GTC Global Gyrokinetic Simulations of W7-X

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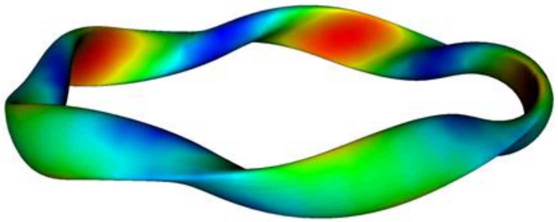
Outlines

- Motivation
- Verification of GTC simulation of stellarators
- Helically-trapped electron mode (HTEM) in W7-X
- Conclusion and future work



Motivation

- Optimized stellarators exhibit anomalous transport that cannot be explained by **neoclassical transport** [*Klinger, NF2019*]
- Phase contrast imaging (PCI) in W7-X shows characteristics of **microturbulence** due to driftwave instabilities [*Edlund, RSI2018*]
- Local (flux-tube) gyrokinetic simulations of W7-X find strong ion temperature gradient (**ITG**) turbulence that drives large heat conductivity but small particle diffusivity. Trapped electron mode (**TEM**) exited by density gradient can drive large diffusivity, but is predicted to be weakly unstable because of small fraction of toroidally trapped electrons and averaged good curvature [*Proll, PoP2013, PRL2012*]
- Stellarator optimization focuses on suppressing ITG based on flux-tube simulations [*Mulholland, PRL2023*]

GTC global simulation finds large particle transport by HTEM

- Hellically trapped electron mode (**HTEM**) excited by density gradient is localized at inner midplane of triangular section in W7-X due to bad curvature and large fraction of helically trapped electrons *[Nicolau, IAEA2021]*
- HTEM turbulence drives large particle diffusivity: implications on confinement of tritium and removal of alpha ash in reactor?
- HTEM had not been found by flux-tube simulations focusing on magnetic fieldline at the outer midplane of bean section in W7-X
- Flux-tube simulation results could depend on the choice of magnetic fieldlines being simulated *[Sánchez, NF2021]*, need to be verified by global simulation

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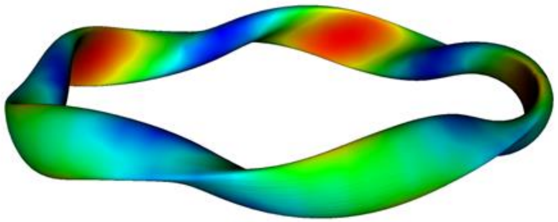
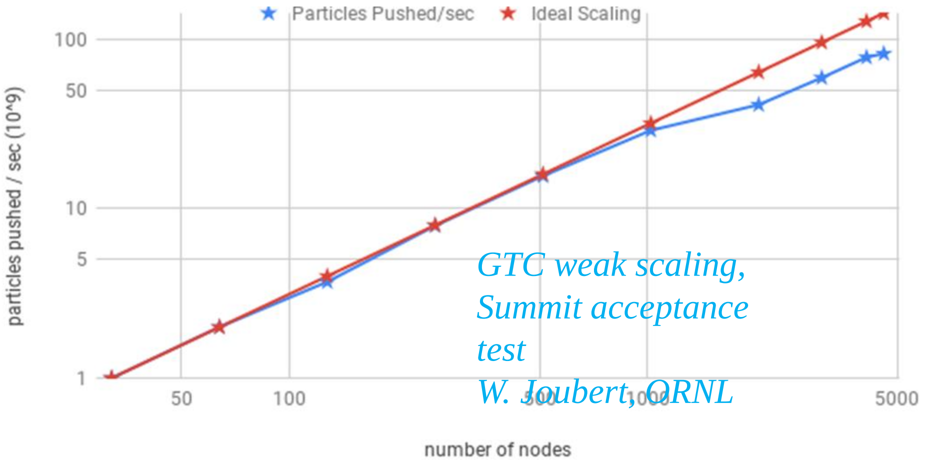


GTC gyrokinetic simulation of instability, turbulence, and transport

- Global integrated simulation for nonlinear interactions of multiple kinetic-MHD processes

  →Neoclassical transport, Microturbulence, Alfven eigenmode, MHD instability
- Tokamak, stellarator, FRC
- Fully optimized & scalable for GPU supercomputers
- Supported by SciDAC since 2001 & INCITE/ALCC since 2010



GTC weak scaling, Summit acceptance test
W. Joubert, ORNL

Open source
https://sun.ps.uci.edu/gtc/resources

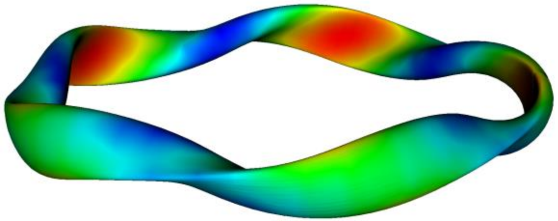
[*Z. Lin, Science 1998*]

GTC global simulation of 3D toroidal equilibrium

- GTC simulation of 3D geometry developed for DIII-D RMP experiment [*Holod, NF2017*]
- 3D equilibrium calculated by VMEC/M3D-C1 & transformed to Boozer coordinates (ψ,θ,ζ)
- Equilibrium quantities represented by a 3D spline in **equilibrium mesh**, fluctuating quantities in **turbulence mesh** using global field-aligned mesh in real space
- Recent GTC simulation of stellarators:

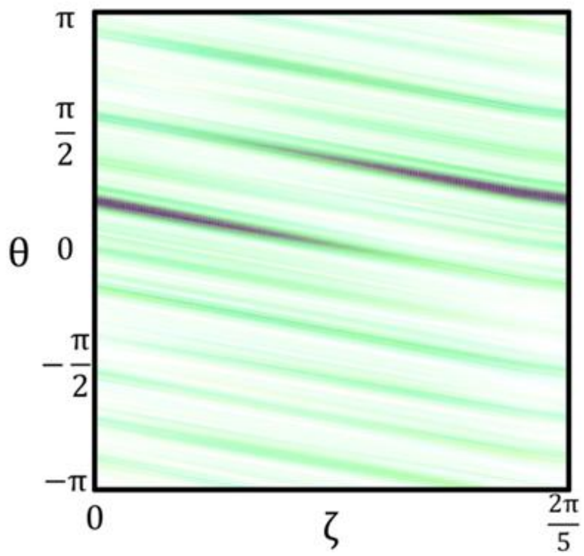
⟶Toroidal Alfven eigenmode in LHD [*Spong, NF2017*]
⟶ITG turbulence in LHD & W7-X [*Wang, PoP2020*]
⟶ITG suppression by neoclassical ambipolar electric field in W7-X [*Fu, PoP2021*]
⟶Collisionless damping of zonal flows [*Nicolau, NF2021*]
⟶TEM [*Singh, NF2022*] and impurity transport [*Singh, NF2024*] in LHD
⟶Fast ion transport in LHD & W7-X

Equilibrium calculated by Joachim Geiger
[Riemann, Kleiber, and Borchardt, PPCF2016]

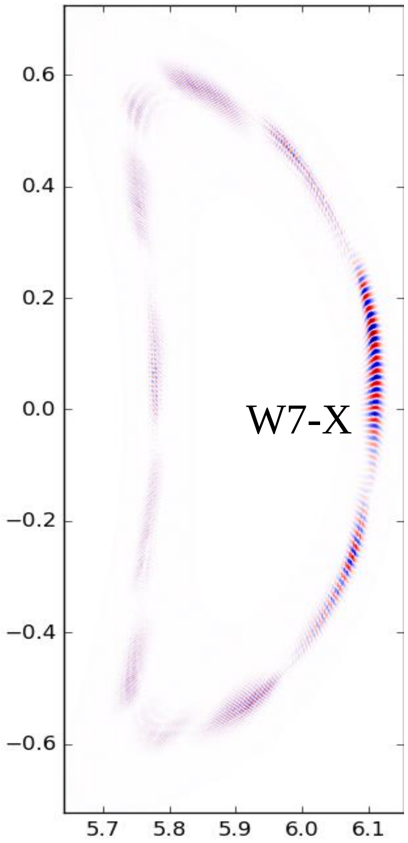


GTC and EUTERPE agree well in ITG simulations

- Both global simulation using gyrokinetic ion and adiabatic electron
- Linear ITG eigenmode **localizes** to discrete fieldlines in W7-X due to linear toroidal coupling
- ITG instability nonlinearly saturates by self-generated zonal flows



[*Wang, PoP2020*]



ITG in W7-X	$\gamma (x10^3\ s^{-1})$	$\omega (x10^3\ s^{-1})$	(m,n)
EUTERPE	33.8	176	-219, 200
GTC	34.3	157	-219, 200

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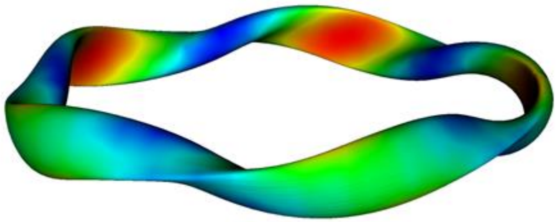
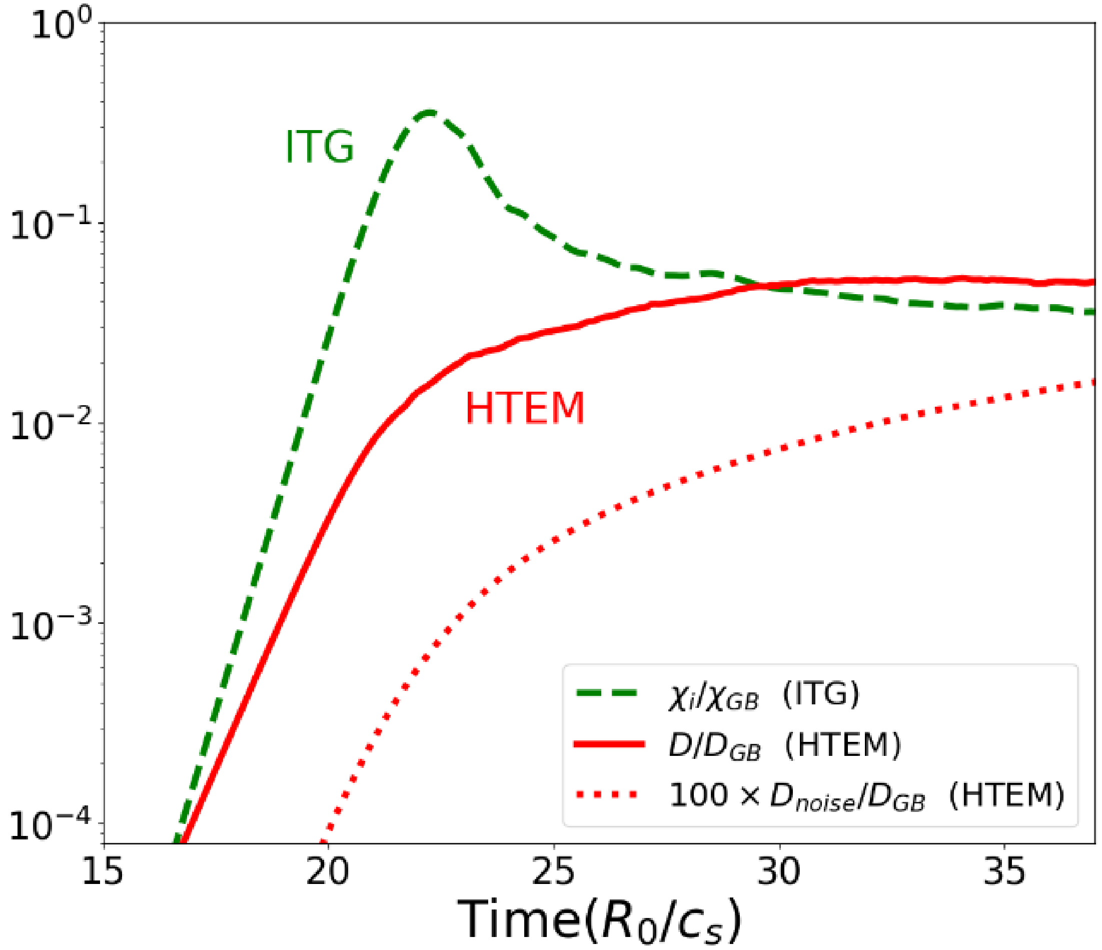


GTC finds HTEM can drive large particle transport in W7-X

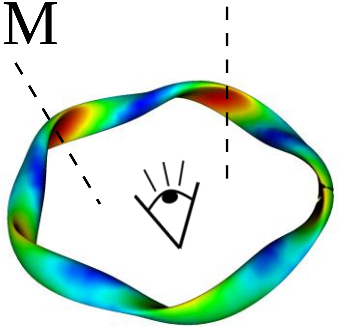
- GTC global simulations with kinetic electrons find HTEM is excited by density gradients and drives large particle diffusivity
- ITG and HTEM with similar normalized gradient show comparable transport
- Global simulations contradicts flux-tube simulations

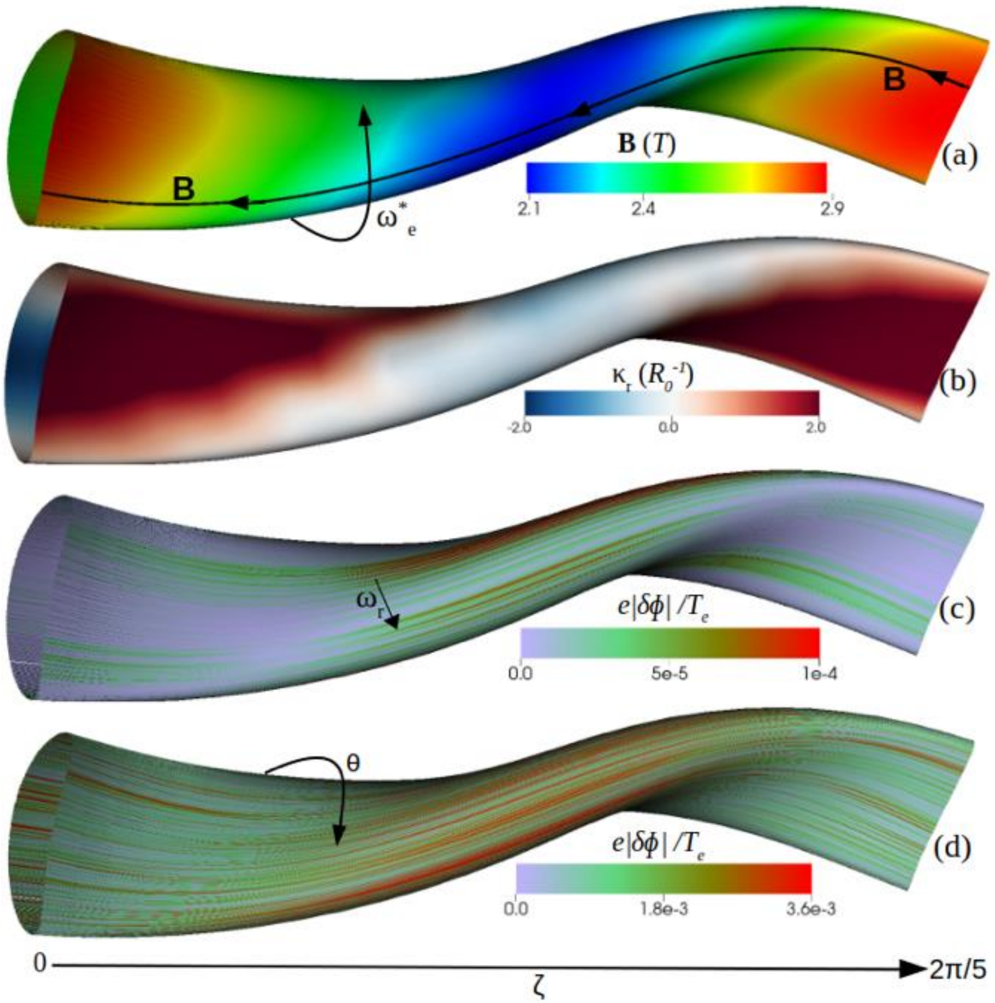
Nicolau
submitted to PRL, 2023



HTEM localized at inner side of triangular section in W7-X

- Stable with adiabatic electrons
- HTEM localizes at inner side of triangular section with bad curvature and large fraction of HTE
- ITG & TEM localize at outer side of bean section, similar to tokamak
- W7-X has more helically trapped than toroidally trapped electrons
- Linear properties of HTEM similar to earlier theory [*Plunk, JPP2017*]





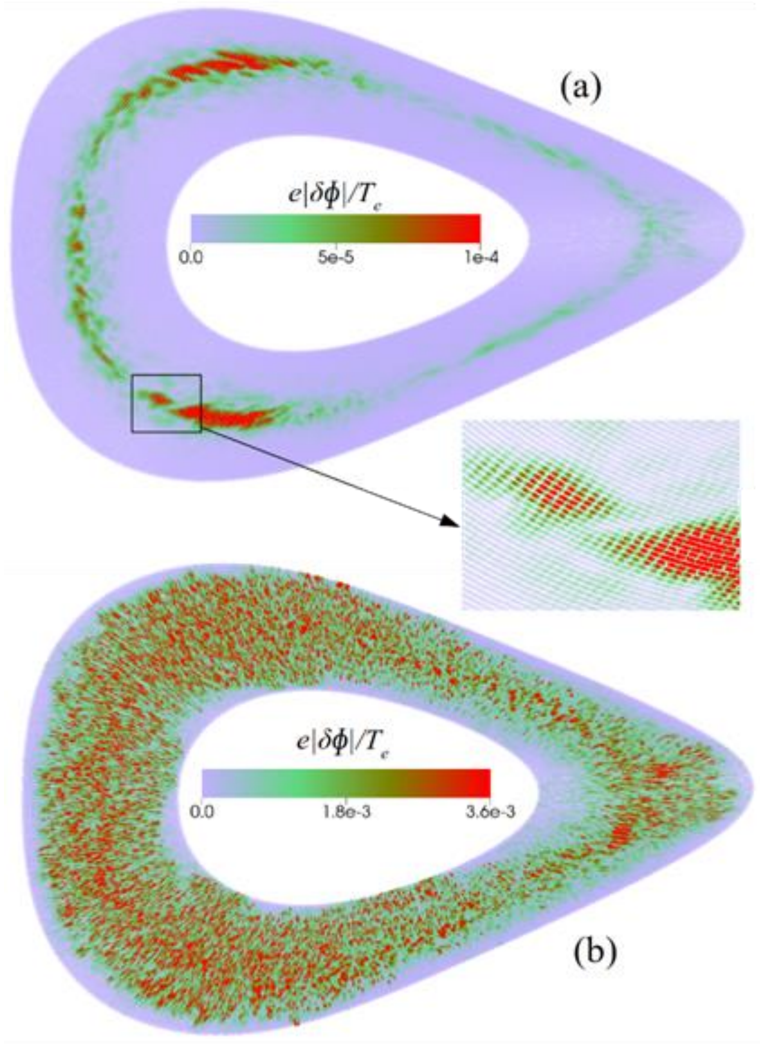
HTEM saturates via spectral cascade and turbulence spreading

- HTEM nonlinearly spreads to linearly stable regions in radial and poloidal directions

  →Nonlinear HTEM dynamics missed by flux-tube simulation

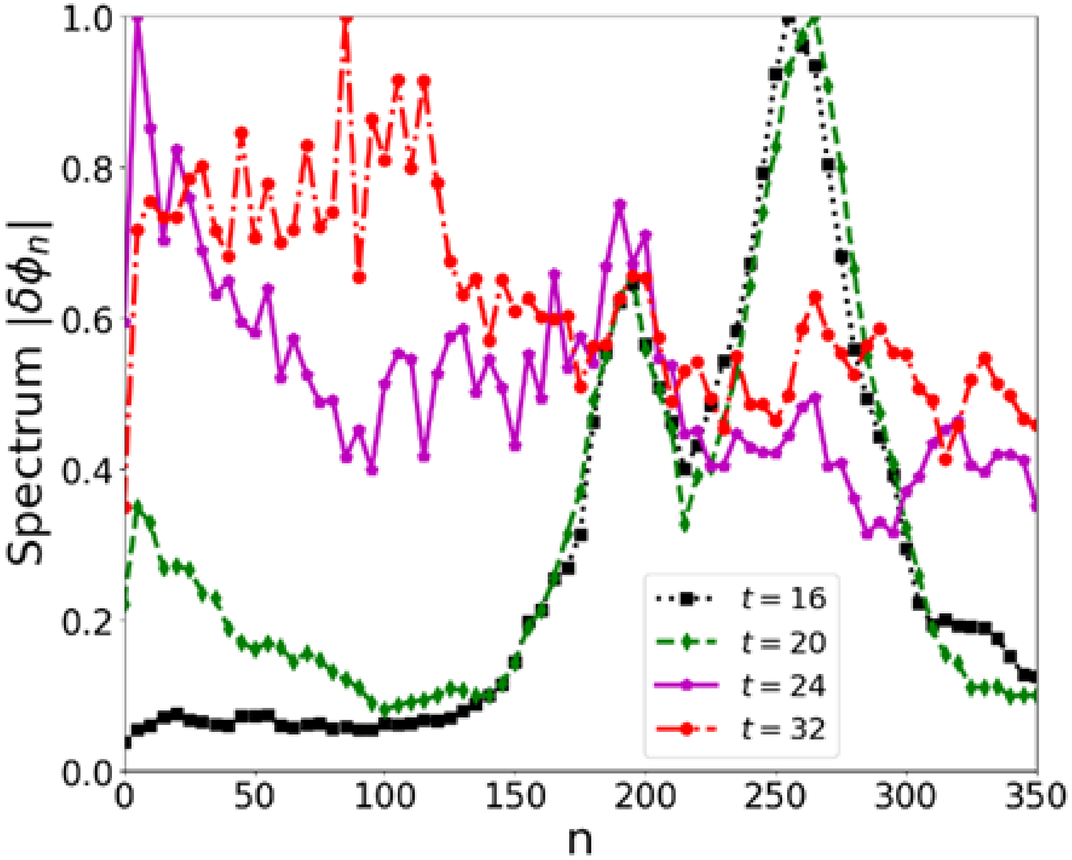
- GTC Turbulence field-aligned mesh (121, 4400, 27) & Equilibrium mesh (200, 799, 51) over one-field period

  →First & largest global simulation using kinetic electrons with real mass-ratio and realistic parameters in W7-X



HTEM saturates via spectral cascade and turbulence spreading

- Linear HTEM eigenmode coupling n=[100,300] requires full flux-surface simulations
- Nonlinear spectral cascade to lower-n and higher-k_r
- Zonal flows do not dominate HTEM saturation
- Excitation of low-n harmonics by linear toroidal coupling with zonal flows *[Nicolau, NF2021]* and nonlinear toroidal coupling *[Lin, PoP2005]* enhance inverse cascade



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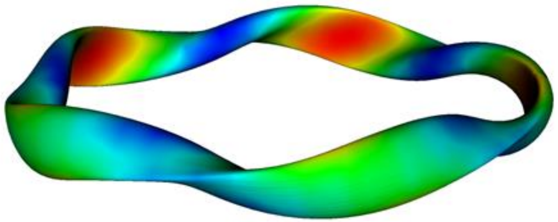


Summary and future GTC simulation of stellarators

- First full flux-surface gyrokinetic simulation with kinetic electrons find a new mode in W7-X: helically trapped electron mode (HTEM)

  → HTEM can cause significant particle transport in W7-X

- New physics of microturbulence and fast ion confinement in 3D toroidal plasmas requires full flux-surface and radially global gyrokinetic simulation
- Future GTC global simulation of stellarators

  → Coupled neoclassical and turbulence simulation. Neoclassical and turbulent transport intrinsically coupled in stellarators

  → Alfven eigenmode and energetic particle transport in stellarators

GTC global simulation of neoclassical transport in stellarator

- Alpha transport, thermal plasma & impurity transport
- Bootstrap current: Does bootstrap current affect QS/QA/QI?
- Effects of self-consistent ambipolar electric field Er

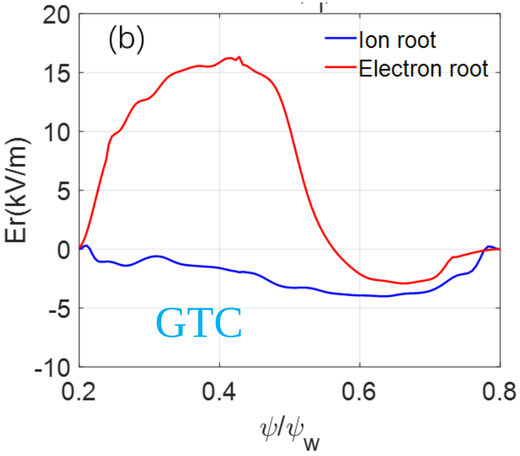
⟶Er could change orbit topology, affecting alpha loss, and wave-particle resonance

⟶Er shear could suppress microturbulence

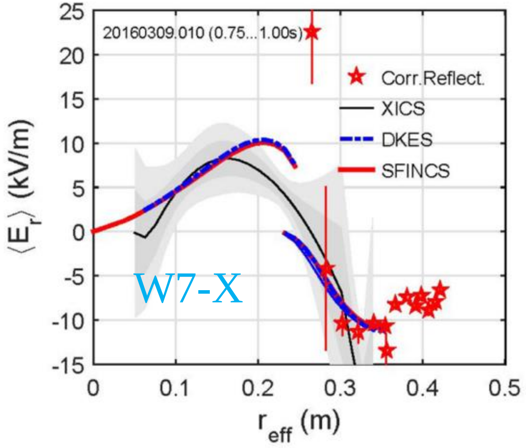
⟶Effects of energetic particles on Er & plasma rotation: control of Er for ITB?

⟶Spontaneous toroidal spin-up in W7-X without external torque?

Electron root Er greatly suppresses ITG in W7-X [*Fu, PoP2021*]

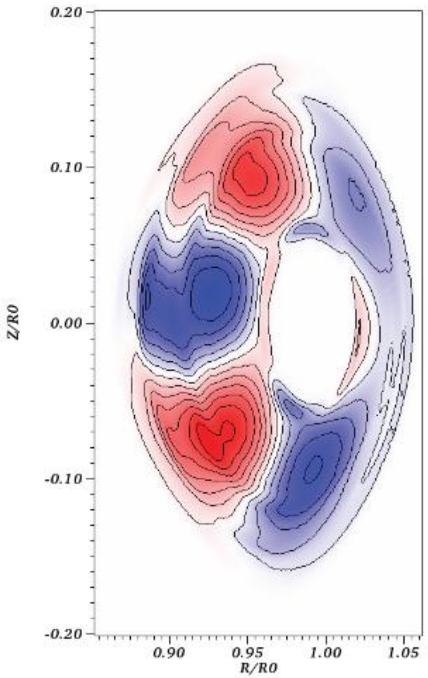


[*Wolf, NF2017*]



GTC global simulation of Alfven eigenmode in stellarator

- No experimental data on α-particle transport in burning plasmas dominated by alpha heating
- Reactor design/scenario assumes classical α-particle transport (τ_{SD}~1s, $D_{neo}<1m^2/s$)
- However, α-particle & NBI/ICRH energetic particles (EP) can be re-distributed by meso-to-macro scale Alfven eigenmode (AE) and macroscopic MHD modes
- NBI & ICRH in W7-X offers opportunity to study EP transport in optimized stellarator
- Stellararor reactor: what are self-consistent alpha and thermal plasma profiles with neoclassical transport, MHD, AE, microturbulence?



GTC simulation of Alfven eigenmode in LHD [*Spong, NF2017*]

Prediction of energetic particle confinement in ITER operation scenarios

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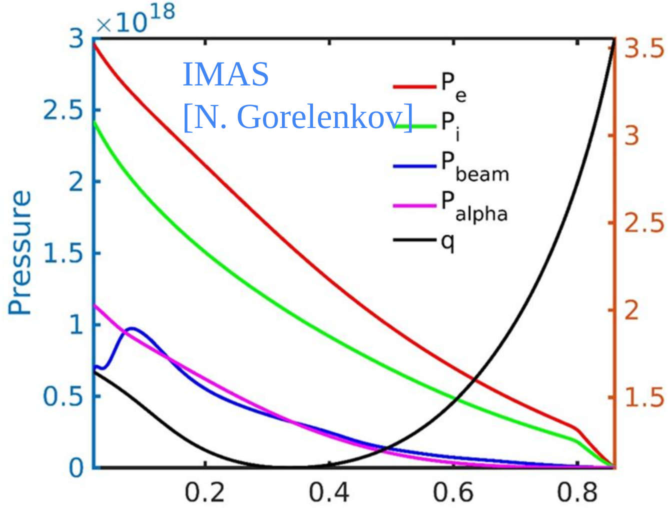
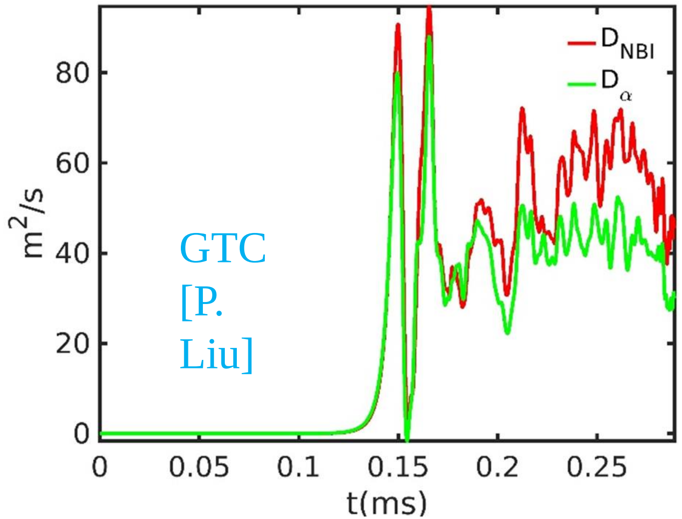
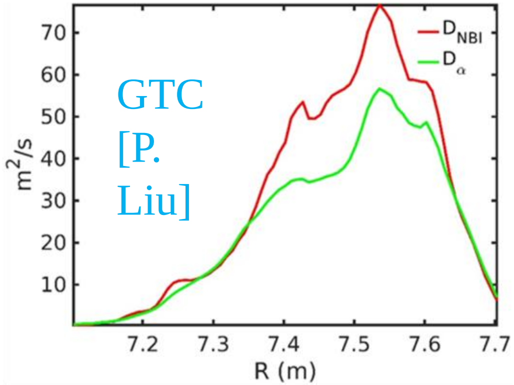
α-particles: the most important free energy source in burning plasmas

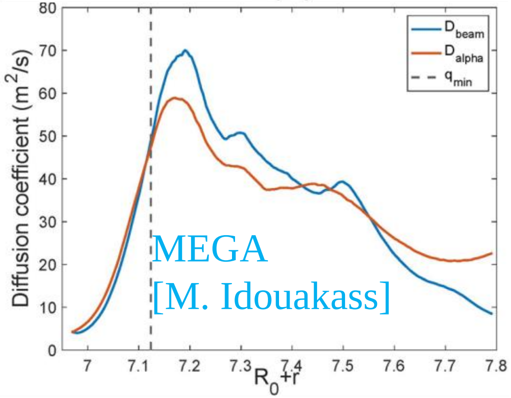
- ITER steady state scenario with Q=10: thermal plasma profiles calculated assuming classical confinement of α-particles
- GTC simulations find classical α-particles profile drives strong AE turbulence & huge EP transport D~50m^2/s, similar results from global kinetic-MHD MEGA simulations

Z. Lin, 29th IAEA FEC 2023, TH/2, P2-2505, Prediction of energetic particle confinement in ITER operation scenarios









Visible profile flattening from gyrokinetic & kinetic-MHD simulations

- Visible EP profile relaxation within <0.35ms after nonlinear saturation in gyrokinetic GTC, kinetic-MHD FAR3D, M3D-C1, and MEGA simulations
- Classical α-particle profiles are not realistic!
- To achieve targeted fusion gain, ITER/FPP reactor design and scenario development must predict:

What are self-consistent alpha and thermal plasma profiles in the presence of MHD, AE, microturbulence?