



Alpha particle physics in ARC burning plasmas

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Commonwealth Fusion Systems

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 - Alpha-induced torque
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- Summary & Future Work



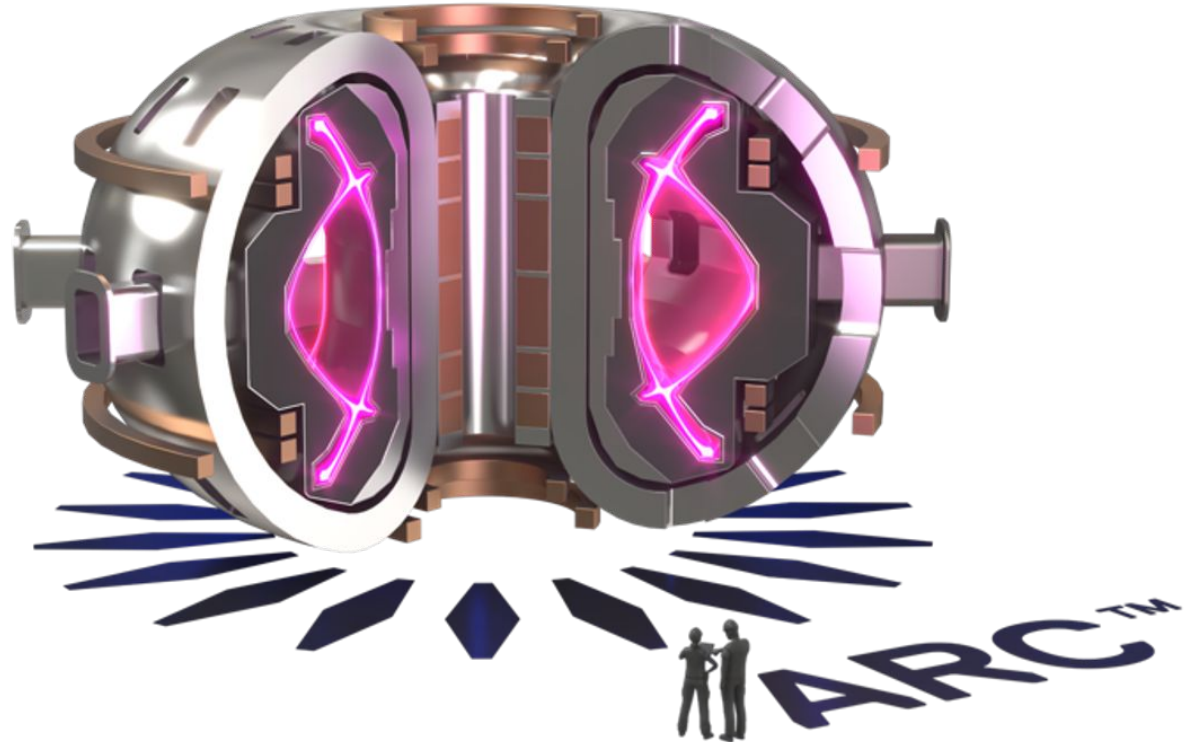
ARC overview & progress

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ARC V3A described in 2026 physics basis papers



- ARC: first fusion power plant, aiming to put electricity on the grid
- $R_0 = 4.62$ m
- $a = 1.18$ m
- $B_0 = 11.4$ T
- $I_p = 12.0$ MA
- $P_{fus} = 1.13$ GW
- $Q = 51$
- 400 MW net electric

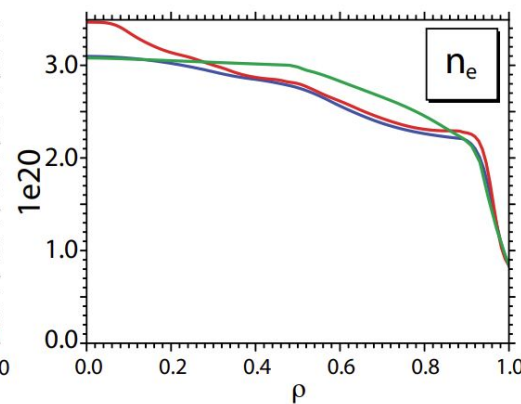
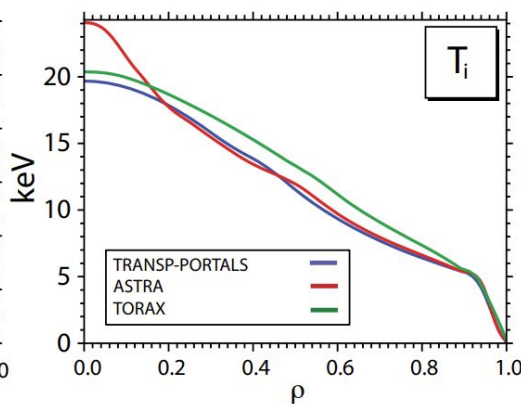
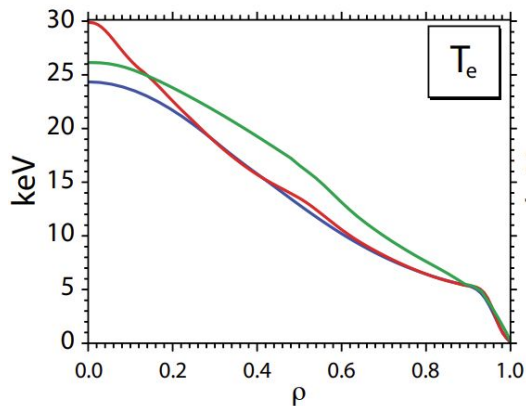
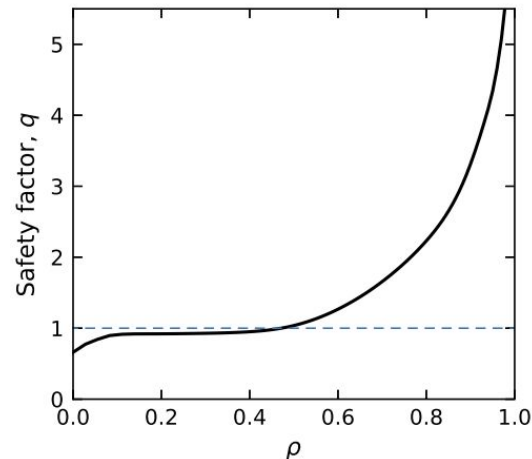


ARC V3A described in 2026 physics basis papers



- Kinetic profiles calculated with three different solvers^[1]
 - TRANSP-PORTALS version used here except where otherwise stated
 - TGLF used for core transport
 - EPED used for the pedestal
- Heated with up to 50 MW ICRH

Profiles & equilibria for V3A available online: <https://zenodo.org/records/19498373>



ARC site determined: Chesterfield County, Virginia



- In the heart of one of the fastest growing electricity markets
- Access to interconnection to the grid
- Access to ports and other transportation to support supply chain
- Signed power purchase agreements with first two customers — Google and Eni
- Operation early 2030's



EP physics in ARC will be different than any device before



- Strongly burning plasma → alphas determine plasma performance
- >200 MW power carried by alphas
 - Can drive TAEs and zonal flows
- Comparably compact device w/ small outer gap → lost alpha power highly spatially concentrated
- Near steady-state operation → need to withstand alpha loading of first wall, consider not just heat loads but long-term erosion/sputtering
- Very limited diagnostic set → predictive capabilities important!



Neoclassical & ripple alpha losses in ARC

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Simulation methods



- ASCOT5 ^[1] is a Monte Carlo orbit-following code widely used for simulating EP physics in tokamaks
- Magnetic field creation:
 - 3D ripple fields, created from perfectly aligned TF coils or misalignments selected from normal distribution with chosen σ
 - Misalignments $> 1.5 \sigma$ discarded
 - Vacuum field assumption (no plasma contribution to B_ϕ)
 - Created by translating and rotating a high-res field from a single coil “pancake”
- Simulation parameters:
 - # markers: 10k (misaligned coils) - 100k (aligned coils)
 - Evenly distributed in real & velocity space outside $\rho_{\min}$ of 0.6 or 0.7
 - Born at 3.52 MeV & weighted by normalized local fusion rate
 - No radial electric field, MHD
 - Full-orbit mode, 10 steps/orbit
 - Followed for 80 - 200 ms, or until LCFS or thermalized
 - 80 ms determined to be long enough to capture 99.9% of lost power

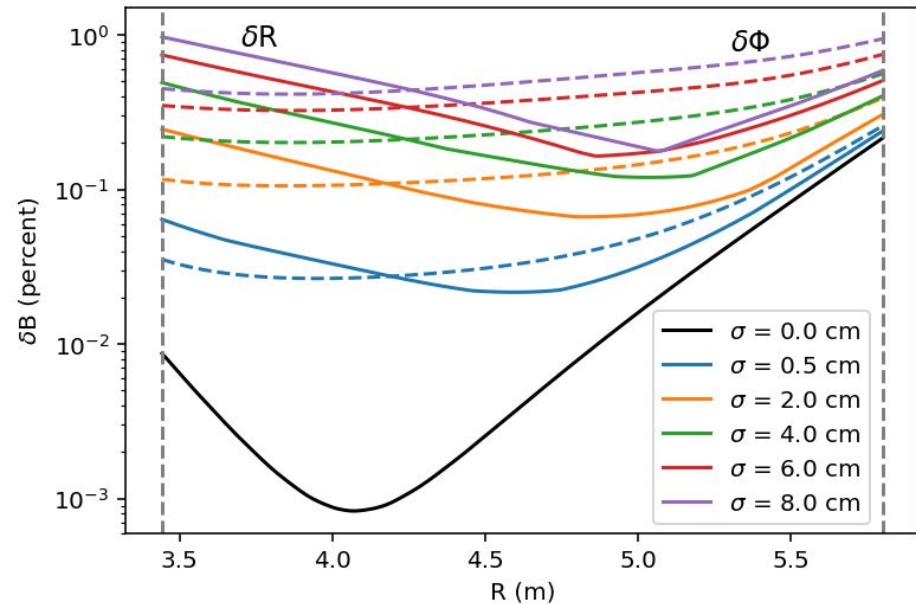
[1]: Varje, PhD thesis, Aalto University 2022



Ripple under 1% even with large TF misalignments

- Considered radial and toroidal TF misalignments
- TF misalignments σ of up to 8 cm were allowed
 - Such large misalignments would preclude ARC assembly
 - Actual SPARC TF tolerances are only ~ 1 -2 mm
- Even with large misalignments, ripple at the midplane remains below 1%
- Calculated as

$$\delta B(R, Z) = \frac{B_{\max}(R, Z) - B_{\min}(R, Z)}{B_{\max}(R, Z) + B_{\min}(R, Z)}$$



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Power loss under 2% with all but worst misalignments

- “Loss” calculated as fraction of alpha power crossing the LCFS in full-orbit mode; most conservative assumption
- Simulation to a 2D wall with aligned TF coils gave a power loss to the wall of 0.57%, only $\frac{2}{3}$ of the 0.87% crossing the LCFS
- Even with unreasonably high TF misalignments, alphas in ARC are well-confined

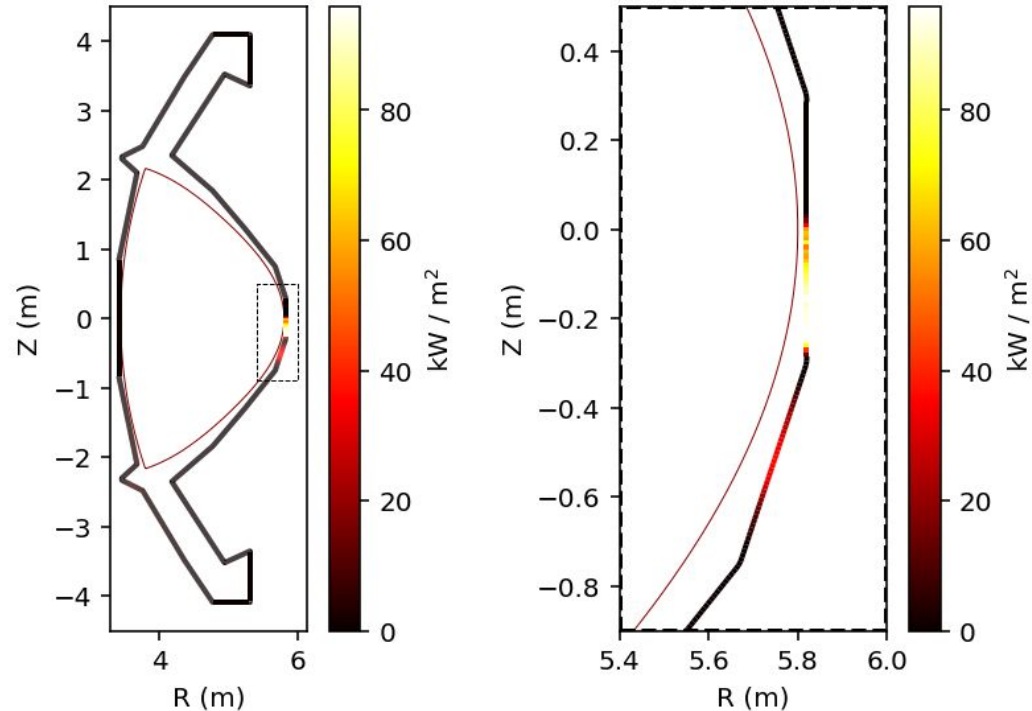
σ (cm)	Radial (total) (%)	Toroidal (total) (%)	Radial (ripple) (%)	Toroidal (ripple) (%)
0 (axisymmetric)		0.82		0.00
0 (well-aligned)		0.87		0.05
0.5	0.89	0.88	0.07	0.05
2	1.07	0.91	0.25	0.08
4	1.31	1.07	0.48	0.24
6	1.80	1.39	0.98	0.57
8	3.82	1.57	2.99	0.75

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Heat loads to 2D wall with perfectly aligned TF coils

- Multiple simulations in ASCOT performed with varying # markers and max. sim. time, combined ^[1]
- Toroidally averaged alpha heat loads reach 100 kW/m^2
 - Poloidal bins $\sim 1 \text{ cm}$
- Divided into toroidal bins of $4^\circ \rightarrow 140 \text{ kW/m}^2$
- Highly concentrated at outer midplane
- Loads may increase with:
 - TF misalignments
 - first wall misalignments
 - ports/other leading edges



[1]: See upcoming paper, LeViness *et al* (2026, under review)

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Impact of MHD on alpha transport in ARC

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Reduced energetic particle transport models



- Simplified frameworks for examining linear & nonlinear EP physics
- Resonance-broadened quasilinear model (RBQ) ^[1]
 - Computes diffusion coefficients in constants-of-motion (COM)-space while considering resonance overlap and broadening from pitch-angle collisions
 - Uses NOVA generated TAE mode structures and NOVA-C computed wave-particle interaction matrices
 - Prepares diffusion and convective WPI matrices for NUBEAM processing
- Kick model ^[2]
 - Evaluates transport coefficients in COM space using ORBIT framework for subsequent NUBEAM simulations
- In this work:
 - AE stability assessed w/ analytic model & quasilinear model
 - Long timescale alpha transport (multiple slowing-down times) assessed with NUBEAM ^[3] module of TRANSP ^[4] w/ transport coefficients from RBQ modeling
 - Alpha transport from tearing modes & sawteeth are evaluated with ORBIT-kick ^[5]

[1]: Gorelenkov *et al* (NF 2018)

[2]: Podestà *et al* (PPCF 2014)

[3]: Pankin *et al* (Comput. Phys. Commun. 2004)

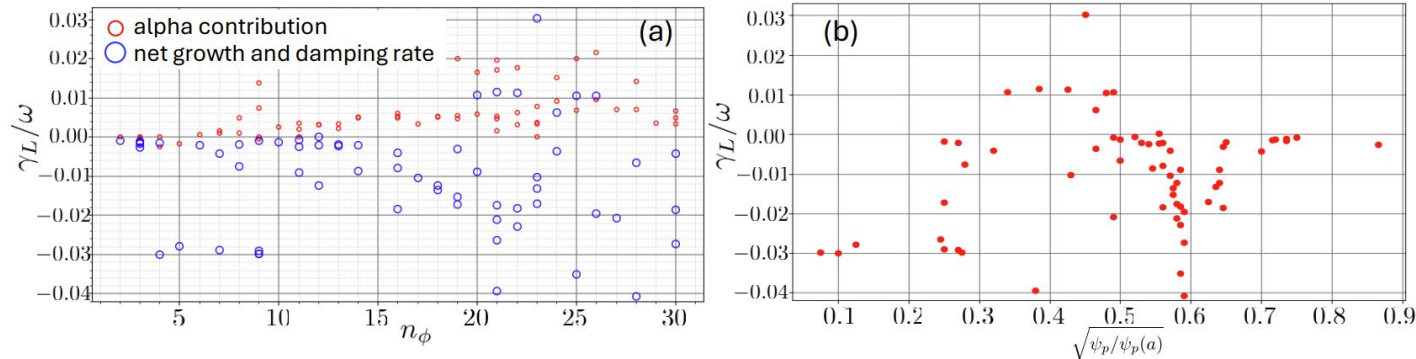
[4]: Pankin *et al* (Comput. Phys. Commun. 2025)

[5]: Podestà *et al* (PPCF 2014, 2022)



Multiple unstable AEs found for ARC

- Global, ideal MHD code NOVA ^[1] w/ kinetic extension NOVA-C used to calculate the shear-Alfvén continuum, eigenmode structures, growth rates and WPI matrices
 - (Formerly NOVA-K)
 - Damping mechanisms: radiative damping, ion/electron Landau damping, trapped electron collisional damping, continuum damping
- Multiple unstable eigenmodes found
 - Agrees qualitatively w/ previous ARC studies using FAR3D ^[2]



Reprinted from Bonfiglio *et al* (under review)

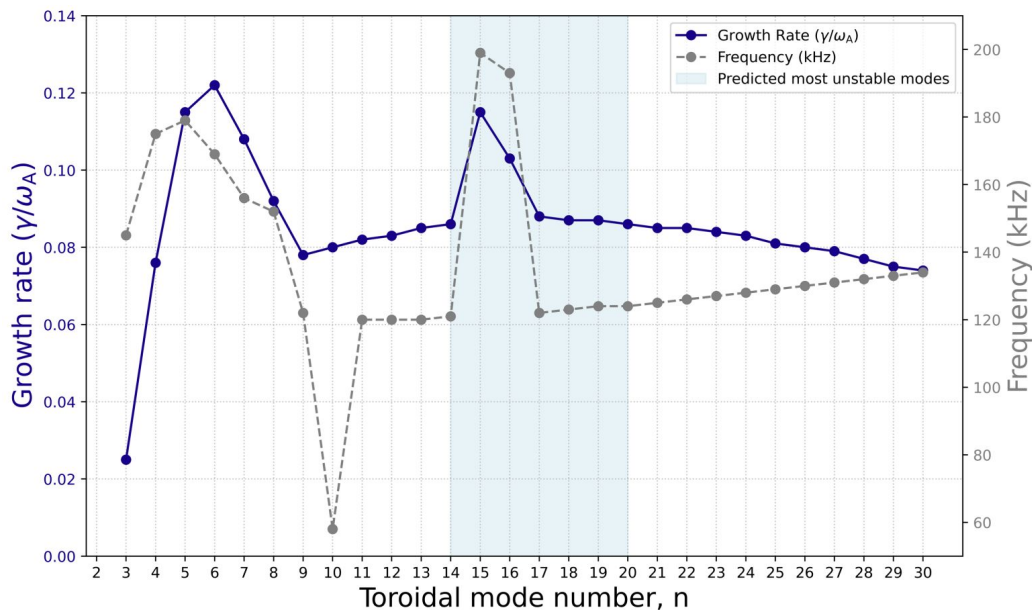
[1]: Cheng (Phys. Rep. 1992)

[2]: Hillesheim *et al* (JPP 2026)



FAR3D also shows a wide range of unstable TAEs

- FAR3D ^[1] solves the reduced MHD equations with gyrofluid closure and includes the kinetic drive of a modelled energetic alpha population
- Simulations show a wide range of unstable TAEs, qualitatively agreeing with NOVA-C results



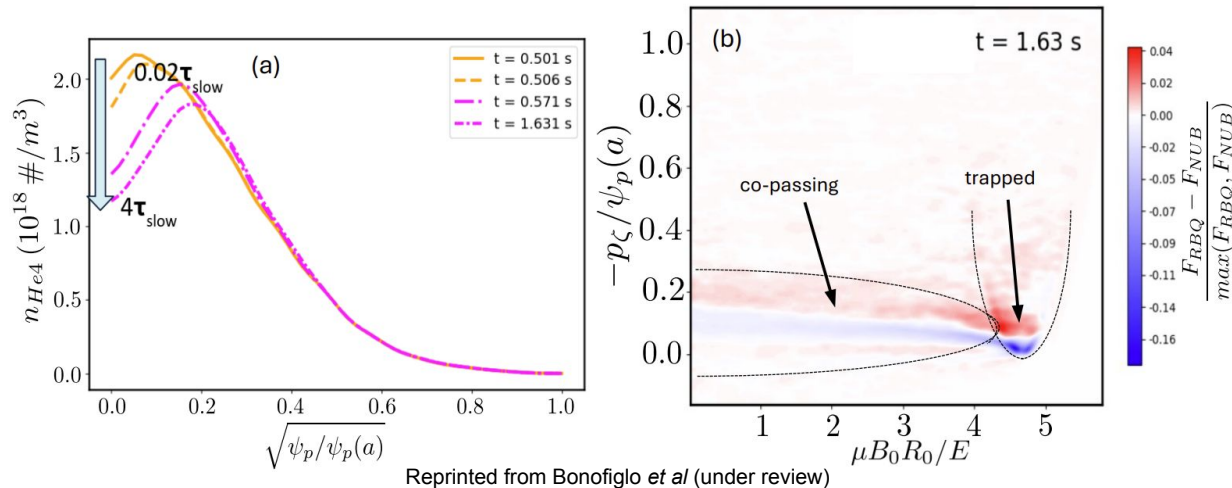
[1]: Varela *et al* (2024)

Reprinted from Hillesheim *et al* (JPP 2026)



Alpha transport by AEs in ARC appears benign

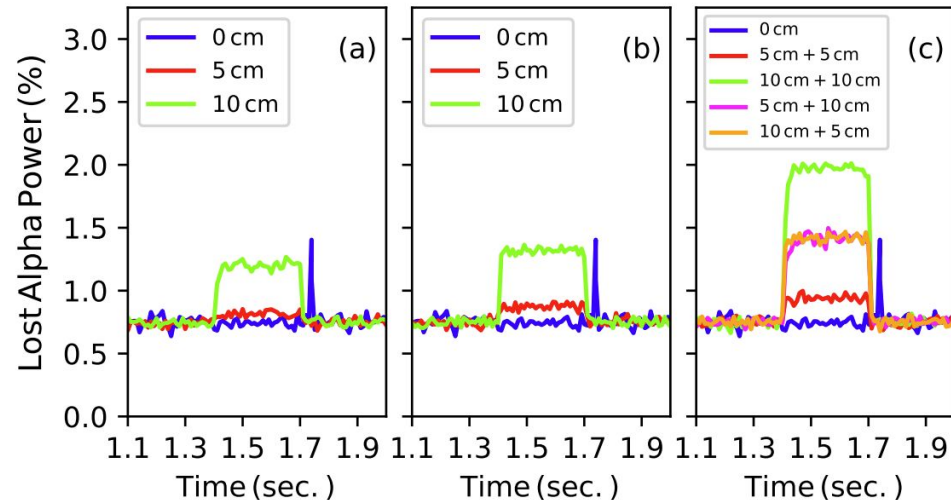
- RBQ coupled to NUBEAM to find resulting alpha transport
 - NOVA-C modes passed to RBQ → RBQ calculates diffusion coefficients → NUBEAM used for alpha transport
 - RBQ model includes resonance broadening effects from pitch-angle collisions
 - Performed for several slowing-down times (~ 290 ms at core), necessary to see the relaxation of the distribution function!
- Result: changes mostly redistributive, negligible change in losses





Alpha transport by low-frequency instabilities

- Tearing modes (NTMs) and sawteeth simulated using ORBIT-kick for transport coefficients, TRANSP/NUBEAM for time-dependent sims.
- Assumed worse-case scenario:
 - full reconnection for sawtooth crashes, maximal island widths/mode amplitudes for NTMs, and prolonged periods of NTM saturation near sawtooth events
 - (2,1) and (3,2) NTMs considered as they're expected to be highest risk for ARC ^[1]
- Even with non-physically large island widths, only see 2-3% losses from NTMs
- Sawteeth (not shown) transiently increase losses 2-3x
- NTMs + sawteeth increase losses 2x from NTMs alone



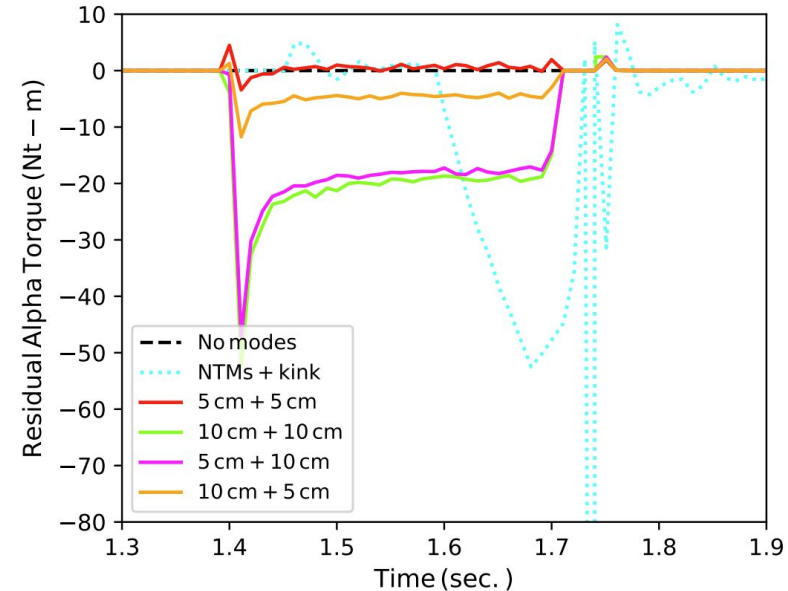
Reprinted from Bonfiglio *et al* (under review)

[1]: Leuthold *et al* (JPP 2026)



Alpha-induced torque could be an issue

- Even in worst-case scenarios, losses are mostly benign, and prompt losses dominate
- MHD effects mostly cause redistribution of alphas
- No significant change to alpha heating or current drive
- **But** NTMs with island width ≥ 5 cm can cause significant alpha torque, surpassing intrinsic torque of ARC (5 - 20 Nt-m^[1])
- Could cause profound changes to the plasma rotation, MHD, & global stability



[1]: Leuthold *et al* (JPP 2026)

Reprinted from Bonofiglio *et al* (under review)



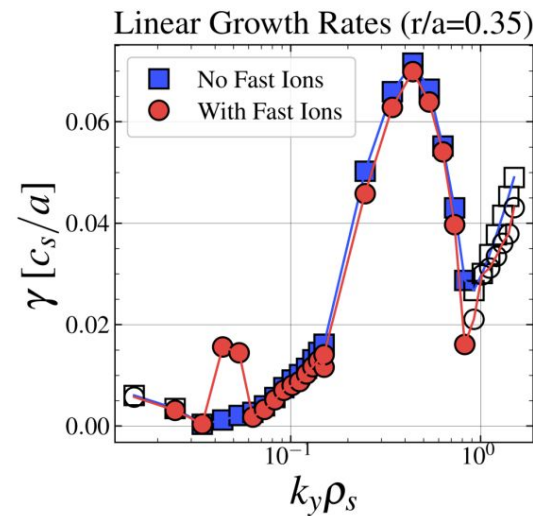
ITG stabilization by alphas in ARC

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Modeling turbulence in a reduced-current ARC



- $I_p = 9$ MA version of ARC V3A produced for ease of numerical simulation
 - Input profiles calculated w/ medium-fidelity modeling in MAESTRO ^[1] w/ TGLF SAT2 ^[2]
- Global-spectral gyrokinetic code CGYRO ^[3] used for turbulence simulations with and without alphas included ^[4]
- Linear CGYRO simulations performed first
 - No reduction in ion-scale turbulence growth rates, but found $n \sim 14$ -17 TAEs, agreeing with other results for ARC



From Hall *et al* (TTF contributed, 2026)

[1]: Rodriguez-Fernandez *et al* (under review, arXiv 2605.07047)

[2]: Staebler *et al* (PPCF 2020)

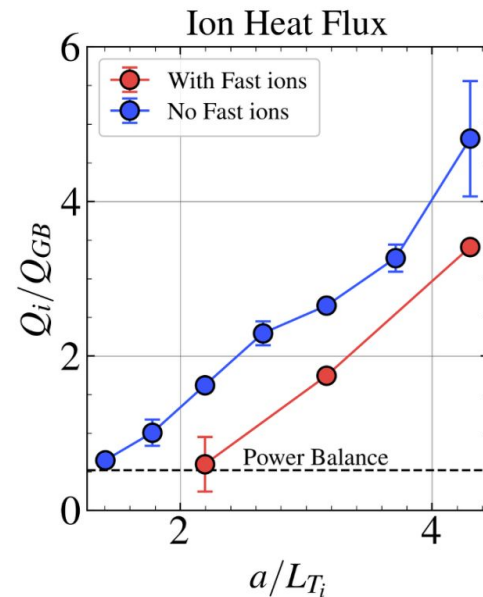
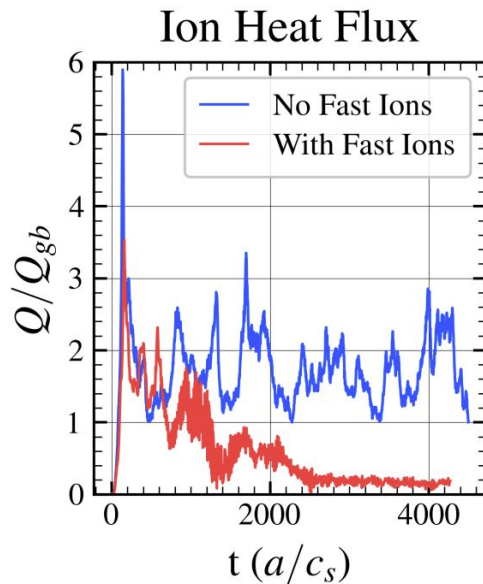
[3]: Candy *et al* (J Comp Phys 2016)

[4]: Hall *et al* (under review, arXiv 2606.15965)

Nonlinear simulations show a reduction in ITG turbulence



- With nonlinear CGYRO, turbulent ion heat fluxes much lower at $r/a = 0.35$ (where alpha density gradient is largest)
 - $k_y \rho_s = [0.026, 1.234]$ (48 modes)
 - $[L_x, L_y] = [241\rho_s, 239\rho_s]$
 - $\delta\phi, \delta A_{\parallel}, \delta B_{\parallel}$ fluctuations, Sugama collisions
- Increasing alpha density leads to increased turbulence suppression
- Initial global simulations don't show increased Q
 - Alpha pressure too low?
- Full-current ARC simulations may be more promising, like results for SPARC ^[1]



[1]: Di Siena *et al* (under review, arXiv 2605.10694)

From Hall *et al* (TTF contributed, 2026)



Summary & Future Work

- Prompt alpha power losses from ARC low ($< 1\%$)
- Even with TF misalignments up to 6 cm, ripple + prompt losses $< 2\%$
- Maximum toroidally averaged heat loads to ARC first wall: 100 kW/m^2
 - Could be worse with misalignments, ports, diagnostics
- Large range of unstable TAEs predicted
 - But alpha transport by TAEs is benign: no loss, only redistribution
- Even unrealistically large NTM islands only cause 2-3% power loss total
- Sawteeth transiently increase alpha power losses 2-3x
 - But NTMs could cause residual alpha torque on par with ARC's intrinsic torque!
- Simulations of a reduced current ARC show alphas reduce ITG turbulence locally, but may not globally improve performance
 - But the effect scales favorably with alpha pressure: a full-power version of ARC may see performance improvements