ARCHER2 Celebration of Science
8th March 2024

Plasma HEC

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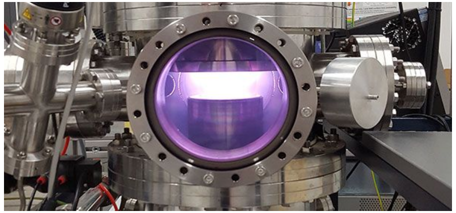
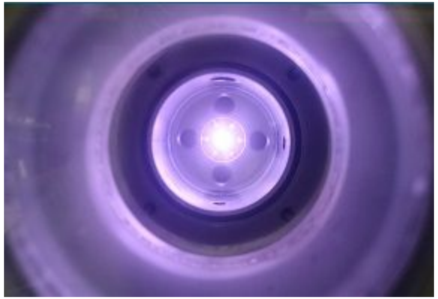
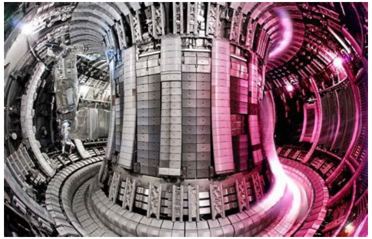
Engineering and Physical Sciences Research Council

Plasma HEC

- PlasmaHEC: ~5M CUs across 11 partners (York, Oxford, Warwick, Imperial, Strathclyde, Durham, Lancaster, Manchester, QUB, UKAEA, STFC CLF)
- 83 registered users (43 active)

Plasmas

- Gas of charged particles but overall electrically neutral
- Responds to self-generated EM fields
- Large-scale, long-range collective behaviour
- Phenomena cover wide range of spatial and temporal scales
- Highly coupled systems
- Applications include: biomed, agriculture, space thrusters, manufacturing, semiconductors, **particle accelerators, nuclear fusion**

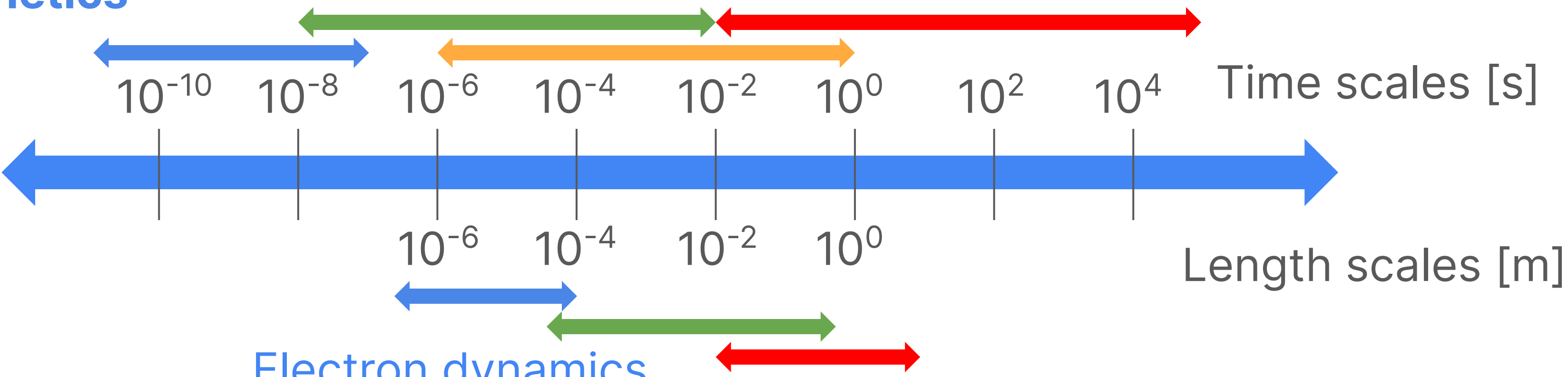
Computational Challenges

Microwave heating
Doppler backscatter
Ray tracing
Kinetics

Microinstabilities
Turbulence
Particle-in-Cell
Gyrokinetics
Fluid codes

Magnetic Islands
Zonal flows
Magneto-Hydrodynamics
Drift kinetics

Energy confinement
Integrated modelling
Transport codes



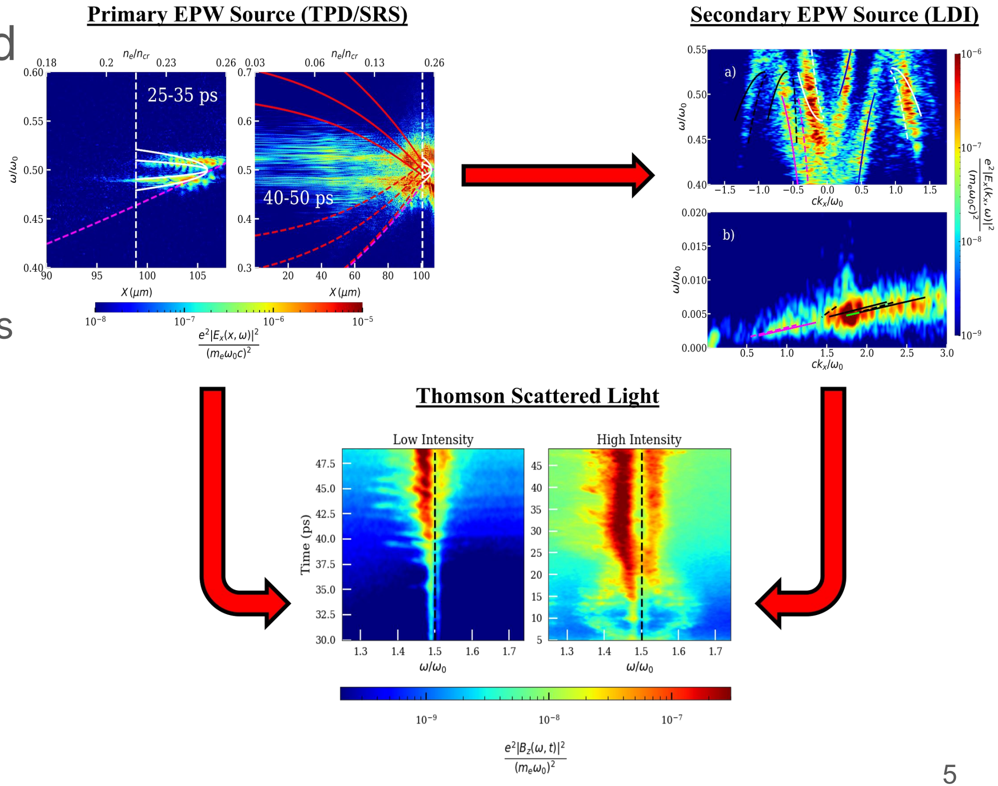
Electron dynamics

Ion dynamics

System size
Mesoscale instabilities

Laser-Plasma Interactions

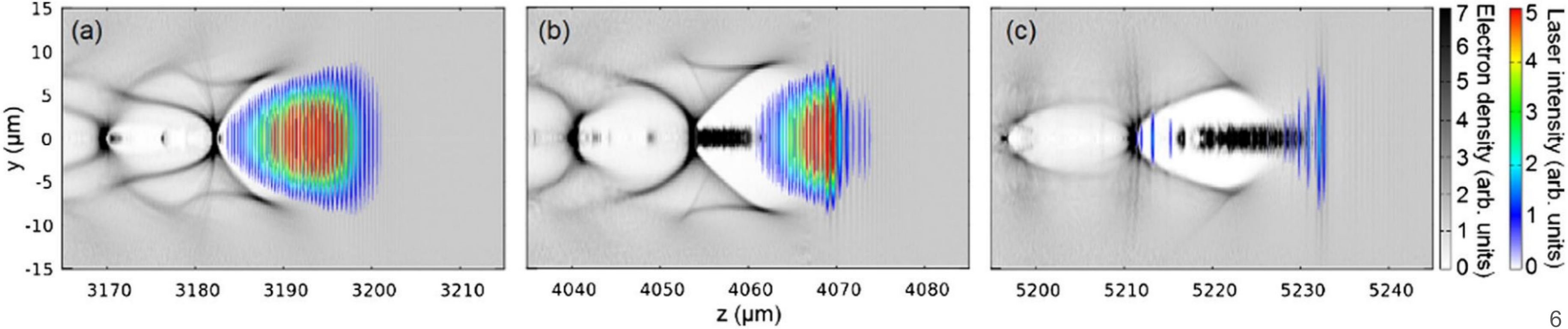
- LPIs can reflect laser energy, bad for fusion schemes
- Can also accelerate particles — double edged sword!
    - Enables novel accelerators — e.g. table-top GeV wakefield accelerators
    - Or can harm compression and energy gain in fusion
- Experiments can be expensive, slow, difficult to diagnose
- Simulations crucial tool in understanding physics



Gosling, Arber et al, in progress

Laser Wakefield Acceleration

- Drive laser through plasma, accelerates particles, causing charge separation
- Cavity behind drive pulse has intense electric fields 1 GV/m ~ 1 TV/m (upto 10,000x greater than RF cavities!)
- Can accelerate particles to GeV energies in cm~m
- Can use to generate tunable X-rays and THz beams
- Wide range applications include medical and scientific diagnostics

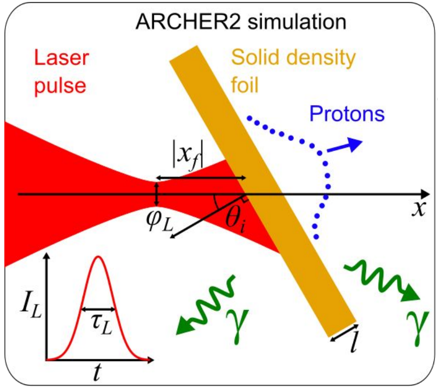


Genoud et al, Phys. Rev. ST Accel. Beams **17**, 051302 https://doi.org/10.1103/PhysRevSTAB.17.051302

Laser-driven particle and radiation sources optimised using machine learning

- High energy particles and radiation can be produced from intense (>10^{20} Wcm^{-2}) laser-solid interactions
- Generation dependant on many parameters such as target thickness, pulse duration, etc.
- Automated Bayesian optimisation for:
  - Laser-driven proton acceleration [1]
  - High energy synchrotron emission [2]

ARCHER2 simulation

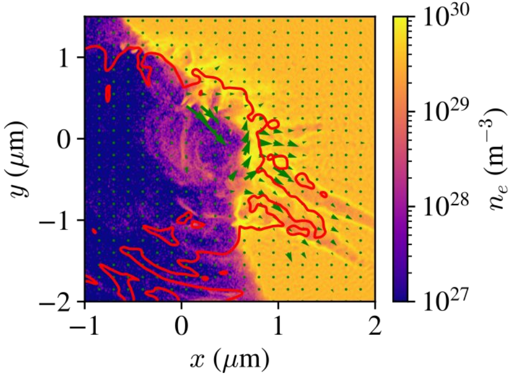


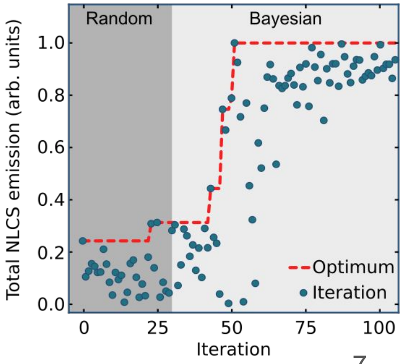
Automated Bayesian optimisation

Measure output e.g. proton energy, γ-ray yield or multi-parameter combination

Update Gaussian regression model

Inputs new initial conditions such as target thickness, pulse duration, etc.

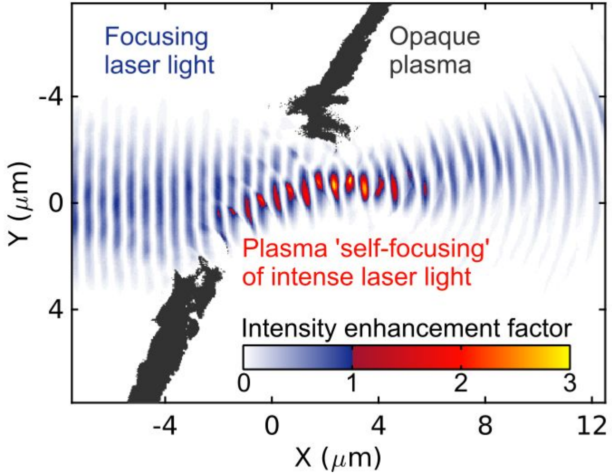


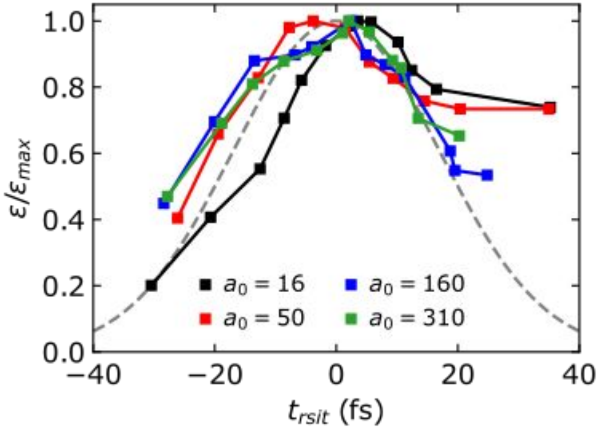


[1] Dolier E. J. et al. New J. Phys. 24, 073024, (2022)
[2] Goodman J. et al. High Power Laser Sci. Eng. 11, e34 (2023)

Laser-driven proton acceleration

- Laser-driven proton acceleration from nanometre-thick foils is a hybrid of many acceleration mechanisms
- This is enhanced by the onset of relativistic self-induced transparency (RSIT) producing ~100 MeV protons [1]
- ARCHER2 was used to simulate long pulses and/or large interaction volumes at high-resolution
- Self-focusing through the target was found to produce comparable intensities for different focal diameters [2]
- Spatial intensity contrast of the laser impacts proton energy and conversion efficiency for multipetawatt lasers [3]
- The onset time of RSIT is a critical factor in optimising the maximum proton energy [4]

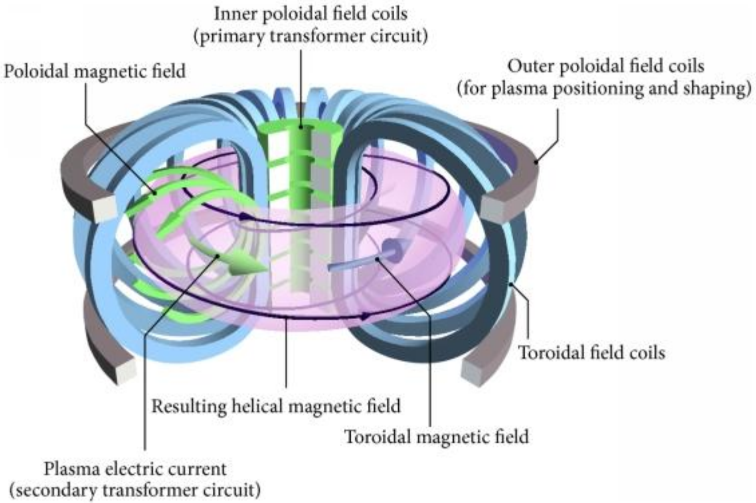


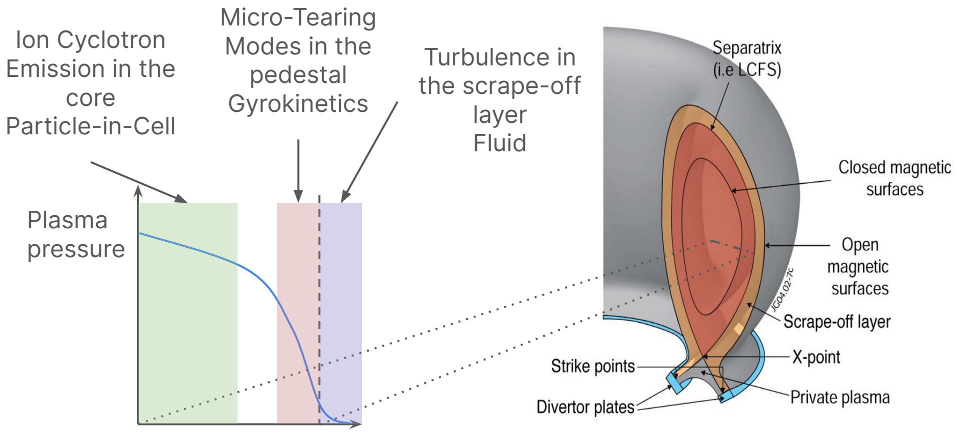


[1] Higginson A. et al. Nat. Comms. 9, 724 (2018)
[2] Frazer T. P. et al. Phys. Rev. Research 2, 042015 (2020)
[3] Wilson R. et al. Sci. Rep. 12, 1910 (2022)
[4] Goodman J. et al. New J. Phys. 24 053016 (2022)

Magnetic Confinement Fusion

- Plasma confined by helical magnetic field
- Challenges around boundary conditions: large gradients at edge drive instabilities, neutrals in exhaust complicate simulations
- ARCHER2 important for understanding fundamental physics, diagnosing experiments, optimising scenarios, designing future machines





Ion Cyclotron Emission in the core
Particle-in-Cell

Micro-Tearing Modes in the pedestal
Gyrokinetics

Turbulence in the scrape-off layer
Fluid

Images from EFDA-JET/EUROfusion

Tritium mix effects on Ion Cyclotron Emission spectra

- Ion cyclotron emission (ICE) is suprathermal emission visible at multiple harmonics of ion species, Fig. 1
- ICE is caused by magnetoacoustic cyclotron instability, driven by strong velocity-space gradients due to fast, minority species
- Measurement of ICE is passive and multi-angled
- Simulations of ICE in D-T have avoided including tritium
- EPOCH simulations varying tritium concentration from 0% to ITER ratios of 50%

➢ Power spectral features shift down in frequency in a roughly inverse linear relationship

➢ PIC simulated ICE spectra of JET plasma 26148 is better represented with an 11% tritium concentration than with 0%

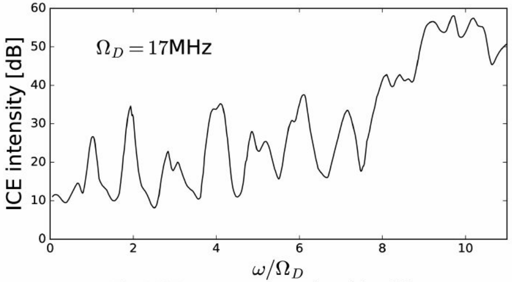


Fig. 1 ICE power spectrum, adapted from [1]

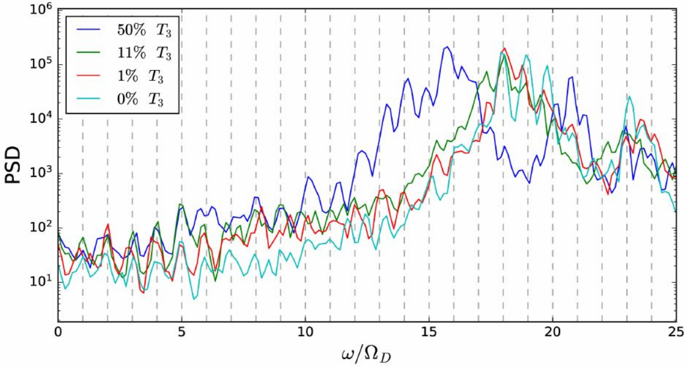
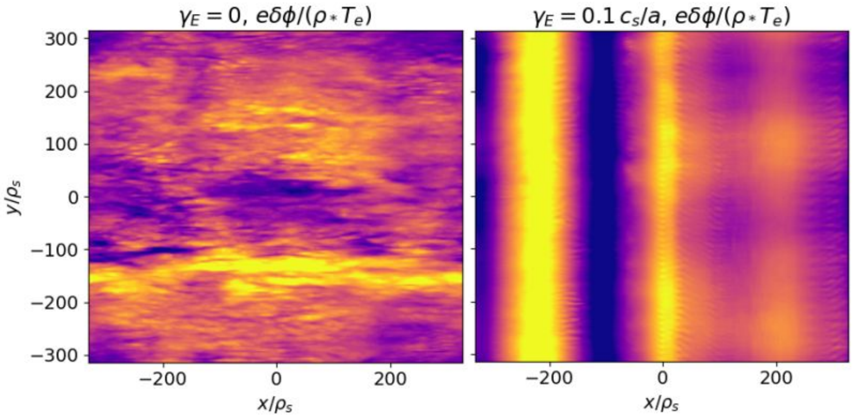


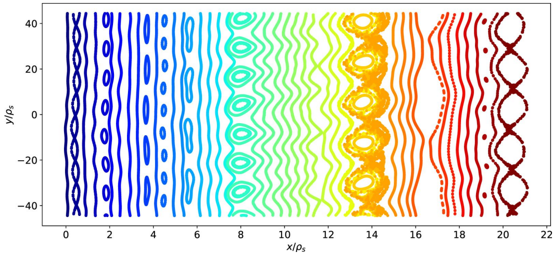
Fig. 2 Power spectral density of 0%, 1%, 11% (JET 26148 plasma) and 50% tritium concentration PIC simulations

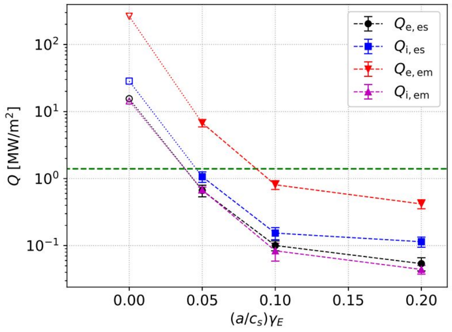
[1] Cottrell G A, Bhatnagar V P et al. 1993 Nucl. Fusion 33 1365–87
Slade-Harajda, Dendy, et al, in progress

Simulations of plasma turbulence in tokamaks

- Trying to understand turbulent transport in existing tokamaks – physics underlying saturation amplitude
    - Inform reduced models able to make faster predictions, enabling more exploration of design space.
- Microtearing modes in MAST-U: Fine radial scale and larger structures – expensive!
- Sheared plasma flows can have a strong impact, suppressing turbulent transport and reducing radial scale of structures.

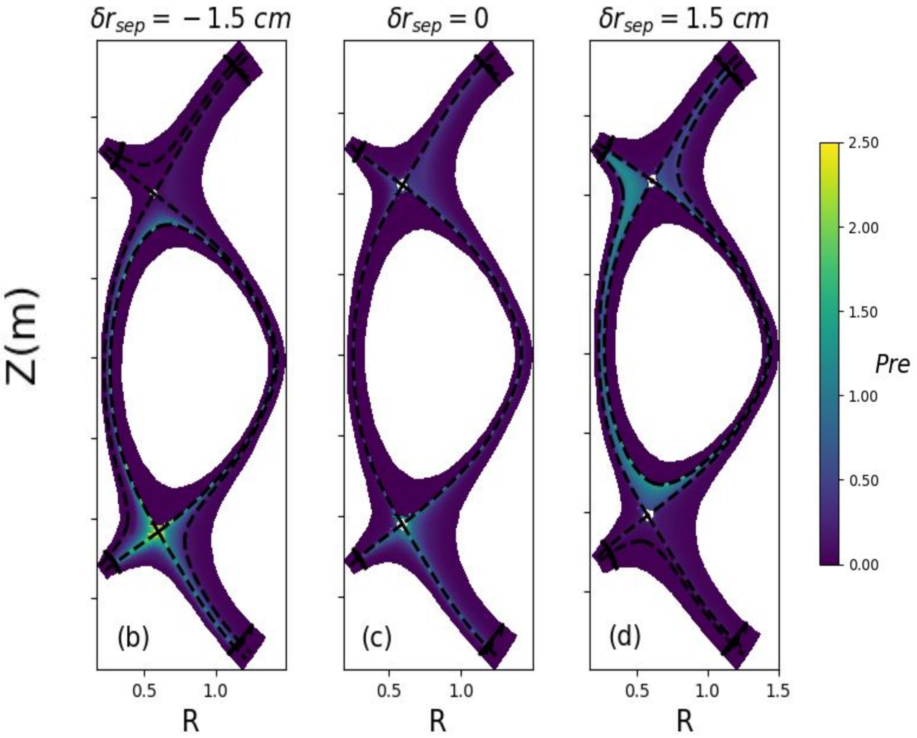




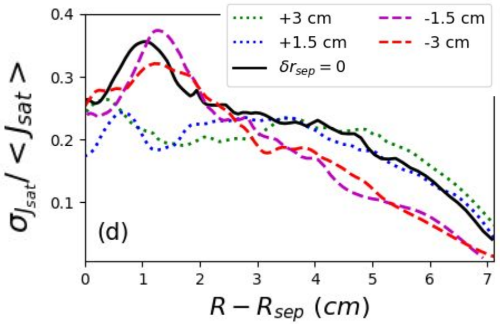


Giacomin, Dickinson, et al, in progress

In-out, up-down asymmetries in lower- and upper- connected double-null configurations



- The effects of different magnetic configurations on the power balance are critical for protecting the more vulnerable inner targets,
- Simple models and SOLPS underestimate the in-out asymmetry, etc.
- Plasma turbulence simulations show drift is responsible for those asymmetries, and give better agreement with experiments.



Osawa, R. T., et al. (2023). Nuclear Fusion, 63(7):076032.
Riva, et al. (2019). PPCF, 61(9):095013

Preparing for exascale

- EPOC++: rewriting EPOCH (Fortran) in C++ to take advantage of performance portable frameworks
- Fusion one of the case studies for ExCALIBUR
- New tokamak edge code led by UKAEA, and developed in collaboration with UK universities, using advances in algorithms
- Some models with elliptical equations particularly challenging to scale
  - Larger problem sizes not always desired!
- Uncertainty quantification, active machine learning as alternative routes to large(r) scale compute