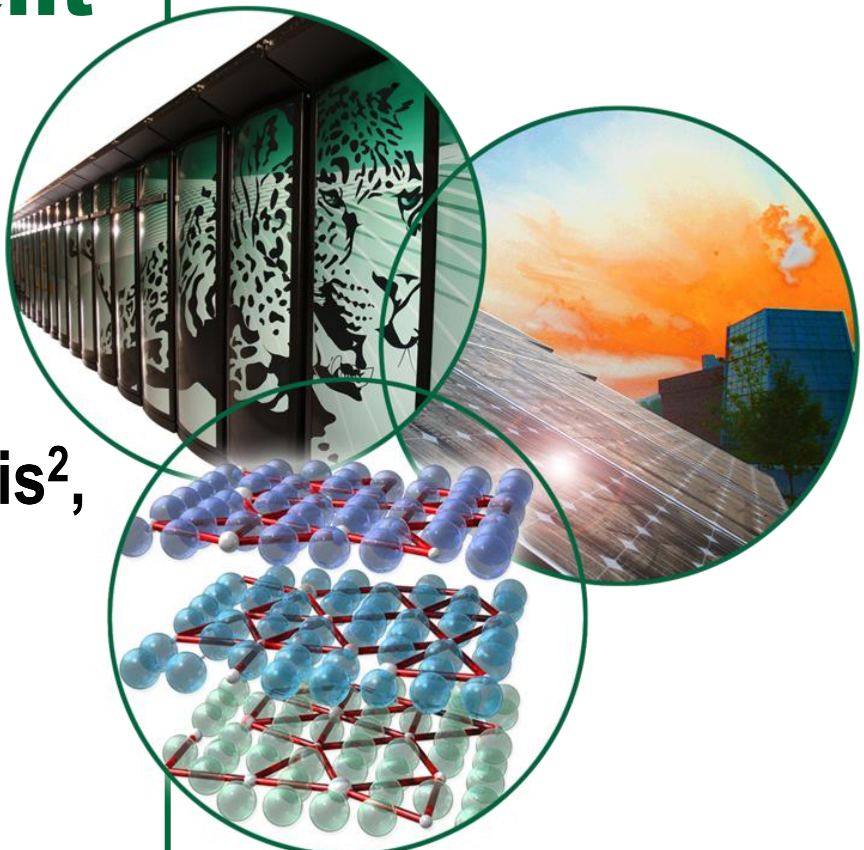
Physics design calculations for the W7-X divertor scraper element



J.D. Lore[1,2], J.M. Canik[2], J.H. Harris[2], J. Tipton[3], A. Lumsdaine[2]

[1] *Oak Ridge Associated Universities*

[2] *Oak Ridge National Laboratory*

[3] *University of Evansville*

U.S. DEPARTMENT OF ENERGY

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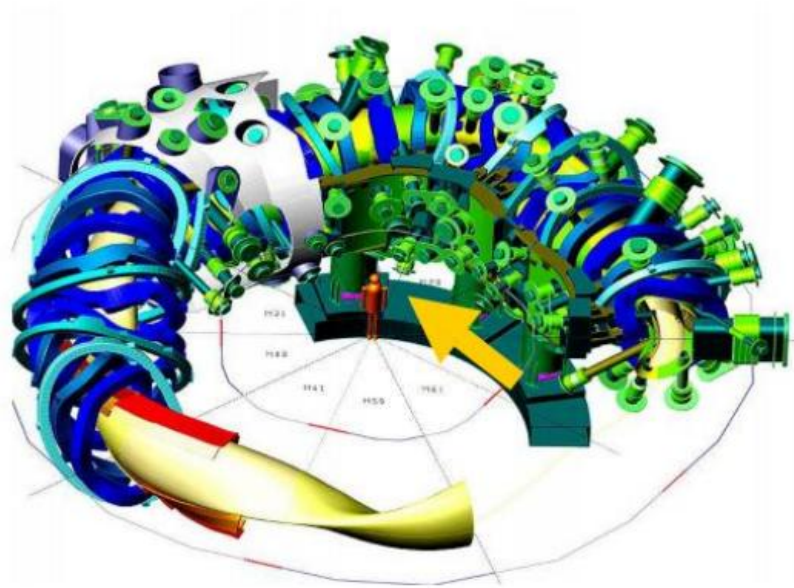
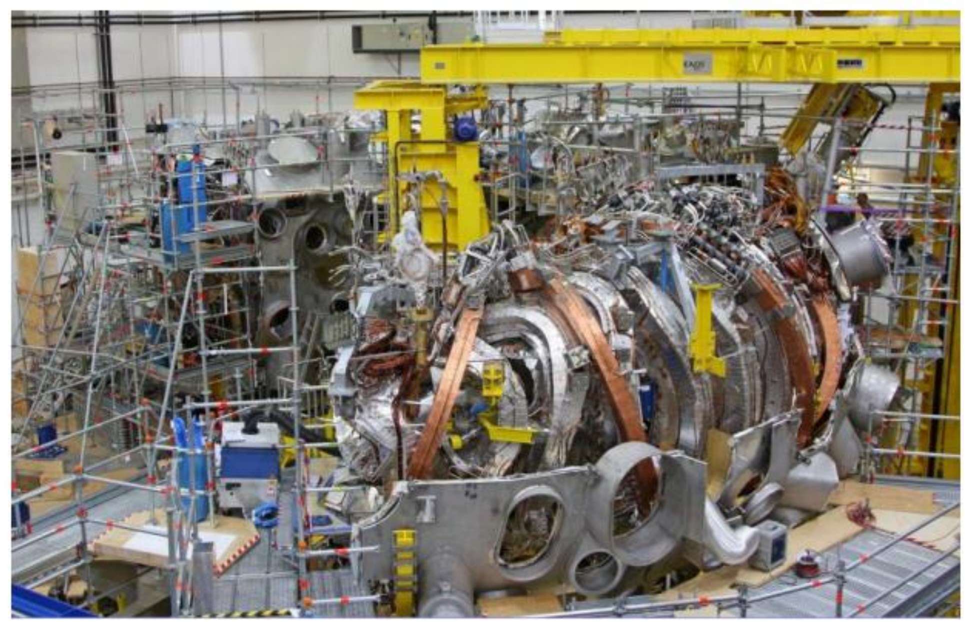
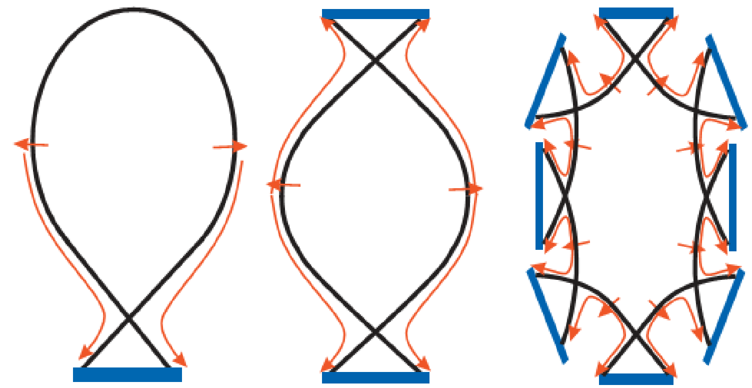
W7-X: a high-performance, long pulse stellarator



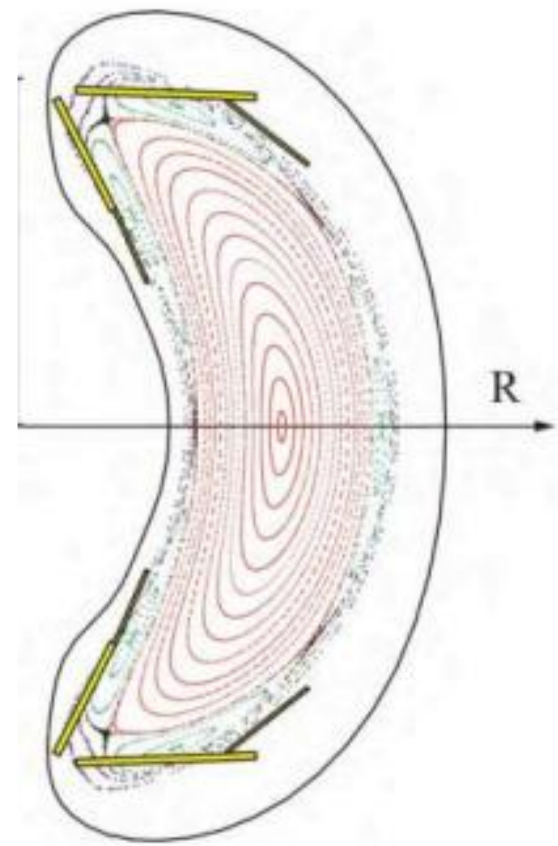
- Optimized for low neoclassical transport, small bootstrap current
- R= 5.5 m
- a= 0.53 m
- B= 3.0 T
- ECRH = 10MW (CW)
- ICRH = 2MW
- NBI = 4-8MW
- Superconducting coils
- Pulse length= 30 min
- Operations begin in 2015

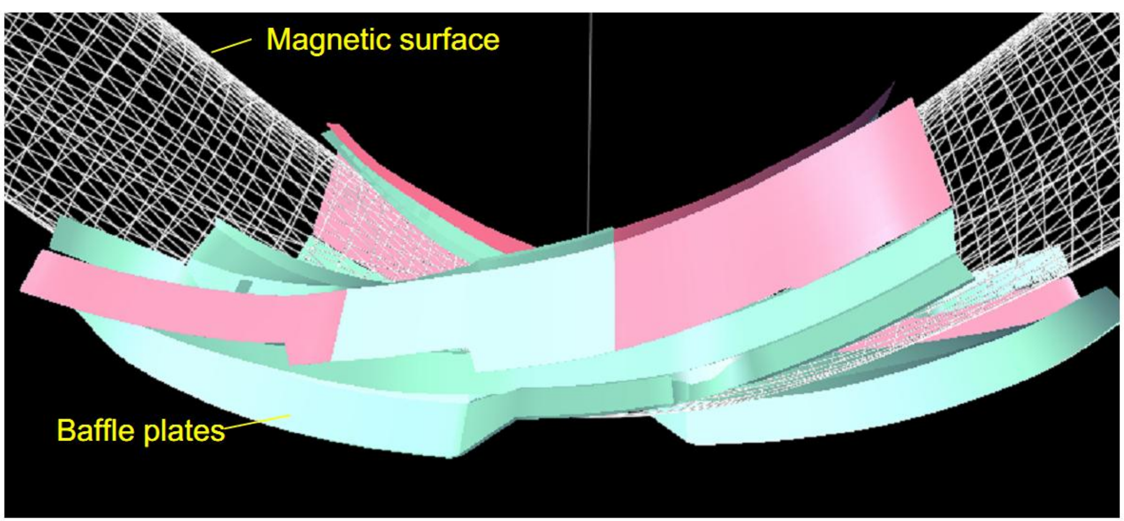


W7-X will use an island divertor for power exhaust



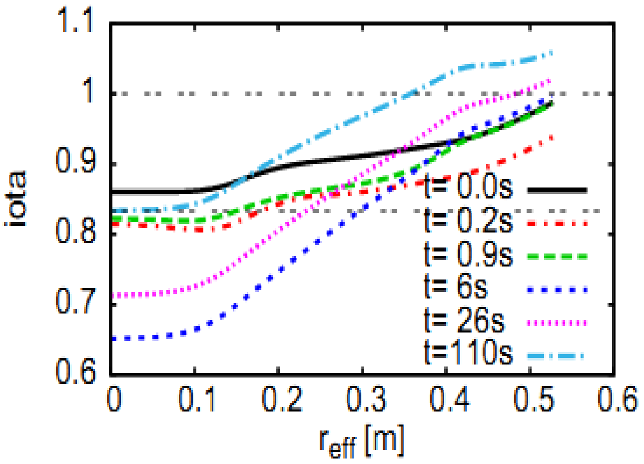
- Island chain at edge defines last closed flux surface
- Helical X-point, qualitatively similar to poloidal divertor in tokamak
- Concept validated in W7-AS
- Restricts edge transform value allowable
  - $\iota_b \sim 1$ in W7-X (5/5 islands)

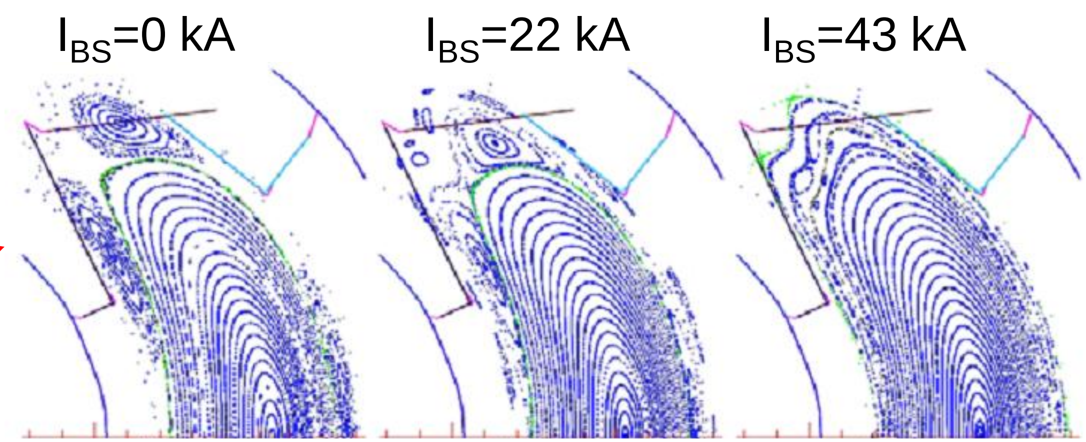




Edge transform changes as bootstrap current evolves

- Some configurations have finite bootstrap current
- Evolves on L/R time ~ 30s
- Changes boundary transform by ~5%
  - Alters island topology
  - With ι_b^{vac} ~ 1, full bootstrap current results in limiter configuration





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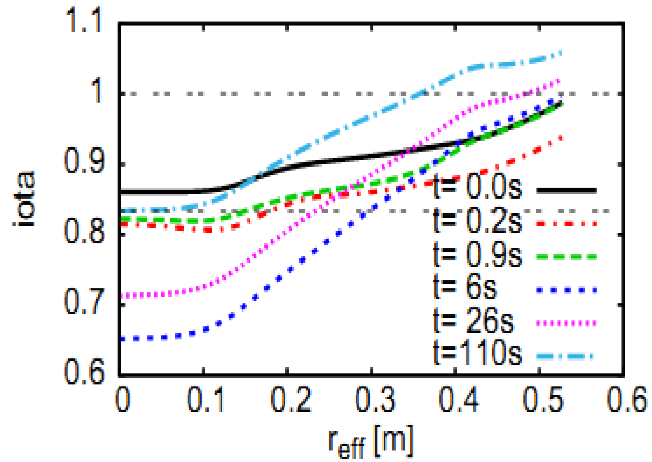

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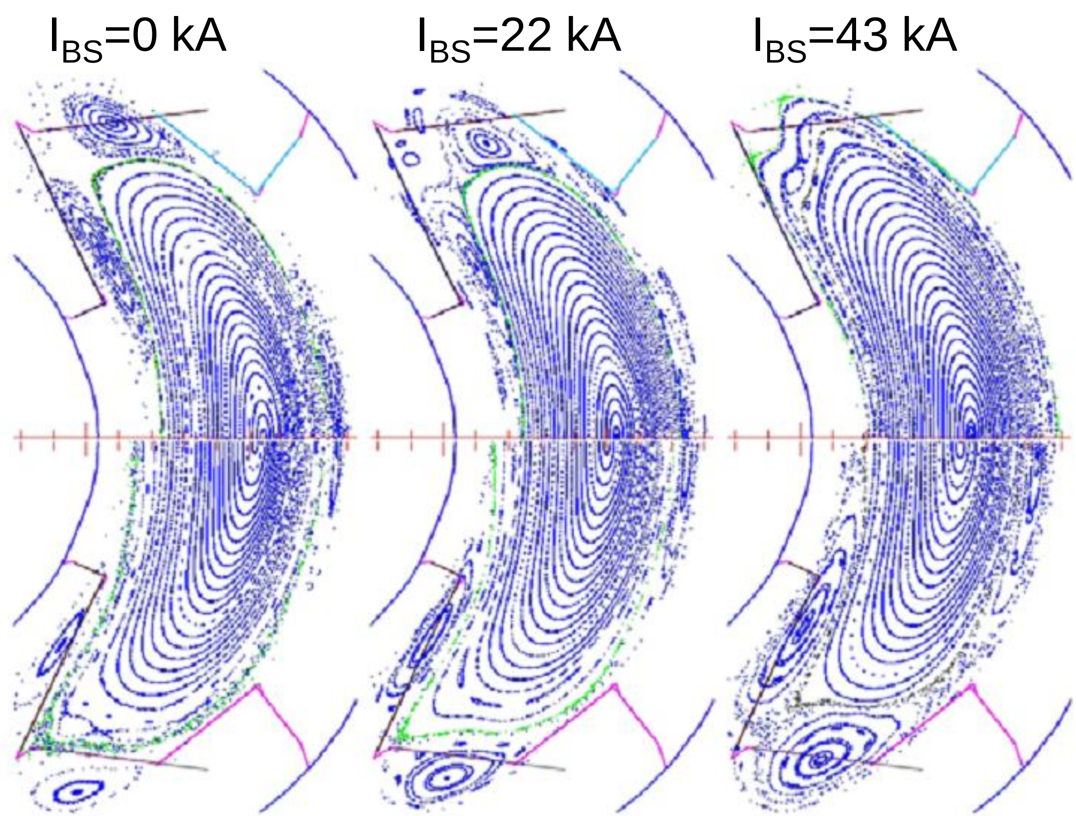
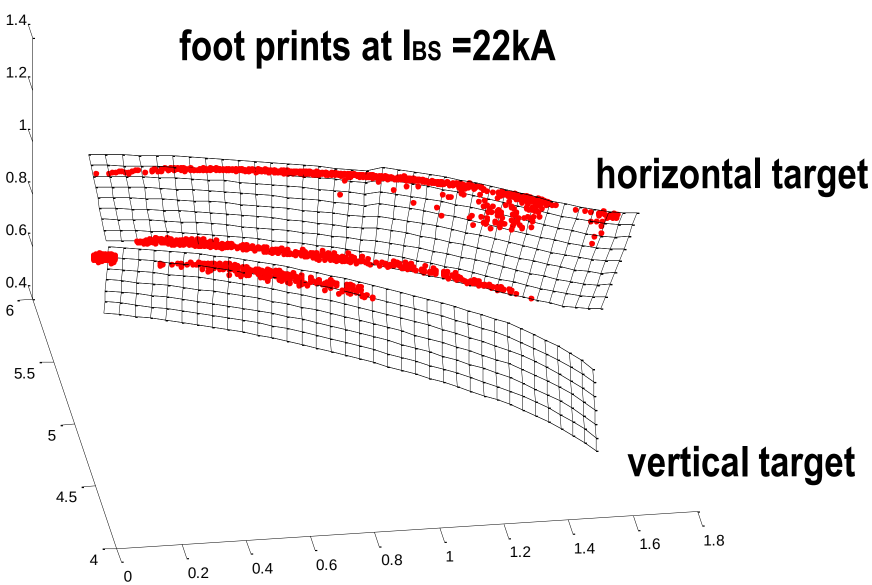
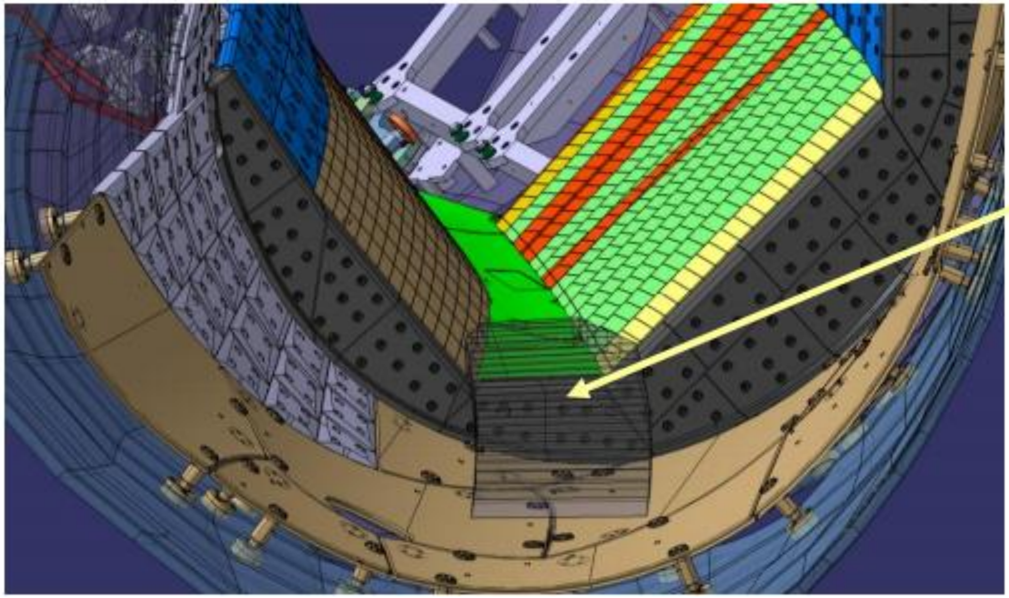
- Evolves on L/R time ~ 30s
- Changes boundary transform by ~5%
  - Alters island topology
  - With ι_b^{vac} ~ 1, full bootstrap current results in limiter configuration
  - Present plan: start with vacuum transform reduced so that island divertor is formed with full I_{BS}



Scraper element added to protect tile edges during intermediate I_{BS} phase

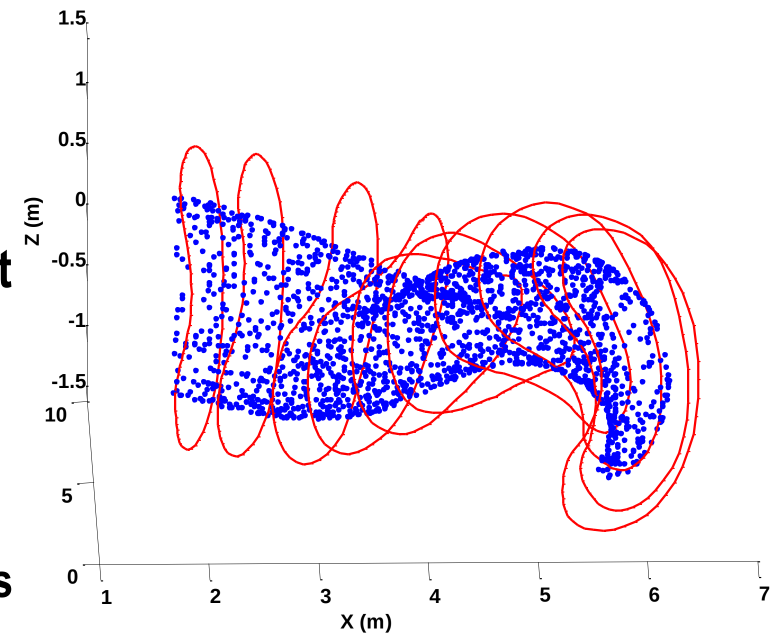
- During bootstrap current build-up, field line footprints focus excessive heat flux on divertor tile edges
- New 'scraper element' is being designed to block field lines from reaching divertor edges in intermediate I_{BS} configurations





Field line tracing is used to estimate heat flux

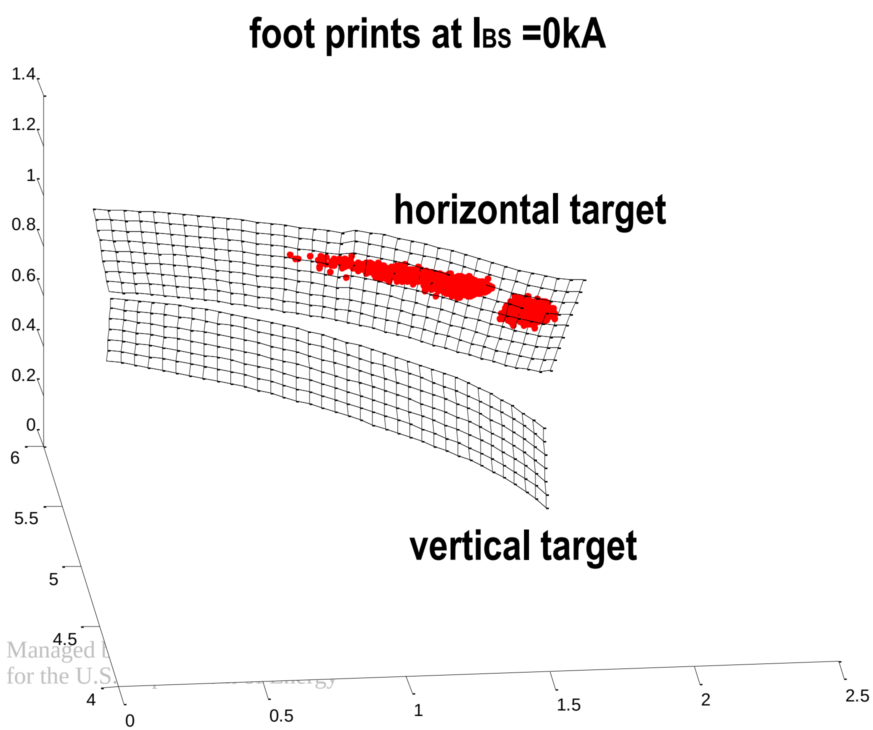
- Field lines are followed in 3D including plasma contribution
  - VMEC[1] for 3D equilibrium (only gives field inside LCFS)
  - Extender[2] for plasma+coil fields outside LCFS
- Lines are initialized randomly along a field line that traces out a closed surface
  - Lines are then diffused with a given D_m
  - Example: 2000 lines, 10000 transits, D_m=1e-6 m^2/m
  - For 50eV electrons this corresponds to χ_e = 4.2 m^2/s
  - Sensitivity studies to be performed with respect to these parameters
- Intersections of field lines with targets used to estimate plasma fluxes

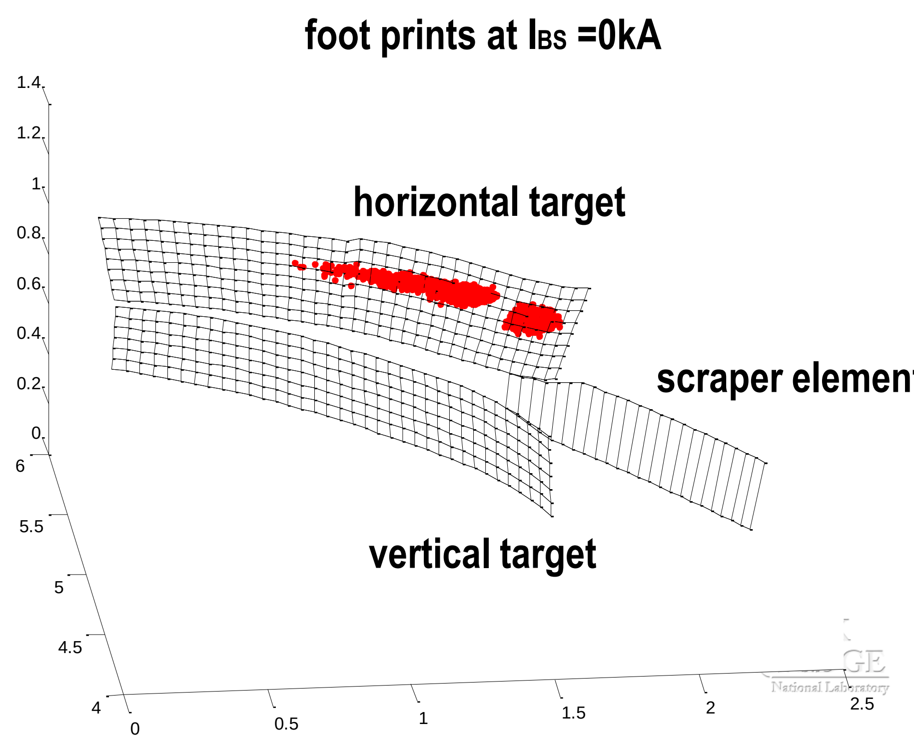


[1] S.P. Hirshman, et al, Comp. Phys. Commun. 43, 143 (1986).
[2] M. Drevlak, et al, Nucl. Fusion, 45, 731 (2005).

Field line tracing shows function of divertor scraper element

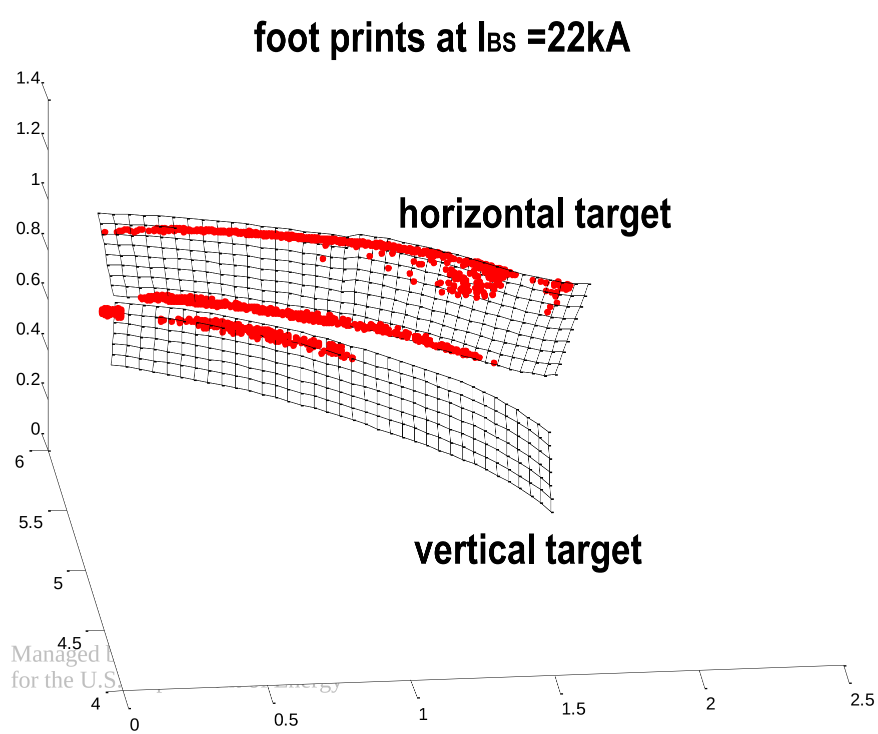
- Intersections are found both with and without the scraper element
- 0kA: Load is near middle of horizontal target, no load on scraper

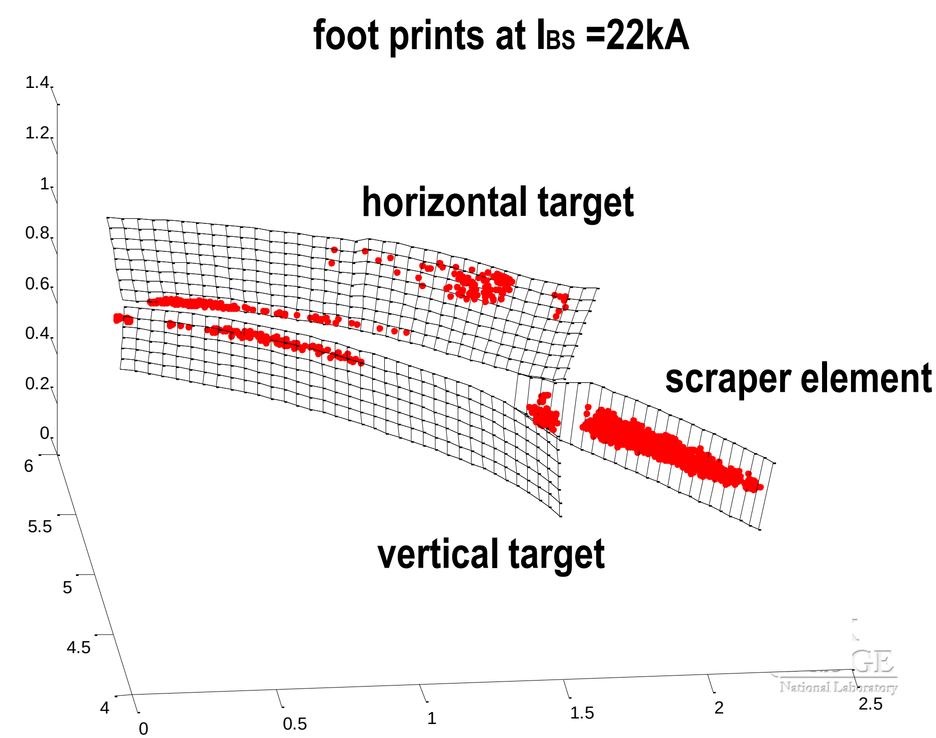




Field line tracing shows function of divertor scraper element

- Intersections are found both with and without the scraper element
- 0kA: Load is near middle of horizontal target, no load on scraper
- 22kA: Without scraper edges of target are loaded; scraper catches most of this flux

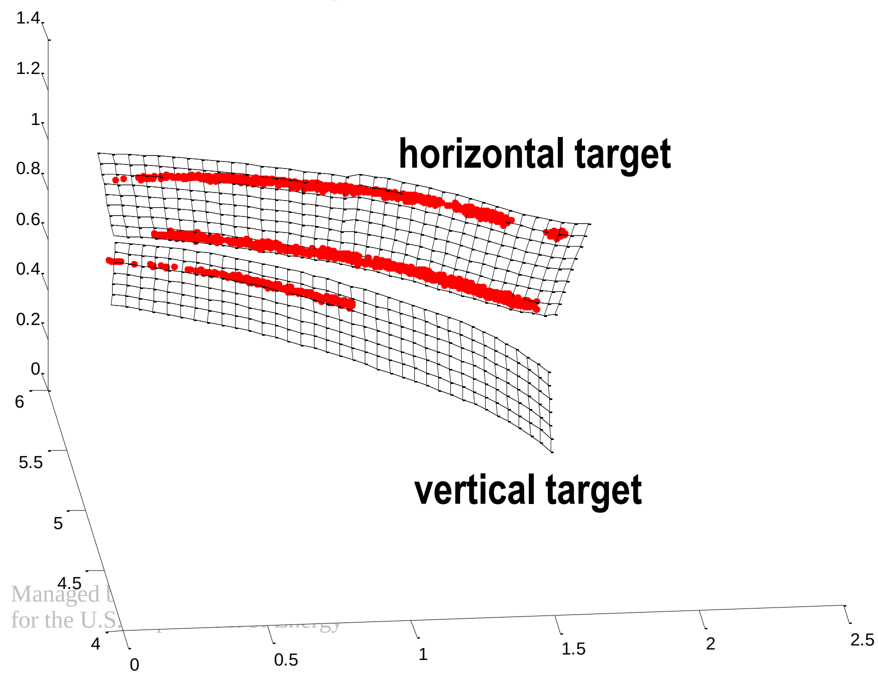




Field line tracing shows function of divertor scraper element

- Intersections are found both with and without the scraper element
- 0kA: Load is near middle of horizontal target, no load on scraper
- 22kA: Without scraper edges of target are loaded; scraper catches most of this flux
- 43kA: Footprint has moved away slightly from the target edge, scraper load reduced

foot prints at I_{BS} =43kA



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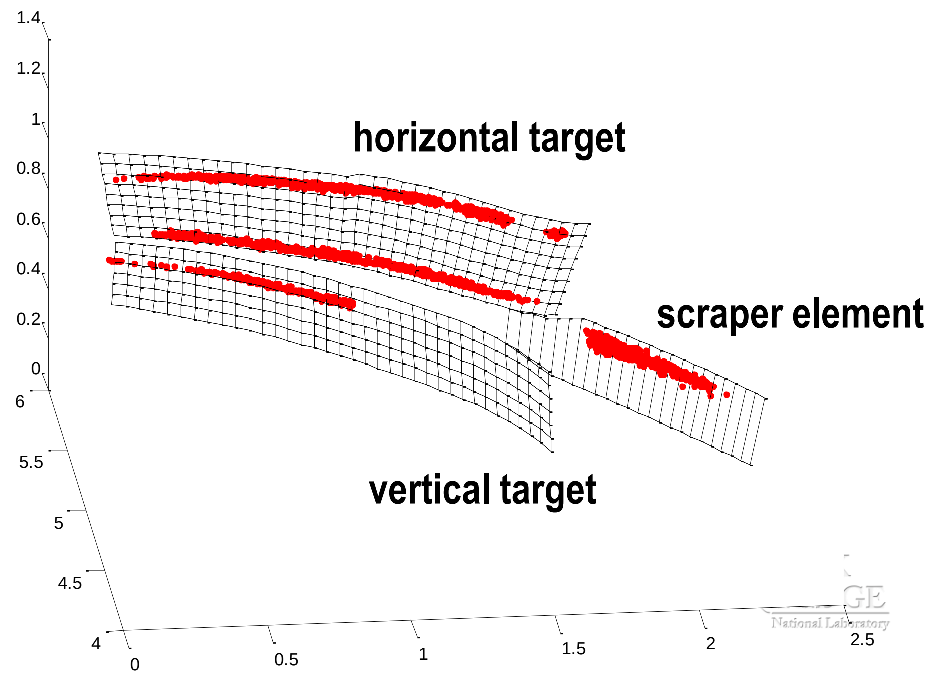
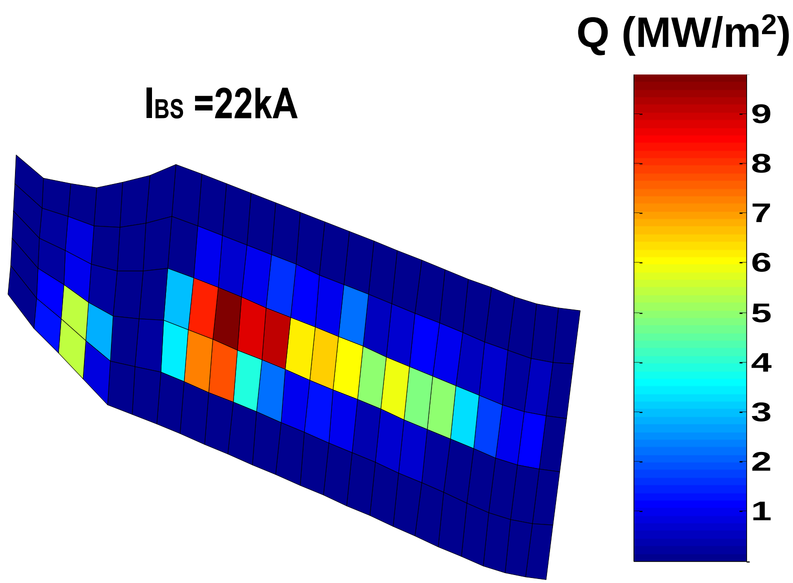


Field line density used to estimate heat flux

- Heat flux is calculated by assuming each field line carries a fraction of the power through the LCFS
  - $P_{line} = P_{LCFS}/N_{line}$
- Surface is then split into area 'bins', with $Q = (\# \text{ strikes})\cdot P_{line}/A_{bin}$
- Highest scraper heat flux in current scan occurs for 22kA of bootstrap current
- Heat flux calculations act as input to engineering design



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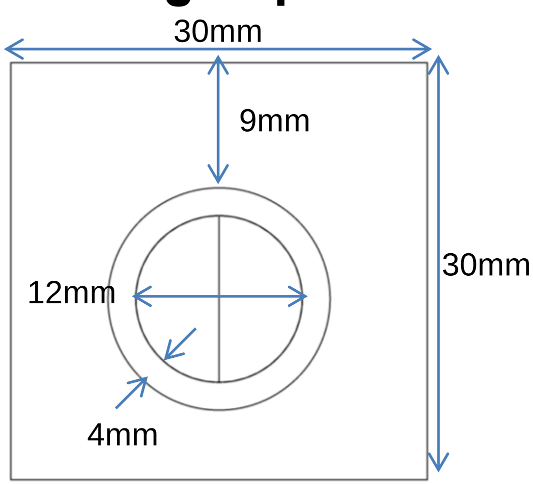
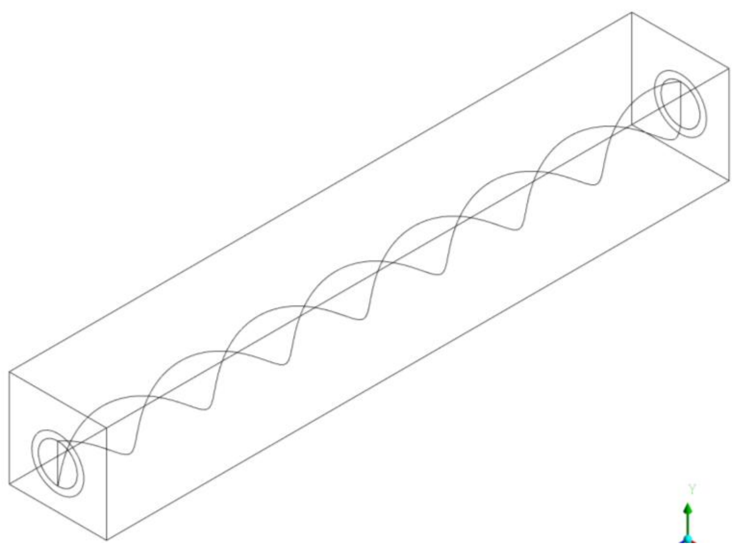
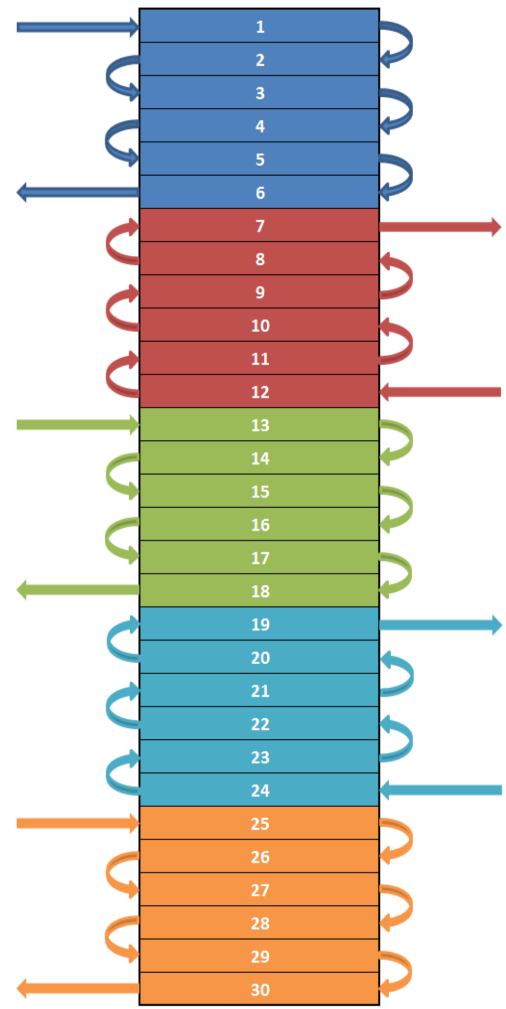
Heat flux feeds into heat transfer calculations*

- Scraper elements will be constructed from CFC monoblocks (qualified for ITER)
  - Rated for $20 MW/m^2$ steady state, design goal for SE is $12 MW/m^2$
- Water cooled with twisted tape piping
- Monoblocks can be arranged toroidally or poloidally (shown), with number of circuits as a design option



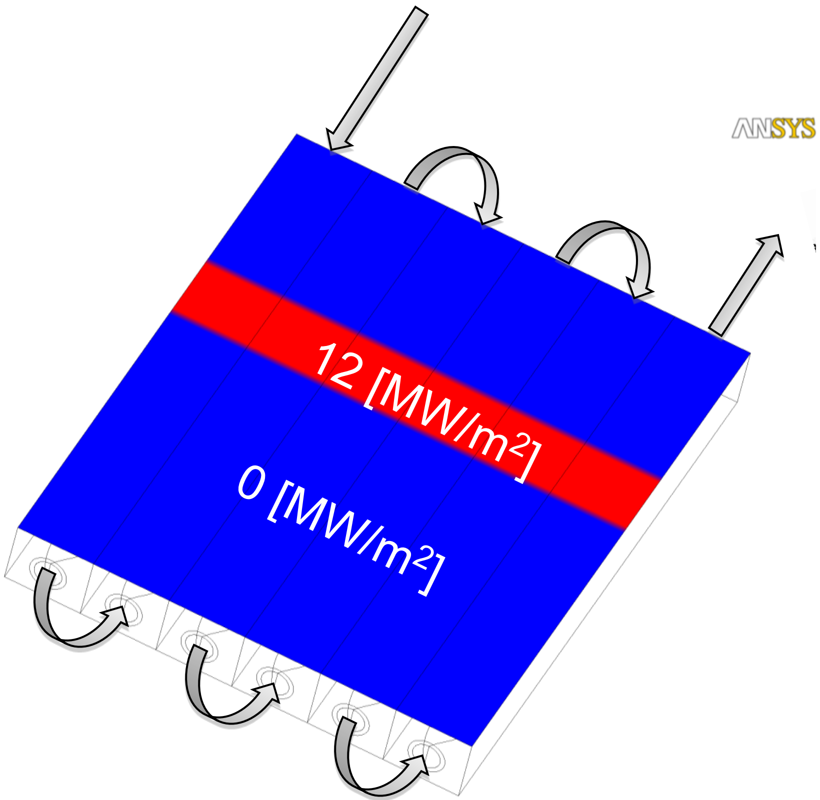


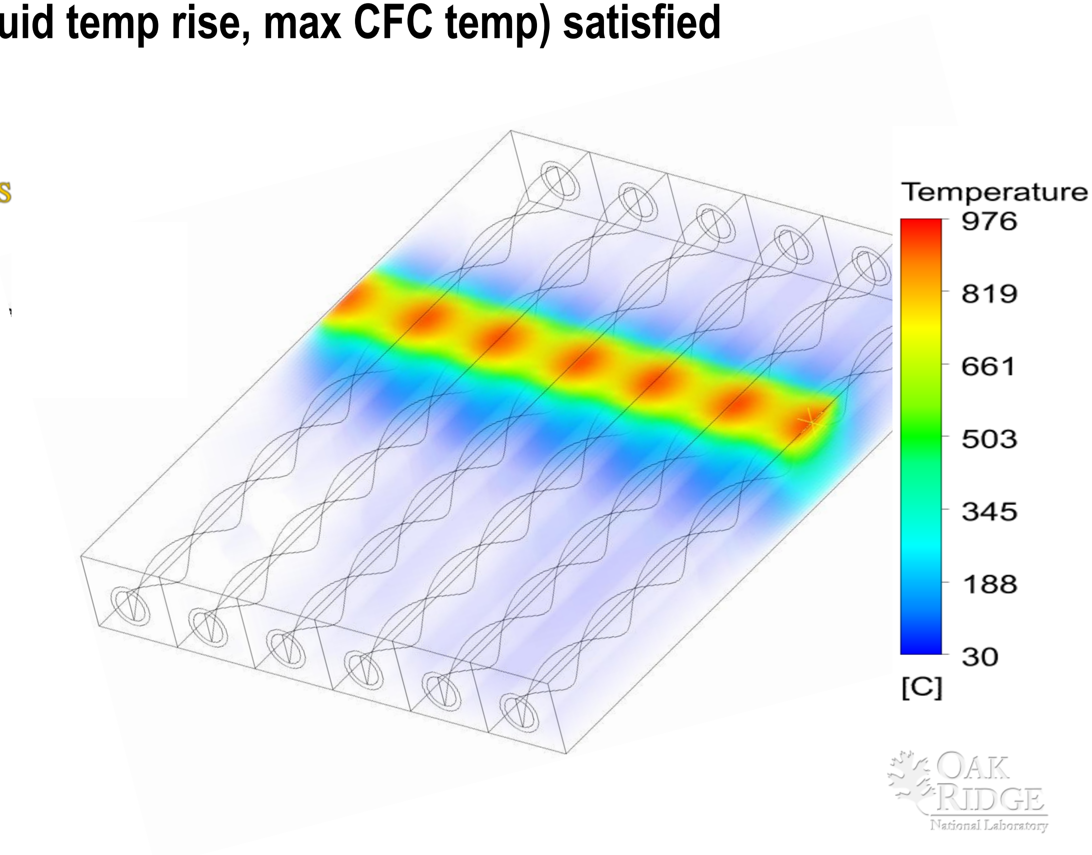


***Modeling performed by J. Tipton**

Initial calculations indicate peak temperature of 976° C

- Calculations are for a conservative model of the highest heat flux in steady state
  - The peak heat flux was applied over a single band with the wetted area chosen to match the total power to the scraper (400kW)
  - Fluid and thermal modeling performed using ANSYS CFX
  - All design criteria (pressure drop, fluid temp rise, max CFC temp) satisfied





Future work

- Heat flux calculations
  - Sensitivity studies must be performed, e.g., number of field lines, magnetic diffusivity, number of transits
  - Scan magnetic configuration space to determine if other high flux scenarios exist
  - Geometric studies to determine effects of misalignments of elements, gaps between tiles
- Thermal and structural modeling and design
  - Modeling/design of 180° connections between monoblock channels
  - Structural modeling of elements
  - Changes to scraper geometry to meet constraints
- Iteration between flux calculations and engineering design
- Longer term: 3D modeling using the EMC3-Eirene [1] to investigate the effect of the scraper element on neutrals and recycling

[1] Y. Feng, et al, Plasma Phys. Controlled Fusion **44, 611** (2002)

Extra slides

All design criteria satisfied even for conservative model of 'worst case'

Variable	Limit	Type	Result	Source
Pressure Drop	14 [bar]	Constraint	8.5 [bar] $\pm$ 10%	Semi-Empirical
Mean Fluid Temp Rise	50 [C]	Constraint	34 [C]	Energy Balance
Local Fluid Temp	224 [C]	Constraint	N/A	Assumed Non-active
Max CFC Temp	$\approx$1200 [C]	Objective	976 [C] $\pm$ 10%	CFD (Grid Convergence)