Fast ion driven instabilities, transport, and diagnostic opportunities in SPARC

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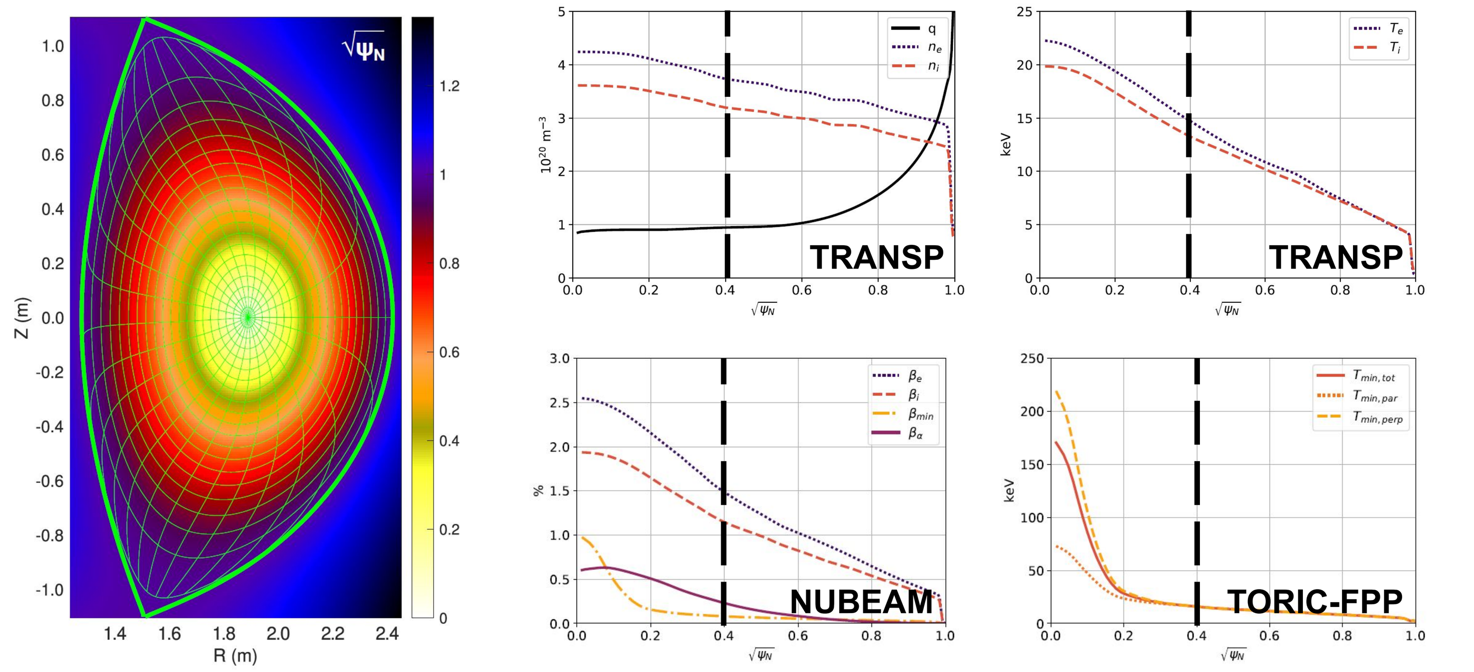
SPARC

RA Tinguely[1]*, J Gonzalez-Martin[2], S Scott[3], M Muraca[1], PJ Bonofiglo[4], L Nichols[1], E Panontin[1], W Burke[1], P Rodriguez-Fernandez[1], S McKanas[3], C Myers[3]

[1]*MIT Plasma Science and Fusion Center* [2]*University of Seville* [3]*Commonwealth Fusion Systems* [4]*Princeton Plasma Physics Laboratory* **rating@mit.edu*

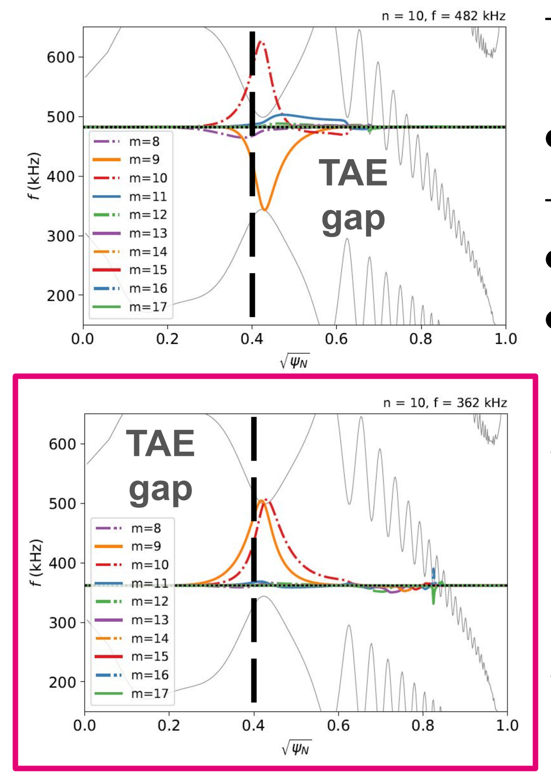
SPARC Primary Reference Discharge

- High-field, compact tokamak under construction in Devens, MA
- B_0 = 12.2 T, I_P = 8.7 MA, R_0 = 1.85 m, a = 0.57 m [1]
- DT fusion power ~111 MW → alpha power ~22 MW [2]
- ICRH auxiliary power ~11 MW, 5% He3 minority species [3]



Linear TAE stability [4] with NOVA-K [5]

$$n^* \approx \frac{Z_{FI} e B r_m}{m_{FI} q^2 v_\parallel}$$



- Alfven velocity on-axis v_{A0} ~ 9e6 m/s
- Alpha birth velocity $v_{\alpha 0}$ ~ 13e6 m/s

→ Alphas and He3 fast ions (>1 MeV) could destabilize Toroidal Alfven Eigenmodes (TAE)

- "Most unstable" tor. mode number: n* ~ 8-18

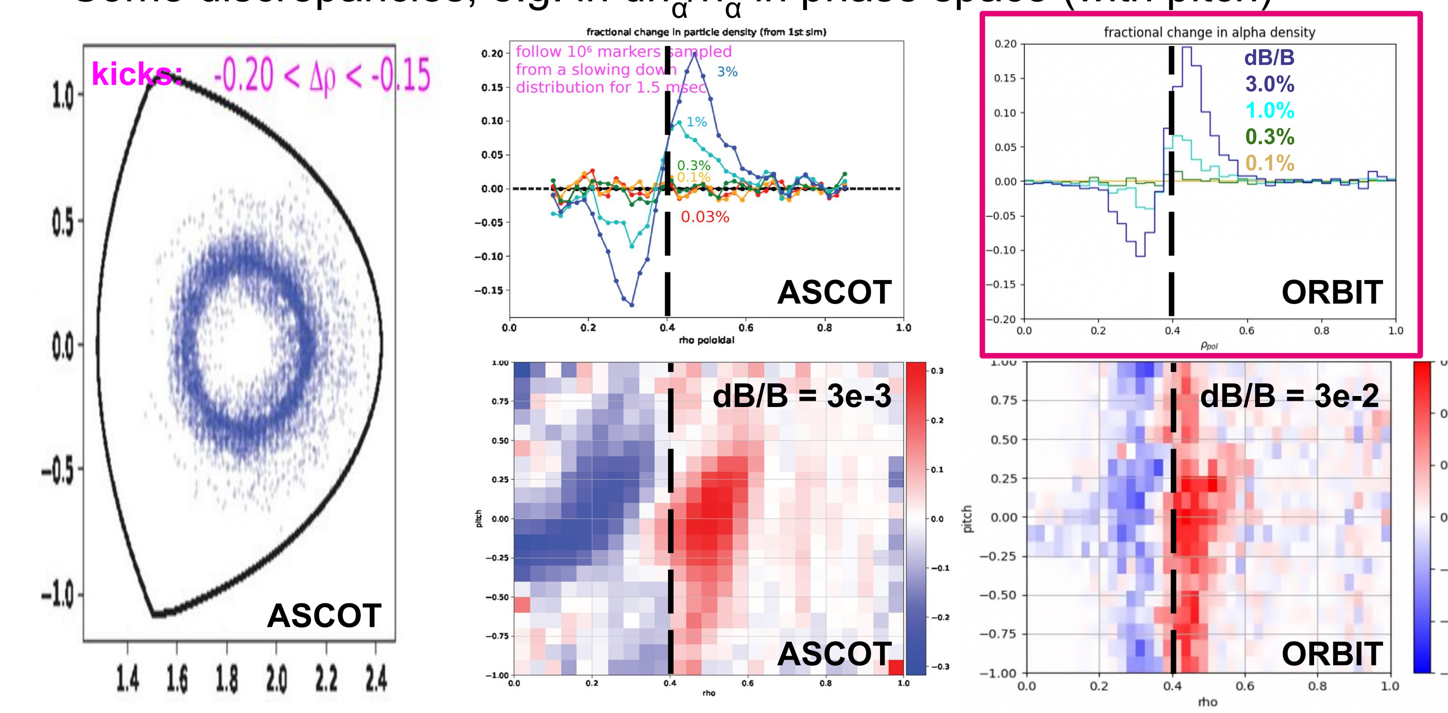
→ Scan n = 5, 10, 15, 20 → **n = 10, 15 unstable**

- Mode localized near q ~ 1, $\sqrt{\psi_N} = \rho_{pol}$ ~ 0.4
- See [A] for complementary FAR3D analysis

n	5		10		15		20	
f (kHz)	292	350	362	482	361	481	371	487
Continuum	−0.06	−0.01	−0.02	−0.00	−0.02	−0.01	−0.00	−0.00
Radiative	−2.69	−0.29	−1.35	−0.00	−0.95	−0.01	−2.63	−0.03
Electron collisional	−0.01	−0.01	−0.02	−0.01	−0.01	−0.01	−0.01	−0.01
Electron Landau	−0.08	−0.13	−0.01	−0.01	−0.01	−0.02	−0.00	−0.01
Ion Landau	−0.02	−0.08	−0.08	−0.03	−0.05	−0.02	−0.08	−0.01
He3 fast ions	−0.17	−0.07	−0.19	−0.06	−0.17	−0.07	−0.35	−0.11
Alphas	+0.06	+0.01	+0.61	+0.29	+0.79	+0.25	+0.71	+0.13
Total w/o FI	*−2.86*	*−0.44*	*−1.48*	*−0.05*	*−1.04*	*−0.06*	*−2.72*	*−0.06*
Total w/ FI	**−2.98**	**−0.49**	**−1.05**	**+0.18**	**−0.42**	**+0.12**	**−2.35**	**−0.04**

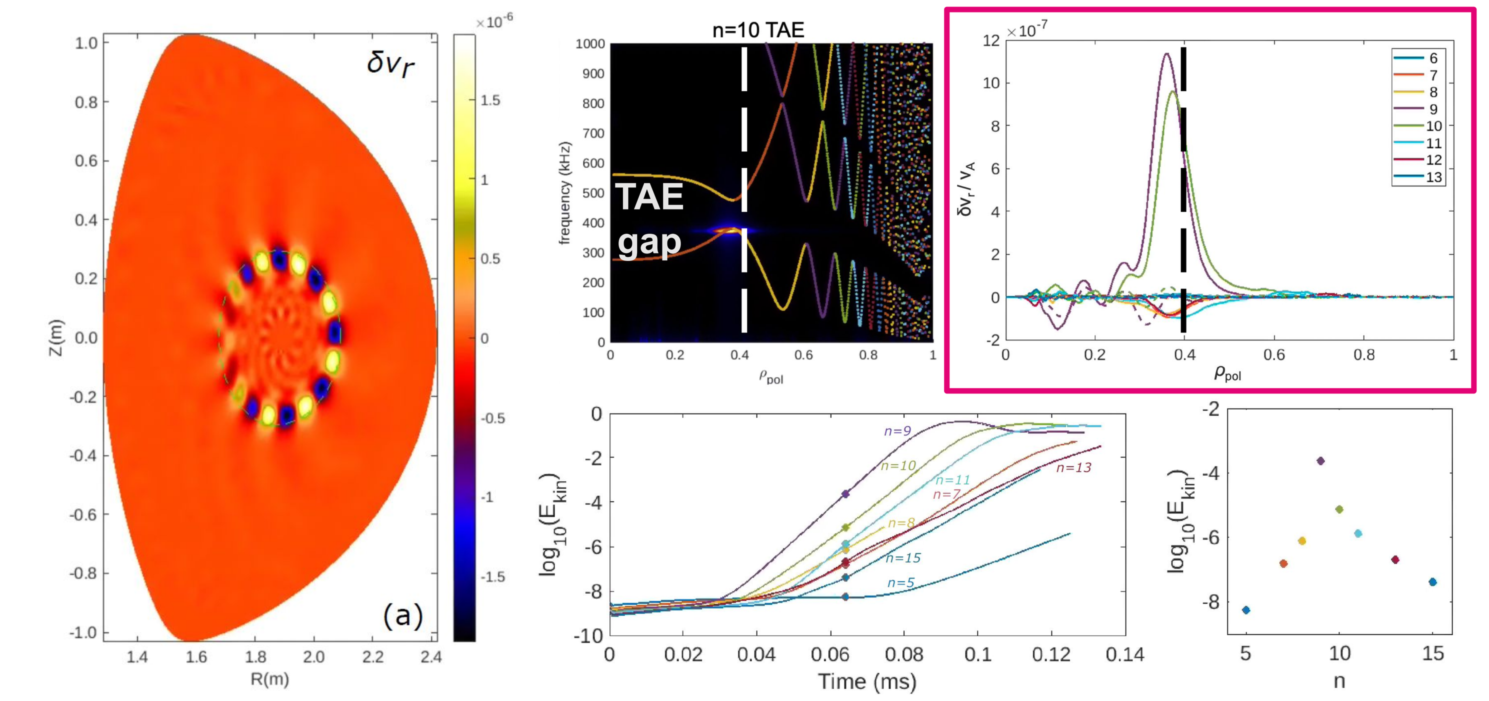
Alpha transport with ORBIT [6] & ASCOT [7]

- n = 10 TAE input from NOVA-K, with scan in amplitude dB/B
- Guiding center motion (GC) in ORBIT; GC and gyro-orbit in ASCOT
- Good agreement, e.g. in fractional change of alpha density profiles
- Some discrepancies, e.g. in dn_α/n_α in phase space (with pitch)



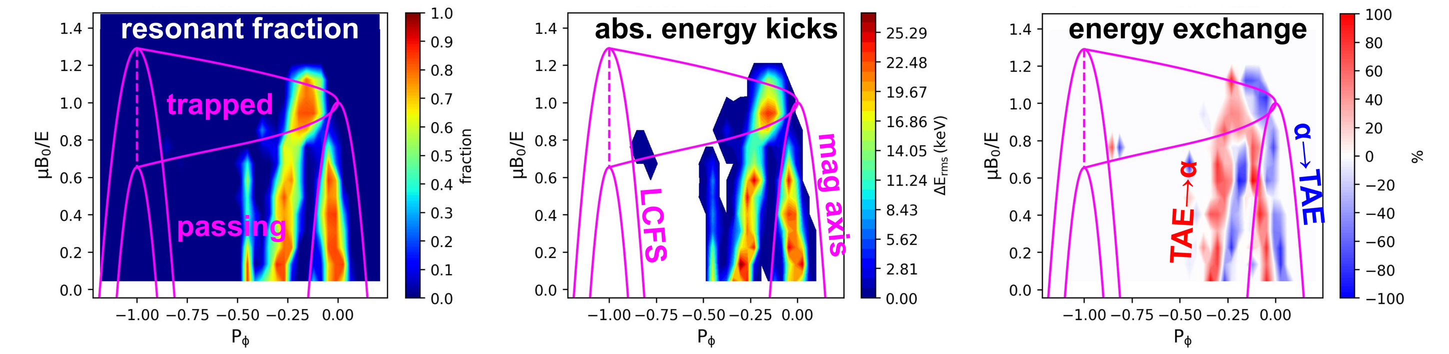
Nonlinear TAE stability [4] with MEGA [8]

- Identify same low-frequency (even) n = 10 TAE as NOVA-K
- Marginally unstable: (only) alpha drive +0.66%, intrinsic damping –0.58%
- Most unstable mode number spectrum peaks at **n = 9**
- Saturation amplitude: **dB/B ~1e-4 to 1e-3** for 2.5x alpha drive



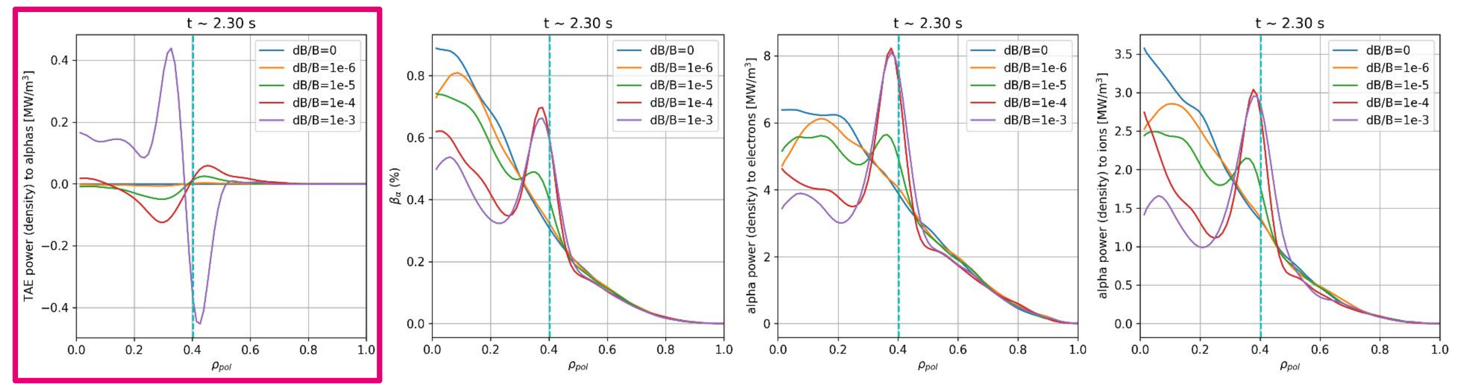
n = 10 TAE impact on plasma performance

- ORBIT "kicks" in phase space [9] → validated in NSTX [10], JET [11]
- Plots show alpha-TAE interaction for $v_\alpha = v_{A0}$ ~ 9e6 m/s (E_α ~ 1.7 MeV)
- Because TAE amplitude is unknown, scan dB/B = 1e-6 to 1e-3



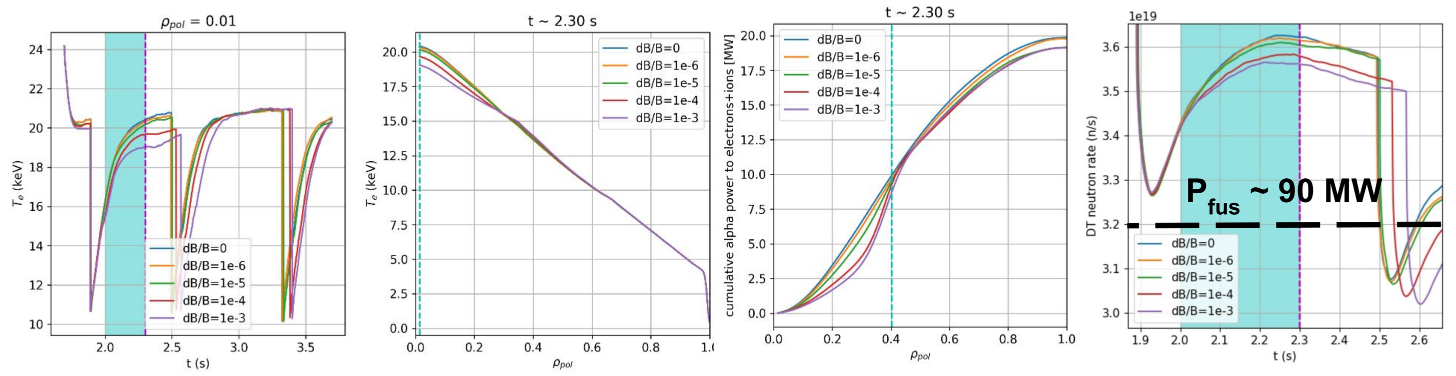
Interpretive TRANSP [12] modeling → fixed n(r), T(r)

- Apply TAE from t = 2 – 2.3 s, ~ alpha slowing down time O(250 ms)
- Caution: this is not self-consistent as TAE is always "driven"
- β_α decreases in the core, but increases near TAE location ρ_{pol} ~ 0.4
- A similar story for alpha power to electrons and ions



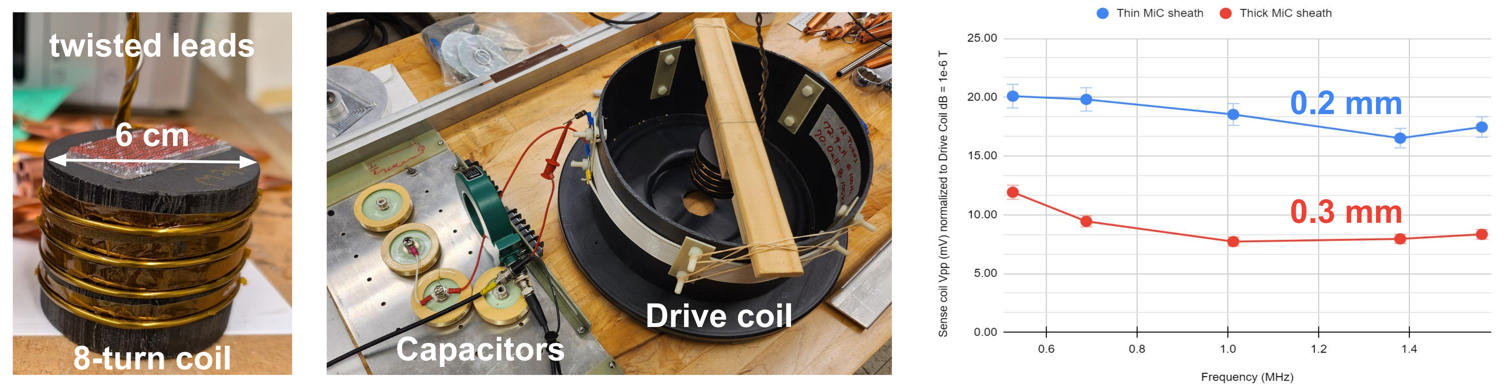
Predictive TRANSP modeling → variable n(r), T(r)

- TGLF-SAT2 EM → no direct effect of FI on turbulence, only indirect
- n_e, n_i, T_i relatively unaffected, but noticeable decrease in ΔT_{e0} ~ 1.5 keV
- Sawtooth period increases with dB/B→FI stabilization in Porcelli model
- Cumulative alpha power to ions + electrons consistent with β_α drop
- **Total DT fusion power only decreases by ~2 MW! (~2%)**



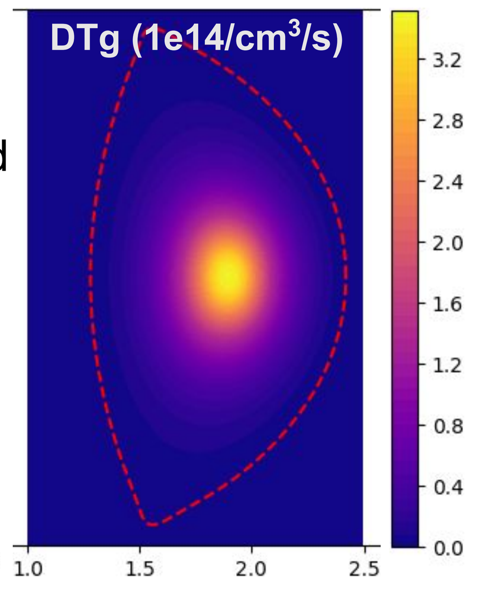
High-frequency Mirnov coil prototyping

- Nominal coil geometry: diameter ~6 cm, height ~4 cm, 12 turns
- 2 mm-diameter mineral insulated cable (MiC) with conducting sheath [B]
- Relatively flat frequency response for 0.5 – 1.5 MHz (EAEs < 2 MHz)
- Signal reduced ~50% by (i) 50%-thicker sheath, (ii) 100 ft long leads

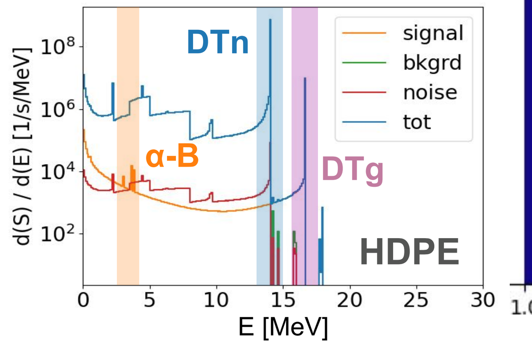


Gamma ray spectroscopy opportunities

- Independently measure P_{fus} [C] with DT-gammas
- D-He3 gamma can inform ICRH in DD plasmas
- α-B10 gammas may be swamped by n background
- HDPE vs LiH shielding under assessment [D]



Reaction	Energy (MeV)
T(D,g)^{5}He	13.5, 16.7
^{10}B(α,pg)^{13}C	3.09, 3.68, 3.85
D(^{3}He,g)^{5}Li	16.4



Diagnostics [E,F]	Opportunities	Challenges
Interferometry (AEs)	dn_e/n_e > 4e-5 → dB/B > 1e-4	n < 10, f < 1 MHz
Soft X-Ray (AEs)	full poloidal coverage, m < 10	dB/B > 1e-3, f < 100 kHz
Imaging (FI loss)	resolution ~ 1 mm – 1 cm	dT < 50 C, low SNR?
Spectroscopy (FIDA)	spectral range 350-950 nm	passive, edge-localized, SNR?
Neutral Particle Analyzer	utilize toroidal B-field w/in port	passive, low SNR?
Fast Ion Loss Detector	large fluxes	B ~ 9 T → r_L < 3 cm

To be explored: Electron Cyclotron Emission [G], Doppler Back Scattering, Reflectometry
Also see: Collective Thomson Scattering [https://doi.org/10.48550/arXiv.2408.13669]

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References

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[11] AA Teplukhina PPCF 2023
[12] J Breslau TRANSP 2018

This conference

[A] L Nichols NP12.00105 Wed AM
[B] E Fox-Widdows NP12.00098 Wed AM
[C] S Mackie TO06.00006 Thu AM
[D] E Panontin GP12.00121 Tue AM
[E] ML Reinke NP12.00098 Wed AM
[F] V Nikolaeva NP12.00099 Wed AM
[G] M Kopanski GP12.00114 Tue AM