ISTW 2022
UK Atomic Energy Authority

ISTW 2022

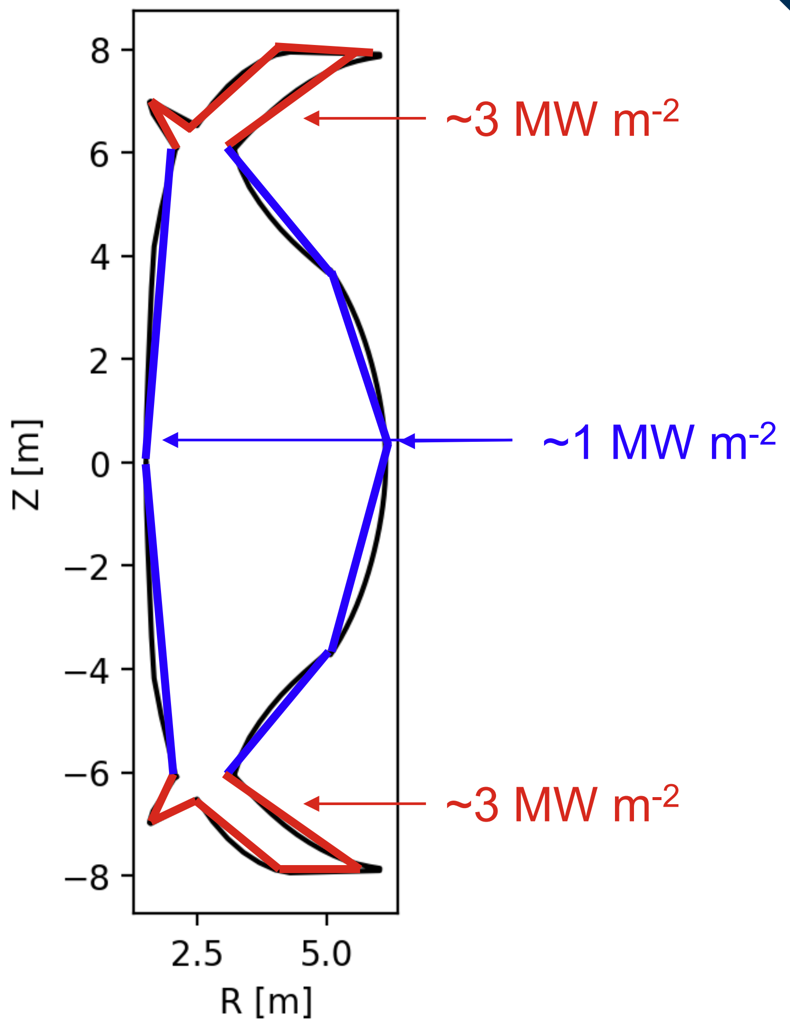
The 21st International Spherical Torus Workshop

STEP's steady-state α-particle losses

A. P. K. Prokopyszyn, H. J. C. Oliver, K. G. McClements, D. A. Ryan and the STEP team

Aims

- Calculate steady-state α flux on wall of latest STEP design
- Model losses in:
  - Axisymmetric/2.5D magnetic field
  - 3D field:
    - Toroidal field (TF) coil's ripple field
    - Resonant magnetic perturbation (RMP) field
- Discuss:
  - How we calculate the results
  - Importance of 3D effects



Approximate, steady-state maximum tolerable heat loads

LOCUST

(Lorentz Orbit Code for Use in Stellarators and Tokamaks)

- Solves:

$$m_{He}\frac{d^2\boldsymbol{r}_j}{dt^2} = \underbrace{2e\frac{d\boldsymbol{r}_j}{dt}\times\boldsymbol{B}(\boldsymbol{r}_j)}_{Lorentz\ force} + \underbrace{\boldsymbol{F}_{\alpha,i}(\boldsymbol{r}_j) + \boldsymbol{F}_{\alpha,e}(\boldsymbol{r}_j)}_{\substack{\alpha-ion+\alpha-electron \\ collision\ force}}$$

  where j = marker #
- We use GPU hardware
- Follow $\sim 0.5 \times 10^6$ markers
- Until thermalisation/collision with wall (< 1s)
- $\Delta t = 1\text{ ns } \left({}^{2\pi}/_{\omega_{c,\alpha}} \approx 20\text{–}50\text{ ns}\right) \implies \#\text{ timeteps} \approx 10^9$
- $\sim 10\text{–}40$ hours with 4 Nvidia A100 GPUs
- See e.g. Akers et al. (2018) and Ward et al. (2021)

UK Atomic
Energy
Authority

Setting up LOCUST

LOCUST

(Lorentz Orbit Code for Use in Stellarators and Tokamaks)

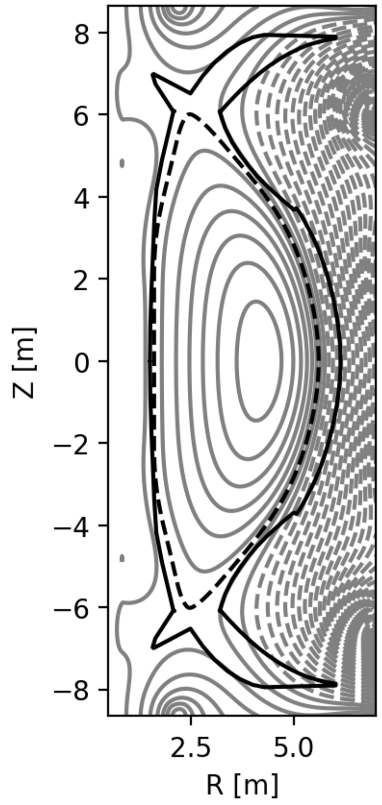
Input:

- **Wall**
- Magnetic field
  - **Axisymmetric field (2D)**
  - Ripple field (3D)
  - RMP field (3D)
- Temperature and density profiles
- x_{initial} and v_{initial}

↓

Output:

- x_{final} and v_{final}



Obtained from the FIESTA code (SPR-045-6.5)

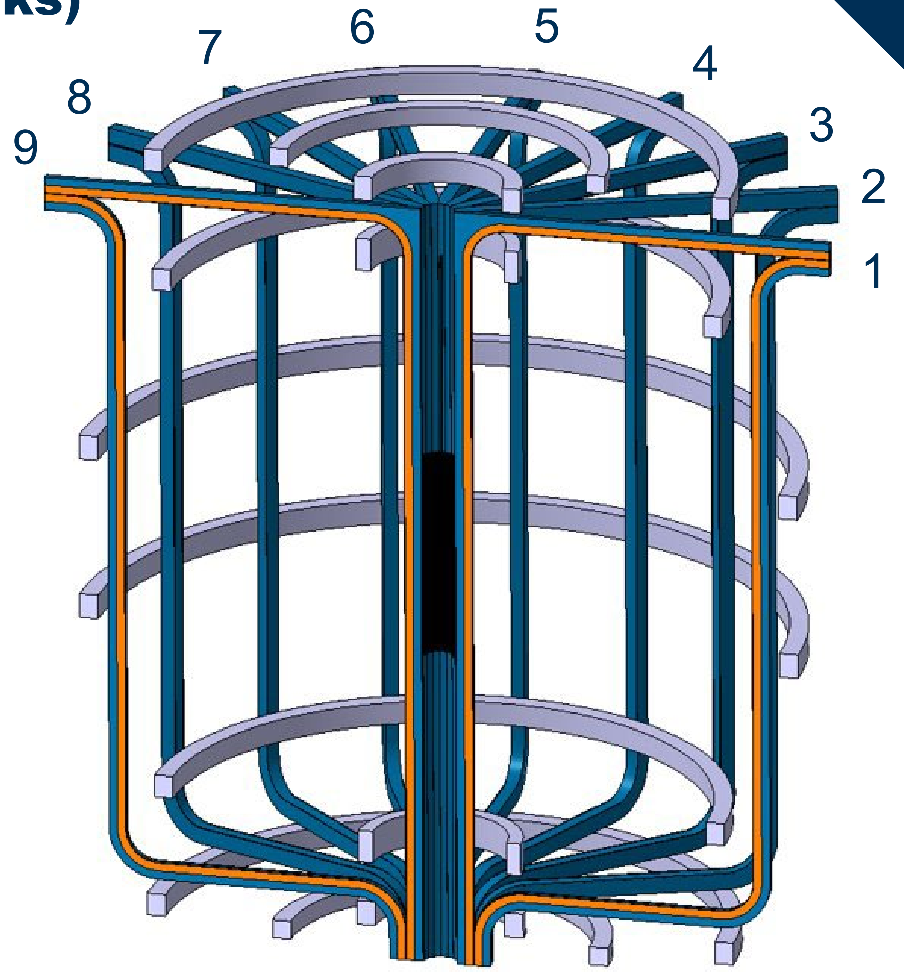
LOCUST

(Lorentz Orbit Code for Use in Stellarators and Tokamaks)

Input:
- Wall
- Magnetic field
  - Axisymmetric field (2D)
  - **Ripple field (3D)**
  - RMP field (3D)
- Temperature and density profiles
- x_{initial} and v_{initial}

↓

Output:
- x_{final} and v_{final}



Courtesy of Aziz Zaghloul and the STEP magnet and design team

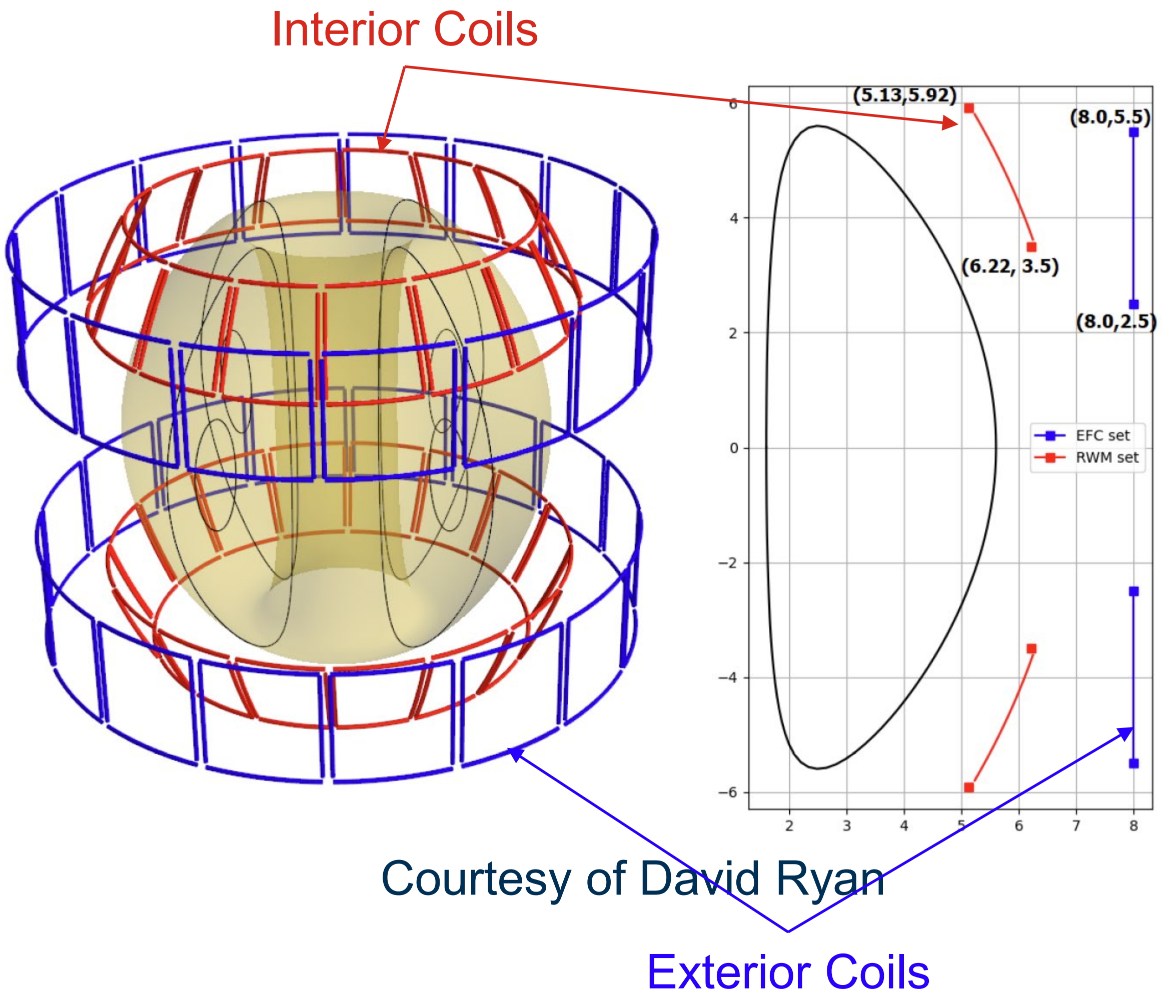
LOCUST

(Lorentz Orbit Code for Use in Stellarators and Tokamaks)

Input:
- Wall
- Magnetic field
  - Axisymmetric field (2D)
  - Ripple field (3D)
  - **RMP field (3D)**
- Temperature and density profiles
- x_{initial} and v_{initial}

↓

Output:
- x_{final} and v_{final}

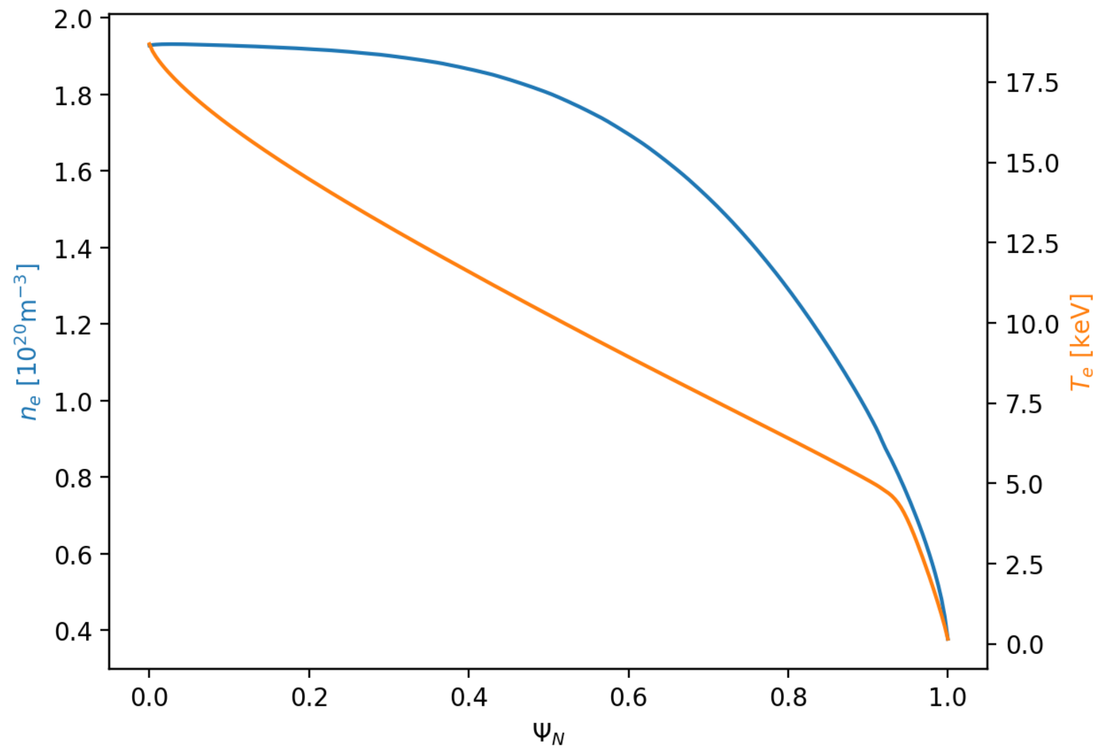


Courtesy of David Ryan

LOCUST
(Lorentz Orbit Code for Use in Stellarators and Tokamaks)

Input:
- Wall
- Magnetic field
  - Axisymmetric field (2D)
  - Ripple field (3D)
  - RMP field (3D)
- **Temperature and density profiles**
- $\boldsymbol{x}_{\text{initial}}$ and $\boldsymbol{v}_{\text{initial}}$

Output:
- $\boldsymbol{x}_{\text{final}}$ and $\boldsymbol{v}_{\text{final}}$



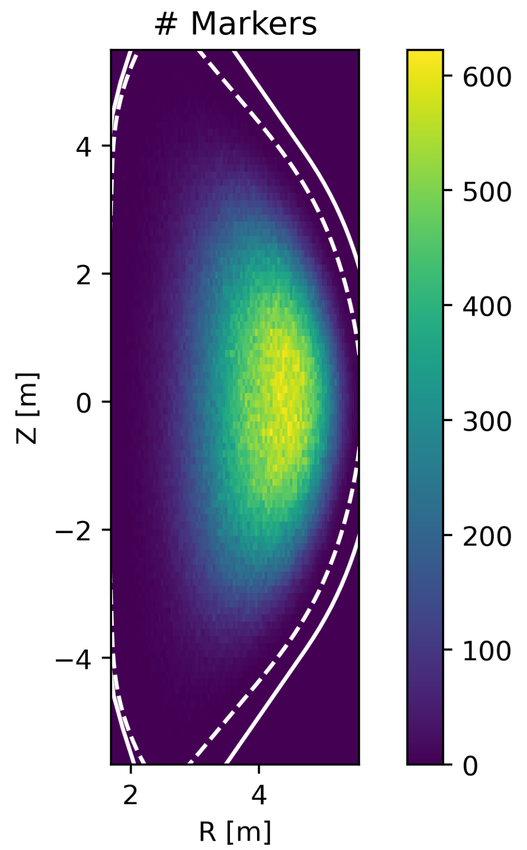
Obtained from the JETTO code (SPR-045-9)

LOCUST

(Lorentz Orbit Code for Use in Stellarators and Tokamaks)

Input:
- Wall
- Magnetic field
  - Axisymmetric field (2D)
  - Ripple field (3D)
  - RMP field (3D)
- Temperature and density profiles
- x_{initial} and v_{initial}

Output:
- x_{final} and v_{final}



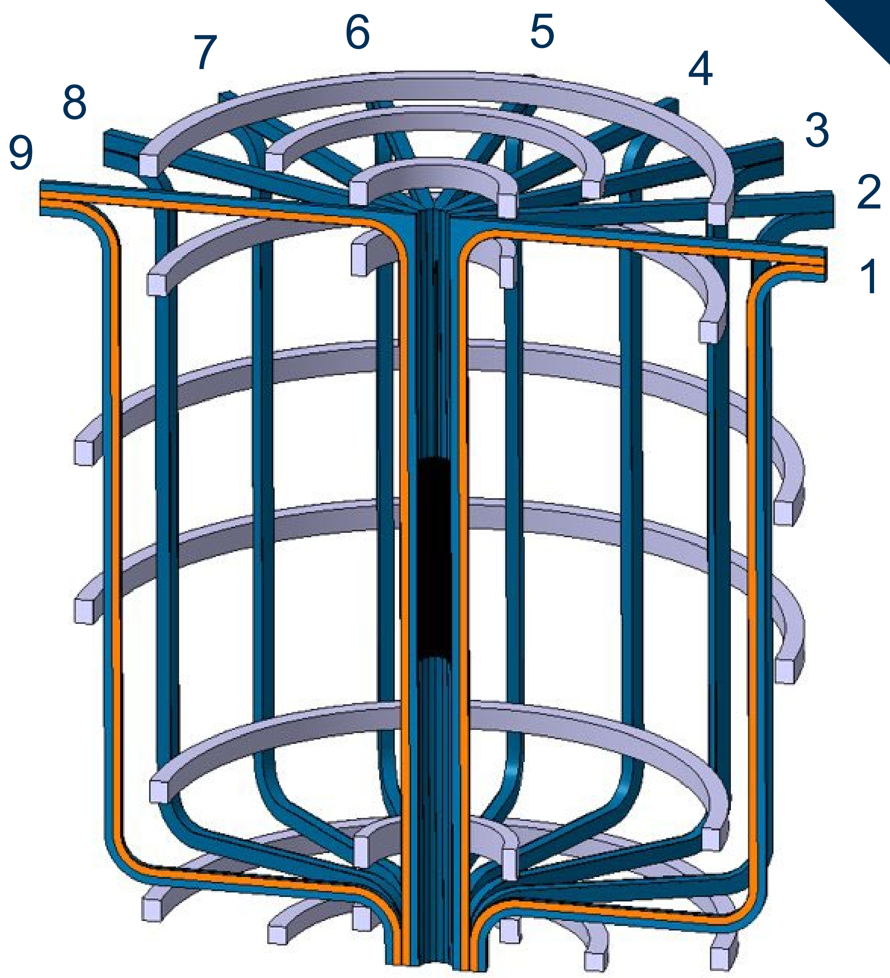
- Markers generated randomly with a probability given by the Bosch-Hale reactivity:

$$R \sim \frac{P^2\langle\sigma v\rangle}{T^2}.$$

3D Fields

TF Ripple field

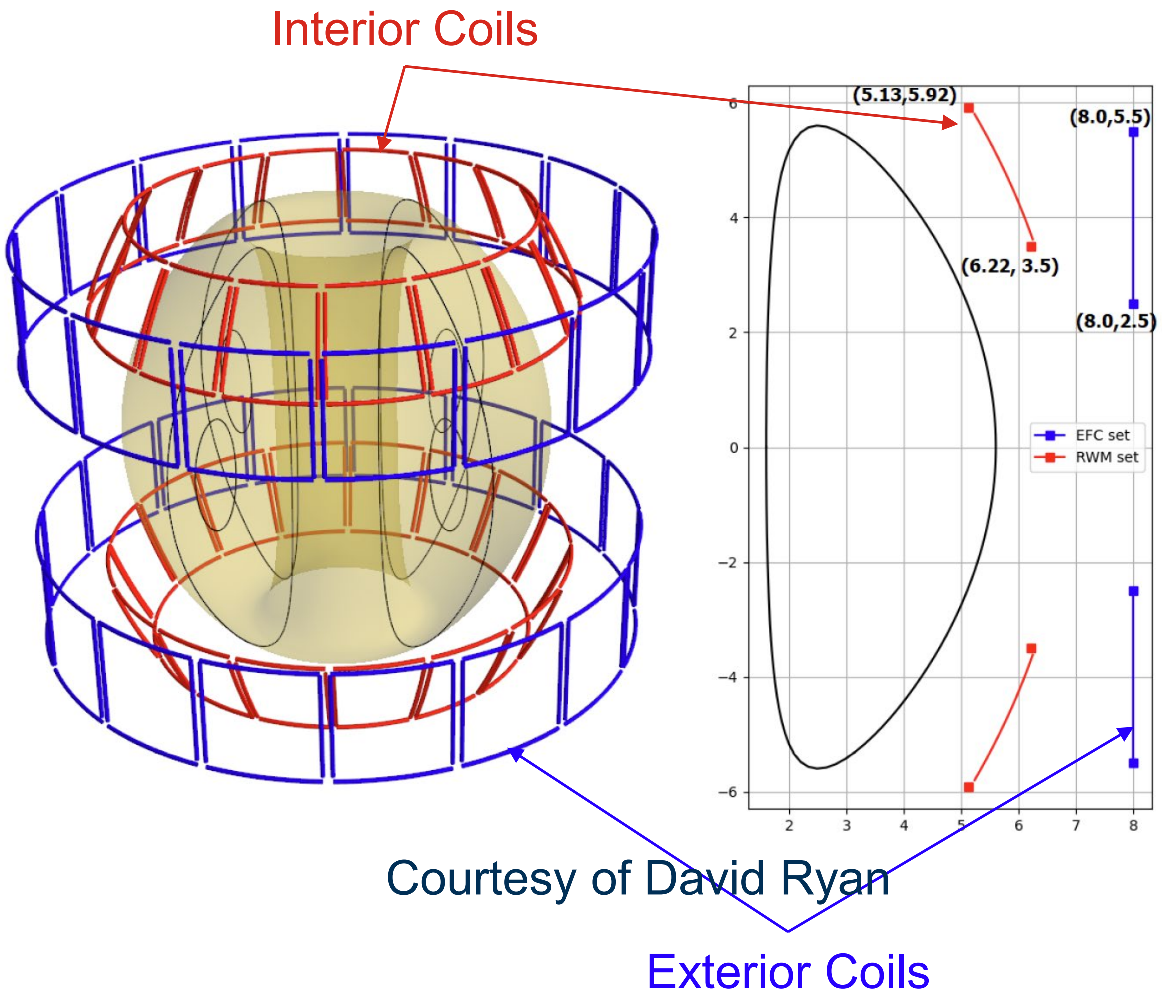
- Calculated numerically
- Amplitude $\propto \left(\frac{R}{R_{coil}}\right)^{N_{coil}}$
- Plasma response not included yet
- Ripple losses studied in e.g.:
  - Goldston and Towner (1981)
  - McClements (2005)
  - Yingfeng et al. (2022)



Courtesy of Aziz Zaghloul and the STEP magnet and design team

RMP (Resonant Magnetic Perturbation) field

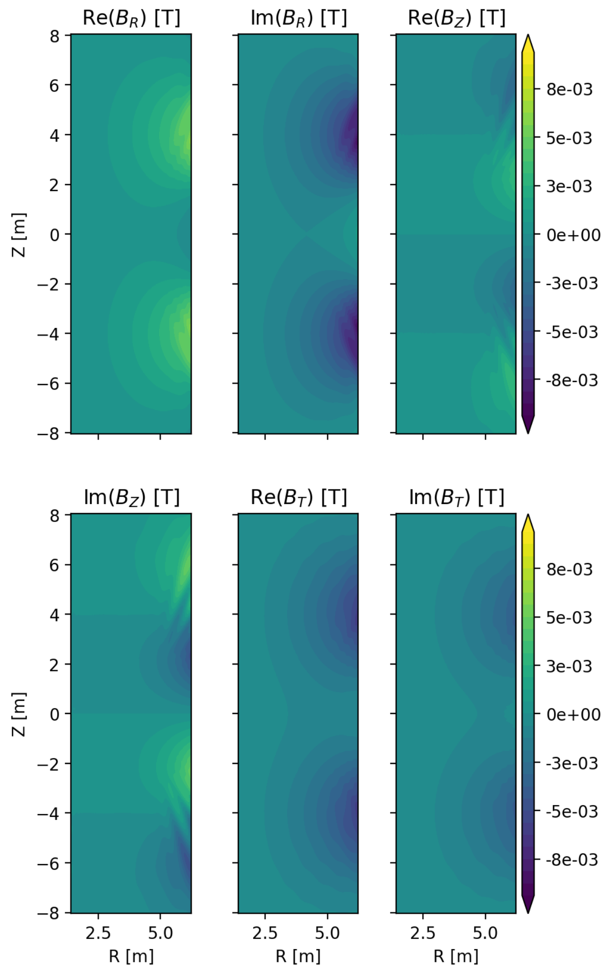
- Used to suppress ELMs (Edge Localised Modes), see e.g.
  - Ryan et al. (2015)
  - Haskey et al. (2014)
- Plasma response modelled using MARS code, see e.g.
  - Liu et al. (2015)
- Alpha particle losses in an RMP field studied in e.g.:
  - Sanchis et al. (2018)
  - Ward et al. (2022)



Courtesy of David Ryan

RMP (Resonant Magnetic Perturbation) field

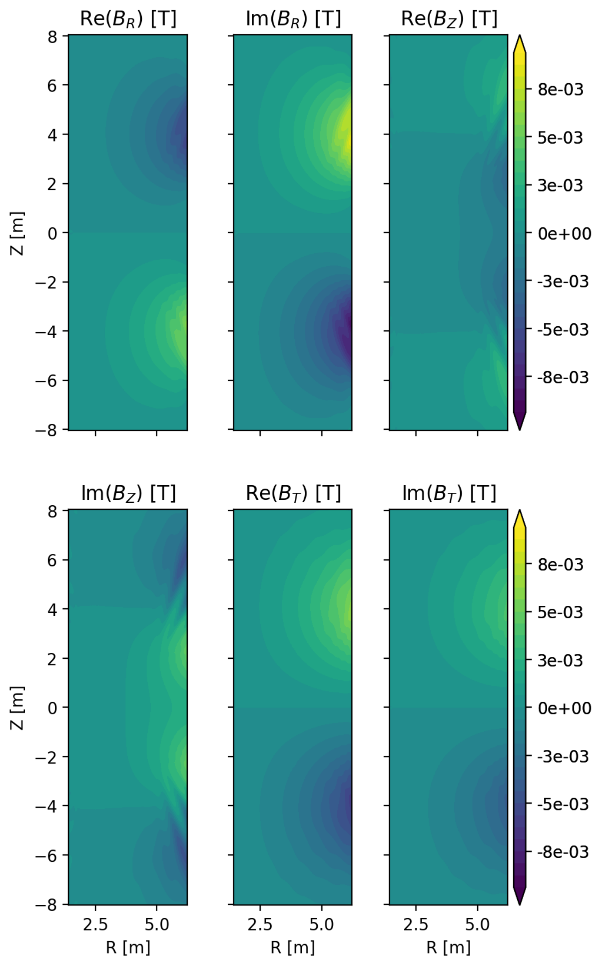
- RMP field components given by:
  $\mathrm{Re}\left[(\mathrm{Re}[B_R(R,Z)] + i\,\mathrm{Im}[B_R(R,Z)])e^{in\phi}\right]$
- Parameters:
  - Toroidal number (n)
  - Exterior vs interior coils
  - Coil current [kAt]
  - Phase difference between upper and lower coil sets ($\Delta\phi$)
  - Vacuum vs plasma response



(Exterior coils, Vacuum $n = 3$, $\Delta\phi = 0°$, 182 kAt)

RMP (Resonant Magnetic Perturbation) field

- RMP field components given by: $\mathrm{Re}\left[(\mathrm{Re}[B_R(R,Z)] + i\,\mathrm{Im}[B_R(R,Z)])e^{in\phi}\right]$
- Parameters:
  - Toroidal number (n)
  - Exterior vs interior coils
  - Coil current [kAt]
  - Phase difference between upper and lower coil sets ($\Delta\phi$)
  - Vacuum vs plasma response

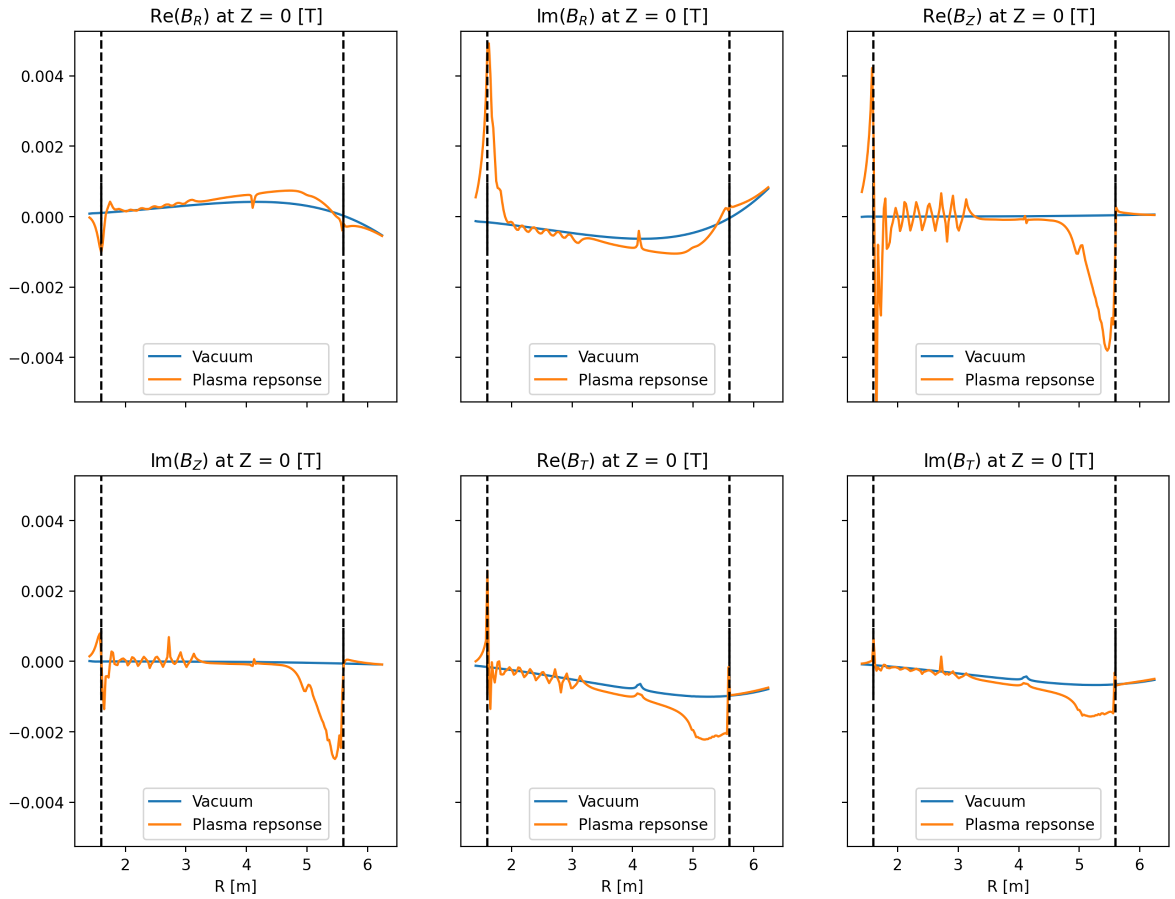


(Exterior coils, Vacuum $n = 3$, $\Delta\phi = 180°$, 182 kAt)

RMP (Resonant Magnetic Perturbation) field

ISTW 2022 | UK Atomic Energy Authority

- RMP field components given by: $\mathrm{Re}\left[(\mathrm{Re}[B_R(R,Z)] + i\,\mathrm{Im}[B_R(R,Z)])e^{in\phi}\right]$
- Parameters:
  - Toroidal number (n)
  - Exterior vs interior coils
  - Coil current [kAt]
  - Phase difference between upper and lower coil sets ($\Delta\phi$)
  - Vacuum vs plasma response



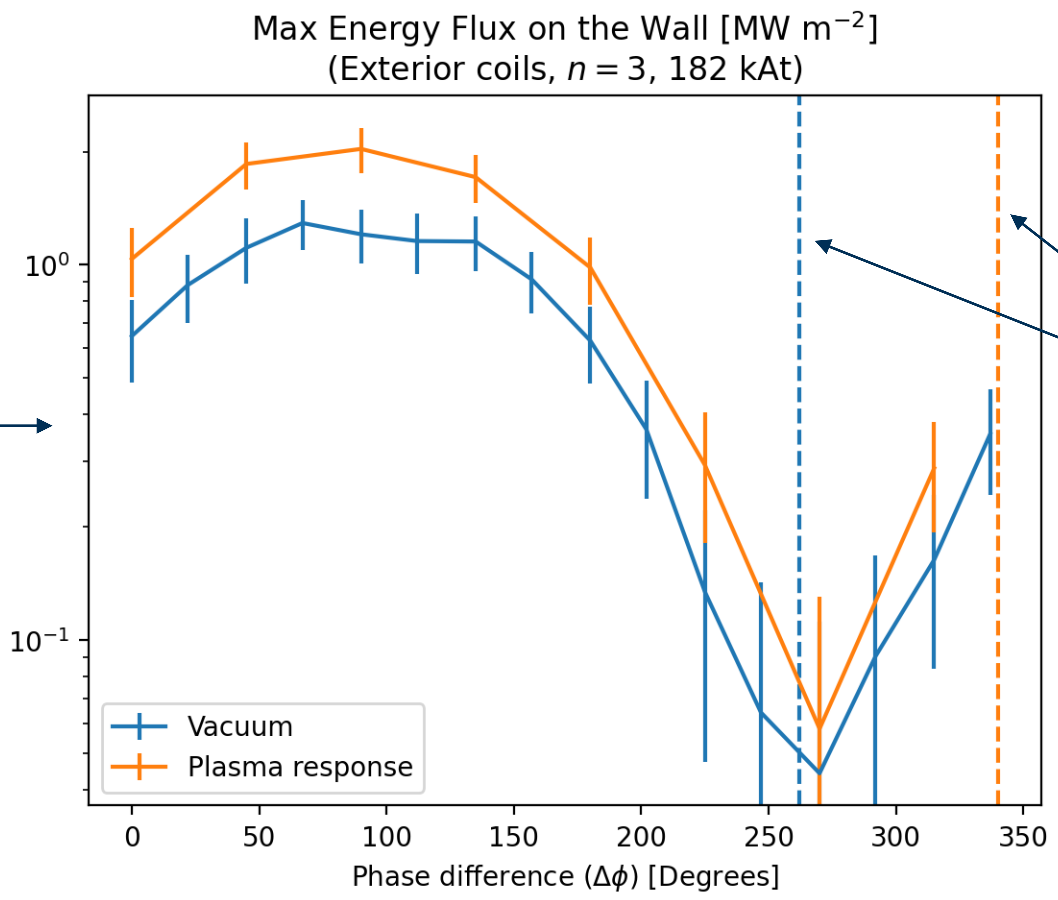
(Exterior coils, $n = 3$, $\Delta\phi = 0$, 182 kAt)

Results

Results

3D Field	% α power lost	~ Peak flux on the wall	Peak flux location
None (axisymmetric)	0.15%	0.02 MW m^{-2}	Upper outer wall
TF Ripple ($R_{coil} \approx 7.5$ m)	0.15%	0.02 MW m^{-2}	Upper outer wall
TF Ripple ($R_{coil} \approx 6.8$ m)	0.50%	0.4 MW m^{-2}	Upper outer wall
TF Ripple ($R_{coil} \approx 6.5$ m)	2.7%	2.2 MW m^{-2}	Upper outer wall
Ripple + RMP ($R_{coil} \approx 7.5$ m, Exterior-coil, $n = 3$, Vacuum, $\Delta\phi = 270°$, 182 kAt)	0.16%	0.04 MW m^{-2}	Upper outer wall
Ripple + RMP ($R_{coil} \approx 7.5$ m, Exterior-coil, $n = 3$, Vacuum, $\Delta\phi = 45°$, 182 kAt)	1.2%	1.1 MW m^{-2}	Upper inner wall
Ripple + RMP ($R_{coil} \approx 7.5$ m, Exterior-coil, $n = 3$, Plasma Response, $\Delta\phi = 270°$, 182 kAt)	0.19%	0.06 MW m^{-2}	Upper outer wall
Ripple + RMP ($R_{coil} \approx 7.5$ m, EFC, $n = 3$, Plasma Response, $\Delta\phi = 45°$, 182 kAt)	1.8%	1.9 MW m^{-2}	Lower outer wall
RMP (Interior Coil, $n = 3$, Plasma Response, $\Delta\phi = 217°$, 84 kAt)	0.96%	0.14 MW m^{-2}	Upper Inner wall
RMP (Exterior Coil, $n = 1$, Plasma Response, $\Delta\phi = 217°$, 60 kAt)	0.19%	0.02 MW m^{-2}	Upper outer wall

Heat load vs. $\Delta\phi$

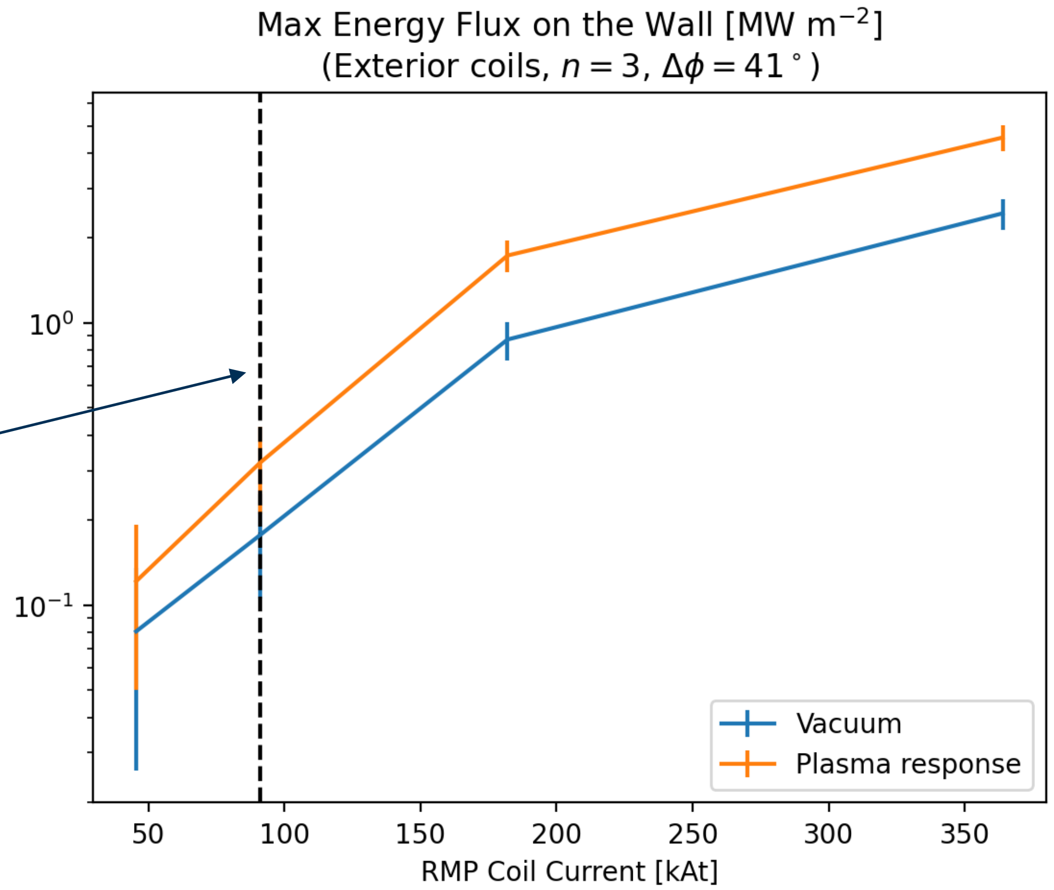


Similar results observed and explained in e.g. Sanchis et al. (2018)

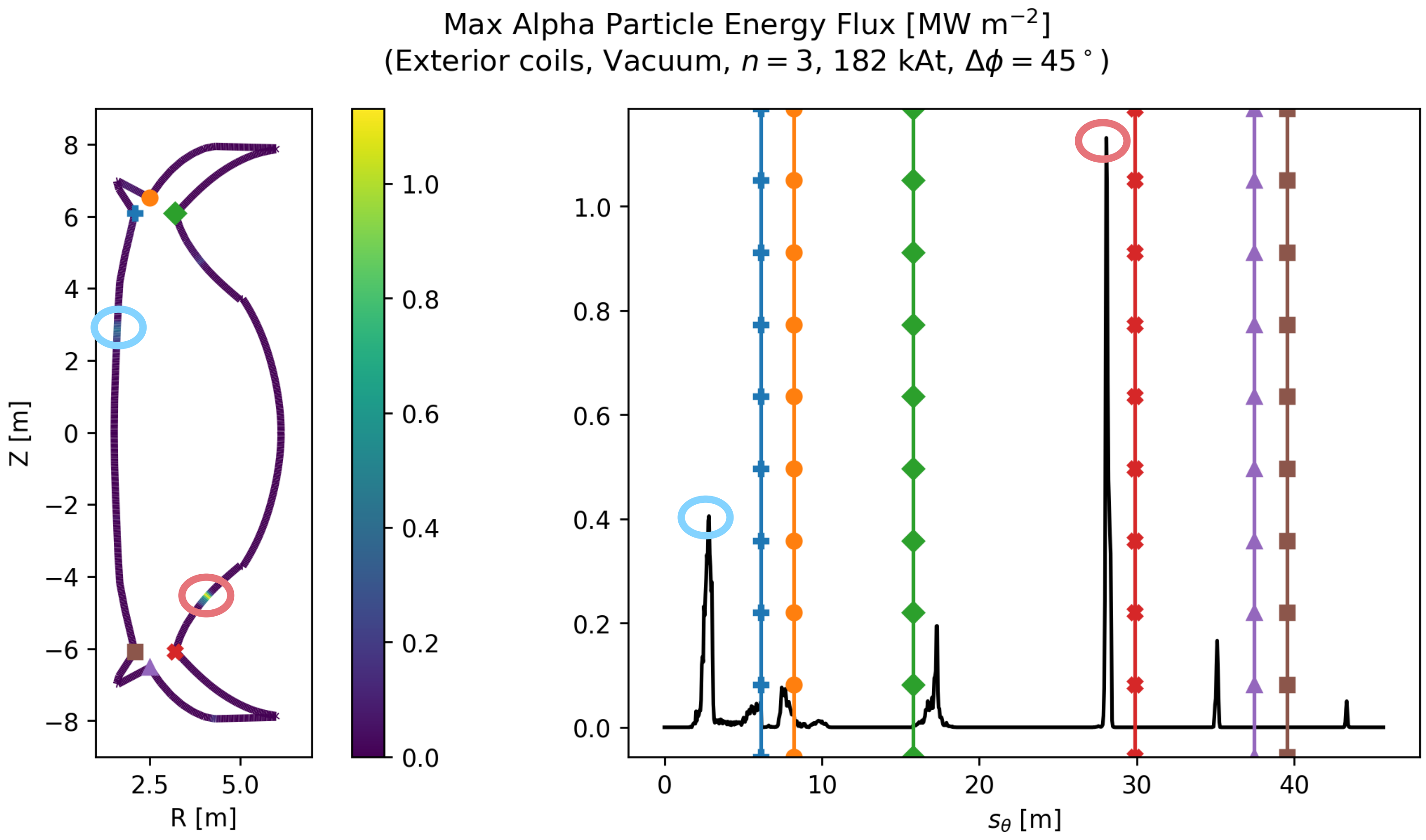
Estimated optimum phases for ELM control

Heat load vs. coil current

Estimated optimum current for ELM control



Heat load distribution



Summary and further study

Summary:

- Results suggest α heat loads should be acceptable with refinement of parameters
- Axisymmetric peak flux ~ 0.02 MW m^{-2}
- 3D peak flux can be as large as ~ 2 MW m^{-2}
- Heat loads are sensitive to RMP parameters
- Changing $\Delta\phi$ can reduce heat load by a factor of 10

Further study:

- Why does changing $\Delta\phi$ have such a large affect on the α confinement?
- Will the RMP fields used on ASDEX Upgrade/DIII-D upgrade work for STEP?
- Include 3D field from ferromagnetic structures

Thank you for listening

谢谢！

References

Akers, R., B. Colling, J. Hess, Y. Liu, A. Turner, S. Äkäslompolo, J. Varje, K. Särkimäki, S. D. Pinches, and M. Singh. 2018. "High fidelity simulations of fast ion power flux driven by 3D field perturbations on ITER." In.

Goldston, R. J., and H. H. Towner. 1981. 'Effects of toroidal field ripple on suprathermal ions in tokamak plasmas', *Journal of Plasma Physics*, 26: 283-307.

Haskey, S. R., M. J. Lanctot, Y. Q. Liu, J. M. Hanson, B. D. Blackwell, and R. Nazikian. 2014. 'Linear ideal MHD predictions for n= 2 non-axisymmetric magnetic perturbations on DIII-D', *Plasma Physics and Controlled Fusion*, 56: 035005.

Liu, Y., R. Akers, I. T. Chapman, Y. Gribov, G. Z. Hao, G. T. A. Huijsmans, A. Kirk, A. Loarte, S. D. Pinches, and M. Reinke. 2015. 'Modelling toroidal rotation damping in ITER due to external 3D fields', *Nuclear Fusion*, 55: 063027.

McClements, K. G. 2005. 'Full orbit computations of ripple-induced fusion α-particle losses from burning tokamak plasmas', *Physics of plasmas*, 12: 072510.

Ryan, D. A., Y. Q. Liu, A. Kirk, W. Suttrop, B. Dudson, M. Dunne, R. Fischer, J. C. Fuchs, M. Garcia-Munoz, and B. Kurzan. 2015. 'Toroidal modelling of resonant magnetic perturbations response in ASDEX-Upgrade: coupling between field pitch aligned response and kink amplification', *Plasma Physics and Controlled Fusion*, 57: 095008.

Sanchis, L., M. Garcia-Munoz, A. Snicker, D. A. Ryan, D. Zarzoso, L. Chen, J. Galdon-Quiroga, M. Nocente, J. F. Rivero-Rodriguez, and M. Rodriguez-Ramos. 2018. 'Characterisation of the fast-ion edge resonant transport layer induced by 3D perturbative fields in the ASDEX Upgrade tokamak through full orbit simulations', *Plasma Physics and Controlled Fusion*, 61: 014038.

Ward, S. H., R. Akers, A. S. Jacobsen, P. Ollus, S. D. Pinches, E. Tholerus, R. G. L. Vann, and M. A. Van Zeeland. 2021. 'Verification and validation of the high-performance Lorentz-orbit code for use in stellarators and tokamaks (LOCUST)', *Nuclear Fusion*, 61: 086029.

Ward, S. H., R. Akers, L. Li, Y. Q. Liu, A. Loarte, S. D. Pinches, A. R. Polevoi, R. G. L. Vann, and M. A. Van Zeeland. 2022. 'LOCUST-GPU predictions of fast-ion transport and power loads dueto ELM-control coils in ITER', *Nuclear Fusion*, 62: 126014.

Yingfeng, X., Z. Debing, C. Jiale, and Z. Fangchuan. 2022. 'Simulations of energetic alpha particle loss in the presence of toroidal field ripple in the CFETR tokamak', *Plasma Science and Technology*, 24: 105101.