Preparing disruption solutions for tokamak power plants

IAEA-TM on Disruptions, ITER, France, 2024 Sep. 5

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Commonwealth Fusion Systems

Michael has indirectly had a significant influence on the design of SPARC

Main characteristics of the fast disruption mitigation valve

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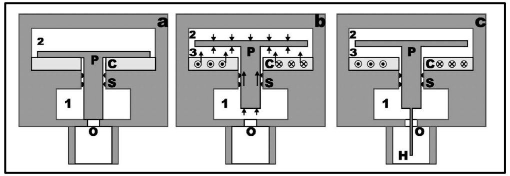
S. A. Bozhenkov, K.-H. Finken, M. Lehnen, and R. C. Wolf



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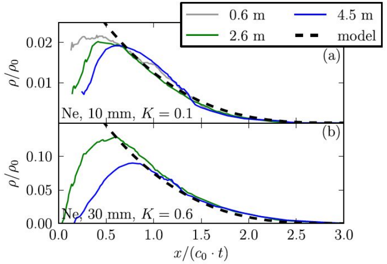
Fuelling efficiency of massive gas injection in TEXTOR: mass scaling and importance of gas flow dynamics

S.A. Bozhenkov[1], M. Lehnen[2], K.H. Finken[2], G. Bertschinger[2], H.R. Koslowski[2], D. Reiter[2], R.C. Wolf[1] and TEXTOR Team

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0,$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x},$$

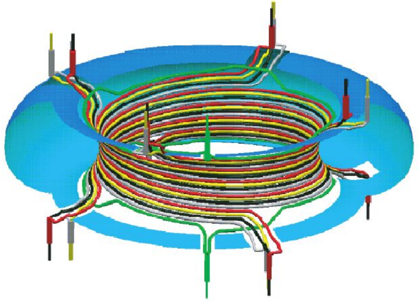
$$p \cdot \rho^{-\gamma} = \text{const},$$



PRL **100**, 255003 (2008) PHYSICAL REVIEW LETTERS week ending 27 JUNE 2008

Suppression of Runaway Electrons by Resonant Magnetic Perturbations in TEXTOR Disruptions

M. Lehnen, S. A. Bozhenkov, S. S. Abdullaev, and TEXTOR Team
Institute of Energy Research-Plasma Physics, Forschungszentrum Jülich GmbH, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany



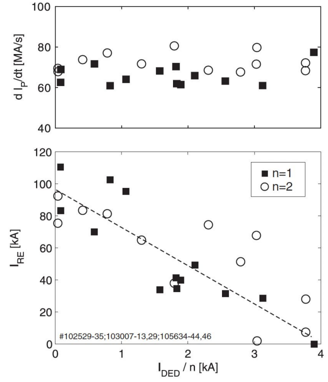


FIG. 2. Maximum runaway current as function of the coil current divided by the toroidal mode number of the perturbation field. The open symbols represent the maximum current decay rate.

I feel fortunate that I had the opportunity to see him at the ITPA-MDC in Japan this spring,

and I’m glad that we are here at this conference to honor him and to keep the fire that he had for this work alive.

Outline

- SPARC Progress Update
- Update on SPARC Disruption Systems
- Preparing Solutions for Power Plants
  - Disruption prediction
  - Runaway electrons
  - Gaps in disruption load prescription

SPARC Project Overview

1:00

CFS is on a path to deliver commercial fusion energy

- CFS was founded in 2018, spun out of MIT with the goal of commercializing fusion energy to combat climate change
- CFS has raised more than $2 billion from venture capital investors
- There are now more than 750 employees in the diverse, high caliber team
- We work with university, national lab, and other partners around the world

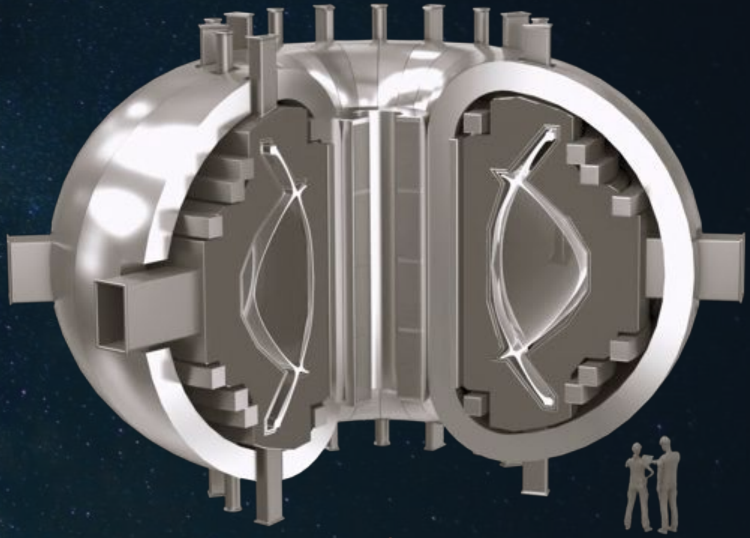
The CFS Path to Commercial Fusion

R&D — Commercial demo — Commercial powerplant

Physics
Demonstrated on tokamaks around the world

Magnet tech
COMPLETED

SPARC
UNDER CONSTRUCTION



ARC
EARLY 2030s

CFS is building magnets for others in addition to SPARC

- In addition to magnets for SPARC, CFS is building HTS magnets for other applications
- The same magnet technology could have large impact in other areas
- Built a pair of 17T mirror magnets for the University of Wisconsin for the WHAM experiment

SPARC buildings and site are largely complete

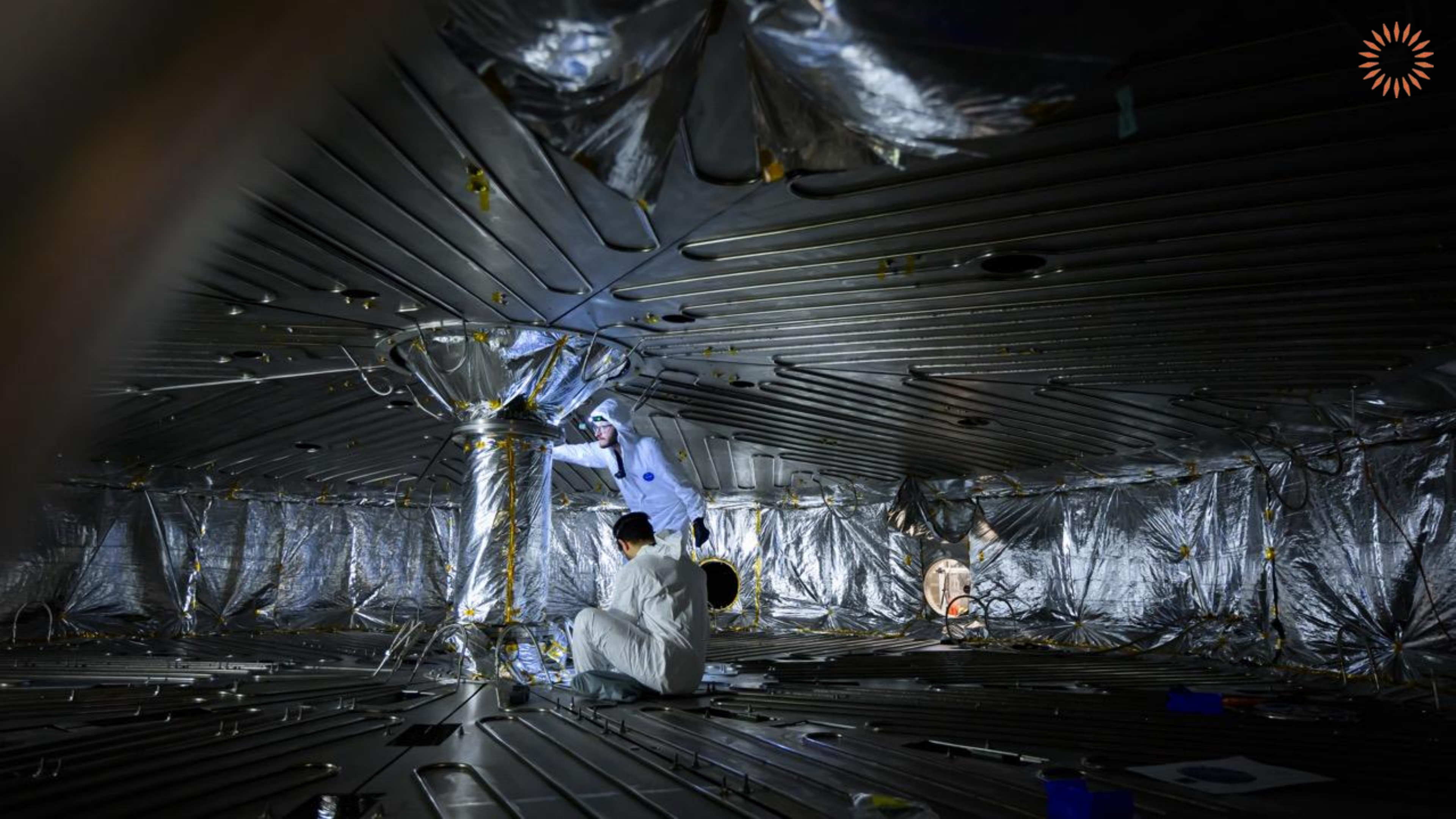

CAPACITY 50 TON
Commonwealth Fusion Systems
FRAGILE


EXIT
SAFE
DISCHARGE
Micro19 mec

SPARC heated with 25 MW of ICRH

SPARC magnets are in production and will test soon

TF field on axis is 12.2 T



Prototypes are complete and have informed production

Update on SPARC Disruption Systems

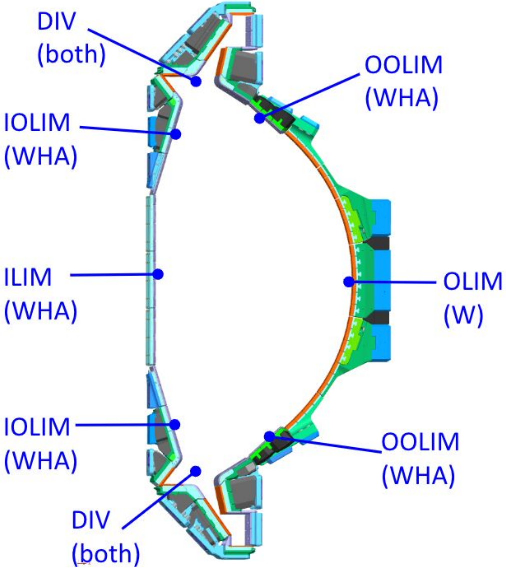
4:00

SPARC provides a platform to access power plant disruption physics to address the risks/unknowns

- SPARC will operate with plasma currents up to 8.7 MA and can thereby produce high current runaway beams
  - No active cooling of the tungsten first-wall means that strikes are not catastrophic
- SPARC can achieve ARC/ITER relevant thermal quench heat fluxes
  - What happens to tungsten tiles under these loads?
  - How well can these loads be mitigated?

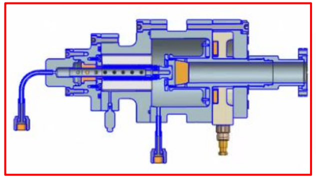
Thermal Load	Expression	Units	SPARC	ITER	ARC
Divertor Heat Flux Proxy	$W_{th}I_p/a^{1.5}R$	$MJ\text{-}MA/m^{2.5}$	290	310	340
Radiation Flash	$W_{th}/S_{fw}t_{tq}^{0.5}$	$MJ/m^2s^{0.5}$	43	27	53

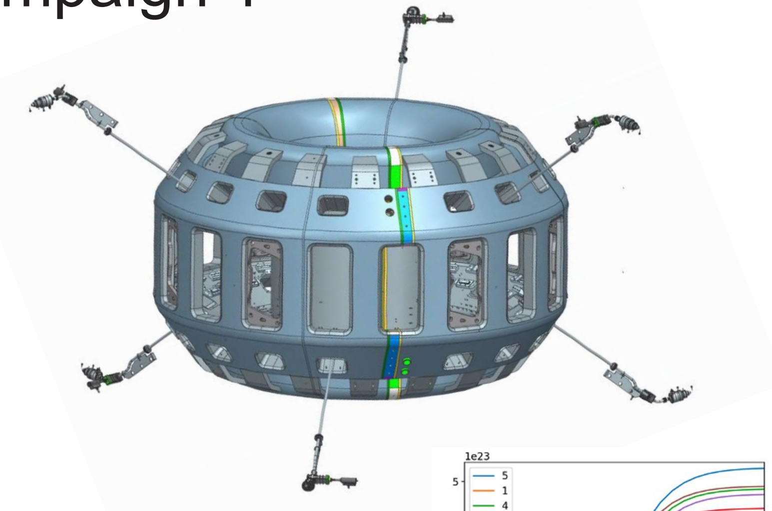
W = Tungsten
WHA = Tungsten Heavy Alloy

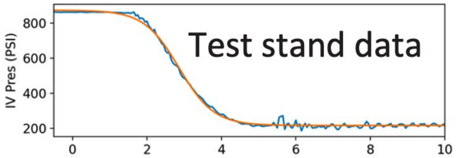


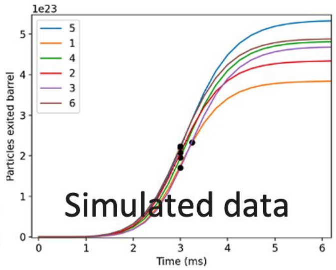
A 6-valve MGI system has completed final design review, and will be deployed on SPARC for campaign 1

- Each of the 6 injectors are identical
  - Eddy current flyer plate technology
  - 30 mm ID aperture, 3 m barrel
  - Plenum=0.5 L, max pressure=6 Mpa
- All the usual gases are available
  - Propellants = H, D2, (limited use of He)
  - Radiators = Ne, Ar, Kr, Xe
  - Two mixtures of any composition can be distributed amongst the 6 valves
- Valves distributed to reduce pre-TQ peaking
  - 3 above, 3 below the midplane (*n*=3)
  - Top-bottom clocking non-resonant when q_{95}=3.4
- Prototyping has been successful
  - Full injection delivered in 2 ms slug
  - >80% fueling efficiency when using 6 valves!
  - Full delivery possible with 2 valves (~40% fueling efficiency)
- Design of magnetic shielding and structural support ongoing





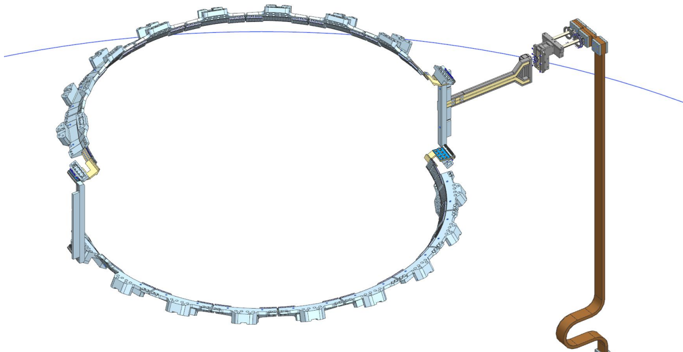


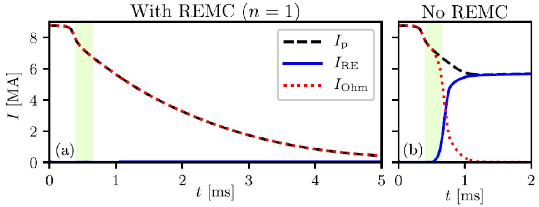


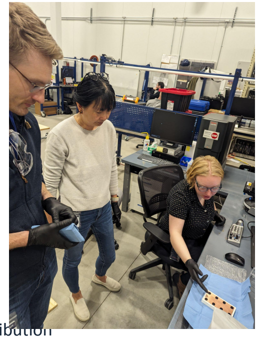
*See APS-DPP 2024 Invited Talk by V. Izzo on NIMROD modeling of SPARC DMS
**For M3D-C1 modeling of SPARC DMS, see A. Kleiner et al. 2024 NF *submitted*

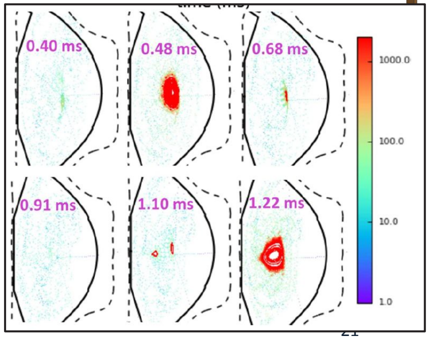
A passively powered runaway electron mitigation coil will be deployed in campaign 1

- No power supply → driven by plasma mutual inductance[1]
  - Upgradeable should power supply be desired
- REMC is switched to avoid interference with nominal operations
  - Early operations will utilize a mechanical switch and require PCS triggering (~50 ms closing time)
    - Anticipate upgrading to passively-triggered solid-state switch, <100 us closing time
- Carries up to 350 kA in an *n*=1 winding
  - Full prevention likely during high current operation[2-6]
  - Study at hiqh q_{95}, as expected in early campaign 1, suggests REMC might not be effective in these plasmas
  - Side effects? e.g. shorter CQ duration observed in simulations[6]
- Prototyping for structural, electrical, and assembly tests ongoing









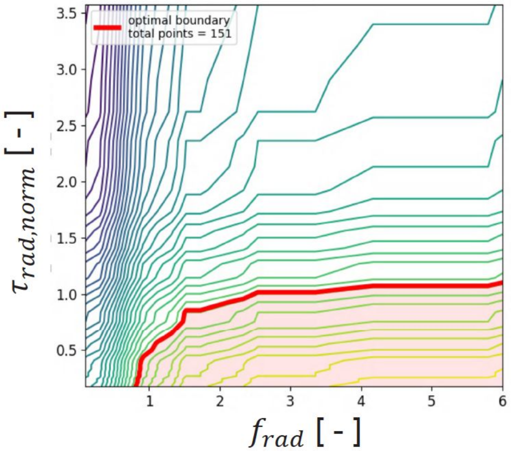
[1]Boozer PPCF 11, [2]Tinguely NF 21, [3]Izzo NF 22, [4]Tinguely PPCF 23, [5]Battey NF 24, [6]Izzo NF 24

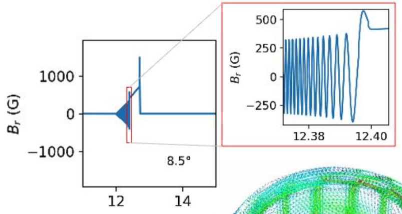
Preparing disruption prediction for power plants

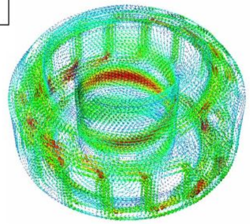
7:00

The SPARC disruption prediction software is under active development

- Focus on physics-based detectors for campaign 1 *[refer to talk by A. Saperstein]*
  - Machine learning also under development – deployed after validation on SPARC data
- Validation of physics-based detectors on C-Mod, TCV, and with simulations of off-normal events
  - First complete version targeted for the end of this year
- Collaboration with MIT + EPFL + Columbia
  - Leveraging (soon to be open-source) DEFUSE code
- This work could benefit ITER
  - Benchmarking on more machines would improve these tools







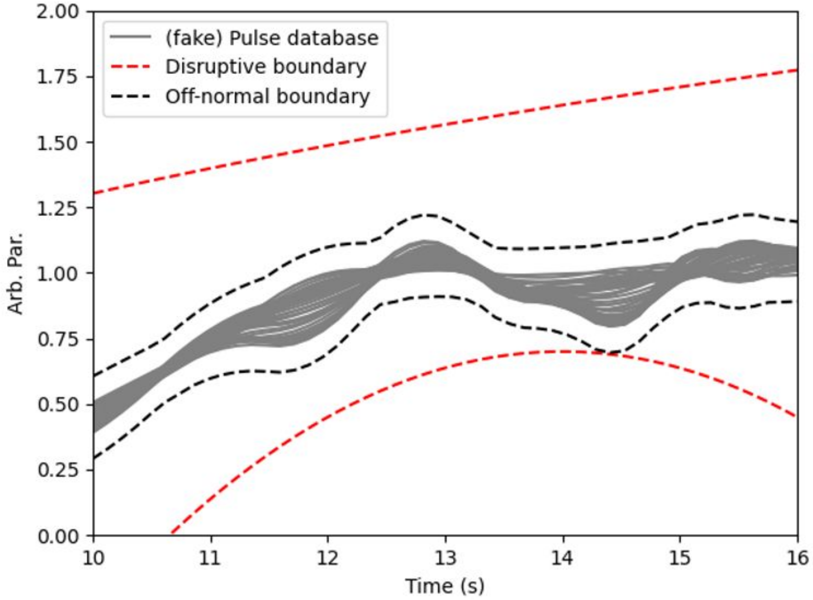
Plasma Science & Fusion Center EPFL COLUMBIA UNIVERSITY

Many of us have ignored prediction during ramp-up/down: *we cannot ignore this in pulsed power plants like ARC!*

- ARC will operate ~90 plasma pulses per day
- Will flattop detectors fail during ramp-up or ramp-down?
- Do we need unique detectors?
  - Ramp-up detectors
    - *Slideaways (some precedent for this)*
    - *Double tearing modes*
    - *Others?*
  - Ramp-down detectors
    - *Runaway beams*
    - *Others?*
- Recent works by the DECAF team starting to explore this
  - Zamkovska et al. 24 NF, Tobin et al. 24 PPCF
- This is a largely unexplored area ripe for discovery!

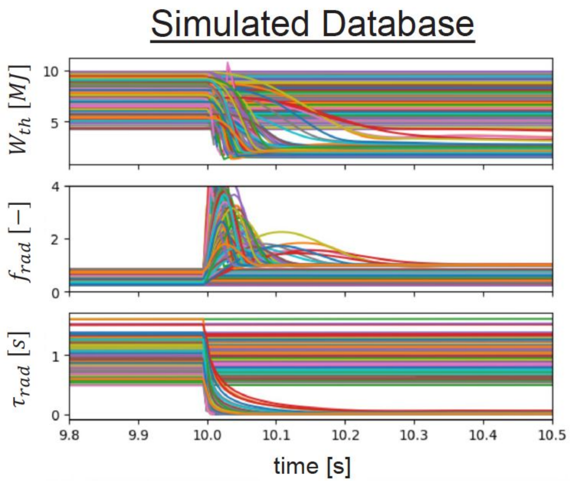
Power plants provide an opportunity for a new approach to disruption prediction

- Pulsed power plants will build massive databases of the same plasma pulse (or the same operating point)
  - ARC will operate >30,000 pulses/year
- Deviations from statistics provides a low-risk warning
  - Deviation implies something is different/wrong, but may still be far from disruption boundary
  - Acting on deviations will reduce false negatives
  - Power plants will require a very low false negative rate, increasing the risk for large false positive rates
- Similar to “anomaly detection” presented by W. Zheng [this conference]



Off-**N**ormal event **Sim**ulation**s** provide an opportunity to prepare for power plants before the first one is built

- Significant ongoing/growing effort by the SPARC team to develop these ONSims
- These types of off-normal simulations are commonplace in aerospace
- Providing learnings already
  - Alpha heating makes plasmas less prone to radiation collapse from momentary loss of auxiliary heating power
- Will be injected into full tokamak control simulations in early 2025 to start training/tuning control
- This is an area of research the disruption community should explore



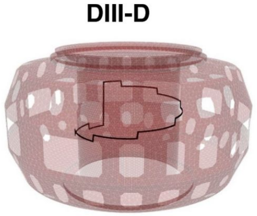
Credit A. Saperstein, A. Wang

Preparing runaway solutions for power plants

10:00

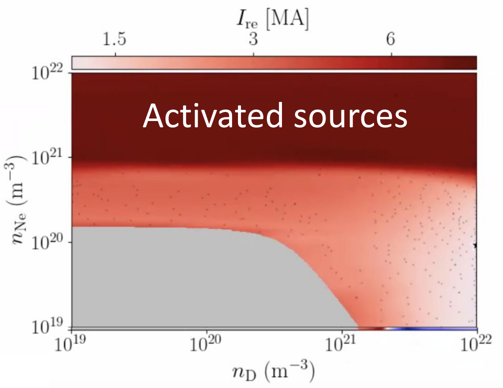
We can work together to understand the REMC approach; seeking alternatives is also a worthwhile endeavour

- **REMC systems are being deployed on multiple machines**
  - SPARC, HBT-EP, DIII-D, TCV (intent to install)
- **REMC physics questions**
  - Critical current for prevention
  - Side effects
  - Operating closed circuit (switched coils in power plants might not be possible)
- **… and what if the REMC doesn't work?**
  - Far lower risk if runaway avoidance is passive
    - Efficacy of gas injection questionable and requires trigger
  - Can we envision other passive solutions, or low latency active solutions?
    - Solid tungsten injection [V. Sergeev 21 NF, Lively arXiv:2310.16998]?
    - Wave-particle interactions [A. Battey, P. Aleynikov, A. Lvovskiy, this conference]?
    - Others?



V. Izzo 24 NF,
D. Weisberg 21 NF

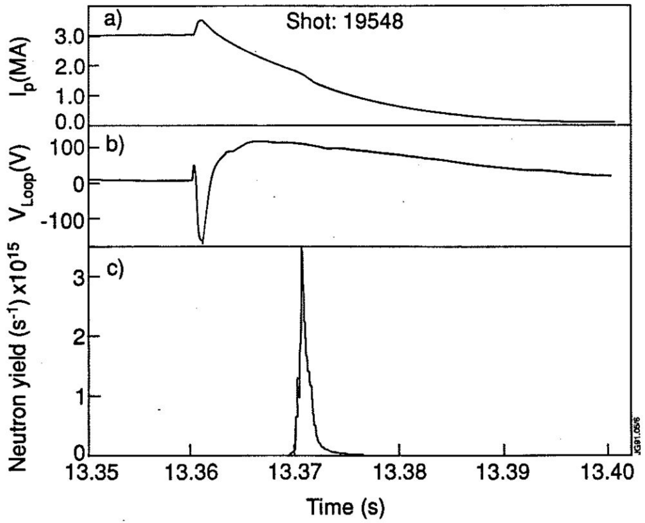
C. Hansen
[this conference]

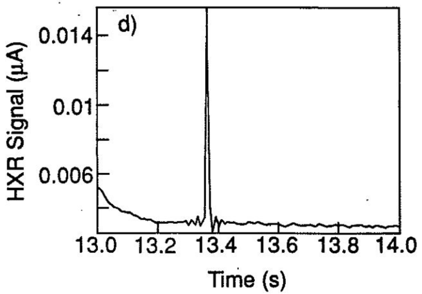


Credit I. Ekmark

Do our RE models well reproduce 5-6 MA JET disruptions from the late 80's?

- Arguably the best data to validate runaway models on is late 80's JET
  - https://scipub.euro-fusion.org/wp-content/uploads/2014/11/JETR90007.pdf
- **Limited plasmas**
  - Many natural runaway beams are seen for carbon wall operation
- **Diverted plasmas**
  - No plateaus reported
    - Makes sense as these should all go vertically unstable
  - A "knee" is seen during the current quench followed by a neutron/HXR spike
    - Conclusion: runaways are produced





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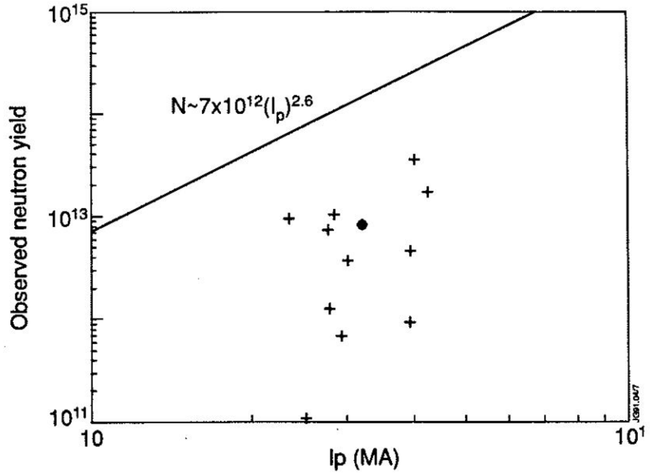

Do our RE models well reproduce 5-6 MA JET disruptions from the late 80’s?

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  - No
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    conclusion: runaways are produced
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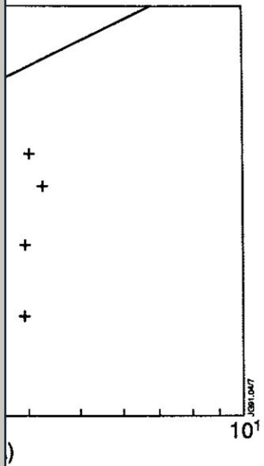
How do our runaway models perform on this dataset?

Data might be limited from late 80’s JET, but can we find similar results within uncertainties?



Filling in gaps in thermal load modeling for power plant first walls

13:00

Comprehensive models of the unmitigated thermal quench are needed to calculate divertor and first-wall loads

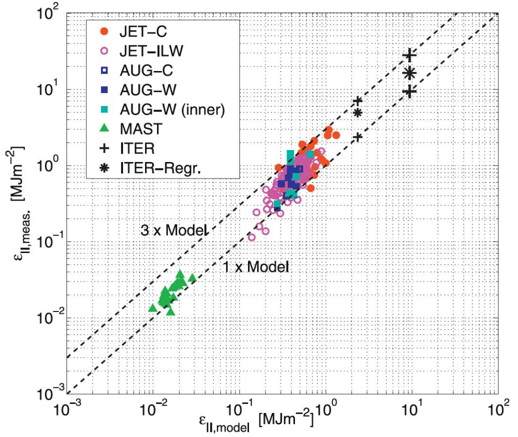
- It is clear from 0D estimates that an unmitigated thermal quench in a power plant will cause melting
- Thermal quench heat fluxes are often crudely calculated as follows

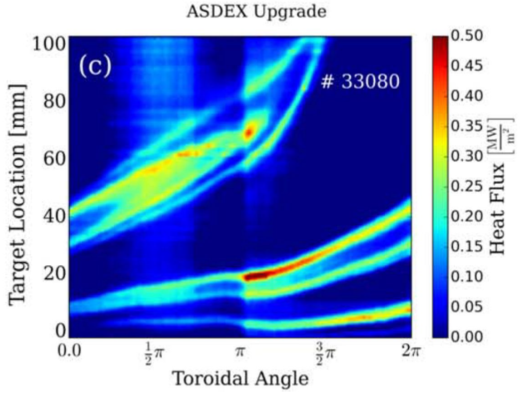
$$HFF = Wth/S(\Delta t)^{0.5}$$
$$S=2\pi R\lambda_q f_x f_b$$

- Is a simple $\lambda_q f_b$ broadening correct? Does it scale like $1/B_{pol}$?

- What does the 3D wetted area look like?
  - Like locked mode footprints in AUG?
- CFS funded postdoc Raphael Schramm is looking for the analog to the ELM heat flux scaling for the thermal quench (study includes AUG and JET)
- TQ duration under active study by H. Strauss [this conference]

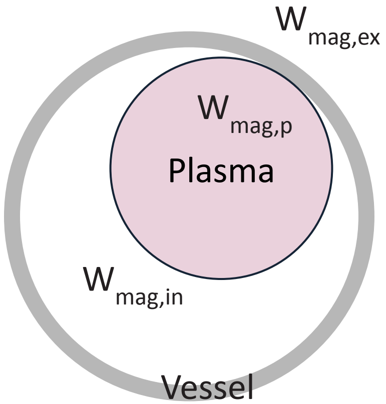
Eich et al. 2017 NME



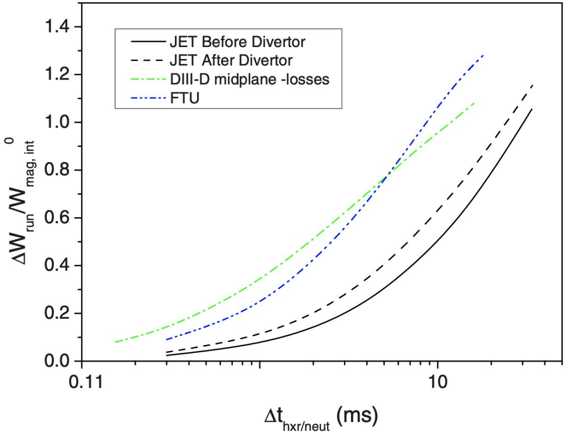


Faitsch et al. 2018 PPCF

Magnetic energy has the potential to significantly increase first-wall melting: **can we bound** the worst case?



- Halo current heat loads [Kiramov 43rd EPS, Coburn 2021 NME, Artola 2024 PPCF]
  - *Assumption:* $W_{halo,max} = W_{mag,in} + f\,W_{mag,ex}$ where *f* in [0,1]
  - Is this right? Can we bound *f* (i.e. how much energy outside the vessel penetrates)?
- Runaway strike heat loads
  - SPARC 5 MA beam with E_{ave}=10 MeV has W_{kin} = **2 MJ**
  - This is dwarfed by $W_{mag,in} + W_{mag,p}$ = **70 MJ**
  - Total poloidal magnetic energy W_{mag} = **150 MJ**
  - Which is it?
    - Martin-Solis suggests ~70 MJ
    - Is there some logical upper bound on this?



Martin-Solis et al. 2014 NF

Filling in gaps in EM load modeling for power plant design

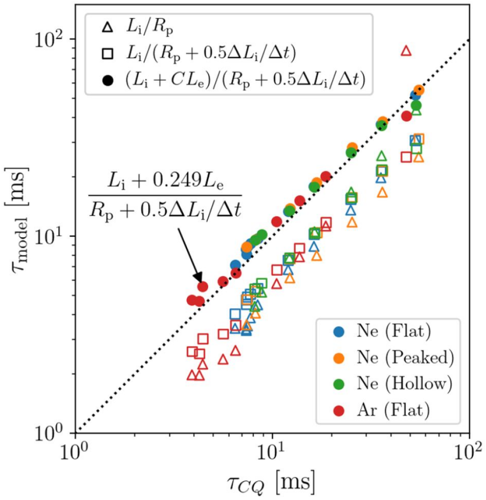
16:00

The ITPA minimum τ_{CQ} is missing a mutual, and does not offer **a bound** for the longest

- The mutual inductance with the vessel has a strong effect on τ_{CQ}
  - Tight fitting vessels lead to shorter τ_{CQ}
  - Yokoyama provides a prescription for calculating the L/R time including this (see figure)
- The longest τ_{CQ} determines the maximum vertical and sideways forces
  - How do we constrain the longest τ_{CQ}?
  - Artola proposes a max temperature [J. Artola et al. 24 PPCF]

$$T_{e,\max}^{eV} \approx 25\left(Z_{\rm eff} B_\phi / \gamma_{\rm sh}\right)^{2/5}$$

- Does this explains the longest τ_{CQ} in the IDDB?



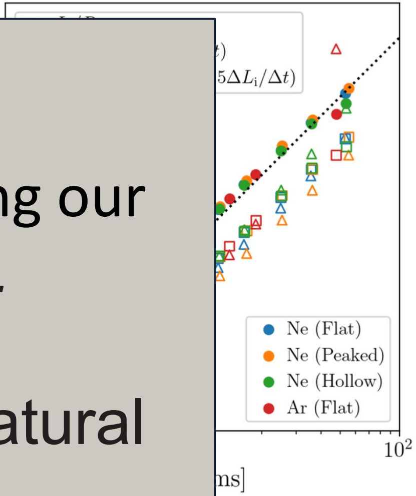
Yokoyama 2023 NF

The ITPA minimum τ_{CQ} is missing a mutual, and does not offer **a bound** for the longest

- The m... strong...
  - Ti...
  - Yo... L/...
- The lo... vertica...
  - Ho...
  - Ar... PP...

Power plants will benefit from sharpening our understanding of min and max τ_{CQ}.

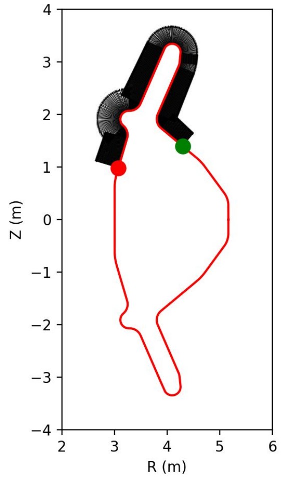
Extending/improving the IDDB is a natural way to do this work.



2023 NF

- Does this explains the longest τ_{CQ} in the IDDB?

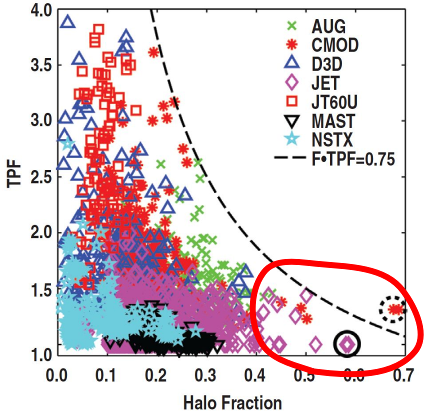
There is likely a poloidal arc length dimension missing from the ITPA halo current scalings



1. There is a well-defined prescription for the maximum vertical force $F_{v,max}$ [Miyamoto 2011 PPCF, Clauser 2019 NF]
   a. Fixed by plasma scenario and first-wall contour

2. The vertical force imparted by poloidal halo currents is given by $F_v \propto I_{halo} \Delta R$

3. With $F_{v,max}$ and $I_{h,max}=0.7I_p$ we can define a maximum $\Delta R_{max} \propto F_{v,max}/I_{h,max}$



4. For the ARC example shown, the ΔR pictured is larger than ΔR_{max}, and the maximum halo current that can flow here is $I_h/I_{p0}=0.25$

5. The ITPA data circled in red likely have short poloidal arc lengths

Disruptions challenge all future tokamaks.

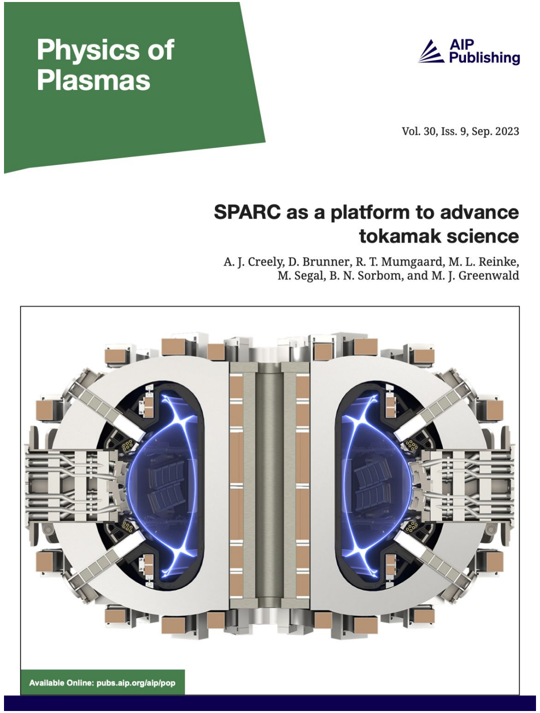
Let’s work together.

19:00

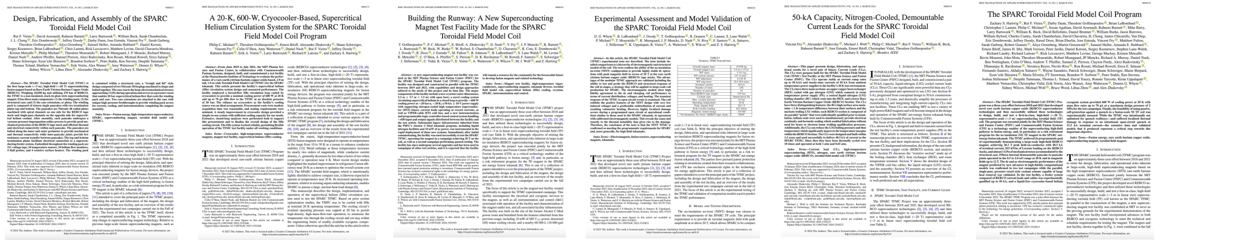
CFS works with physics and operations collaborators from around the world

- There are roughly 100 physics and operations collaborators working on the SPARC project
- The largest contingent is at MIT, but other groups include: Columbia University, ORNL, PPPL, EPFL, IPP, Chalmers, KTH, VTT, DIFFER, University of Milano, Aalto, and UCSD
- Collaborators work on a wide variety of projects, but are generally focused on projects that are not critical path to design
- These collaborators are organized through the CFS Affiliate program, which manages computer accounts and access to Devens

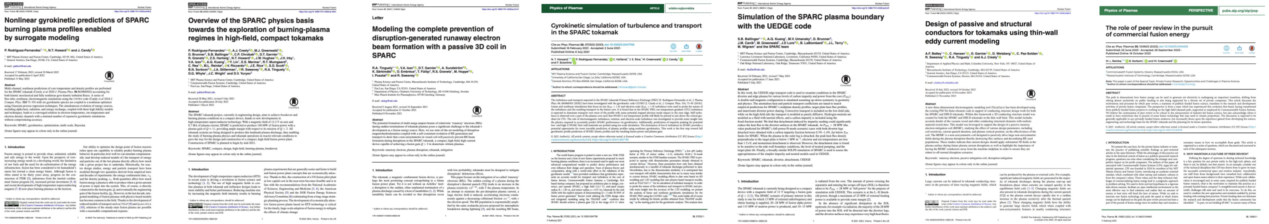
CFS and partners publish in peer-reviewed journals



2020 Journal of Plasma Physics - SPARC physics basis papers



2024 IEEE Trans. On Applied Superconductivity - TFMC Papers



Continued publishing in other journals…

There is lots more going on that I was unable to discuss today..

- SPARC work at this conference
  - Alex Saperstein - *"Development and preliminary calibration of an off-normal warning system for SPARC"*
  - Arunav Kumar - *"Machine learning model for real-time SPARC vertical stability observers"*
  - Cesar Clauser - *"Validating Hot and Cold VDEs in C-Mod with M3D-C1"*
  - Chris Hansen - *"Prediction and validation of disruption-induced eddy currents and forces within engineering design cycles using ThinCurr and Tokamaker"*
- CFS Affiliates at this conference presenting on other works
  - Alex Battey
  - Val Izzo
  - Ben Stein-Lubrano
- Please come find me or another member of the SPARC team to learn more about SPARC

Conclusions

- SPARC continues to make rapid progress toward first plasma in 2026
- As a disruption community, we must envision power plant solutions today in order to build the requisite knowledge/tools
  - **Disruption prediction**
    - Common prescriptions for physics-based detectors
    - Ramp-up/down
    - Deviation based detectors
  - **Runaway electrons**
    - Vet the REMC
    - Alternate *prevention* techniques
  - **Gaps in disruption load prescription**
    - Unmitigated thermal quench
    - Bounds on magnetic contributions to thermal loading
    - Sharpen CQ durations
    - Poloidal arc length and halo current fraction

Extra Slides

SPARC diagnostics provide high resolution of disruption structural and thermal loading, and inform prediction

EM Loads

Halo current: 100 Rogowski coils for global distribution, halo current shunts to address width, B_T sensors

Eddy current: 4 vessel Rogowskis, equilibrium magnetics

Forces: displacement sensors on port extensions and coils, vacuum vessel strain sensors

Thermal Loads

Runaway strikes: hard X-ray, neutron detectors, visible cameras

PFC Temp: IR cameras, thermocouples, spectroscopy, visible cameras

Mitigation performance: 96 dedicated disruption foil bolometers, thermocouples, IR cameras

SPARC is demonstrating that disruption forces are not a showstopper: *the risk is in getting the requirements right*

- Disruption force requirements risk
  - *Underpredict* - you break stuff
  - *Overpredict* - you inflate the cost of the power plant
- ARC disruption forces
  - Max vertical force 70 MN is 2x SPARC and comparable to Starship
    - Engineers know how to deal with these forces
  - Sideways force is 20 MN, comparable to SPARC
    - TF applies this force to vessel, but also reacts this force via magnetic stiffness from induced currents during sideways motion
    - Displacement expected to be < 1 cm
  - ARC Physics Basis will be published early in 2025 including a paper on disruptions