U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Progress, challenges and plans in transport research in NSTX-Upgrade

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Plasma Physics Seminar Series
UCLA Dept. of Physics and Astronomy
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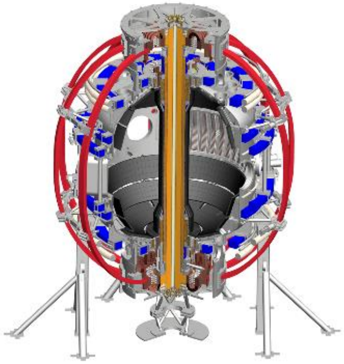
PPPL



Big picture: Magnetic fusion energy

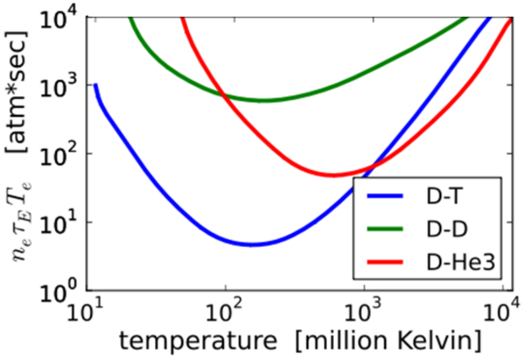
- Goal: use thermonuclear fusion to generate electricity

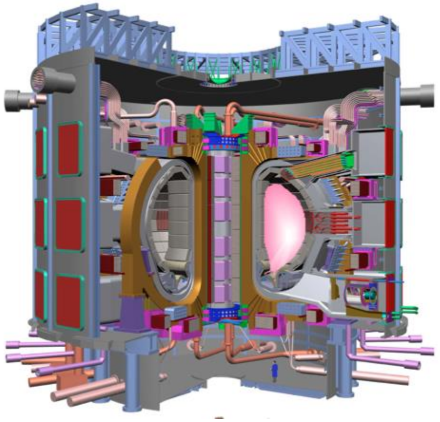
- Need T~150 million °C & sufficient triple product, $nT\tau_E$, to generate fusion gain, $Q=P_{fusion}/P_{loss}>1$

- 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 (V) to increase τ_E – what about trying to minimize P_{loss} at smaller V (cheaper)?





Outline

- Tokamaks, confinement, micro-instabilities & turbulence

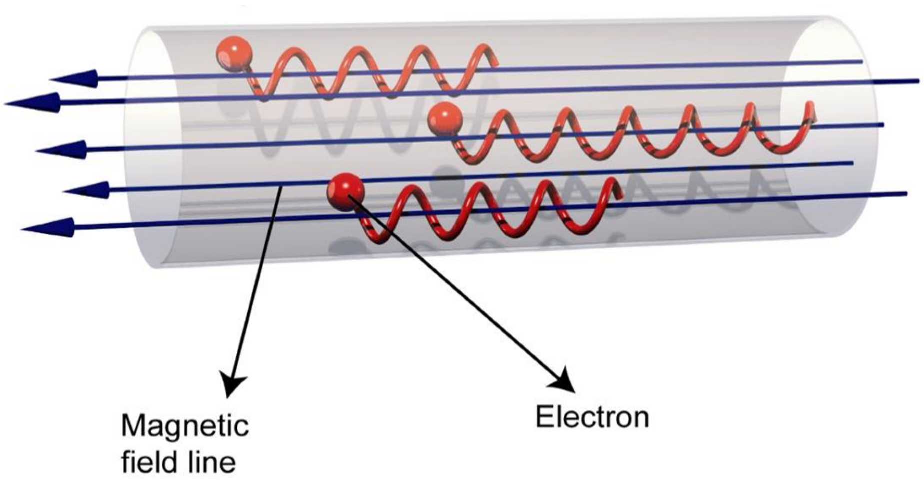
- Uniqueness of spherical tokamaks (STs)

- Status of NSTX-Upgrade

- NSTX transport results, challenges & research plans

Tokamak confinement

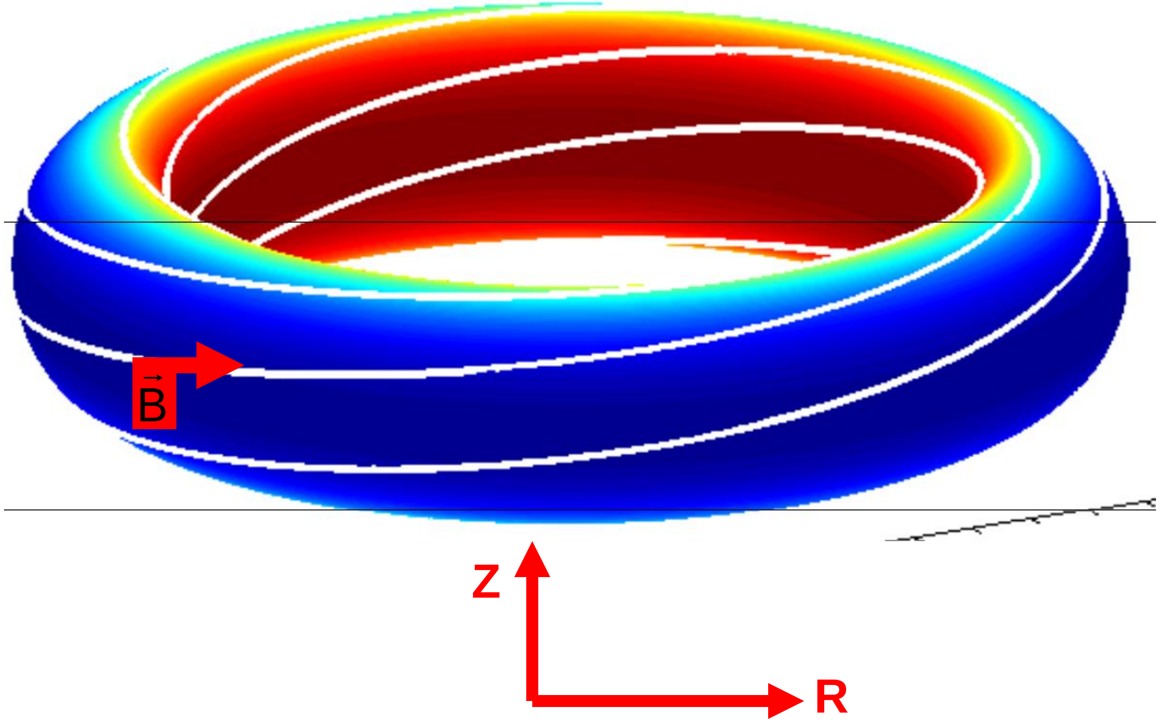
Charged particles confined by magnetic fields

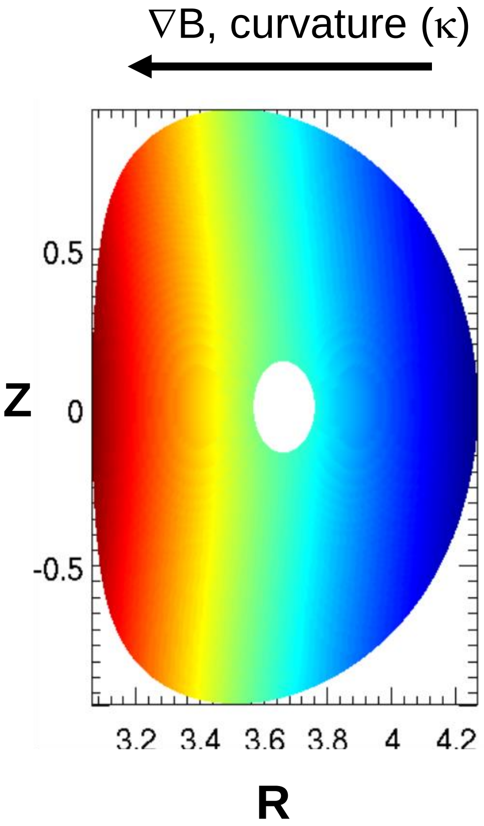


- F=qv×B → gyromotion → perpendicular confinement
- But large end losses → bend into a torus

Toroidicity Leads To Inhomogeneity in |B|

- Magnetic field strength varies as B ~ 1/R, weaker on the outboard side
- ∇B and curvature (κ) point towards symmetry axis, leads to additional perpendicular drifts





∇B & Curvature Lead To Perpendicular Drifts, charge separation

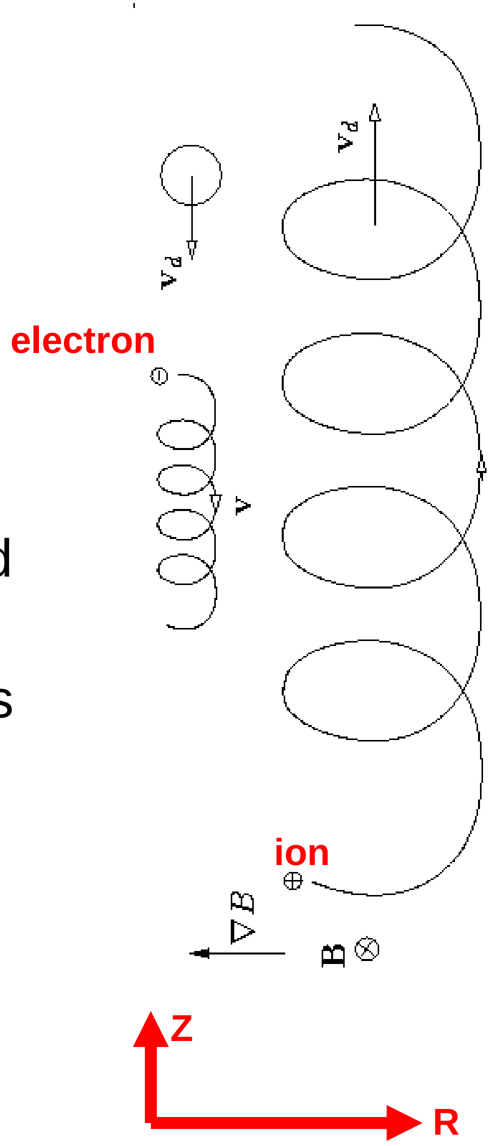
Assuming $\rho\cdot\nabla B/B=\rho/L_B<<1$

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

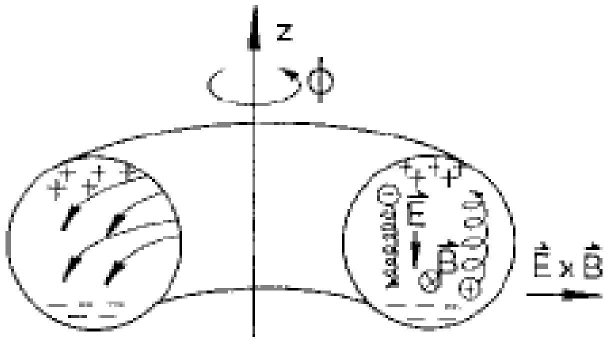
$$\vec{v}_{\nabla B} = \frac{m v_\perp^2}{2}\,\frac{\hat{b}\times\nabla B/B}{qB}$$

If $\beta=nT\cdot 2\mu_0/B^2 << 1$

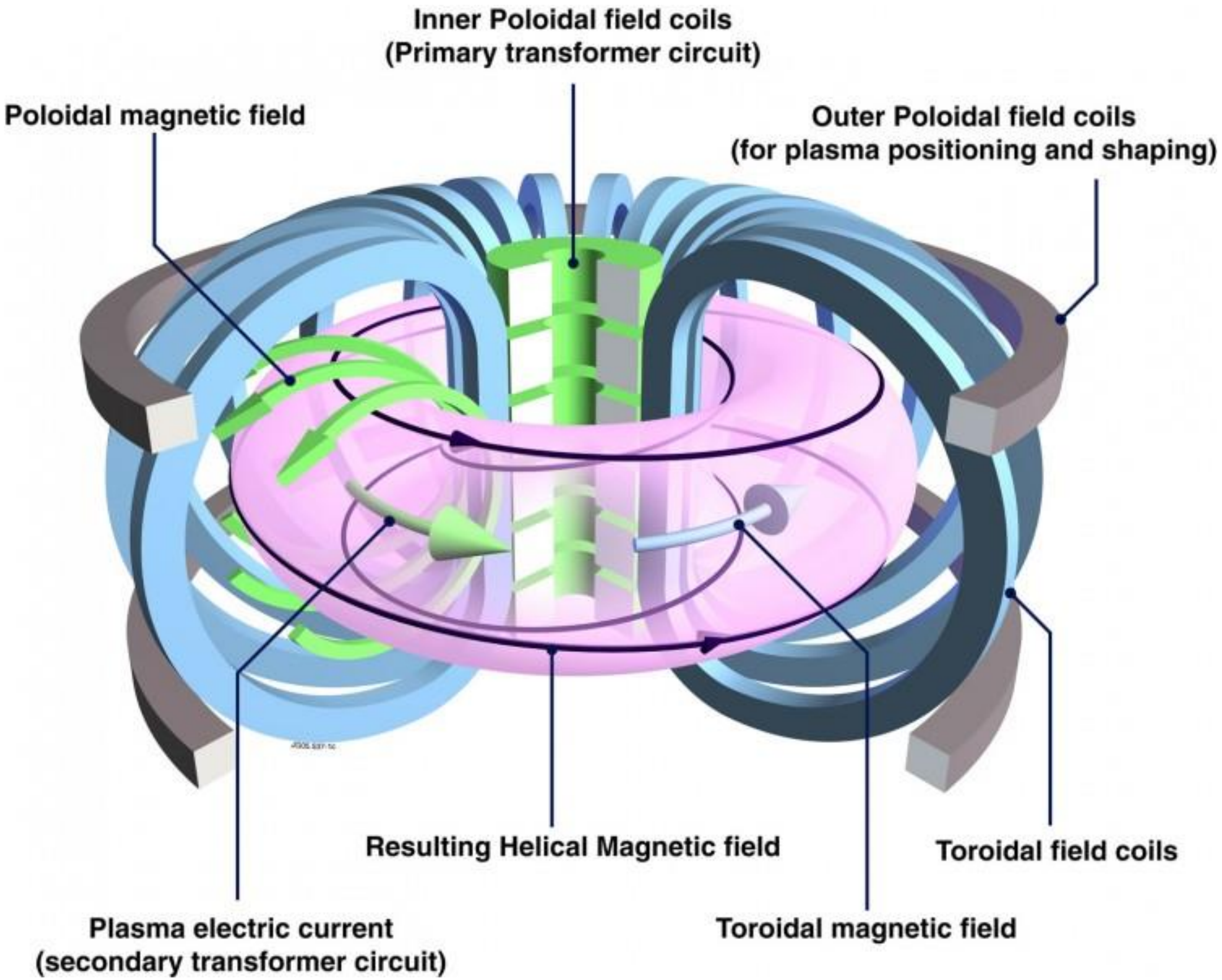
$\nabla B/B \approx \kappa \approx 1/R$



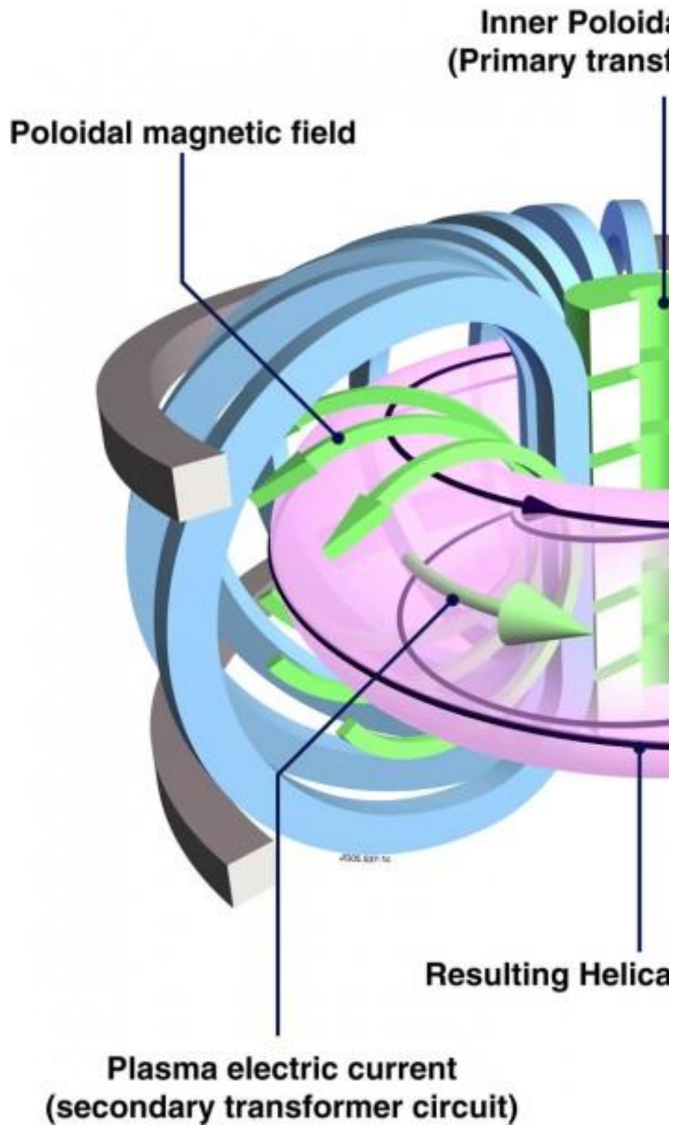
- Drifts mostly vertical (Z direction), oppositely directed for ions and electrons → charge separation
- E×B drift of particles would limit confinement to ~1 μs

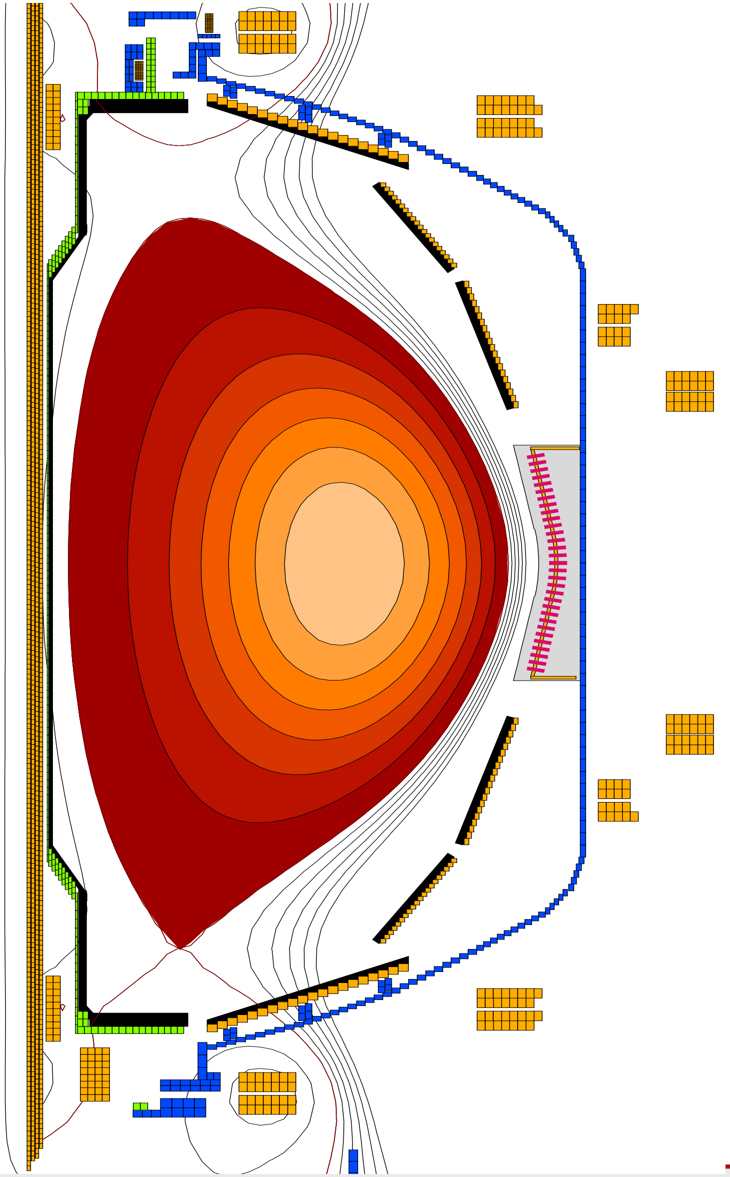


Use helical field lines to short-circuit perpendicular equilibrium drifts: The Tokamak



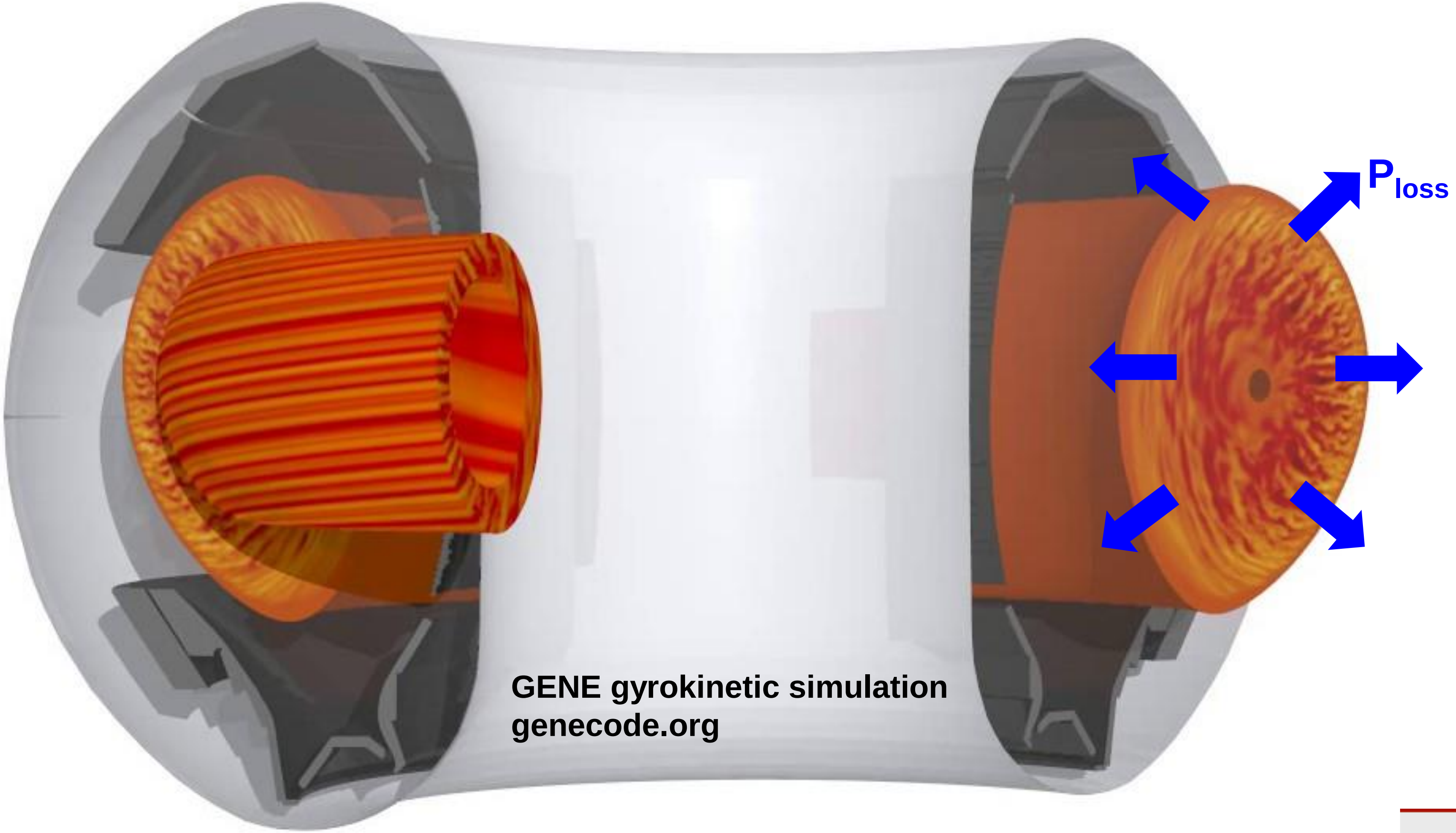
Nested flux surfaces confine hot, high pressure plasma





Increasing gradients eventually cause small scale micro-instability → turbulence

- Quasi-2D dynamics: small perpendicular scales ($L_\perp \sim \rho_i$), elongated along field lines
- Small amplitude ($\delta n/n < 1\%$), **still effective at transport, limiting $\tau_E = 3nT/P_{loss}$**



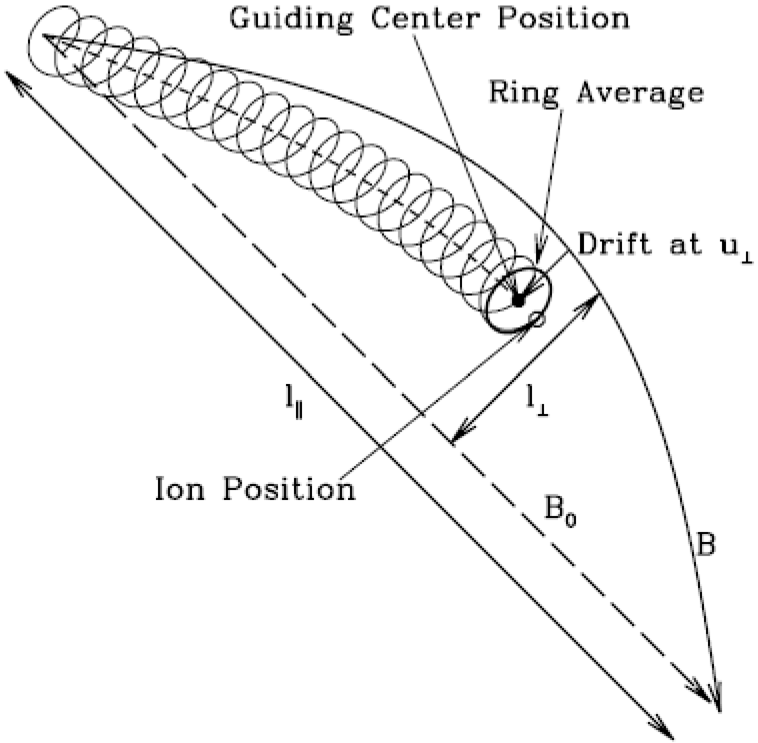
GENE gyrokinetic simulation
genecode.org

Gyrokinetics in brief – evolving 5D gyro-averaged distribution function

$$\boxed{\frac{\omega}{\Omega} << 1}$$

$$f(\vec{x},\vec{v},t) \xrightarrow{\text{gyroaverage}} f(\vec{R},v_\parallel,v_\perp,t)$$

- Average over fast gyro-motion → evolve a distribution of gyro-rings



Howes et al., Astro. J. (2006)

Gyrokinetics in brief – evolving 5D gyro-averaged distribution function

$$\frac{\omega}{\Omega}, \frac{\rho}{L}, \frac{\delta f}{f_0}, \frac{k_{||}}{k_\perp} << 1 \qquad f(\vec{x}, \vec{v}, t) \xrightarrow{\text{gyroaverage}} f(\vec{R}, v_\parallel, v_\perp, t) \qquad f = F_M + \delta f$$

$$\frac{\partial(\delta f)}{\partial t} + \underbrace{v_\parallel \hat{b} \cdot \nabla \delta f}_{\text{Fast parallel motion}} + \underbrace{\vec{v}_d \cdot \nabla \delta f}_{\text{Slow perpendicular toroidal drifts}} + \underbrace{\delta\vec{v} \cdot \nabla F_M}_{\text{Advection across equilibrium gradients } (\nabla T_0, \nabla n_0, \nabla V_0)} + \underbrace{\vec{v}_{E0}(r) \cdot \nabla \delta f}_{\text{Dopper shift due to sheared equilibrium } E_r(r)} + \underbrace{\delta\vec{v} \cdot \nabla \delta f}_{\text{Perpendicular non-linearity}} = \underbrace{C(\delta f)}_{\text{Collisions}}$$

$$\boxed{\begin{aligned} \vec{v}_\kappa &= m v_{||}^2 \frac{\hat{b} \times \vec{\kappa}}{qB} \\ \vec{v}_{\nabla B} &= \frac{m v_\perp^2}{2} \frac{\hat{b} \times \nabla B / B}{qB} \end{aligned}}$$

$$\delta\mathbf{v}_a \doteq \frac{c}{B}\mathbf{b} \times \nabla \Psi_a$$

$$\Psi_a(\mathbf{R}) \doteq \left\langle \delta\phi(\mathbf{R} + \rho) - \frac{1}{c}(\mathbf{V}_0 + \mathbf{v}) \cdot \delta\mathbf{A}(\mathbf{R} + \rho) \right\rangle_{\mathbf{R}}$$

- Must also solve gyrokinetic Maxwell equations self-consistently

Why does turbulence develop in tokamaks?

Example: Linear stability analysis of Ion Temperature Gradient (ITG) “ballooning” micro-instability

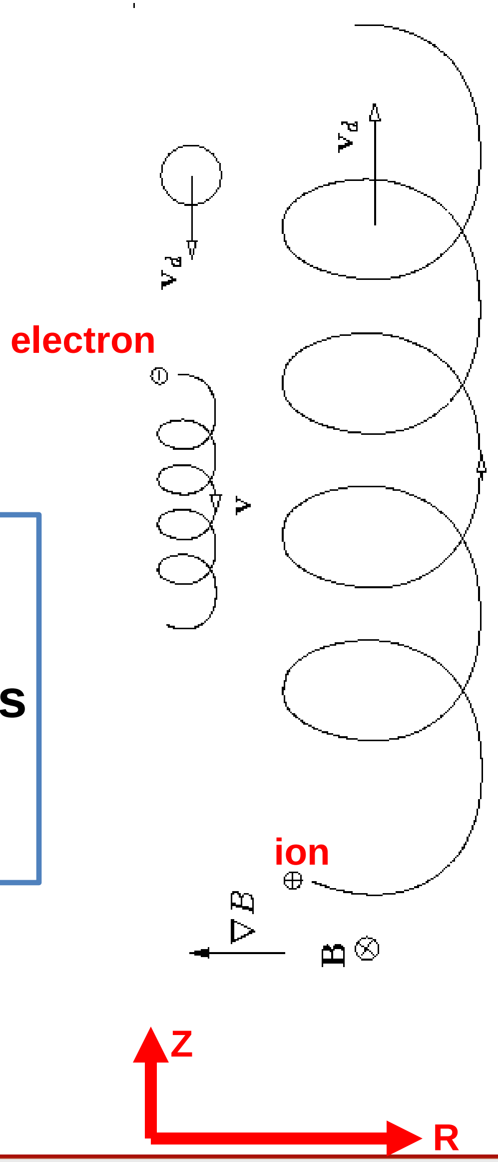
∇B & Curvature Lead To Perpendicular Drifts

Assuming $\rho \cdot \nabla B/B = \rho/L_B << 1$

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

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

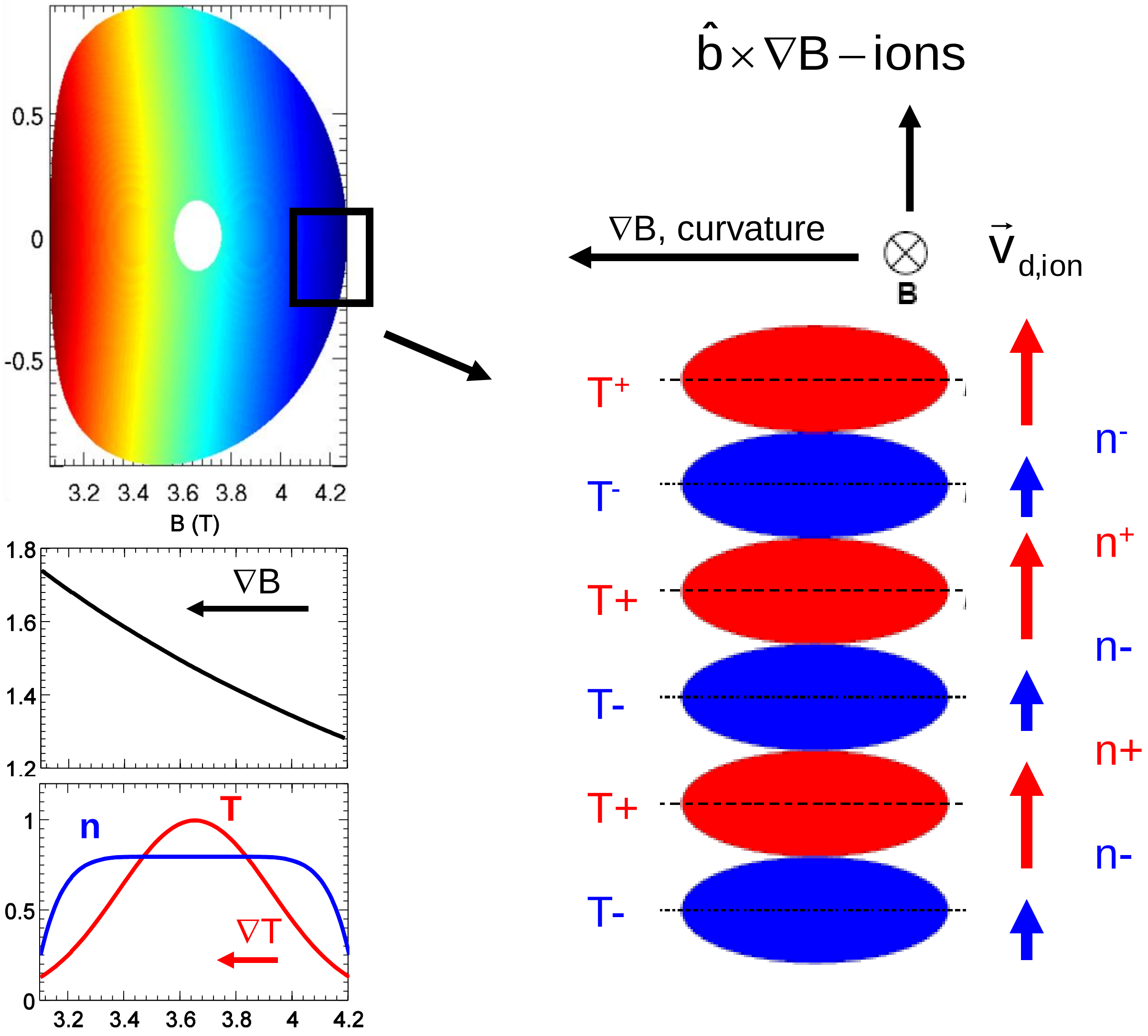
If $\beta = nT \cdot 2\mu_0/B^2 << 1$
$\nabla B/B \approx \kappa \approx 1/R$



- **Curvature, ∇B drifts depend on particle energy ($v_{||}^2$, $v_\perp^2$) ~ ($T_{||}$, $T_\perp$)**
- **What happens when there are small perturbations in $T_{||}$, $T_\perp$?**

⇒Linear stability analysis…

Temperature perturbation leads to compression



- Fourier decompose perturbations in space, assume small δT perturbation
- Spatial variation in $T(\theta)$ leads to variation in toroidal drifts
- Resulting compression $(\nabla\cdot v_{di})$ causes a density perturbation – 90° out-of-phase with δT

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

$$\omega < k_{||}v_{Te}$$

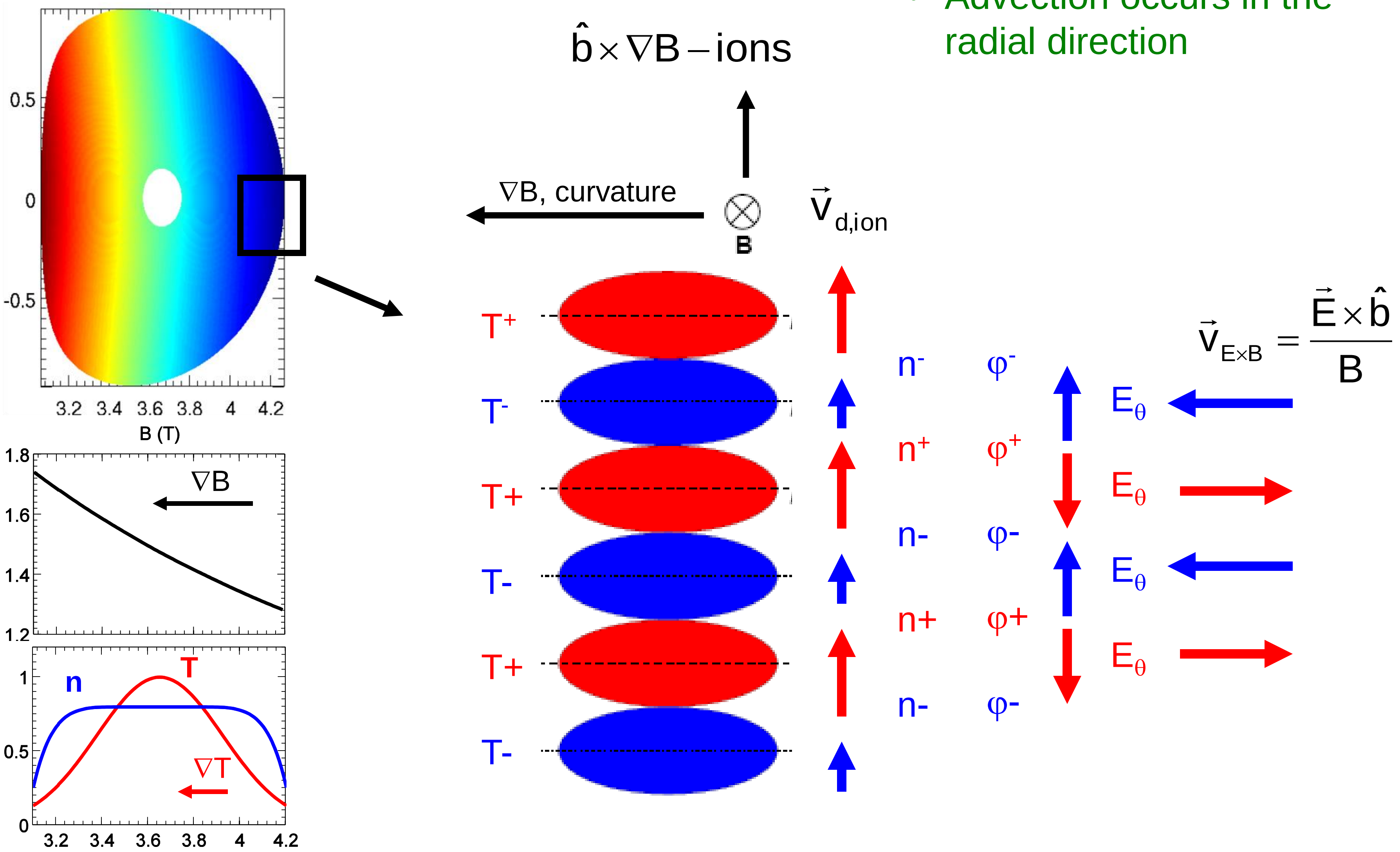
⇒Electrons (approximately) maintain a Boltzmann distribution

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

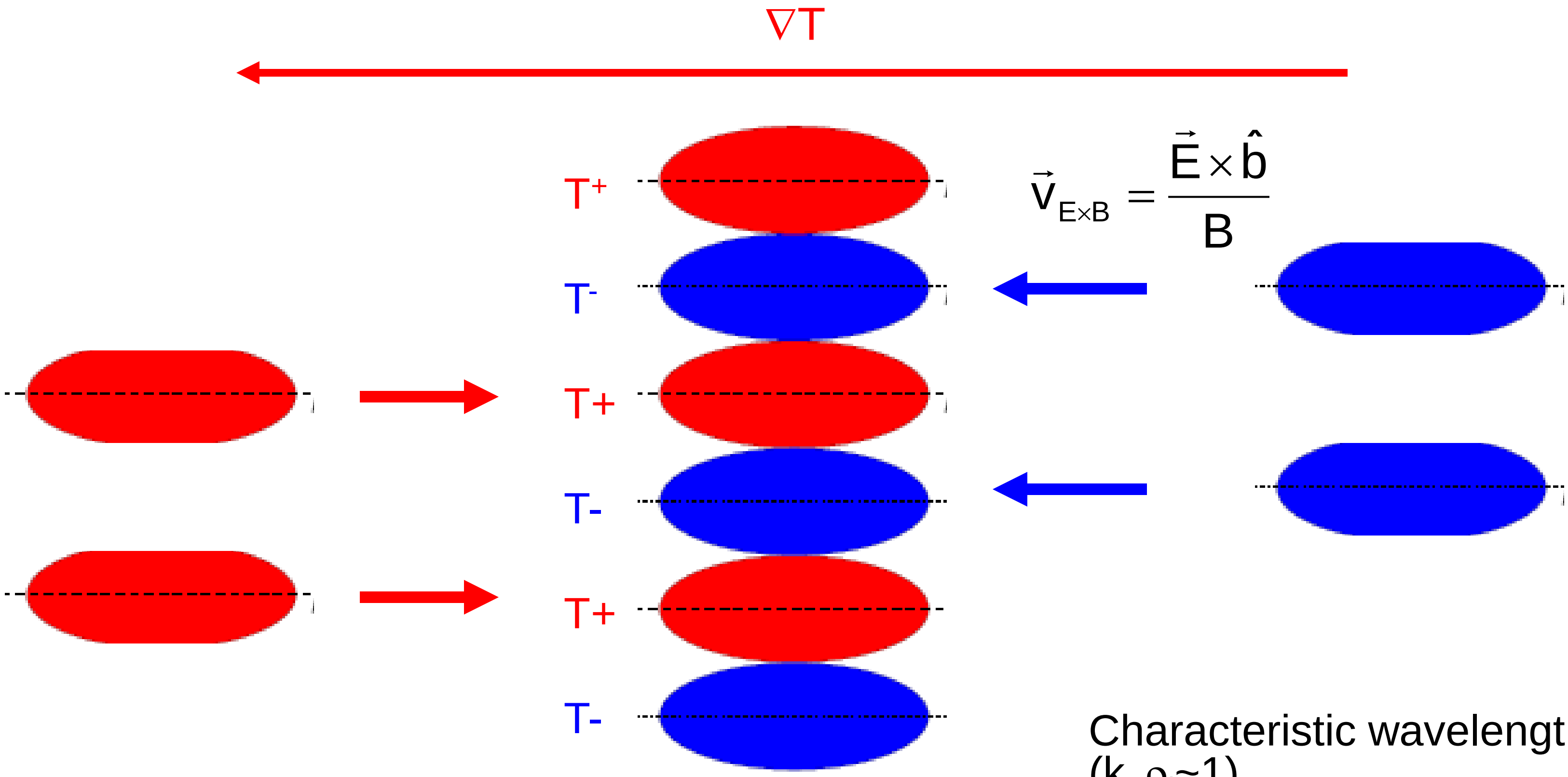
$$\tilde{n}_e \approx n_0 e\tilde{\varphi}/T_e \Rightarrow \underline{\tilde{n}_e \approx \tilde{\varphi}}$$

Perturbed Potential Creates E×B Advection

- Advection occurs in the radial direction



Background Temperature Gradient Reinforces Perturbation ⇒ Instability

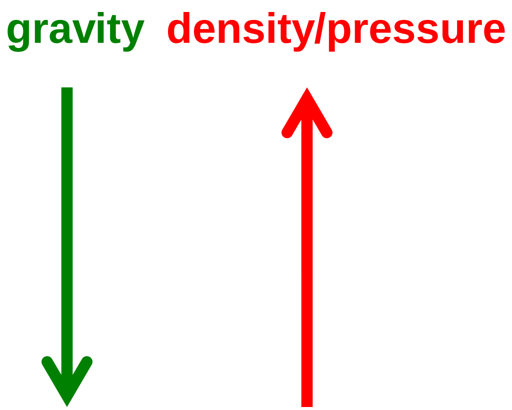


$$\vec{v}_{E\times B} = \frac{\vec{E}\times\hat{b}}{B}$$

Characteristic wavelength ~ ρ_i
($k_\perp\rho_i$~1)

Analogy for turbulence in tokamaks - density gradient in the presence of gravity

- Higher density on top of lower density, with gravity acting downwards (Rayleigh-Taylor instability)
- Any small perturbation becomes unstable
- Convection mixes regions of different density

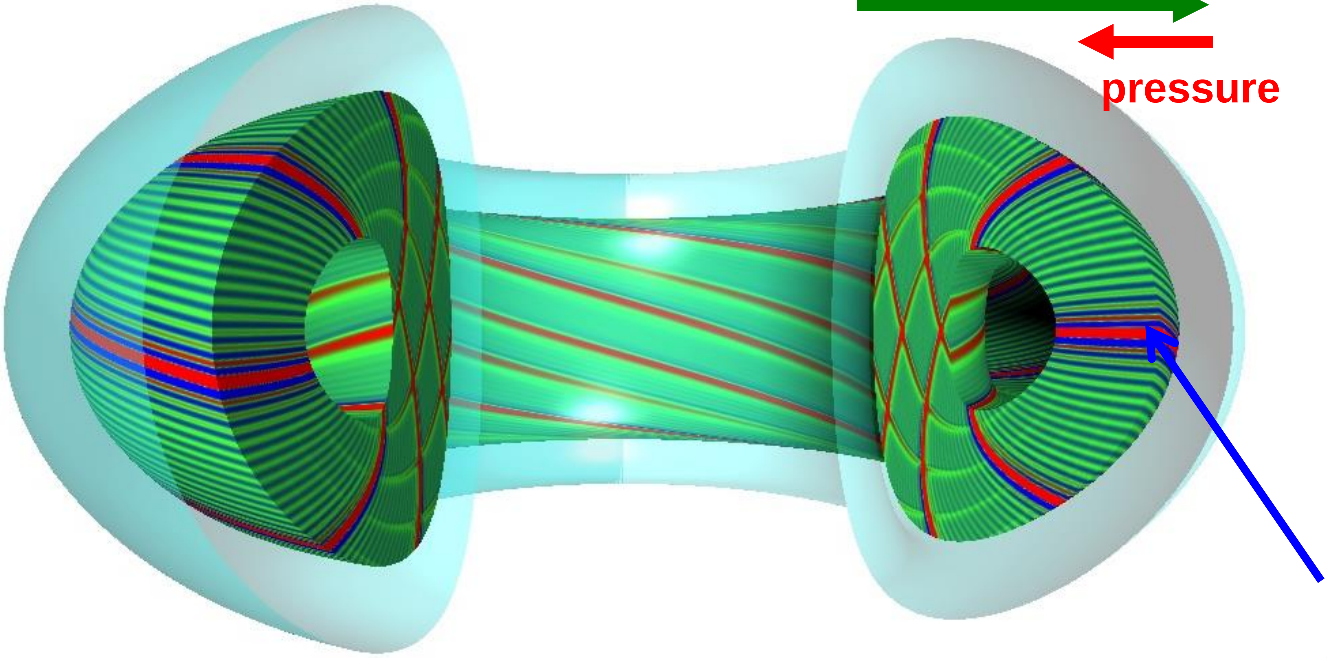


Inertial force in toroidal field acts like an effective gravity

centrifugal force

→effective gravity

pressure



Unstable in the outer region

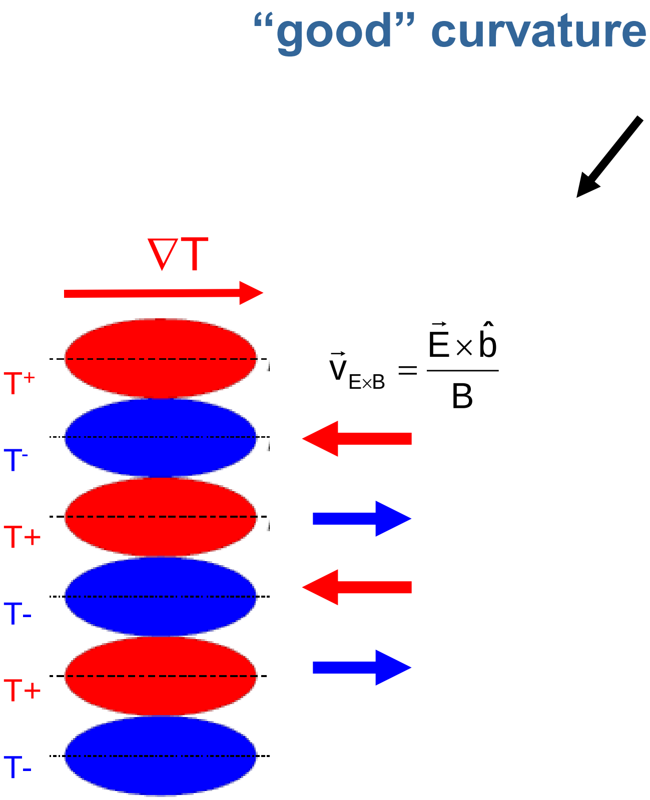
gravity

pressure

GYRO code
https://fusion.gat.com/theory/Gyro

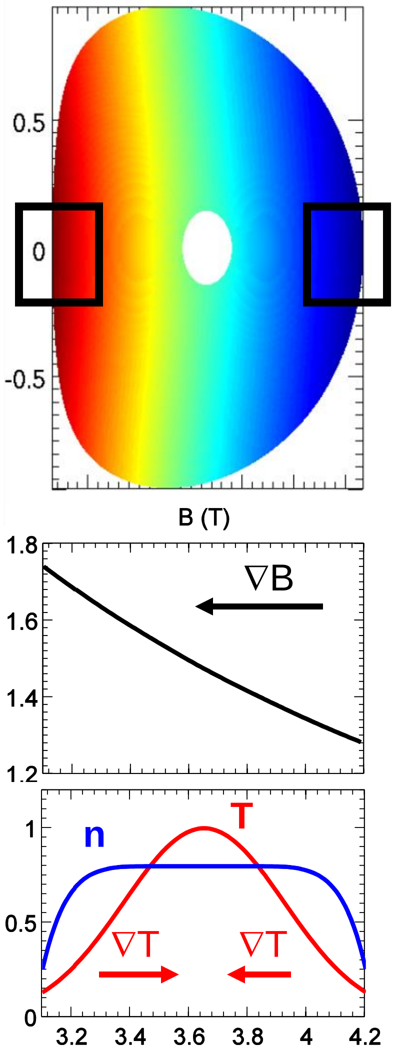
Same Dynamics Occur On Inboard Side But Now Temperature Gradient Is Stabilizing

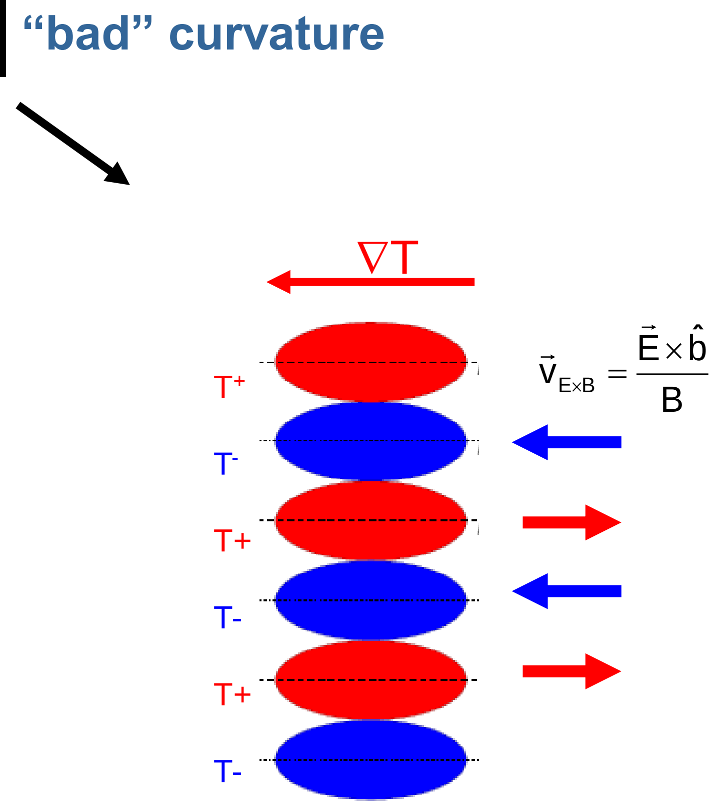
- Advection with ∇T counteracts perturbations on inboard side – “good” curvature region



“good” curvature

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



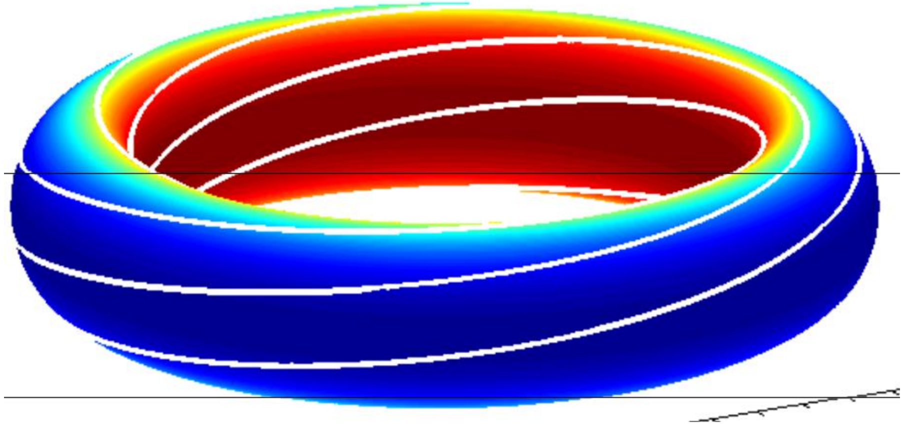


“bad” curvature

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

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

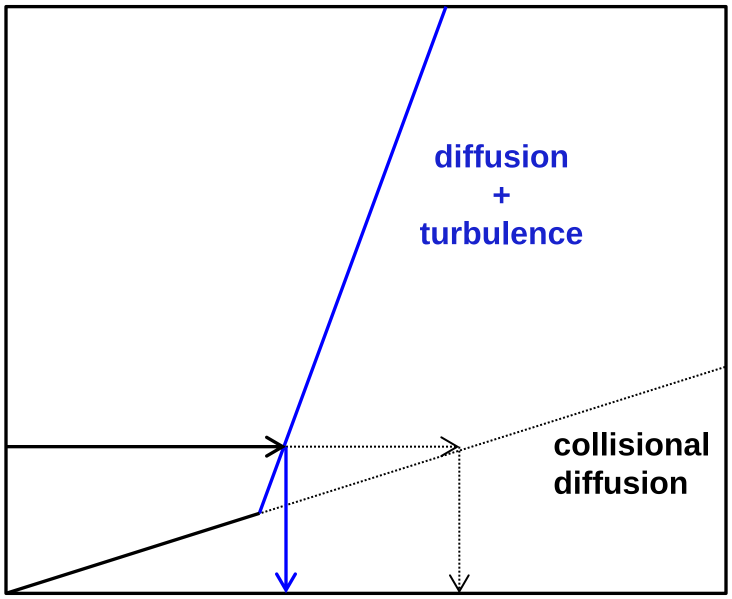
- Approximate growth rate on outboard side $\gamma_{instability} \sim \frac{v_{th}}{\sqrt{RL_T}}$ $1/L_T = -1/T \cdot \nabla T$
- Parallel transit time $\gamma_{parallel} \sim \frac{v_{th}}{qR}$



- Expect instability if $\gamma_{instability} > \gamma_{parallel}$, or $\left(\frac{R}{L_T}\right)_{threshold} \approx \frac{1}{q^2}$

Threshold like behavior analogous to Rayleigh-Benard instability

Heat flux ~ heating power



Temperature gradient
(T_{hot} - T_{cold})

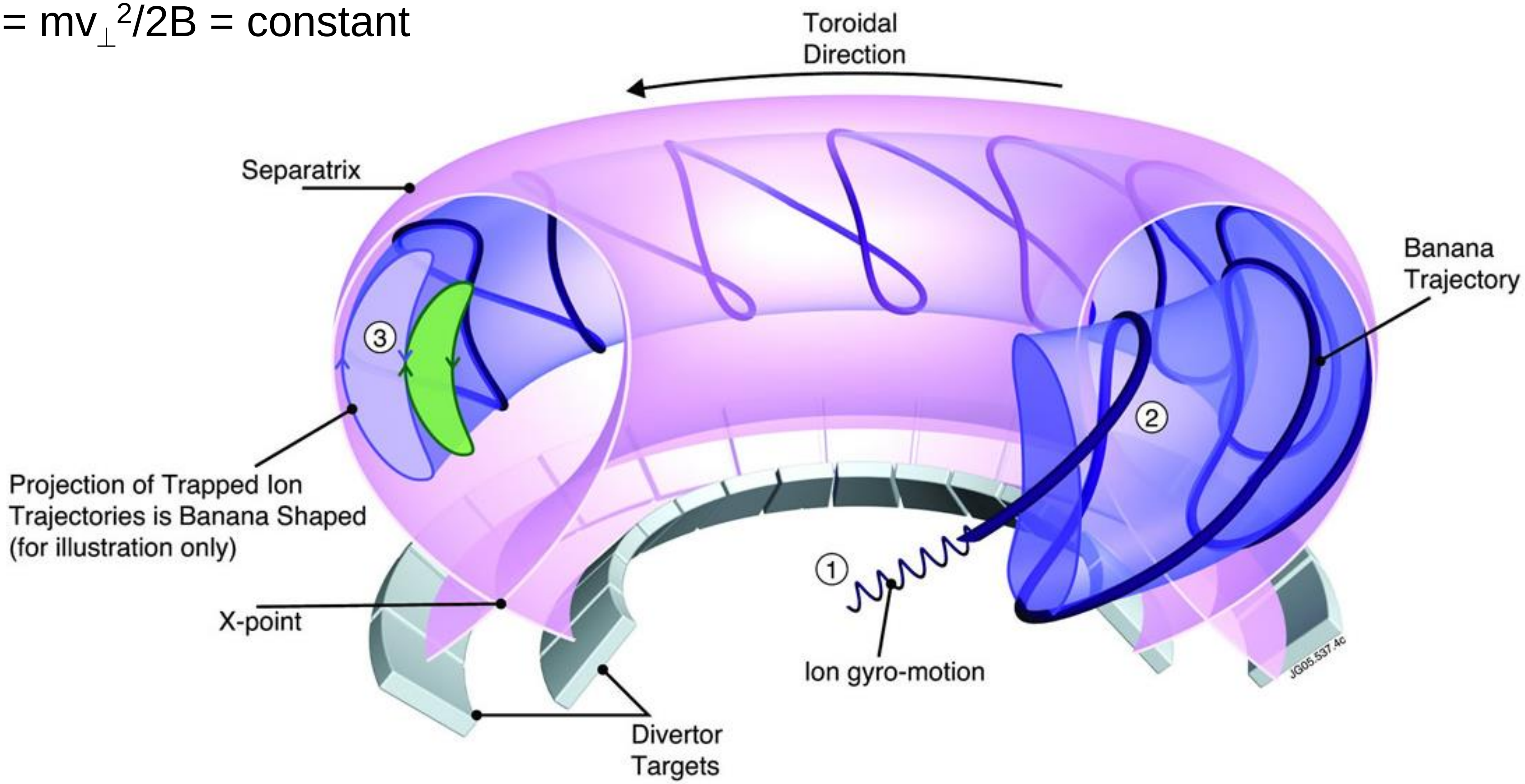
Analogous to convective transport when heating a fluid from below … boiling water (before the boiling)

Rayleigh, Benard, early 1900's

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

Inhomogeneous magnetic field causes trapped particles to precess toroidally

$E = 1/2mv^2 = \text{constant}$
$\mu = mv_\perp^2/2B = \text{constant}$



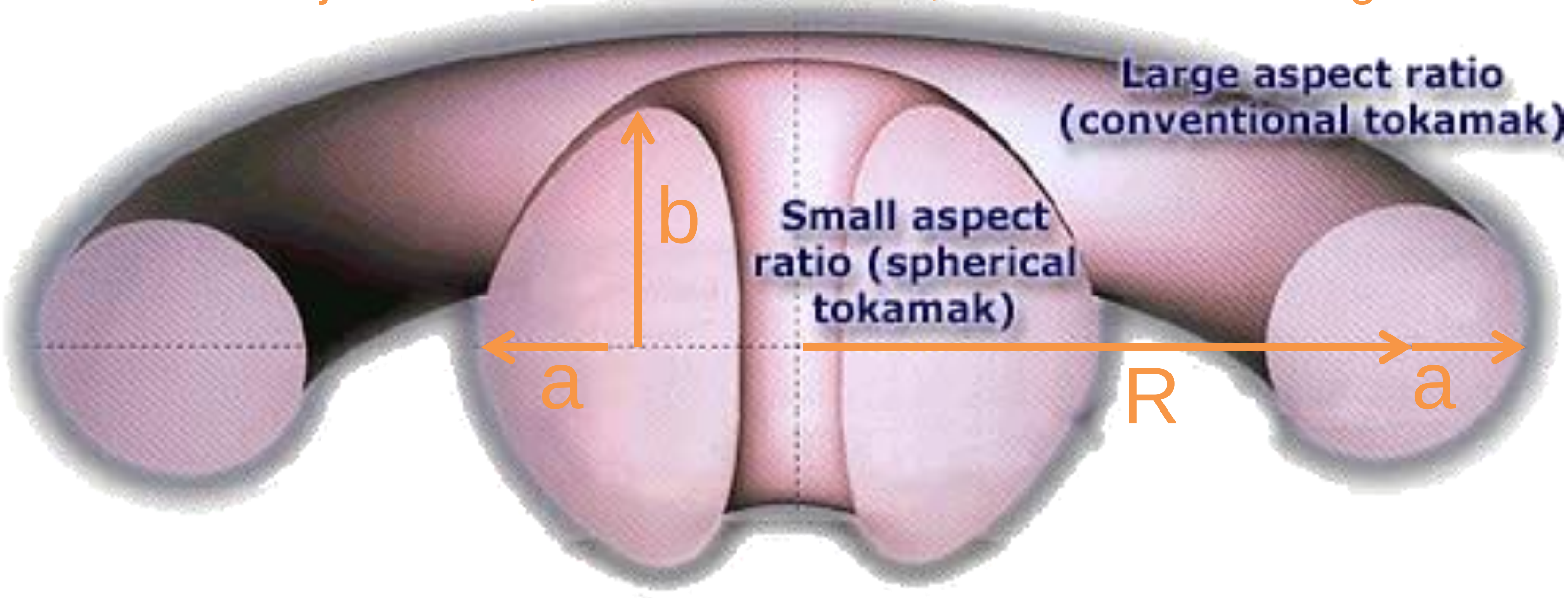
Trapped electron precession frequencies can be comparable to drift wave frequency ($\omega \sim v_{Ti}/R$) $\Rightarrow$ **resonance can enhance ITG instability and lead to distinct trapped electron mode (TEM) instabilities driven by ∇T_e, ∇n_e**

Where do spherical tokamaks enter the picture?

Aspect ratio is an important free parameter, can try to make smaller reactors (i.e. cheaper)

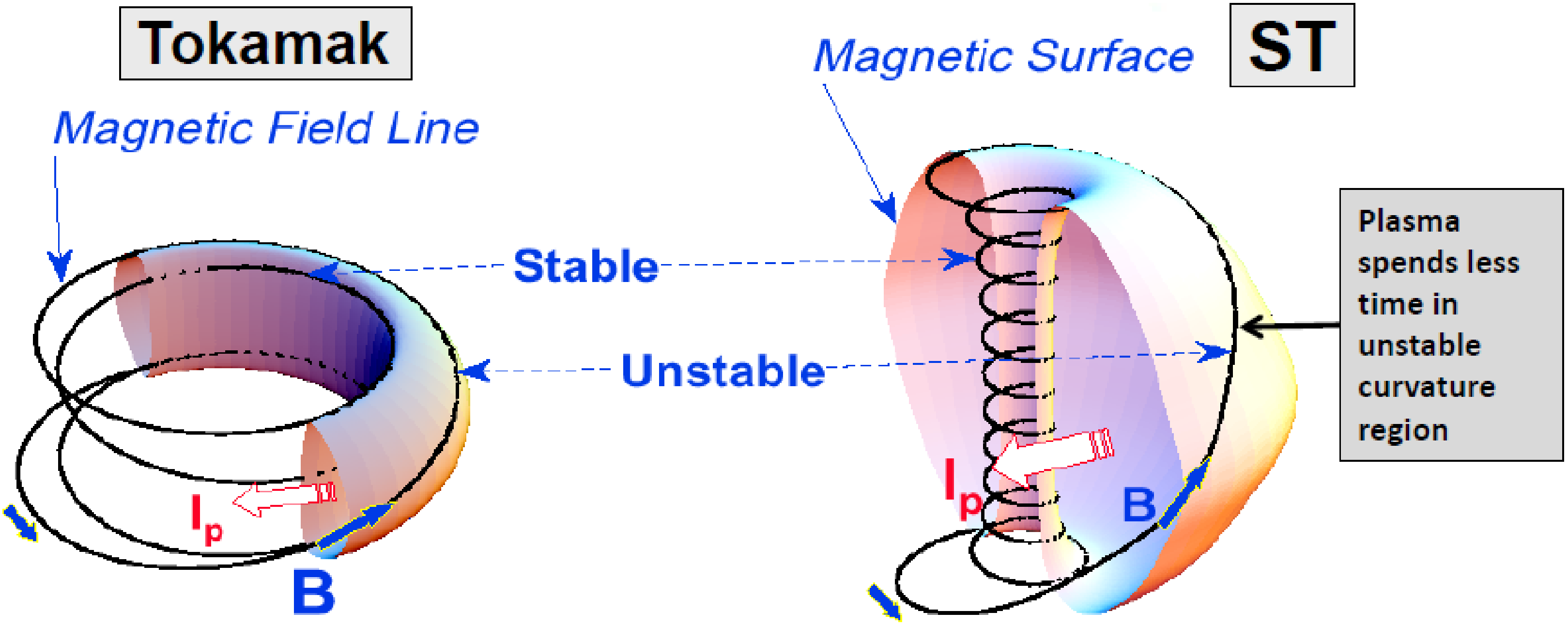
Aspect ratio A = R / a
Elongation κ = b / a

R = major radius, a = minor radius, b = vertical ½ height



But smaller R = larger curvature, ∇B (~1/R) -- isn't this terrible for "bad curvature" driven instabilities?!?!?!

Field lines spend more time in good curvature region → improved average curvature



Plasma spends less time in unstable curvature region

A ~ 3

$\kappa = 1.5\text{-}2$

$\beta_T = 3\text{-}10\%$

$$\boxed{\beta = \frac{p}{B^2/2\mu_0}}$$

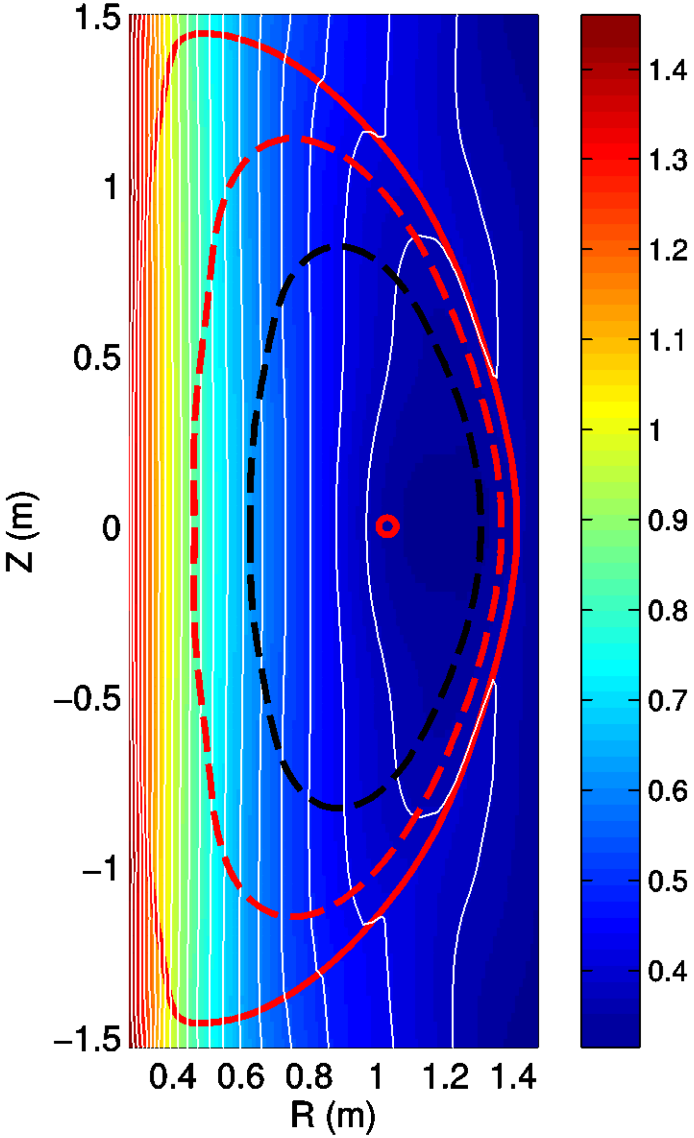
A ~ 1.5

$\kappa = 2\text{-}3$

$\beta_T = 10\text{-}40\%$

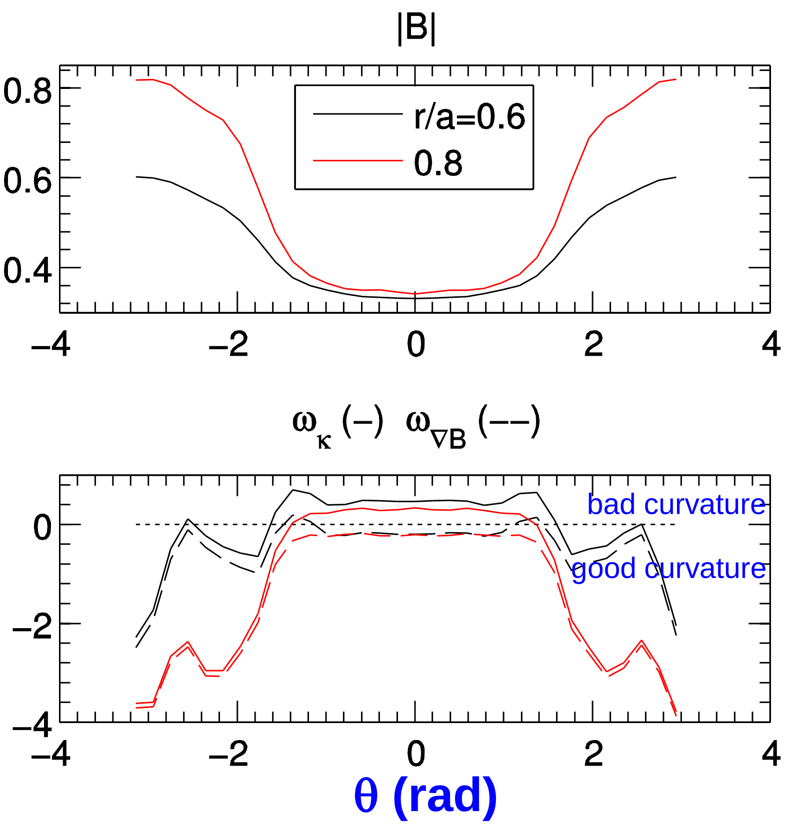
- STs naturally elongated, also contributes to improved stability
- **High beta achievable → can use weaker field (cheaper)**

High-beta STs become quasi-isodynamic (region of ~constant |B|)



- Field strength does not simply follow |B|~1/R
- A nearly uniform |B| exists in the outboard region

$\Rightarrow\nabla$B drifts are stabilizing in bad curvature region



Peng & Strickler, NF (1986)

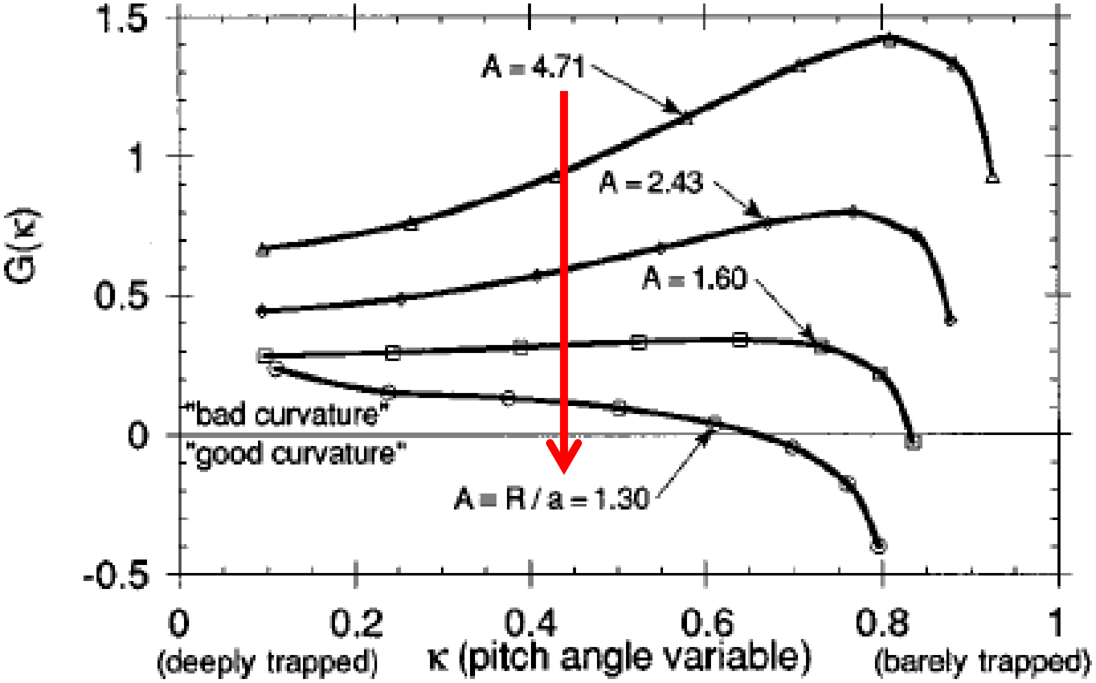
$$\vec{v}_\kappa = m v_{||}^2 \frac{\hat{b}\times\vec{\kappa}}{qB}$$

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

Trapped electron precession weaker in STs

- Large variation in |B| along a field line gives large fraction of trapped electrons, BUT orbit-averaged drifts more favorable at low-aspect ratio →**Good for TEM stability**

Orbit-averaged drift of trapped particle



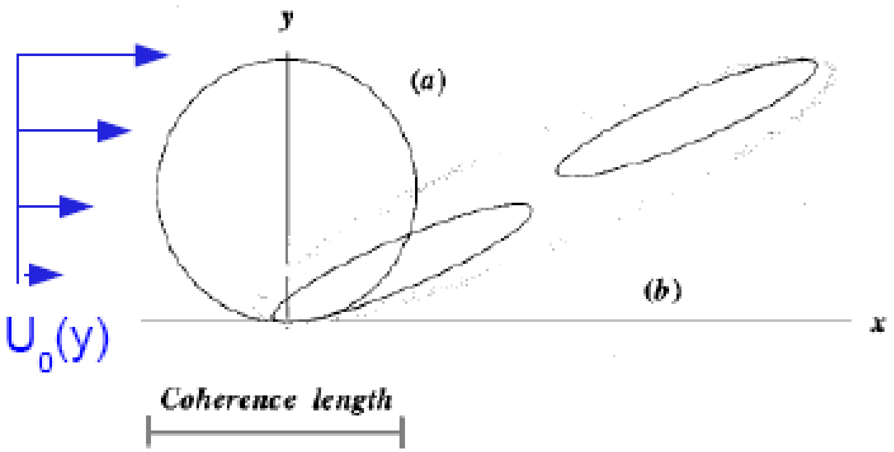
Rewoldt et al., PoP (1996)

ITG instability typically stabilized at high beta by coupling to magnetic fluctuations

- Tries to bend field lines, energetically unfavorable → stabilizing

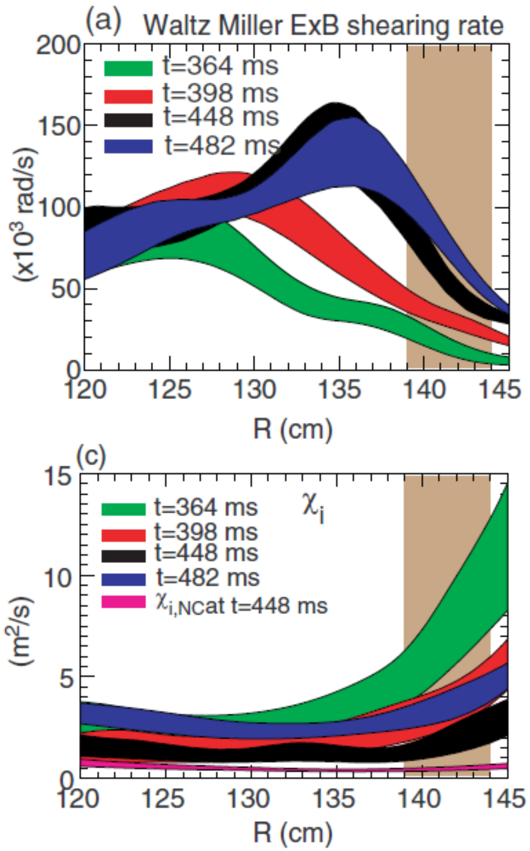
With low moment of inertia, ST plasmas can rotate rapidly (Mach≥0.5)

- Perpendicular (E×B) shear can tear apart turbulent eddies
- Turbulent transport expected to be reduced as the mean flow shear rate ($\omega_s \sim dU_0/dy$) approaches the turbulence decorrelation rate ($\Delta\omega_D$)



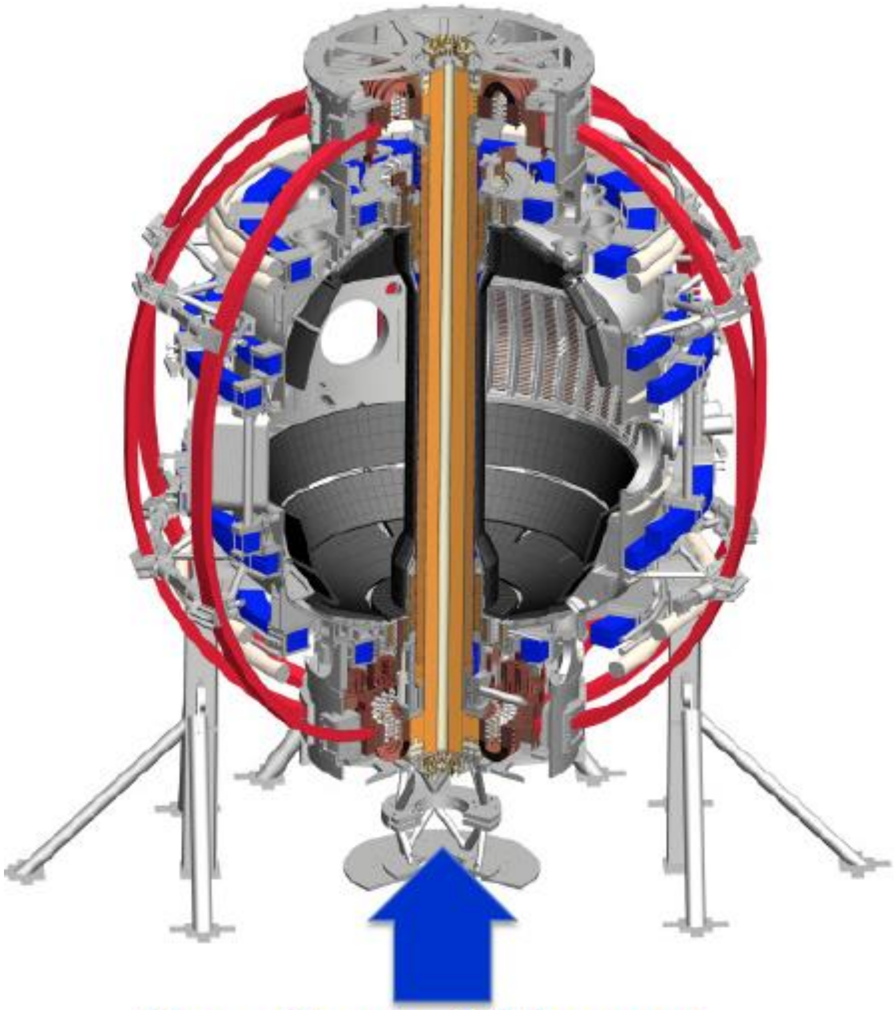
Biglari, Diamond, Terry 1990

- Correlation between E×B shearing rate and transport reduction observed experimentally (Ren, NF 2013)



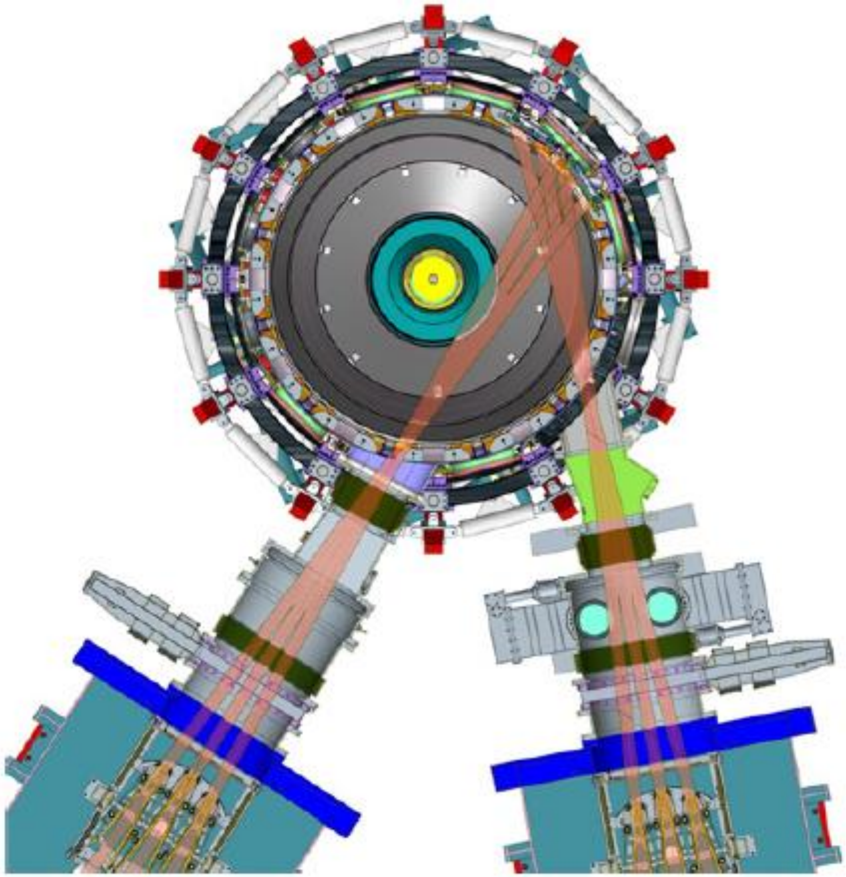
NSTX-U

NSTX recently completed major upgrade: ~2× higher B_T, I_p, P_{NBI}, ~5 × longer pulse length



New Central Magnet

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

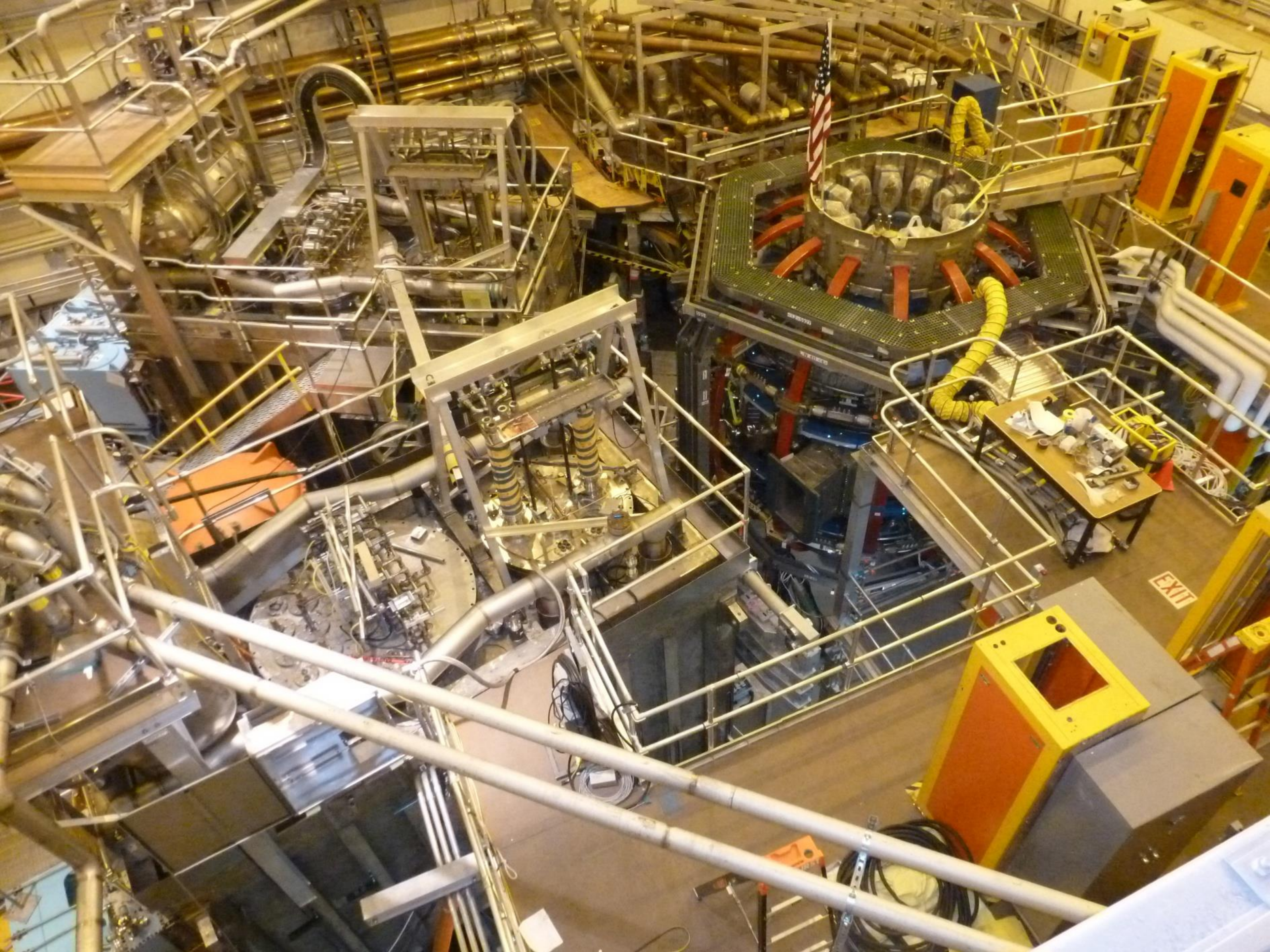


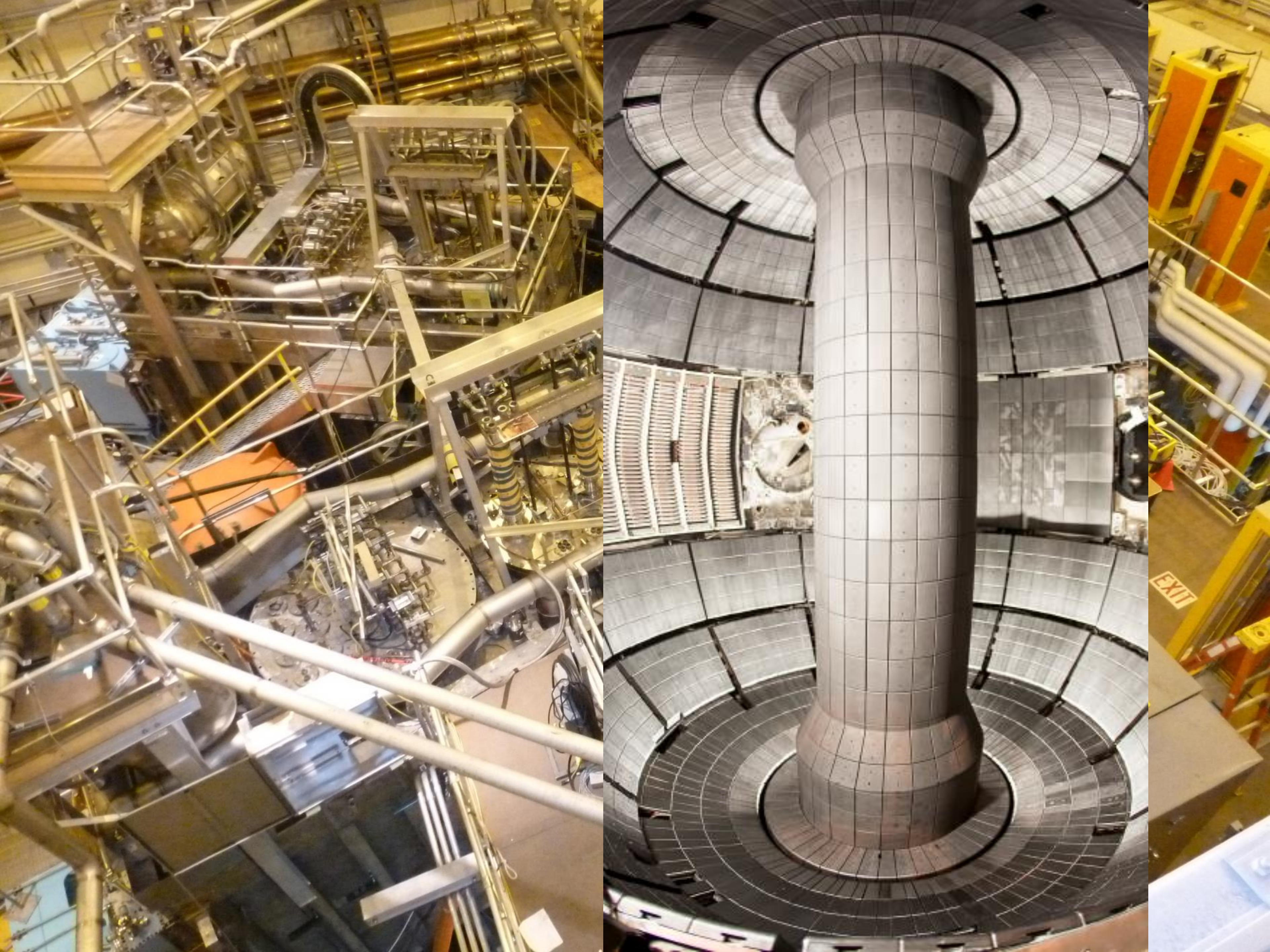
Original NBI

(R_{TAN} = 50, 60, 70cm)
5MW, 5s, 80keV

New 2nd NBI

(R_{TAN}=110, 120, 130cm)
5MW, 5s, 80keV


EXIT


EXIT

Commissioning of NSTX-U began Dec. 2015!

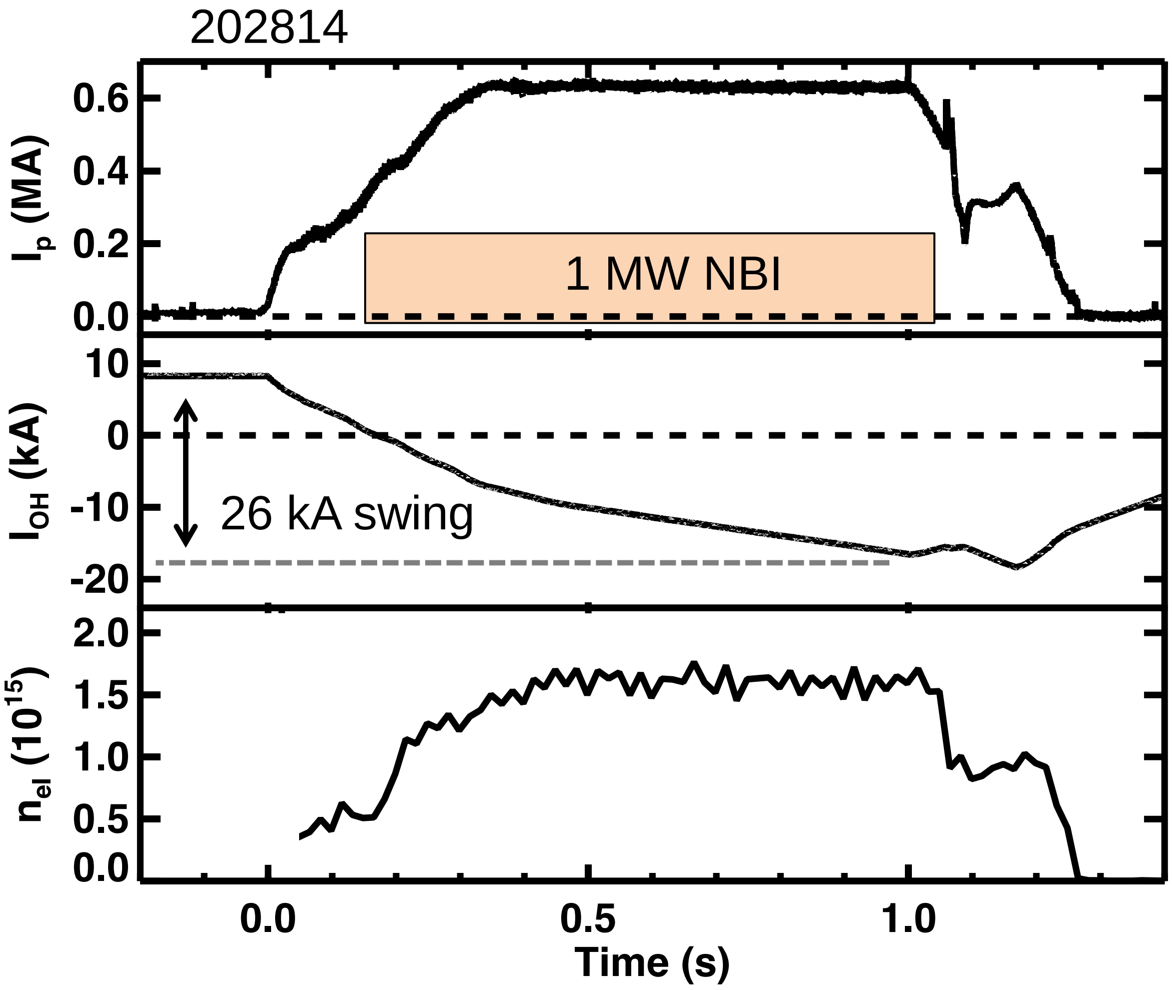
- After ~3 weeks of baking the vacuum vessel:

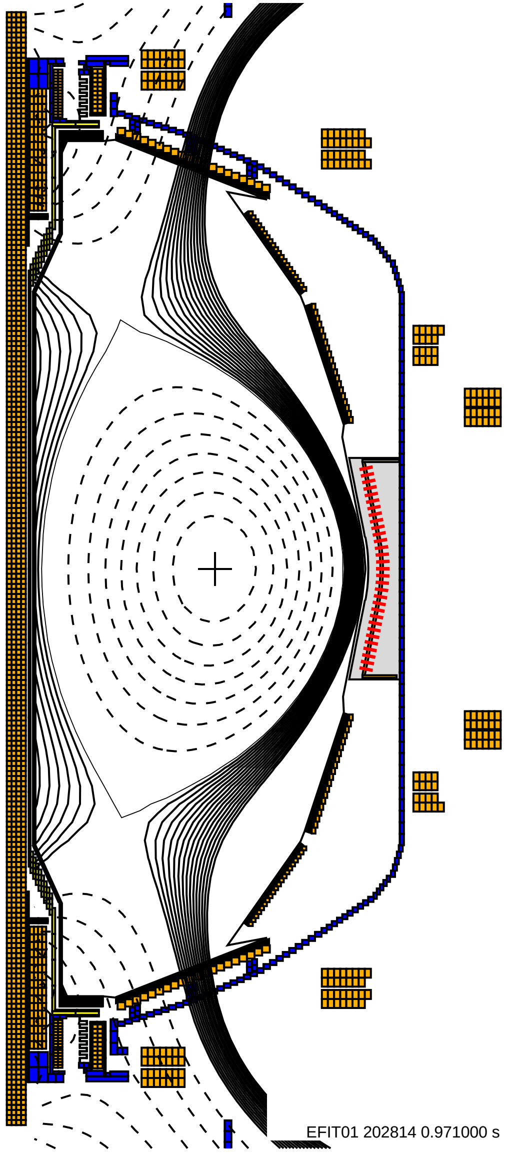
- First days spent optimizing plasma breakdown and current ramp-up

- Continued by optimizing feedback control of plasma current flat-top, outer gap and vertical stability of plasma (i.e. simple position control)

- Began injecting neutral beam power up to 3-4 MW
  - Able to divert and achieve H-mode

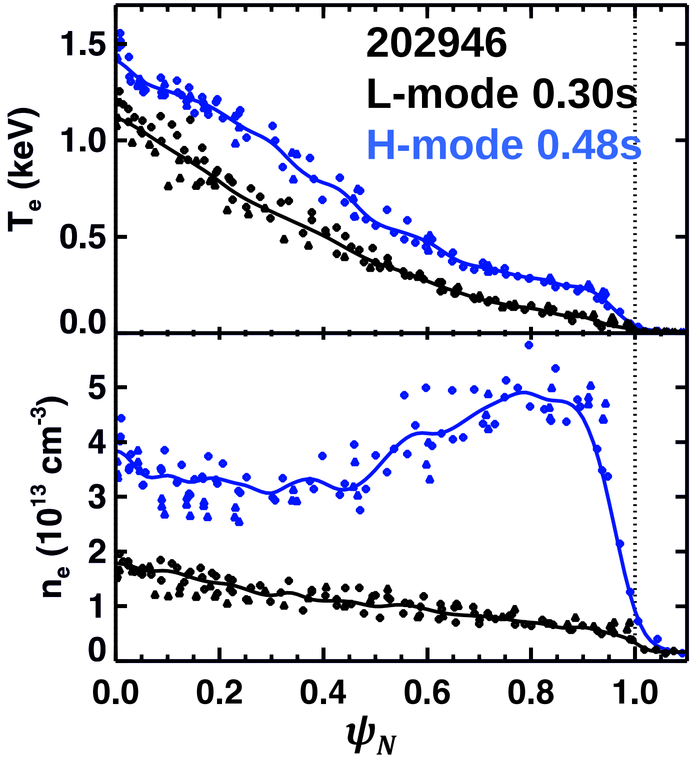
Stationary discharges achieved, limited only by ohmic flux/current

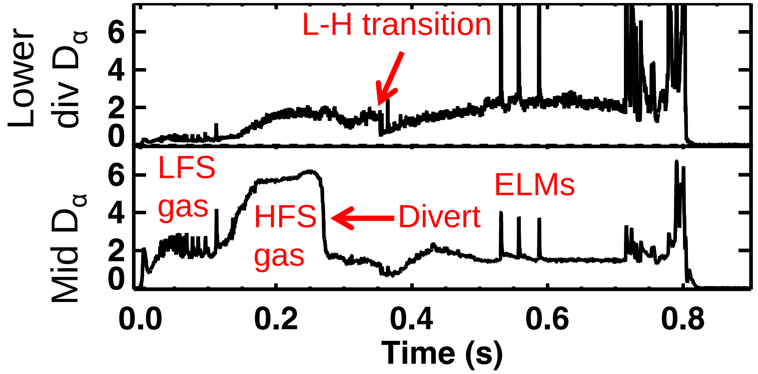


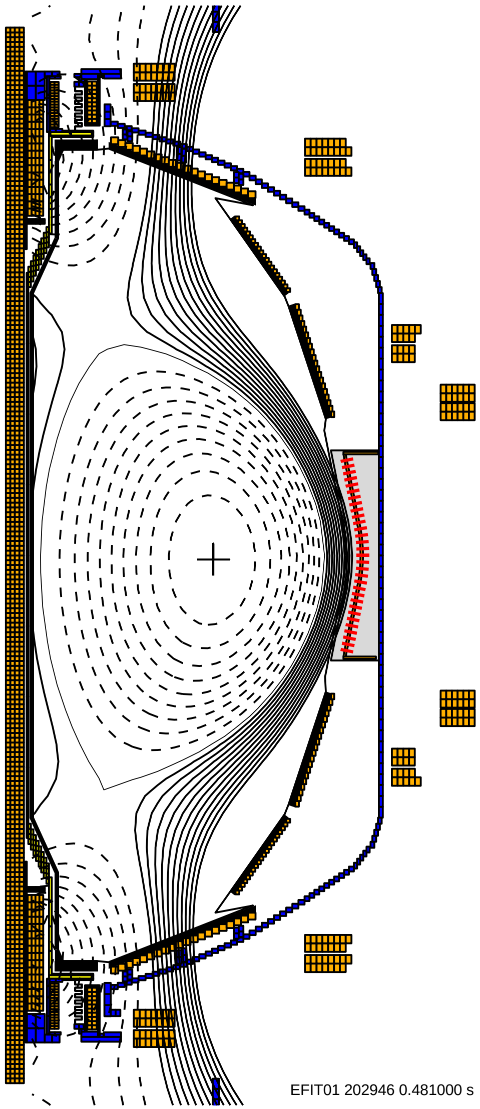


Also limiting length of discharge to limit coil heating → increased shot rep rate (~15 min)

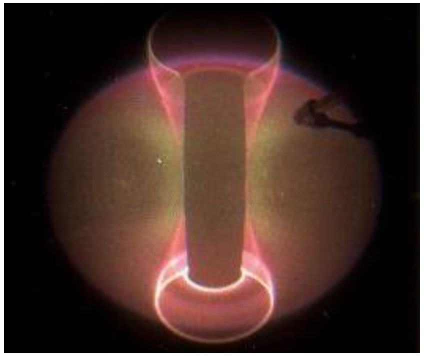
Routine operation at 0.65 T (0.55 T max for NSTX), H-mode access achieved







I_p	0.58 MA
B_{T0}	0.61 T
P_{NBI}	3 MW
P_{OH}	0.2 MW
A	1.6
κ	1.53
l_i	0.97
δ_{lower}	0.55
W	150 kJ
β_T	7.9%
β_P	1.2%
β_N	4.6
τ_e	50 ms



Status and operations in FY16

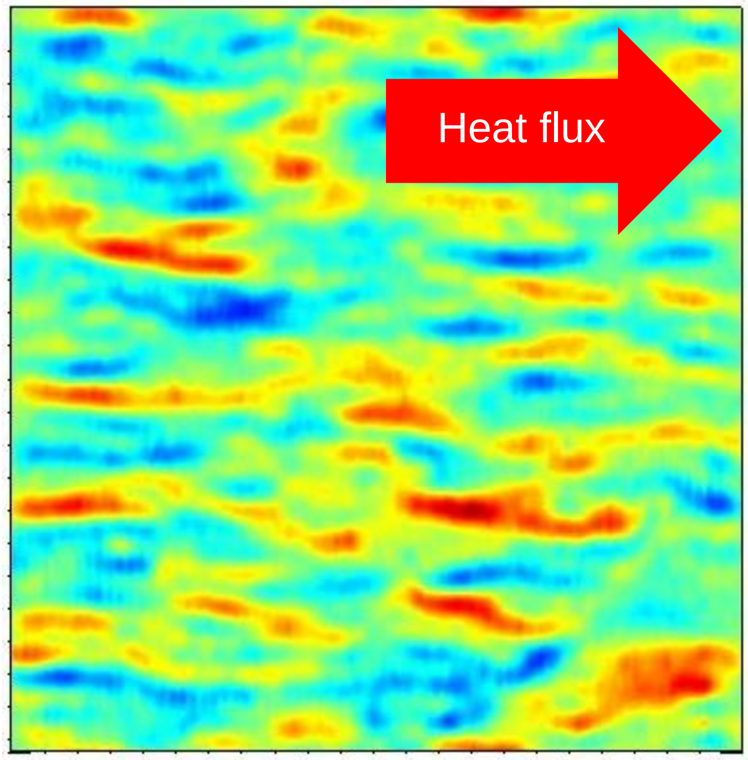
- Will move into research operations after 4-8 weeks of machine commissioning (improved plasma shape control, wall conditioning, diagnostic commissioning, …)
  - 18 run weeks in FY16, through ~July
- Field & current limits in 1st year: B_T=0.8 T, I_p=1.6 MA
  - 2nd year will utilize full field, current: 1.0T, 2 MA
- Have done various boronizations to condition plasma facing components
  - Plan to introduce Lithium after ~9 weeks of operation

Some general NSTX transport observations

L-mode (i.e. lower beta) – ITG/TEM predicted unstable

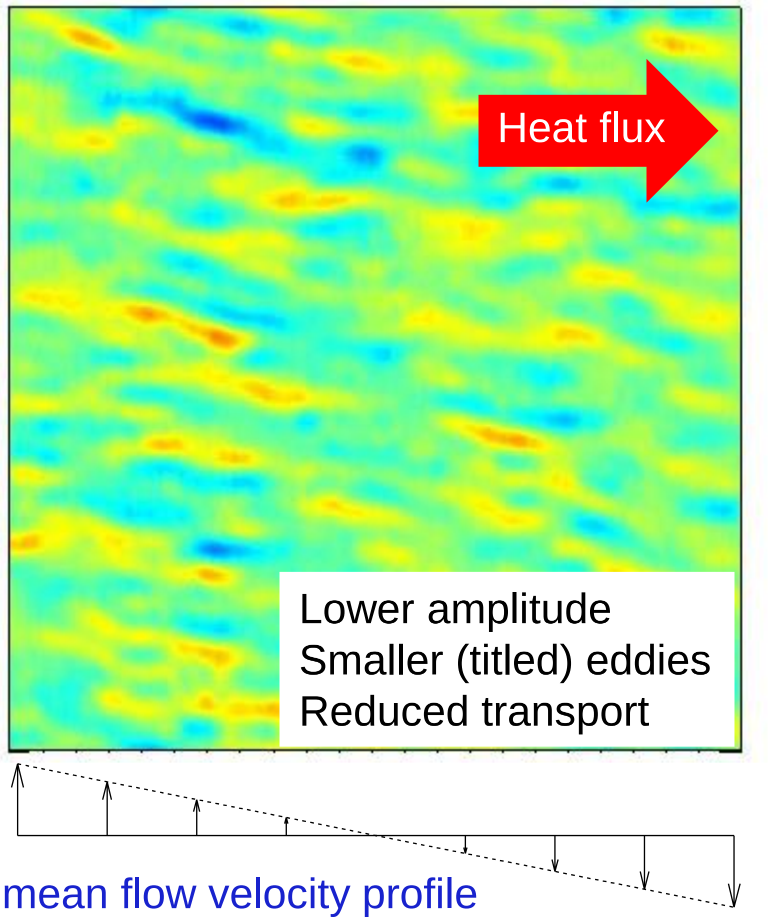
GYRO* simulations illustrate reduction in ITG/TEM turbulence due to E×B shear in NSTX L-mode plasma

Snapshot of density without E×B shear



100 ion radii
6,000 electron radii
~50 cm

Snapshot of density with E×B shear



Lower amplitude
Smaller (titled) eddies
Reduced transport

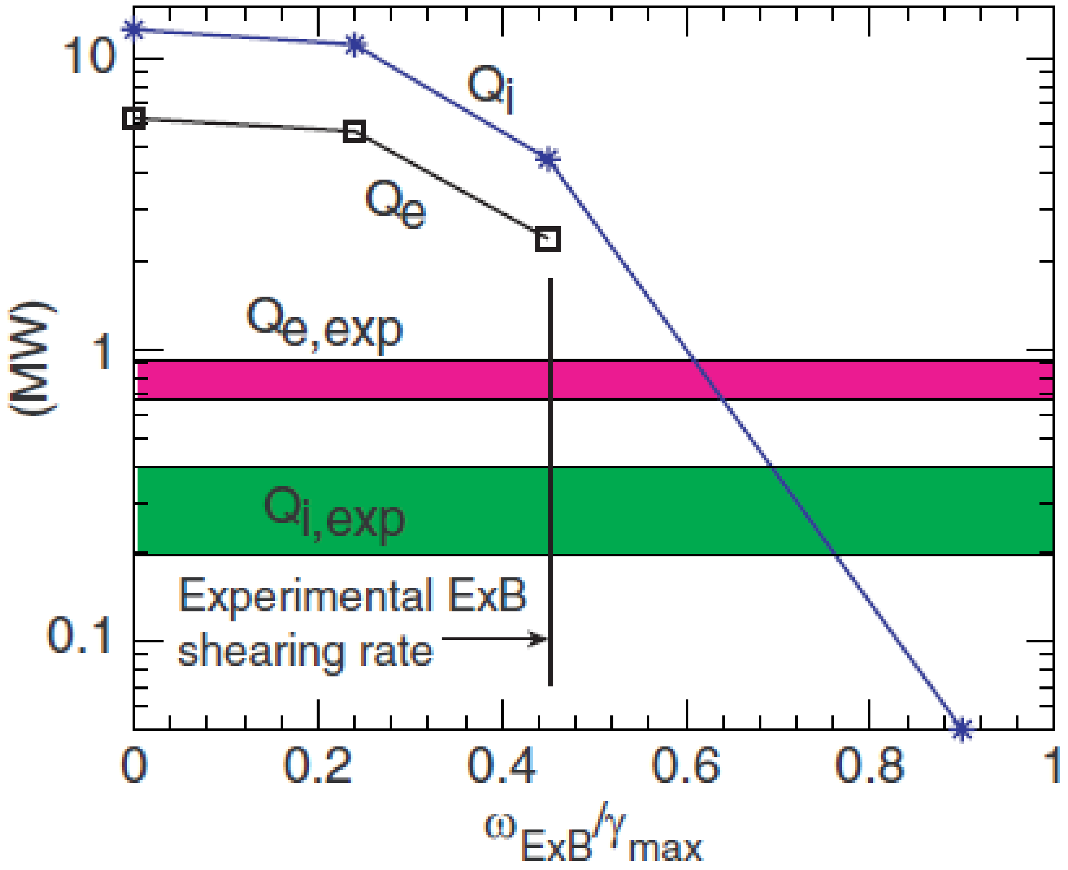
mean flow velocity profile

*Candy, Waltz, PRL (2003)

Ren, NF (2013)

GYRO* simulations illustrate reduction in ITG/TEM transport due to E×B shear in NSTX L-mode plasma

- Experimental fluxes not matched by predictions

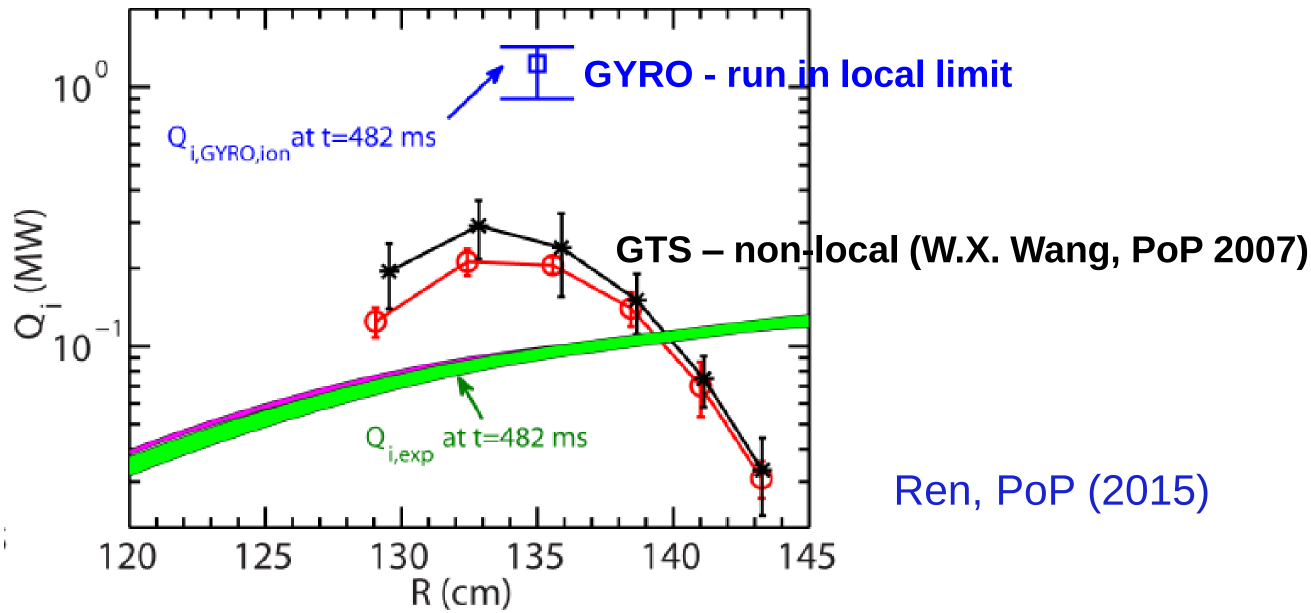


E×B shearing rate

Ren, NF (2013)

Previous simulations run in *local* limit, non-local simulations tend to reduce predicted transport

Local limit: Assume $\rho_* = \rho_i/R \rightarrow 0$ (OK for ITER, $\rho_* \sim 1/1000$) → use equilibrium parameters from one flux surface


Ion energy flux

GYRO - run in local limit

GTS – non-local (W.X. Wang, PoP 2007)

Ren, PoP (2015)

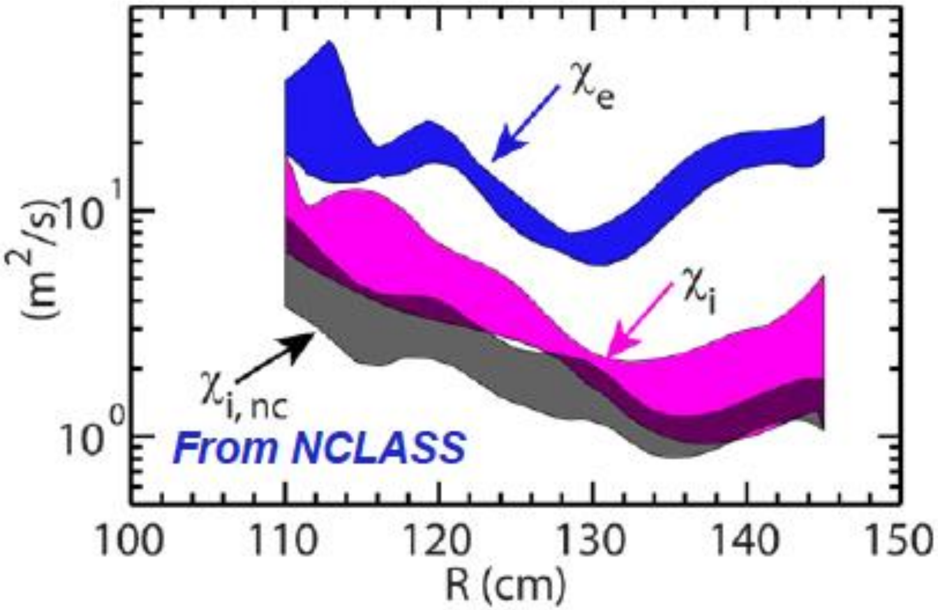
- Nature of instability can also change with radius in plasma, e.g. strong flow shear can drive a Kelvin-Helmholtz-like instability deeper in core (W.X. Wang, PoP 2015)
- **Challenge #1: Likely need robust non-local simulations ($\rho_* \sim 1/100$)**
- **Also need ion scale turbulence measurements → 2D BES in NSTX-U**

Some general NSTX transport observations

H-mode

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

- Follows simple argument that traditional ion scale turbulence (ITG/TEM) suppressed by equilibrium configuration and/or strong E×B flow shear



Courtesy Y. Ren

- Impurity transport (intrinsic carbon, injected Ne, …) also usually well described by neoclassical theory
  - Toroidal angular momentum transport is anomalous (Kaye, NF 2009)

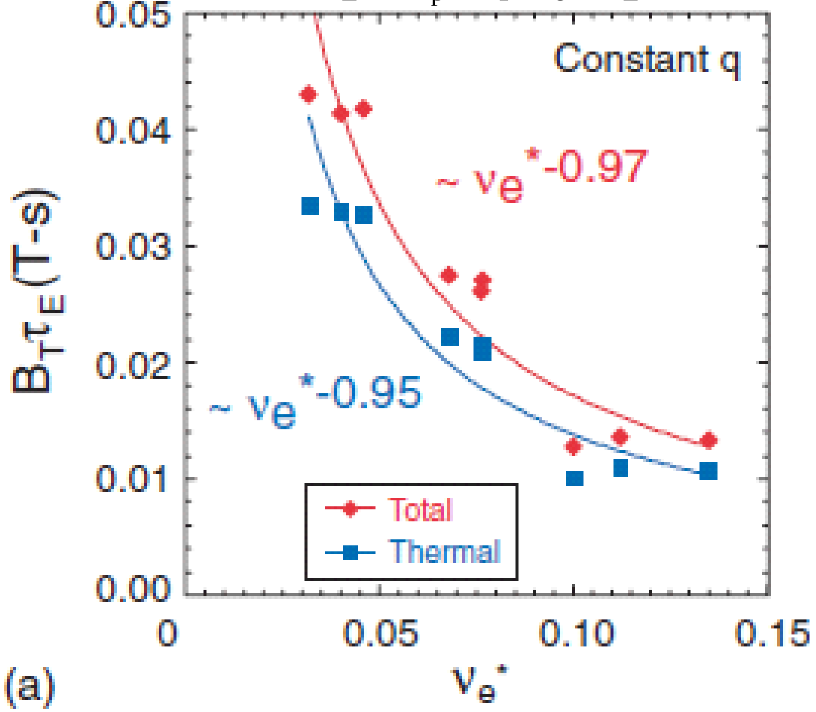
- **Electron energy transport always anomalous**

Normalized energy confinement time scales favorably with collisionality in STs

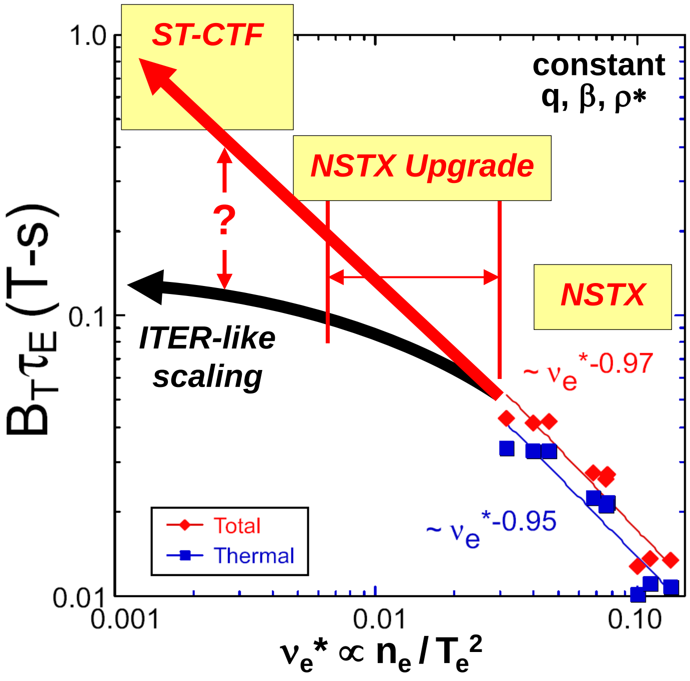
- Different from ITER scaling law ($\tau_{E,98y2} \sim \nu_{*e}^{-0.1}$)
- Next generation STs (FNSF, CTF, Pilot Plant) likely to be at lower ν_*
- Present ST confinement scaling with ν_* favorable $\Rightarrow$ will it hold at lower ν_*?
  - Hints at lower ν_* that $\chi_i > \chi_{i,NC}$ ($D_{imp} > D_{imp,NC}$)

Kaye et al. (2007)

$$\tau_E^{th} \sim I_p^{0.6} B_T^{1.0} n_e^{0.35} P_L^{-0.6}$$



NSTX upgrade (Menard)



At increasing β, ITG/TEM predicted to be much weaker or absent

$\rightarrow$Electron scale (ETG) turbulence

Electron scale (~mm) turbulence can dominate when ITG/TEM suppressed

- Electron temperature gradient (ETG) instability "isomorphic" to ITG, same ballooning instability mechanism but reversed role of ions and electrons

- $L_\perp \sim \rho_e$, $\omega \sim v_{Te}/R$ (~60 times smaller, ~60 times faster than ITG)

- Characteristic gyroBohm transport expected to be 1/60 of ITG transport

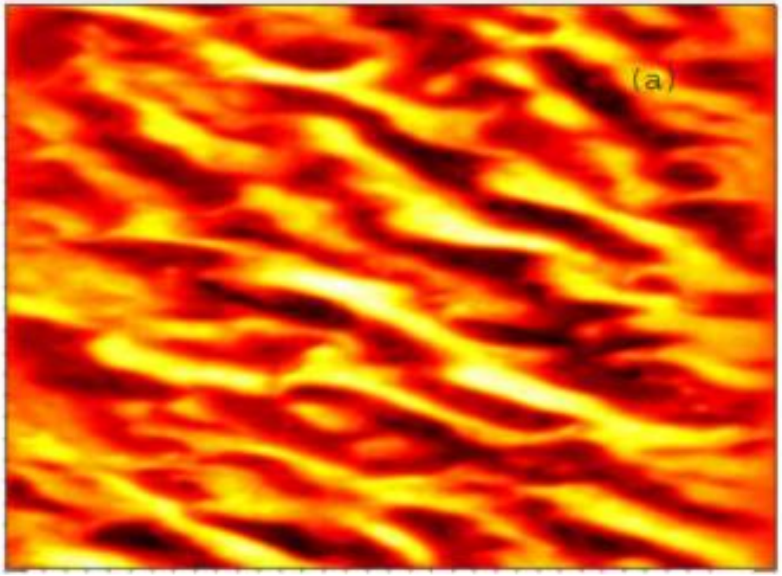
$$\chi_{ETG} \sim (\Delta x)^2/\Delta t \sim \rho_e{}^2 v_{Te}/R \sim (1/60) \cdot \rho_i{}^2 v_{Ti}/R$$

- "Streamers" can exist nonlinearly (Jenko, Dorland, 2000, 2001)

$$\Delta x \sim L_r > L_\theta \; (k_\theta >> k_r)$$

$\Rightarrow$**Much larger transport than expected**

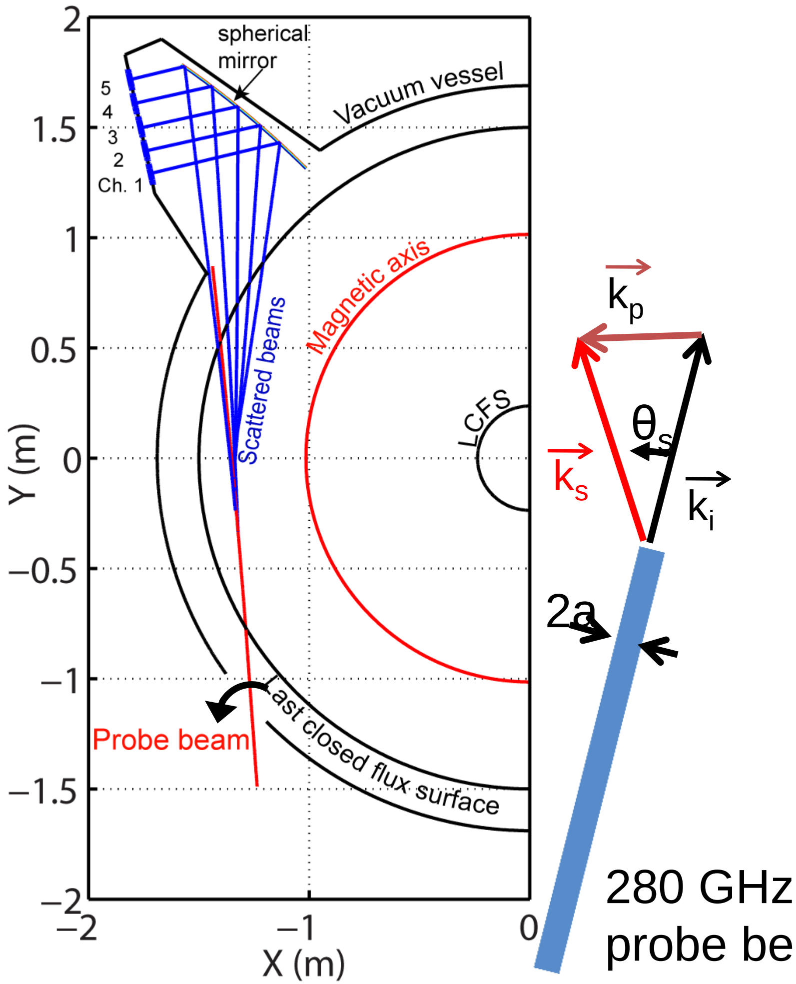
density fluctuations from ETG simulation



6 ion radii
360 electron radii
~2 cm

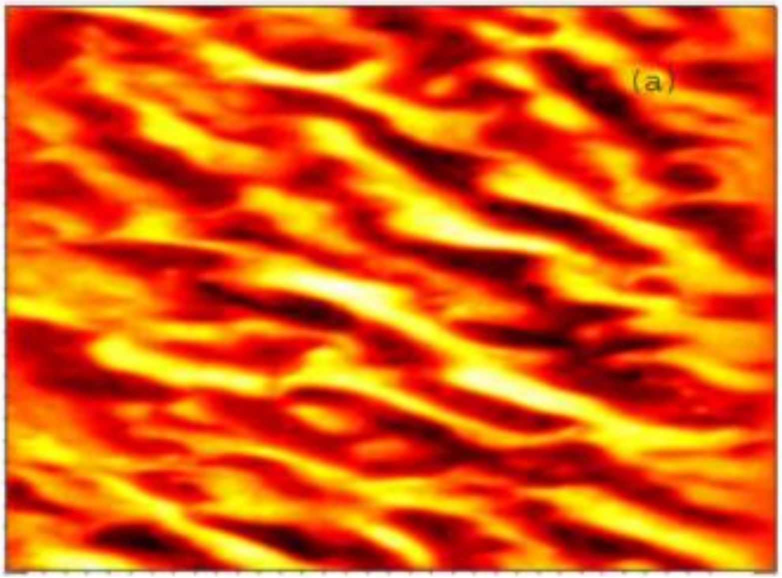
Guttenfelder, PoP (2011)

Not easy to image electron scale (mm) fluctuations → "microwave scattering" used to detect high-k fluctuations



280 GHz
probe beam

density fluctuations from ETG simulation



6 ion radii
360 electron radii
~2 cm

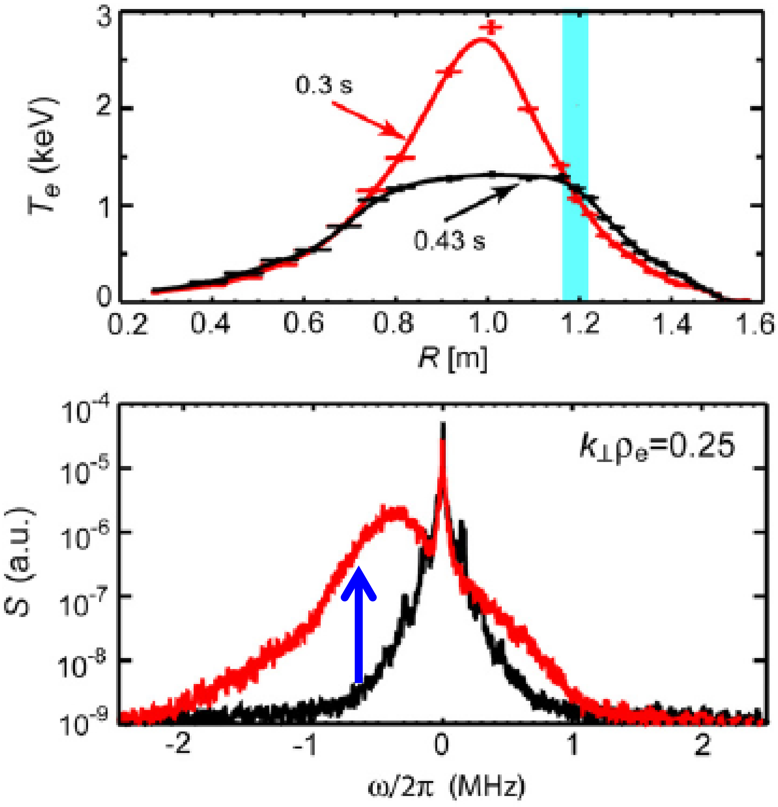
Smith, RSI (2008)

Correlation observed between high-k scattering fluctuations and ∇T_e

- Applying RF heating to increase Te
- Fluctuations increase as expected for ETG turbulence

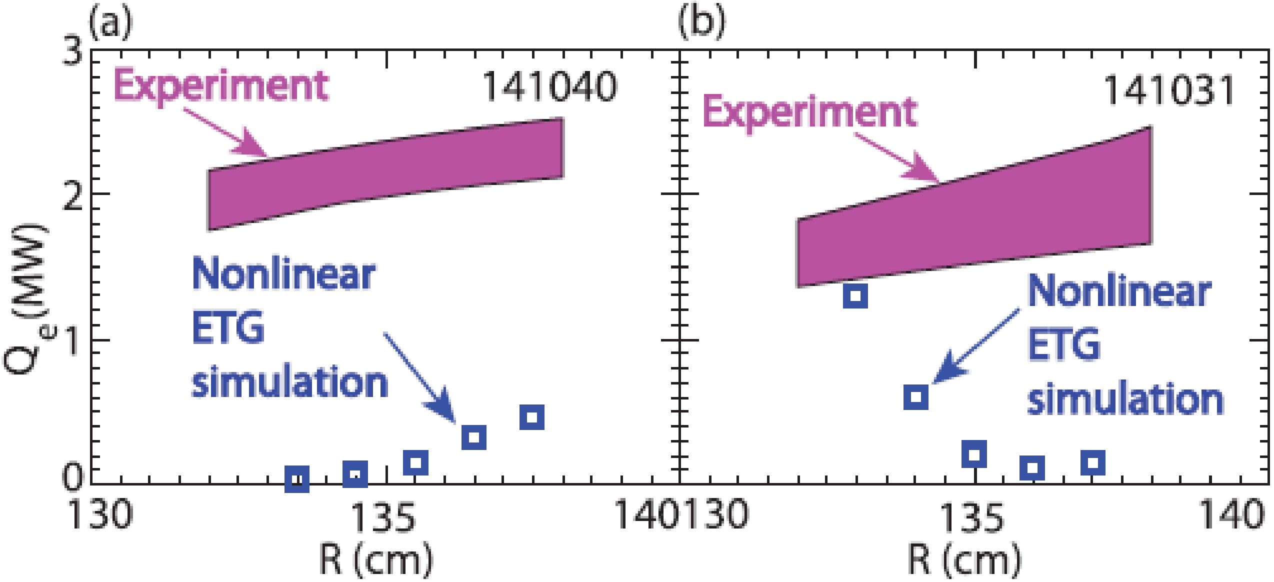
- Other trends measured that are consistent with ETG expectations, e.g. reduction of high-k scattering with**:**

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)

While many high-k trends correlate with ETG predictions, predicted transport often too small

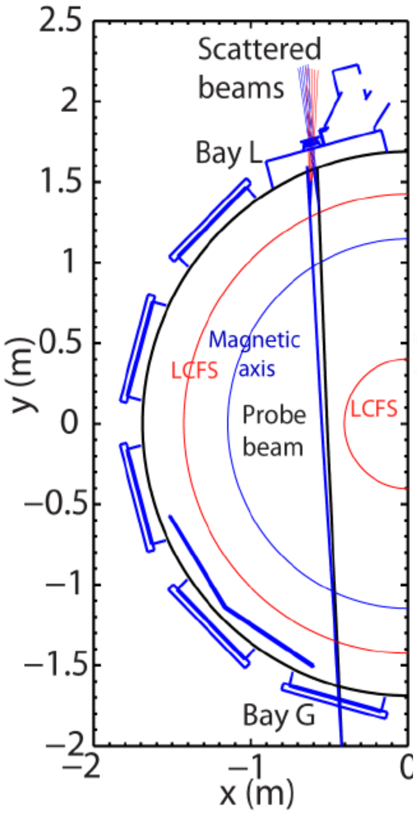


Ren, PoP (2012)

- **Challenge #2: May need multi-scale simulations (recall UCLA seminar by N. Howard, Jan. 22, 2016) and improved high-k scattering measurements**

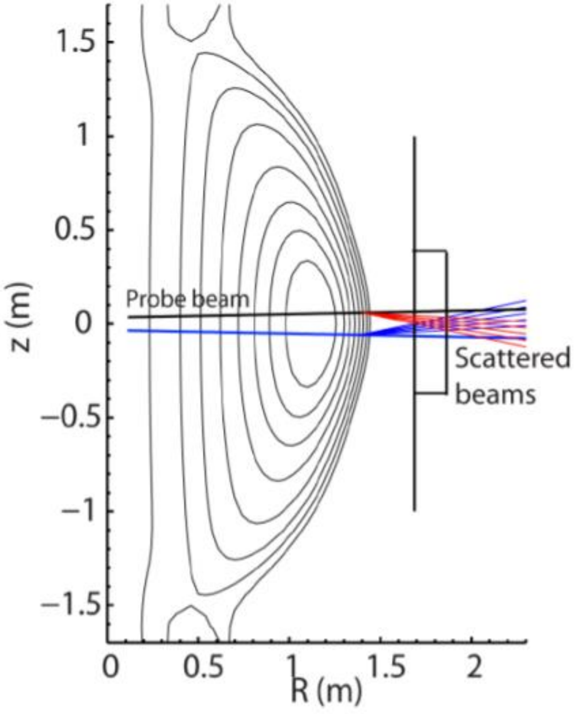
New high-k scattering configuration should allow improved spectral coverage

- Will allow better overlap with streamer like structure ($k_\theta >> k_r$)

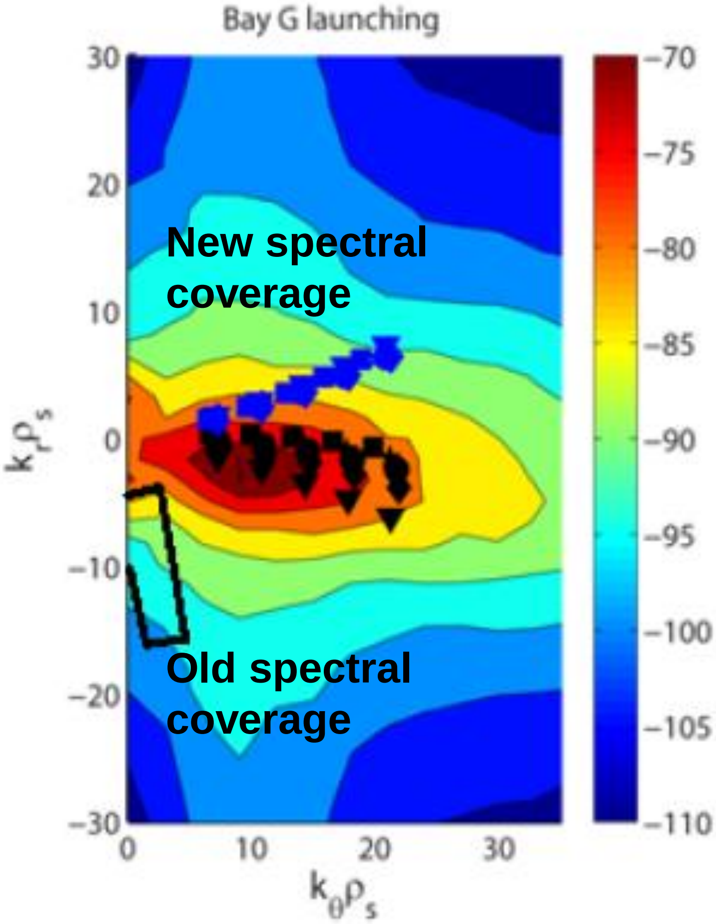


Top View

PPPL/UCD collaboration



Side View



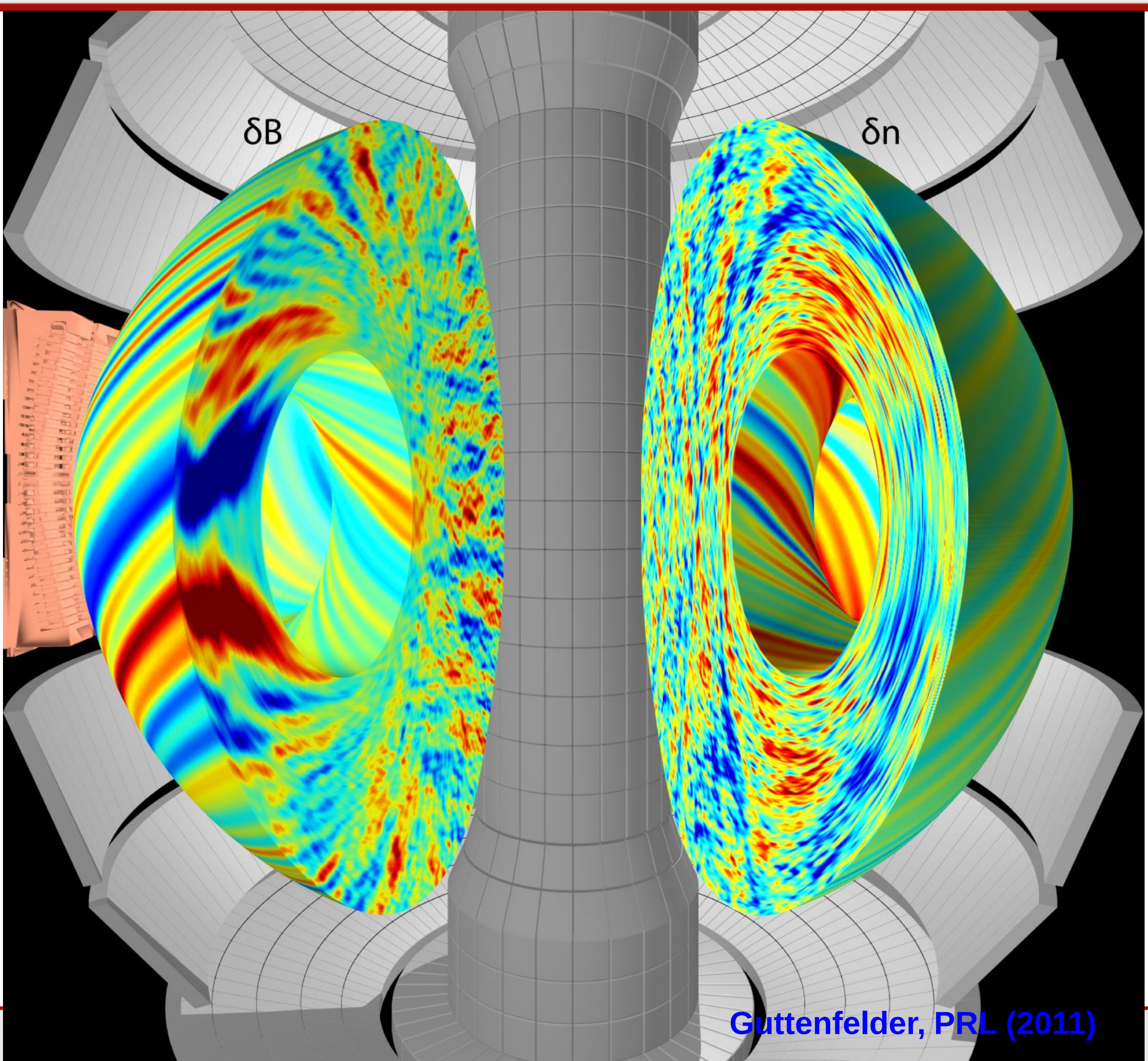
New spectral coverage

Old spectral coverage

At highest β's, electromagnetic turbulence is predicted

→Microtearing mode (MTM) turbulence

Simulations of microtearing turbulence predict $\delta B/B \sim 10^{-3}$



Guttenfelder, PRL (2011)

Linear microtearing instability

- High-m tearing mode around a rational $q(r_0)=m/n$ surface ($k_{||}(r_0)=0$)
  (Classical tearing mode stable for large m, $\Delta'\approx-2m/r<0$)
- In the core, driven by ∇T_e with* time-dependent thermal force $\Rightarrow$ *requires collisionality*

Conceptual linear picture

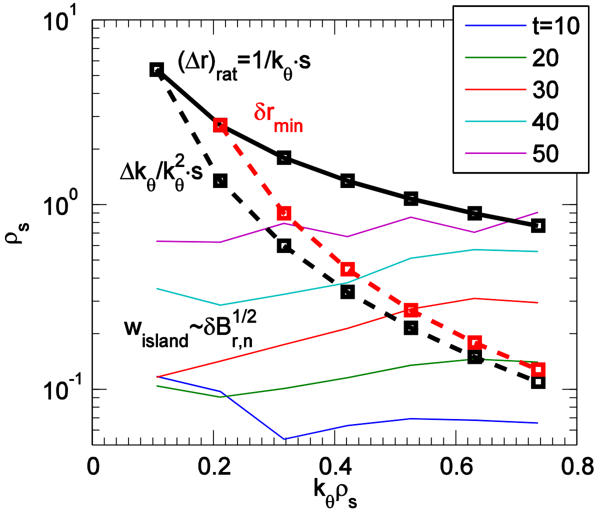
- Imagine helically resonant ($q=m/n$) δB_r perturbation $\quad \delta B_r \sim \cos(m\theta - n\varphi)$
- δB_r leads to radially perturbed field line, finite island width $\quad w = 4\left(\dfrac{\delta B_r}{B}\dfrac{rR}{n\hat{s}}\right)^{1/2}$
- ∇T_e projected onto field line gives parallel gradient $\quad \nabla_{||}T_{e0} = \dfrac{\vec{B}\cdot\nabla T_{e0}}{B} = \dfrac{\delta B_r}{B}\nabla \underline{T_{e0}}$
- Time-dependent parallel thermal force (phase shifted, $\sim i\omega/\nu^* n_e \nabla_{||} T_e$) balanced by inductive electric field $E_{||}=-dA_{||}/dt$ with a δB_r that reinforces the instability

- Instability requires sufficient ∇T_e, β, ν_e (differences predicted in the edge)
- **Not explicitly driven by bad-curvature**

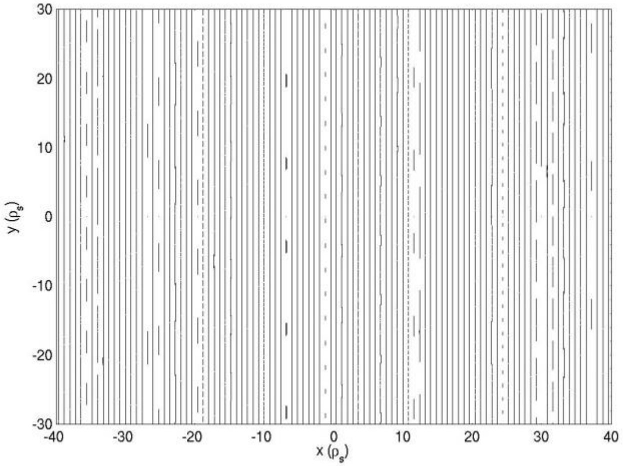
*e.g. Hazeltine et al., Phys. Fluids (1975); Drake & Lee, Phys. Fluids (1977); A. Hassam (1980)

Onset of magnetic stochasticity leads to large electron thermal transport, $Q_e \sim v_{Te}|\delta B/B|^2$

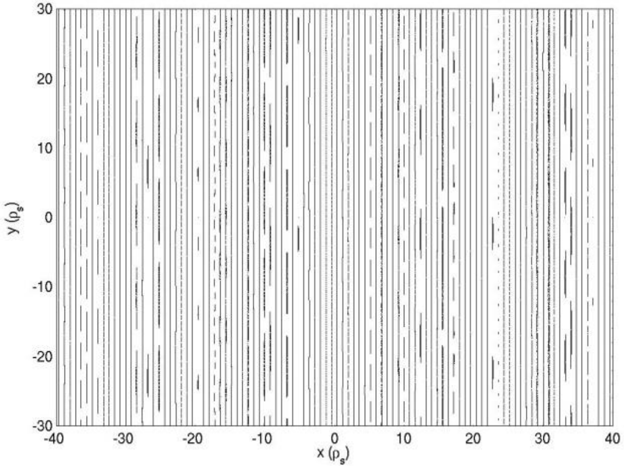
- Inspecting Poincare plots during early phase of simulation (before saturation)



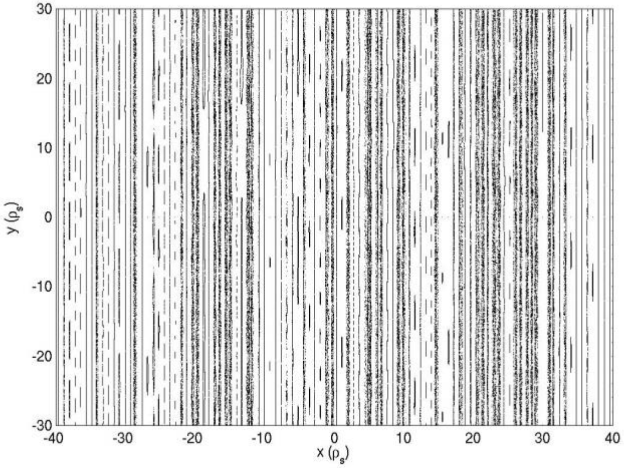
t=10 a/c_s



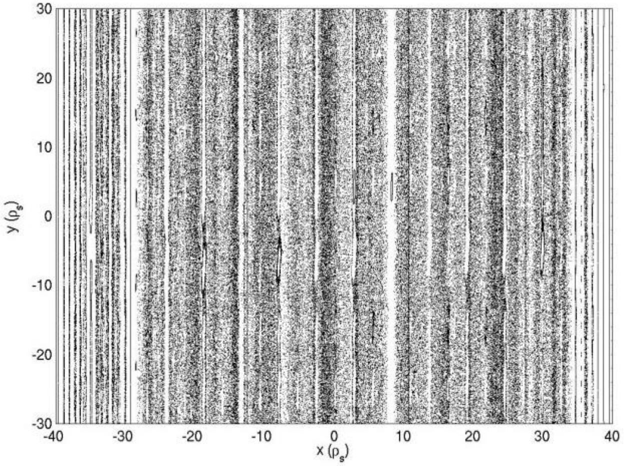
t=20 a/c_s



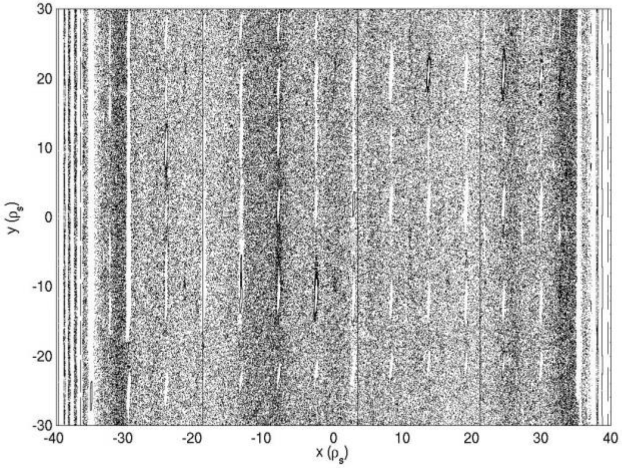
t=30 a/c_s



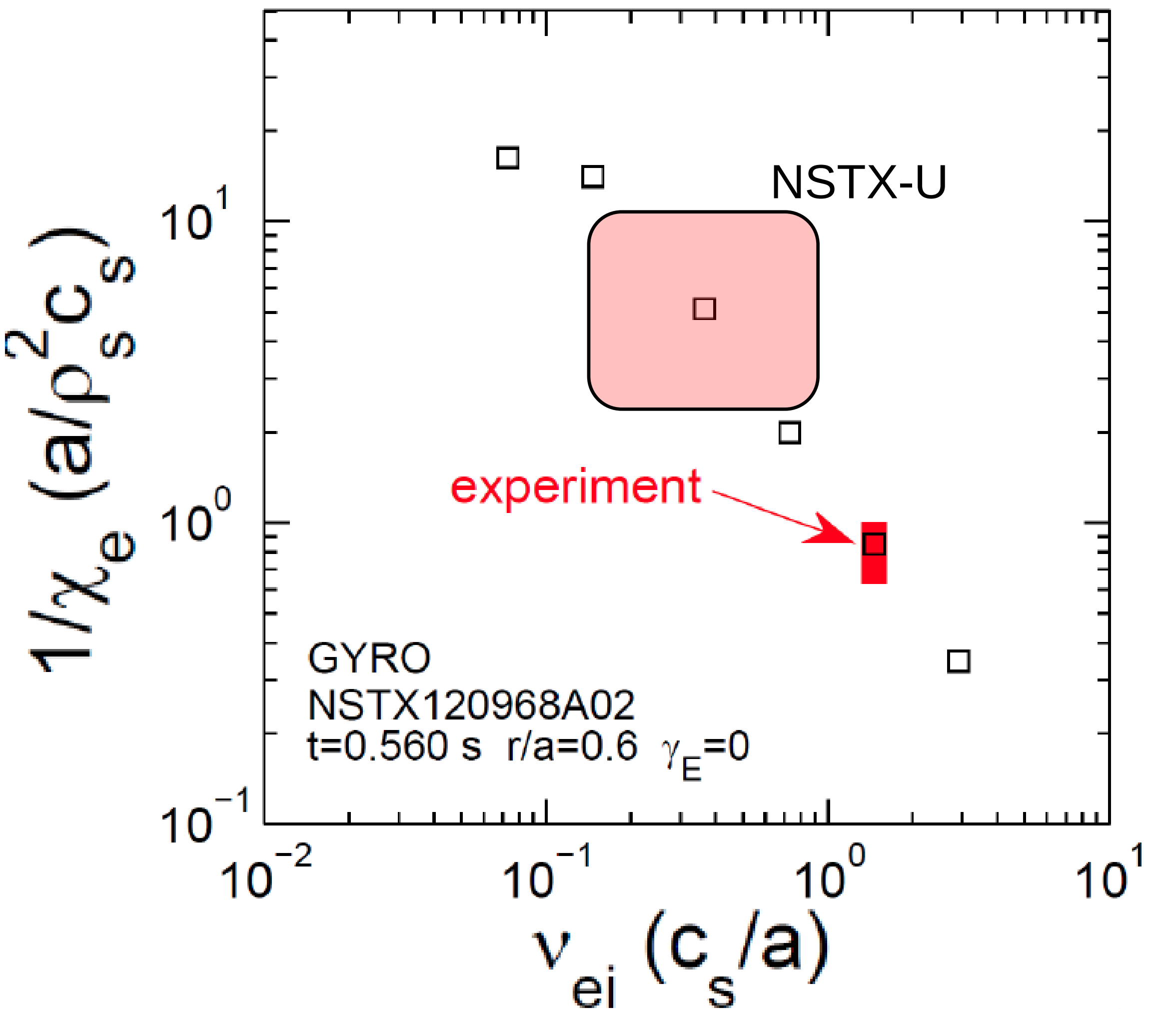
t=40 a/c_s



t=50 a/c_s



Microtearing-driven (MT) transport may explain ST collisionality scaling



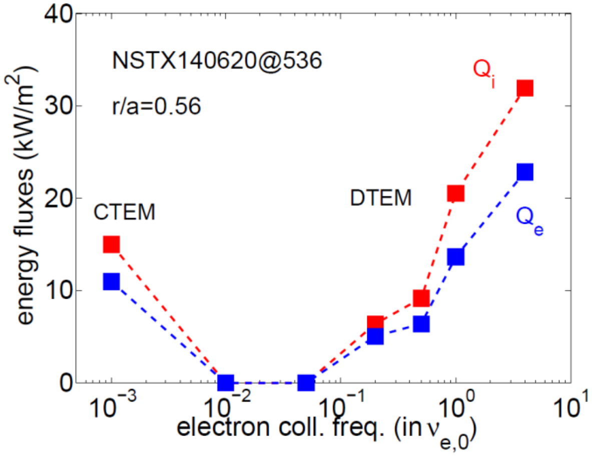
Guttenfelder, et al., PoP (2012)

Challenge #3: Simulation and measurement of electromagnetic at high beta

- Numerically challenging to simulate, susceptible to E×B shear suppression? (Doerk, PRL 2011; Hatch, UCLA seminar 2015)

- **Strongly desire internal magnetic fluctuation measurements to validate simulations (ongoing collaboration with UCLA diagnostic group)**

- A unique “dissipative” TEM predicted to have similar collisionality scaling to MTM (W.X. Wang, PoP 2015)
  - From global ***ES*** simulations
  - Highlights need for global ***EM*** sims, see Challenge #1



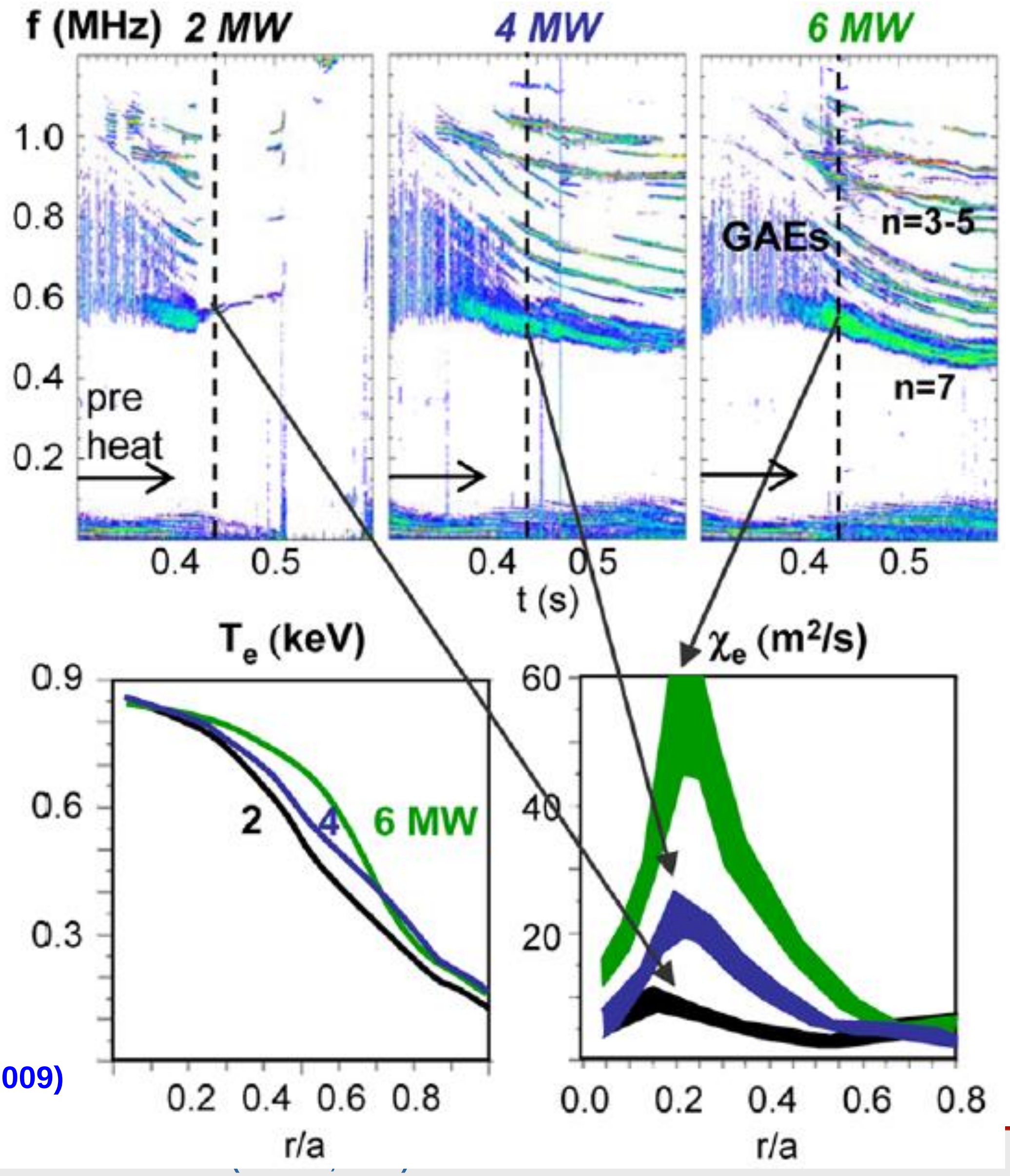
Other mechanisms that are not drift wave micro-turbulence

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

- Gradient-driven microinstabilities unlikely to explain flattened profiles (unless substantial non-local effects are important)

- GAE and CAE (compressional Alfven eigenmodes) driven unstable by gradients in fast-ion phase space

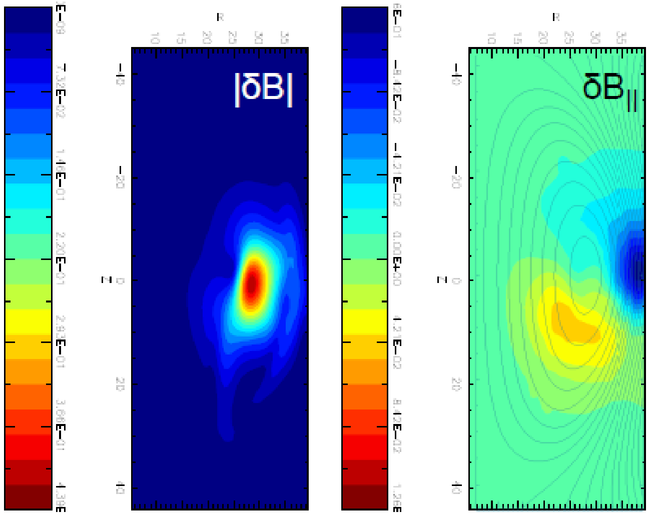
- How do they influence electron thermal transport?



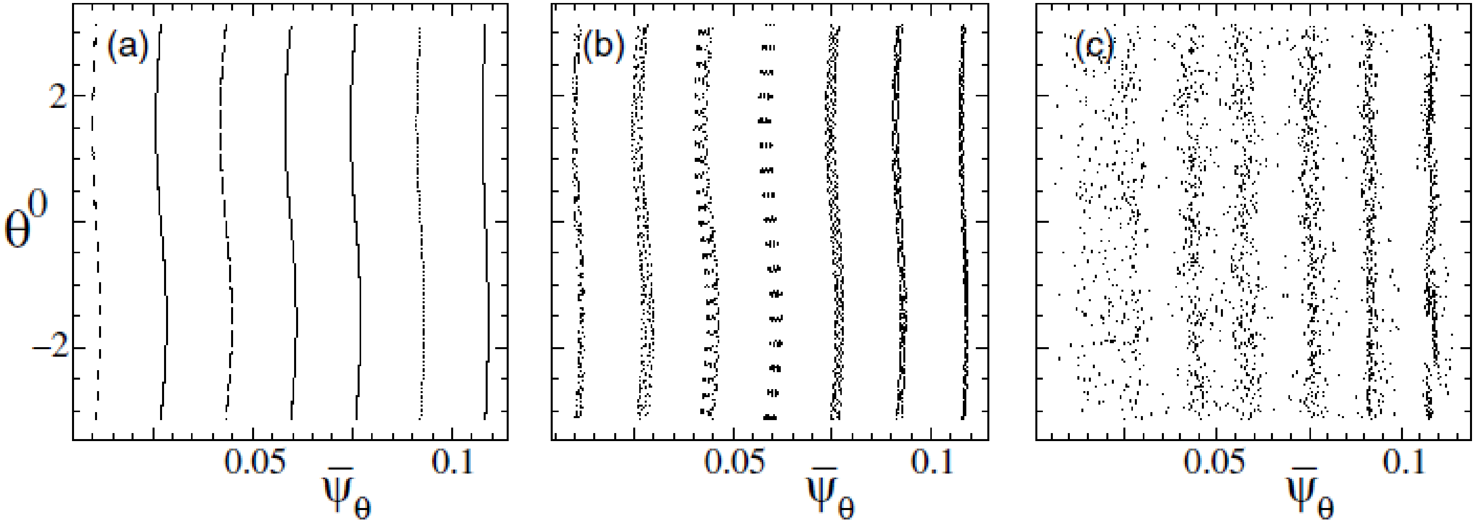
Stutman, PRL (2009)

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

- Global structure simulated (Belova, PRL 2015) ⟶ and measured by reflectometry (Crocker, NF 2013)

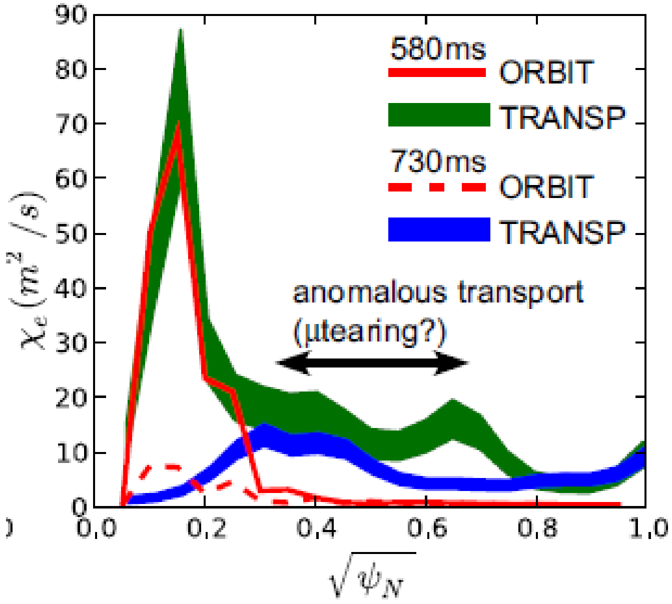


- Computed electron orbits become stochastic with sufficient number & amplitude of overlapping GAE & CAE modes



Gorelenkov, NF (2010); Crocker (2016)

Stochastic orbits can give very large $\chi_{e,st} \sim \langle \Delta r^2 \rangle / \Delta t$



Tritz, APS (2012)

- CAEs also couple to kinetic Alfven waves (KAW) near mid-radius (Belova, PRL 2015) → may redistribute beam energy before heating electrons

- **Challenge #4: Must consider mechanisms beyond drift wave micro-turbulence**

Summary of observations and challenges

- Numerous transport observations and simulations give hints as to the nature of transport in NSTX, complicated by broad range of operating regime (especially beta)

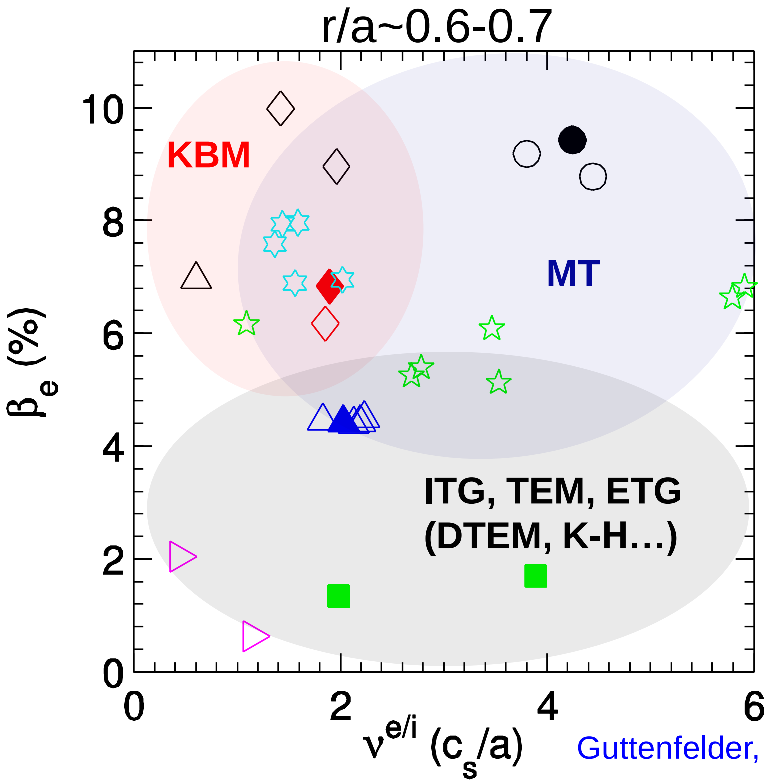
- Continuously improving diagnostics to validate predictions, verify transport mechanisms
  - Upgraded BES
  - New “2D” high-k scattering
  - Internal δB measurement?
- Gyrokinetic simulations have advance considerably, but still require reliable and robust simulations that are:
  - Global, electromagnetic, possibly multiscale, with strong flow/flow shear (haven’t even mentioned equilibrium centrifugal effects)
- Likely need to account for mechanism beyond drift wave turbulence
  - GAE/CAE stochastic orbit
  - CAE-KAE coupling

- **Ultimately want to improve our predictive capability for next generation tokamaks (ITER, FNSF, CTF, Pilot Plant, …)**

NSTX-U transport and turbulence research aims to establish predictive capability for performance of FNSF & ITER

- Challenging and exciting as:
  - NSTX-U accesses a variety of drift wave transport mechanisms

All potentially relevant for ITER & other tokamaks

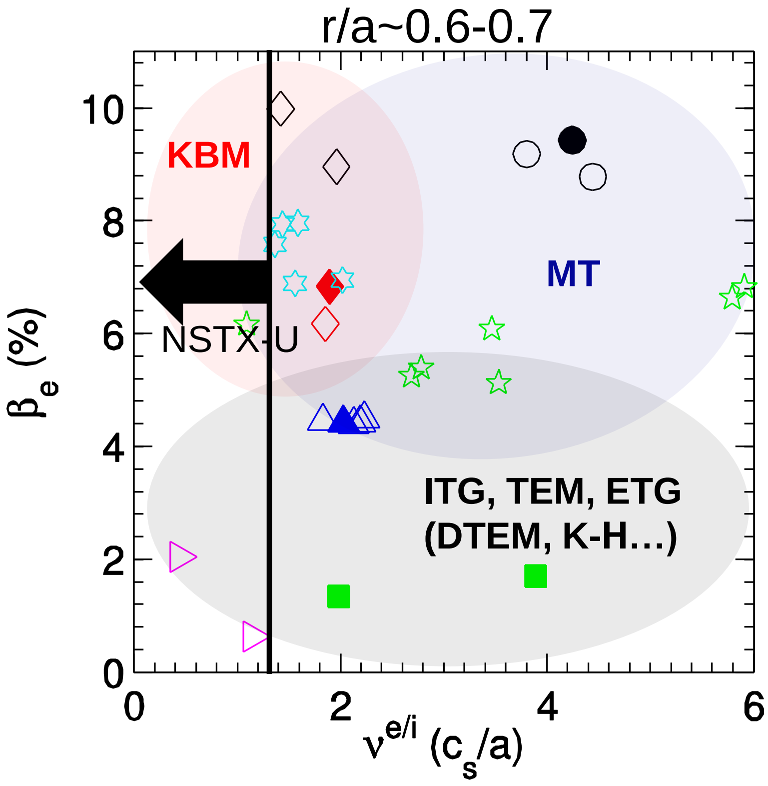


Guttenfelder, NF (2013)

NSTX-U transport and turbulence research aims to establish predictive capability for performance of FNSF & ITER

- Challenging and exciting as:
  - NSTX-U accesses a variety of drift wave transport mechanisms
  - NSTX-U is unique in achieving high β and low collisionality regime

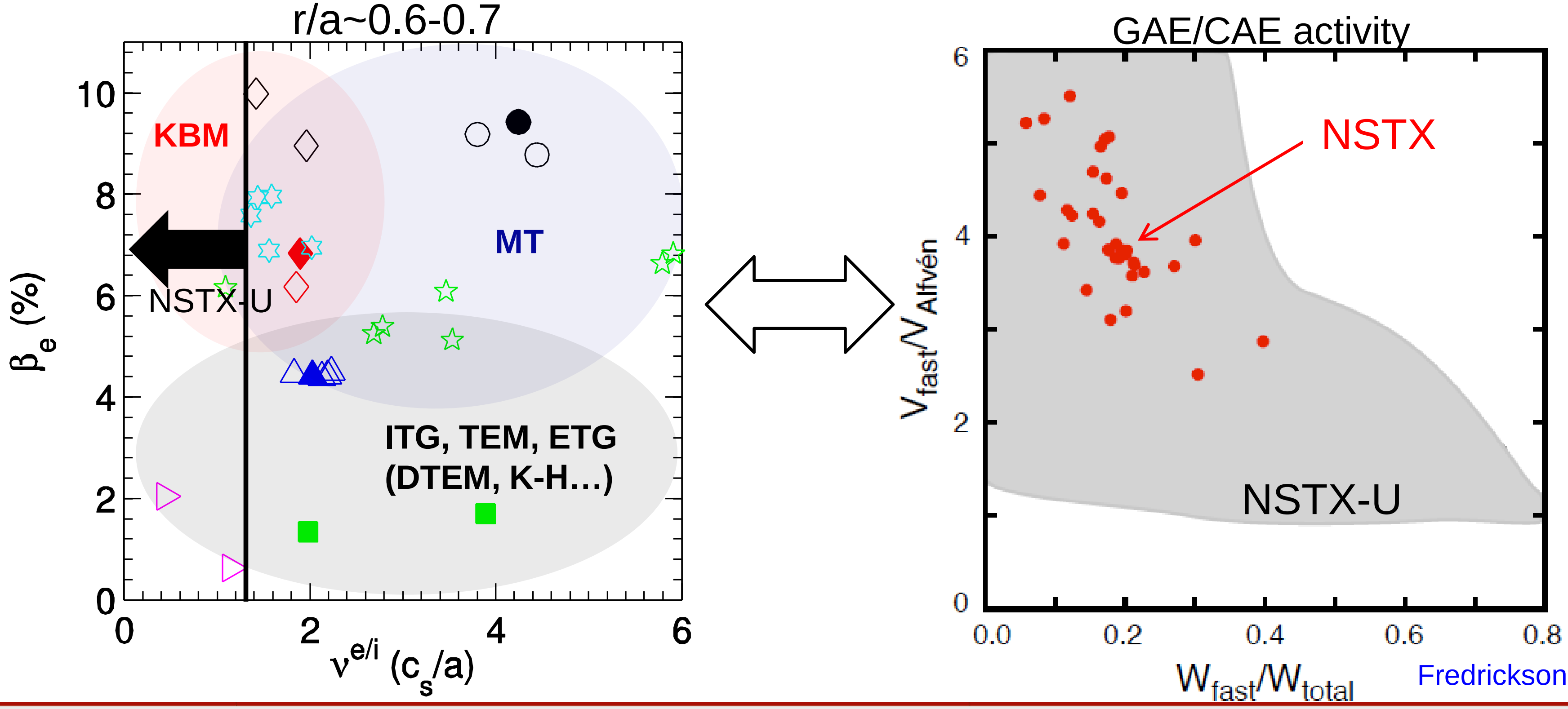
Will $\tau_E \sim 1/\nu_*$ remain valid?
Will microtearing be suppressed?
Will $\chi_i \approx \chi_{i,NC}$ & $D_{imp} \approx D_{imp,NC}$ hold?



NSTX-U transport and turbulence research aims to establish predictive capability for performance of FNSF & ITER

- Challenging and exciting as:
  - NSTX-U accesses a variety of drift wave transport mechanisms
  - NSTX-U is unique in achieving high β and low collisionality regime
  - Electron thermal transport can also be driven by Global & Compressional Alfvén eigenmodes (GAE/CAEs)

What is role of GAE/CAE setting $T_{e,0}$?
How will GAE/CAE respond for higher field, 2nd NBI?



Fredrickson

NSTX-U transport and turbulence research thrusts

- Thrust 1: Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U
- Thrust 2: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U
  - Low-k modes ($k_\perp \rho_s \leq 1$): ITG/TEM/KBM, MT
  - High-k mode: ETG
  - CAE/GAE

$\}$ drift waves

$\}$ Alfvén eigenmodes

- Thrust 3: Establish and validate reduced transport models

The End!!!