Edge Transport Calculations using XGC0 for QH-mode on DIII-D

by
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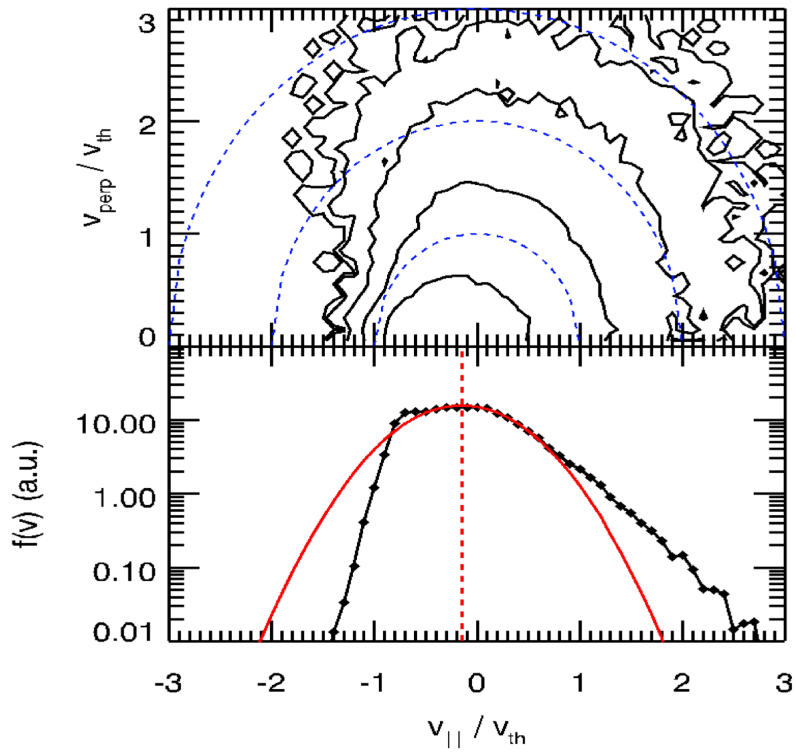

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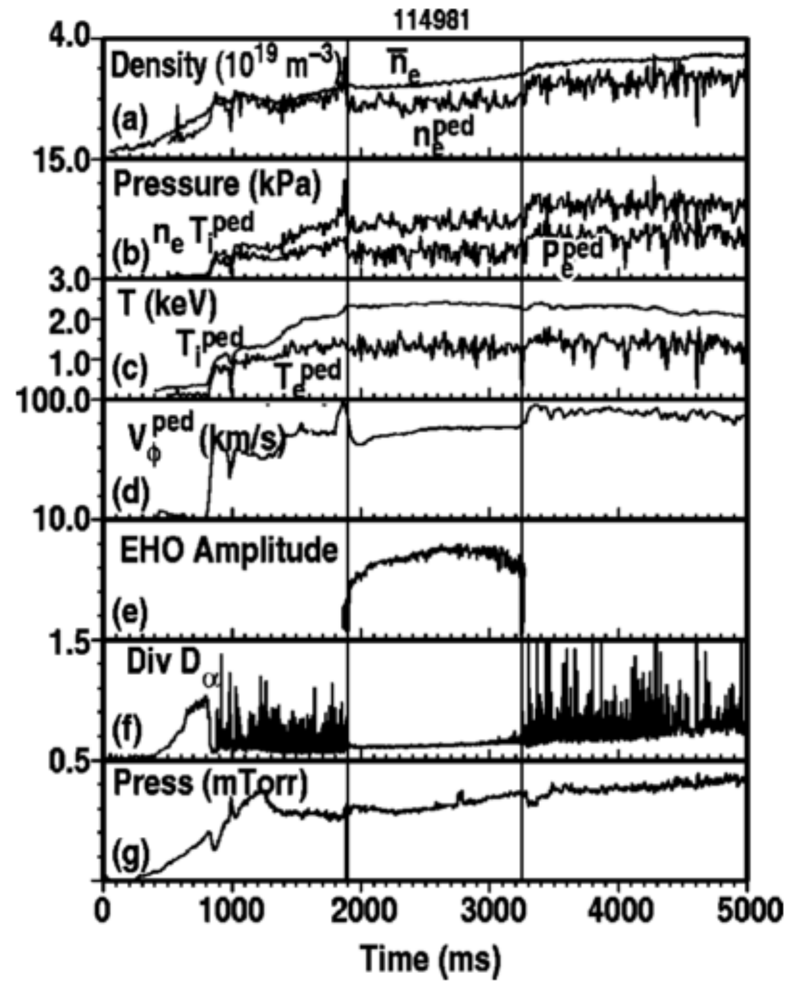
EPSI Edge Physics Simulation
NERSC
PPPL PRINCETON PLASMA PHYSICS LABORATORY

QH-mode: Stationary ELM-free H-mode is Maintained with an Edge Harmonic Oscillation (EHO)

- **EHO increases edge particle transport**
  - EHO – multiple n-harmonic EM mode
  - Maintains edge pressure less than (or equal to) peeling-ballooning stability
  - Stationary ELM-free H-mode with good thermal confinement

- **Typically achieved with counter-I_p torque, strong pumping, large T_i, low density**



K. Burrell et al., PoP **12** (2005)

Interpretive XGC0 Calculations Toward Elucidating Transport Mechanisms in H-mode Regimes

- **JRT13: Stationary ELM-free H-modes**
  - QH-Mode, I-mode, EPH-mode, RMP ELM suppression
    - Suitable particle transport while maintaining good thermal barrier
  - Common thread: edge plasma mode or applied 3D fields

- **Apply interpretative XGC0 calculations to elucidate the role of neoclassical and anomalous transport in standard and enhanced H-mode regimes**
  - XGC0: Full-f Neoclassical with neutrals + ad-hoc anomalous
  - What is the nature of the pedestal transport in different regimes?
  - Ultimate goal: quantitative model for predicting and optimizing pedestal and SOL transport
    - Pedestal height, width and stability
    - Intrinsic rotation, momentum transport and E_r
    - Divertor particle and energy loads

Outline and Conclusions

- **Interpretive XGC0 pedestal transport calculation**
  - Tune free parameters of calculation to match experiment data

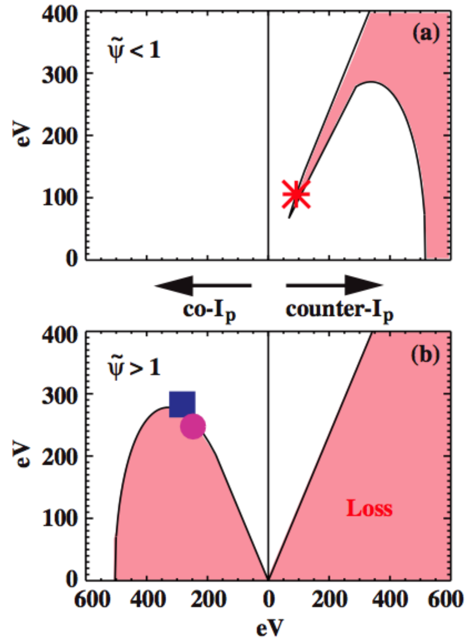
- **Neoclassical transport in low-power H-mode**
  - Ion transport through the pedestal is neoclassical
  - Measured intrinsic rotation implies an anomalous radial current in the pedestal (consistent with anomalous electron transport)

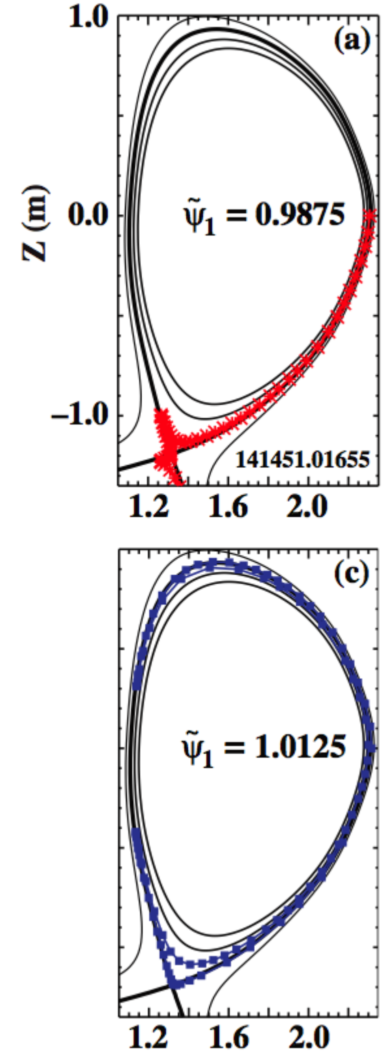
- **Neoclassical transport in QH-mode**
  - Nature of transport is very similar to H-mode
    - Ions are neoclassical, electrons are anomalous
  - Single particle orbit effects seen in experiment are quantitatively reproduced by XGC0
    - Temperature anisotropy, SOL ion temperatures and intrinsic rotation

Thermal Ion Orbit Loss Impacts Transport within Pedestal and SOL

- **Loss of counter-I_p ions and confinement of co-I_p ions**
  - Non-ambipolar since ion banana width >> electron
  - Leads to "intrinsic" flows and energy anisotropy

- **Maintain ambipolar transport by…**
  - Negative E_r to squeeze orbits
  - Or, remove orbit effects through large collisionality
  - Or, Ion orbit loss balanced by some other non-ambipolar process





J.S. deGrassie et al. Nucl. Fusion **52** (2012) 013010

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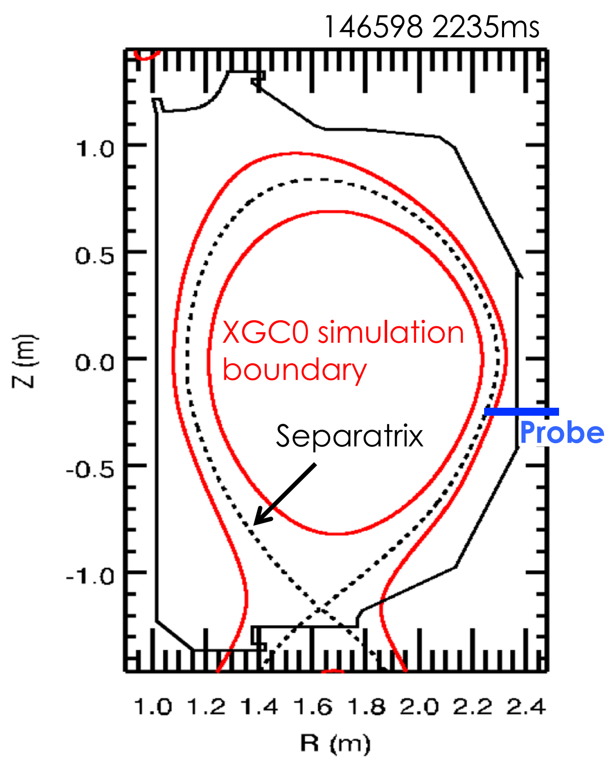
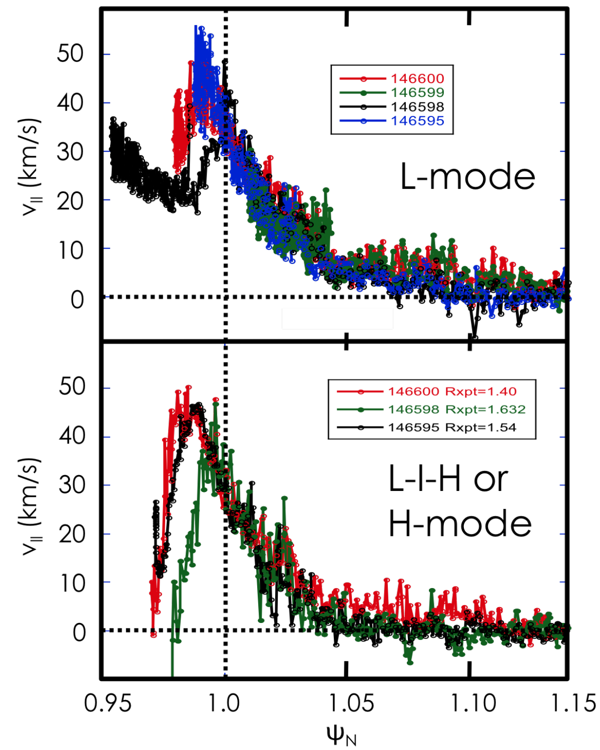
Edge Main-Ion Flows are Consistent with a co-I_p Intrinsic Torque due to Loss Hole

- **Plunging probe provides high resolution edge measurements**
  - Large edge deuterium flows in both ECE-heated L- and H-mode
  - Edge co-I_p flows can be >> core, peak near separatrix
- **ELM-free H-mode period with small fluctuation amplitudes**





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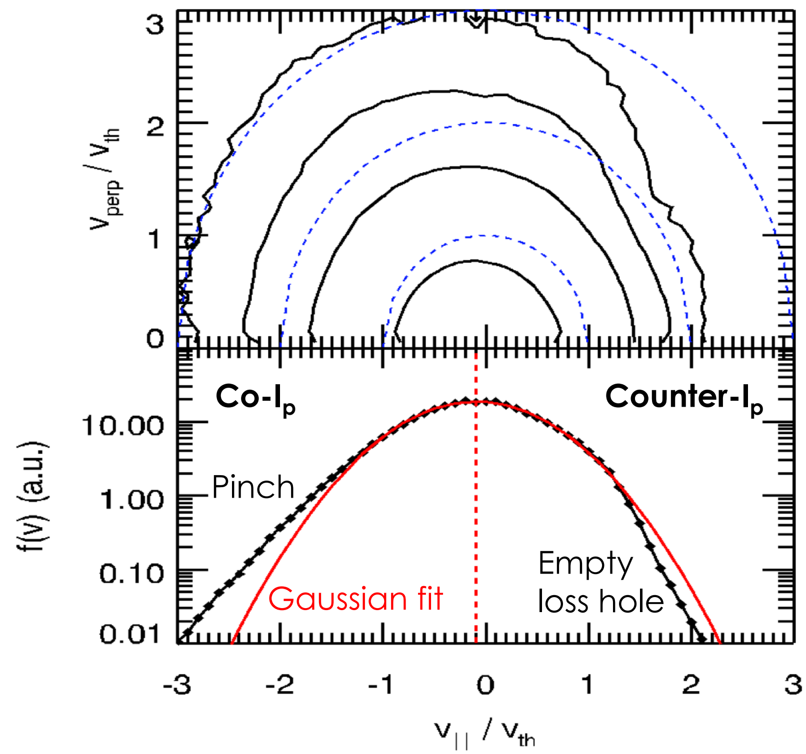
XGC0: Self-consistent Neoclassical Ion Transport, Realistic Sources and Sinks, and Magnetic Geometry

- **Full-f calculations using XGC0**
  - Solve drift kinetic equations for millions of particles (C^{+6}, D^{+}, e^{-})
  - Axisymmetric (2D space), Full-f gyrokinetic (2D velocity)
  - Magnetic geometry from EFIT
  - Monte-carlo neutral fueling calculation
  - Potential adjusted to maintain ambipolar transport
    - Potential is a flux function ($E_{||} = 0$)

Outboard midplane, deuterium ions
$0.98 < \psi_N < 0.99$, $-10° < \theta < 10°$



- **H-mode pedestals have Non-Maxwellian Ion Distributions**

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Interpretive XGC0 Modeling used to Elucidate Transport Mechanisms in Low-Power H-mode Pedestal

- **Initial simulations with reduced physics model**
  - Self-consistent recycling is only particle source
  - C^{+6} is the only impurity
  - Adiabatic electrons (electron profiles held constant)

- **Four free parameters**
  - Anomalous random-wallk diffusion step-size
    - Pedestal ($\psi_N < 1$)
    - SOL ($\psi_N > 1$)
  - Anomalous radial current
    - Anom viscosity or apply external torque
  - Core ion heating ($\psi_N < 0.95$)

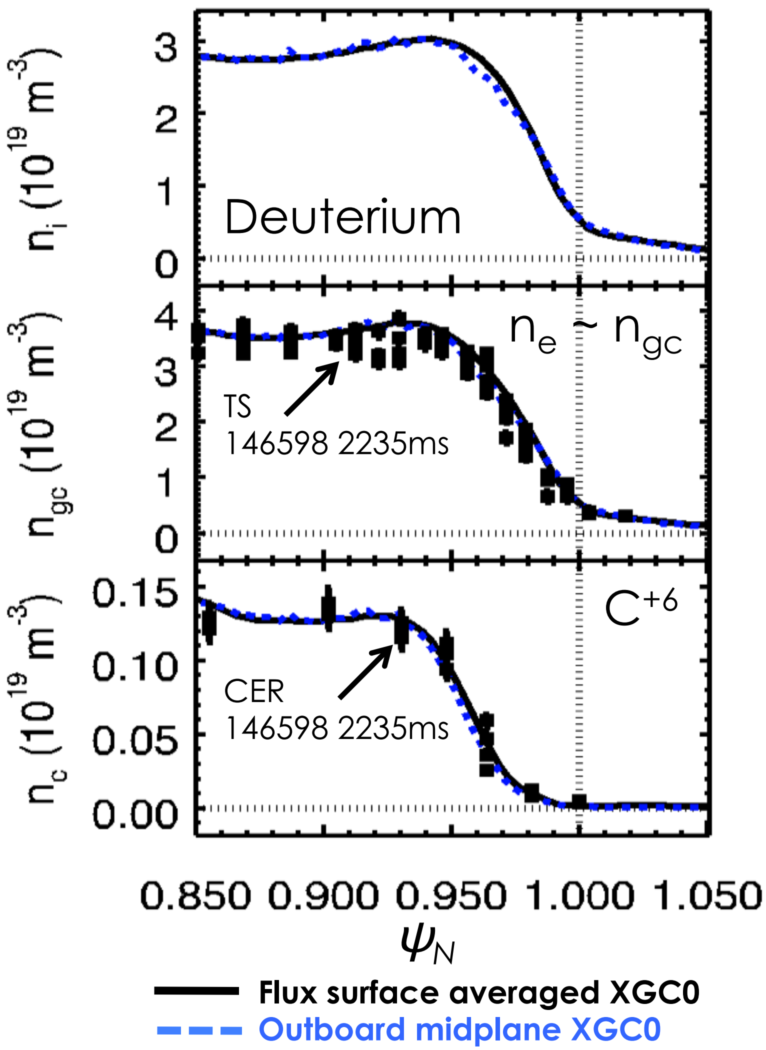
	H-mode
$D_{anom\text{-}ped}$	0
$D_{anom\text{-}SOL}$	0.2 m^2/s
η_{anom}	0.6 m^2/s
Ion heat	0.55 MW

- **Values chosen so steady-state XGC0 profiles = experiment**

Excellent Quantitative Agreement for the Density Profiles is Achieved with Self-consistent Recycling

- **Edge GC density profiles match experiment with recycling source**
  - No core source, recycling sufficient to maintain pedestal
  - C and D density profiles are different
  - Density mostly constant along a flux surface for $\psi_N < 1$

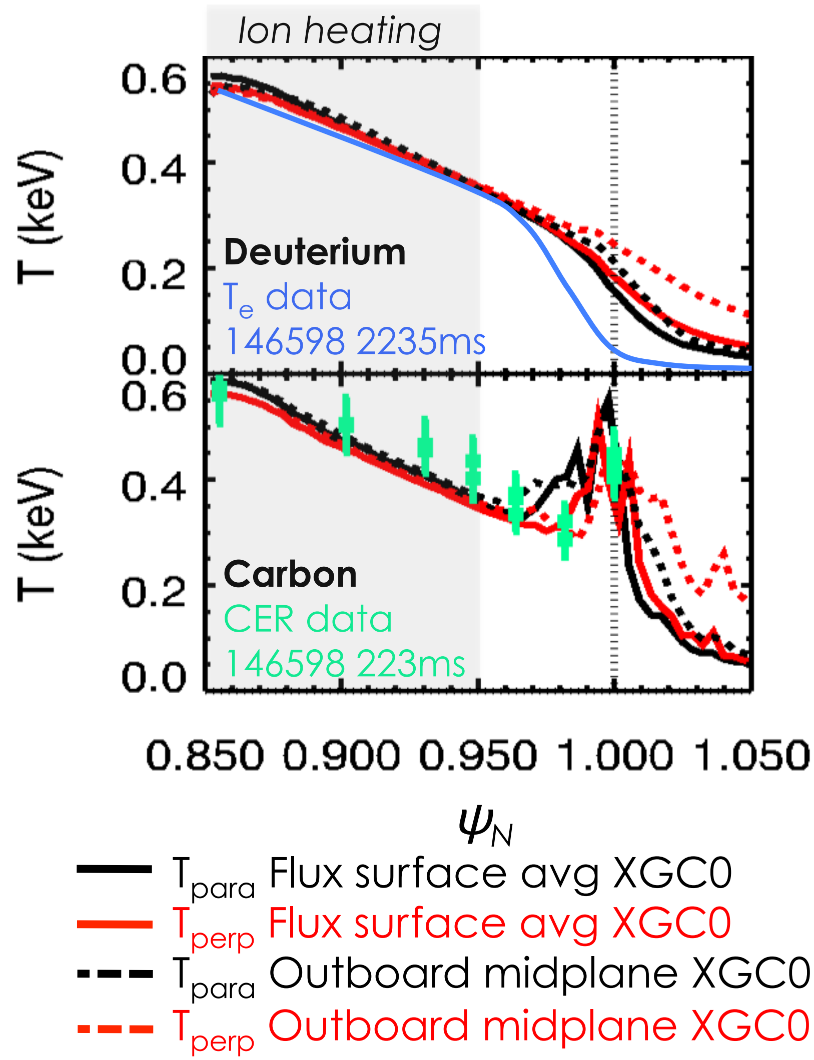
- **Neoclassical ion transport in the H-mode pedestal**
  - ELM-free and low turbulence
  - $D_{anom} = 0.2\ m^2/s$ in SOL



Ion Orbits in the Pedestal Lead to Anisotropic Temperatures Near the Separatrix

- **Ion temperatures reproduced**
  - Ion heating 0.55MW
    - ~ 33% of P_{loss}
  - $T_i > T_e$ around separatrix
  - Spike in T_C at separatrix

- **Temperatures are anisotropic around separatrix**
  - Discussed later in more detail



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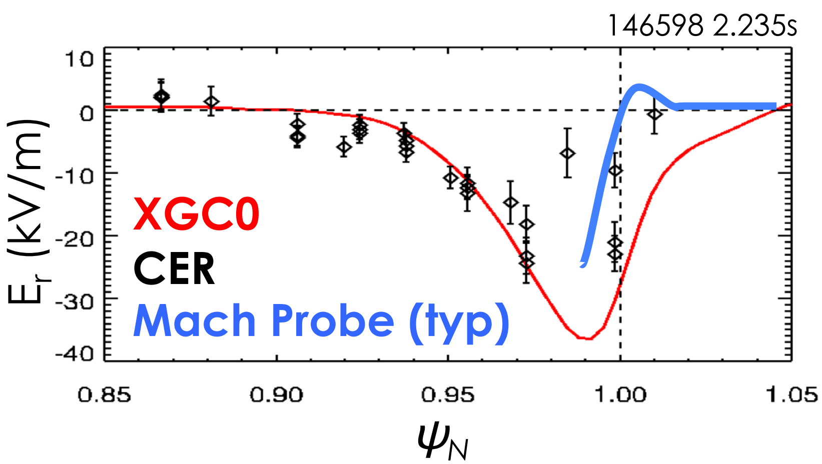
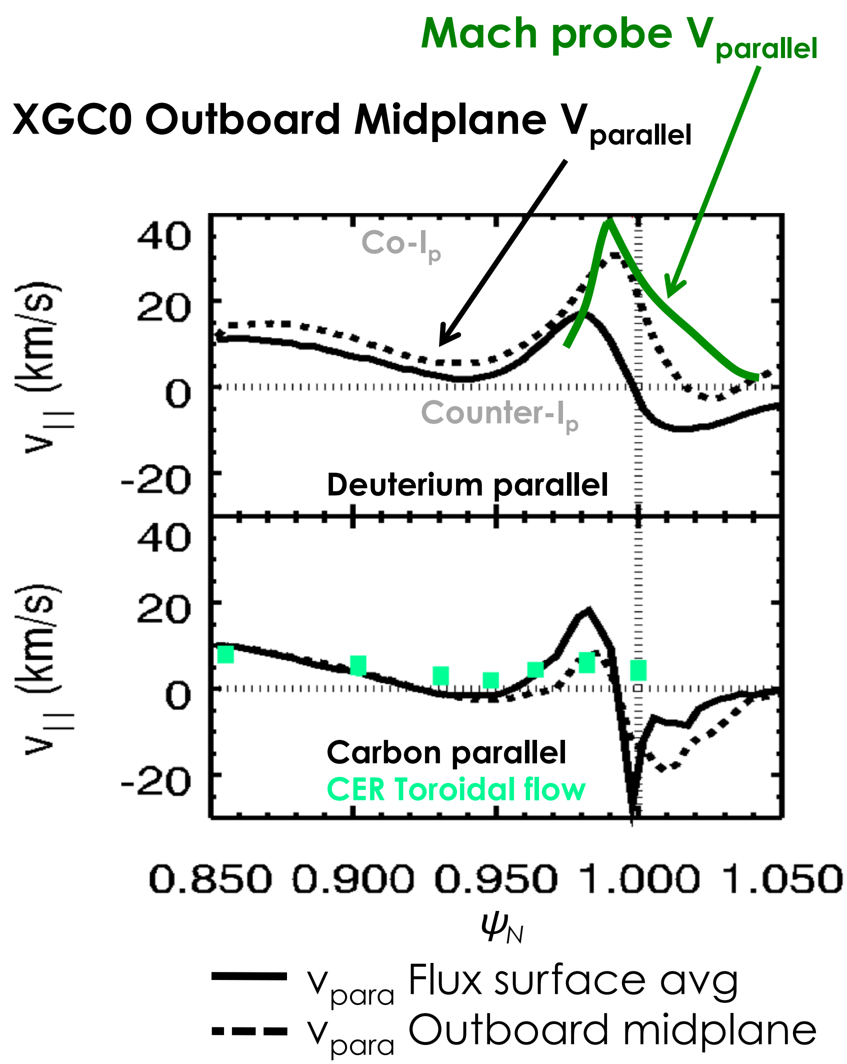
Parallel Deuterium Flow and E_r in Good Agreement with Mach Probe and CER measurements

- **Anomalous Viscosity (η) …**
  - Reduces E_r well
  - Increases edge v_{para}
- **Flow peaked at outboard midplane**
  - Flux surface averaged $v_{||}$ for D and C^{+6} are similar

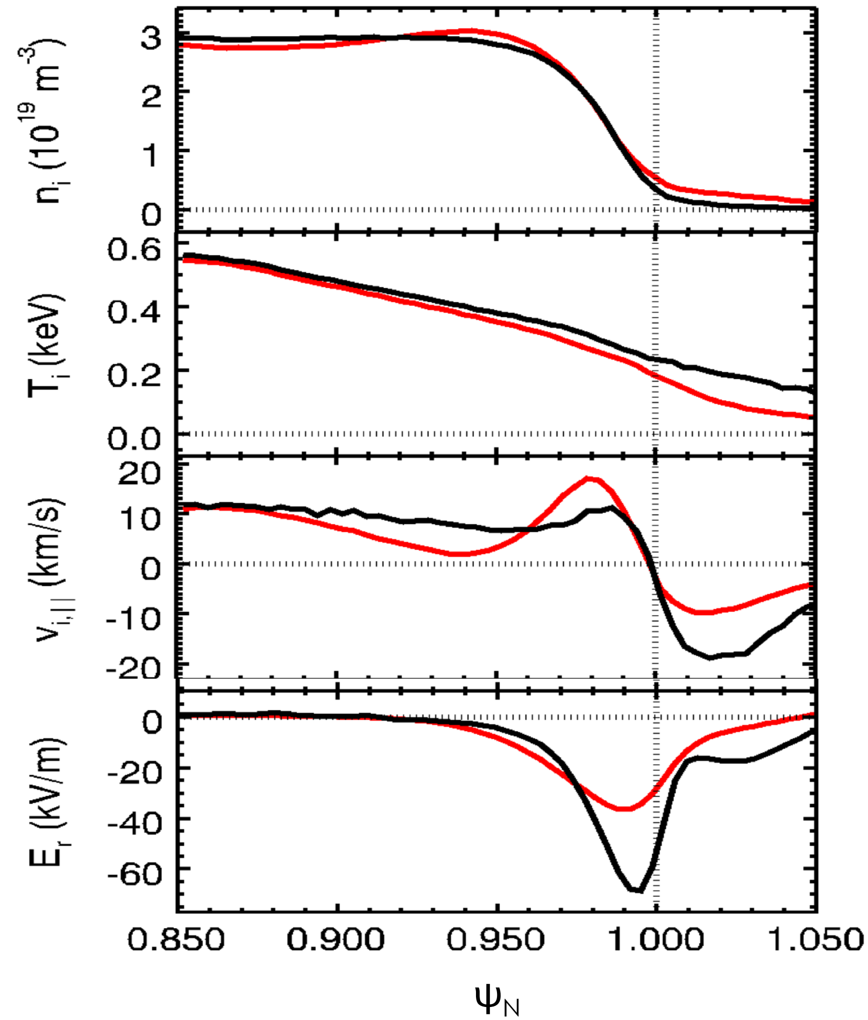




Density and Temperature Profiles Reproduced with Two Flavors of Anomalous Transport in the Pedestal

	Non-ambi	Ambi
$D_{anom\text{-}ped}$	0	0.02 m²/s
$D_{anom\text{-}SOL}$	0.2 m²/s	0.2 m²/s
η_{anom}	0.6 m²/s	0
Ion heat	0.55 MW	0.50 MW
$\Gamma_{i,neo}$ =	Γ_{anom}	0

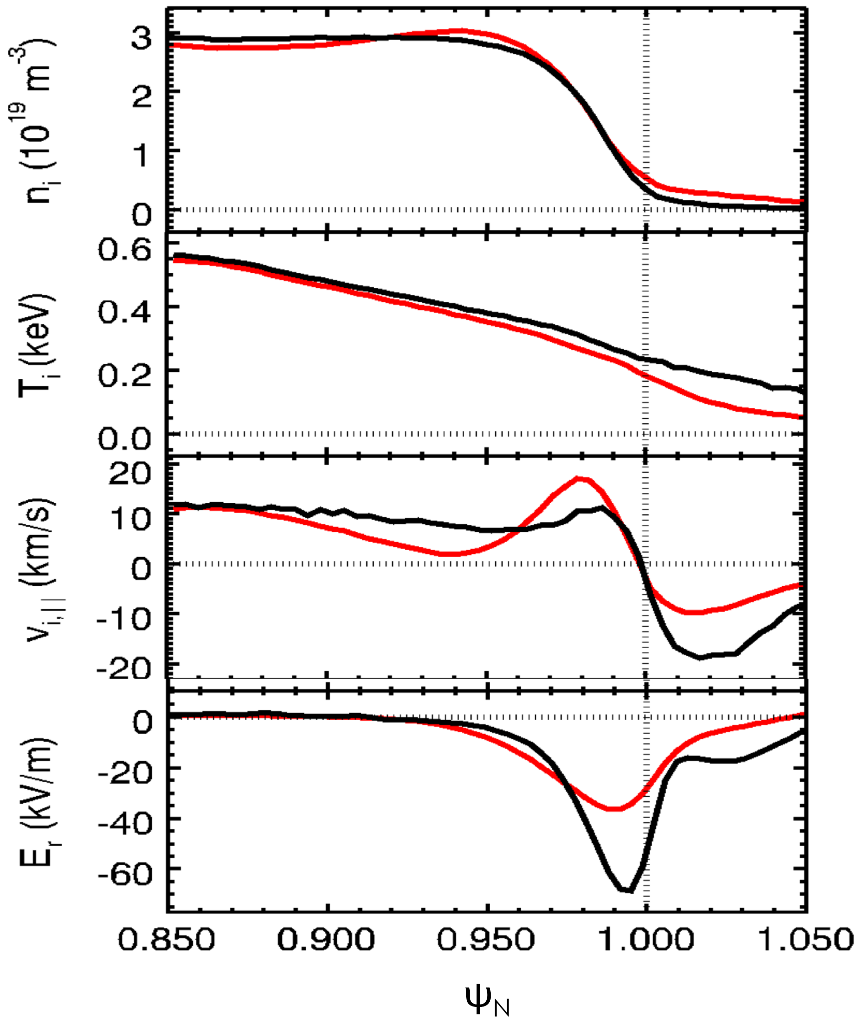
- **Best agreement: Ion orbit loss balanced by anomalous radial current**
  - More positive E_r well
  - More peaked intrinsic flow due to loss of counter-I_p ions



Initial Prediction: Edge Modes (like EHO) Switch Transport from Non-ambipolar to Ambipolar

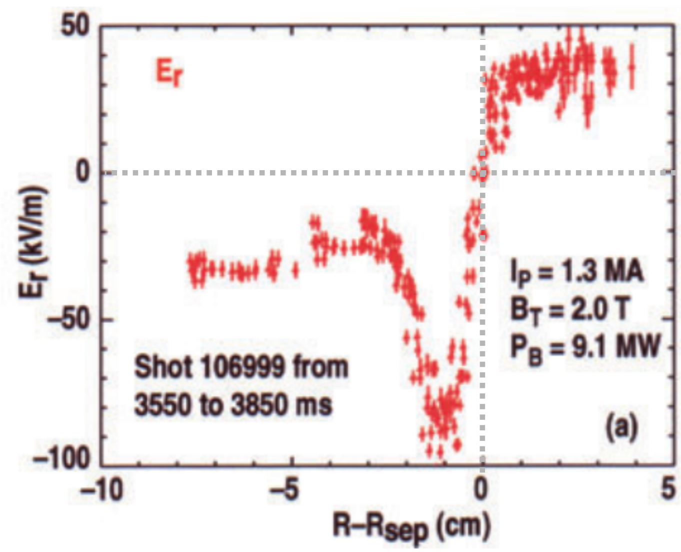
- **Maintain same particle transport, but …**
  - E_r is more negative, shutting off ion orbit loss
  - Improves thermal confinement
  - Reduces edge co-I_p torque

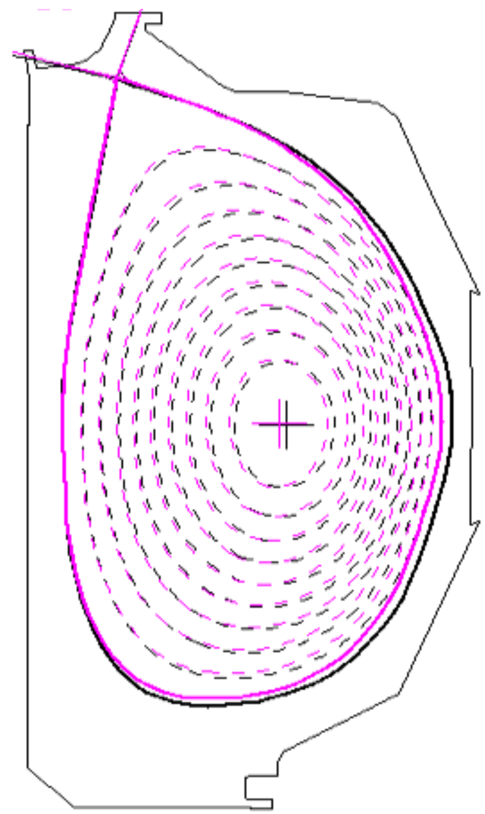
- **A good idea (?), but it doesn't seem to be the case**
  - QH-mode transport qualities similar to H-mode
  - Focus of the rest of the talk



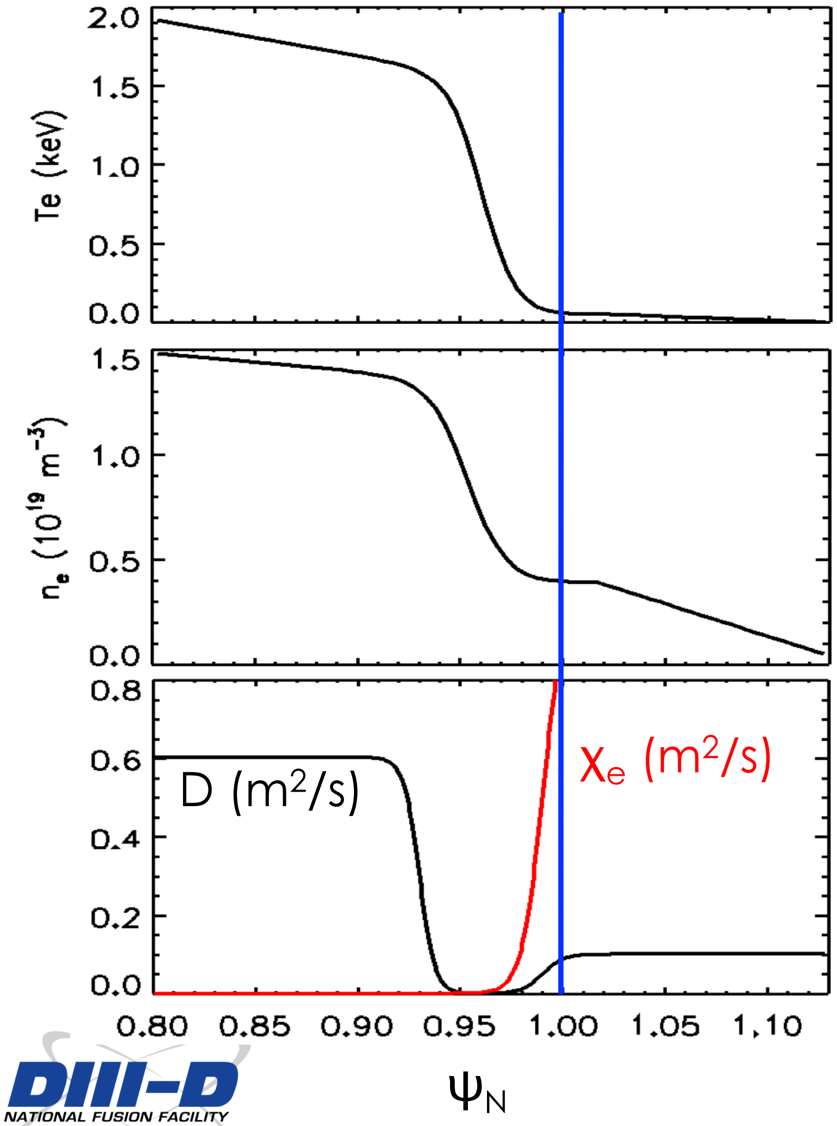
Edge Sweep Data Provides High Resolution Measurements to Compare to XGC0 Results

- **QH-mode edge sweep**
  - Stationary profiles with 400ms edge sweep across diagnostic channels
  - E_r from C^{+6} force balance



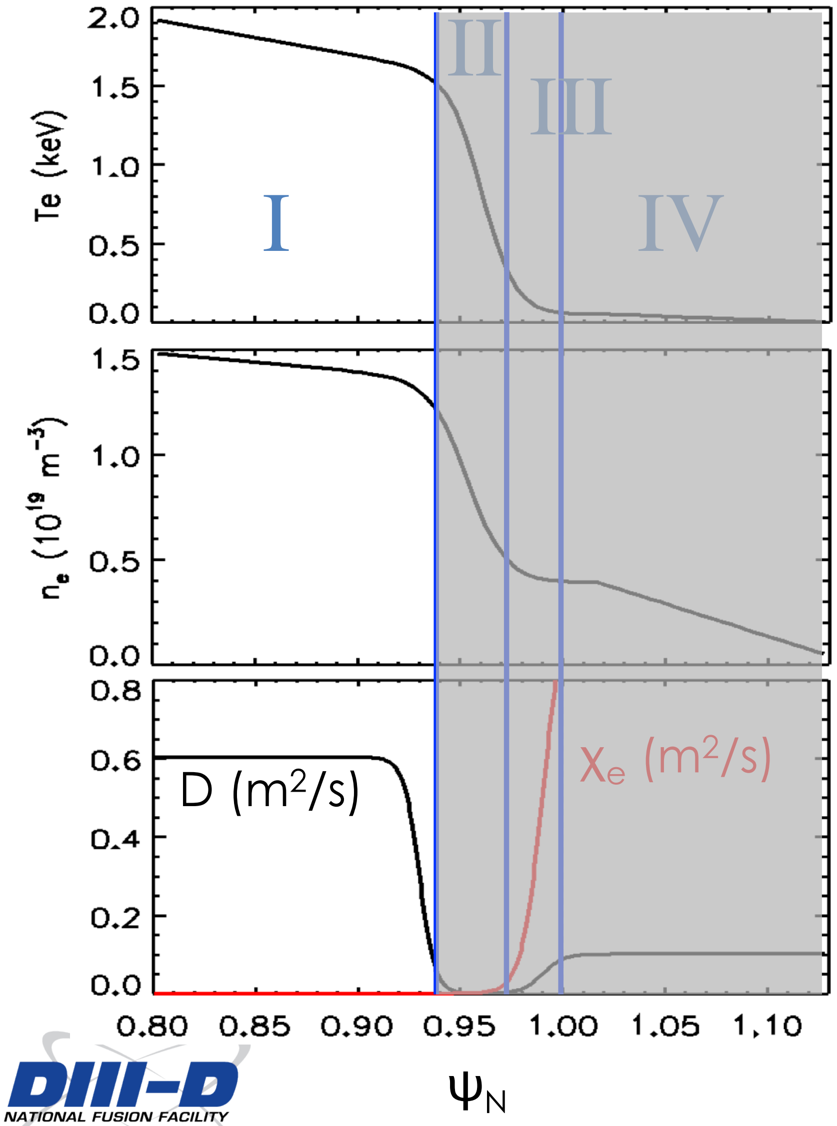


Pedestal Transport Model in XGC0 for Shot 106999



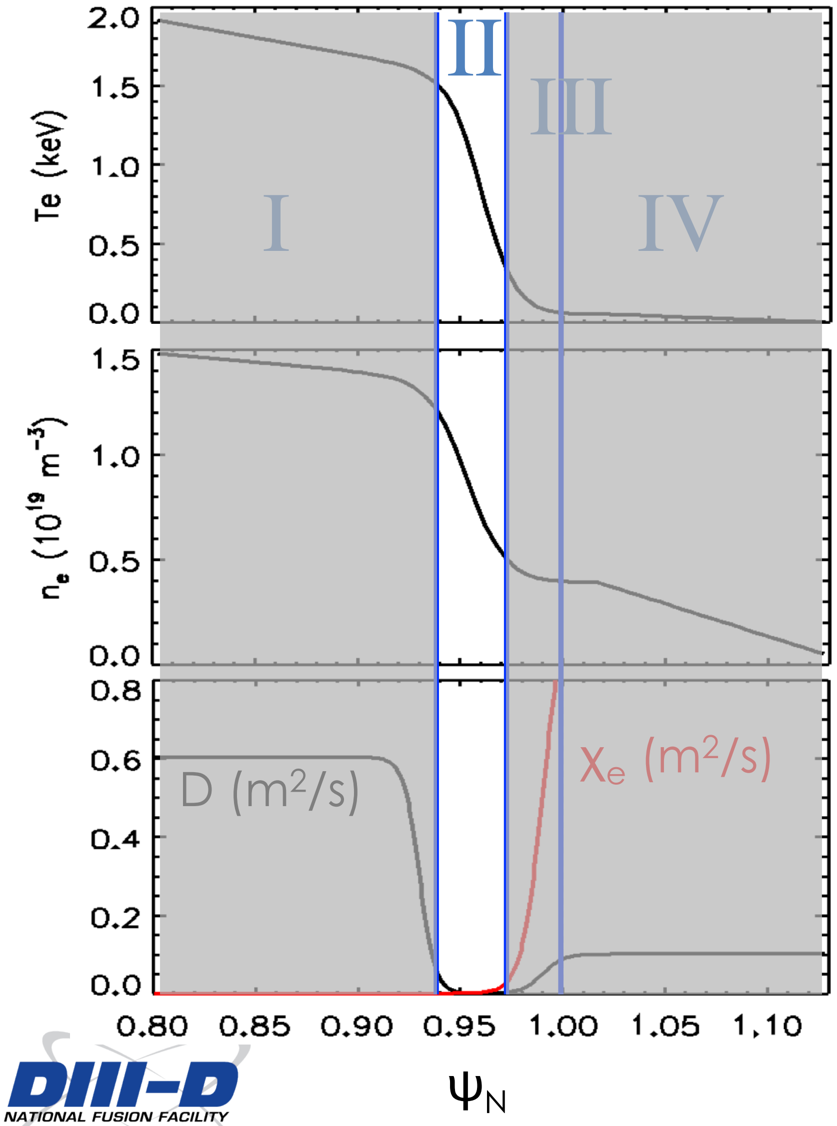
- **New: including full-f electron calculations**
  - Self-consistent sheath
  - Elucidate electron transport properties
- **New: finite D needed at top of pedestal**
  - Large turbulent transport in high power H-mode

Pedestal Transport Model in XGC0 for Shot 106999



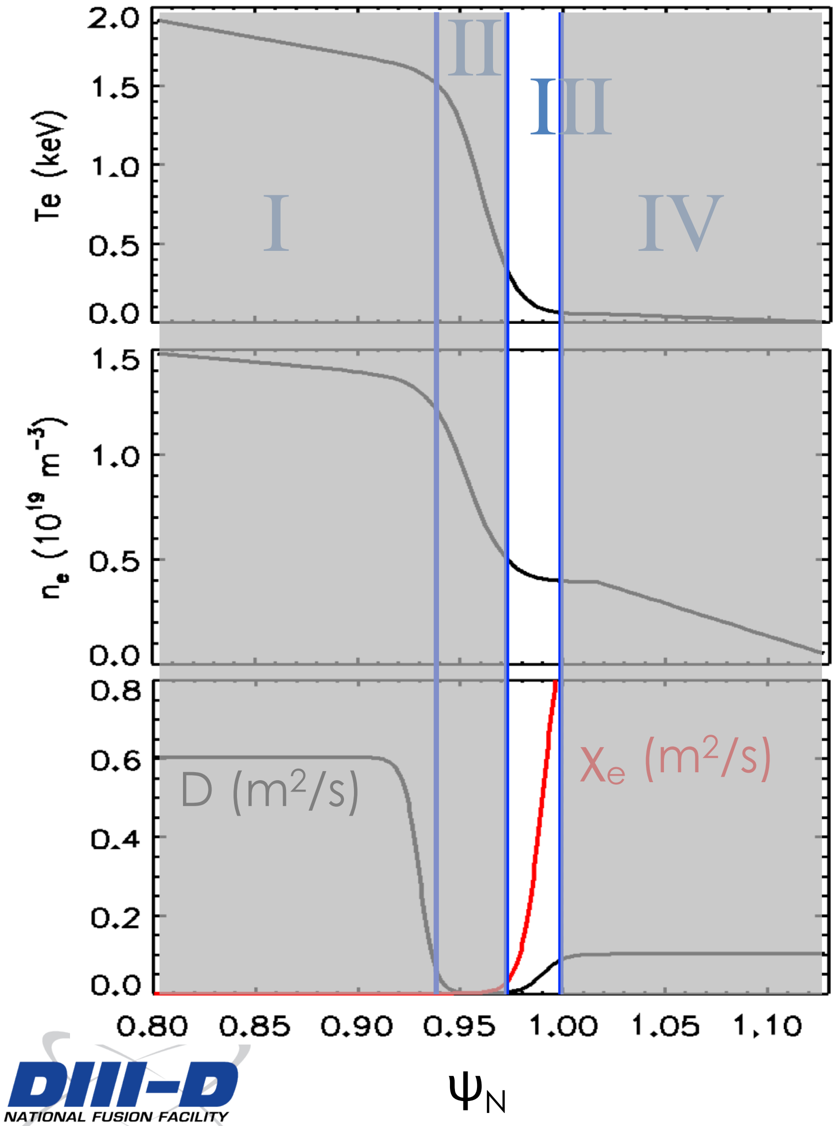
- **Top of pedestal (I)**
  - 3.0 MW Ion heating
  - 5.0 MW Electron heating
    - 9 MW beam power
  - 110 Amps of D^+, e^-
    - 75% beam flux
  - Inner boundary E_r fixed
    - Fixed core rotation
  - 0.5 – 0.8 m^2/s random-walk ambipolar diffusion
    - Kick guiding centers ~ 0.1 mm step in random direction

Pedestal Transport Model in XGC0 for Shot 106999



- **Steep gradient region (II)**
  - Similar to low-power H-mode case …
  - 0 – 0.01 m^2/s random-walk diffusion
    - Ion transport is neoclassical
  - Anomalous radial current
    - In model, anom viscosity or apply ~0.5 Nm Co-I_p torque

Pedestal Transport Model in XGC0 for Shot 106999



- **Bottom of pedestal (III)**
  - Paleoclassical-like random-walk ambipolar diffusion
  - Order-of-magnitude larger anomalous electron thermal transport
  - $D_{anom} \sim T_e^{-3/2} \sim 0.1$ m^2/s
  - $\chi_e \sim T_e^{-3/2} \sim 1$ m^2/s

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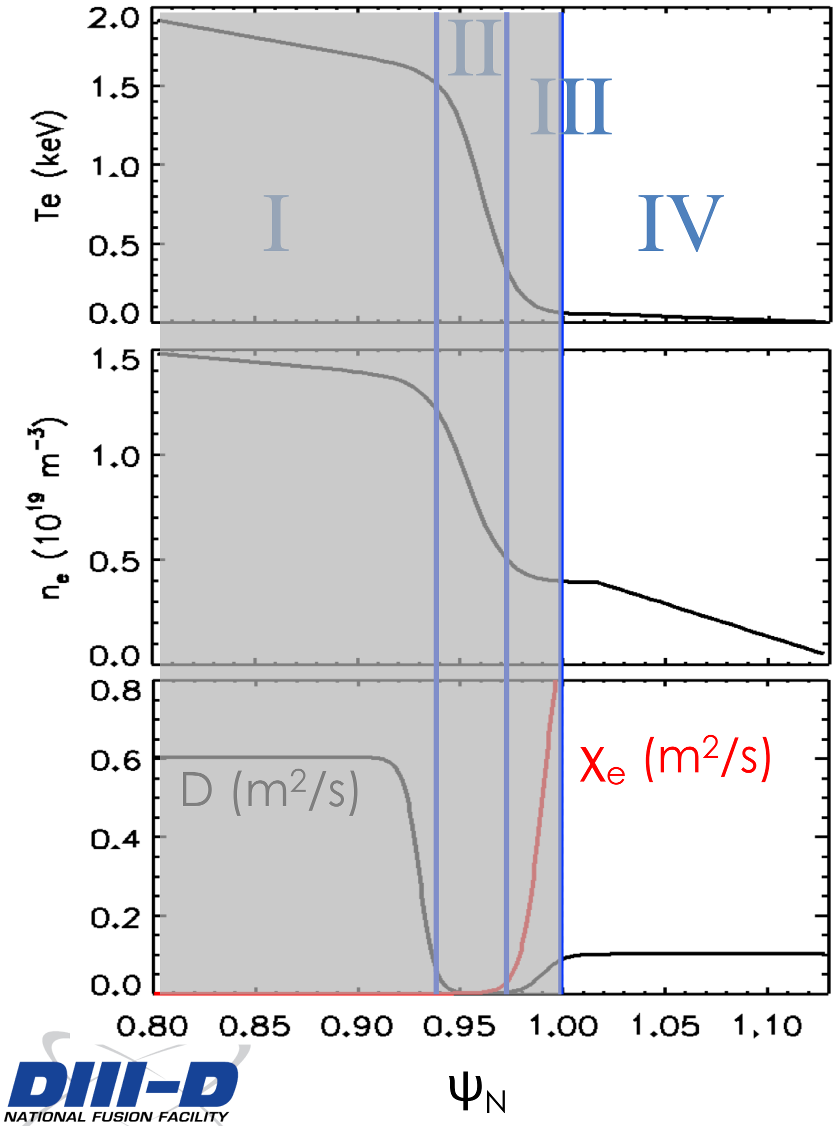
Pedestal Transport Model in XGC0 for Shot 106999



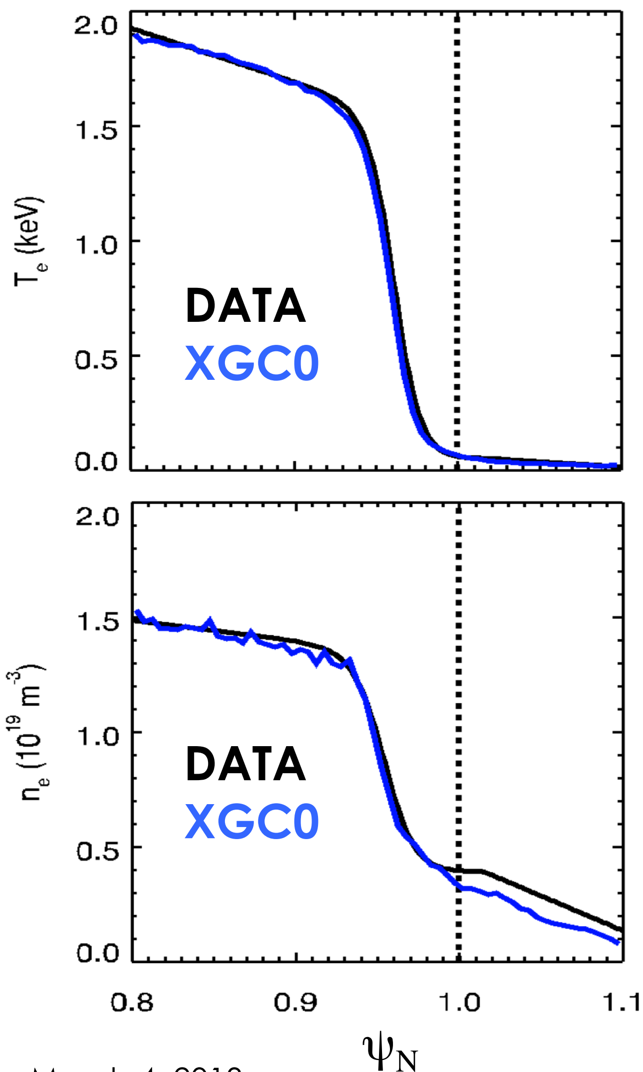
- **SOL (IV)**
  - D recycling ~ 97%
  - C recycling = 100%
  - Random-walk diffusion ~ 0.1 m^2/s and χ_e ~ 1 m^2/s
  - "Global" sheath
    - Potential adjusted to maintain ambipolar transport to wall
    - Zero resistance to wall currents
  - Carbon line emission loss model

Electron Profiles in Good Agreement with Measured Profiles

- **Electron profiles very sensitive to sources, sinks and anomalous transport levels**
  - Density in SOL is usually under predicted

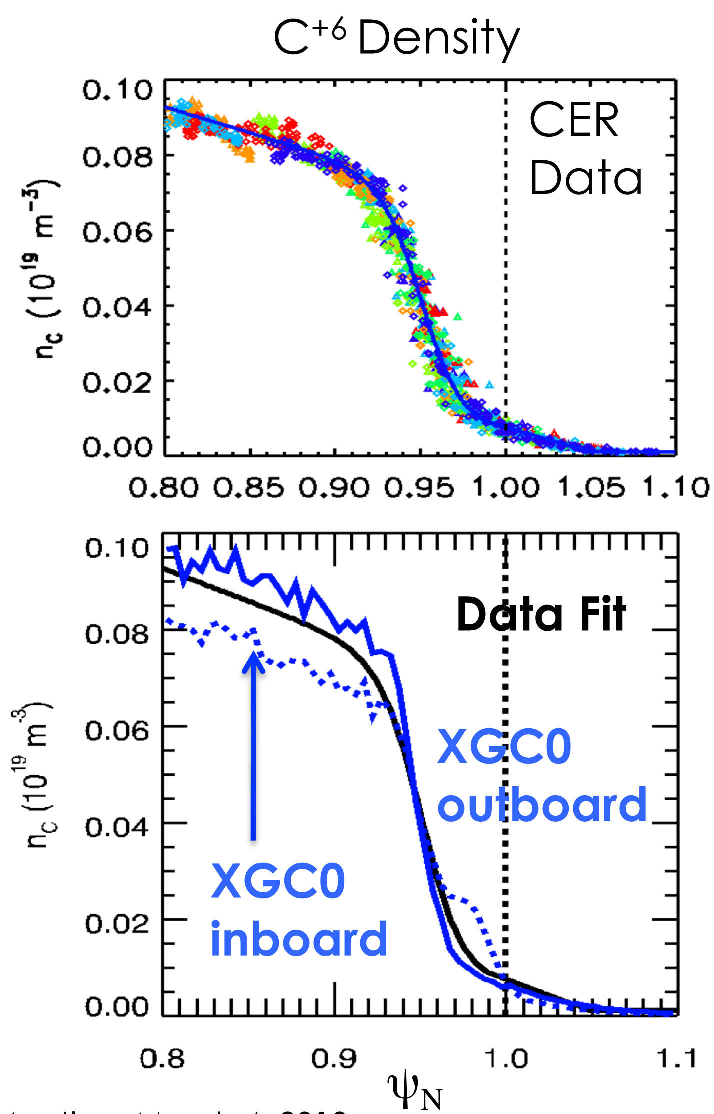
- **Primitive impurity line radiation calculation based on average Z_{eff}**

- **T_e is constant and n_e is mostly constant on a flux surface inside separatrix**
  - Poloidal asymmetries requires $E_{||}$
  - XGC-A will fix this



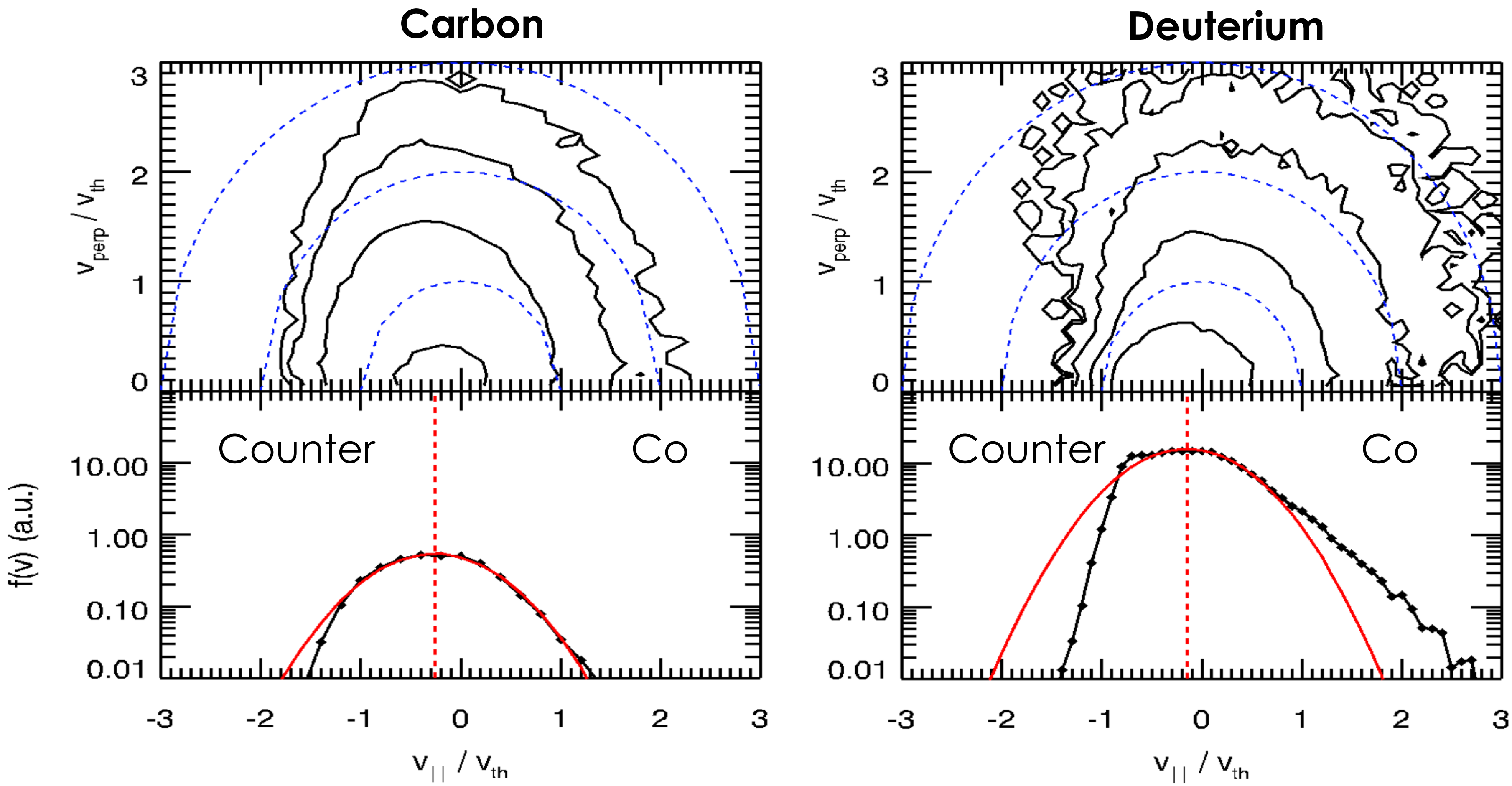
Carbon Density Profile Reproduced with Only Recycling as a Source

- **Carbon GC density close to experimental profile**
  - Some poloidal asymmetry in carbon GC density at top of pedestal and around separatrix
  - Current task: Translating GC density into true density

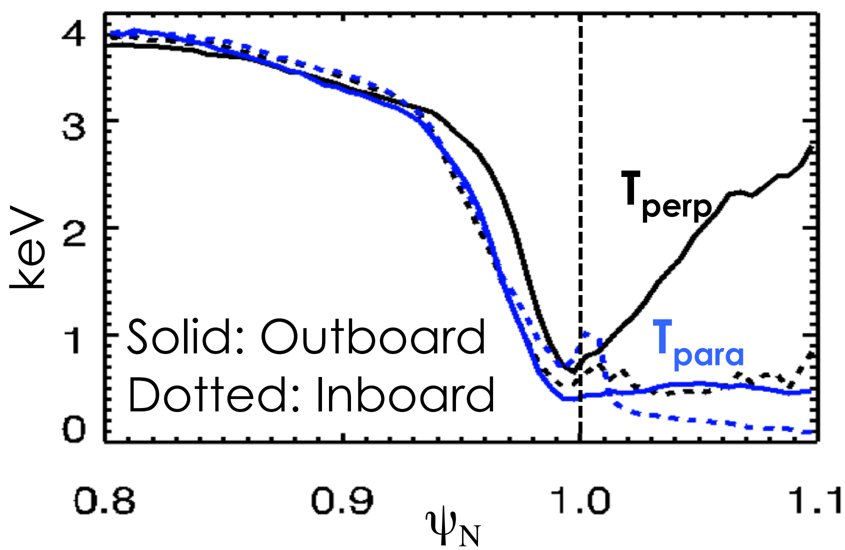


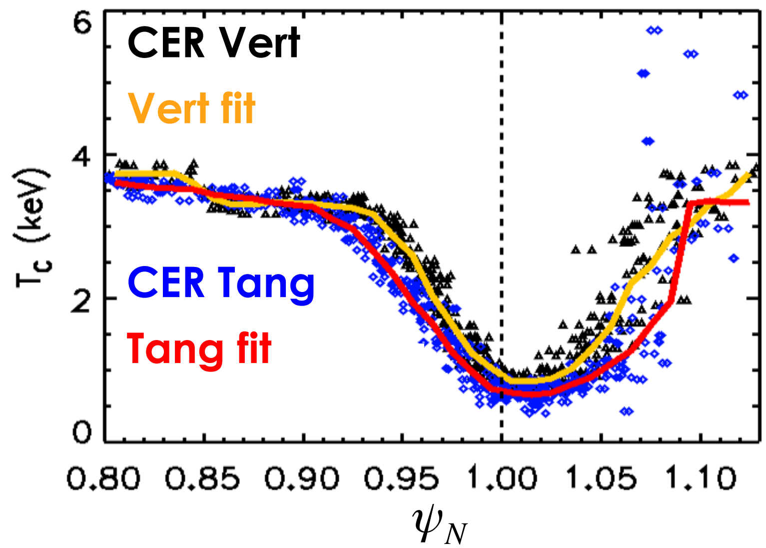
Ion Distributions are Non-Maxwellian Throughout the Pedestal

Outboard midplane, top of pedestal ($0.93 < \psi_N < 0.95$)



XGC0 Reproduces Anisotropic C^{+6} Temperatures at Outboard Midplane

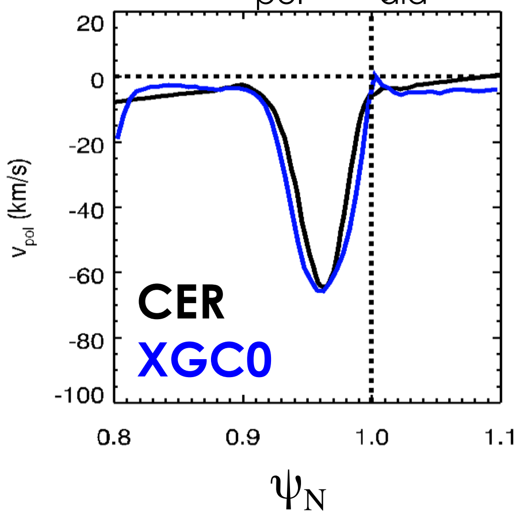




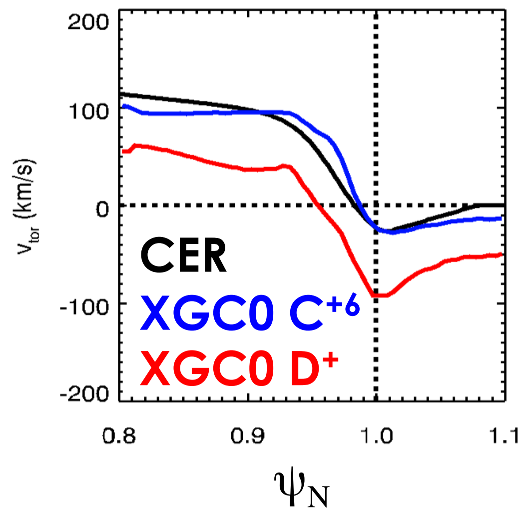
- **XGC0 and CER agree …**
  - $T_{perp} > T_{para}$ in steep gradient (mostly on outboard)
  - T_{perp} soars in SOL: deeply trapped orbits from top of pedestal
- **XGC0 has yet to reproduce $T_{para} > T_{perp}$ in far SOL**
  - Beam physics? Finite $E_{||}$? Atomic physics? Diagnostic effect ?

Self-consistent E_r Calculation in Good Agreement with E_r Derived from CER Profiles

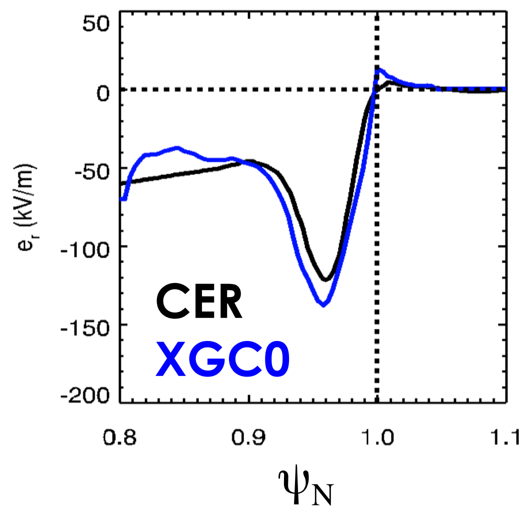
Poloidal GC flow
$= V_{pol} - V_{dia}$



Toroidal flow velocity



Radial Electric Field



- **Good agreement between XGC0 and CER when …**
  - At least 0.5 Nm of toroidal Co-I_p torque in steep pedestal region

- **Gives confidence that non-Maxwellian effects are a small correction to force-balance E_r calculation from CER**

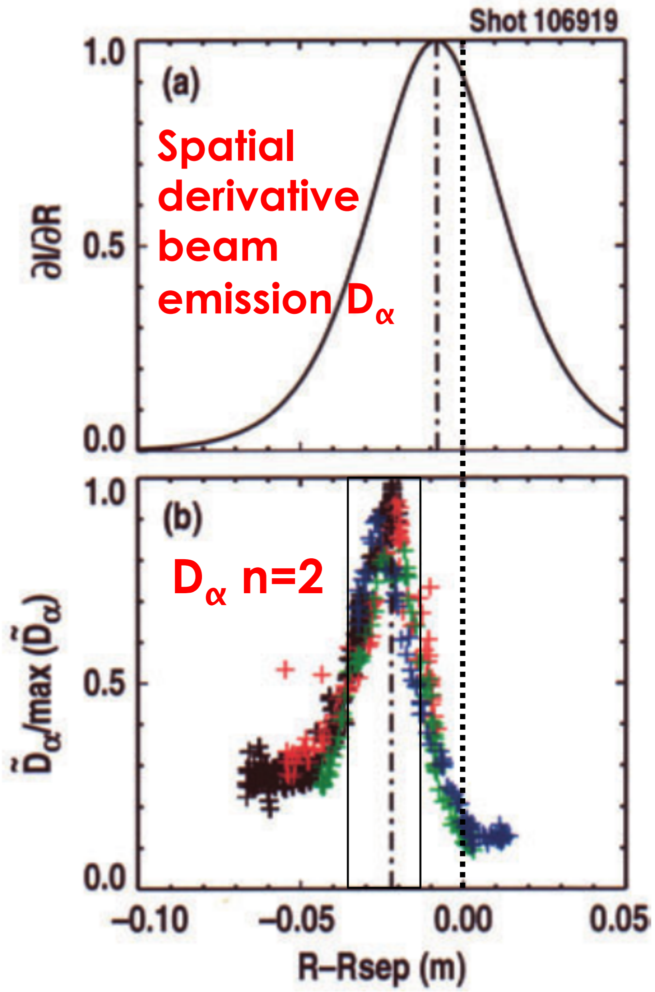
Conclusions from Interpretive XGC0 Calculations of Edge Transport in H- and QH-mode

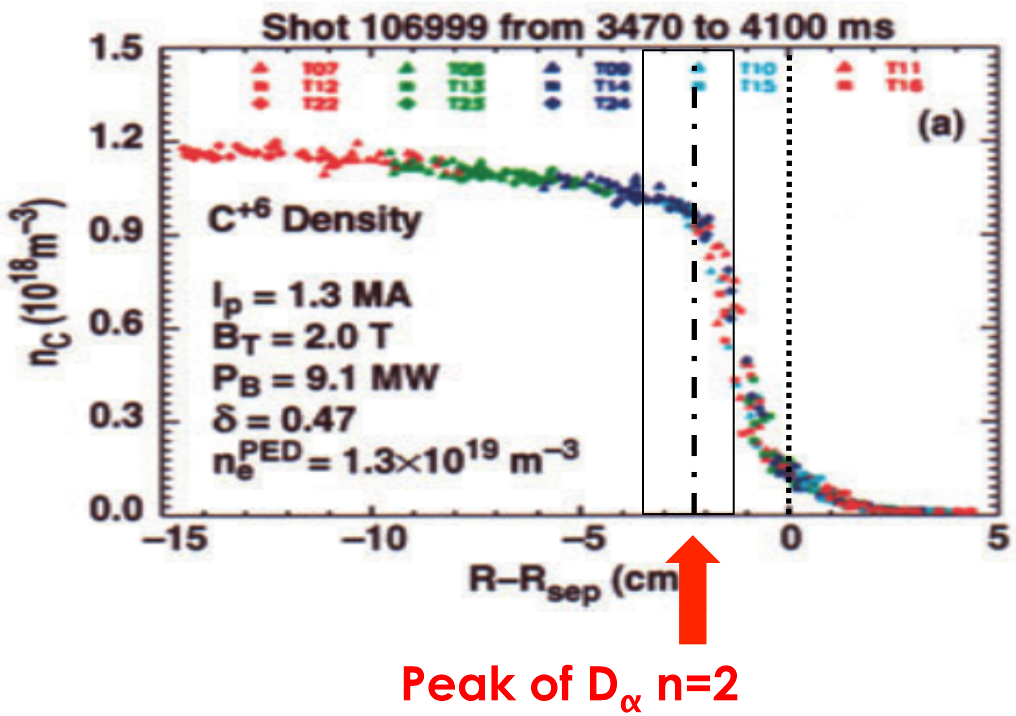
- **Transport in steep gradient region: Kinetic neoclassical ion transport balanced against anomalous radial current ($\Gamma_{i,neo} = \Gamma_{anom}$)**
  - Radial current equivalent to about 0.5 Nm co-I_p torque
  - Density maintained by including recycling physics
- **Anomalous transport at the bottom of the pedestal (Paleo-like)**
- **Single-particle orbit effects drive temperature anisotropy, intrinsic flows and poloidal asymmetries in the pedestal and SOL**
  - Separation of particle and thermal transport (JRT13)
- **H- and QH-mode have similar transport properties with very small anomalous ion transport in steep gradient region**
  - EHO only impacts electron transport?
  - EHO only impacts transport at top of pedestal?

Future Work

- **Full-f synthetic diagnostics for CER and Mach probe ion measurements**
  - Quantify agreement between experiment and model
  - Guide interpretation of CER spectrum, especially edge Main Ion
- **Include more physics to possibly reduce free parameters**
  - Directly calculate Paleoclassical transport levels
  - Gyro-averaging may capture anomalous viscosity
  - Add KBM or EHO level EM fluctuations
  - Impact of $E_{||}$
- **JRT13: Compare transport mechanisms of H-mode to ELM-free H-modes (QH-mode, EPH-mode, I-mode …)**
- **H-mode intrinsic rotation scaling vs edge parameters**

EHO oscillation amplitude peaks at top of pedestal





- **Good channel-to-channel alignment**
  - Profiles stationary through sweep
- **Spatial calibration suggests EHO peaks at top of pedestal**

Anomalous transport in XGC0

- **Random walk diffusion and convection**
  - *D* in m²/s at outboard midplane
  - χ in m²/s at outboard midplane for each species

$$R = R + \left(\frac{D}{R} + \frac{dD}{d\psi}\frac{d\psi}{dR} \pm \sqrt{\frac{2D}{\Delta t}} \right)\Delta t + \chi V \frac{d\psi}{dR}\Delta t$$

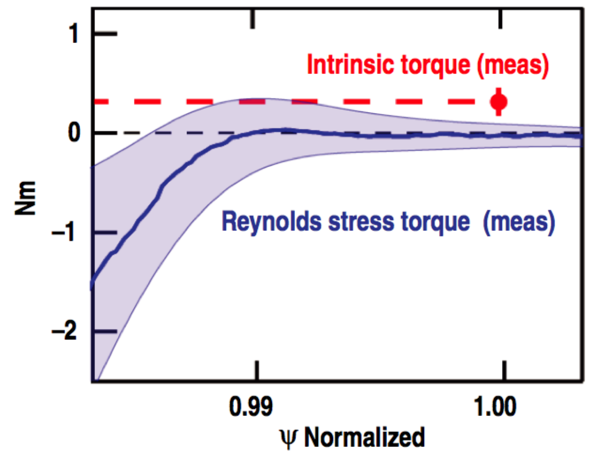
$$Z = Z + \left(\frac{dD}{d\psi}\frac{d\psi}{dZ} \pm \sqrt{\frac{2D}{\Delta t}} \right)\Delta t + \chi V \frac{d\psi}{dZ}\Delta t \quad V = -\frac{2}{3}\left(\frac{K}{T} - \frac{3}{2}\right)\frac{dT/d\psi}{T}$$

- **Radial smoothing of $d\phi/d\psi$**
  - η in m²/s at outboard midplane

$$\frac{d\phi}{d\psi} = \frac{d\phi}{d\psi} + \eta\left(\frac{d\psi}{dr}\right)^2 \frac{d^3\phi}{d\psi^3}\Delta t$$

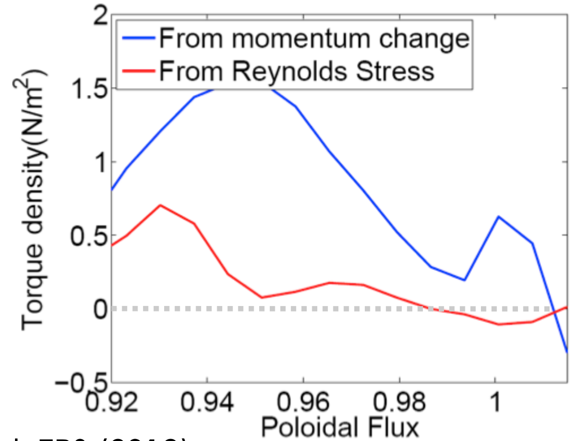
X-transport torque is thought to be a significant source of edge intrinsic rotation

- **Reynolds stress from Mach probe measurements under-predict intrinsic edge torque**
  - Solomon empirical DIII-D scaling for edge intrinsic torque has improved fit when including X-transport parameters



W.M. Solomon et al.
Nucl. Fusion **51** (2011) 073010

- **XGC1 simulations qualitatively agree with experiment**
  - Co-I_p Reynolds stress from first-principles turbulence model is small
  - Counter-I_p neutral torque is small
  - Co-I_p X-transport torque dominates near separatrix



S. Ku et al. EPS (2012)

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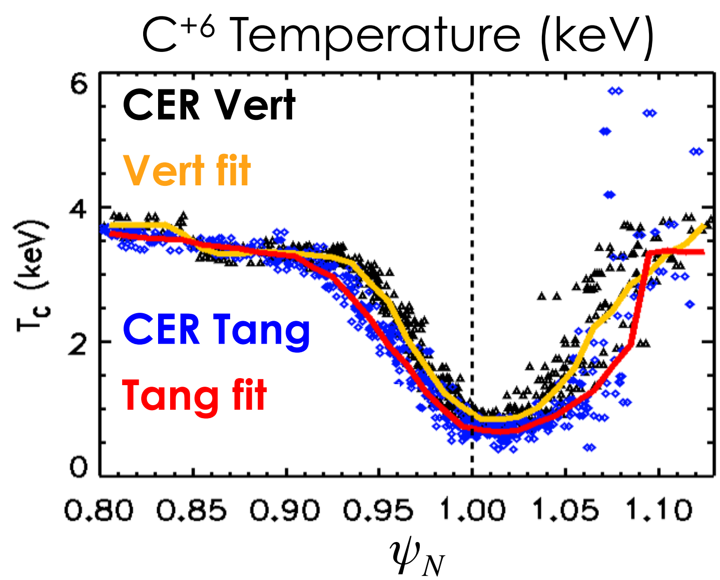
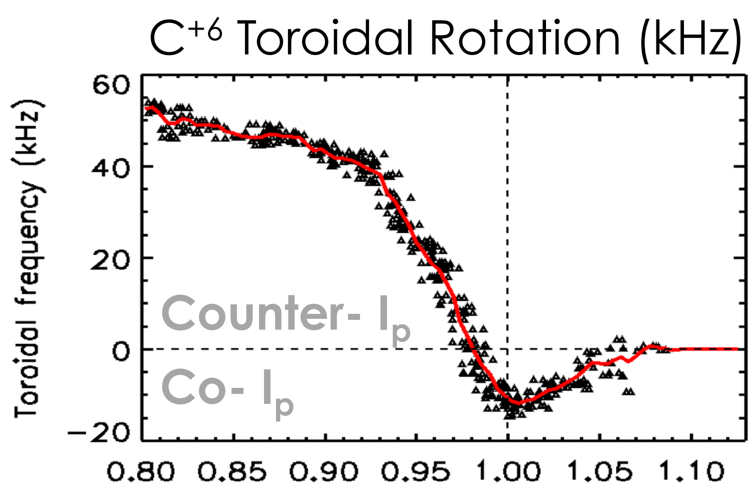
Measurements Suggest Single Particle Physics and Sheath Physics is Important

- **Ion Temperature Anisotropy**
  - T_{perp} > $T_{parallel}$
  - Large C^{+6} temperatures in SOL with T_{para} > T_{perp} in far SOL
- **Rotational shear in pedestal**
  - Torque from non-Maxwellian distributions and orbit loss
  - Switch from negative E_r in plasma to positive E_r in SOL

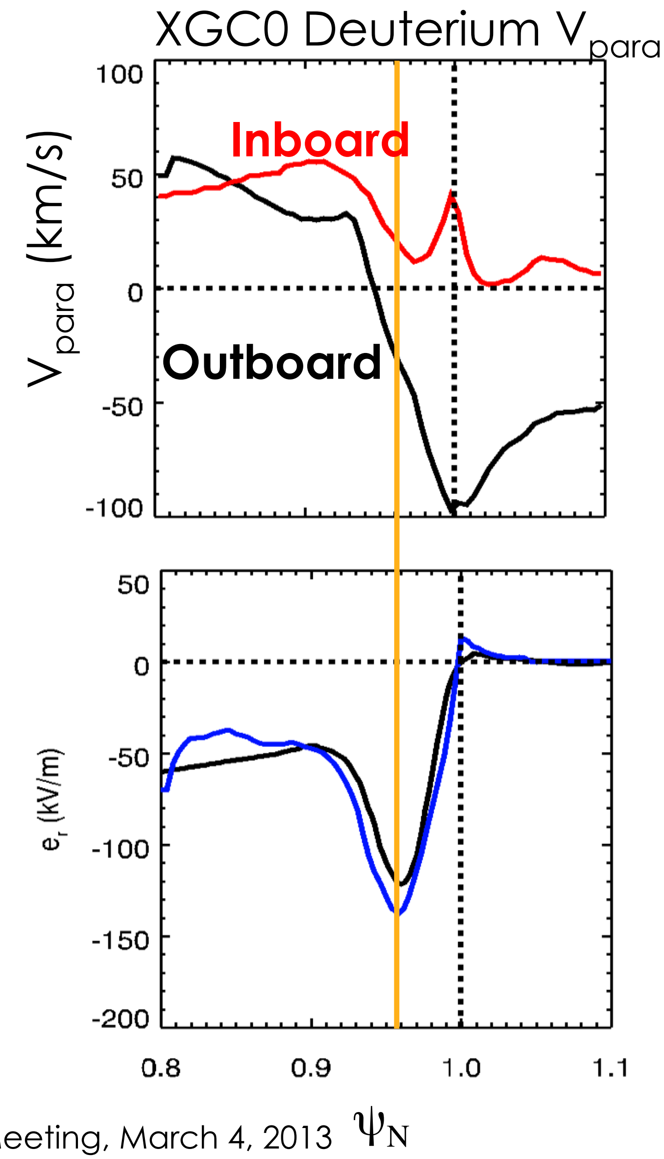




106999 3470 – 4100 ms ψ_N

Observation: Both Main Ion Toroidal Flow and Poloidal Flow Shear ~ 0 at E_r well … EHO Requirement?

- **Counter-I_p torque from beams, Co-I_p intrinsic edge torque**
  - Main Ion flux-surface-averaged parallel flow zero crossing aligns with bottom of E_r well
- **Low perpendicular flow shear, low parallel flow …**
  - A recipe for resonant kink?
- **Also note …**
  - Ions flowing into divertor in SOL
  - Large main-ion outboard flow



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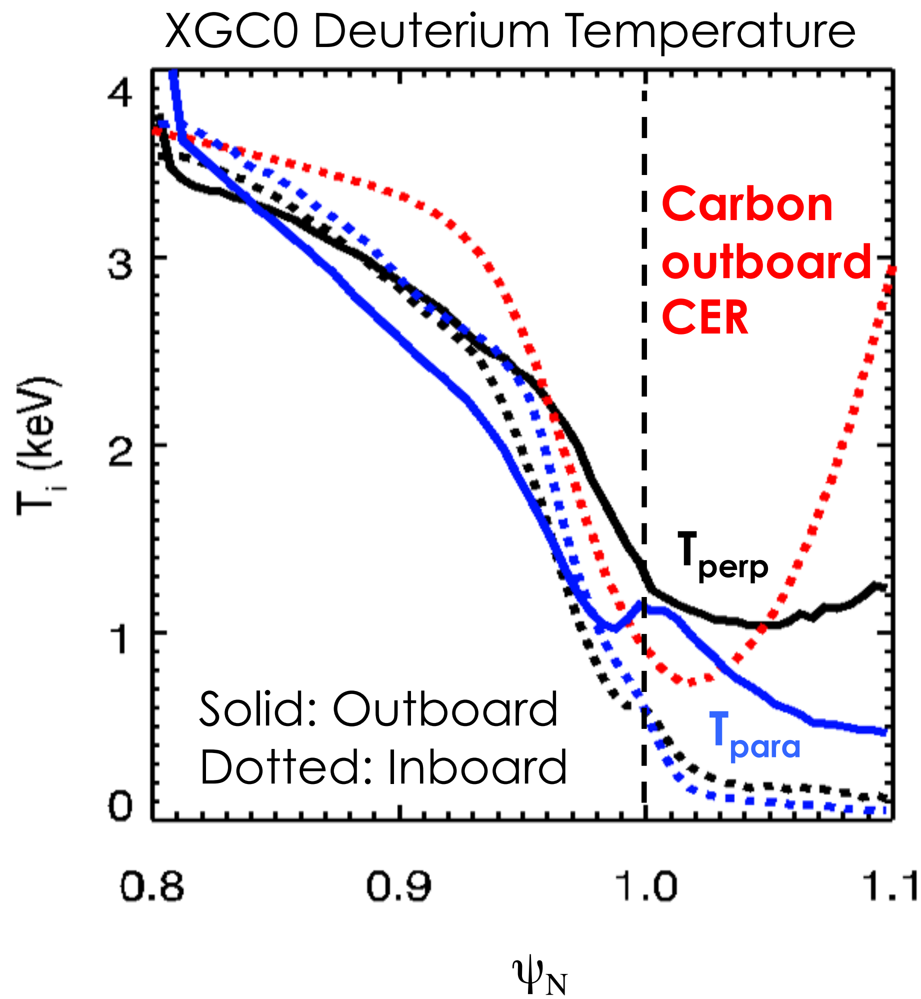
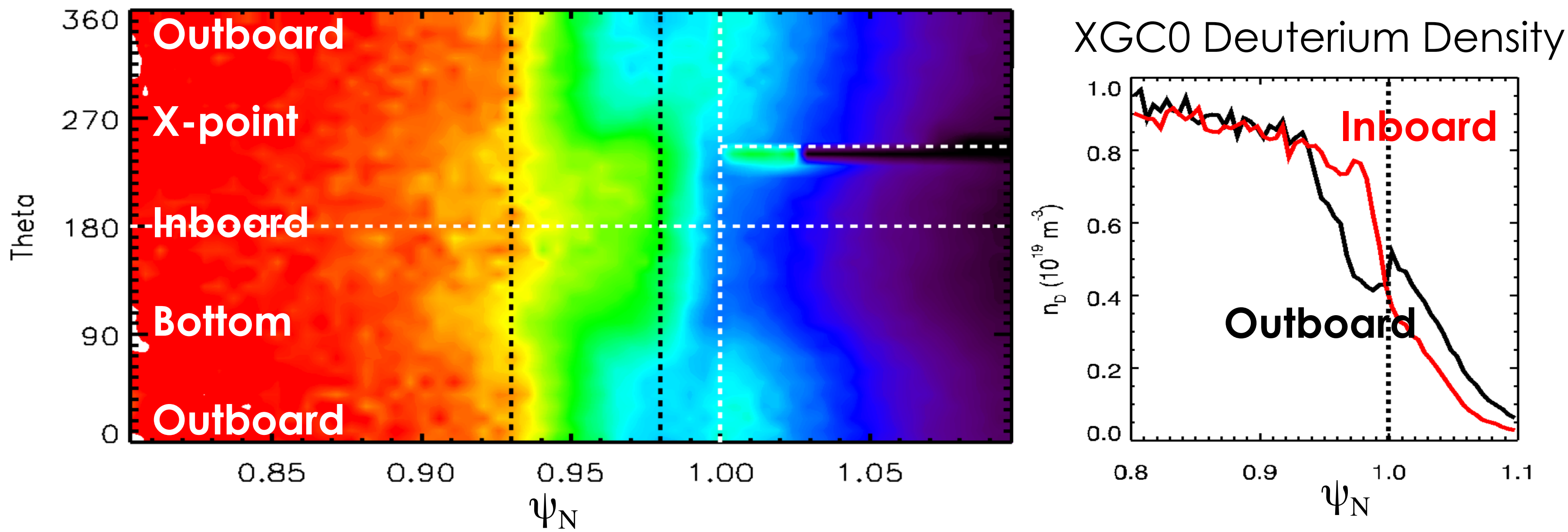
Deuterium Temperature Anisotropy is Similar to Carbon

- **Deuterium temperature typically lower at top of pedestal**
  - Code or physics?
- **T_{perp} > T_{para} in outboard steep gradient region**
  - Opposite for inboard
- **SOL temperatures different than carbon**
  - Large, but not soaring



Strong In-Out Asymmetry in GC Deuterium Density due to Orbit Physics



- **Inboard and outboard density inverts around separatrix**
  - Inside separatrix: Loss hole of trapped counter-I_p ions
  - Outside separatrix: Confinement hole of passing co-I_p ions
  - Large ion temperatures and rotation enhance these effects
  - Outstanding question: How large is $E_{||}$?