# ELM Coils: Nuclear Environment and Shielding Issues

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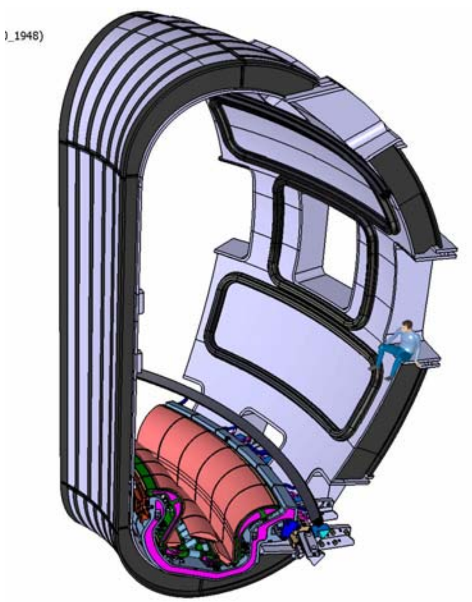
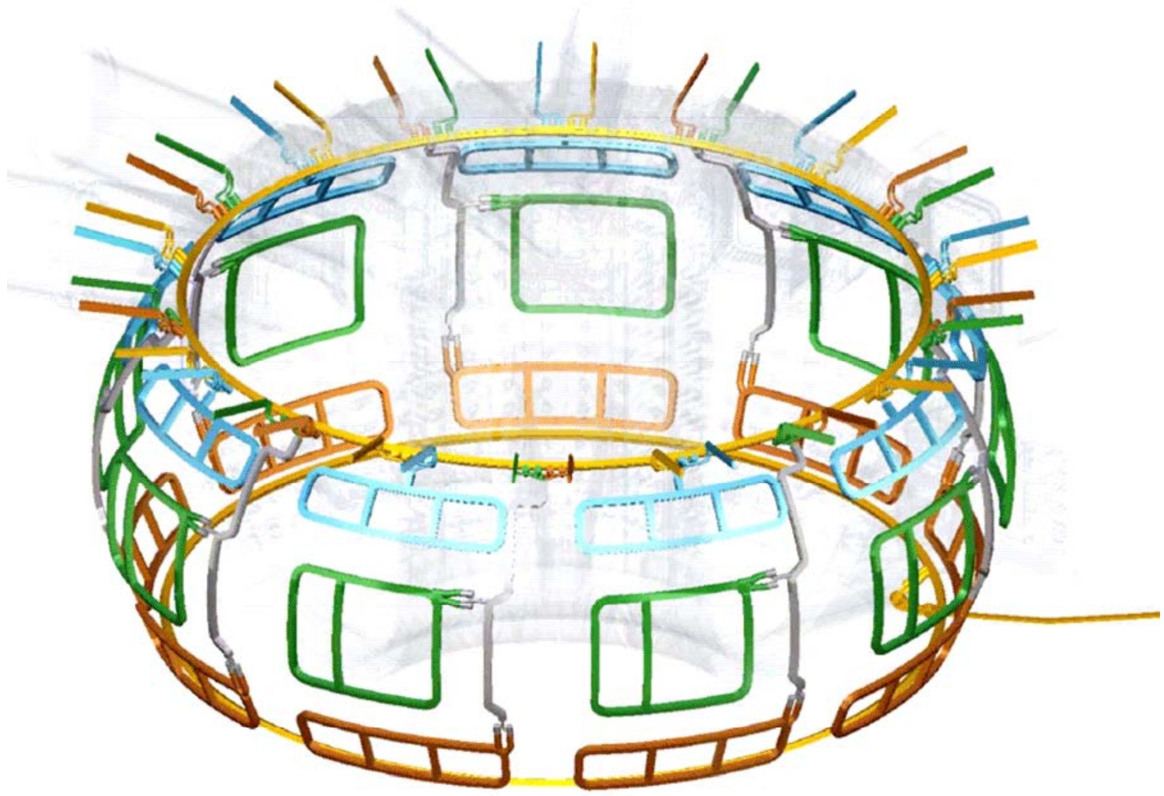
# ITER ELM and VS Coils

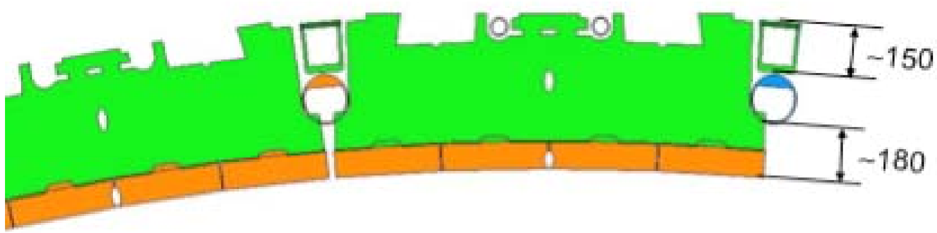
In-vessel coils (IVCs) are used in ITER to provide control of Edge Localized Modes (ELMs) in addition to providing control of moderately unstable resistive wall modes (RWMs) and vertical stability (VS) of the plasma

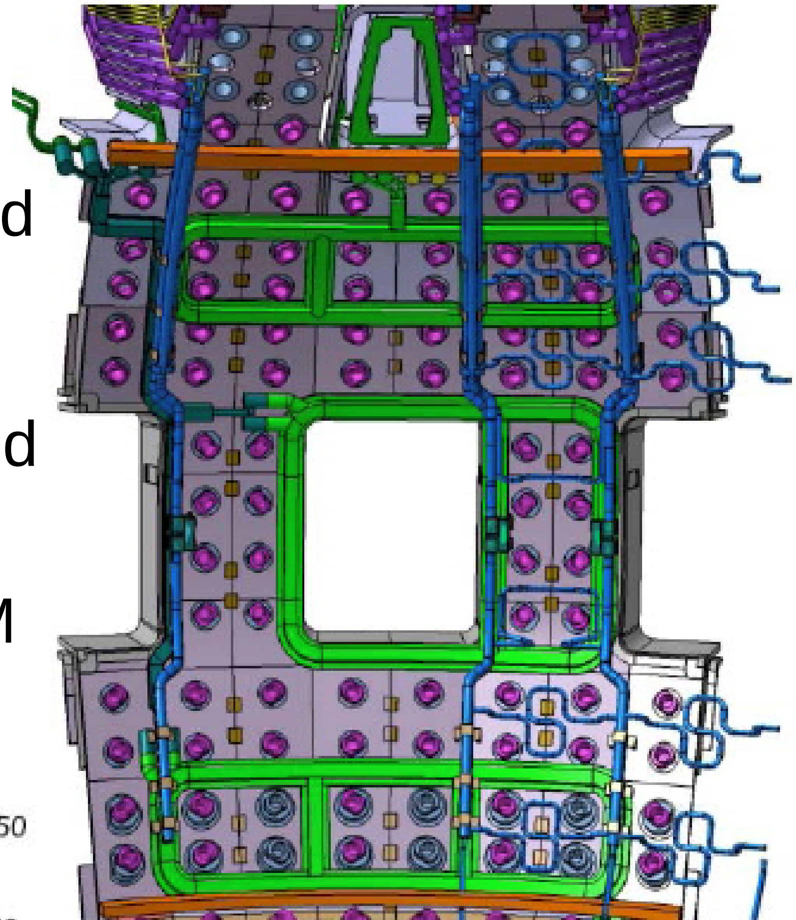




# ELM Coils Shielding

- ELM coils imbedded in shield module
- Poloidal legs of ELM coils shielded by 18 cm FWS and 10 cm manifold
- Toroidal legs of ELM coils shielded by 28 cm FWS
- 3-D neutronics performed for ELM coils in baseline design

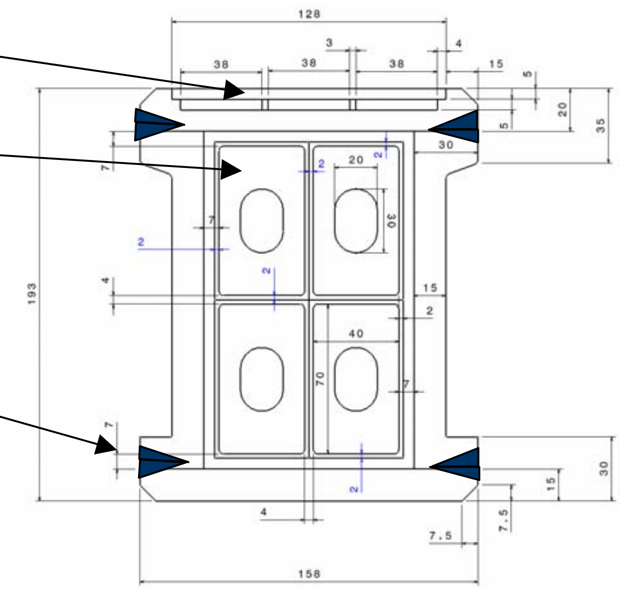


# ELM coils

➢ There are 27 ELM coils; each have 4 turns.  The total conductor length/coil is ~45 m.

- Case water cooling channel
- Ceramic polymer insulated hollow copper conductor
- Welds (4 corners)
- Geometry facilitates NDT of welds.
- Coils are designed for 94 kAt / coil.
- Conductor:  40 x 70 mm with a 20 x 30 mm racetrack shaped coolant channel.



ELM coil cross-section

# ELM Coil Composition

- Homogenized ELM coil composition used in preliminary analysis (provided by Brad Nelson):
  34.3% SS316LN-IG
  46.3% CuCrZr
  12.3% ceramic insulator
  7.1% water coolant

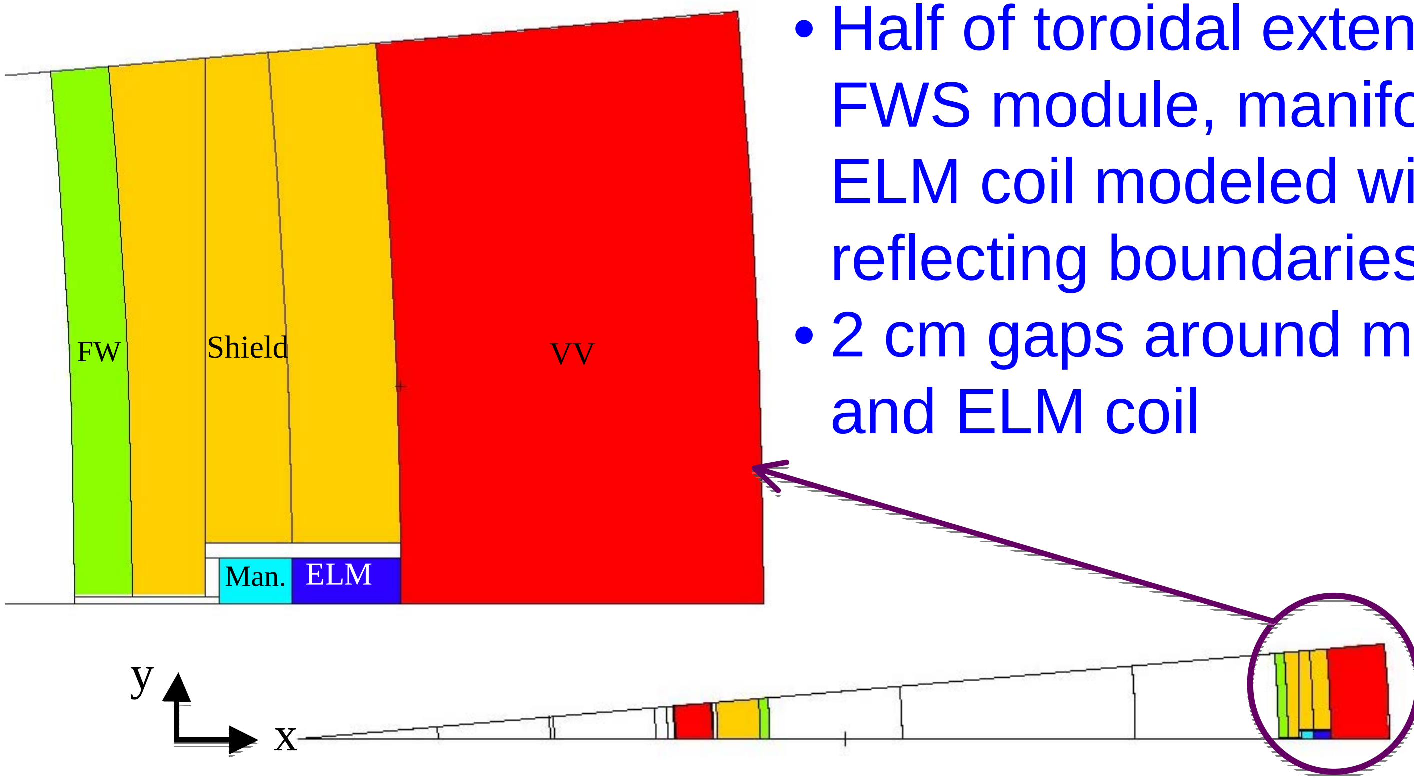
- Options for ceramic insulator: Alumina, MgO, Spinel
- Spinel [$MgO-Al_2O_3$] used in analysis

- Poloidal manifold composition used is 20% SS316, 80% water

# ELM Coils Analysis with Gap Streaming

- Initial 1-D analysis was performed to determine radiation parameters expected in both poloidal and toroidal legs of the ELM coils (memo dated 7/7/2008)
- The 1-D results represent expected parameters away from the 2 cm gaps between outboard FWS modules
- To quantify this effect we performed 3-D analysis using a simplified MCNP model with mid-plane radial build and homogenized composition in FW, shield block, and VV
- Analysis was performed for both poloidal and toroidal legs of ELM coils
- Results were normalized for the peak outboard neutron wall loading of 0.75 MW/m$^2$ and cumulative end-of-life parameters calculated for the 0.3 MWa/m$^2$ total average FW fluence (based on 0.56 MW/m$^2$ average NWL that corresponds to 0.54 FPY)

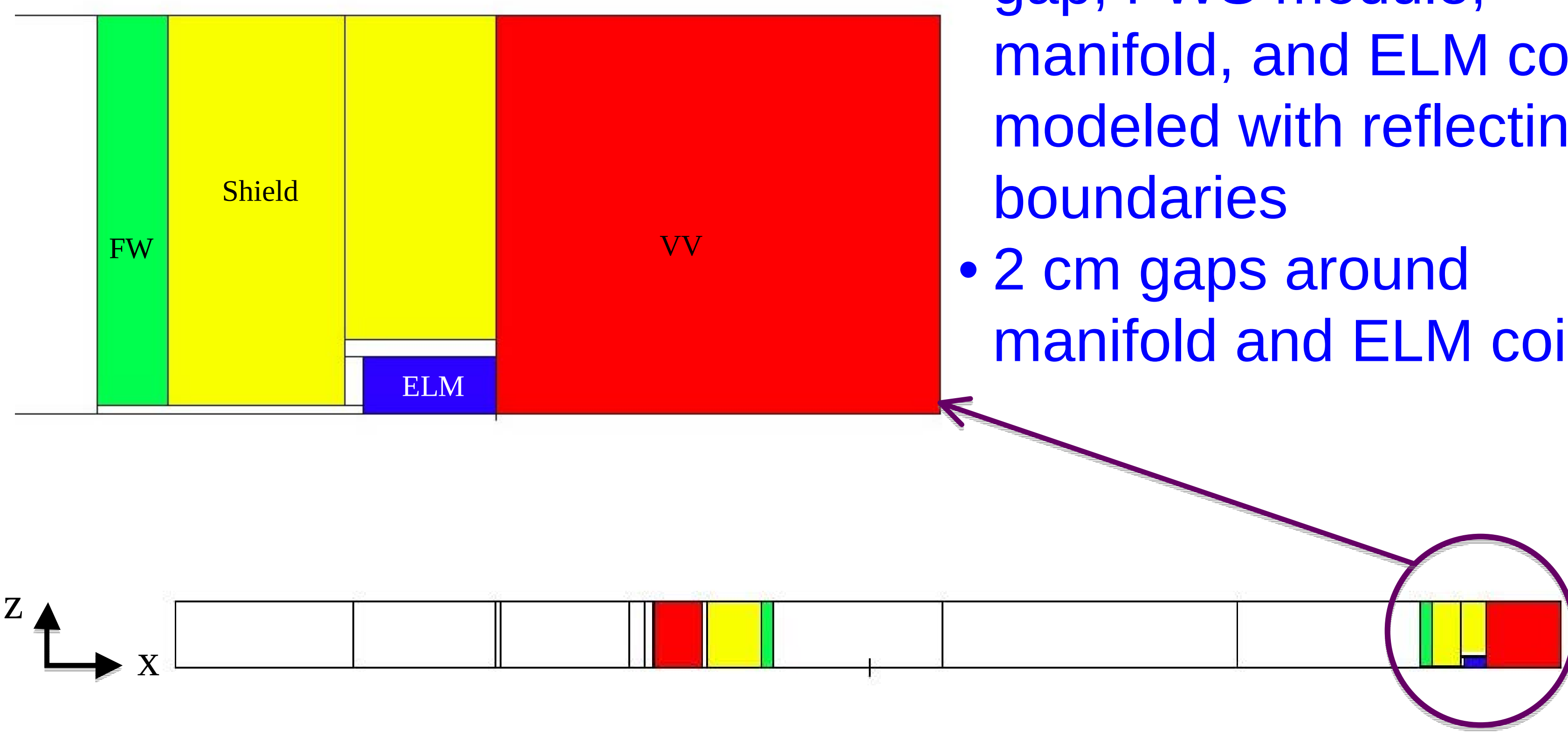
# MCNP Model for Gap Streaming Effect on Poloidal Legs of ELM Coils




- 5 degree sector representing half of FWS module
- Half of toroidal extent of gap, FWS module, manifold, and ELM coil modeled with reflecting boundaries
- 2 cm gaps around manifold and ELM coil

# MCNP Model for Gap Streaming Effect on Toroidal Legs of ELM Coils

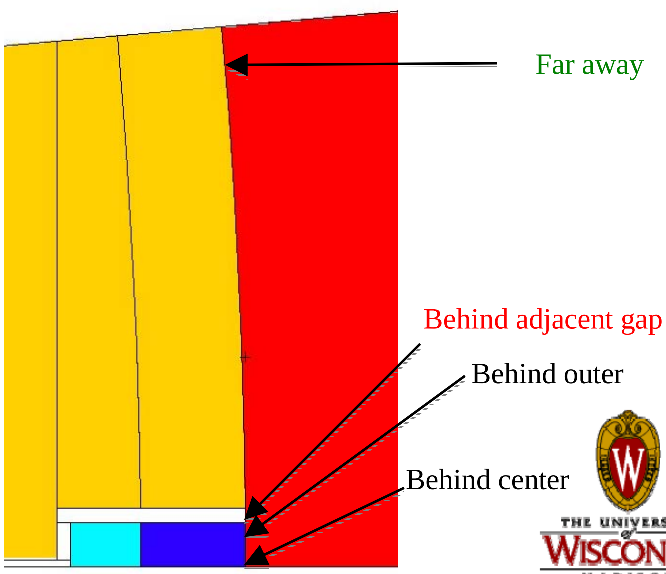
- 5 degree sector with 45 cm height representing half of FWS module
- Half of poloidal extent of gap, FWS module, manifold, and ELM coil modeled with reflecting boundaries
- 2 cm gaps around manifold and ELM coil



# VV Inner Surface Parameters (poloidal)

| | | Nuclear Heating ($mW/cm^3$) | End-of-life He appm | End-of-life Fast Neutron Fluence ($n/cm^2$) |
|---|---|---|---|---|
| Poloidal ELM Coil Leg | Behind Center | 109 | 0.25 | $2.48 \times 10^{19}$ |
| | Behind Outer | 129 | 0.27 | $2.65 \times 10^{19}$ |
| | Behind adjacent gap | 235 | 0.61 | $4.08 \times 10^{19}$ |
| | Far away | 64 | 0.13 | $0.90 \times 10^{19}$ |
| | Average | 86 | 0.18 | $1.32 \times 10^{19}$ |

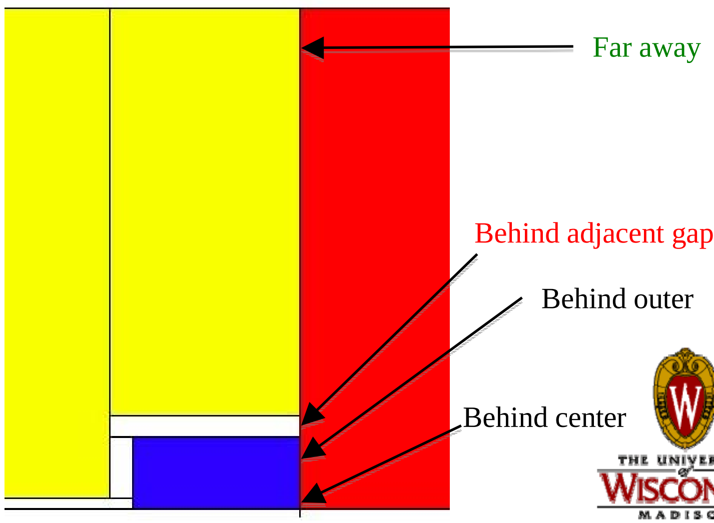
- Peaking in VV is primarily caused by gap streaming
- Peak parameters occur behind the 2 cm gap adjacent to ELM coil with peaking factors (peak/average) of 2.7-3.4
- VV Parameters behind ELM coil are higher than 1-D by a factor of 1.2-1.6 due to added contribution from streaming in straight section of gap



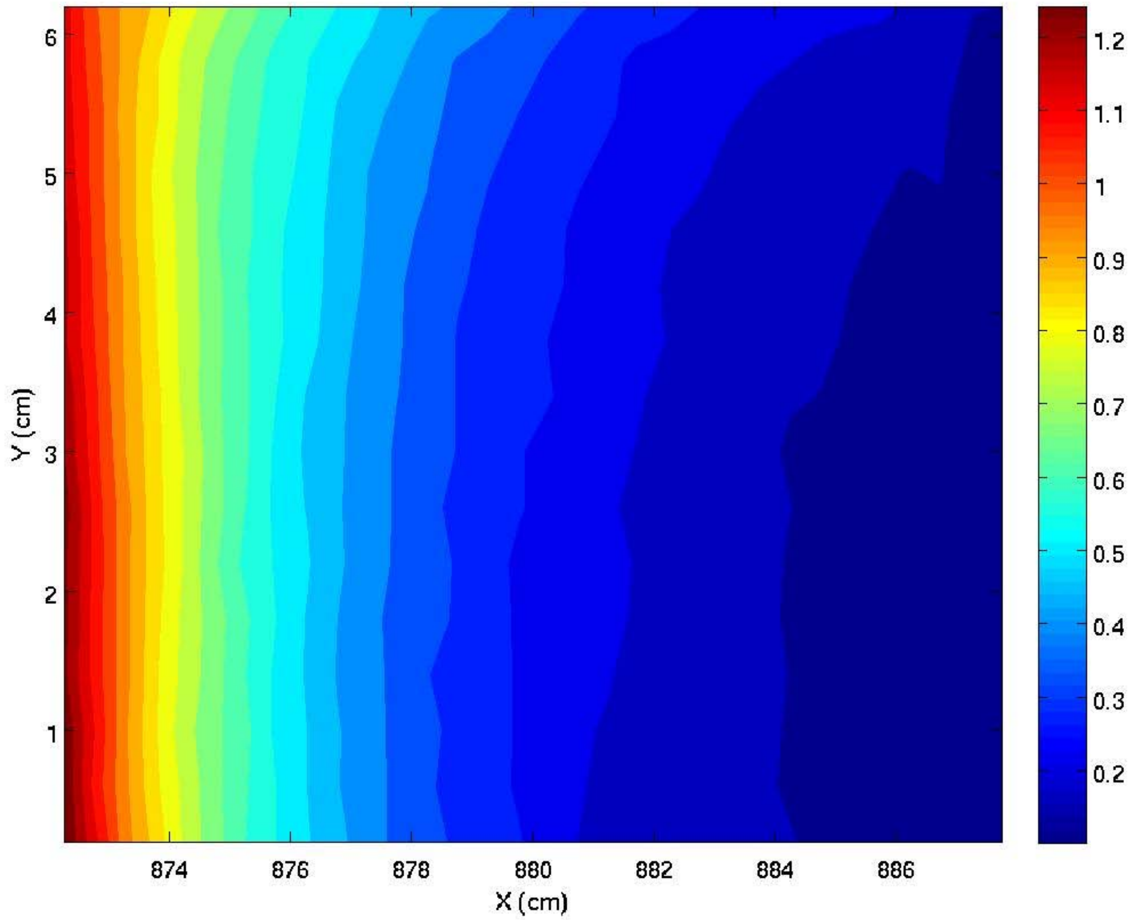
# VV Inner Surface Parameters (toroidal)

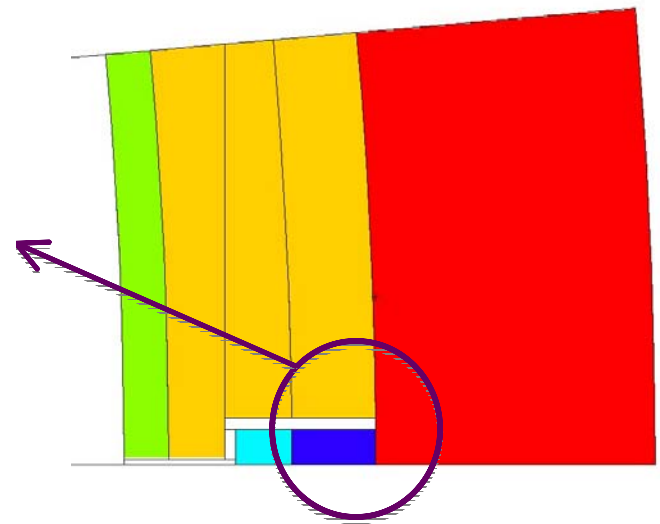
| | | Nuclear Heating (mW/cm³) | End-of-life He appm | End-of-life Fast Neutron Fluence (n/cm²) |
|---|---|---|---|---|
| Toroidal ELM Coil Leg | Behind Center | 114 | 0.28 | $2.74x10^{19}$ |
| | Behind Outer | 120 | 0.27 | $2.66x10^{19}$ |
| | Behind adjacent gap | 167 | 0.41 | $3.20x10^{19}$ |
| | Far away | 67 | 0.13 | $0.96x10^{19}$ |
| | Interface ave | 92 | 0.19 | $1.51x10^{19}$ |

- Peak parameters occur behind the 2 cm gap adjacent to ELM coil with peaking factors (peak/average) of 1.8-2.2
- These peak parameters are lower than poloidal values by ~25%
- VV parameters behind poloidal and toroidal legs of ELM coil are comparable

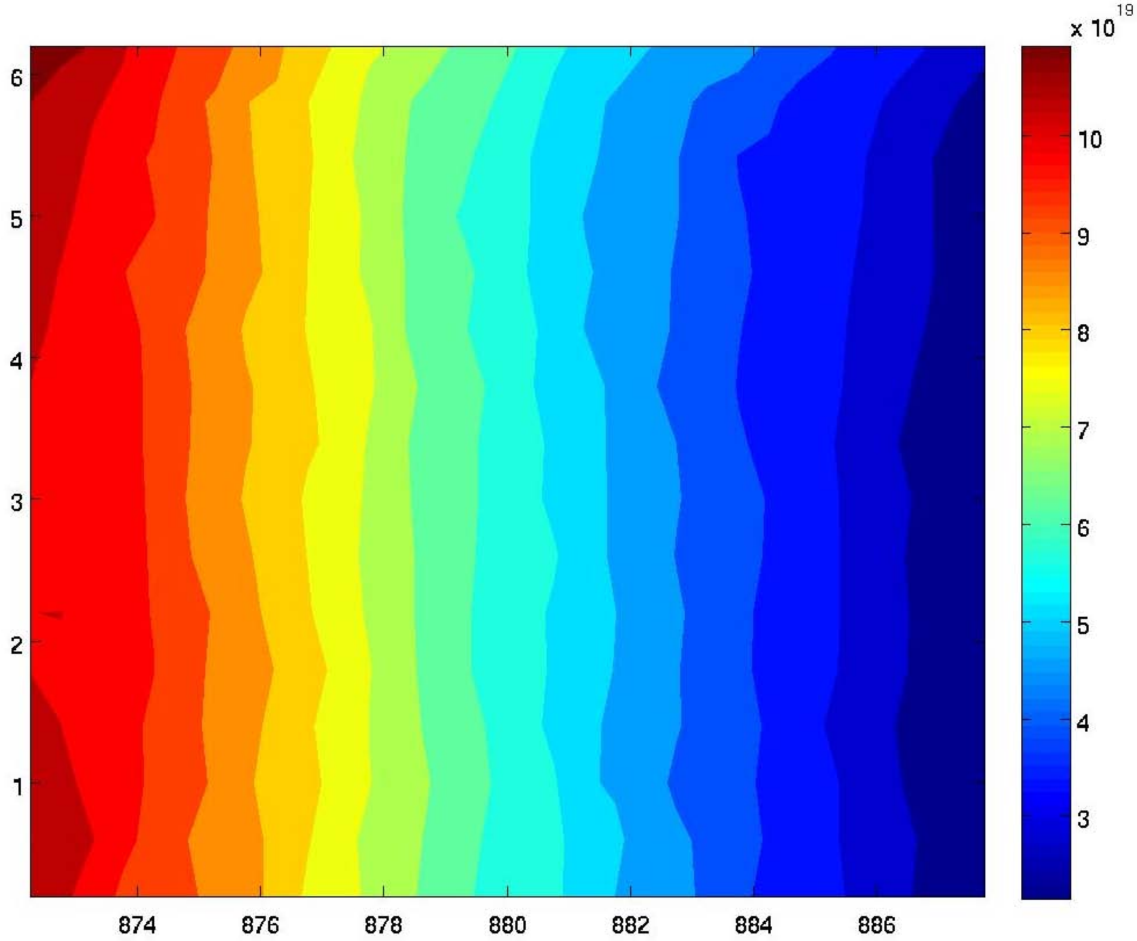


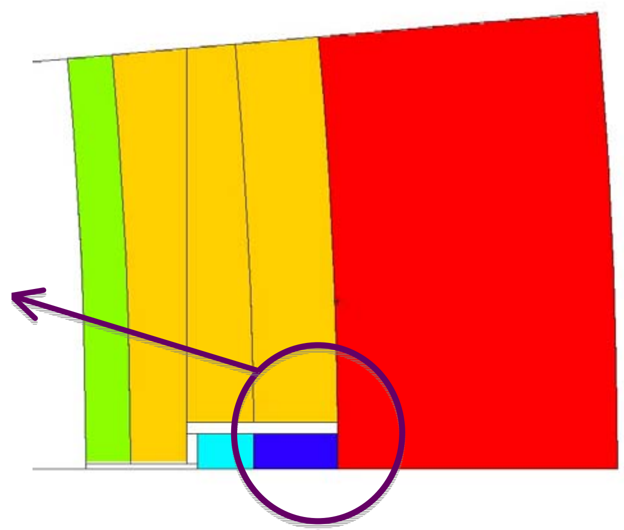
# Nuclear Heating (W/cm$^3$) in Poloidal Leg of ELM Coil



# Fast Neutron Fluence (n/cm$^2$) in Poloidal Leg of ELM Coil @0.3 MWa/m$^2$

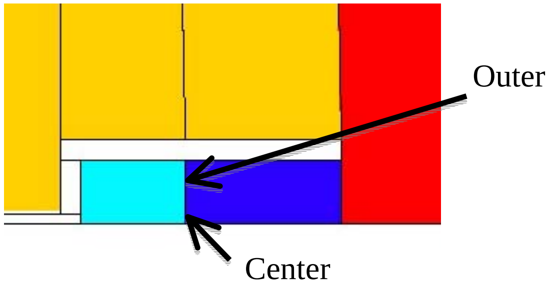


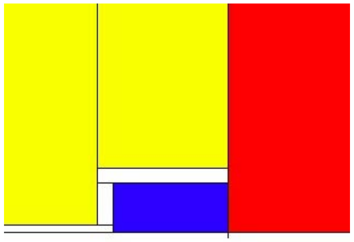
# Nuclear Parameters at Inner Surface of ELM Coil

| | | Nuclear Heating (W/cm$^3$) | Fast Neutron Fluence (n/cm$^2$) | Cu dpa (dpa) | Insulator Dose Rate (Gy/s) |
|---|---|---|---|---|---|
| Poloidal Leg | Center | 1.42 | $1.04 \times 10^{20}$ | 0.121 | 177 |
| | Outer | 1.35 | $1.05 \times 10^{20}$ | 0.116 | 168 |
| | Average | 1.37 | $1.05 \times 10^{20}$ | 0.117 | 170 |
| Toroidal Leg | Center | 1.11 | $2.22 \times 10^{20}$ | 0.229 | 160 |
| | Outer | 0.86 | $1.49 \times 10^{20}$ | 0.128 | 114 |
| | Average | 0.90 | $1.61 \times 10^{20}$ | 0.143 | 121 |

- Only very small peaking (<4%) occurs in the poloidal leg
- Larger peaking factors (1.2-1.6) observed in toroidal leg due to streaming in straight part of gap



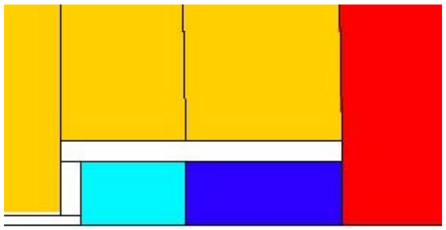
Poloidal

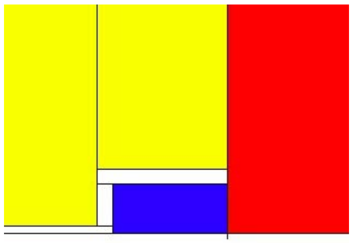

Toroidal

# Peak ELM Coil Nuclear Parameters

| | Nuclear Heating ($W/cm^3$) | Fast Neutron Fluence ($n/cm^2$) | Cu dpa (dpa) | Insulator Dose Rate (Gy/s) | End-of-life Insulator Dose (MGy) |
|---|---|---|---|---|---|
| Poloidal Leg | 1.42 | $1.05 \times 10^{20}$ | 0.121 | 177 | 3011 |
| Toroidal | 1.11 | $2.22 \times 10^{20}$ | 0.229 | 160 | 2722 |

- Nuclear heating and insulator dose are higher by about a factor of 1.5 in the poloidal leg of ELM coil due to vicinity to large water content in manifold that results in more neutron spectrum softening and enhanced gamma generation
- On the other hand fast neutron fluence and Cu dpa produced by high energy neutrons are reduced in the poloidal leg due to softened spectrum


Poloidal


Toroidal

# Basic conductor & insulation requirements

| Specification | Technical Requirements |
|---|---|
| Ambient temperature | 100 C |
| Peak Operating Temperature | ~130 ° C |
| Operational Life | 30,000 experimental pulses. |
| Bakeout Temperature | 240 ° C |
| Coolant | Deionized , deoxygenated Water |
| Water Pressure In coolant channel | ~5 MPa |
| Water velocity | 8 m/s (max.) |
| Peak Nuclear Heating | ~1.4 $W/cm^3$ |
| Max. Cu Dpa | ~0.2 |
| Max. Insulator Dose Rate / total dose | ~200 Gy/S / 3000 MGy |
| Max. Voltage, Conductor-jacket | ~ 3 kV (test voltage) |
| Operating Lifetime | 20 Yrs. |

# Limits on Nuclear Parameters in ELM Coils

- A good review of radiation limits for normal-conducting magnets in fusion environment:
  - L.J. Perkins, "materials Considerations for Highly Irradiated Normal-Conducting Magnets in Fusion Reactor Applications," J. of Nuclear Materials, vol. 122&123, pp. 1371-1375 (1984).
  - M. Sawan, H. Khater, and S. Zinkle, "Nuclear Features of the Fusion Ignition Research Experiment (FIRE)," Fusion Engineering & Design, vol. 63-64, pp 547 - 557 (2002).
- Main concerns:
  - Mechanical and structural degradation in ceramic insulation under long-term neutron fluence
  - Resistivity degradation in ceramic insulation under instantaneous absorbed dose rates (n+$\gamma$)
  - Resistivity increase in Cu conductor due to neutron induced transmutations
  - Mechanical and structural degradation in Cu (similar to considerations for ITER FW heat sink)

# Resistivity Increase in Cu Conductor

- Increase in electrical resistivity of copper results from displacement damage (production of defects and dislocations) and solute transmutation products
- At high doses the displacement damage component approaches rapidly a constant saturation value due to displacement cascade overlap effects with a saturation value of 1-4 n$\Omega$m depending on purity and Cu alloy Expected only to be second order consideration since most effects could be annealed by baking out at 200-300°C
- Transmutation products are Ni, Zn, Co that build up as impurities with time resulting in changing conductor resistivity

| Solute | Transmutation rate | Solute resistivity ($\mu\Omega$m/at. Frac.) | Resistivity increase for the peak 0.23 dpa (p$\Omega$m) |
|---|---|---|---|
| Ni | 190 | 1.12 | 48.9 |
| Zn | 90 | 0.3 | 6.2 |
| Co | 7 | 6.4 | 10.3 |
| Total | | | 65.4 |

# Issues for Ceramic Insulators

- Candidate materials include $Al_2O_3$, MgO, and spinel ($MgAl_2O_4$)
- Degradation of mechanical and electrical properties is main concern
- Mechanical and structural degradation in polycrystalline solid insulators depends on the crystal structure
- Non-cubic materials such as $Al_2O_3$ swell anisotropically leading to the onset of structural microcracking even at modest fluences
- Swelling in solid ceramics with cubic structure (e.g. MgO and $MgAl_2O_4$) is isotropic under neutron irradiation
- Fracture toughness increases at elevated fluences for cubic ceramics. Fluence limit is determined only by maximum swelling to be tolerated
- A maximum swelling of 3% corresponds to fast neutron fluences of $1.1 \times 10^{22}$ and $4 \times 10^{22}$ n/cm$^2$ for polycrystalline solid MgO and spinel, respectively
- Neutron damage has no effect on strength of compacted powder ceramics since each grain is affected individually

# Present insulations being considered

- Ceramic polymer
  - Irradiation results for S-glass / CP laminates were disappointing:
    - Compressive strength dropped 520-490 MPa to 120-160 MPa for specimens irradiated to $5x10^{23}$ n/$m^{2.}$ total fluence ($5x10^{22}$ n/$m^2$ fast)
    - Peak compression stress is ~30 MPa; desired minimum compressive strength is 100 MPa.
- Cyanate ester
  - Can a ceramic fiber / cyanate ester laminate meet our requirements? Probably not. Tested to $10^{22}$ n/$m^2$ fast with no degradation
- MgO (or Spinel)
  - Compacted powder can work up to ~$10^{26}$ n/$m^2$ fast
  - If only we can get it made in the sizes we need!

# Conclusions

- ELM coils exposed to severe nuclear environment compared to TF coils
- Expected peak radiation parameters determined
- Results helped defining the conductor and insulator design requirements
- R&D activity underway to determine appropriate insulator that can survive in the ELM coils nuclear environment