



Recent progress in modeling and diagnosing energetic particles in the SPARC tokamak

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MIT Plasma Science and Fusion Center

19th Technical Meeting on Energetic Particles
in Magnetic Confinement Systems
28 Sep - 2 Oct 2026



This work is supported by Commonwealth Fusion Systems, the U.S. Department of Energy FIRE Collaborative "Mitigating Risks from Abrupt Confinement Loss (MiRACL)", and US DOE CTC SPARC program. This research uses resources of the National Energy Research Scientific Computing Center (NERSC), a Department of Energy User Facility.

With many contributions from...

W Wang, R Datta, A Feyrer, L Singh,
M Muraca, R Chandra, L Nichols,
G Hu, C Clauser, S Mackie, E Panontin,
J Kunimune, S Huber, N Fensterheim
MIT Plasma Science and Fusion Center

A LeViness, P Snyder, R Sweeney,
S McKanas, P Raj, D Vezinet,
A Rosenthal
Commonwealth Fusion Systems

Additional thanks to...

- C Kim - *SLS2 Consulting*
- P Bonofiglio - *PPPL*



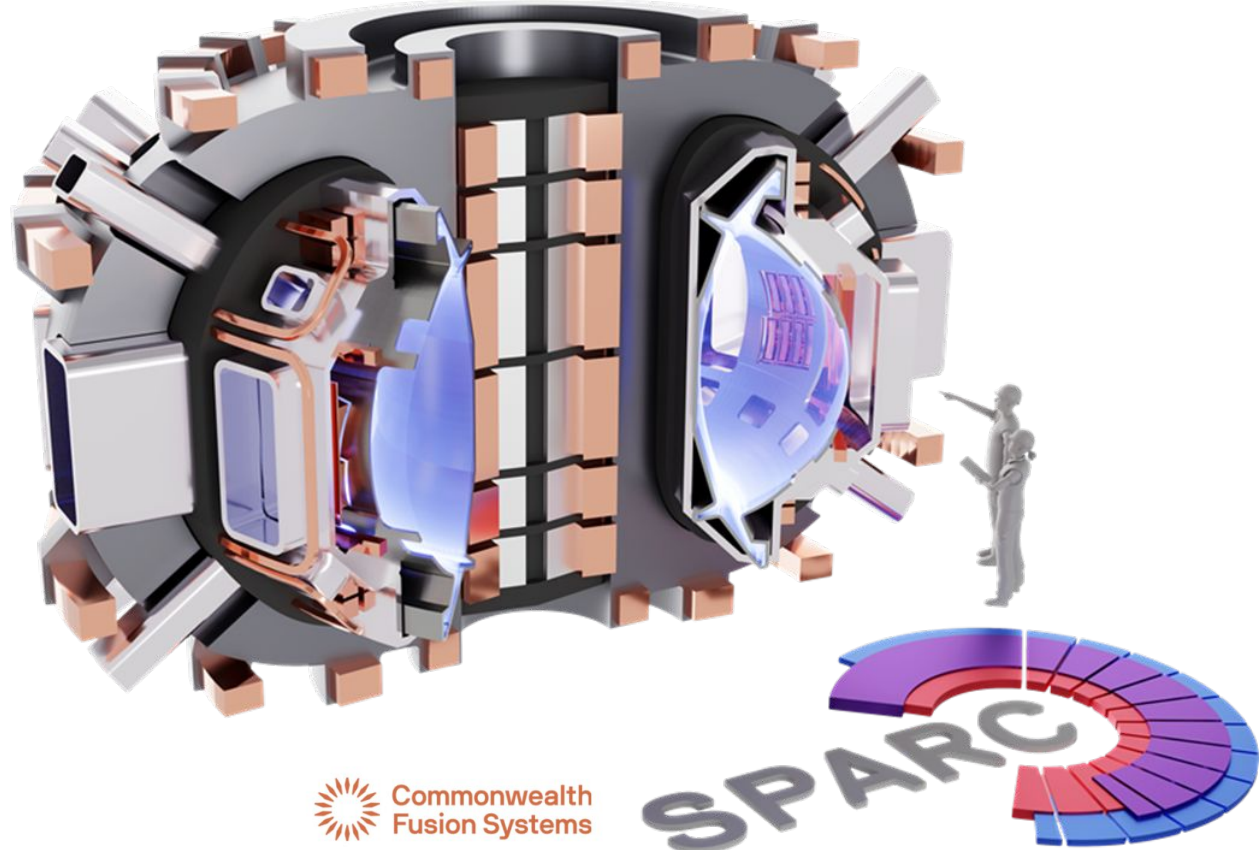
Outline

- SPARC
- Energetic particles = fusion alphas + runaway electrons
 - MHD
 - Transport
 - Diagnosis (backup)
- Summary & future work

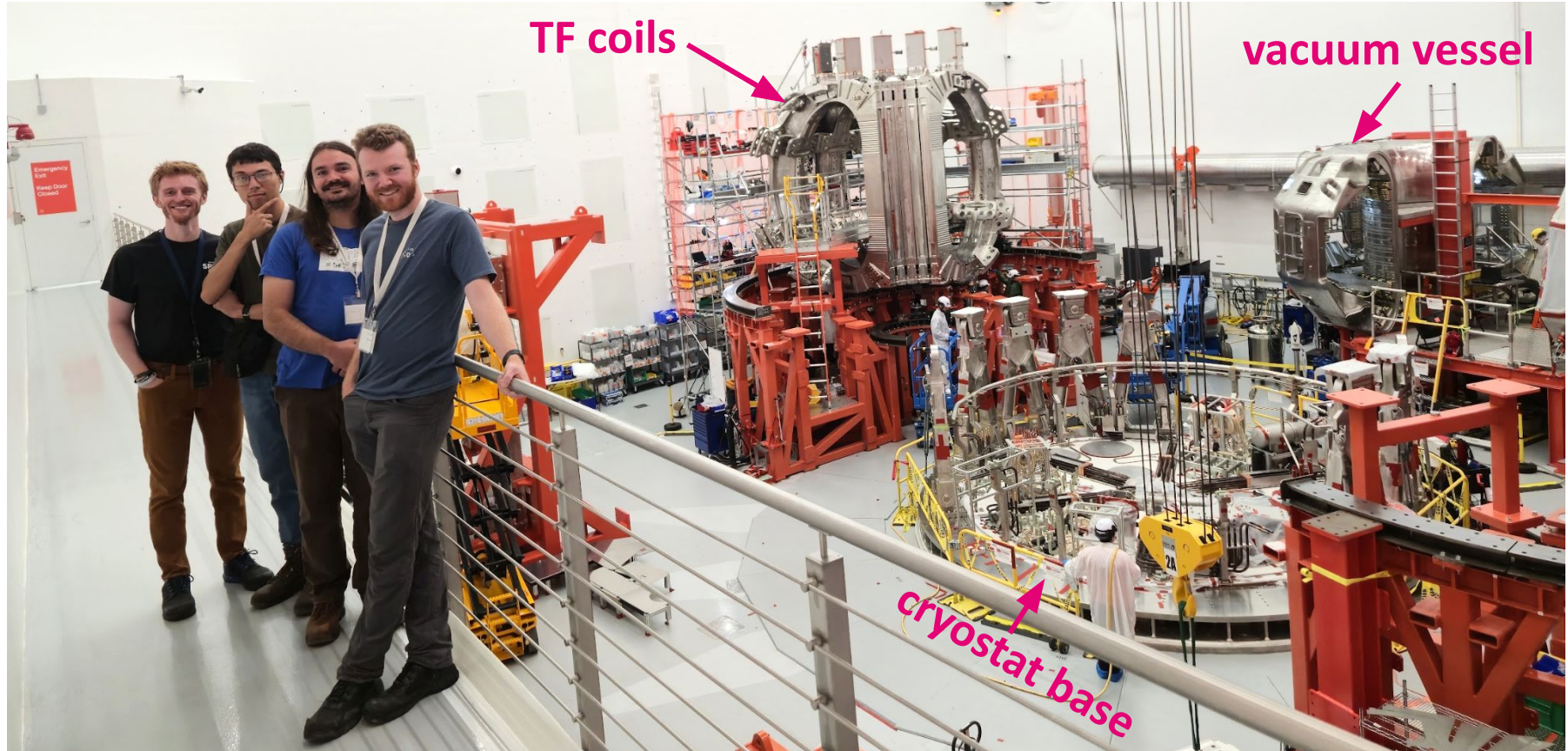
SPARC is a net-fusion-power tokamak built by CFS



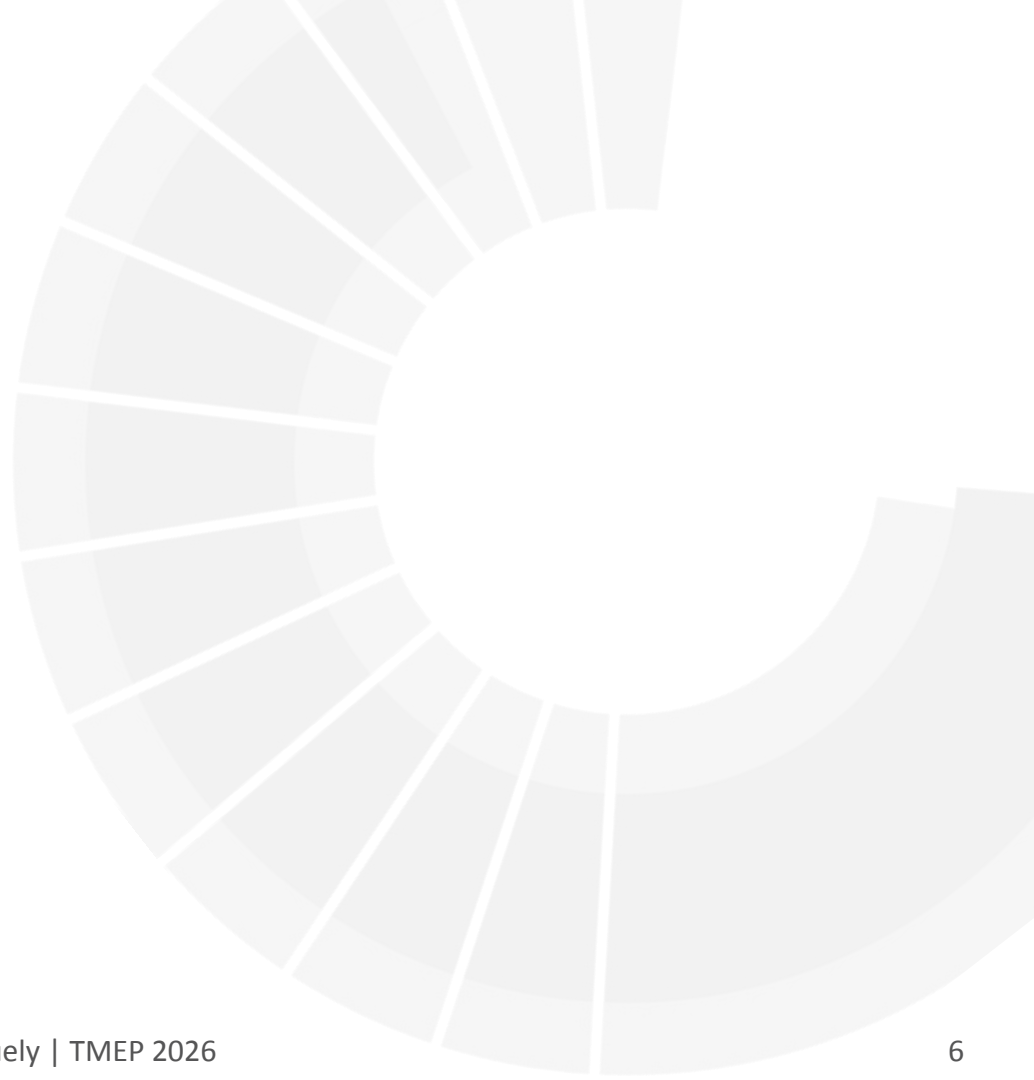
- $R_0 = 1.85 \text{ m}$
- $a = 0.57 \text{ m}$
- $B_0 = 12.2 \text{ T}$
- $I_P = 8.7 \text{ MA}$
- $Q > 1$

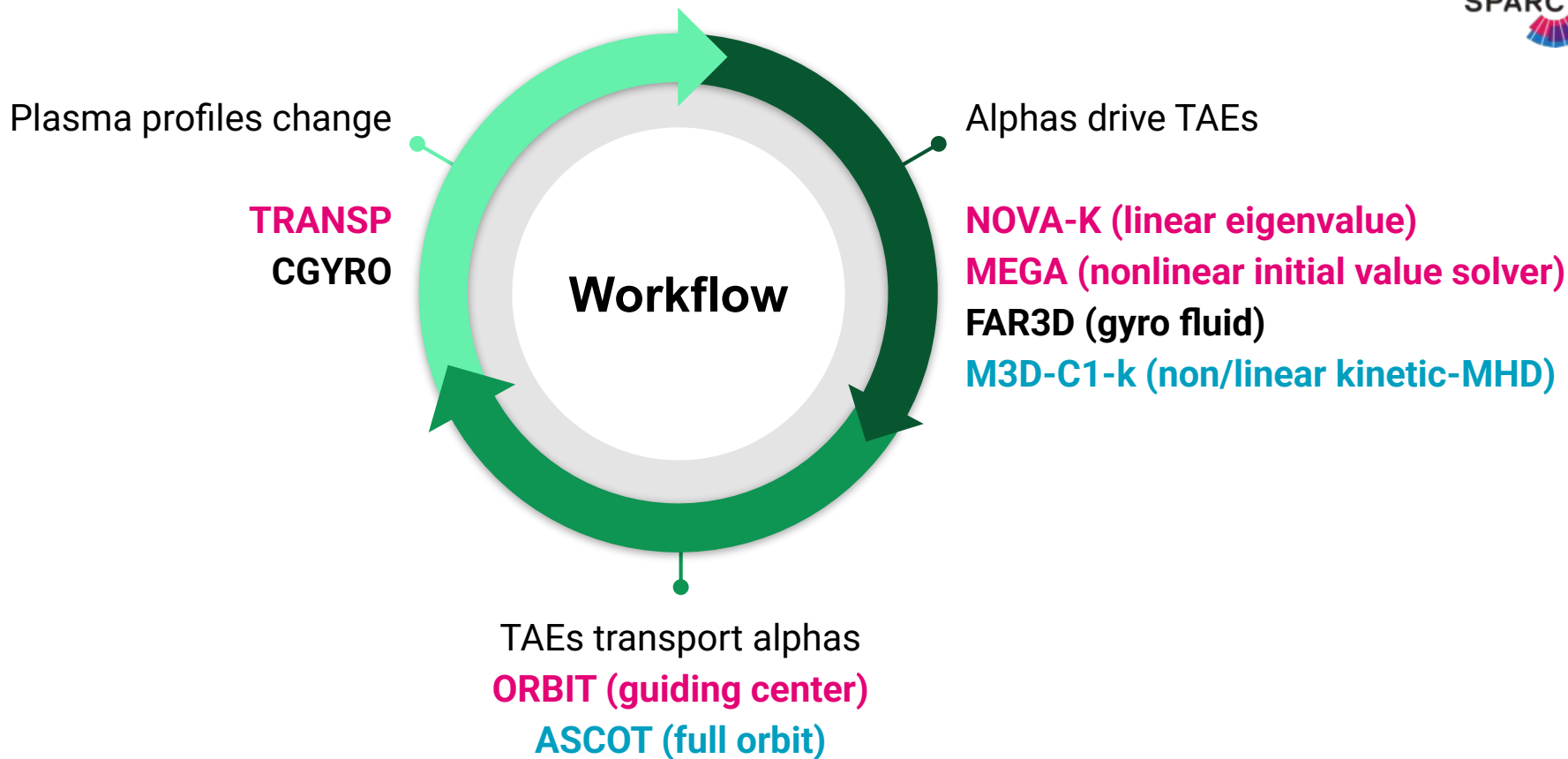


SPARC assembly is progressing rapidly in Devens, MA

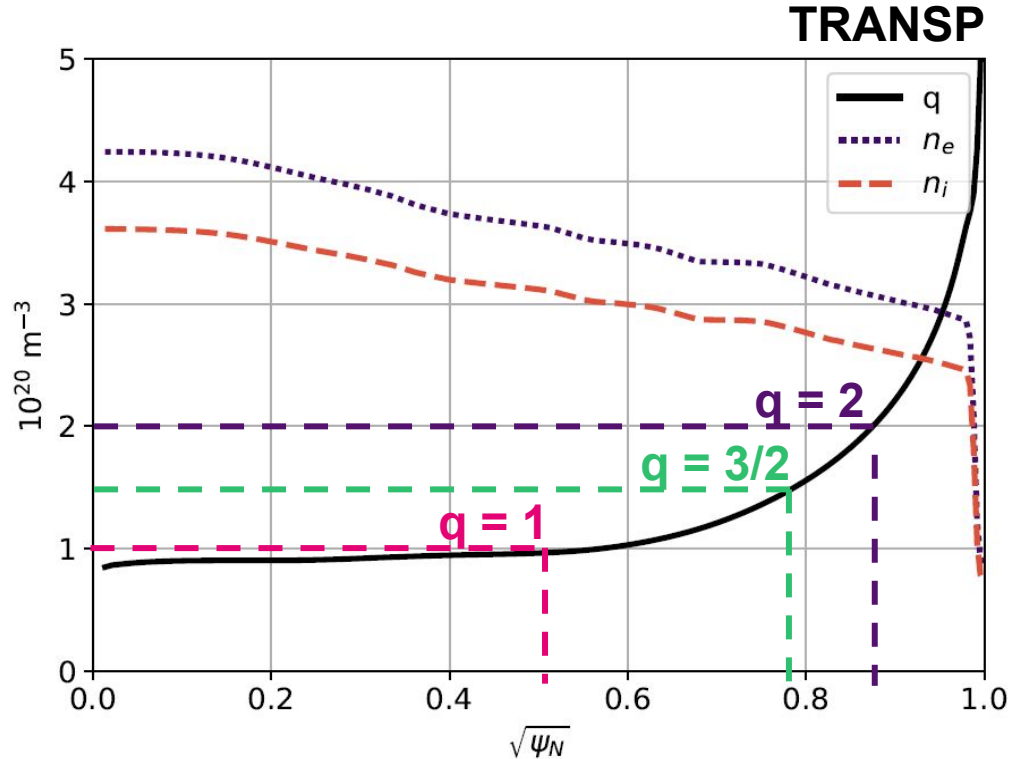
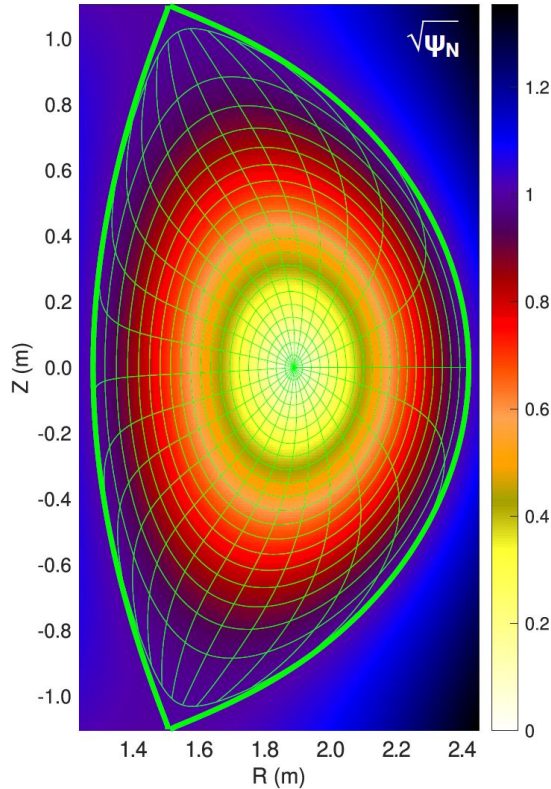


Fast ions





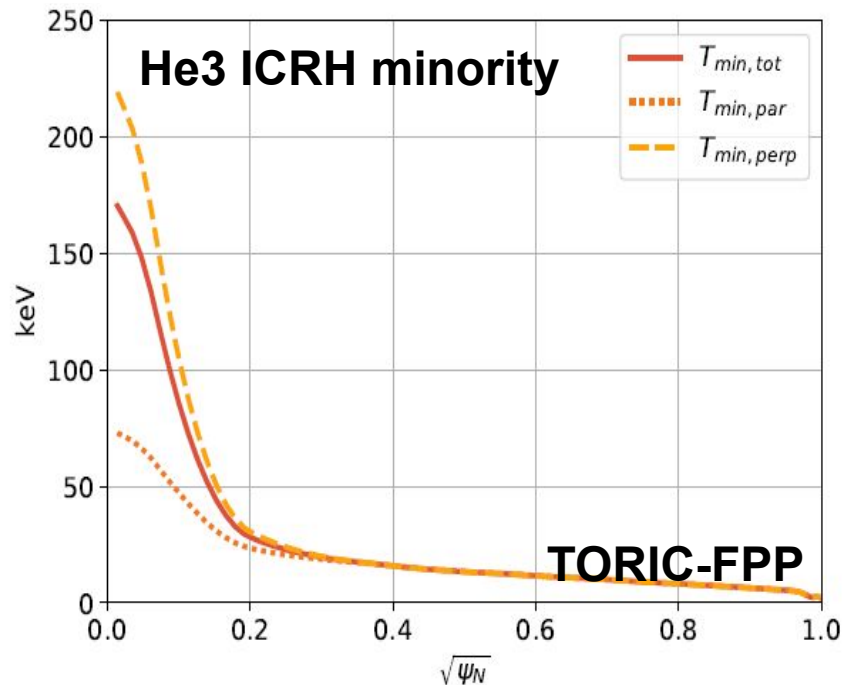
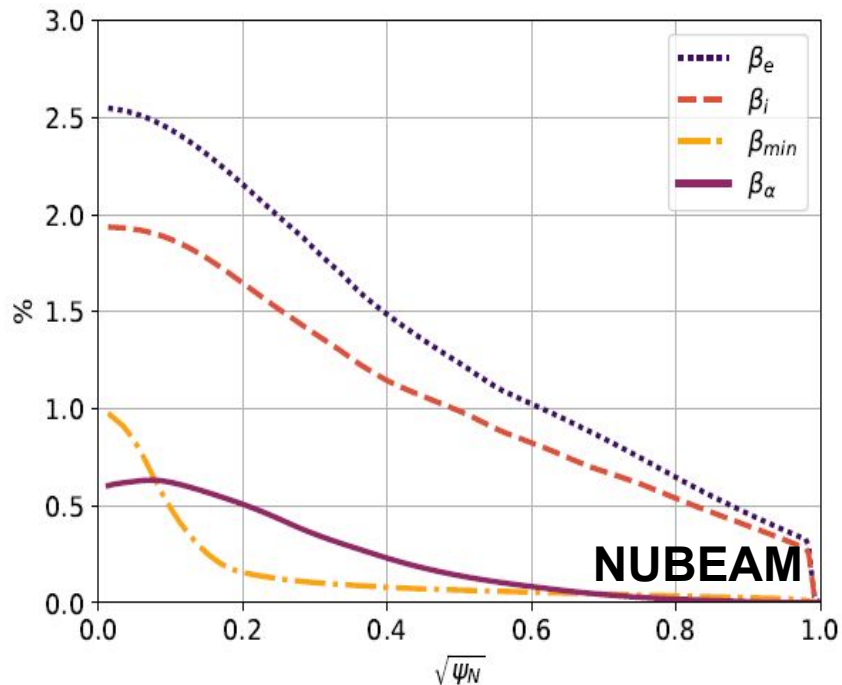
SPARC's “Primary Reference Discharge” → $Q \sim 10$ DT fusion power > 100 MW, ICRH power > 10 MW



Alpha birth velocity exceeds the on-axis Alfvén speed



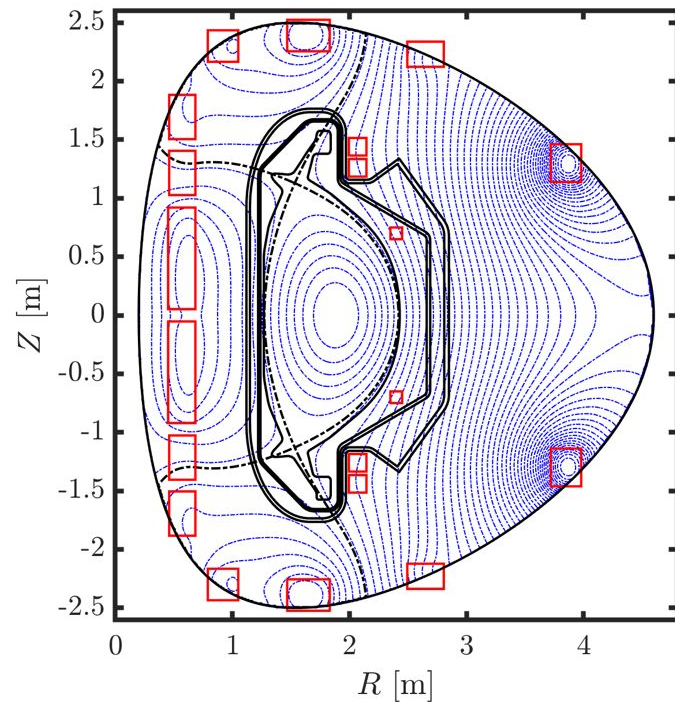
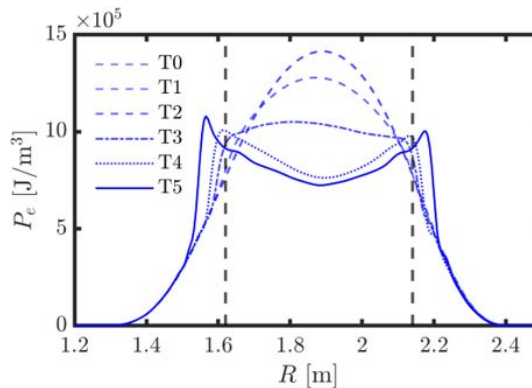
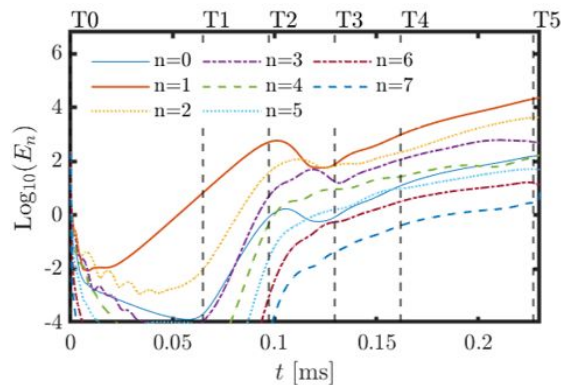
$$\rightarrow v_{\alpha 0} = 13 \text{e6 m/s} > v_{A0} \sim 9 \text{e6 m/s} (\sim B/n^{1/2})$$



M3D-C1-k is a 3D nonlinear extended MHD code



- Single/multiple toroidal modes, non/linear runs
- Includes wall geometry and coil currents for high-fidelity free-boundary simulations
- Drift/gyro-kinetic model for fast ions and thermal ions
- Particle tracing for fast ions and runaway electrons
- Example: SPARC PRD sawtooth simulations [Wang]

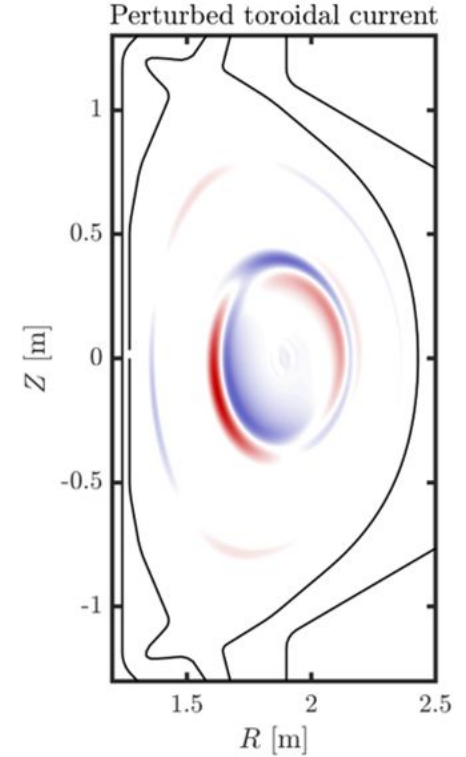
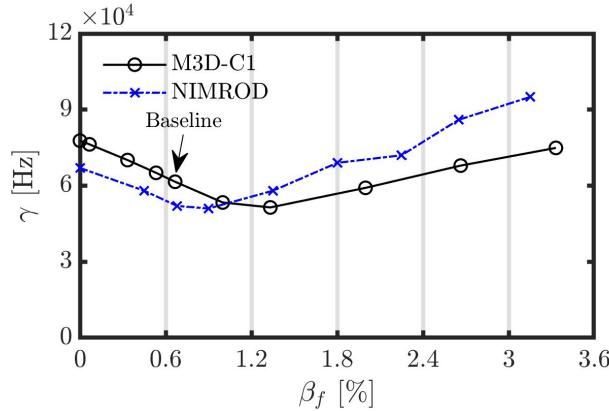
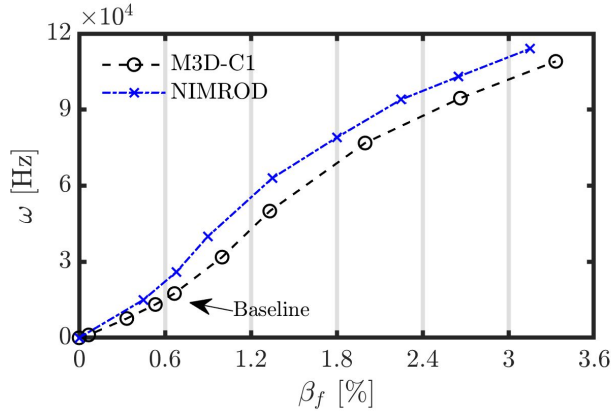


Jardin, et al. Computational Science & Discovery 5, 014002 (2012)
Liu, et al. Computer Physics Communications, 275, 108313 (2022)

Ferraro, et al. Nucl. Fusion 59 (2019) 016001
Wang, et al. In press (2026)

M3D-C1-k: n=1 fishbones [W Wang, C Kim]

- Alpha β_f scan shows the reduction of n=1 internal kink and the excitation of fishbone mode
 - Low β_f : growth rate reduction with small frequency
 - Higher β_f : the growth rate increase and the mode becomes a fishbone [1-3]
- A benchmark study is in progress with **NIMROD** simulations, showing good agreement!



[1]. Fu, G.Y., et al., 2006. Physics of plasmas, 13(5).

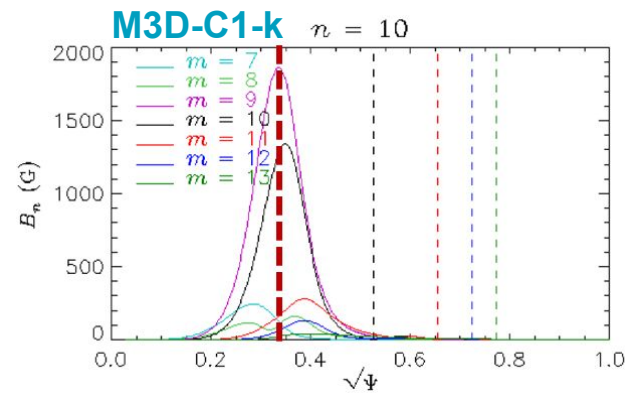
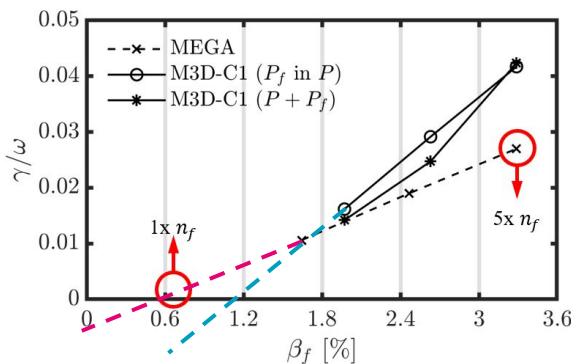
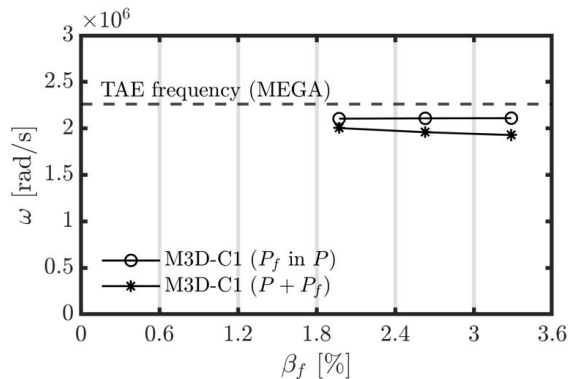
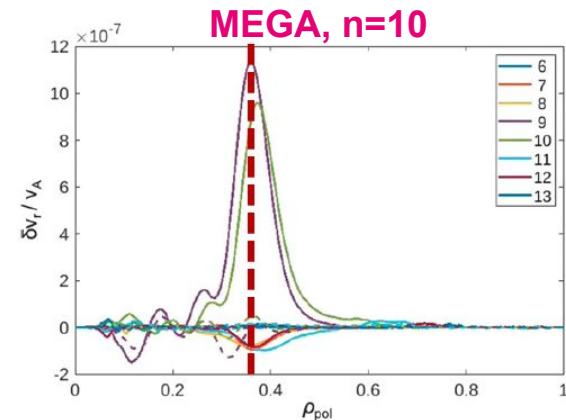
[2]. Brochard, G., et al., 2020. Nuclear Fusion, 60(12), p.126019.

[3]. Liu, C., et al., 2022. Computer Physics Communications, 275, p.108313.

M3D-C1-k: alpha-driven TAEs [W Wang]

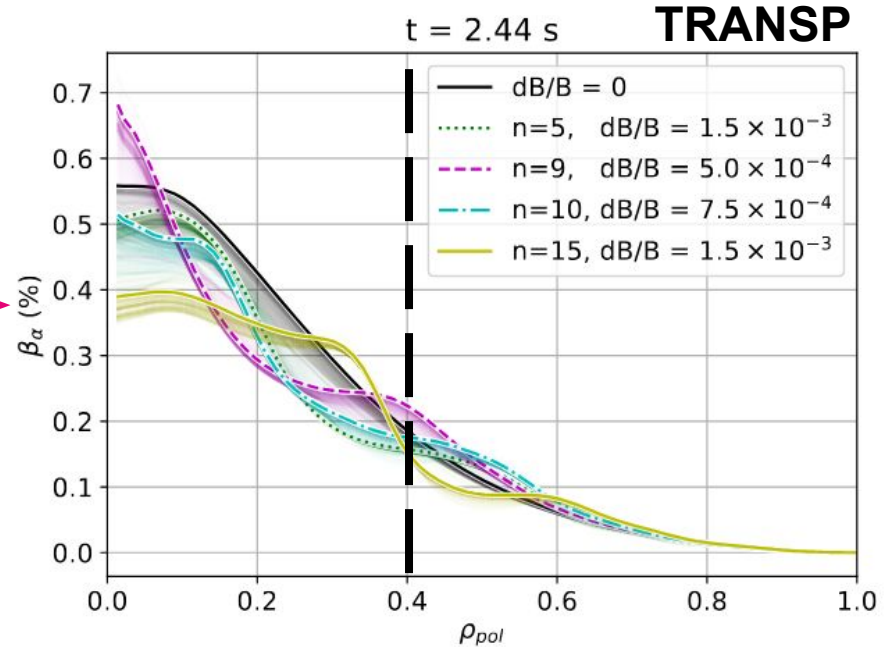
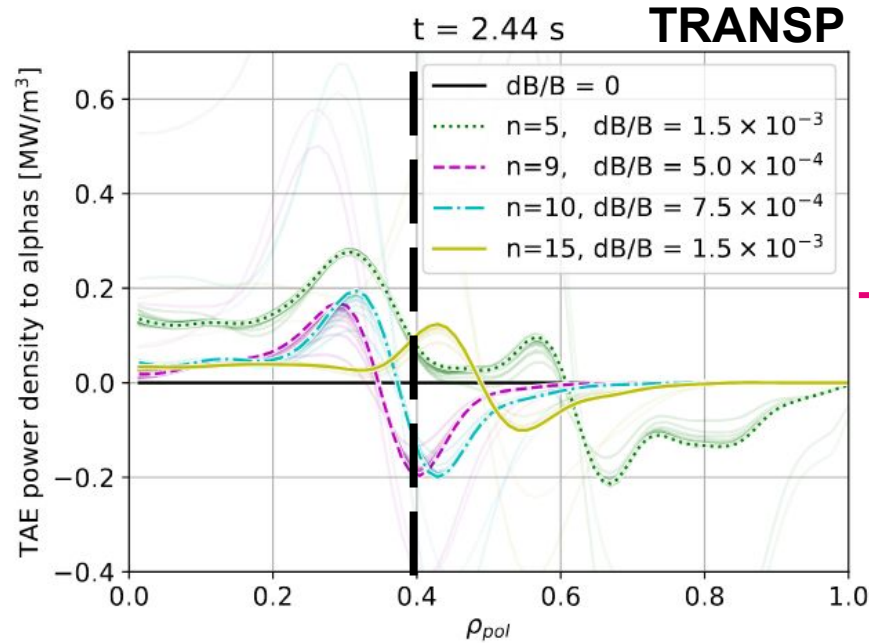


- Benchmark against previous **MEGA** (and **NOVA-K**) sims [1], specifically for **n=10 TAE**
- Mode frequencies agree well, and mode structures are similar around $q = 1$ surface, $r/a \sim 0.35$
- Linear mode growth is observed by multiplying the alpha density profile $\sim 3\text{-}5\times$
 - Growth rates agree at $\sim 3\beta_f$, but trends diverge
 - **MEGA** predicts **marginally unstable** TAE at nominal β_f
 - But **M3D-C1-k** predicts **stable** TAE...



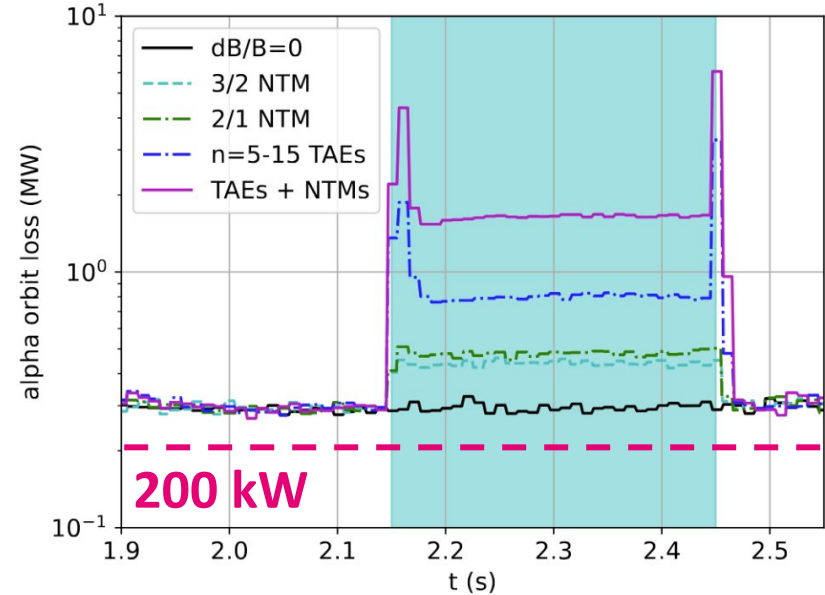
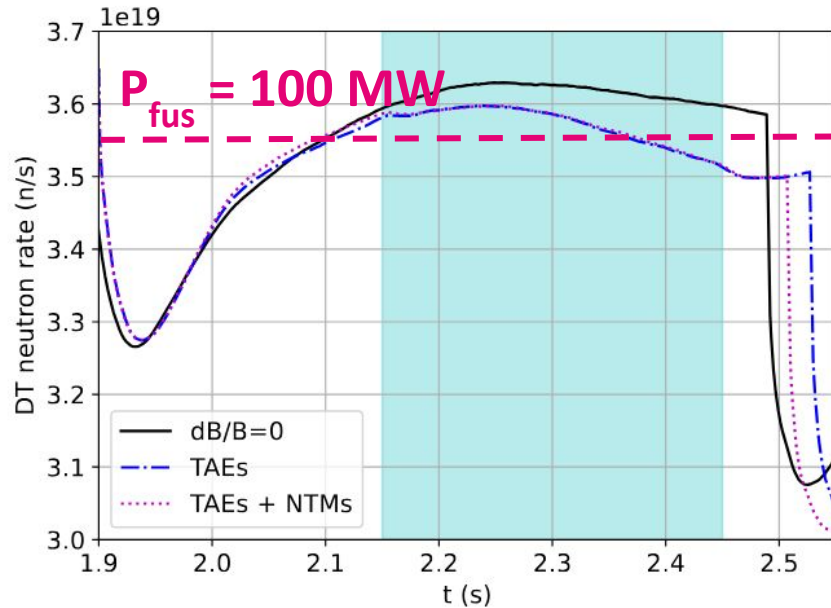
[1]. Tinguely, R.A., Gonzalez-Martin, J. and Todo, Y., 2025. Nuclear Fusion, 65(3), p.036021.

Challenge to determine the “correct” saturation amplitudes → Look for alpha profile gradient flattening



[M Muraca, P Bonofiglio]

TAEs lead to ~3% reduction in total *fusion* power and >2x increase in lost *alpha* power (mostly n=5 TAE)



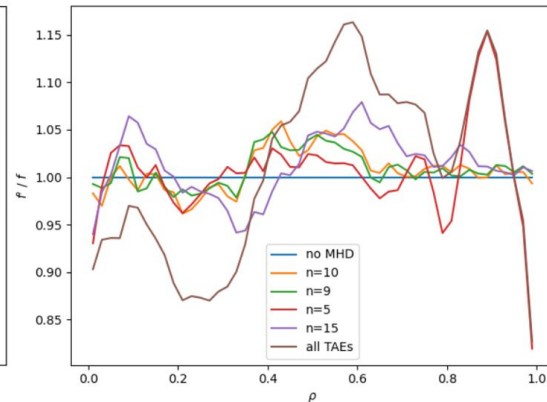
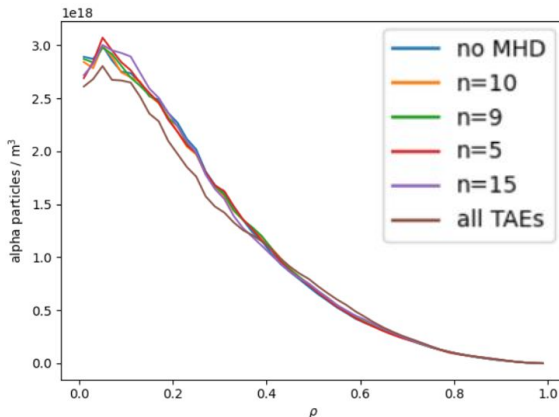
ASCOT5: TAE-induced alpha transport [A LeViness]



- **ASCOT5** is a Monte Carlo orbit-following code which can simulate the effect of TAEs on EP transport [1]
- Fixed equilibrium & kinetic profiles, no ripple
- TAEs taken from **NOVA-K**, amplitudes from **TRANSP**
 - TAEs simulated individually and together
- Followed virtual alphas:
 - 131,072 per simulation
 - 3.52 MeV at start of sim
 - evenly distributed in real & velocity space
 - weighted by fusion rate
 - in guiding center mode
 - until LCFS/thermalized
- **Only $n = 5$ and all 4 combined showed statistically significant increase in losses!**
 - Uncertainties calculated by bootstrapping

TAEs simulated	% alpha power loss
None	$1.126 \pm 0.009\%$
$n = 5$	$1.270 \pm 0.010\%$
$n = 9$	$1.122 \pm 0.009\%$
$n = 10$	$1.119 \pm 0.009\%$
$n = 15$	$1.123 \pm 0.009\%$
$n = 5, 9, 10, \& 15$	$1.280 \pm 0.010\%$

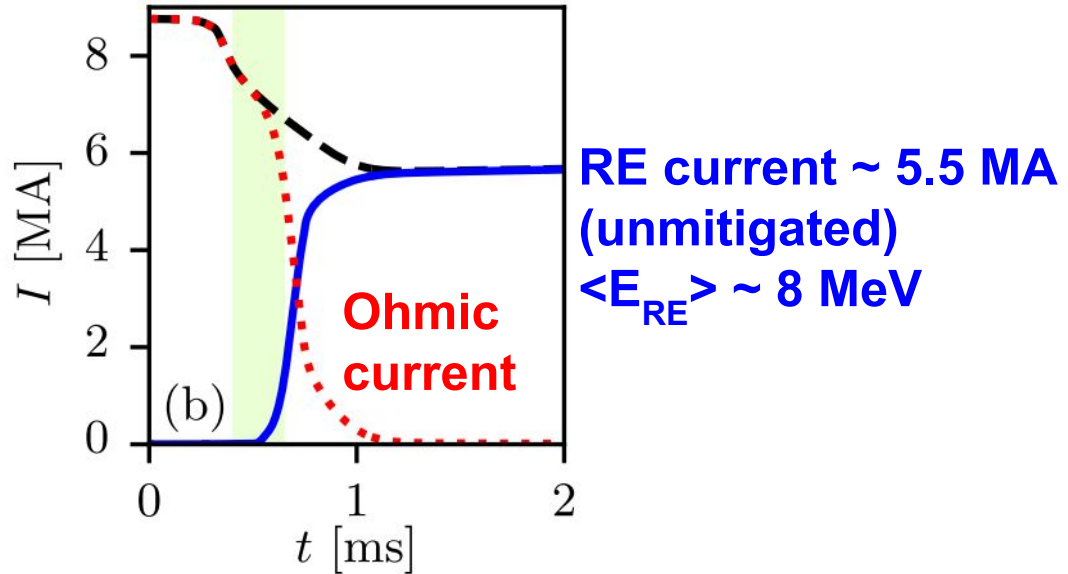
TAEs redistribute alpha slowing-down distribution



Runaway electrons

Disruption heat and electromechanical loads and runaway electrons are a concern for SPARC

full-field DT H-mode	
R_0	1.85 m
a	0.57 m
B_T	12.2 T
I_P	8.7 MA
q_{95}	3.4
κ	1.75
n_{e0}	$4 \times 10^{20} \text{ m}^{-3}$
T_{e0}	>20 keV
P_{ICRH}	11.1 MW
P_{fusion}	140 MW
Q	11
Δt	10 s

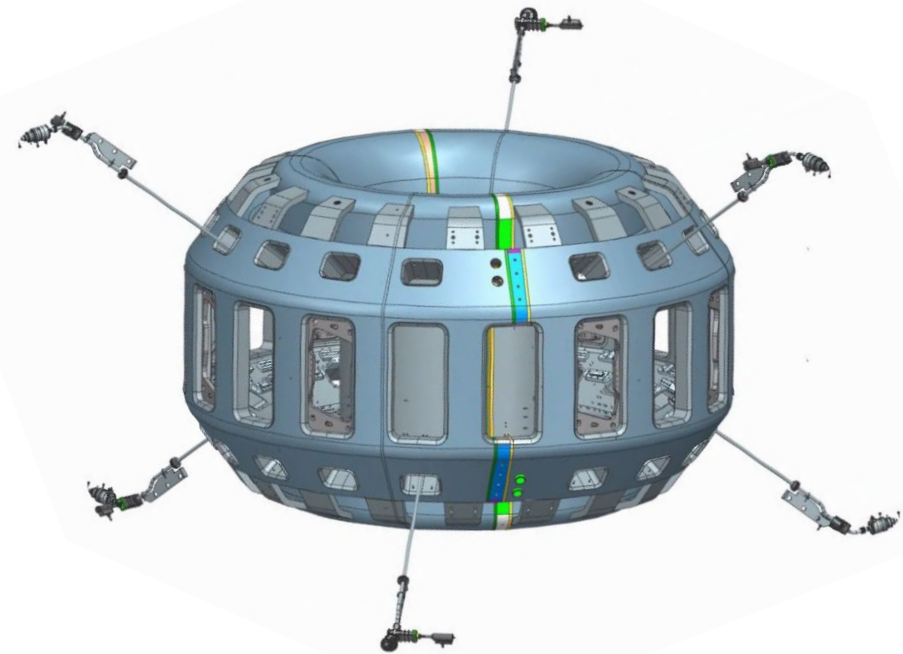


DREAM [Hoppe, Fülöp, Pusztai, Ekmekçi]

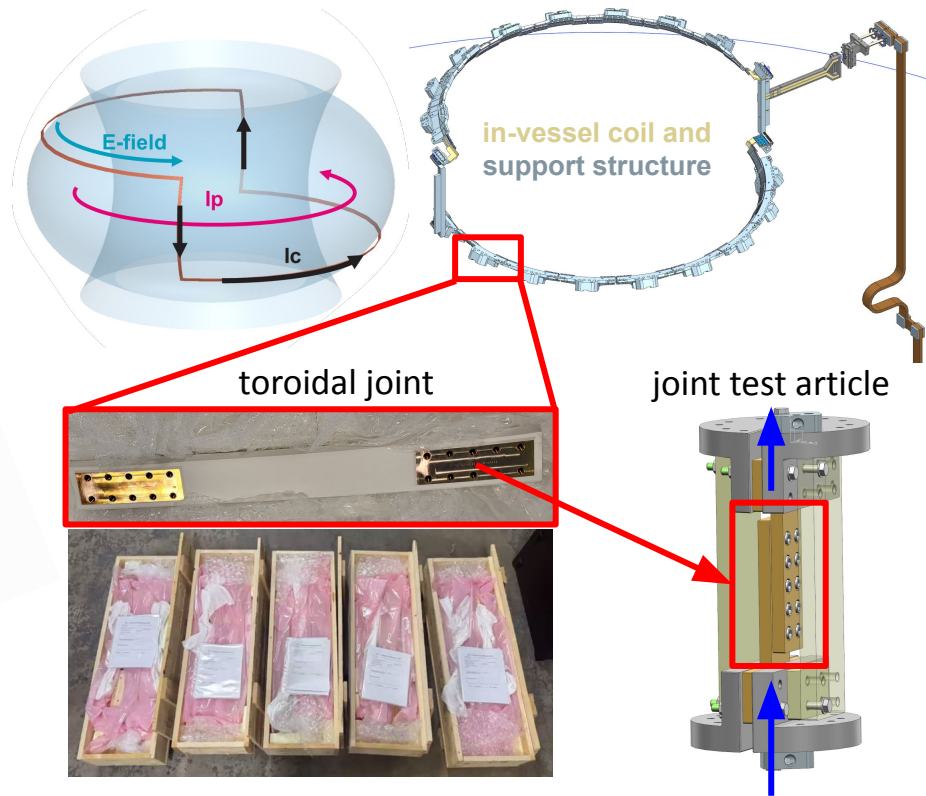
[R.A. Tinguely et al 2021 Nucl. Fusion 61 124003]

Two primary RE mitigation methods

Massive Gas Injection: 10/90 Ne/D2



Runaway Electron Mitigation Coil

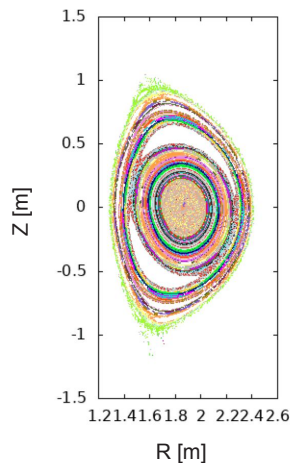


Self-Consistent MHD+RE modeling in M3D-C1 [R Datta]

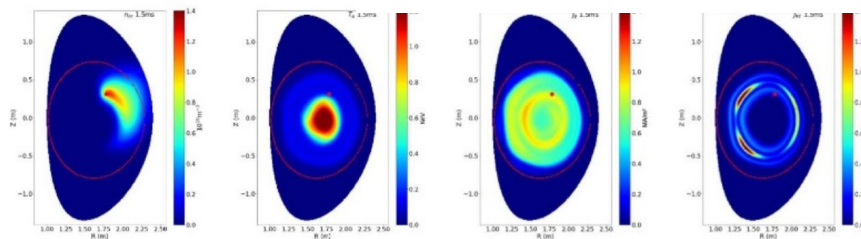
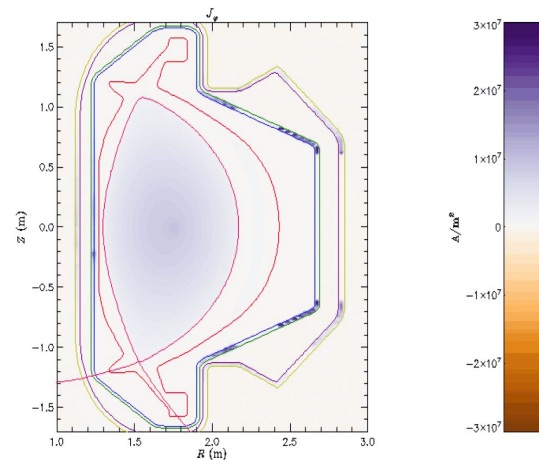
- M3D-C1 couples the MHD equations for the bulk plasma with a **RE fluid model** [Jardin+ 2012]
- Combining **RE generation + MGI + 3D MHD instabilities** in SPARC disruption simulations [Zhao+ 2025]
- Used to model RE + MHD physics
 - DIII-D [Zhao+ 2025],
 - JET [Liu+ 2021],
 - SPARC [Datta+2025,2026]

Magnetic Stochasticity in a SPARC disruption simulation

$t = 0.658$ ms



Plasma current density in a “cold” VDE simulation
 $t = 2.367$ ms

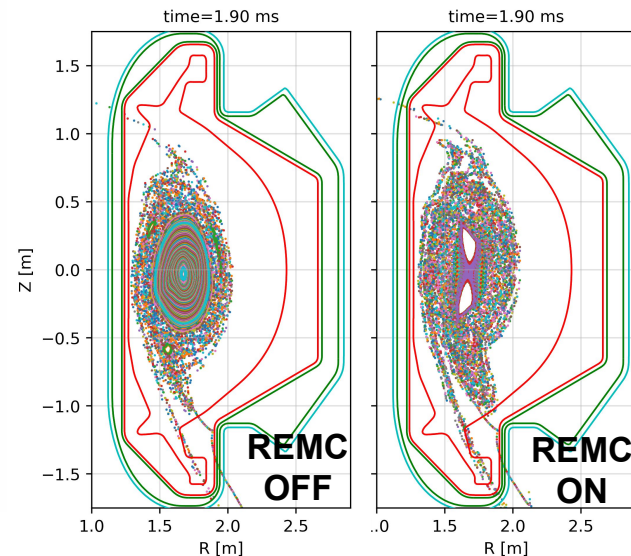
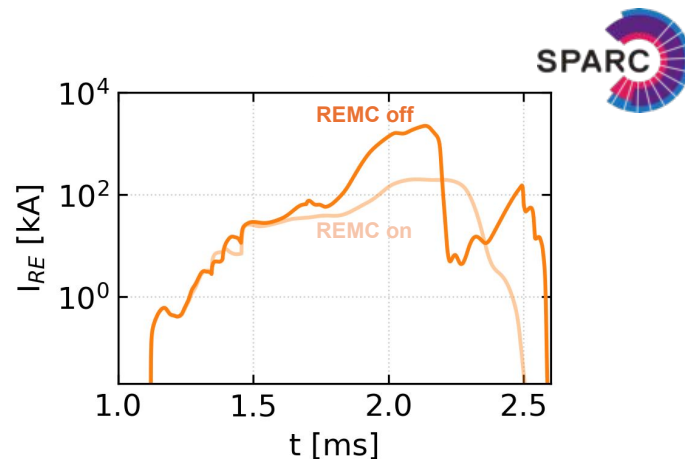
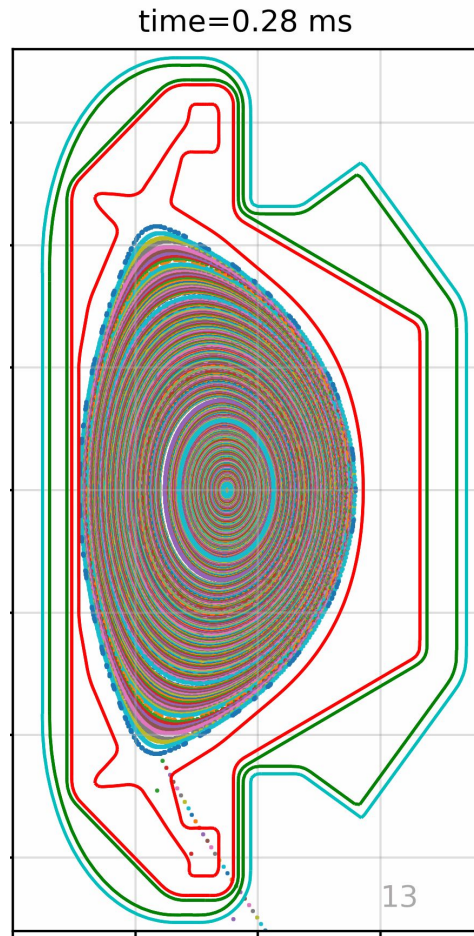


**[Zhao+ 2024]
RE + MHD
Disruption
Simulations of
DIII-D discharge
in M3D-C1**

M3D-C1 + REMC

[R Datta]

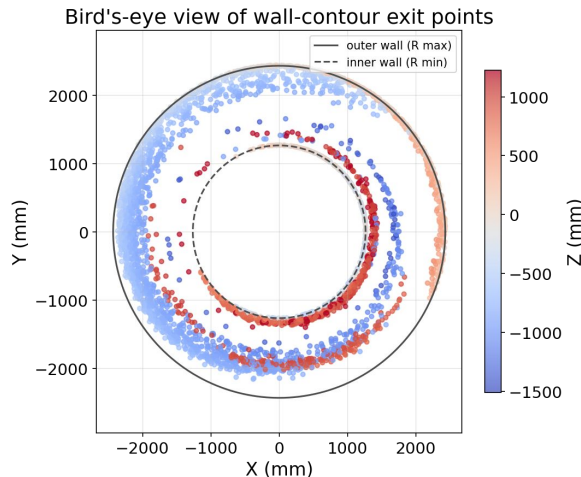
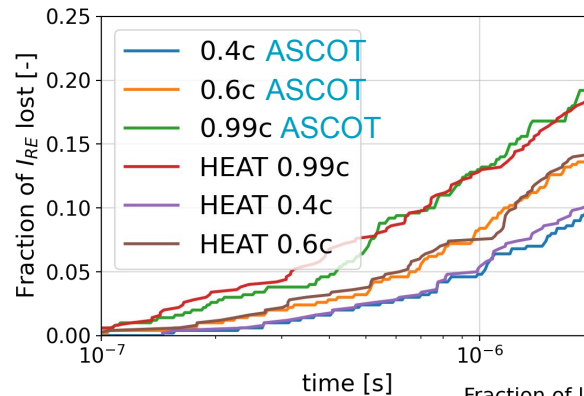
- M3D-C1 simulations combine **3D MHD activity, RE generation and transport, and the REMC** in full midplane disruption simulations
- We capture various important effects such as **TQ MHD activity, Ip-spike, and the 3D post-TQ cold VDE**
- Simulations indicate that the REMC can produce over an order-of-magnitude reduction in the RE current during the CQ by delaying the **re-healing of flux surfaces**



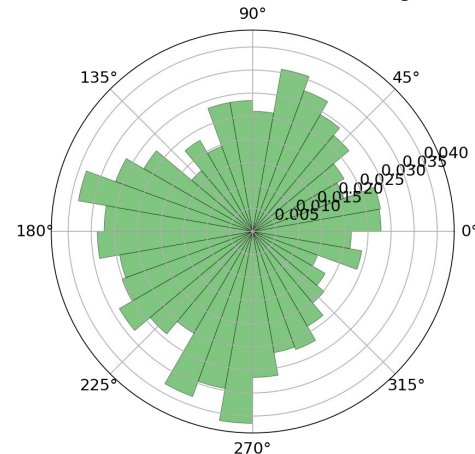
RE transport benchmarking [A Feyrer, A LeViness]



- We connect M3D-C1 simulations to the **HEAT** RE module to simulate RE transport and heat fluxes to realistic CAD
- **HEAT** is being benchmarked against **ASCOT**
 - Good agreement so far
 - **M3D-C1-k** verification efforts also underway
- Ongoing work:
How do REMC fields affect losses and heat flux patterns?
 - Clear $m/n = 1/1$ structure



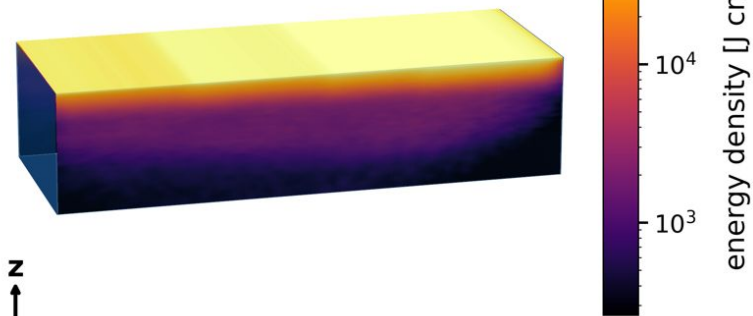
Fraction of losses vs toroidal angle



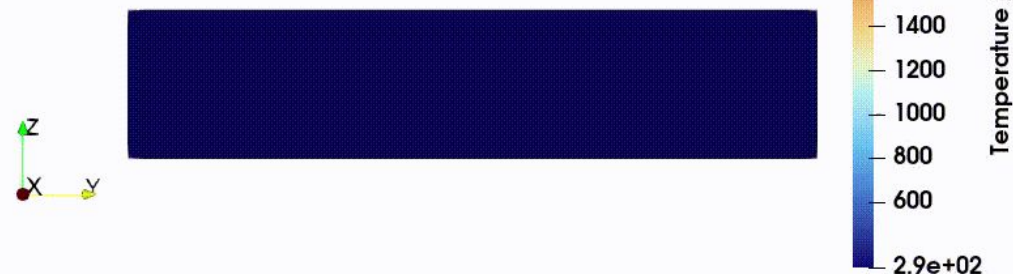
Modeling RE impacts on PFCs [L Singh]

- The material response to RE impacts is investigated through a one-way coupling between
 - **GEANT4** - Monte Carlo charged particle interactions + **volumetric energy deposition**
 - **ELMER** - **thermal response**
- Current objective is to predict the onset of melting resulting from RE impacts on different regions of the first wall
- As an example, a **10 MeV RE beam** depositing 20 kJ over 10 ms on a limiter surface is shown.
 - Shows good agreement with MEMENTO modeling [Rizzi et al PPCF 2026]

GEANT4 with a RE beam depositing 20 kJ in a limiter tile



ELMER temperature evolution over 10 ms



Summary & future work

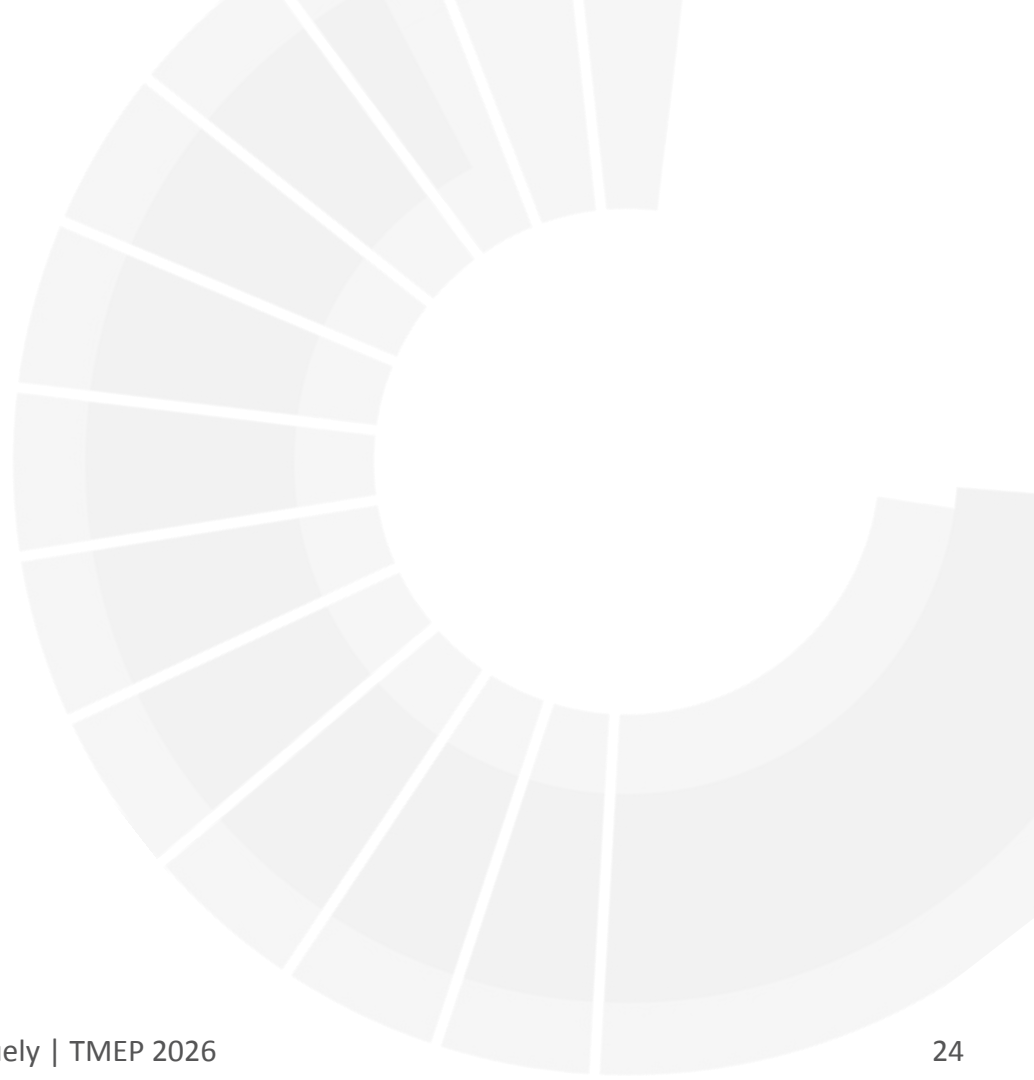
Alphas

- Good agreement found among many codes for alpha-driven MHD and transport
- TAEs may reduce performance slightly, but losses to wall could be more severe
- **Future**
 - Better understand damping among various codes
 - Evaluate AE $\rightarrow$ zonal flow $\rightarrow$ turbulence suppression

Runaways

- MGI + REMC will likely mitigate runaways (at least by 10x)
- **Future**
 - Accurately capture kinetic effects and runaway transport
 - Better understand losses to and impacts on the first wall

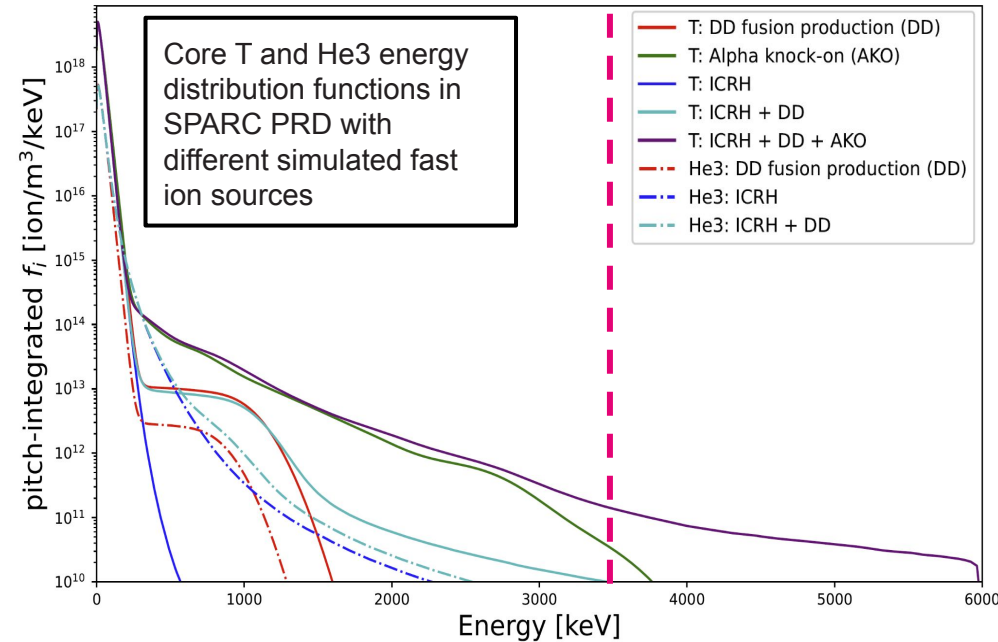
Bonus slides



Coupling fusion + ICRH + nuclear scattering [S Mackie]



- In the SPARC burning plasmas, there are three fast ion mechanisms:
 1. ICRH-resonant species (He3, T, H)
 2. Fusion products (alpha, T, He3, H)
 3. Alpha knock-on scattering (AKO)
- Fast ions generated by nuclear processes modify the plasma dielectric properties, enhancing harmonic ICRH tails
- A numerical workflow has been developed to study these effects and their observable consequences [1]
 - CQL3D: Fokker Planck solver
 - DRESS: nuclear kinematics
 - AORSA: ICRH + quasi-linear diffusion

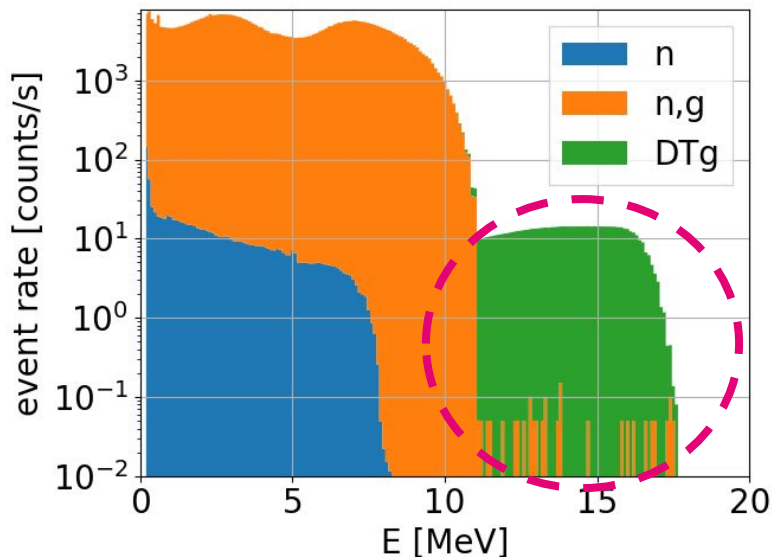


[1] S. Mackie, et al. *Physics of Plasmas* 33, 072513 (2026)

Opportunities for dedicated gamma diagnostics

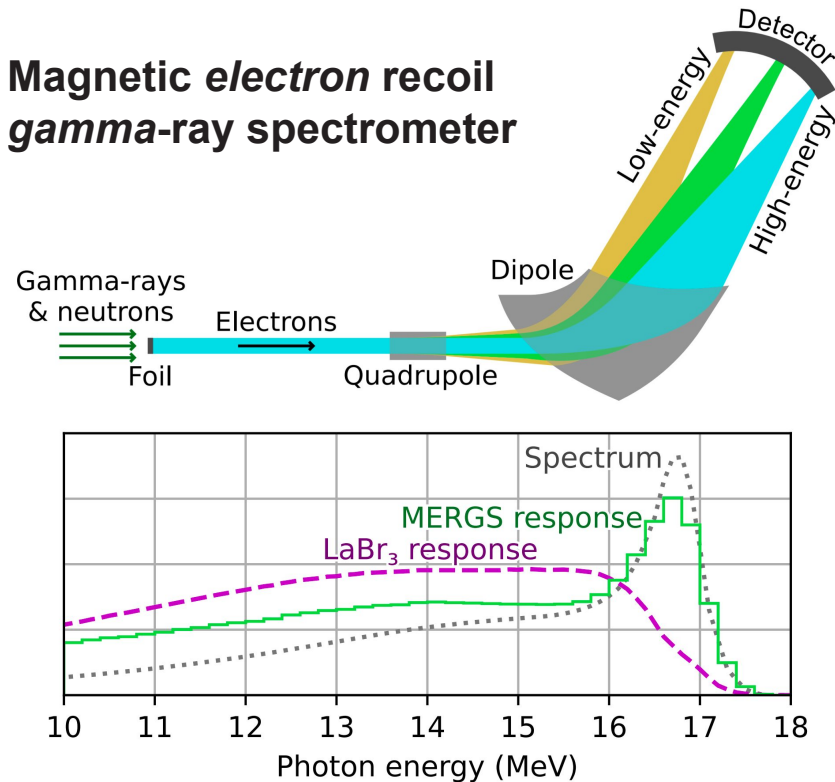


LaBr₃ detectors can measure
DT gamma-rays on SPARC



[E Panontin, in press, 2026]

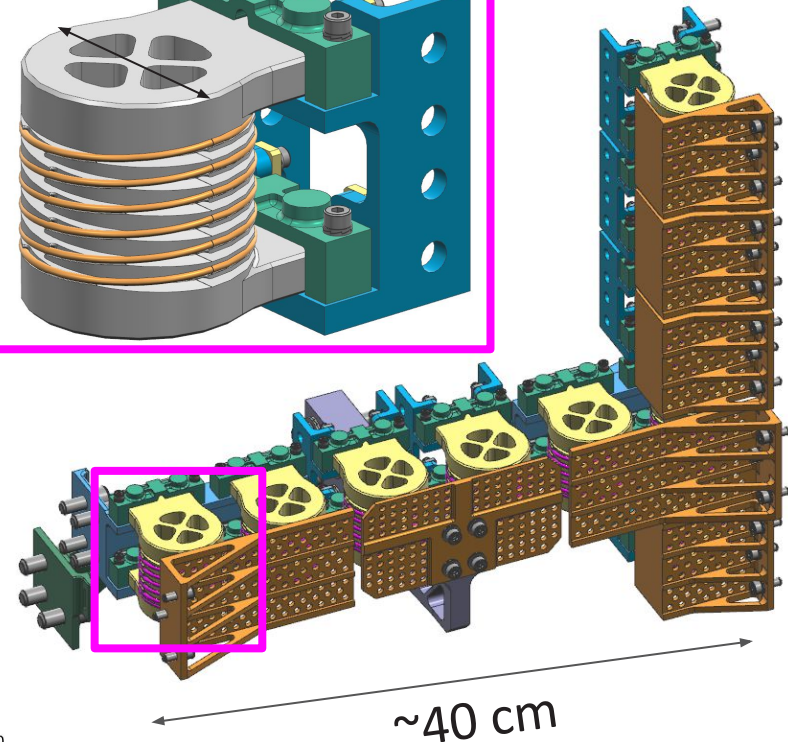
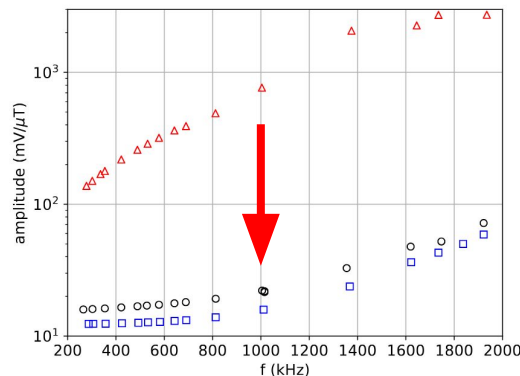
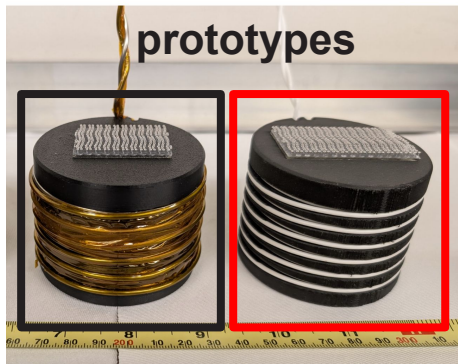
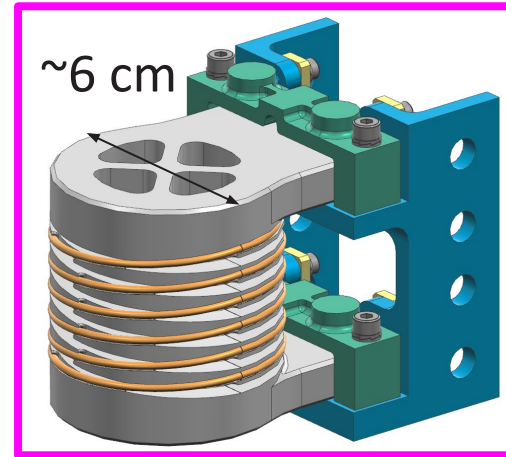
Magnetic *electron* recoil
gamma-ray spectrometer



[J Kunimune, S Huber, N Fensterheim - HTPD 2026]

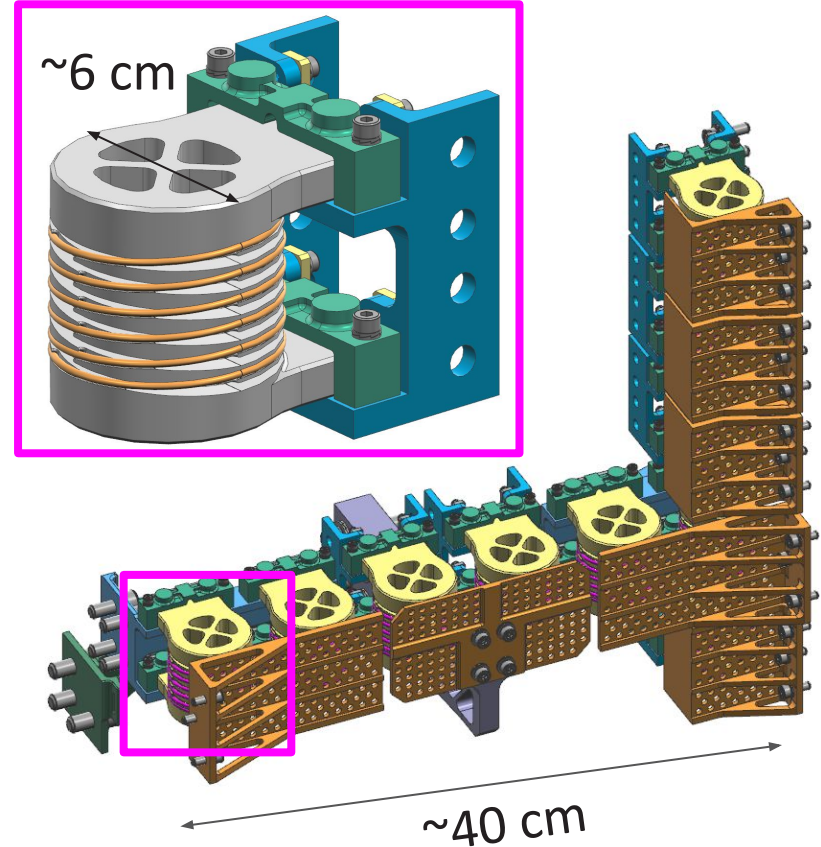
Two sets of Mirnov coil arrays are planned [R Chandra]

- Toroidally separated by $\sim 180^\circ$
- Horizontal and vertical arrays to inform poloidal and toroidal mode numbers
- Mineral-insulated Cable (MIC) + heat shields required for harsh environment
 - Outer conducting sheath
→ $>10\times$ reduced signal level
 - Noise floor dB $\sim 0.1 \mu\text{T}$
 - Characterized from $\sim 5 \text{ kHz}$ to 2 MHz
 - Expecting digitization up to 1 MHz



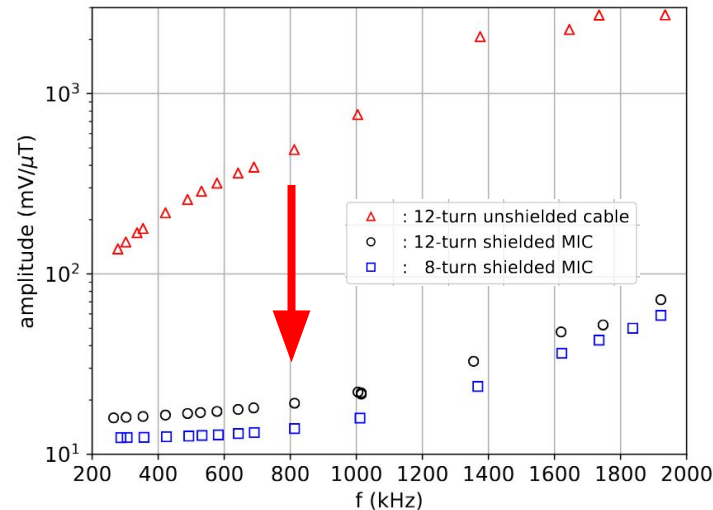
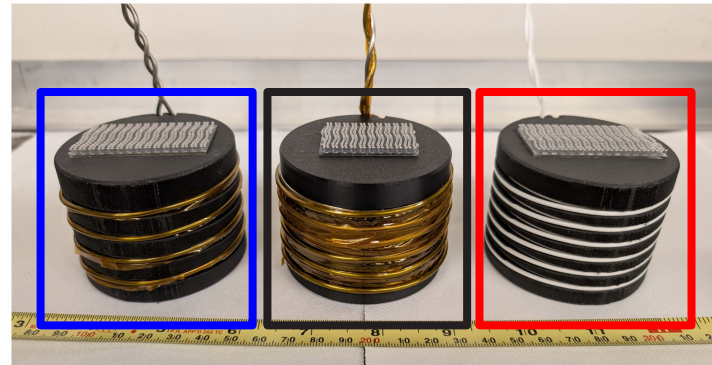
Two sets of Mirnov coil arrays are planned [R Chandra]

- Toroidally separated by $\sim 180^\circ$
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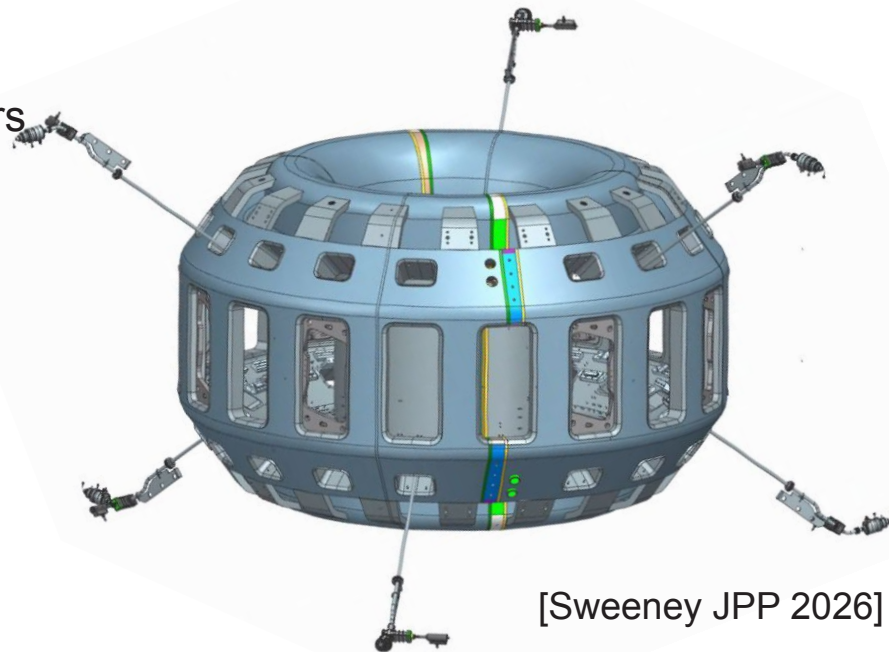
Two sets of Mirnov coil arrays are planned [R Chandra]

- Toroidally separated by ~ 180 deg
- Horizontal and vertical arrays to inform poloidal and toroidal mode numbers
- Mineral-insulated Cable (MIC)
 - and heat shields - required for harsh environment
 - Outer conducting sheath
 - $\sim 10\times$ reduced signal level
 - Noise floor dB ~ 0.1 μT
 - Prototypes characterized from $f \sim 0.2$ -2 MHz
 - Expecting digitization up to 1 MHz



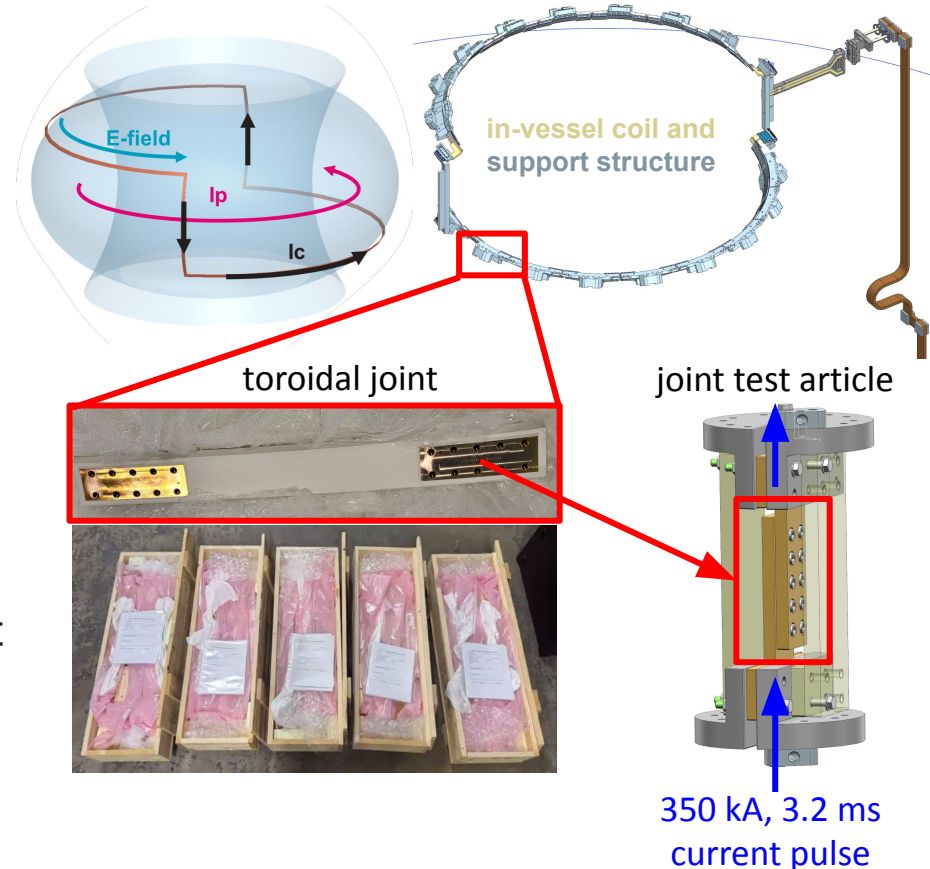
Massive Gas Injection deployed in Campaign 1 (C1)

- Baseline mix: 10/90 Ne/D₂
- 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
- Benign termination is possible, but not planned
 - 6 total valves with arbitrary distribution of 2 gas mixes (one could be pure D₂)
- MGI general characteristics:
 - H₂, D₂, He, Ne, Ar, Kr, Xe
 - 0.5 L plena, 0-6 MPa



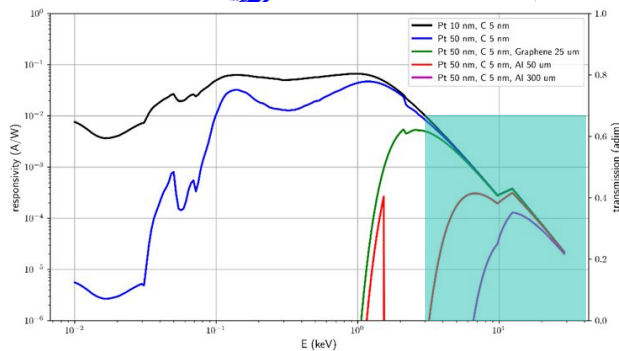
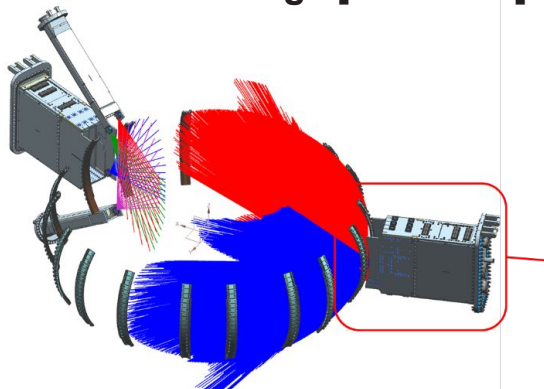
Hardware is arriving for the RE Mitigation Coil

- 19 toroidal conductors machined, now being alumina spray-coated
- Variable resistor delivered, while “slow” switch (~ 50 ms) will not be used
- Open-circuit loop-voltages continue to be a concern $\rightarrow$ evaluating feasibility of closed-circuit REMC
 - EFCCs can mitigate error fields during I_p ramp-up and ramp-down
 - Flat-top 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

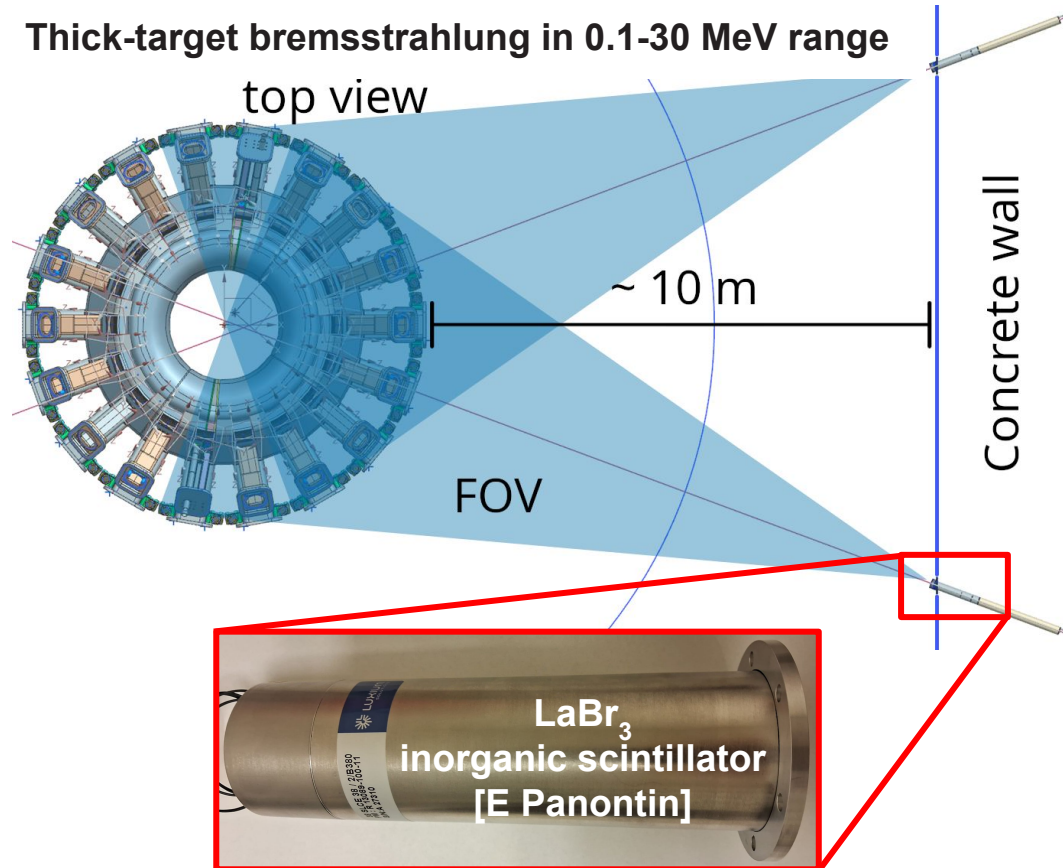


In- and ex-vessel HXR spectrometers for start-up REs

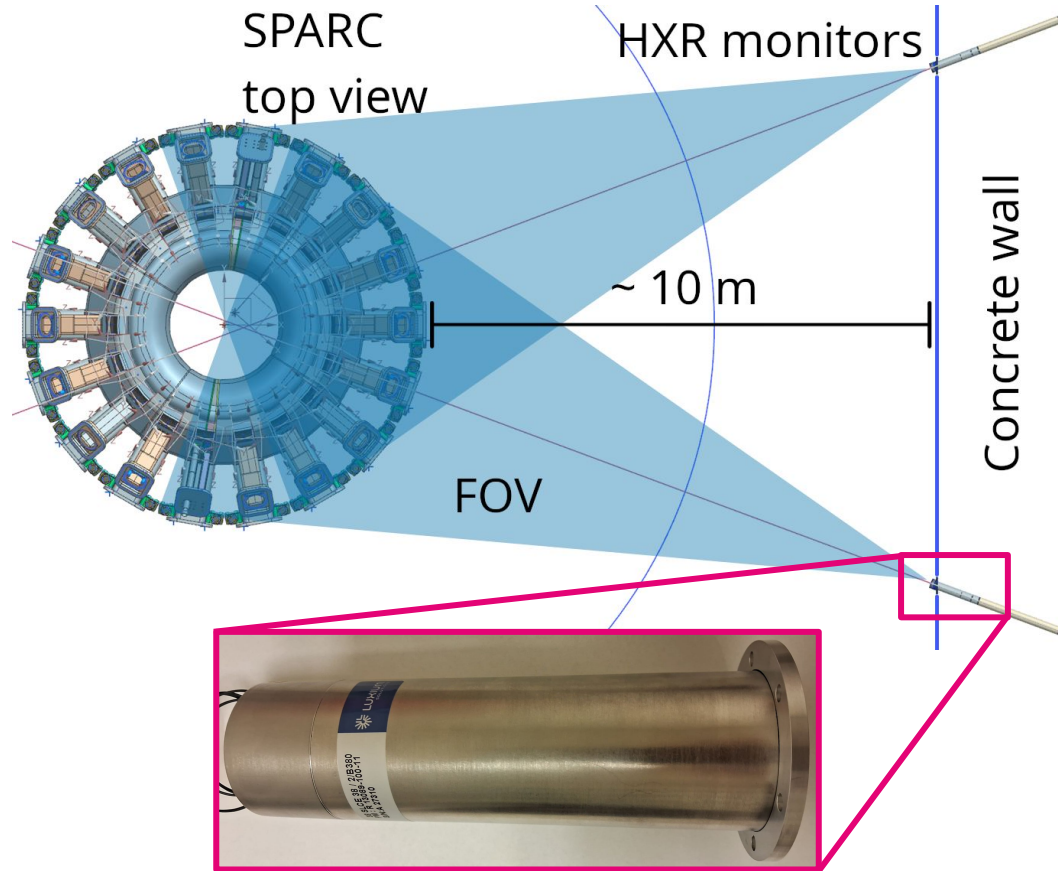
Rad-hard 5 μm diamond CVD sensors
 → in-flight thin-target Bremsstrahlung
 in 10-30 keV range [D Vezinet]



Thick-target bremsstrahlung in 0.1-30 MeV range

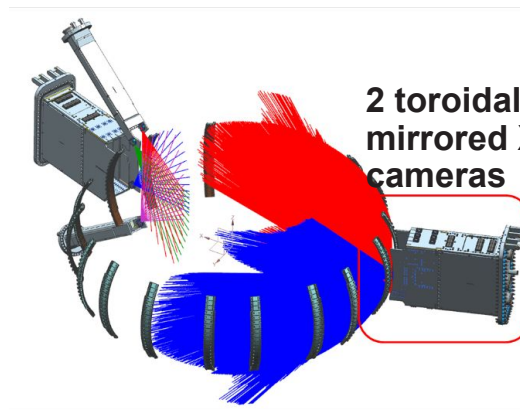


Two ex-vessel HXR spectrometers dedicated to start-up REs

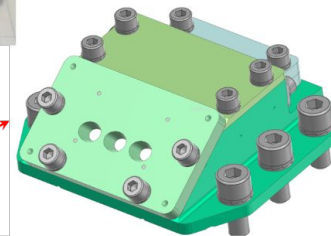
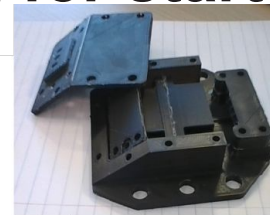
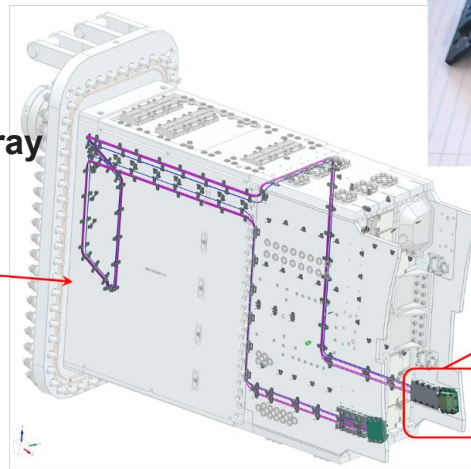


- LaBr_3 inorganic scintillators
 - 1.5" diameter, 1.5" height
 - 3.2% energy resolution @ 662 keV
 - Count rates up to 1 MCps
 - Anode currents < 310 μA
- Wide fields of view
 - co- and counter- I_p
- Data acquisition modes
 - Current (baseline)
 - Spectroscopic

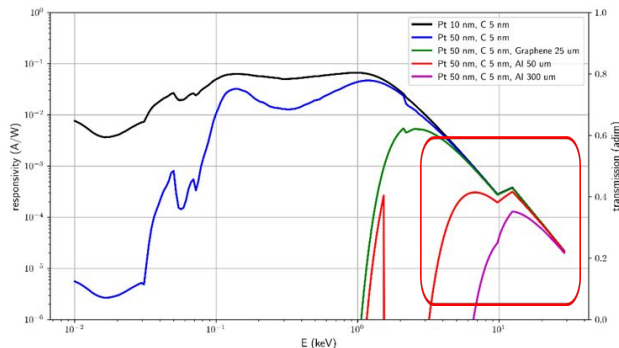
In-vessel SXR arrays are also planned for start-up REs



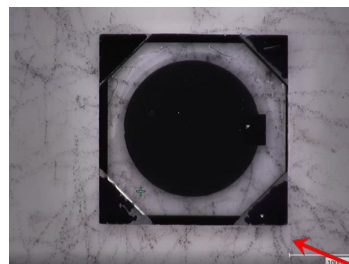
2 toroidally mirrored X-ray cameras



SXR CVD responsivity
bias = 0 V A = $\pm 1.5^\circ$ mm²
active = 2.07 depleted + 2.60 diffusion = 4.67 μ m



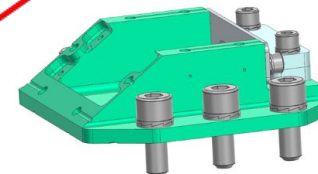
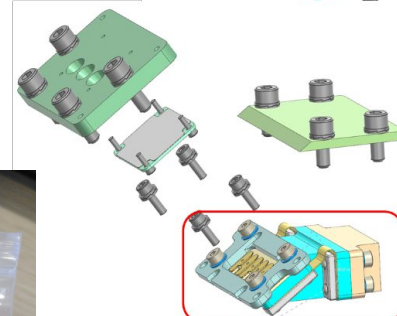
Aiming for in-flight thin-target
Bremsstrahlung in 10-30 keV range



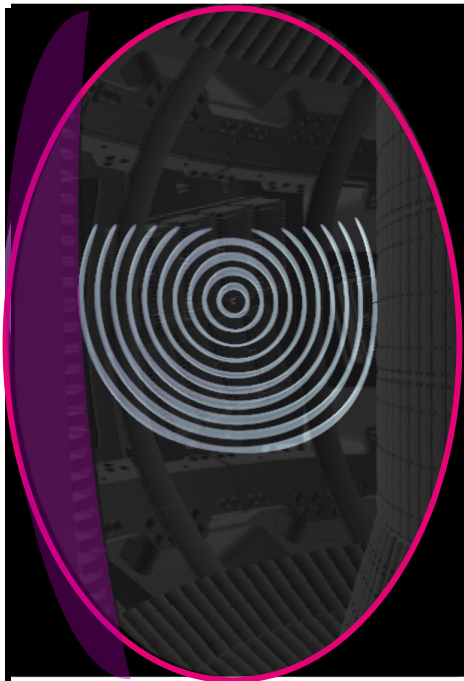
Rad-hard 5 μ m
diamond CVD sensors



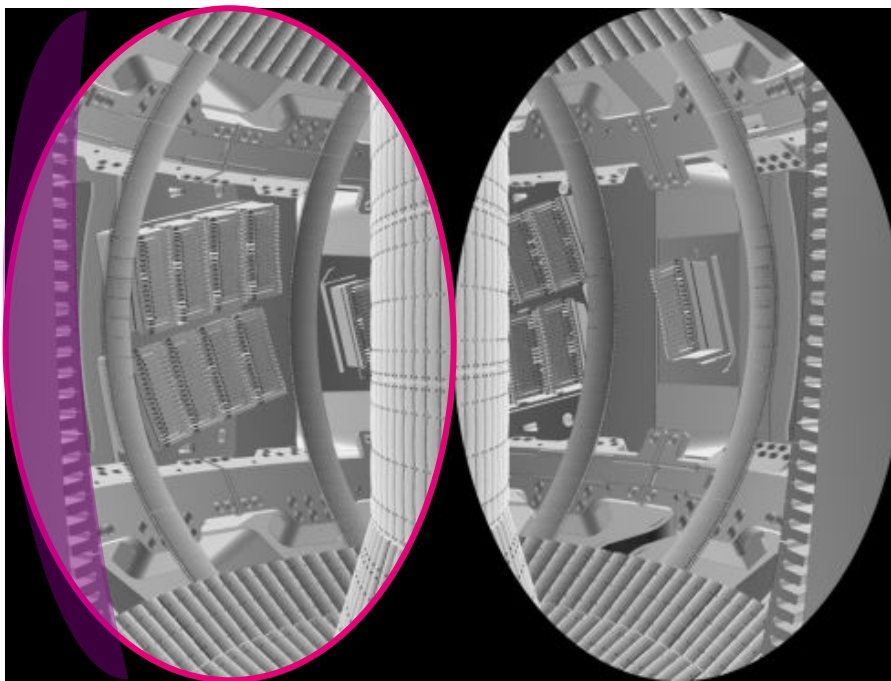
CVD diamond
Size: 3*3*0.3mm
Qty: 100pcs
Date: June 10, 2025



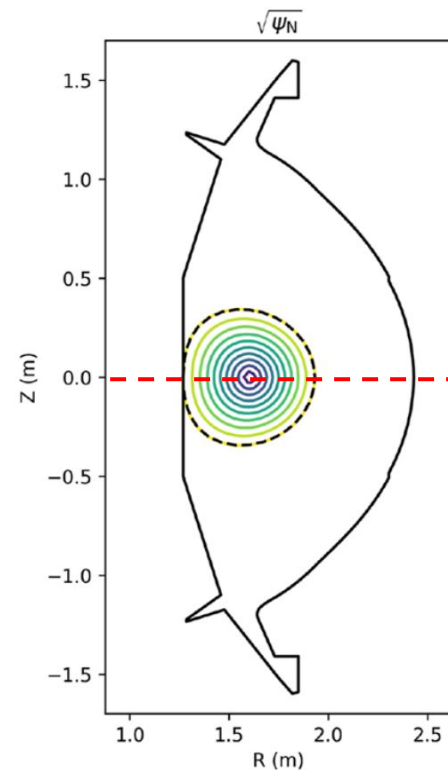
Visible/infrared synchrotron emission can diagnose spatial distribution of start-up REs “in flight”



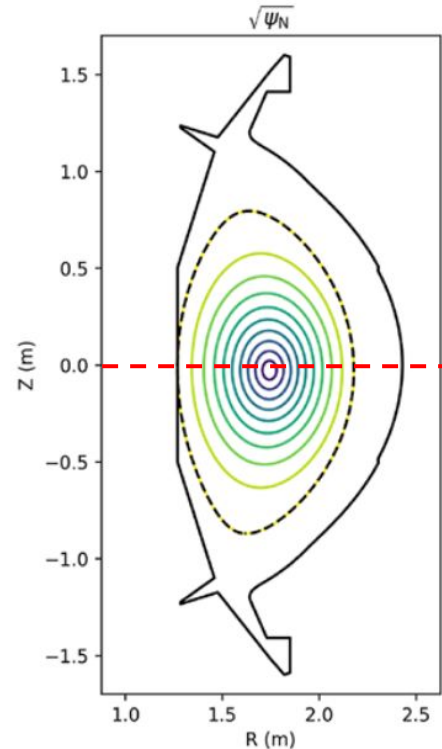
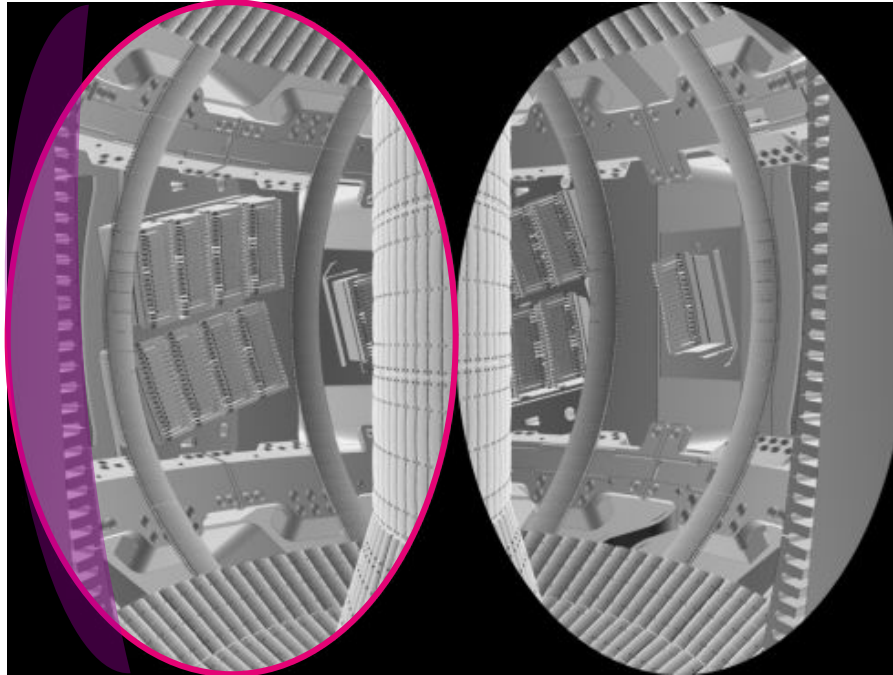
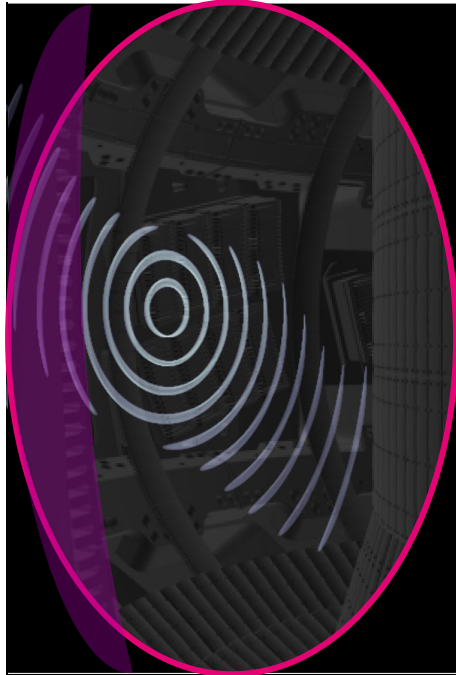
SOFT [Hoppe]



[RA Tinguely et al 2024 RSI]



Visible/infrared synchrotron emission will diagnose spatial distribution of REs “in flight” – VDE, $Z \sim -3$ cm



SOFT [Hoppe]

29 Sep 2026

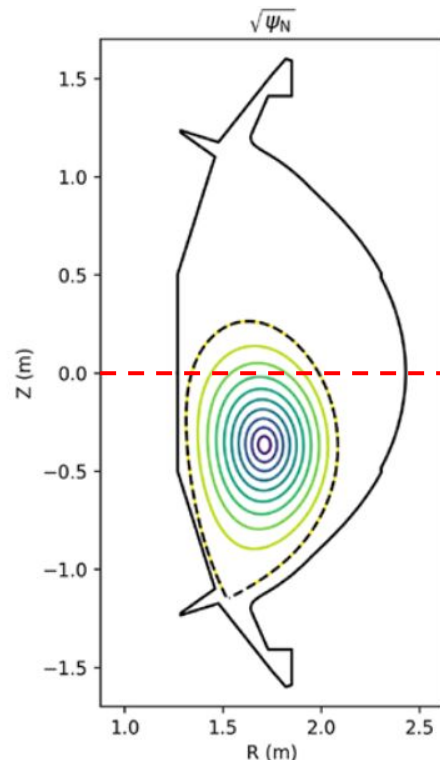
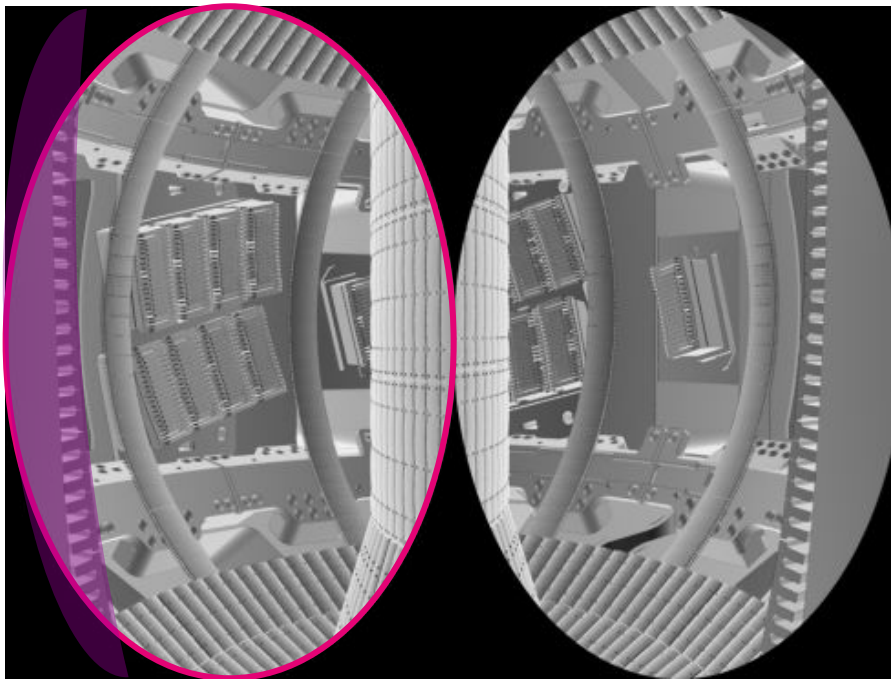
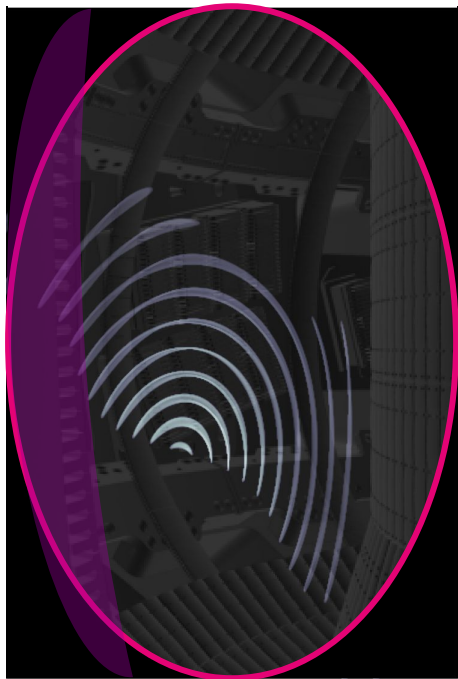
[RA Tinguely et al 2024 RSI]

Tinguely | TMEP 2026

M3D-C1 [Clauser]

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Visible/infrared synchrotron emission will diagnose spatial distribution of REs “in flight” – VDE, $Z \sim -38$ cm



SOFT [Hoppe]

29 Sep 2026

[RA Tinguely et al 2024 RSI]

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M3D-C1 [Clauser]

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Acknowledgements

This work is supported by Commonwealth Fusion Systems, the U.S. Department of Energy FIRE Collaborative “Mitigating Risks from Abrupt Confinement Loss (MiRACL)”, and US DOE CTC SPARC program.

This research uses resources of the National Energy Research Scientific Computing Center (NERSC), a Department of Energy User Facility.



**Commonwealth
Fusion Systems**



MiRACL