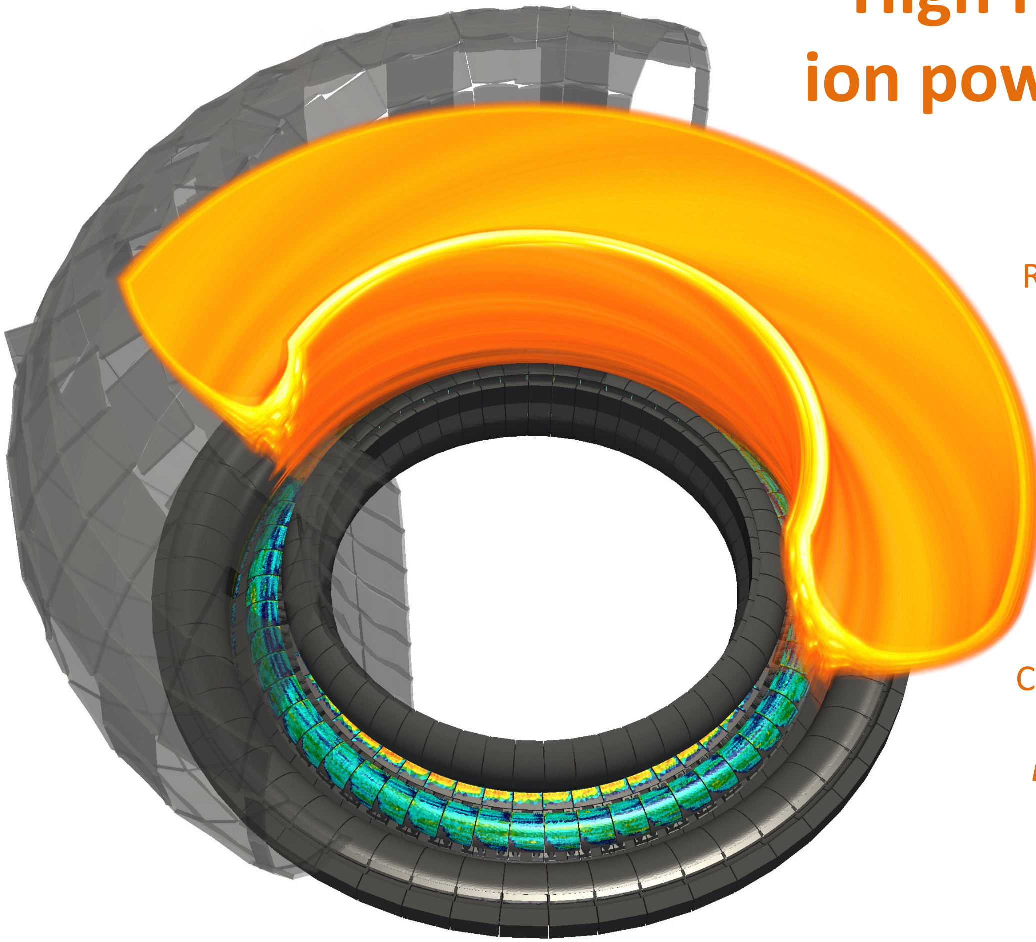

High fidelity simulations of fast ion power flux driven by 3D field perturbations on ITER

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UK Atomic Energy Authority

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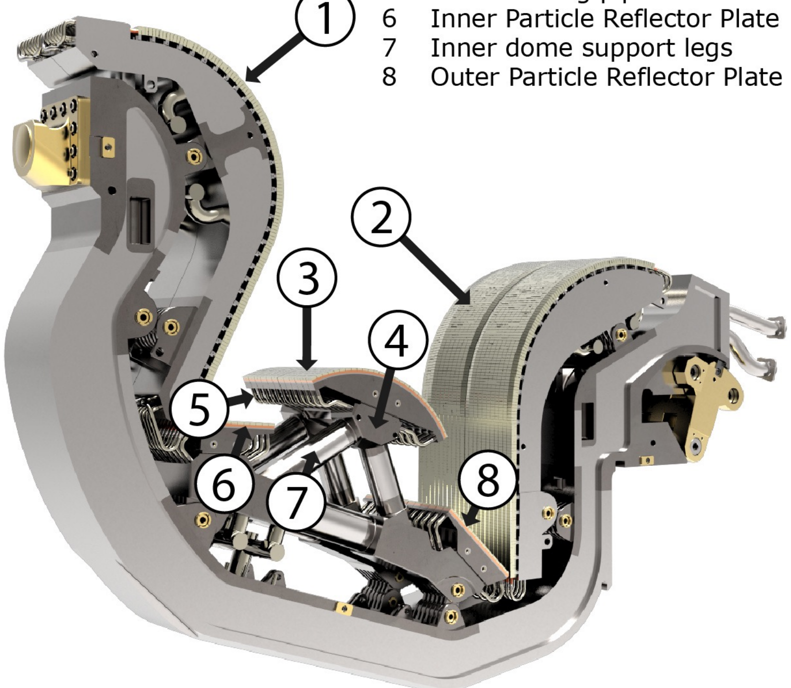
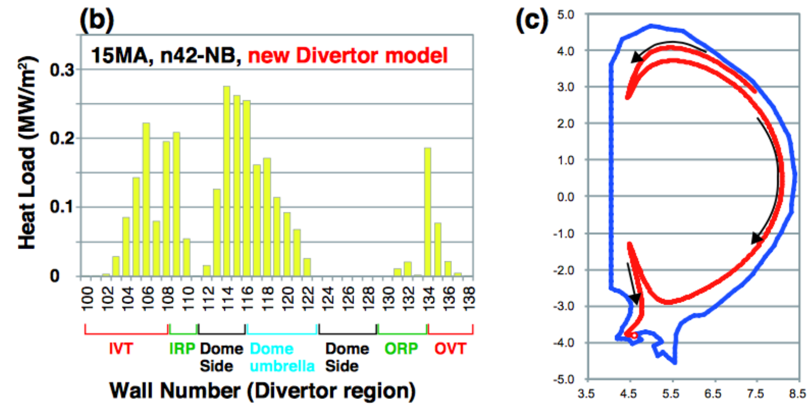
IAEA Fusion Energy Conference 2016, TH/4-1

Code development motivated by problem posed FEC2012

1 Inner Vertical Target (IVT)
2 Outer Vertical Target (OVT)
3 Dome Umbrella
4 Manifold
5 Inner cooling pipes
6 Inner Particle Reflector Plate
7 Inner dome support legs
8 Outer Particle Reflector Plate



T Oikawa et al., IAEA FEC 2012, paper ITR/P1-35.



0.2-0.3MW/m^2 (vacuum ECC field @90kAt)
(0.1MW/m^2 expected from thermal/radiative load)

Need:

- Accurate plasma response field
- High statistics
- Higher fidelity first wall model
- Gyro-motion

We have developed a new Monte Carlo code to solve this challenge:
LOCUST-gpu (the Lorentz Orbit Code for Use in Stellarators and Tokamaks)

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LOCUST-gpu solves the following equations using GPUs:

Lorentz equation of motion

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{v}\times\mathbf{B})$$

Based upon Boris pusher, math light!

Guiding Centre equations

$$\dot{\chi} = \frac{qB}{m},$$
$$\dot{\mu} = 0,$$
$$\dot{v}_\parallel = \frac{q}{m}\frac{\mathbf{B}^\star}{B^\star_\parallel}\cdot\mathbf{E}^\star,$$
$$\dot{\mathbf{R}} = v_\parallel\frac{\mathbf{B}^\star}{B^\star_\parallel} + \mathbf{E}^\star\times\frac{\mathbf{b}}{B^\star_\parallel},$$

$$\mathbf{E}^\star = -\partial\mathbf{A}^\star/\partial t - \nabla\Phi^\star$$

$$\mathbf{B}^* = \nabla\times\mathbf{A}^*$$

$$\Phi^\star(\mathbf{R},\mu,t) = \Phi + \frac{\mu B}{q},$$
$$\mathbf{A}^\star(\mathbf{R},v_\parallel,t) = \mathbf{A} + \frac{m v_\parallel \mathbf{b}}{q}.$$

Based upon RKF45, math heavy!

Collision operator

$$\Delta\xi = -\nu\xi\Delta t + \delta_1\left[(1-\xi^2)\nu\,\Delta t\right]^{1/2},$$
$$\Delta\epsilon = -\sum_j 2\nu_{\epsilon,j}\Delta t\left[\epsilon - \left(\frac{3}{2} + \frac{\epsilon}{\nu_{\epsilon,j}}\frac{d\nu_{\epsilon,j}}{d\epsilon}\right)k_B T_j\right] + \delta_2\left(\sum_j 2k_B T_j \epsilon\,\nu_{\epsilon,j}\,\Delta t\right)^{1/2},$$

Time/spatial scale	Value (ITER 15MA H-mode, 1MeV D injection)
Gyro frequency	$3.8\mathrm{x}10^7$ Hz
Field structure scale length	>2cm (poloidal plane)
Slowing down time	~1.5s (core born)

Choice of 9 tracking integrators.

Here we use **Boris**,
2ns time-step.

"Why is Boris Algorithm So Good?"
Hong Qin et. al., PPPL-4872, April 2013.

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LOCUST-gpu deploys a detailed tetrahederal mesh

Raw CAD (e.g. Catia, STEP etc.)

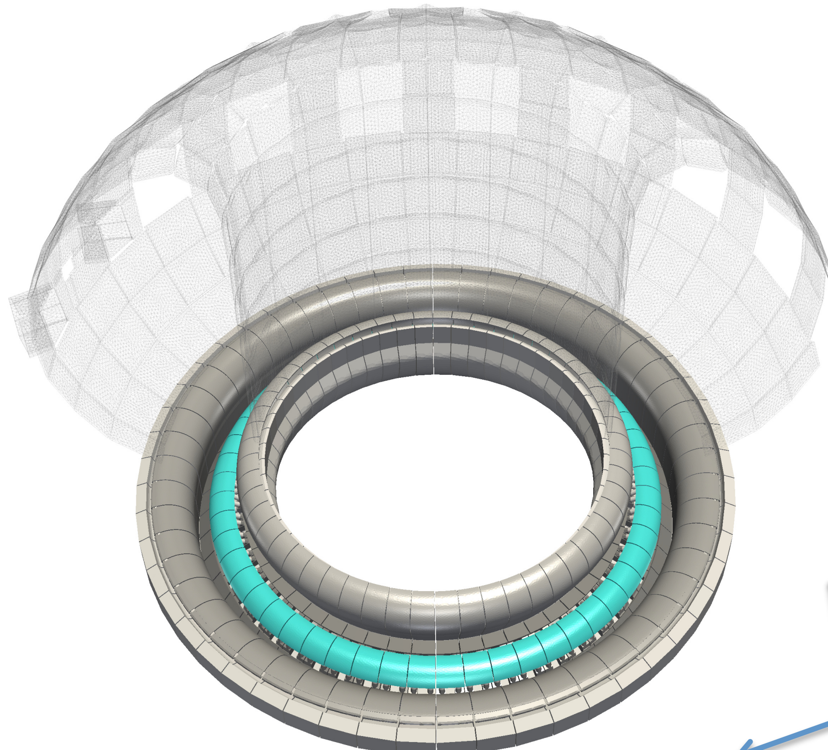
Fix broken parts + de-feature

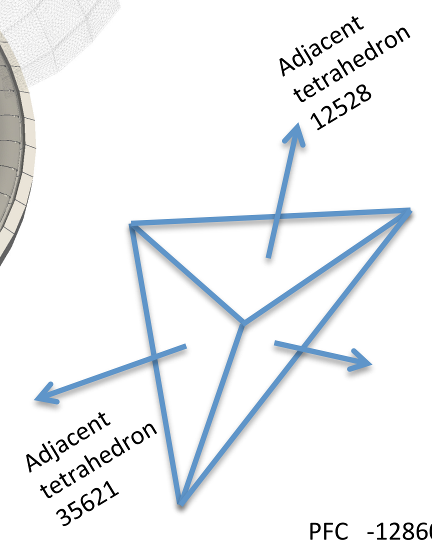
CADfix

ANSYS SpaceClaim

Mesh (<12GB)

Attila



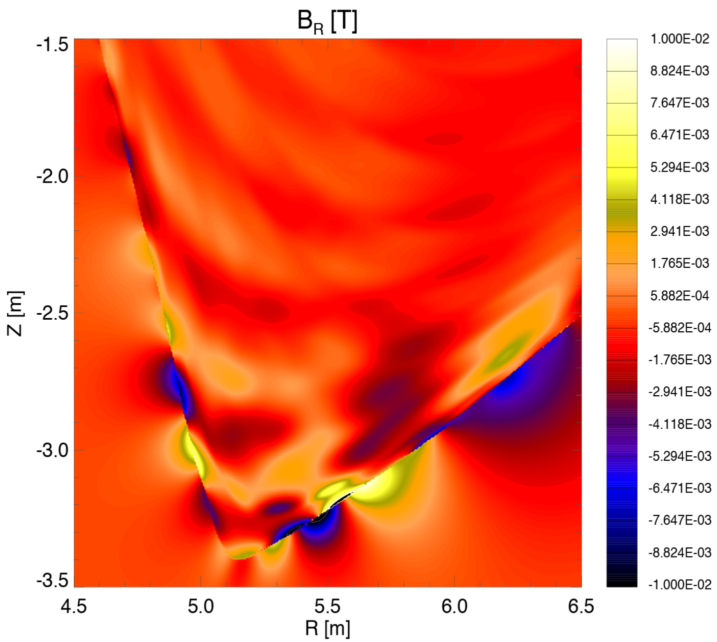


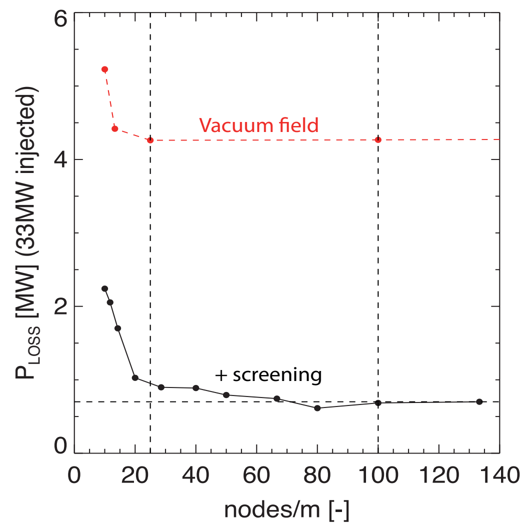
ITER LOCUST-gpu mesh

# tetrahedra	:	57570062
# nodes	:	17620565
# components	:	13
# surface triangles	:	2528454

Assous F., Degond P., Segre J. Comput. Phys. Commun. 72, 1992, p105.

ECC field map built from MARS-F field components





$$
\begin{aligned}
\mathbf{B1}(s,\chi,\phi) &= \sum_{m=\mathbf{M1}}^{\mathbf{M2}} \mathbf{B1}(s,m)e^{im\chi+in\phi} \\
\mathbf{B2}(sm,\chi,\phi) &= \sum_{m=\mathbf{M1}}^{\mathbf{M2}} \mathbf{B2}(sm,m)e^{im\chi+in\phi} \\
\mathbf{B3}(sm,\chi,\phi) &= \sum_{m=\mathbf{M1}}^{\mathbf{M2}} \mathbf{B3}(sm,m)e^{im\chi+in\phi} \\
B_R &= \frac{1}{J}\left(\mathbf{B1}\frac{\partial R}{\partial s}+\mathbf{B2}\frac{\partial R}{\partial \chi}\right) \\
B_Z &= \frac{1}{J}\left(\mathbf{B1}\frac{\partial Z}{\partial s}+\mathbf{B2}\frac{\partial Z}{\partial \chi}\right) \\
B_\phi &= \frac{1}{J}R\mathbf{B3} \\
J &= \left(\frac{\partial R}{\partial s}\frac{\partial Z}{\partial \chi}-\frac{\partial R}{\partial \chi}\frac{\partial Z}{\partial s}\right)R
\end{aligned}
$$

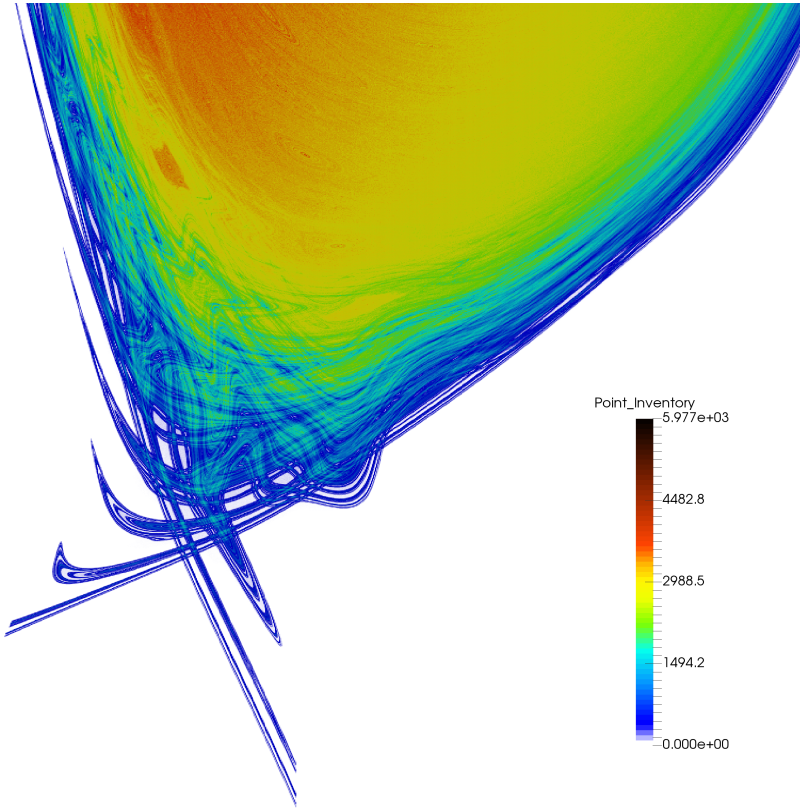
- Separate radial splines for s<1 and s>1.
- Large values of M0=240, M1=-109 & M2=+109 needed.
- LOCUST-gpu uses bi-cubic spline of ψ for 2D field and either tri-cubic spline or summation over toroidal Fourier harmonics using bi-cubic splines of the Real and Imaginary components of the field vectors for a given n.

$$
\begin{aligned}
R(s,\chi) &= \mathbf{RF}(s,1)+2Re[\sum_{m=2}^{\mathbf{M0}} \mathbf{RF}(s,m)e^{i(m-1)\chi}] \\
Z(s,\chi) &= \mathbf{ZF}(s,1)+2Re[\sum_{m=2}^{\mathbf{M0}} \mathbf{ZF}(s,m)e^{i(m-1)\chi}]
\end{aligned}
$$

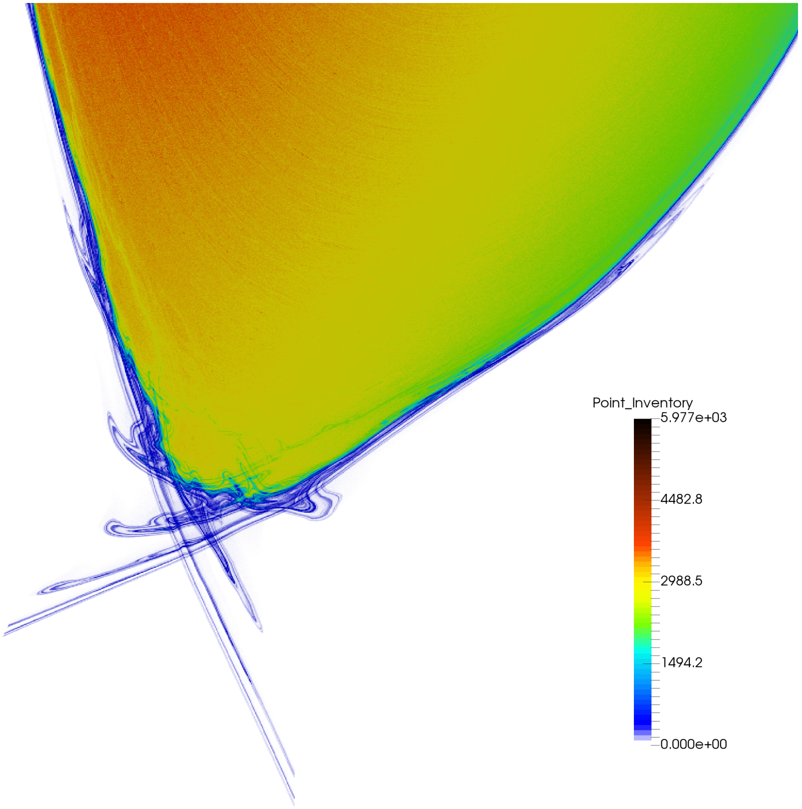
Chosen grid res: 0.5cm x 0.5cm

LOCUST-gpu can efficiently follow field lines as well as orbits…

Colour rendered Poincare plots of the ITER homoclinic tangle



ITER 15MA baseline H-mode with
45kAt n=3 ECC (vacuum, incl. n=6 sideband)



ITER 15MA baseline H-mode with
45kAt n=3 ECC (incl. n=6 sideband &
plasma screening)

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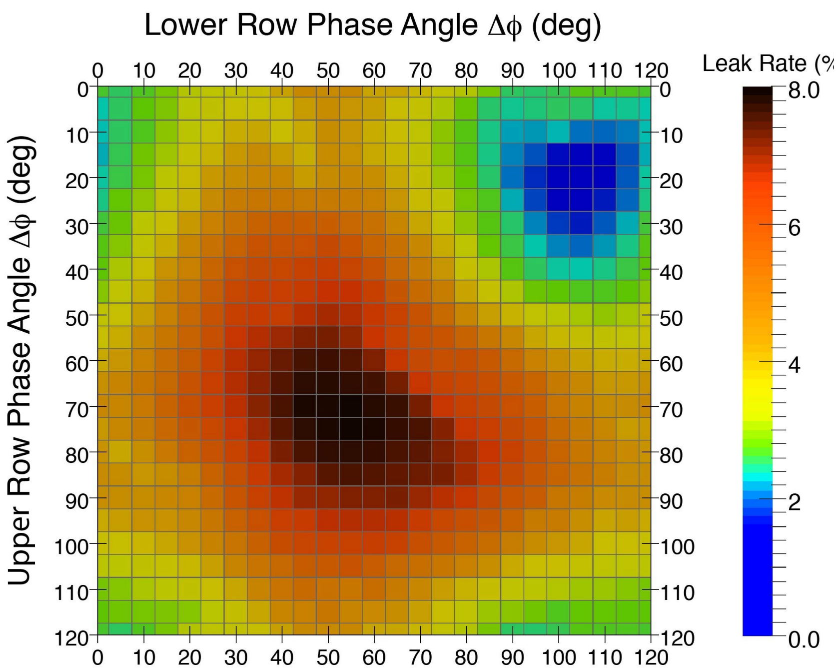
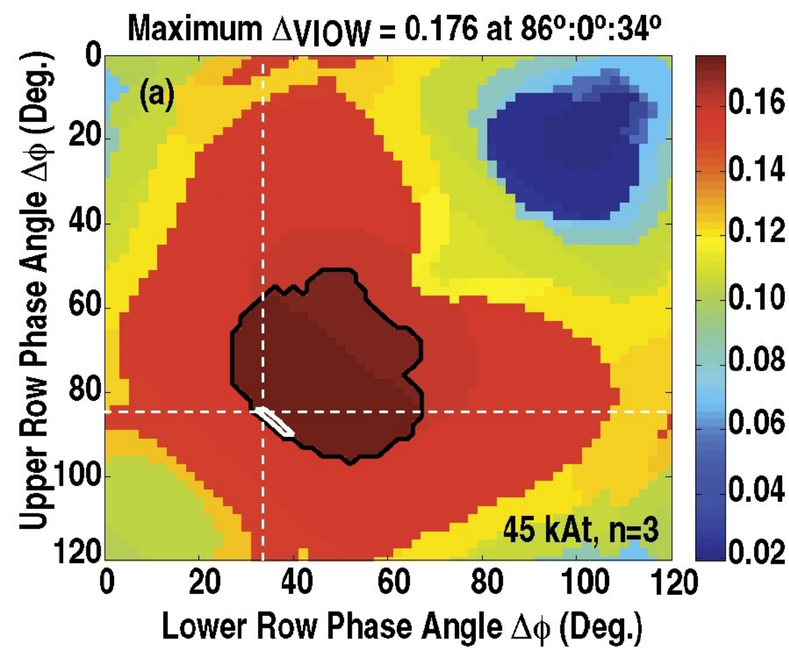
[86º,0º,34º] U,M,L phase settings generate close to maximum stochasticity for a given ECC drive current





T.E.Evans et al., IAEA FEC2012 paper ITR P1-25

- MARS-F runs done for each coil set independently, separated into toroidal harmonics.
- Scan of field line leak rate vs. upper & lower coil set phase offset looks very similar to that of vacuum island overlap width.

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Is our cooling pipe problem tractable?

In 24 hours, the 3 K80 nodes at CCFE can integrate up a distance (with 2cm resolution, 1MeV D + 2D field) of: 5.4×10^{12}m

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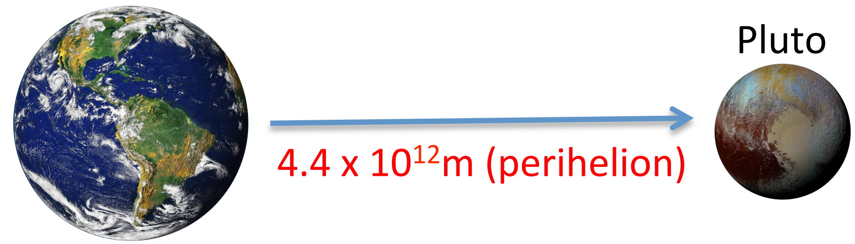

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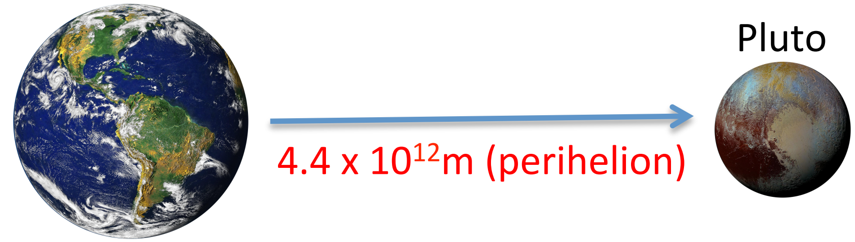

For a 10% statistical error...
(very rough back of the envelope calculation):

100	markers per triangle
400	triangles "painted" area per pipe
12	pipes per cassette
54	cassettes
~1.0×10^{7}m/s	"average" velocity over slowing down
~0.5s	Time to impact
50kW	Power deposited to pipes (0.15% injected)

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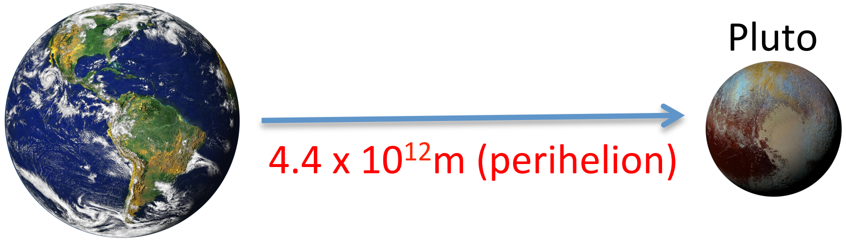
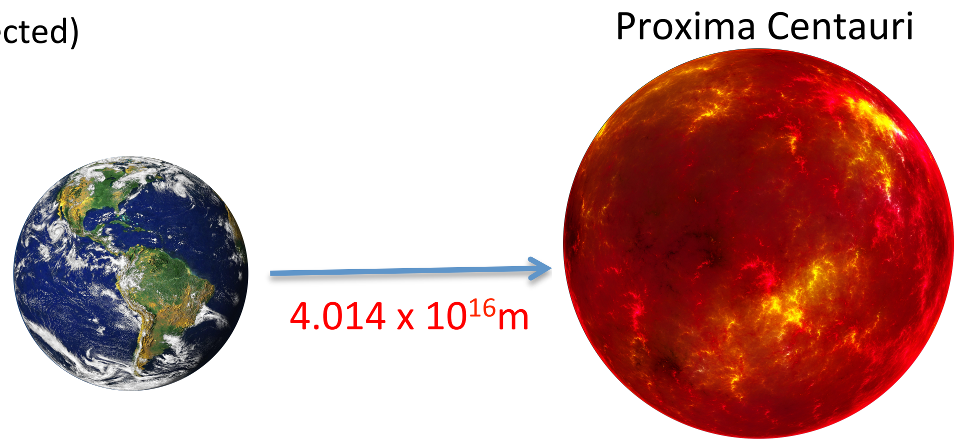


$100 \times 400 \times 12 \times 54 \times 1.0 \times 10^{7} \times 0.5 / (0.05 / 33.0)$
= 8.6×10^{16}m (~9 light years)



We are going to need some Monte Carlo “tricks”.

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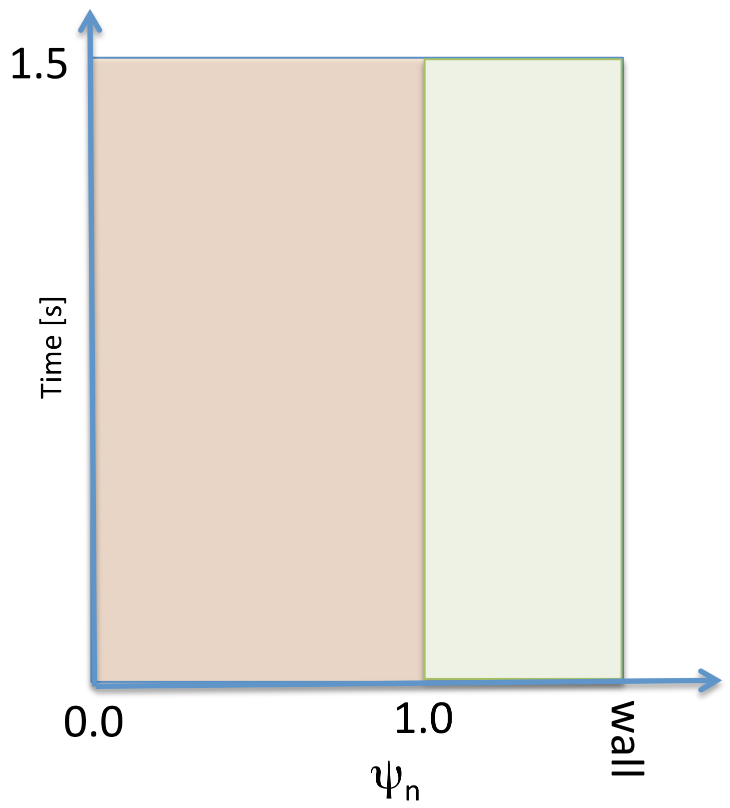
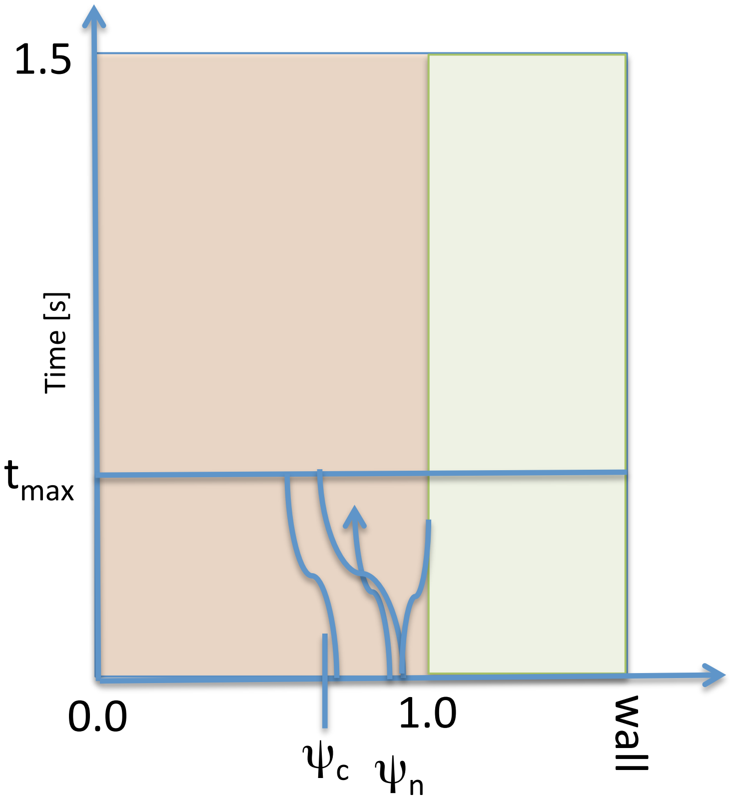
Monte Carlo Enhancement methods



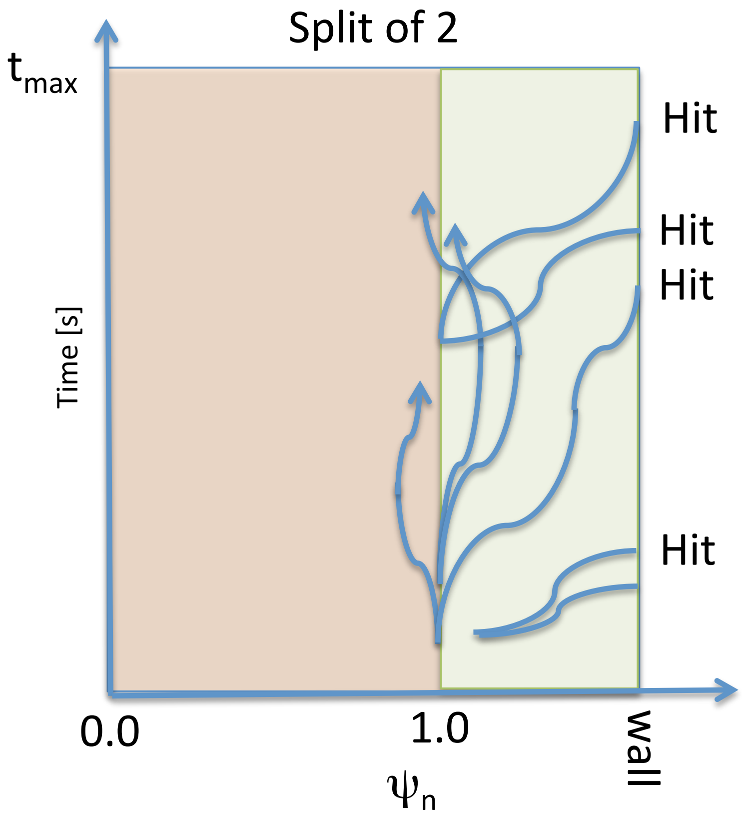
Tracking Stage 1



Stage 1: Track w/o PFC hit testing

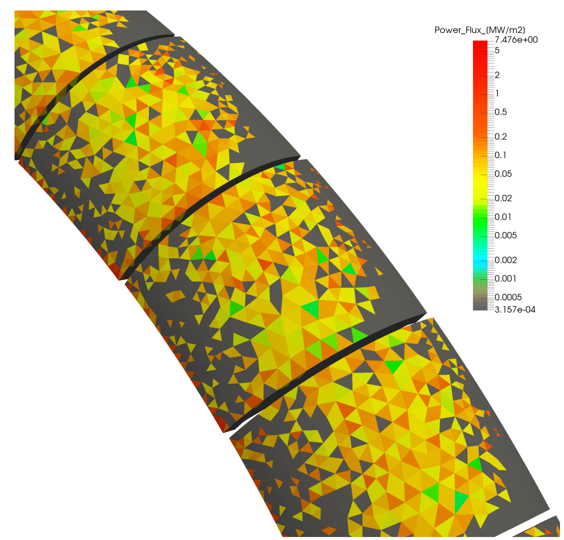
- Reject markers born inside $\psi_n = \psi_c$ (use a low stats run to determine ψ_c and also maximum tracking time)
- Follow markers inside $\psi_n = 1$ until they cross the separatrix (when they do, cache them) or until they thermalize or reach t_{max}.
- Every n kernal calls, cache all the marker state parameters, keeping m copies.

Tracking Stage 2

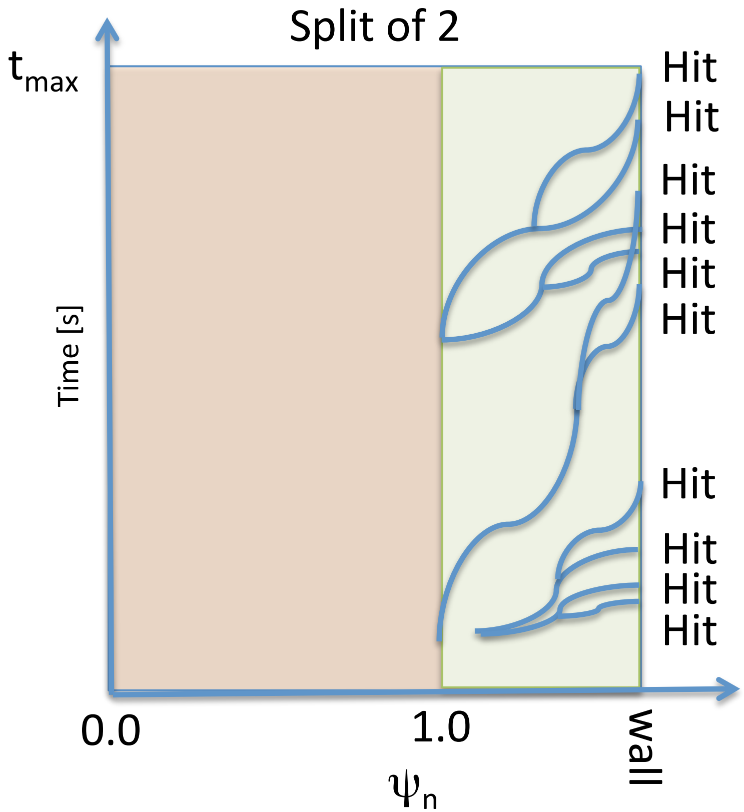


Stage 2: Track with PFC hit testing

- "Split" markers that were either born outside the separatrix or were cached from stage 1 until they hit the wall, are thermalized or reach t_{max}.

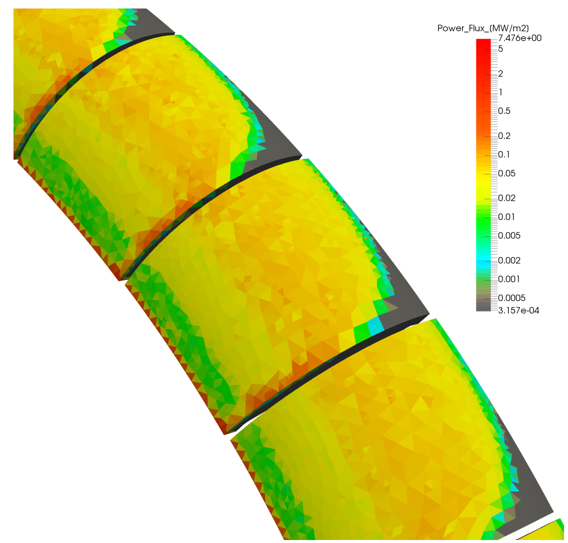


Tracking Stage 3



Stage 3: Step markers which hit wall back in time

- Use marker state cache to step markers which hit wall back in time and "massively split" them to form a new ensemble.



Stepping back ~0.2-0.4ms sufficient for collisions to smear out markers and produce smooth maps.

Caveat: Must step far enough back in t to prevent problems with shadow areas. Power accounting maintained by normalizing newly collected power from siblings to their parent marker.

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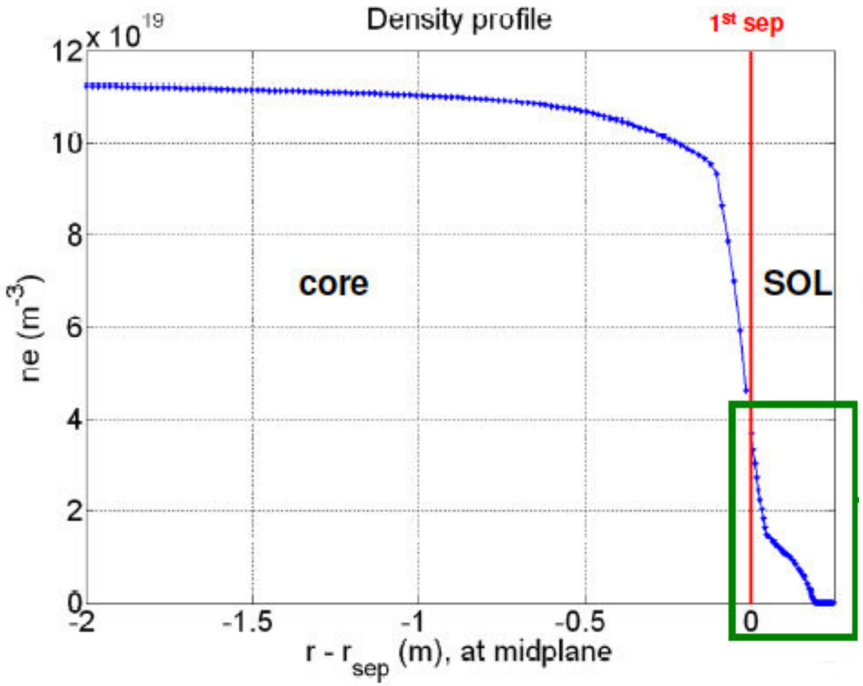
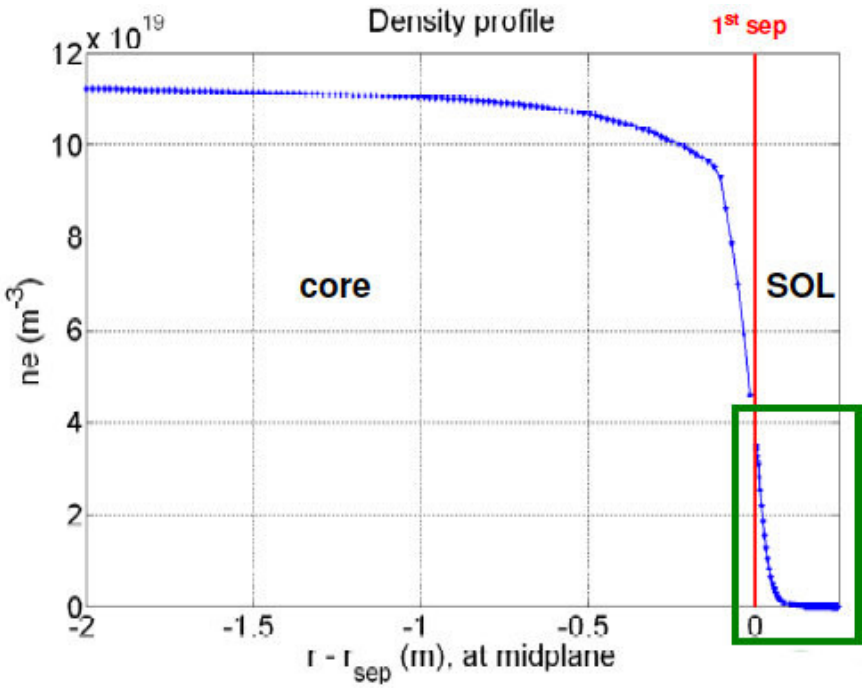
Results: Location dependent losses

15MA baseline H-mode, 1 beam on-axis, 1 off-axis. (33MW D injection) n=3 ECC (including n=6 sideband)

ITER_D_33Y59M – v2.3



High Density SOL (H)



Low Density SOL (L)

Results: Location dependent losses

2D field:

- Losses are negligible for low density SOL.
- 0.26MW (0.8%) loss, mainly prompt to 1st wall and OVT for high density SOL.

LOCUST-gpu: Bicubic spline ECC field (n=3 + n=6 sideband)

I_c [kAt]	Plasma Response ?	$n_{e(SOL)}$ High/ Low [MW]	1st wall [MW]	Dome Umbrella [MW]	Inner Support legs [MW]	Outer PRP [MW]	Inner Cooling pipes [MW]	OVT [MW]	IVT [MW]	
0	-	L	0.0032± 0.0004	0.0062± 0.0006	0.00007± 0.00006	0.0004± 0.0001	0.000± 0.000	0.0081± 0.0004	0.00118± 0.00005	0.01MW (0.04%)
45	✗	L	0.0038± 0.0008	0.216± 0.004	0.0085± 0.0007	0.0029± 0.0004	0.0227± 0.0013	0.296± 0.003	0.591± 0.004	
45	✓	L	0.0036± 0.0005	0.078± 0.001	0.0032± 0.0004	0.0028± 0.0002	0.0069± 0.0004	0.0486± 0.0008	0.0206± 0.0006	
90	✗	L	0.0076± 0.0011	0.962± 0.012	0.044± 0.002	0.0091± 0.0013	0.156± 0.004	1.251± 0.011	1.821± 0.016	
90	✓	L	0.0077± 0.0006	0.262± 0.003	0.0197± 0.0007	0.0104± 0.0008	0.043± 0.001	0.239± 0.002	0.146± 0.002	
0	-	H	0.109	0.0472± 0.0018	0.0002± 0.0001	0.0049± 0.0004	0.0001± 0.0001	0.108	0.0025± 0.0003	0.26MW (0.8%)
45	✗	H	0.111± 0.004	0.295± 0.004	0.0087± 0.0010	0.0116± 0.0009	0.0239± 0.0018	0.461± 0.006	0.573± 0.005	
45	✓	H	0.113± 0.003	0.171± 0.003	0.0029± 0.0003	0.0118± 0.0006	0.0067± 0.0005	0.180± 0.002	0.0211± 0.0007	
90	✗	H	0.128± 0.002	1.049± 0.006	0.0477± 0.0015	0.0151± 0.0005	0.151± 0.002	1.454± 0.008	1.808± 0.008	
90	✓	H	0.128± 0.004	0.357± 0.005	0.019± 0.001	0.0173± 0.0007	0.049± 0.001	0.414± 0.005	0.149± 0.002	

Results: Location dependent losses

45kAt vacuum ECC field:

- Losses to dome umbrella increase to 0.2(L)-0.3(H)MW
- Losses to OVT increase by 0.3(L)-0.35(H)MW
- Losses to IVT increase by ~0.6MW (similar for both Low and High density SOL)
- 1st wall losses don't increase very much (prompt, poorly confined orbits in SOL)

LOCUST-gpu: Bicubic spline ECC field (n=3 + n=6 sideband)

I_c [kAt]	Plasma Response ?	$n_{e(SOL)}$ High/ Low [MW]	1st wall [MW]	Dome Umbrella [MW]	Inner Support legs [MW]	Outer PRP [MW]	Inner Cooling pipes [MW]	OVT [MW]	IVT [MW]	
0	-	L	0.0032± 0.0004	0.0062± 0.0006	0.00007± 0.00006	0.0004± 0.0001	0.000± 0.000	0.0081± 0.0004	0.00118± 0.00005	
45	✗	L	0.0038± 0.0008	0.216	0.0085± 0.0007	0.0029± 0.0004	0.0227± 0.0013	0.296	0.591	➡ 1.11MW (3.4%)
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0	-	H	0.109	0.0472± 0.0018	0.0002± 0.0001	0.0049± 0.0004	0.0001± 0.0001	0.108± 0.002	0.0025± 0.0003	
45	✗	H	0.111	0.295	0.0087± 0.0010	0.0116± 0.0009	0.0239± 0.0018	0.461	0.573	➡ 1.47MW (4.5%)
45	✓	H	0.113	0.171± 0.003	0.0029± 0.0003	0.0118± 0.0006	0.0067± 0.0005	0.180± 0.002	0.0211± 0.0007	
90	✗	H	0.128	1.049± 0.006	0.0477± 0.0015	0.0151± 0.0005	0.151± 0.002	1.454± 0.008	1.808± 0.008	
90	✓	H	0.128	0.357± 0.005	0.019± 0.001	0.0173± 0.0007	0.049± 0.001	0.414± 0.005	0.149± 0.002	

Results: Location dependent losses

45kAt ECC field incl. plasma screening (MARS-F):

- For low density SOL, losses reduce dramatically down to ~0.5%.
- High density SOL – losses reduce by 2/3 to 1.5% (DU, OVT, IVT). Prompt loss to wall and OVT remain.
- Under dome cooling pipes – power flux still negligible.

LOCUST-gpu: Bicubic spline ECC field (n=3 + n=6 sideband)

I_c [kAt]	Plasma Response ?	$n_{e(SOL)}$ High/ Low [MW]	1^{st} wall [MW]	Dome Umbrella [MW]	Inner Support legs [MW]	Outer PRP [MW]	Inner Cooling pipes [MW]	OVT [MW]	IVT [MW]	
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45	✗	L	0.0038± 0.0008	0.216± 0.004	0.0085± 0.0007	0.0029± 0.0004	0.0227	0.296± 0.003	0.591± 0.004	1.11MW (3.4%)
45	✓	L	0.0036± 0.0005	0.078± 0.001	0.0032± 0.0004	0.0028± 0.0002	0.0069	0.0486± 0.0008	0.0206± 0.0006	0.15MW (0.5%)
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90	✓	L	0.0077± 0.0006	0.262± 0.003	0.0197± 0.0007	0.0104± 0.0008	0.043± 0.001	0.239± 0.002	0.146± 0.002	
0	-	H	0.109± 0.003	0.0472± 0.0018	0.0002± 0.0001	0.0049± 0.0004	0.0001± 0.0001	0.108± 0.002	0.0025± 0.0003	
45	✗	H	0.111	0.295	0.0087± 0.0010	0.0116± 0.0009	0.0239	0.461	0.573	1.47MW (4.5%)
45	✓	H	0.113	0.171	0.0029± 0.0003	0.0118± 0.0006	0.0067	0.180	0.021	0.50MW (1.5%)
90	✗	H	0.128± 0.002	1.049± 0.006	0.0477± 0.0015	0.0151± 0.0005	0.151± 0.002	1.454± 0.008	1.808± 0.008	
90	✓	H	0.128± 0.004	0.357± 0.005	0.019± 0.001	0.0173± 0.0007	0.049± 0.001	0.414± 0.005	0.149± 0.002	

Results: Location dependent losses

90kAt vacuum ECC field:

- Losses increase dramatically compared with 45kAt (by >3MW for L and similar for H SOL)
- Losses are mainly to dome umbrella, OVT and IVT
- Divertor under-dome cooling pipes hit ~150kW (spread over an area of order 1m – but not uniformly)

LOCUST-gpu: Bicubic spline ECC field (n=3 + n=6 sideband)

I_c [kAt]	Plasma Response ?	$n_{e(SOL)}$ High/ Low [MW]	1st wall [MW]	Dome Umbrella [MW]	Inner Support legs [MW]	Outer PRP [MW]	Inner Cooling pipes [MW]	OVT [MW]	IVT [MW]	
0	-	L	0.0032± 0.0004	0.0062± 0.0006	0.00007± 0.00006	0.0004± 0.0001	0.000± 0.000	0.0081± 0.0004	0.00118± 0.00005	
45	✗	L	0.0038± 0.0008	0.216	0.0085± 0.0007	0.0029± 0.0004	0.0227± 0.0013	0.296	0.591	1.11MW (3.4%)
45	✓	L	0.0036± 0.0005	0.078± 0.001	0.0032± 0.0004	0.0028± 0.0002	0.0069± 0.0004	0.0486± 0.0008	0.0206± 0.0006	
90	✗	L	0.0076± 0.0011	0.962	0.044± 0.002	0.0091± 0.0013	0.156	1.251	1.821	4.3MW (13%)
90	✓	L	0.0077± 0.0006	0.262± 0.003	0.0197± 0.0007	0.0104± 0.0008	0.043± 0.001	0.239± 0.002	0.146± 0.002	
0	-	H	0.109± 0.003	0.0472± 0.0018	0.0002± 0.0001	0.0049± 0.0004	0.0001± 0.0001	0.108± 0.002	0.0025± 0.0003	
45	✗	H	0.111± 0.004	0.295	0.0087± 0.0010	0.0116± 0.0009	0.0239± 0.0018	0.461	0.573	1.47MW (4.5%)
45	✓	H	0.113± 0.003	0.171± 0.003	0.0029± 0.0003	0.0118± 0.0006	0.0067± 0.0005	0.180± 0.002	0.0211± 0.0007	
90	✗	H	0.128± 0.002	1.049	0.0477± 0.0015	0.0151± 0.0005	0.151	1.454	1.808	4.7MW (14%)
90	✓	H	0.128± 0.004	0.357± 0.005	0.019± 0.001	0.0173± 0.0007	0.049± 0.001	0.414± 0.005	0.149± 0.002	

Results: Location dependent losses

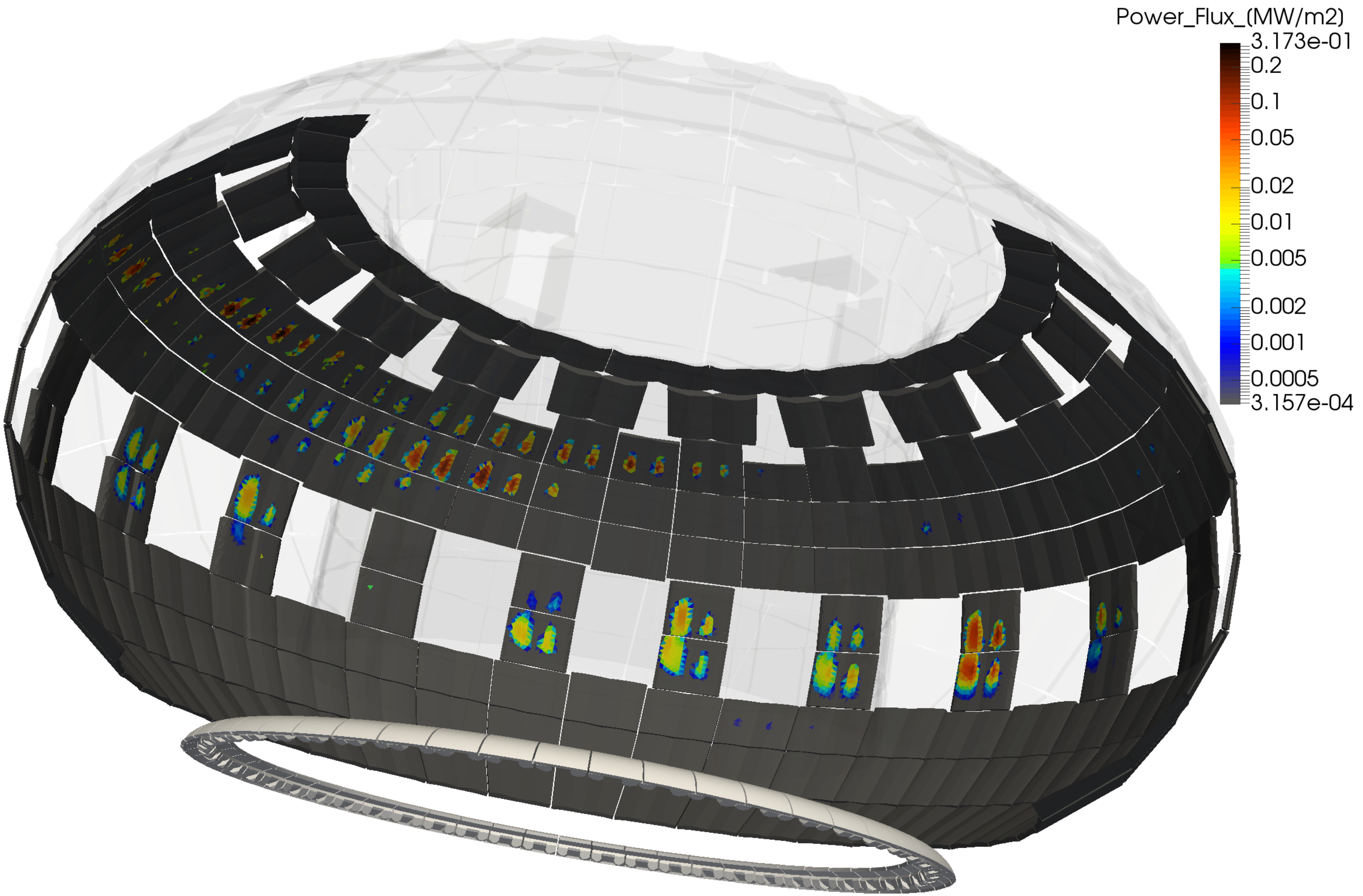
90kAt ECC field incl. plasma screening (MARS-F):

- Sharp rise in Dome umbrella, OVT and IVT losses relative to 45kAt.
- Plasma response effective at reducing losses (by over ¾) (reduction to DU, OVT and IVT).
- Screening reduces losses to the under dome cooling pipes by factor 3.

LOCUST-gpu: Bicubic spline ECC field (n=3 + n=6 sideband)

I_c [kAt]	Plasma Response ?	$n_{e(SOL)}$ High/ Low [MW]	1st wall [MW]	Dome Umbrella [MW]	Inner Support legs [MW]	Outer PRP [MW]	Inner Cooling pipes [MW]	OVT [MW]	IVT [MW]	
0	-	L	0.0032± 0.0004	0.0062± 0.0006	0.00007± 0.00006	0.0004± 0.0001	0.000± 0.000	0.0081± 0.0004	0.00118± 0.00005	
45	✗	L	0.0038± 0.0008	0.216± 0.004	0.0085± 0.0007	0.0029± 0.0004	0.0227± 0.0013	0.296± 0.003	0.591± 0.004	
45	✓	L	0.0036± 0.0005	0.078	0.0032± 0.0004	0.0028± 0.0002	0.0069± 0.0004	0.049	0.021	
90	✗	L	0.0076± 0.0011	0.962	0.044± 0.002	0.0091± 0.0013	0.156	1.251	1.821	4.3MW (13%)
90	✓	L	0.0077± 0.0006	0.262	0.0197± 0.0007	0.0104± 0.0008	0.043	0.239	0.146	0.74MW (2.2%)
0	-	H	0.109± 0.003	0.0472± 0.0018	0.0002± 0.0001	0.0049± 0.0004	0.0001± 0.0001	0.108± 0.002	0.0025± 0.0003	
45	✗	H	0.111± 0.004	0.295± 0.004	0.0087± 0.0010	0.0116± 0.0009	0.0239± 0.0018	0.461± 0.006	0.573± 0.005	
45	✓	H	0.113± 0.003	0.171	0.0029± 0.0003	0.0118± 0.0006	0.0067± 0.0005	0.180	0.021	
90	✗	H	0.128± 0.002	1.049	0.0477± 0.0015	0.0151± 0.0005	0.151	1.454	1.808	4.7MW (14%)
90	✓	H	0.128± 0.004	0.357	0.019± 0.001	0.0173± 0.0007	0.049	0.414	0.149	1.17MW (3.5%)

Results: Prompt losses from high density SOL



High density SOL: ~0.1MW of loss to first wall – power flux well below $2MW/m^2$ Beryllium limit

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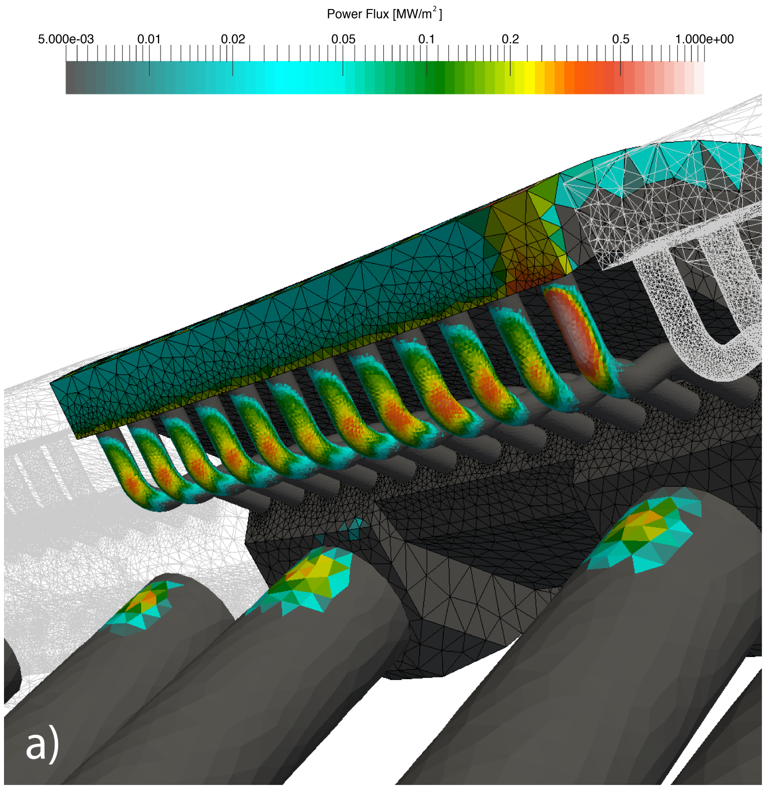
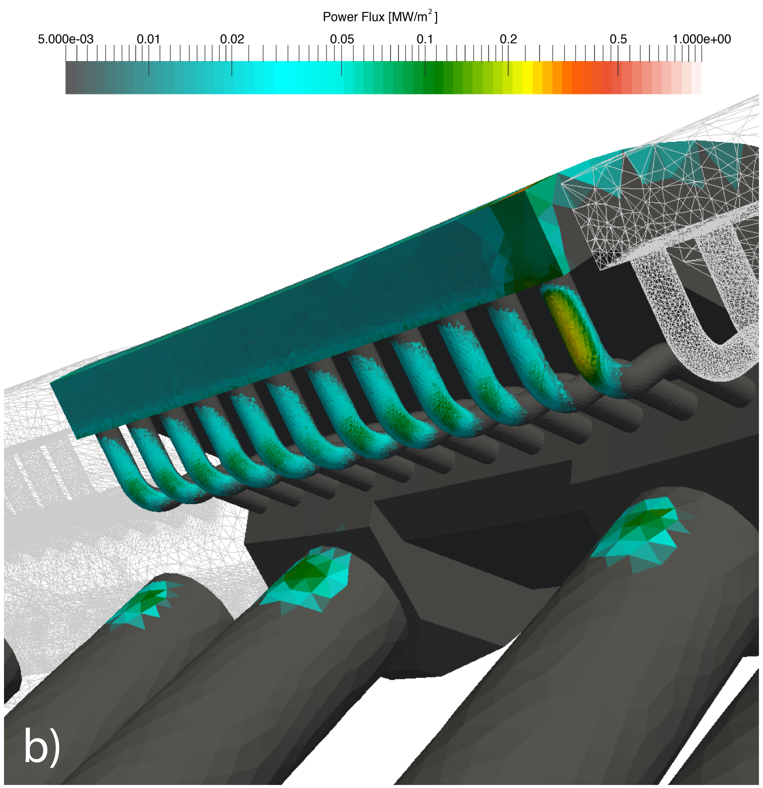
Results: Cooling pipe assembly power loading (90kAt)

Vacuum field



+ plasma screening



- Gaps between cassettes mean that the end most pipe and edge of each cassette dome take an increased load, by roughly a factor of two (gap~1 missing pipe).
- For vacuum field, flux to pipes broadly consistent with OFMC 0.2-0.3MW/m^2.
- With plasma screening, power flux to the end most pipe reduced from ~0.7MW/m^2 to ~0.2MW/m^2, close to the expected level for thermal/radiative load.

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Summary – concluding remarks & future work

- To address an important engineering question, requiring the coupling of fast ion physics to a detailed model of the ITER divertor, we have developed the LOCUST-gpu code for ITER conditions.

- LOCUST can model the power flux to the ITER under-dome sub structure, which occupies a small wetted area (~1m^2) but takes appreciable flux (~0.2MW/m^2) even though the loss to the components is <1% of injected HNB power.

- We have improved the mapping of MARS-F data to cylindrical coordinates, and now deploy a fine resolution mesh to capture structure in the plasma response (0.5cm x 0.5cm in R,Z).

- Scans now need to be extended to more ITER scenarios (in particular, lower plasma current than the 15MA baseline H-mode) and more n's, phase settings etc.

- More field structure needs to be included (with low numerical divergence), in particular, the TF ripple field, TBMs and Fe inserts.

Thank you

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