The impact of FENDL-3.2 on ITER and FNSF fusion reactor computational benchmarks

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U.S. National Nuclear Data Week/CSEWG Meeting
Online
November, 2021

Outline

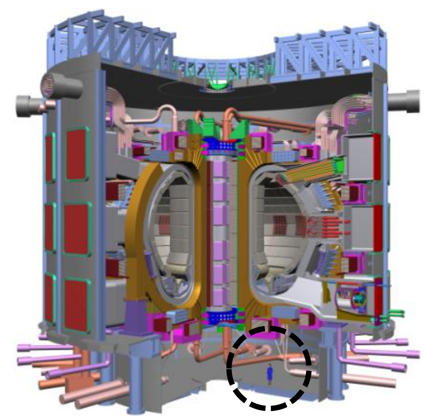
1) Introduction
2) Nuclear data libraries examined
3) Benchmark/Systems Analyzed:
   - ITER-1D computational benchmark
   - FNSF-1D computational benchmark
4) Future Work

Current D-T Fusion Experiments/Reactors

$$D + T \rightarrow He\text{-}4\ (3.5\ MeV) + n\ (14.1\ MeV)$$

JET (UK)
- 1983-present
- R_{major}=3 m
- Vol_{plasma}=100 m^3
- pulse ~1 sec
- 16 MW_{fusion}

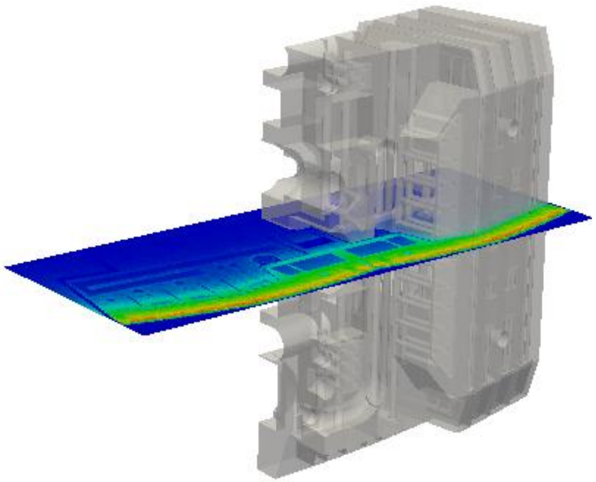
ITER (France)
- under construction
- R_{major}=6 m
- Vol_{plasma}=840 m^3
- pulse ~400-600 sec
- 500 MW_{fusion}



Soon, maybe? private start-ups (not all D-T or Tokamak based)
- Helion, Common Wealth Fusion, General Fusion, TAE Technologies
- Several others

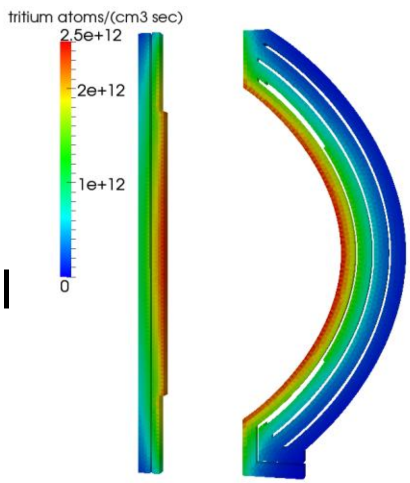
Important Fusion Neutronics Responses

- **Neutron flux/fluence**
  - structure, magnets
- Total nuclear heating **(neutron+photon)**
  - coolant system design, thermal stress, etc. for structure, magnets
- Tritium production **(neutron)**
  - breeding fuel, environmental concerns
- Radiation damage/dpa (**neutron**)
  - structural material, magnet degradation
- Helium production (**neutron**)
  - re-weldability
- Radiation dose (**neutron+photon**)
  - insulators, electronics, personnel
- Activation
  - shutdown dose-maintenance robotics, personnel
  - decay heat-safety (LOCA, LOFA)
  - radioactive waste disposal, recycling



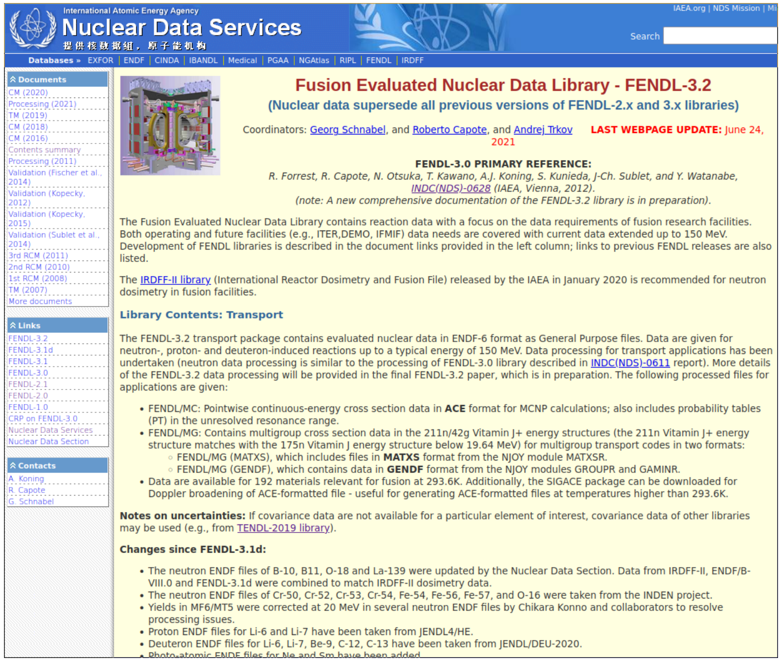
Nuclear heating in ITER FW/Shield Block

Tritium production in FNSF breeding channel



FENDL Library

- The Fusion Evaluated Nuclear Data Library (FENDL) is an international effort coordinated by the IAEA Nuclear Data Section
- Assembles a collection of the best nuclear data from national cross section data libraries **for fusion applications**
    - ENDF/B (US), JENDL (Japan), JEFF (Europe), TENDL (EU), RUSFOND/BROND (Russia)
- Process uses **fusion specific** experimental and calculational benchmarks to evaluate the data
- Data available on-line:



Source of FENDL Data

- 65/180 isotopes in FENDL-3 come from ENDF/B-VII.1
  - See Table 1 in INDC(NDS)-0628
- Some key isotopes for this work:

Isotope	FENDL-2.1*	FENDL-3.1	FENDL-3.2
H-1	JENDL-3.3	ENDF/B-VII.1	ENDF/B-VII.1
0-16	ENDF/B-VI.8	ENDF/B-VII.1	INDEN1.0/Murata et al.**
Cr-52	ENDF/B-VI.8	ENDF/B-VII.1	INDEN?/Nobre et al.**
Fe-56	JEFF-3	JEFF-3.1.1	INDEN1.0/IAEA consort.**
Ni-58	JEFF-3	ENDF/B-VII.0	ENDF/B-VII.0
Cu-63,65	ENDF/B-VI.8	ENDF/B-VII.0	ENDF/B-VII.0

*FENDL-2.1 is the reference library for ITER neutronics
**INDEN https://www.nds.iaea.org/INDEN/

Goal of this work

- Look at the neutronics impact of using the updated neutron libraries in a **realistic model of fusion systems** using MCNP
- Libraries examined:
  - *Neutron:*
    1. FENDL-2.1 (21c)
    2. FENDL-3.1 (31c)-current version 3.1d
    3. Initial INDEN evaluations for O, Cr, Fe*
    4. FENDL-3.2 (32c)-june 24, 2021 version
       - Includes *newer* INDEN evaluations for O, Cr, Fe
    5. ENDF/B-VII.1 (80c)
    6. ENDF/B-VIII.0 (00c)
  - *Photon:*
    1. mcplib84 (84p)**

standard MCNP id

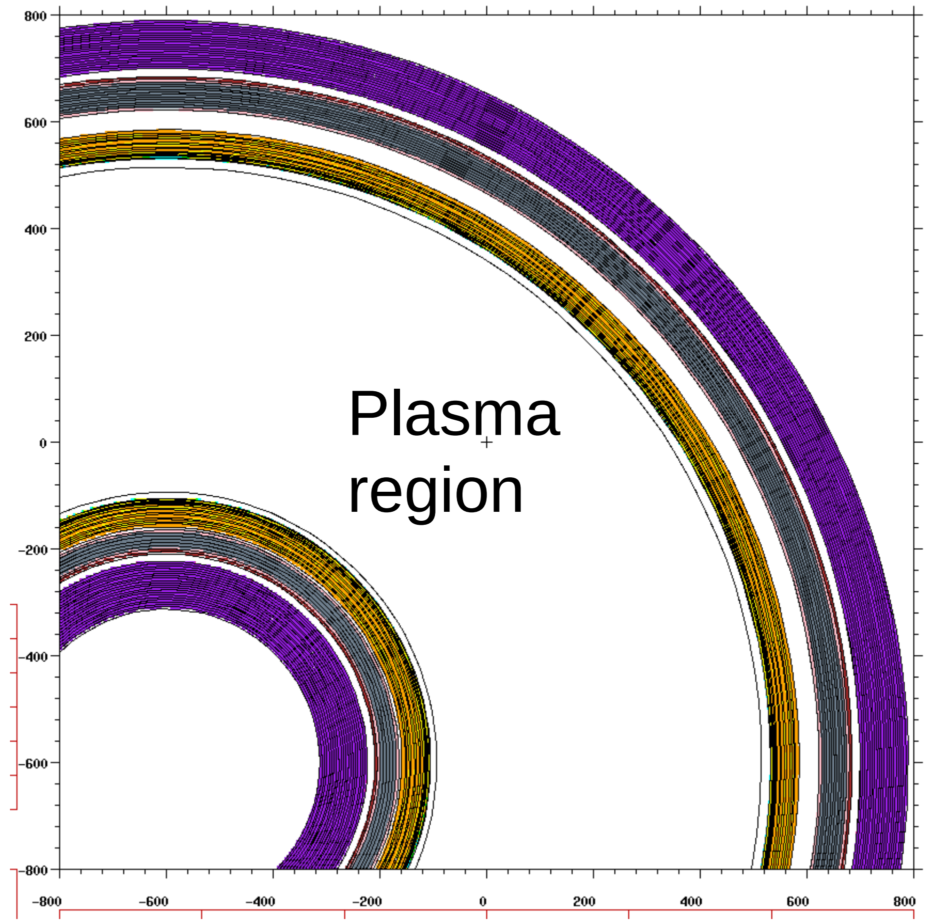
New work

- *Previous work has shown that mcplib84 produces results similar to the newer MCNP eprdata12 library, the latest MCNP photon library (eprdata14) has not been tested yet*

* *Bohm T.D, Sawan M.E. "Neutronics calculations to support the Fusion Evaluated Nuclear Data Library (FENDL)", Fusion Science and Technology, on-line early access August 2021.*
** *Bohm T.D, Sawan M.E. "The impact of updated cross section libraries on ITER neutronics calculations", Fusion Science and Technology, Vol 68, p. 331-335, 2015.*

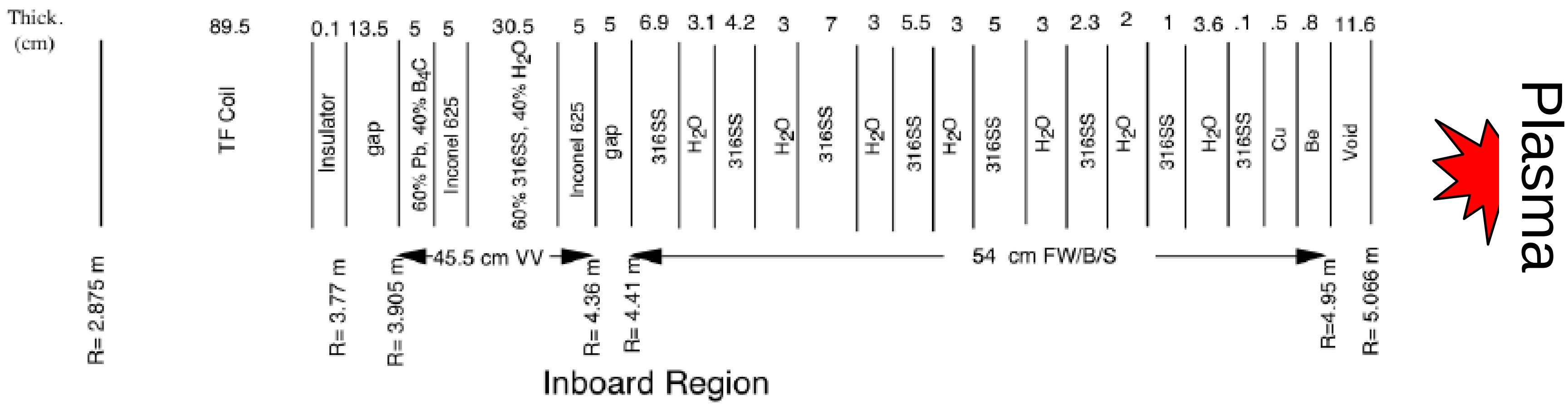
ITER 1-D Cylindrical Calculation Benchmark

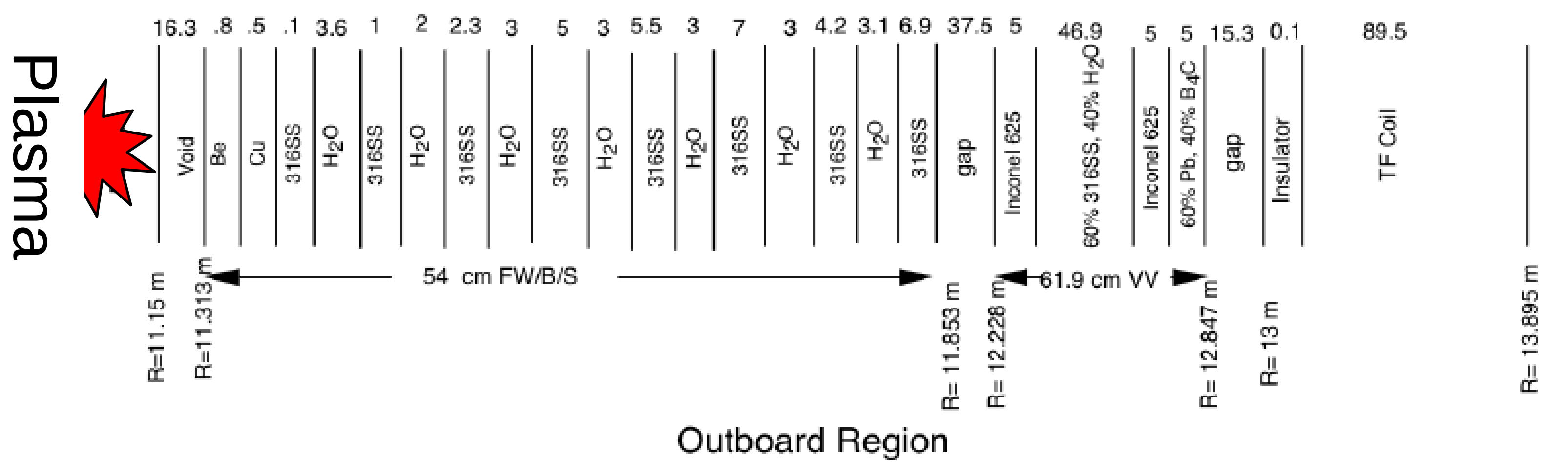
- Based on an **early** ITER design
- Developed for the FENDL evaluation process
- Simple but realistic model of ITER with the Inboard and Outboard portions modeled with the plasma in between
- D-T fusion (14.1 MeV neutrons)
- Flux (neutron and photon), heating, dpa, and gas production calculated



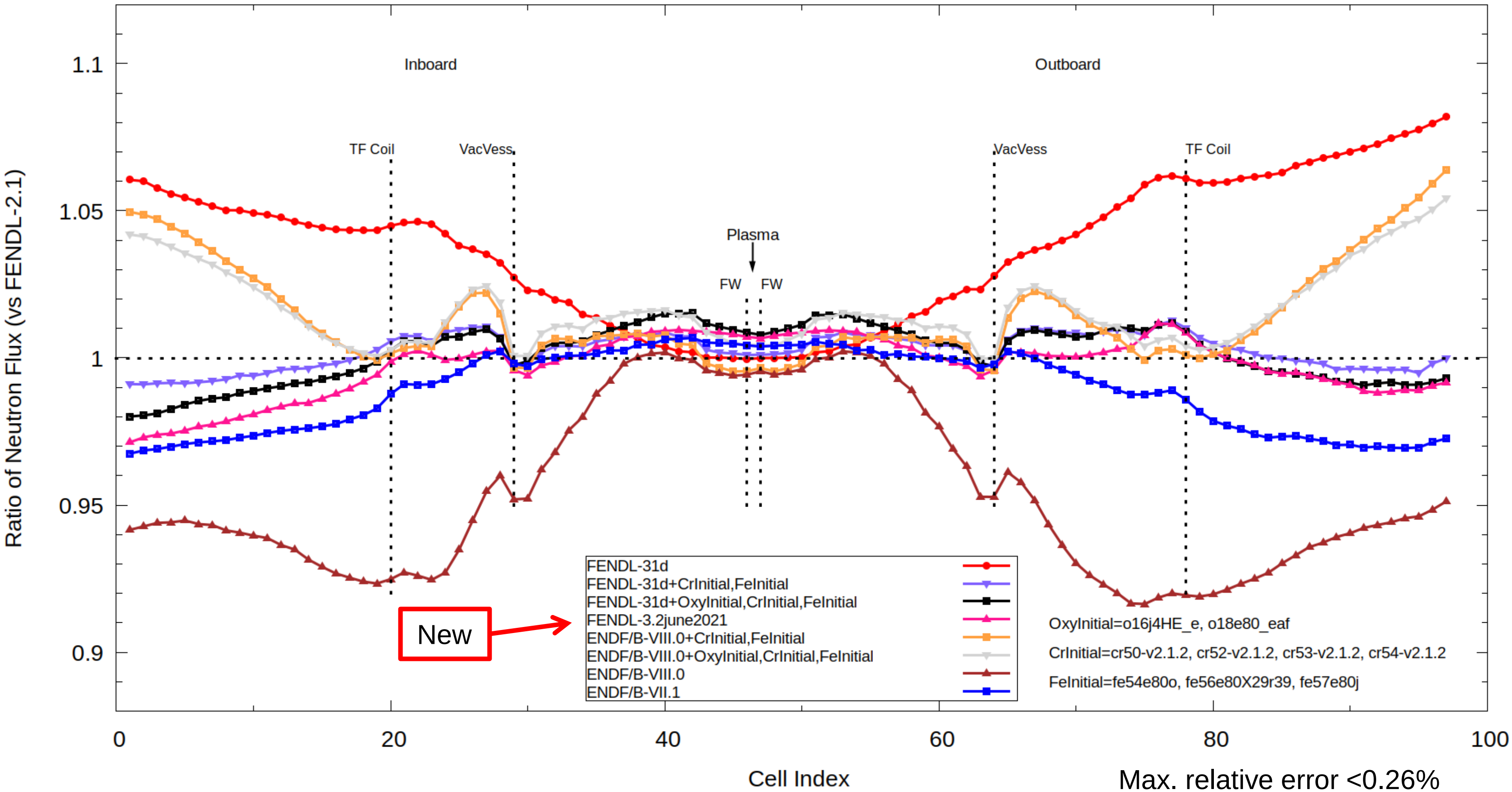
M. Sawan, FENDL Neutronics Benchmark: Specifications for the calculational and shielding benchmark, INDC(NDS)-316, December 1994

ITER 1-D Cylindrical Benchmark continued





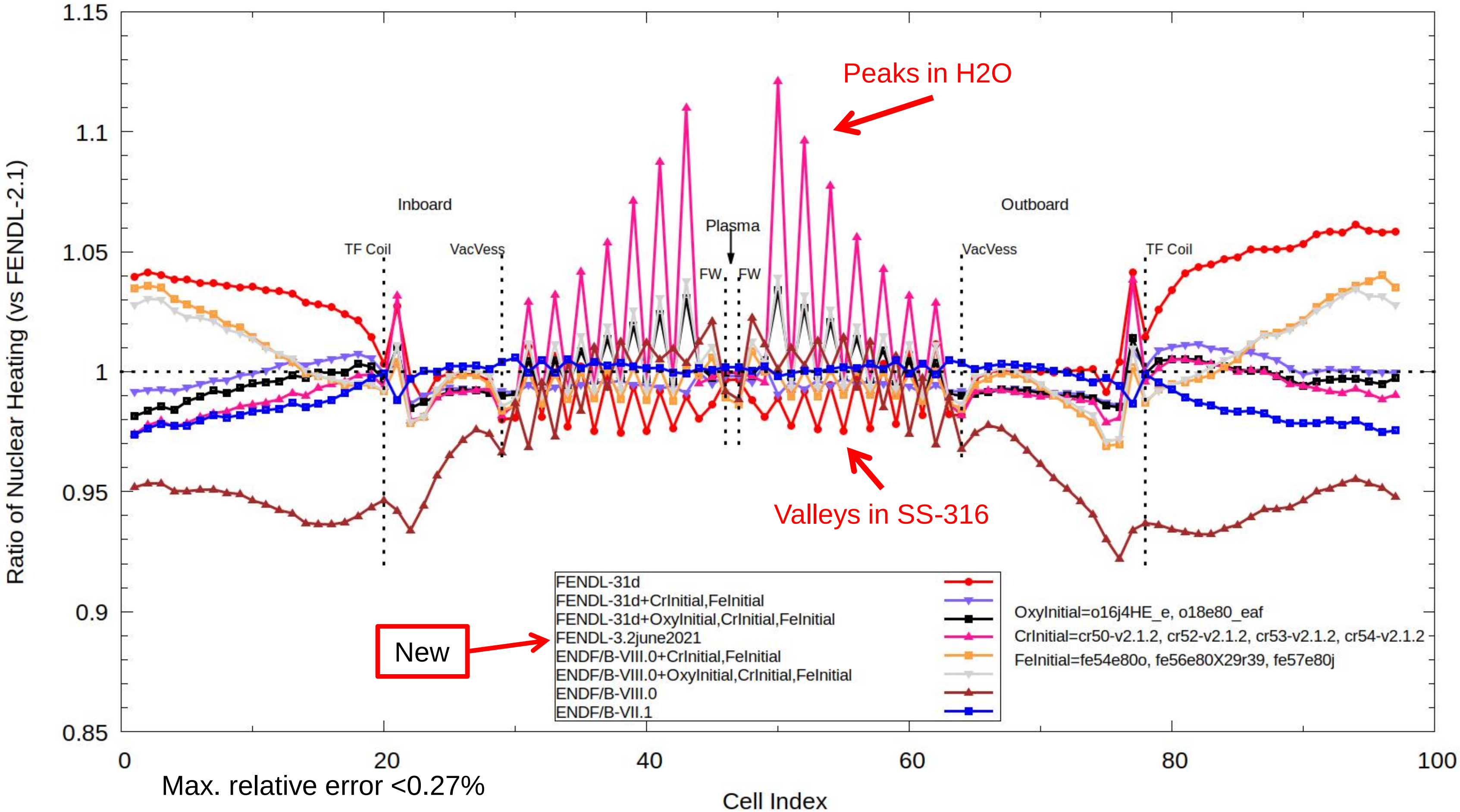
Results: Neutron Flux ITER



- ENDF/B-VIII.0+CrInitial,FeInitial closer to FENDL-2.1 but see structure at VV, TF Coil
  - main difference due to Ni and Cu XS respectively
- FENDL-3.1+CrInitial,FeInitial quite close to FENDL-2.1 but structure at VV (Ni)

➢ FENDL-3.2 even closer to FENDL-2.1

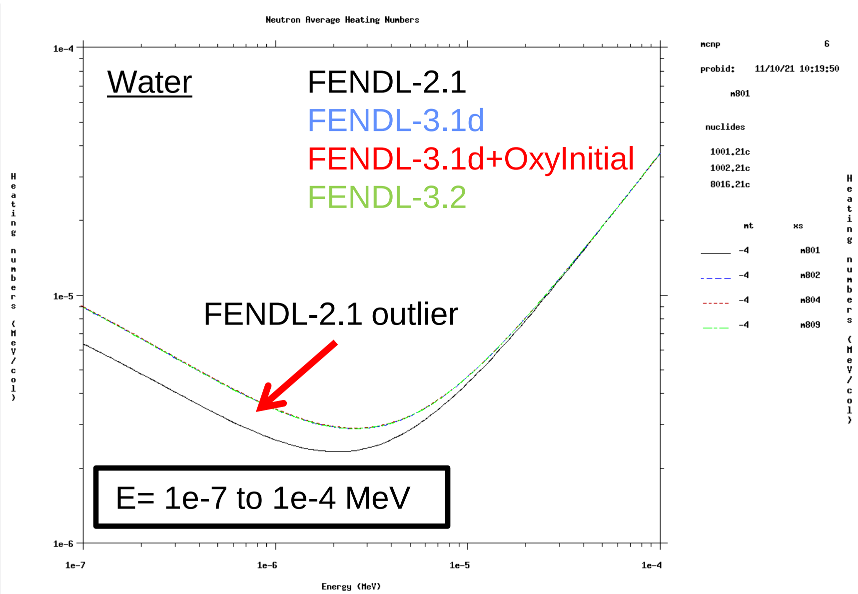
Results: Total Nuclear Heating ITER

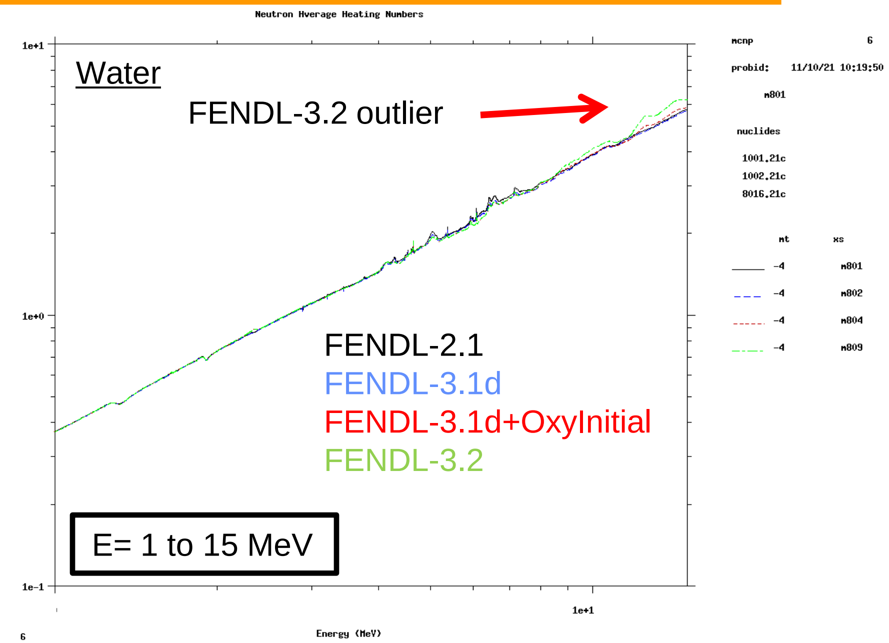


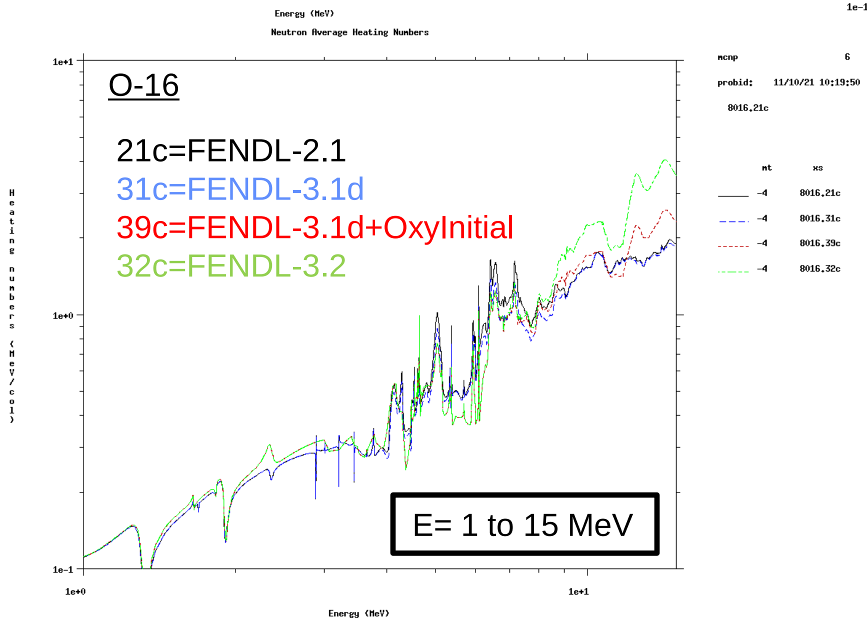
Max. relative error <0.27%

- FENDL-3.2 see peak at H2O regions and TF coil insulator (low Z)
  - neutron heating up to 4X>photon heating in water regions

Neutron Heating Numbers in Water



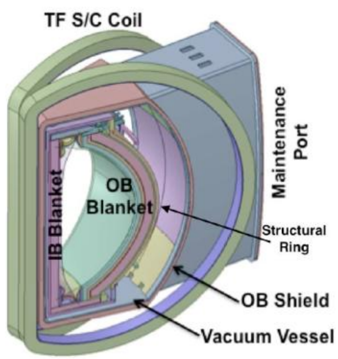


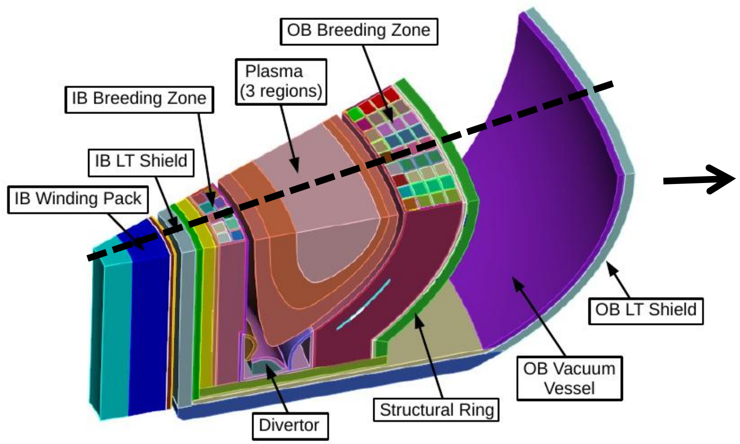


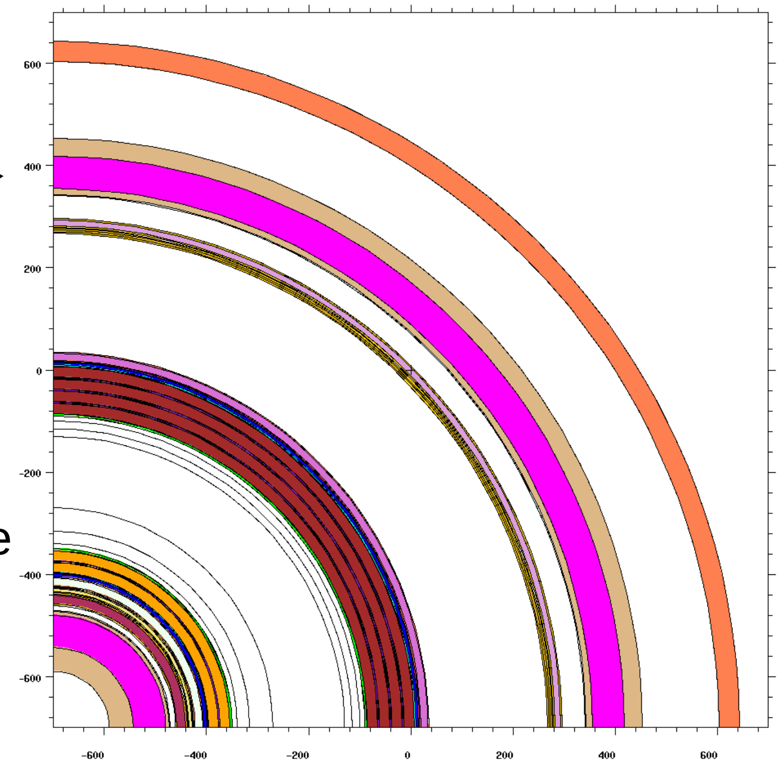
- Neutron fluxes similar in water regions
- Neutron heating numbers in water are similar **except** at very low and very high energies (8-15 MeV)
- Using FENDL-2.1 for transport and heating tallies with variety of XS libs indicates that different heating numbers are the cause for the FENDL-3.2 heating differences in water

1-D FNSF Cylindrical Computational Benchmark

- Need to test XS libraries on fusion designs other than ITER (different structural materials, coolants)
- Created 1-D model of Fusion Energy Systems Studies Fusion Nuclear Science Facility (FESS-FNSF)
- Breeding Zone: He cooled steel structure (90 w/o Fe, 7.5w/o Cr, 2w/o W, 0.2w/o V), PbLi breeder



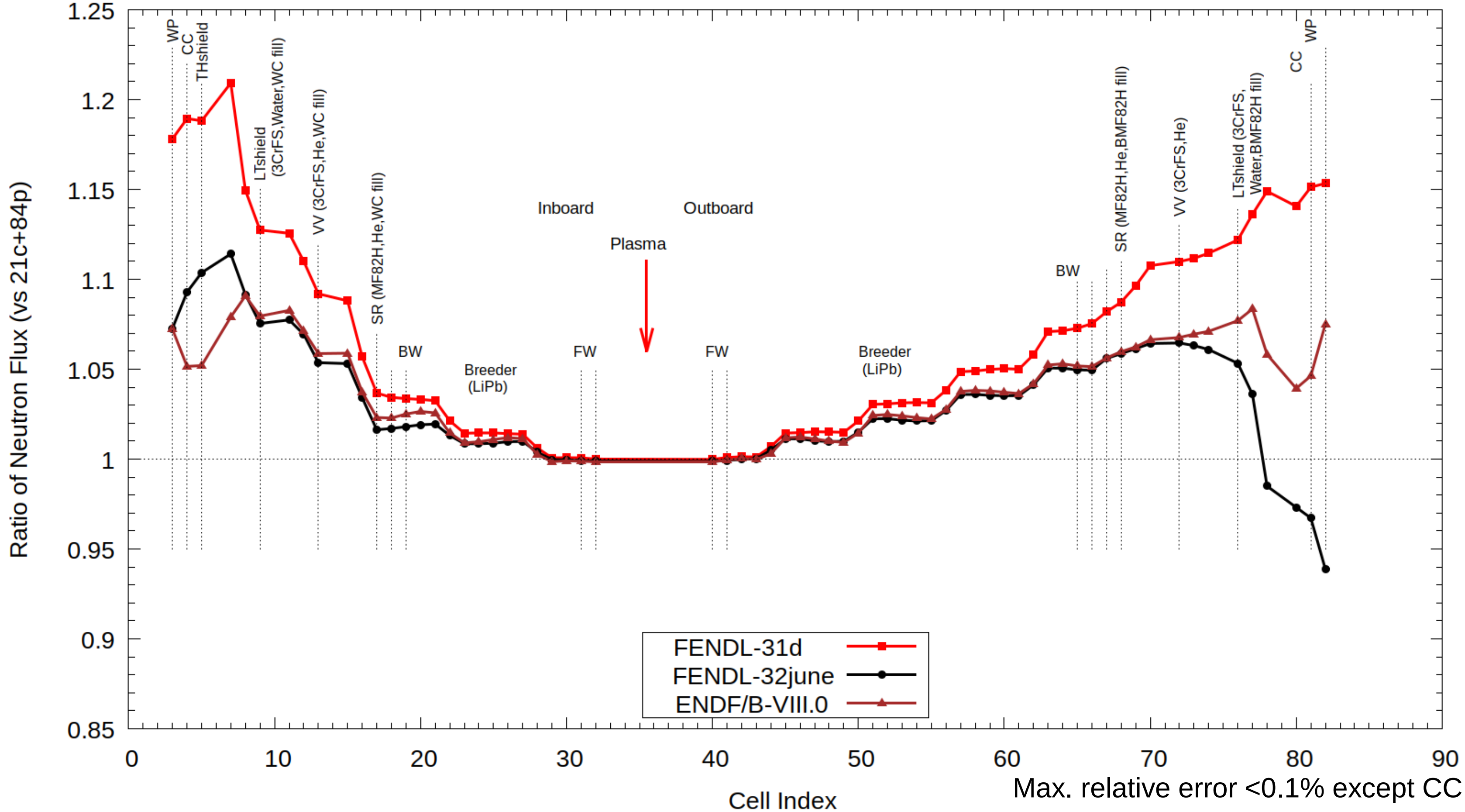




- 85 radial zones
- Includes SiC flow channel inserts in breeding zone
- Includes face plates and filler for SR, VV, Ltshield
- Includes IB, OB magnet and cryostat
- MCNP materials created with PyNE

T. Bohm et al. “Initial Neutronics Investigation of a Liquid Metal Plasma Facing Fusion Nuclear Science Facility, *Fusion Science and Technology*, 2019.

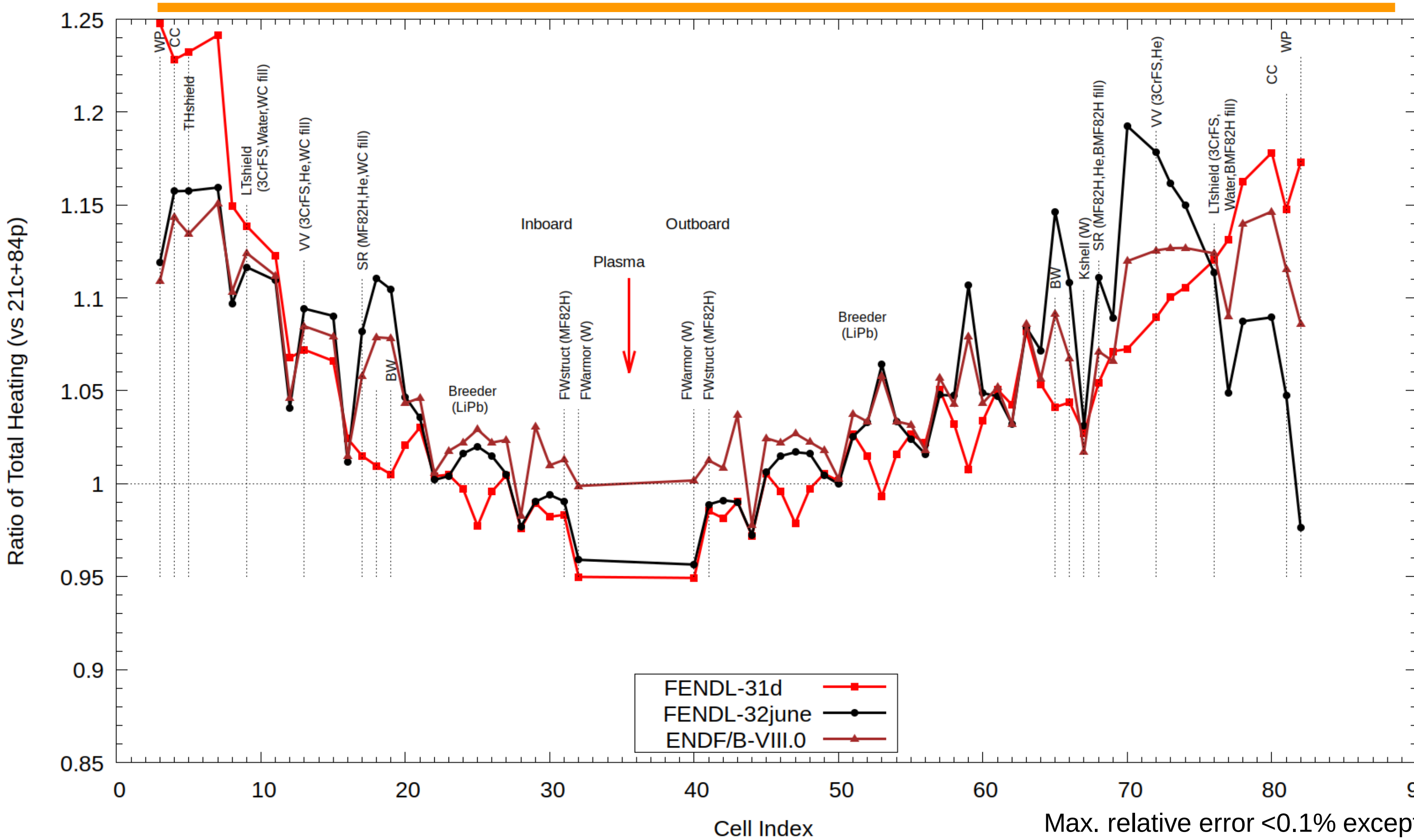
Results: Neutron Flux FNSF



Max. relative error <0.1% except CC, WP 1-2%

- All libs show higher flux than FENDL-2.1 (except FENDL-3.2 at OB CC, WP)
- FENDL-3.1d shows highest flux (also seen in ITER benchmark)
- ENDF/B-VIII.0 & FENDL-3.2 quite close up to depth of IB LTshield and OB VV
- FENDL-3.2 vs FENDL-3.1d flux values 6% lower at IB CC, 15% lower at OB CC

Results: Total Nuclear Heating FNSF



Max. relative error <0.1% except CC, WP 1-2%

- Heating in tungsten at FW is lower for FENDL-3.2 and 3.1d compared to FENDL-2.1
- All libs show higher heating than FENDL-2.1 beyond the Breeder except FENDL-3.2 at OB WP (not seen in the ITER benchmark)
- All newer libs show some significant differences esp. at deep locations (LT, CC,WP)
- FENDL-3.2 peaks are in BZ channel walls, BW, OB SR back plate (MF82H)

Results-Tritium Breeding Ratio FNSF

- FNSF uses PbLi for breeding:
  - 84.3 atomic% Pb
  - 15.7 atomic% Li (enriched to 90% Li-6)
- Recall 1-D model includes He cooled flow channels for the PbLi with thin SiC inserts

Library	IB TBR	Ratio	OB TBR	Ratio
FENDL-2.1	0.4016	1	0.9992	1
ENDF/B-VIII.0	0.4076	1.015	1.0168	1.017
FENDL-3.1d	0.4070	1.013	1.0173	1.018
FENDL-3.2	0.4065	1.012	1.0154	1.016

Max. relative error <0.01%

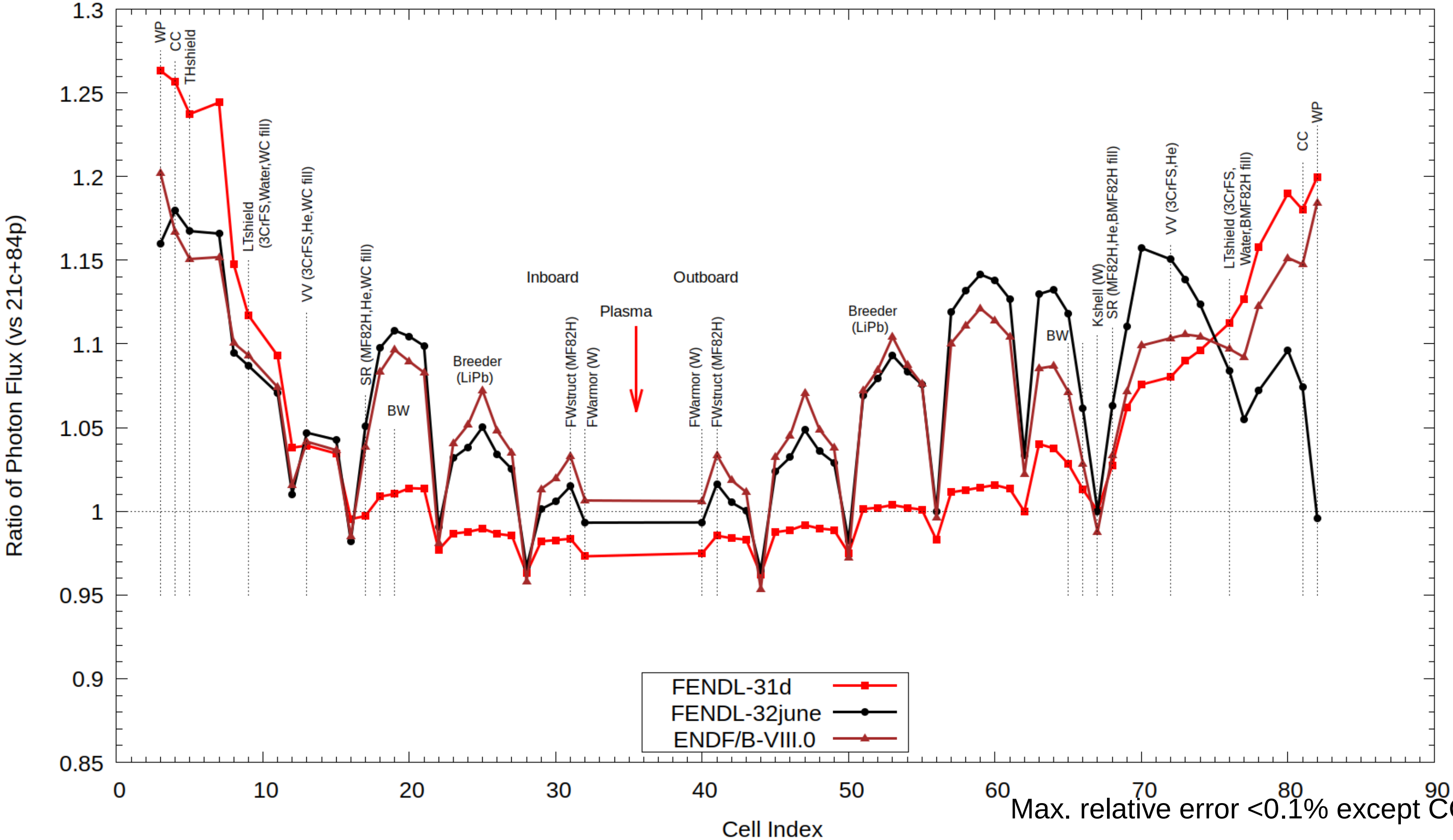
- TBR ~1.2-1.8% higher than that calculated with FENDL-2.1
- Newer libraries are quite close to each other

Future Work

- ➢ Plot dpa, He production, T production results (for both benchmark models)
    - already calculated but not plotted and studied in detail
- ➢ Dig into differences of heating in FNSF model
- ➢ Add more resolution for heating tallies

Backup slides

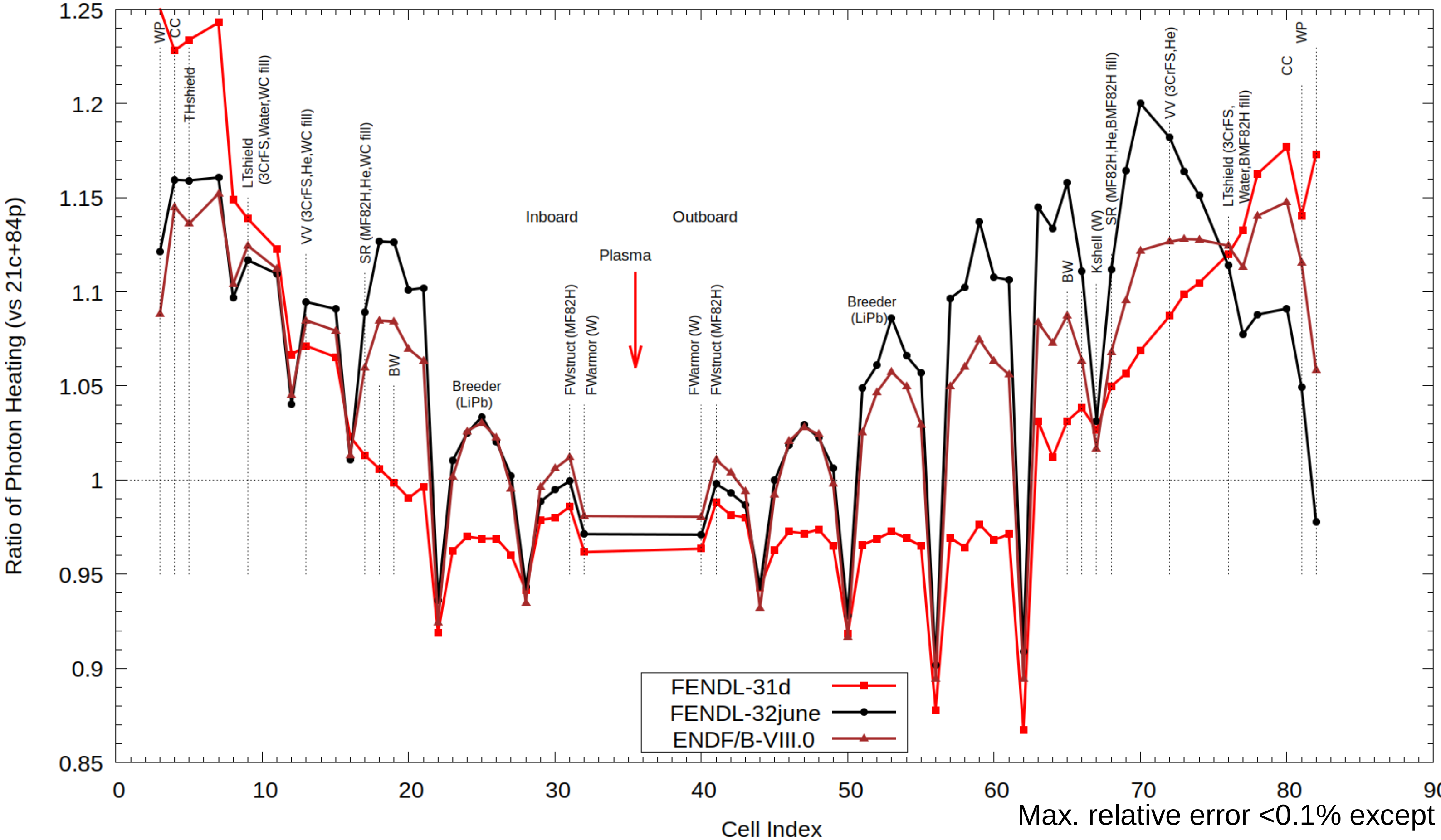
Results: Photon Flux FNSF



Max. relative error <0.1% except CC, WP 1-2%

- Valleys are PbLi
- Peaks are BZ channel walls, BZ SiC channel liners

Results: Photon Heating FNSF

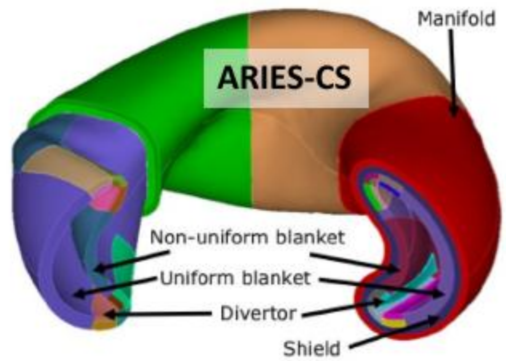


Max. relative error <0.1% except CC, WP 1-2%

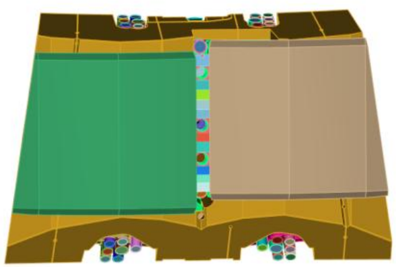
- Valleys are in PbLi
- FENDL-3.2 peaks are in BZ channel walls, BW, OB SR back plate (MF82H)

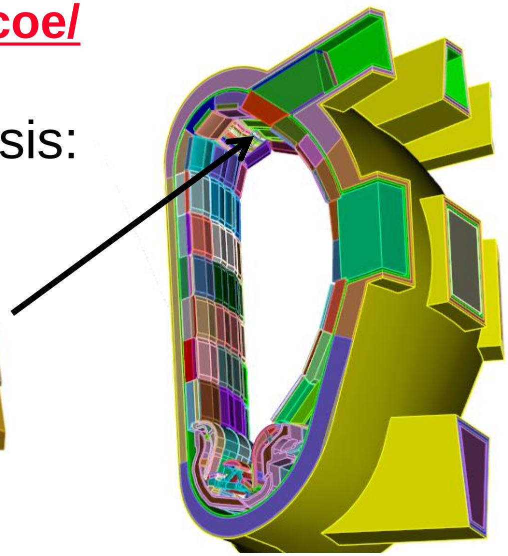
UW Neutronics Capabilities (3-D)

- DAGMC (detailed 3-D CAD based Monte Carlo transport)
  - Transports directly in the CAD model (not a translator)
  - Handles complex surfaces without simplification
  - Couples to MCNP, Geant4, FLUKA, SHIFT, OpenMC
  - Provides a common domain for coupling to other analysis
  - **http://fti.neep.wisc.edu/ncoe/**
  - **http://github.com/svalinn**
- 3-D CAD model based analysis:



ITER BM08





Nuclear heating mapped to ANSYS mesh for thermal analysis