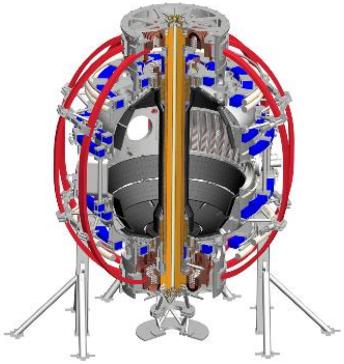
NSTX-U first results, and progress in transport research

Walter Guttenfelder

Princeton Plasma Physics Laboratory

Plasma Seminar
University of Washington, Dept. of Aeronautics & Astronautics
Feb. 7, 2017



Outline

- Motivation for spherical tokamak (ST) research
- NSTX-U & first results from 2016

- Transport research:
- Microstability properties related to STs
- Some transport observations & theory

Big picture: Magnetic fusion energy

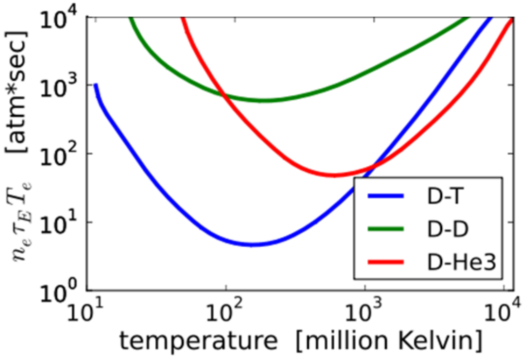
- Goal: thermonuclear fusion to generate electricity

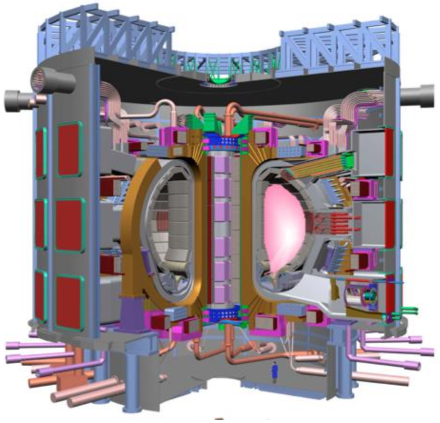
- Need T~150 million °C & sufficient triple product, $nT\tau_E$, to generate fusion gain, $Q=P_{fusion}/P_{loss}>1$

- Magnetically confined plasmas have generated 11-16 MW of fusion power using 46-22 MW (**Q=0.23-0.7**) (TFTR & JET tokamaks)

- Remaining obstacle → need higher energy confinement time, $\tau_E=3nT\cdot V/P_{loss}$

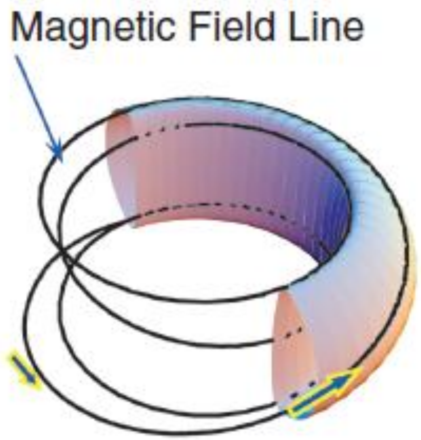
- ITER being built to demonstrate Q=5-10, uses very large volume & strong field ($$$) to increase τ_E



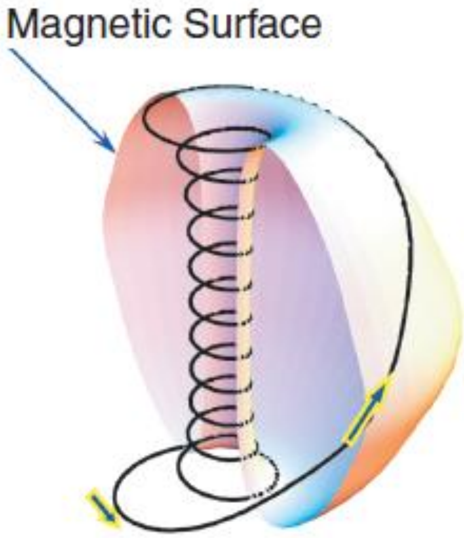


Spherical tokamak (ST) has aspect ratio A<2, many parameters intermediate to tokamak – spheromak, FRC

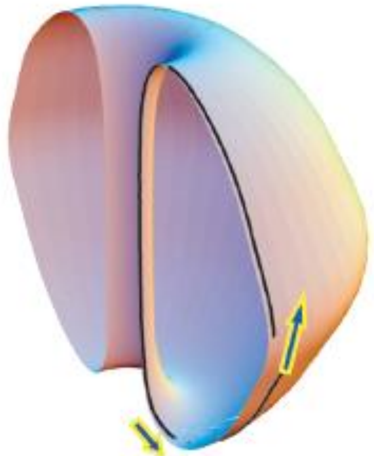
Tokamak



ST



Spheromak, FRC



Peng

	Tokamak	ST	Spheromak, FRC
A=R/a	3	1.2-2	≥1, 1
q_{edge}	3-4	6-20	→0, ~0
β	3-10%	10-40%	≤20%, 100%
$\rho_*=\rho_i/a$	1/200	1/100	1/50, 1/30

- ST is naturally elongated, favorable average curvature improves MHD stability, allowing higher β & use of smaller B_T, also more compact → **cheaper to build**

Why explore spherical tokamaks?

- Potentially attractive for electricity production - Pilot Plant (Menard, NF 2011)

- High neutron wall loading in small device - Fusion Nuclear Science Facility, FNSF (Menard, NF 2016)

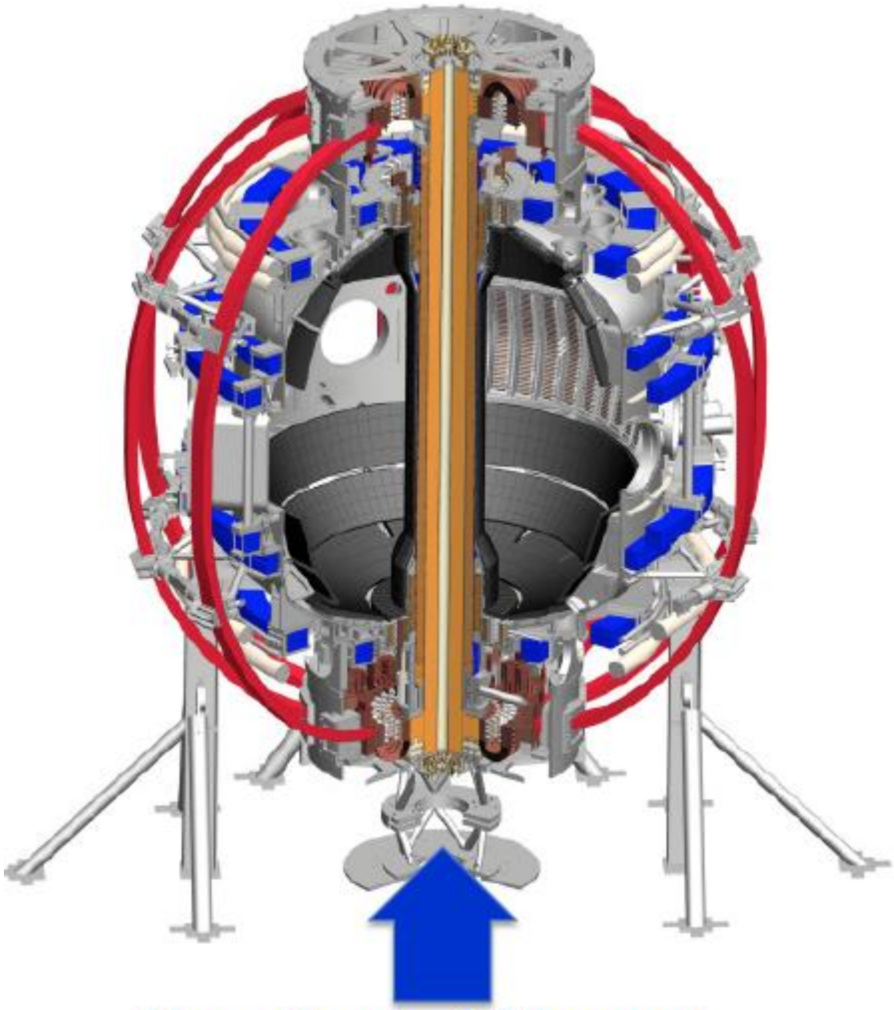
- Improve toroidal physics predictive capability
  - High β and at low collisionality
  - Understand confinement, fast-ion physics for ITER

NSTX-U:
National Spherical Torus Experiment – Upgrade

Not addressing many NSTX results in this talk:

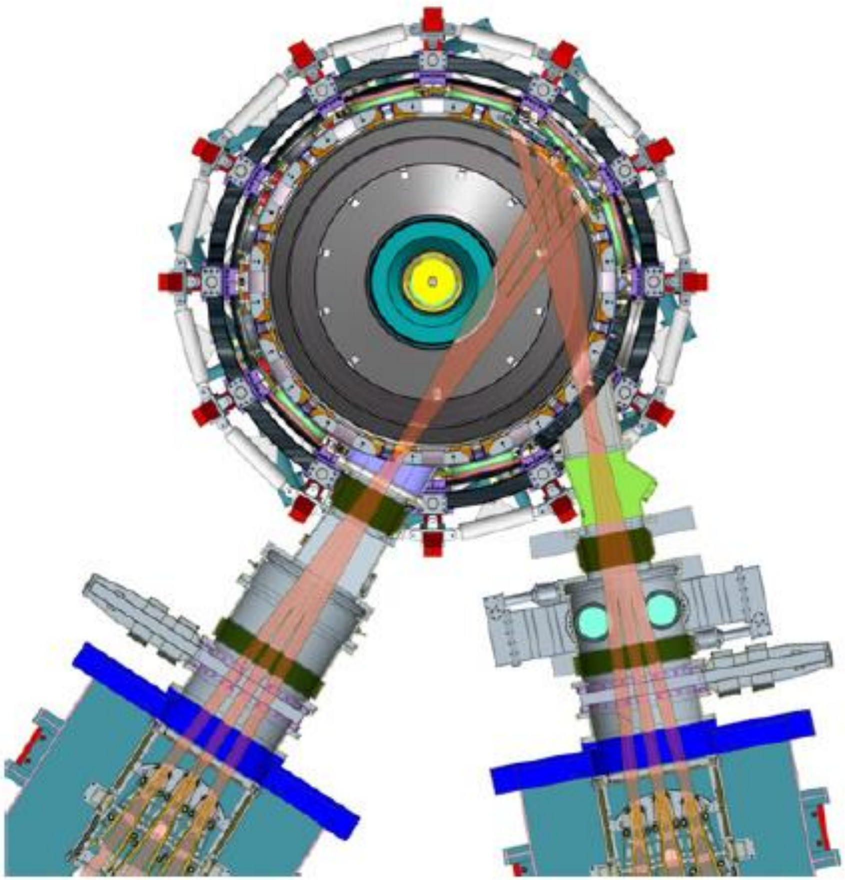
- Achieved 40% beta
- Observed favorable confinement scaling with collisionality ($\tau_E \sim 1/\nu_{*e}$)
- Improved edge and core confinement with lithium wall conditioning
- Achieved 70% non-inductive fraction
- Achieved 300 kA non-inductive startup current via coaxial helicity injection (CHI)
- Heat flux mitigation using “snowflake” divertor
- ….

NSTX completed major upgrade in 2015 with goal of: 2 × higher B_T, I_p, P_{NBI} & 5 × longer pulse length



New Central Magnet

1 Tesla at plasma center, I_p = 2MA, 5s



Original NBI

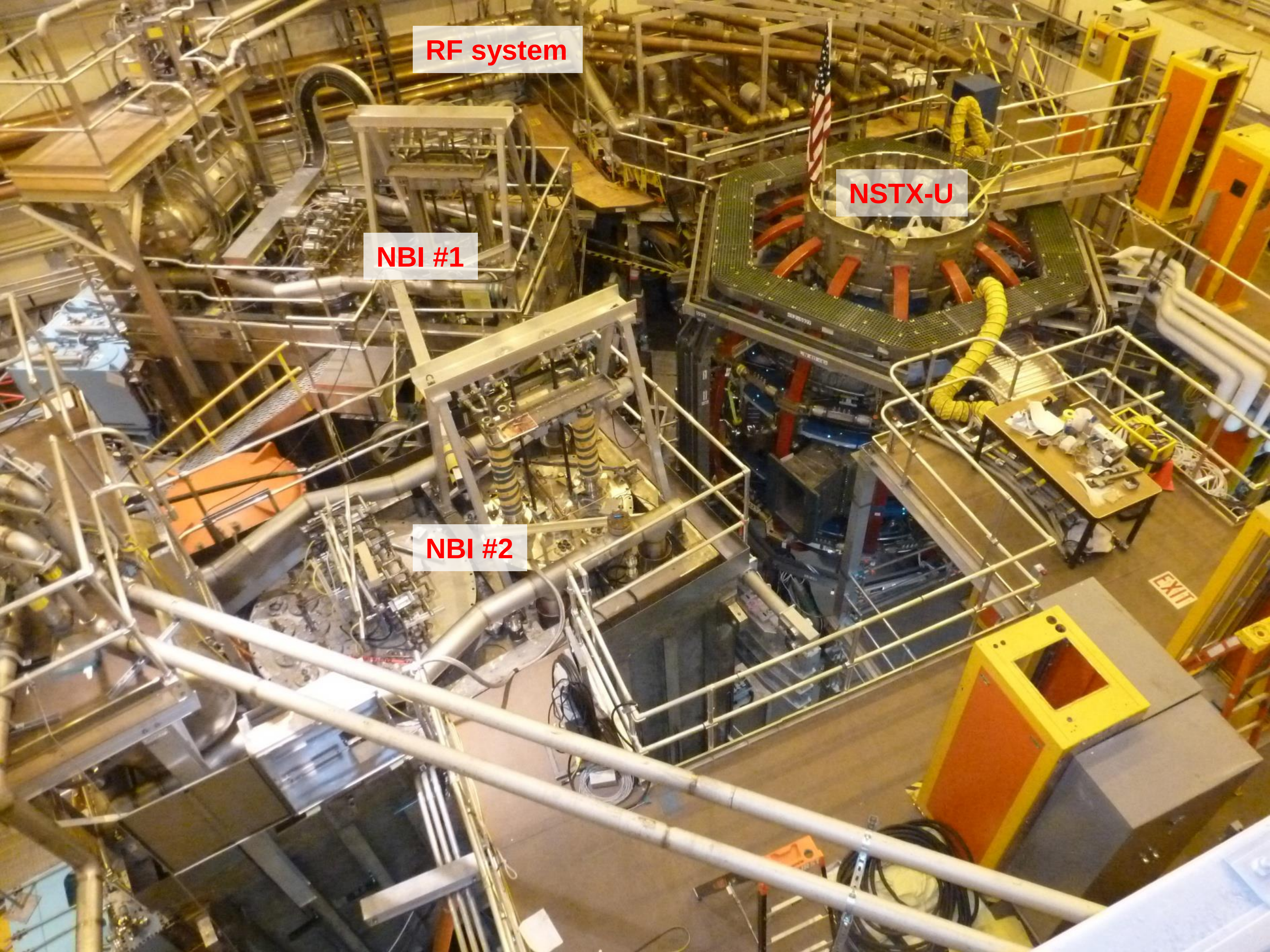
(R_{TAN} = 50, 60, 70cm)

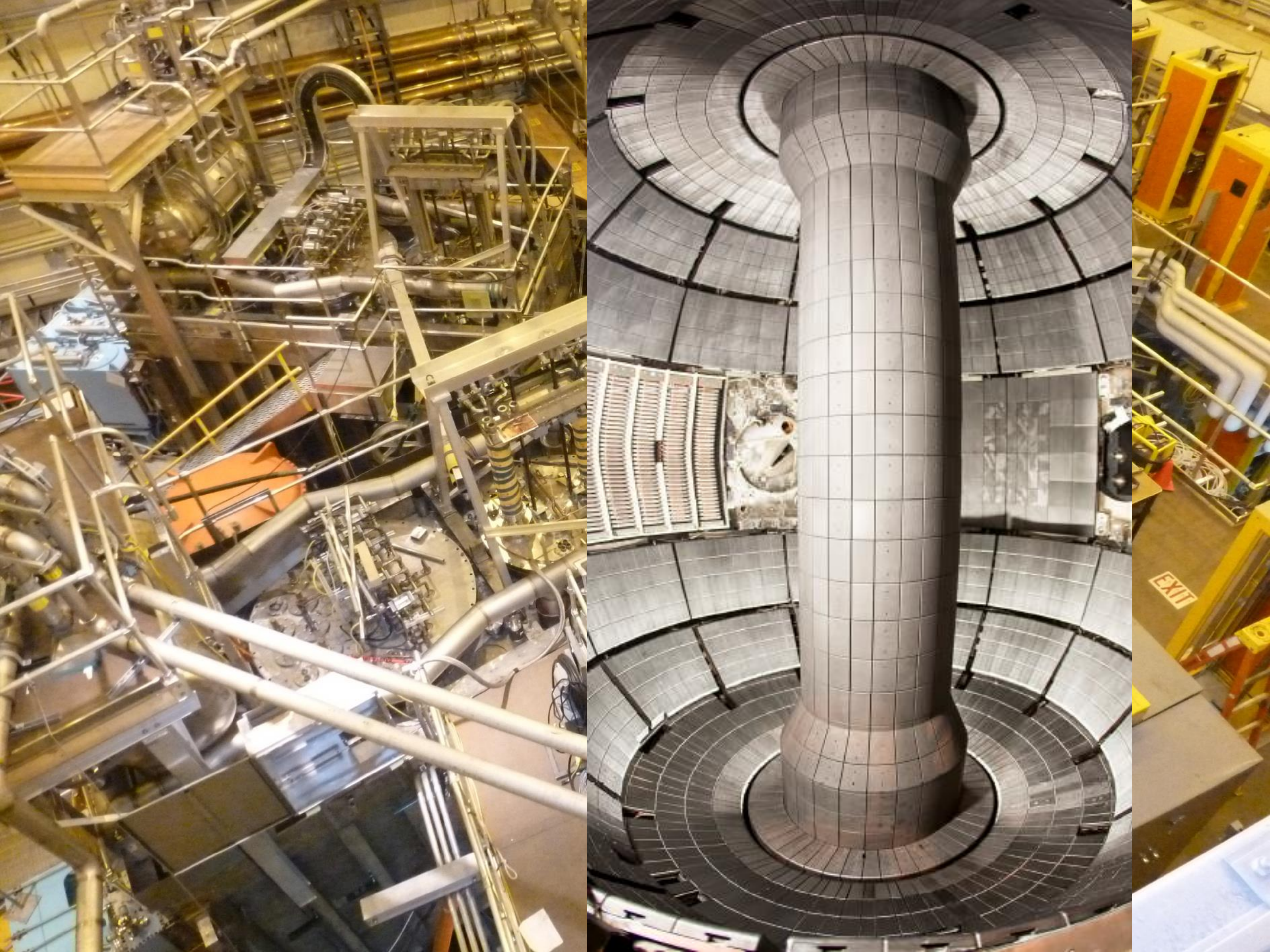
5MW, 5s, 80keV

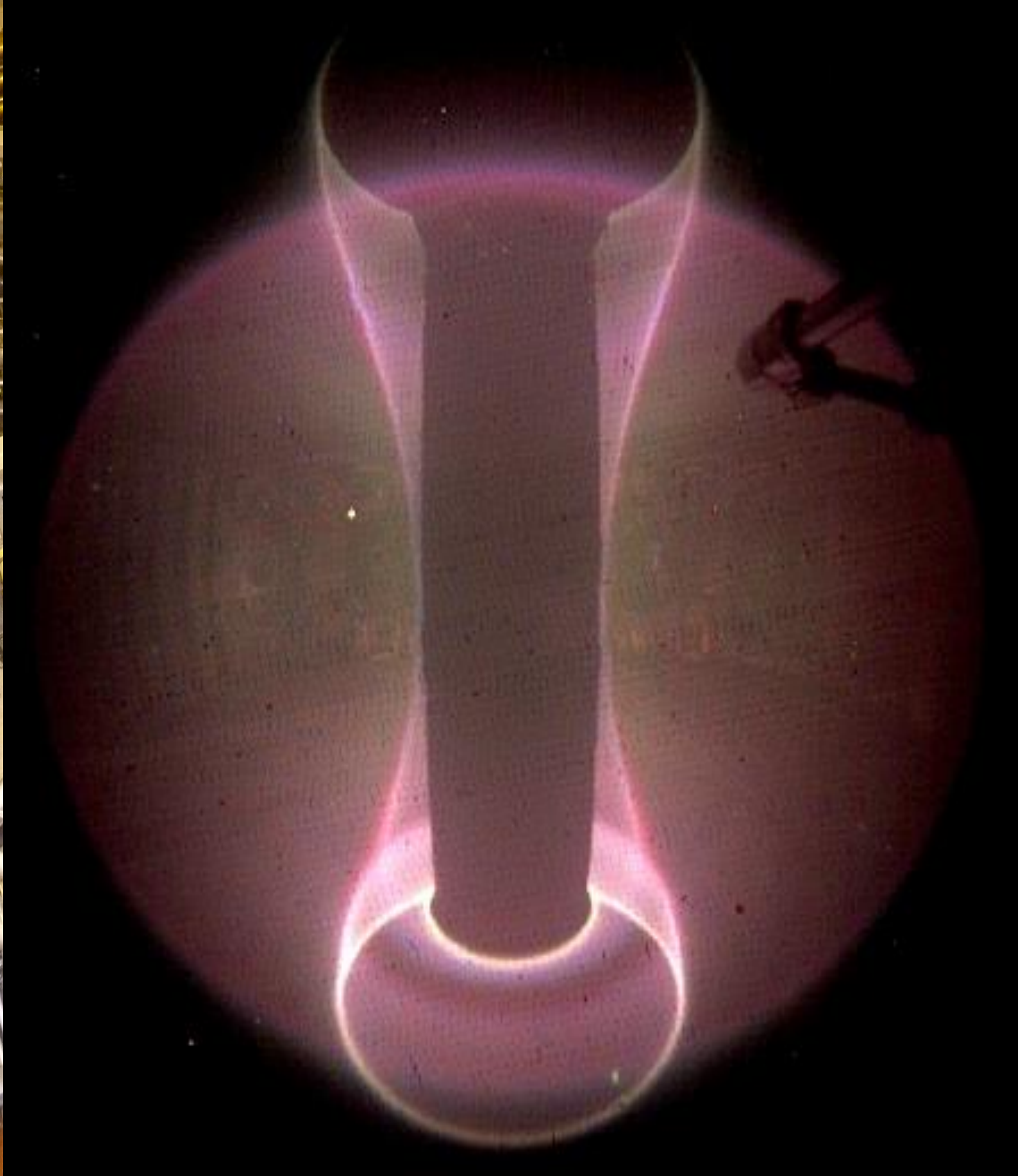
New 2nd NBI

(R_{TAN}=110, 120, 130cm)

5MW, 5s, 80keV

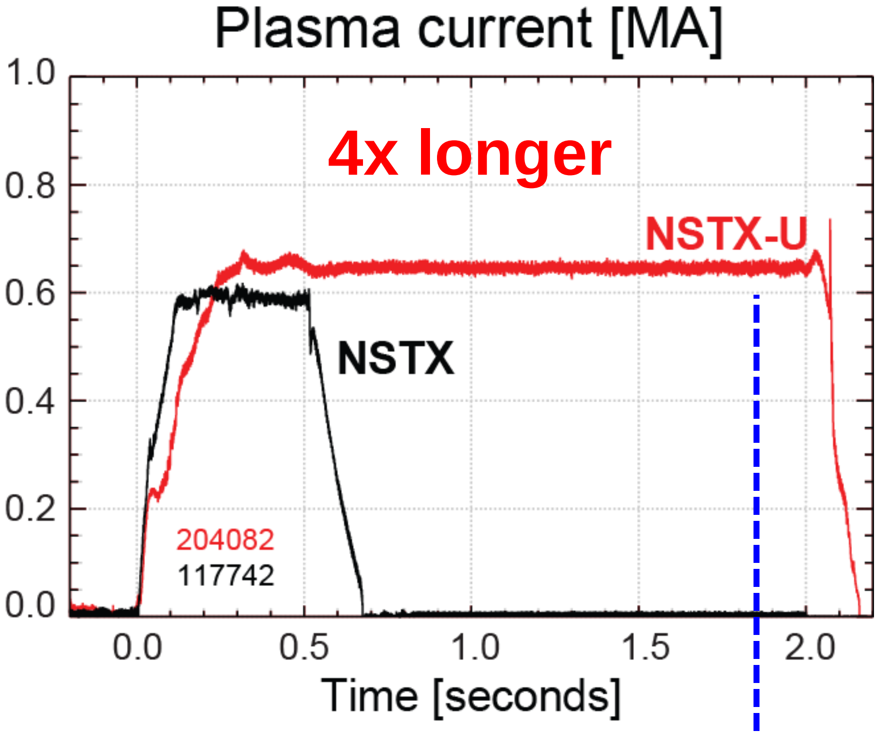

RF system
NSTX-U
NBI #1
NBI #2
EXIT


EXIT

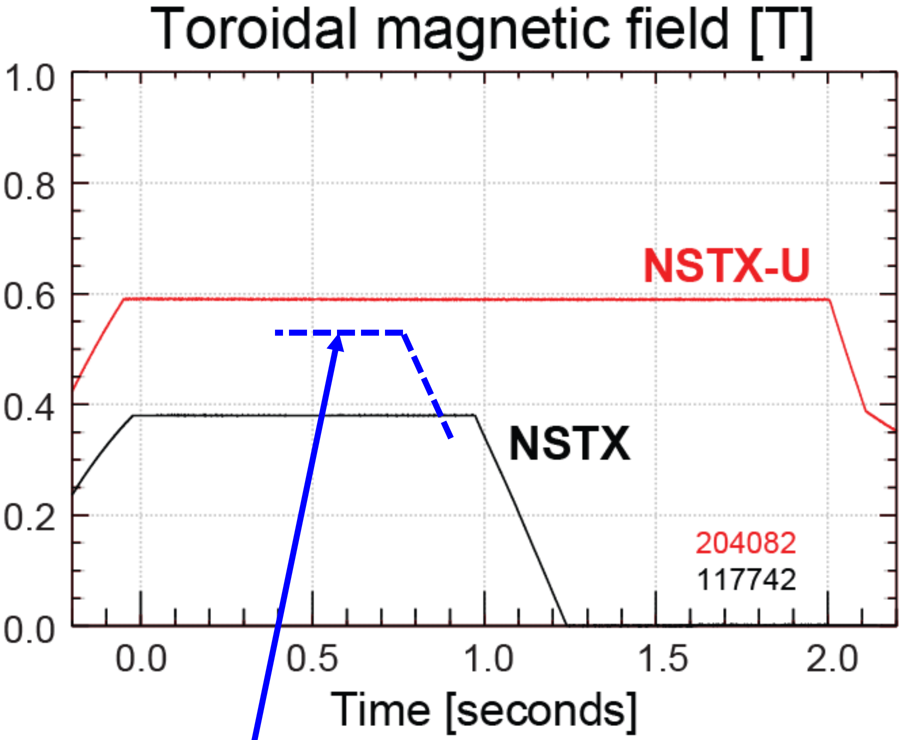


NSTX-U has surpassed maximum pulse duration and magnetic field of NSTX

Compare similar **NSTX** / **NSTX-U** Boronized L-modes, P_{NBI}=1MW

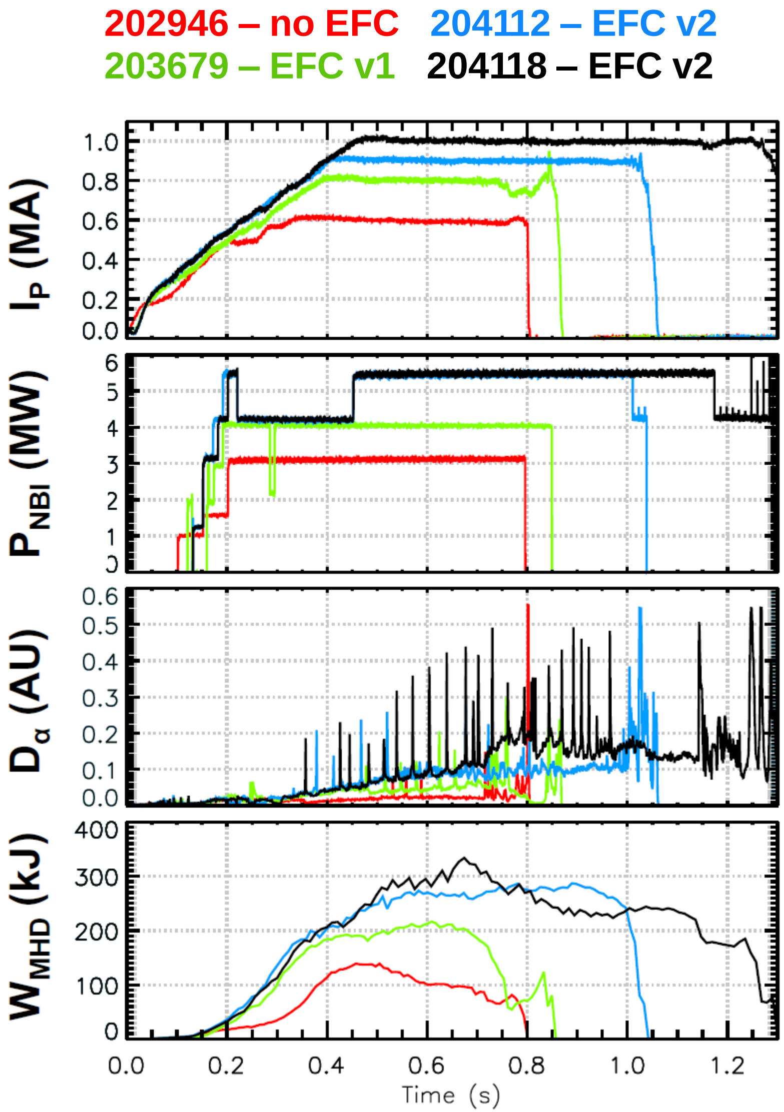


NSTX-U L-mode duration exceeds longest NSTX H-mode

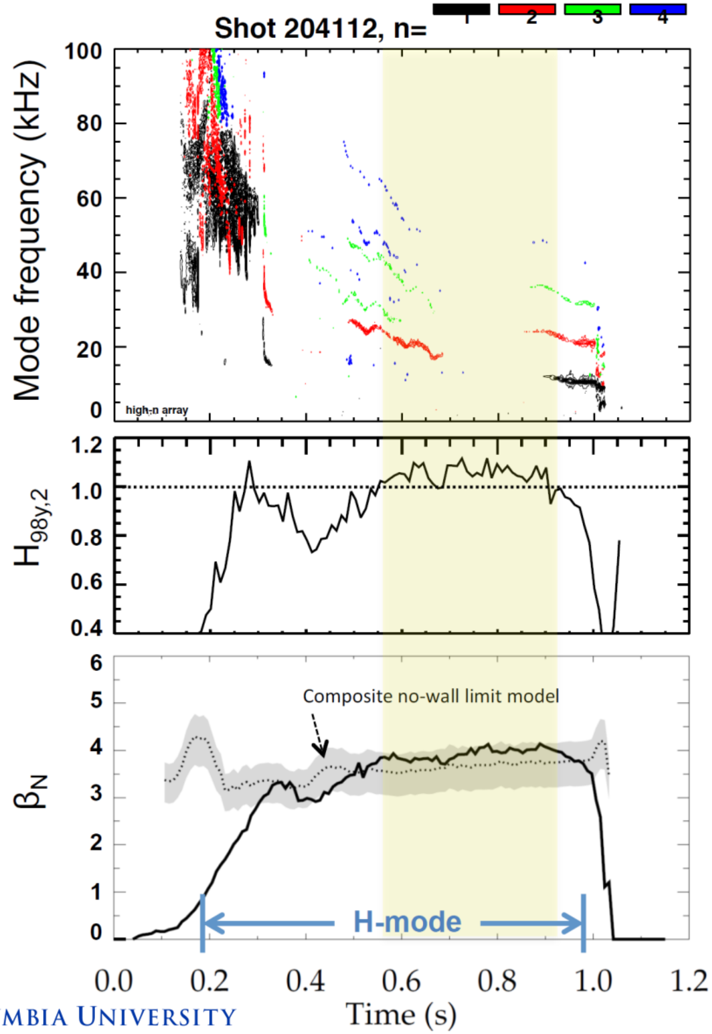


NSTX-U B_T > highest NSTX B_T

Recovered ~1MA H-modes with performance comparable to best NSTX plasmas at similar current

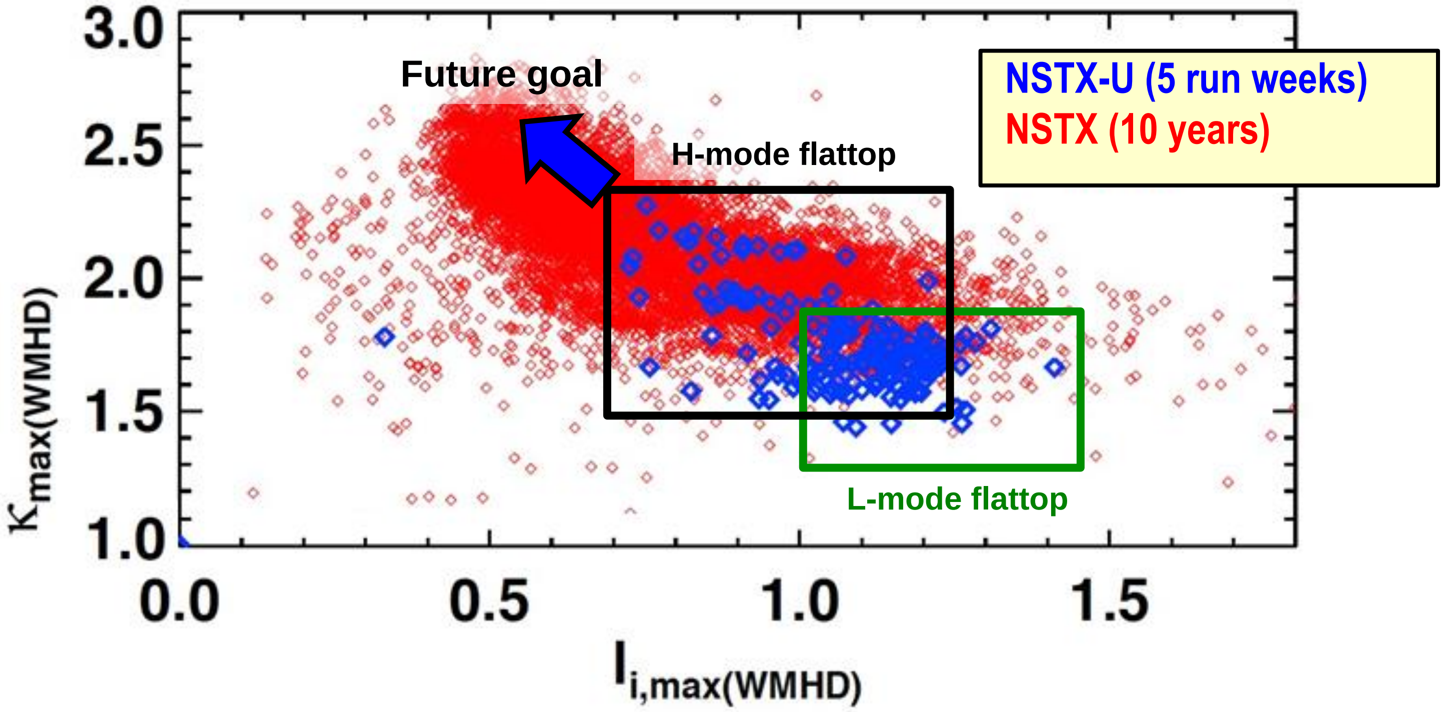


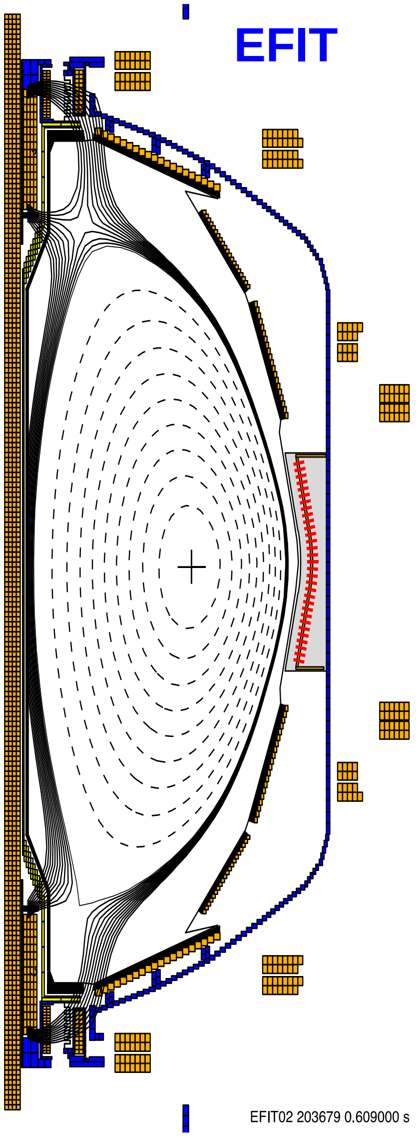
$H_{98} \geq 1$, β_N ~ 3.5-4 ≥ n=1 no-wall limit



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

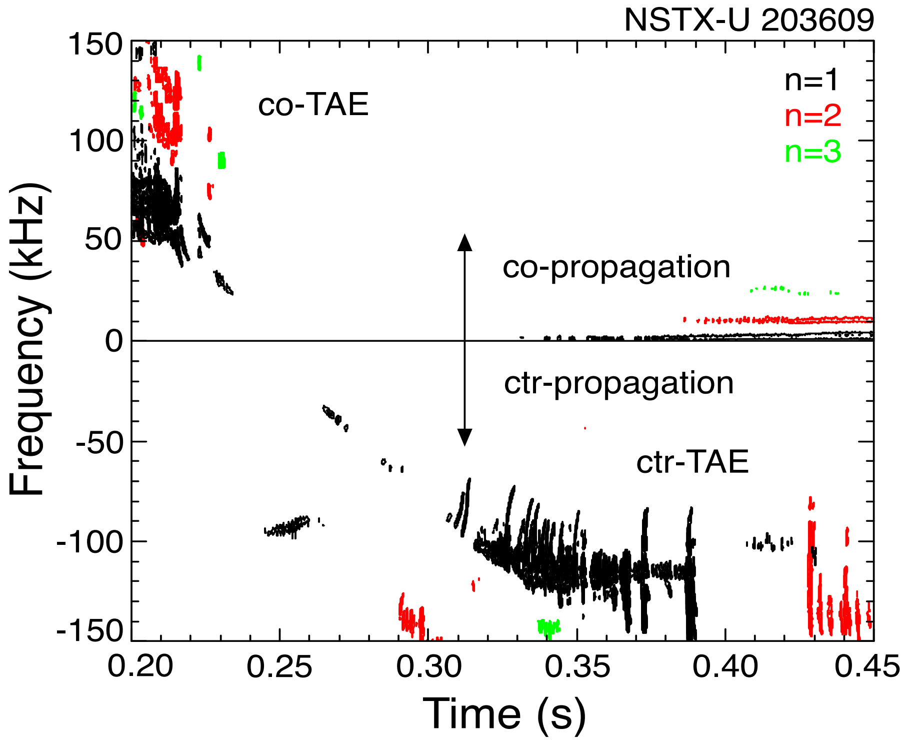
Accessed high elongation κ using progressively earlier H-mode and heating + optimized EFC





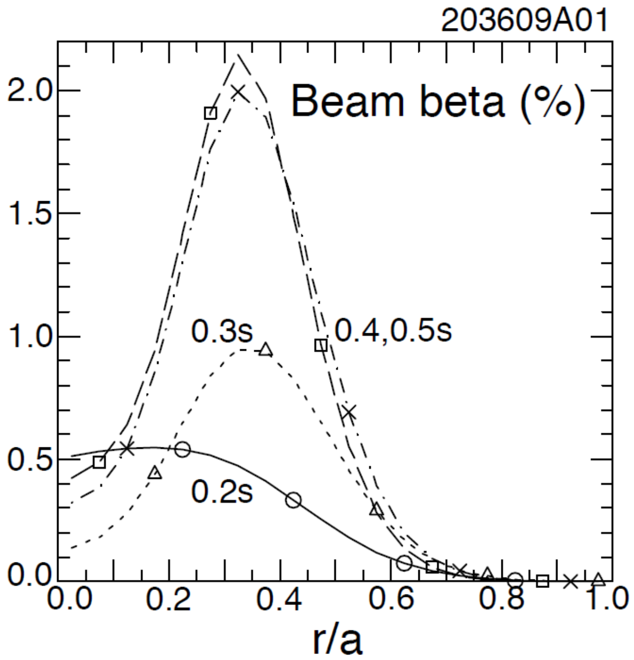
- **Goal: Internal inductance l_i = 0.5-0.7 → κ = 2.4-2.7**

New: Most tangential NBI generates counter-propagating Toroidal Alfvén Eigenmodes (TAEs)



- Counter-propagating TAE predicted for **hollow** fast-ion profiles

H.V. Wong, H. Berk, Phys. Lett. A ***251*** *(1999) 126.*



- TRANSP: As current builds up beam fast-ion beta profile predicted to become hollow
- **1st evidence of off-axis NBI in NSTX-U**

NSTX-U had scientifically productive 1st year

- Achieved H-mode on 8th day of 10 weeks of operation
- Surpassed magnetic field and pulse-duration of NSTX
- Matched best NSTX H-mode performance at ~1MA
- Identified and corrected dominant error fields
- Commissioned all magnetic and kinetic profile diagnostics
- Discovered new 2nd NBI modifies several fast-ion modes
- Injected up to 12MW NBI power into armor by end of run
- Implemented techniques for controlled plasma shut down, disruption detection, commissioned new tools for mitigation

- 2016 run ended prematurely due to fault in divertor PF coil
  - Coil forensics, Extent of Condition → new coil fab, other repairs
  - Aim to resume plasma operation during 2018

Goals for future NSTX-U operation

- Increase field to 0.8-1T, current to 1.6-2MA, extend flat-top duration (H-mode) to 2-5s
- Assess global stability, energy confinement, pedestal height/structure, edge heat-flux width
- Characterize 2nd beam: heating, current drive, torque / rotation profiles, fast-ion instabilities
- Push toward full non-inductive startup & current drive
- Test advanced divertor heat flux mitigation

Goals for future NSTX-U operation

- Increase field to 0.8-1T, current to 1.6-2MA, extend flat-top duration (H-mode) to 2-5s

(my expertise 🙂 *)*

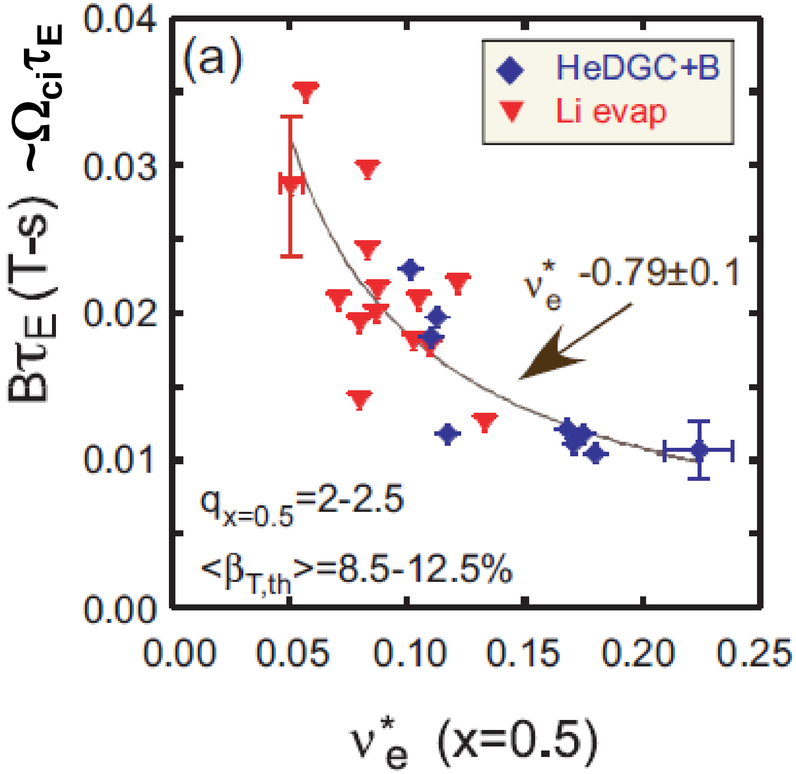
- Assess global stability, **<u>energy confinement</u>**, pedestal height/structure, edge heat-flux width
- Characterize 2nd beam: heating, current drive, torque / rotation profiles, fast-ion instabilities
- Push toward full non-inductive startup & current drive
- Test advanced divertor heat flux mitigation

Normalized energy confinement time scales favorably with collisionality in STs

- $\tau_E \sim I_p^{0.4} B_T^{1.0}$ (boronization + between-shots He GDC)
- $\tau_E \sim I_p^{0.8} B_T^{-0.15}$ (between-shots Lithium evap.) – similar to ITER $\tau_{E,98y2} \sim I_p^{0.9} B_T^{-0.15}$

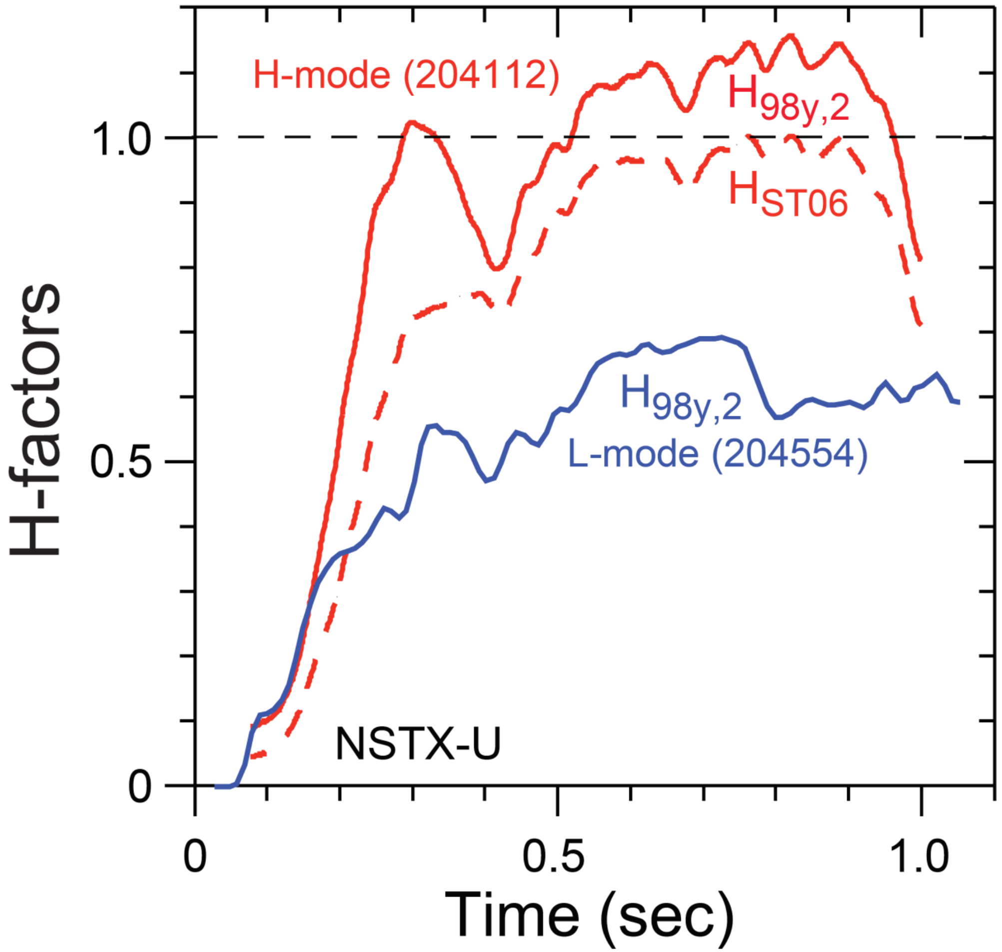
- Considering dimensionless scaling ($\sim\rho_*$, q, β, ν_*), $\boldsymbol{\Omega_{ci}\tau_E \sim \nu_*^{-0.8}\, \beta^{0.0}}$
- **Next generation STs (FNSF, CTF, Pilot Plant) likely to be at lower ν_***
  - Will favorable ν_* scaling continue?
  - Hints at lower ν_* that $\chi_i > \chi_{i,NC}$

NSTX



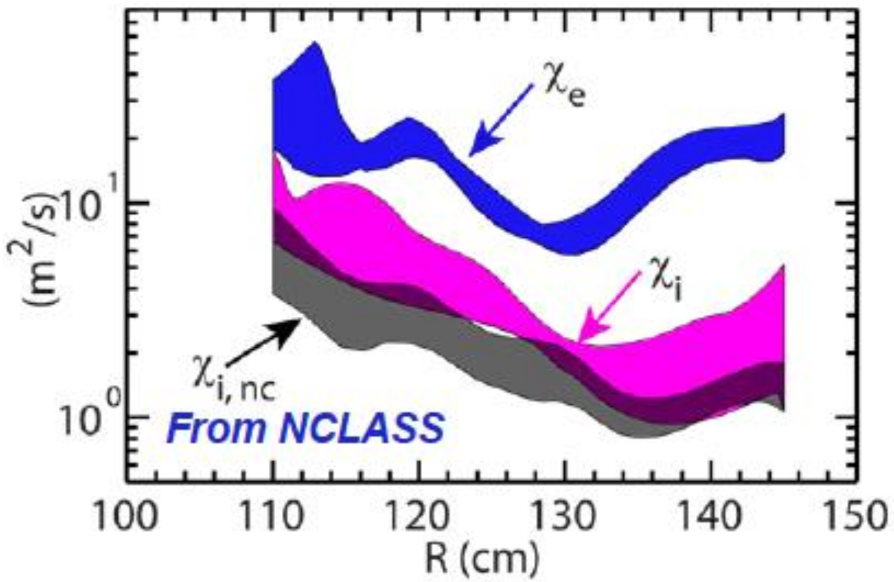
Kaye, NF (2013)

NSTX-U H-mode confinement consistent with ST scaling (so far) – need higher I_P, B_T to test



NSTX-U

Ion thermal transport in H-modes (higher beta) usually very close to collisional (neoclassical) transport theory



Courtesy Y. Ren

- Conventional tokamaks usually observe anomalous ion heat transport, attributed to microturbulence e.g. from Ion Temperature Gradient (ITG) instability

Why does turbulence develop in tokamaks?

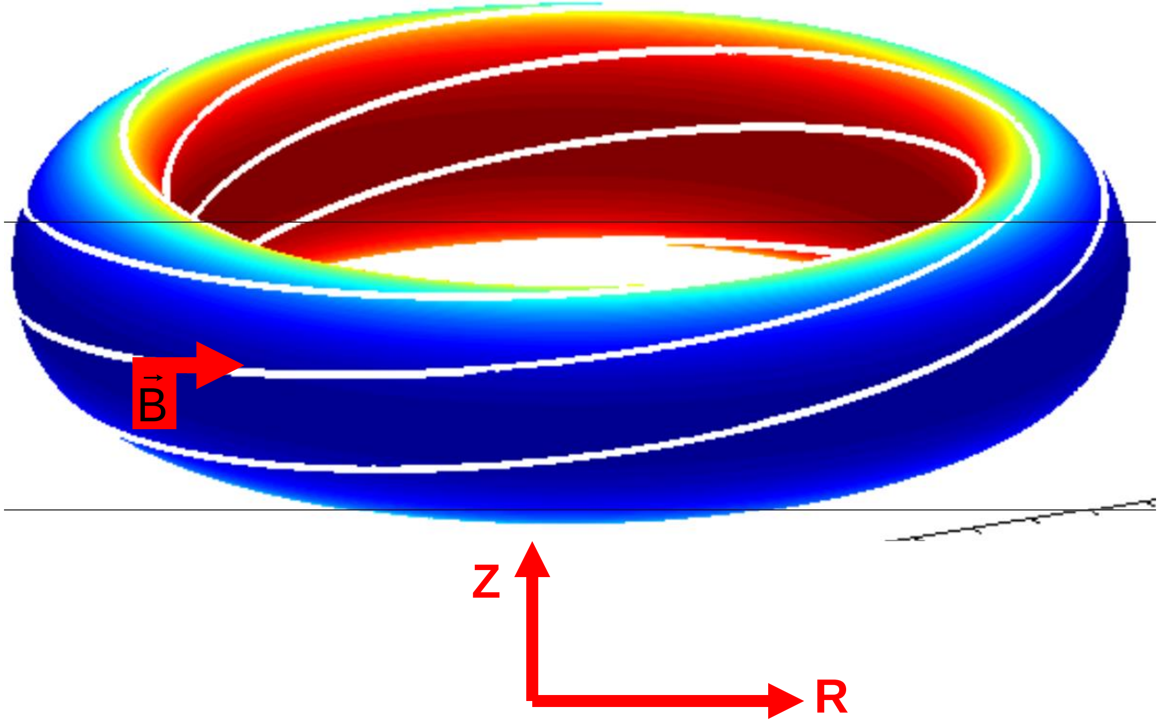
Example: Linear stability analysis of Ion Temperature Gradient (ITG) “ballooning” micro-instability (expected to dominate in ITER)

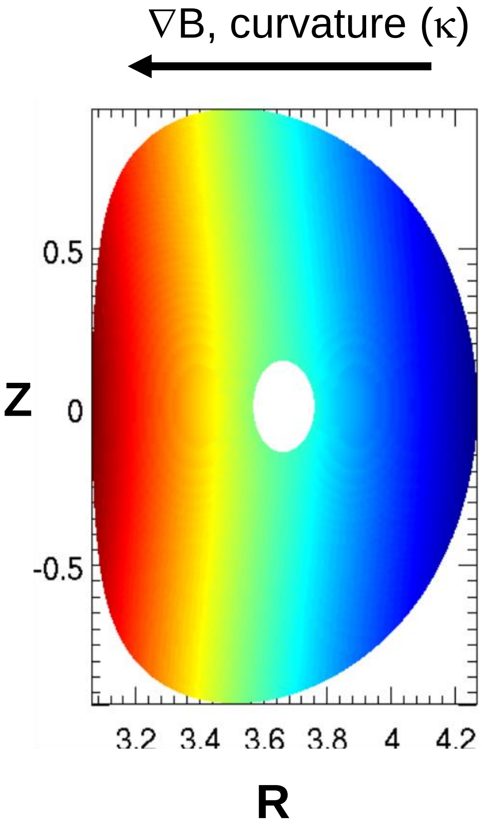
Toroidicity Leads To Inhomogeneity in |B|, gives ∇B and curvature (κ) drifts

$$\vec{v}_\kappa = m v_\parallel^2 \frac{\hat{b}\times\vec{\kappa}}{qB} \sim T_\parallel$$

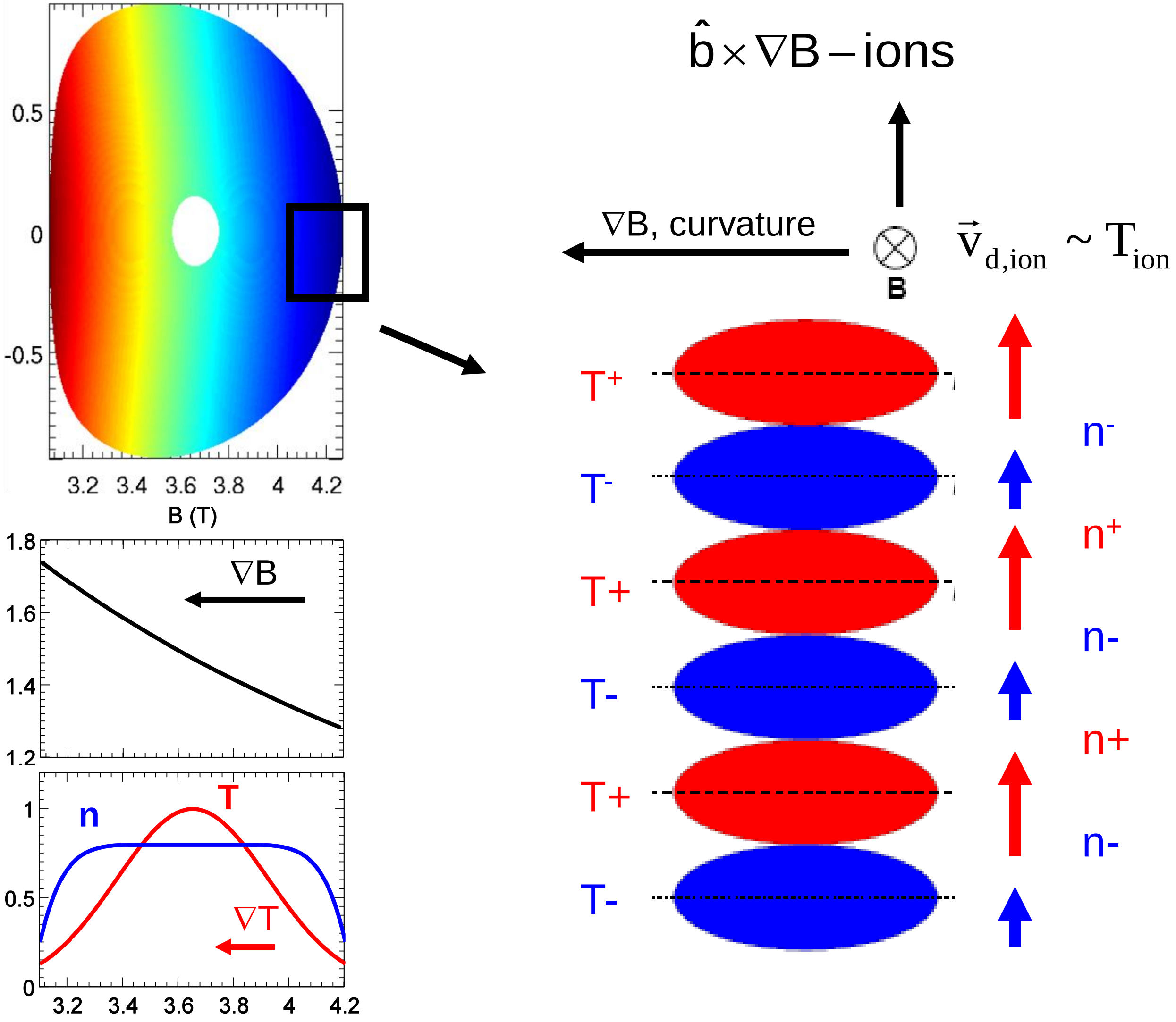
$$\vec{v}_{\nabla B} = \frac{m v_\perp^2}{2}\frac{\hat{b}\times\nabla B/B}{qB} \sim T_\perp$$

- What happens when there are small perturbations in $T_\parallel$, $T_\perp$? ⇒ Linear stability analysis…





Temperature perturbation (δT) leads to compression ($\nabla\cdot v_{di}$), density perturbation – 90° out-of-phase with δT



- Fourier decompose perturbations in space ($k_\theta\rho_i \lesssim 1$)
- Assume small δT perturbation

Dynamics Must Satisfy Quasi-neutrality

- Quasi-neutrality (Poisson equation, $k_\perp^2\lambda_D^2 << 1$) requires

$$-\nabla^2\tilde{\varphi} = \frac{1}{\varepsilon_0}\sum_s eZ_s \int d^3v f_s$$

$$\left(k_\perp^2\lambda_D^2\right)\frac{\tilde{\varphi}}{T} = \frac{\tilde{n}_i - \tilde{n}_e}{n_0}$$

$$\boxed{\tilde{n}_i = \tilde{n}_e}$$

- For this ion drift wave instability, parallel electron motion is very rapid

$$\omega < k_{\|}v_{Te} \;\rightarrow\; 0 = -T_e\nabla\tilde{n}_e + n_e e\nabla\tilde{\varphi}$$

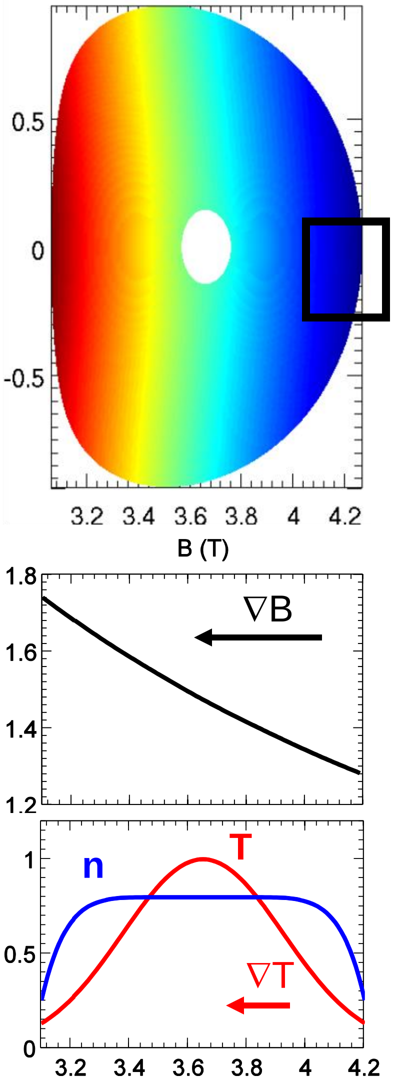
$\Rightarrow$Electrons (approximately) maintain a Boltzmann distribution

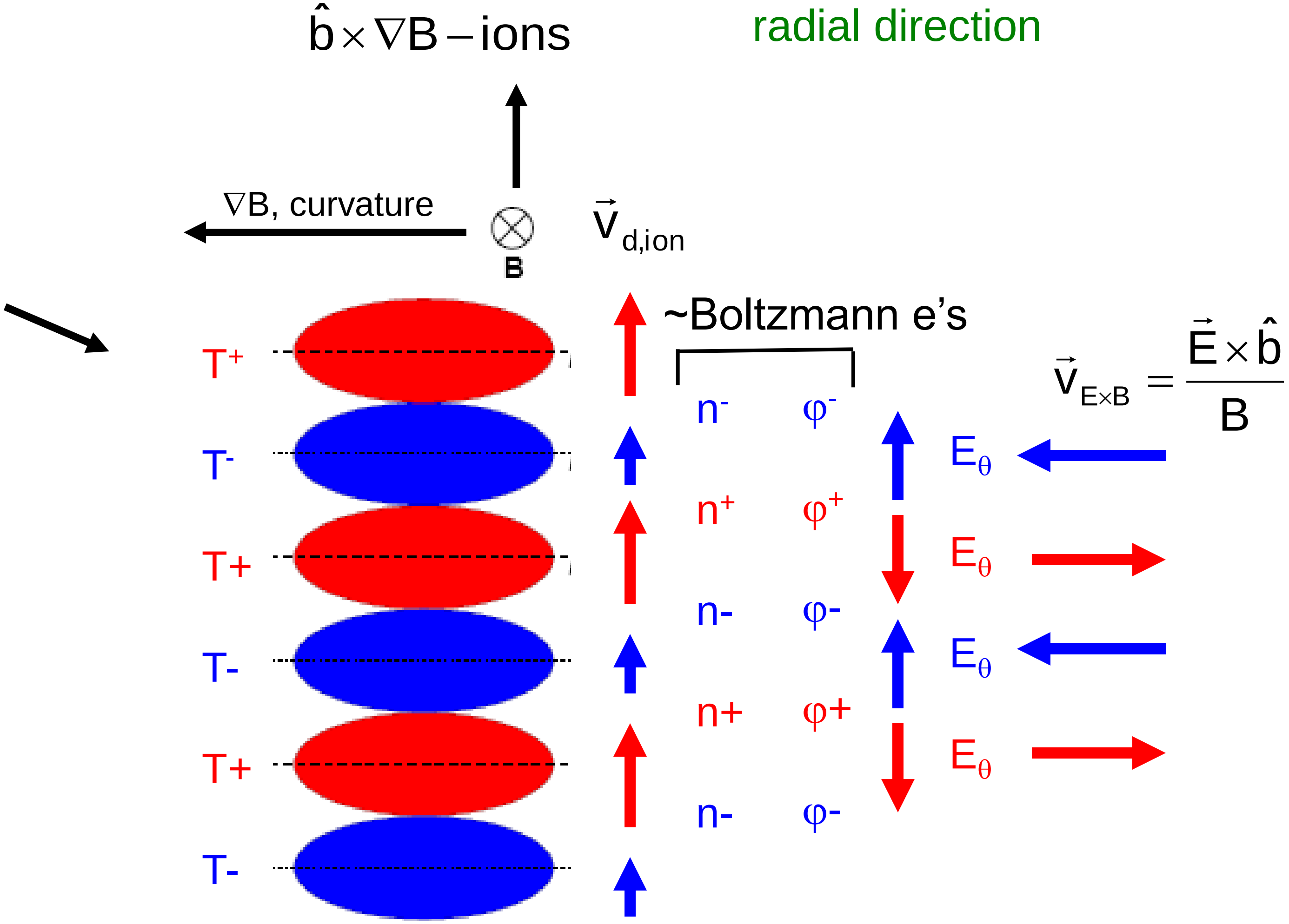
$$\left(n_0 + \tilde{n}_e\right) = n_0\exp\left(e\tilde{\varphi}/T_e\right)$$

$$\tilde{n}_e \approx n_0 e\tilde{\varphi}/T_e \Rightarrow \underline{\tilde{n}_e \approx \tilde{\varphi}}$$

Perturbed Potential Creates E×B Advection

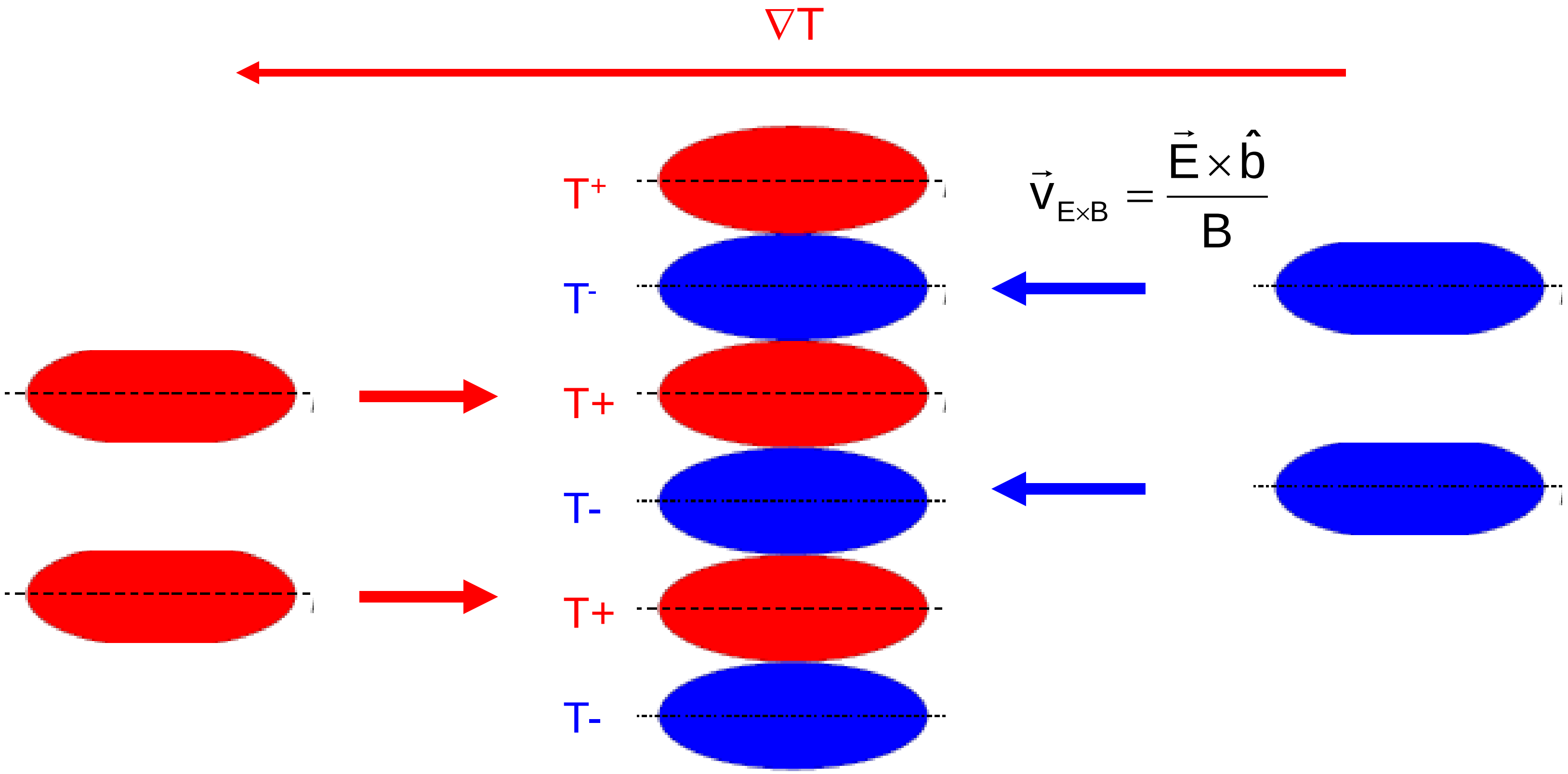
- Advection occurs in the radial direction





$$\vec{v}_{E\times B} = \frac{\vec{E} \times \hat{b}}{B}$$

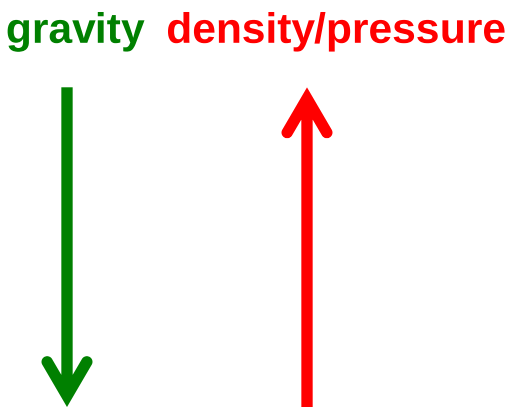
Background Temperature Gradient Reinforces Perturbation ⇒ Instability



$$\vec{v}_{E\times B} = \frac{\vec{E}\times\hat{b}}{B}$$

Analogy for turbulence in tokamaks – Raylor-Taylor instability

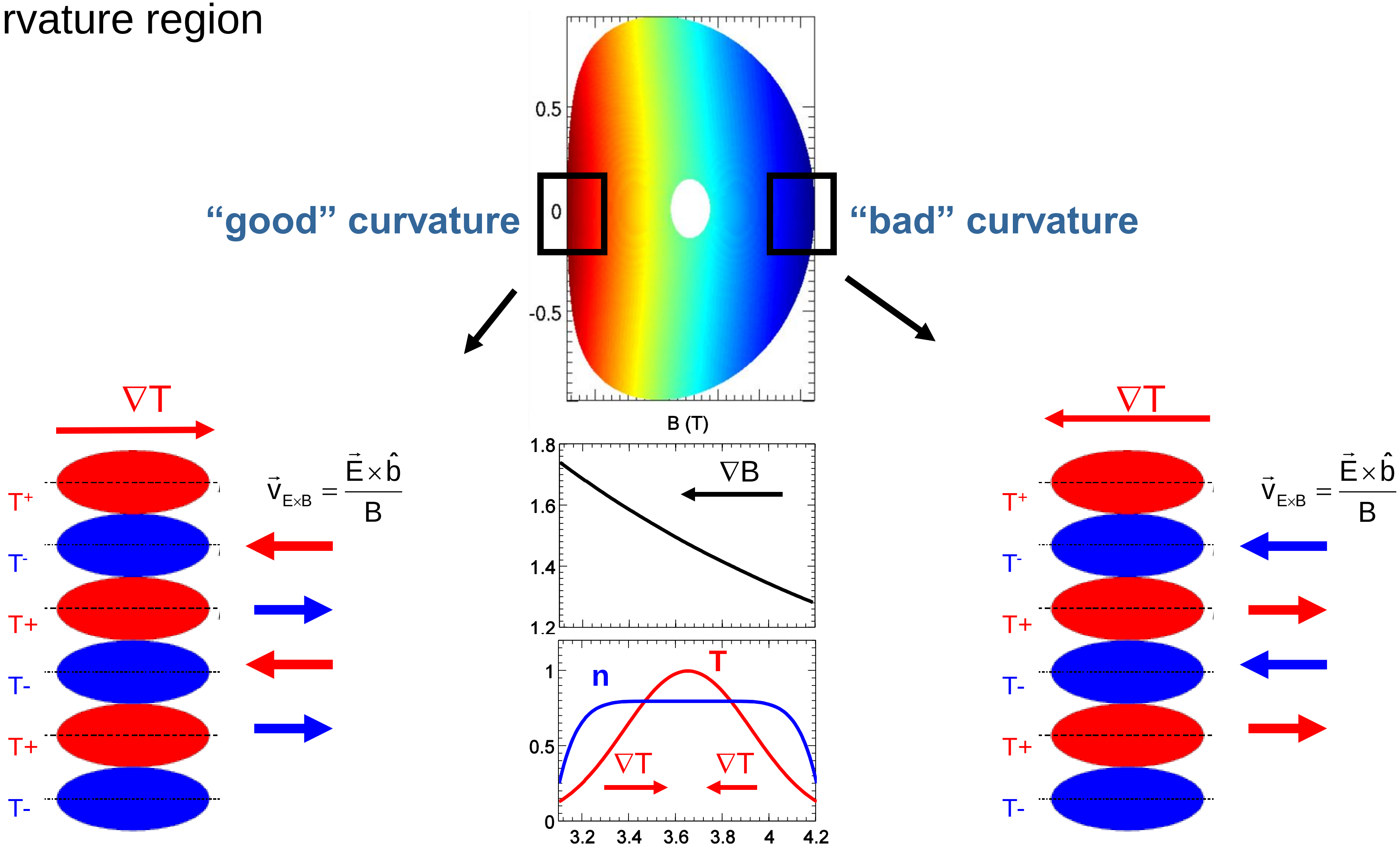
- Higher density on top of lower density, with gravity acting downwards



gravity **density/pressure**

Same Dynamics Occur On Inboard Side But Now Temperature Gradient Is Stabilizing

- Advection with ∇T counteracts perturbations on inboard side – “good” curvature region



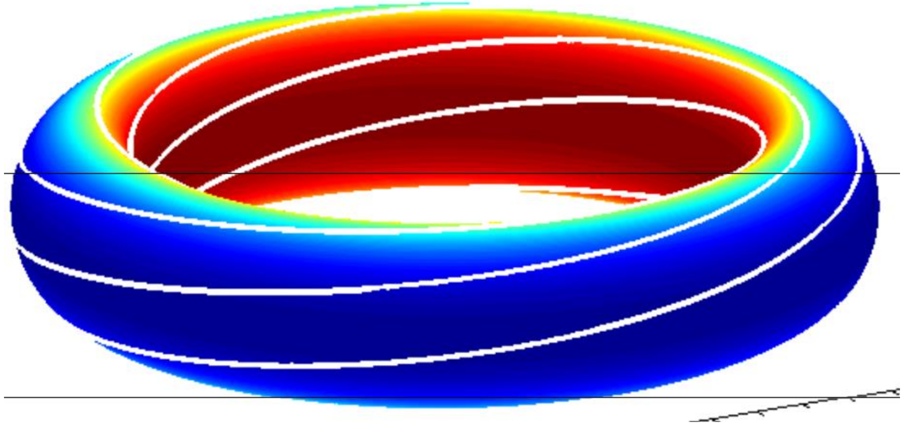
Fast Parallel Motion Along Helical Field Line Connects Good & Bad Curvature Regions

- Approximate growth rate on outboard side

$$\gamma_{\mathrm{instability}} \sim \frac{v_{\mathrm{th}}}{\sqrt{R L_T}} \qquad 1/L_T = -1/T \cdot \nabla T$$

- Parallel transit time

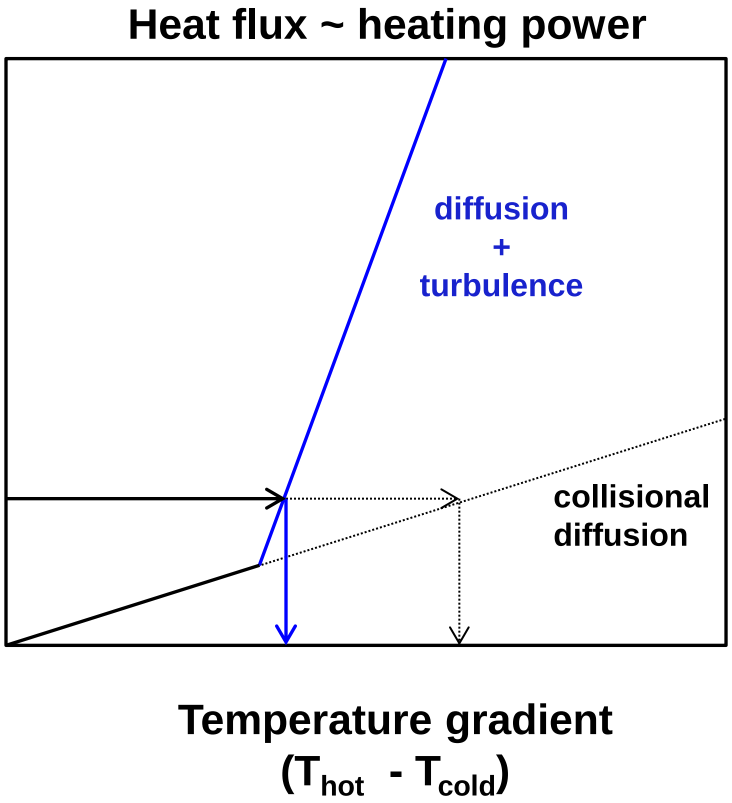
$$\gamma_{\mathrm{parallel}} \sim \frac{v_{\mathrm{th}}}{qR}$$



- Expect instability if $\gamma_{\mathrm{instability}} > \gamma_{\mathrm{parallel}}$, or

$$\left(\frac{R}{L_T}\right)_{\mathrm{threshold}} \approx \frac{1}{q^2}$$

Threshold like behavior analogous to Rayleigh-Benard instability



Analogous to convective transport when heating a fluid from below … boiling water (before the boiling)

Rayleigh, Benard, early 1900's

Threshold gradient for temperature gradient driven instabilities have been characterized over parameter space with gyrokinetic simulations

ITG/TEM & ETG turbulence appears to describe tokamak transport in many cases

Ion scales ($k_\perp \rho_i$~1)

- Ion temperature gradient (**ITG**, $\gamma \sim \nabla T_i$) via ion compressibility (~∇B, κ)
- Trapped electron mode (**TEM**, $\gamma \sim \nabla T_e, \nabla n_e$) from electron trapping (~f_t)

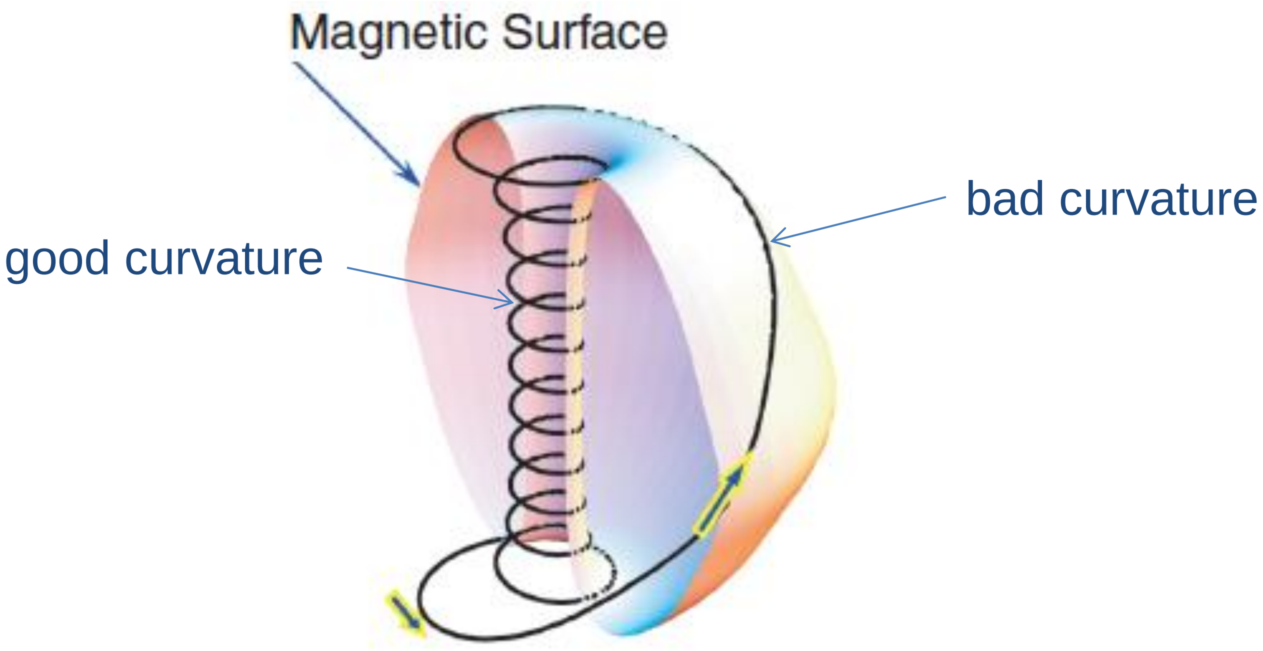
Electron scales ($k_\perp \rho_e$~1)

- Electron temperature gradient (**ETG**, $\gamma \sim \nabla T_e$), analogous to ITG (~∇B, κ)

- Instabilities driven by gradients (∇T_i, ∇ T_e, ∇n) surpassing thresholds which depend on: connection length (~qR), magnetic shear (dq/dr), temperature ratio (T_e/T_i), **additional equilibrium effects** …

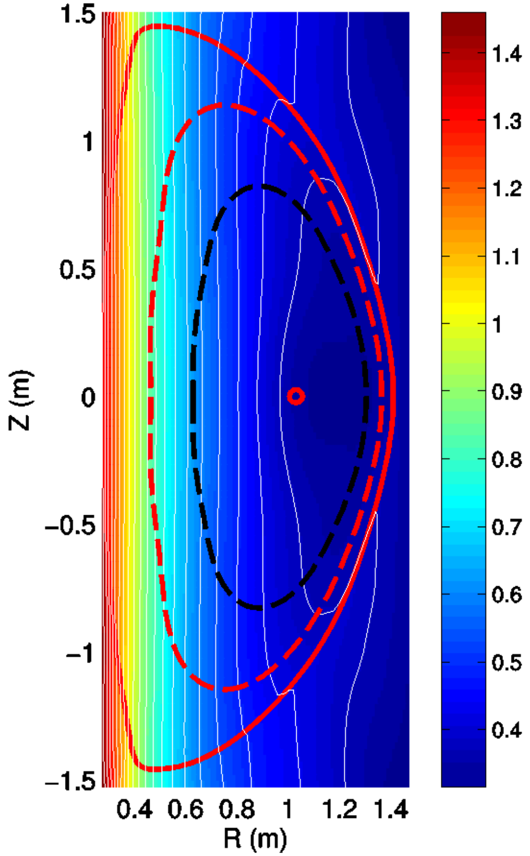
Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

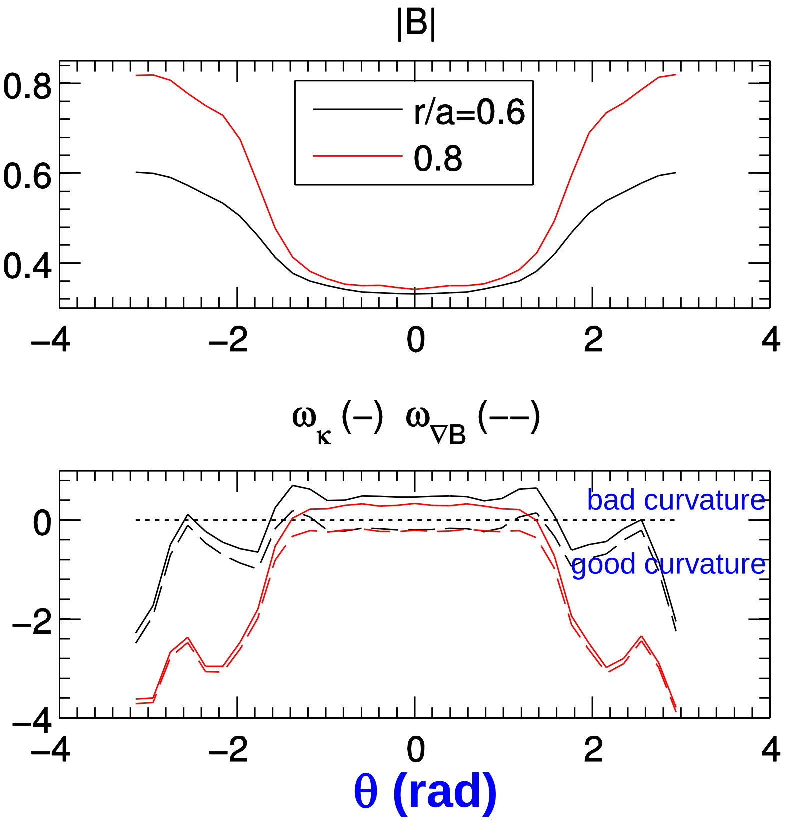
- Short connection length → **smaller average bad curvature**



Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length → **smaller average bad curvature**
- Quasi-isodynamic (~constant B) at high β → **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**



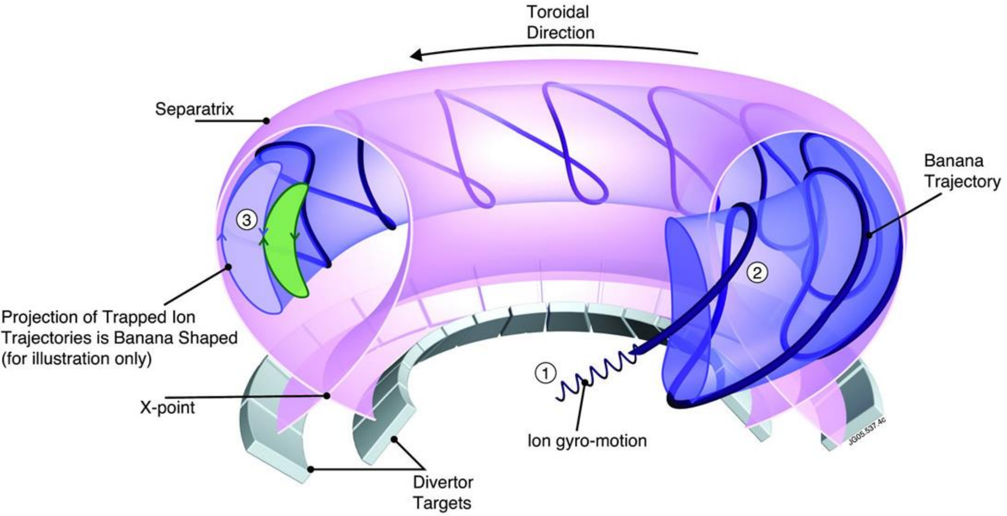


$$\vec{v}_{\kappa} = m v_{||}^2 \frac{\hat{b}\times\vec{\kappa}}{qB}$$

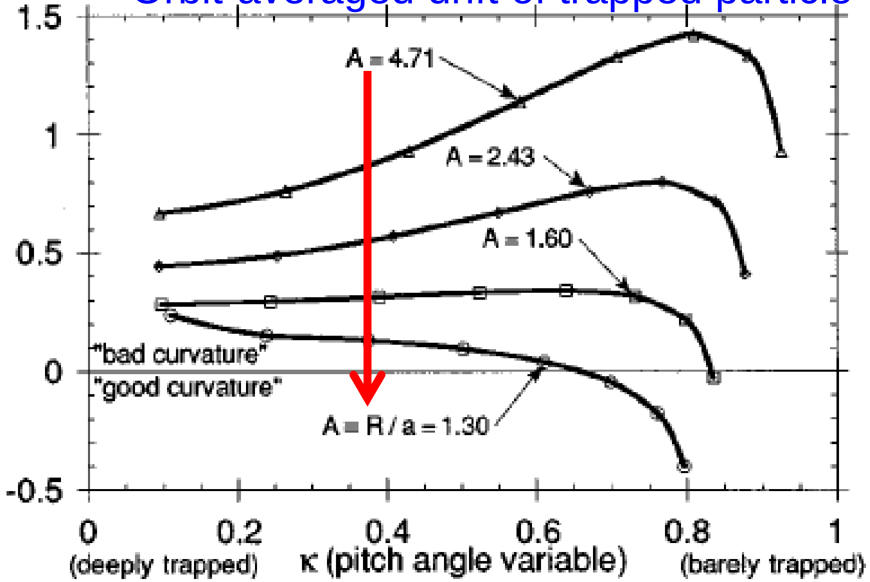
$$\vec{v}_{\nabla B} = \frac{m v_{\perp}^2}{2}\frac{\hat{b}\times\nabla B/B}{qB}$$

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length → **smaller average bad curvature**
- Quasi-isodynamic (~constant B) at high β → **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**
- Large fraction of trapped electrons, BUT precession weaker at low A → **reduced TEM drive [Rewoldt, Phys. Plasmas 1996]**

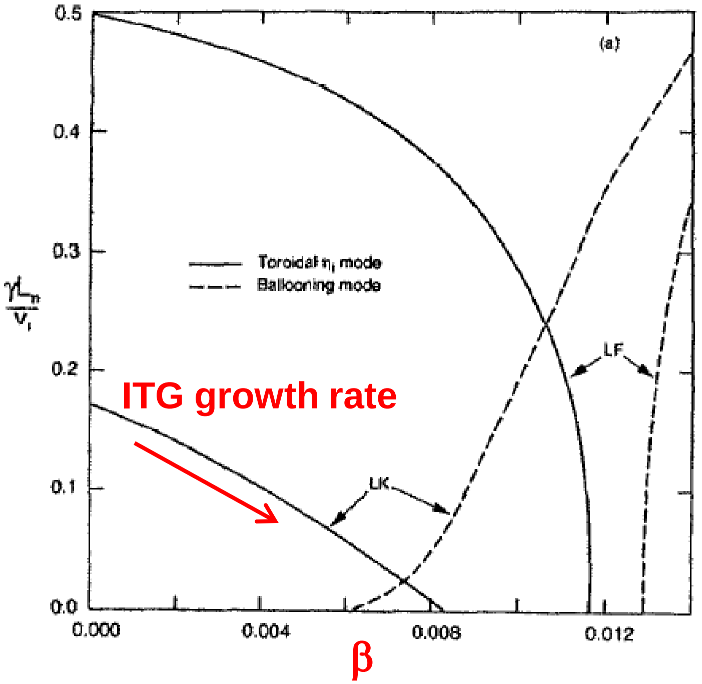


Orbit-averaged drift of trapped particle



Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

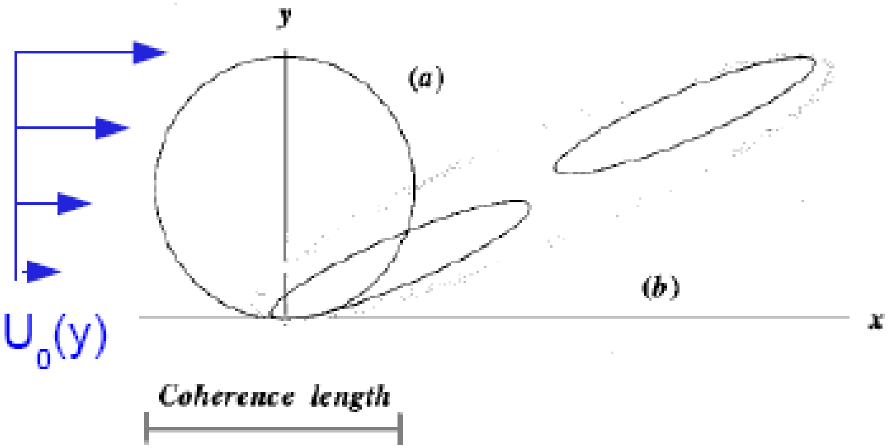
- Short connection length → **smaller average bad curvature**
- Quasi-isodynamic (~constant B) at high β → **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**
- Large fraction of trapped electrons, BUT precession weaker at low A → **reduced TEM drive [Rewoldt, Phys. Plasmas 1996]**
- Strong coupling to $\delta B_\perp \sim \delta A_{||}$ at high β → **stabilizing to ES-ITG**



Kim, Horton, Dong, PoFB (1993)

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length → **smaller average bad curvature**
- Quasi-isodynamic (~constant B) at high β → **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**
- Large fraction of trapped electrons, BUT precession weaker at low A → **reduced TEM drive [Rewoldt, Phys. Plasmas 1996]**
- Strong coupling to $\delta B_\perp \sim \delta A_{||}$ at high β → **stabilizing to ES-ITG**
- Small inertia ($nm\underline{R}^2$) with uni-directional NBI heating gives strong toroidal flow & flow shear → **E×B shear stabilization ($dv_\perp/dr$)**



Biglari, Diamond, Terry, PoFB (1990)

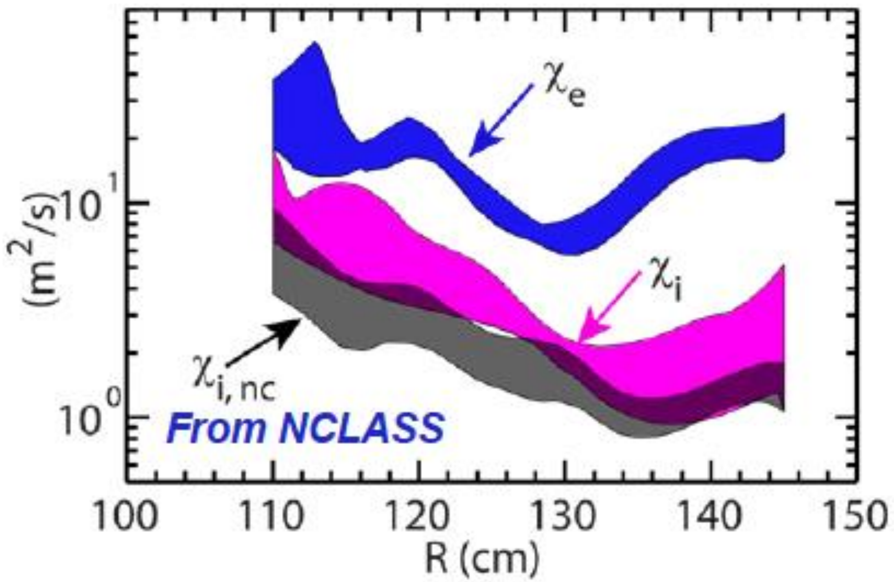
Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length → **smaller average bad curvature**
- Quasi-isodynamic (~constant B) at high β → **grad-B drifts stabilizing [Peng & Strickler, NF 1986]**
- Large fraction of trapped electrons, BUT precession weaker at low A → **reduced TEM drive [Rewoldt, Phys. Plasmas 1996]**
- Strong coupling to $\delta B_\perp \sim \delta A_{||}$ at high β → **stabilizing to ES-ITG**
- Small inertia (nmR^2) with uni-directional NBI heating gives strong toroidal flow & flow shear → **E×B shear stabilization ($dv_\perp/dr$)**

⇒**Not expecting strong ES ITG/TEM instability (much higher thresholds)**

- <u>BUT</u>
- High beta drives EM instabilities: microtearing modes (**MTM**) ~ $\beta_e \cdot \nabla T_e$, kinetic ballooning modes (**KBM**) ~ $\alpha_{MHD} \sim q^2 \nabla P / B^2$
- Large shear in parallel velocity can drive Kelvin-Helmholtz-like instability $\sim dv_{||}/dr$

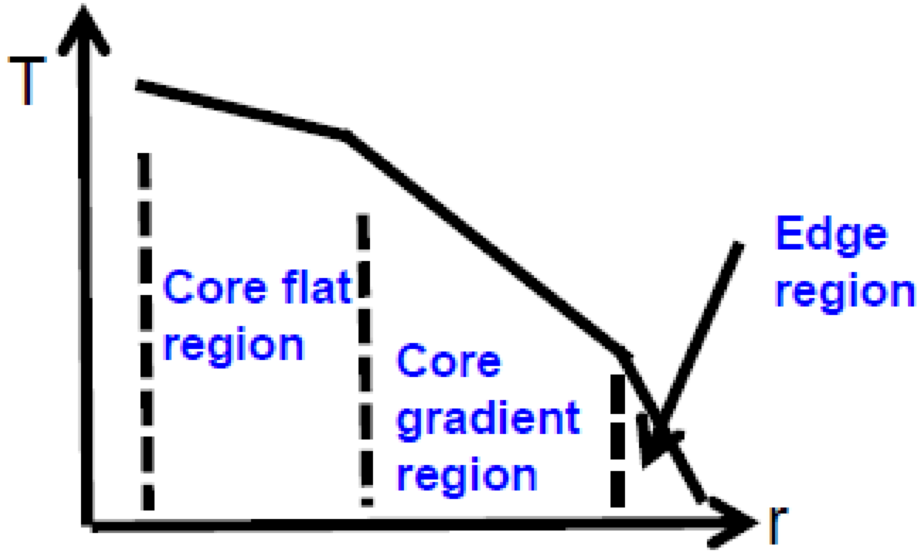
Ion thermal transport in H-modes (higher beta) usually very close to collisional (neoclassical) transport theory



Courtesy Y. Ren

- Consistent with ITG/TEM stabilization by equilibrium configuration & strong E×B flow shear
  - – Impurity transport (intrinsic carbon, injected Ne, …) also usually well described by neoclassical theory [Delgado-Aparicio, NF 2009 & 2011 ; Scotti, NF 2013]
- **Electron energy transport always anomalous**
  - – Toroidal angular momentum transport also anomalous (Kaye, NF 2009)

Typically address transport mechanisms in three regions of the plasma

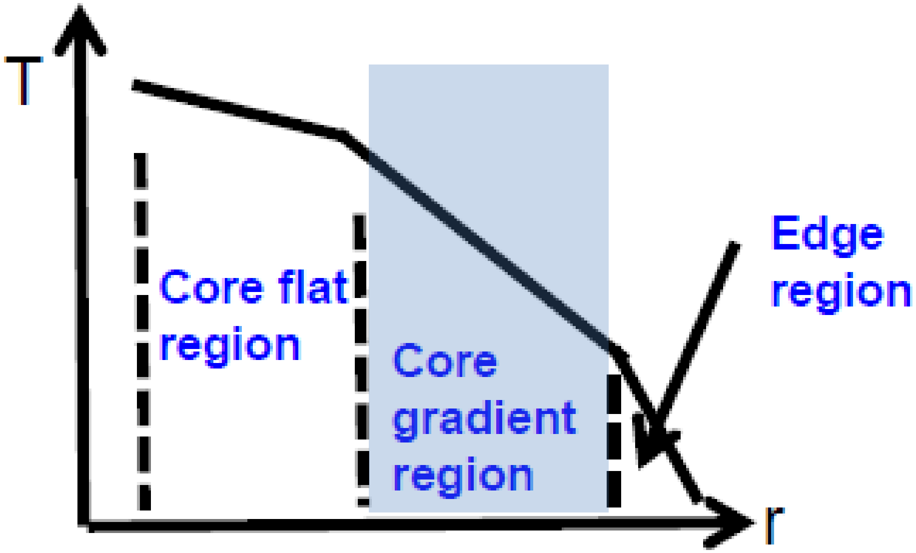


- H-mode edge pedestal – strong gradients
- Core gradient region – inside pedestal
- Core flat region – region of weak ∇Te

} Susceptible to gradient-driven instabilities (e.g. drift-waves)

} Must consider other mechanisms (e.g. driven by fast-ions)

Typically address transport mechanisms in three regions of the plasma



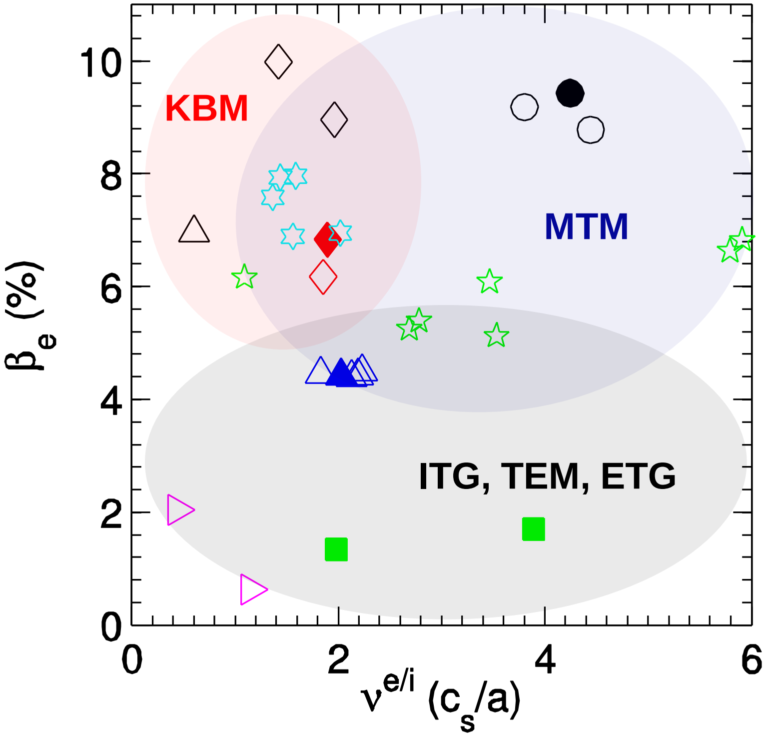
- H-mode edge pedestal – strong gradients
- **Core gradient region – inside pedestal**
- Core flat region – region of weak ∇Te

} Susceptible to gradient-driven instabilities (e.g. drift-waves)

} Must consider other mechanisms (e.g. driven by fast-ions)

Predicted dominant core-gradient instability correlated with local beta and collisionality

- For sufficiently small β, ES instabilities can still exist (ITG, TEM, ETG)
- At increasing β, MTM and KBM are predicted → depending on ν
  - Various instabilities often predicted in the same discharge – global, nonlinear EM theory & predictions will hopefully simplify interpretation (*under development*)



Guttenfelder, NF (2013)

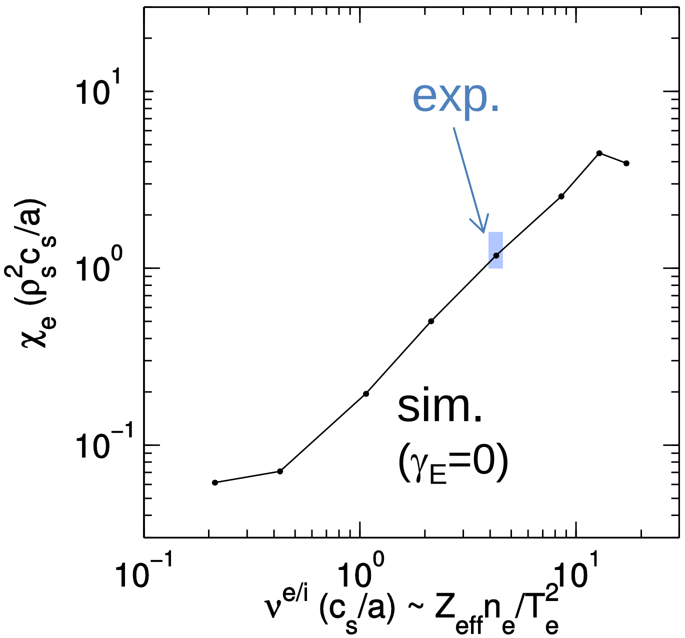
Local gyrokinetic analyses at ~2/3 radius

NSTX

Simulations of core microtearing mode (MTM) turbulence predict significant transport at high β & ν

- Collisionality scaling ($\chi_{e,MTM} \sim \nu_e$) consistent with global confinement ($\tau_E \sim 1/\nu$), follows linear stability trends:
  - In the core, driven by ∇T_e with time-dependent thermal force (e.g. Hassam, 1980)
  - *Requires collisionality → **not explicitly driven by bad-curvature***

Predicted transport



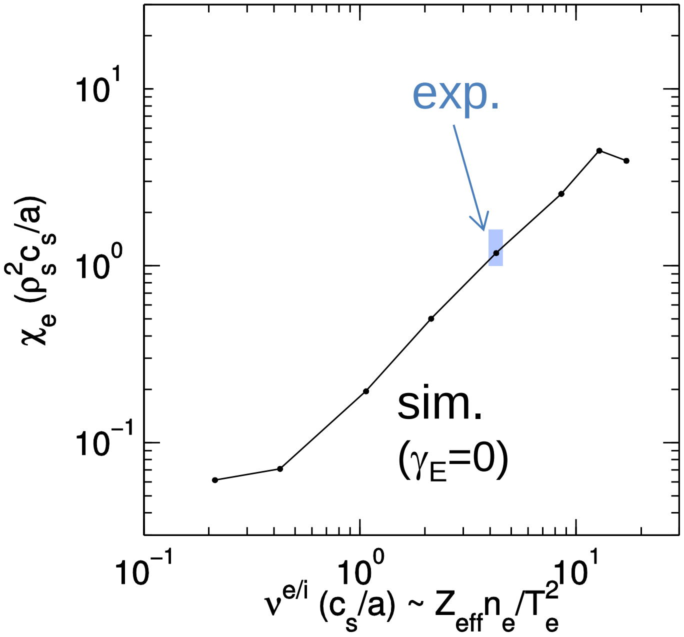
Guttenfelder, PRL (2011), PoP (2012)

NSTX

Simulations of core microtearing mode (MTM) turbulence predict significant transport at high β & ν

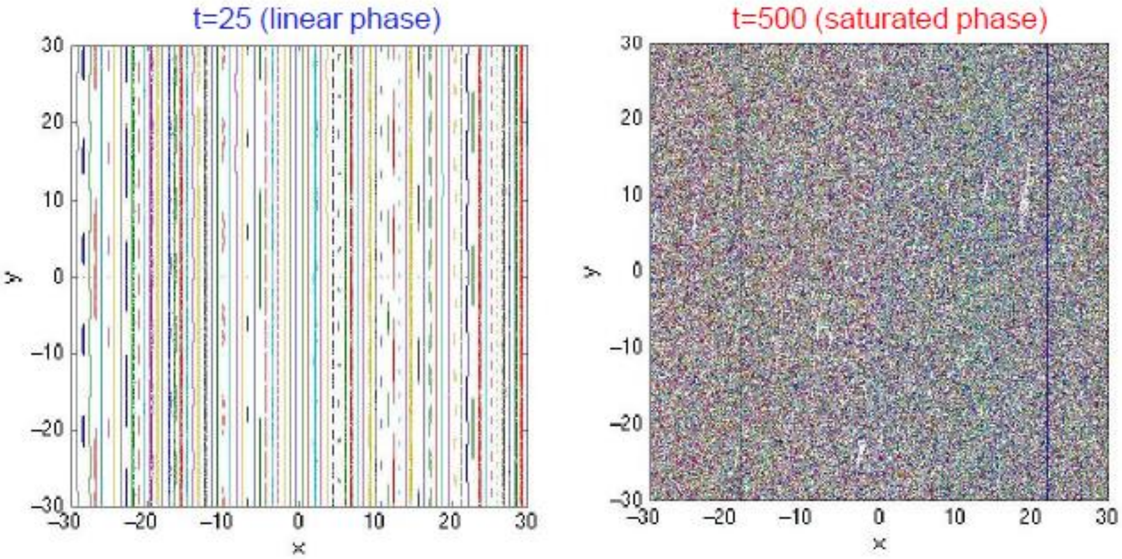
- Collisionality scaling ($\chi_{e,MTM}$~ν_e) consistent with global confinement (τ_E~$1/\nu$), follows linear stability trends:
  - In the core, driven by ∇T_e with time-dependent thermal force (e.g. Hassam, 1980)
  - *Requires collisionality $\rightarrow$* ***not explicitly driven by bad-curvature***
- δB leads to flutter transport (~$v_{||}\cdot\delta B^2$) consistent with stochastic transport

Predicted transport



Guttenfelder, PRL (2011), PoP (2012)

Poincare plots of flux-tube surfaces

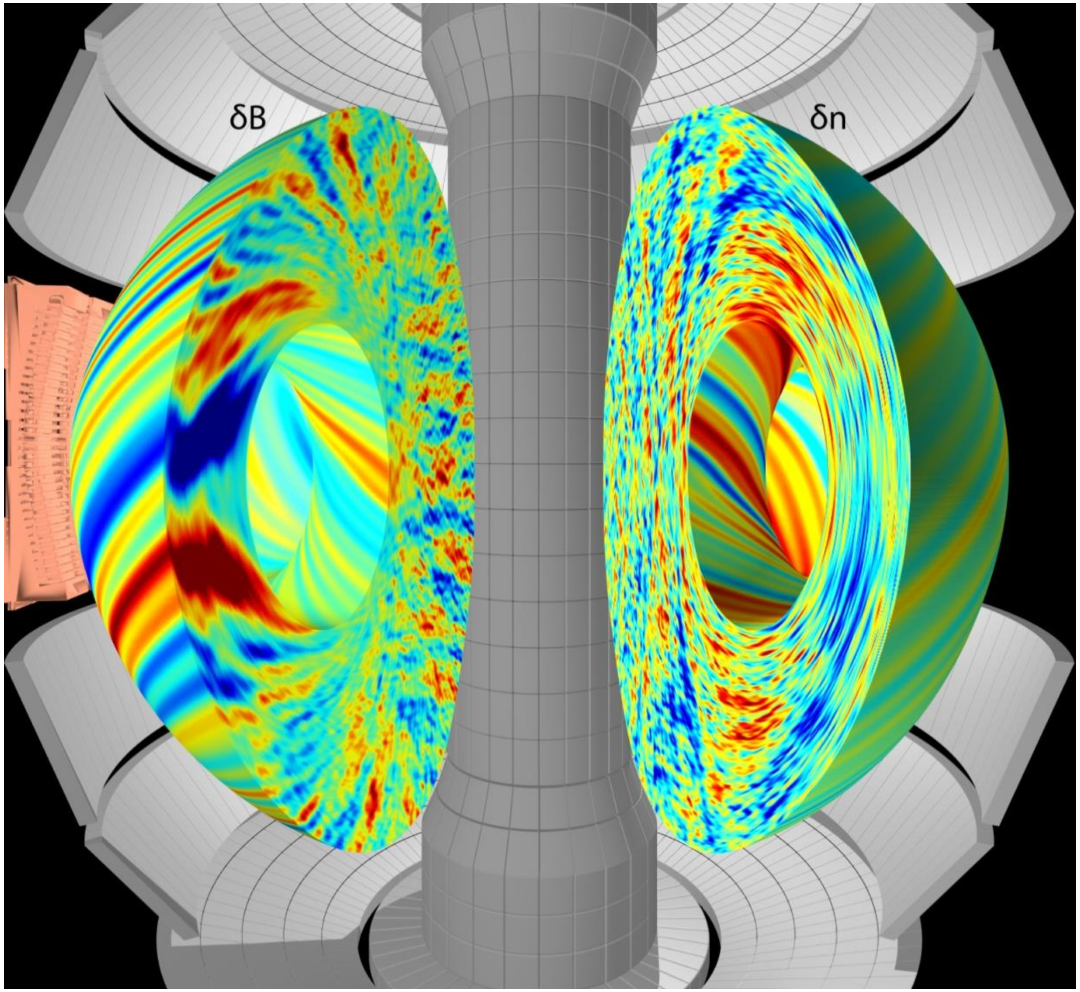


NSTX

E. Wang, PoP (2011)

MTM structure distinct from ballooning modes

Predictions from MTM simulation

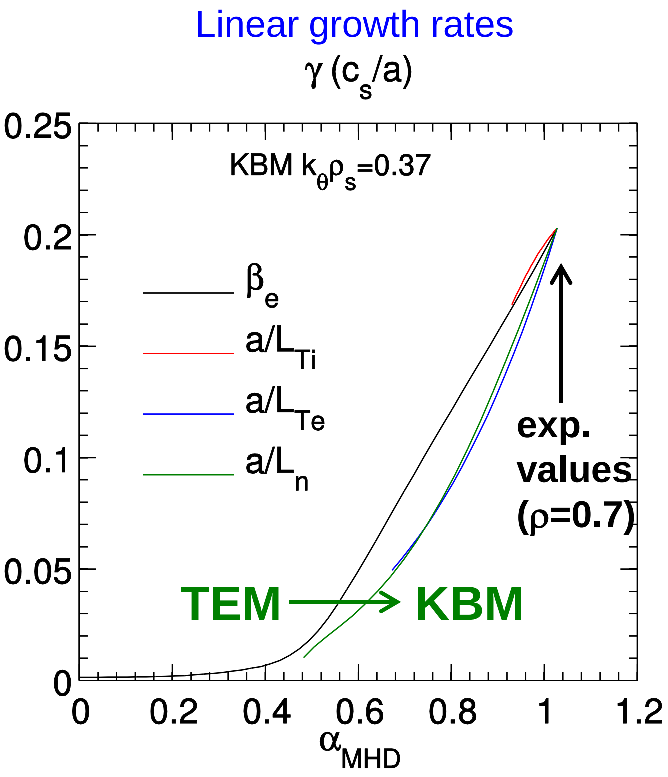


Visualization courtesy F. Scotti (LLNL)

- Narrow density perturbations due to high-m tearing mode around rational surfaces q=m/n
  - Potential to validate with beam emission spectroscopy (BES) imaging [Smith, RSI (2012)]
- Large $\delta B/B \sim 10^{-3}$
  - Potential for internal δB measurements via Cross Polarization Scattering, CPS (UCLA collaboration) $\Rightarrow$ **focus of a 2017 DIII-D National Campaign experiment**

At high β & lower ν, KBM modes predicted; Sensitive to compressional magnetic ($B_{||}$) perturbations

- Kinetic analogue of MHD high-n ballooning mode, driven by total ∇P (α_{MHD})
- Smooth transition from ITG/TEM at reduced ∇P
- Transport has significant compressional component ($\sim\delta B_{||}$)



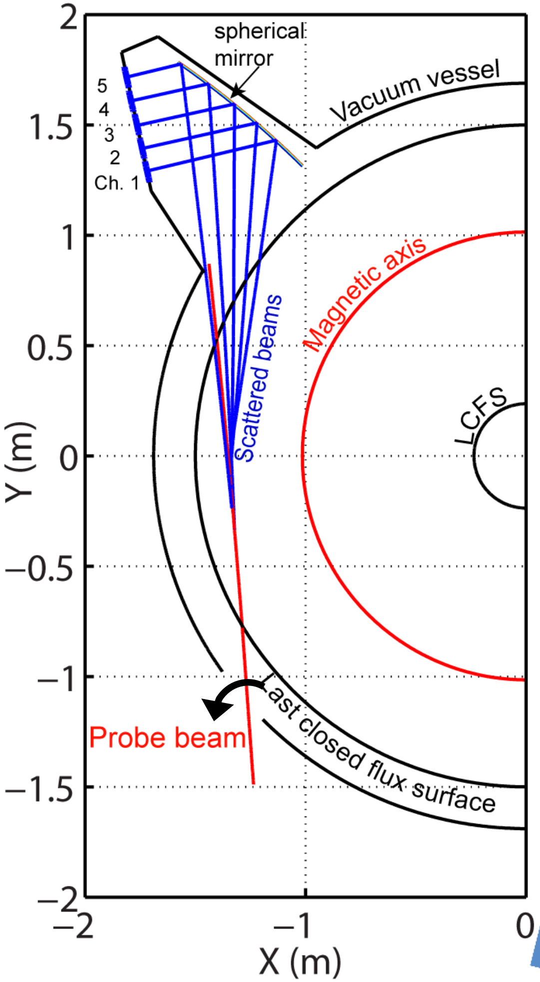
$$\boxed{\alpha_{MHD} = -q^2 R \cdot 2\mu_0 \nabla P / B^2}$$

NSTX

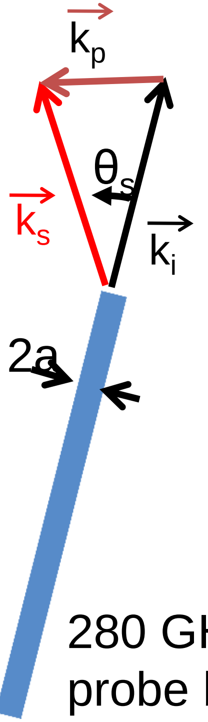
Guttenfelder, NF (2013)

Electron scale turbulence measured and predicted at lower beta

Microwave scattering used to detect high-$k_\perp$ (~mm) fluctuations

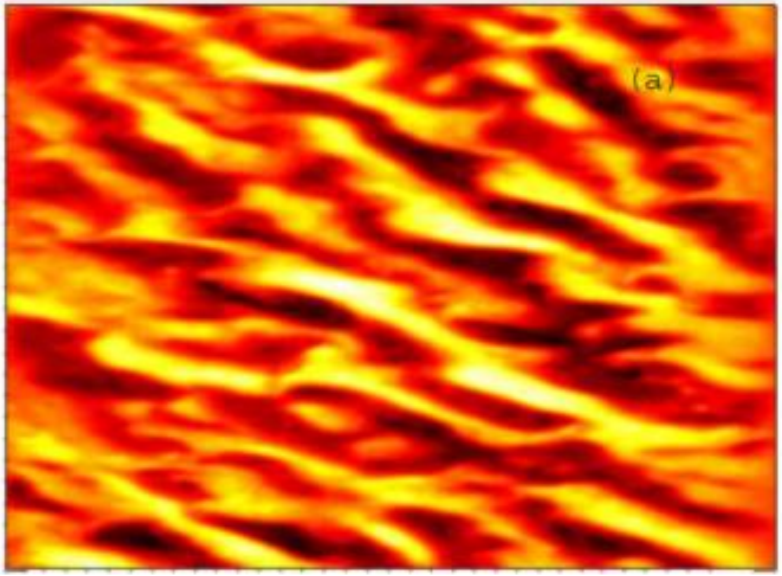


Mazzucato, PRL (2008)
Smith, RSI (2008)



280 GHz
probe beam

density fluctuations from ETG simulation



6 ion radii
360 electron radii
~2 cm

Guttenfelder, PoP (2011)

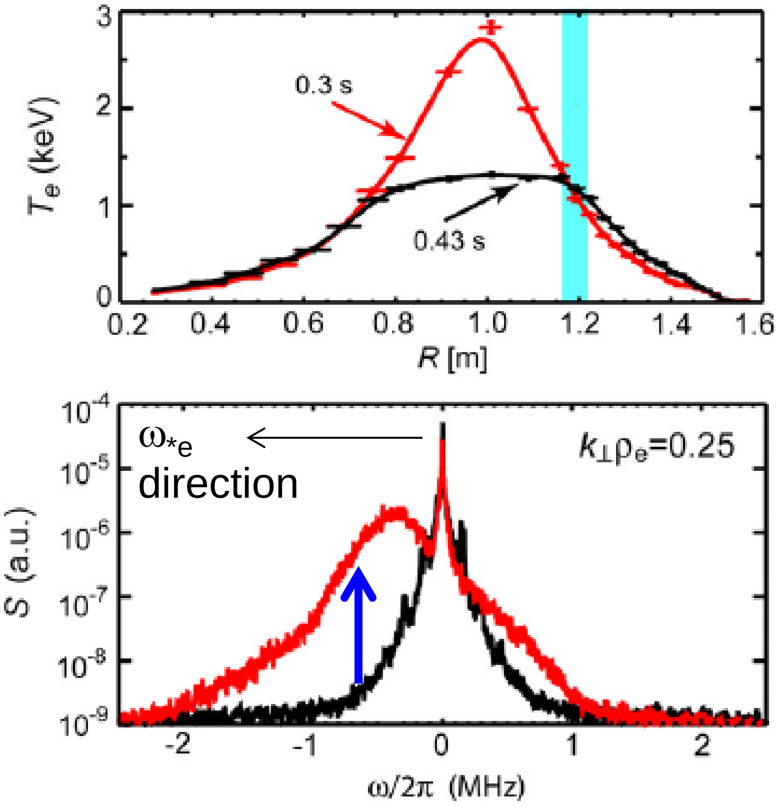
NSTX

Correlation observed between high-k scattering fluctuations and ∇T_e

- Applying RF heating to increase Te
- Fluctuations increase as expected for ETG turbulence ($R/L_{Te} > R/L_{Te,crit}$)

- Other trends measured that are consistent with ETG expectations, e.g. reduction of high-k scattering fluctuations with**:**

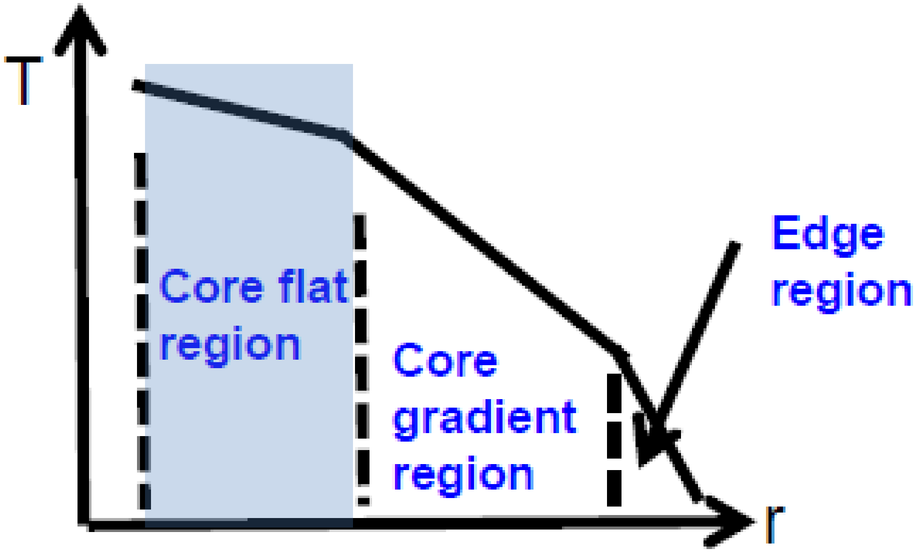
1. Strongly reversed magnetic shear (Yuh, PRL 2011)
   - Simulations predict comparable suppression (Peterson, PoP 2012)
2. Increasing density gradient (Ren, PRL 2011)
   - Simulations predict comparable trend (Ren, PoP 2012, Guttenfelder NF, 2013, Ruiz PoP 2015)
3. Sufficiently large E×B shear (Smith, PRL 2009)
   - Observed in ETG simulations (Roach, PPCF 2009; Guttenfelder, PoP 2011)



E. Mazzucato et al., NF (2009)

NSTX

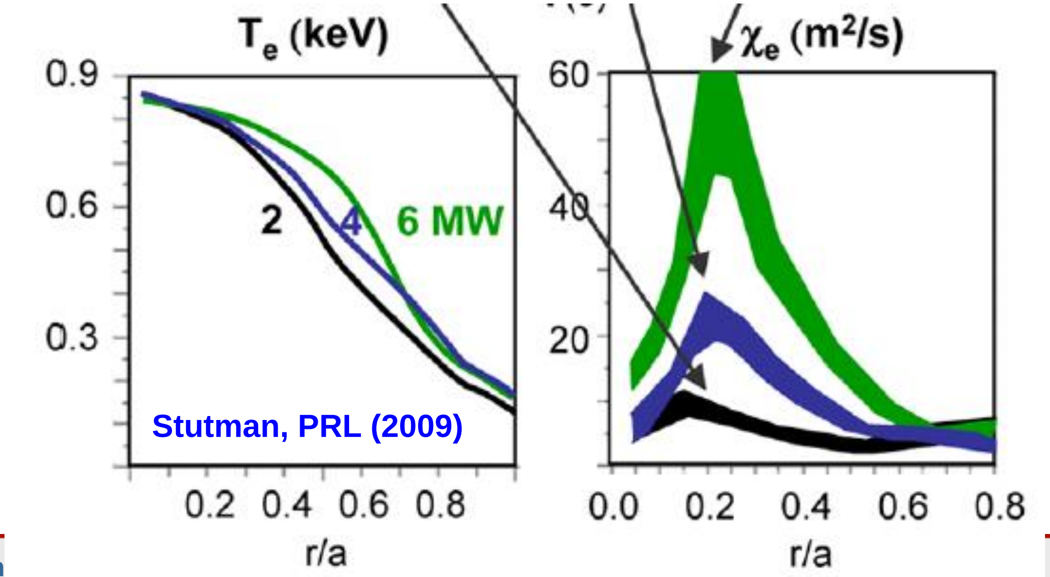
Non drift wave mechanisms may also influence thermal transport



Max T_e limited in high power H-modes,

- Thermal-gradient-driven microinstabilities unlikely to explain flattened profiles

NSTX



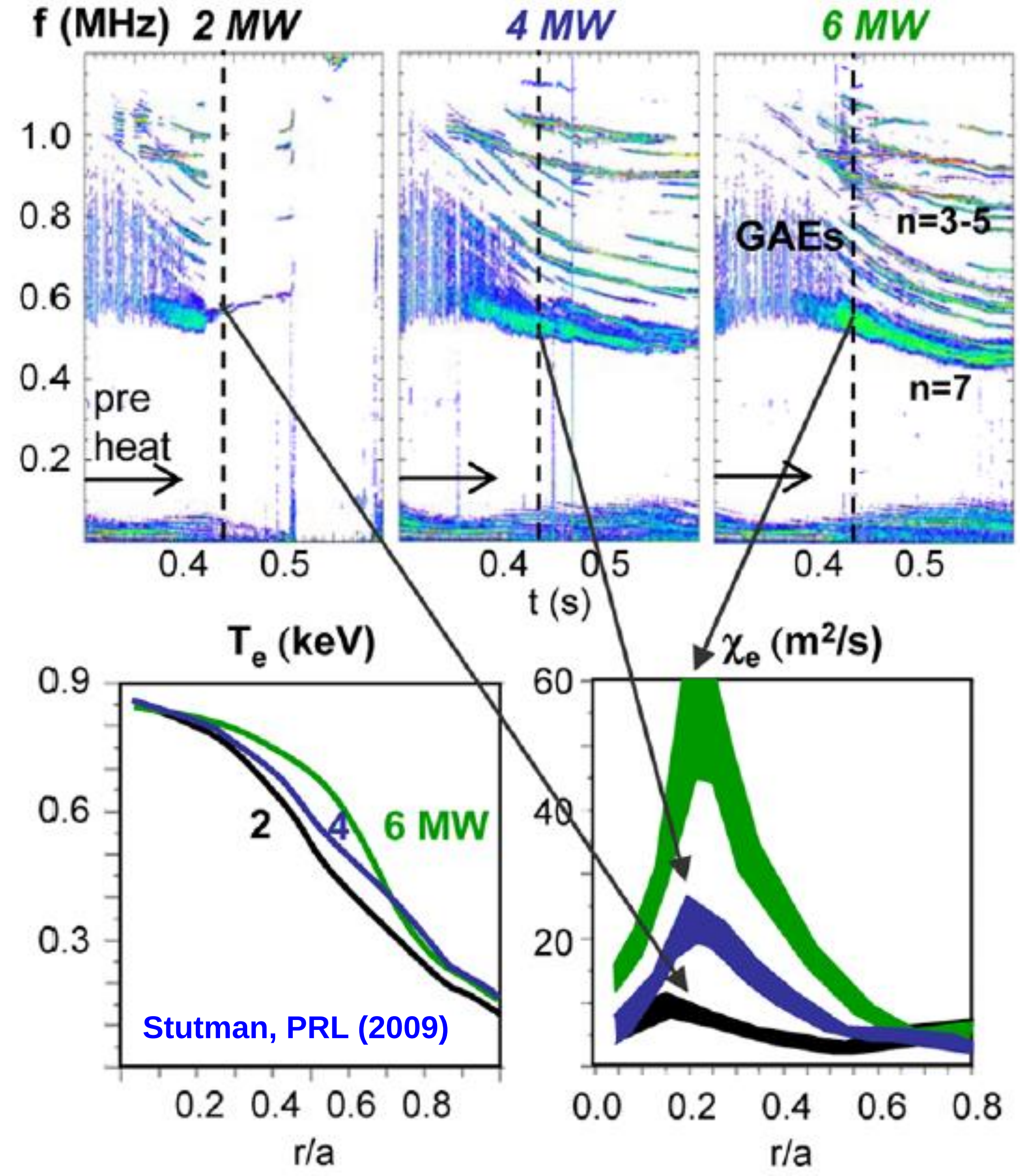
Stutman, PRL (2009)

Max T_e limited in high power H-modes, correlated with presence of Global Alfven eigenmodes (GAE)

- Thermal-gradient-driven microinstabilities unlikely to explain flattened profiles

- High-frequency ($\omega/\Omega_{ci}<1$) Global/Compressional Alfven eigenmodes (GAE/CAE) present
  - Driven unstable by gradients in fast-ion phase space

- **How do they influence electron thermal transport?**

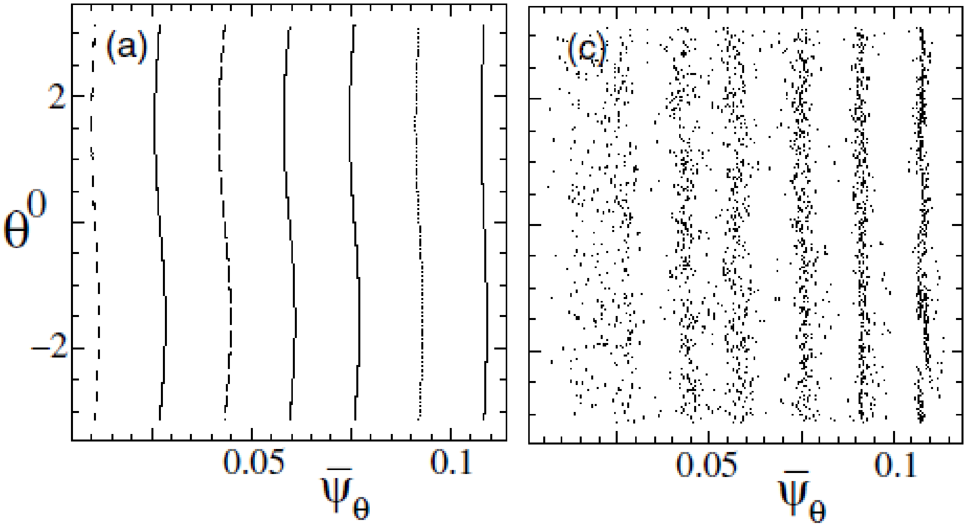


Stutman, PRL (2009)

NSTX

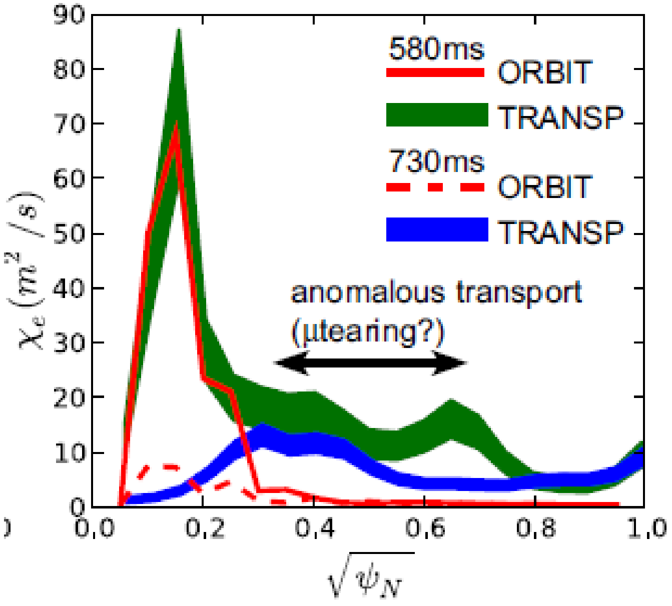
The presence of a large number of GAE/CAEs can stochasticize electron orbits

- Computed electron orbits become stochastic with sufficient number & amplitude of overlapping GAE & CAE modes [Gorelenkov, NF 2010]
- Stochastic orbits can give very large $\chi_{e,st} \sim \langle \Delta r^2 \rangle / \Delta t$



Gorelenkov, NF (2010); Crocker (2016)

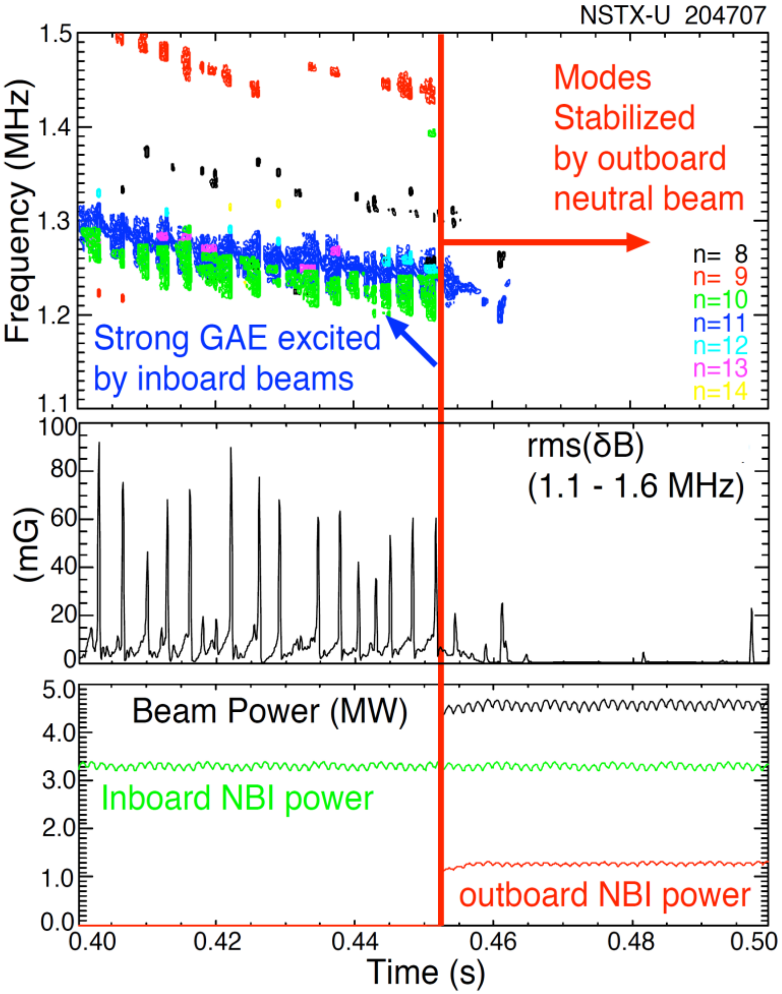
NSTX



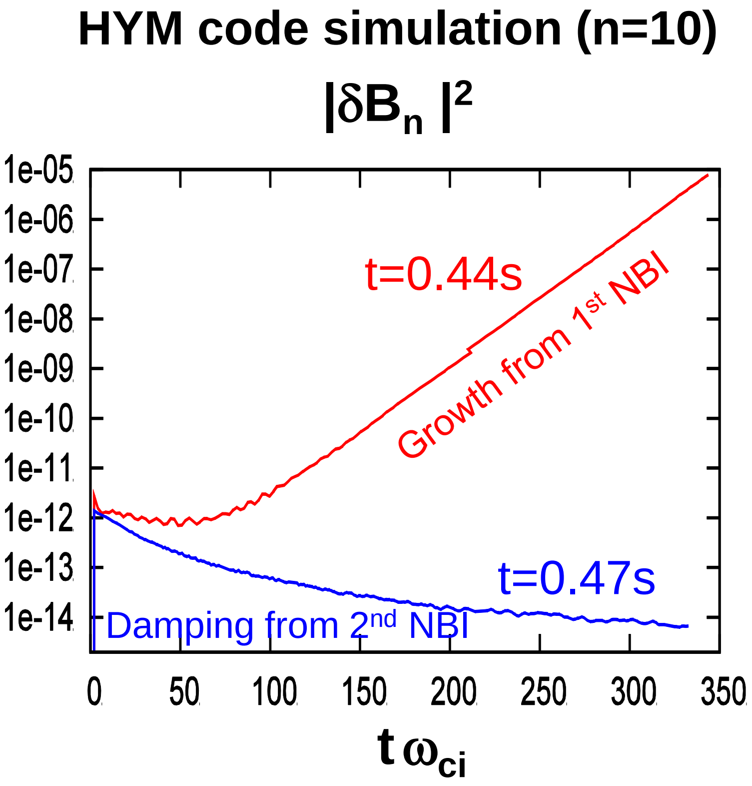
Tritz, APS (2012)

- CAE's also couple to kinetic Alfven waves (KAWs) near mid-radius → redistributes fast-ion energy to KAWs that damp on thermal electrons [Belova, PRL 2015]

New: Tangential 2nd neutral beam suppresses Global Alfven Eigenmode (GAE) – consistent with simulation



NSTX-U



Summary & outlook

- First NSTX-U operation completed, with significant commissioning of control, heating, diagnostics, and scientific progress

- Future goals (2018 and beyond):
  - Assess global stability, energy confinement, fast-ion stability, pedestal height/structure, edge heat-flux width using full operational parameters (1 T, 2 MA, 12 MW, 5 sec)
  - Push toward full non-inductive current drive
  - Test advanced divertor heat flux mitigation

- Future transport experiments will take advantage of facility enhancements and improved diagnostic capabilities to validate transport theories and improve predictive capability

THANK YOU!