Feasibility Investigation of MPACT for Core Design Studies of NBSR-2

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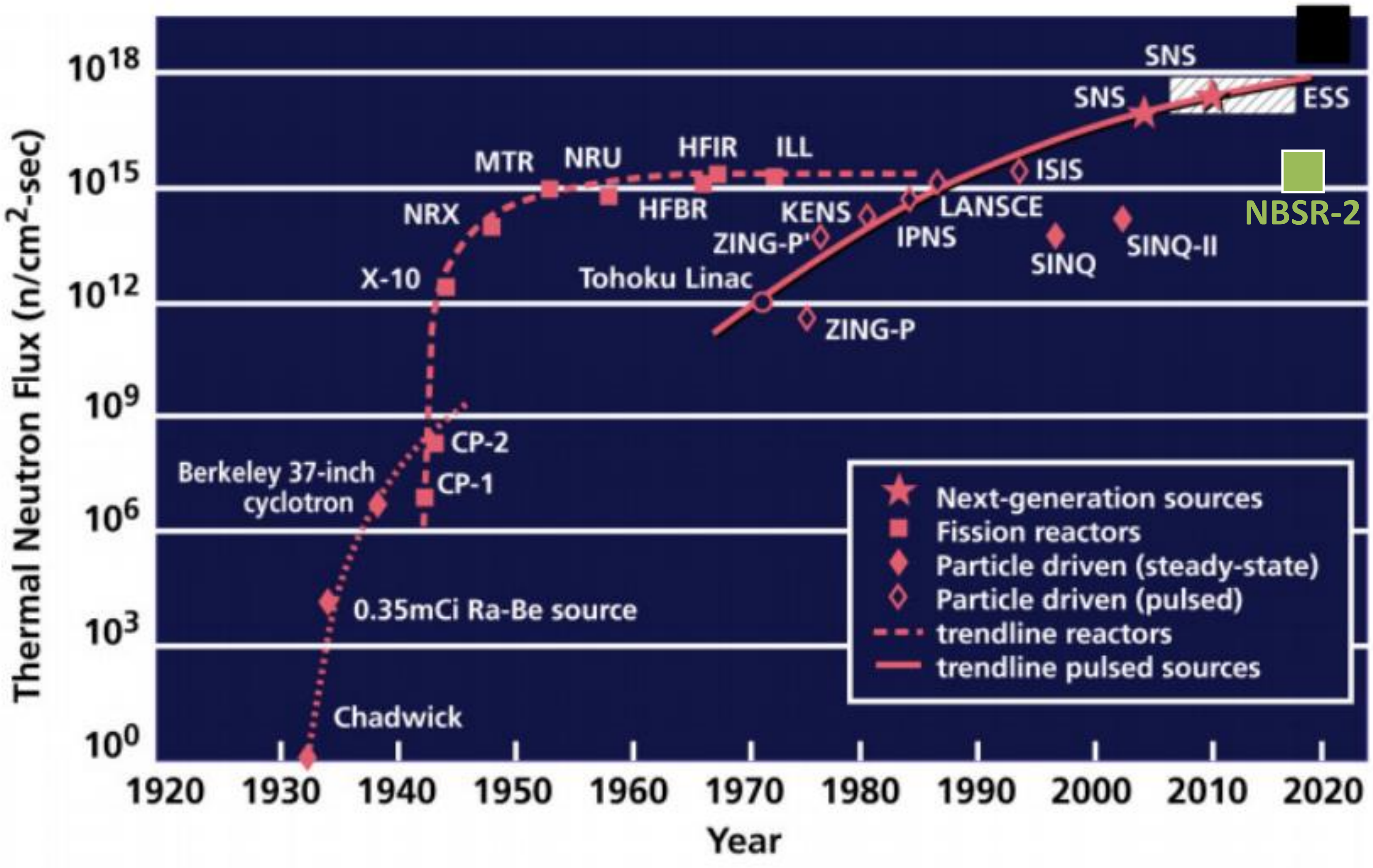
Outline

- Prior neutronics work on NBSR-2 (MCNP6)
- Modeling NBSR-2 in MPACT
- Preliminary results
  - k_{eff} and flux comparisons with existing MCNP model
  - Design study: optimal placement of the cold source
- Modeling limitations and future work

NBSR-2 and Cold Neutron Scattering

- The original NBSR is a MTR-type reactor
  - Commissioned in 1967
  - D_2O coolant in a “tank” design
  - HEU fuel plate assemblies
- Accelerators can offer higher fluxes, but:
  - Higher cost per neutron
  - Large epithermal flux
  - Larger footprint
  - Complexity: more systems, staff
- Demand for continuous neutron scattering sources continues to rise
  - NIST @ 3x capacity and rising
    - Protein delivery vehicles
    - Basic physics experiments
    - Hydrogen fuel cells
  - Active 245 days/year



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

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Cold Neutron Economies in the 21st Century

Reactor	Power (MW_{th})	Fuel	Max Φ_{th} ($\times 10^{14}$ n/cm^2-s)	Quality factor ($\times 10^{13}$ MTF/MW_{th})
Pulstar (NC State)	1	LEU	0.1	1
HFIR (ORNL)	85	HEU	10	1.2
PIK (Russia)	100	HEU	13	1.3
CARR (China)	60	LEU	8	1.3
OPAL (Australia)	20	LEU	3	1.5
NBSR (NIST)	**20**	**HEU**	**4**	**2**
BR-2 (Belgium)	60	HEU	12	2
NBSR-2 (NIST)	**20**	**LEU**	**5**	**2.5**
RHF (ILL, France)	58	HEU	15	2.6
FRM-II (Germany)	20	HEU	8	4

- RHF and FRM-II have single-element cores, so their fuel burnup is much poorer

Design Features of NBSR-2

Power: 20 MW (?)

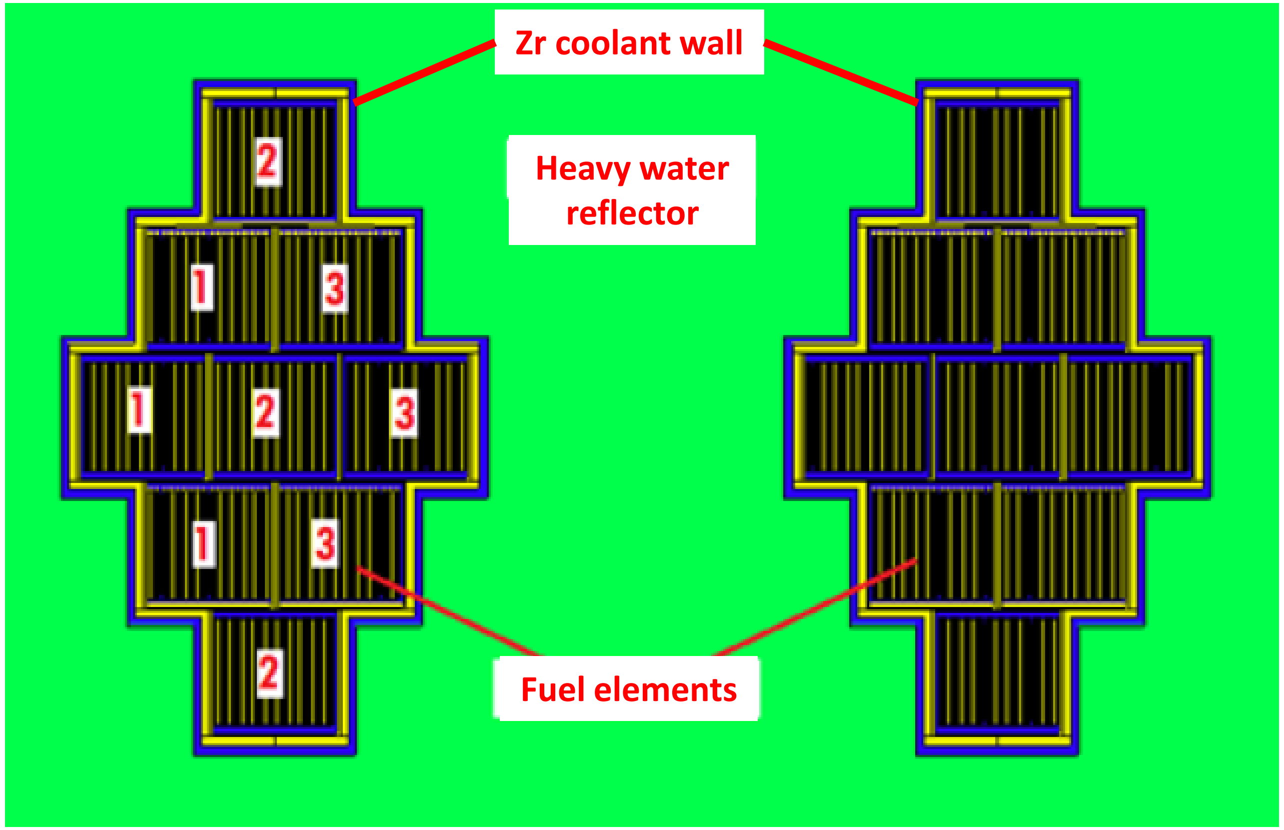
Fuel dim: $(8.4\ \text{cm})^2 \times 60$ cm

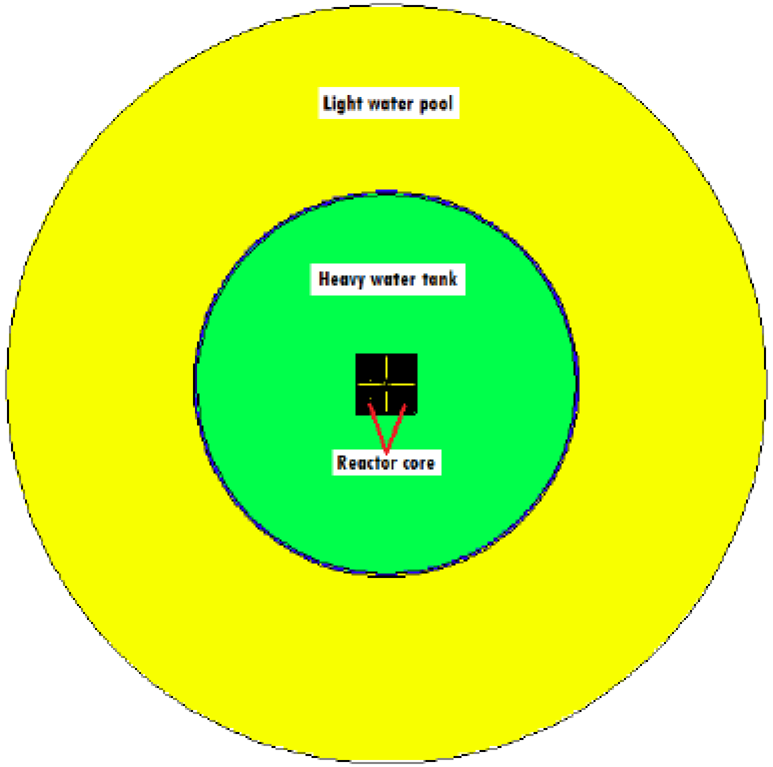
Fuel Cycle: 30 d, x3

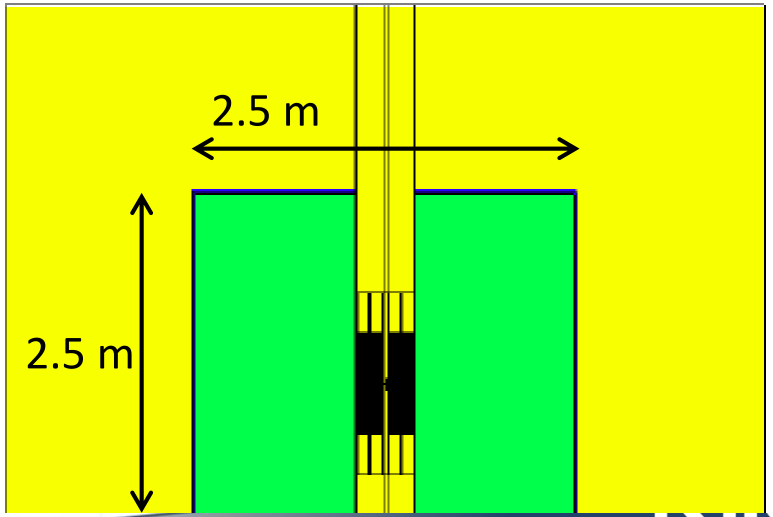
Fuel: U_3Si_2/Al @ 19.75 % (MTR)

Moderator: High purity D_2O

Coolant: H_2O @ 100 F

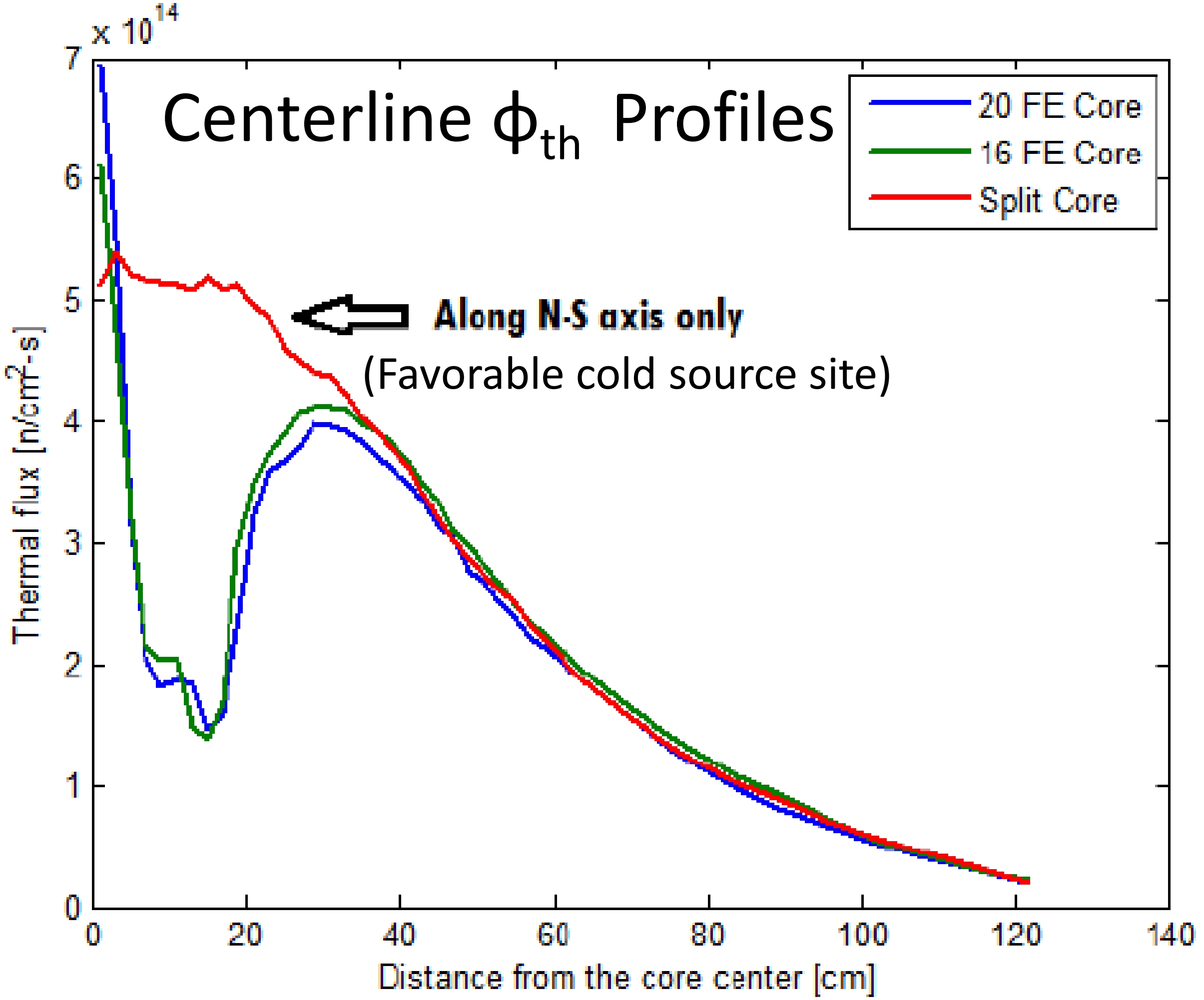


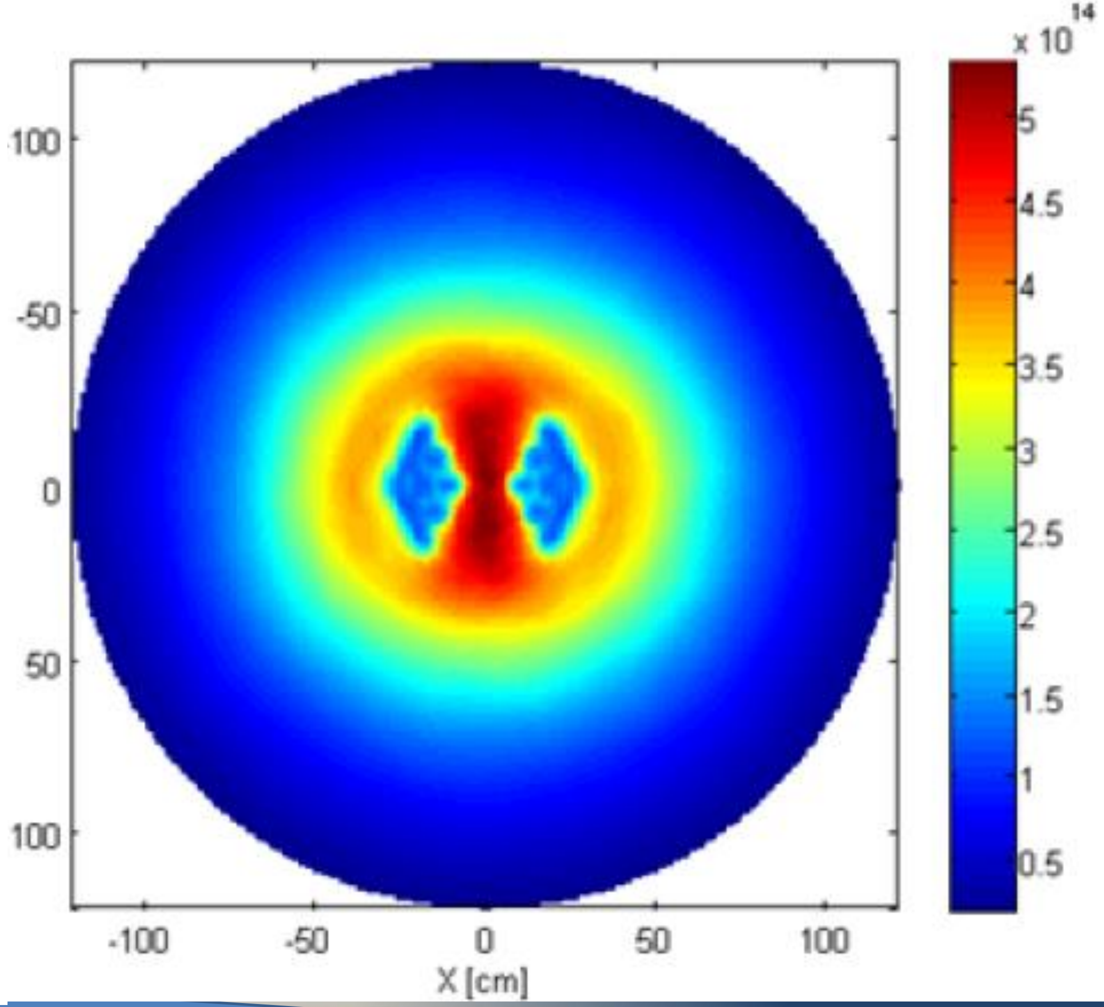




Why choose a split core design?

1. Higher cryostat flux due to being nearer the center of the core
2. More fuel positioned at optimal slowing-down length in the moderator
3. Gammas have no optical path from fuel to beam (equivalent to a tangential beam)





Michigan Parallel Characteristics Code (MPACT)

UNIVERSITY OF MICHIGAN

- Research code being developed at University of Michigan
- Uses MOC to perform modular ray tracing to solve the BTE in small, efficient steps.
- Neutronics solver for the VERA simulation environment (CASL)
  - Primary goal is commercial LWRs
    - Neutronics w/ depletion
    - T/H and CFD
    - CRUD deposition
  - Physics coupling to MOOSE framework adds additional computational tools

CASL | The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

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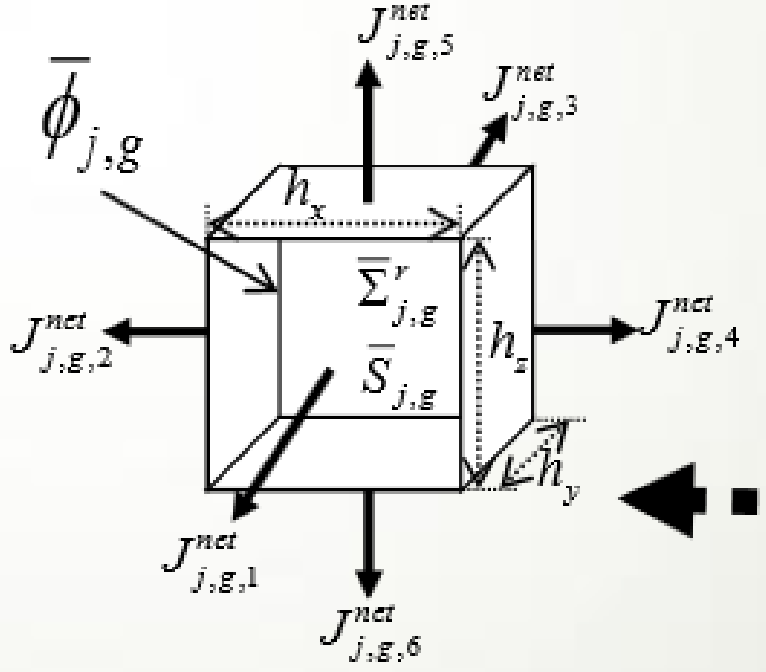
The Case for MPACT

MCNP6	MPACT
Very little support for reactor simulations at LANL in recent years.	Young, but active, project at the University of Michigan and ORNL.
Lower utility for multiphysics calculations - Many plugins exist, but multi-cycle calculations tend to be clumsy and academic.	Part of VERA (CASL), can couple to MOOSE – T/H, depletion, and material performance simulations are all realistic.
Geometric subdivisions are simple but labor intensive, especially during early design studies.	Requires lattice-based “modular” geometry, but arbitrarily fine submeshing. - Potential for excellent resolution
Stochastic method (Monte Carlo)	Deterministic method (Method of Characteristics w/ CMFD)

Coarse Mesh Finite Differencing (CMFD)

- Non-linear synthetic acceleration method
  - Solve the transport equation with "blocks" of flux-weighted cross sections
    - $\bar{\Phi}_{j,g} = \frac{\sum_{i \in j} \Phi_{i,g} V_i}{\sum_{i \in j} V_i}$
    - $\bar{\Sigma}_{s,j,g} = \frac{\sum_{i \in j} \Sigma_{s,j,g} \Phi_{i,g} V_i}{\sum_{i \in j} \Phi_{i,g} V_i}$
  - Blocks are linked using a radial coupling correction term that preserves the leakage rates between faces
- Dramatically reduces computation time, improves convergence (when it works)
  - # iterations required reduced by 1 order of magnitude

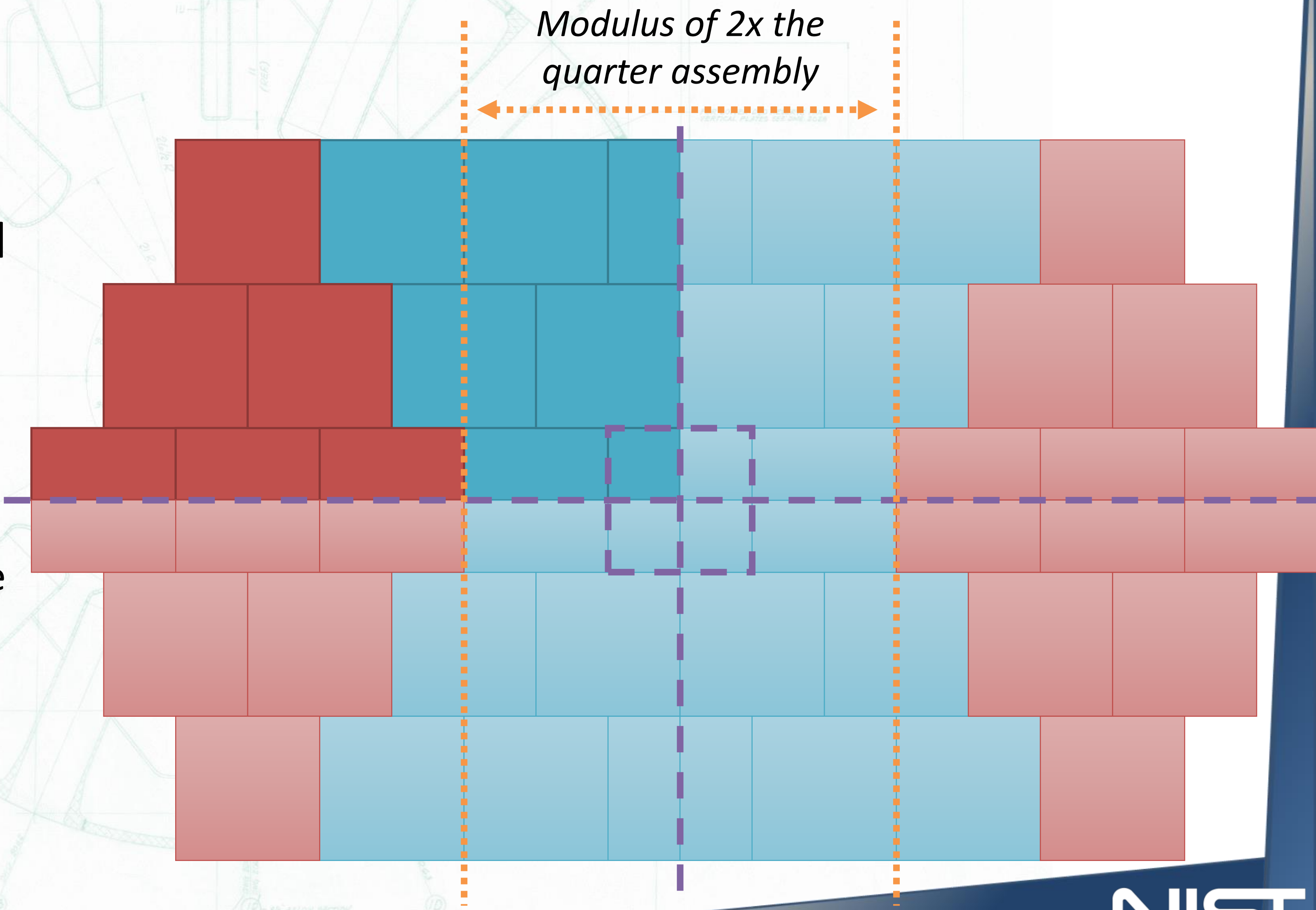


CMFD Node

CMFD Blocks and Symmetry

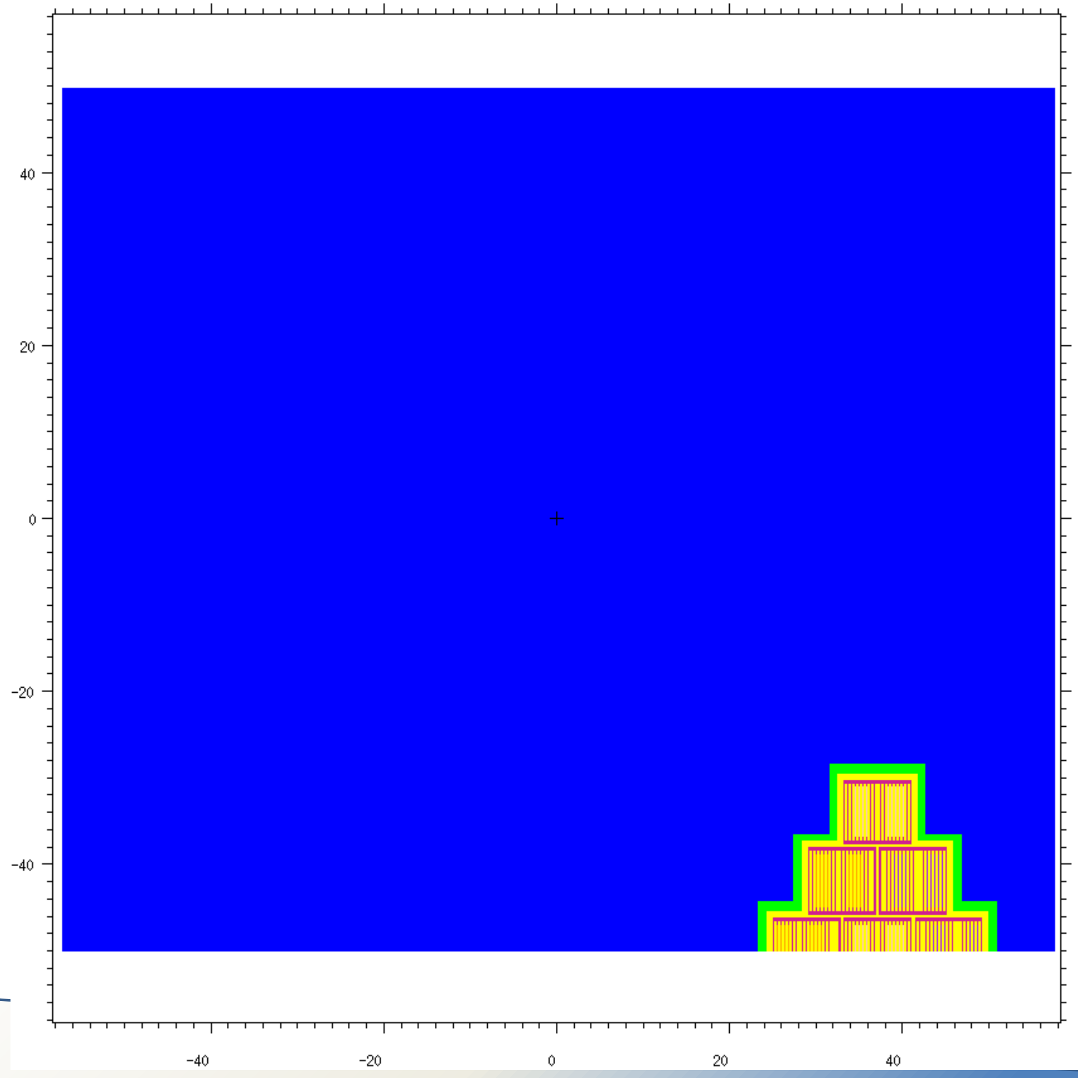
- CMFD applied in a modular lattice
- NBSR's ¼ symmetry with staggered blocks requires 4 modules per element
- Artificial constraints:
  - Core gap adjusted in moduli of 2x the quarter assembly.
  - Square reflector tank

(MCNP model adjusted accordingly)

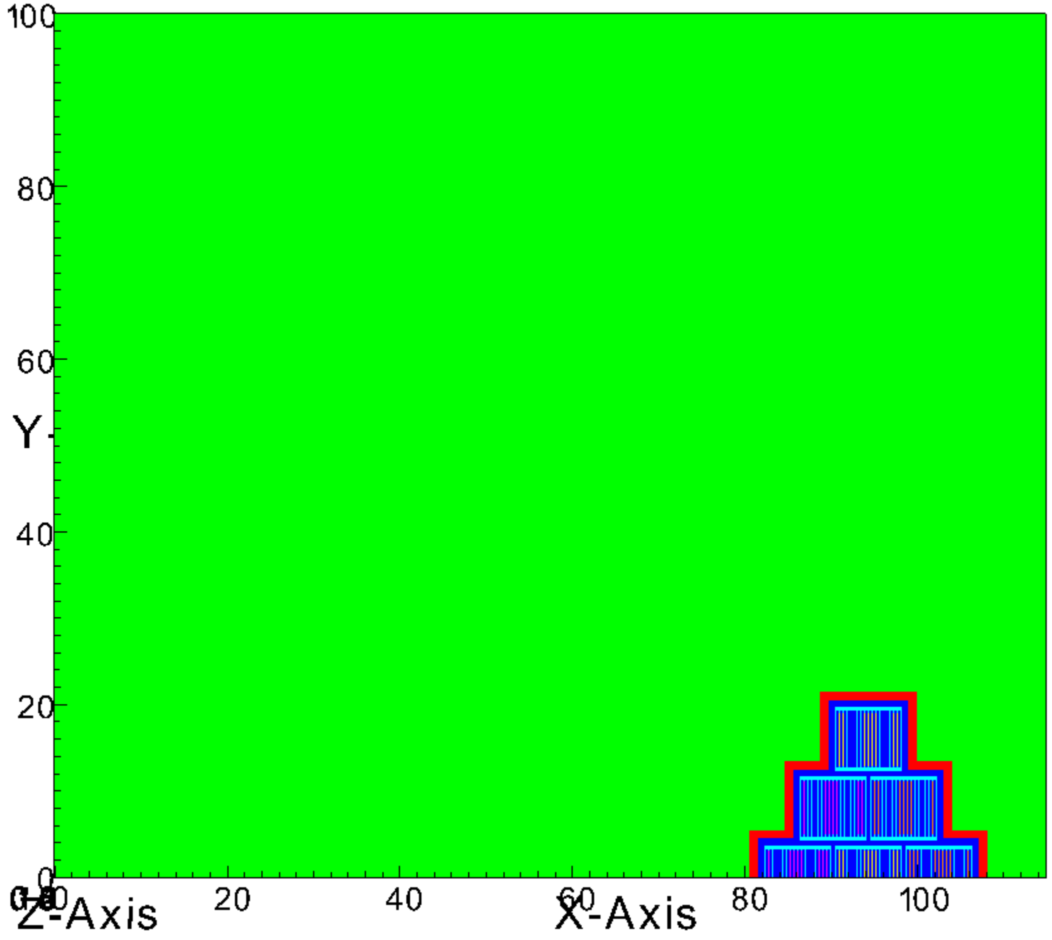


Final MCNP and MPACT Models (2-D only)

MCNP6 (via Xming)



MPACT (via VisIt)

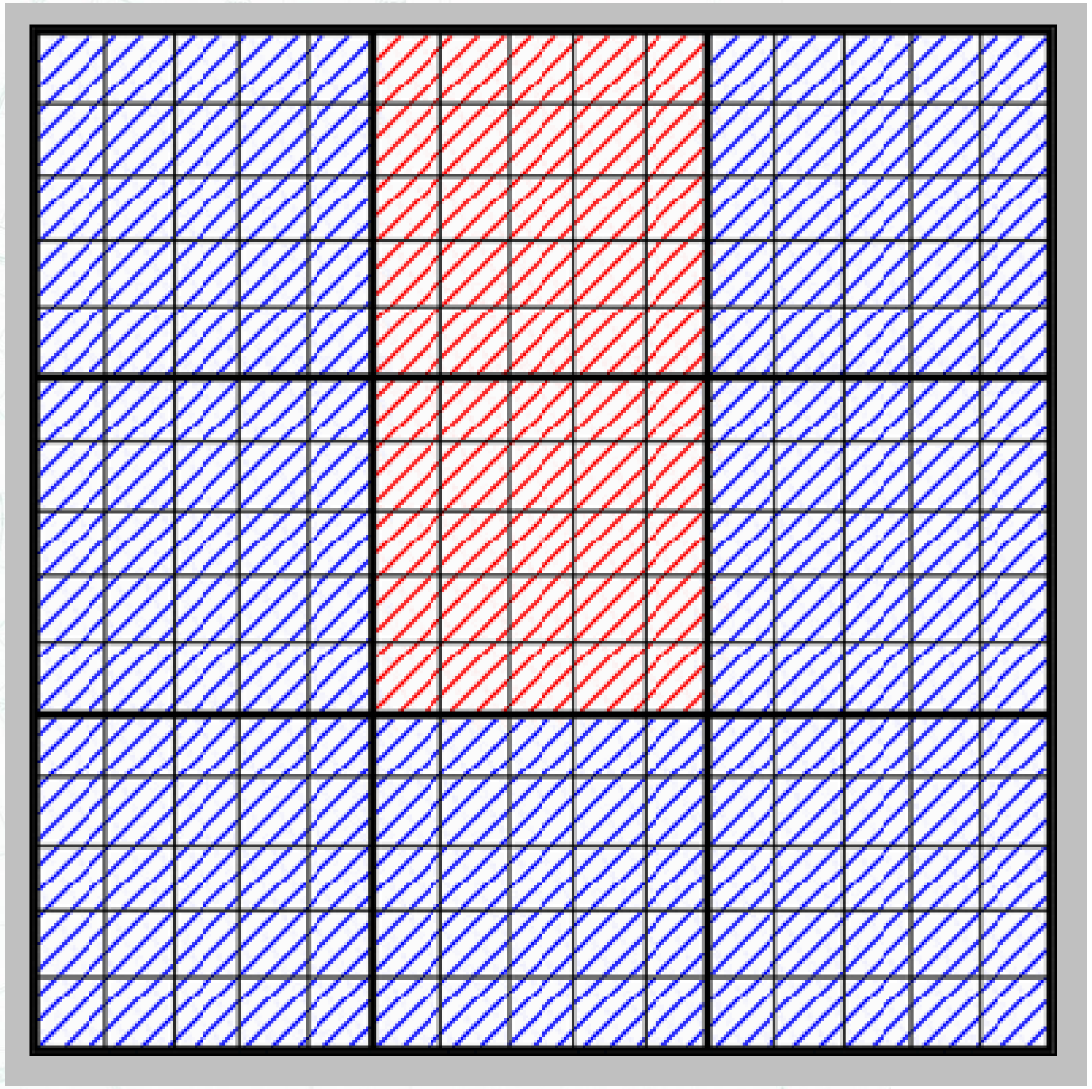


Modular Ray Tracing

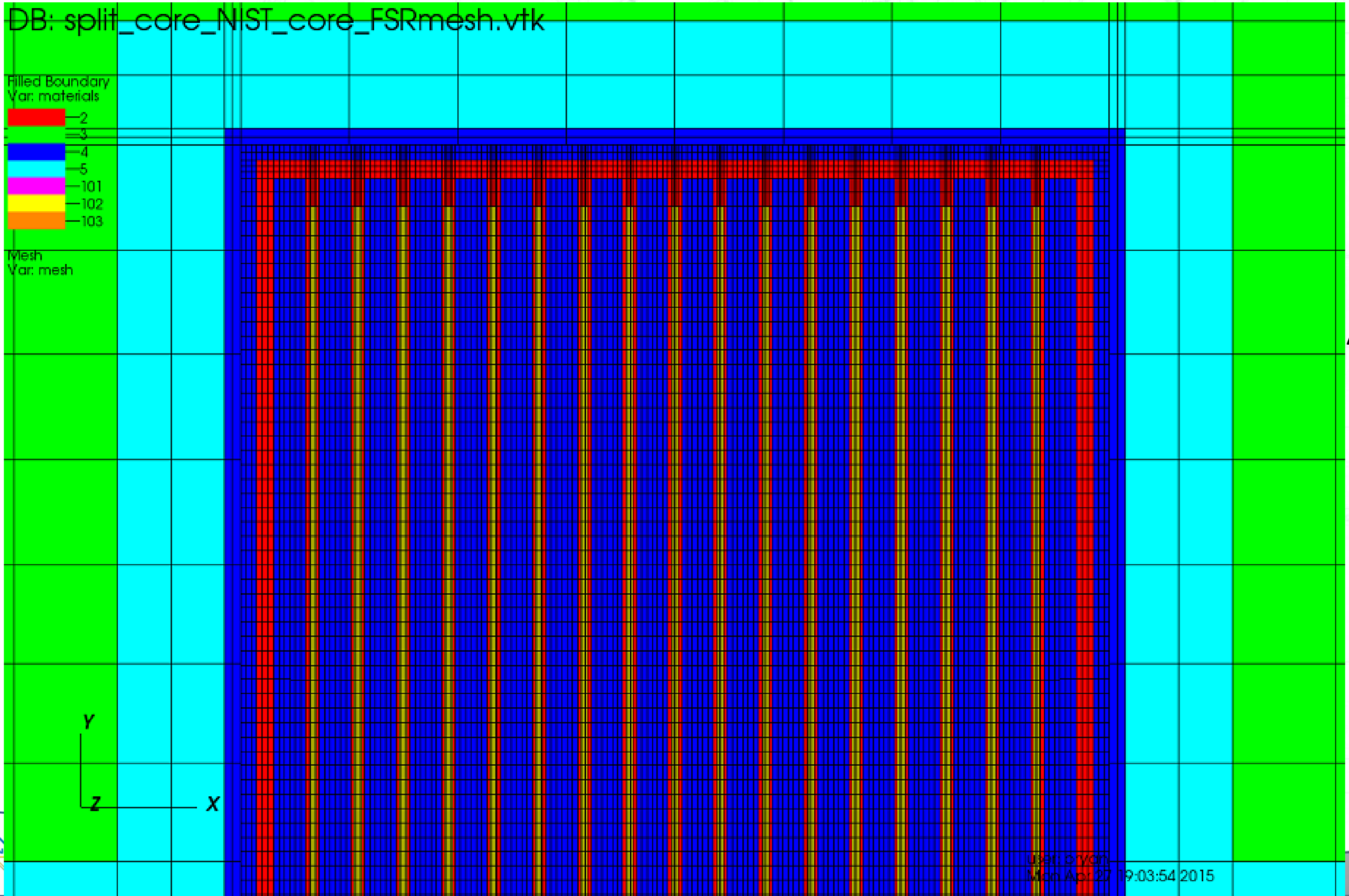
- MOC used on this level
  - Ray tracing is only performed once for each module type, regardless of usage.
  - Typical module: one fuel assembly

- Significant performance gains
  - Memory reduced by 10^7 (in 3D)

- Artificial constraints for NBSR-2:
  - Minimal (heterogeneous plates lacked slight curvature)



Submeshing: One Fuel Element



<u>Core Model</u>

Dimensions: 2 (reflective Z)

Symmetry: ¼

<u>Submeshing</u>

Total # cells: 1,173,556

Average cell size: 0.3 mm^2 (fuel)

<u>Work Station (“Abacus”)</u>

cores: 8 @ 1.15 MHz

threads/core: 1

Environment: Linux

Run time: ~5 hrs

Relevant program settings

MCNP6 Parameters

- `kcode 10000 1 10 210`
- endfb-7.1
- fmesh4 (in 0.1 mm^2 increments)
- Geometry modified to match MPACT.

MPACT Parameters

- 28 modular assemblies
- MOC: 1-gp linear sweep w/ Gauss-Seidel iters
- Ray tracing: 0.2 mm, Chebyshev-Yamamoto, ϕ=16, θ=3
- Convergence criteria: 2e-6
- 0.3 mm^2 submeshes (in fuel)
- mpact47g_70s_v4.0_11032014.fmt
  - Mg, Si, and Ti must be natural.

MPACT vs MCNP: Excellent Agreement

MPACT: 1.22276 ± 0.00001 (converged)

MCNP6: 1.22456 ± 0.00047 (1-σ)

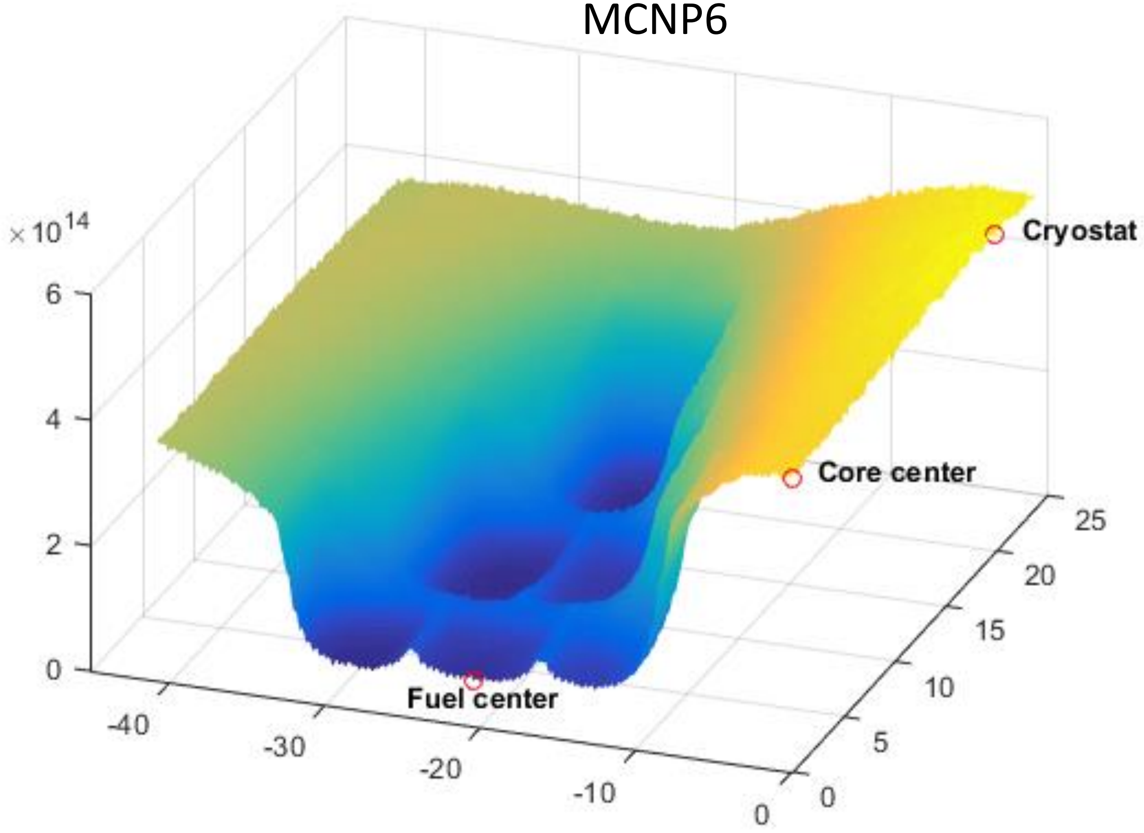
k_{eff} within 120 pcm

- Σ libraries a likely source of error

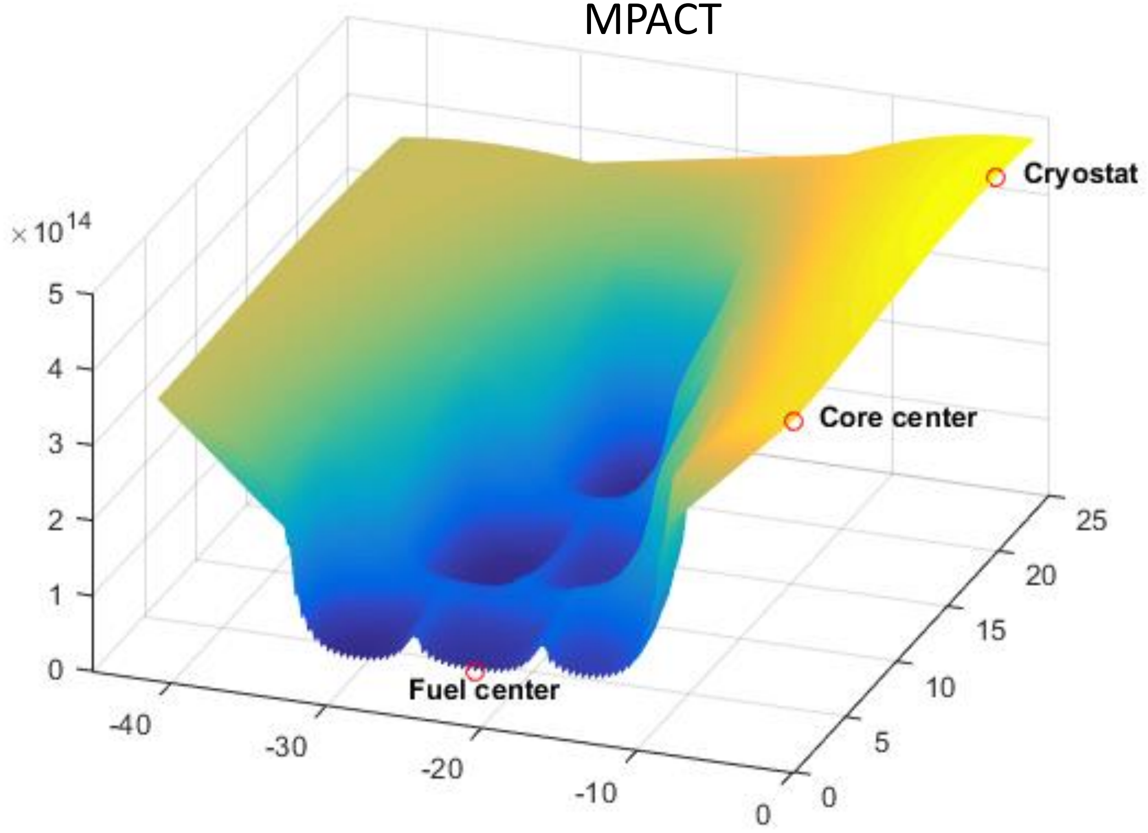
ϕ_{th} within 1.5 % (1-σ)

- Small cell mismatches

MCNP6



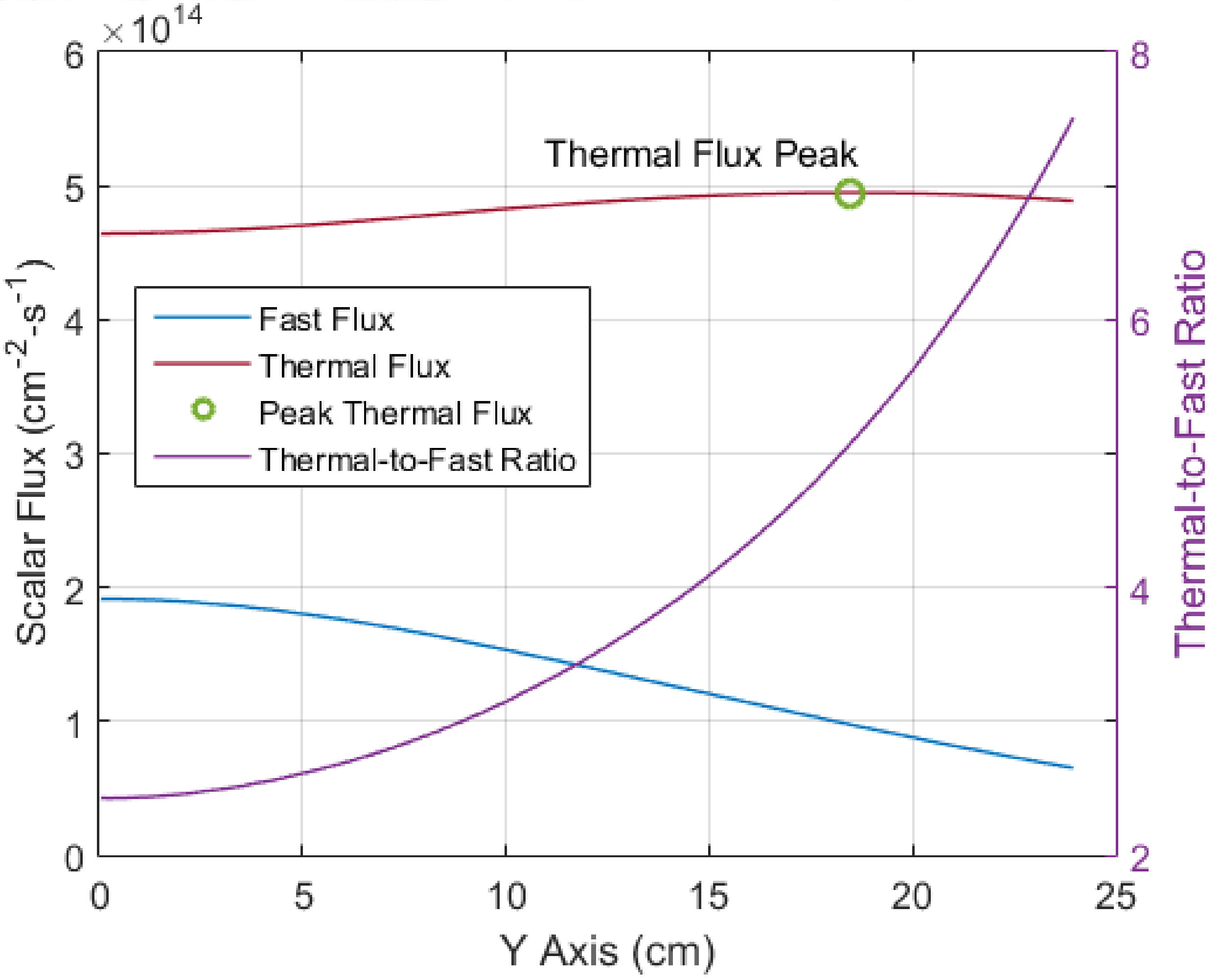
MPACT



Optimization of Cryostat Placement

- Cryostat uses ~40 K liquid LH_2 (or 30 K LD_2) to slow neutrons to a Boltzmann temperature of ~3 meV.
- Refrigerative capability becomes a limiting factor, so fast neutrons dramatically reduce performance.
- Cryostat site moved from 18 cm to 20 cm to improve neutron efficiency by 22%.
  - @ 18 cm, F/T: 4.6
  - @ 20 cm, F/T: 5.6

  (This is neglecting gamma heat)



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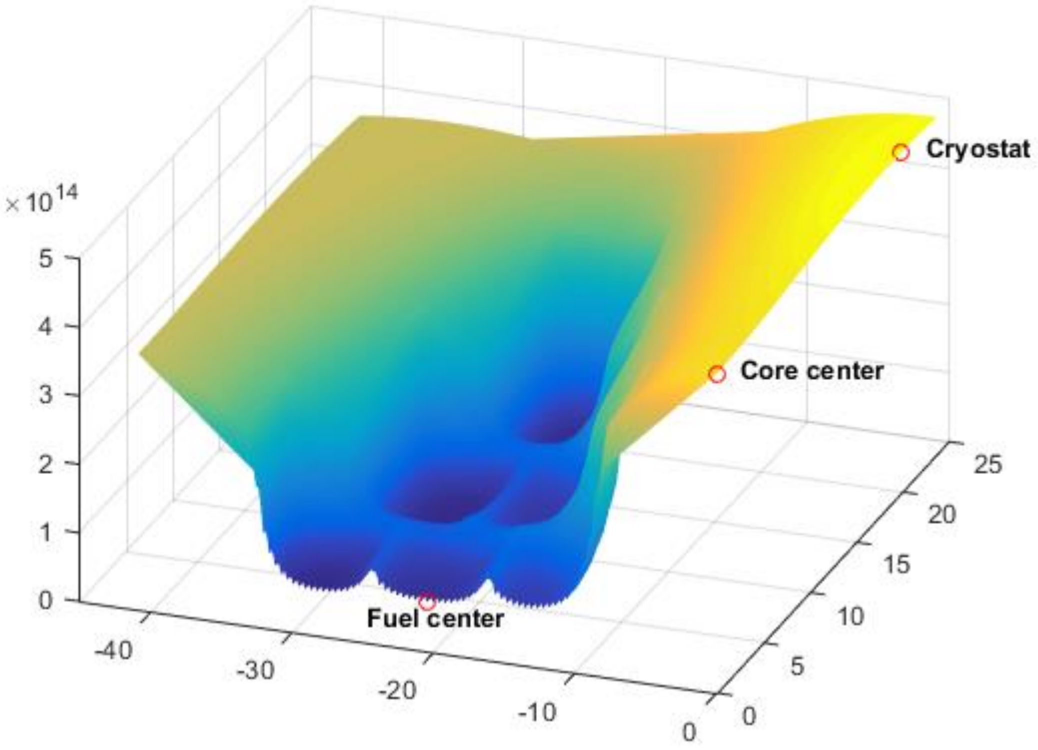
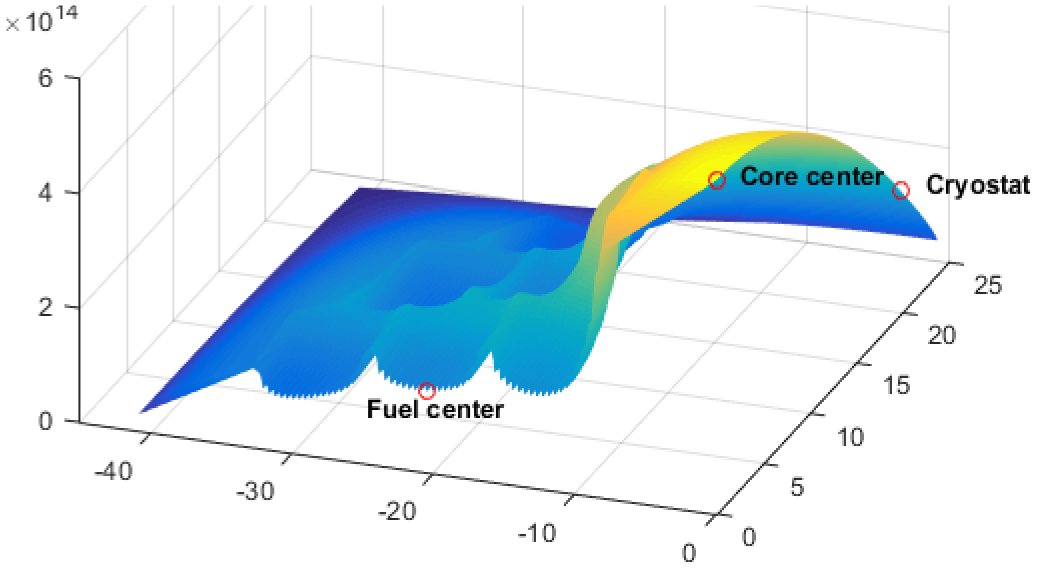
Run Time: A Limiting Factor

- MPACT run time: ~5 hours in 2-D
  - ¼ symmetry applied
  - TCP_0 cross sections broken; used P_2 instead
  - No CMFD acceleration!!!
    - Code bug, possibly due to large reflector
- Smaller reflector shown to be a poor approximation along centerline
- Not having a local copy of MPACT at NIST slowed troubleshooting





Concluding Remarks

- MPACT is capable of producing results comparable to MCNP6 for NBSR-2.
  - k_{eff} agreement within 120 pcm; ϕ_{th} within 1.5 %.
  - Structured lattice created some minor geometric limitations.
  - Large D_2O reflector may have inhibited CMFD.
    - Disabling CMFD gave accurate results, at the cost of computation time.

- CMFD and TCP_0 limitations are holding up 3-D work for now.
  - (At least as long as we're limited to U-M computational resources)

- Future studies of T/H and fuel depletion using VERA are anticipated.
  - This may require migration from native MPACT inputs to the VERA input format.
  - Coupling to BISON could also be explored.

References

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