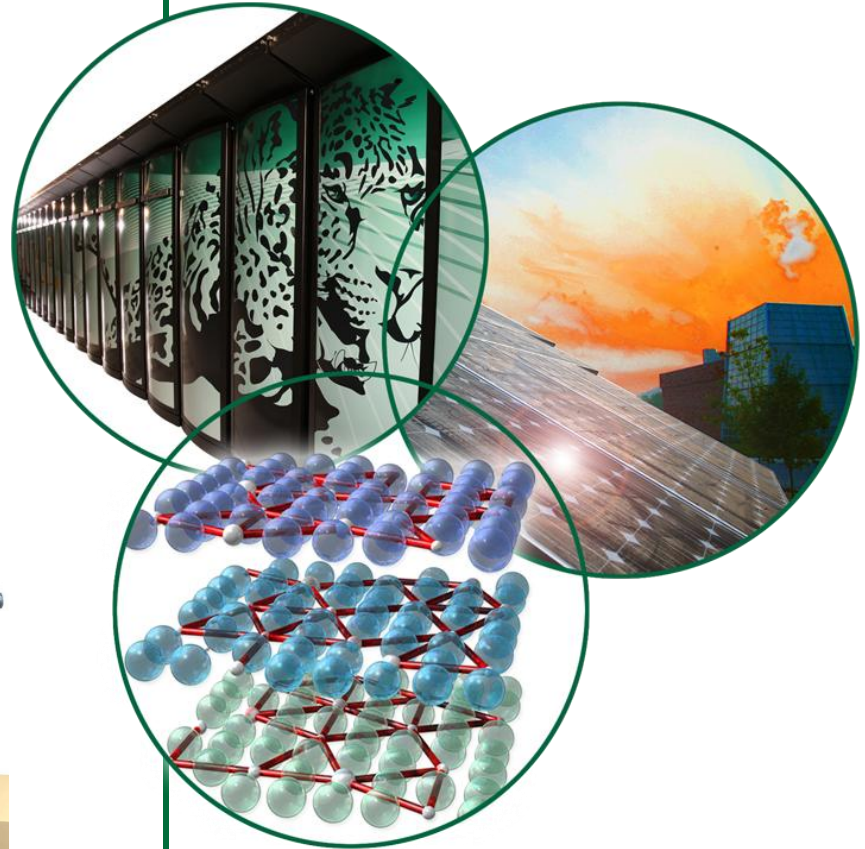
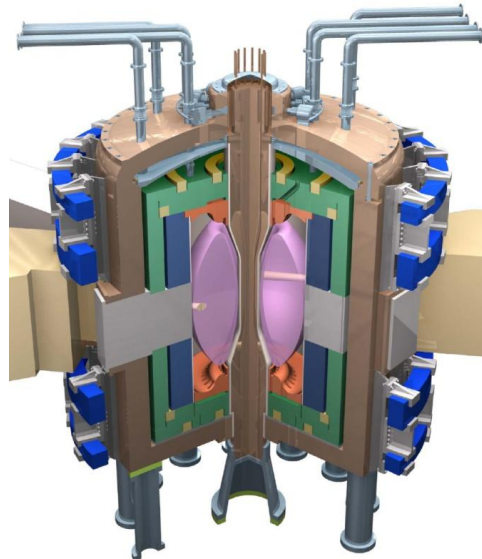


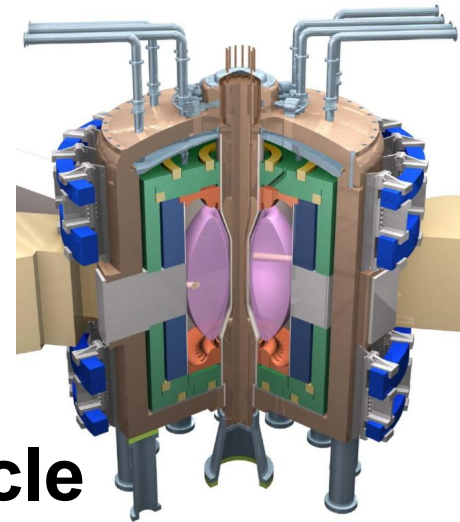
Optimal Design of Active Cooling for High Duty Cycle Spherical Tokamak Centerpost

A. Lumsdaine and M. Peng
Oak Ridge National Laboratory



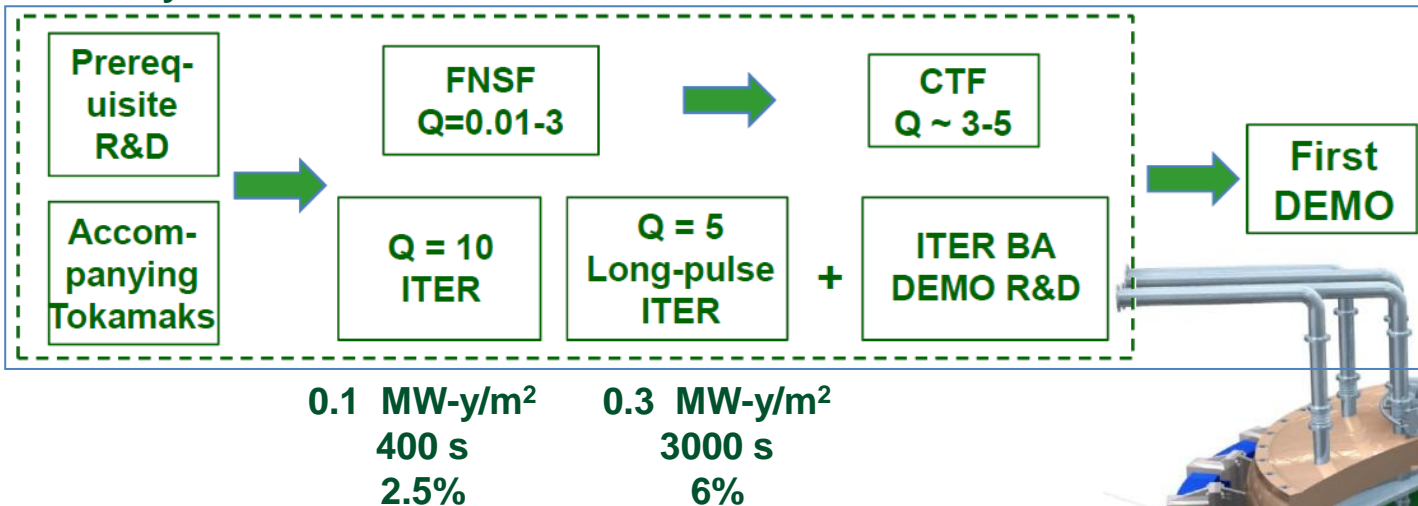
Fusion Nuclear Science Facility

- **Mission: Provide an integrated, continuously driven fusion nuclear environment of neutrons that can be used to test multiscale interacting phenomena involving:**
 - plasma material interactions
 - tritium fuel cycle
 - power extraction
 - nuclear effects on materials
- **1 MW-yr/m² & 10 dpa @ ≤10% duty cycle**
- **Allows upgrade to CTF (≤6 MW-yr/m² & 60 dpa; ≤30%)**
- **Tests material synergies to 2-6 MW-yr/m², 20-60 dpa**

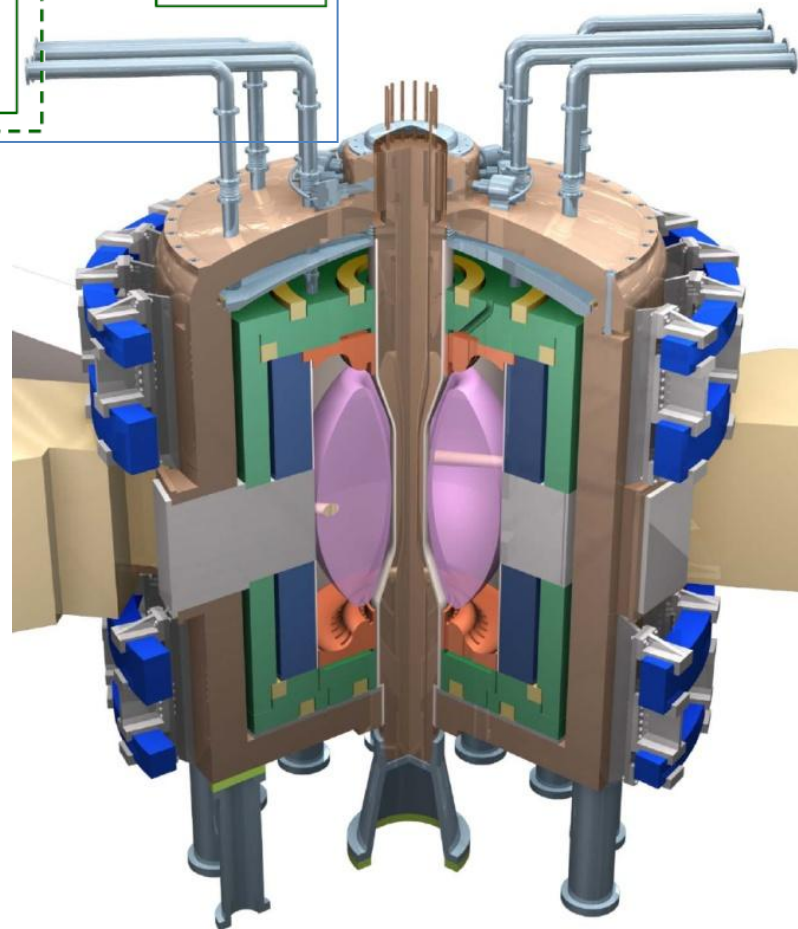


Fusion Nuclear Science Facility

Fluence:	1 MW-y/m ²	6 MW-y/m ²	≥ 6 MW-y/m ²
Pulse length:	≤ 2 wks	2 wks	Months
Duty factor:	≤ 10%	30%	50%

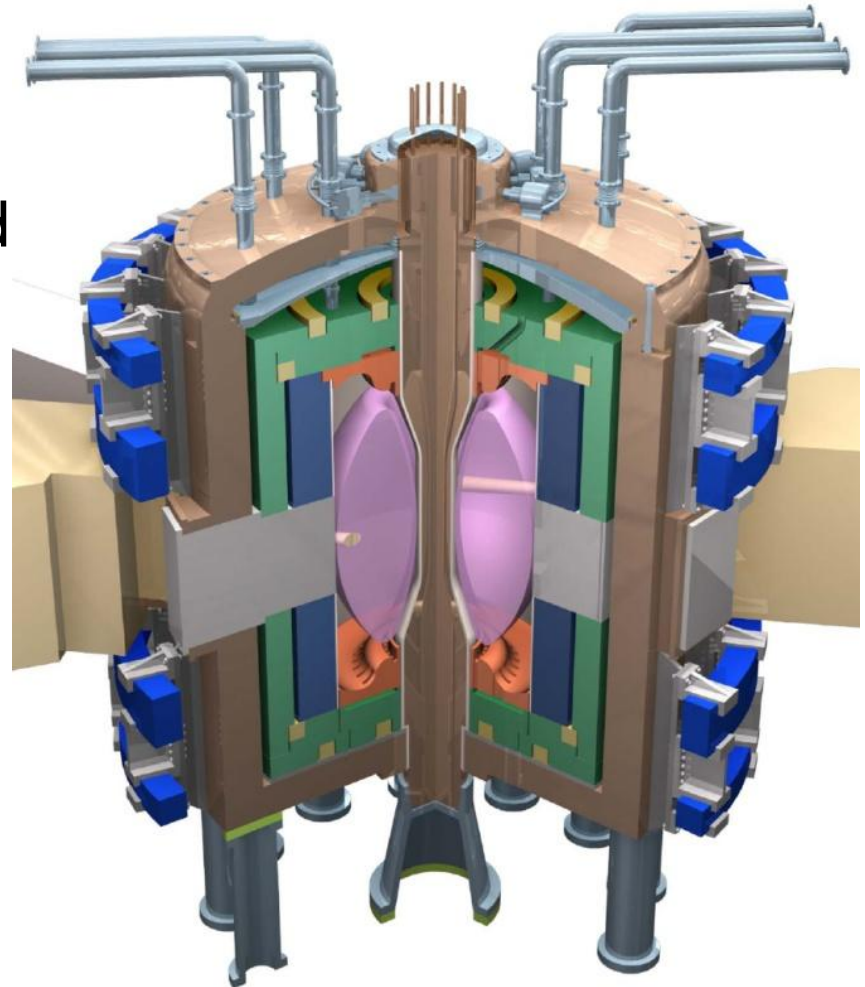


- One concept for FNSF – Spherical Tokamak



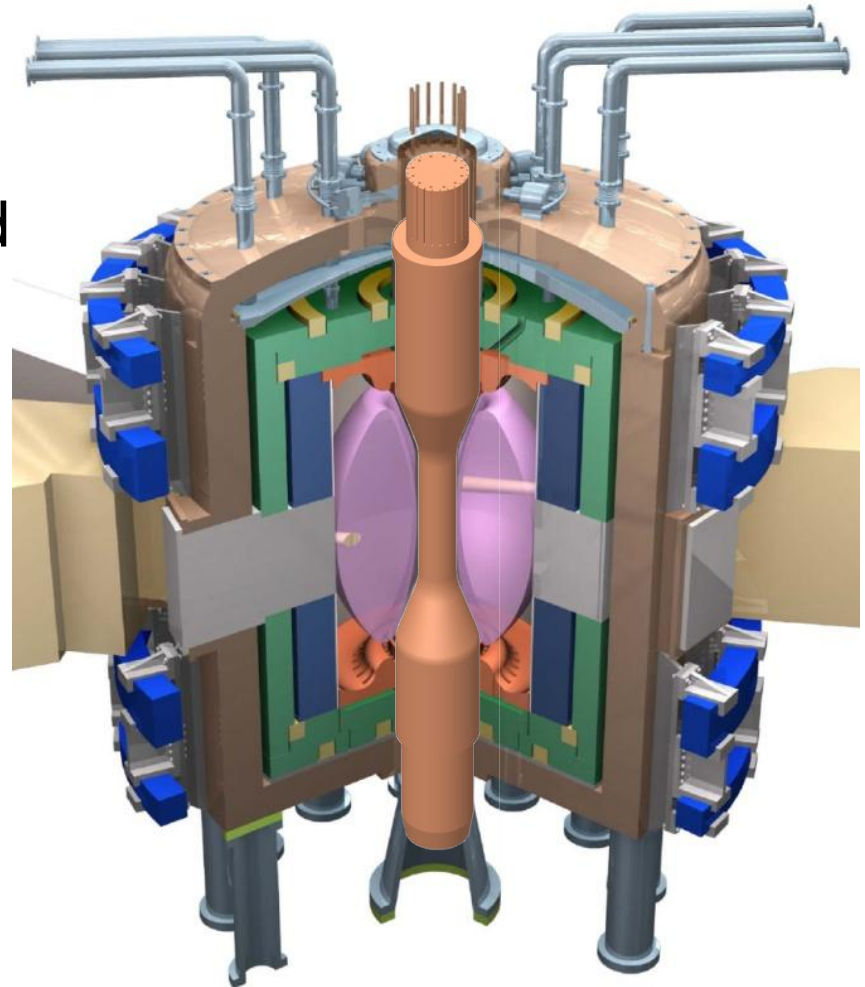
FNSF-ST Centerpost

- The centerpost is a critical component of the spherical tokamak design.
- This will be shielded with helium cooled tungsten, and actively water cooled.
- **The purpose of this study is to demonstrate the capability of optimally designing the water cooling channels in this region to minimize the peak steady-state temperature.**



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FNSF-ST Design Parameters

Performance level	JET-DD	JET-DT	2xJET	3xJET
Tests enabled	divertor	FNS	FNST	FNST
W_L (MW/m ²)	0.005	0.25	1.0	2.0
Current, I_p (MA)	4.2	4.2	6.7	8.4
Field, B_T (T)	2.7	2.7	2.9	3.6
Safety factor, q_{95}	12.7	12.7	8.6	8.6
Toroidal beta, β_T (%)	4.4	4.4	10.1	10.8
Normal beta, β_N	2.1	2.1	3.3	3.5
Avg density, n_e (10 ²⁰ /m ³)	0.54	0.54	1.1	1.5
Avg ion T_i (keV)	7.7	7.6	10.2	11.8
Avg electron T_e (keV)	4.2	4.3	5.7	7.2
BS current fraction	0.45	0.47	0.50	0.53
NBI H&CD power (MW)	26	22	44	61
Fusion power (MW)	0.4	19	76	152
NBI energy (kV)	120	120	235	330

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Some Previous Centerpost Studies . . .

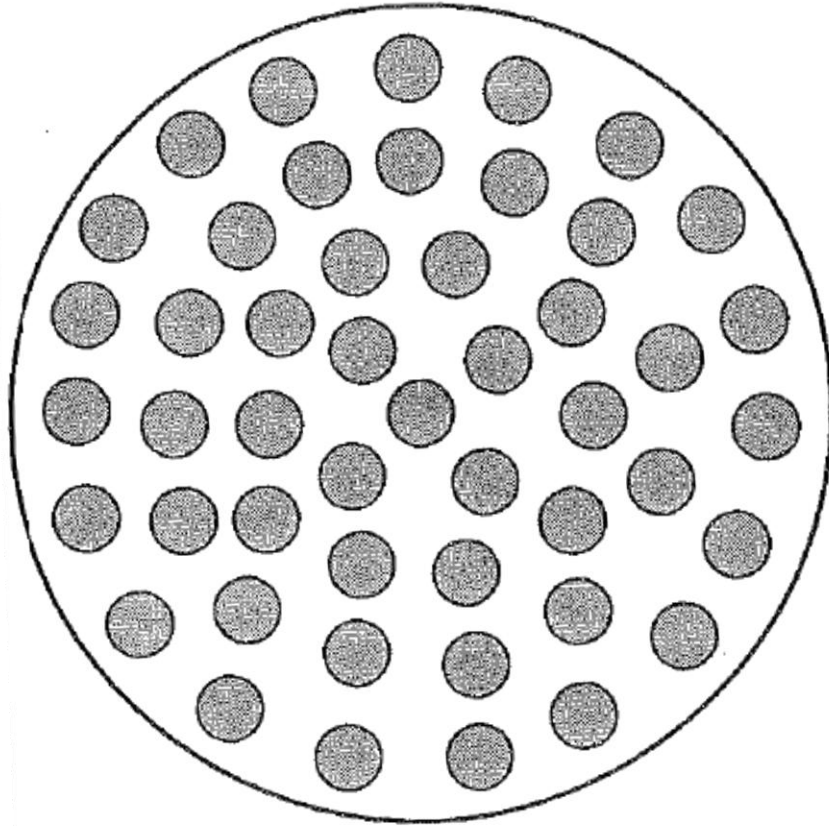


Fig. 8. TF core with 35% cooling and 48 cooling tubes.

Colchin, et al, "The Design of the Center Core of a Spherical Tokamak, *Fusion Technology*, 1997.

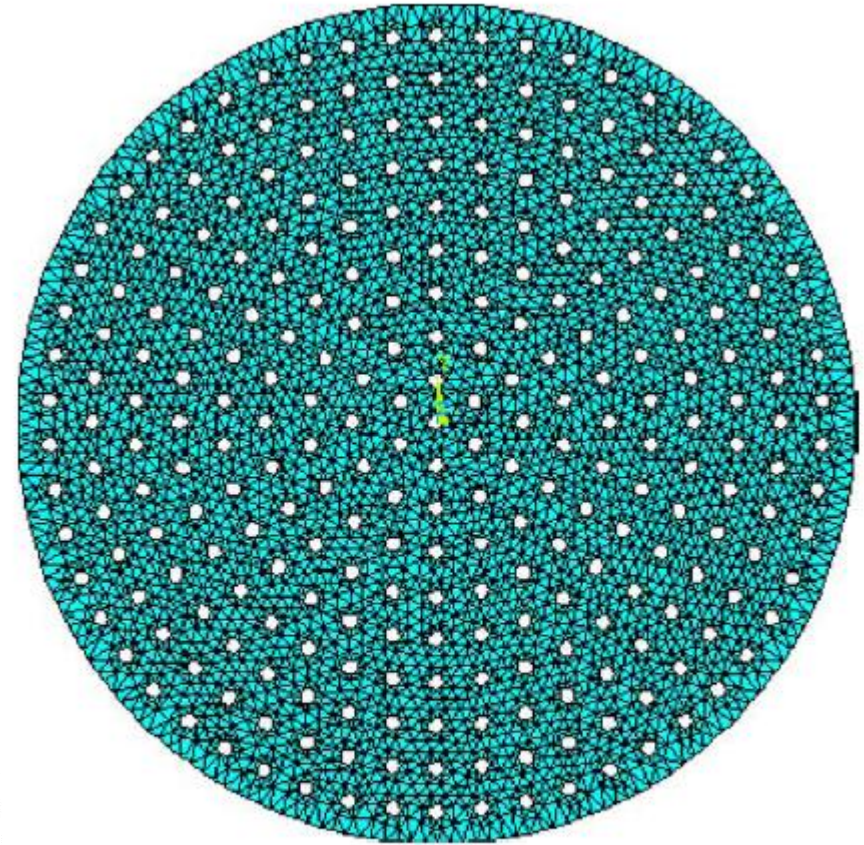


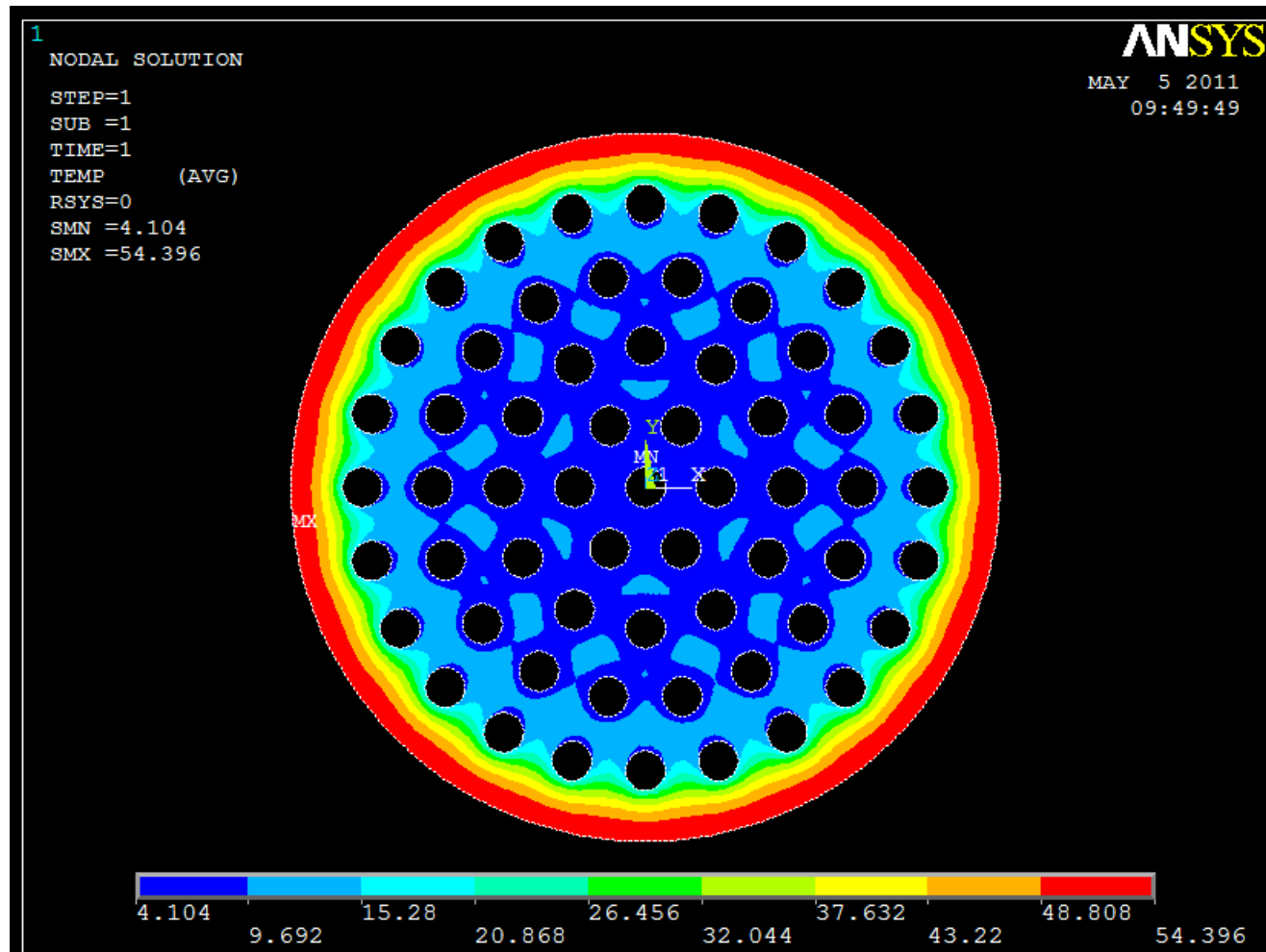
Fig. 11. Finite element model for the factor of stress concentration.

Song and Nishio, "Optimization Study on the Normal Conducting Center Post for the Low Aspect Ratio Tokamak Reactor," *Fusion Engineering and Design*, 2005.

Modeling Assumptions

The centerpost is modeled using the ANSYS commercial finite element code. A two-dimensional model is used for this initial study. Only the centerpost and the cooling flow channels are modeled.

The centerpost is assumed to be made of Glidcop AL-15.



Modeling Assumptions (cont'd)

2D Modeling Assumptions:

- No thermal conduction in the longitudinal direction.
- Water temperature is constant in both within the cross-section and along the length of the centerpost.

Other Modeling Assumptions:

- Water flow is at a constant velocity regardless of flow channel diameter.
- Glidcop electrical and thermal conductivities are constant with temperature.

Modeling

Heat flux on surface

- Heat load on the first wall = 100 kW/m²
- Heat load on copper centerpost = 25 kW/m²

Joule heating

The heat from the current through the centerpost is constant across the cross-section and is equal to (volumetrically):

$$P = \rho_c \left(\frac{I}{A} \right)^2$$

ρ_c = resistivity of Copper

I = current in centerpost

A = cross-sectional area

Modeling (cont'd)

Nuclear Heating

Neutronic and gamma heating are applied as body loads as calculated by Song and Nishio

$$P_n = P_0 \left(1.415 e^{-(0.35-x)/0.10582} \right)$$
$$P_\gamma = P_0 \left(4.024 e^{-(0.35-x)/0.13} \right)$$

Where x is the radial distance from the center of the centerpost.

Modeling (cont'd)

Convection from water flow

Thermal transfer to the water is proportional to the convection coefficient (h)

$$h = \frac{Nu \cdot k}{D}$$

h = convection coefficient

k = thermal conductivity of fluid

D = diameter of the pipe

$$Nu = 0.023 Re^{0.8} Pr^{0.5}$$

Nu = Nusselt number

Re = Reynolds number

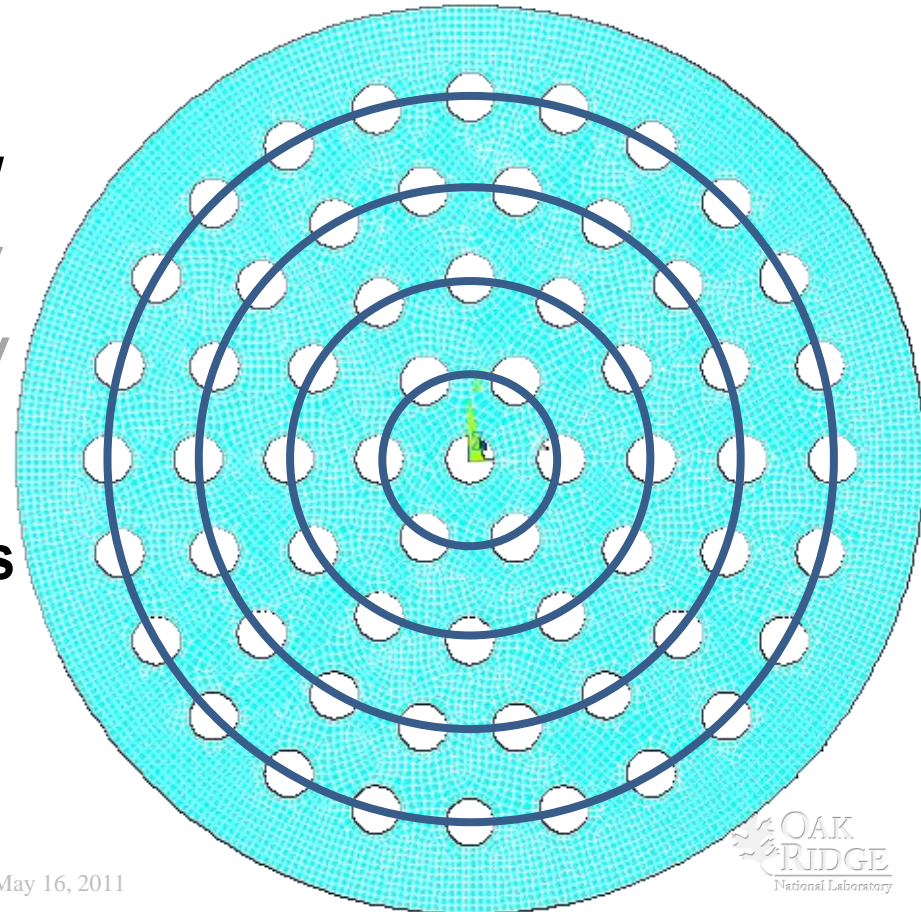
Pr = Prandtl number

Optimization Process

- **VisualDOC Commercial Software**
- **Optimization methods used:**
 - **Method of Moving Feasible Directions**
 - Objective assumed to be quadratic at each design point
 - Constraints placed in “active set” when violated
 - **Sequential Quadratic Programming**
 - Objective assumed quadratic, constraints linear at each design point
 - **Particle Swarm**
 - Global optimization algorithm
- **Unconstrained technique**
 - **Broyden, Fletcher, Goldfarb, and Shanno**
 - Inverse Hessian is approximated using only gradient information
 - Gradient is computed numerically (finite difference)

Optimization Problem Definition

- **Objective**
 - Minimize maximum temperature in the cross-section
- **Design Variables**
 - Position of each row
 - Diameter of channel in each row
 - *Angle of orientation of each row*
 - *Number of channels in each row*
- **Constraints**
 - 5mm distance between channels



Finite Element Model

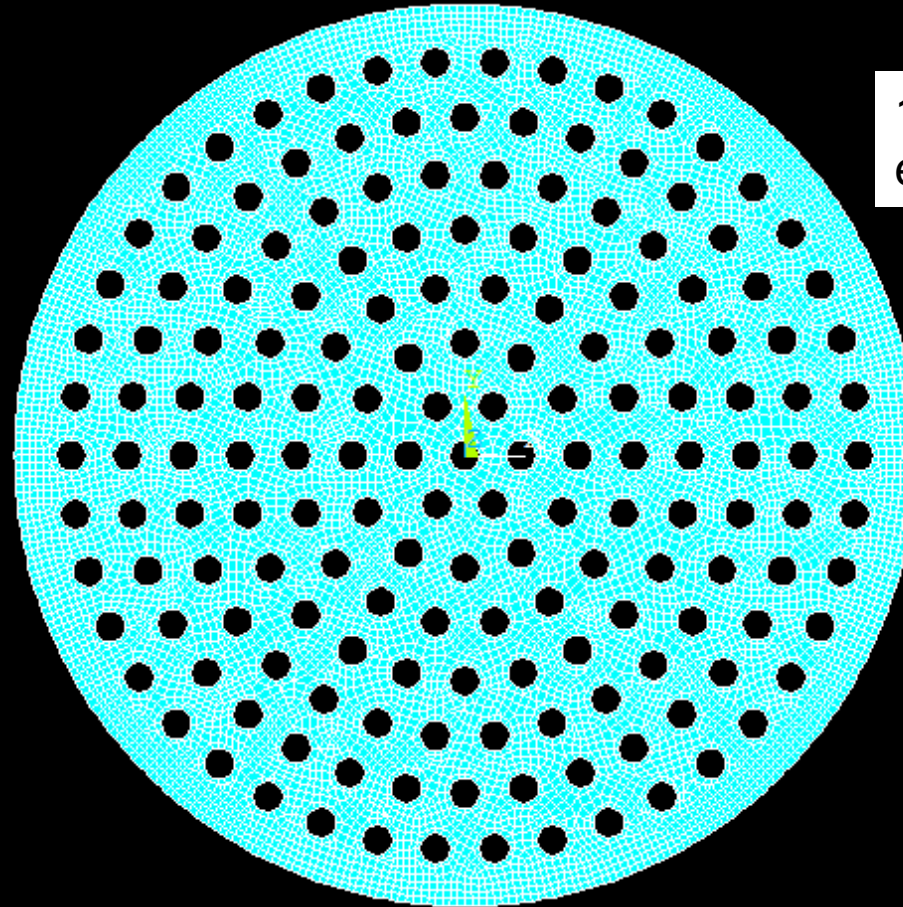
ANSYS

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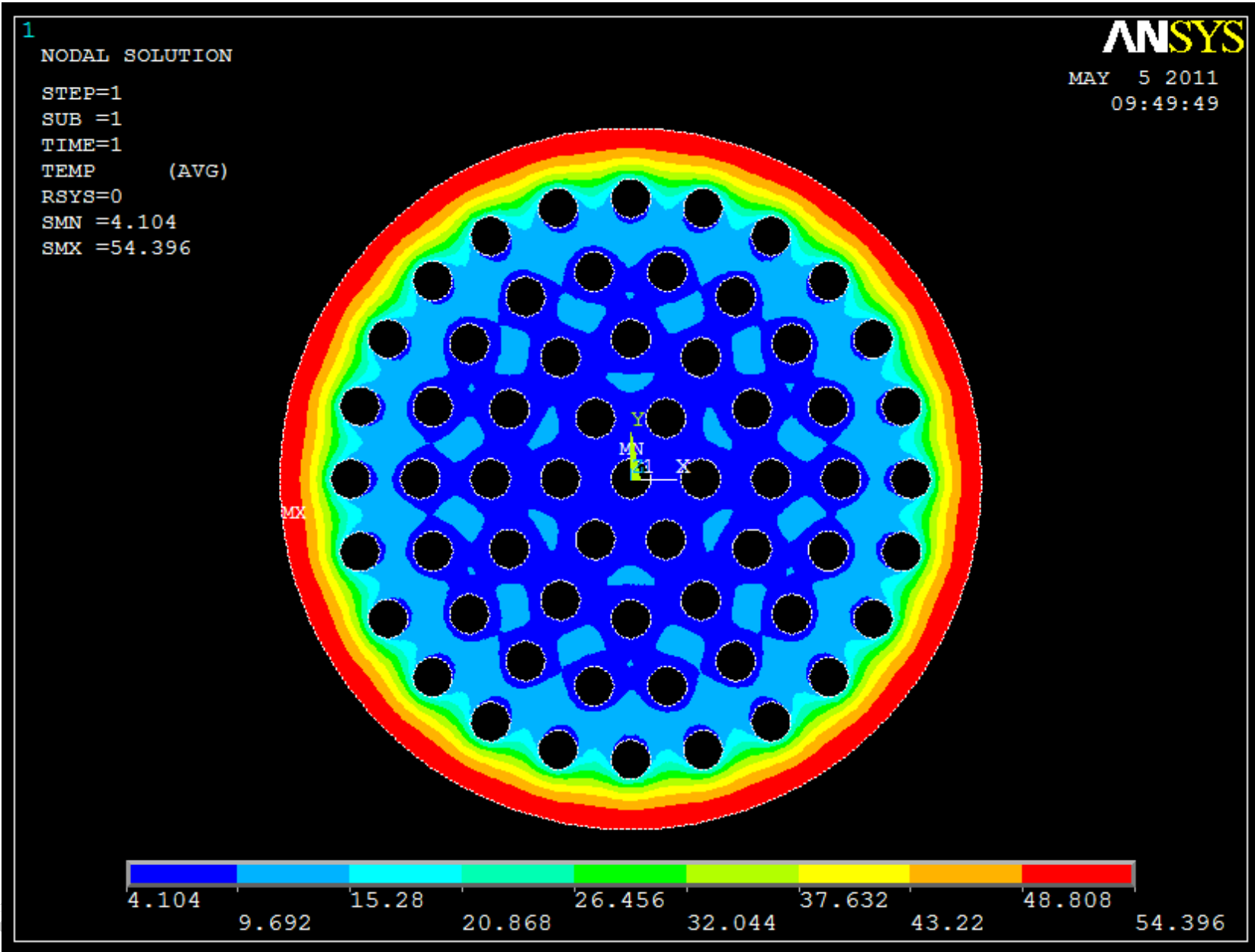
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ELEMENTS

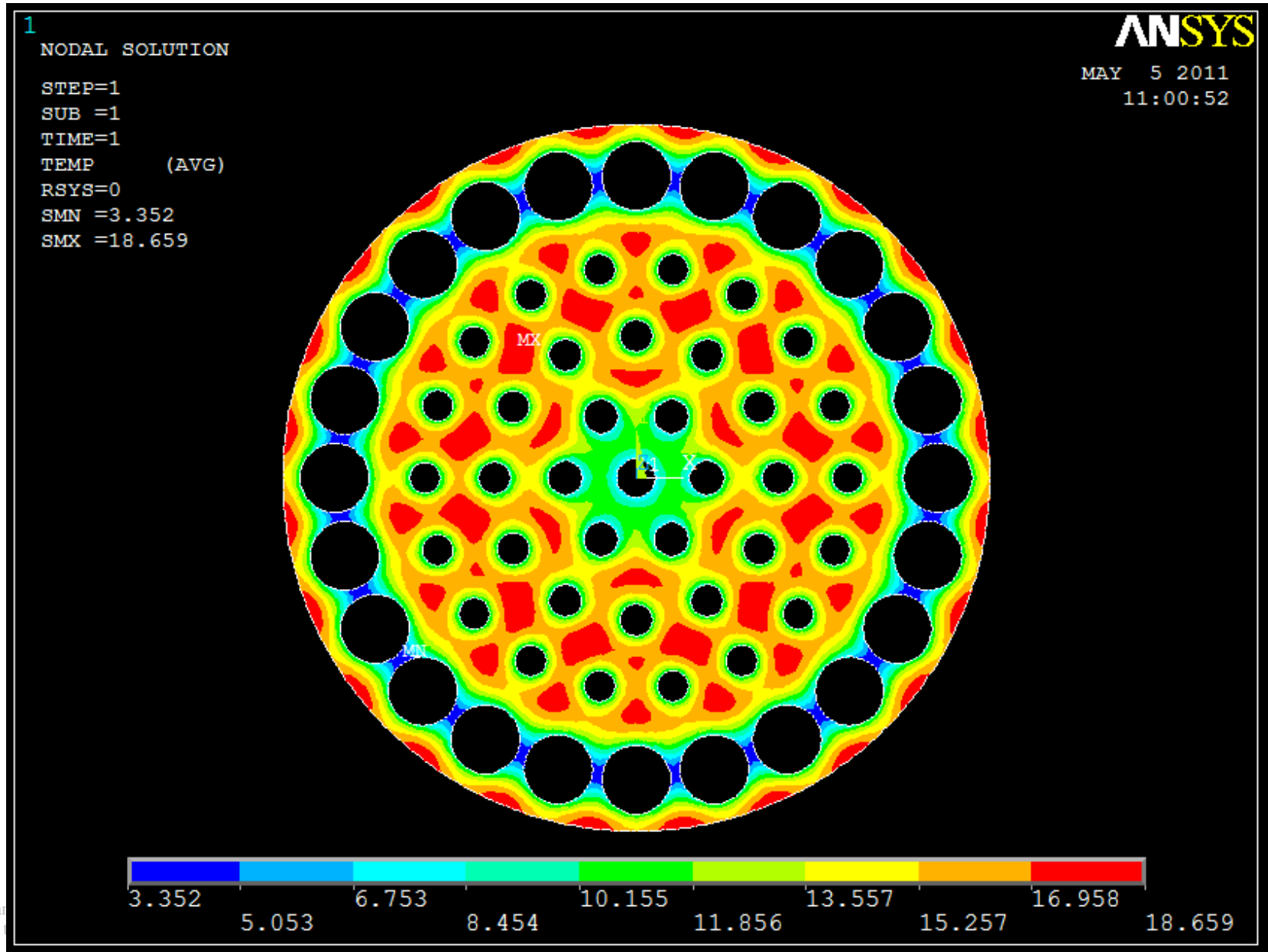


10,267 8-noded
elements

Results – FNS Conditions



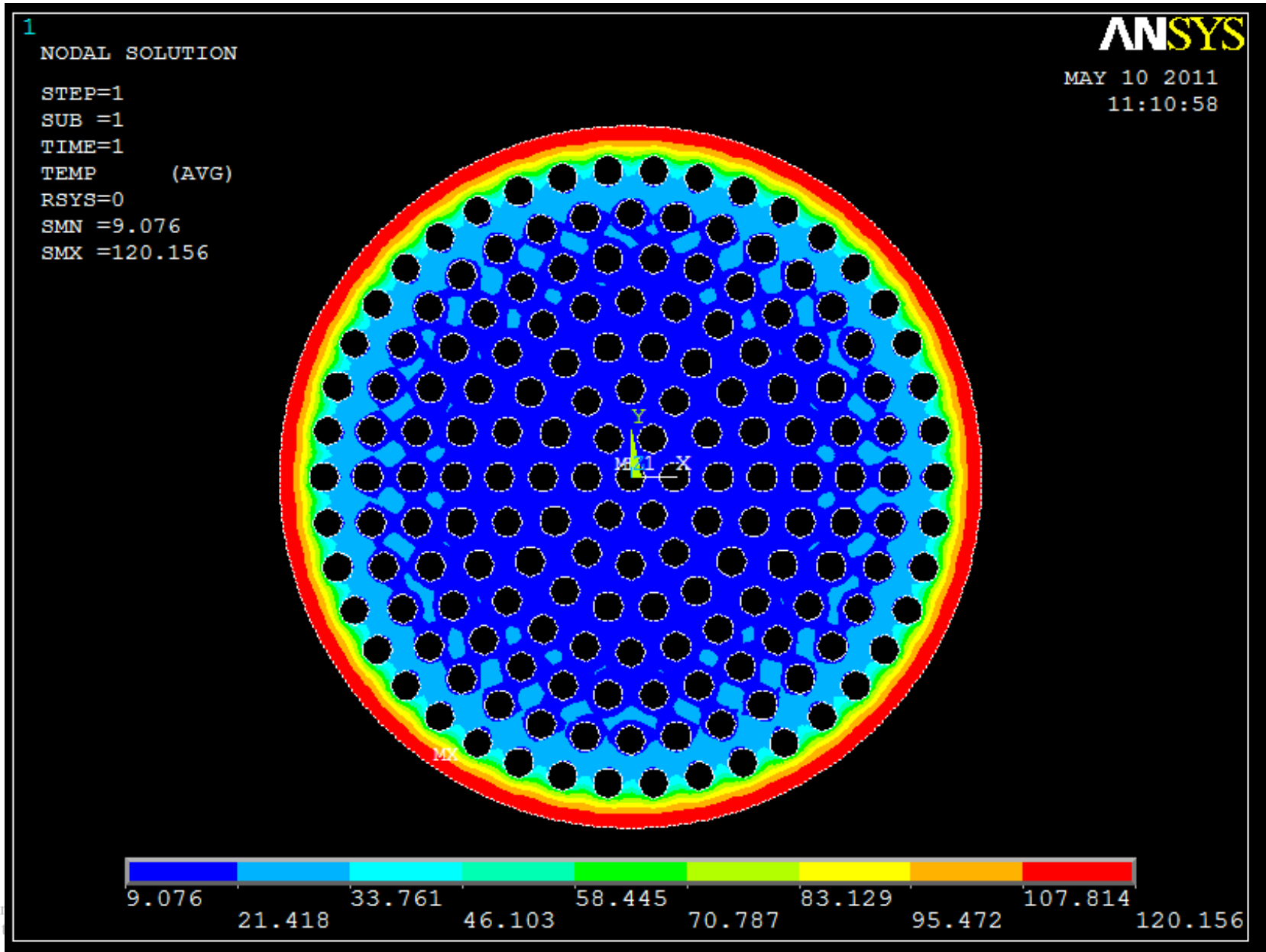
Results – FNS Conditions



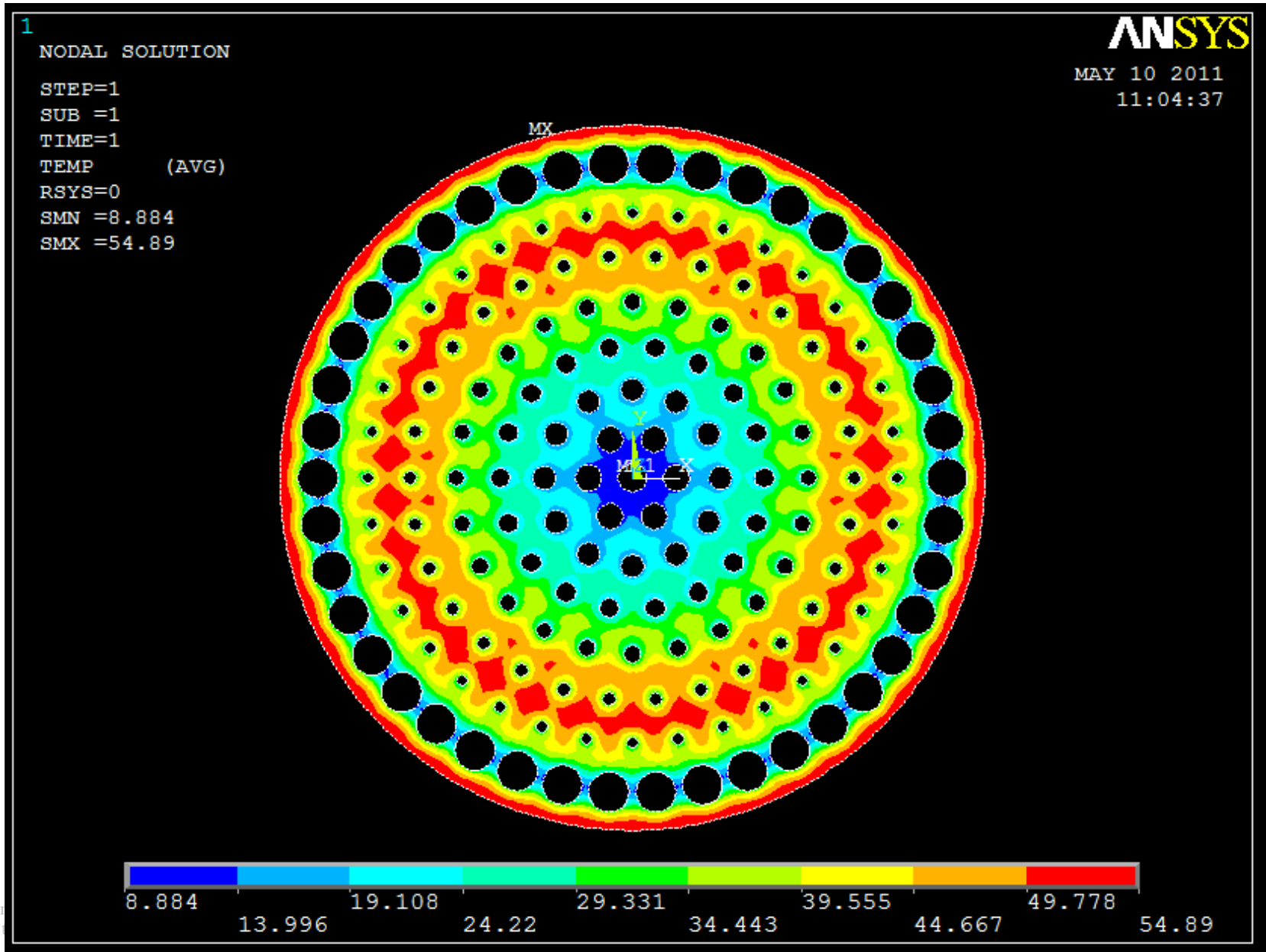
Sources of Error – Material Properties

- **Convection coefficient, water properties – 25% to 10%**
 - Viscosity, thermal conductivity, density, specific heat
- **Convection coefficient, Gnielinski correlation – 10%**
- **Glidcop electrical resistivity – 15% ↑ from RT to 100°C**
- **Glidcop thermal conductivity – 3% ↓ from RT to 100°C**
- **Glidcop electrical resistivity – 10% ↑ at 50 dpa irradiation, 20% ↑ at 100 dpa irradiation**
- **Water velocity – 12% to 8% temperature on optimal design temperature**

Results – FNST Stretch Conditions

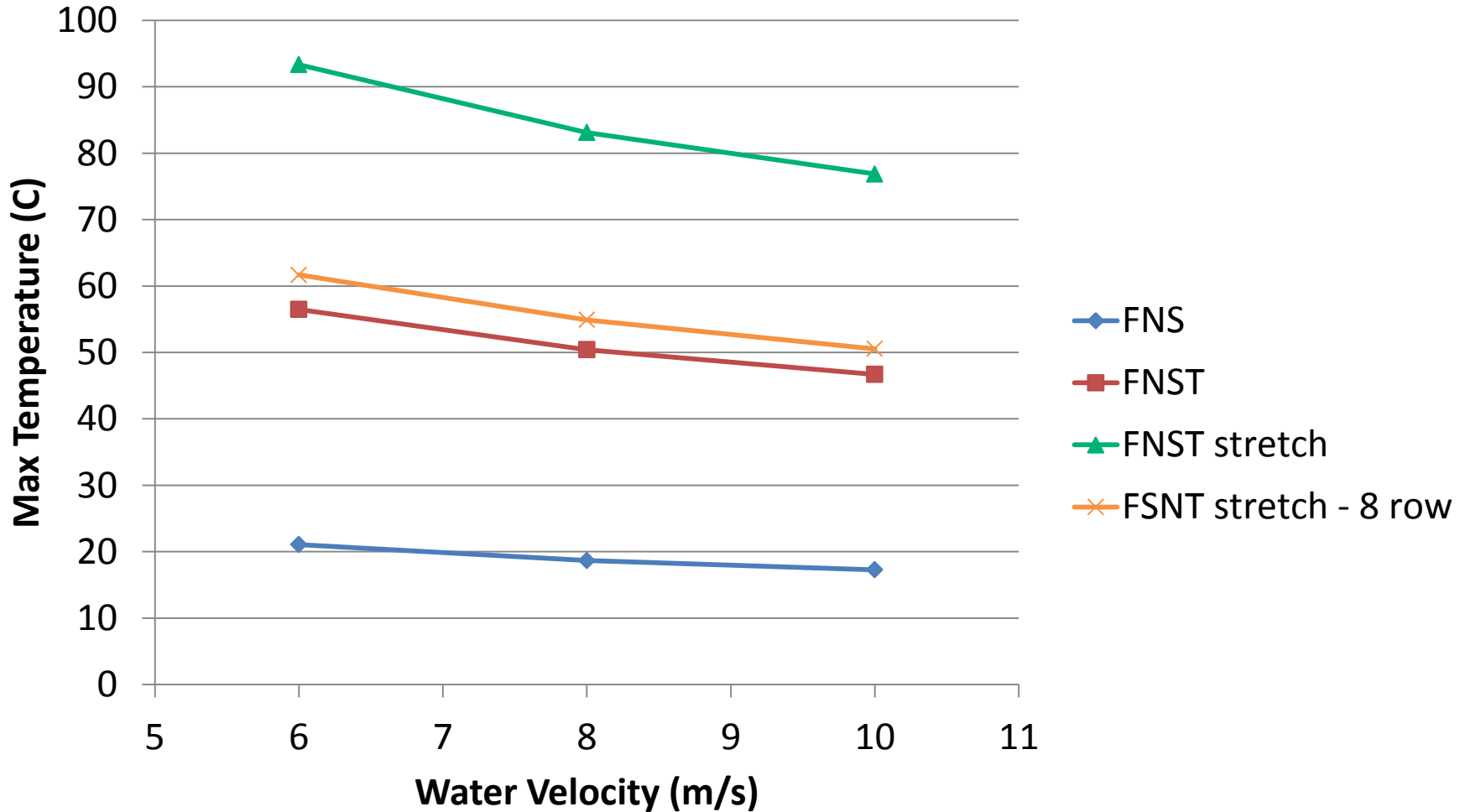


Results – FNST Stretch Conditions

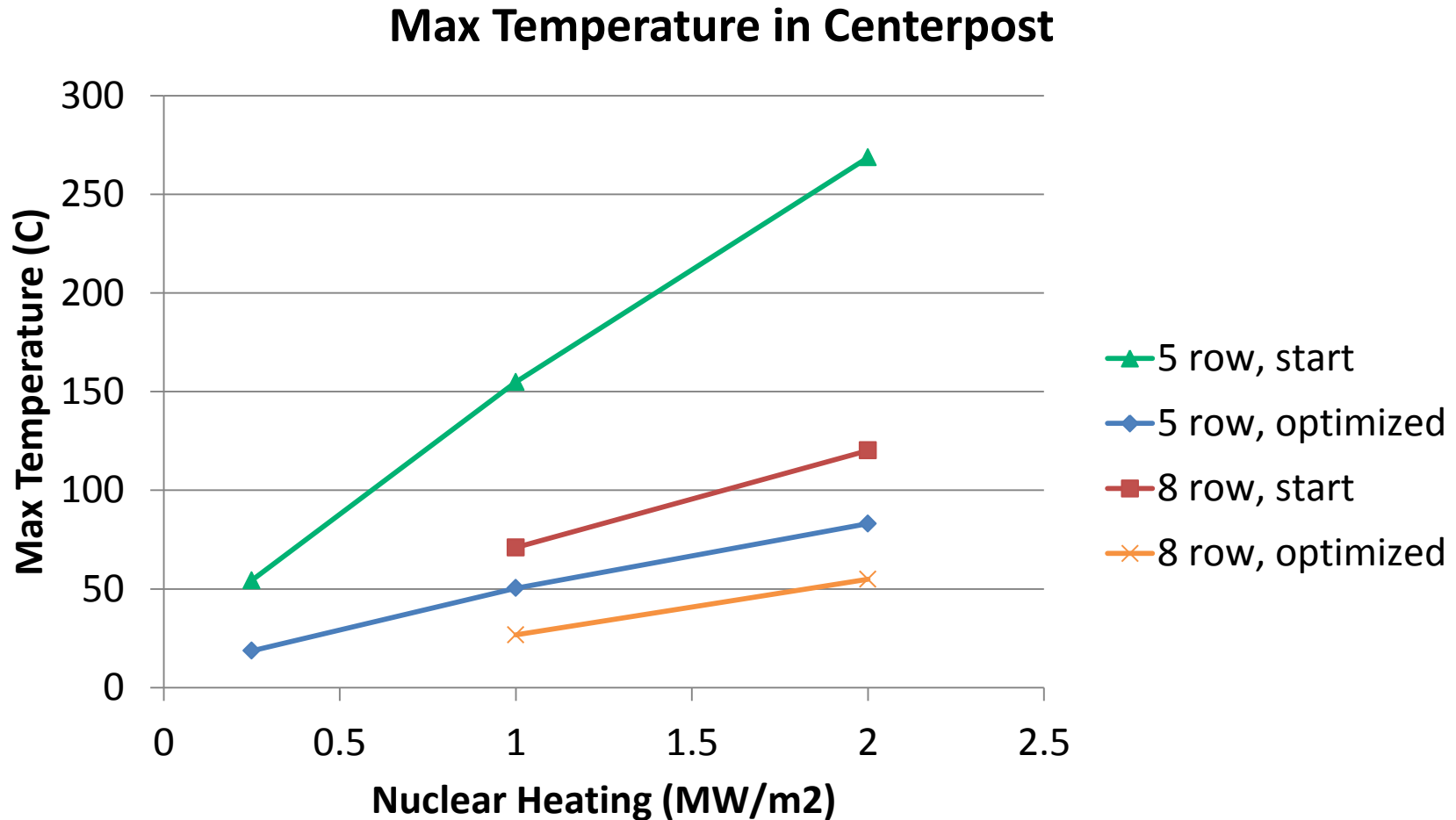


Maximum Temperature in Optimized Centerpost vs. Water Velocity

Max Temperature in Centerpost



Maximum Temperature in Centerpost vs. Nuclear Heating



Summary of Results

Start	Water velocity			Rows	Current	Nuclear	Cooling	Current Density
	6 m/s	8 m/s	10 m/s					MA/m ²
C	C	C	C		MA	MW/m ²		MA/m ²
54.30	21.06	18.66	17.27	5	4.2	0.25	30.8%	21.46
154.84	56.47	50.41	46.68	5	6.7	1	30.9%	34.29
70.97		26.71		8	6.7	1	18.0%	28.89
268.71	93.34	83.10	76.87	5	8.4	2	33.0%	44.32
120.16	61.67	54.89	50.54	8	8.4	2	21.1%	37.64
268.71		81.39		5	8.4	2	40.0%	49.54
268.71	87.41	77.59	71.37	5	8.4	2	27.8%	41.13
268.71	81.67	72.38	68.51	5	8.4	2	22.6%	38.38
268.71	78.48	69.51	63.82	5	8.4	2	23.2%	38.67

Conclusions

- **Optimally designed cooling channels are capable of effectively cooling a long pulse FNSF spherical tokamak.**
- **The design optimization process is effective in the development of effective cooling channel design.**
- **A 3D multiphysics analysis is required to demonstrate the robustness of the FSNF-ST centerpost design under full FNST conditions.**

Future Study

The next steps for centerpost design include:

- Performing multiphysics structural analysis, including electromagnetic loading for normal and abnormal (i.e. plasma disruption) operating conditions.
- Conducting three-dimensional analysis.
- Modeling fluid flow with computational fluid dynamics code (ANSYS CFX).
- Including temperature and damage dependent material properties.
- Conducting parameter study for extraordinary loading conditions.
- Including a more accurate nuclear heating input.

Acknowledgments

- **This research is sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy.**

