Utilization of SPARC to investigate divertor solutions for fusion pilot-plants

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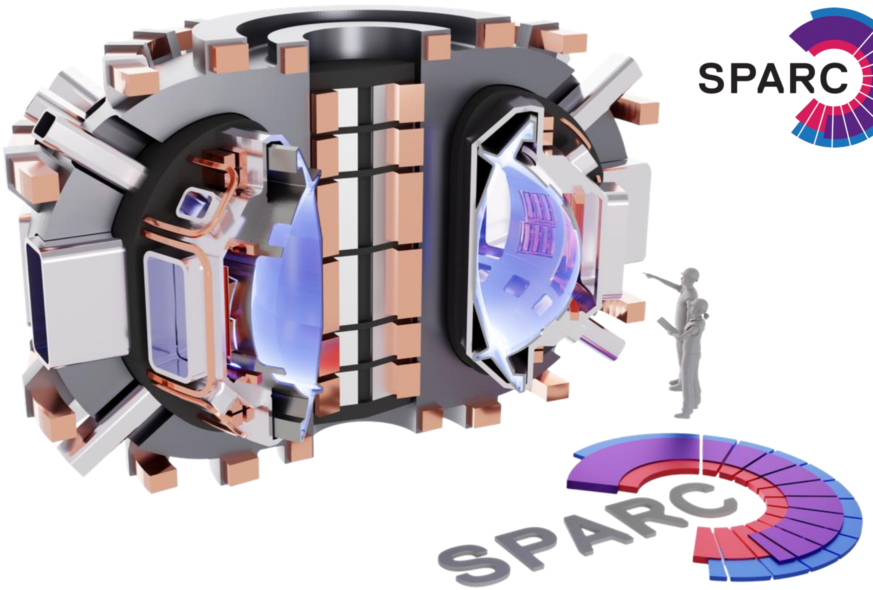
Summary

- SPARC is a compact, high-field device designed to achieve Q>1 on an accelerated timescale – target completion in 2025.
- The US Fusion community (private and public) is pushing strongly for a fusion pilot plant in the 2030s but there are large gaps in our knowledge basis.
- A key issue being the particle and power exhaust handling in the divertor.
- Activities are being planned on how best to utilize SPARC to close these critical gaps for a next-step device – community input is welcome.



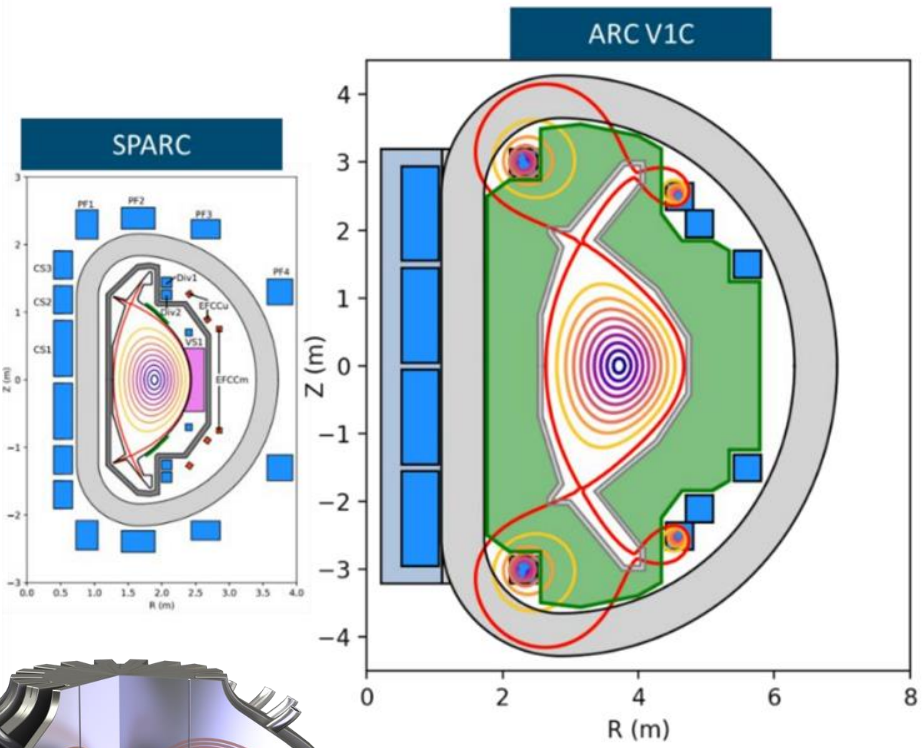
SPARC Primary Reference Discharge		
B_0	12.2	T
I_p	8.7	MA
q^*	3.1	(q_{95} = 3.4)
κ_a	1.75	
κ_{sep}	1.98	
$\langle T_e \rangle$	7.33	keV
$\langle n_e \rangle$	3.13	10^{20} m^{-3}
τ_E	0.77	s
f_g	0.37	
P_{ohmic}	1.7	MW
$P_{ICRF,coupled,operating}$	11.1	MW
$P_{ICRF,max}$	25.0	MW
P_{fus}	141	MW
Q	11.0	

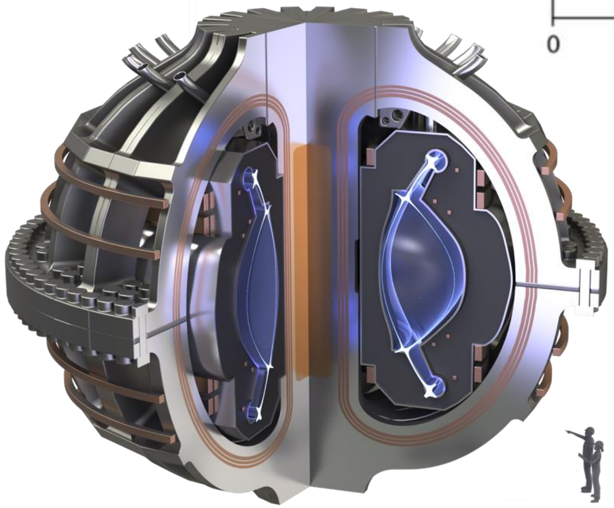
For CFS, “ARC-Class” is the target fusion pilot plant

- Expanded set of “ARC-class” designs
  - The original ARC concept was published in two papers in Fusion Engineering and Design (2015/2018)
  - A wide array of design points since been presented at APS DPP 2020 and 2021
  - Development of a baseline scenario will continue to be tuned and incorporate learnings from SPARC
- Major characteristics of an “ARC-Class” device are:
  - High field (B_0>8 T)
  - Standard aspect ratio (R_0/a~3-4)
  - Liquid immersion blanket
  - Replaceable vacuum vessel

“Why can’t we build ARC today?”

- Key technological and scientific issues remain

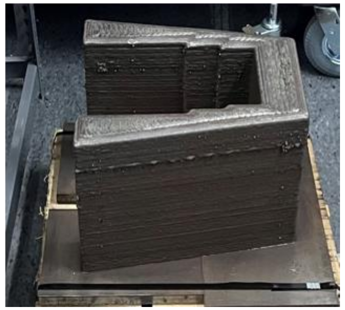




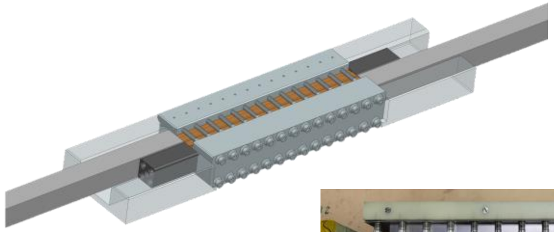
Technological R&D projects are currently underway in parallel with ARC design

Sub-system	R&D Activities for ARC
Superconducting Magnets	High temperature superconductor magnets Demountable TF or PF coils
Vacuum Vessel and Internal Components	Blanket for breeding loop High temperature VV operations Radiation resistant materials manufactured to be replaceable Remote handling
Divertor and PFC design	Actively cooled designed for long pulse operations
Fuel Cycle	Continuous tritium processing loop Tritium breeding and recovery (TBR > 1)

- An acknowledgement that much of this is not ready for deployment



Examples of intermediate-scale, additive manufacturing test articles produced in collaboration with industrial partners

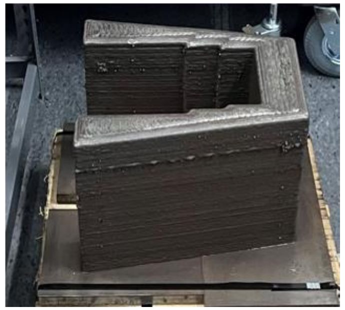


Benchtop-scale superconducting joints that have been fabricated for ARC magnets

Technological R&D projects are currently underway in parallel with ARC design

Sub-system	~~R&D Activities for ARC~~ SPARC Design
Superconducting Magnets	High temperature superconductor magnets ~~Demountable TF or PF coils~~
Vacuum Vessel and Internal Components	~~Blanket for breeding loop~~ ~~High temperature VV operations~~ ~~Radiation resistant materials manufactured to be replaceable~~ ~~Remote handling~~ Cooled with room temperature gas with peak operating temperatures over the day at <150°C
Divertor and PFC design	~~Actively cooled~~ ~~designed for long pulse operations~~ inertially cooled and designed for transient high heat fluxes
Fuel Cycle	Continuous tritium processing loop ~~Tritium breeding and recovery (TBR > 1)~~

- An acknowledgement that much of this is not ready for deployment
- Simplifications were made on SPARC to accelerate design and constructions



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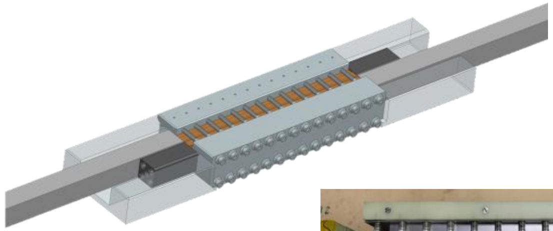
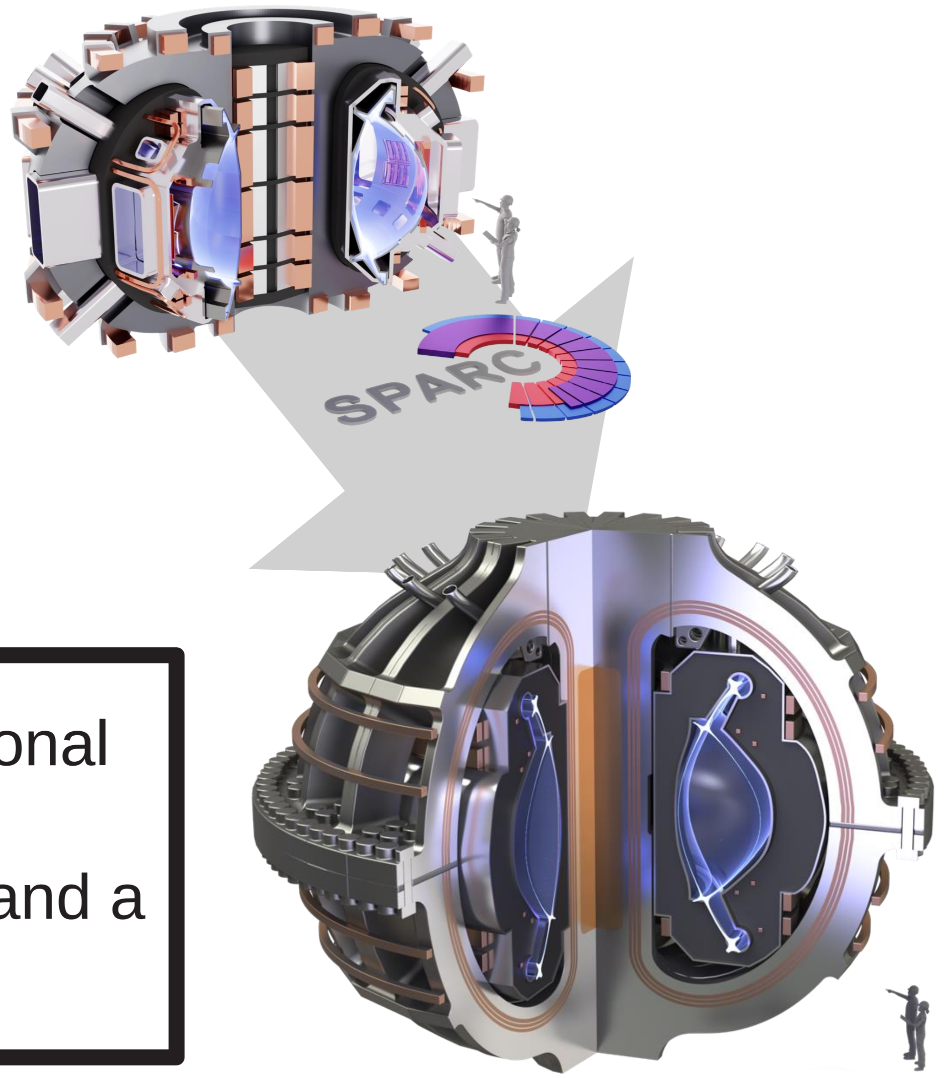


Benchtop-scale superconducting joints that have been fabricated for ARC magnets

Focus of SPARC is to retire scientific risk for ARC but potential to benefit the international reactor design effort

- Technological simplifications on SPARC mean that we can build it now! *Construction has begun*!
- Mission driven approach is beneficial to the community since the same issues will affect ITER, DEMO, others…
  - Burning plasma physics and control
  - Power exhaust management
  - Particle exhaust management



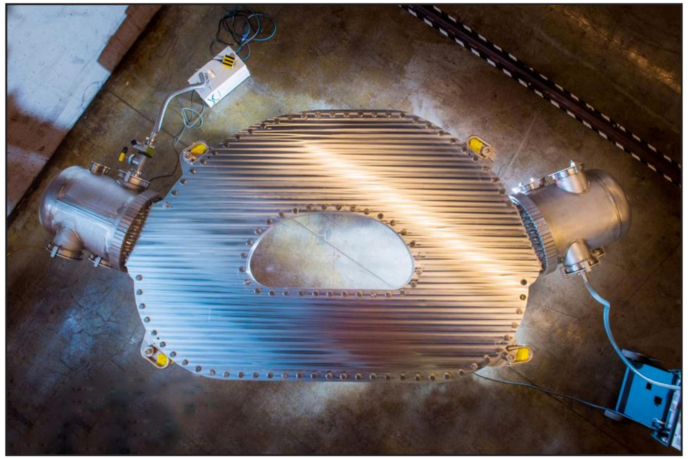
Strong overlap of risks for ARC with the international reactor design effort.
Clear unknowns from the fusion community exist and a strong need for a device to answer them.

SPARC is scheduled to be completed in 2025

- Design of SPARC has been underway since 2018
  - Major long lead components (cryoplant, vacuum vessel) have been ordered
- Development and demonstration of HTS magnet technology
  - Large bore (~2 m) 20T on tape magnet was tested in Sep. 2021
  - More test coils (central solenoid) and others currently underway
- Site selected and purchased in Devens, Massachusetts
- Construction of manufacturing and office buildings complete
- Tokamak hall is being built and scheduled for completion next year

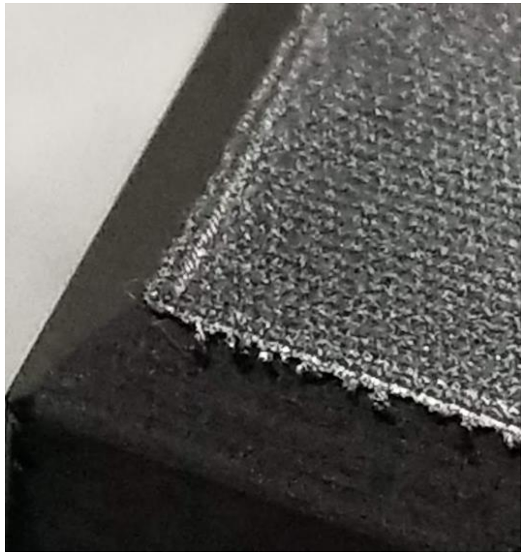
mid Oct 2021 (Google Earth)

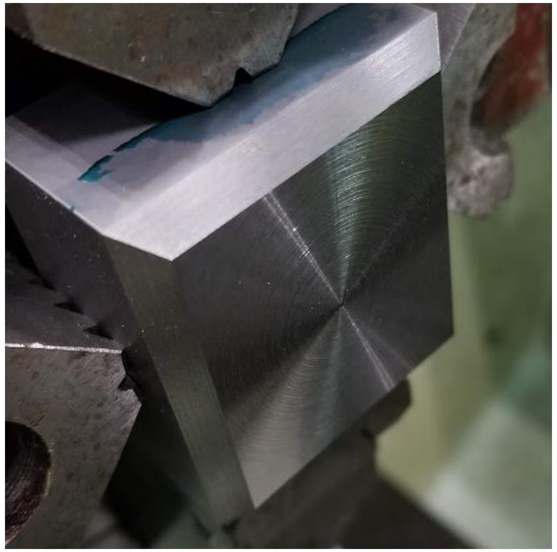
mid Sept 2022 (@CFS_energy)



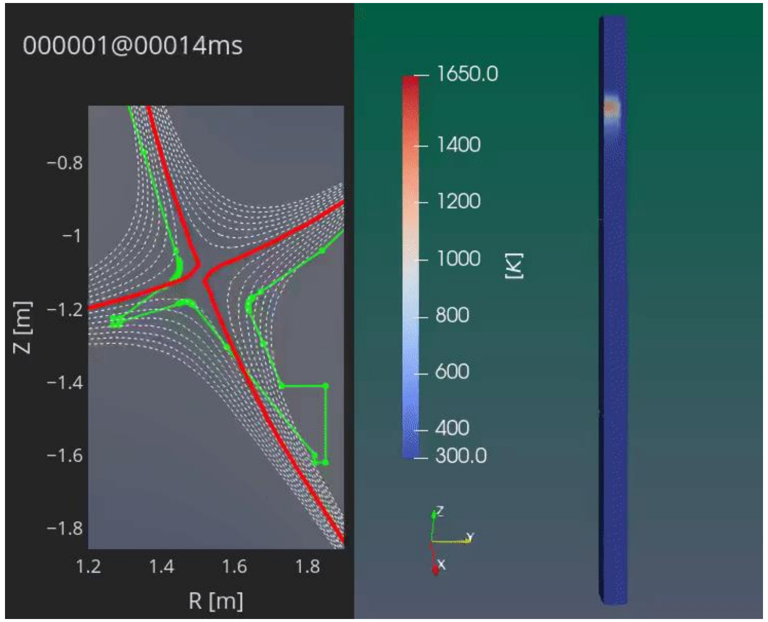
SPARC divertor design was driven by conservative loading assumptions

- Fundamentally we're trying to build the strongest divertor we can:
  - Inertially cooled (10 sec flattop)
  - Tungsten high heat flux components, WHA otherwise
  - Baseline thermal design driven by a fast-sweeping strike point

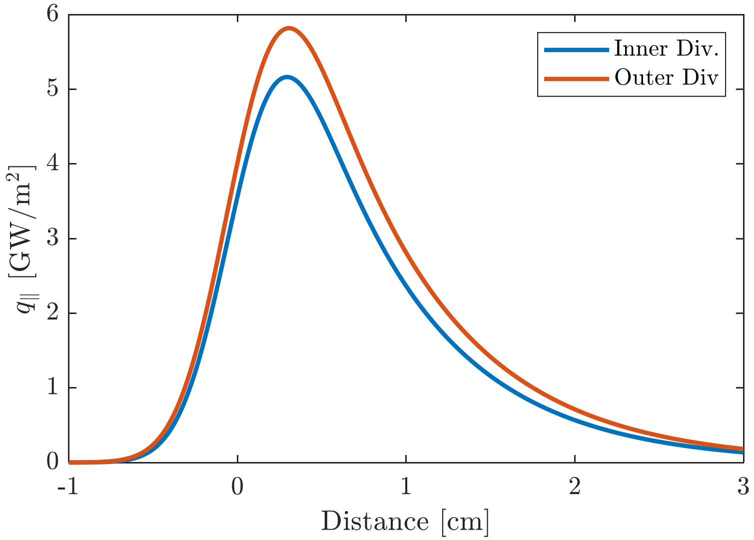




Use of WHA in tokamaks established by IPP-Garching. Further in-house testing was performed to qualify use in low heat flux regions of the PFCs



Simulations by T. Looby in HEAT used to defined 3D enhancement due to fishscaling



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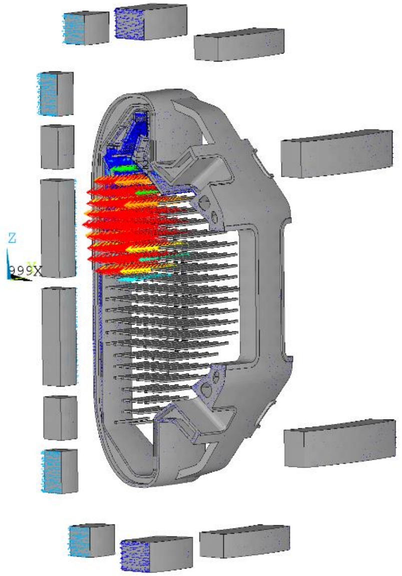
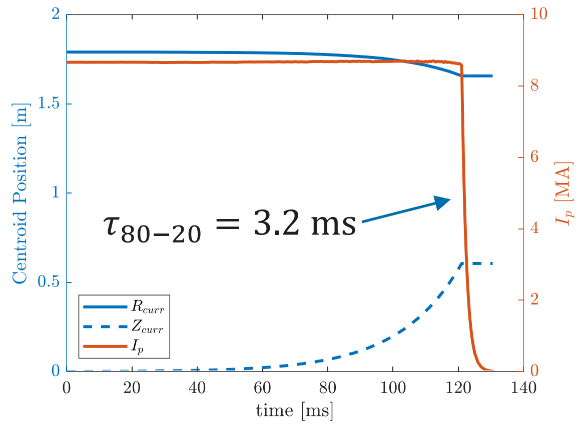
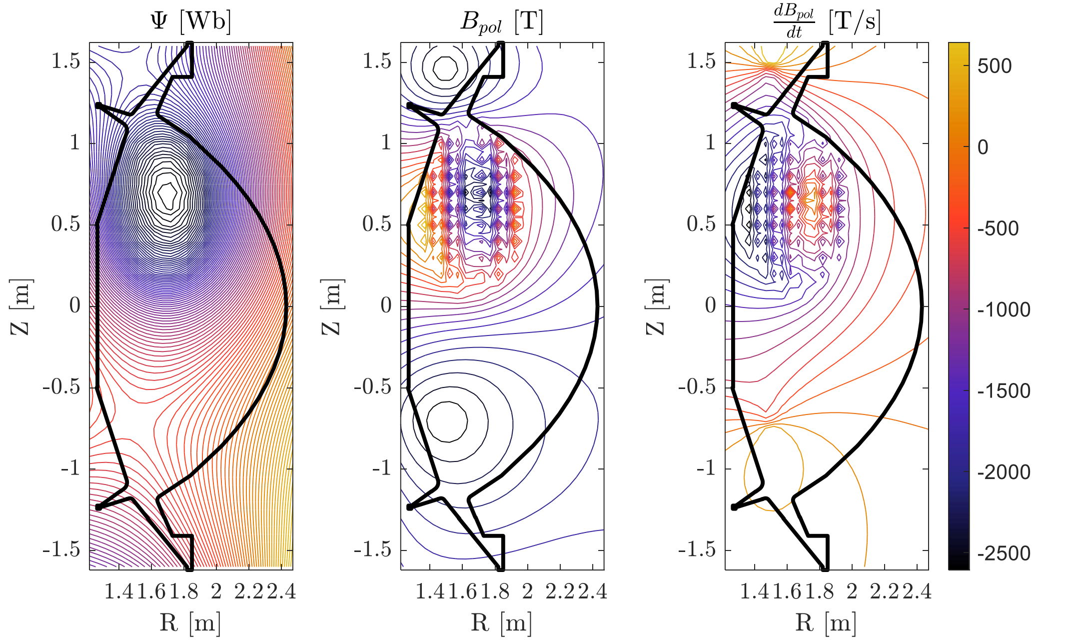
    - Inertially cooled (10 sec flattop)
    - Tungsten high heat flux components, WHA otherwise
    - Baseline thermal design driven by a fast-sweeping strike point
- Design criteria:
    - Thermal: operate a full RF power (25 MW) DD discharge every 40 min, up to 12 a day or a full fusion power (140 MW) discharge every 4 hrs, up to 4 a day.
    - Structural: Withstand full current (8.7 MA, 12.2 T) midplane disruptions; or a full current vertical displacement event (VDE). Whichever is more limiting.

Overall design of the divertor to be closed by Q1 2023
Focus of physics team is pivoting from design to operations







Mission driven approach designed to answer key critical gaps between SPARC and a fusion pilot plant

1. Predictive understanding of PFC heat loads (divertor and main chamber)
   - Global energy balance and power sharing
   - Divertor heat loads
2. Search for solutions to controllable, dissipative divertor operation
   - Low steady state erosion divertor conditions
   - Neutral pumping levels sufficient for helium ash removal
3. Methods to avoid damaging edge transients
4. Managing main chamber erosion
   - RF enhanced impurity sputtering is seen as a risk
5. Ensuring compatibility with core plasma performance

There will be topics though that SPARC cannot tackle:

- Long pulse material migration
- Long term radiation induced material degradation

In line with critical gaps developed by the Boundary Group during the APS-DPP Community Planning Process, building on multiple layers of reports driven by the US community, most heavily the 2015 PMI Workshops

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Due to time limitations, we will discuss only the first two of these gaps today

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Next step devices will not use the same assumptions as what has been used for design for SPARC

- Fundamental SOL assumptions

Parameter	Value
P_{SOL}	29 MW
λ_q	0.306 mm *[Eich 2013 Regression 15]*
S/λ_q	0.5
$f_{rad,div}$	0.5
P_{idiv}:P_{odiv}	4:6

High level of physics uncertainties in these parameters

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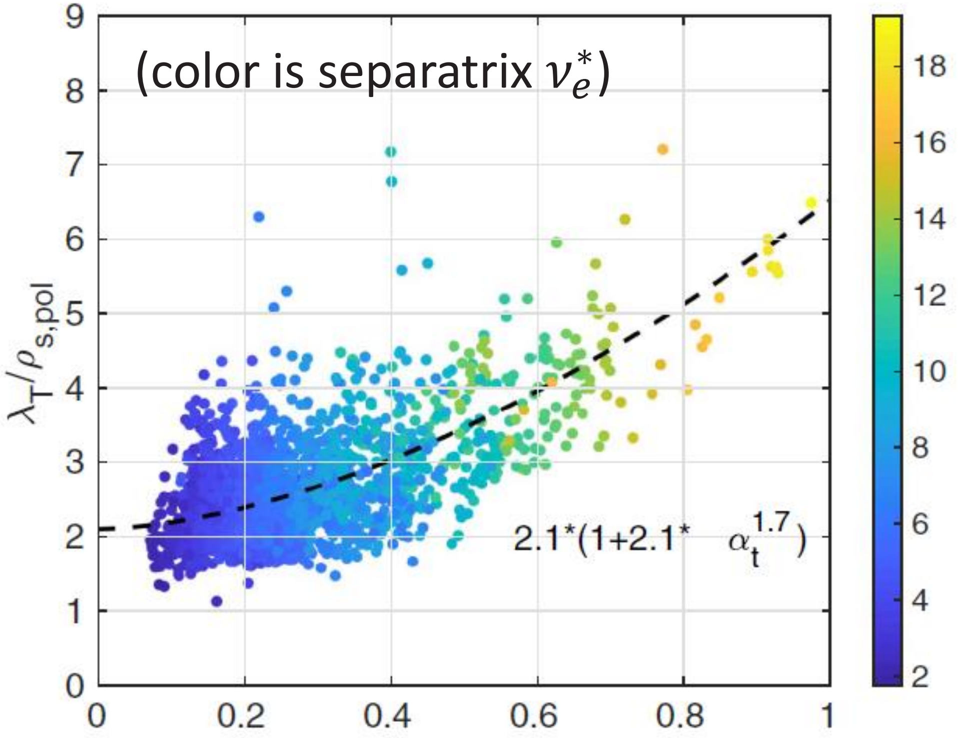
Scalings	λ_q [mm]
Eich 2013 Regression 14	0.18
Eich 2013 Regression 15	0.31
Brunner 2018	0.29
Goldston 2011	0.41
Eich 2020*	0.45
Chang 2021*	$>300\lambda_q^{Eich(14)}$

~2.5 times

**Upsteam assumptions: $n_{e,sep} = 0.3\langle n_e \rangle$, $T_{e,sep}$ calculated using simplified 2-point model by Stangeby consistent with T. Eich et al, Nuclear Fusion, 2018.*

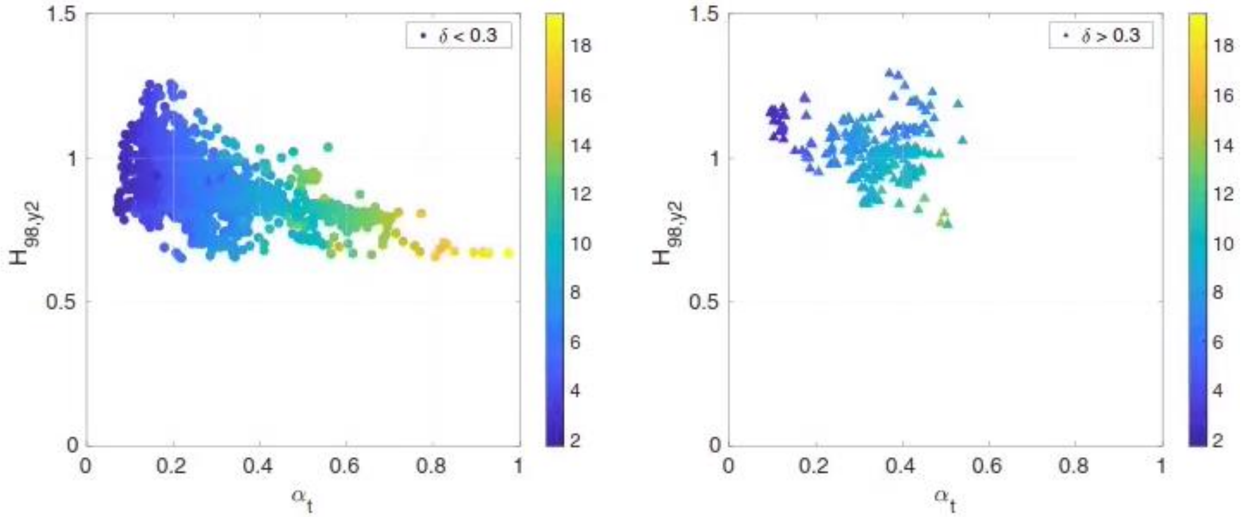
Recent experimental and modelling results suggest that there is more physics at play



$$\alpha_t \approx \frac{1}{100}\,\hat{q}_{cyl}\nu_e^*$$

T. Eich et al, Nuclear Fusion, 2020

- Recent scaling suggest a connection with edge collisionality
  - Building on work by Rogers, Scott, and Xu
  - More recent developments by Eich, Manz, Goldston
- this collisionality was correlated with H-mode performance in ASDEX Upgrade
  - Higher collisionality tended towards low $H_{98,y2}$



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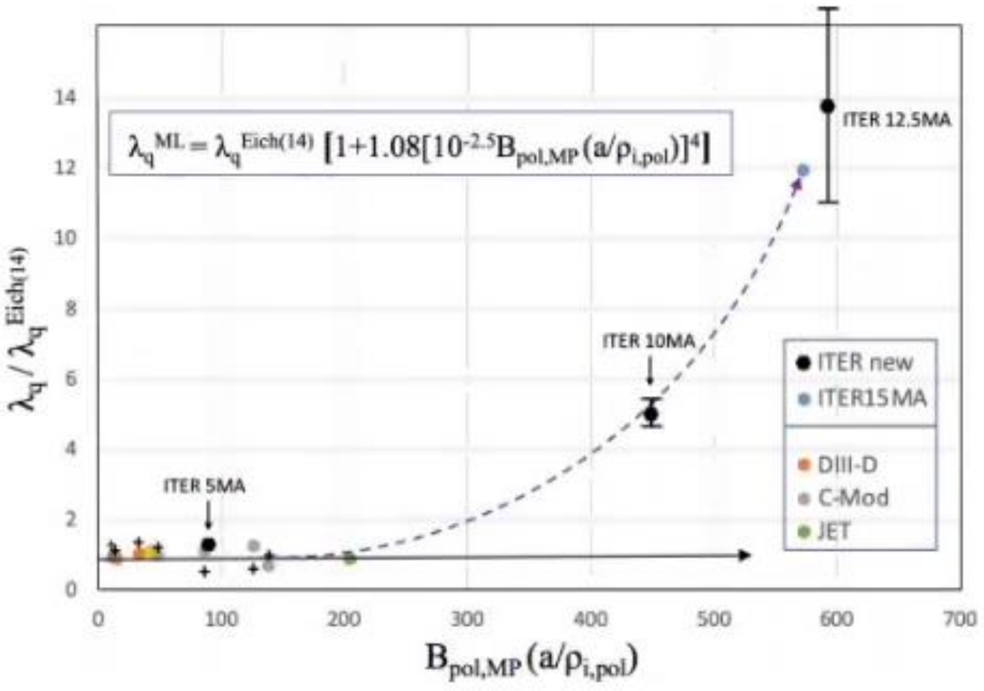

C.S. Chang et al, Physics of Plasmas, 2021

- XGC predictions show a strong increase in the λ_q associated with weakly collisional, TEM turbulence
  - $B_{pol,MP}(a/\rho_{i,pol}) > 1000$, on the exponential rise of the fit
- SPARC will have qualitative but not quantitative indication of broadening at full performance:
  - Limited diagnostics on the high heat flux tiles
  - Strong desire to maximize allowable divertor seeding
  - But we will notice if $q_{\parallel}$ is significantly lower than anticipated
  - Quantitative measurements likely possible at low-Ip, 8 T H-modes, and probably low-Ip, 12 T L-modes

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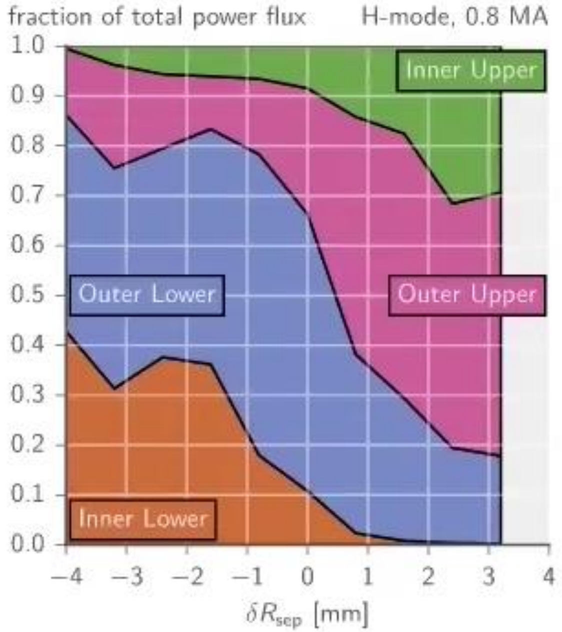
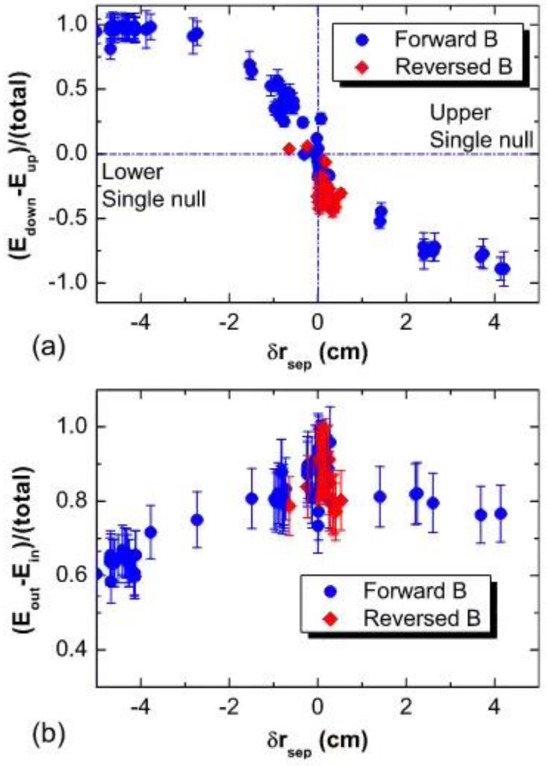


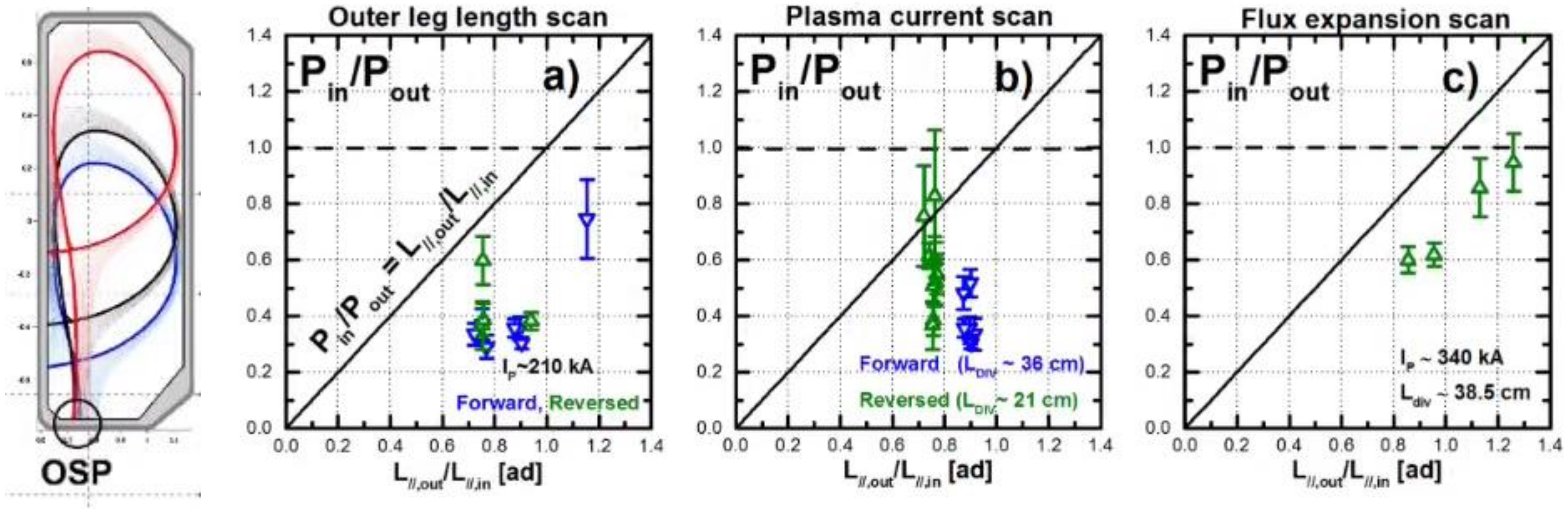
D. Brunner, et al., Nuclear Fusion, 2018



G. De Temmerman, et al., Plasma Physics and Controlled Fusion, 2010

- Use of lower single null power sharing assumptions but SPARC is up-down symmetric.
- Strong desire to examine power sharing close to double null since ARC and most next step devices would like to rely on double-null.

Recent results though suggest more than just ΔR_{ssep}



R. Maurizio, et al., Nuclear Fusion, 2018

- TCV experimental results and UEDGE simulations (*M. Umansky*)
- New results pending from MAST-U experiments
- SPARC will similarly be able to expand the dataset:
  - Device is configured to allow a wide ΔR_{ssep} scan at reduced elongation
  - Dependence with λ_q - how controllable is the power sharing?

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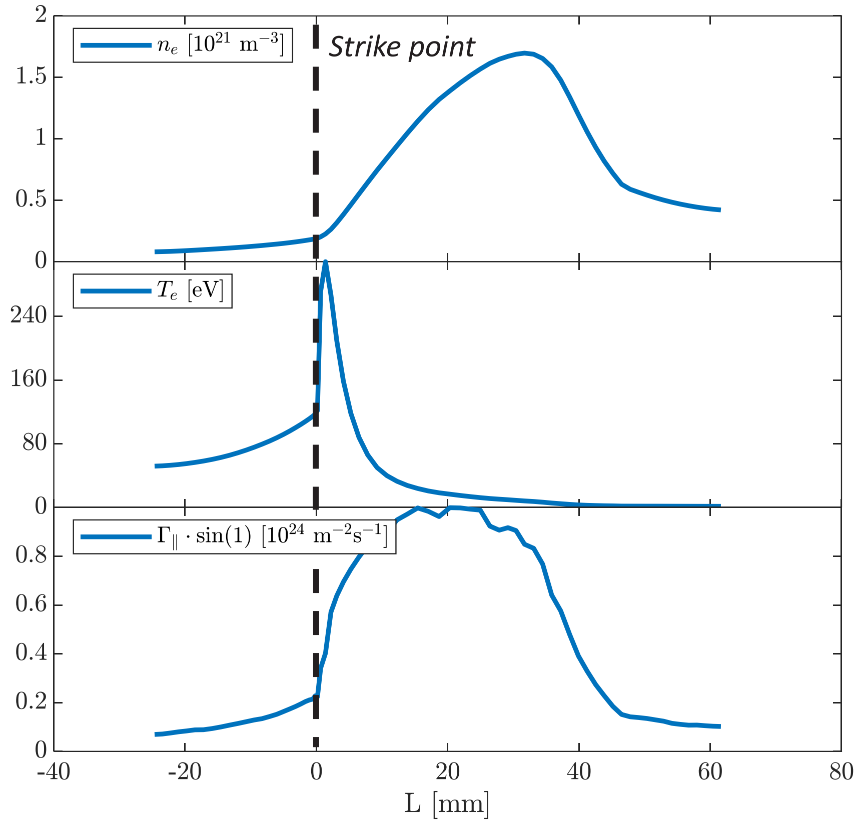
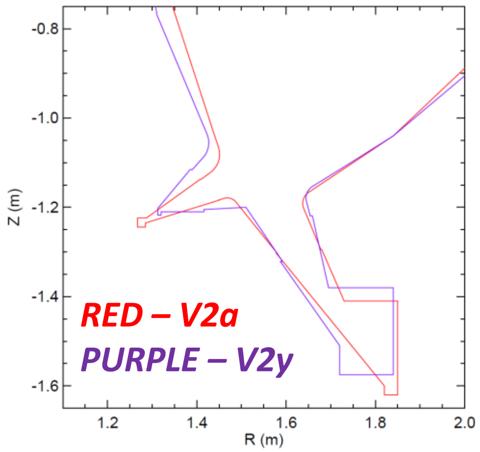


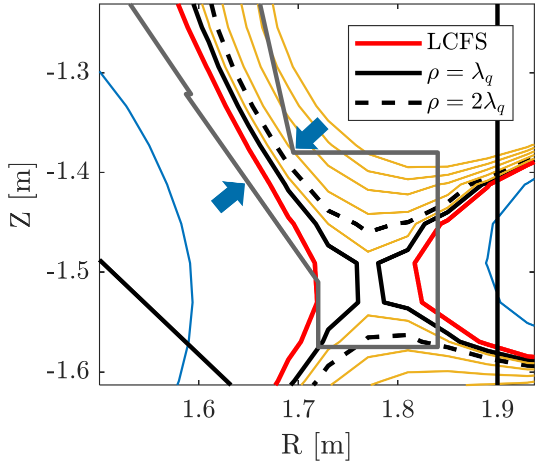
SOLPS-ITER simulations of unmitigated heat fluxes by J.D. Lore

- Unmitigated outer strike point will lead to non-negligible tungsten sputtering levels ($O(10^2)$ g W per discharge)
- A next step device will need to reduce target plasma temperatures to below sputtering thresholds and reduce ion fluxes

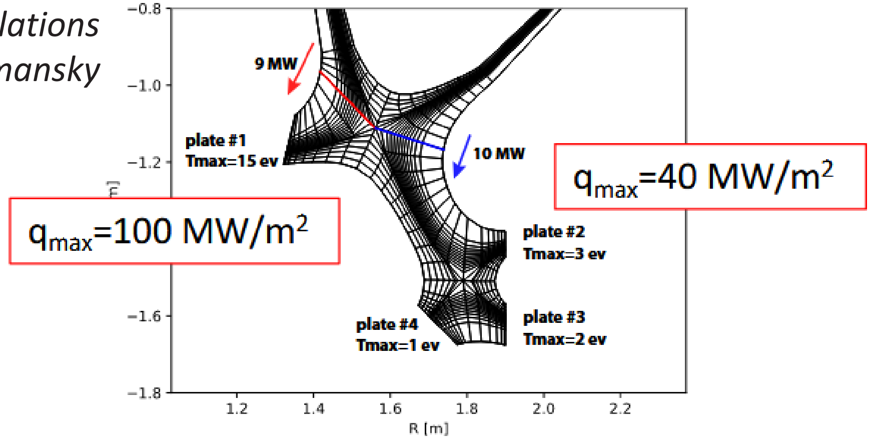
Divertor contour has been optimized for increased flexibility in magnetic geometry

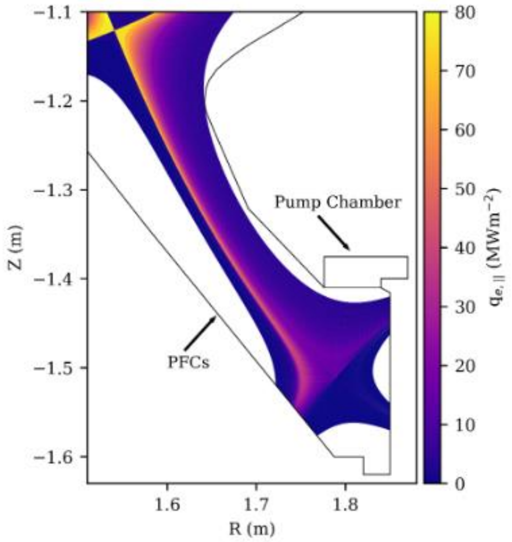
- outer divertor contour is being optimized to enable sweeping, different static vertical target plate configurations and the novel X-Point Target
    - Desire for physics flexibility being traded against the risk of melt damage on low flux expansion surfaces
- Simulation tools are being deployed to provide preliminary results of alternative divertor configurations and guide experimental planning

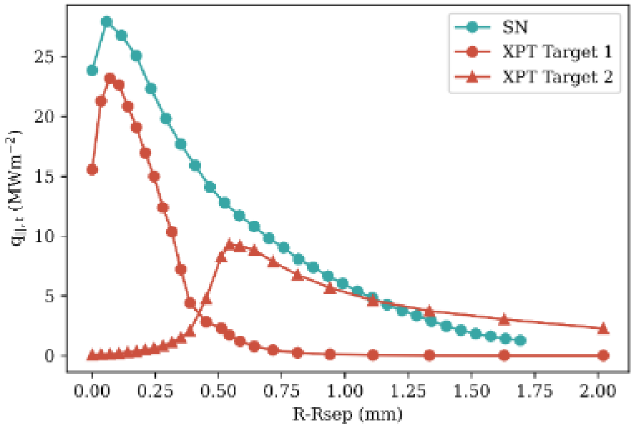




UEDGE simulations by M. Umansky

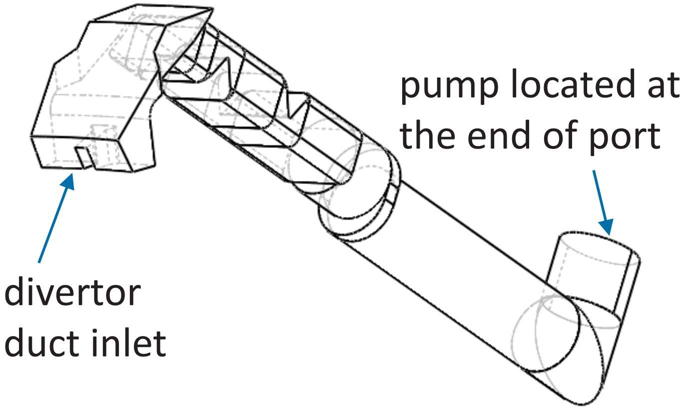


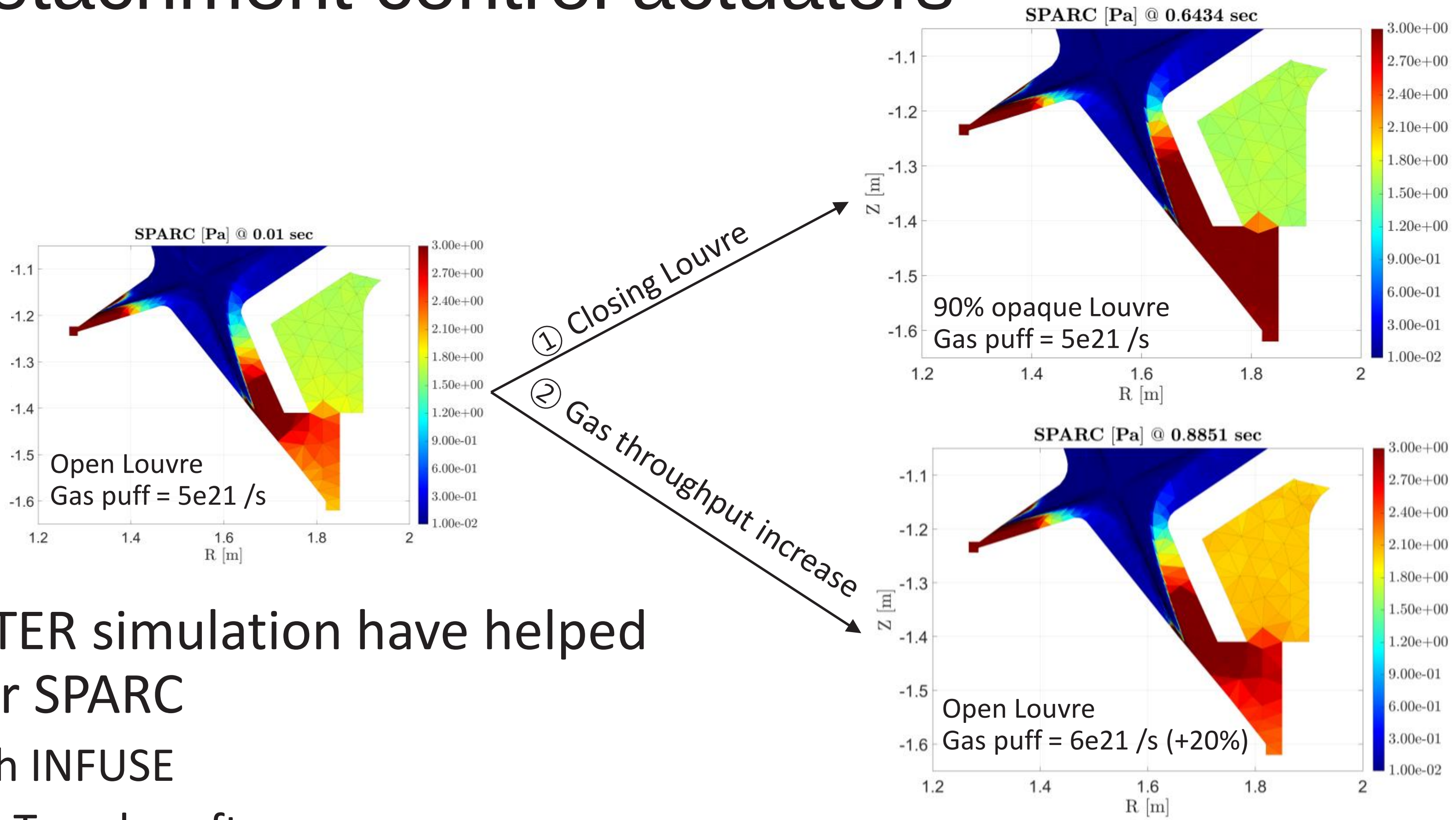




SOLPS-ITER simulations by C. Cowley, using a workflow similar to O. Pan, et al., Plasma Physics and Controlled Fusion, 2020

Time-dependent SOLPS-ITER being used to inform the design of divertor detachment control actuators





- Time-dependent SOLPS-ITER simulation have helped inform actuator design for SPARC
  - Funded by US DoE through INFUSE
  - J.S. Park, Poster Session II, Tuesday afternoon
- Identification of hysteresis in the detachment of the inner and outer divertor target.
- Independent impurity injection control required.

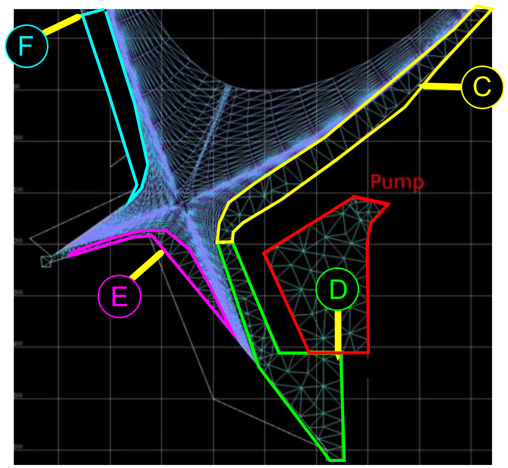
Gas injection manifold expanded to allow for divertor detachment control experiments

Plasma fueling outlets

- Tritium fueling (D2/T2 mixtures)
- Gas fueling (Gas mixtures)
- D2 Pellet Injection (ELM, PFS)

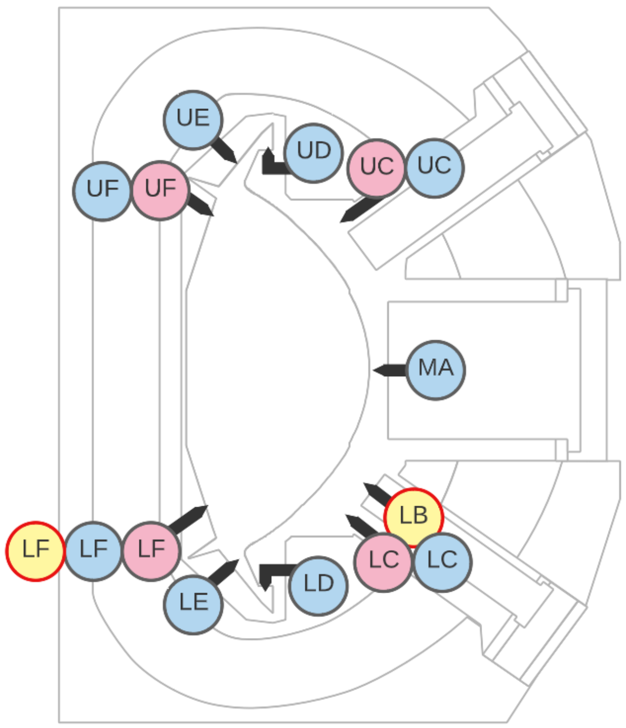
Other gas outlets (non-FINJ)

- Vessel Conditioning Gas
- Disruption mitigation valves

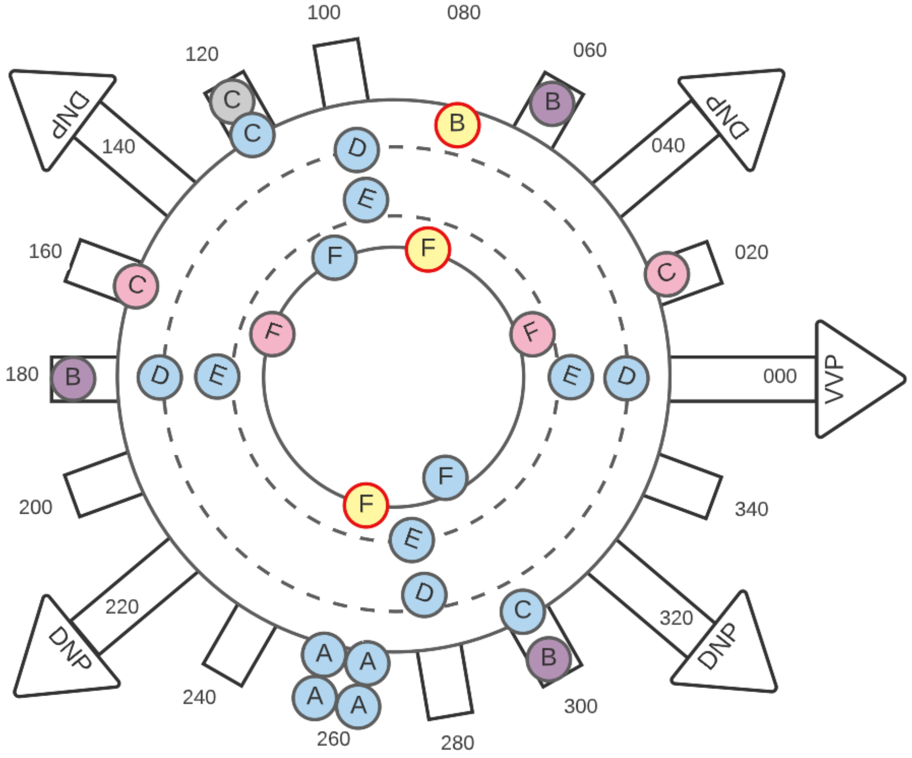


- total of 24 independent gas (impurity and H_2/D_2) delivery locations
- up down symmetric

Poloidal layout of gas injector locations

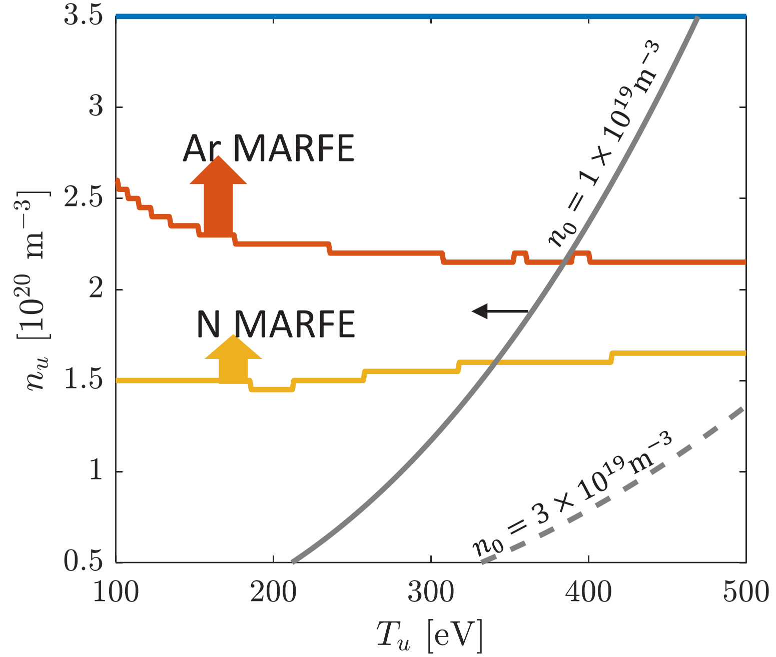


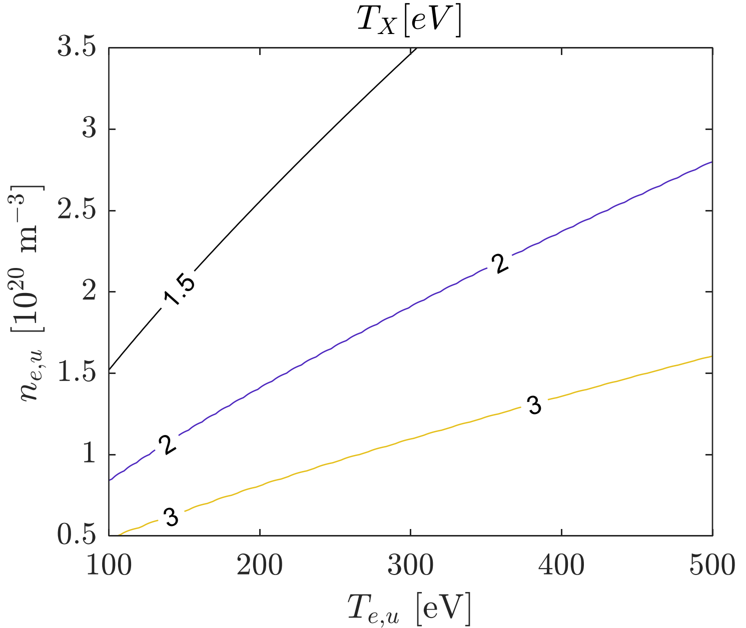
Toroidal layout of gas injector locations



Exploration of the ASDEX Upgrade X-point radiator regimes

- Application of the model developed by U. Stroth, et al., Nuclear Fusion, 2022, to SPARC parameters.
- Observed potential operating space at moderate $T_{e,sep}$ (~200 eV) and high $n_{e,sep}$ with Argon impurity fractions of ~5%.
- Ne cooling curve peaks at higher temperature, in principle very difficult to get MARFE onset.
  - Present day experiments suggest it is possible (M. Bernert, et al., Nuclear Material and Energy, 2017)
  - Potential for X-point radiator to be observed without MARFE onset on SPARC





Collaborations are welcome and needed to maximize the utilization of SPARC

- The SPARC team is determined to use SPARC to inform ARC design and do it fast.
- Even then, SPARC will not answer all the physics questions
  - Other scientific and technological R&D will be needed in parallel
- CFS is responding to the call for an accelerated timescale for fusion energy and is already actively collaborating with institutes around the world
- We welcome new enquiries and discussions