Recent progress in modeling runaway electrons and their mitigation in SPARC

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Joint REM and WPTE RT03 Analysis meeting
17 June 2026

Commonwealth Fusion Systems

Supported by Commonwealth Fusion Systems

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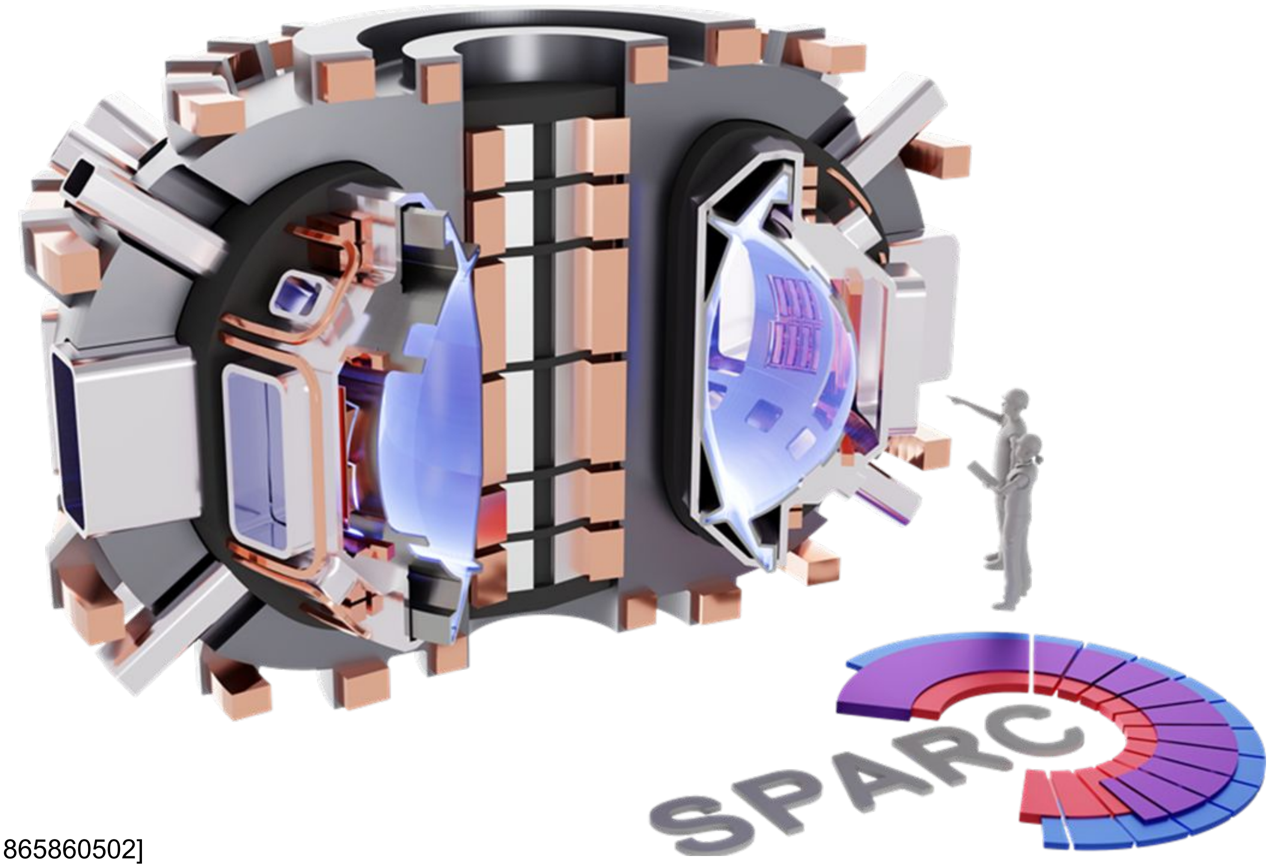
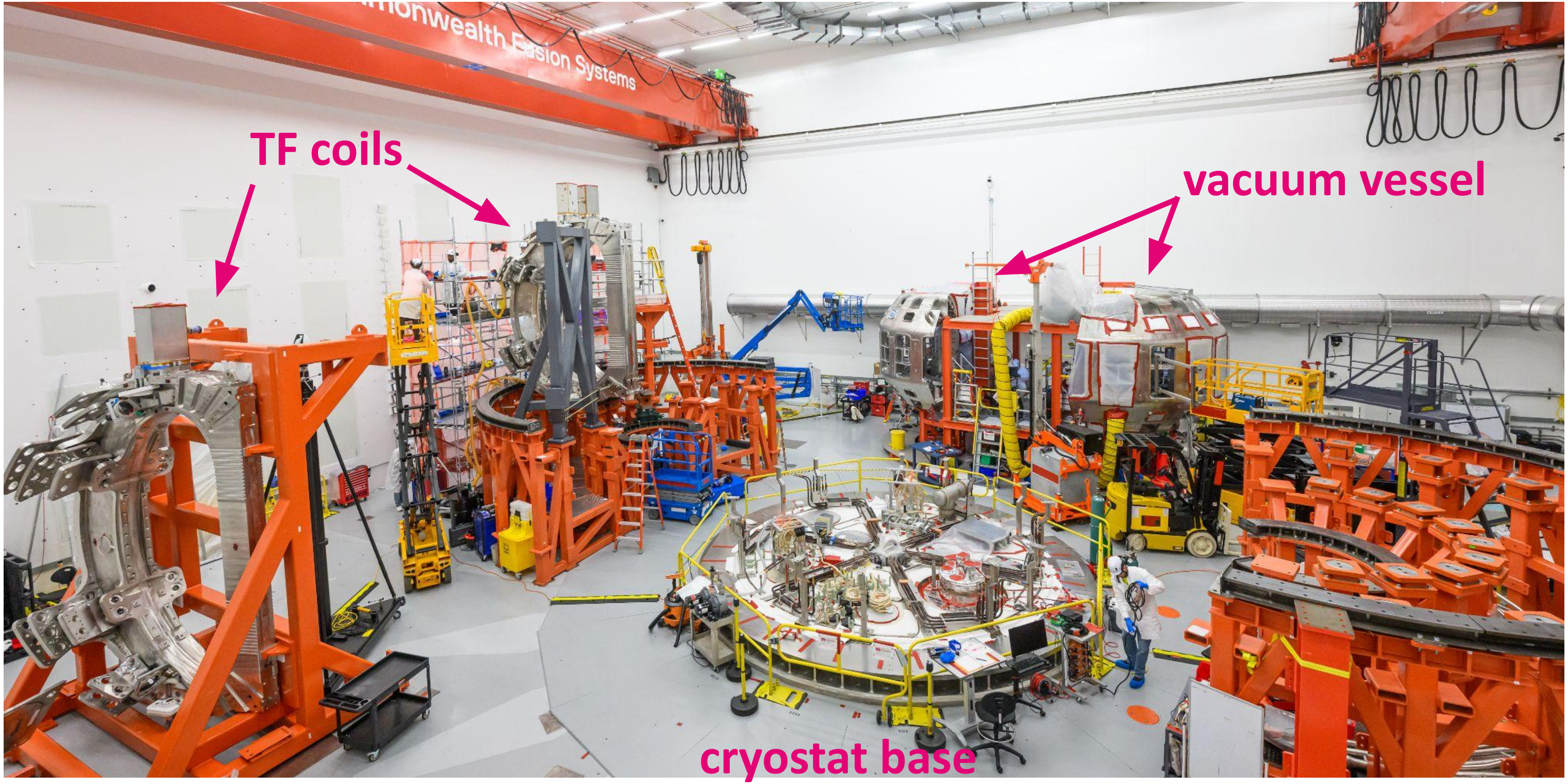
SPARC is a net-fusion power device

- R_0 = 1.85 m
- a = 0.57 m
- B_0 = 12.2 T
- I_P = 8.7 MA
- Q > 1



[A Creely et al, J. Plasma Phys (2020) 86 865860502]

SPARC assembly is progressing rapidly in Devens, MA



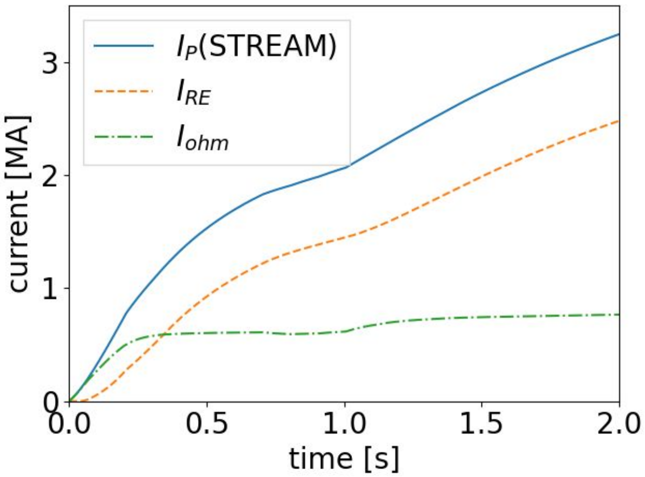
Outline

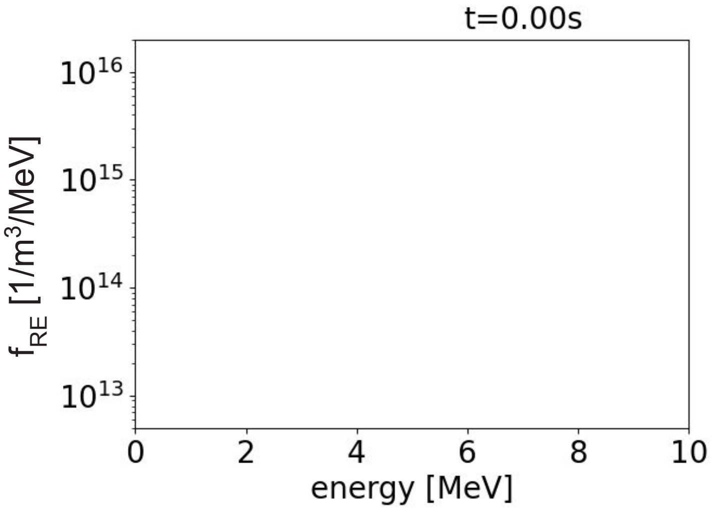
- Disruption REs (upcoming talks)
  - Generation - G Hu
  - Mitigation - R Datta
  - Termination - L Singh
  - Impacts - A Feyrer
- Start-up REs - E Panontin, D Vezinet (and huge help from I Ekmark, M Hoppe!)
- Updates for SPARC Campaign 1
  - Massive Gas Injection - R Sweeney
  - RE Mitigation Coil - J Boguski
- Musings (as time allows) - RA Tinguely
  - JET high-I_P validation data set - R Sweeney
  - Compton (volumetric) source term + geometric effects
  - Lost RE distribution functions - drift orbit losses
  - Alpha thermalization during TQ - S Mackie
- Summary & outlook

Start-up REs

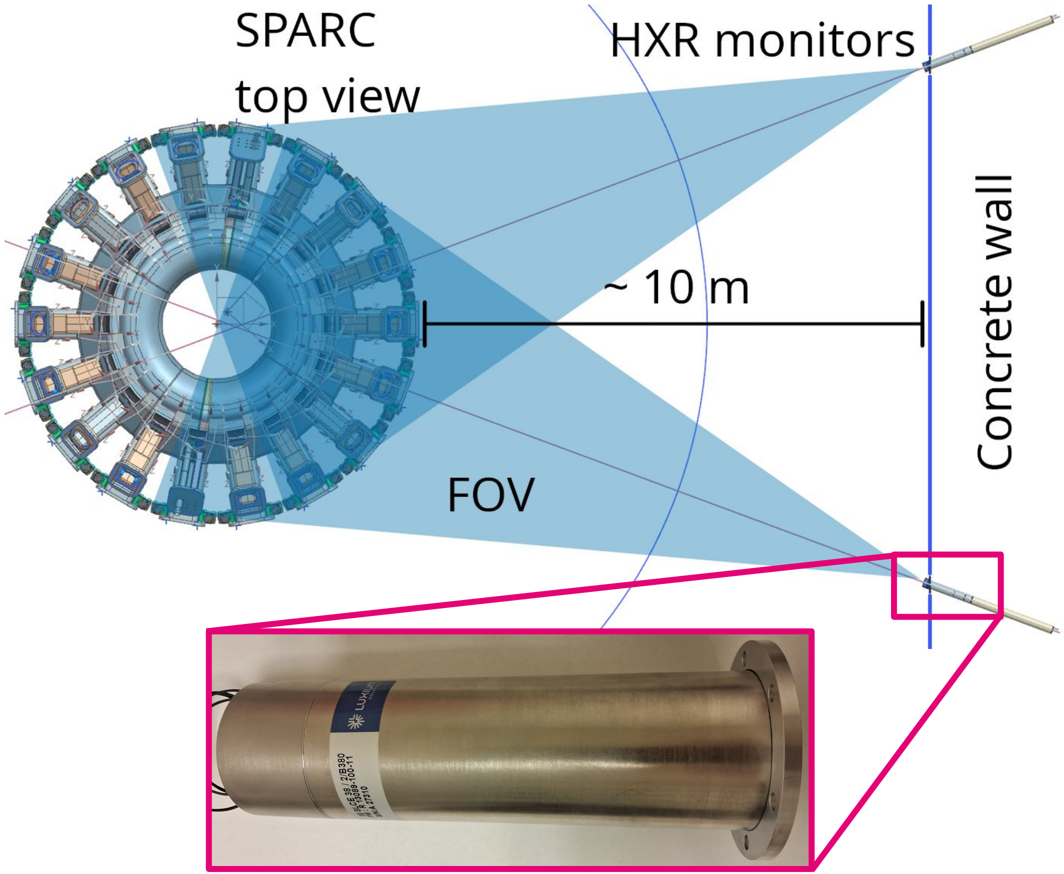
STREAM and DREAM coupled to simulate start-up RE evolution and energy distribution

- "Worst-case example"
  - Driving loop voltage: V_{loop} = 6 V
  - Initial neutral pressure: P_0 = 3 mPa
  - Fueling rate: dP/dt = 3 mPa/s





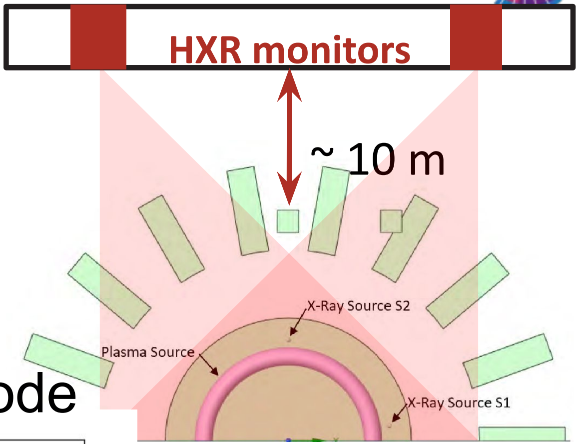
Two ex-vessel HXR spectrometers dedicated to start-up REs



- $LaBr_3$ inorganic scintillators
  - 1.5" diameter, 1.5" height
  - 3.2% energy resolution @ 662 keV
  - Count rates up to 1 MCps
  - Anode currents < 310 uA
- Wide fields of view
  - co- and counter-I_P
- Data acquisition modes
  - Current (baseline)
  - Spectroscopic

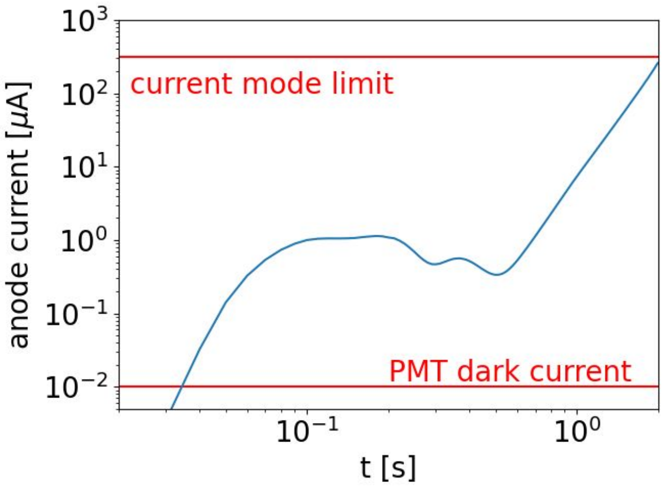
Synthetic modeling of HXR spectrometer signal

- Current mode expected to saturate at I_{RE} ~ 2 MA
- Spectroscopic mode saturates at I_{RE} ~ 1 MA

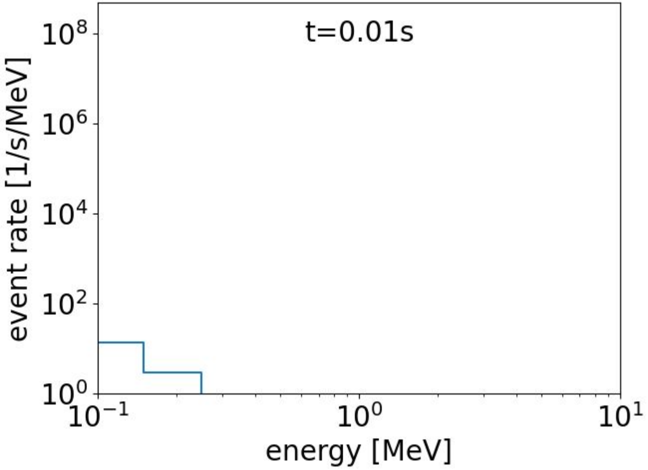


Simplified MCNP model of SPARC
(Courtesy of CFS-Neutronics team, not to scale)

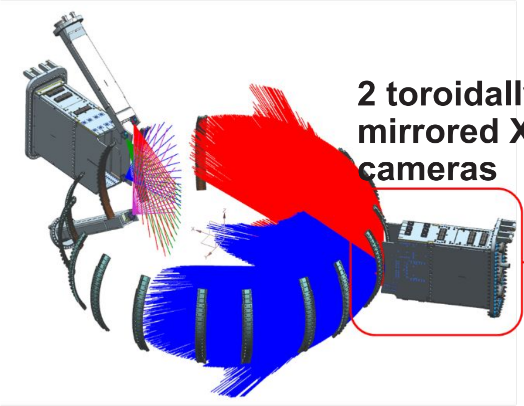
Current mode



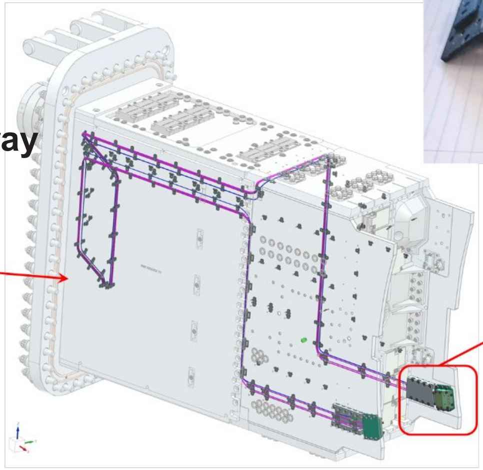
Spectroscopic mode

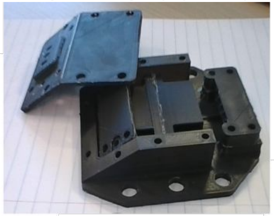


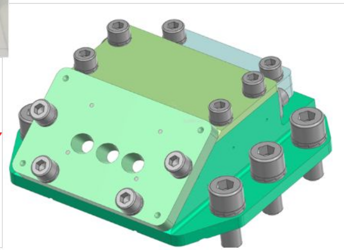
In-vessel SXR arrays are also planned for start-up REs

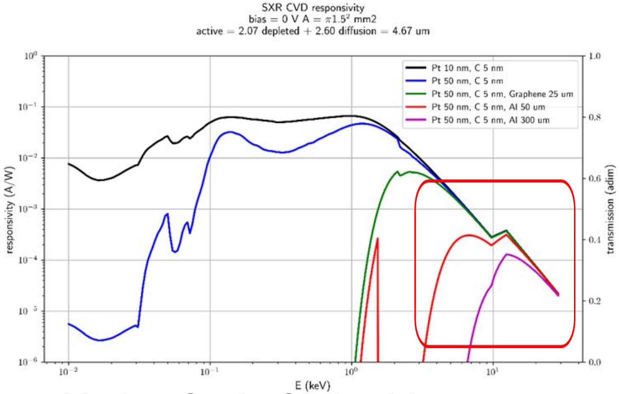


2 toroidally mirrored X-ray cameras

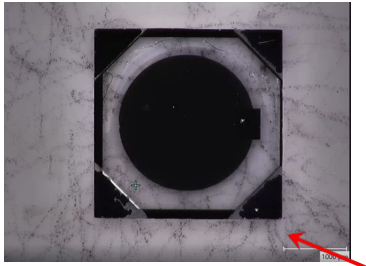


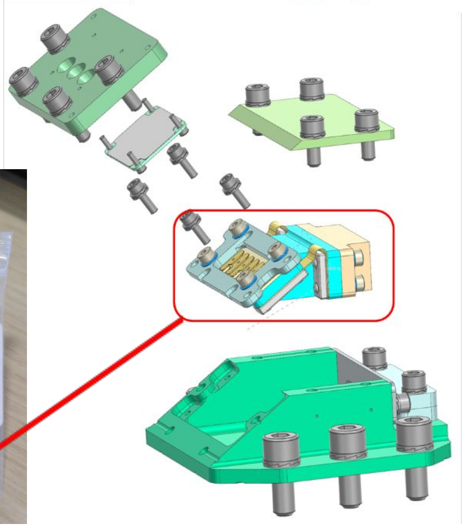






Aiming for in-flight thin-target Bremsstrahlung in 10-30 keV range



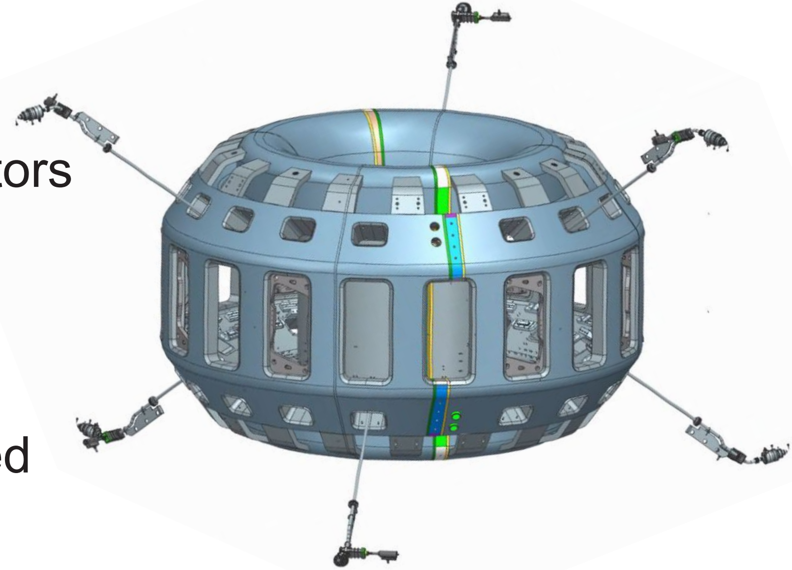


Rad-hard 5 um diamond CVD sensors

Campaign 1 Updates

Massive Gas Injection deployed in Campaign 1 (C1)

- Baseline mix: 10/90 Ne/D_2
- Staged, risk-motivated deployment
  - Early: Halo current melting → 1 valve
  - Later: Thermal quench melting → 4 injectors
- No MGI physics experiments in C1,
  unless baseline mitigation plan is insufficient

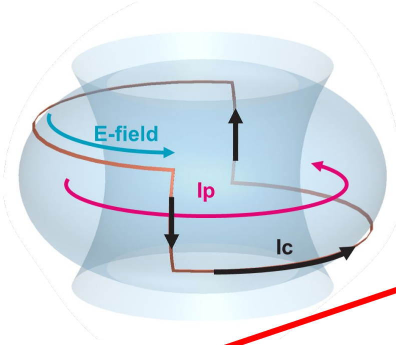


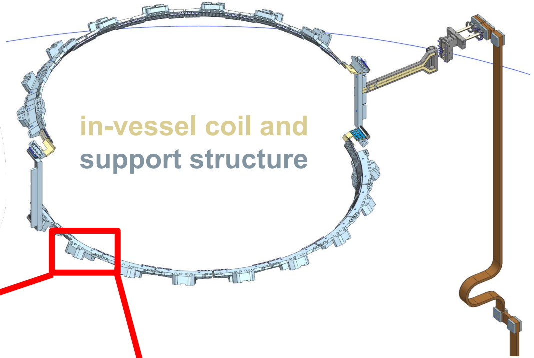
[Sweeney JPP 2026]

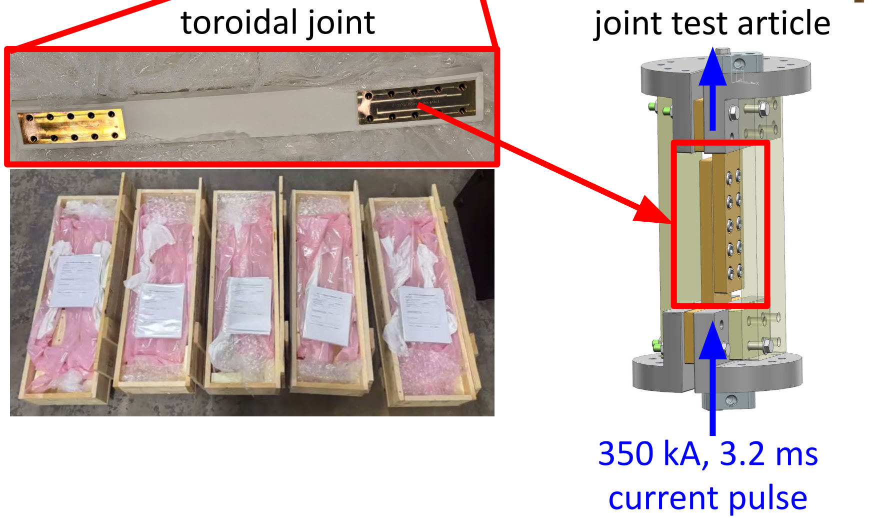
- Benign termination is possible, but not planned
  - 6 total valves with arbitrary distribution of 2 gas mixes (one could be pure D_2)
- MGI general characteristics:
  - H_2, D_2, He, Ne, Ar, Kr, Xe
  - 0.5 L plena, 0-6 MPa

Hardware is arriving for the RE Mitigation Coil

- 19 toroidal conductors machined, now being alumina spray-coated
- Variable resistor and “slow” switch (~50ms) are delivered
- Open-circuit loop-voltages continue to be a concern → evaluating feasibility of closed-circuit REMC
  - EFCCs can mitigate error fields during I_P ramp-up and ramp-down
  - Flattop I_P transients can induce multi-Gauss error fields
- New testing effort underway to address concern over joint melting due to high current
- Feasibility study and joint testing will inform REMC deployment strategy







Musings

JET high-I_P validation

- Harris 1990 JET–R(90)07 “Comparisons of the Current Decay During Carbon-Bounded and Beryllium-Bounded Disruptions in JET”
- $I_P < 6$ MA → $I_{RE} < 2.7$ MA

Hypotheses:

- Ryan: limited → diverted → enhanced losses → no REs
- Alex: limited → diverted → VDE → scrape-off → “less-obvious” REs

Great data set for validation!

This paper presents results of preliminary investigations of the current decay phase in recent JET major disruptions, where the plasma is bounded by beryllium limiters and a beryllium gettered wall. The average decay time of the current is 175 ms, about 14 times longer than the initial decay time for carbon-bounded disruptions. Vertical stability is often lost before the current has decayed significantly in Be-bounded disruptions, leading to substantial net vertical forces on the vacuum vessel. Subsequent interaction of the plasma with the top or bottom divertor tiles leads to increased impurity contamination, cooling of the plasma and a second phase of more rapid current decay. Unlike carbon limiter disruptions, no runaway current plateau is observed for carbon-bounded x-point disruptions, although in some cases a small hesitation in the current decay is observed that is coincident with the hard x-ray and photoneutron signals associated with runaway electrons. The total photoneutron yield in x-point disruptions is at least 10 times smaller than that measured from limiter discharges. Both x-point and limiter disruptions in Be-bounded discharges show no runaway production, except for a few cases where carbon contamination is also suspect. Direct ECE measurements indicate the temperature T_d following thermal quench in Be-bounded disruptions is at least 30 eV, and often higher. Plasmas of such temperatures have resistive decay times consistent with the observed current decay rates. The observed lack of runaway production is also consistent with these temperatures as, for $n_e = 1 \times 10^{19} m^{-3}$, the runaway production rate for $T_d = 30\,eV$ is estimated to be a factor 10^{-6} less than that at 5 eV. Even greater reductions are estimated for higher densities.

Geometric considerations for Compton source term

- Consider a circular, infinitely long plasma and an isotropic *volumetric* photon source Y(r) [ph/m^3/s]
- The photon flux from *inside to outside* surface r is

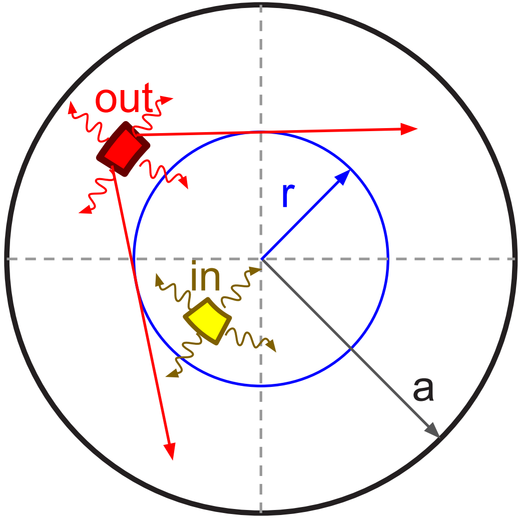
$$\Gamma_{\mathrm{in}\to\mathrm{out}}(r) = \frac{\mathrm{d}N_{\mathrm{in}}(r)}{2\pi r\mathrm{d}z\mathrm{d}t} = \frac{1}{2\pi r}\int_0^r Y(r')\cdot 2\pi r'\mathrm{d}r' = \frac{1}{r}\int_0^r Y(r')r'\mathrm{d}r'$$

- And from *outside to inside* surface r is

$$\Gamma_{\mathrm{out}\to\mathrm{in}}(r) = \frac{\mathrm{d}N_{\mathrm{out}}(r)f_{\mathrm{out}\to\mathrm{in}}}{2\pi r\mathrm{d}z\mathrm{d}t} = \frac{1}{\pi}\int_r^a Y(r')\frac{r'}{r}\arcsin\left(\frac{r}{r'}\right)\mathrm{d}r'$$

- The *total* flux through surface r is

$$\Gamma_{\mathrm{tot}}(r) = \Gamma_{\mathrm{in}\to\mathrm{out}}(r) + 2\Gamma_{\mathrm{out}\to\mathrm{in}}(r)$$



- The ratio of core/edge flux is **2/π ~ 0.64** (>1/3 reduction)
  - For edge-localized source (e.g. activated walls)
  - For volumetric source (e.g. DT gammas)
- Application to both fluid and kinetic pictures

Quantifying lost RE distribution functions - drift orbits

- The grad-B and curvature drifts are given by

$$v_Z = \frac{1}{\omega_c}\left(v_\parallel^2 + \frac{v_\perp^2}{2}\right)\frac{\vec{R}_c \times \vec{B}}{R_c^2 B} = \frac{v^2}{\omega_c R_c}\left(\xi^2 + \frac{1-\xi^2}{2}\right) = \frac{v^2(1+\xi^2)}{2\omega_c R_c}$$

- And the drift from the surface r is

$$\mathrm{d}r = v_r \mathrm{d}t = (v_Z \cdot \hat{r})\mathrm{d}t = v_Z \sin\theta \mathrm{d}t$$

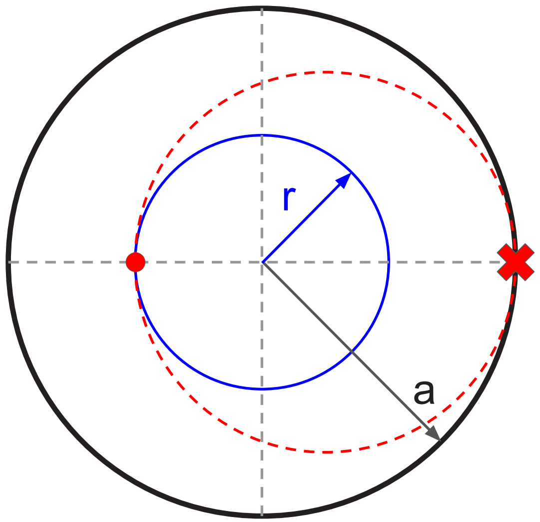
- The trajectory r(θ) is the integral solution to

$$\frac{\mathrm{d}r}{\mathrm{d}\theta} = \frac{v}{\omega_c}\frac{B}{B_\theta}\frac{r\sin\theta}{R_c}\frac{1+\xi^2}{2\xi} = \frac{p}{eB_\theta}\frac{r\sin\theta}{R_c}\frac{1+\xi^2}{2\xi}$$

- With “loss” defined something like **r(θ) > b**
- And the loss time in df/dt evaluated from

$$r\mathrm{d}\theta = v_\theta \mathrm{d}t$$

- Bounce-averaging seems doable, although maybe difficult depending on definition of values at OMP?
- Useful in kinetic picture, but unclear for fluid REs



Alpha thermalization during the Thermal Quench

- Great paper: *The impact of fusion-born alpha particles on runaway electron dynamics in ITER disruptions.* Lier *et al* 2023 NF
- Solves alpha distribution function during TQ

$$f(v,t) = \frac{\tau_{s0} S_0}{v^3 + v_c^3(1 - e^{-3\int \tau_s^{-1} \mathrm{d}t}) + v_{c0}^3 e^{-3\int \tau_s^{-1} \mathrm{d}t}} \mathrm{U}(v_\alpha - v)$$

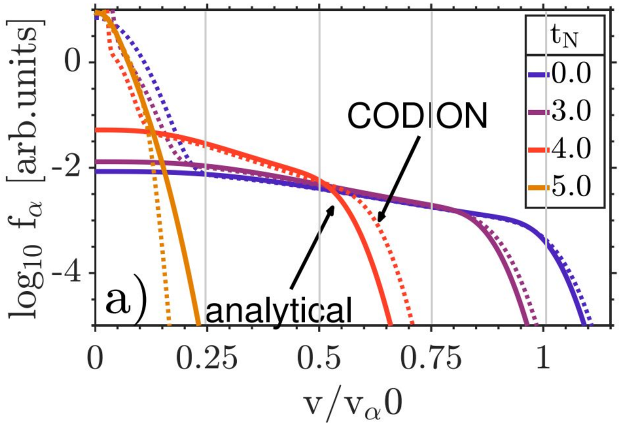
- Assumes functional form for thermal broadening of alpha source

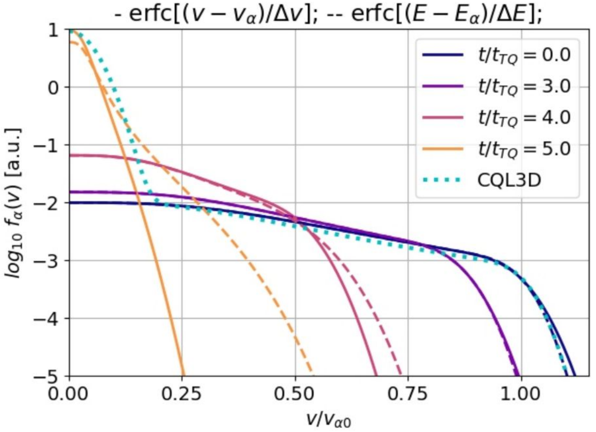
$$\mathrm{U}(v_\alpha - v) \longrightarrow \frac{1}{2}\mathrm{Erfc}\left(\frac{v - v_\alpha}{\Delta v}\right) \qquad \Delta v = \sqrt{2T/m_\alpha}$$

- Kinematics would suggest [Brysk 1973]

$$\frac{1}{2}\mathrm{Erfc}\left(\frac{E - E_\alpha}{\Delta E}\right) \qquad \Delta E = \sqrt{\frac{4 m_\alpha E_{\alpha 0} T_i}{m_\alpha + m_n}} \qquad E_\alpha = \frac{1}{2} m_\alpha v_\alpha^2$$

- Improved agreement with CQL3D; CODION?
- Perhaps important for alpha-driven modes





Summary & outlook

- XR detectors will monitor start-up REs in SPARC
  - Start-up RE distribution functions
  - Synthetic signal modeling ongoing
  - Improving fidelity / losses to the first wall?
- For SPARC's first campaign…
  - 1 → 4 (of 6) MGI injectors to be available
  - REMC deployment strategy is in progress, decision to be made soon
- Opportunities for code development & validation!
- Exciting work ongoing for ARC (see JPP papers)
  - A Braun (Columbia) on non-insulated REMC
  - R Datta on multi-n "optimization" for REMCs
  - L Singh on FW design informed by REs
  - and more!

CFS begins preparing a home for our 100 million degree fusion plasma | The Tokamak Times