Assessment of Critical Neutronics Issues for ITER

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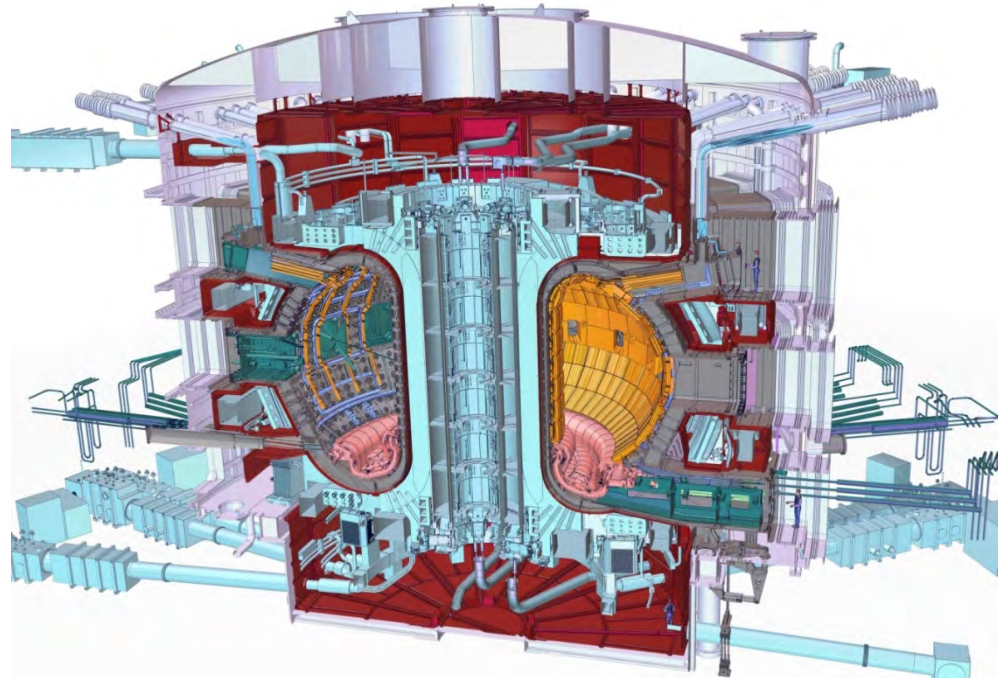
for the USDA Neutronics Team

USBPO web seminar

October 29, 2015

ITER is a Complex *NUCLEAR* Facility

- ITER plasma produces 7.1×10^{22} 14 MeV neutrons in each 400 s pulse and $\sim 3 \times 10^{27}$ over life of facility
- Nuclear heating, radiation damage, transmutation, and radioactivity produced in ITER components
- Complex geometry results in streaming paths and excessive dose rates at some locations
- Many neutronics issues should be addressed

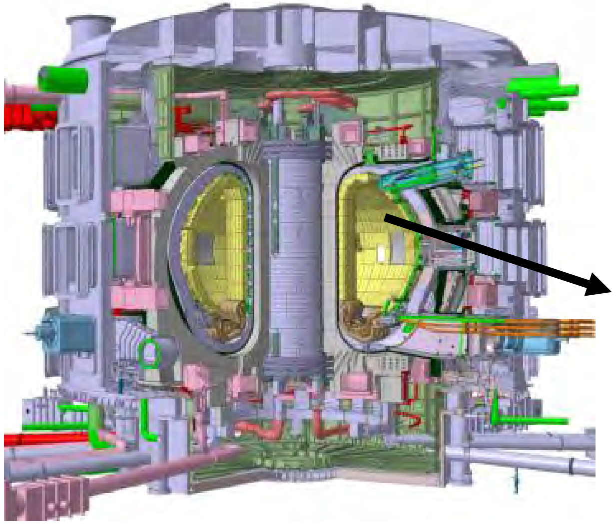


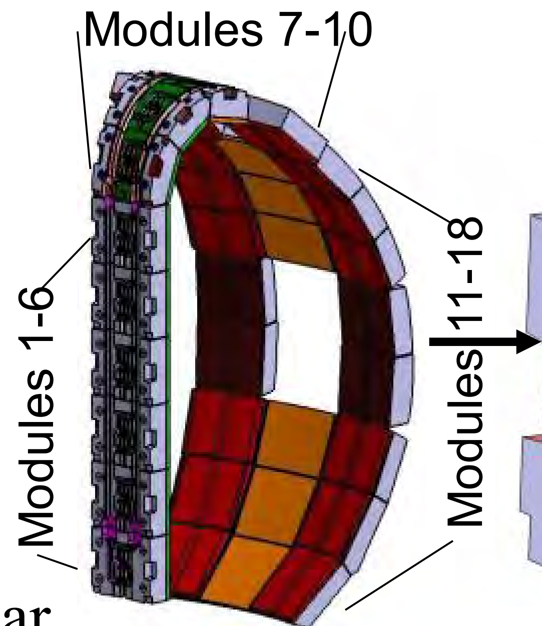
- Role of nuclear analysis initially was to provide specifications for design of components. These have now matured and nuclear analysis has the responsibility to verify the designs

ITER Neutronics Analysis in US

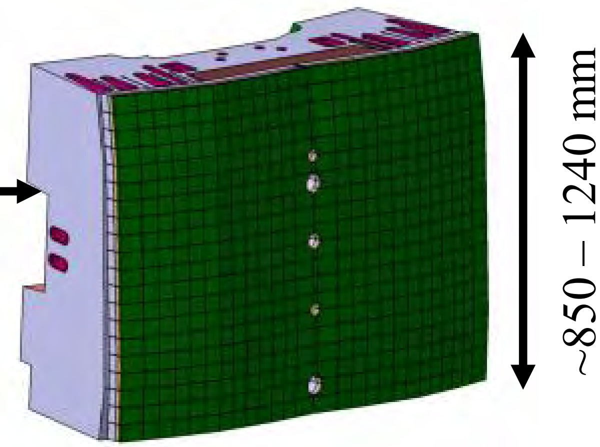
- UW: (DAG-MCNP code) Providing neutronics support for ITER since its inception in 1988. Nuclear analysis for several ITER components such as Blanket, VV, TFC, IVC, TCWS, pellet injector. Detailed SDDR map inside bio-shield
- PPPL: (ATTILA code) Diagnostics ports nuclear analysis
- ORNL: (ADVANTG code) Dose in NBI systems from streaming radiation and activation in cooling water pipes in NBI cell. Dose in assembly hall around ECH/ICH penetrations
- US tools has advantage of being CAD based preserving geometry details and better accuracy

Blanket System

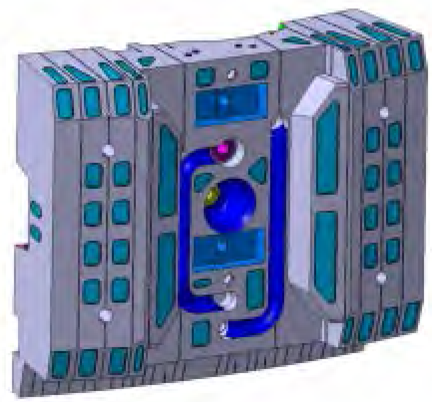




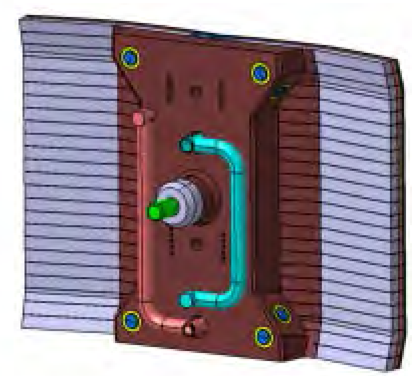
Blanket Module



- Exposed to highest nuclear environment with significant particle heat fluxes from plasma and large EM loads
- Provides shielding to reduce heat and neutron loads in VV, IVCs, and ex-vessel components

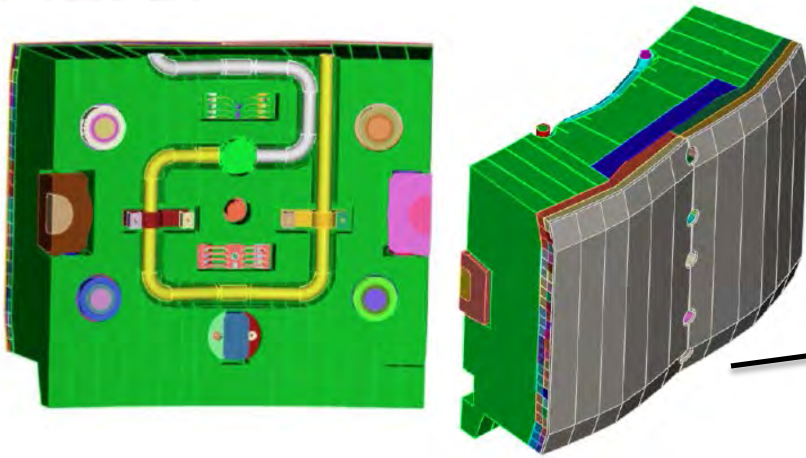


SB (semi-permanent)

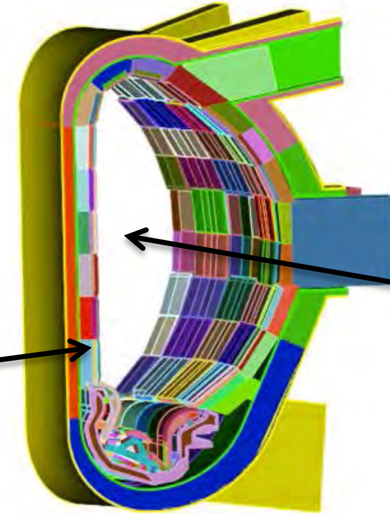


FW Panel (separable)

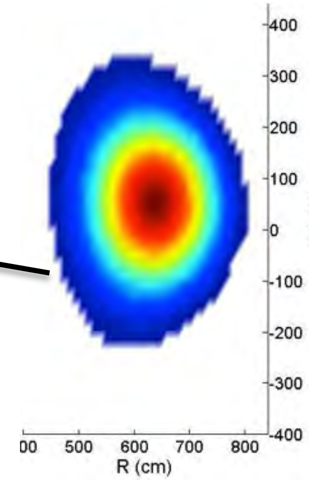
3-D Analysis with Detailed BM01



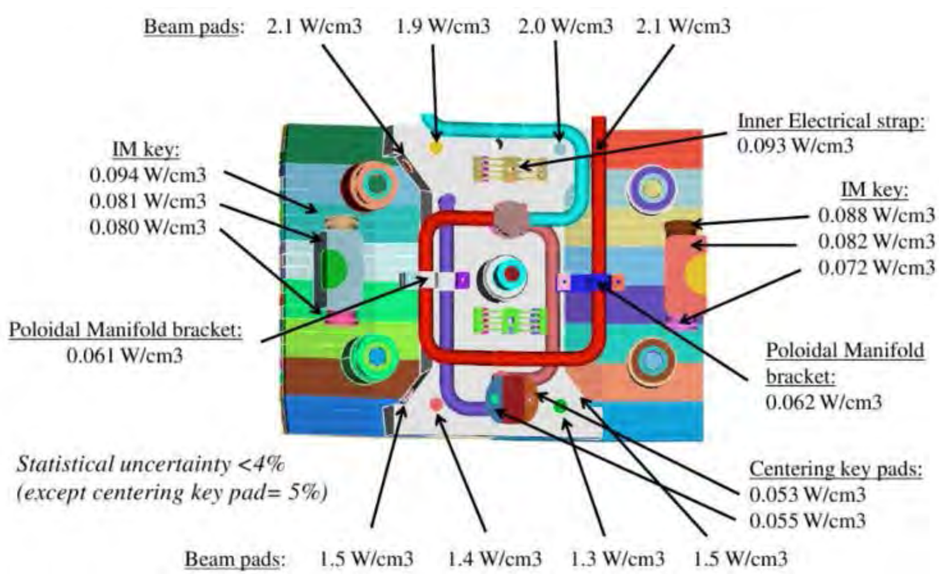
BM01

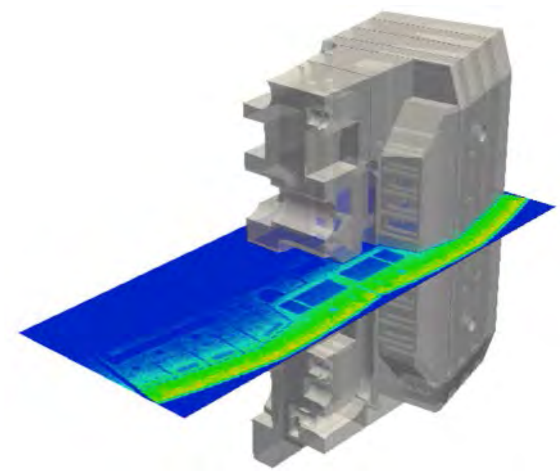


BL-lite



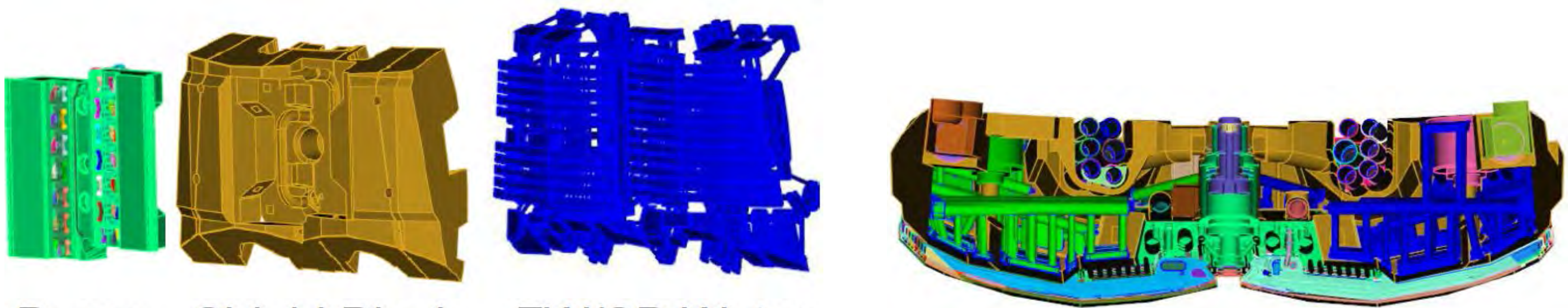
Source



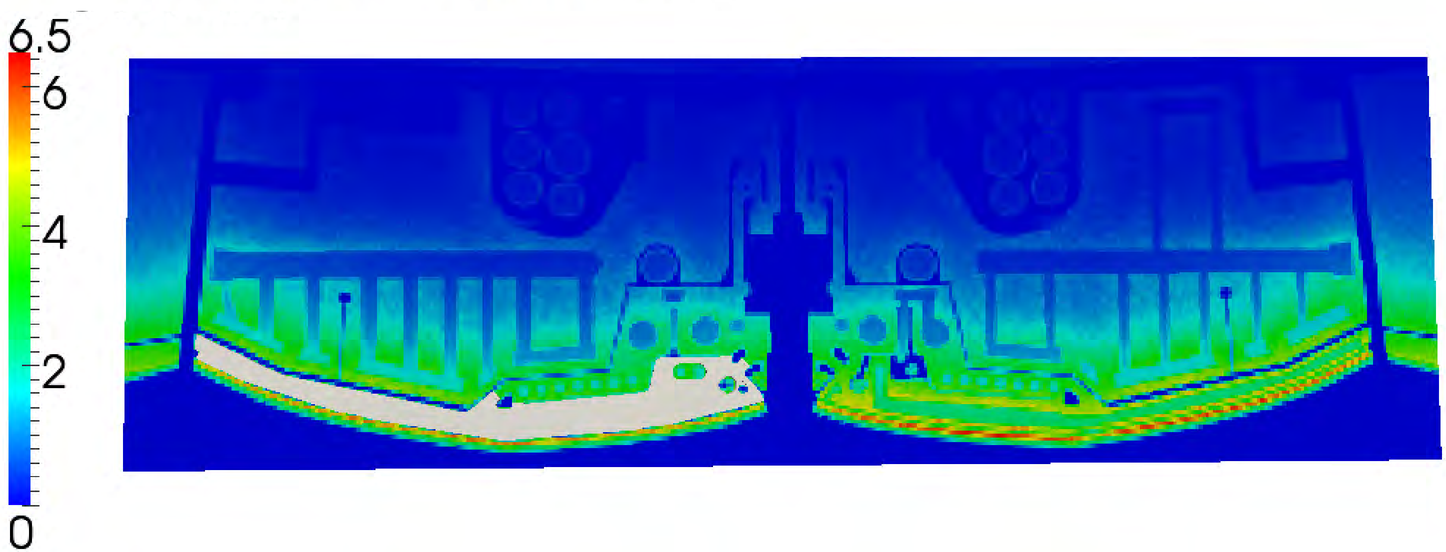


Heating Map in BM08

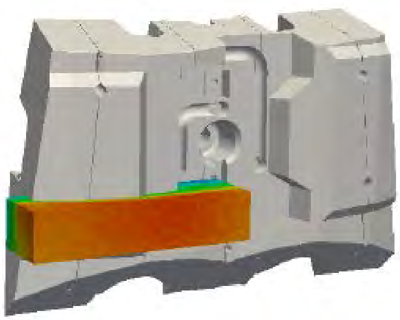
- Entire BM08 model covered with a rectangular (non-conformal) mesh tally

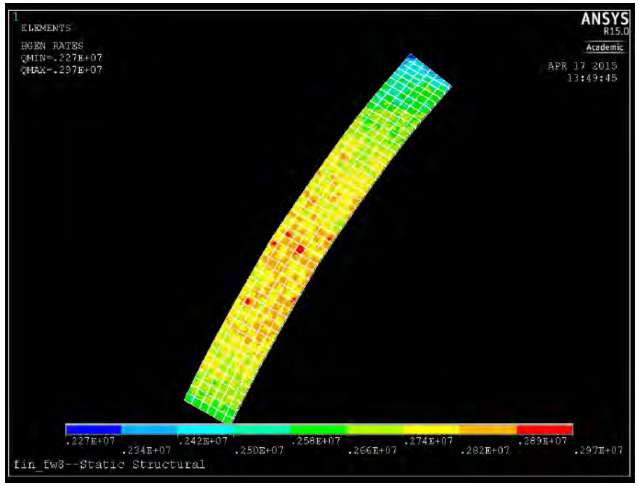


Beam   Shield Block   FW/SB Water

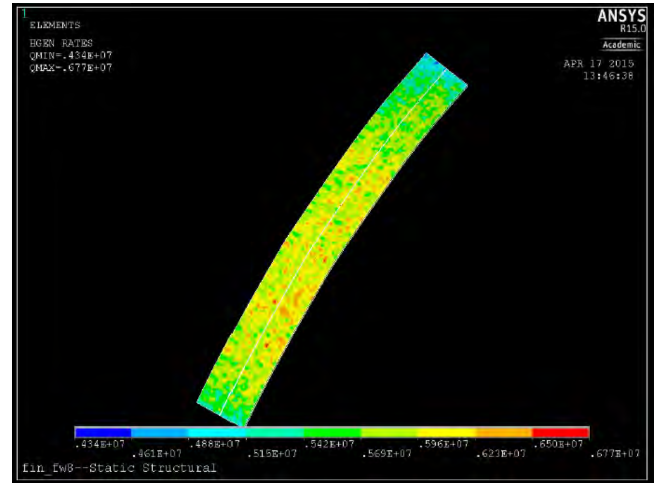


Mapping of Heating in FW08 on ANSYS Mesh for Engineering Analysis

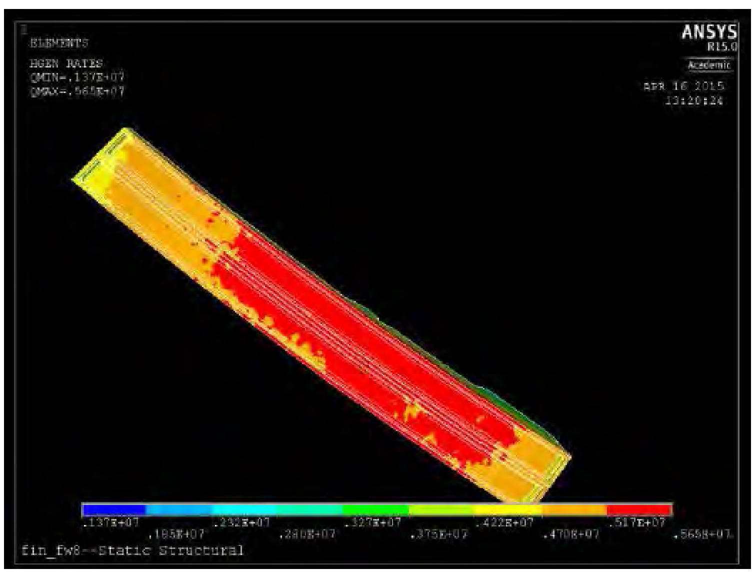




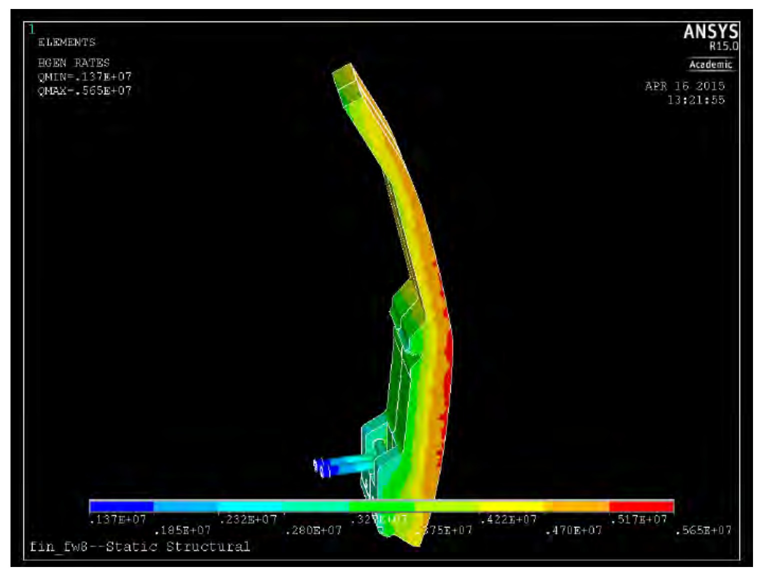
Be



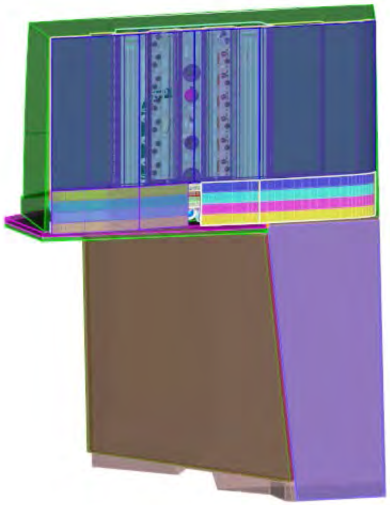
Cu

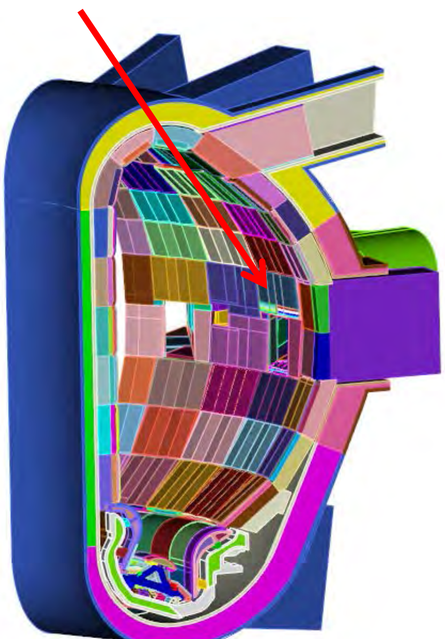


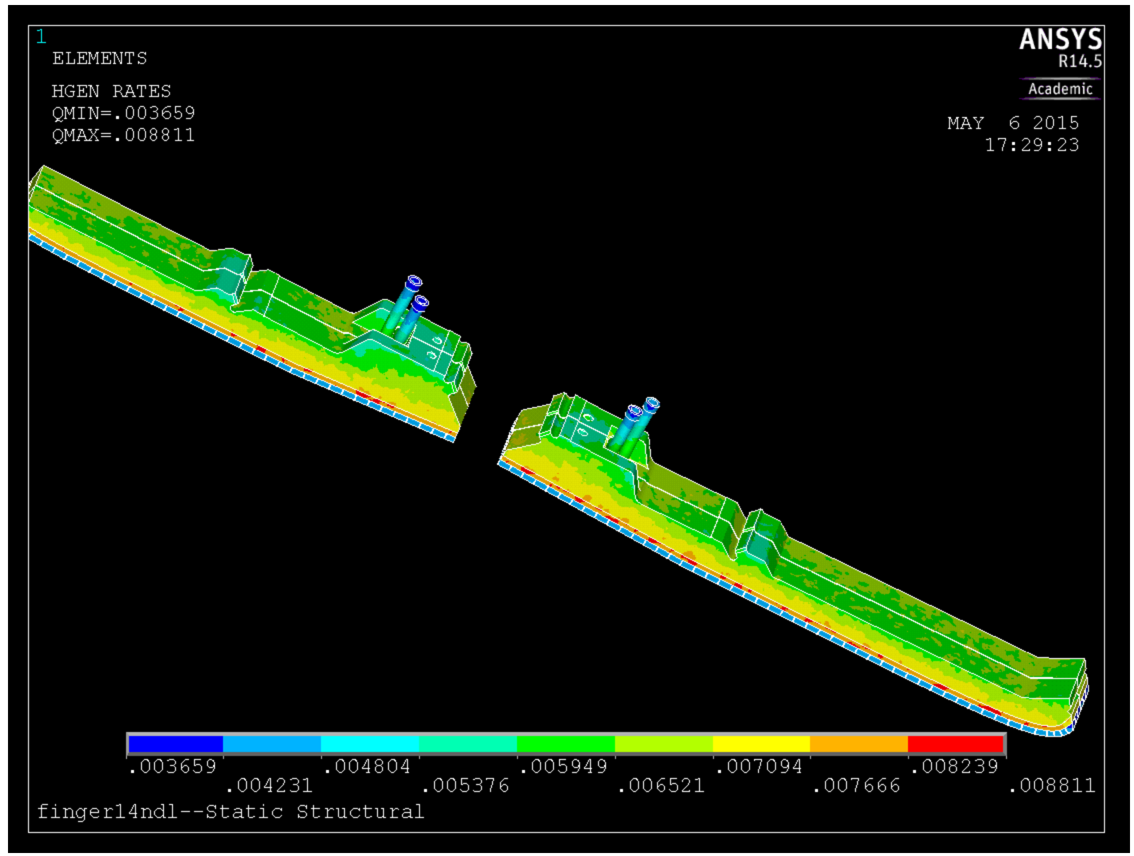
SS



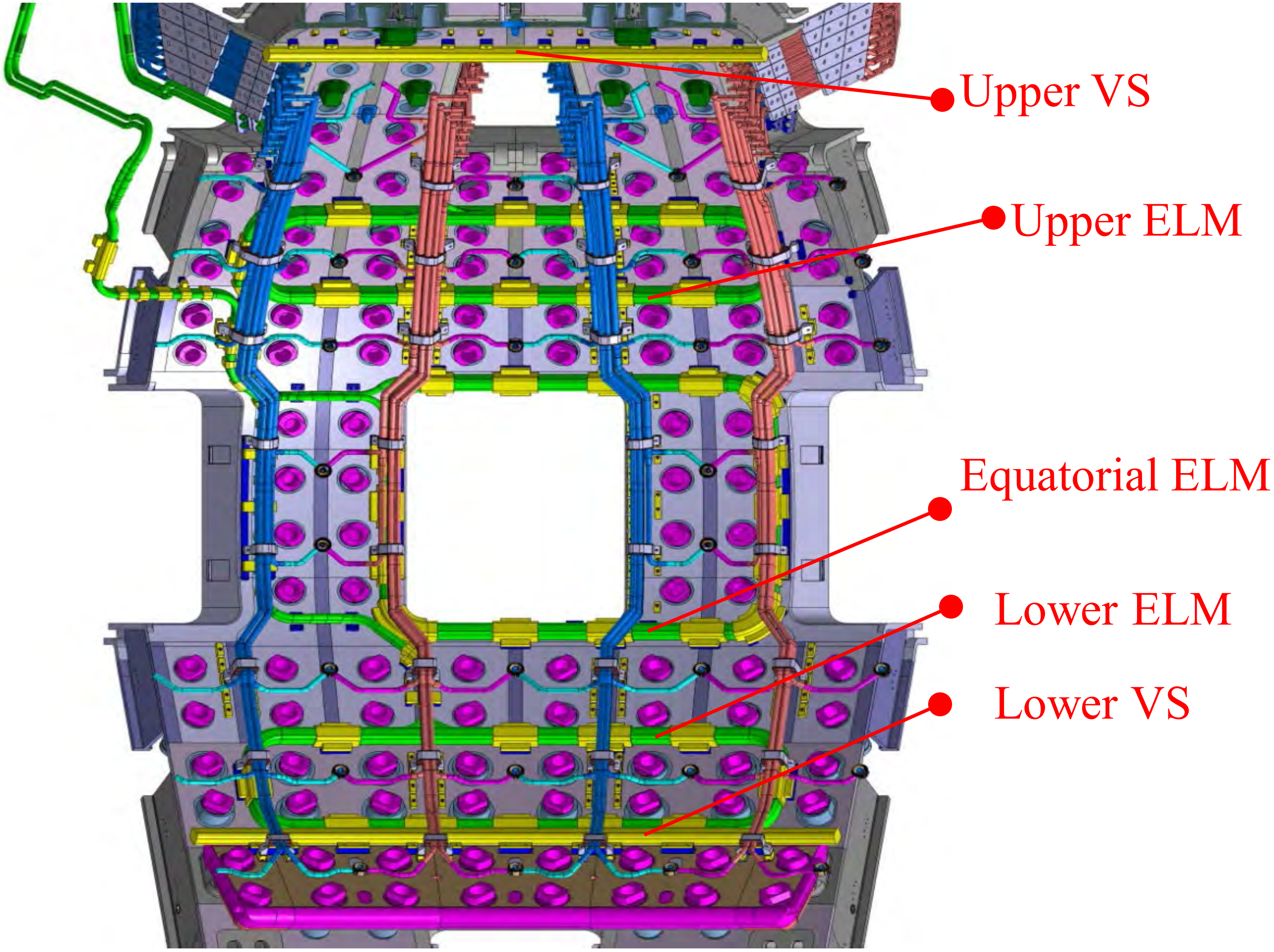
Mapping of Heating in FW14NDL to ANSYS Mesh







Location of Peak Heating and Damage in ITER IVCs



Peak Heating and Damage in IVCs

Peak Power Density (W/cm^3) in IVCs

	Upper ELM	Equatorial ELM	Lower ELM	Upper VS	Lower VS
SS	1.87	1.22	1.12	0.67	1.37
Cu	2.12	1.36	1.17	0.75	1.53
MgO	0.82	0.64	0.49	0.43	0.79
H_2O	0.53	0.55	0.33	0.35	0.74

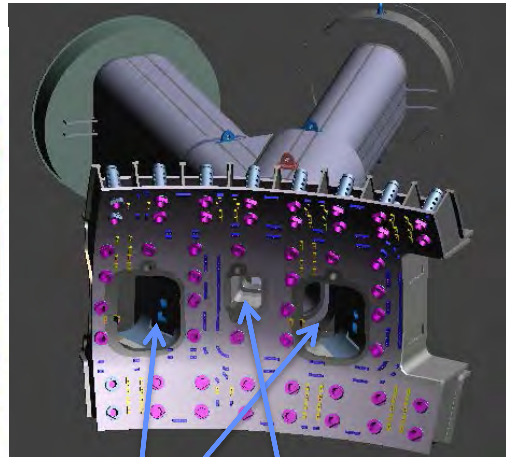
Peak dpa Values for IVCs @ 0.3 MWa/m^2

Coil	CuCrZr	Inconel625
Upper ELM Coil	0.328	0.344
Equatorial ELM Coil	0.349	0.365
Lower ELM Coil	0.334	0.349

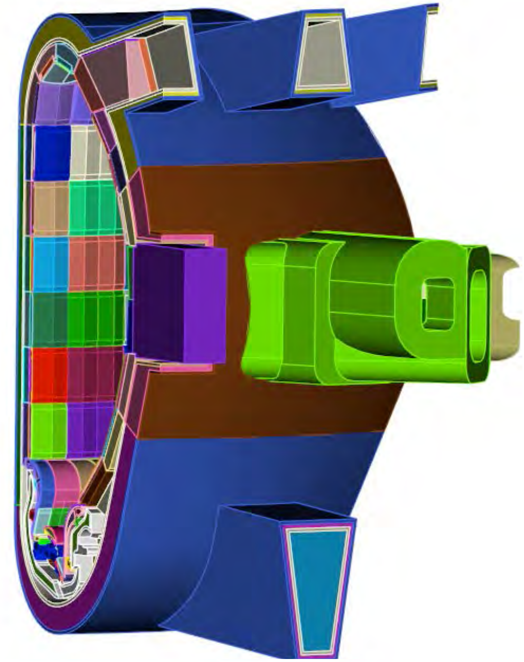
Coil	CuCrZr	SS316L(N)-IG
Upper VS Coil	0.417	0.380
Lower VS Coil	0.296	0.286

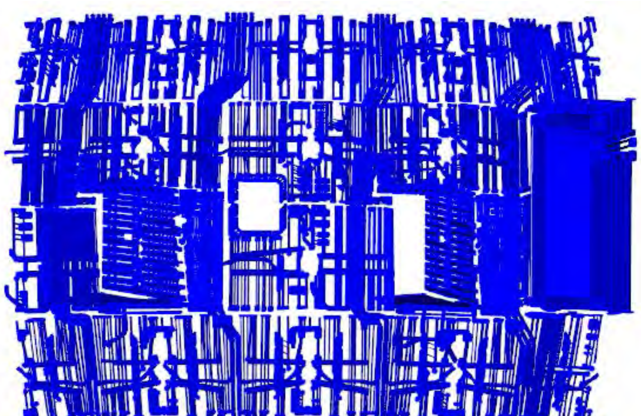
Nuclear Analysis for VV at NBI Port

Detailed BM13-16

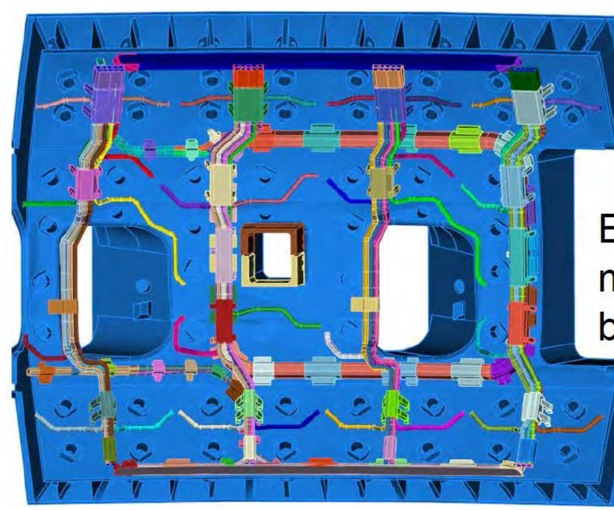


HNB and DNB ports





Water coolant channels



ELM coils, manifolds, brackets

Nuclear Heating at NBI Port Extension

Too high heating

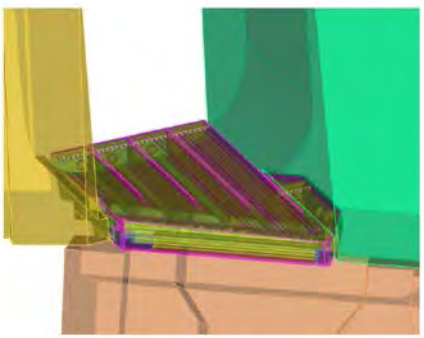
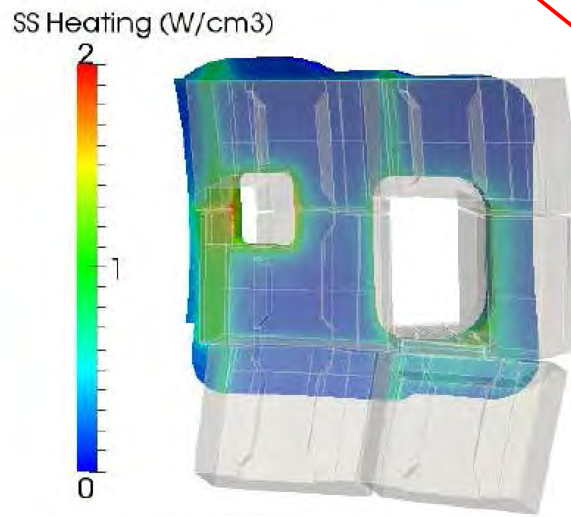
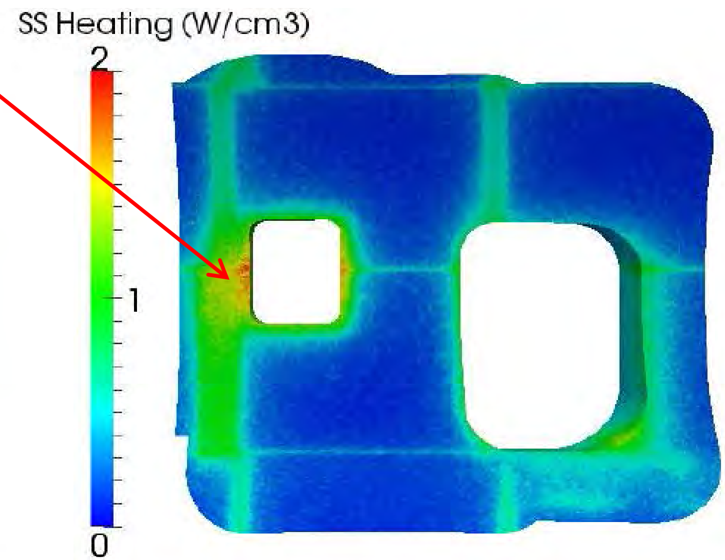
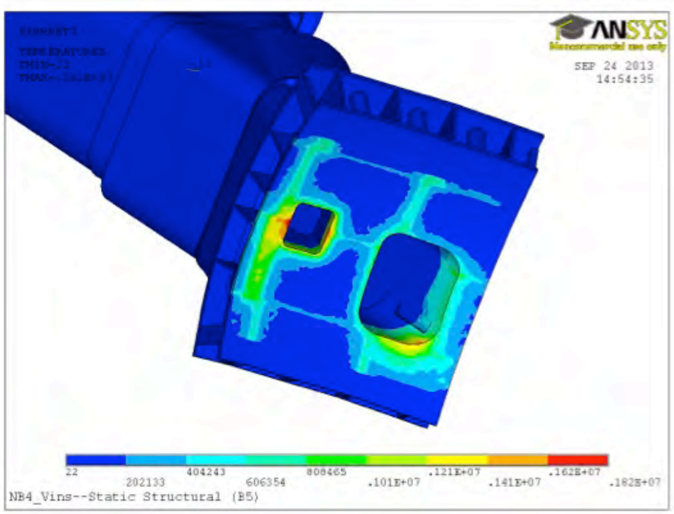


Figure 7-1. New BM16 flap design.

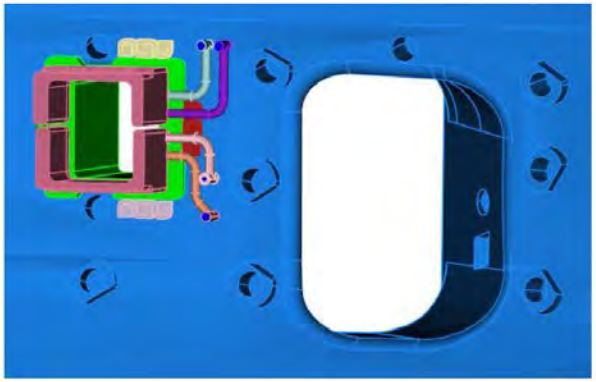




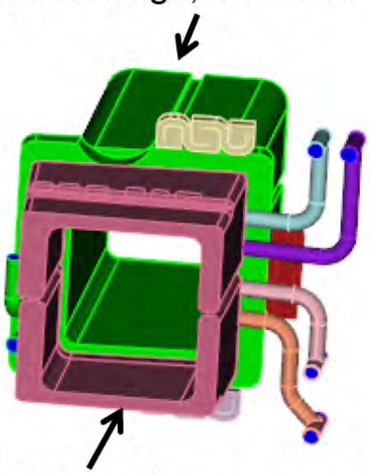


- Stress analysis at HNB implies it is acceptable with 3 cm flap
- Excessive heating at DNB

Heating and Damage in VV at DNB with Different Liner Designs



DNB Liner (green color):
- Shell+ribs version
- 5-6 cm flange, 4 cm wall

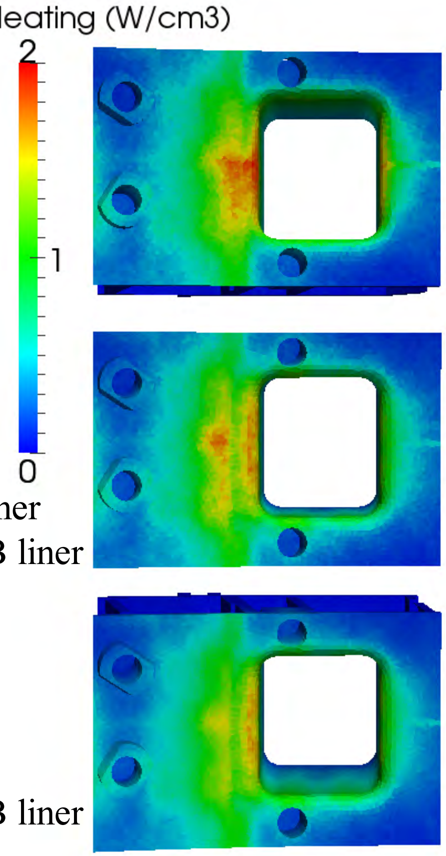


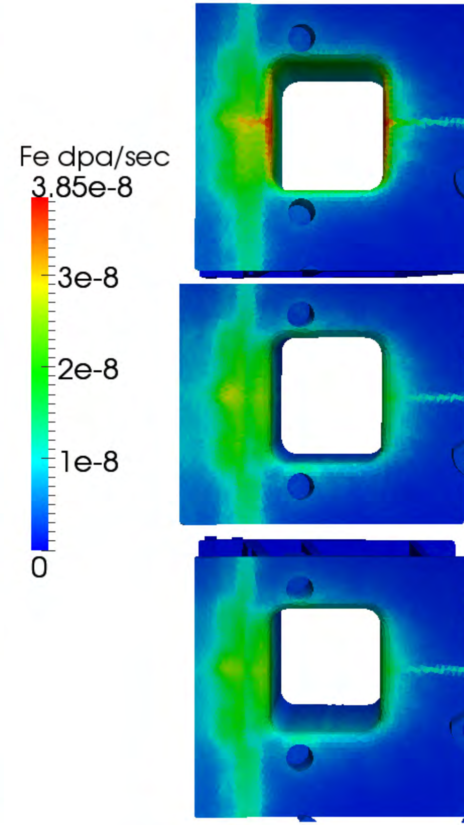
SB Liner (lavender color):
Shell+ribs or Drilled versions

Case 1
drilled SB liner
no DNB liner

Case 2
shell+ribs SB liner
shell+ribs DNB liner

Case 3
drilled SB liner
shell+ribs DNB liner

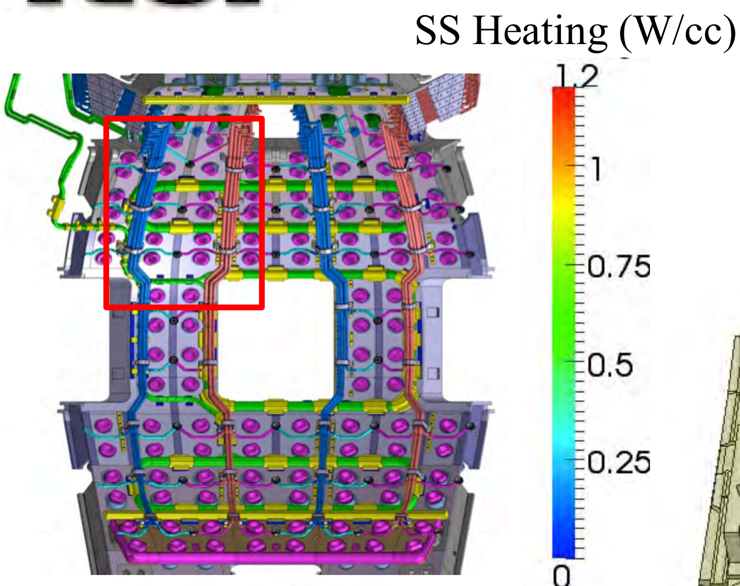




VV heating at DNB for 3 liner designs

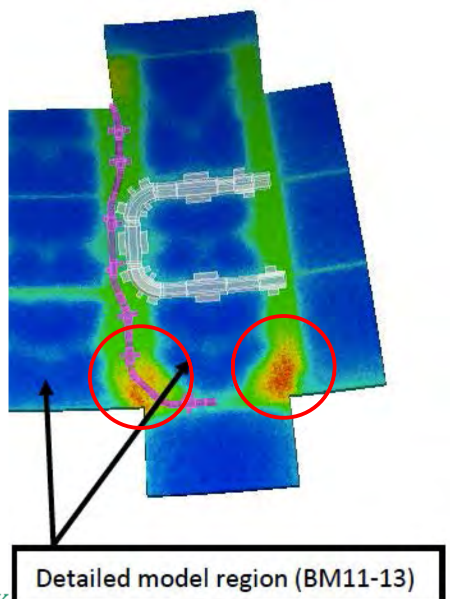
Fe dpa at DNB for 3 liner designs

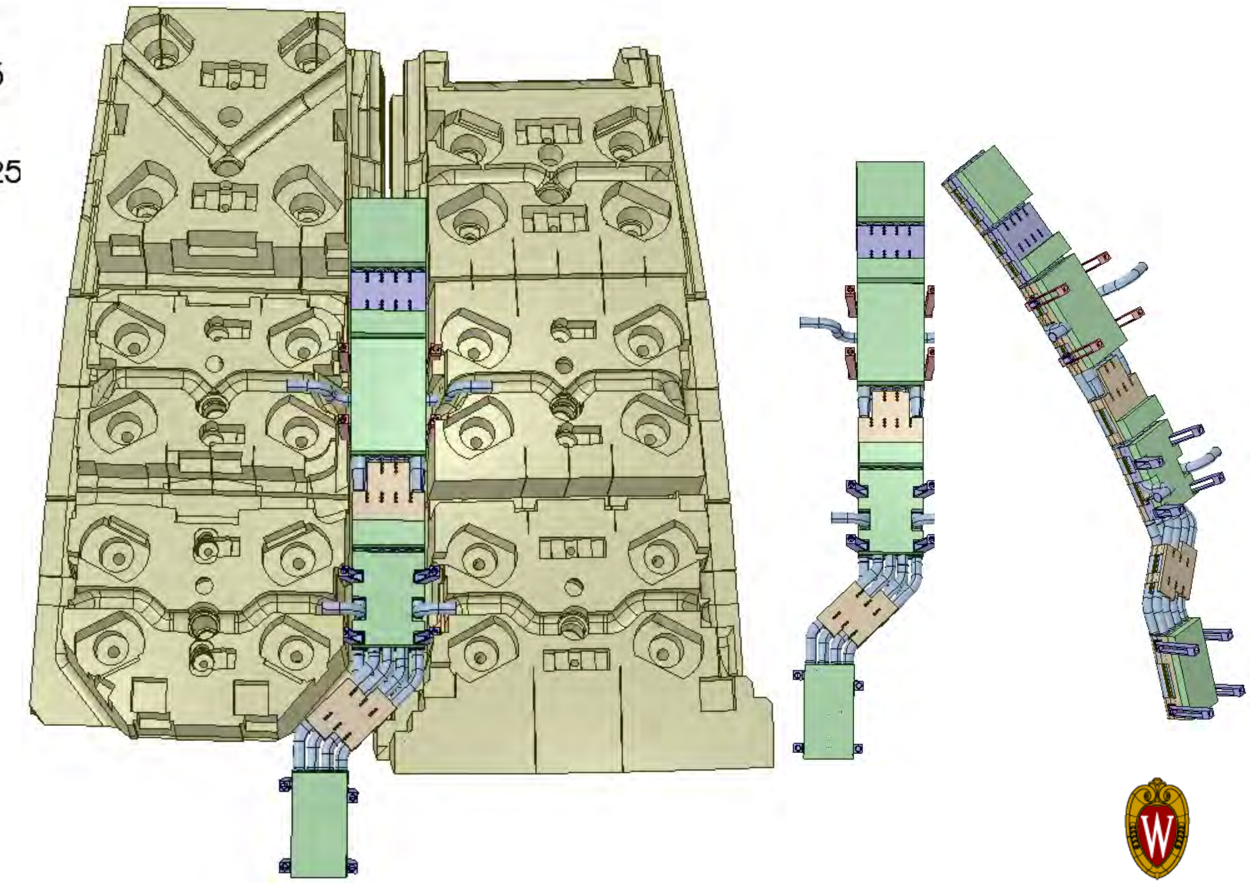
Upper ELM coil region (BM11-13)



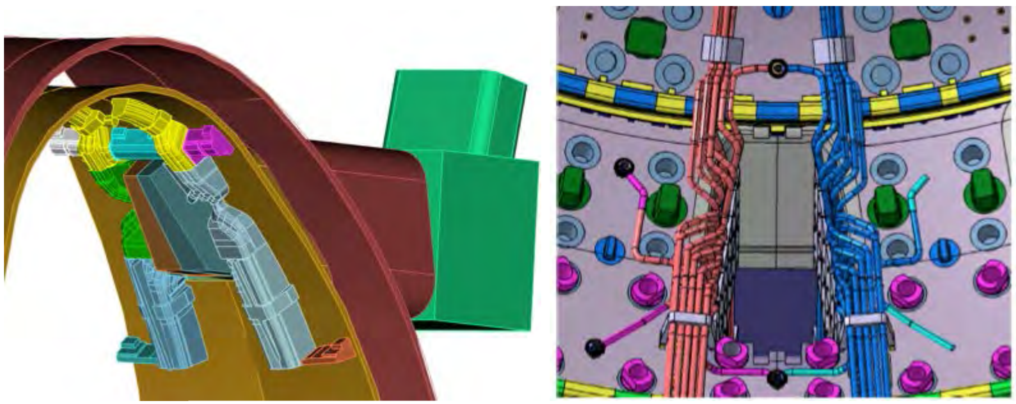
Excessive VV heating >0.6 W/cc

Design modifications with Manifold Attached Shield (MAS) will be assessed

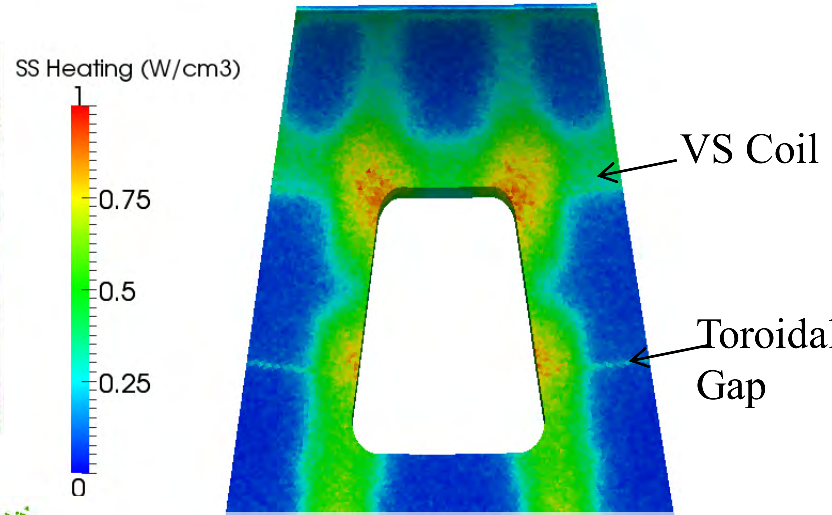




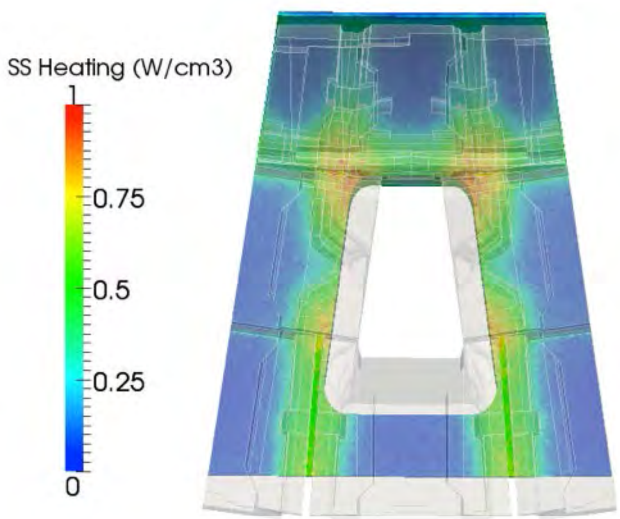
Upper port region (BM09-11)



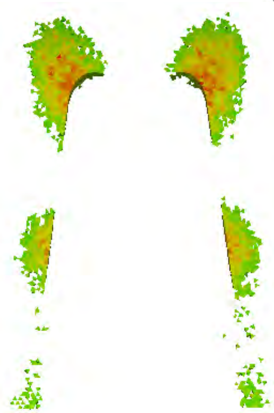
Complex CAD geometry



VV Heating on Conformal Mesh



VV Heating with CAD Model Overlay



VV Heating with 0.6 W/cm^3 Threshold

Design modifications with Manifold Attached Shield (MAS) will be assessed

Estimated Integral VV Heating Based on Refining 3-D CAD Models

- Total VV heating calculated with B-lite model is 12.4 MW →16.7 MW with recent C-lite model
- Model used has detailed inboard blanket models (1-6) only with homogeneous representation of VV inter-wall shield and no water pipes inside upper port
- VV heating dominated by outboard
- Design value is 10 MW
- Estimated integral VV heating based on previous detailed 3-D calculations of VV heating with detailed modeling in different regions

Estimate of Integrated VV Heating

- Use ITER Detailed C-Lite analysis as baseline and add estimated contributions where details are missing

Item	Source	Value (MW)
Baseline	ITER semi-detailed C-lite	16.7
BM07-BM08	UW-BM01	0.1
BM09-BM10	UW BM09-BM11	0.7
BM11-BM12	UW-BM11-13	1.2
NBI (3 HNB,1 DNB)	UW-NB Region	1.0
BM17-BM18	UW BM11-13	1.2
Total	-	**20.9**

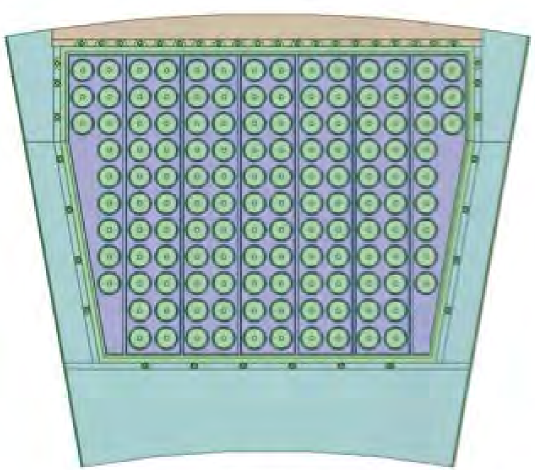
- Additional systematic and random error bars were identified by IO leading to an estimate of 26+/-4 MW. ITER neutronics task force agreed to adopt a conservative upper value of 30 MW for design of cooling system
- Note: heating value is for 500MW. ITER may operate at 700MW

Additional Systematic and Random Errors for VV Heating

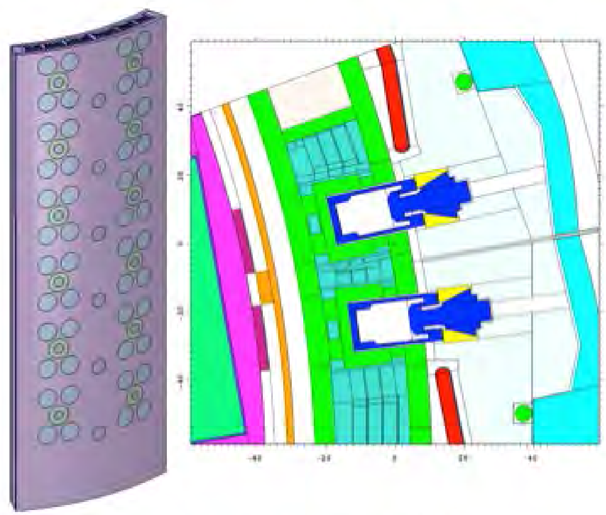
- SYSTEMATIC ERROR
  - SIMPLIFICATION OF VV MODEL
  - EFFECTS OF DIAGNOSTICS EQUIPMENT
  - EFFECT OF 16N PRODUCTION IN BLANKET AND VESSEL COOLING WATER
  - DECAY HEAT
  - DIVERTOR DESIGN
  - ORIENTATION OF COOLING CHANNELS IN BLANKET
  - MANUFACTURING DESIGN vs CATIA DESIGN
  - DETAILS OF MANIFOLDS AND IN-VESSEL COILS
- Known systematic effects indicate VV heating ~26 MW
- RANDOM ERROR
  - STATISTICS OF MONTE CARLO METHOD
  - NUCLEAR DATA
  - MATERIAL CONTENT
  - TOLERANCE
  - DESIGN UNCERTAINTY
  - FUSION POWER MEASUREMENT
- Known random errors amount to ~15% (1σ)

Integrated Heating in TFC

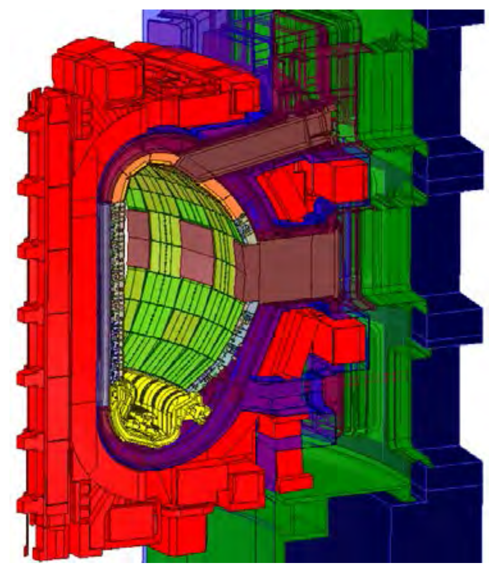
- Total TFC heating calculated with B-lite model is 17.2 kW
- 50% chance actual TFC heating exceeds the 14 kW limit
- Recent C-lite global model (CLITE_V2_REV150304) has detailed geometry (blanket, VV, FSH, TFC) in inboard straight region only. Empty lower port and dummy (50/50 SS/H_2O) EPP and UPP



Detailed Magnet Model
IB Straight Leg

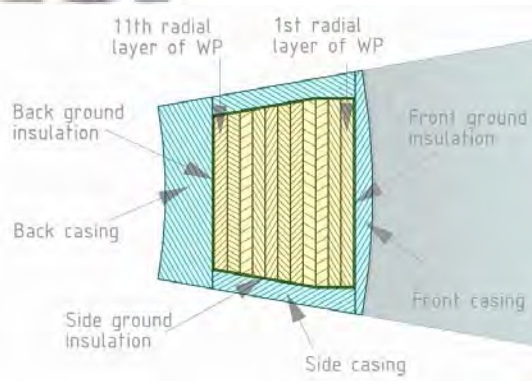


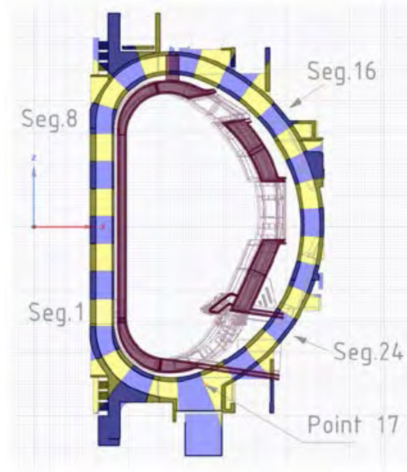
Detailed VV and FSH
in IB Straight Region



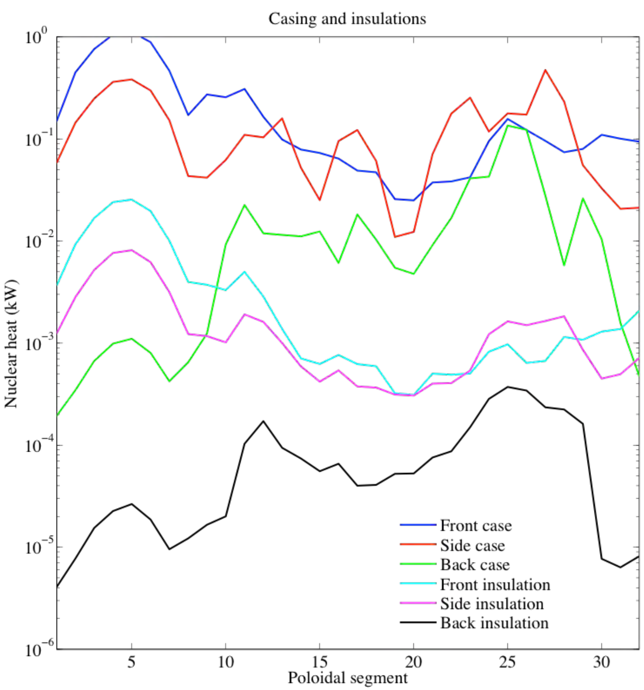
C-lite Model

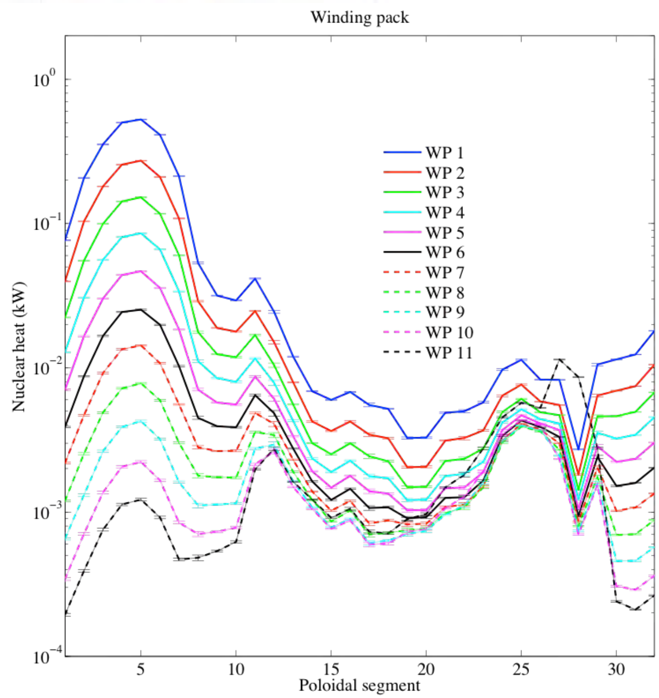
Nuclear Heating Distribution Calculated with ADVANTG

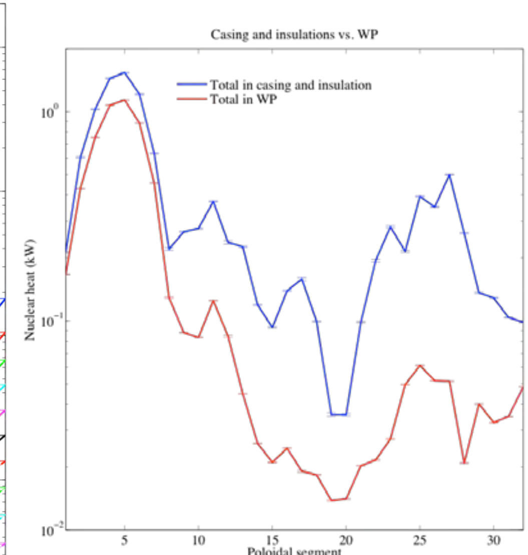




ADVANTG reduces CPU time and statistical uncertainty significantly with FOM improved by ~3 orders of magnitude







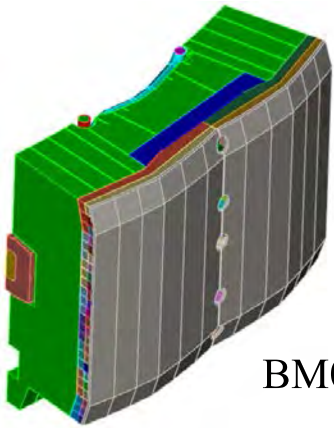
Results with CLITE_V2_REV150304

TFC Region	TFC Nuclear Heating, kW	Relative Error
IB straight leg	12.01	0.006
Outside IB straight leg	6.48	0.007
Total	18.49	0.004

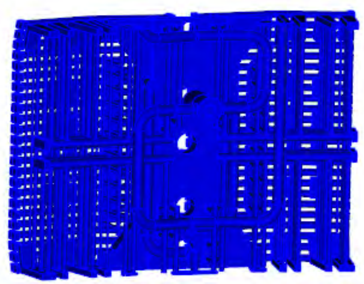
- Supplemental calculations showed that 39% of TFC heating outside IB straight leg contributed by streaming through OB ports
- Generic homogenized (SS/water, 50/50 and no void) port plugs used in UPP and EPP and LPP is empty (very conservative) in C-lite model used
- We assumed that effects of conservative and non-conservative assumptions in PPs of C-lite will cancel (conservative)
- **Contribution of ports to TFC heating is 2.53 kW**
- Correction factors should be applied to remaining 3.95 kW contributed from region outside IB straight leg

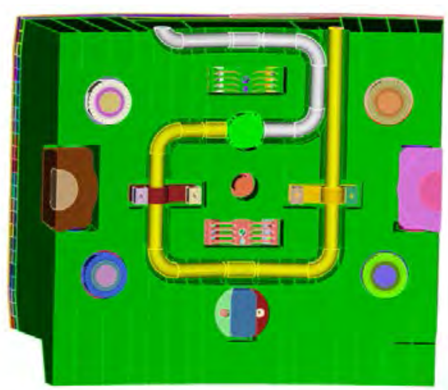
Correction Factors for BM Heterogeneity, VV Heterogeneity, FSH Outside IB Straight Region

- Calculations performed with detailed CAD models of BM01, IB VV, FSH with DAG-MCNP to quantify these effects and estimate correction factors

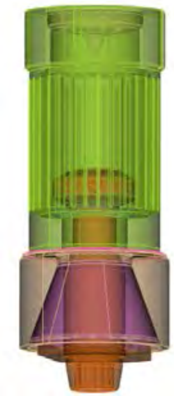


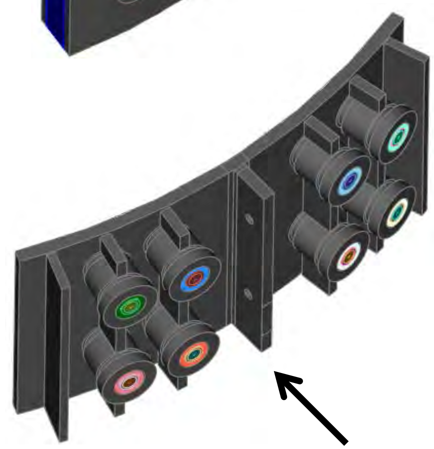
BM01





VV





VV shells, ribs, flex mount housings

- Correction factors used are: 1.2 BM heterogeneity, 1.15 FSH, 1.4 VV heterogeneity

What Are Other Contributions?

- NBI: Estimate by KIT total additional heating 0.97 kW (used outdated A-lite)

Table 1: Additional heating (W) in coils close to NBI

	TF 1	TF 2	TF 3	TF 4
Additional heating (W)	0	291.5	340.2	341.6

- Heating in TF3 and TF4 will be ~30% higher than in other TFCs
- Depending on arrangement of pancakes in WP, some pancakes adjacent to NBI ports might be exposed to about twice the heating that standard pancakes have
- Water activation: 0.16 kW
- Integration of Diagnostics: Estimated at 0.5 kW
- Correction for homogenization of OB TFC WP: 11.5% increase

Estimated TFC Heating with Additional Contributions

TFC Region	TFC Nuclear Heating, kW
IB straight leg	12.01
Outside IB straight leg (ports contribution)	2.53
Outside IB straight leg (BMs and VV contribution)	7.63
NBI ports contribution	0.97
Water activation	0.16
Integration of diagnostics	0.50
Heterogeneity of TFC coil outside IB straight	1.28
Total	25.08

Effect of 2 cm Thicker BM01-06 (PCR-641)

➢ Two independent calculations for effect of added IB BM thickness gave consistent results

Added Thickness (cm)	2	3	4	5
BM analysis during BIPT (e-fold 10 cm)	18%	26%	33%	40%
C-lite with adjusted BM densities	20%	27%	33%	40%

Using conservative 18% reduction yields an expected reduction of ~2.16 kW in total TFC heating with 2 cm thicker BM01-06

Estimated conservative total TFC heating is ***22.9 kW***

Estimated lower bound total TFC heating is ***19.7 kW***

Random Uncertainties

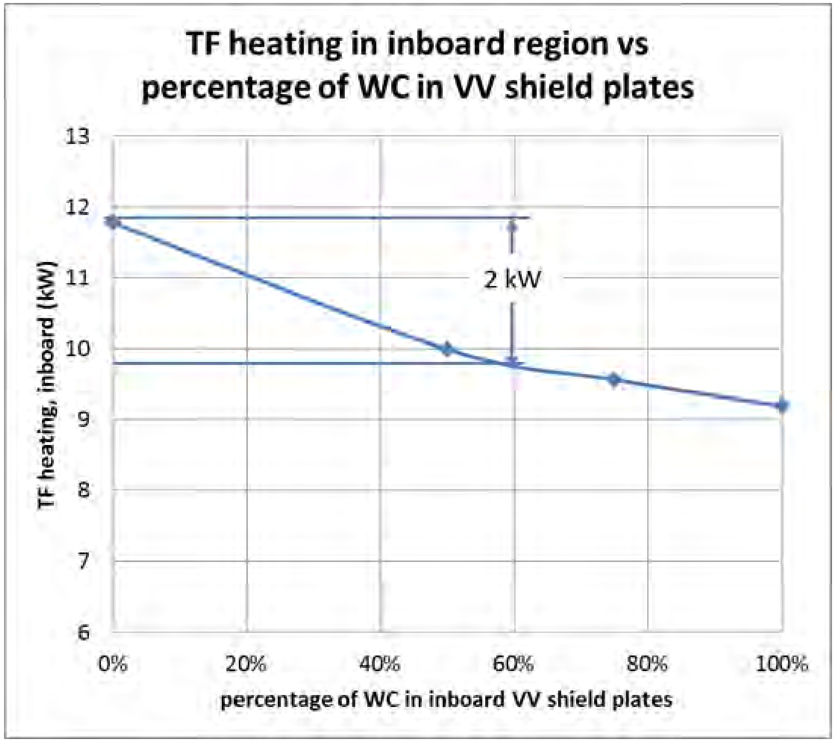
- Statistical error in Monte Carlo calculations: this is very small <<1%
- Error of fusion power measurement: the required precision on fusion power measurement is 10%
- Errors from nuclear data: ~10% based on experiments for dose measurements inside a TFC mock-up
- Sensitivity to design tolerances (materials masses, distributions, gaps, etc): ~1%
- These errors are independent. Total estimated random error is ~14%

Summary of TFC Heating

- Several assumptions made to estimate TFC heating
- Correction factors proposed for regions other than IB straight section
- Proposed correction factors are conservative
- Total TFC heating is 20-23 kW with a 2 cm thicker BM01-06 depending on assumed correction factors for VV heterogeneity and FSH
- Random uncertainties are +/- 14%
- Current best estimate of upper bound on total TFC heating is 23 kW +/- 3.2 kW

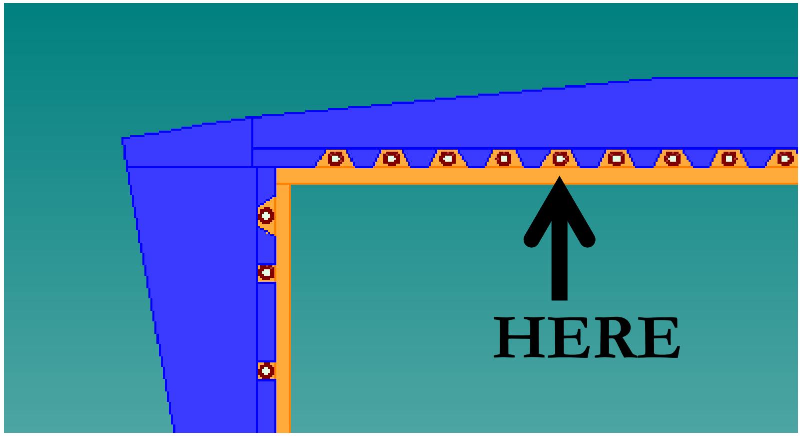
Use of WC in IWS of Inboard VV

- Replacing some of the B-SS IWS plates in the inboard VV by WC reduces total TFC heating
- WC has to be clad in SS
- Several independent calculations at UW and ORNL indicate that ~2 kW reduction can be achieved with partial use of WC
- WC is used only in the inboard straight leg of VV with a very small fraction of total IWS plates



IO Proposal of Adding B4C between Case and WP

- Use 50% B_4C with 95% B-10 in filler between case and ground insulation (mechanical mixture)



- Preliminary calculations show a decrease in heat in TFC straight leg of 2 kW
- The crude guess on reduction of heat in TFC at outboard in case of the proposed material of the filler is ~1-2 kW

Determine accurate source term from $^{16}N/^{17}N$ for L3/L4 shielding

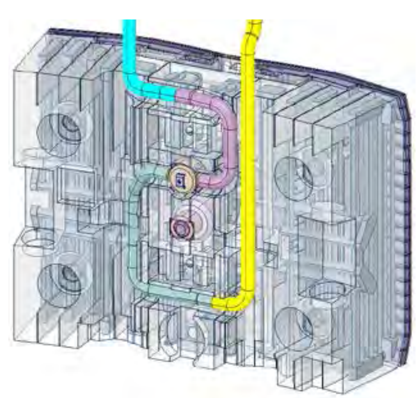
- Water activated by several reactions
  - o $^{16}O(n,p)^{16}N$ (β-) →~ 7 MeV gamma $T_{1/2}$ 7.13 s
  - o $^{17}O(n,p)^{17}N$ →0.9 MeV n $T_{1/2}$ 4.17 s

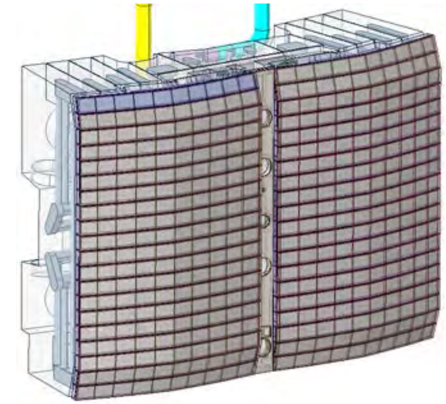
➢ Purpose of the analysis
  - ➢ Perform best in class analysis of the activation of the cooling water in ITER
    - ➢ Detailed CAD model of pipe network
    - ➢ Semi Detailed ITER model
  - ➢ To provide the best estimate of the cooling water activation estimate

➢ Previous analysis **IDM432LTAv1.1** used a very coarse resolution for the calculation casting doubts on how conservative/pessimistic

- With a sufficiently detailed CAD model of pipes we can determine how the pipes connect and build a flow network
- We targeted BM04 on the inboard. Working on divertor
- Water residence time in each segment determined from flow rate and segment volume

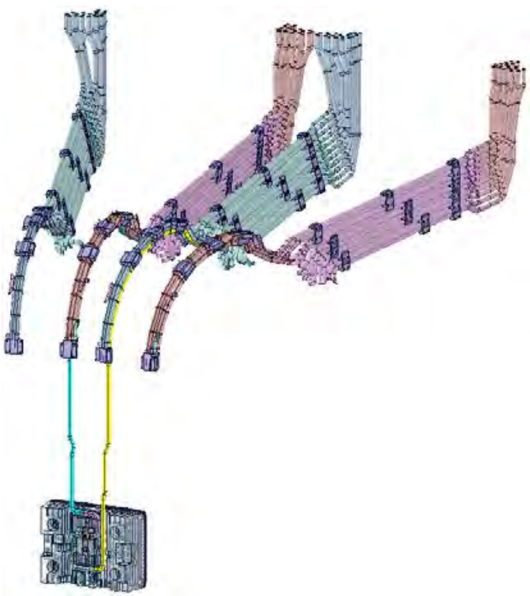
CAD Model for the TCWS with detailed water path in Tokamak

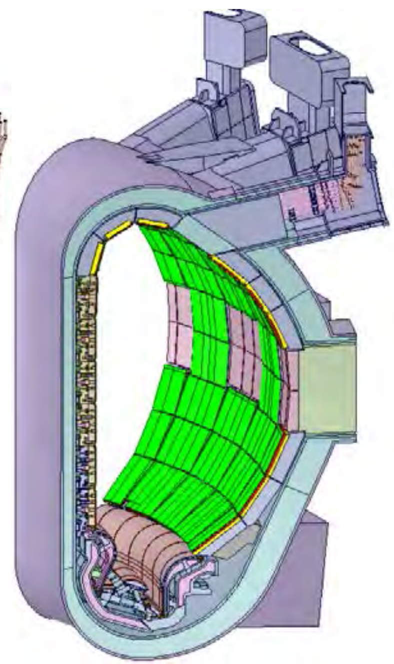


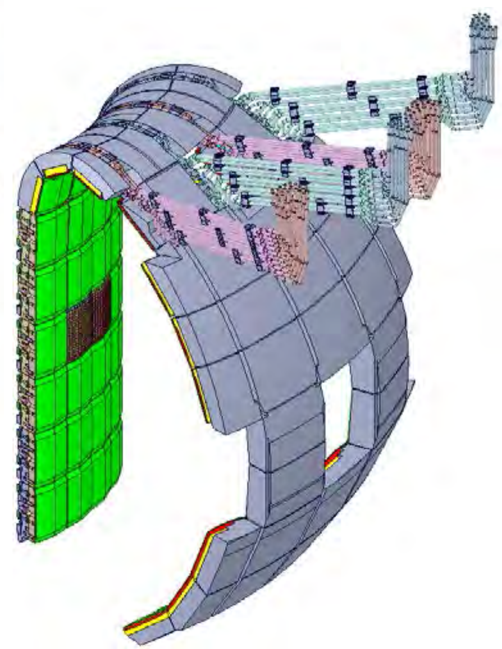


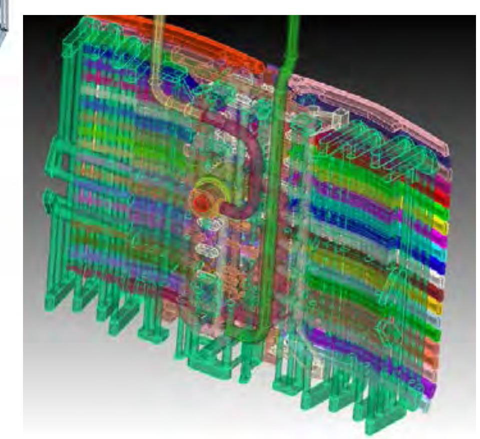
Performed water activation analysis to determine the accurate source term from ^{16}N and ^{17}N for L3/L4 shielding analysis

Model is very complex. The most complex model ever used for this purpose

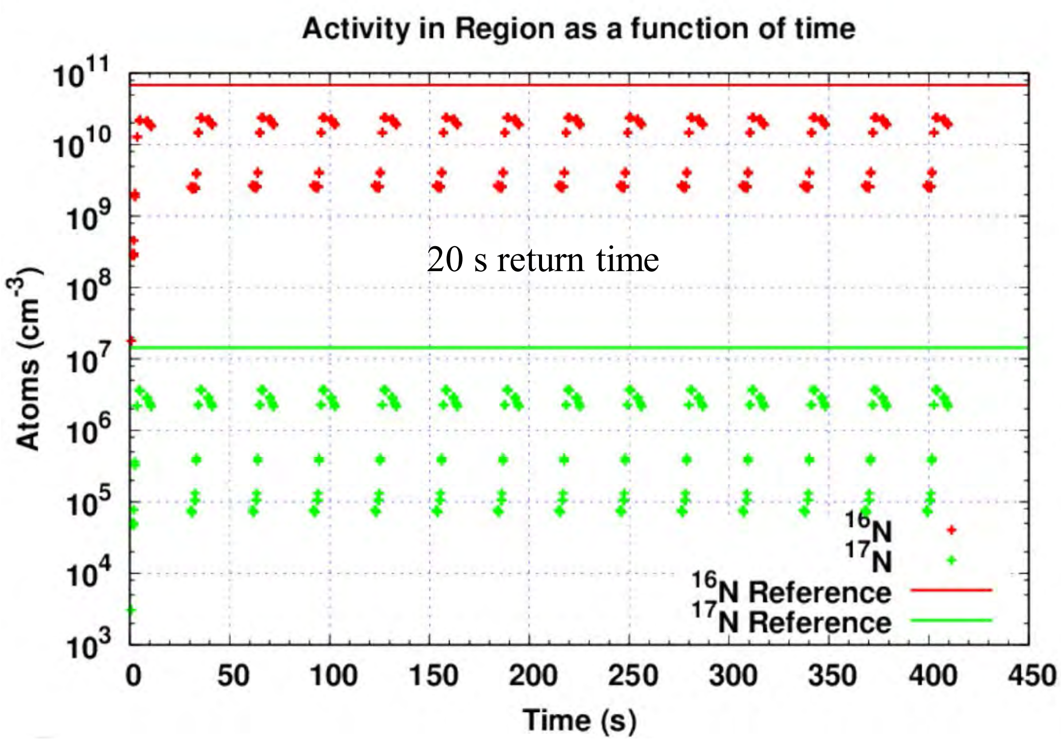


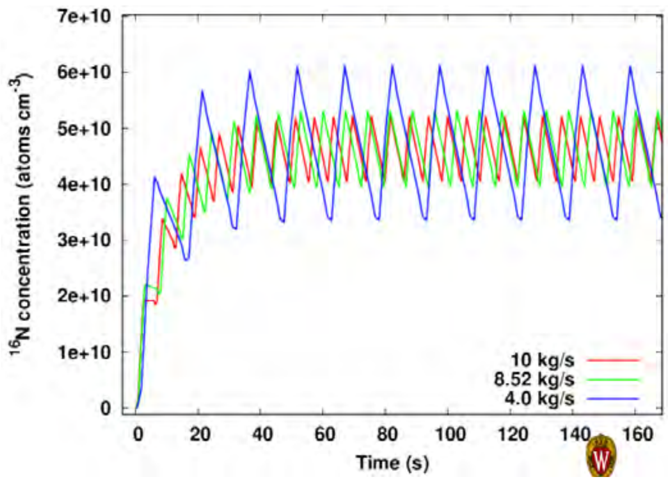


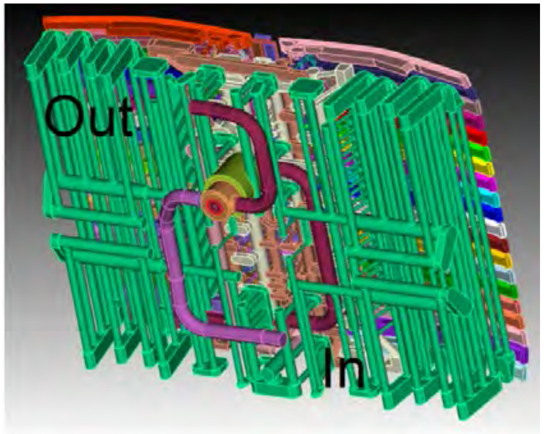




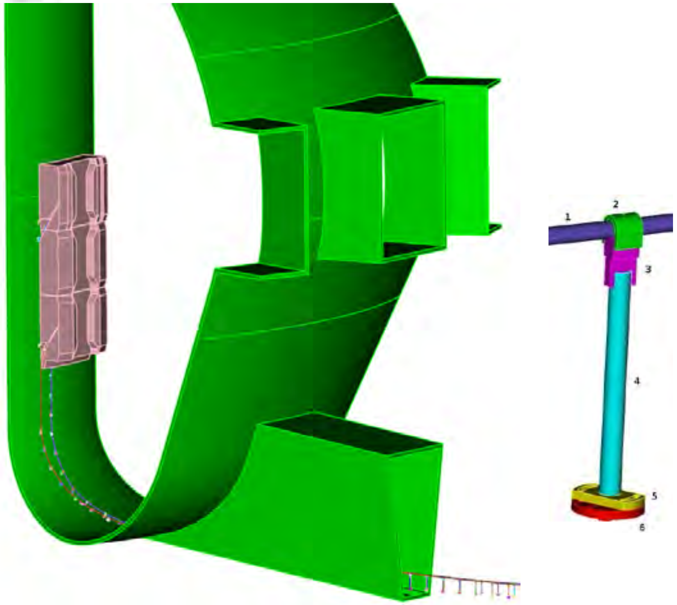
Source Term from Activated Water

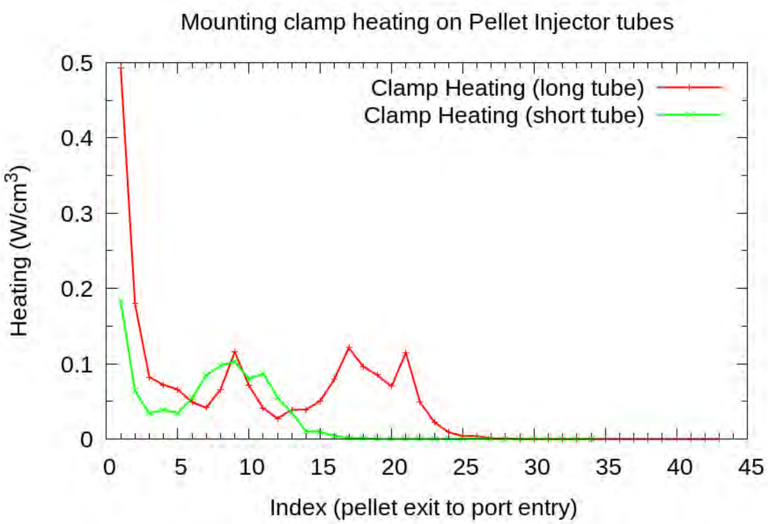


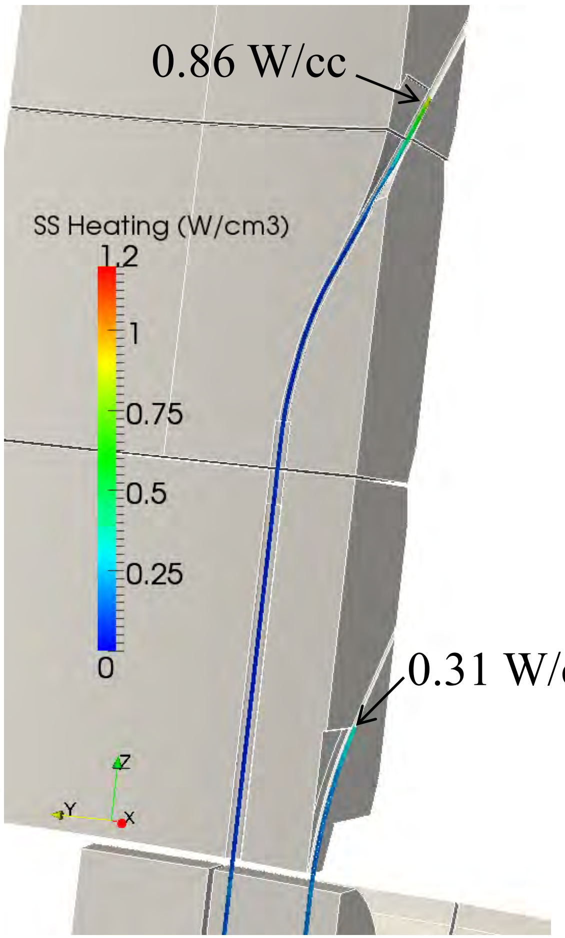




Heating in Pellet Injector Tube



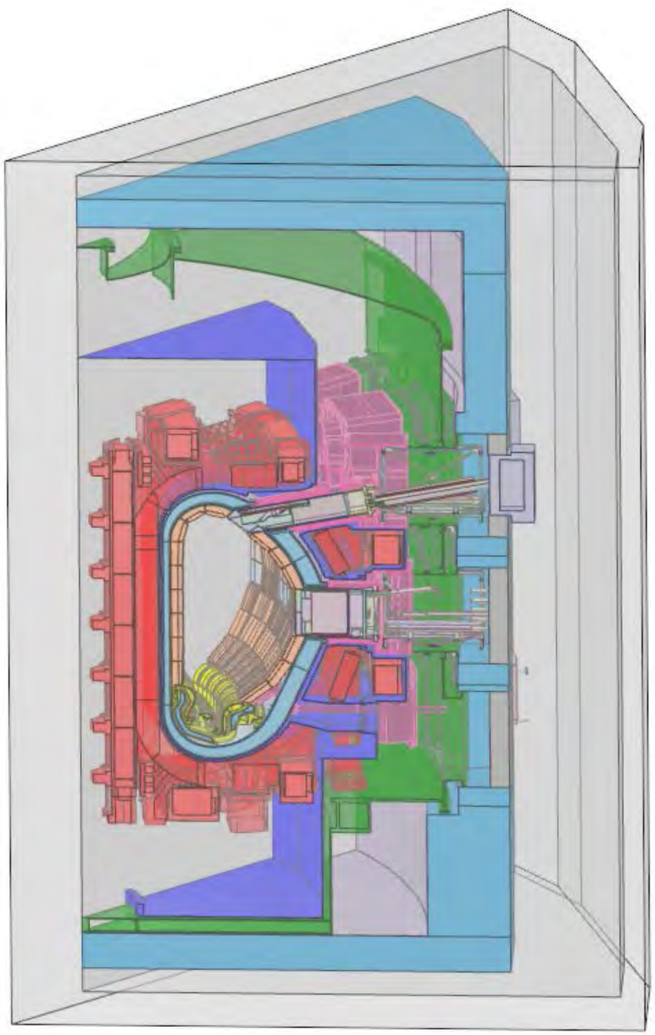


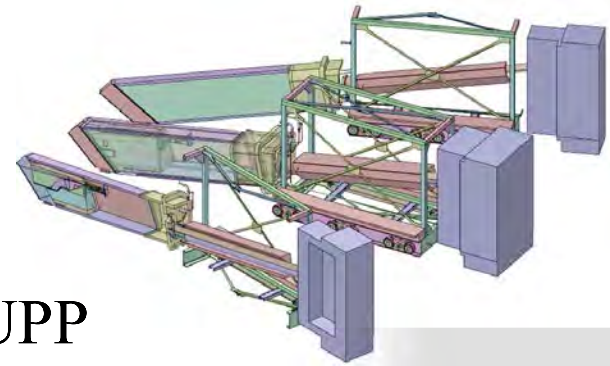


Dose rates inside the bio-shield

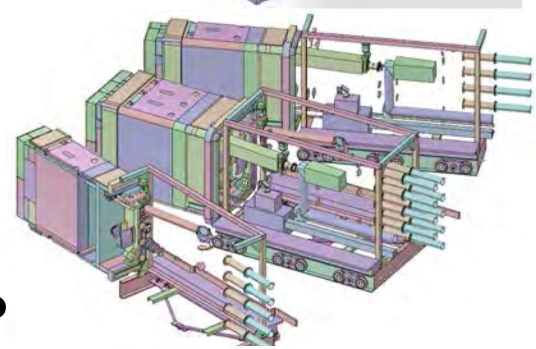
- Where planned maintenance is required dose-rate <100μSv/hr
- For unplanned maintenance dose-rate <2mSv/hr
- Important locations around ports (diagnostics, ICH, ECH, NBI) with cross-talk
- Deep penetration problem with streaming issues through narrow path
- Need detailed modeling based on CAD and computational tools that accurately model gaps
- C-lite CAD model developed with detailed representation of port plugs
- ADVANTG will provide weight windows and source biasing parameters to run the SDDR calculations with DAGMCNP and ALARA
- Standard ITER irradiation scenario (SA2) with cooling times 10^5 sec, 10^6 sec and 10^7 sec
- Two calculations with and without B_4C liner on the bio-shield

Detailed CAD Model for Generating SDDR Map inside the Bio-shield

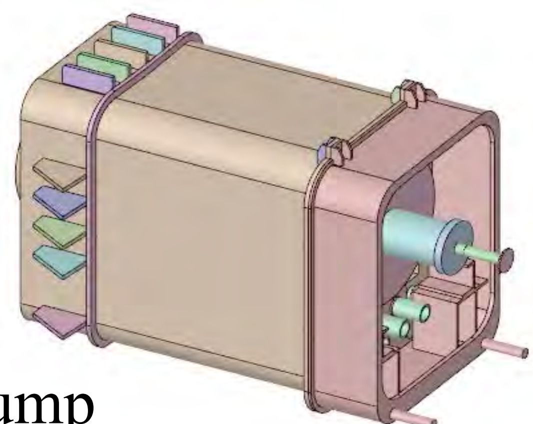




UPP



EPP



Cryopump

Conclusions

- ITER is a geometrically complex nuclear facility with significant source of energetic neutrons
- Many design issues arise from the severe nuclear environment
- CAD-based neutronics tools allow addressing these issues and aid or verify the design of several ITER components