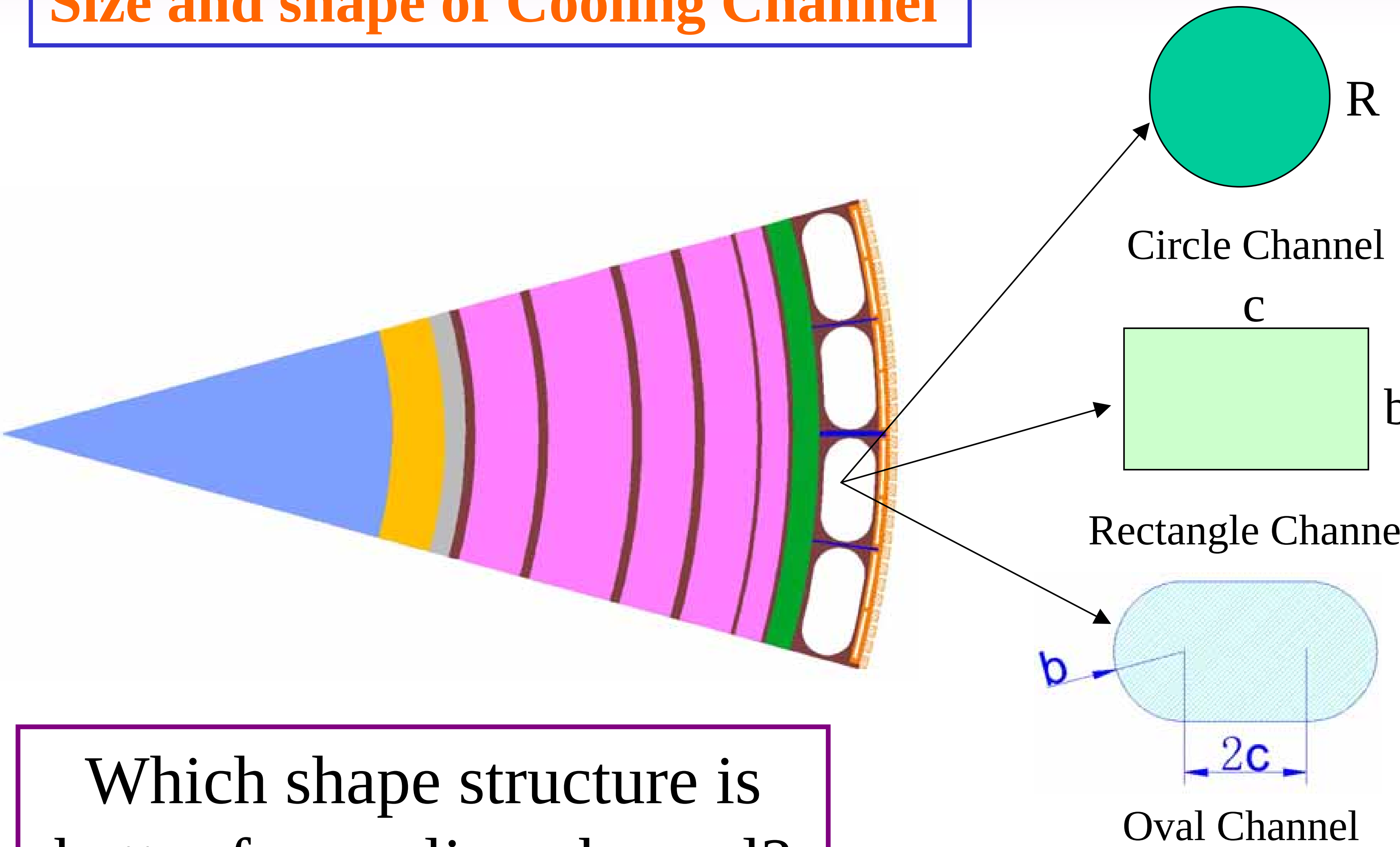
# Concept Design Structure of OB for Low Aspect Ratio Tokamak



**Outer board**


First wall
SiC
Be
LiPb
VH2
Vacuum Vessel

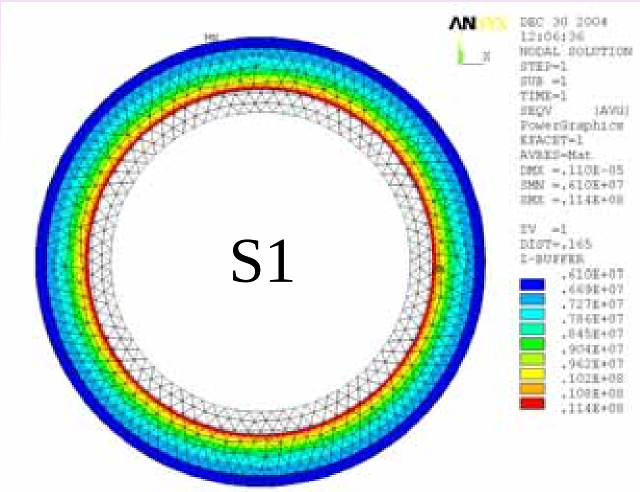
# Size and shape of Cooling Channel




Which shape structure is better for cooling channel?

**Optimization**

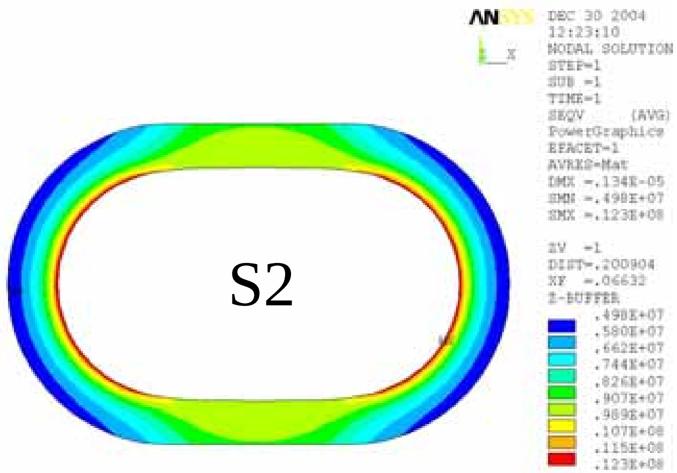
c/b =?

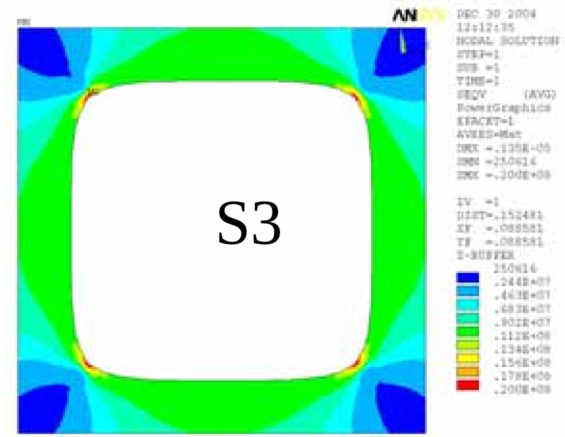



•**Cooling channel area: S1=S2=S3**

Perimeter: L1 < L3 < L2

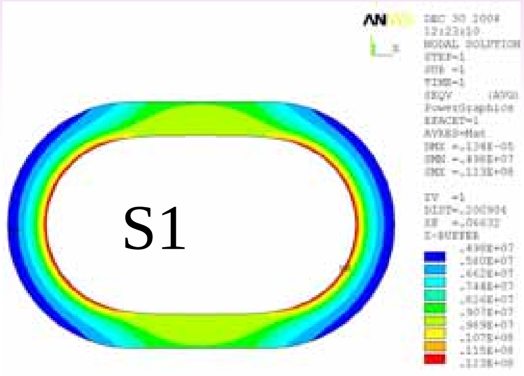
**Best**
**Candidate**
**Structure**

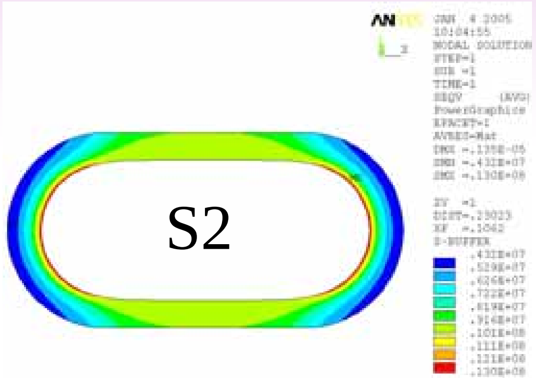


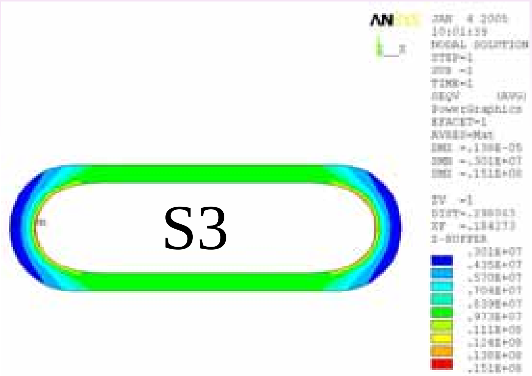




**Maximum Stress Intensity**

**Circle:Oval:Rectangle** ***1 : 1.2 : 2***

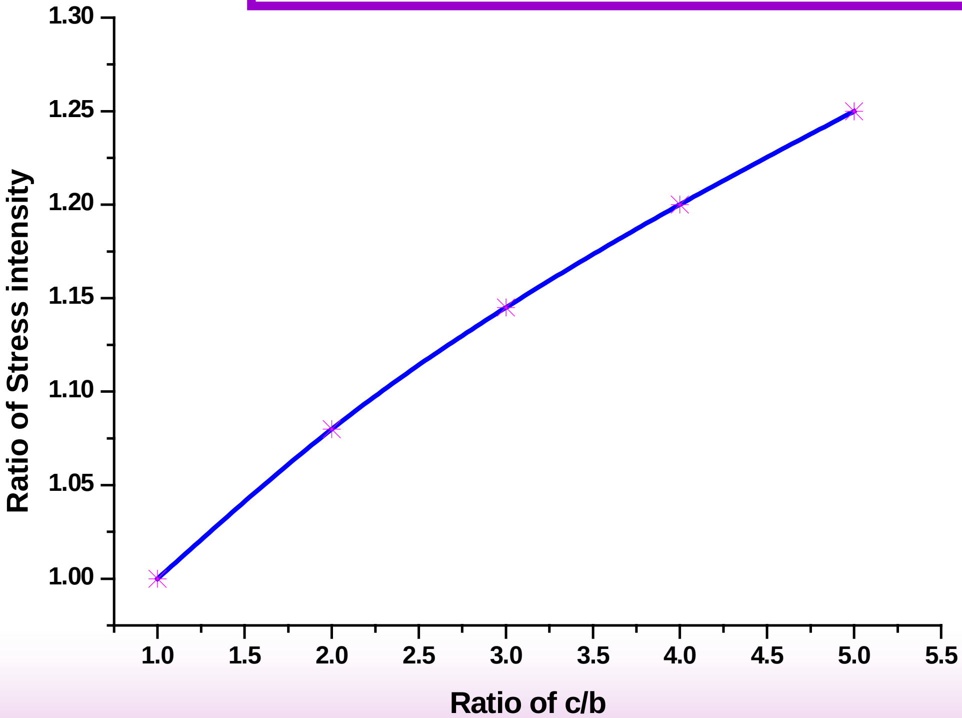


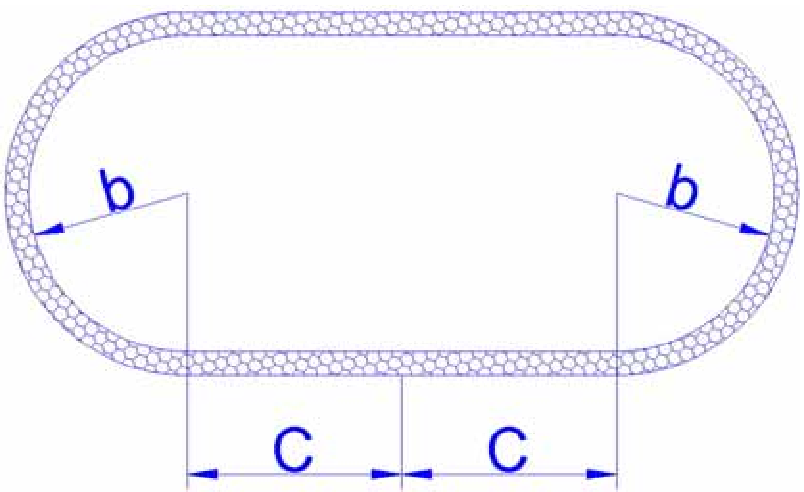


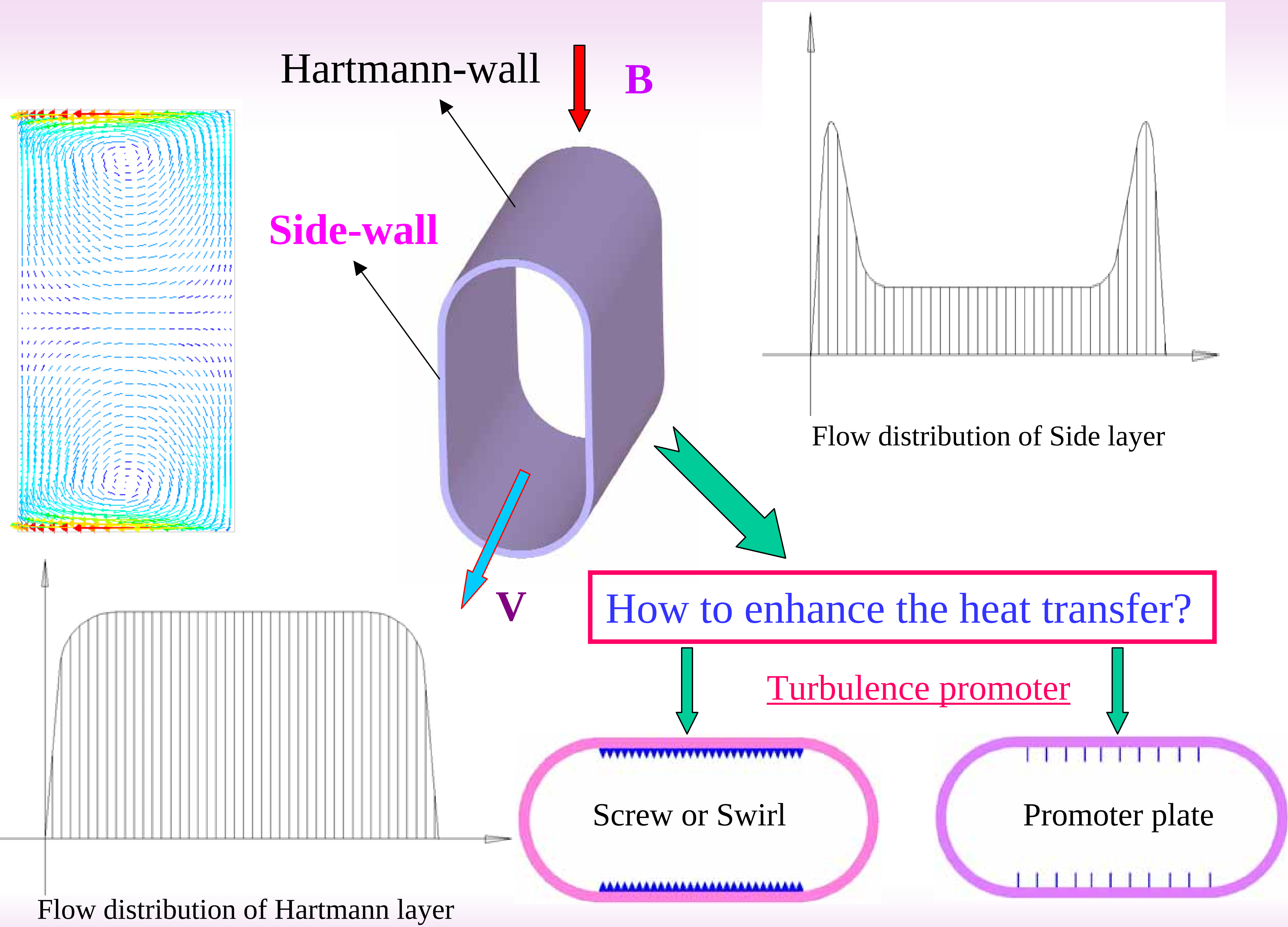



Area:  S1=S2=S3 ; Inner Pressure:P1=P2=P3

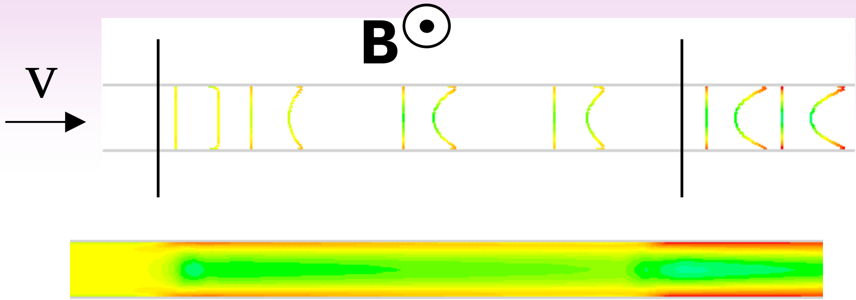
Stress intensity    1 : 1.2 : 1.5






Hartmann-wall
B
Side-wall
V
Flow distribution of Side layer
Flow distribution of Hartmann layer
How to enhance the heat transfer?
Turbulence promoter
Screw or Swirl
Promoter plate

# *MHD pressure drop*




1.Effect of material properties:

Conducting and Non-Conducting wall be compared

2. Effect of Channel shape:

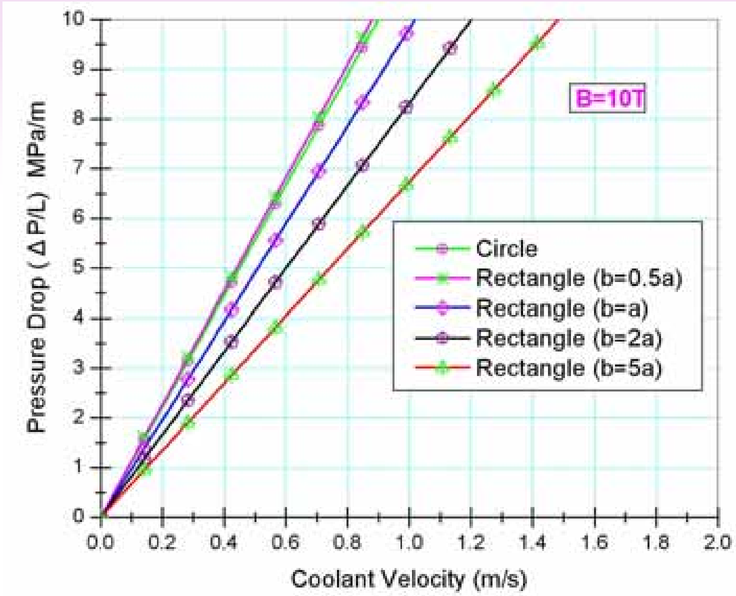
Irregular cross section, non-uniform wall thickness

3.Effect of Complex magnetic field (future work)

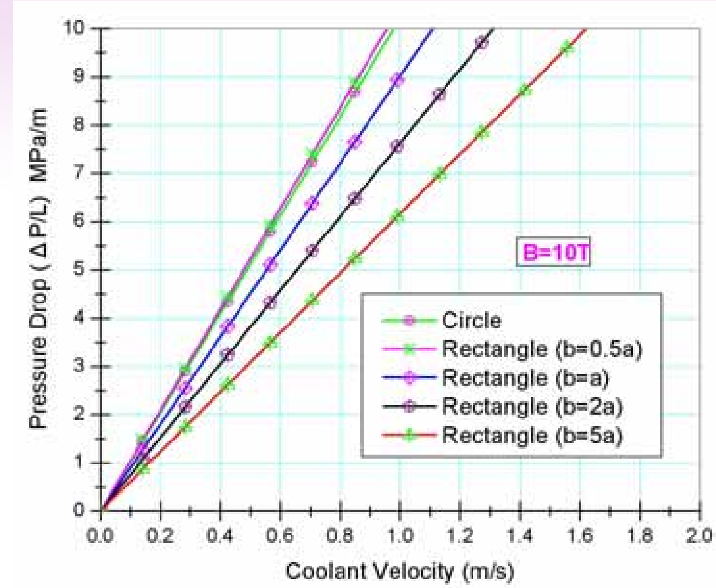
Angled field, field gradient, field ripple

4. Source of Turbulence and its effects(future work)

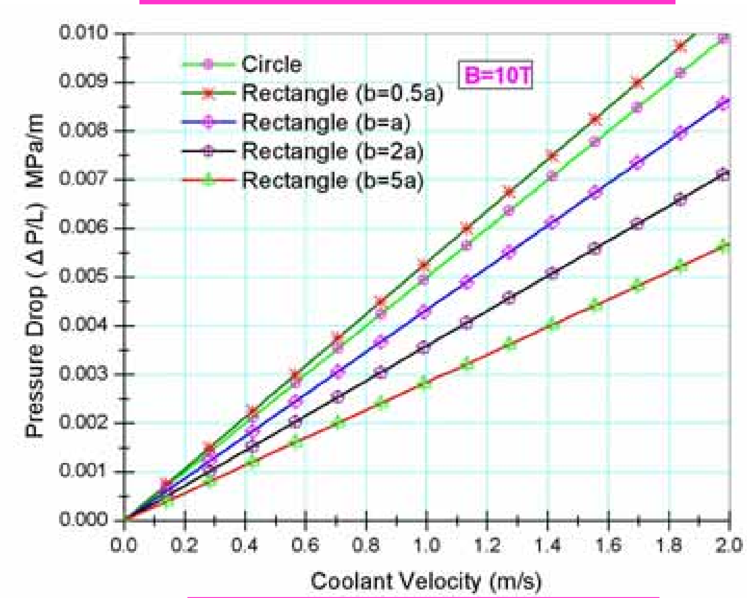
5. Effect of eddy current (future work)



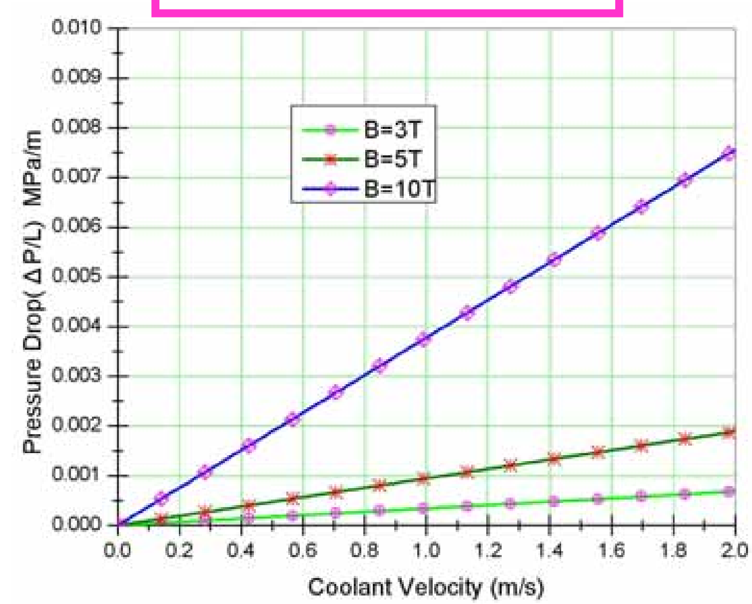

**Ferritic steel-LiPb**




**V-alloy-LiPb**

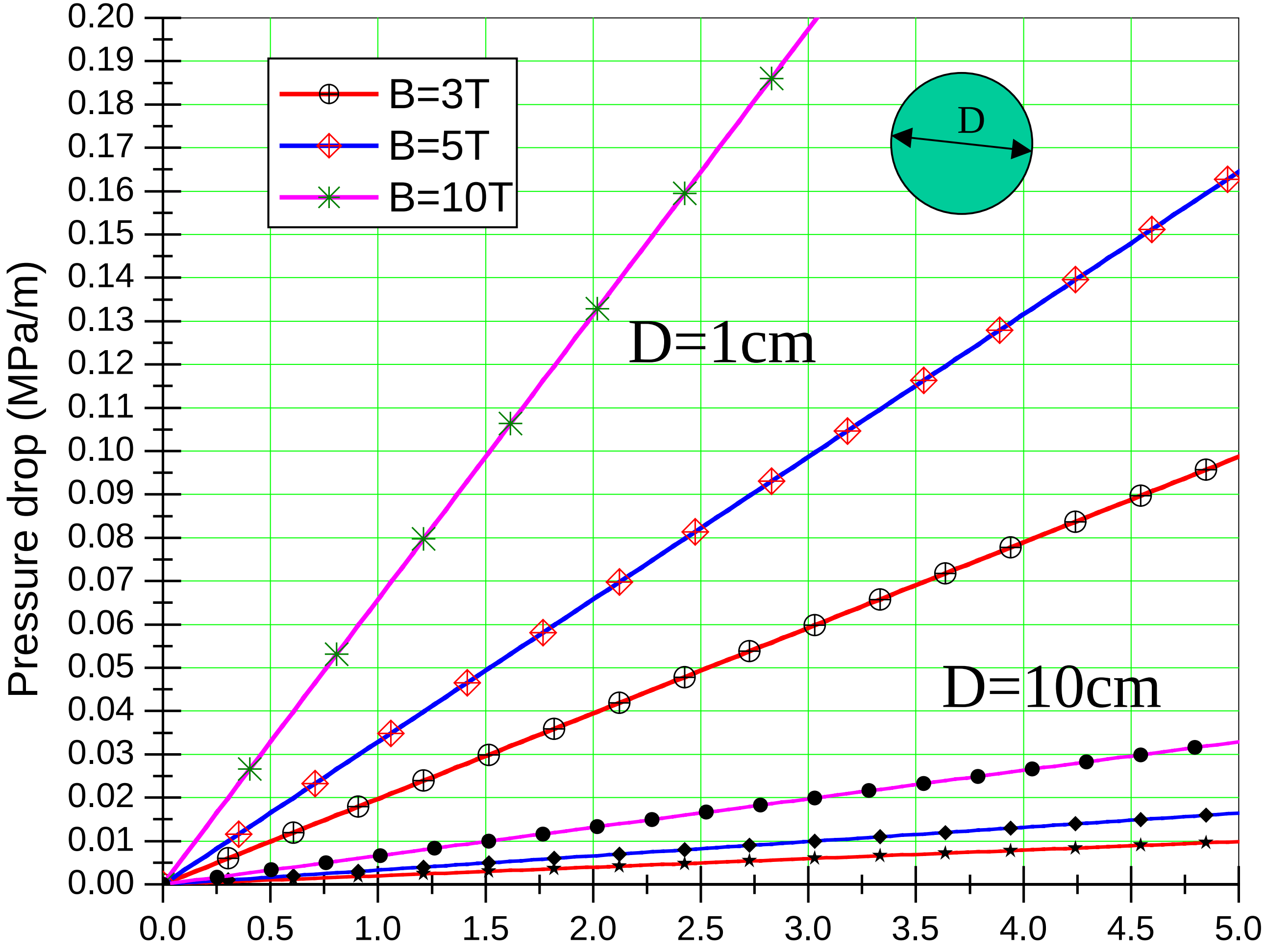



**SiC-LiPb**

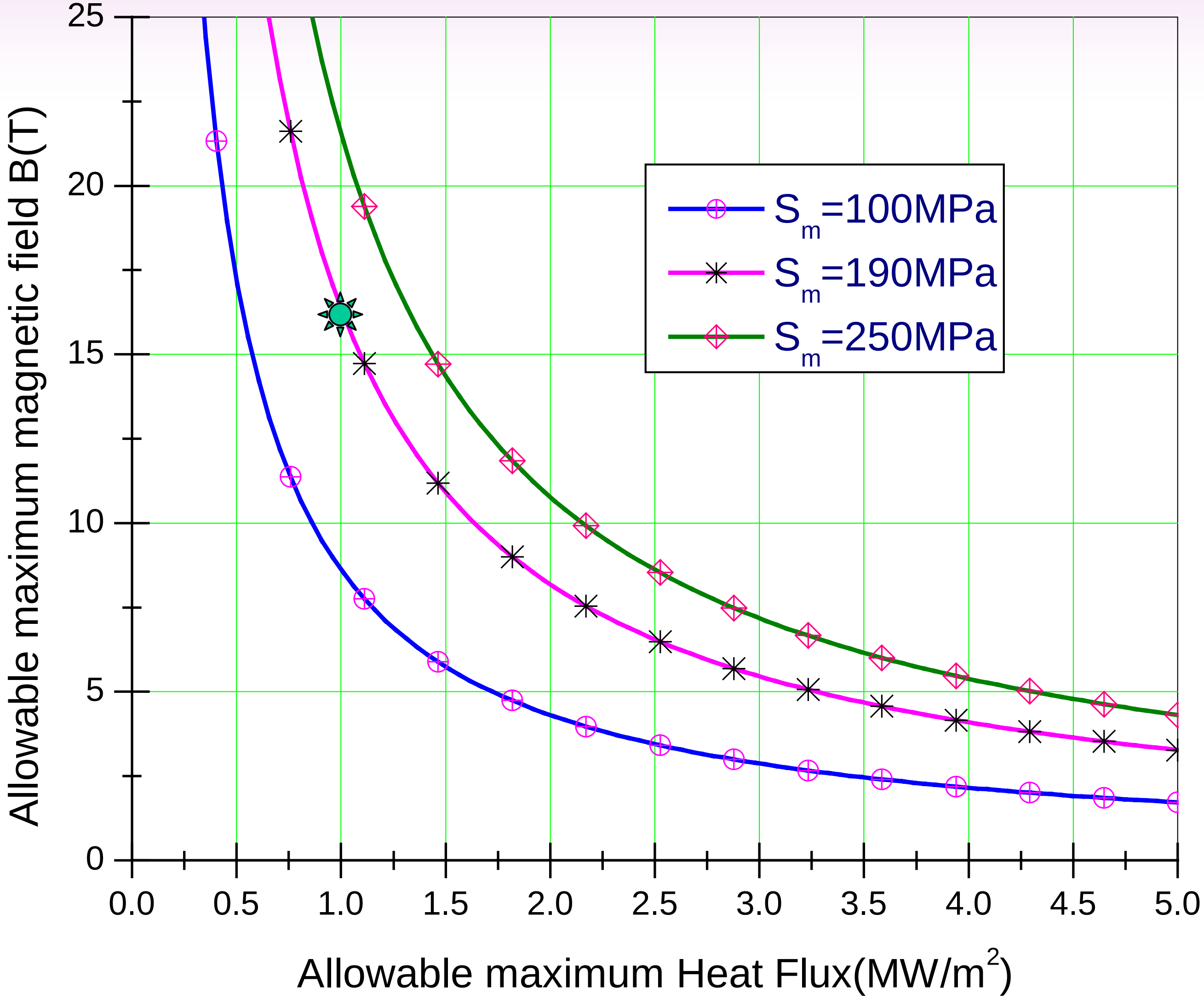



**SiC-FLiBe**

## Non-conducting or insulated wall




Pressure drop depended on the size of cooling channel and velocity




Allowable maximum magnetic field and heat flux depended on the allowable stress of structure material

## ***Plasma Facing Components (FW and divertor):***

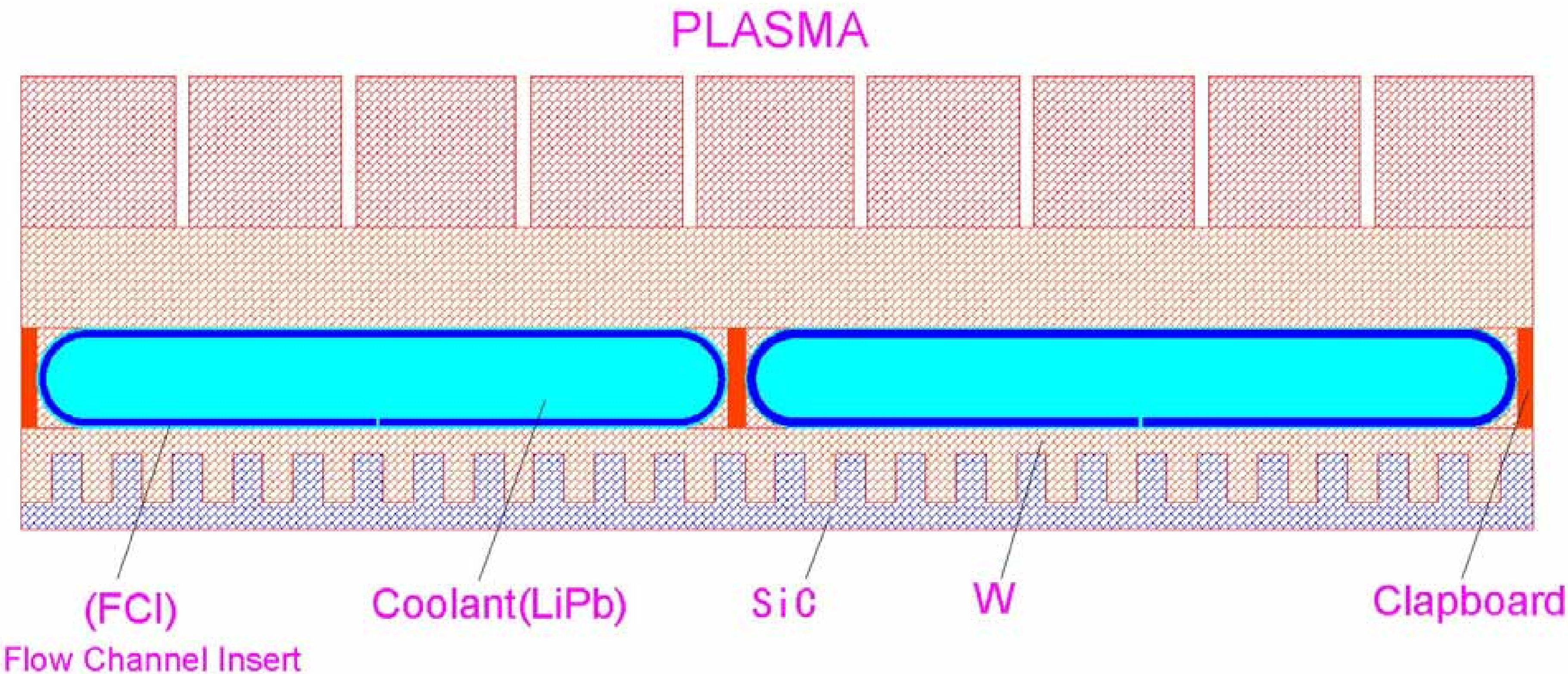
1.Material choice based on the thermal hydraulic, thermal stress, Surface erosion and other conditions

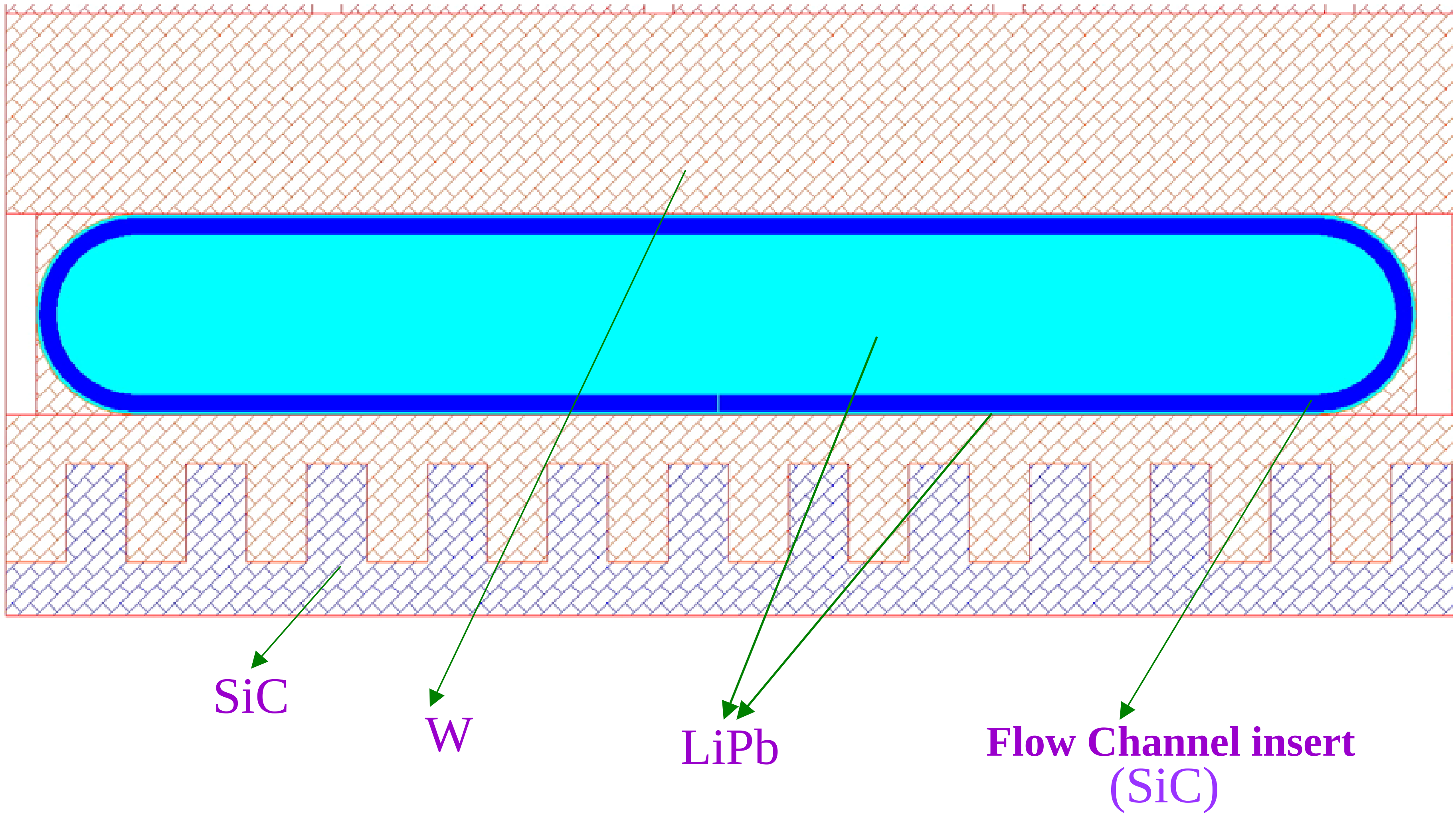
2. Safety of structure due to large EM force, especially the First wall structure due to HALO current.

3. High heat flux removal

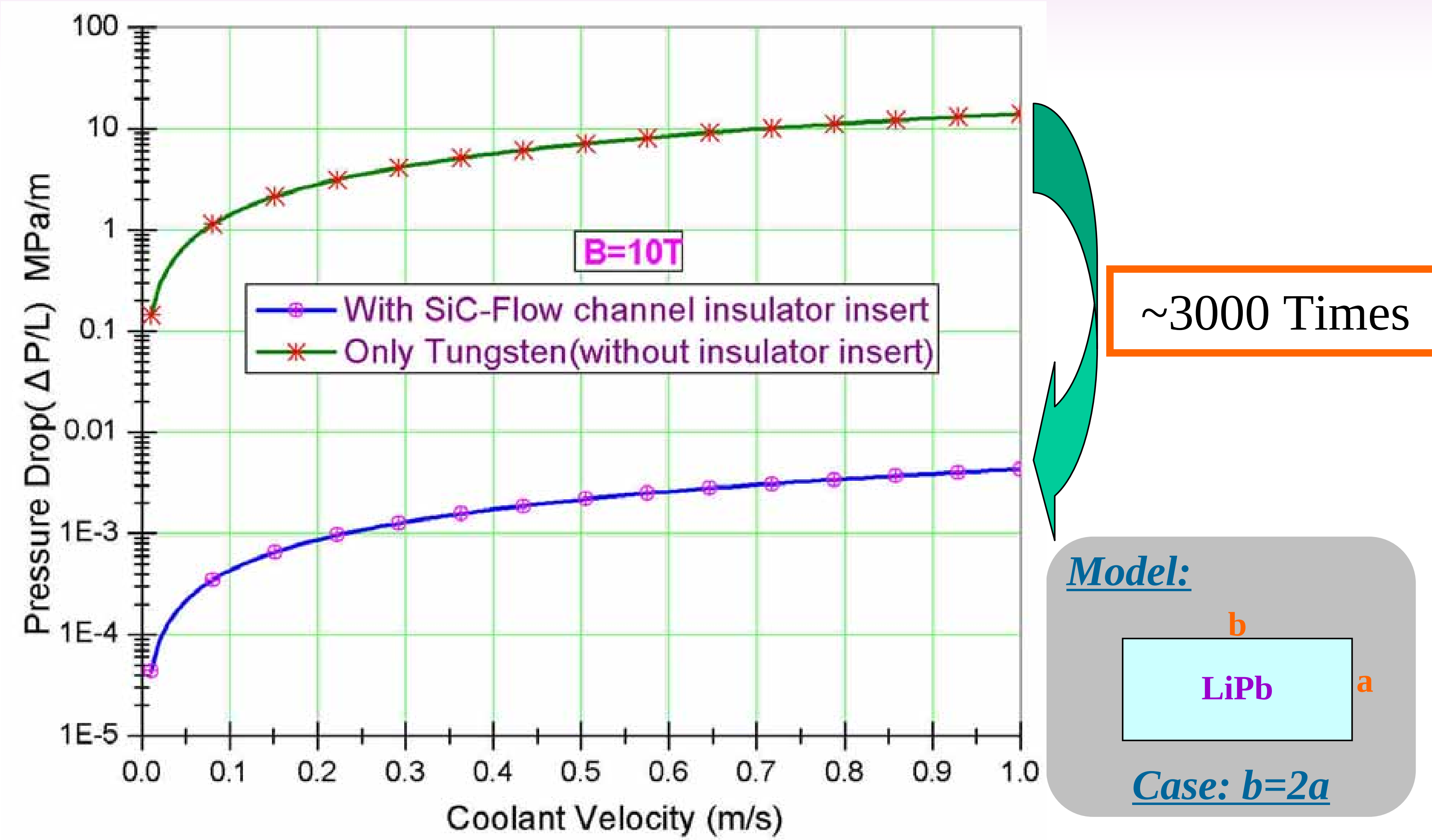
Normal design: Laminar or turbulent flow in smooth-walled channels, flow velocity, pressure drop and channel erosion and flow stability

Development of various options to increase heat transfer including swirl flow , turbulent promoters and roughened surfaces

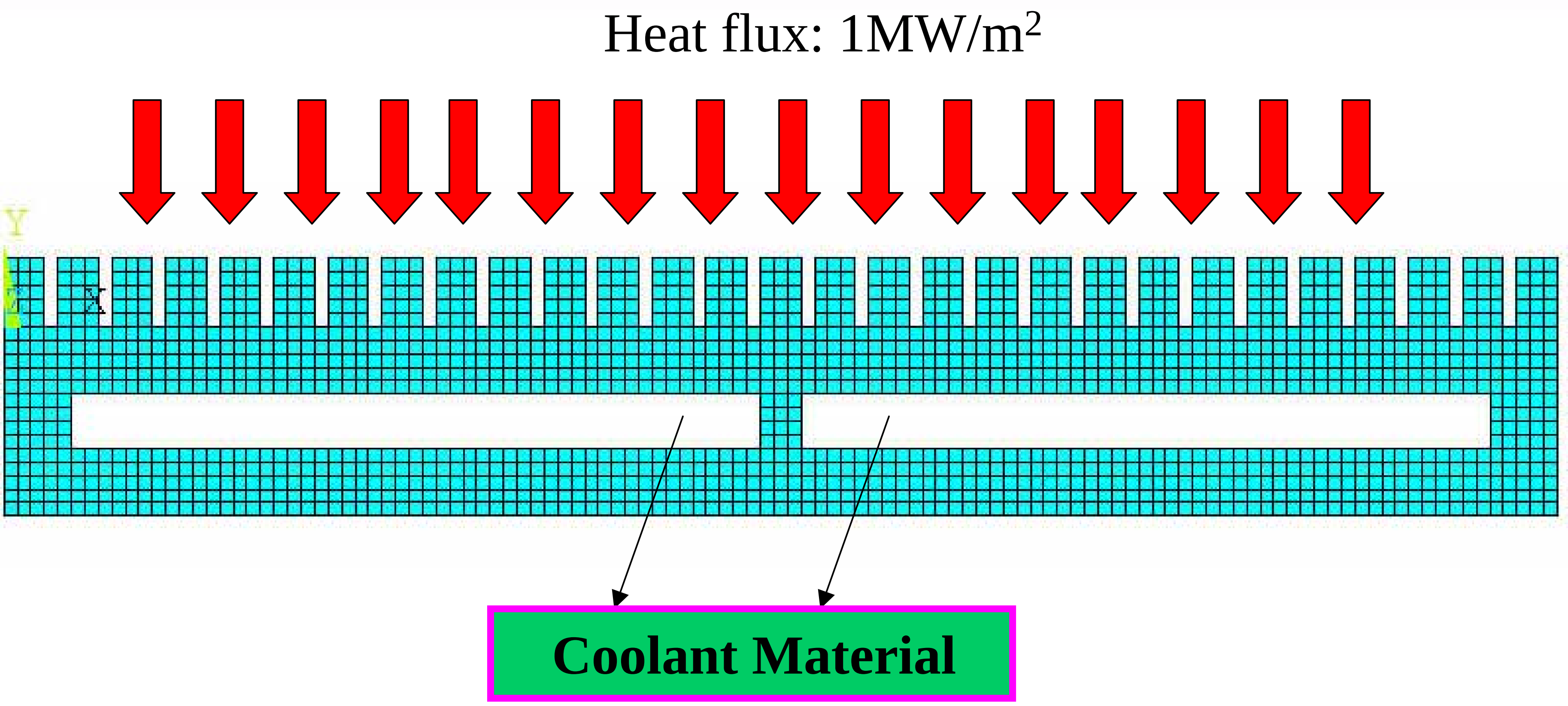

PLASMA
(FCI)
Flow Channel Insert
Coolant(LiPb)
SiC
W
Clapboard



SiC
W
LiPb
Flow Channel insert
(SiC)

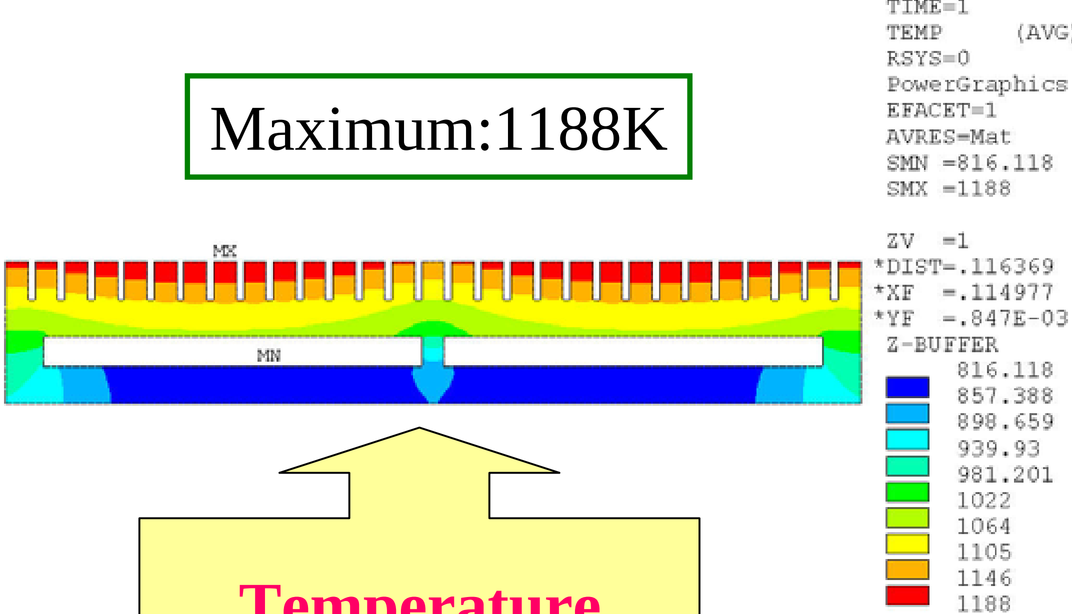



**MHD for First Wall depended on the Conducting and Non-Conducting wall**




# Finite Element Analysis Model

Maximum:1188K

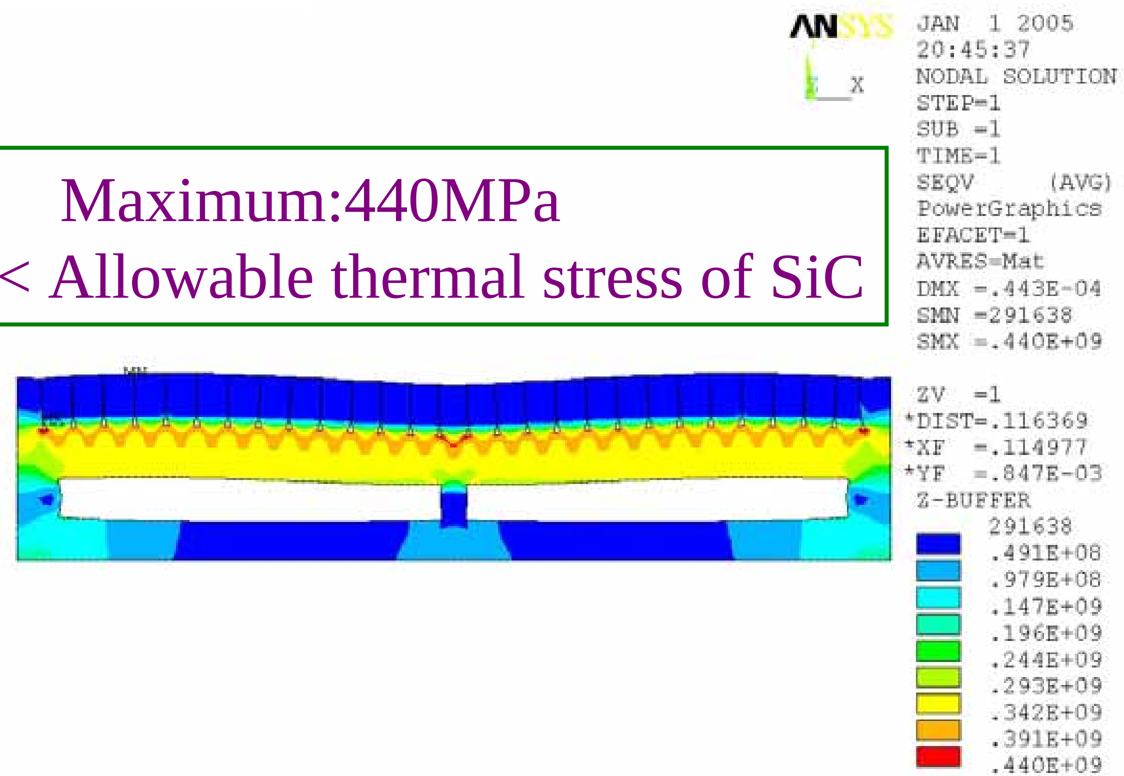



Temperature

Thermal stress

Maximum:440MPa

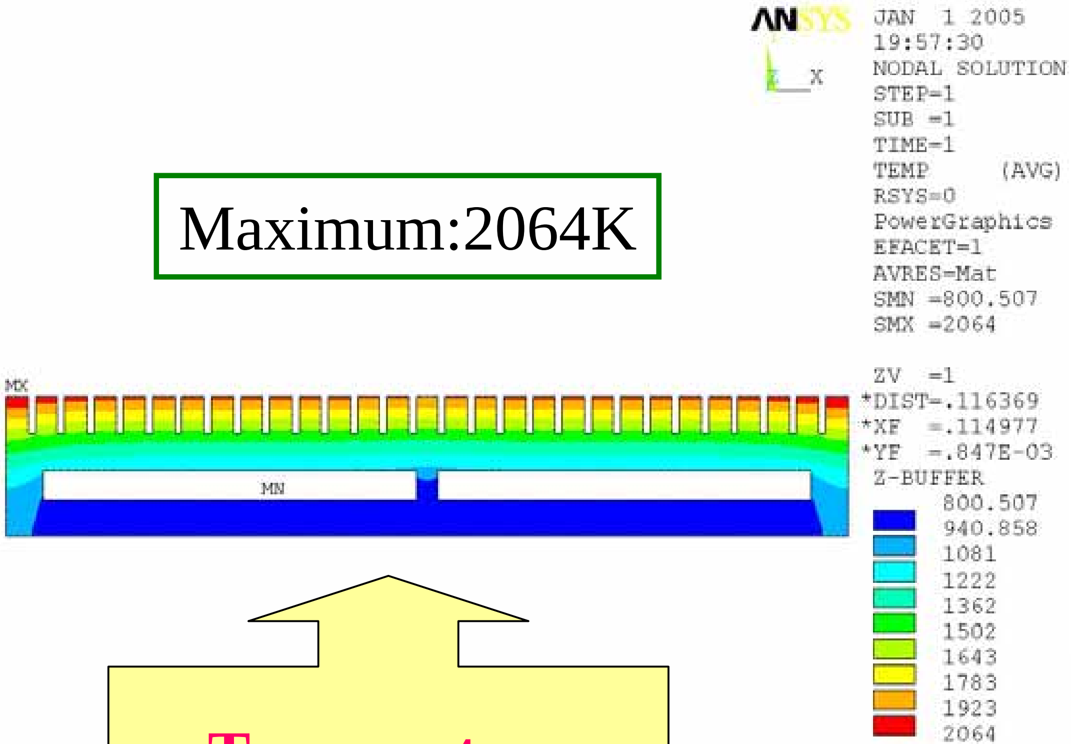
< Allowable thermal stress of SiC




**Note:** **V=0.05m/s (LiPb)**

**Material of FW: Tungsten**

Maximum:2064K

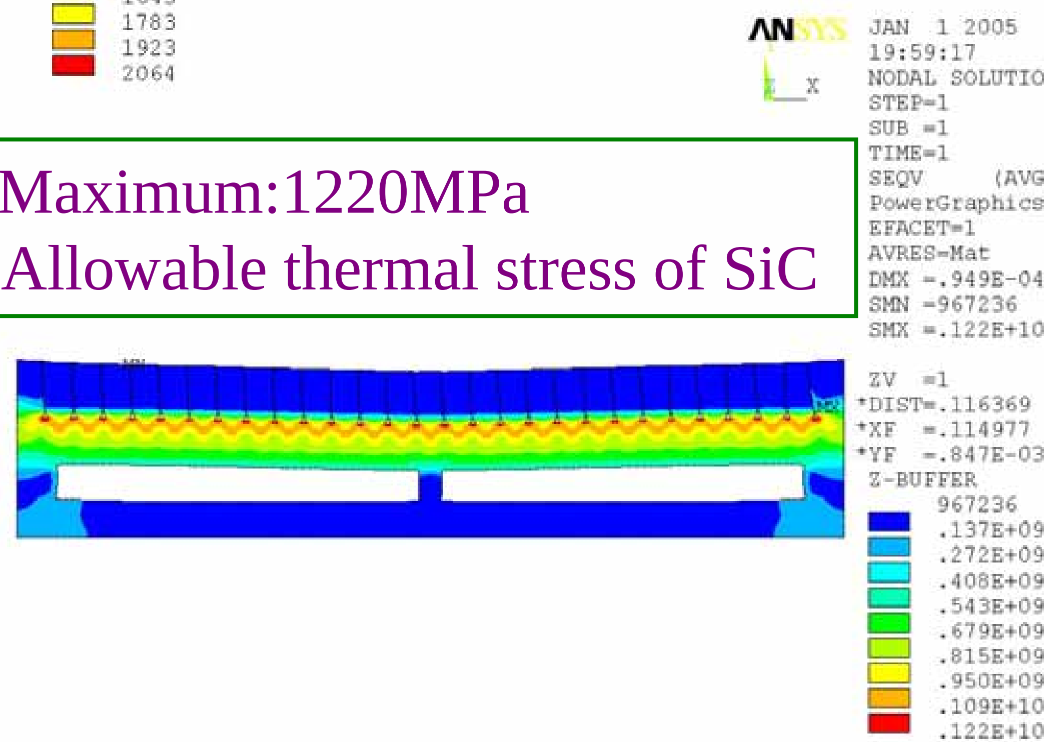



Temperature

Thermal stress

Maximum:1220MPa

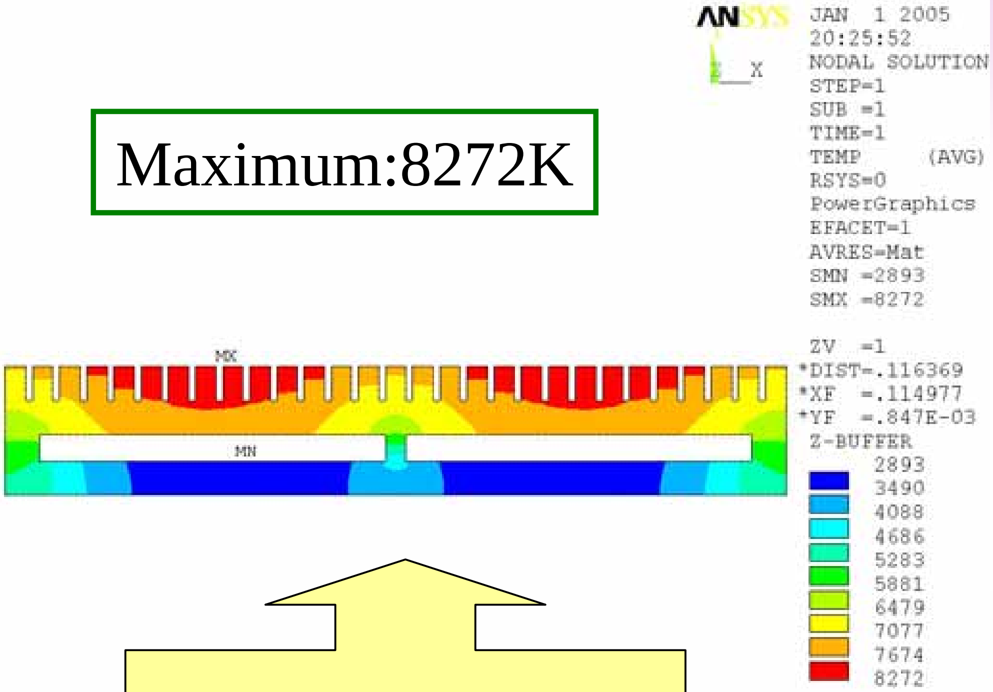
> Allowable thermal stress of SiC




**Note: V=0.05m/s (LiPb)**

**Material of FW: SiC/SiC**

Maximum:8272K

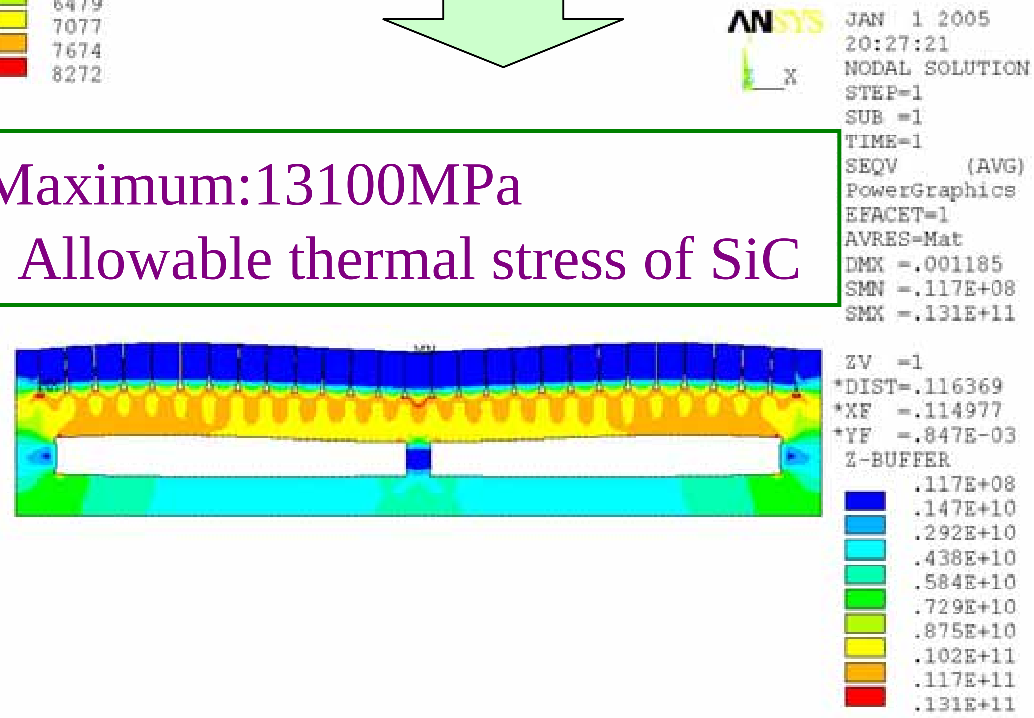



Temperature

Thermal stress

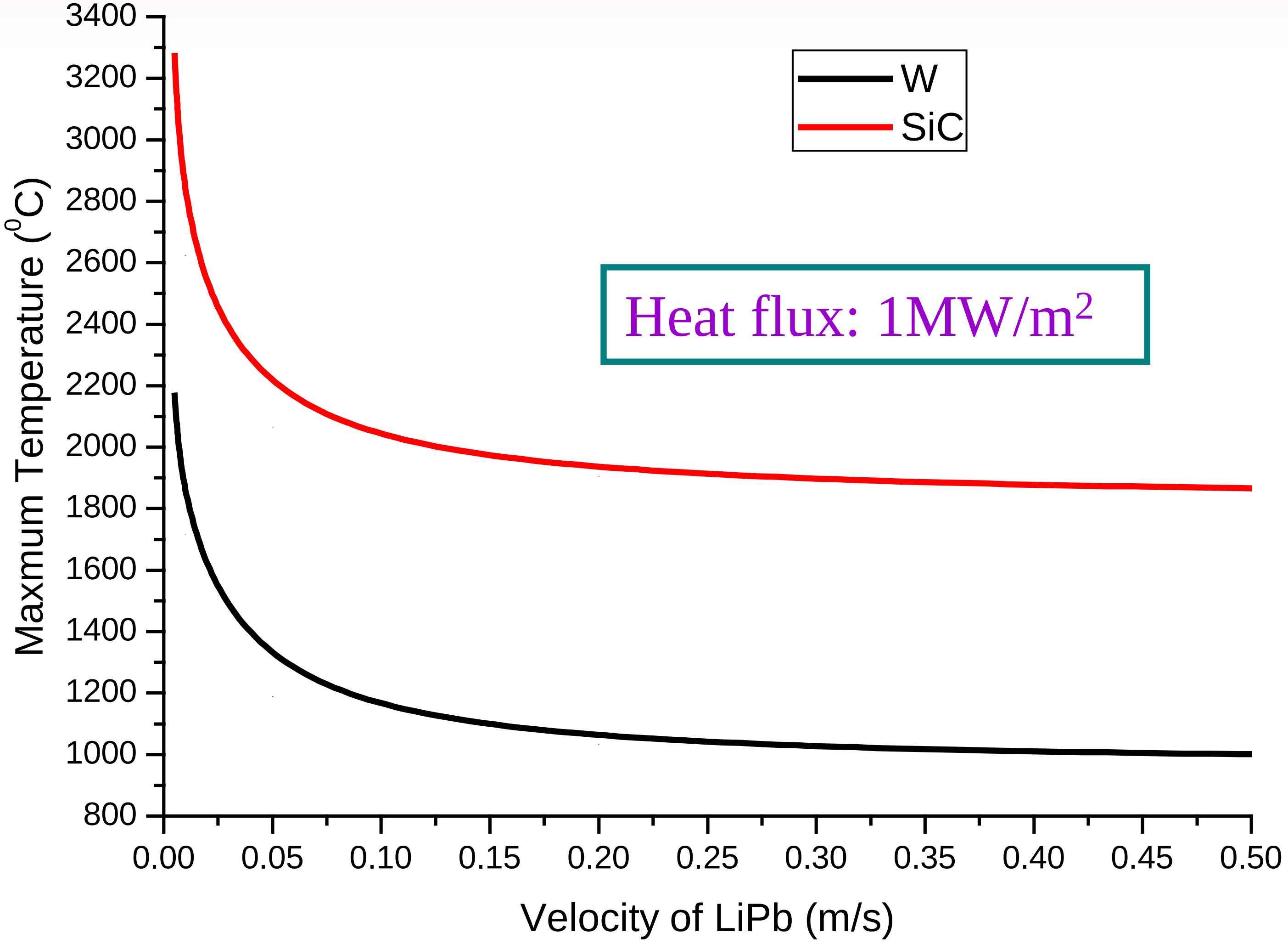
Maximum:13100MPa

>> Allowable thermal stress of SiC

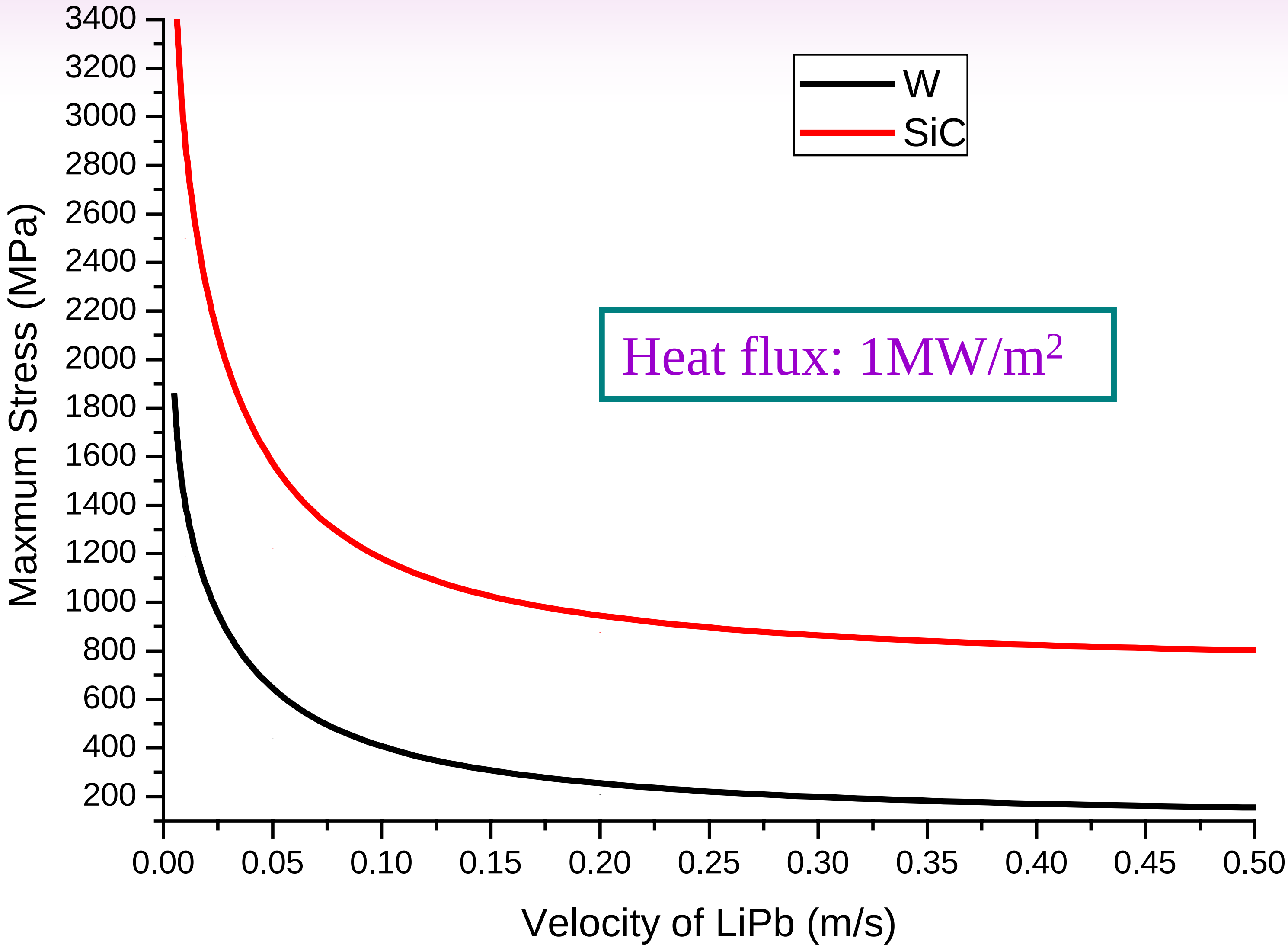



**Note:** **V=0.05m/s (FLiBe)**

**Material of FW: SiC/SiC**




Maximum Temperature on the First Wall with different velocity of LiPb




Maximum Stress on the First Wall with different velocity of LiPb

# Summary and future work plan

•My work just begin and lots of work need to be developed. It's my honor if I can get some comments or suggestions from all of the specialists.

•Next I will design detailed structure and then do some assessment for each structure and choose a better structure based on the results of MHD,Heat transfer and mechanical analysis.

•Finally I will considered all of the effect factors and then give some detailed **design windows** for LAR Tokamak Reactor engineering design.

## ***Plasma disruption and Electromagnetic issues:***

1.Effects on Liquid Metal Flow and its heat transfer

2.Time constants for control Field penetration due to LM blanket:

Deep blanket penetration mainly depends on the details of geometry and conducting paths available. How to connect each sector? And how to evaluated the blanket time constants?

3.Halo current due to vertical displacement events effect on the fluid flow in first wall including stress concentration on its supporting system

4.EM Force in LM due to the plasma disruption and quench of superconduting coils

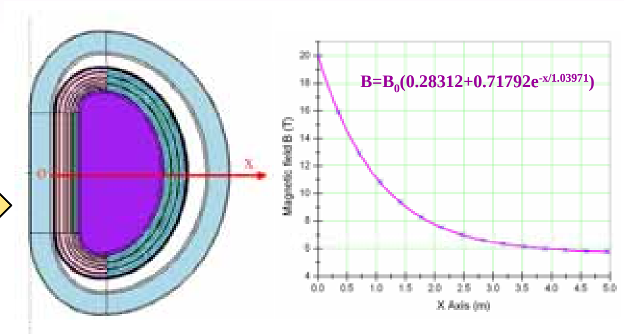
5.Additional stress on structure materials of Blanket due to EM force

6. Arcing in some small gap area, leading to insulator damage and welding of structure break

**During design how to consider these factors?**

# Future work: Analysis, Experiment and Assessment

- ***Mechanical stress analysis***
- ***Thermal hydraulic analysis***
- ***EM force and eddy current analysis***
- ***MHD under non-uniform magnetic field***




Declining curve of magnetic field in Vacuum vessel

- ***Connection and Supporting system of Blanket***

- Predict the lifetime based on the swelling limit
- Evaluate of the effects of radiation creep on the allowable design stresses
- Fracture mechanics analysis to understand the micro-crack propagation
- Fatigue analysis from the engineering design
- Assessment of Loss of coolant accident and Loss of flow accident

We also want to corporate with Kyoto University,Osaka University and other Institute for some further experiments.

Thanks!