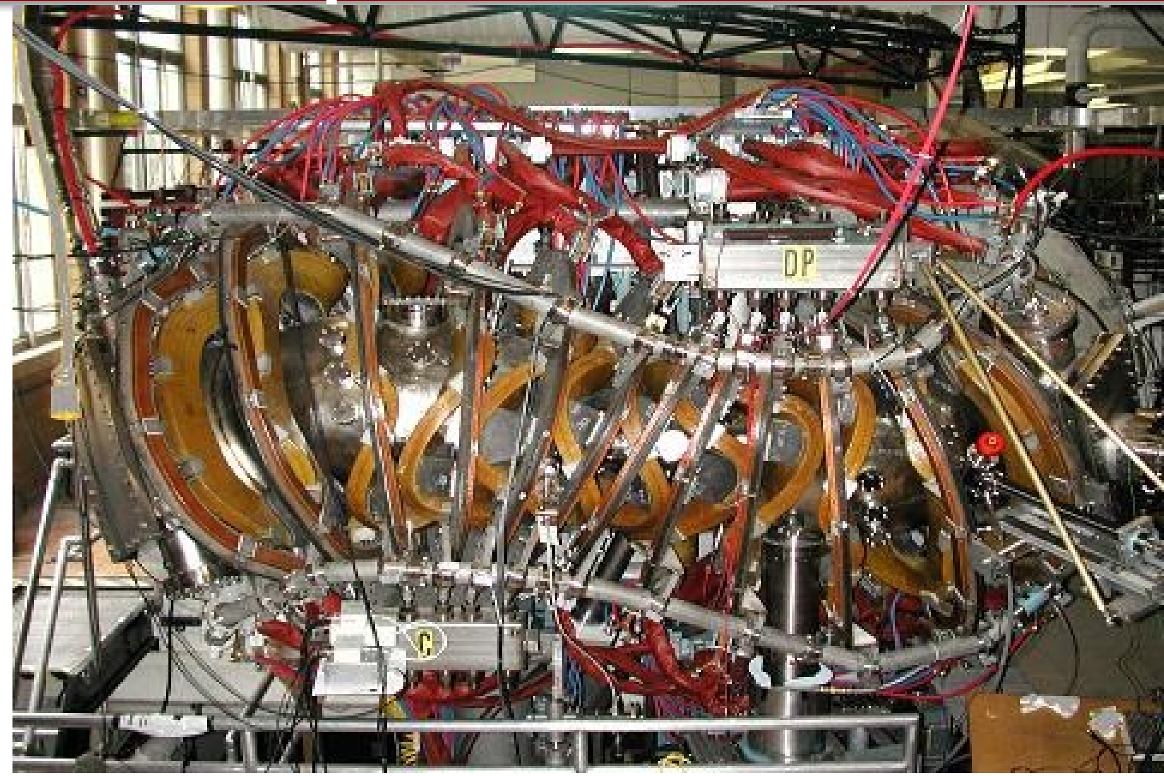
Recent Experimental Results on the Helically Symmetric Experiment



EPR/CT Meeting, August 5-8, 2014
University of Wisconsin, Madison, WI

G.M. Weir on behalf of the HSX Plasma Laboratory,
University of Wisconsin – Madison

The role of the Helically Symmetric Experiment (HSX) in the world stellarator program

- HSX is optimized for neoclassical transport and therefore dominated by anomalous transport. Excellent position to contribute to W7-X.
- The bootstrap current will alter the edge magnetic structure required for W7-X divertor
  - On HSX we've performed magnetic reconstruction of the bootstrap current profile and its evolution
- Do stellarators need pedestals to achieve high core temperatures?
  - Heat flux measurements using power balance and heat pulse propagation show that the core electron temperature in HSX can react independently from the edge
  - Gyrokinetic modeling of micro-instabilities using the GENE code, include
    - Collaborative benchmarking with the W7-X group
    - First non-linear calculations using two kinetic species to model the TEM in stellarator geometry

The role of the Helically Symmetric Experiment (HSX) in the world stellarator program

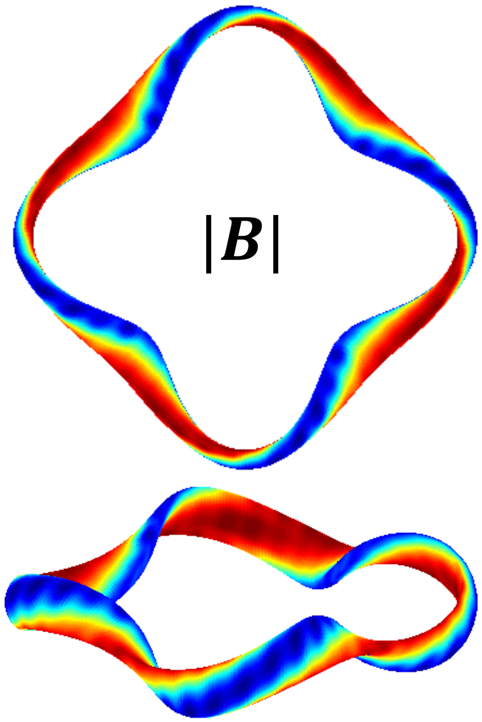
- Is the radial electric field and parallel flow still determined by neoclassical theory in a quasi-symmetric stellarator?
  - CHERS measurements of Pfirsch-Schluter flows and the radial electric field
  - Reynolds stress measurements of flow drive in the edge where the radial electric field is not neoclassical

- Why are high recycling regimes observed in tokamaks and not in stellarators?
  - Counter streaming flows, thought to inhibit high recycling regimes, are predicted by EMC3-EIRENE but not observed through probe measurements
  - Limiting structures will be used to control wall recycling and investigate heat and particle transport

The Helically Symmetric eXperiment (HSX)

- **HSX is a modular stellarator with a helical direction of symmetry in |B|**
  - **4 field periods**
  - **48 modular coils**
  - **48 planar coils can be independently energized to break the symmetry**

Average Major Radius	1.2 m
Average Minor Radius	0.12 m
Rotational Transform (axis,edge)	1.05, 1.12
On-axis field	1T
Two 200 kW ECRH Systems	28 GHz
Pulse length	50 ms
Maximum core temperature (deeply collisionless)	2.5 KeV



HSX combines good particle confinement with the benefits of the conventional stellarator

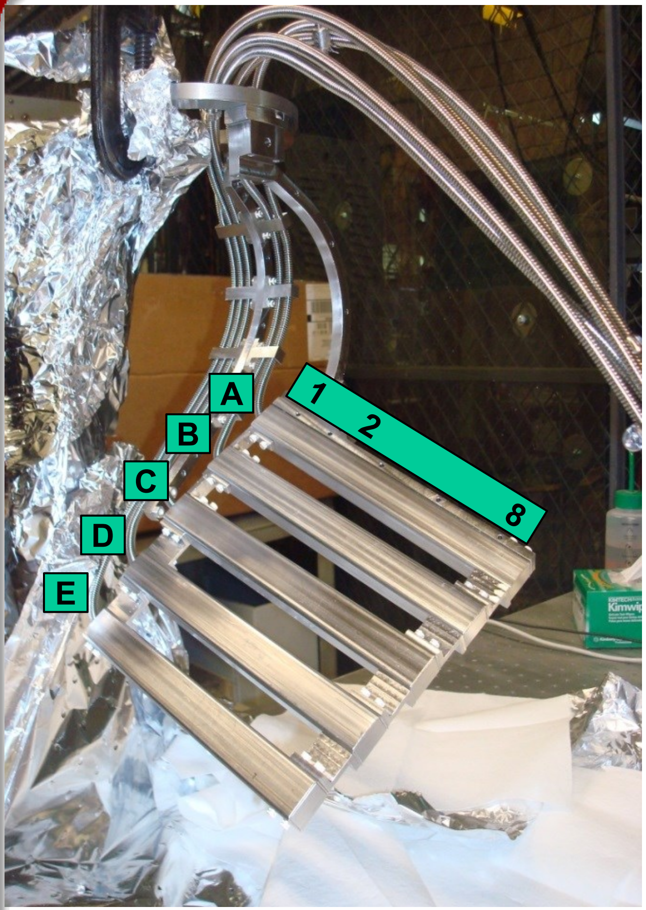
Tokamak	Conventional stellarator
Good single-particle confinement	Intrinsically steady-state
Simple coils	Low recirculating power and no disruptions
Low-aspect ratio	High density limit

- **HSX is the world's first and only operating quasi-symmetric stellarator**
- **HSX has experimentally verified the benefits of Quasi-Helical Symmetry (QHS):**
  - **Reduced thermodiffusion and very low neoclassical transport** [J.M. Canik, PRL 2007]**,**
  - **Decreased parallel viscous damping** [S.P. Gerhardt, PRL 2004]**,**
  - **Large parallel flows in the symmetry direction** [Briesemeister, PPCF],
  - **Reduced parallel currents** [Schmitt, Nucl. Fusion 2013],
  - **Reduced passing particle deviation from flux-surfaces** [Talmadge, PoP, 2002]**.**
  - **Good trapped particle confinement** [A. Abdou, Ph.D. Thesis 2005]**.**

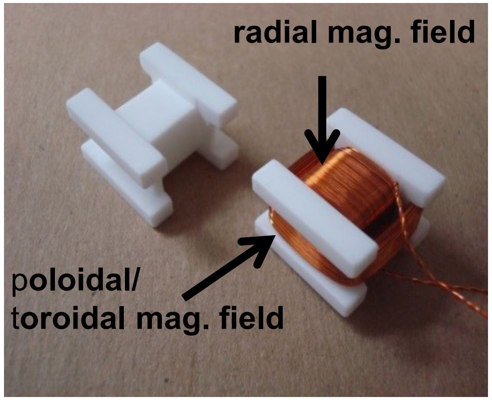
Outline

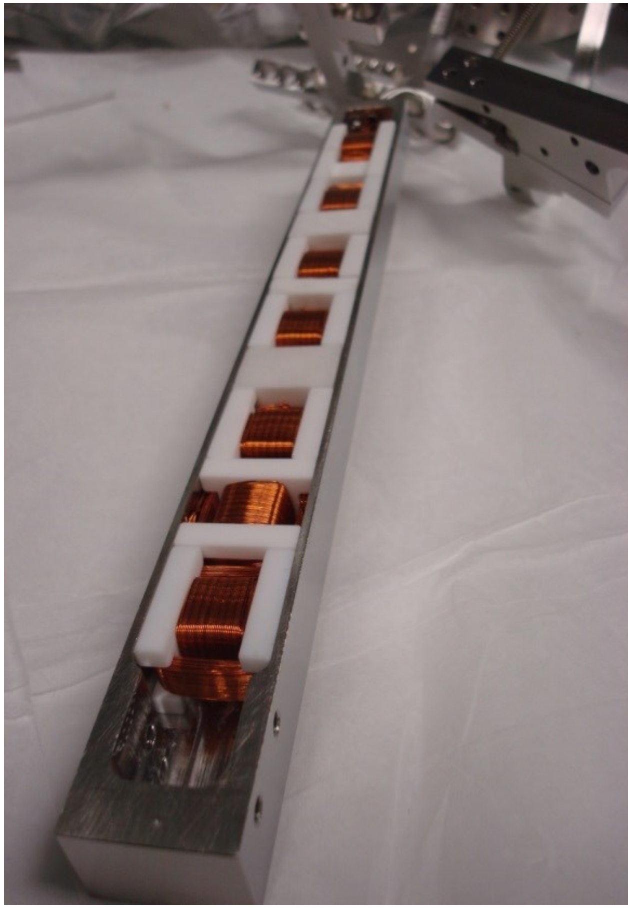
- **Equilibrium Reconstruction**
- **Heat transport measurements and gyrokinetic calculations**
- **Flows and the radial electric field**
- **Edge measurements**

An internal set of magnetic diagnostics are used for equilibrium reconstruction of the plasma pressure and current density



- Equilibrium reconstruction using V3FIT code [1]
- Location of new magnetic diagnostics optimized for profile reconstruction
- Eddy currents investigated using the SPARK code [2]





[1] James D. Hanson *et al* 2009 *Nucl. Fusion* 49 075031
[2] D.W. Weissenburger *PPPL-2494* (1988)

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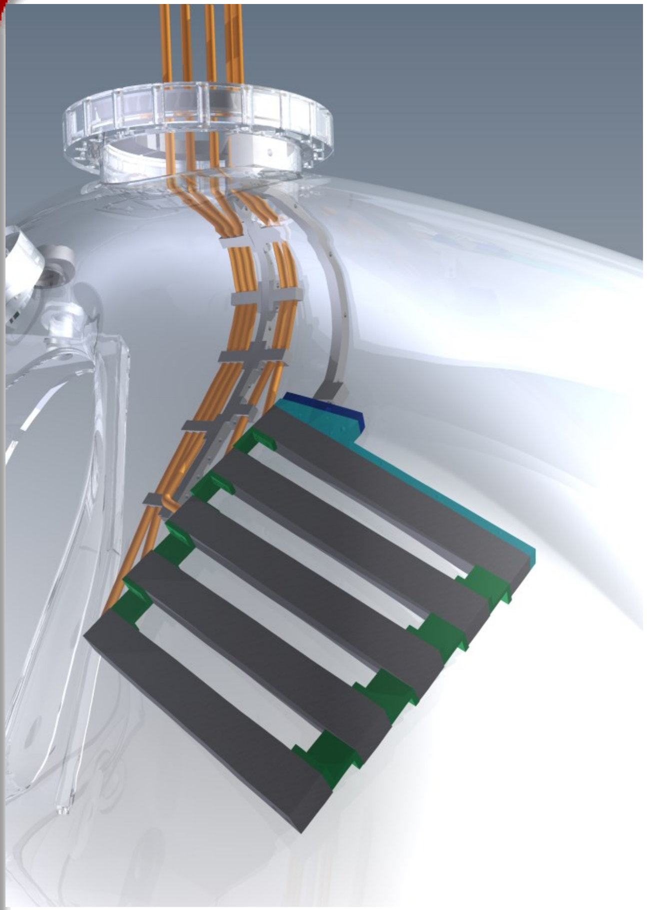

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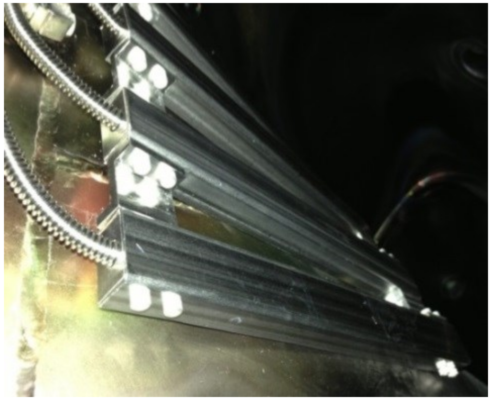

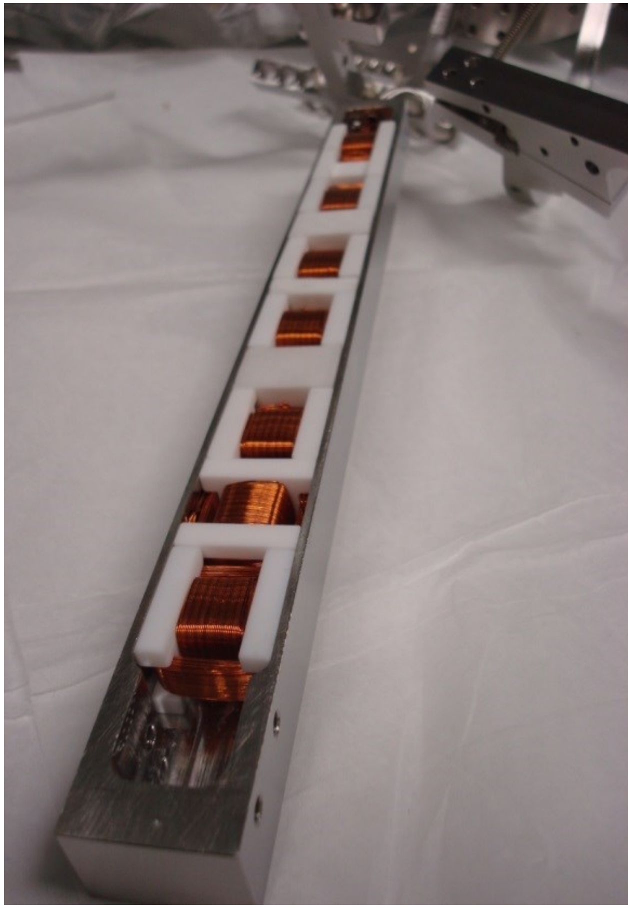

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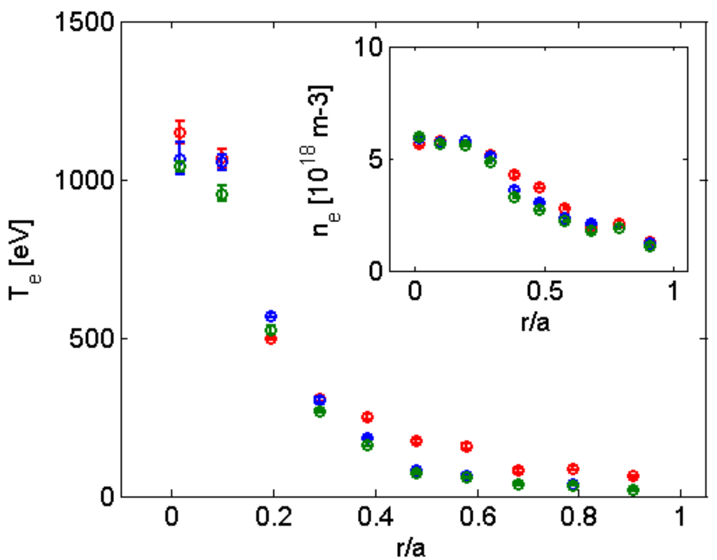
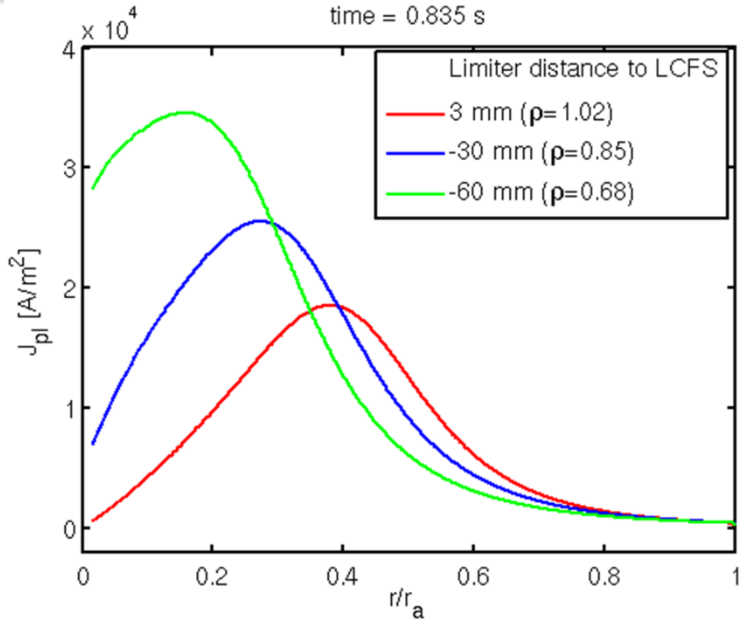
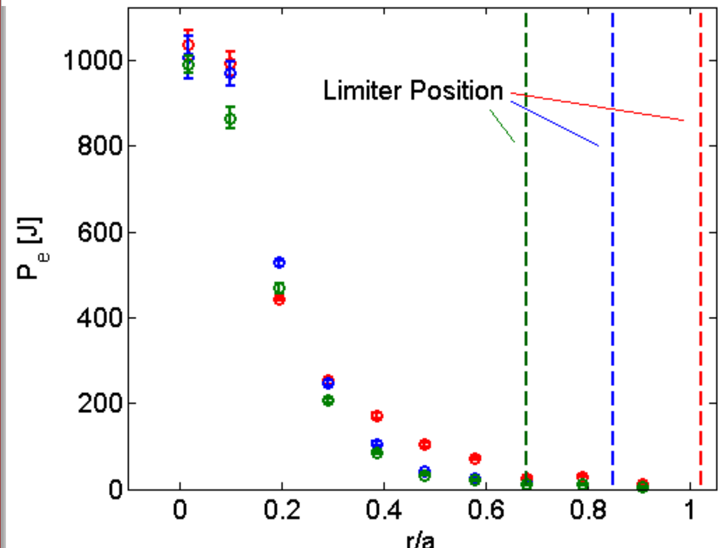
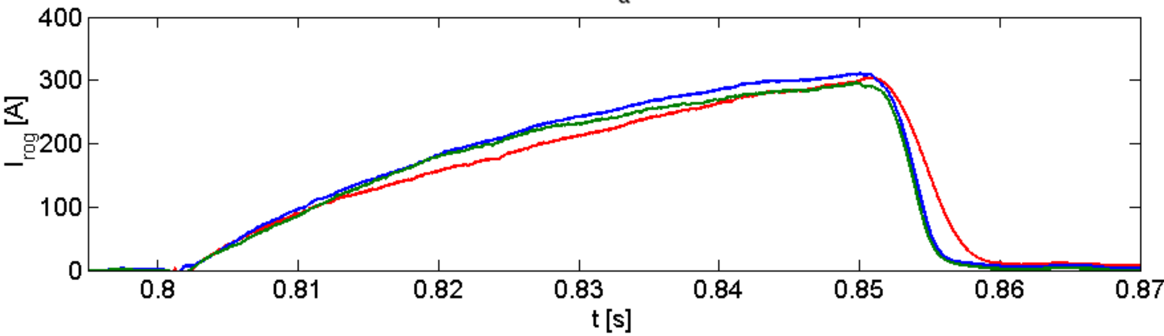
Plasma equilibrium reconstruction yields the temporal evolution of the plasma current density









The temporal evolution of the bootstrap current is crucial to the operation of the island divertor on W7-X

Outline

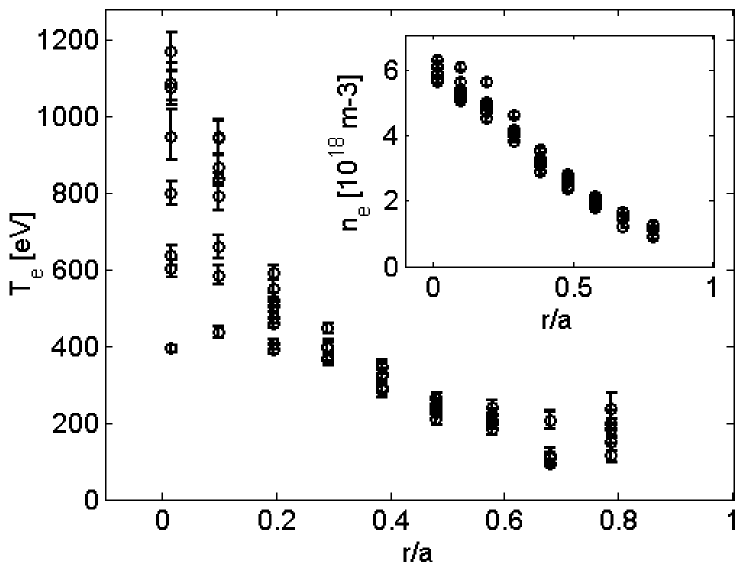
- Equilibrium Reconstruction
- **Heat transport measurements and gyrokinetic calculations**
- Flows and the radial electric field
- Edge measurements

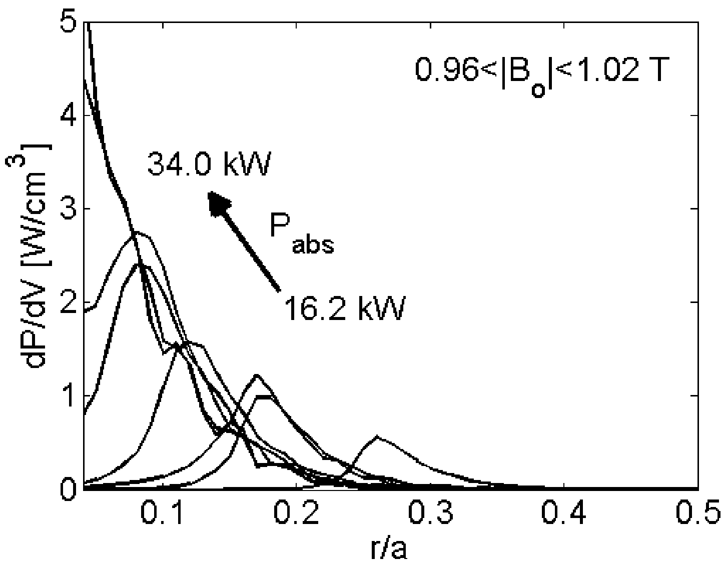
Tokamaks have resilient temperature profiles while stellarators do not. Does a QHS stellarator have any profile resiliency?

- **Profile resiliency is quantified by the stiffness in the electron heat flux, $S = \chi_e^{HP}/\chi_e^{PB}$**

$$\chi_e^{PB} = -q_e/n_e\nabla T_e \qquad\qquad \chi_e^{HP} = -\partial q_e/n_e\partial\nabla T_e$$

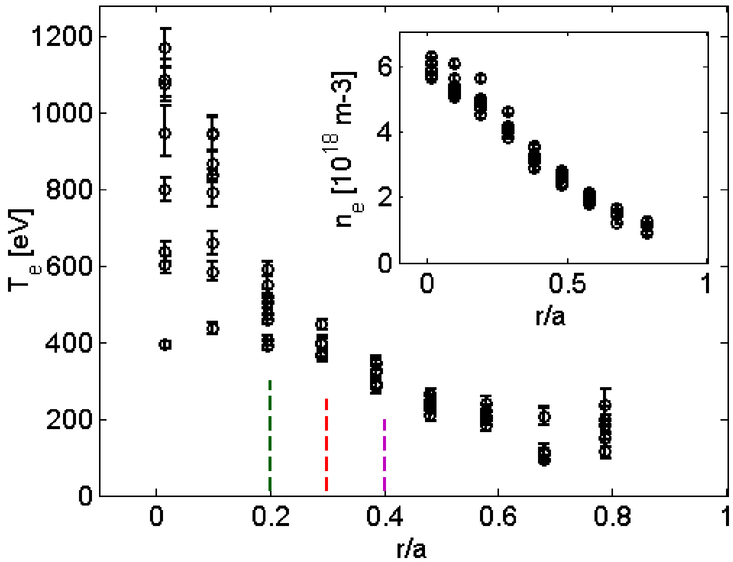
- **Heat flux scans to study q_e/n_e vs ∇T_e by varying the ECRH power deposition**
  - **Nearly constant n_e, T_e for $0.2 < r/a < 0.4$ measured by Thomson scattering**
  - **ECRH absorption from multi-pass ray tracing (3 passes)**
  - **Concurrent ECRH power modulation for heat pulse propagation**



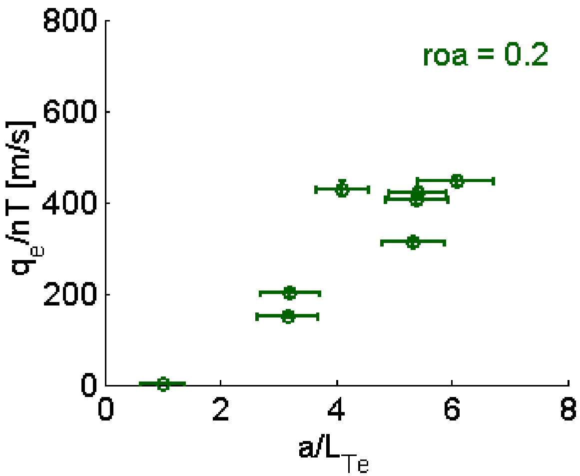


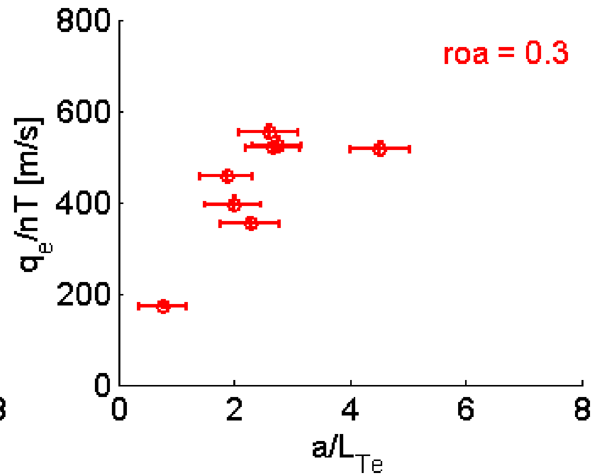
HSX

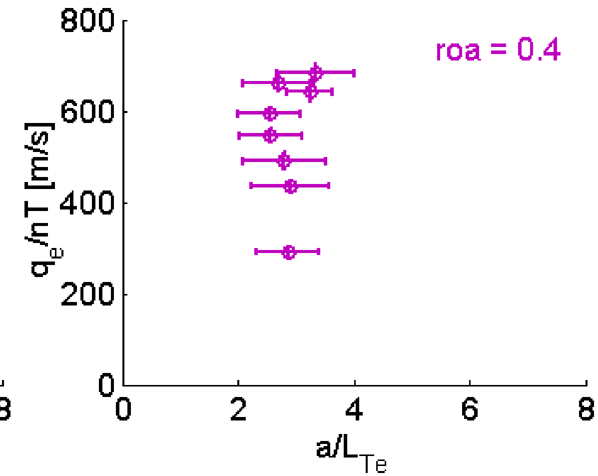
Power balance indicates a lack of stiffness in the core



- Core transport appears diffusive ($q/n \propto \nabla T$)
- Edge transport appears convective

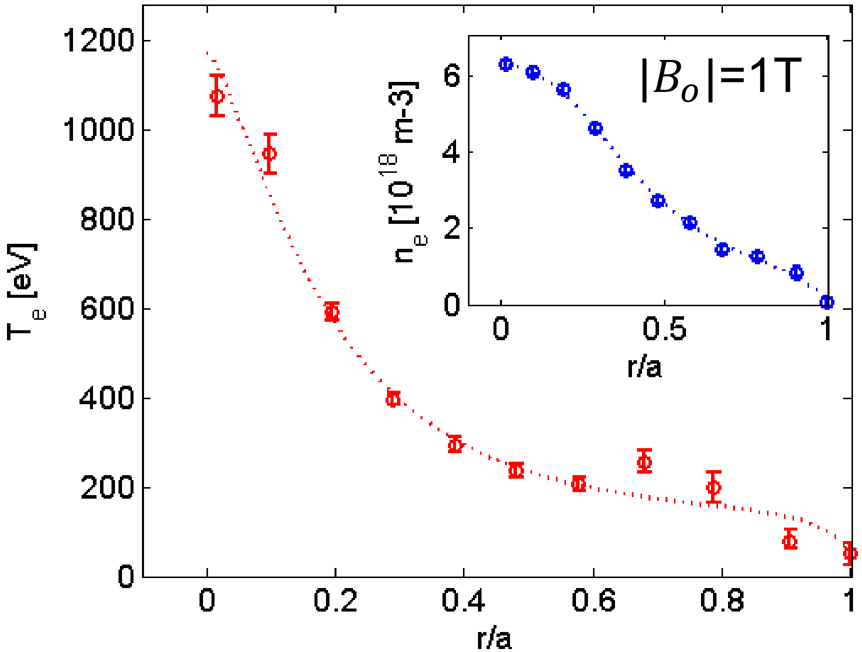


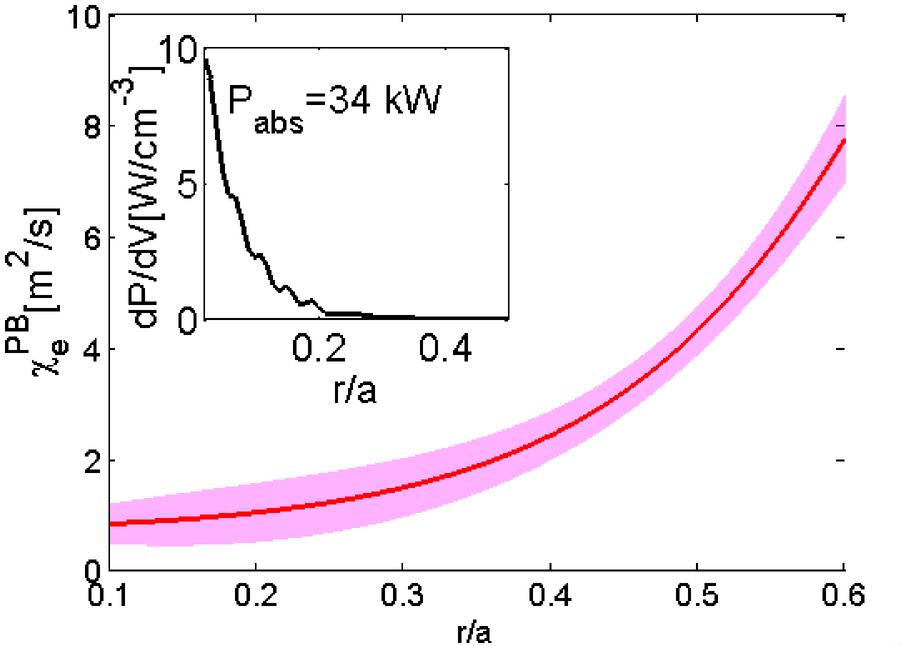




χ_e^{PB} quantifies the steady-state heat transport

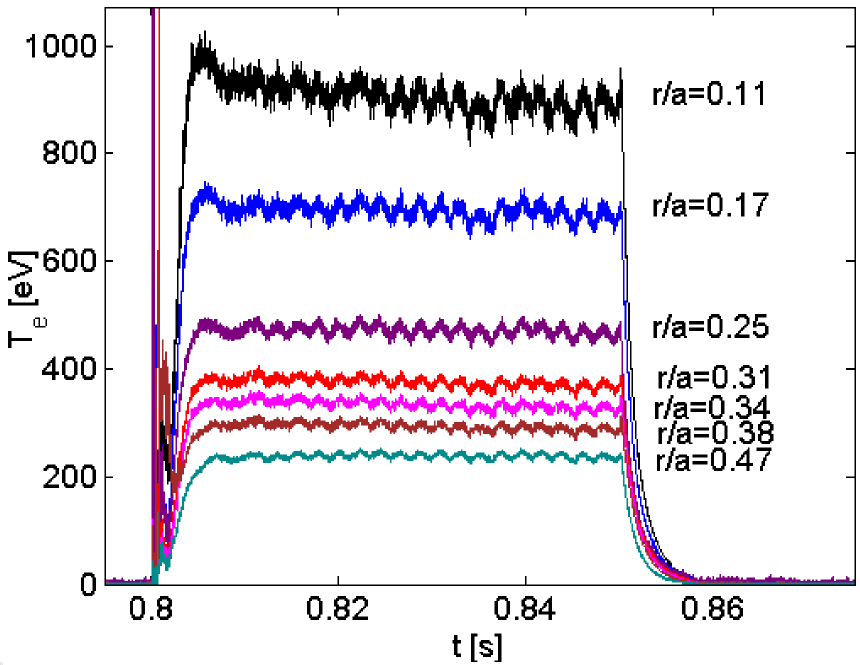
- **Power balance yields an effective diffusivity**
  - **χ_e^{PB} is calculated from least-squares analysis of the electron temperature**
  - **Combines all heat transport into one "diffusive" parameter (including convection)**

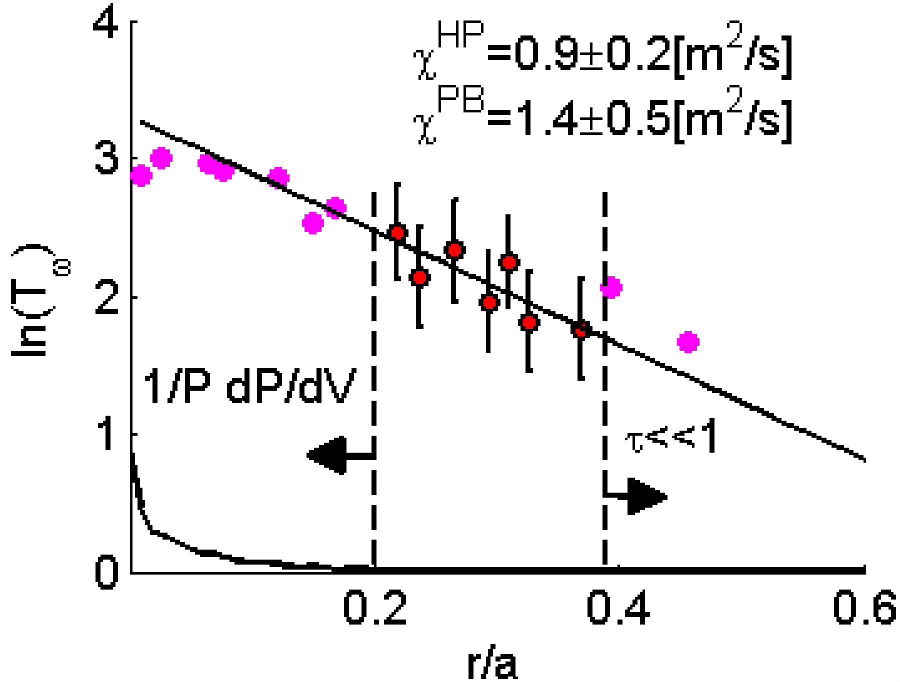




Heat pulse propagation confirms the lack of stiffness in core

- ECRH modulation at 500 Hz with a 6% modulation depth
  - Electron temperature monitored using the electron cyclotron emission
  - The radial amplitude decay of heat pulses yields χ_e^{HP},
- For $|B_o|$=1T, the average stiffness between $0.2 < r/a < 0.4$ is $\chi_e^{HP}/\chi_e^{PB} \approx 0.6 \pm 0.3$

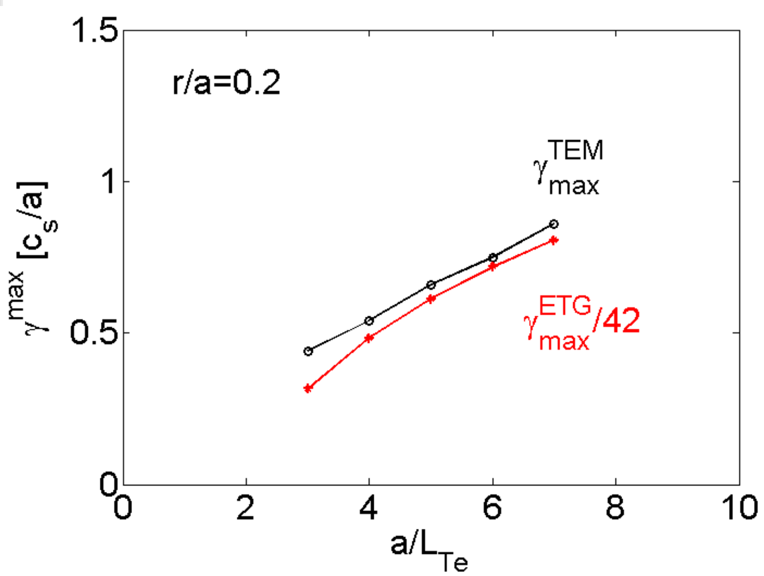


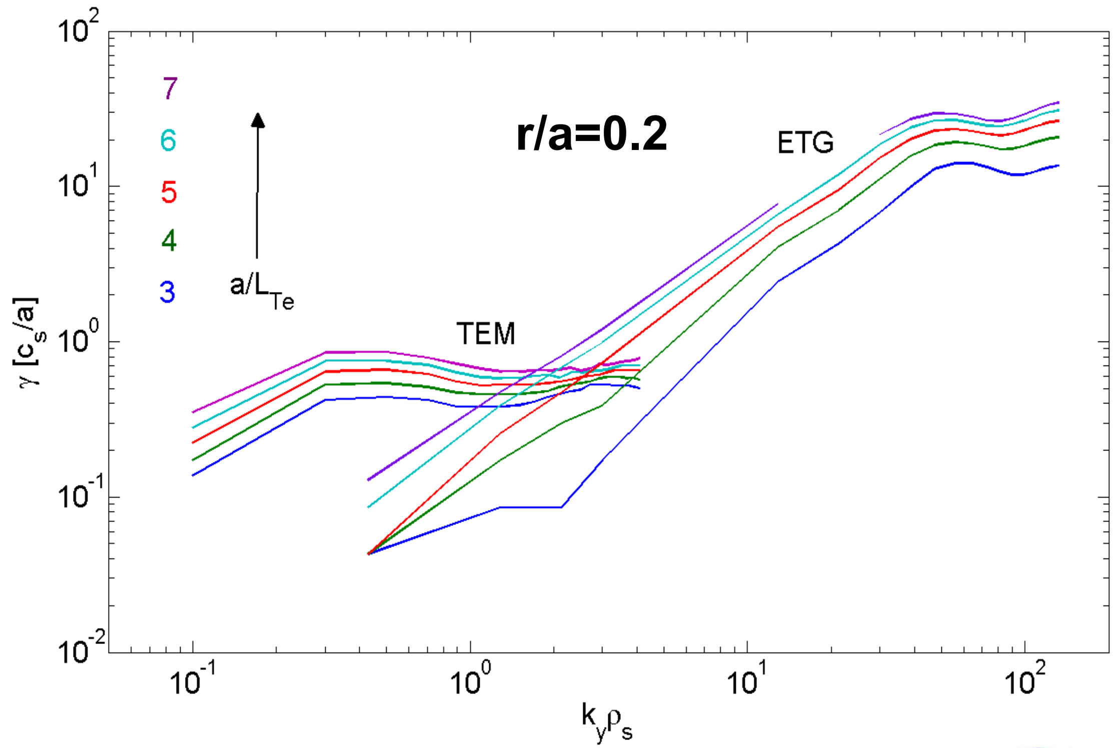


HSX

The TEM and ETG are linearly unstable in the core

- Linear gyrokinetic modeling in a flux-tube geometry using the GENE code.
- The TEM is modeled using two kinetic species, while the ETG is modeled using an adiabatic ion response.

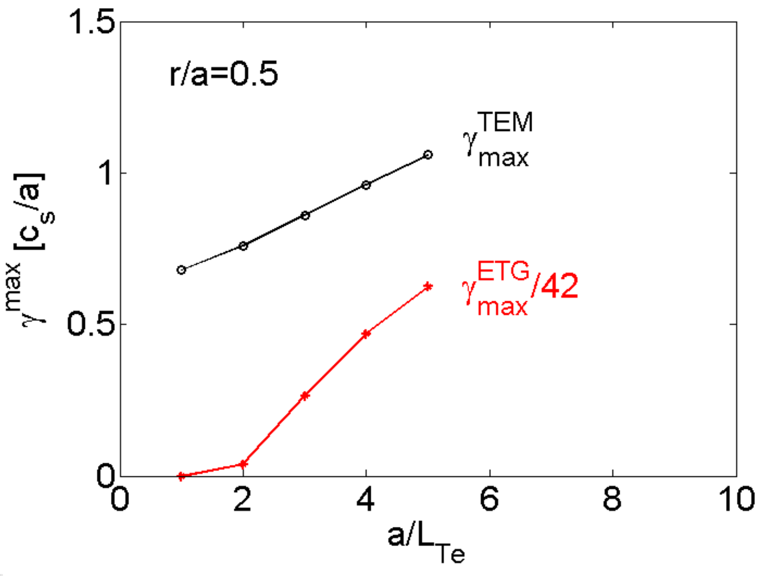


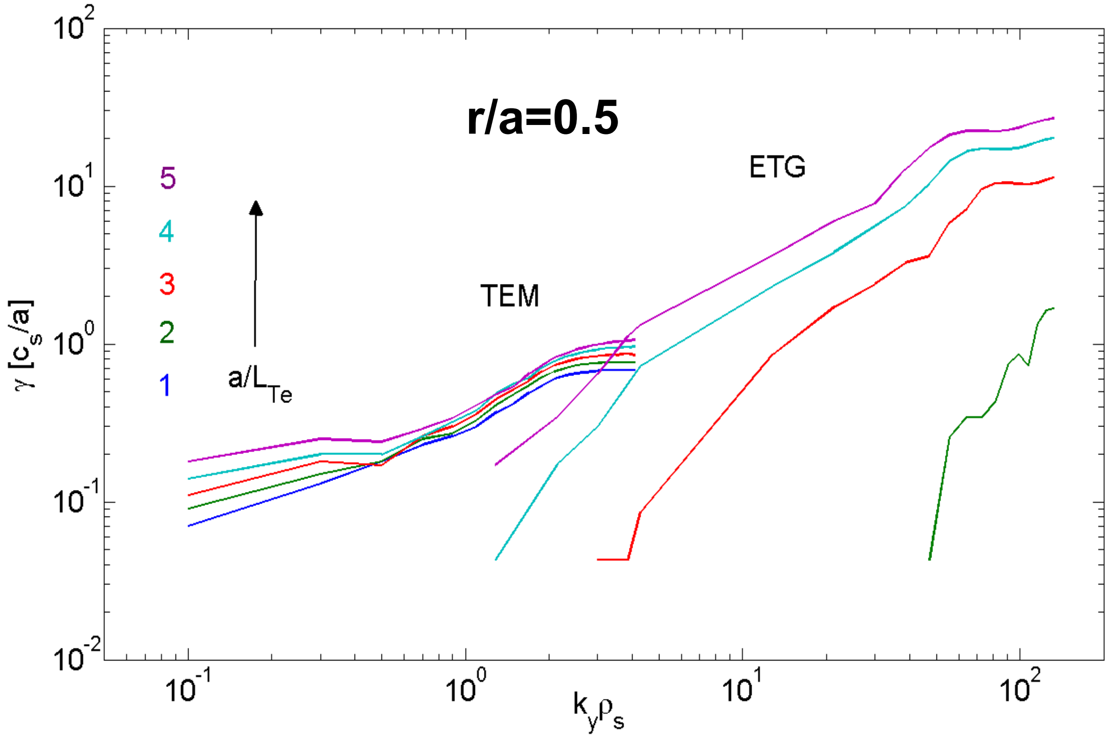


Te = 10Ti, a/Lne = 1

The TEM is more unstable at the half-radius than the core

- **The ETG is linearly stabilized at r/a=0.5 by the decreased electron temperature gradient and increased electron density gradient.**
- **Non-linear calculations are in progress and all of this work is done in collaboration with the W7-X group**



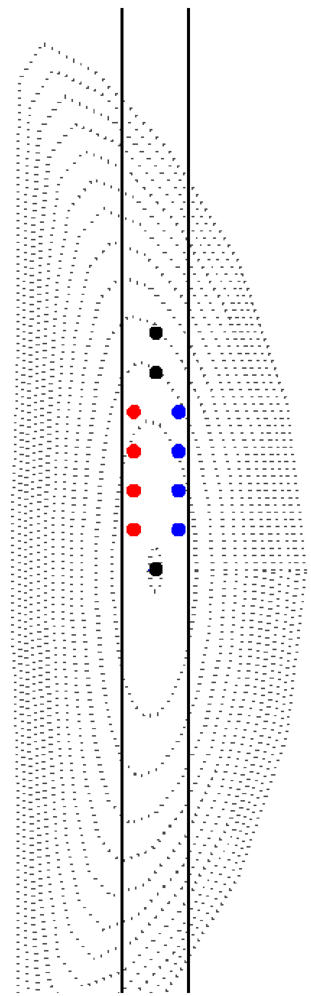


Te = 5Ti, a/Lne = 2.5

Outline

- Equilibrium Reconstruction
- Heat transport measurements and gyrokinetic calculations
- **Flows and the radial electric field**
- Edge measurements

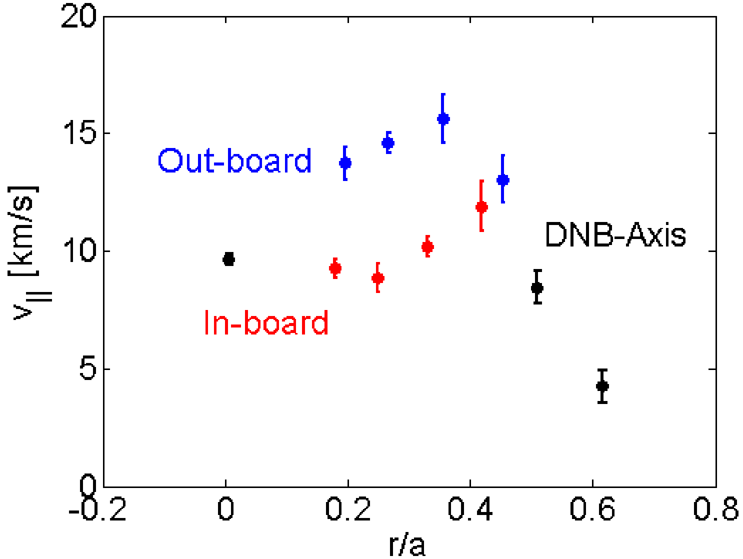
E_r is now measured from the Pfirsch-Schluter flows through Charge Exchange Recombination Spectroscopy (CHERS)

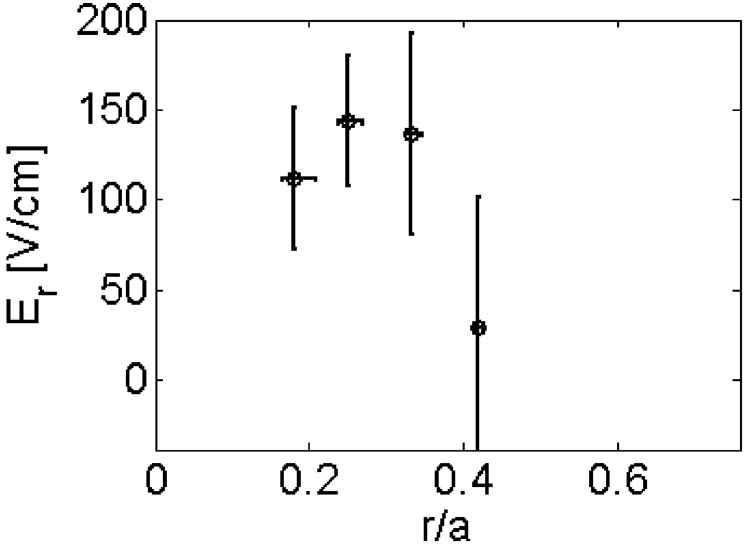


Toroidal CHERS Views

Impurity ion (C+6) flows are measured through CHERS on HSX

- **Reconfigured viewing optics have improved localization and allow measurement of counter-streaming Pfirsch-Schluter flows.**

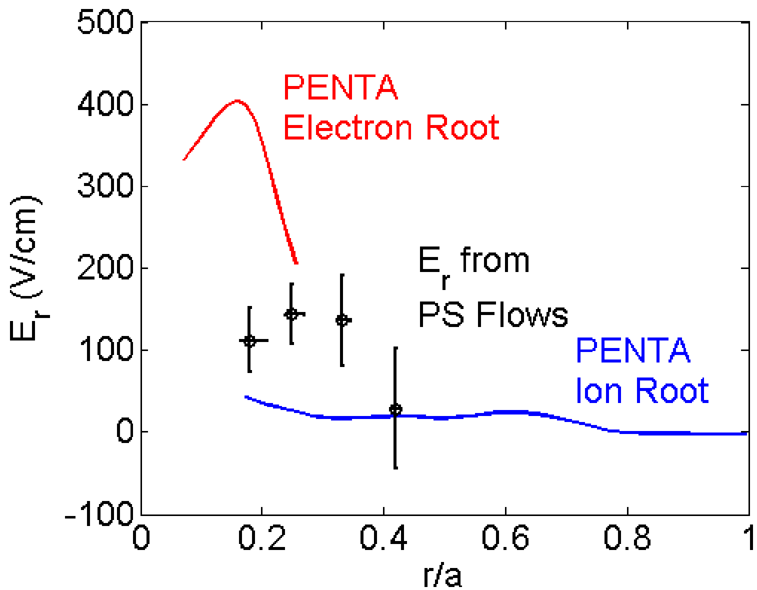




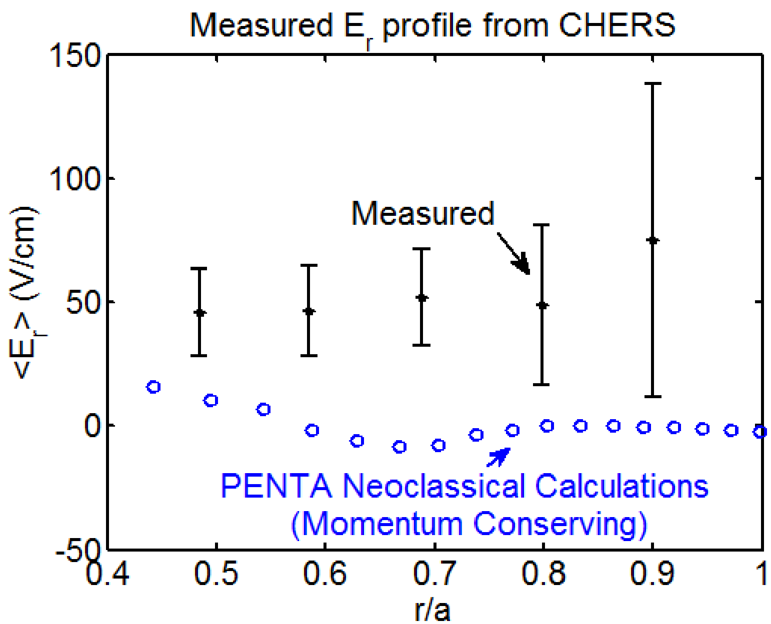
Improved localization has increased the precision of radial electric field measurements near the core of HSX

- **Core radial electric field measurements lie between the electron- and ion-root Neoclassical predictions**
  - **Estimated from the magnitude of the Pfirsch-Schluter flows.**

- **Edge radial electric field measurements do not agree with Neoclassical predictions**
  - **Measured from poloidal and toroidal flows using ion force balance.**



85 kW ECRH



44 kW ECRH

[Briesemeister, PPCF 2013]

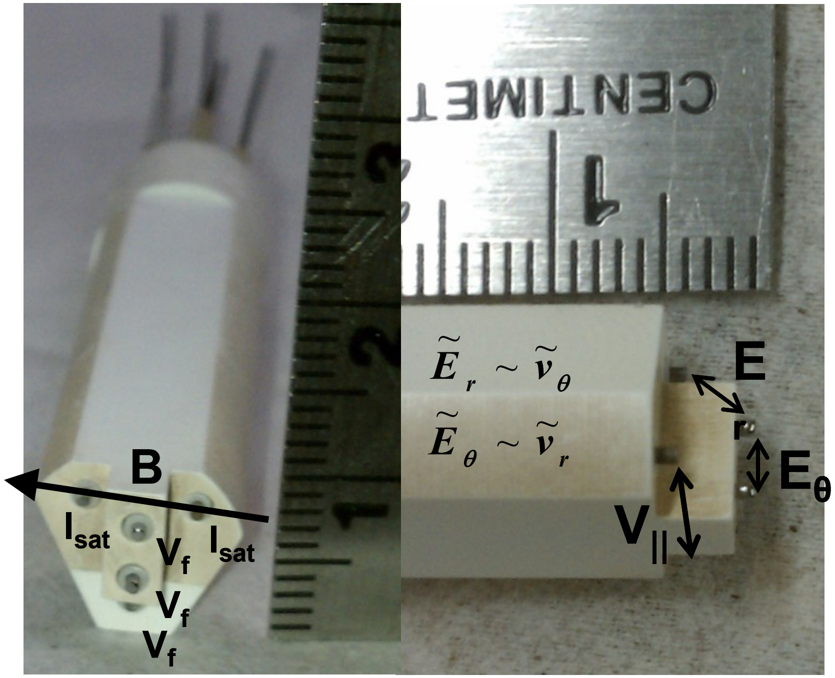
HSX

Langmuir probes are used to measure local fluctuations for Reynolds stress studies

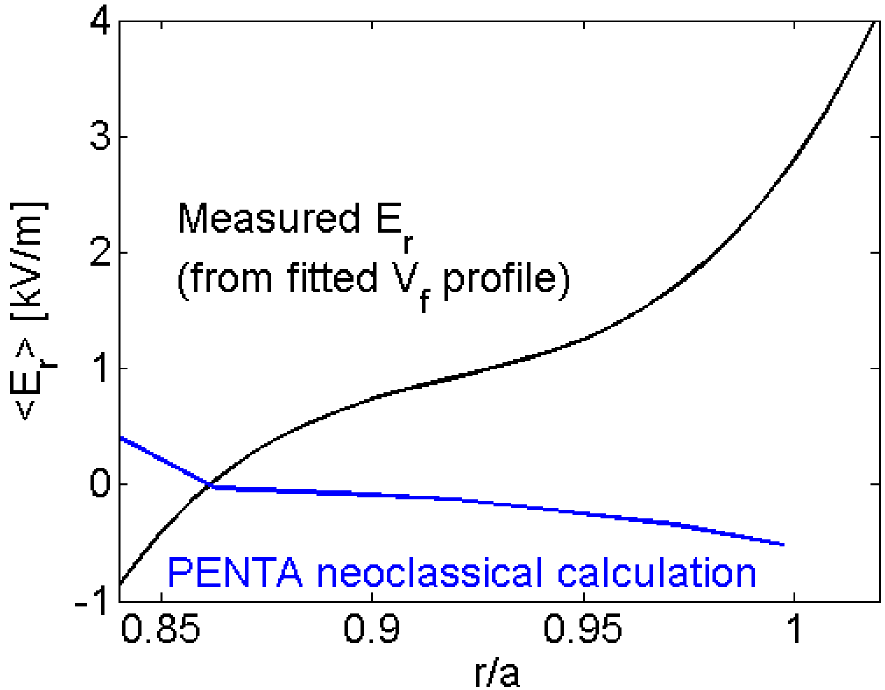
- **Neoclassical non-ambipolar transport is reduced in the QHS configuration of HSX and other terms may significantly modify momentum balance**

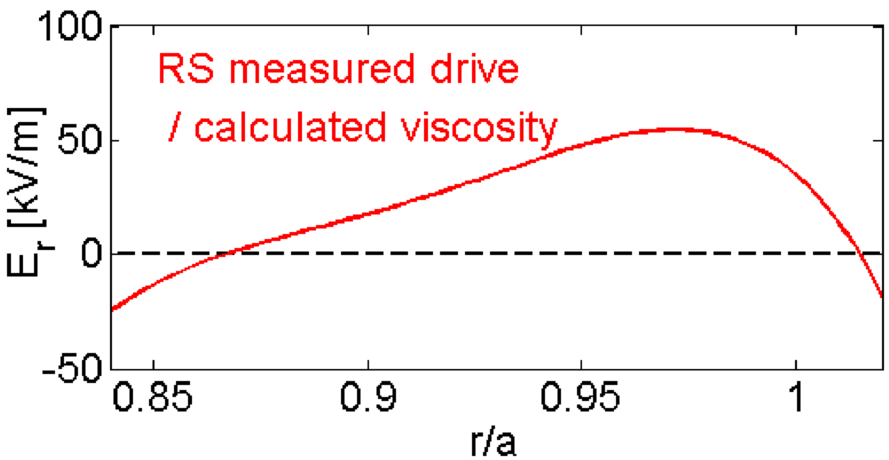
- **The Reynolds stress may contribute to momentum balance in the edge of HSX**

$$\tilde{v}_r \tilde{v}_\theta = -\tilde{E}_r \tilde{E}_\theta / B^2$$



Reynolds stress measurements show large drive in edge region where Er deviates from PENTA neoclassical calculations





- The radial electric field determined from V_f, is larger than the neoclassical prediction
- The Reynolds stress gradient implies flow drive from fluctuations just inside the LCFS
- Reynolds stress measurements imply unphysically large flow drive
- This measurement is local and may not be representative of a flux-surface average

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- Equilibrium Reconstruction
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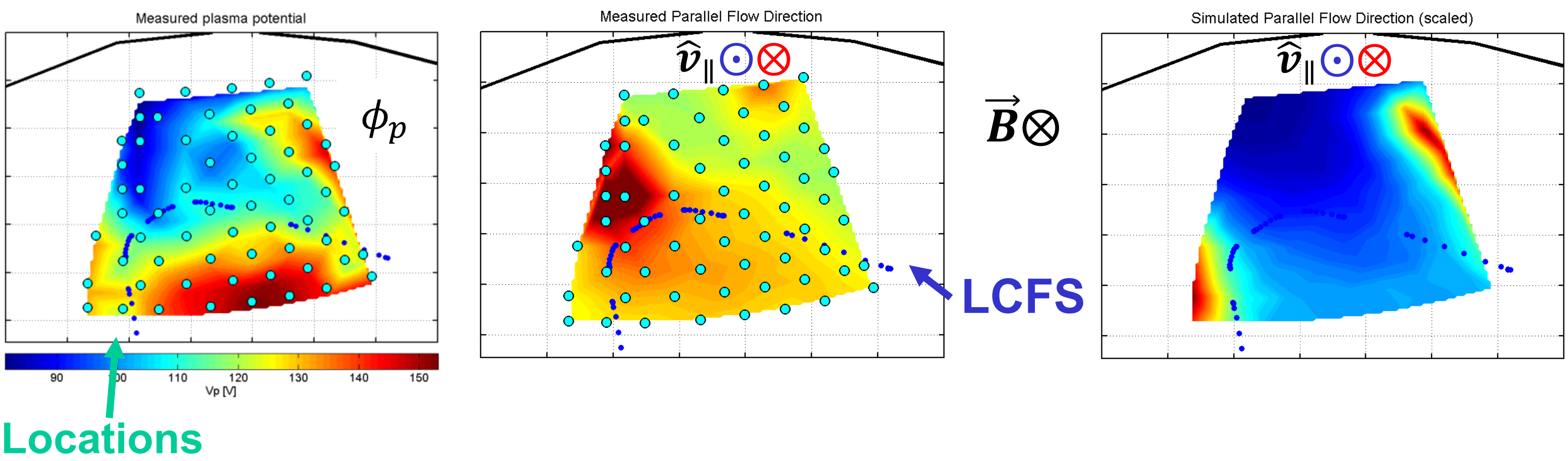
- Flows and the radial electric field
- **Edge measurements**

Counter streaming flows are predicted by EMC3-EIRENE but not observed through probe measurements

- 2D profiles of edge N_e, T_e, V_p and $V_{||}$ have been measured using a probe
- Differences between simulated [1] and measured T_e, N_e, and $V_{||}$ profiles are observed
- The discrepancies may be related to prominent potential structures, which are not included in EMC3-EIRENE [2]

Probe Measurements **EMC3-EIRENE**



[1] A. Bader et al. "Simulations of edge configurations in quasi-helically symmetric geometry using EMC3-EIRENE." Nucl. Fusion 53 (2013)
[2] Y. Feng et al. "3D edge modeling and island divertor physics." Contrb. Plasma Physics. 44 (2004).

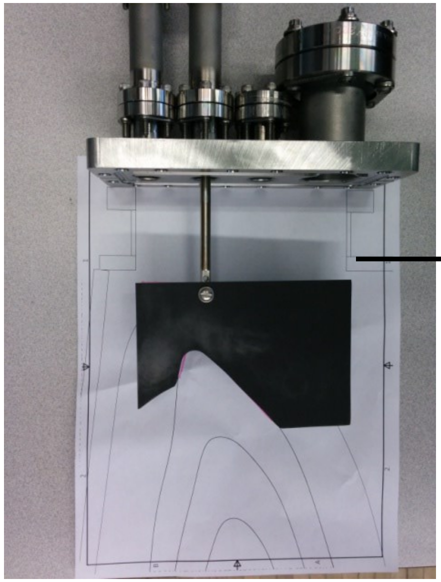
HSX

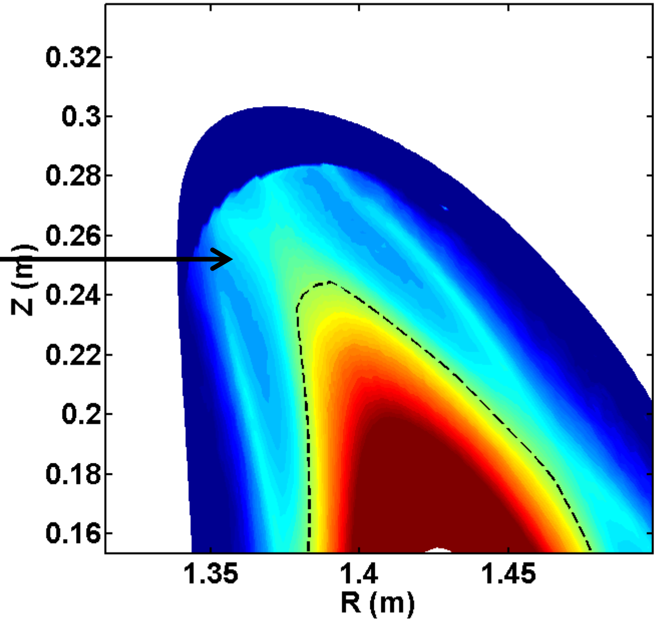
Limiting structures are used to localize the recycling and study its impact on parallel momentum balance

- HSX currently has a carbon limiter which is inserted into the natural 8/7 island and has been shown to reduce global wall-recycling by 5-10%.

- A new pumped limiter is being constructed to control the recycling and examine the impact on pressure along edge magnetic field lines.

- Optical measurements at the limiter will be compared to upstream probe measurements





Summary

Plasma equilibrium reconstruction

- The temporal evolution of the plasma current density is reconstructed using an optimized array of magnetic diagnostics

Heat transport measurement and gyrokinetic calculations

- Heat pulse propagation measurements indicate that the core is not stiff
- The ETG and TEM are linearly unstable, full non-linear calculations with two kinetic species are in progress

Flows and radial electric field

- Pfirsch-Schluter flows are measured in the plasma core through CHERS
- Reynolds stress measurements show large drive in the edge region where E_r deviates from neoclassical calculations

Edge measurements

- Counter streaming flows are predicted by EMC3-EIRENE but not observed through probe measurements
- Limiting structures are used to concentrate the plasma source and study its impact on parallel momentum balance