Overview of SPARC Disruptions

Theory and Simulation of Disruptions Workshop, PPPL 2023

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What’s the goal of this talk?

- Help us identify gaps in the SPARC disruption plan/design…
- Gain your interest in contributing to the ARC physics basis, which is starting soon!
  - I will show some of the physics uncertainties that caused engineering pain for SPARC, and these are areas where advancements in our understanding will greatly benefit ARC design
- SPARC will start operating in 2025 and we want you to use it to benchmark your models!

Outline

- Status of SPARC and the ARC mission
- Disruption load expectations
- Measuring disruption loads
- Prediction and avoidance
- Disruption mitigation

SPARC is a compact, high-field tokamak designed to achieve net energy gain in DT plasmas

- Designed based on the same physics basis as ITER
- High field reduces size
- Initial operation aims for Q>1, but designed to achieve Q=11 and P_{fusion} = 140 MW
- Physics basis published in 2020 in the Journal of Plasma Physics
- SPARC is under construction now in Devens, MA


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Overview of the SPARC tokamak

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The SPARC tokamak is a critical next step towards commercial fusion energy. SPARC is designed as a high-field ($B_0 = 12.2$ T), compact ($R_0 = 1.85$ m, $a = 0.57$ m), superconducting, D-T tokamak with the goal of producing fusion gain $Q > 2$ from a magnetically confined fusion plasma for the first time. Currently under design, SPARC will continue the high-field path of the Alcator series of tokamaks, utilizing new magnets based on rare earth barium copper oxide high-temperature superconductors to achieve high performance in a compact device. The goal of $Q > 2$ is achievable with conservative physics assumptions ($H_{98,y2} = 0.7$) and, with the nominal assumption of $H_{98,y2} = 1$, SPARC is projected to attain $Q \approx 11$ and $P_{fusion} \approx 140$ MW. SPARC will therefore constitute a unique platform for burning plasma physics research with high density ($\langle n_e \rangle \approx 3 \times 10^{20}$ m^{-3}), high temperature ($\langle T_e \rangle \approx 7$ keV) and high power density

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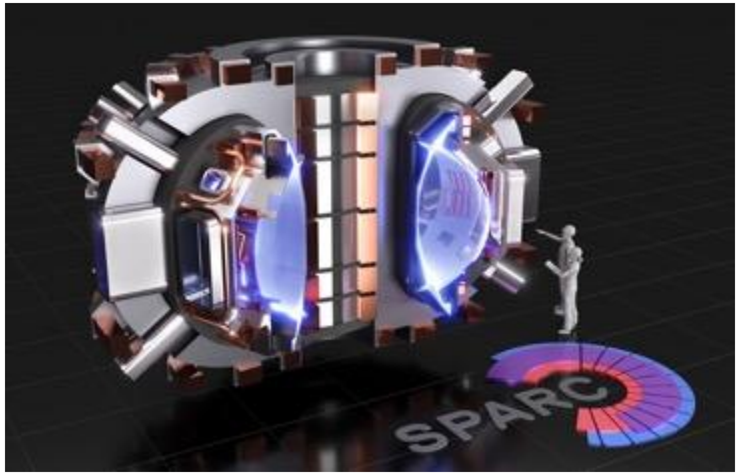
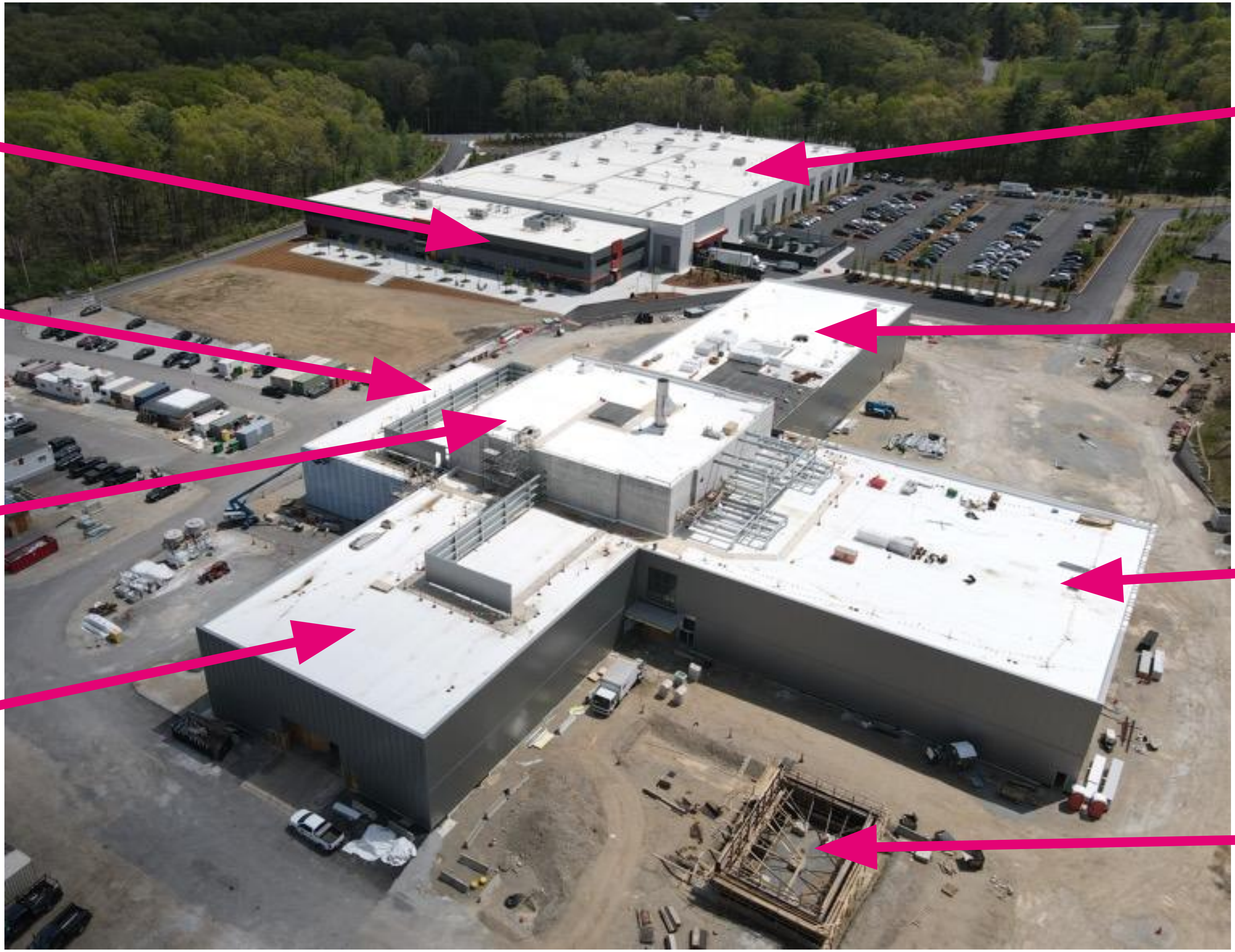


Construction of SPARC and magnet factory in Devens, MA

Construction of SPARC and magnet factory in Devens, MA



CFS Headquarters

Diagnostics Building

Tokamak Building

RF and Assembly Building

Magnet Factory

Utility Building

Power Building

Cooling Water Building

SPARC components have begun manufacturing

CFS is working with academic partners to accelerate goals

SPARC

Commonwealth Fusion Systems

MIT PSFC Plasma Science and Fusion Center

Columbia University

University of California San Diego

Lawrence Livermore National Laboratory

UK Atomic Energy Authority

University of Rochester

Princeton University

University of Michigan

SRNL Savannah River National Laboratory

Sandia National Laboratories

Aalto University

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

University of York

PPPL Princeton Plasma Physics Laboratory

Brookhaven National Laboratory

Politecnico di Torino

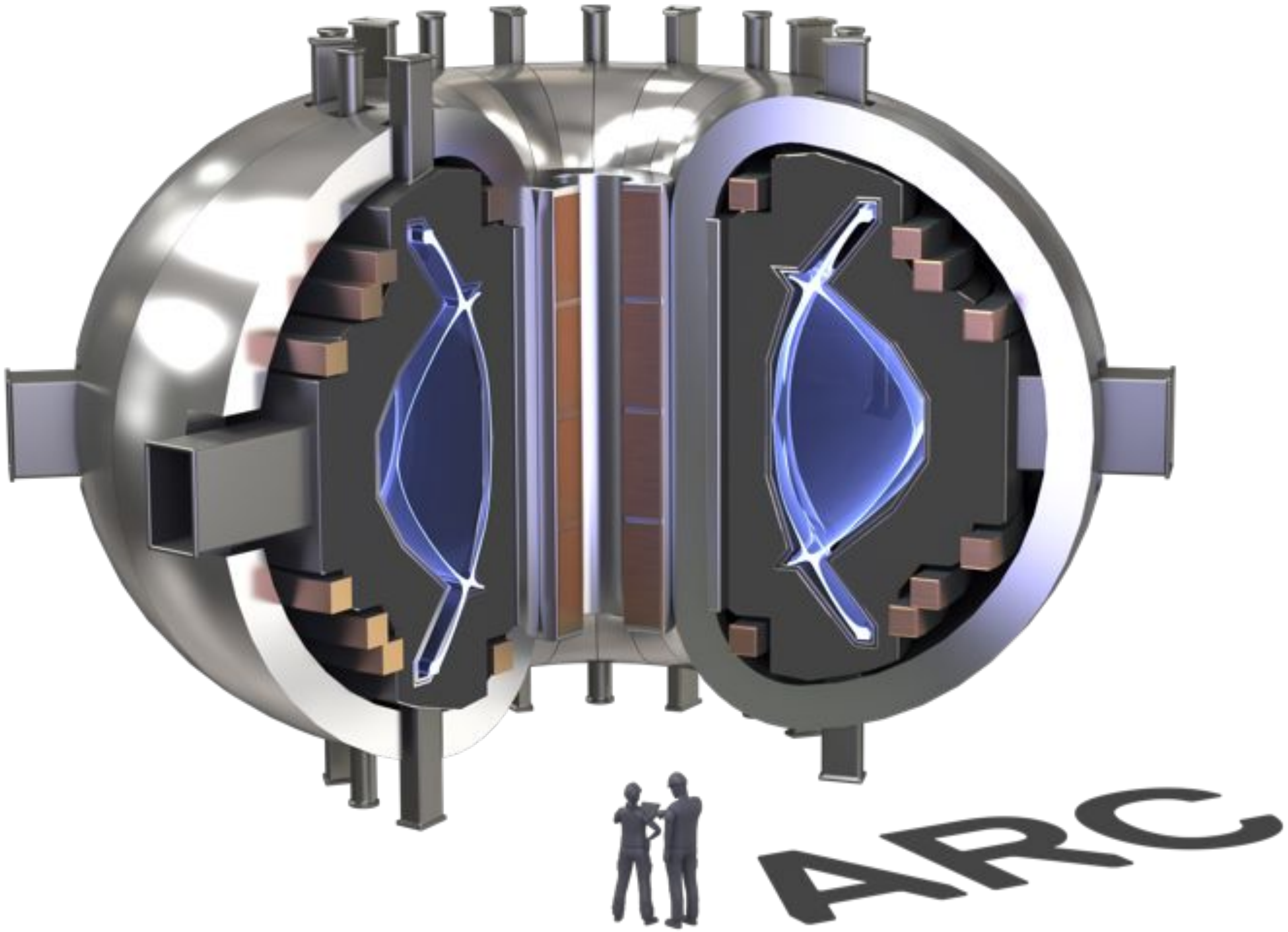
Victoria University of Wellington Te Herenga Waka

EPFL

Chalmers

ARC will be a commercial fusion power plant

- SPARC provides key learnings for the design and operation of ARC:
  - **Physics** de-risked using SPARC operations, including boundary physics, core performance, disruptions, and alpha physics
  - **Technology de-risked** using SPARC and innovative R&D pathways in parallel
  - **Economics** de-risked using SPARC costs and supply chain
- ARC design is in the early stages and the site search has begun



How can you help to accelerate the development of fusion power plants (ARC, DEMO, etc.)?

- Use SPARC to benchmark your theory/code/prediction
  - You should start preparing predictions for SPARC now, particularly those that will affect power plant design (*e.g. forces, runaway generation, mitigation, etc.*)
  - When SPARC data are available, you can then use SPARC diagnostics to validate/invalidate your predictions

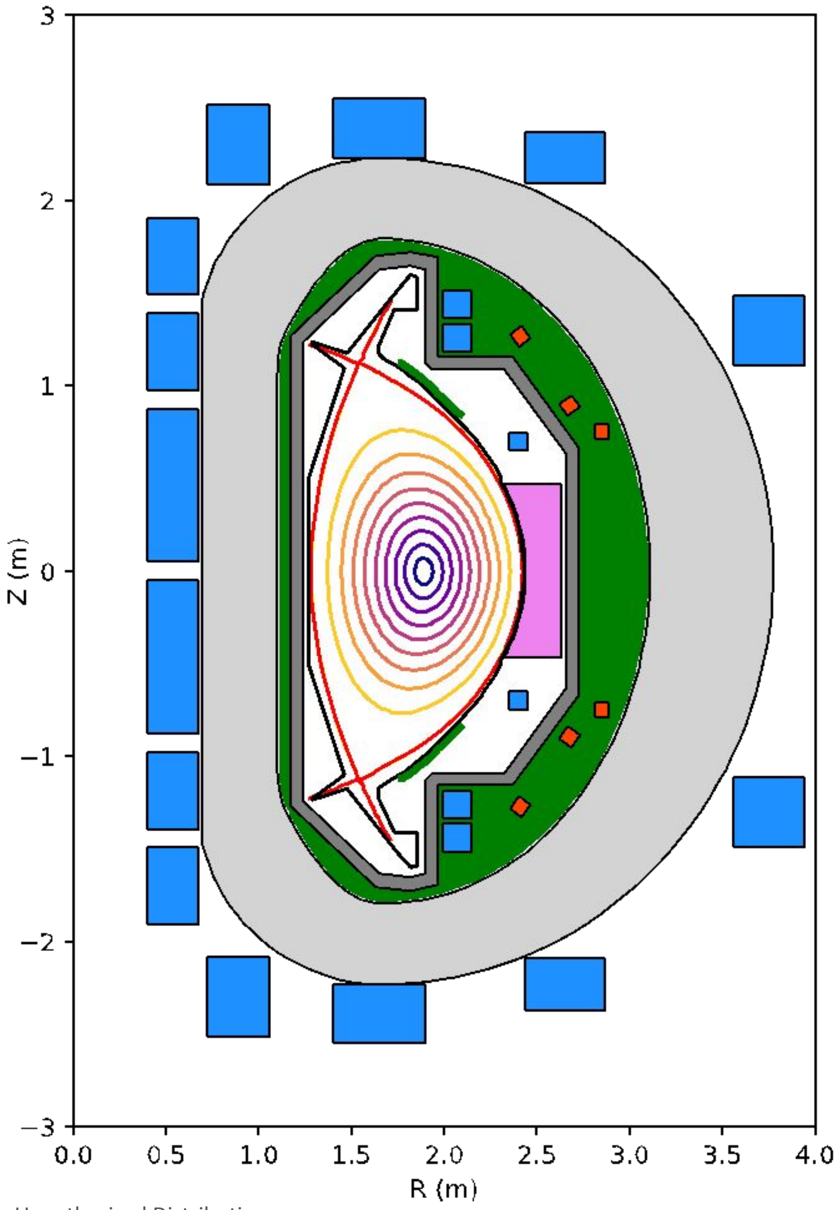
- Benchmarking on existing machines is also valuable

- Some familiar codes were used in the SPARC design:
  - *NIMROD* – motivated the design and engineering of the runaway electron mitigation coil (REMC)
  - *GPEC* – informing the full device tolerancing
  - *M3D-C1 and NIMROD* – informed the DMS layout

Disruption load expectations

SPARC's primary reference discharge baseball card

SPARC Primary Reference Discharge		
R	1.85	m
a	0.57	m
B_0	12.2	T
I_p	8.7	MA
q^*	3.05	(q_{95} = 3.4)
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
$P_{rf,coupled,operating}$	11.1	MW
P_{fus}	141	MW
Q	11.0	

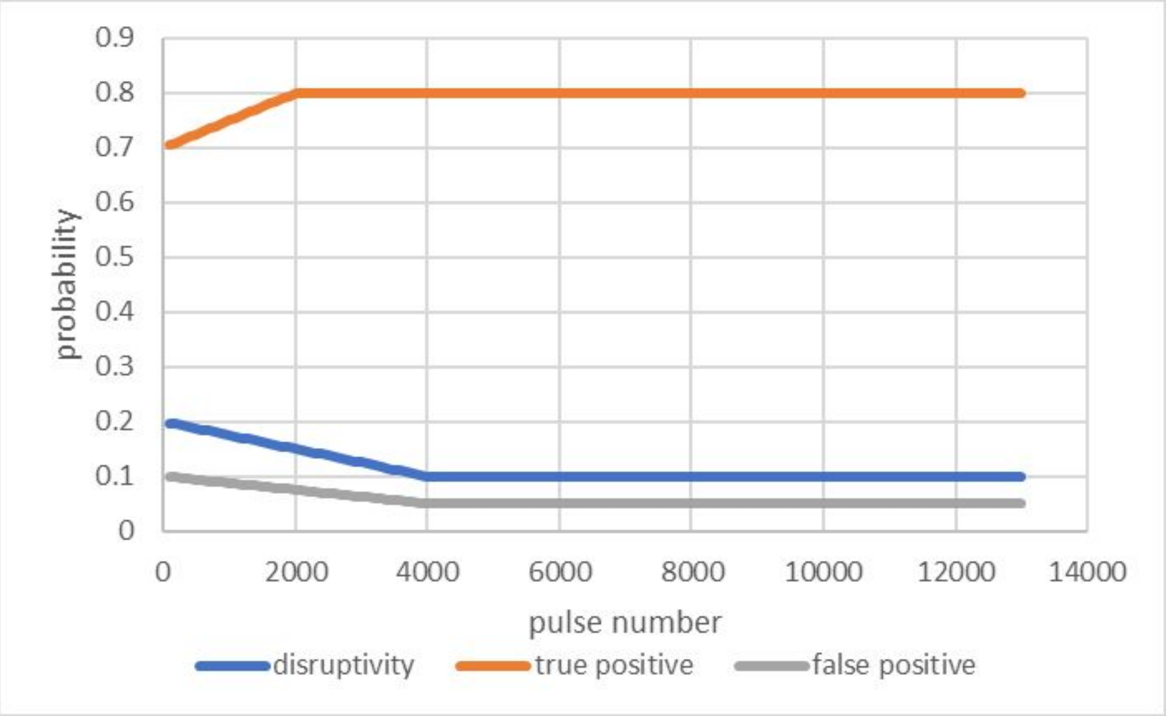


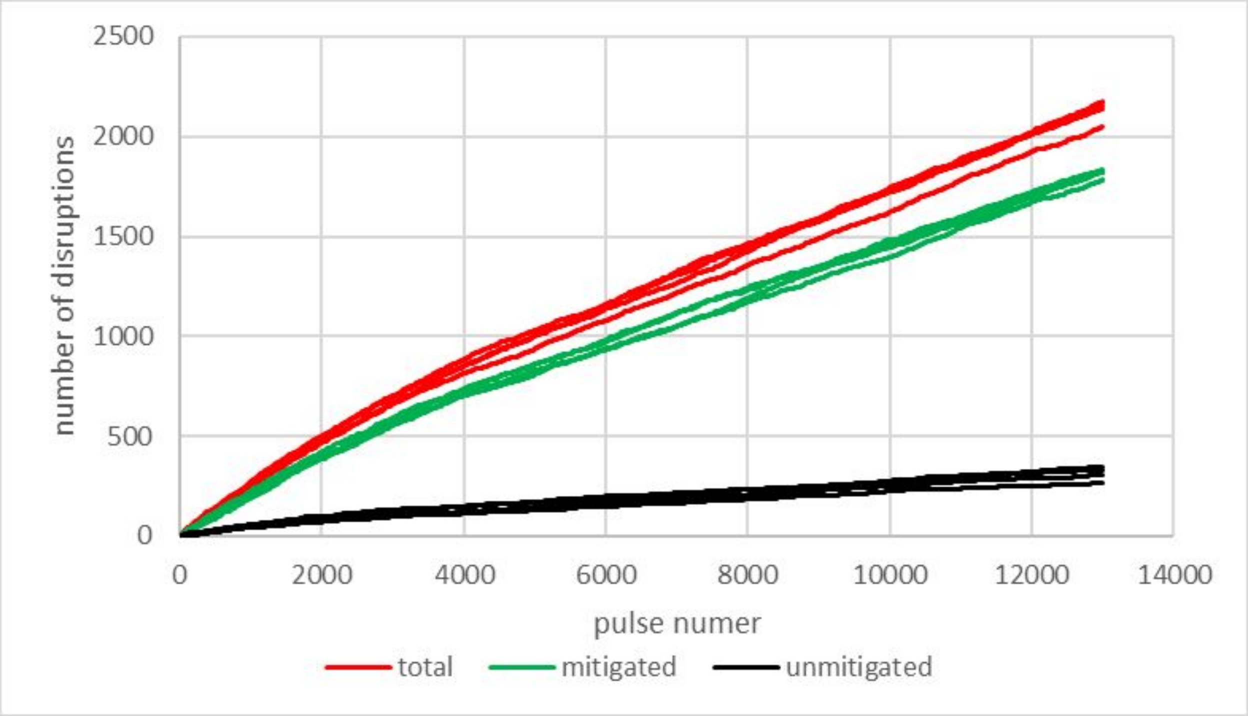
How many disruptions?

V. Riccardo 2nd IAEA TM on Disruptions

SPARC

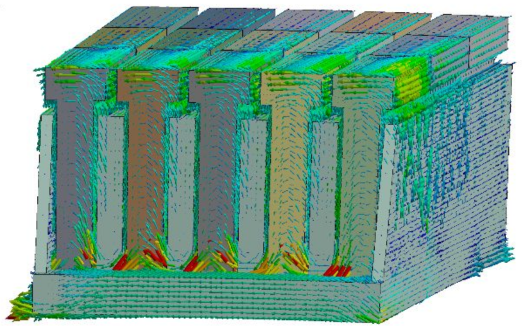
SPARC is designed for 10,000 DD and 3,000 DT pulses.
Disruption probabilities are based on existing tokamaks and ITER assumptions.



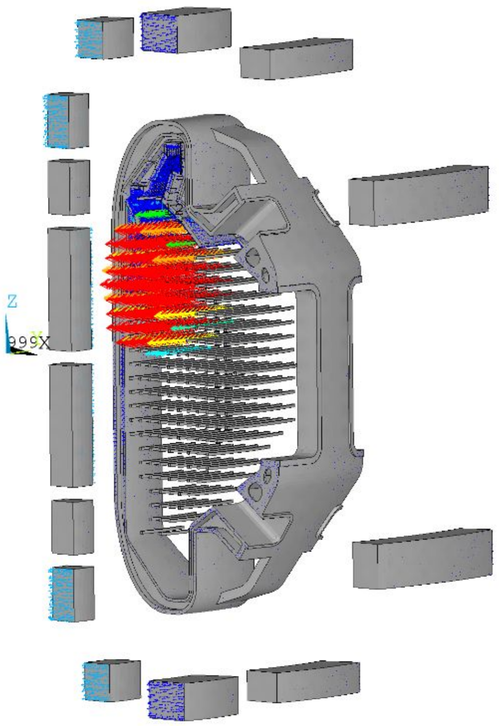


Design number of disruptions: 1800 mitigated and 300 unmitigated, all at full current.
SPARC life consumption will be counted to actual plasma current and disruption outcome.

SPARC disruption structural design assumptions



- Minimum CQ duration of 3.2 ms
  - This caused engineering lots of pain!
  - *Should the minimum CQ duration be longer in high current density machines?*
- 36.5 MN max vertical force
  - Driven by Miyamoto 2011 PPCF theory with q_{edge}=1, no credit taken for screening by vacuum vessel
  - *Is there some minimum vessel screening that we are <u>guaranteed</u>?*
- 16 MN sideways force
  - Noll Force with shielding effects of the vacuum vessel captured with COMSOL
  - Applied together with 26 MN symmetric vertical force
  - Magnetic stiffness and damping greatly reduce the displacement
- Halo currents of f*TPF=0.7, max peaking of 1.4



Disruption thermal loads are expected to be comparable or higher than ITER

- Outboard midplane disruption heat flux factor is expect to be proportional to divertor HFF

$$\mathrm{HFF}_{\mathrm{omp,dis}} = \frac{W_{th}}{S_{omp}\sqrt{\tau_{tq}}}$$

  where S_{omp} is the outboard midplane scrape off layer area which goes like $\lambda_q R$ or aR/I_p (assuming Eich scaling)

- Taking $\tau_{tq} \propto a$ we then have

$$\frac{W_{th} I_p}{a^{1.5} R}$$

  - *Will the H. Strauss RWTM theory buy us 1-2 orders of magnitude on the TQ duration?*

- Radiation flash heat flux factor given by:

$$\frac{W_{th}}{S_{fw}\sqrt{\tau_{tq}}}$$

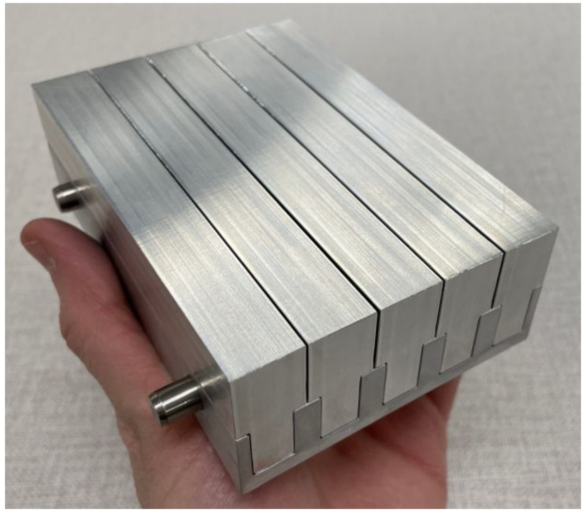
- Halo current heat fluxes
  - Significant melting expected if unmitigated in both machines

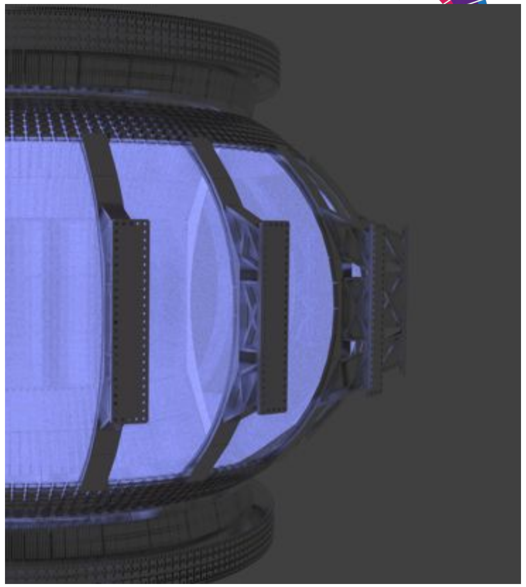
Property	SPARC	ITER
W_{th}	25	350
I_p	8.7	15
a	0.57	2
R	1.85	6
$HFF_{omp,dis}$	290	310

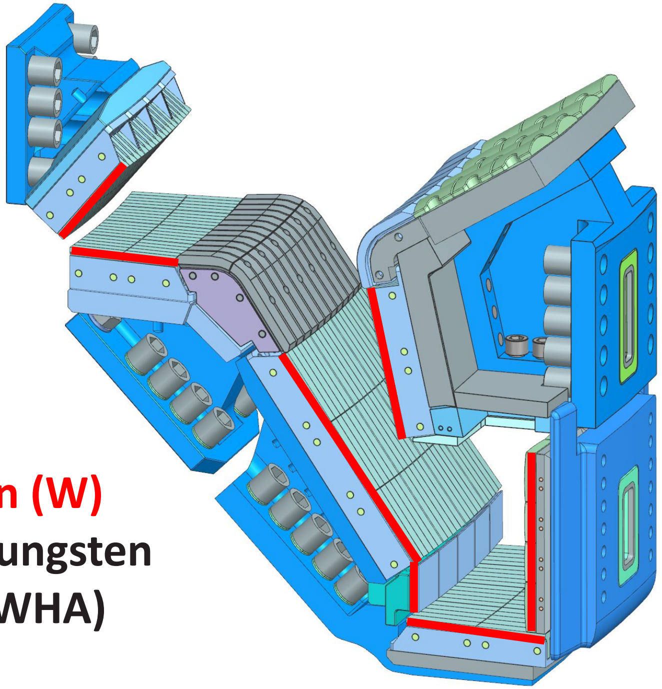
Property	SPARC	ITER
W_{th} (MJ)	25	350
S_{fw} (m^2)	62	680
Tau_{tq} (ms)	0.1	0.35
$HFF_{omp,dis}$	43	27

Tungsten based PFCs will take the disruption heat loads

- Passed Final Design Review
- W and WHA
- Inertially cooled □ runaway strikes will not breach cooling channels
- Designed for fastest current quench (3.2 ms)
- Expect melting for:
  - Unmitigated or insufficiently mitigated TQs
  - Unmitigated halo current heat fluxes
  - Runaway strikes



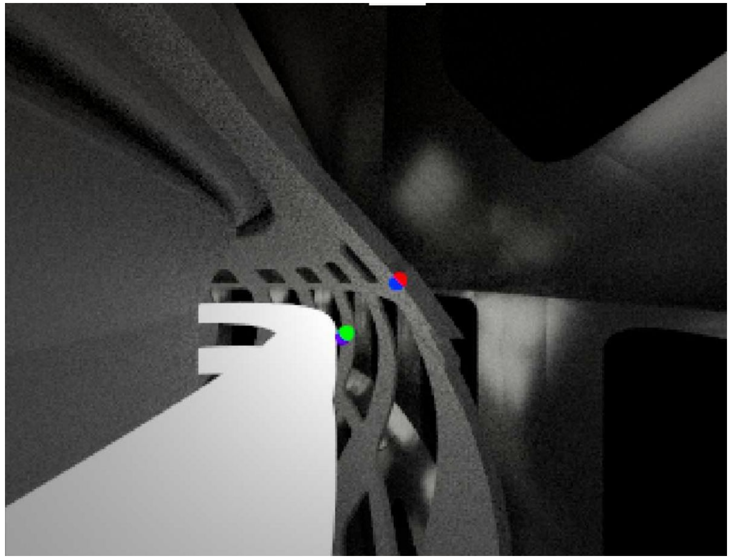


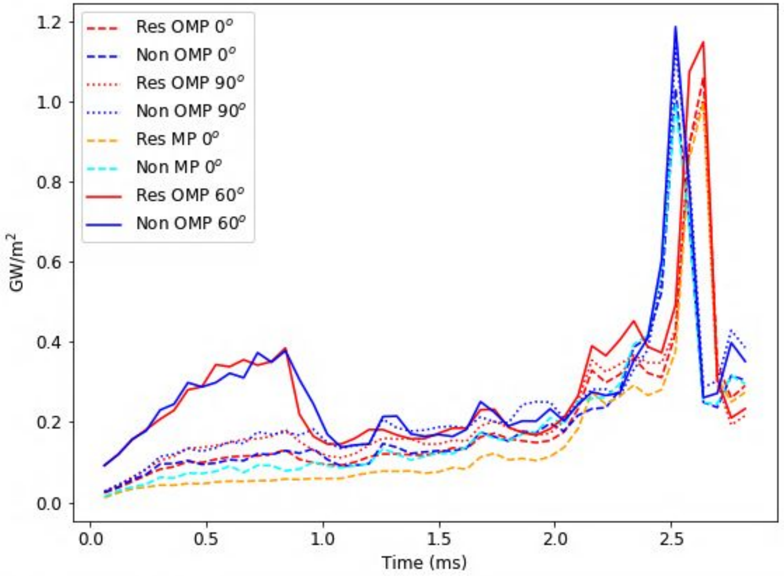


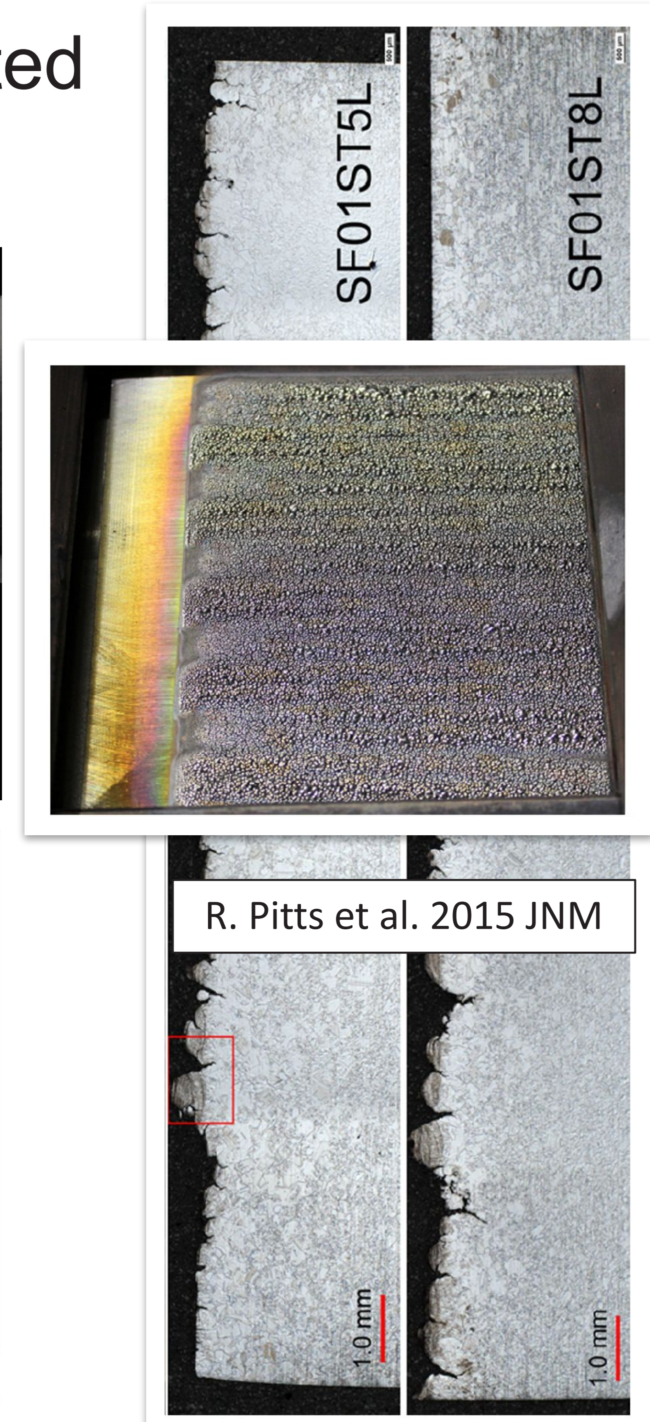
Pure tungsten (W)
All other PFCs tungsten heavy alloy (WHA)

The radiation flash from a mitigated disruption is expected to melt exposed steel, and tungsten will get close

- Disruption mitigation radiation simulated in NIMROD
- Simulation ray traced to first wall using Emis3D/Cherab
- Heat impulse modeling suggests 1100 K surface temp rise on W
- *See poster by B. Stein-Lubrano for more information*



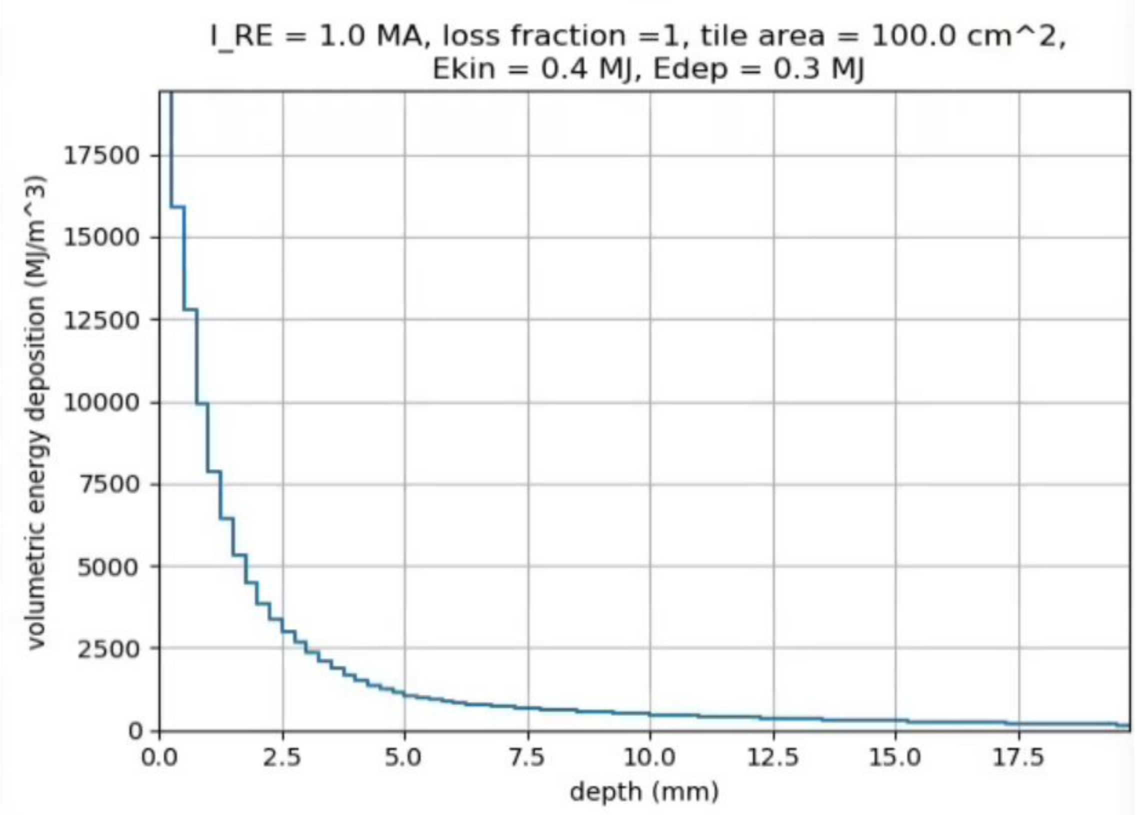




R. Pitts et al. 2015 JNM

GEANT simulations of 1 MA beam energy deposition in 10 cm x 10 cm spot

- Exponential decay pdf of RE energies with E_{avg} ~ 10 MeV
- Uniform pdf of impact angles in 0.1-90 deg
- Significant energy deposition in first ~1 mm of tile
- Further studies of simulated RE beam impacts planned



Measuring disruption loads

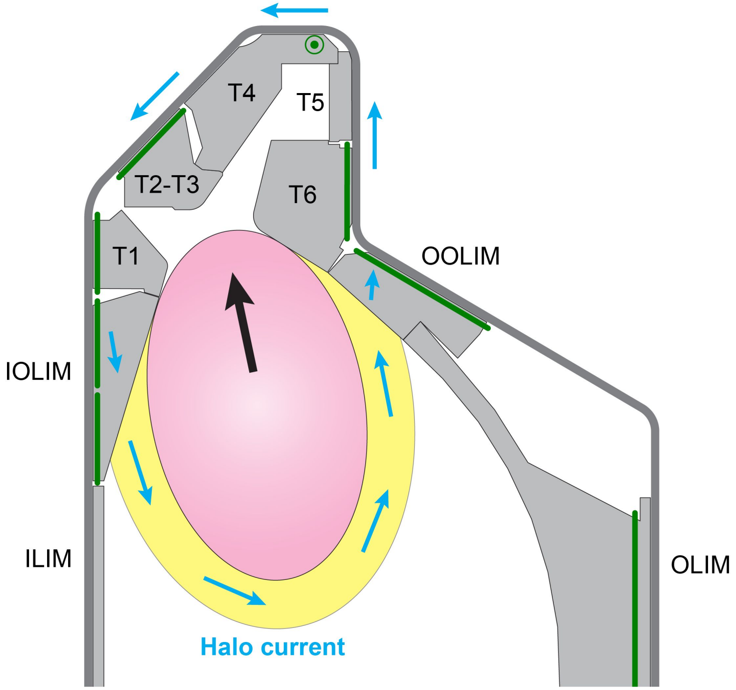
Disruption force estimates can be validated with magnetics and displacement measurements

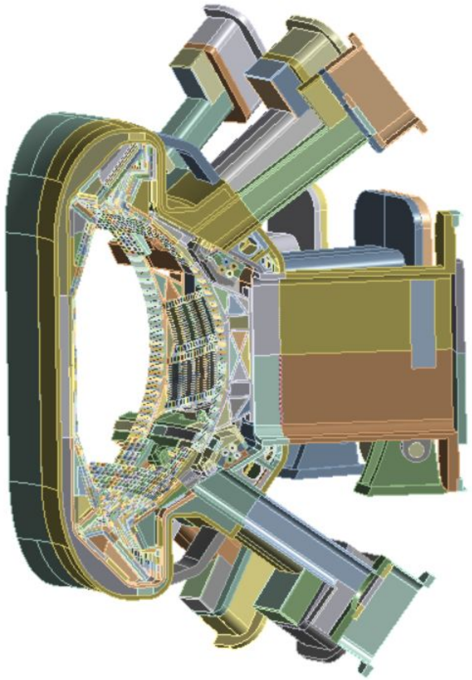
- Magnetics diagnostics
  - Halo current Rogowski coils encircle most limiter pedestals
  - Four dense poloidal arrays of probes and saddle loops

- Displacement sensors measure movement of the ports

- Visible cameras will show vessel movement

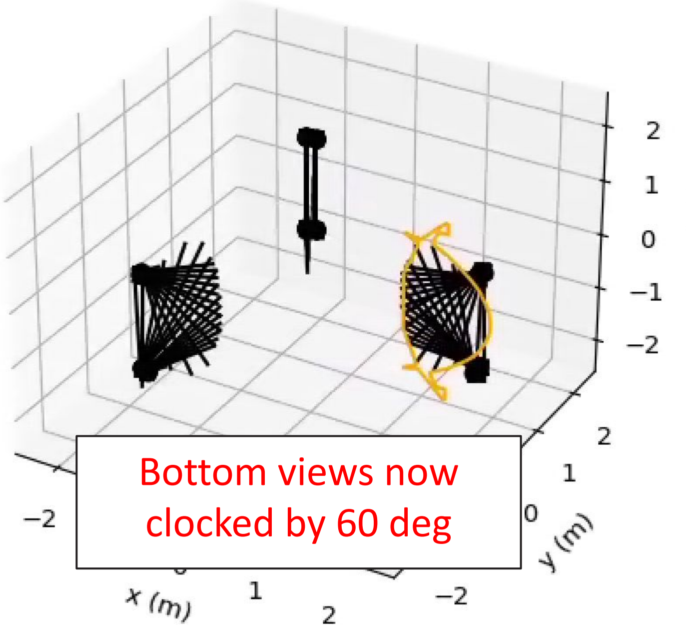
- Gauss' Separation Algorithm for equilibrium reconstruction during VDEs
  - Demonstrated leveraging JOREK simulations by Y. Plessers & J. Artola
  - Ongoing work at MIT (*see poster by G. Trevisan*)

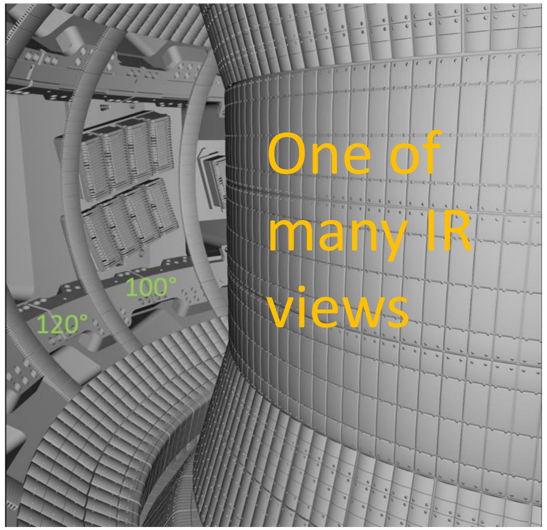




Disruption thermal load predictions can be validated with cameras and calorimeters

- 96 bolometry channels dedicated to disruptions
  - Fans spaced by 60 deg
  - ~1 kHz time resolution
  - *See B. Stein-Lubrano's poster for more details on optimizing the bolometer using Emis3D*
- Extensive set of thermocouples integrated into PFCs and other components
- Infrared (IR) cameras
- Visible cameras
  - Fast for disruption visible emission
  - Slow for post-shot melt observation

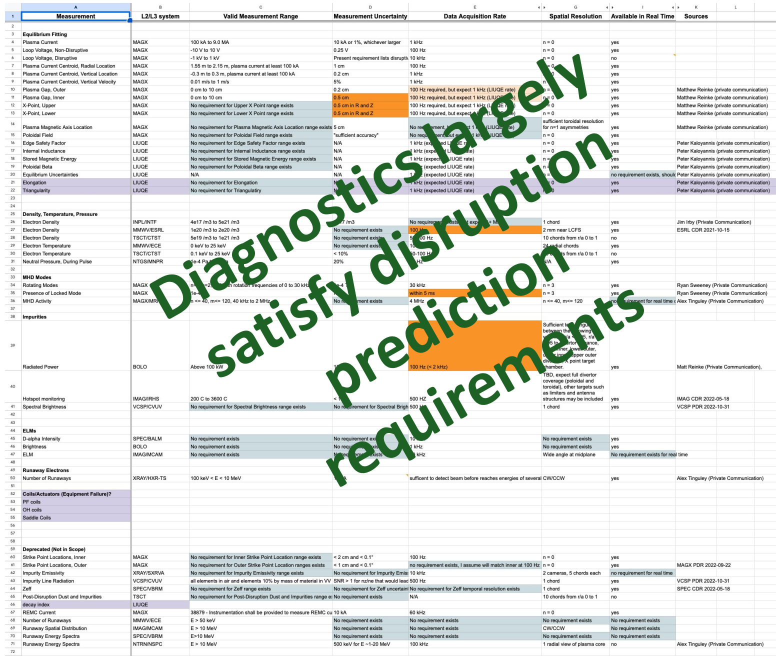


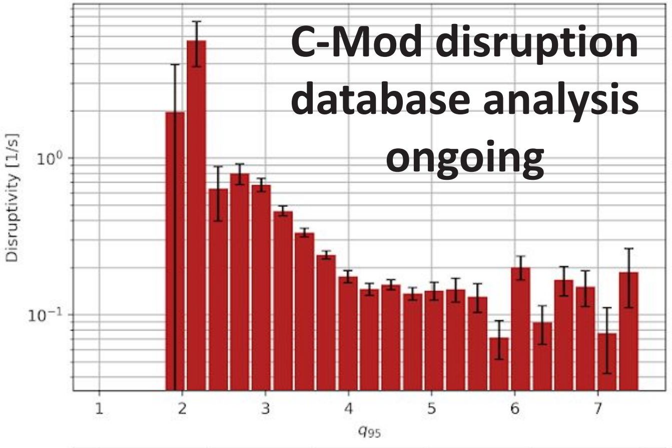


Prediction and avoidance

A notional schedule for deployment of disruption algorithms on SPARC

- **Today** – evaluating diagnostic capabilities, building simulation framework to test (1) triggering off-normal warnings (ONW) by launching (2) synthetic off-normal events
- **Pulse 1** – physics-based ONW algorithms controlling actuators, machine learning running in background
- **Pulse 100** – refining physics-based prediction algorithms, validating ML algorithms
- **Pulse 1000** – continued refinement of physics-based algorithms, "hands on the wheel" deployment of ML algorithms
- **Pulse 2000** – it's anyone's guess, but likely some hybrid of physic-based and ML according to the successes of each
- **Look ahead to ARC** – pulse 2000 will be the same plasma as pulse ~100

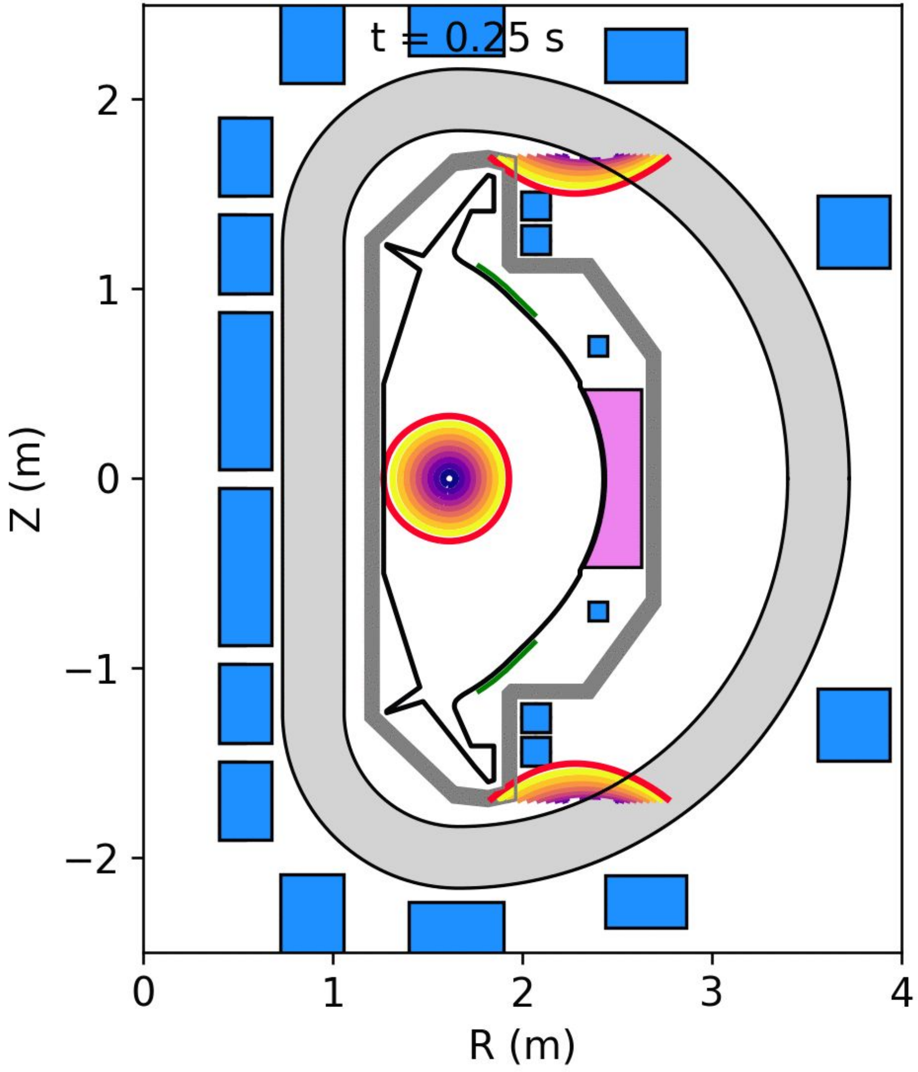


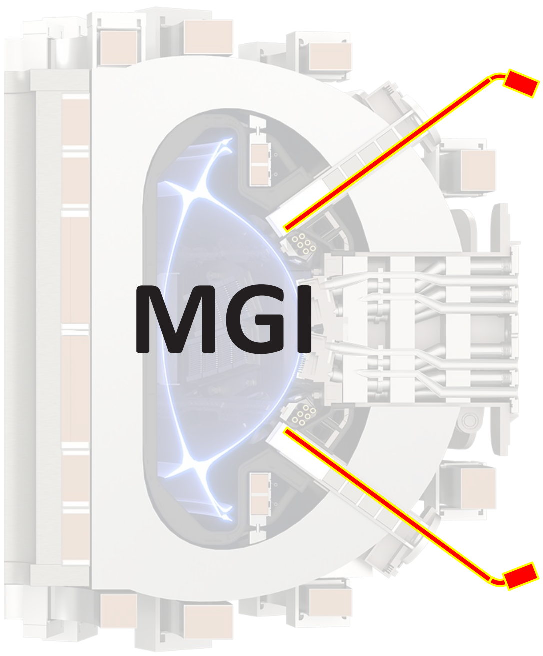


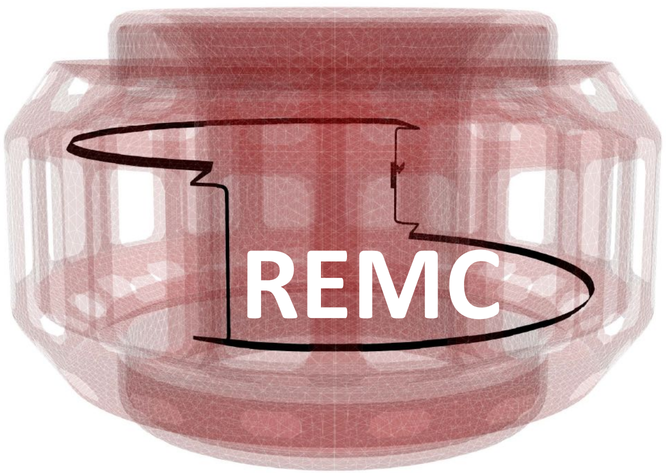
- *See C. Rea's talk for progress on physics and ML based algorithm development*

MOSAIC is a simulation framework for qualifying disruption detection and avoidance algorithms

- MOSAIC: **M**odeling framew**O**rk for **S**cen**A**r**I**o and **C**ontrol
  - Flexible, collaborative framework for time-dependent SPARC simulations that can interface with models at varying fidelity
  - “Bring your tiles, we’ll provide the plaster”
- Interfaces with the SPARC control system in order to develop, test and verify control solutions and model assumptions
- Contact Devon Battaglia to contribute (dbattaglia@cfs.energy)



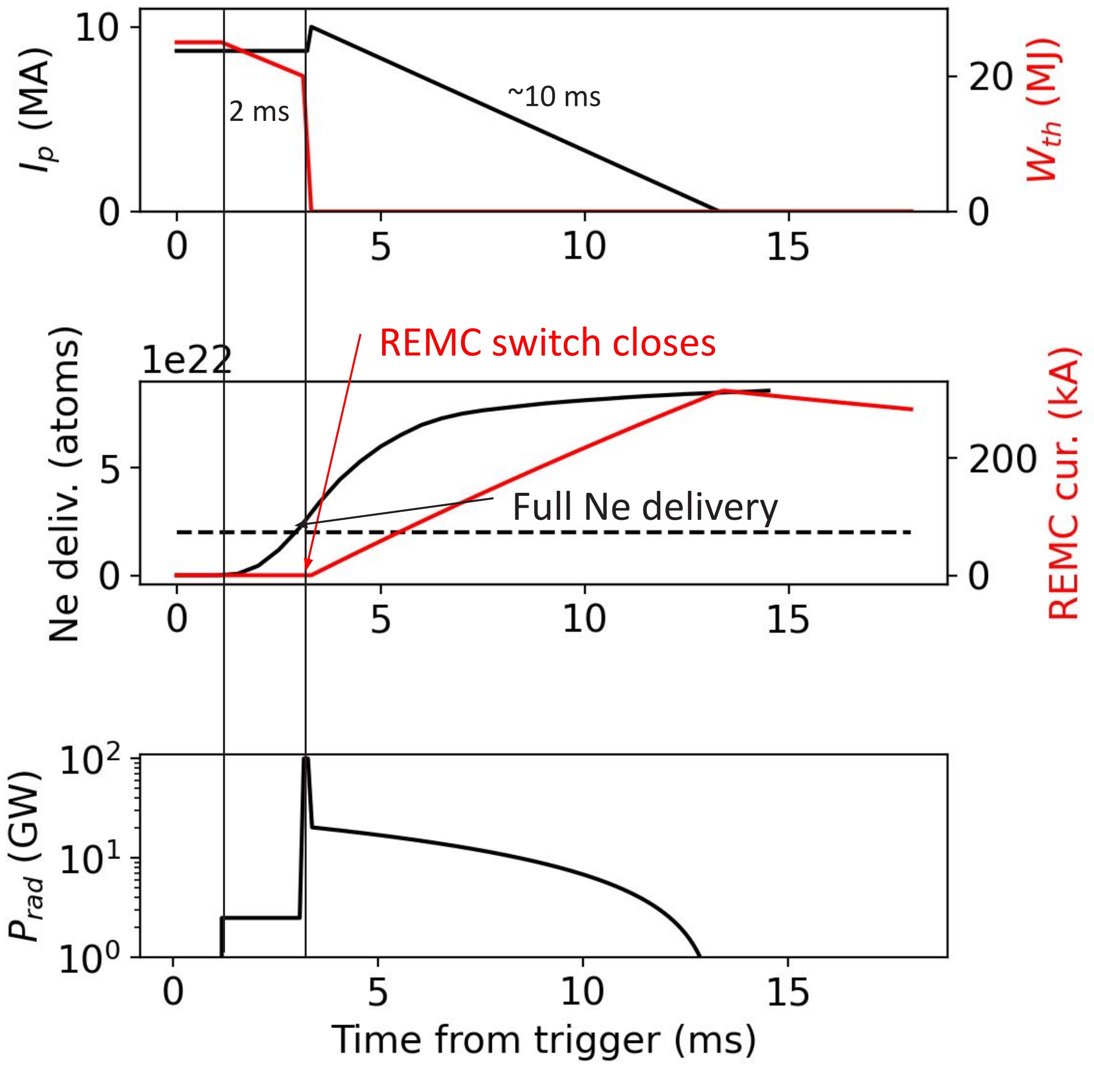




Disruption mitigation

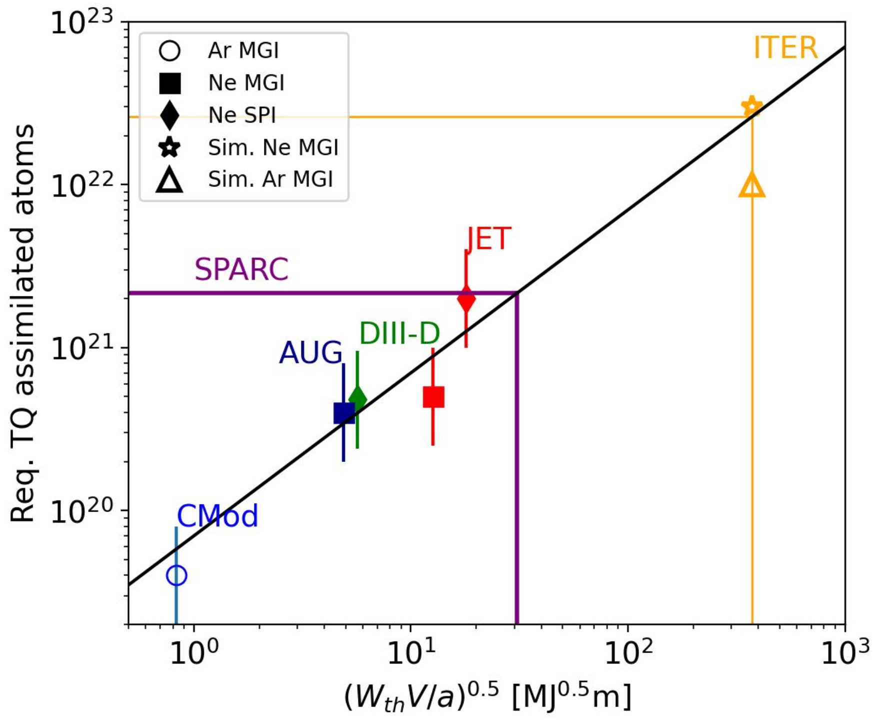
Cartoon of successful mitigation of the primary reference discharge

1. Time t=0 corresponds to the time the 6 massive gas injection valves begin opening
2. In ~1 ms the gas travels the 3 m barrel and reaches the plasma
3. Pre-TQ radiation of a few GW begins
4. In the 2 ms that follows, 2e22 Ne atoms are delivered and 1.8e23 D_2 molecules
5. The thermal energy quenches in 200 μs (*a guess*) and P_{rad} peaks at 100 GW
6. The I_p spike occurs and radiated power drops to 20 GW
7. The loop voltage triggers the passive REMC switch and current begins flowing in the REMC
8. A 10 ms current quench duration is achieved
9. Full neon delivery is 9e22 Ne atoms and REMC current peaks at 315 kA



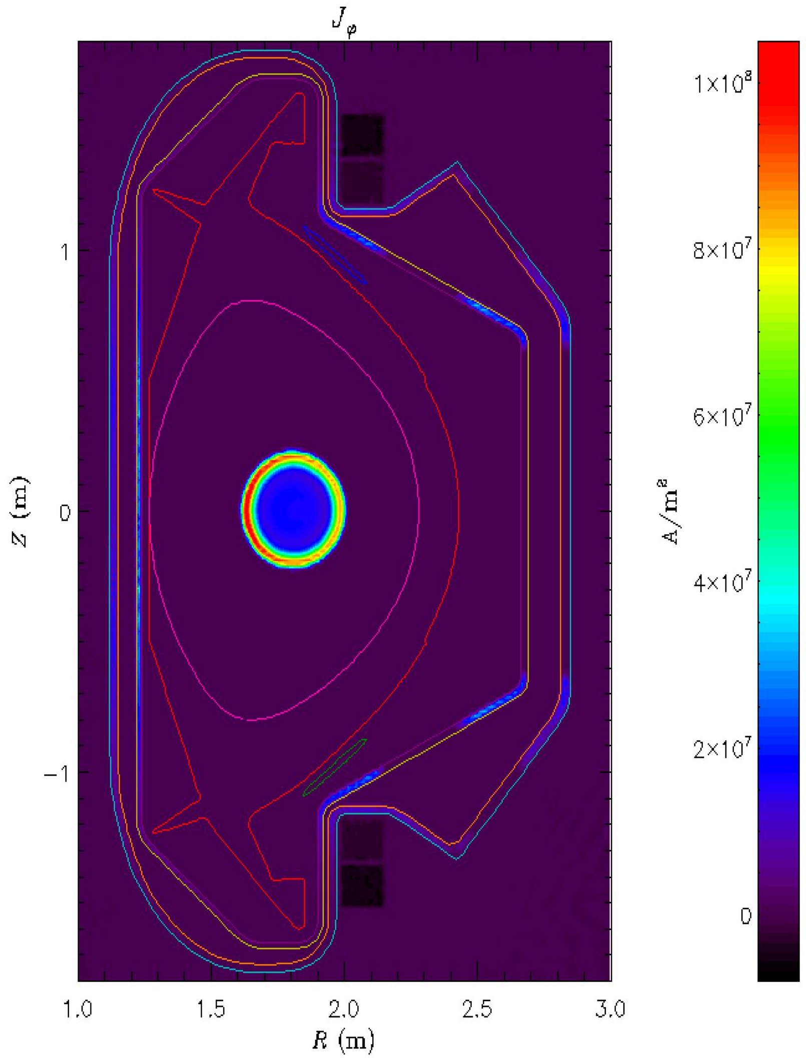
Maximum neon and argon gas loads are fixed at twice the nominal prediction (*max* = 800 Pa-m^3)

- Predict highest performance SPARC plasmas need 2e21 Ne atoms for thermal mitigation (8 Pa-m^3)
- D_2 or He carrier gas
- Assimilation of 10% assumed (need 80 Pa-m^3)
  - 5-40% observed in present devices
- MGI fueling efficiency is 20% (total injection of 400 Pa-m^3)
- Pumping and processing this much gas is painful
  - ***What is the physics of assimilation, and which mitigation approach maximizes it?***



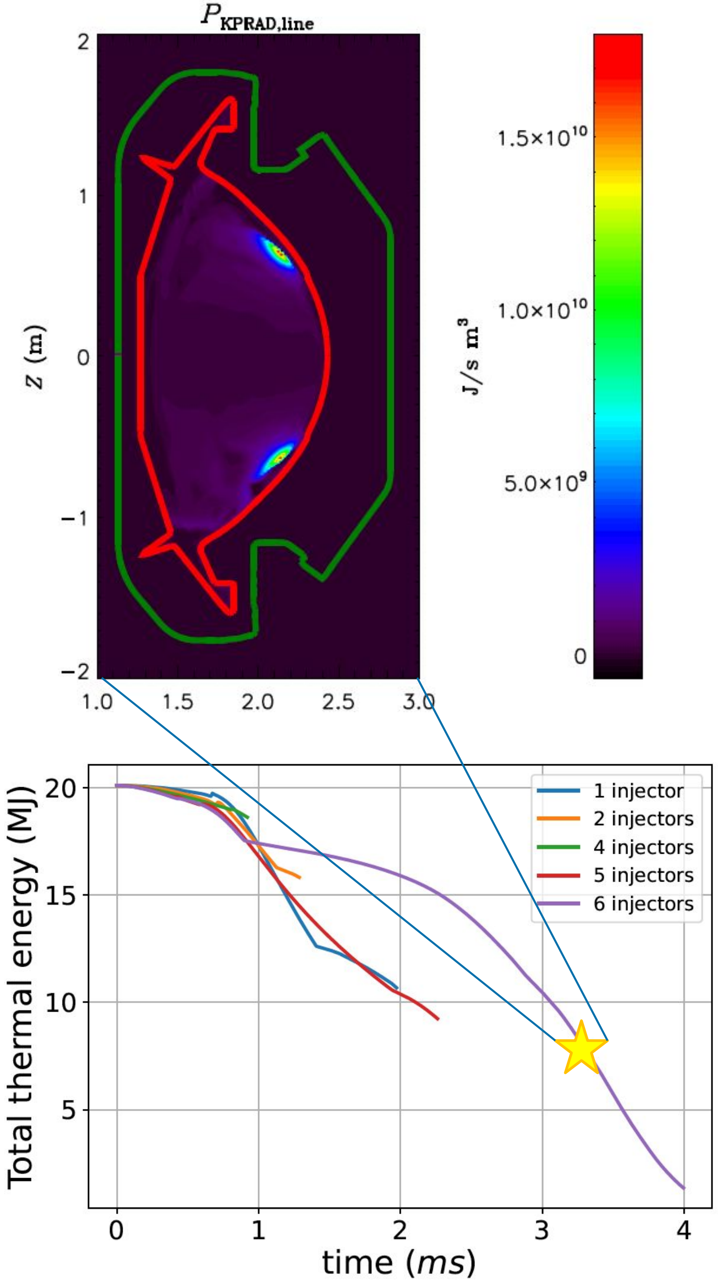
What current quench duration can we get with 800 Pa-m^3 of Ne or Ar?

- Leveraging M3D-C1 for this study:
  - KPRAD radiation model
  - Detailed passive conductor model, including anisotropic resistivity in ports
- Present simulations ongoing with varied impurity loads:
  - Initial impurity distributions scaled by n_e profile
  - “Ring source” MGI on upper and lower ports (i.e. 2D)
  - Low-res 3D simulation in progress to capture sawtooth (low n modes)
- We can inject up to 100 Pa-m^3 of Kr or Xe together with Ne or Ar if shorter durations are needed



M3D-C1 predictions of MGI suggest high peaking and poor transport in the poloidal plane

- Well into the thermal quench the radiation remains localized to the injectors
- Explanation □ radiation sinks energy in flux tube before pressure can drive parallel flows
- ***Q: Present MGI experiments exhibit low peaking. Is this high MGI peaking specific to SPARC?***
- *See A. Kleiner's talk for more details*

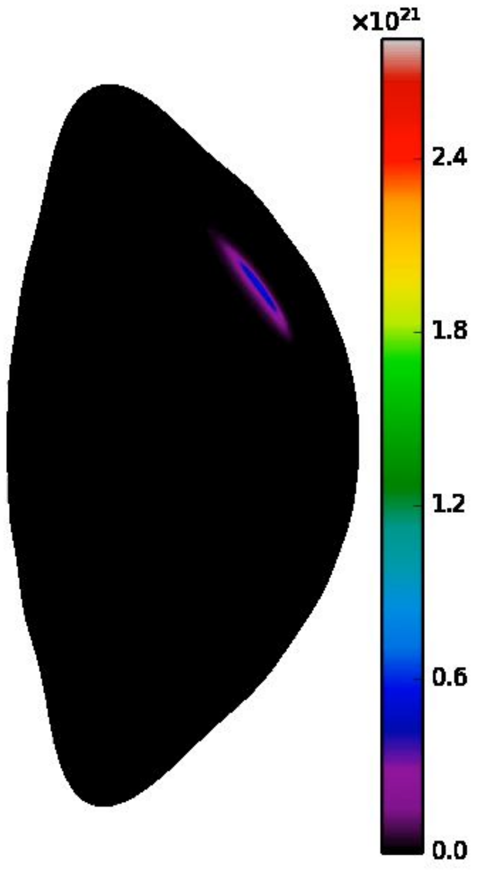


Similar NIMROD simulations predict very encouraging TQ mitigation with low peaking (in contrast to M3D-C1)

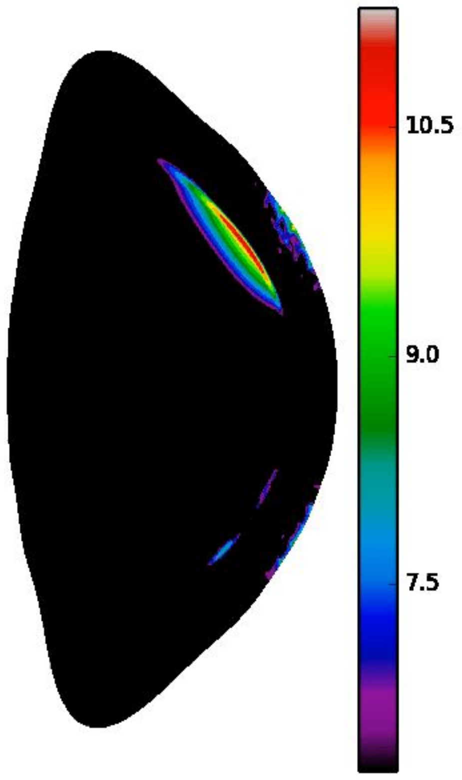
- Simulations suggest near 100% radiation of the thermal energy (good!)
  - Builds confidence in the gas load predictions

- Toroidal peaking <1.5 during all times with appreciable P_{rad} (good!)

Neon density (m^{-3})

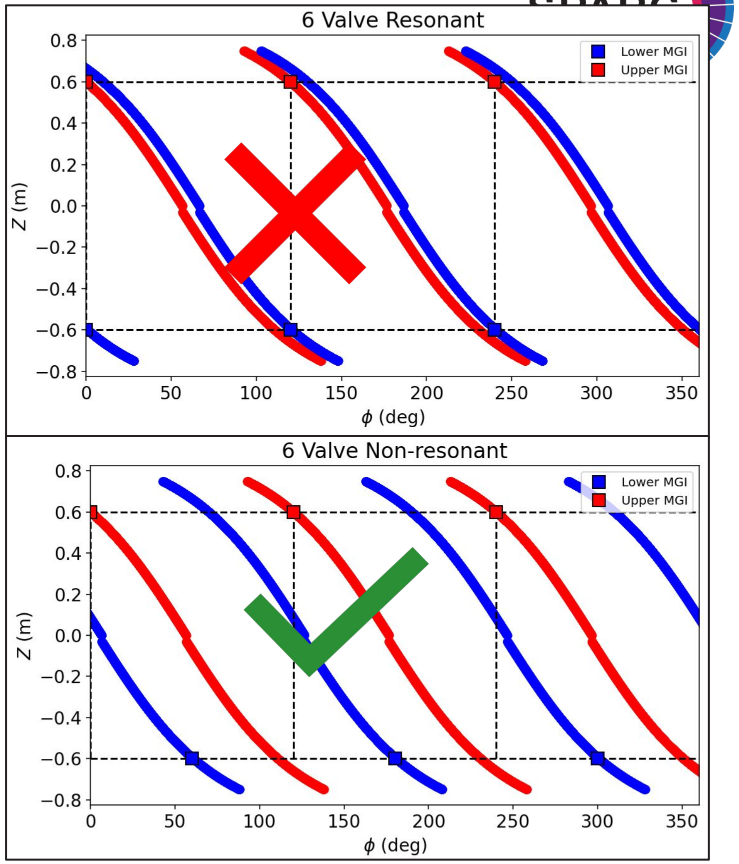


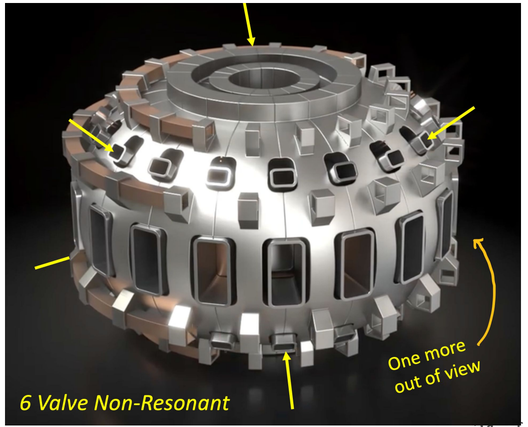
Emissivity log10(W/m3)



MGI layout chosen that might reduce peaking in the highest performance scenarios

- Optimized for 8.7 MA and W_{th}~25 MJ SPARC discharges with q_{95}=3.4
- NIMROD finds very low peaking independent of configuration
- M3D-C1 simulations not complete, but peaking is high and determined by injection locations
    - Expect that independent flux tube fueling would reduce peaking
- Decision was made for the "<u>6-valve non-resonant</u>" layout





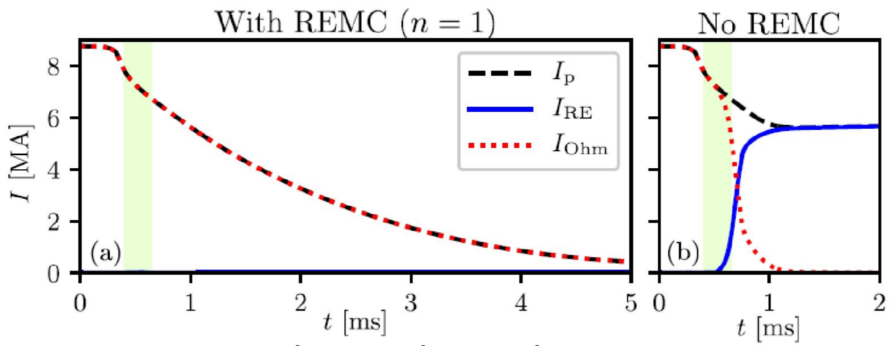
Simulations suggest that runaway electrons will likely be prevented by the runaway electron mitigation coil (REMC)

- Idea for the use of the disruption loop voltage to drive 3D fields originally proposed by A. Boozer 2011 PPCF

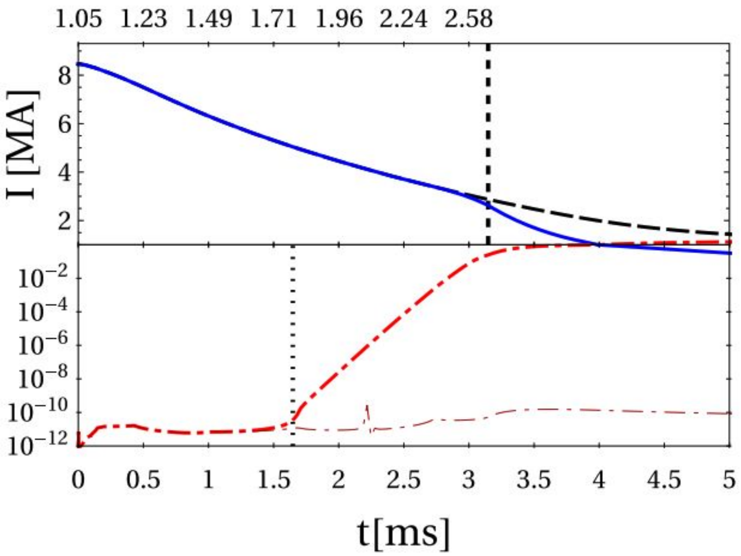
- COMSOL-NIMROD-ASCOT-DREAM predicts its performance:
  - CQ only simulations found complete prevention (good!)
  - Including the TQ led to a different *q*-profile evolution with faster healing of flux surfaces □ low MA beams predicted (bad!)
  - Better modeling of the early REMC current rise leads to full seed loss (good!)

- Thincurr has now replaced COMSOL for 3D field predictions [*see C. Hansen's talk on Friday*]

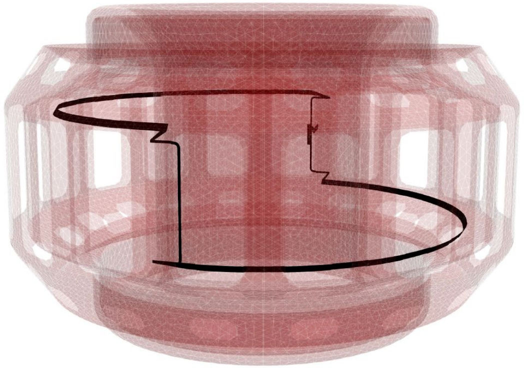
- M3D-C1 simulations of REs in SPARC are beginning



A. Tinguely, et al, *Nucl. Fusion*, 2021



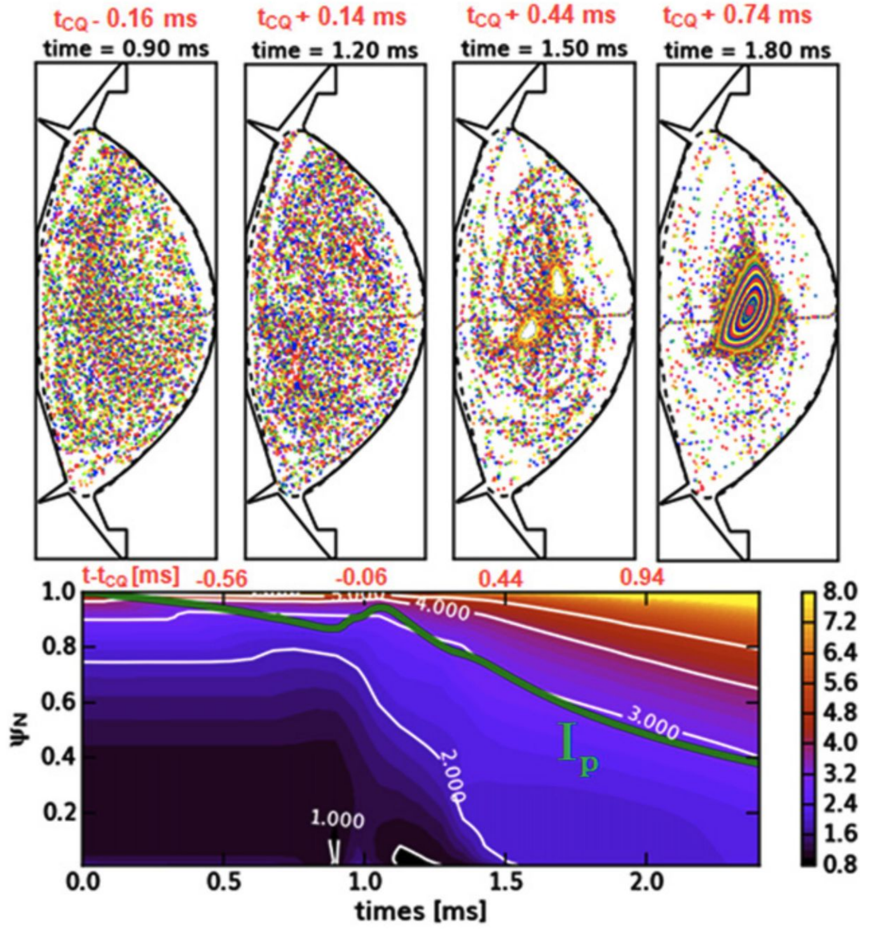
V. Izzo, et al, *Nucl. Fusion*, 2022



A. Battey et al., *Nuclear Fusion*, In Prep.

REMC open physics questions

- What is the first wall heat flux associated with low energy runaways expelled by the REMC?
  - ASCOT simulations are ramping up to address this
- What will side effects of the REMC look like?
  - Will asymmetric VDEs lock to this field?
  - Will the mitigated current quench heat flux be peaked?
- Will flux surfaces heal during the CQ or not?
  - Talk by A. Boozer may address some questions here
- *REMCs on DIII-D and HBT-EP can help to answer some of these questions [see talk by C. Hansen]*



V. Izzo et al 2022 NF

Conclusions

- Status of SPARC and the ARC mission
- Disruption load expectations
- Measuring disruption loads
- Prediction and avoidance
- Disruption mitigation

Open questions that could affect the design of ARC and other future tokamak power plants

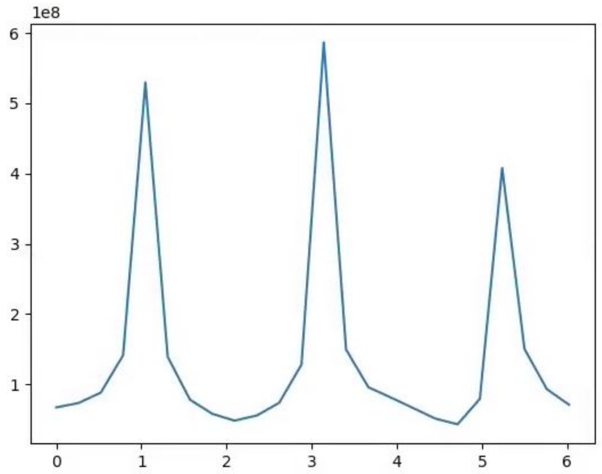
- What determines the minimum CQ duration?
- Can we design a vessel that minimizes disruption forces?
- Can we predict halo current wetted areas and power densities?
- Are we arriving at self-consistent asymmetric VDE force predictions?
- What is the physics of the thermal quench duration?
- How do alternative mitigation techniques perform on SPARC? (e.g. SPI, EPI, shell pellet, divertor MGI, others?)
- How low can we drive the disruptivity on the same repeated plasma pulse?

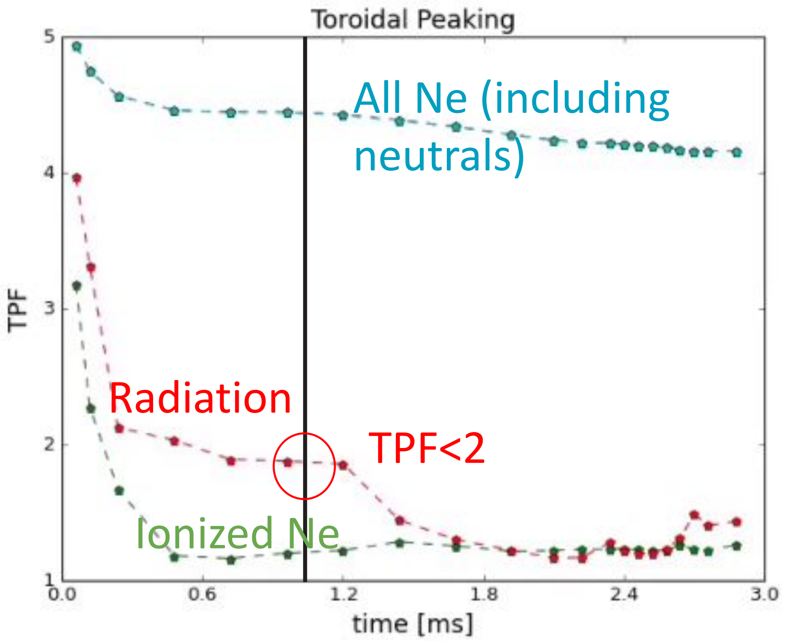
- Public SPARC git repo is a good place to start exploring: https://github.com/cfs-energy/SPARCPublic
- Contact me for more information (rsweeney@cfs.energy)

Extra slides

M3D-C1 predicts less parallel transport than NIMROD

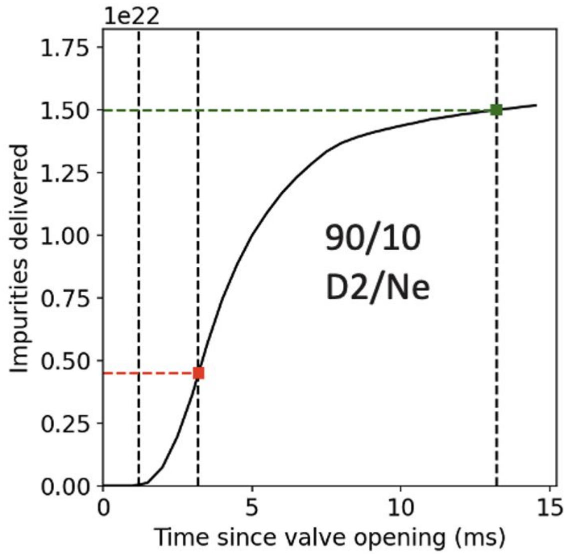
- M3D-C1 running two-temperature model, allowing electron temperature to drop more precipitously under impurity radiation
- NIMROD predictions used single-temperature model, found more parallel transport, more consistent with empirical peaking factors
- Dual injector M3D-C1 simulations found that the injectors determined the asymmetry
- With incomplete information, a decision on the MGI clocking had to be made as drawings for gas line routing are now being finalized
- Both simulation teams together with the SPARC Disruptions Working Group decided that the <u>6 valve non-resonant design</u> is more likely to exhibit lower peaking
- Decision: 6 valve non-resonant layout





With the physics of the injection defined/chosen, we tuned our MGI valves and barrel to meet delivery requirements

- Scanned space of barrel inner diameter and length, plenum pressure and volume, and valve chirp duration
  - Chose 30 mm ID valve orifice and barrel ID



- Eddy current flyer plate valves are aligned with the magnetic field to minimize torque