Divertor Modelling for SPARC

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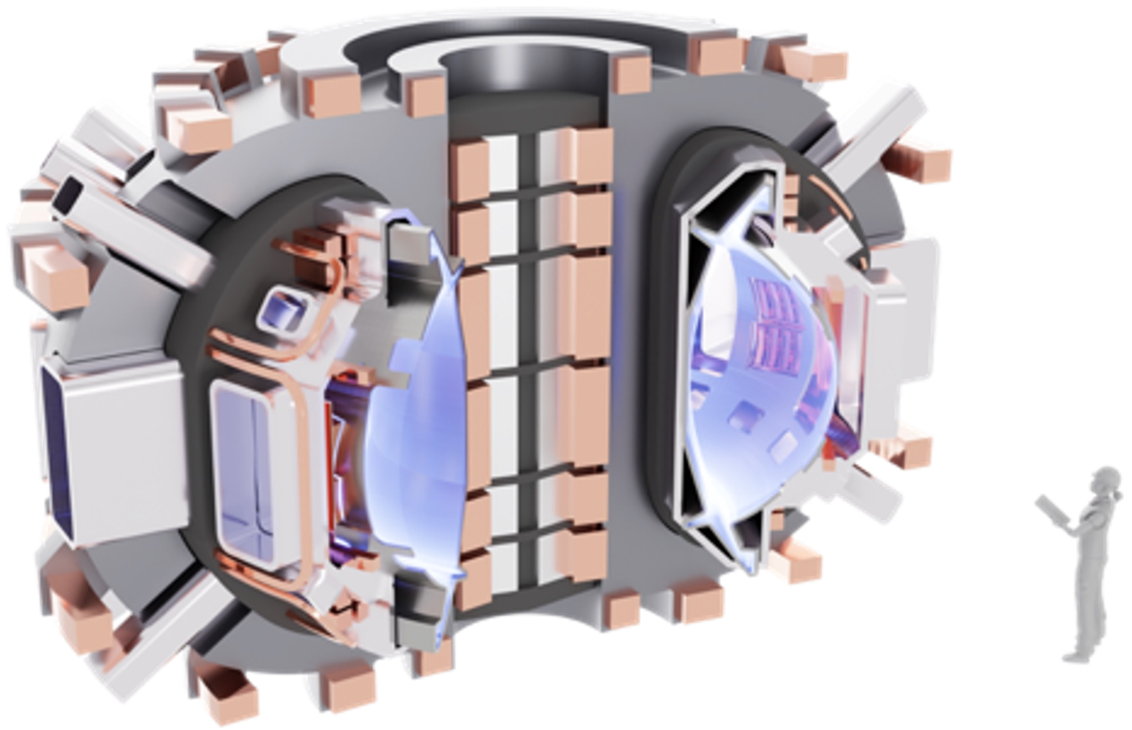
Key take-aways

- SPARC operations are fast approaching!
- SPARC operations will be an opportunity to test heat-exhaust solutions at parameters relevant to ITER, DEMO and ARC.
- We need fast models for the SPARC Pulse Planner — these will be developed open-source in collaboration with the modelling community.
- Predictive turbulence modelling will be validated against SPARC experimental data, providing a key validation at power-plant-relevant parameters.
- Validated divertor models could play a key role in accelerating the schedule for designing and building the first ARC power plant.

The SPARC tokamak



- Compact ($R_0 = 1.85m$), high-field ($B_0 = 12.2T$) DT tokamak[1]
- Mission of Q > 2, as much as ≈ 11
- $P_{fusion} \leq 140MW$ for $t \sim 10s$ (operation limit) from $P_{RF} \leq 25MW$
- High-energy-density $^{P_{fus}}/_{V} \approx 7MW/m^3$
- SPARC Physics Basis published in JPP series[1,2,3]

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1. A. Creely *et al* 2020 *Journal of Plasma Physics* **86(5)**, 865860502. **DOI** 10.1017/S0022377820001257
2. M. Greenwald 2020 *Journal of Plasma Physics* **86(5)**, 861860501. **DOI** 10.1017/S0022377820001063
3. A.Q. Kuang *et al* 2020 *Journal of Plasma Physics* **86(5)**, 865860505. **DOI** 10.1017/S0022377820001117

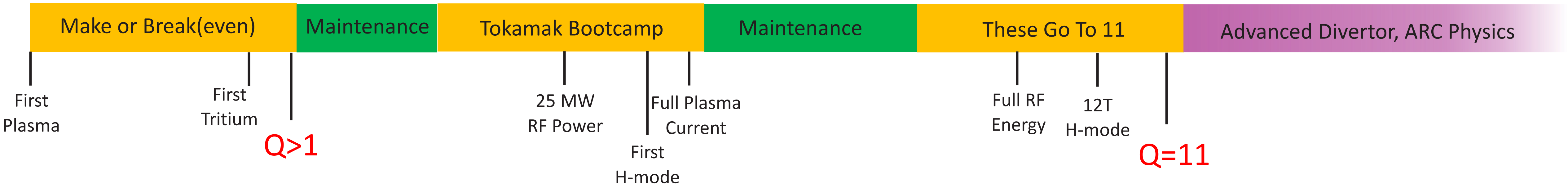
SPARC construction is well underway in Devens, MA

Magnet factory ready for machinery

CFS offices moved to Devens in Dec 2022

SPARC structure nearing completion

First plasma and break-even are fast approaching



Make or Break(even) | Maintenance | Tokamak Bootcamp | Maintenance | These Go To 11 | Advanced Divertor, ARC Physics

First Plasma

First Tritium

Q>1

25 MW RF Power

First H-mode

Full Plasma Current

Full RF Energy

12T H-mode

Q=11

- First plasma in 2025 (< 3 years!) ⇒ planning operations now
- Goal is to achieve $Q > 1$ in low-P_{fusion} L-mode in the first campaign
  ⇒ we'll need to quickly learn how to deal with power crossing the separatrix
- No remote maintenance, so limited in-vessel maintenance after campaign 1 and none after $Q = 11$
  ⇒ we'll need to carefully plan how to inform ARC design and operations without breaking SPARC

Heat fluxes will match or exceed previous devices

$$q_{\parallel} \sim \frac{P_{SOL}(1-f_{rad})f_{share}}{2\pi(R_0+a)\lambda_q} \cdot \frac{B_{OMP}}{B_{pol,OMP}}$$

$P_{SOL} \sim 29MW$
(from 0D POPCON analysis for the $Q \sim 11$ case)

$f_{rad} \sim 50\%$ (not necessarily conservative)

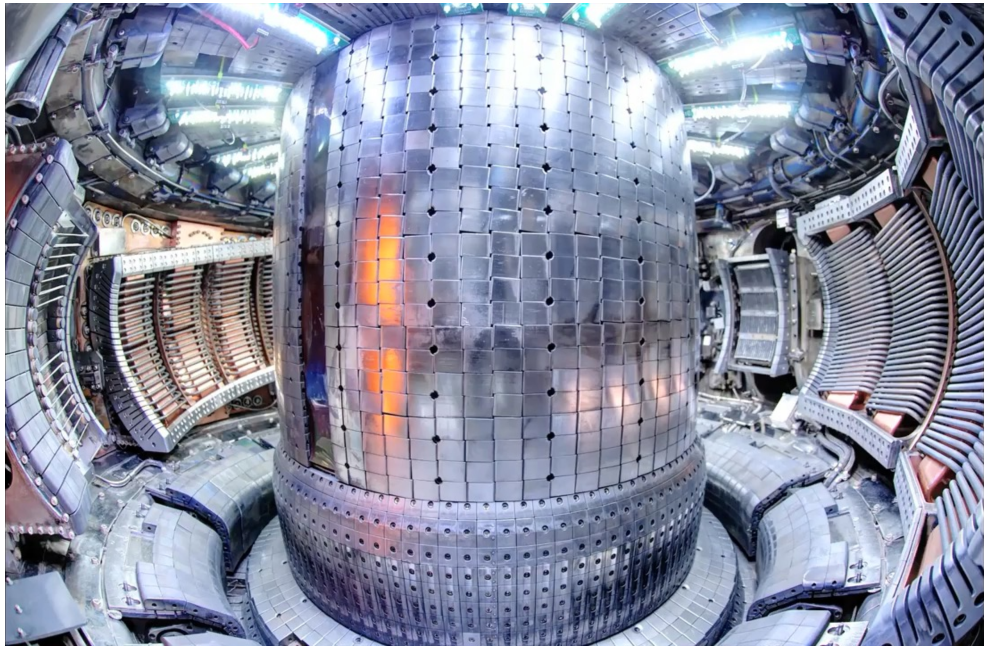
$f_{share} \sim 60\%$ (power sharing[1])

$\lambda_q \sim 0.308$ mm (Eich 15 scaling[2])

$(R_0 + a) \sim 2.42m, \frac{B_{OMP}}{B_{pol,OMP}} \sim 3.43$

gives

$$q_{\parallel} \sim 6.38GW/m^2$$



Previous results from Alcator C-Mod[3] reached heat fluxes of $q_{\parallel} \sim 1 - 2GW/m^2$.

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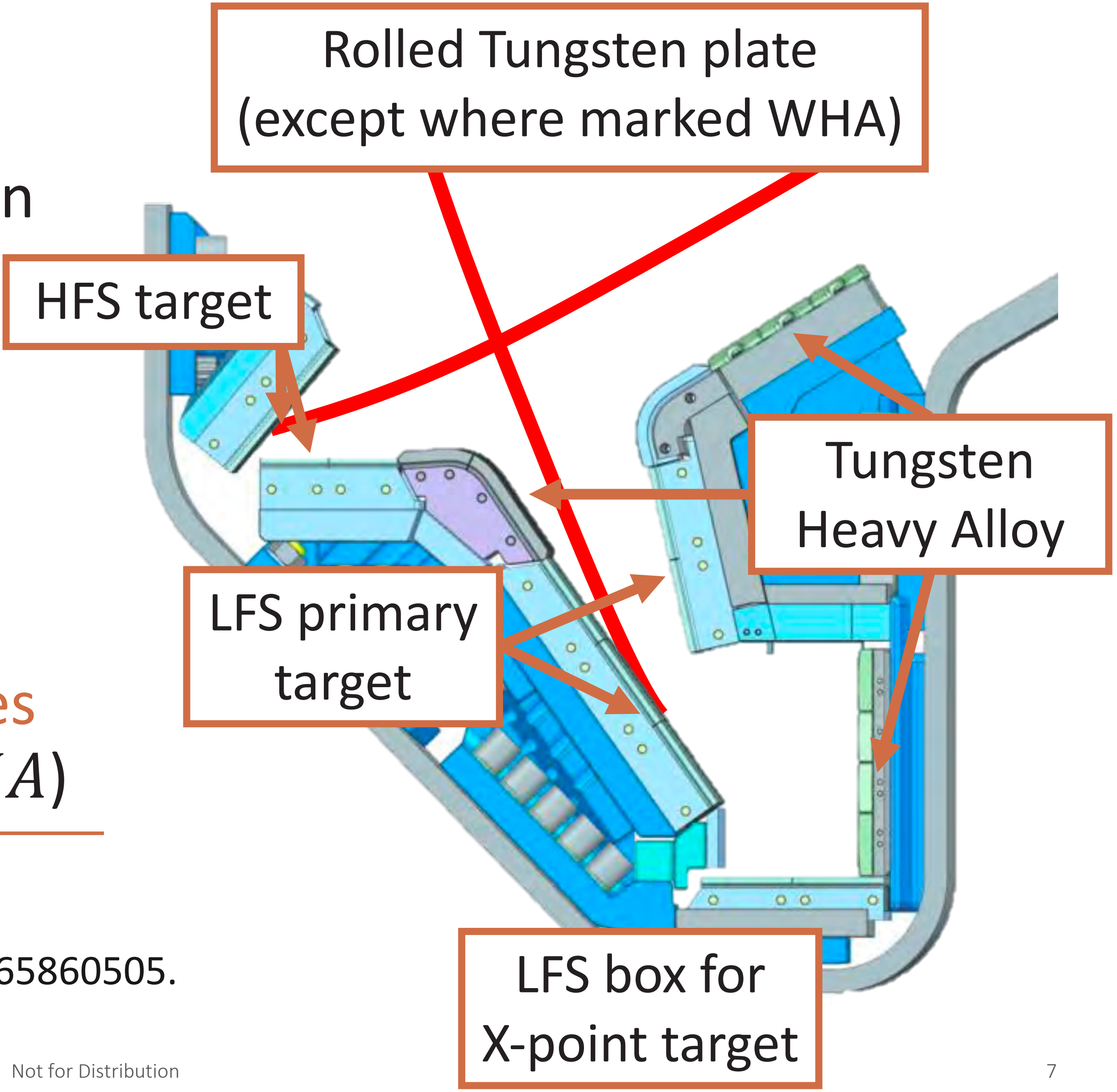
1. D. Brunner *et al* 2018 *Nucl. Fusion* **58** 076010. **DOI** 10.1088/1741-4326/aac006
2. T. Eich *et al* 2013 *Nucl. Fusion* **53** 093031. **DOI** 10.1088/0029-5515/53/9/093031
3. D. Brunner *et al* 2017 *Nucl. Fusion* **57** 086030. **DOI** 10.1088/1741-4326/aa7923

Divertor is designed to handle high-heat fluxes

- Inertially cooled tungsten/tungsten-heavy-alloy divertor[1]
- $t_{flattop} \lesssim 10s$ limits energy deposition
- Up/down symmetric divertors for double-null[1,2]
- Independent gas injection lines for fueling and seeding
- Large low-field-side divertor box to allow for advanced divertor geometries such as X-point target[1,2] (at $I_p < 5.5MA$)



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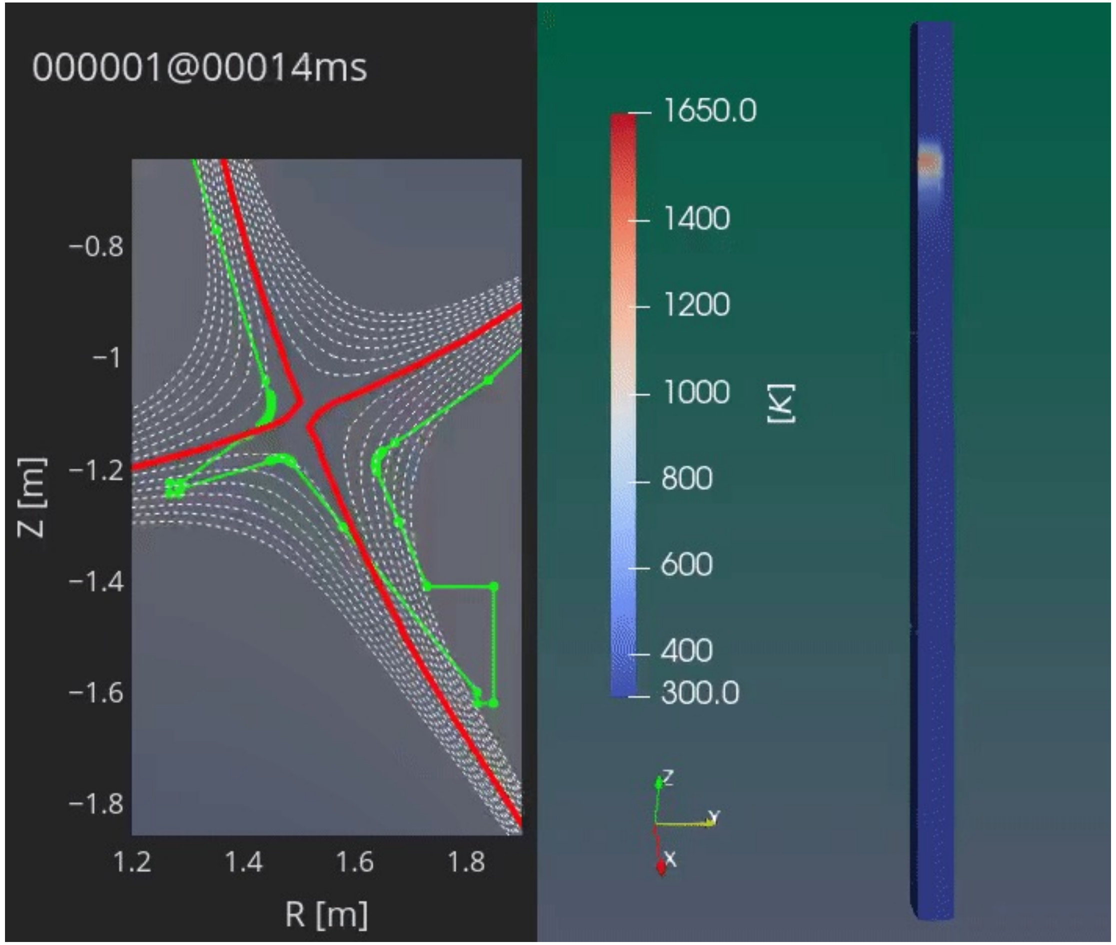
1. P. Rodriguez-Fernandez *et al* 2022 *Nucl. Fusion* **62** 042003. **DOI** 10.1088/1741-4326/ac1654
2. A.Q. Kuang *et al* 2020 *Journal of Plasma Physics* **86(5)**, 865860505. **DOI** 10.1017/S0022377820001117

Heat-fluxes must be controlled to prevent tungsten recrystallization and sputtering

- We have a limit on accumulated tile heating over the whole shot of $T_{bulk} < T_{recrystalization} \sim 1600K$
- To reduce impurity sources due to sputtering, the plasma temperature at the sheath entrance should be kept as low as possible.
- Strike-point sweeping helps to reduce localized target heating, but we'll also need impurity seeding.

LFS target heating during $1Hz$ strike-point sweep — simulated using HEAT[1]



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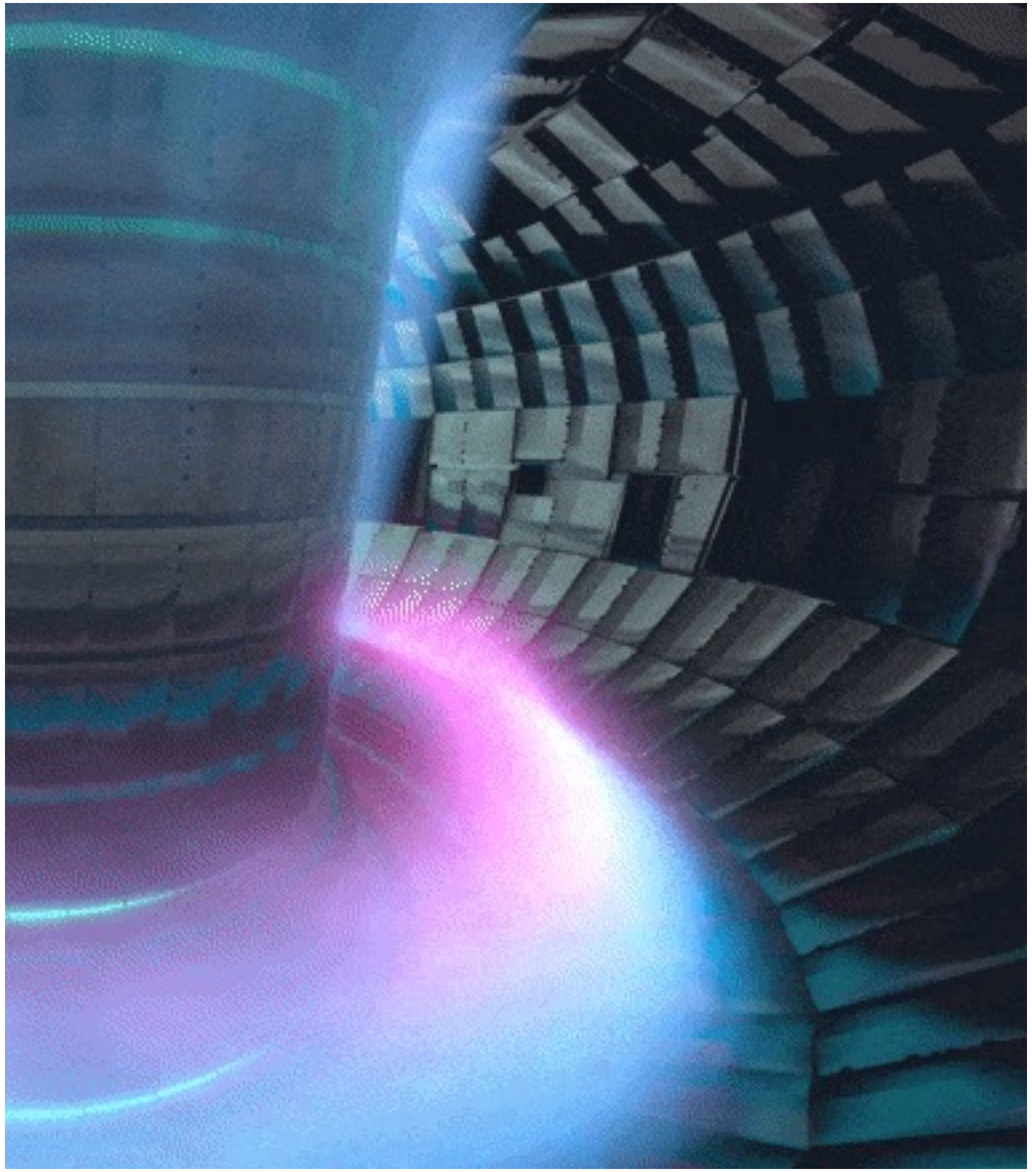
[1] T. Looby *et al* 2022 *Fusion Sci. & Tech.* **78(1)** 10-27
DOI 10.1080/15361055.2021.1951532
https://github.com/plasmapotential/HEAT

The heat-exhaust challenge

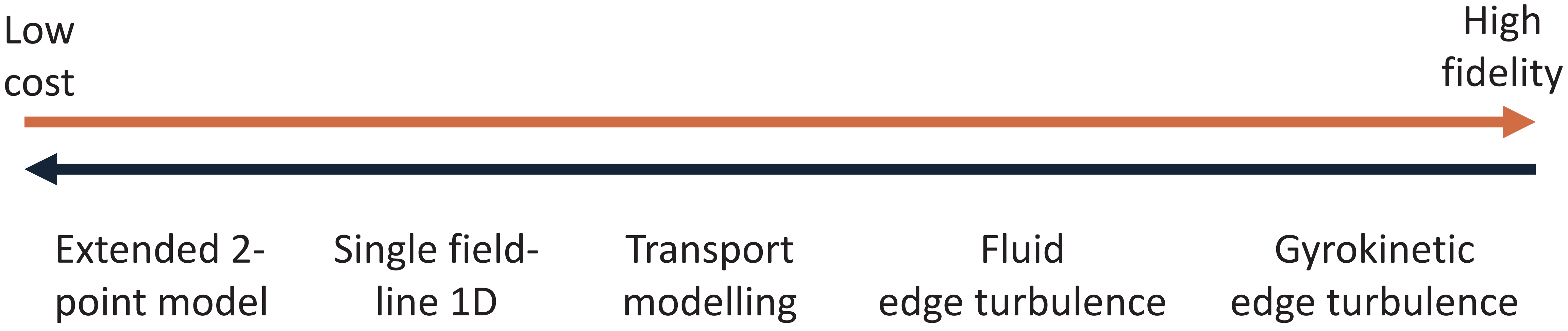
- How can we maximize core performance while protecting the plasma-facing components? This isn't a "new" problem, but it is at a new scale.
- Projected unmitigated heat-fluxes will be an order-of-magnitude higher than in existing devices, and of a similar magnitude to those expected for ITER.
- SPARC will be a key opportunity to test heat-exhaust-solutions at parameters relevant to ITER, DEMO and ARC.



Divertor modelling will play a key role in planning SPARC operations

- Need fast models for real-time-control and pulse-planning, studies of detachment access and control, seeding mixtures/locations/rates, profile prediction across the separatrix, and interpretive models.
- SPARC currently benefits from close collaborations the broader fusion community — such as SOLPS-ITER transport modelling. We're looking to expand the community of SPARC modelers to help design, contribute to, review or run models for SPARC.
- SPARC experimental results will validate divertor models at fusion-power-plant-relevant parameters, assessing and helping to improve their accuracy for ITER, DEMO and ARC.

SPARC needs divertor modelling across a wide range of model fidelity



Low cost

High fidelity

Extended 2-point model

Single field-line 1D

Transport modelling

Fluid edge turbulence

Gyrokinetic edge turbulence

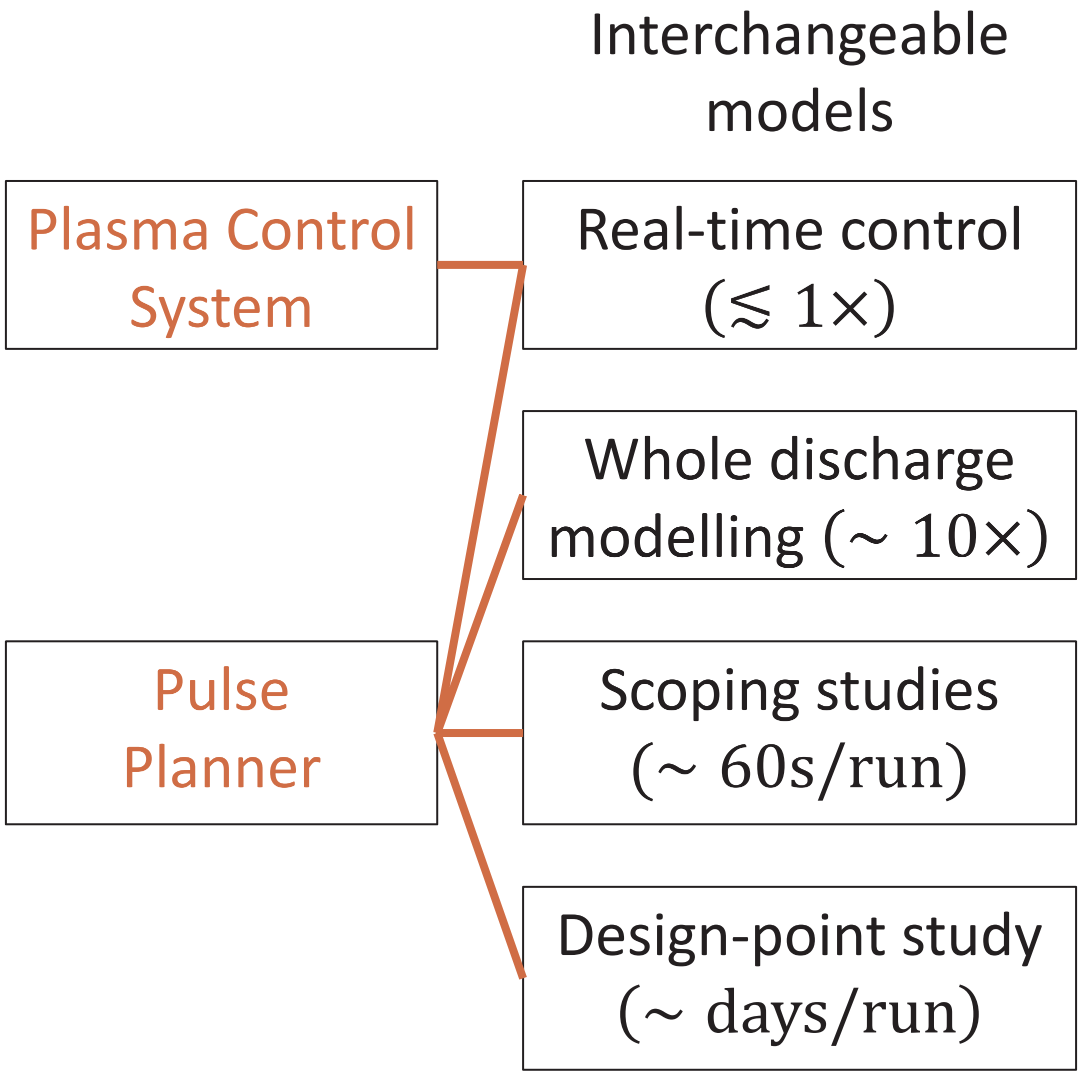
SPARC Pulse Planner
Developed within CFS, contributions encouraged

SOLPS-ITER
Via MIT, ORNL partners

Predictive modelling
Looking for partners!

The SPARC Plasma Control and Pulse Planner

- Due to the high heat fluxes and limited options for in-vessel maintenance, we will check all discharges in advance using the SPARC Pulse Planner.
- The Plasma Control System and Pulse Planner will share interchangeable physics models.
- We need *fast* divertor models — from real-time to ~days/run. We're planning to develop these open-source, in collaboration with the modelling community.



Interchangeable models

Plasma Control System

Pulse Planner

Real-time control $(\lesssim 1\times)$

Whole discharge modelling $(\sim 10\times)$

Scoping studies $(\sim 60\mathrm{s/run})$

Design-point study $(\sim \mathrm{days/run})$

How much fidelity can we get from fast models?

1. Simple 0D models such as the extended 2-point-model
    - Link diagnostics and machine controls to model inputs (i.e. seeding rates to f_{rad})?
2. Machine-learning of higher-fidelity results
    - See [2] for predicting n_e^{OMP} and $T_{e,sep}^{div}$ as a function of fueling using time-dependent SOLPS-ITER simulations
    - Tabulate kinetic corrections to heat conductivity[1], sheath heat transmission, etc?
3. 1D or simple 2D models for detailed studies (i.e. SD1D[3] with corrections)
    - As drop-in replacements for lower fidelity models
    - For detailed design-point studies such as looking at the impact of thermoelectric currents on power sharing or detachment robustness to heat pulses
4. …and more? Suggestions and contributions welcome!

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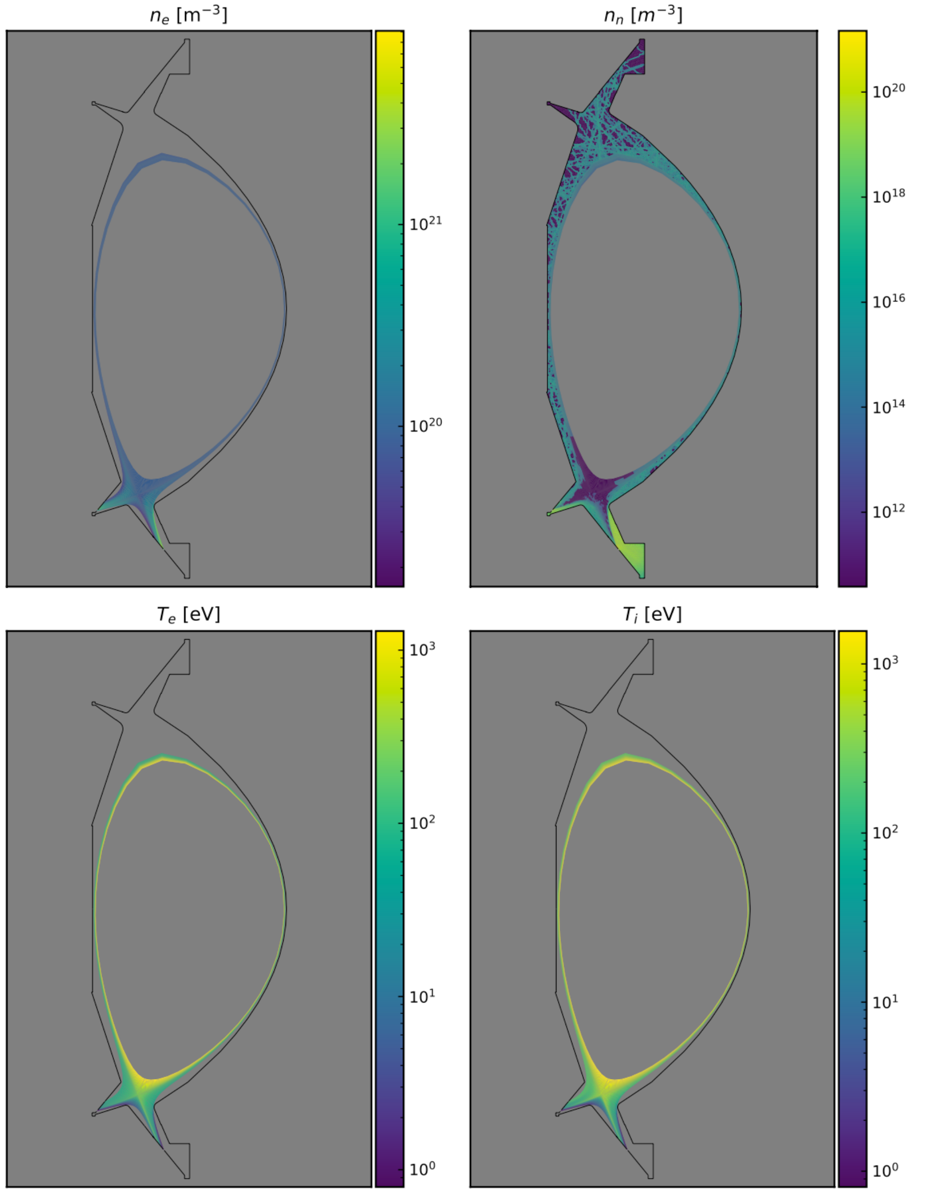
1. D. Power *et al* 2022 *ArXiV* [physics.plasm-ph] 2208.10862 **DOI** 10.48550/arXiv.2208.10862
2. J. D. Lore *et al* 2023 *Nucl. Fusion* — submitted manuscript
3. B. Dudson *et al* 2019 *PPCF* **61** 065008 **DOI** 10.1088/1361-6587/ab1321

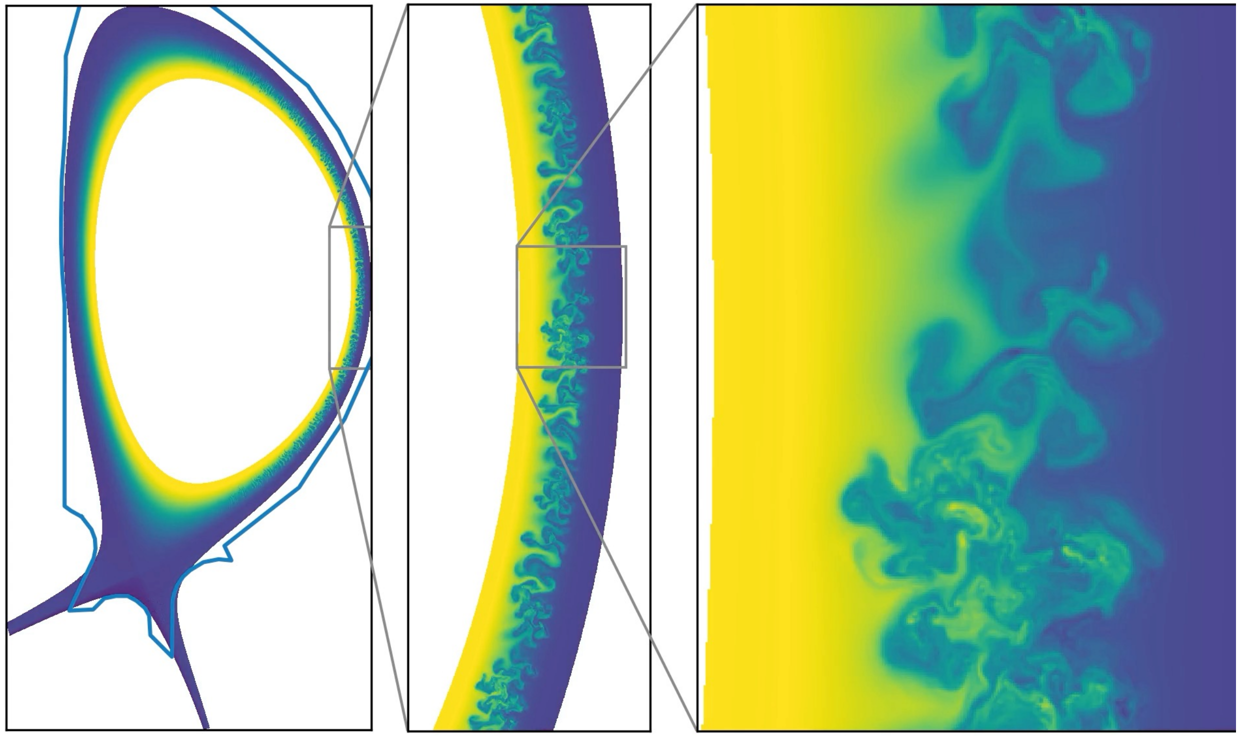
Transport modelling used for detailed studies and simulation of design-points

- SOLPS-ITER simulations for SPARC and ARC performed by MIT and ORNL partners, looking at detachment access and control in neon-seeded plasmas and helping to design plasma-facing-components.
  - Very high energy density in SPARC makes convergence more challenging.
- Open transport modelling topics to explore
  - Wide-grids to cover divertor box, Zhadanov multi-ion model for tracking charged impurities, drifts for power-sharing, kinetic corrections for heat conduction, and exploring MHD modelling of transients.



Predictive modelling for SPARC

- Anomalous diffusion coefficients, profiles across the separatrix and far-SOL profiles near the RF antennas remain uncertain.
- Edge turbulence modelling could play an important role in
  - predicting SPARC profiles, especially for the L-mode $Q > 1$ discharge in campaign 1
  - interpreting SPARC experimental results
  - extrapolating SPARC results to ARC



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1. Figure from A. Stegmeir *et al* 2023
   Comput. Phys. Commun. — submitted manuscript

Predictive modelling for SPARC

To perform accurate simulations at SPARC parameters, edge turbulence models will likely need to be able to simulate

Difficult

1. With high spatial (and velocity-space) resolution due to strong toroidal field, large temperature difference from confined-region to target (req: excellent weak scaling!)
2. Large changes in collisionality from confined-region to target (req: kinetic corrections for fluid models, adv. collision operators for gyrokinetic models)
3. Impurity seeding and detachment (req: impurity radiation models, multi-ion models, advanced neutrals models)
4. Double-null and advanced divertor geometries (req: flexible gridding and drifts)
5. Steep SOL temperature gradients (req: higher-order gyroaveraging, finite-larmor-radius corrections)
6. Far-SOL profiles near RF antennae (req: neutrals with 3D walls, wide-grids)
7. Edge modelling during ramp-up/down

Very difficult!

Predictive modelling for SPARC

- Predictive divertor modelling at power-plant-relevant parameters will be challenging — but it will have a big impact!
- Simulations of SPARC will be validated against SPARC experimental data — informing the use of turbulence models for ITER, DEMO and ARC.
- The ARC design will be finalized during SPARC operations.
  Validated predictive divertor modelling will play a key role in finalizing the ARC design — bringing forward the first net-electrical fusion power plant.
- We're looking for collaborators to perform SPARC simulations. If you're interested, we'd love to hear from you! Please note that your code license should not preclude use for commercial projects, and open-source projects are preferred.

Key take-aways

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Next steps

- Contact tbody@cfs.energy to get involved in SPARC divertor modelling
- Check out github.com/cfs-energy for resources such as code and equilibrium files (WIP)
- Join the team at jobs.lever.co/cfsenergy — positions open include Divertor and Boundary Operations Lead, Disruptions Scientist and Physics Operator