3D Plasma Edge Modeling for NSTX and W7X

J.D. Lore

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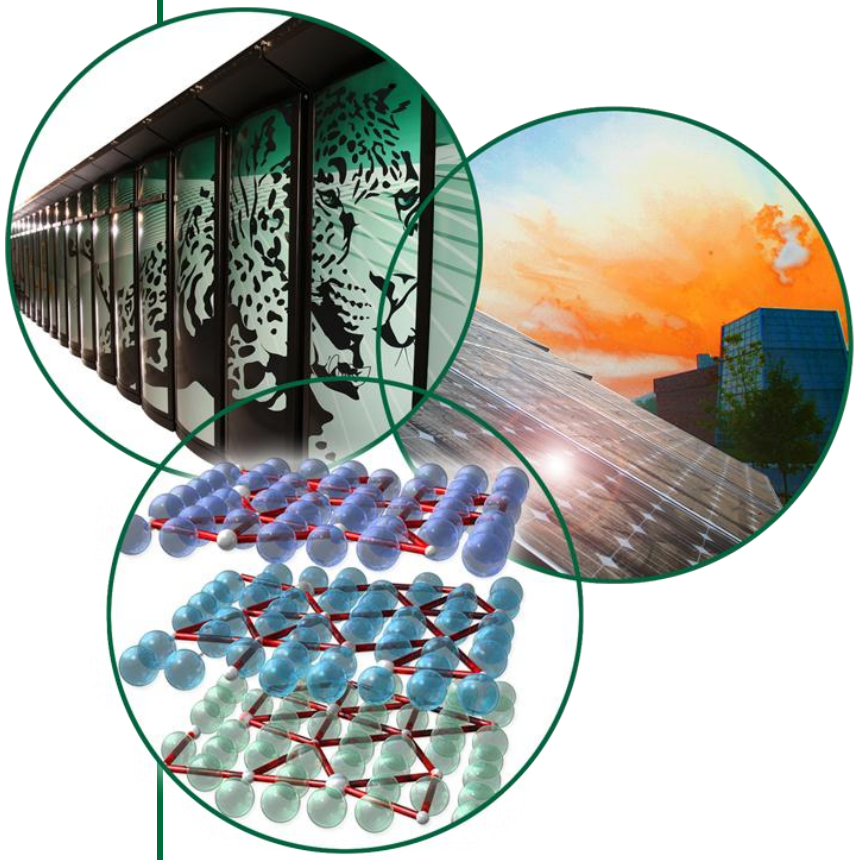

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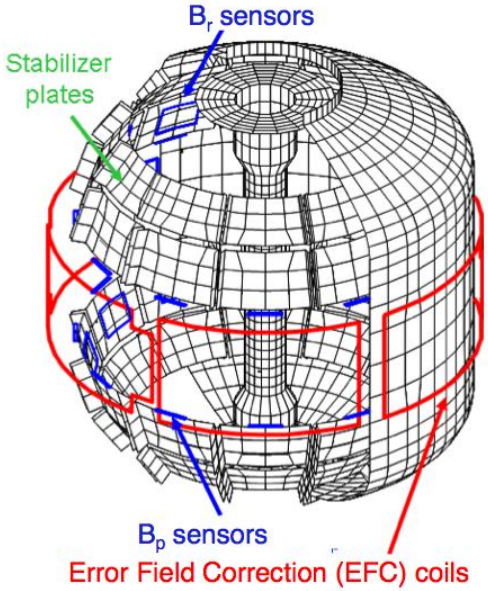
Motivation: 3D edge effects will be critical in future devices

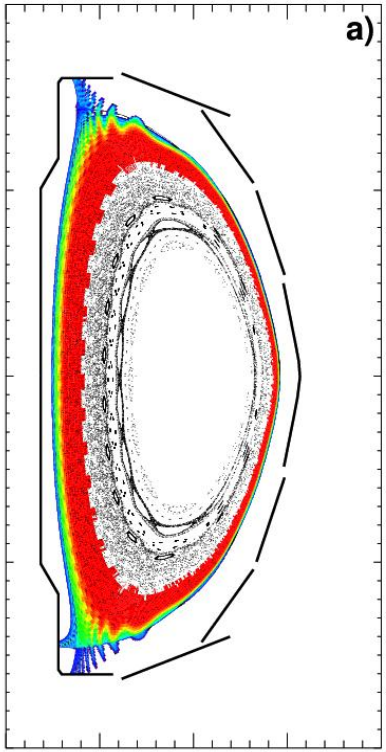
- The edge plasma must meet requirements of both the core and the divertor
  - H-mode pedestal – Requirements on pedestal height due to core parameters, stiff transport. Strong gradients lead to ELMs.
  - Divertor plasma – Maximum fluxes, temperatures limited by PFC cooling limits, sputtering.
  - SOL plasma – Couples pedestal and divertor, large flows, significant neutral particle effects.
- 3D effects are important in the edge plasma
  - Stellarators - 3D plasma, strong shaping, island divertors
  - Tokamaks - 3D fields used for control/optimization (RMPs)
  - 3D PFC geometry (ports, tiles, TBMs,…)
  - Error fields
- **3D edge modeling is critical for understanding current experiments and planning new devices**

Stellarator Tools Are Used To Model W7X and NSTX

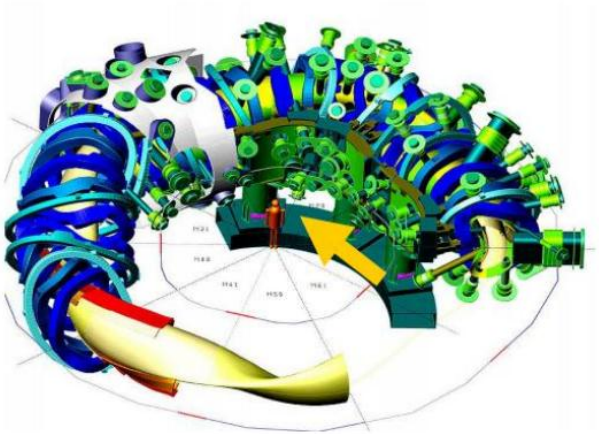
- **NSTX**
  - Effect of applied and intrinsic 3D fields on divertor heat flux and detachment
- **W7X**
  - Dependence of divertor fluxes on magnetic configuration and J_{BS} evolution, divertor optimization and design
- **Fieldline following (with or without plasma effects)**
  - Strike point locations, footprints
  - Heat flux estimates
- **EMC3-Eirene[1] (3D fluid plasma + kinetic neutrals and PSI)**
  - Power and particle exhaust
  - Transport in stochastic fields

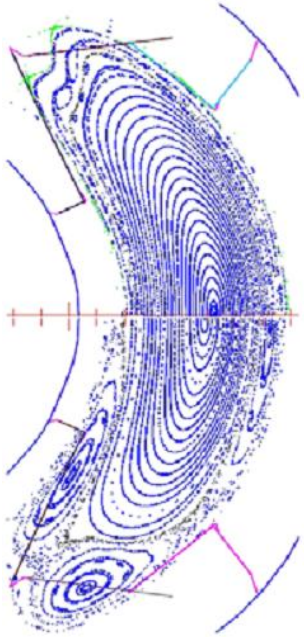
NSTX





W7X





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

Outline

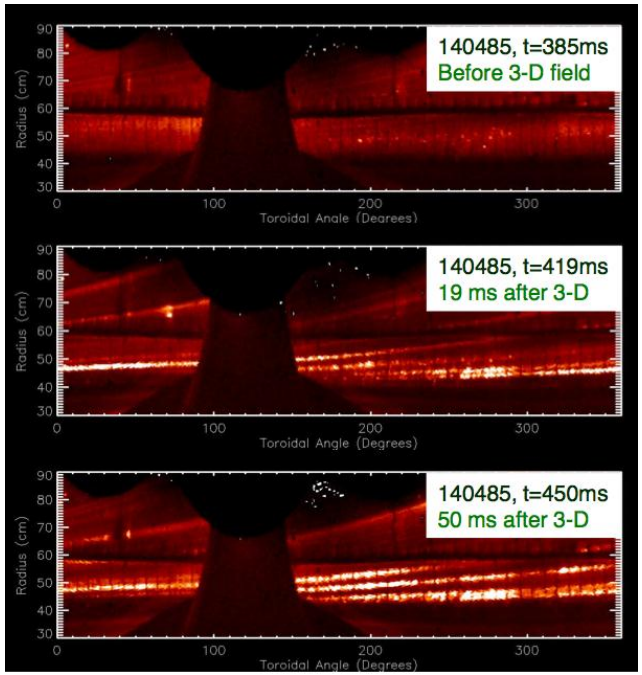
- 3D modeling of NSTX plasmas using EMC3-Eirene
  - Intrinsic and applied 3D fields result in modified transport and stability properties in NSTX
  - Axisymmetric and perturbed NSTX plasmas have been modeled using EMC3-Eirene
  - Measured strike point splitting positions are qualitatively reproduced
- Divertor ‘scraper element’ modeling and design for W7X
  - A new divertor element is proposed to protect the primary targets during the transient bootstrap current (I_{BS}) evolution phase of certain configurations
  - Vacuum and Vacuum+Plasma fields are used to calculate flux patterns and magnitudes
  - Surface heat fluxes are input to a heat transfer and structural analysis

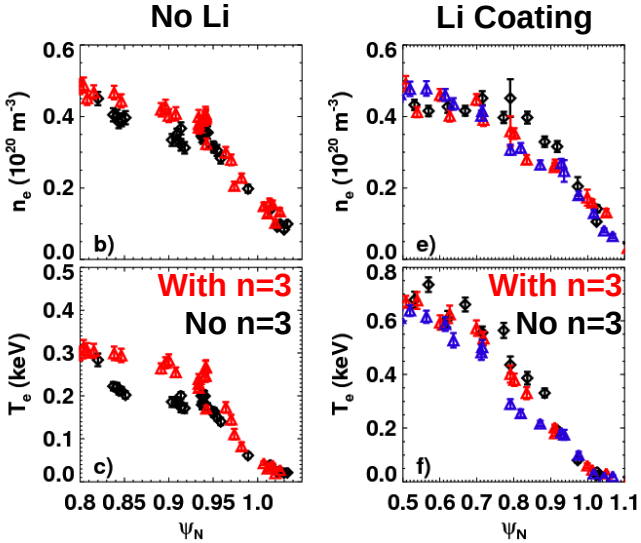
3D field application results in strong modifications to edge transport in NSTX

- Strike point splitting
- Reattachment of divertor plasma with low gas puffing
- Reduction *or* increase in pedestal pressure gradient

Under investigation using EMC3-Eirene

- ELM triggering
- Triggering of enhanced confinement regimes

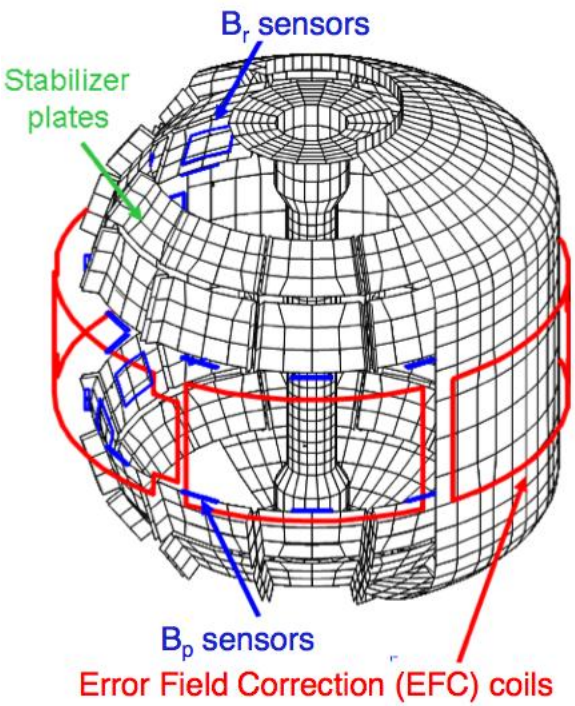




Ahn, ITPA (2011)
Canik, NF (2011, submitted)

3D Field Application In NSTX

- A 3D magnetic field structure is generated in NSTX by applying a nonaxisymmetric field (n=1,2,3).
  - Applied using a midplane EFC coil set, external to vacuum vessel.
- All modeling results shown are for n=3 applied fields.

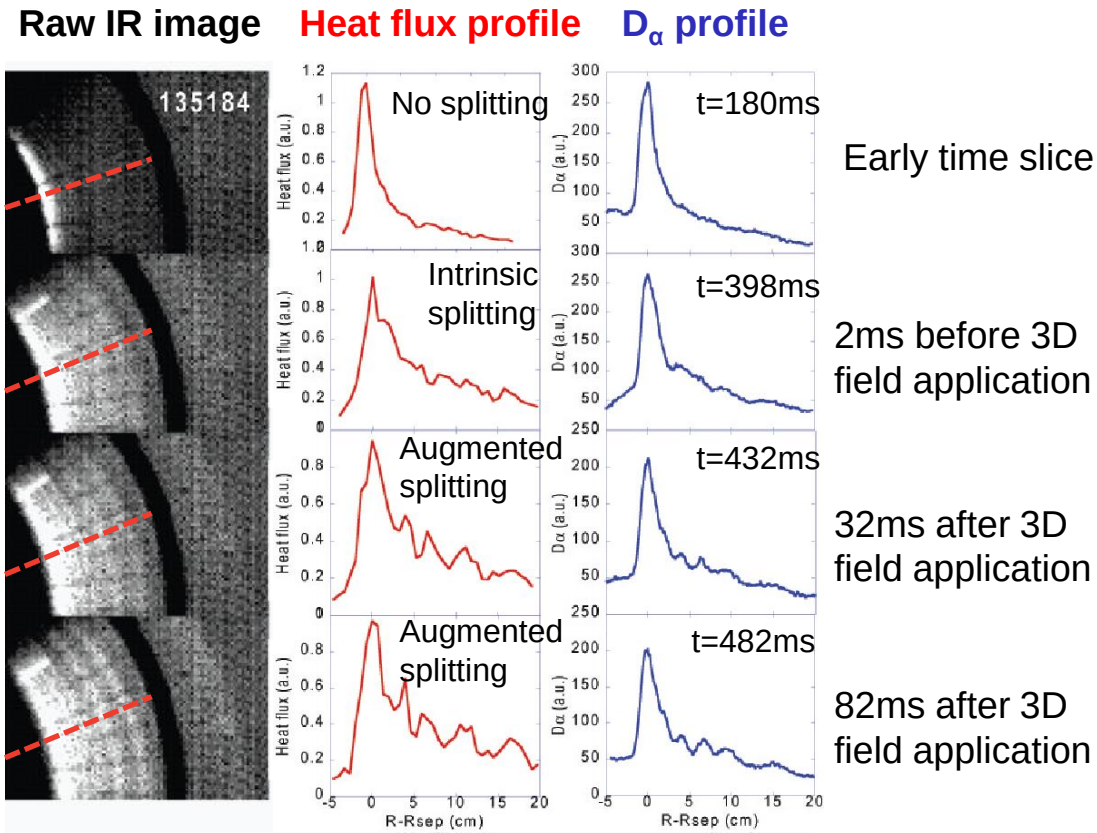


R = 0.85m
a = 0.65m
B_0 ~ 0.5T

Canik, NF (2010)

Strike Splitting Measured as Result of Applied and Intrinsic 3D Fields

- Heat and particle flux measurements show strike point splitting.
  - 1D D_α, 2D fast IR camera data, Phantom cameras
- "Intrinsic" splitting is also observed due to error fields.
  - Intrinsic error fields are largely a result of the non-circularity of the PF5 coil; n=3 is the dominant component[1].

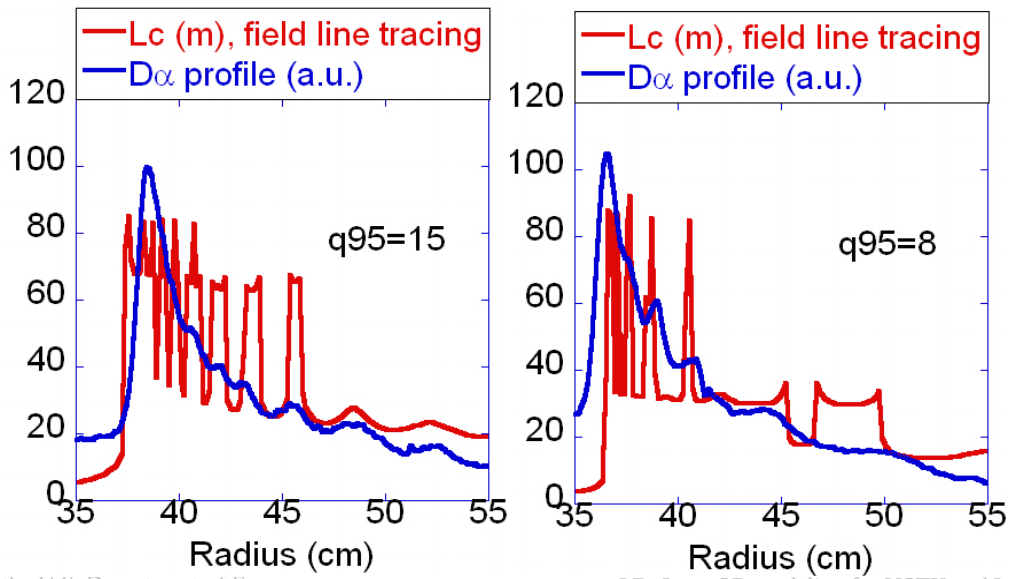


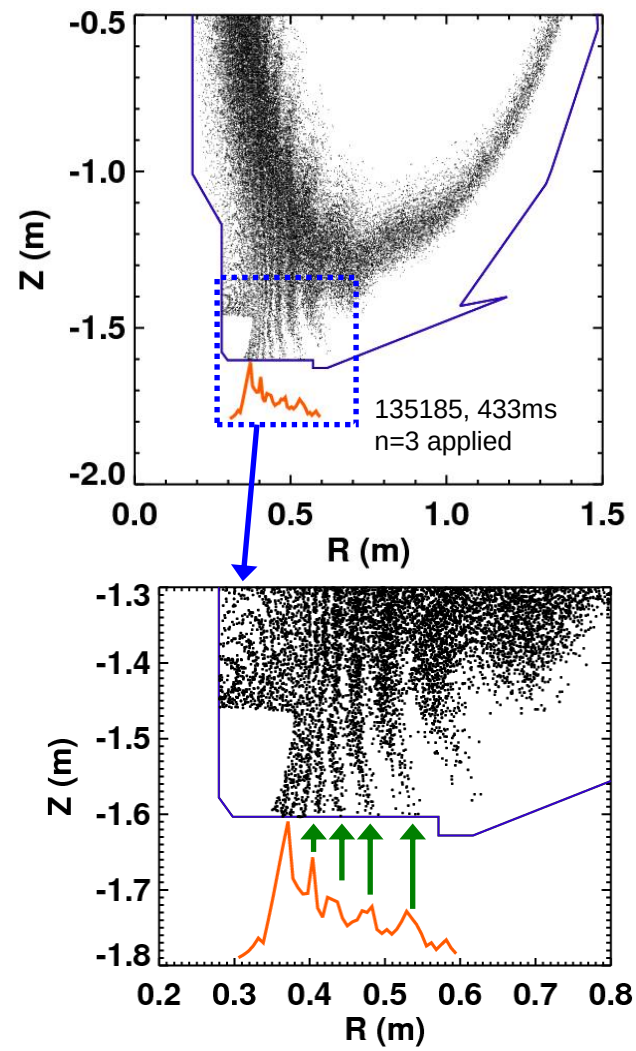
[1]J.E. Menard, Nucl. Fusion (2010), 045008

J-W. Ahn, Nucl. Fusion (2010), 045010

Strike Point Locations Agree Well With Vacuum Field Line Following

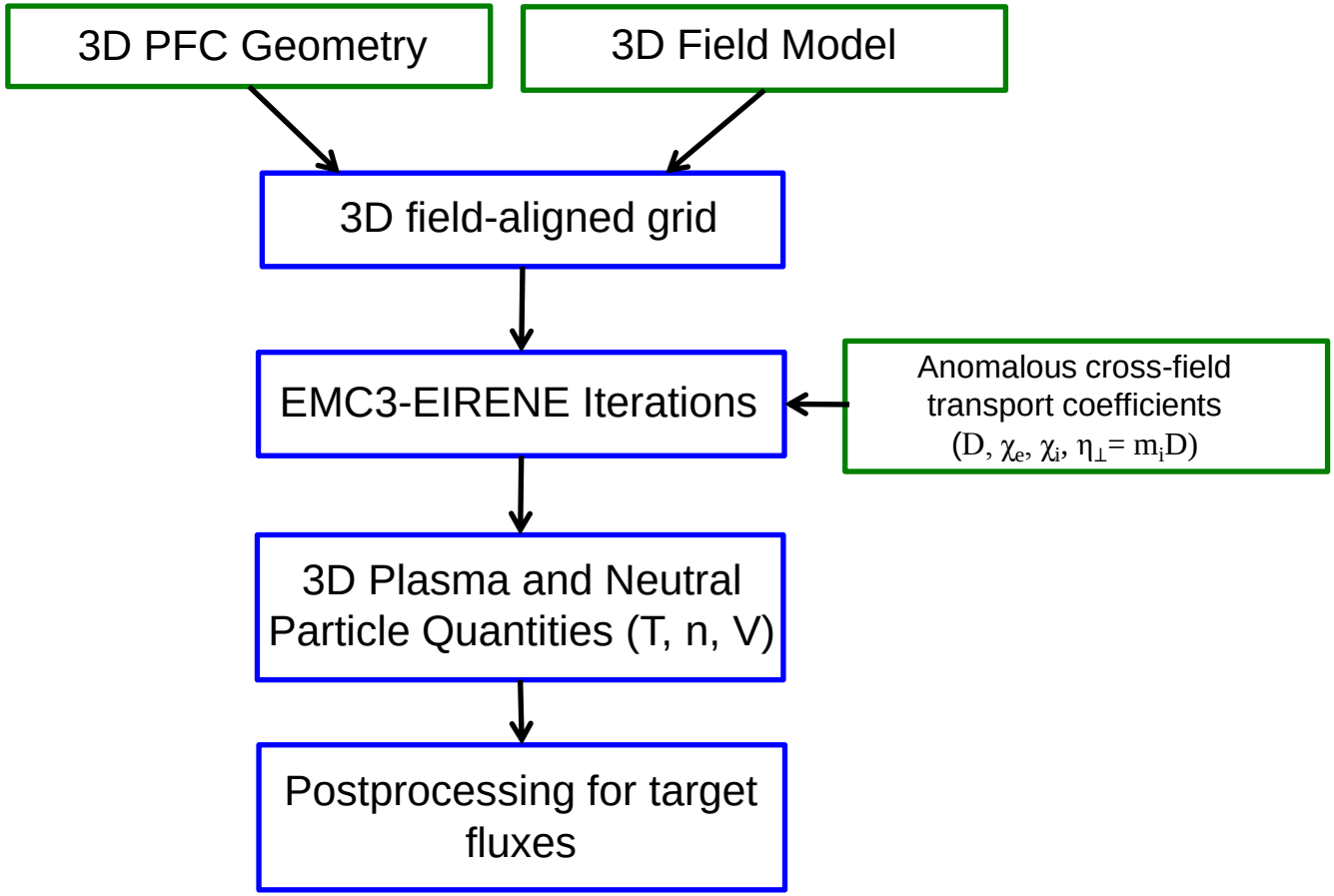
- Superposition of 2D equilibrium and vacuum applied fields
- Peak divertor fluxes align with long connection length fieldlines, where fieldlines connect to pedestal
- Strike points, L_c are useful for estimates, flux magnitudes require a transport model





J-W. Ahn, Nucl. Fusion 50, 045010 (2010).

EMC3-Eirene[1] flowchart



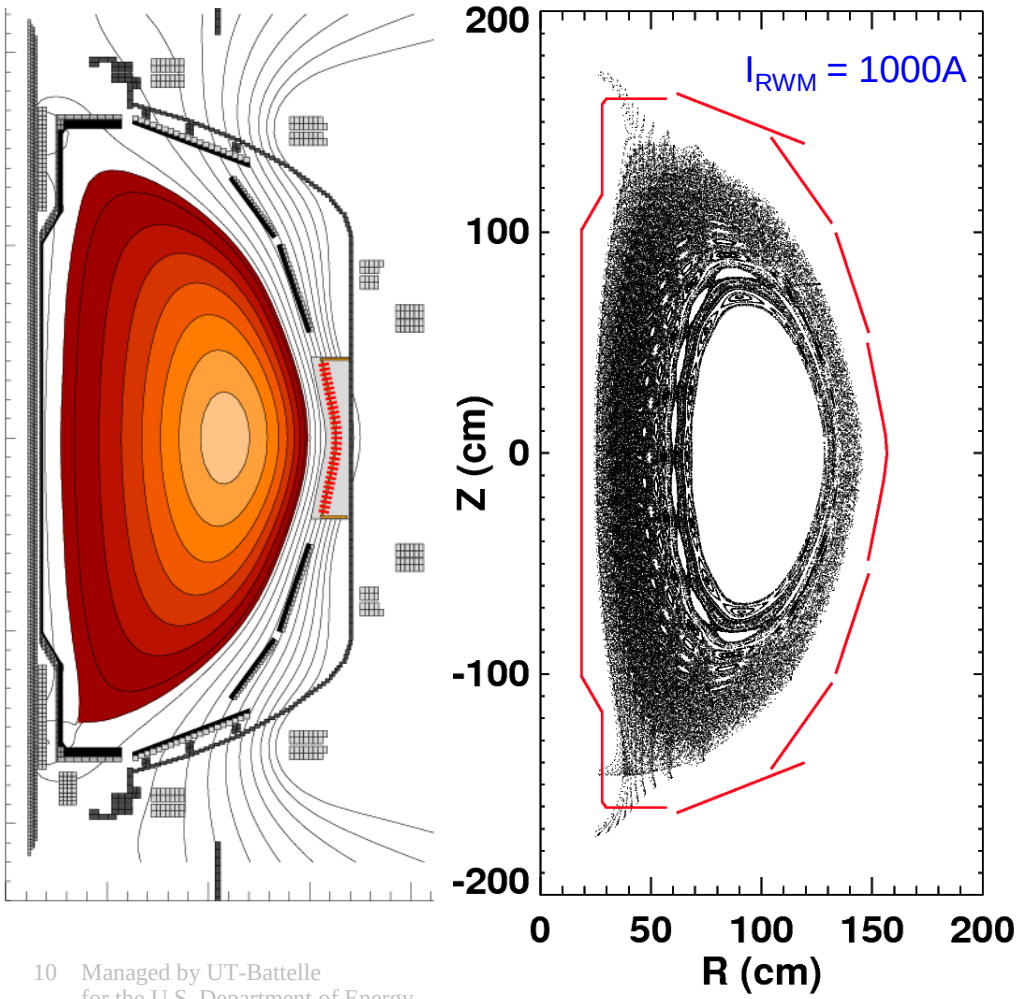
[1] Y. Feng, et al, Plasma Phys. Controlled Fusion **44, 611** (2002)

Fully 3D Geometry used for Plasma and PFCs

3D PFC Geometry

3D Field Model

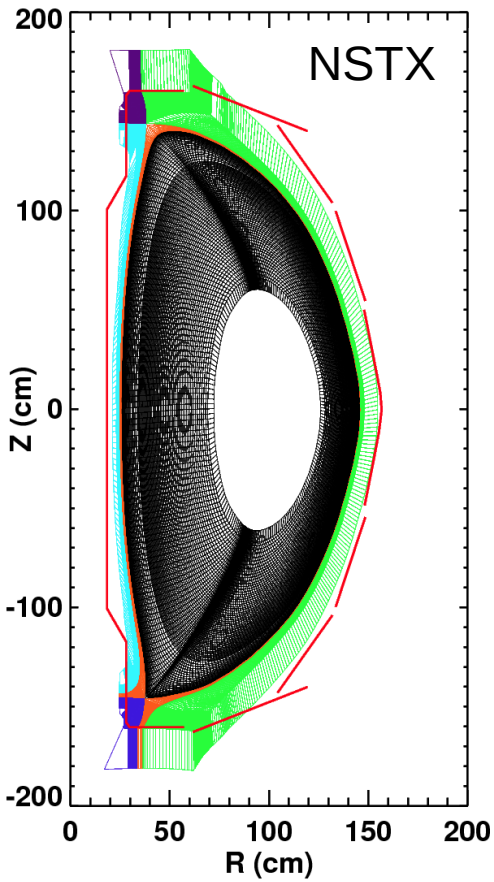
NSTX

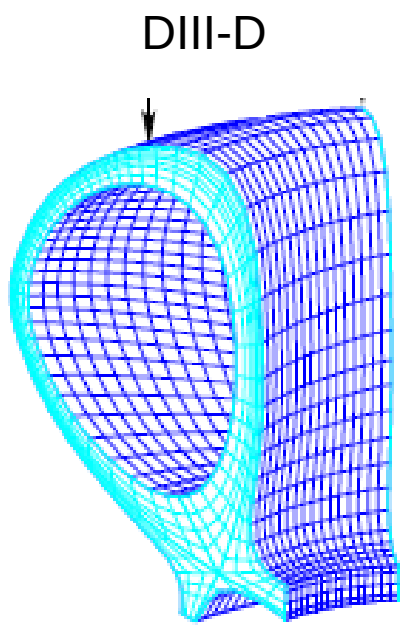


- 3D magnetic field model required
- "Vacuum Paradigm"
  - 2D Equilibrium (EFIT) + 3D Vacuum Perturbation Field
  - Currently implemented for NSTX
- Plasma response model
  - IPEC, SIESTA, current sheets on resonant surfaces
  - In progress

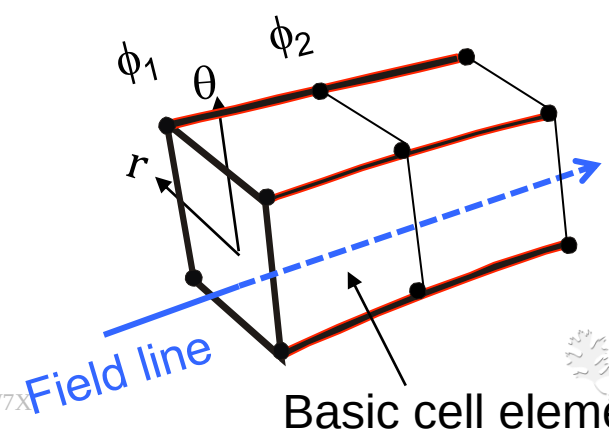
J.D. Lore, *et al.,* Phys. Plasmas, 2012 (accepted)

EMC3 Uses a Field-Aligned Grid



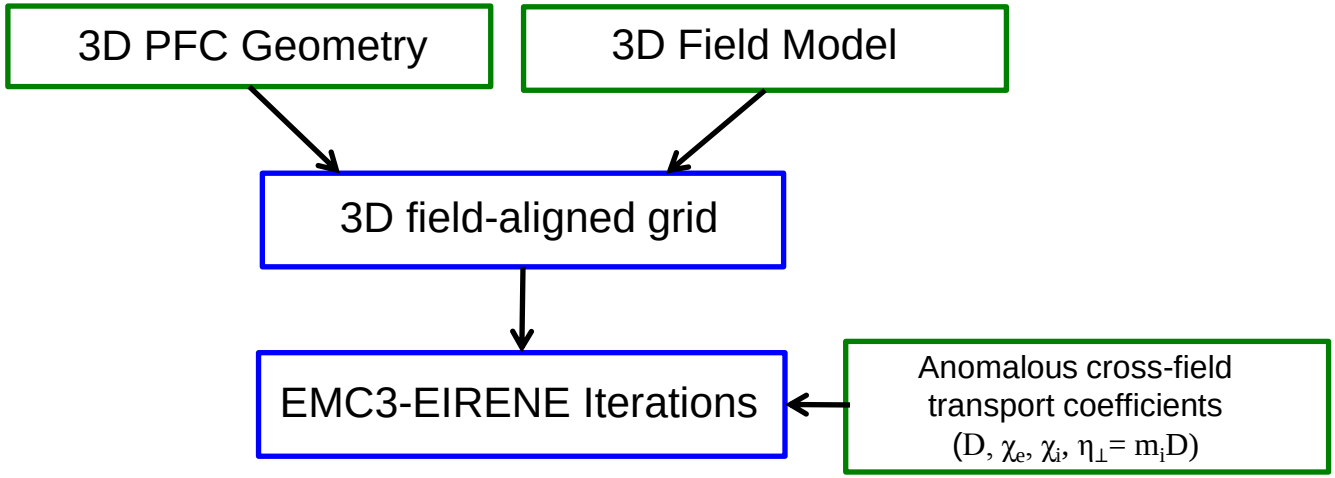


- Grid elements are based on flux tubes
  - Radial, poloidal, and toroidal grid indices
- Field-aligned: holding radial and poloidal indices constant defines a field line
  - Fast computation, no field calculations required during iteration steps
- First implementation of a DDN grid in EMC3
  - $\delta_r^{sep} < \lambda_q^{mid}$ (~5mm vs ~1cm) for modeled shot
  - Single null grid excludes most of the radial extent of lower horizontal target.



J.D. Lore, *et al.*, Phys. Plasmas, 2012 (accepted)
Frerichs, PhD Thesis

Iterate EMC3-Eirene to Obtain Flows, Fluxes



EMC3 (Edge Monte Carlo 3D)

Continuity:

$$\nabla \cdot \left(n_i V_{i\parallel} \boldsymbol{b} - D \nabla_\perp n_i \right) = \boxed{S_p}$$

Momentum Balance:

$$\nabla \cdot \left(m_i n_i V_{i\parallel} V_{i\parallel} \boldsymbol{b} - \eta_\parallel \nabla_\parallel V_{i\parallel} - m_i V_{i\parallel} D \nabla_\perp n_i - \eta_\perp \nabla_\perp V_{i\parallel} \right) = -\nabla_\parallel p + \boxed{S_m}$$

Energy Transport (ion and electron):

$$\nabla \cdot \left(\tfrac{5}{2} n_e T_e V_{i\parallel} \boldsymbol{b} - \kappa_e \nabla_\parallel T_e - \tfrac{5}{2} T_e D \nabla_\perp n_e - \chi_e n_e \nabla_\perp T_e \right) = -k\left(T_e - T_i\right) + \boxed{S_{ee}} + \boxed{S_{imp}}$$

$$\nabla \cdot \left(\tfrac{5}{2} n_i T_i V_{i\parallel} \boldsymbol{b} - \kappa_i \nabla_\parallel T_i - \tfrac{5}{2} T_i D \nabla_\perp n_i - \chi_i n_i \nabla_\perp T_i \right) = +k\left(T_e - T_i\right) + \boxed{S_{ei}}$$

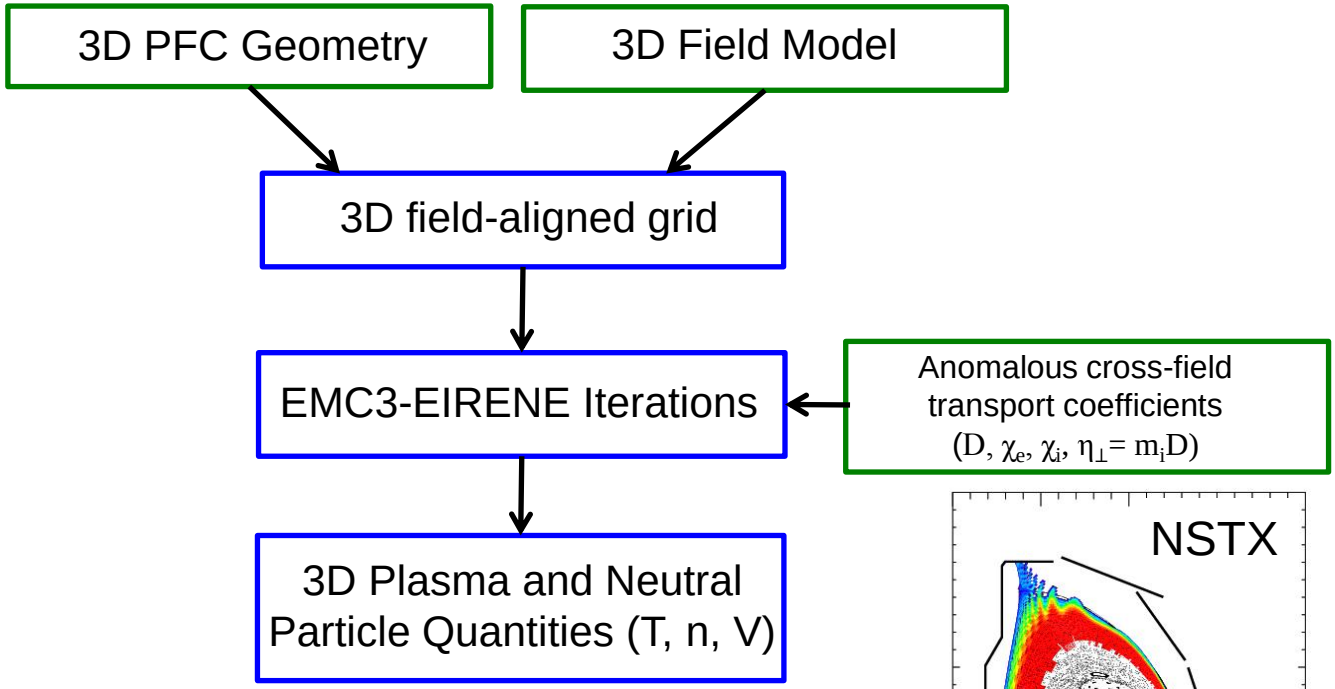
Sources from plasma-neutral interactions provided by Eirene

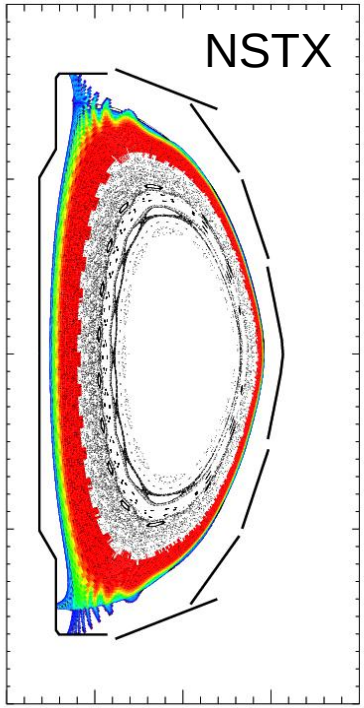
Trace impurity model

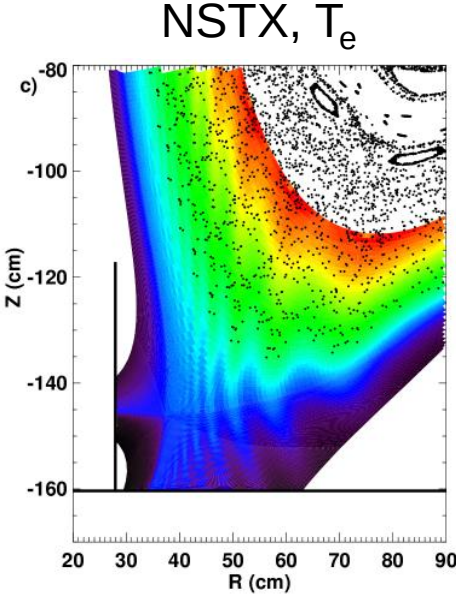
- Fully 3D geometry for plasma, divertor, PFCs
- Self-consistent coupling of fluid ions and electrons, kinetic neutral transport and PSI
- Classical parallel transport ($\eta_\parallel$, κ_e, κ_i)
- Prescribed anomalous cross-field coefficients
- Allows for calculation of fluid transport in stochastic and non-stochastic fields.

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

Output: 3D Distributions of Transport Quantities





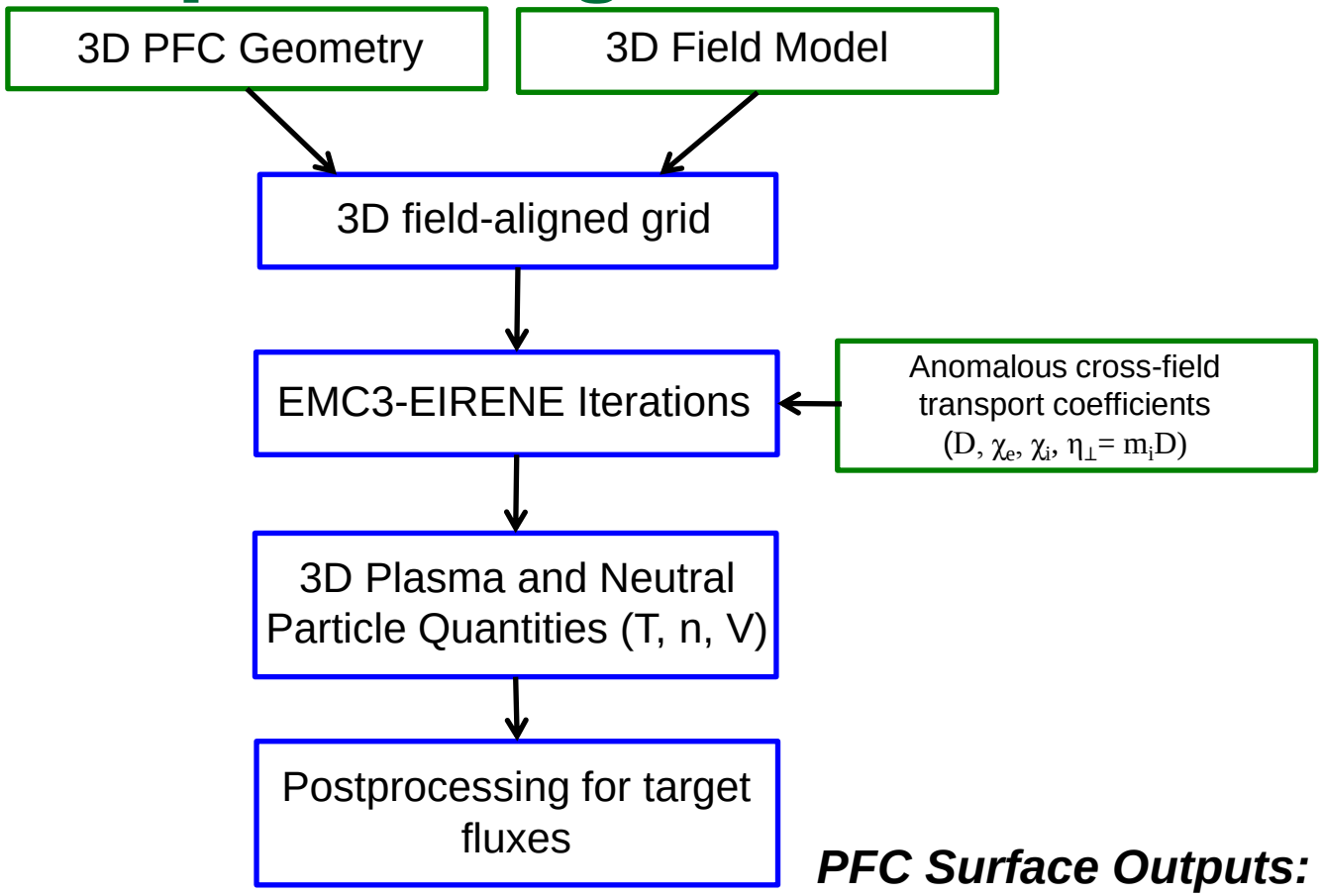


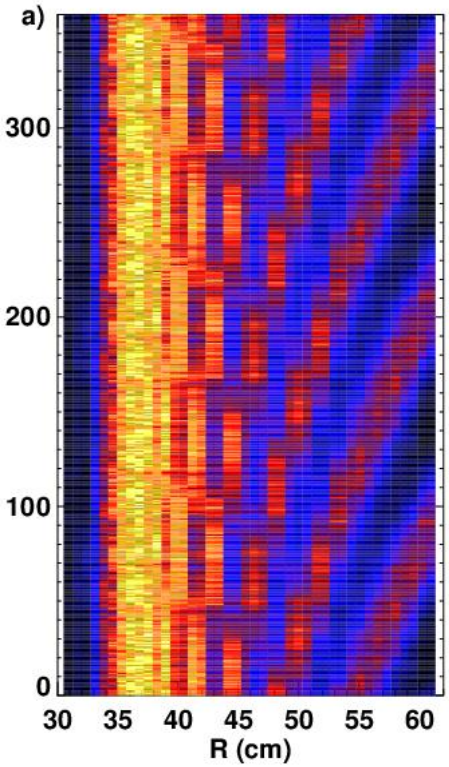
3D distributions of

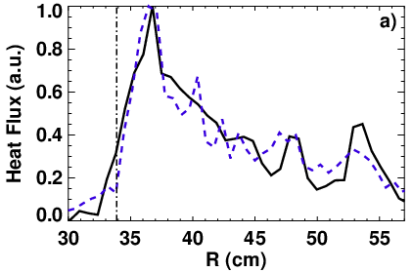
- Plasma density
- Ion & electron temperatures
- Parallel flow velocity
- Neutral density (atoms & molecules)
- Energy of neutrals
- Atomic reactions
- Impurity density
- Impurity radiation

J.D. Lore, *et al.,* Phys. Plasmas, 2012 (accepted)

2D Surface Outputs from Postprocessing





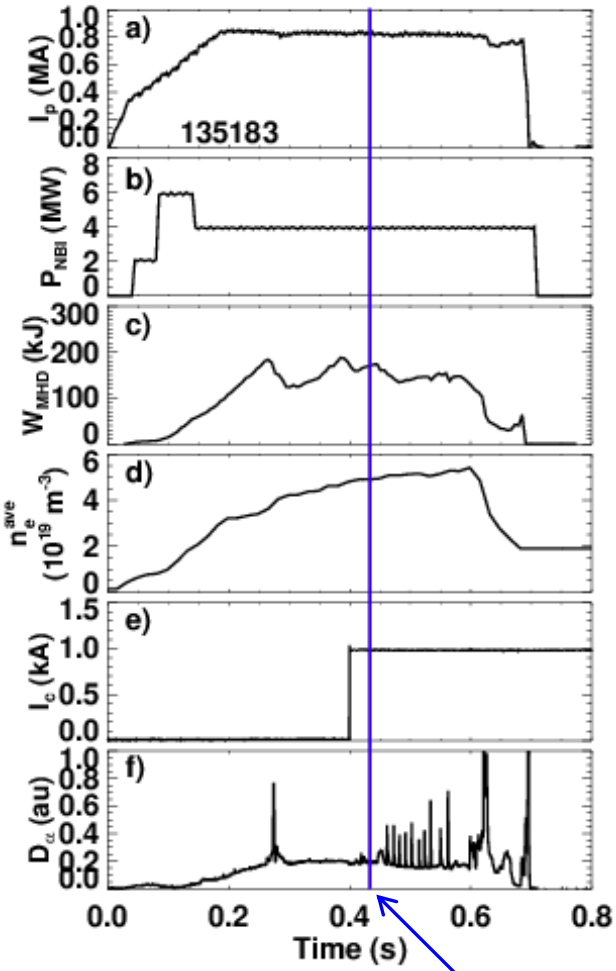


PFC Surface Outputs:

- Power load distribution
- Particle deposition
- Neutral flux distribution
- Energy spectrum of neutral particles

Axisymmetric and perturbed NSTX plasmas have been modeled

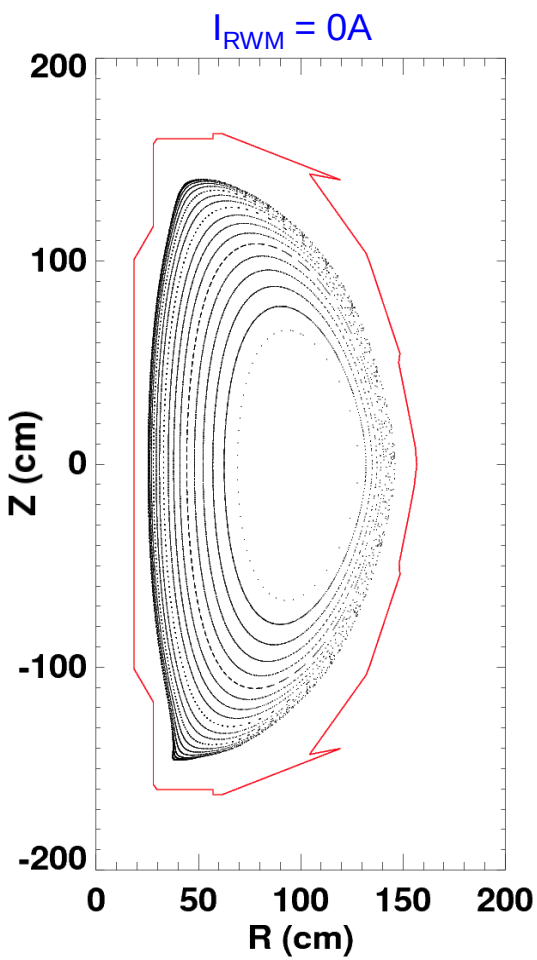
- Modeling of NSTX shot 135183:
  - Divertor camera data available for comparison
  - I_p = 800kA, P_{SOL} = 4 MW
  - I_{RWM} = 1000A
  - δ_r^{sep} ~ 5mm
  - κ ~ 2.3, δ ~ 0.8
- Model parameters:
  - D = 0.25 m^2/s, $\chi_{e,i}$ = 2.5 m^2/s
- Two cases modeled:
  - Only axisymmetric equilibrium fields
  - 2D equilibrium + vacuum applied field with 1kA RWM coil current

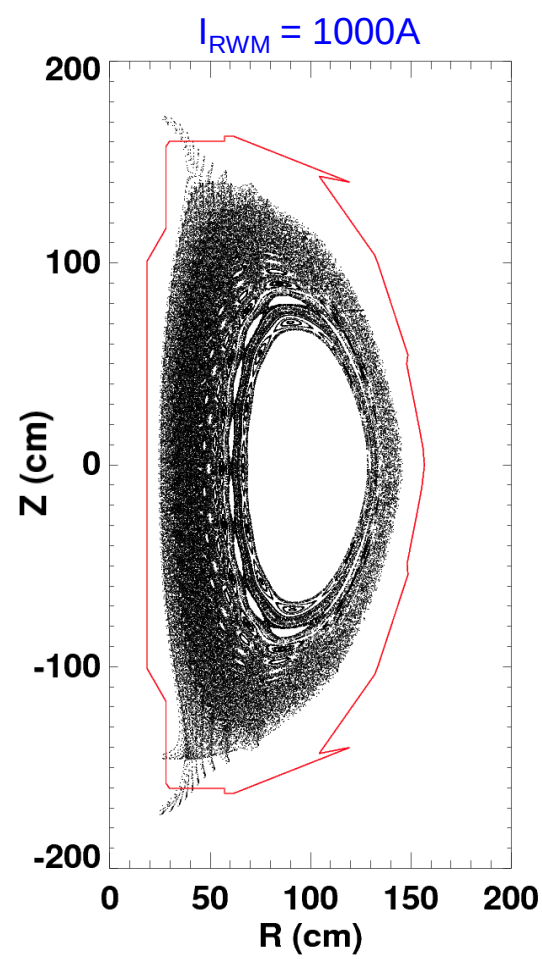


Modeled time point

3D Field Structure is Reflected in Modeled Temperature

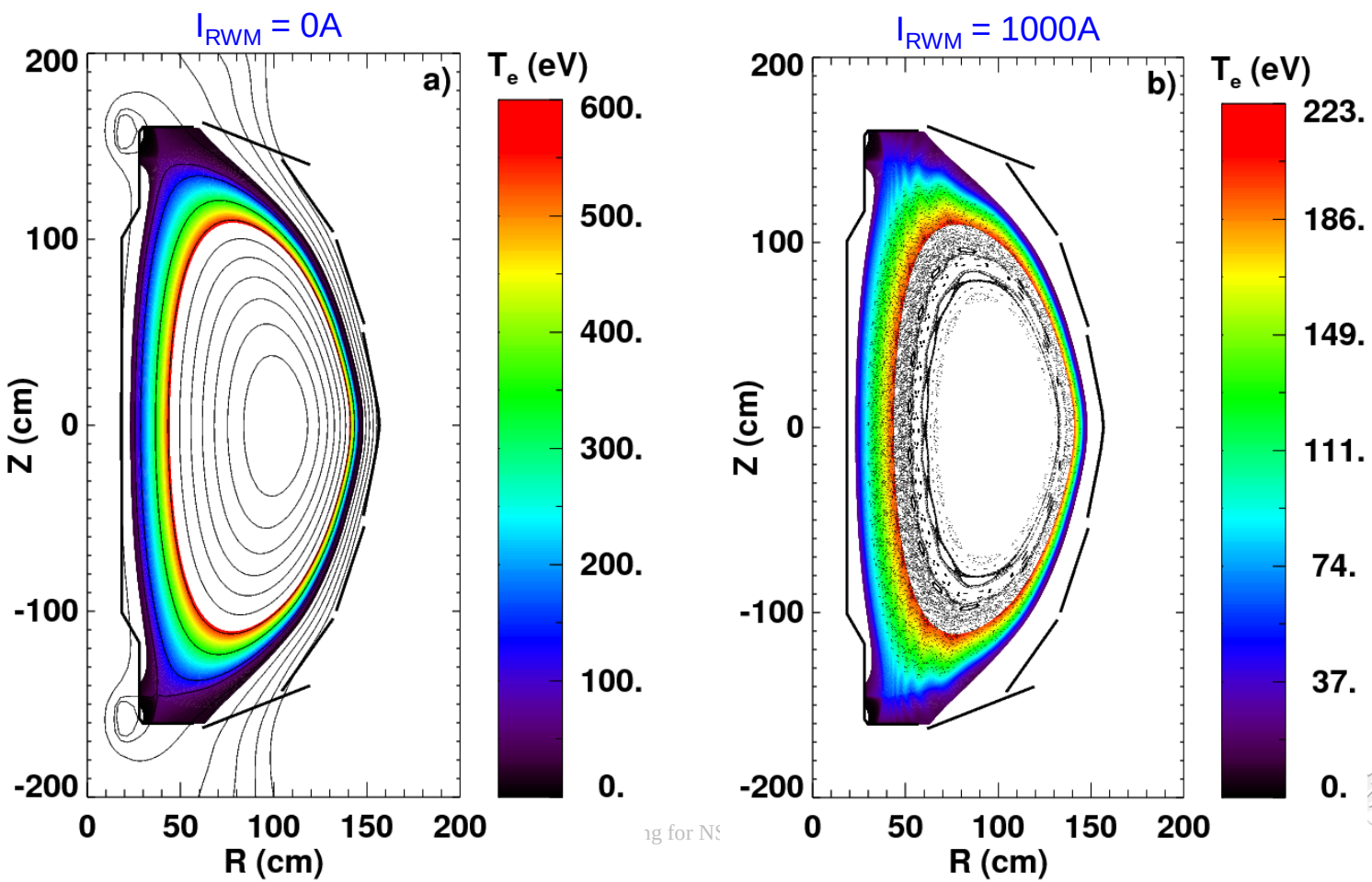
- 1kA of coil current results in significant stochasticity (no surfaces for $\Psi_N > 0.3$)





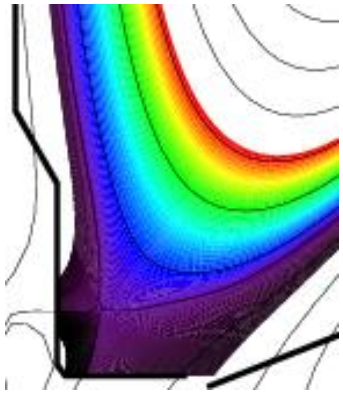
3D Field Structure is Reflected in Modeled Temperature

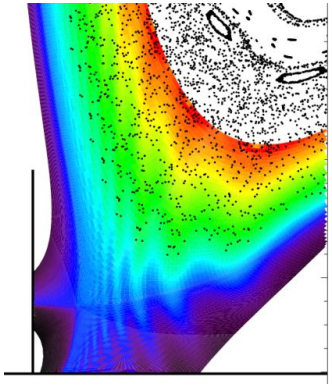
- 1kA of coil current results in significant stochasticity (no surfaces for $\Psi_N > 0.3$)
- For same D, χ, and boundary conditions, $T_{e,i}$ is reduced in nonaxisymmetric case.
- Higher temperature plasma fills in lobes near target.

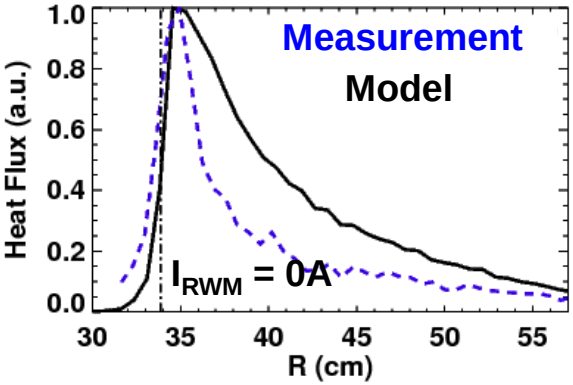


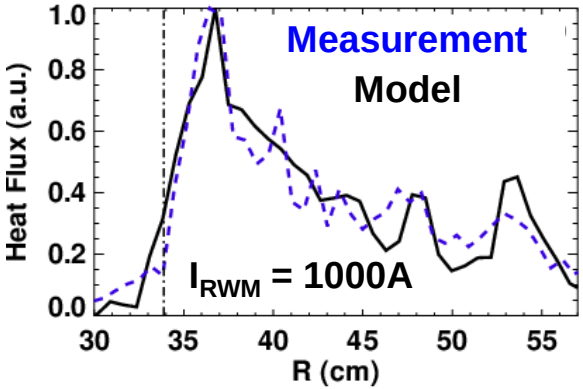
Strike point splitting qualitatively captured

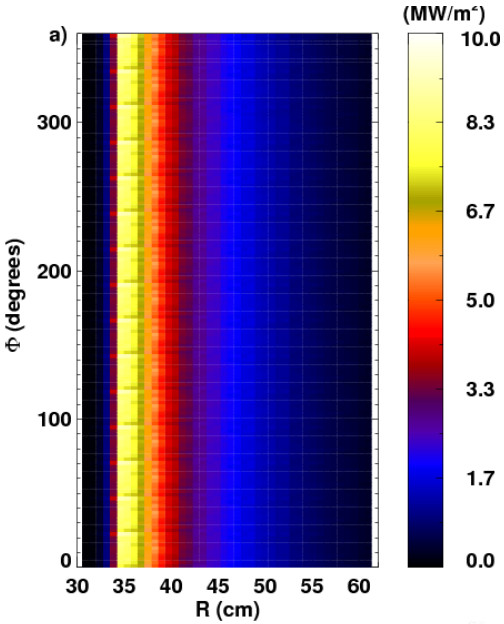
- Results shown for lower horizontal target, at $\phi = 0°$
  - Single peak in heat flux for $I_{RWM} = 0A$
  - Striated patterns with $I_{RWM} = 1kA$

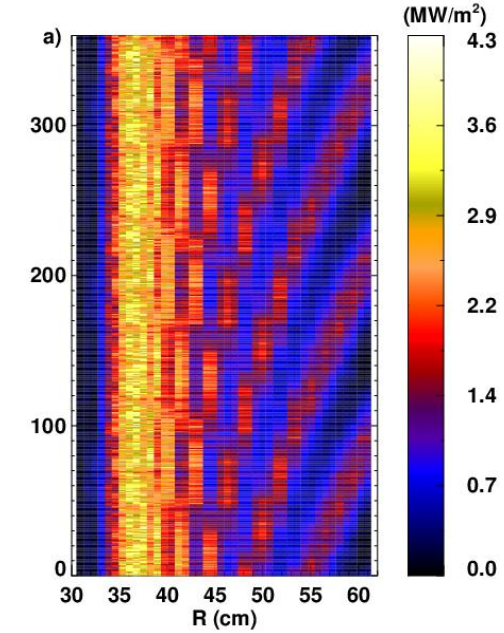








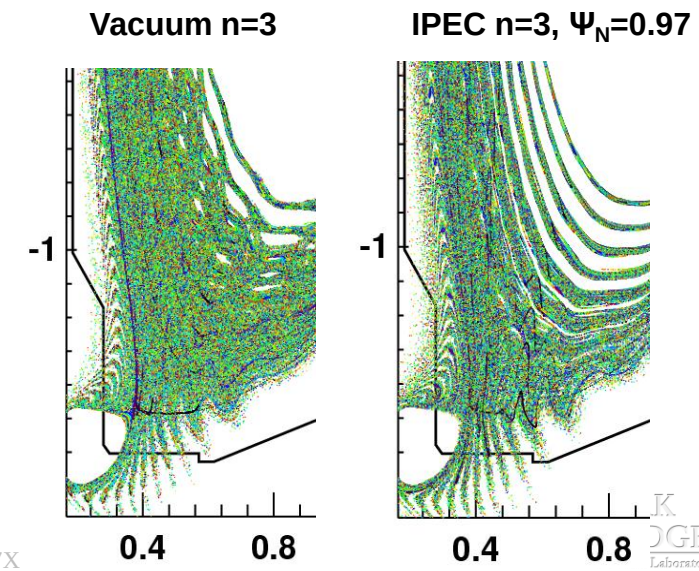




J.D. Lore, *et al.*, Phys. Plasmas, 2012 (accepted)

NSTX Modeling Goals Using EMC3-Eirene

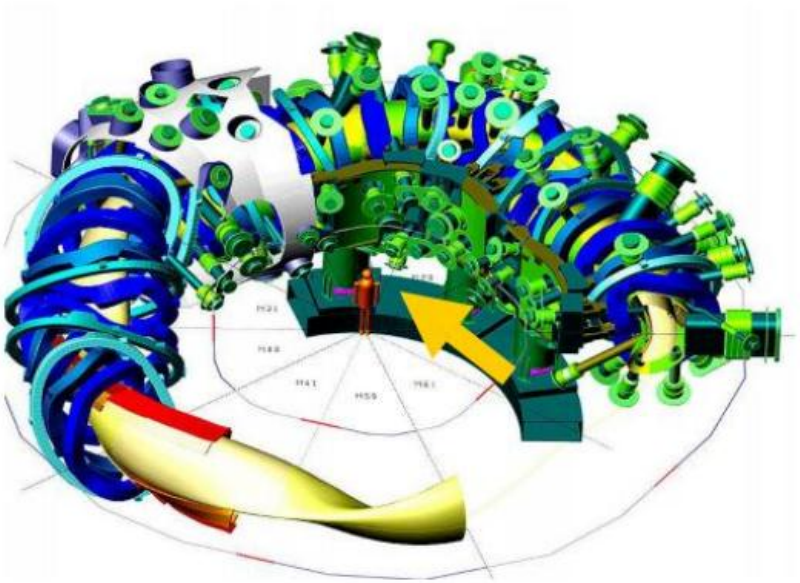
- Further investigations are in progress now that grid generation and postprocessing tools have been developed
  - Vary cross-field transport coefficients to match midplane profiles
  - Modeling of divertor plasma reattachment with 3D fields
  - Addition of synthetic diagnostics for D_α comparison
  - Implementation of field models (e.g., VMEC+EXTENDER, IPEC)
    - Vacuum fieldline following has indicated insensitivity of strike point positions to ideal plasma response

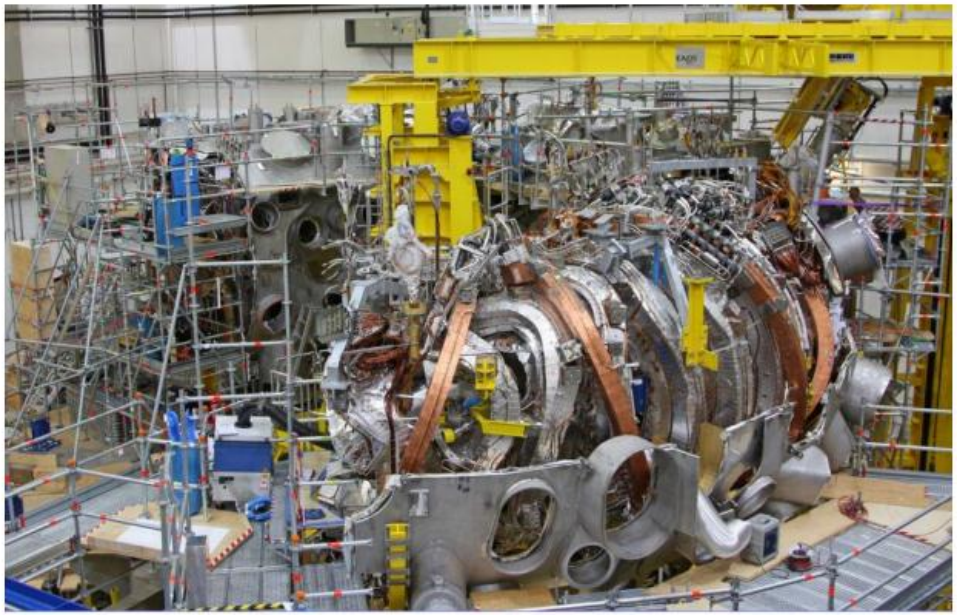


J-W. Ahn, Nucl. Fusion 50, 045010 (2010).

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

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

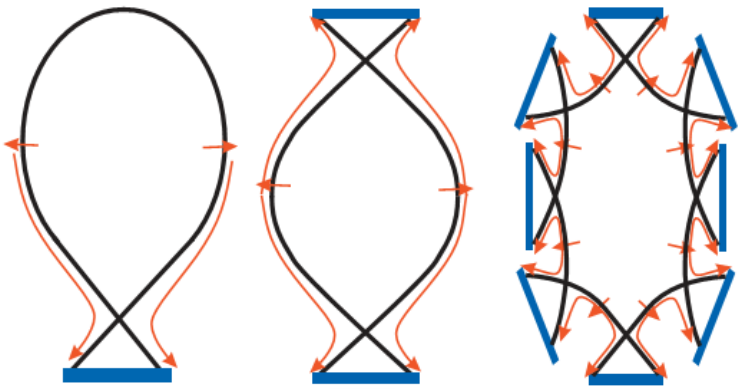


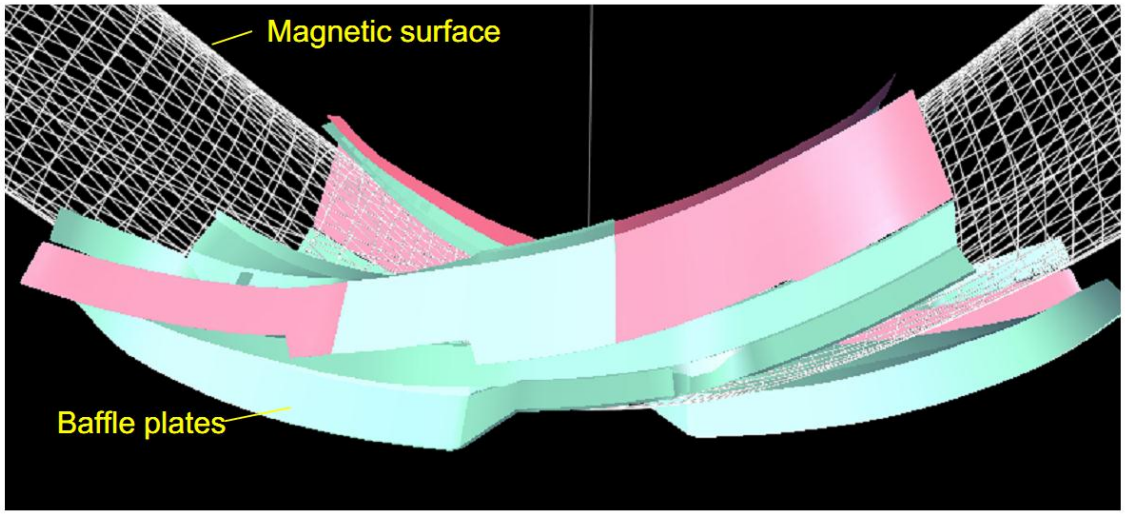


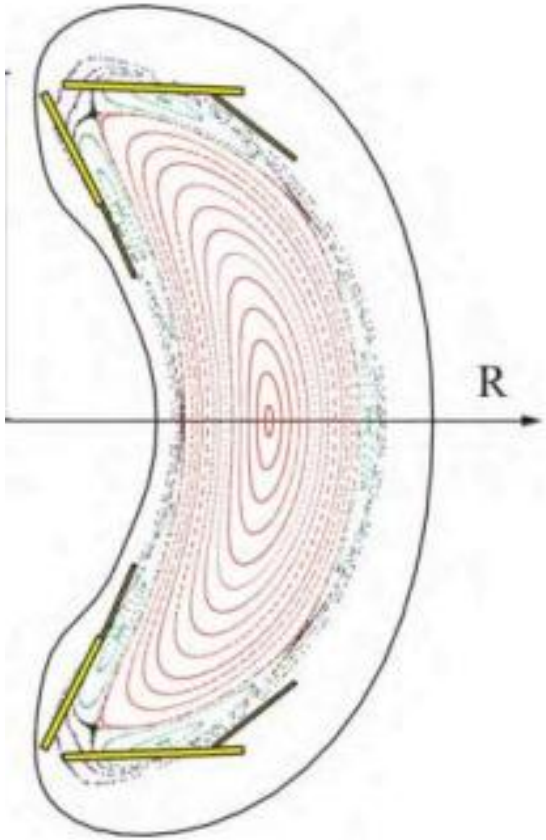
J.D. Lore, 3D mod

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)

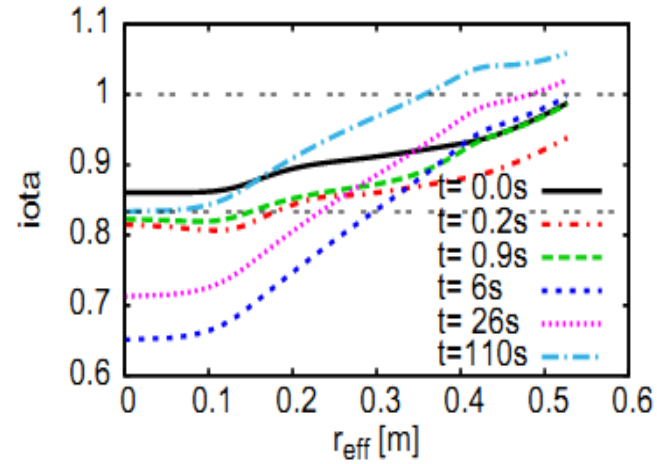


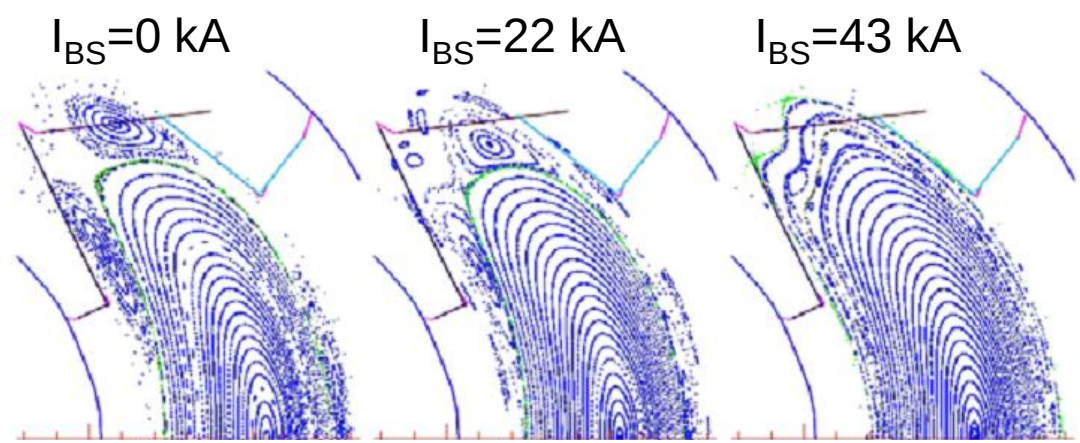




Edge transform changes as bootstrap current evolves

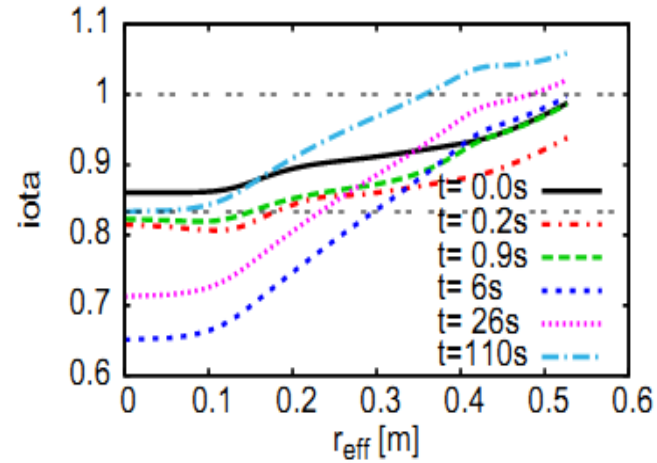
- Some configurations have finite bootstrap current
- Evolves on L/R time ~ 30s
- Changes boundary transform by ~5%
  - Alters island topology
  - With ι_b^{vac} ~ 1, full bootstrap current results in limiter configuration

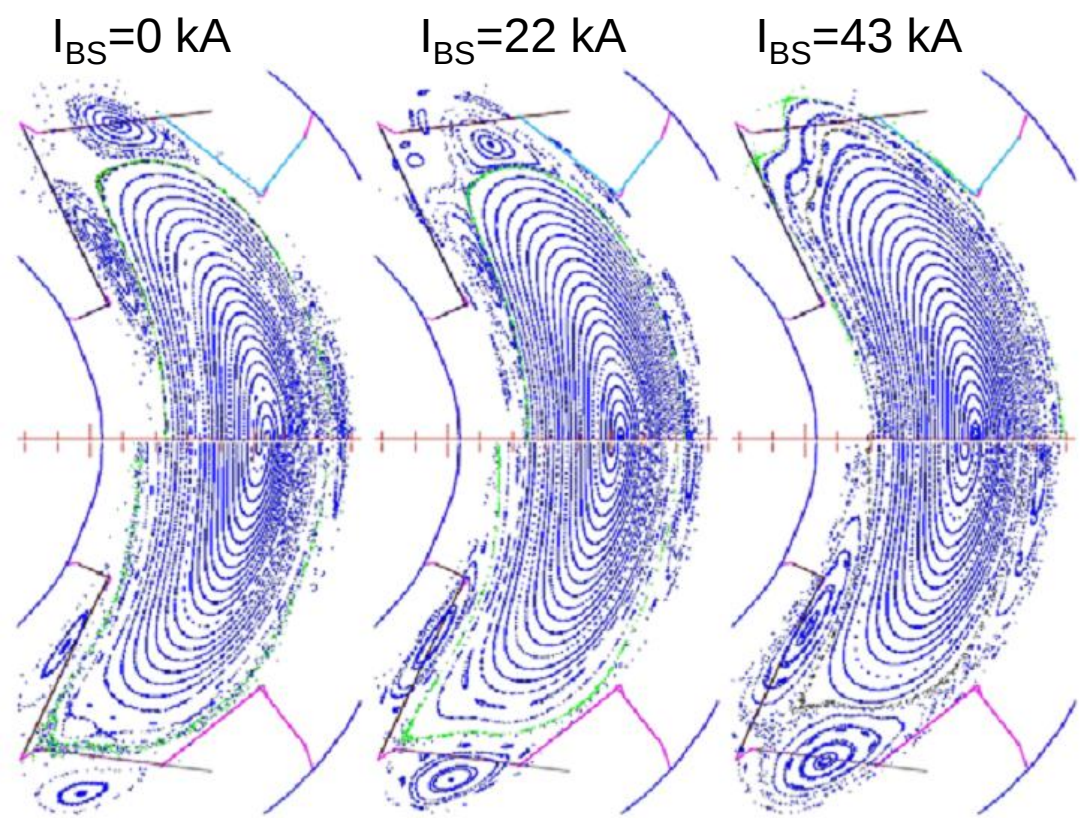




Edge transform changes as bootstrap current evolves

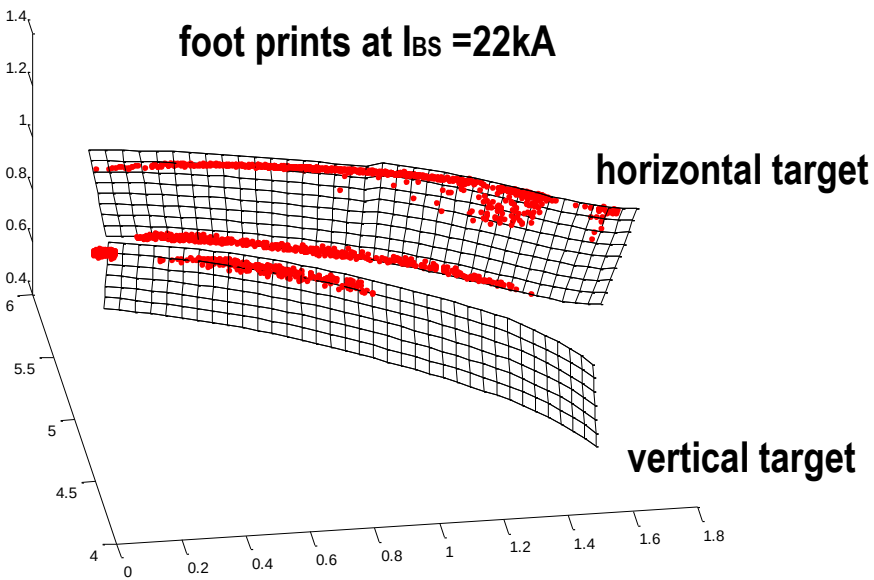
- Some configurations have finite bootstrap current
- Evolves on L/R time ~ 30s
- Changes boundary transform by ~5%
  - Alters island topology
  - With ι_b^{vac} ~ 1, full bootstrap current results in limiter configuration
  - Present plan: start with vacuum transform reduced so that island divertor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

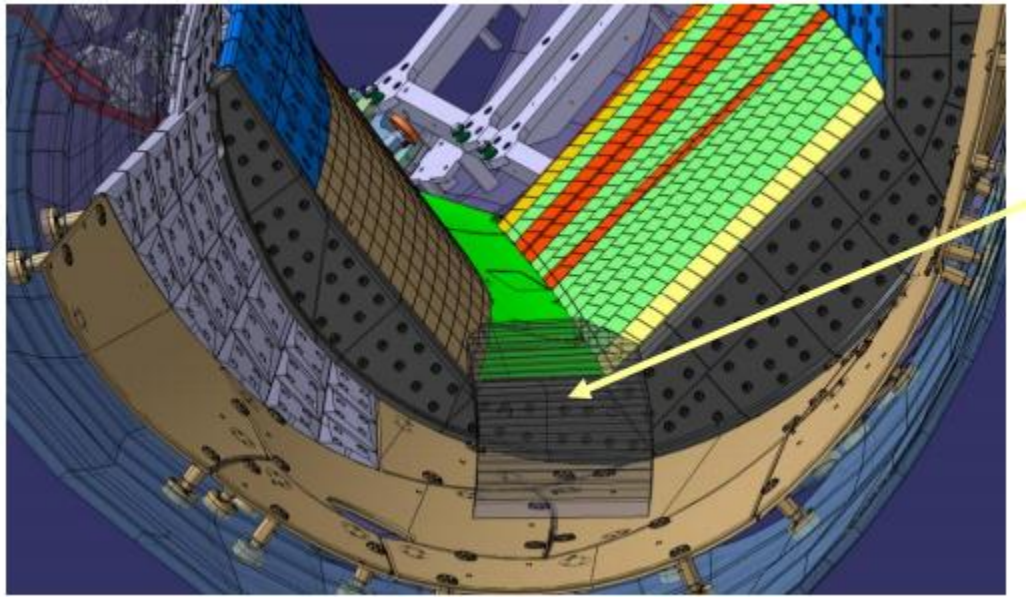




Scraper element added to protect tile edges during intermediate I_{BS} phase

- 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

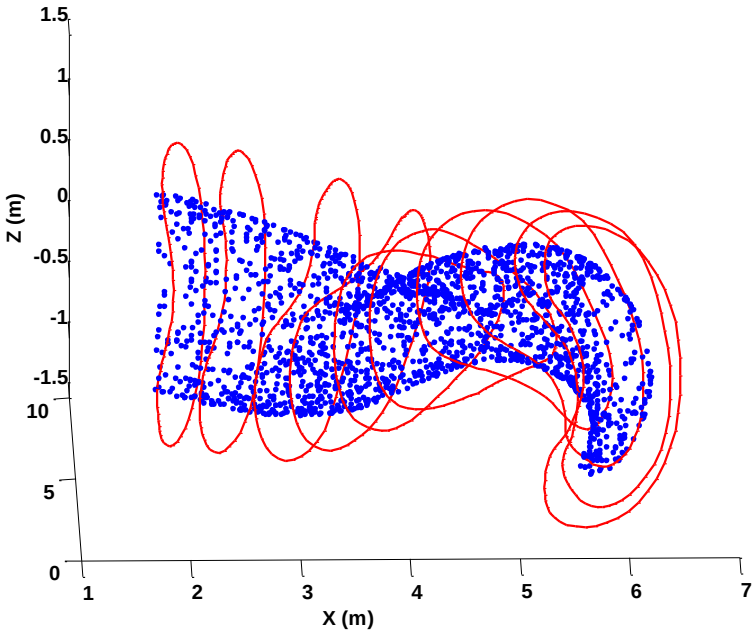




J.D. Lore, 3D

Field line tracing is used to estimate heat flux

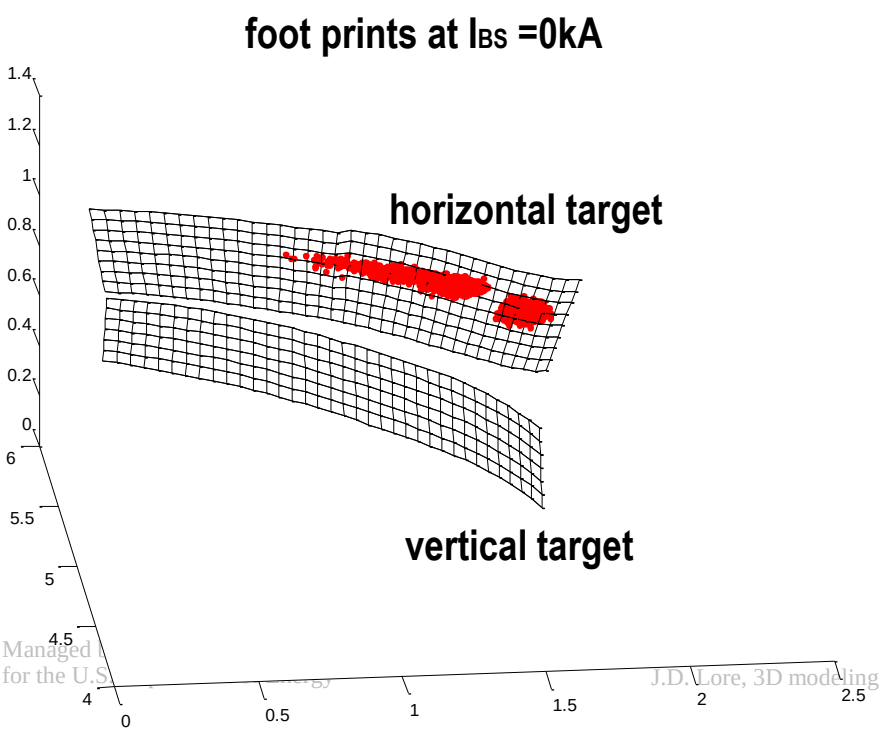
- Field lines are followed in 3D including plasma contribution
  - VMEC[1] for 3D equilibrium (only gives field inside LCFS)
  - Extender[2] for plasma+coil fields outside LCFS
- Lines are initialized randomly along a field line that traces out a closed surface
  - Lines are then diffused with a given 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

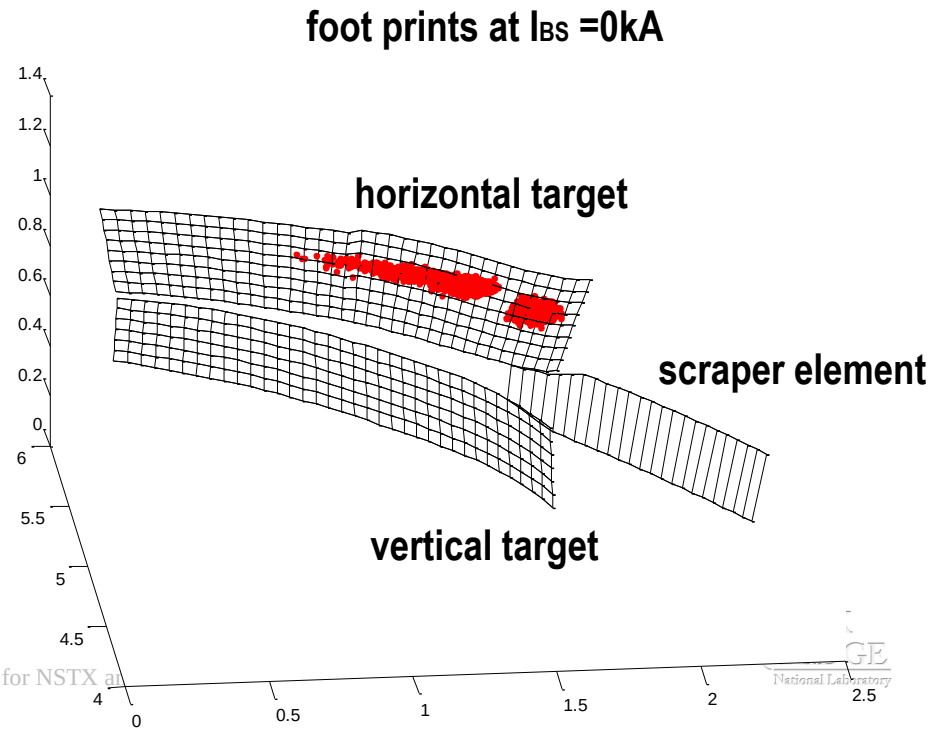


[1] S.P. Hirshman, et al, Comp. Phys. Commun. 43, 143 (1986).
[2] M. Drevlak, et al, Nucl. Fusion, 45, 731 (2005).

Field line tracing shows function of divertor scraper element

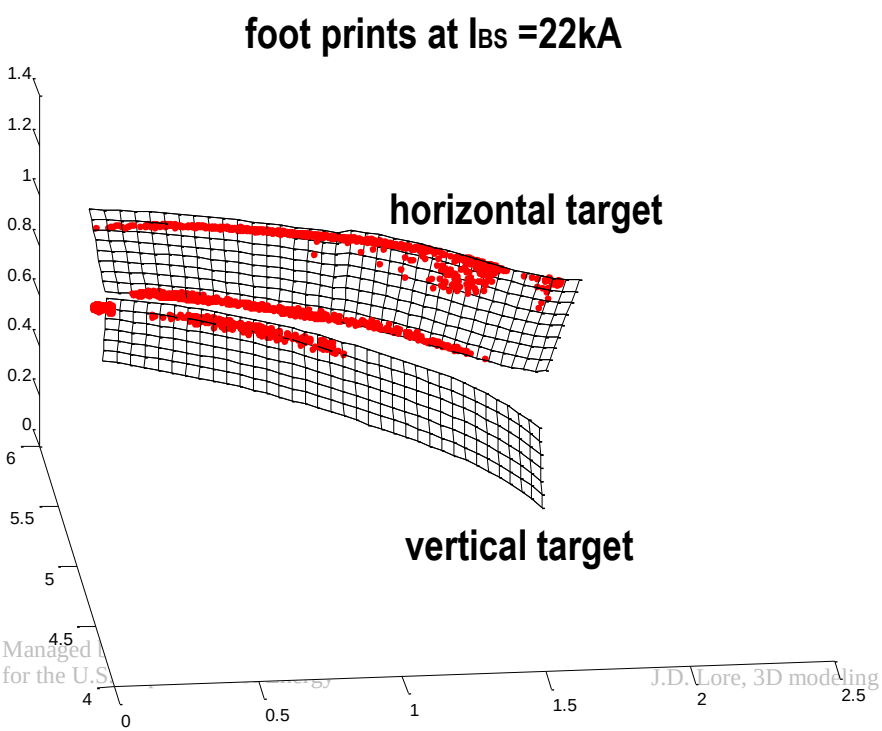
- Intersections are found both with and without the scraper element
- 0kA: Load is near middle of horizontal target, no load on scraper

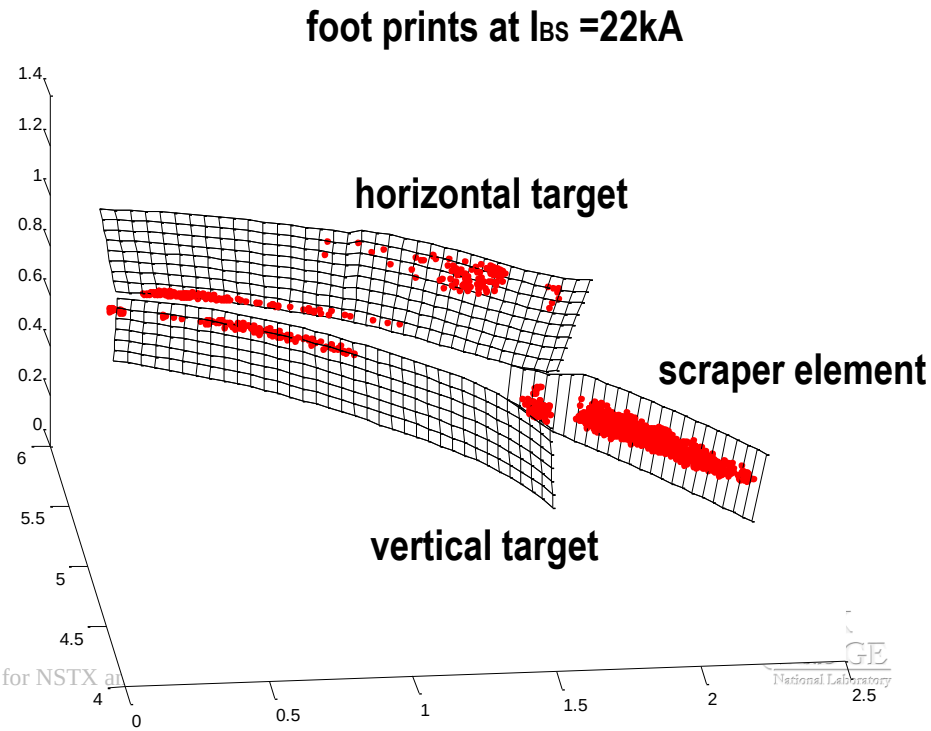




Field line tracing shows function of divertor scraper element

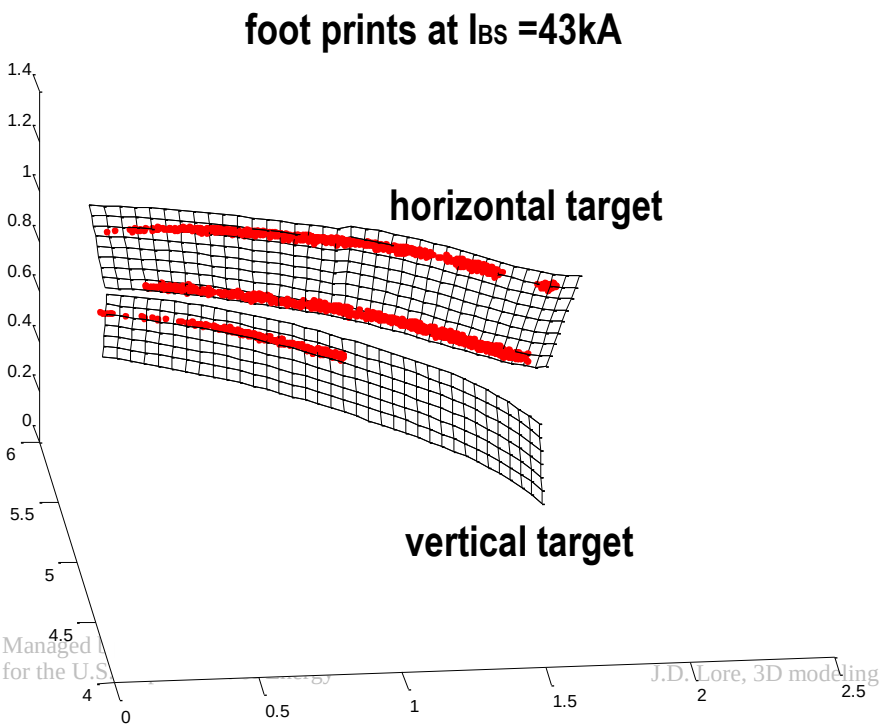
- Intersections are found both with and without the scraper element
- 0kA: Load is near middle of horizontal target, no load on scraper
- 22kA: Without scraper edges of target are loaded; scraper catches most of this flux

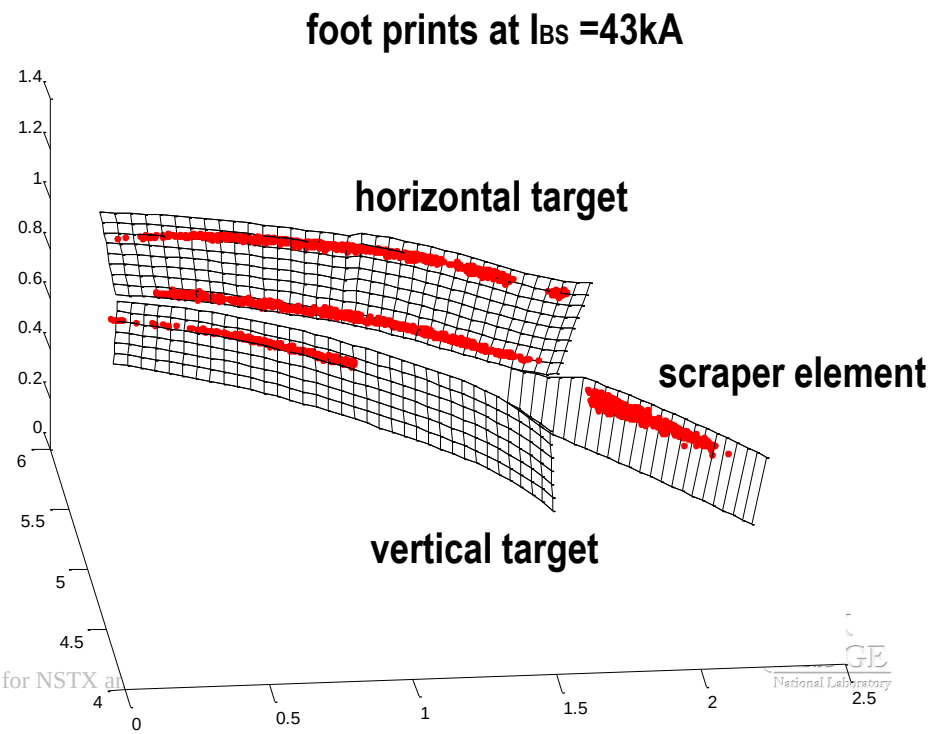




Field line tracing shows function of divertor scraper element

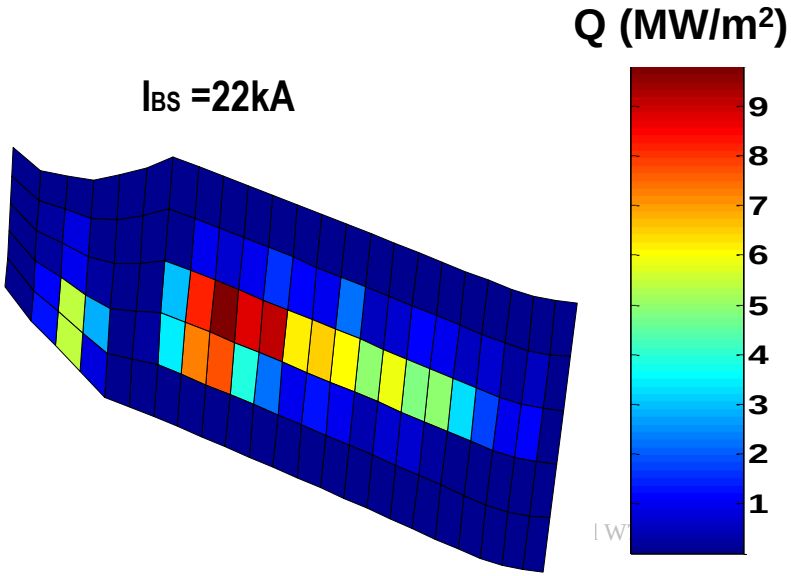
- Intersections are found both with and without the scraper element
- 0kA: Load is near middle of horizontal target, no load on scraper
- 22kA: Without scraper edges of target are loaded; scraper catches most of this flux
- 43kA: Footprint has moved away slightly from the target edge, scraper load reduced





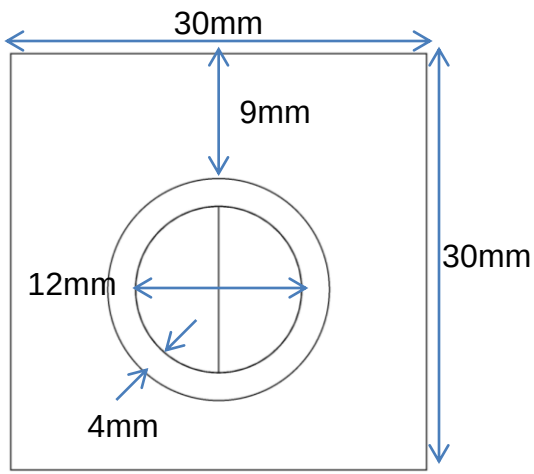
Field line density used to estimate heat flux

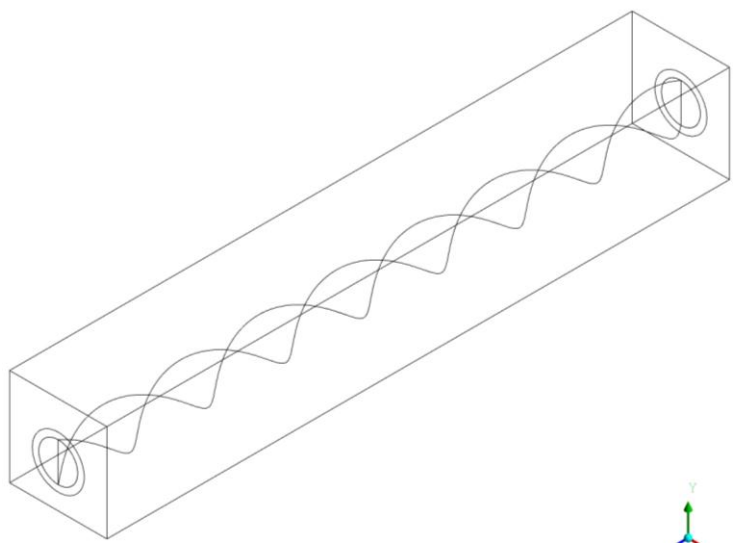
- Heat flux is calculated by assuming each field line carries a fraction of the power through the LCFS
  - $P_{line} = P_{LCFS}/N_{line}$
- Surface is then split into area 'bins', with $Q = (\#\ \text{strikes}) \cdot P_{line}/A_{bin}$
- Highest scraper heat flux in current scan occurs for 22kA of bootstrap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

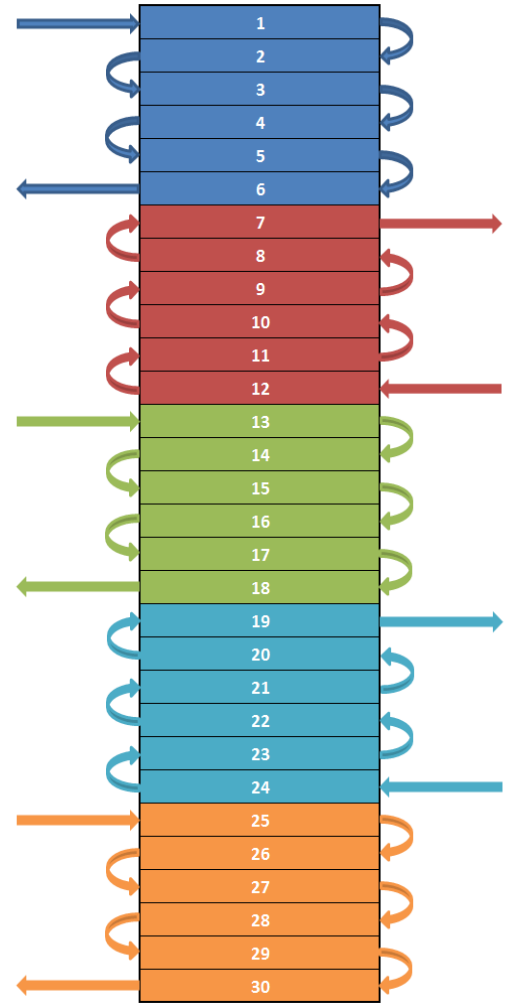


Heat flux is input to heat transfer calculations

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



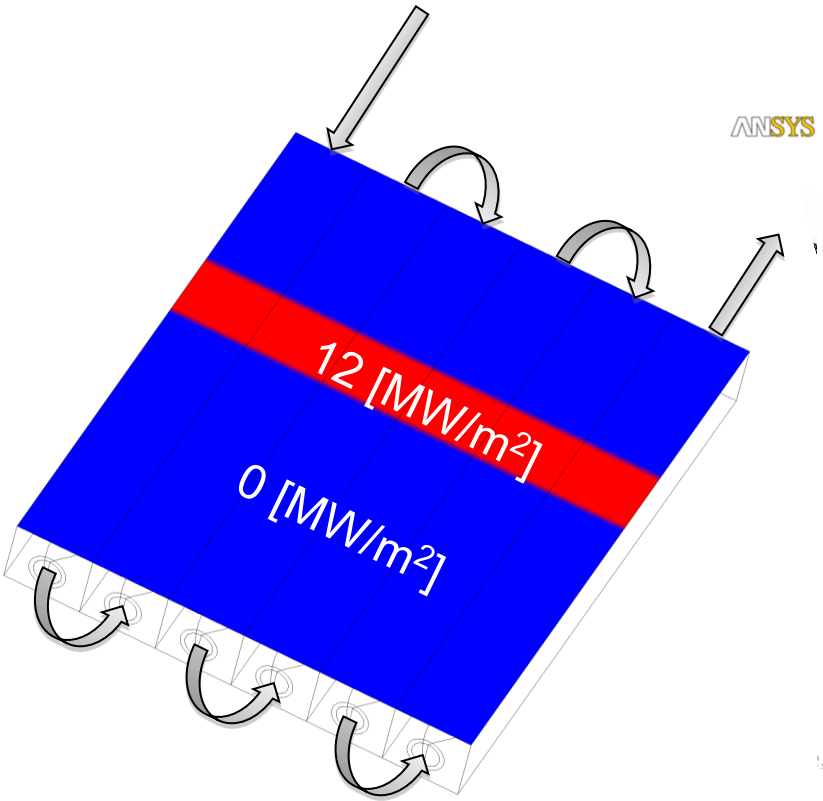


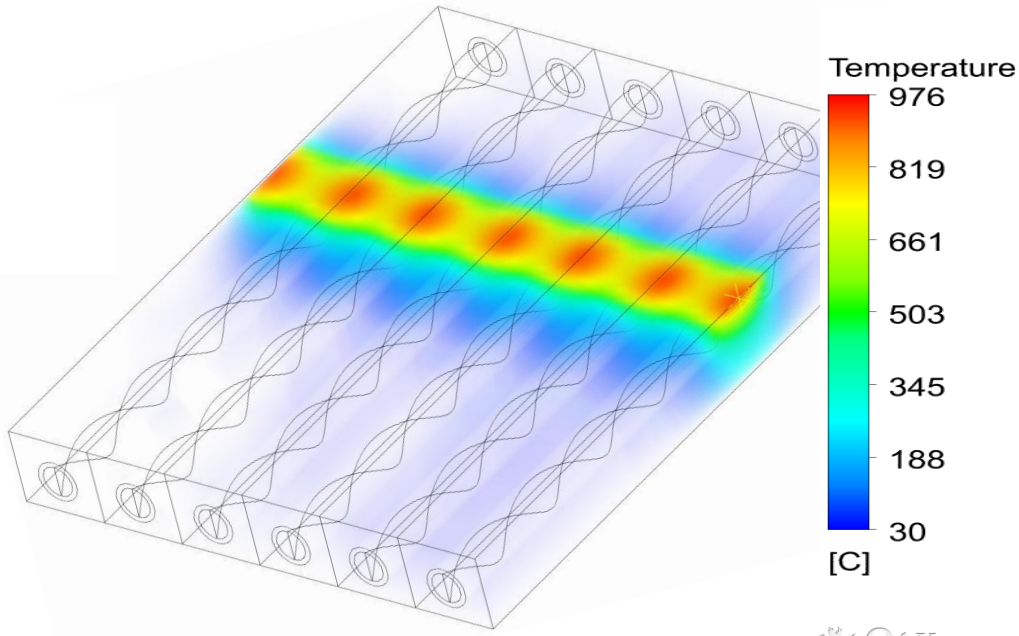


Fluid/FEM Modeling performed by J. Tipton

Initial calculations indicate design criteria satisfied for 'worst case'

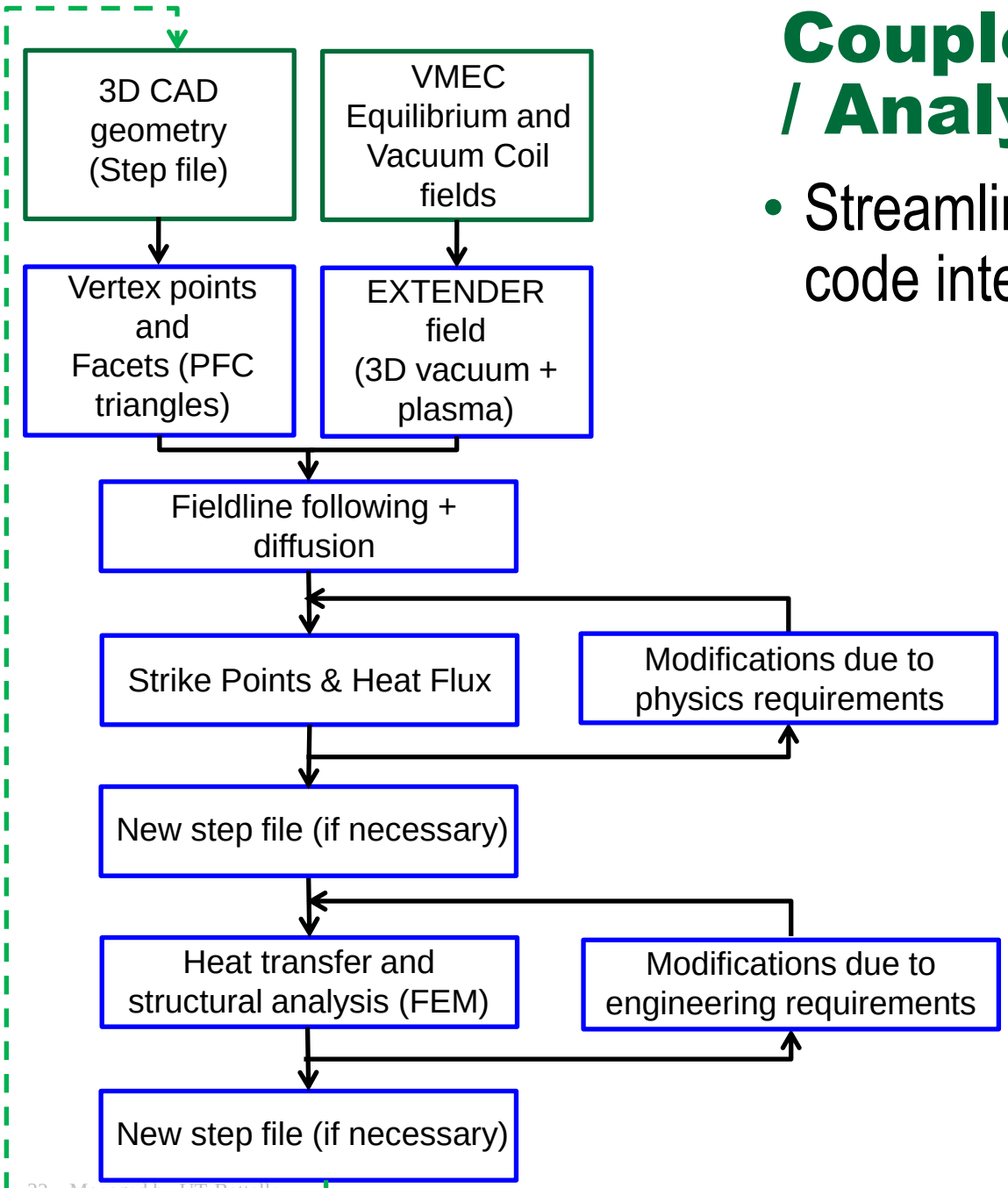
- Calculations are for a conservative model of the highest heat flux in steady state
  - The peak heat flux was applied over a single band with the wetted area chosen to match the total power to the scraper (400kW)
  - Fluid and thermal modeling performed using ANSYS CFX
  - All design criteria (pressure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





Coupled Optimization / Analysis In Progress

- Streamlining CAD-physics code interface is critical



- Max Divertor Flux
- Max Scraper Flux
- Pitch angle
- …

- Pressure drop
- Fluid temp rise
- Max fluid temp
- Max CFC temp
- Stresses
- …

Calculation of Heat Fluxes in Other Configurations is Underway

- 10 ‘reference’ vacuum configurations to be analyzed
  - Identify any other ‘high flux’ scenarios
  - Transport calculations must be performed to determine adjusted vacuum iota configurations, if necessary
- Longer term: EMC3-Eirene for neutrals and finite perp. transport effects
  - Add neutral calculations to physics-engineering iterations

Summary: 3D modeling is in progress for NSTX and W7X

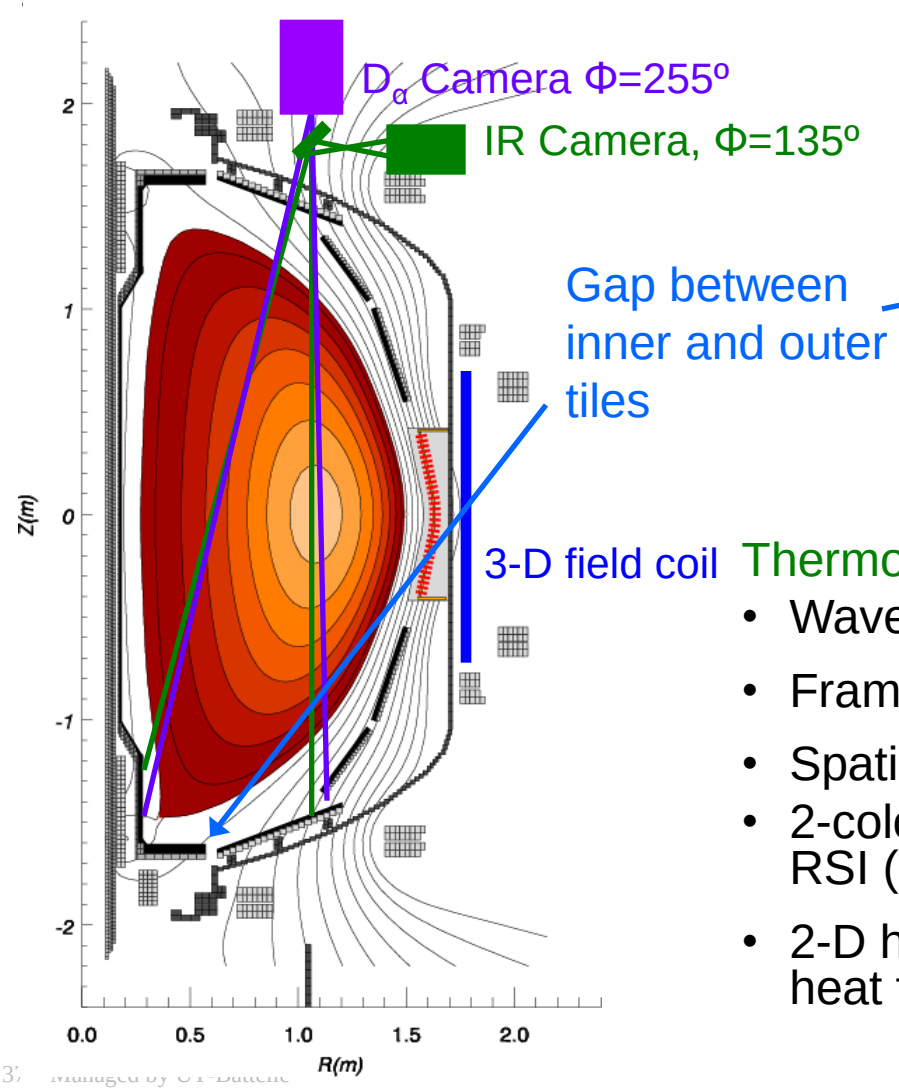
- NSTX
  - Intrinsic and applied 3D fields modify divertor heat fluxes, detachment, and pedestal profiles
  - New DDN EMC3 grid developed and implemented to model NSTX plasmas
  - 3D Vacuum and fluid modeling reproduce positions of strike point splitting peaks
  - Longer term: Implementation of field models, look at detachment case
- W7X
  - ‘Scraper Element’ divertor addition is being designed to protect primary targets during bootstrap current evolution
  - Vacuum and VMEC+Extender fields are used to calculate flux patterns and magnitudes
  - Remaining vacuum ‘reference’ configurations under investigation
  - Longer term: Use of EMC3-Eirene to account for effects of neutral particles, cross-field transport

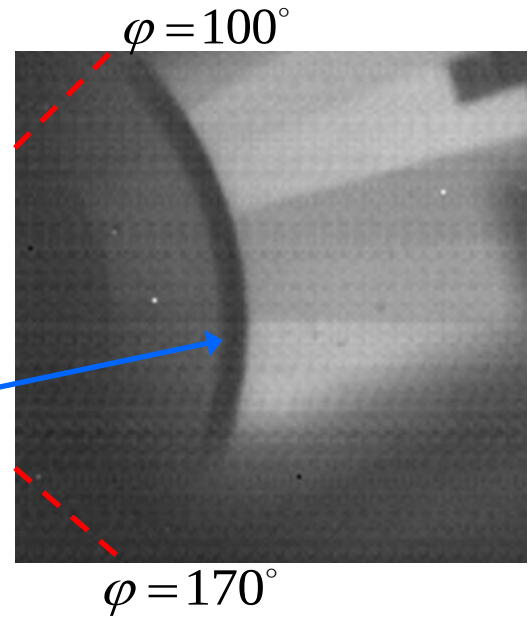
Extra Slides

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

Variable	Limit	Type	Result	Source
Pressure Drop	14 [bar]	Constraint	8.5 [bar] ± 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	≈1200 [C]	Objective	976 [C] ± 10%	CFD (Grid Convergence)

Divertor heat flux and D_α measurement in NSTX





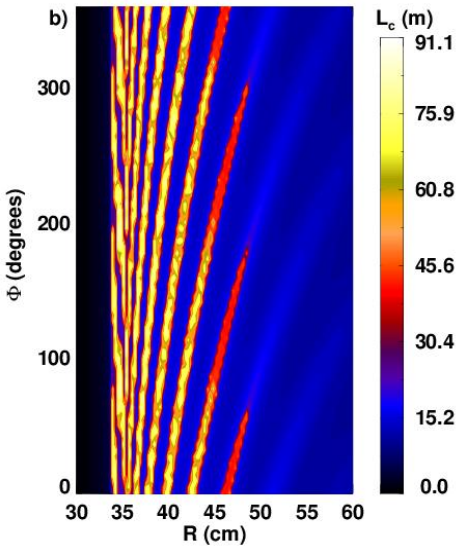
Thermography details: J-W. Ahn. RSI (2010), 023501

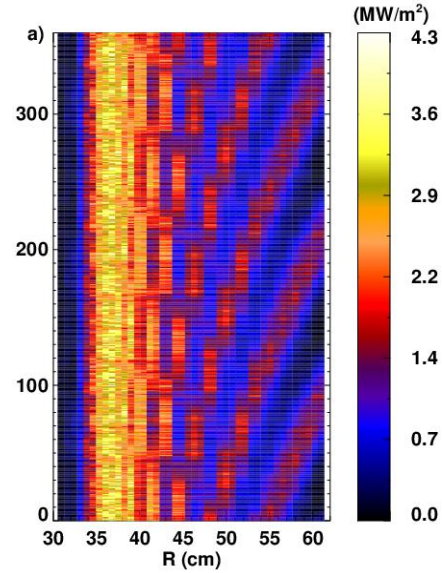
- Wavelength range: 8-10μm → 3-10μm
- Frame speed: 1.6 (128x128) – 6.3 (96x32) kHz
- Spatial resolution : 5-7mm
- 2-color IR data becoming available (A. McLean, RSI (2011))
- 2-D heat conduction model (THEODOR)[1] for heat flux calculation

[1]Collaboration with IPP Garching, A. Herrmann

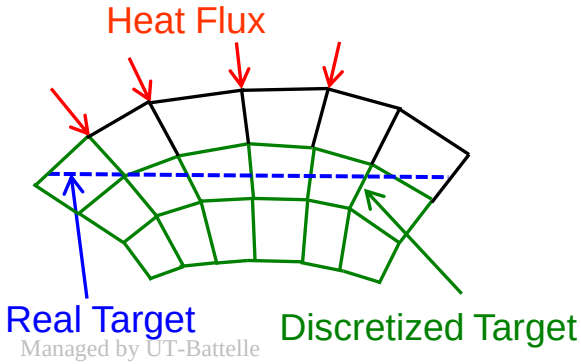
3D Field Results in Striated Energy Flux Footprints

- Results shown for lower horizontal target, at $\phi = 0°$
  - Single peak in heat flux for $I_{RWM} = 0A$
  - Striated patterns with $I_{RWM} = 1kA$
- Some artifacts, possibly from target discretization
  - Plasma quantities are mapped from grid cells to target faces during post-processing
  - Neutrals are launched from real target geometry
  - Further grid optimization, increasing grid resolution near targets should reduce mapping errors

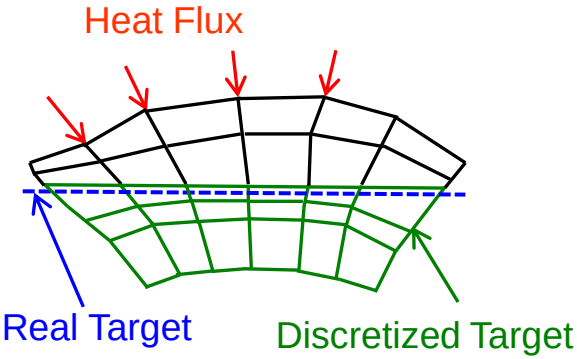




Non-optimized Target Grid



Partially optimized Target Grid



J.D. Lore, *et al.*, Phys. Plasmas, 2012 (accepted)