Engineering Scaling Requirements for Solid Breeder Blanket Testing

Presented by

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With contributions from

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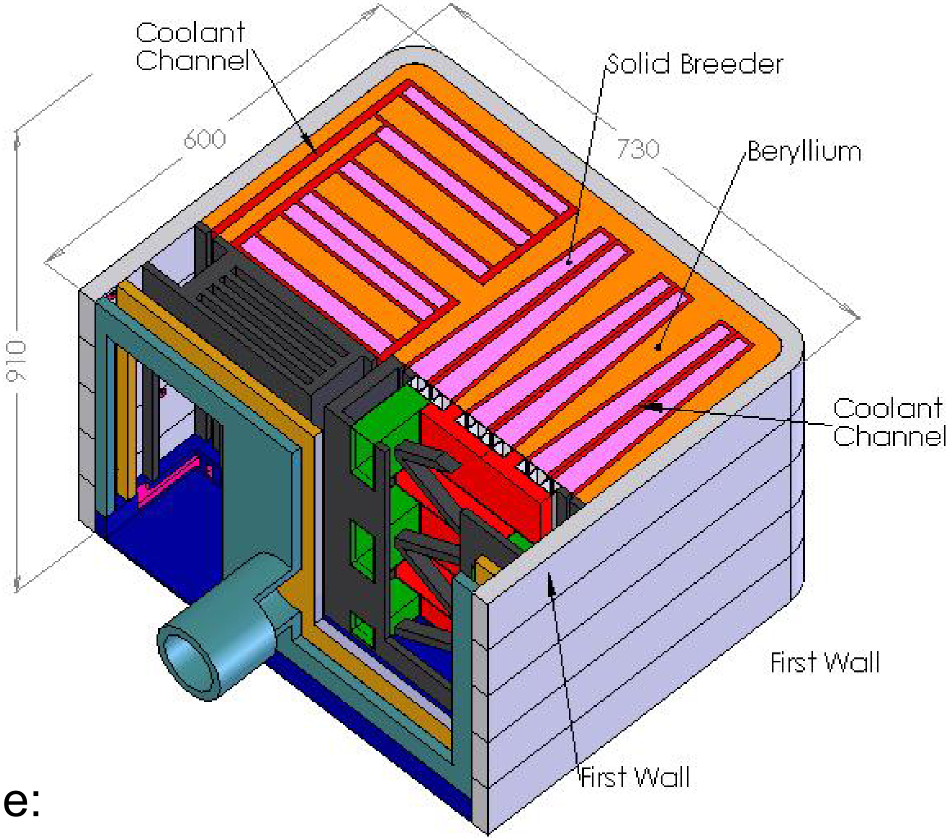
TOFE Meeting
September 14, 2004
Madison, Wisconsin

Engineering scaling is a process to develop meaningful tests at experimental conditions and parameters less than those in a reactor

Aspects of experimental constraints where engineering scaling practices issue

- **Constraints in materials and material properties**
- **Constraints in operating conditions:**
  - **Designed for**
  - **Given**
- **Constraints in geometric dimensions/sizes**



Solid Breeder Test Blanket Submodule Basic Elements

ITER

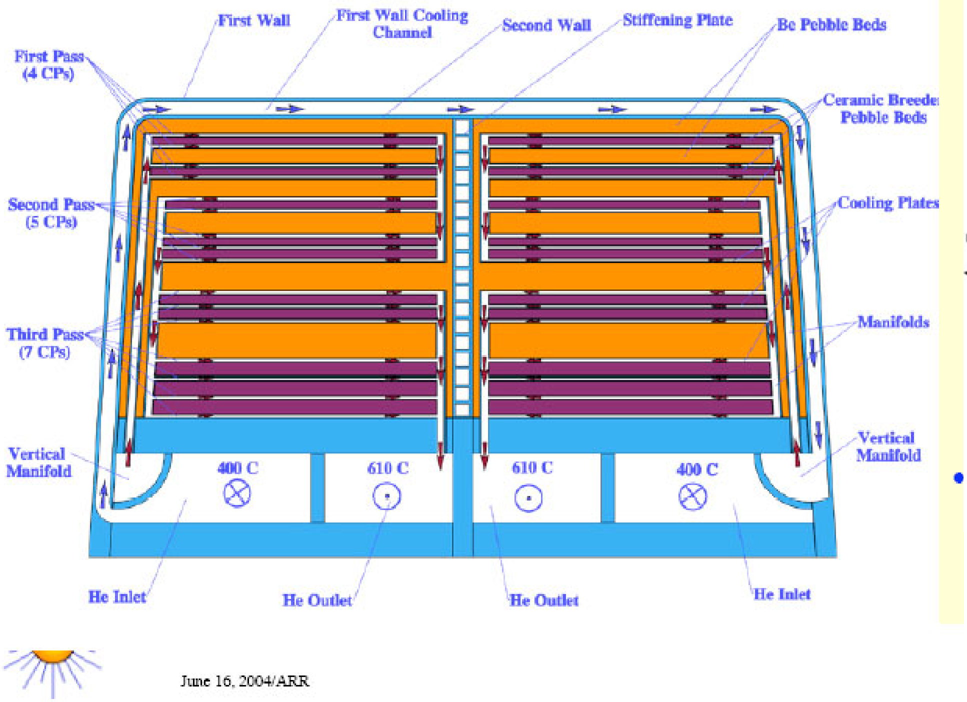
Neutron wall load at outboard mid-plane: 0.78 MW/m^2

Surface heat flux: max. 0.5 MW/m^2

nominal: 0.1 MW/m^2

Design: 0.25 MW/m^2 -0.5 MW/m^2

Reference solid breeder blankets



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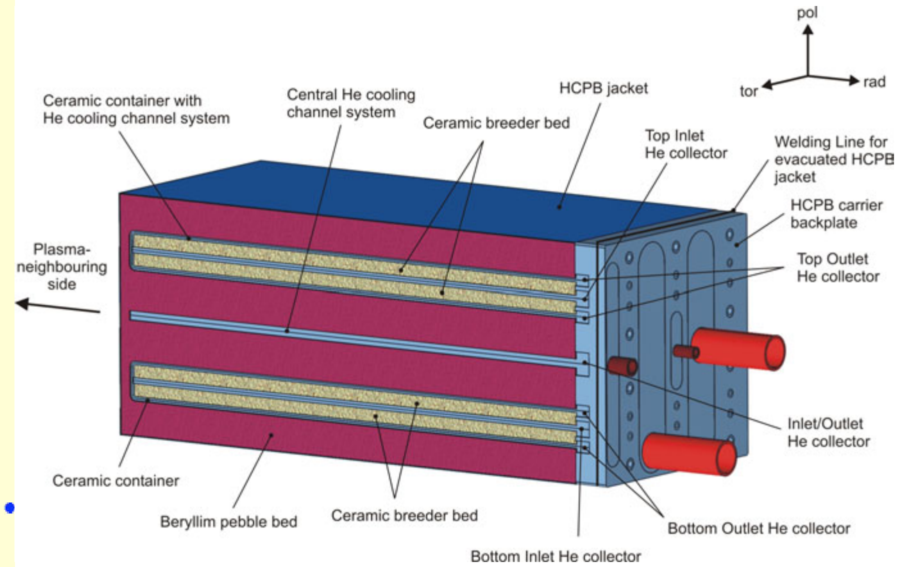


AERIS- CS Ceramic Breeder Blanket Module

Layer configuration approach

EU HCPB Demo blanket breeder unit

Edge-on configuration approach

Engineering scaling laws are exercised in designs to preserve important phenomena

- **However, engineering scaling In “Act-Alike” test modules has limitations**
  - Not all issues can be addressed simultaneously in one submodule

- Important phenomena/issues that “can be studied” during the first phase of ITER testing
  - Structural thermo-mechanical integrity
  - Tritium generation, neutronic code and database validation
  - Instrumentation development
  - Pebble bed thermo-mechanical behavior and impacts on breeder temperature profiles
  - Tritium release, permeation, and inventory
  - Effects of rapid changes in properties in earlier phase of irradaition

- Combined parallel and series tests are applied to address different key issues

Operating parameters that scaling rules would be applied and designed for

- **Temperature/temperature gradients**
- **Stress magnitudes and profiles**
- **Deformation/strain levels**
- **Velocity magnitudes and heat transfer characteristics**
- **Purge gas compositions/flow rates**
- **Tritium breeding ratio/tritium production rate**
- **Tritium release, inventory, permeation**

Color legend:

Design relevance

Design independence

Engineering scaling rules for solid breeder test blanket submodule designs start with preserving helium coolant temperatures

- Temperatures determine blanket thermomechanical behavior, tritium release and permeation
- All elements' temperatures tie to helium coolant's temperature through "an array of heat conductance"
- Preserving helium coolant temperature serves as the basis for meaningful solid breeder TBM designs

$$T_{element} = T_{helium} + \frac{q''}{C}$$

For blankets using ferritic steel as the structural material, helium inlet/outlet temperatures have been set at 300/500°C for achieving adequate thermal efficiency and satisfying structural operating criteria

Simultaneously reducing geometrical size and loading implies a significant reduction of the coolant mass flow rate

$$\Delta T_s^c = \frac{Q_s}{m_s Cp} = \frac{(q_s + n_s) A_s^{FW}}{m_s Cp}$$

$$(q_s + n_s) \approx \tfrac{1}{4.2} (q_p + n_p)$$

$$\Delta T_p^c = \frac{Q_p}{m_p Cp} = \frac{(q_p + n_p) A_p^{FW}}{m_p Cp}$$

$$A_s^{FW} \approx \tfrac{1}{4} A_p^{FW}$$

Scaling rule requires:

$$\Delta T_s^c = \Delta T_p^c$$

or

$$\frac{m_s}{m_p} \approx \frac{1}{16}$$

$$\frac{m_s}{m_p} = \frac{(q_s + n_s) A_s^{FW}}{(q_p + n_p) A_p^{FW}}$$

S: scale model (ITER)
P: prototype

Modification to the first wall coolant routing scheme is needed to preserve first wall heat transfer characteristics

$$q''_{s\,design\,\max}(=0.5MW/m^2)\approx q''_p$$

$$h_s^{FW} \approx h_p^{FW}$$

$$h_s^{FW} \propto v_s^{FW} \propto \frac{m_s}{A_{fs}}$$

$$\frac{m_s}{m_p} \approx \frac{1}{16}$$

Scaling rule requires that:

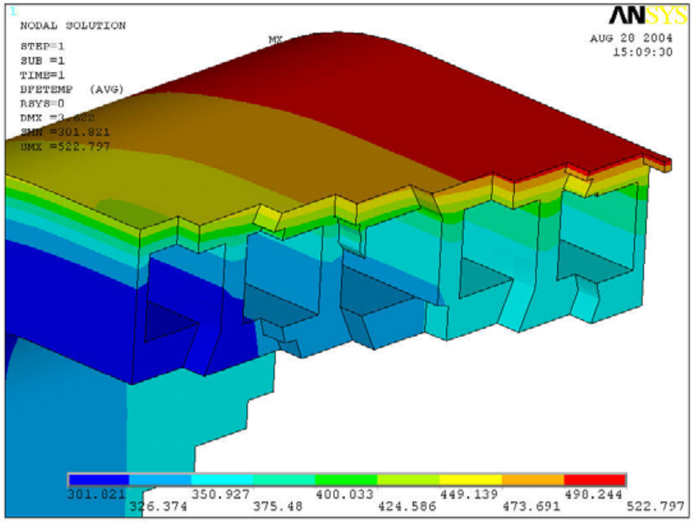
$$\frac{A_{fs}}{A_{fp}} \approx \frac{1}{16} = \frac{L_s^P / C_s^{Pi} x C_s^w x C_s^L}{L_p^P / C_p^{Pi} x C_p^w x C_p^L}$$

Prototype:

1 coolant channel per flow path

Scale model (current design):

5 coolant channels per flow path



C^{Pi}**= coolant channel pitch**

C^{w}**= coolant channel width**

C^{L}**= coolant channel length**

Disproportional heat distribution between surface heat and neutron loads creates complexity in the scale model design

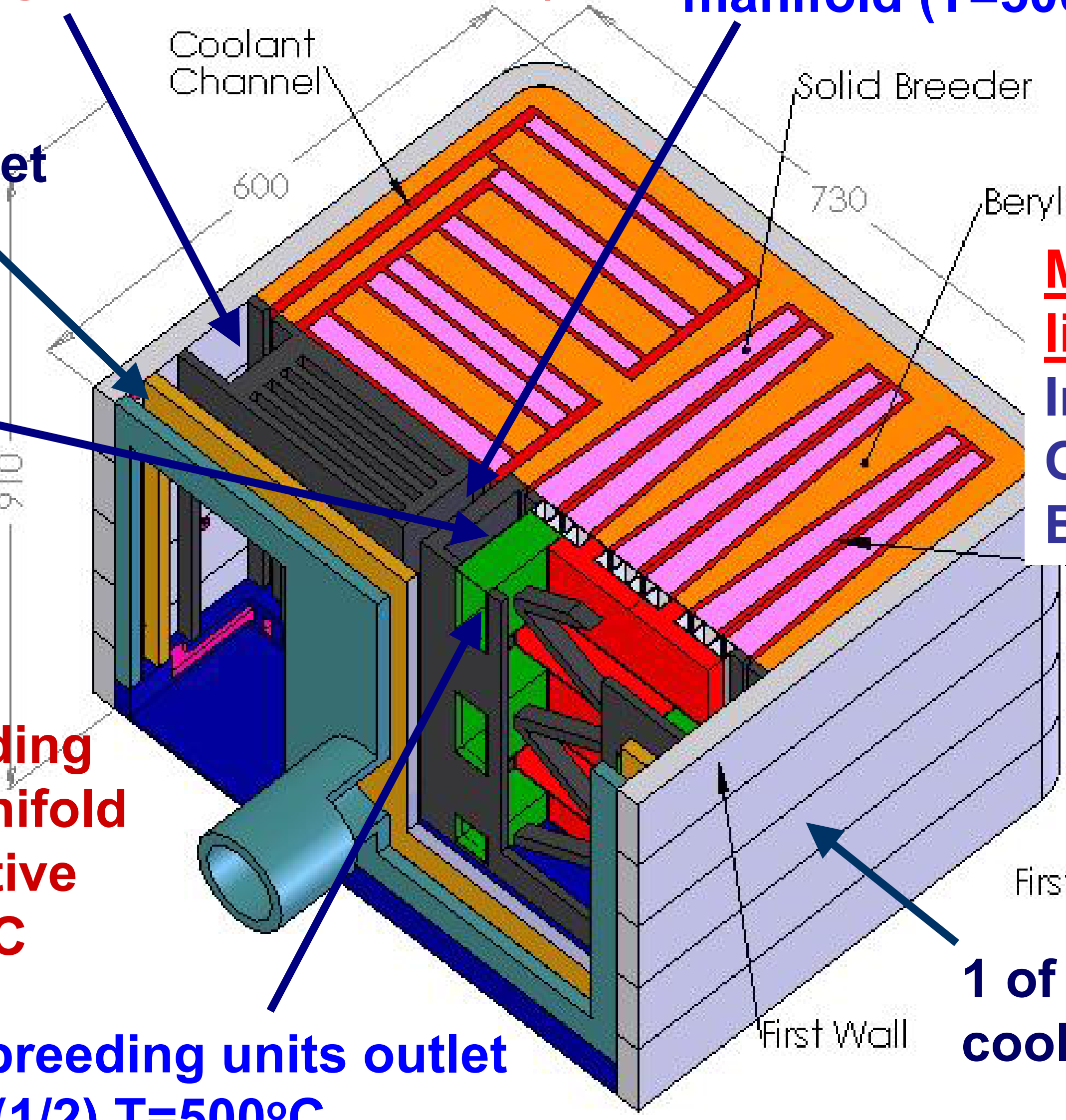
$$\frac{q_s''}{q_p''}=\frac{(0.5x0.5+0.25x0.5)}{0.6}=0.625$$

$$\frac{n_s}{n_p}=\frac{0.78}{4.8}=0.1625$$

Parameter	Value
Power from surface heat flux	0.249 MW
Power from breeding zone with 1.2 multiplication factor)	0.622 MW
Helium inlet/outlet temperature	300/500°C
Mass flow rate to first wall	0.9 kg/s
Mass flow rate to breeding zone	0.82 kg/s
Mass flow rate -bypass	0.08 kg/s
Coolant ΔT first wall	53 °C
Coolant ΔT breeding zone	146°C

- In the scale model, a higher mass flow rate is needed to cool the first wall to satisfy structural temperature limitations
- A bypass flow scheme is used to direct the helium away from entering the breeding zone in order to maintain prototype type coolant temperature and temperature boundary conditions for the breeder units.

Helium thermal-hydraulic design and parameters



First wall outlet manifold (also layer breeding units inlet manifold) (T= 353°C)

Layer breeding units outlet manifold (T=500°C)

First wall inlet manifold (T_{in}= 300°C)

Mass flow rate in lines:

In: 0.9 kg/s

Out: 0.82 kg/s

By-pass: 0.08 kg/s

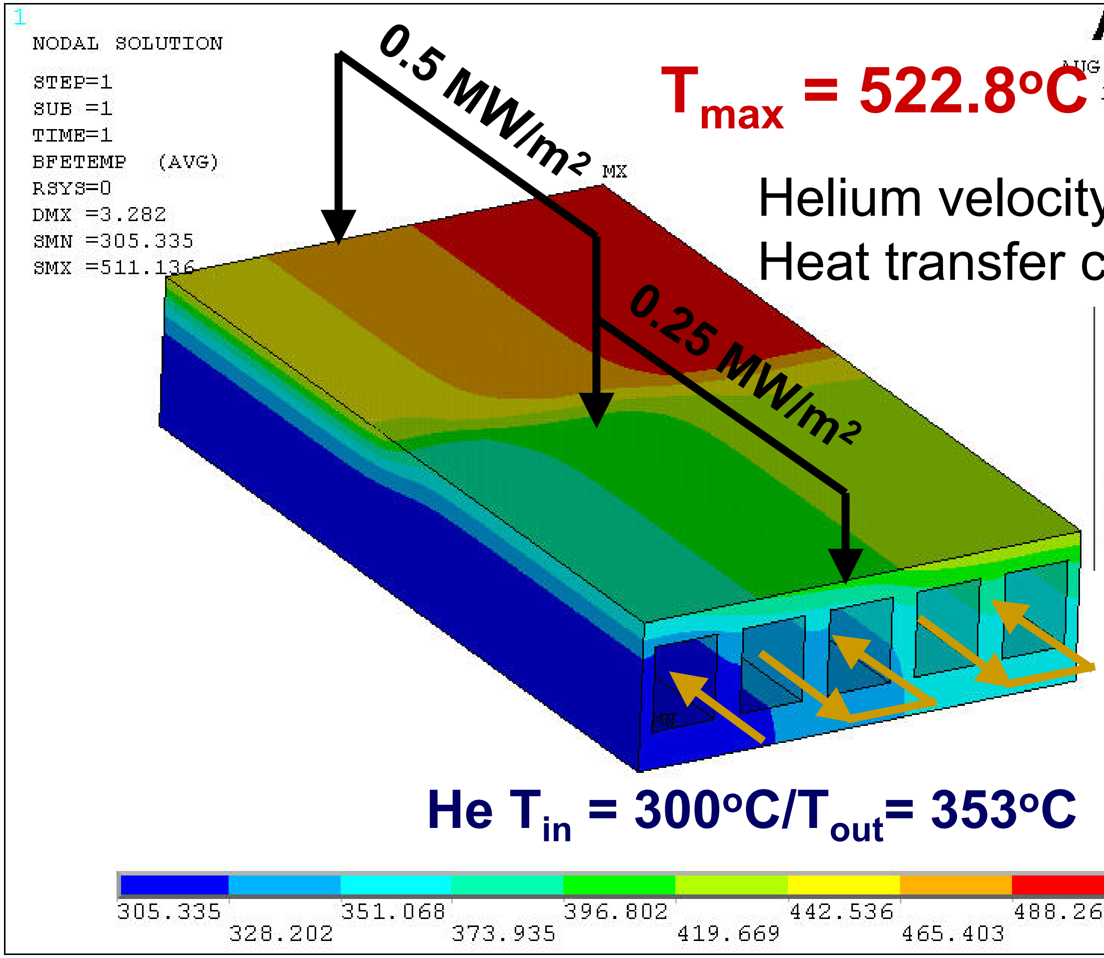
Edge-on breeding units inlet manifold (1 of 2 alternative paths) T=353°C

1 of 10 alternative cooling flow paths

Edge-on breeding units outlet manifold (1/2) T=500°C

First wall thermo-mechanical analysis: temperature analysis

One flow path consists of 5 coolant channels connected in series

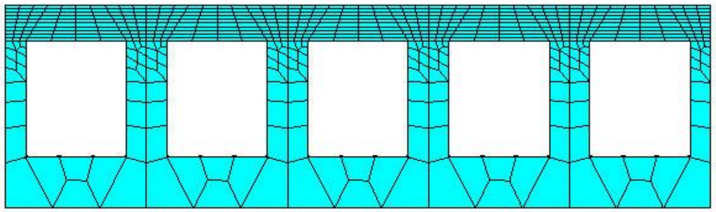


T_{max} = 522.8°C

Helium velocity = 63.6 m/s

Heat transfer coefficient= 5890 W/m^{2}k

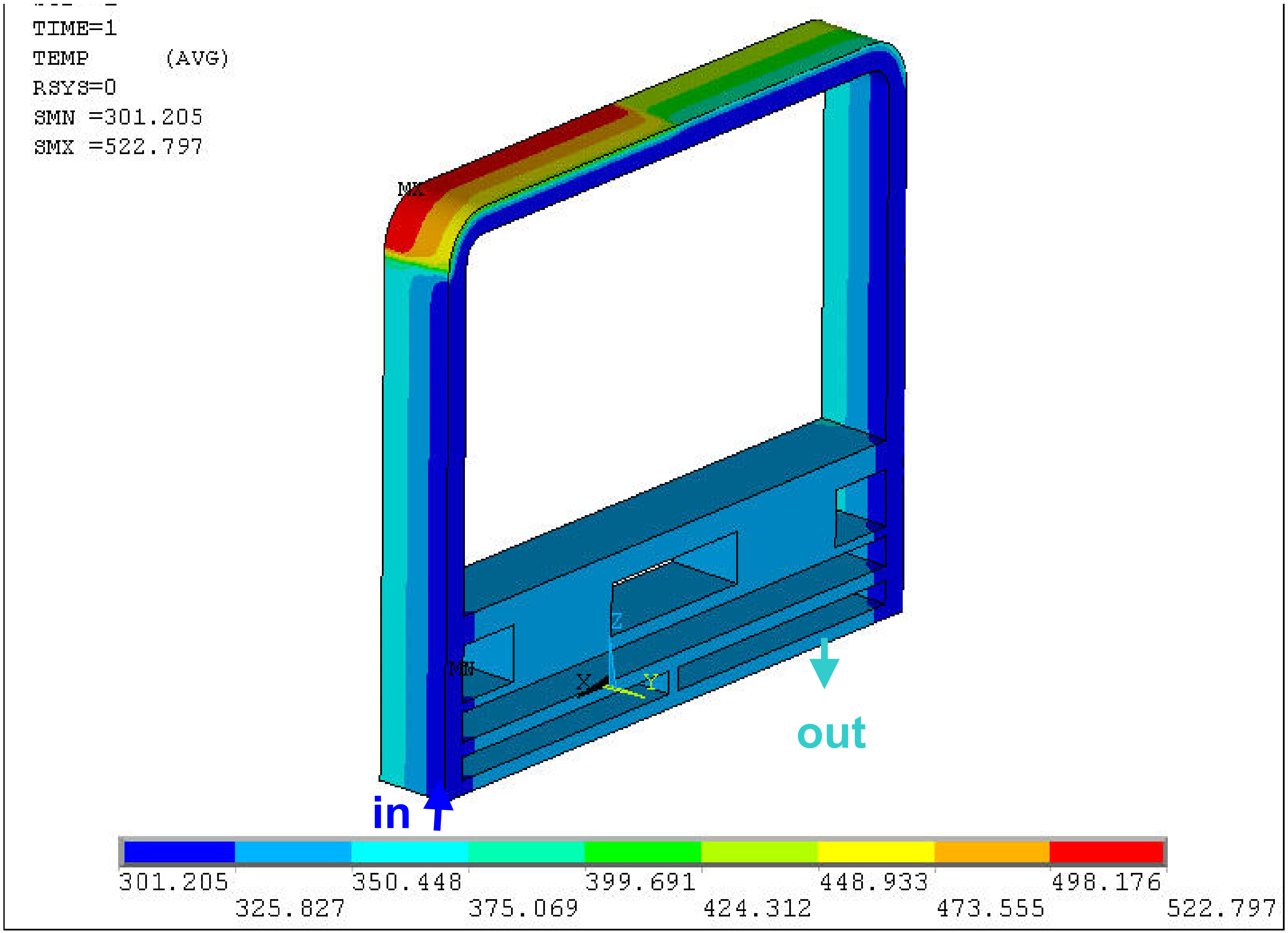
He T_{in} = 300°C/T_{out}= 353°C



Total thickness: 28 mm
(5 mm front/7 mm back)
Channel dimension: 16 x 13 mm^2
Pitch: 14.34 mm

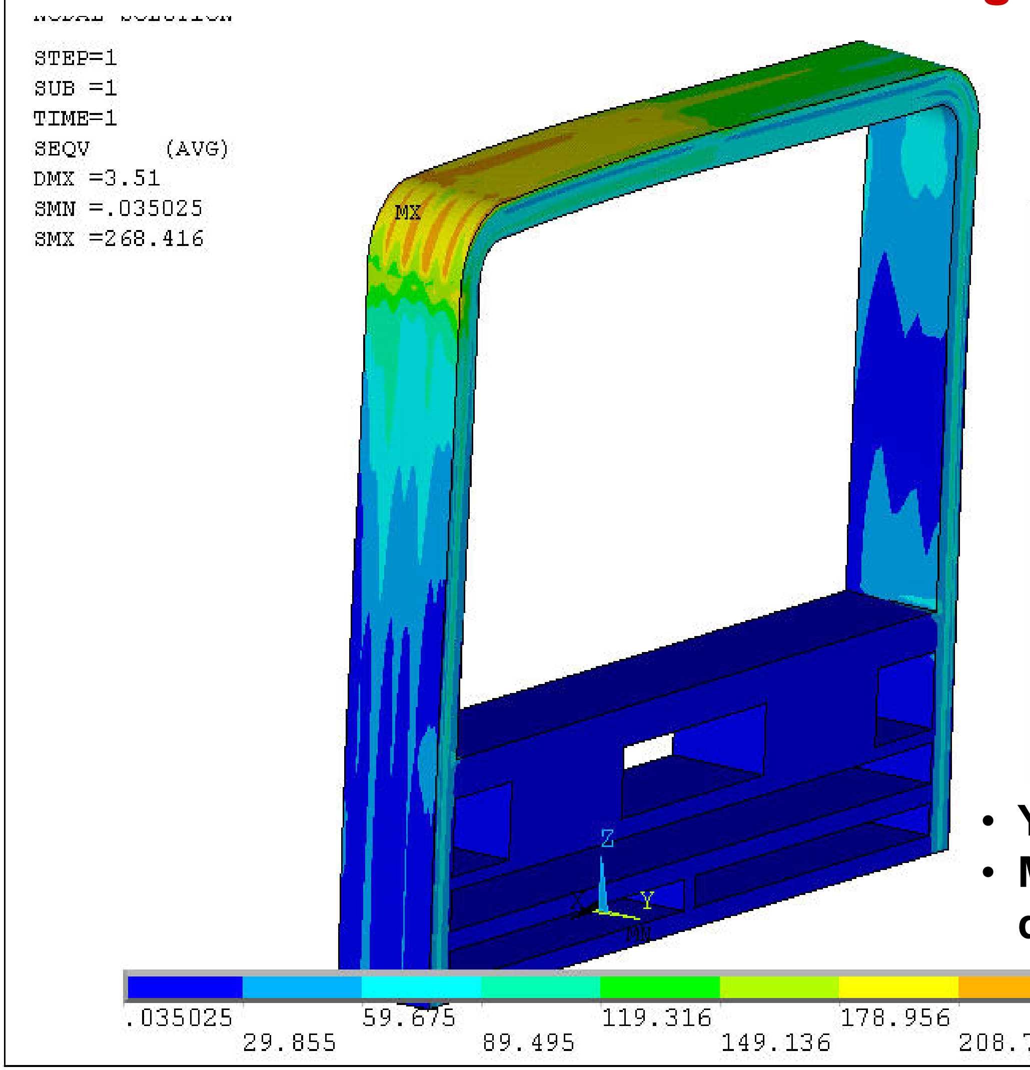
Total elements: 280,570

First wall thermo-mechanical analysis: temperature profile for one flow path

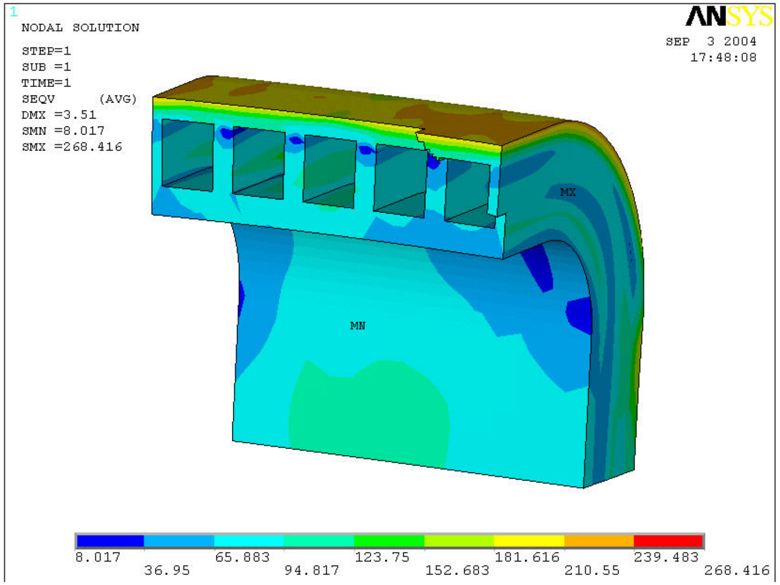


First wall thermo-mechanical analysis: Stress profiles

Maximum stress is lower than the stress limit and is similar to the maximum value of the JA DEMO design



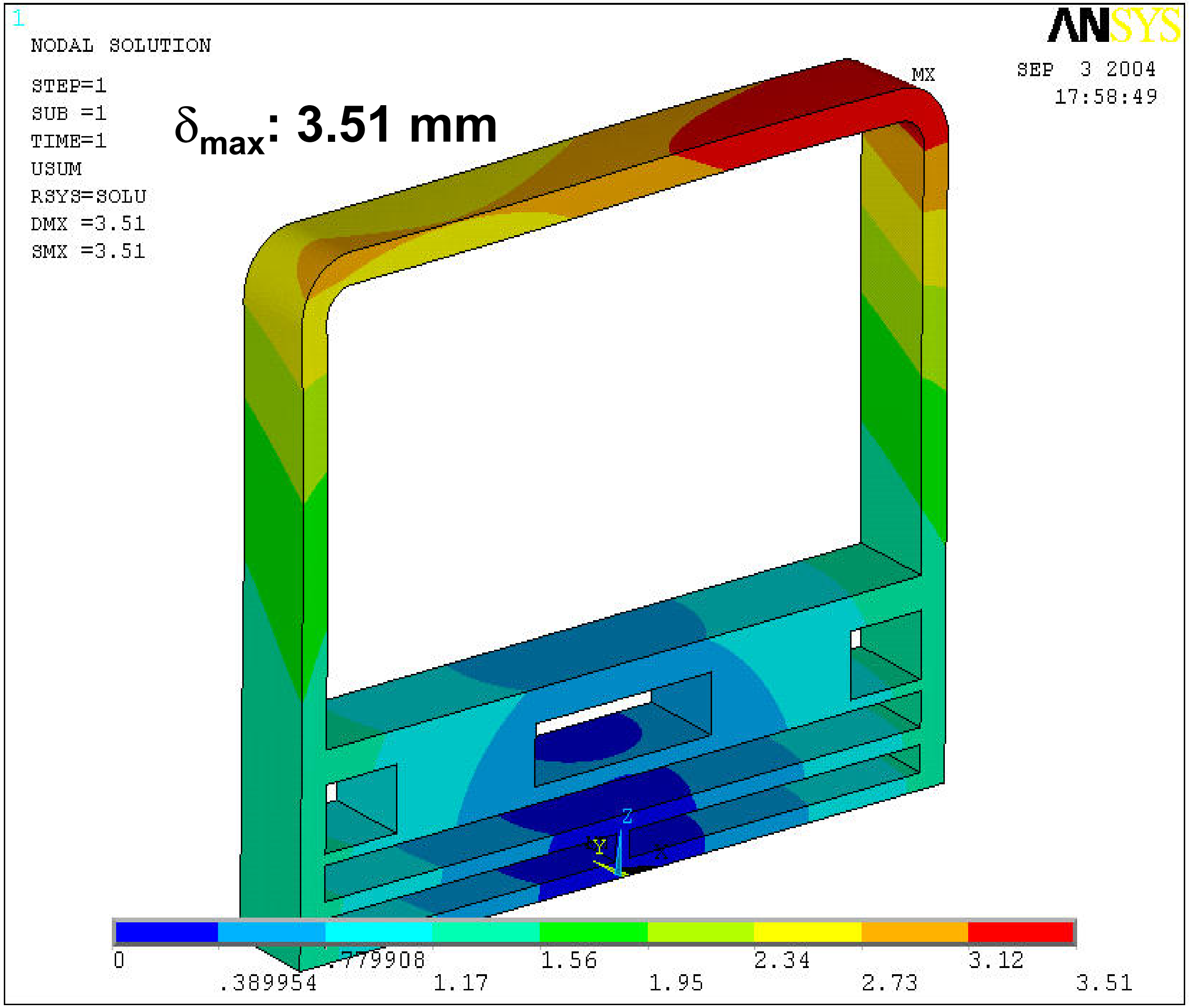
σ_{max} = 268.4 MPa (located at the corner of the front inner wall)

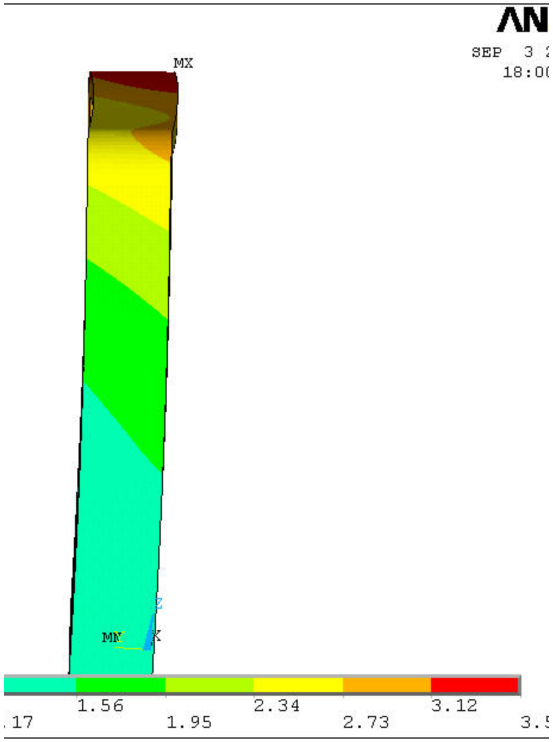


- **Yield strength at 550°C = 380 MPa**
- **Maximum allowable stress for piping design = 2 * yield strength (ASME)**

First wall thermo-mechanical analysis: Displacement profiles

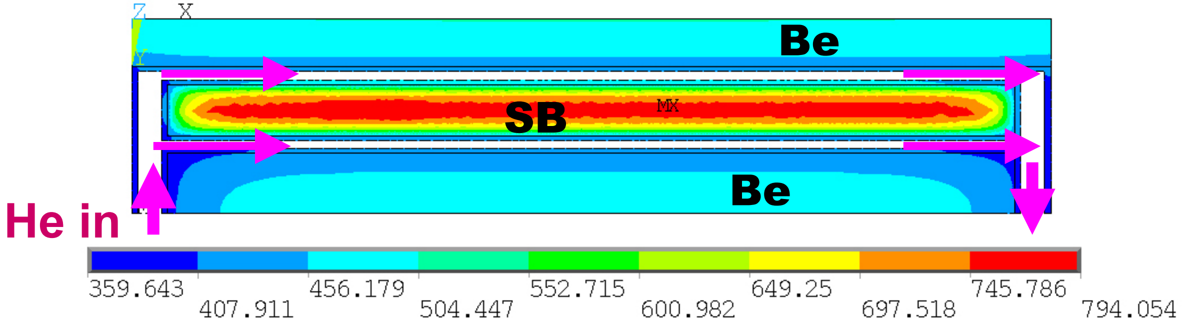
- **A non-uniform displacement due to a non-uniform heating (a non-prototype condition?)**


δ_{max}: 3.51 mm

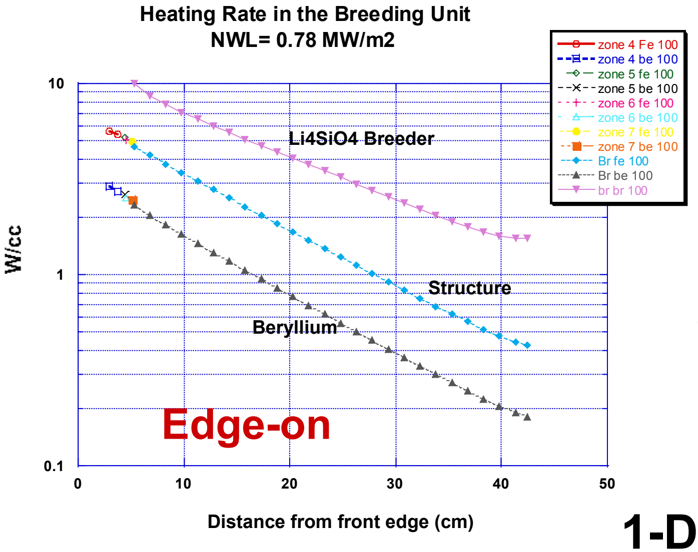


Thermal analysis for breeding units show that prototype temperatures have been preserved

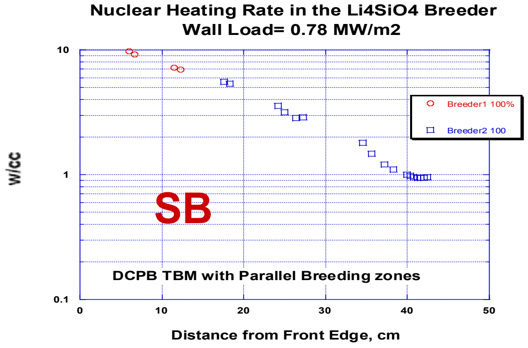
Layer configuration



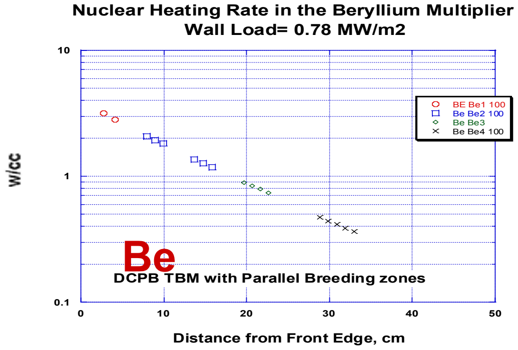
- **Heat transfer coefficient 1200 W/m²k**
- **K_{SB}= f(T); ~ 1W/mk**
- **k_{Be}= f(T,s) 6W/mk used**
- **h_c = 4000 W/m²k**



Heating Rate in the Breeding Unit
NWL= 0.78 MW/m2



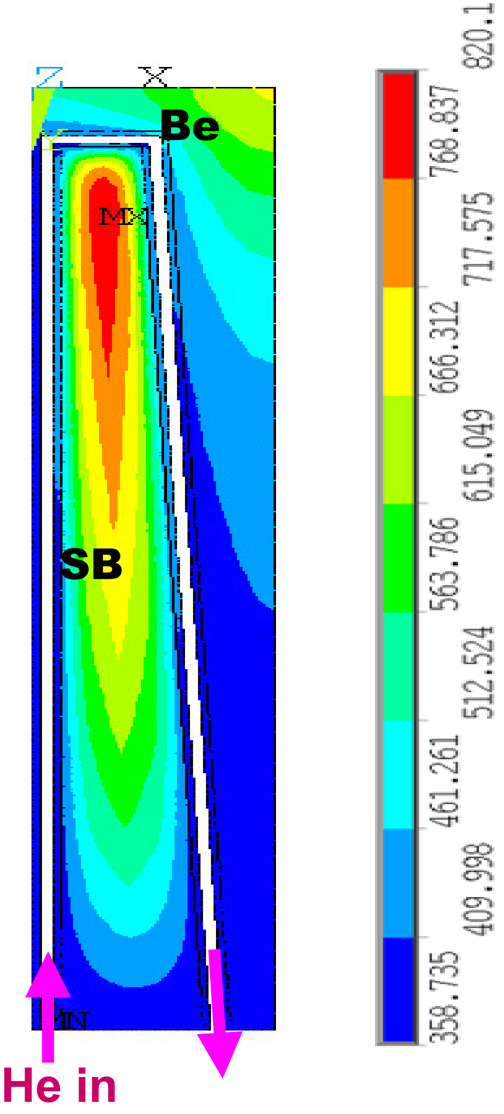
Nuclear Heating Rate in the Li4SiO4 Breeder
Wall Load= 0.78 MW/m2



Nuclear Heating Rate in the Beryllium Multiplier
Wall Load= 0.78 MW/m2

1-D nuclear heating rates

Edge-on configuration



Preserving breeder unit temperature magnitude and gradient is essential for thermo-mechanical tests

- The elastic modulus and creep compaction of a solid breeder pebble bed is related to stress and temperature levels by the expression:

$$E = 130x\sigma^{0.47}$$

and

$$\varepsilon^{c} = 12.12x(\sigma)^{0.65}t^{0.2}e^{\frac{-10,220}{T}}$$

where σ is the axial stress in MPa, **T** temperature in ^{o}C and t time in seconds.

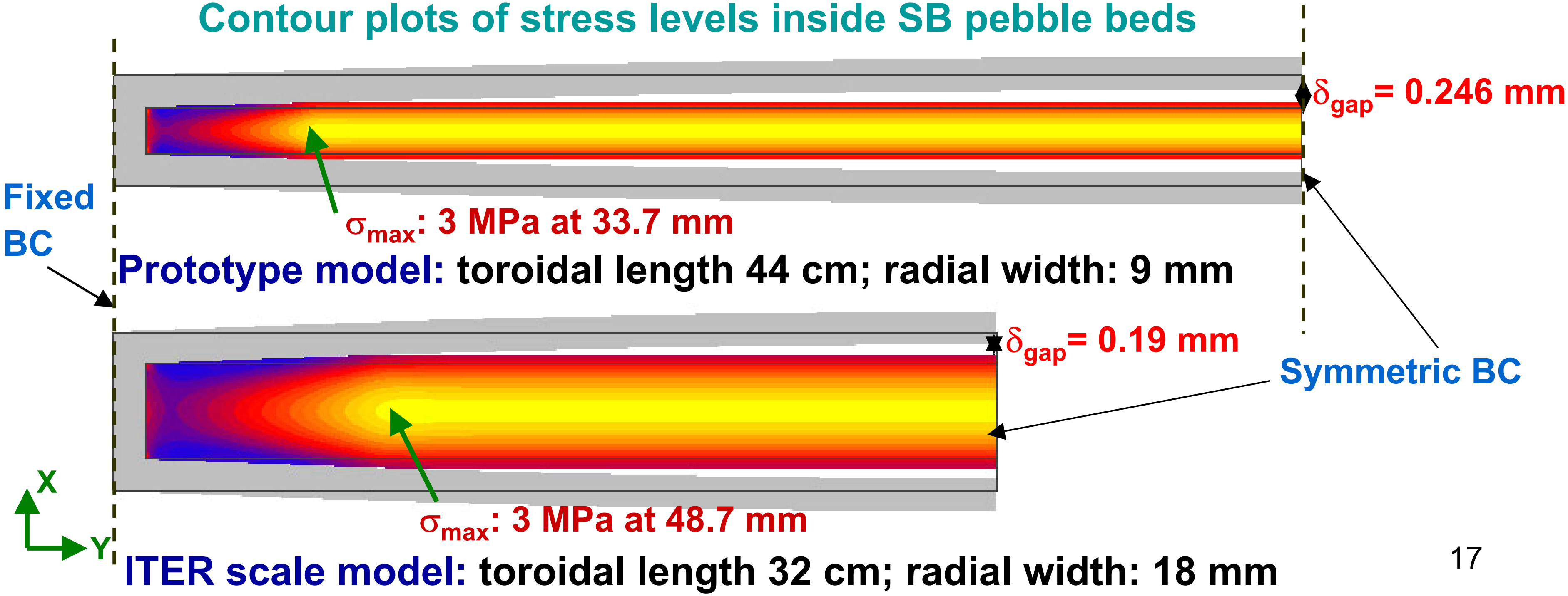
- Stress and temperature are the key parameters affecting pebble bed thermo-mechanical behavior
- The stress is generated through a temperature gradient across the region and differential thermal expansions between coupling elements

Prototype stress levels have been preserved in the scale model (layer configuration)

- FEM analysis using experimentally derived ceramic breeder pebble bed modulus, stress-strain consecutive equations
- Similar stress levels found in prototype and scale models with a maximum stress in the bed of about 3 MPa.
- The coolant plate deformation is a combined effect of thermal expansion, mechanical constraints, and dimensions.

Laboratory R&D goal is to predict thermo-mechanical parameters accurately.

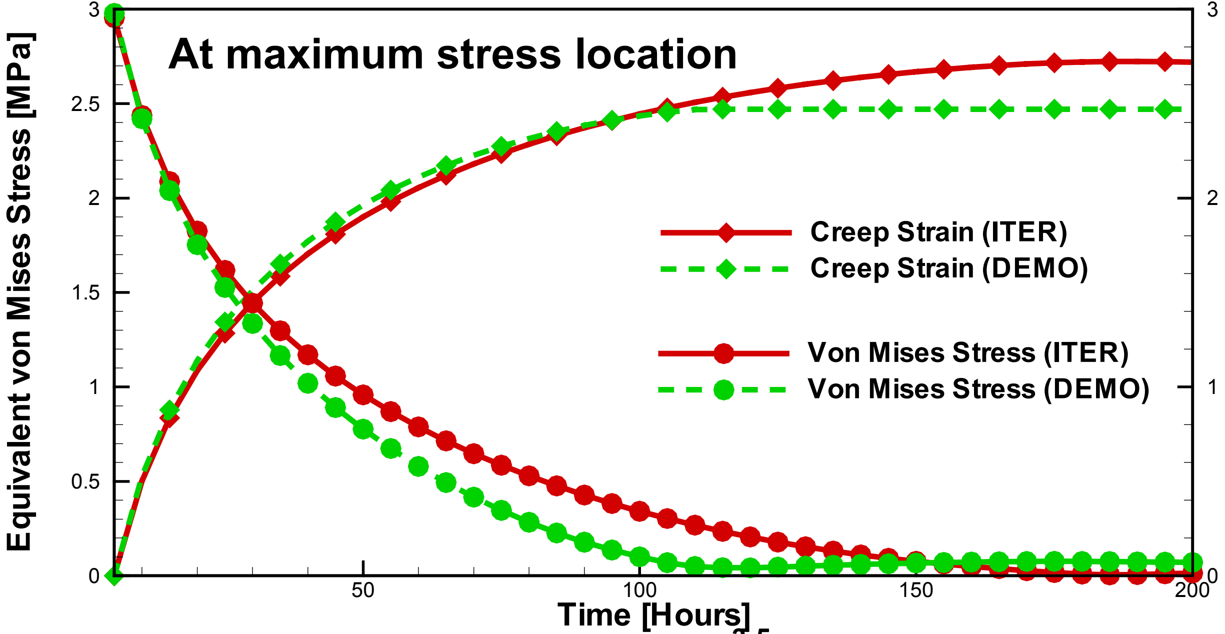
Contour plots of stress levels inside SB pebble beds



Prototype model: **toroidal length 44 cm; radial width: 9 mm**

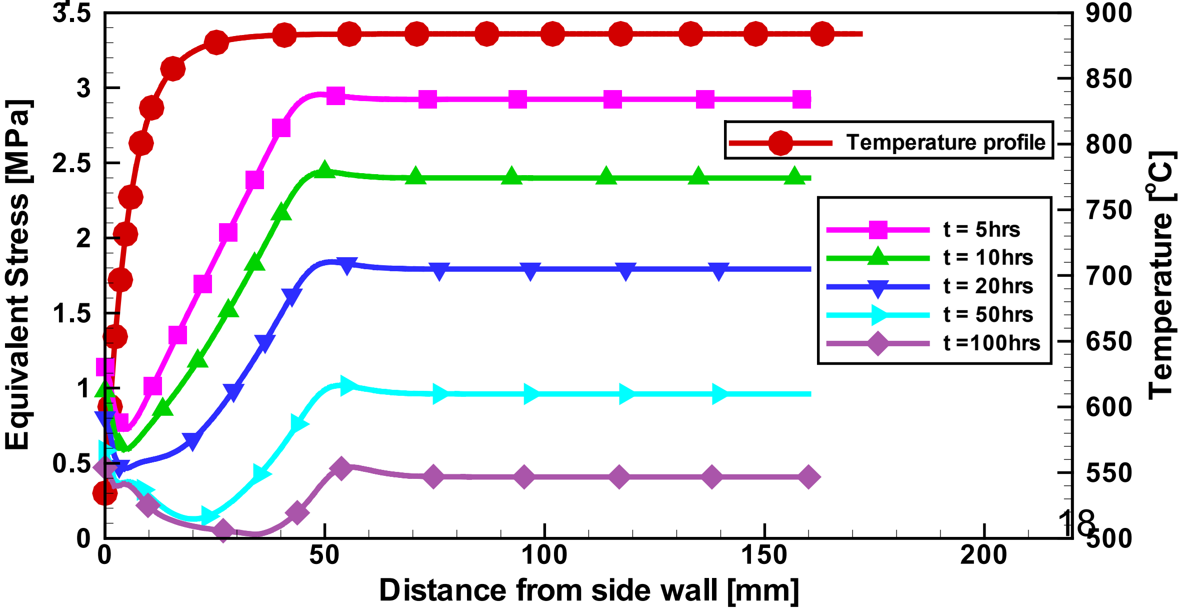
ITER scale model: **toroidal length 32 cm; radial width: 18 mm**

Creep and stress relaxation evolutions are preserved under steady state operations



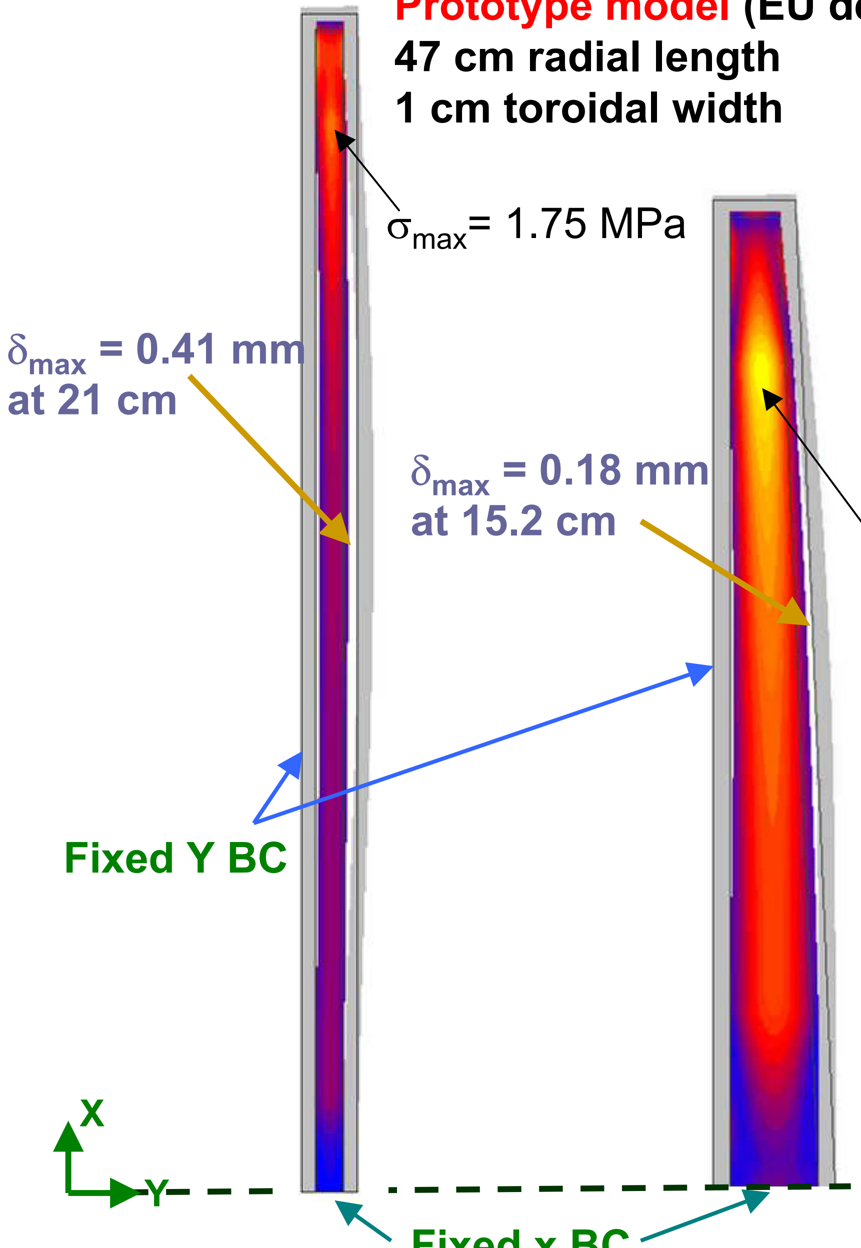
- **A R&D goal is to address and model the effect of pulsed operations on the pebble bed integrities and performance**

von Mises stress evolution at the mid-plane of the ITER scale model



Stress profiles show concentration with 2-D characteristics for edge-on configurations

Li_4SiO_4 pebble bed considered



Prototype model (EU design)
47 cm radial length
1 cm toroidal width

σ_{max}= 1.75 MPa

δ_{max} = 0.41 mm at 21 cm

δ_{max} = 0.18 mm at 15.2 cm

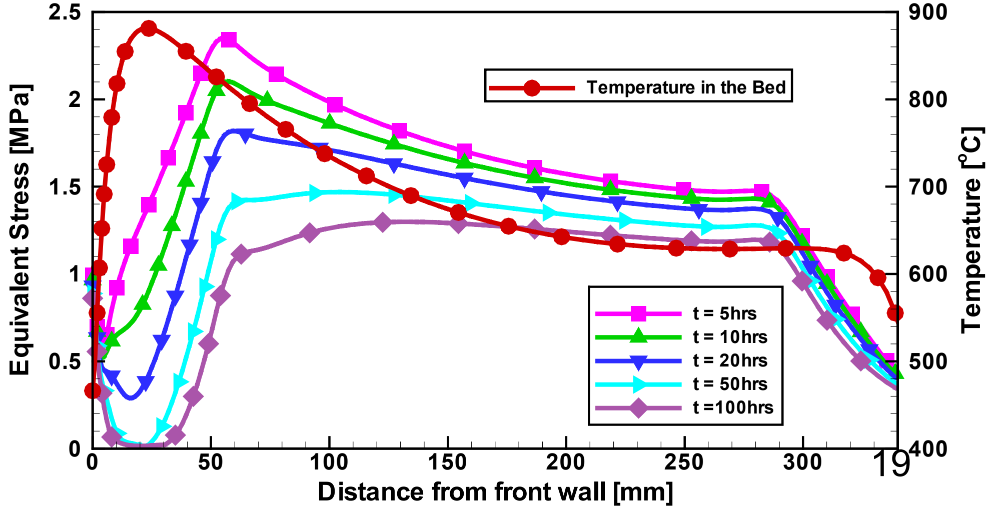
Modified ITER Scale model
reproducing temperature magnitudes
35 cm radial length (geometric constraint)
1.8 cm toroidal width near FW
3.2 cm toroidal width at the back

σ_{max}= 2.35 MPa

Fixed Y BC

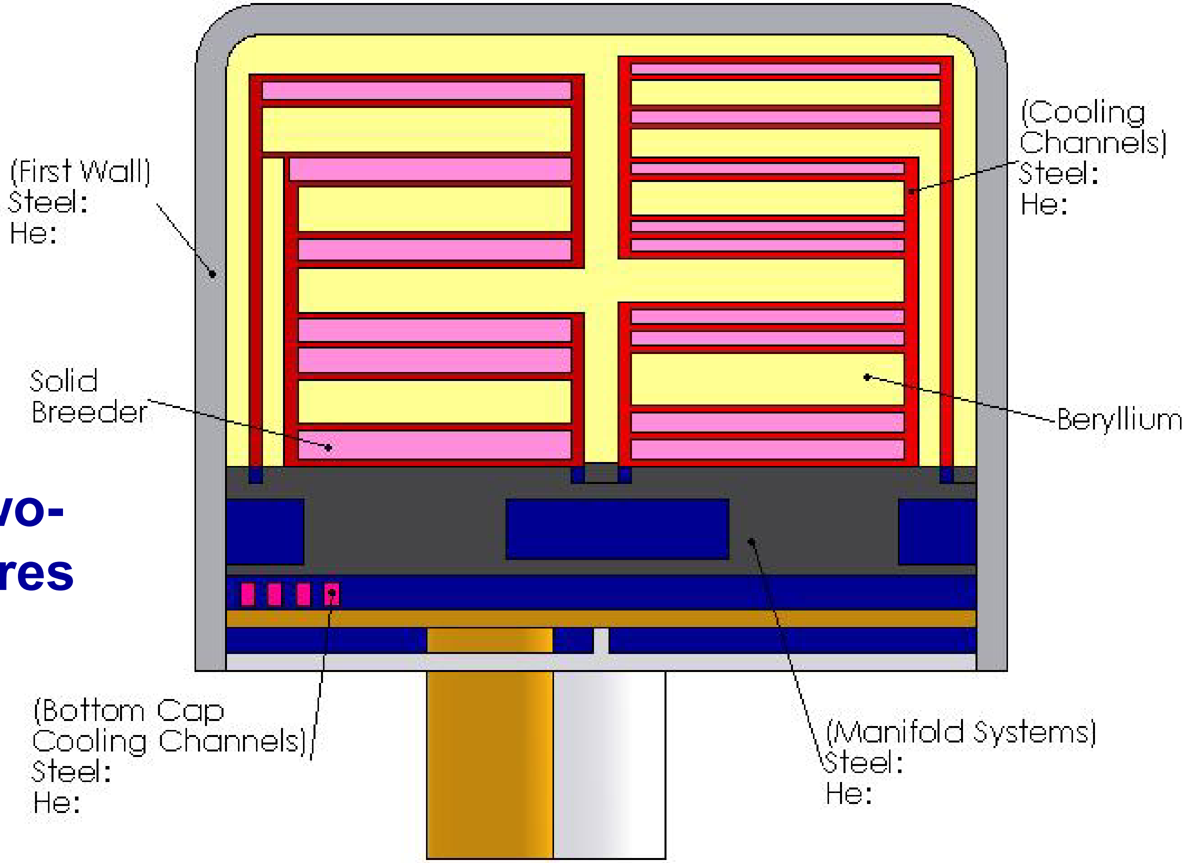
Fixed x BC

Stress evolution at mid-plane of ITER scale model



Neutronic submodule is designed to perform initial check of neutronic code and data (tritium production and heating generation rates)

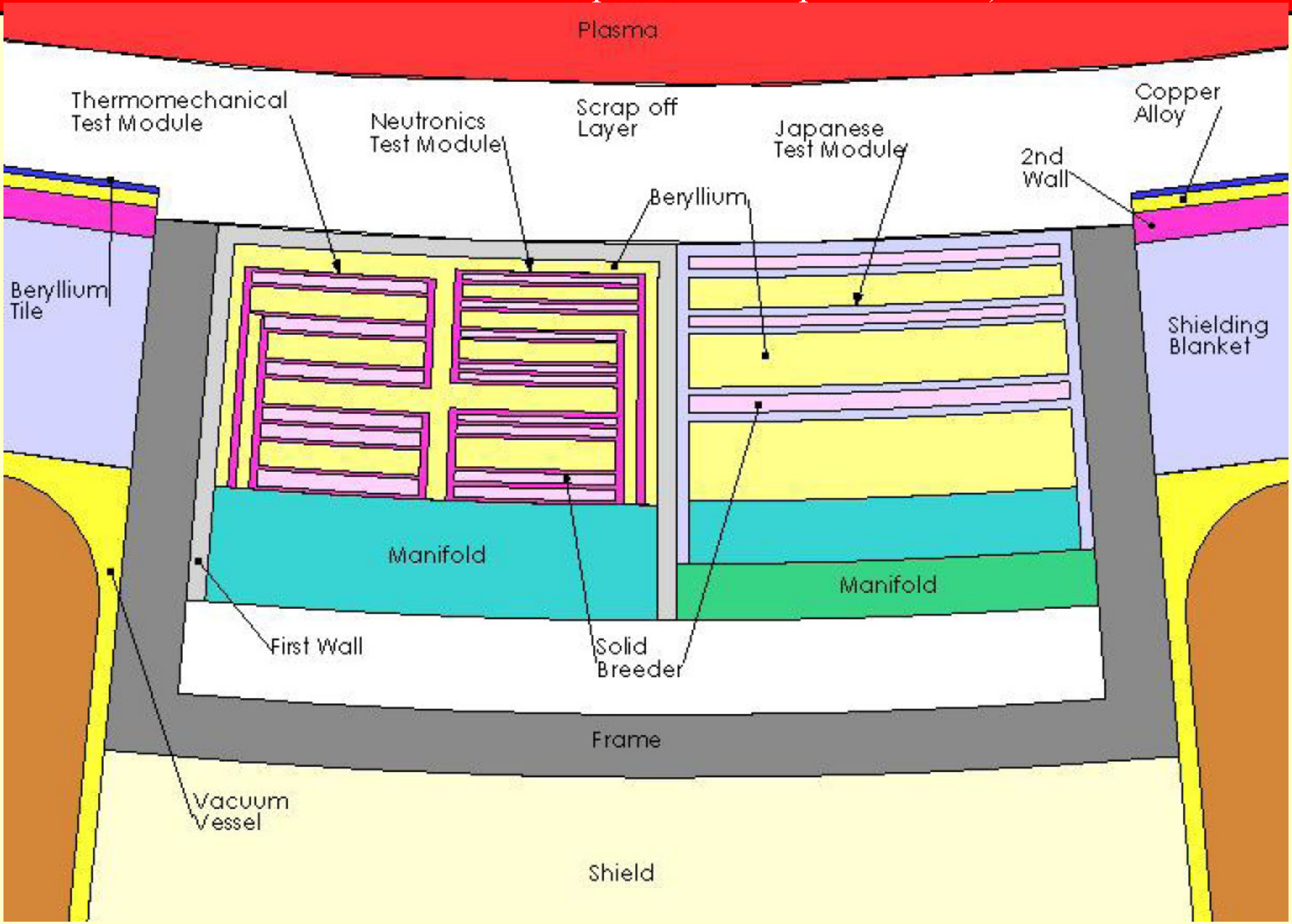
- The submodule incorporates two layer design configurations: one thermally acts alike and the other looks alike



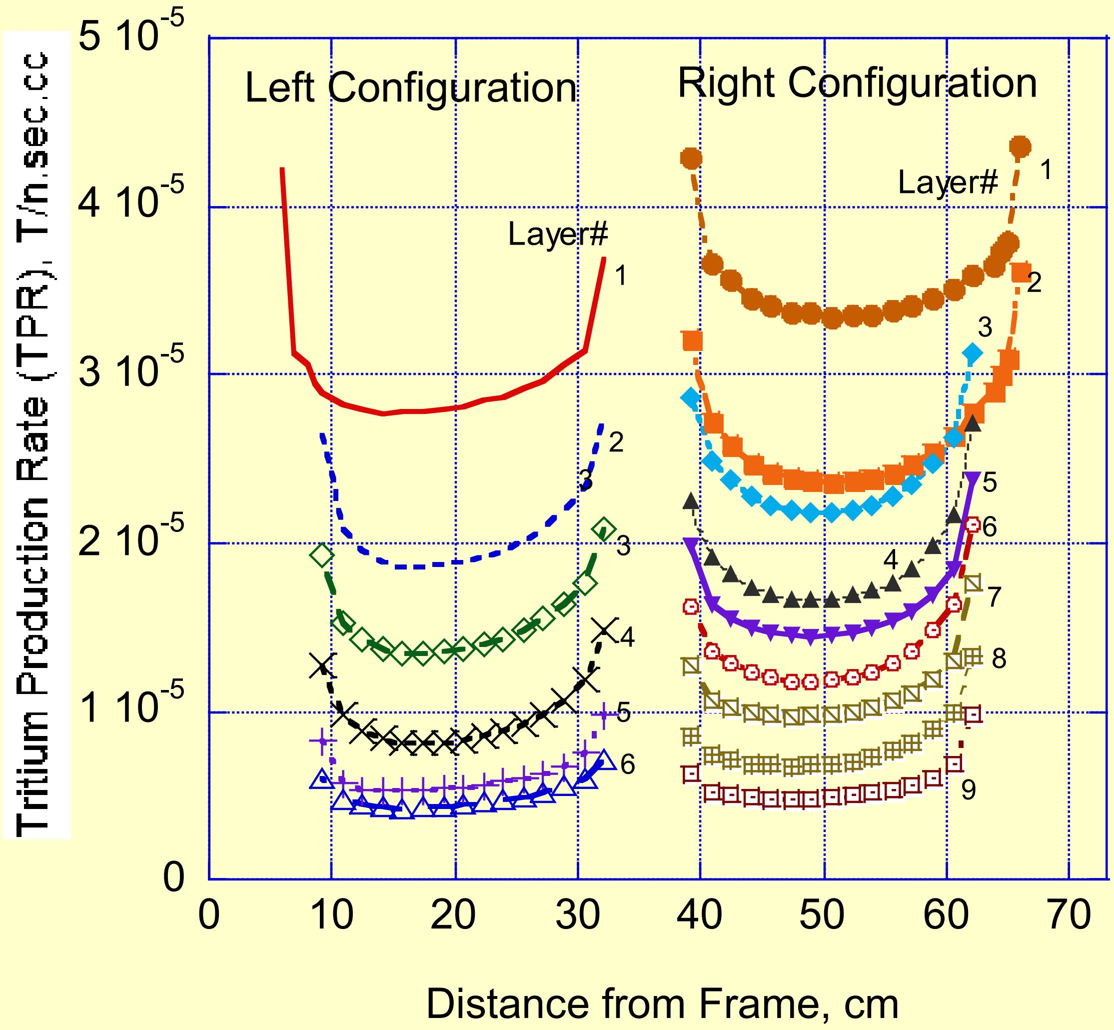
- Complex one- and two-D performance features for code evaluations

Top View of the 2-D nuclear model

(The model includes neutronic submodule and its neighboring submodule, frame structure and vacuum vessel placed in a ½ port in ITER)

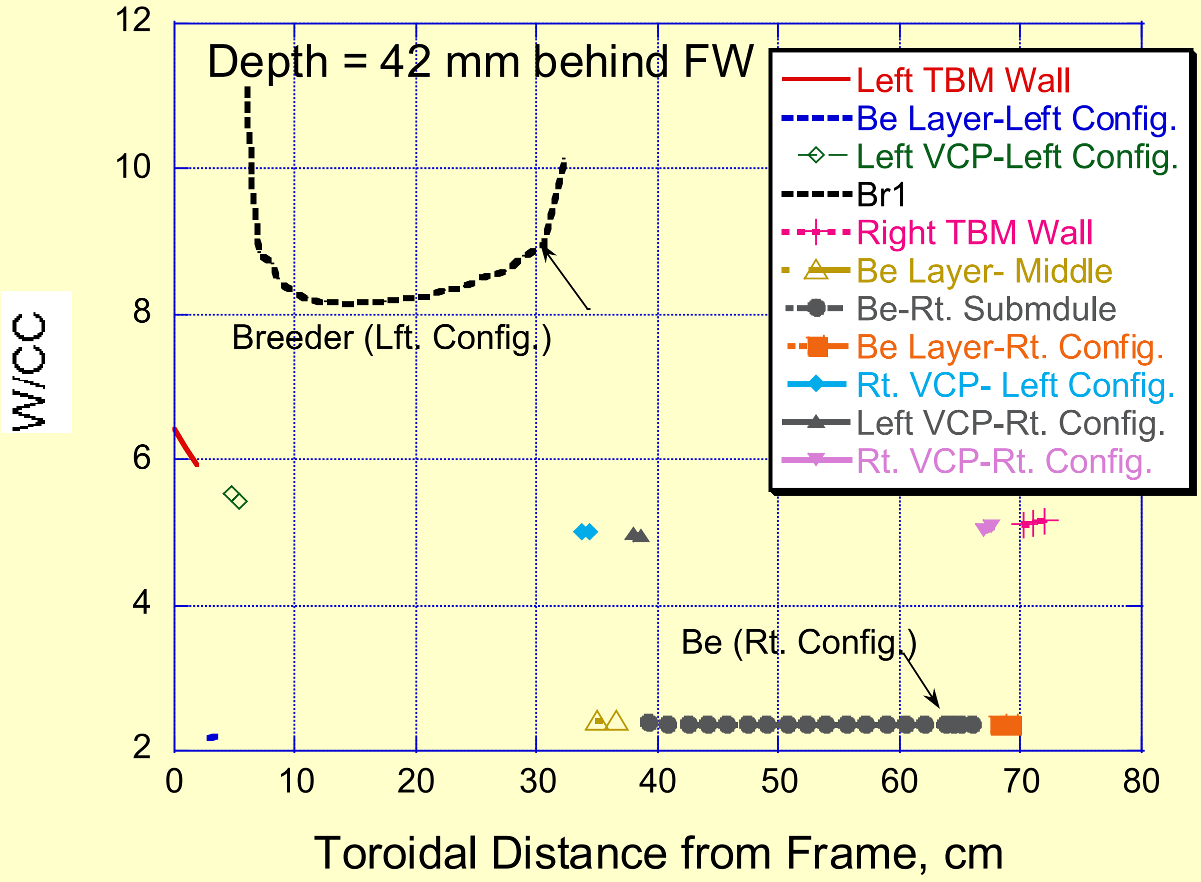


Toroidal Profile of Tritium Production Rate (TPR) in each Breeder Layer of the Two Test Blanket Configurations



- Profiles of the TPR is nearly flat over a reasonable distance in the toroidal direction where measurements can be performed (10-16 cm in the left Config. and 10-20 cm in the right Config.).
- Steepness in the profiles near the ends of layers is due to presence of Be layer and to neutrons reflected by the structure contact in the vertical coolant panels (VCP). This is more pronounced at the outer VCP. TPR values are larger at these locations by a factor of 1.4-1.5

Nuclear Heating Across the U.S. Two Test Blanket Configurations in the Toroidal Direction at Depth 42 mm Behind the FW



- Heating rate in the breeder of the lft. Config. is a factor of ~4 larger than in Be of the Rt. Config. and is flat over ~10 cm. It peaks near the vertical coolant panels.

- Heating profile in beryllium is flat over the entire layer. This feature is applicable to other beryllium layers (not shown)

- The features shown indicate the heterogeneity effect which can’t be produced with 1-D model

Summary

- Engineering scaling analysis has been successfully applied to ITER solid breeder TBM designs
- Primary parameters such as temperature magnitudes, stress and strain levels have been preserved in the scale model
- First wall design has reproduced prototype maximum temperature and stress levels by using a 5 channel per flow path design.
- 2-D nuclear analysis shows that flat tritium production and nuclear heating profiles can be obtained in a quarter port submodule with two design configurations. This ensures that a high spatial resolution for any specific measurement can be achieved in the scale model.