Evidence for Anomalous Effects on the Current Evolution in Tokamak Operating Scenarios

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with
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ABSTRACT:

Alternatives to the usual picture of advanced tokamak (AT) discharges are those that form when anomalous effects alter the plasma current and pressure profiles and those that achieve stationary characteristics through self-organizing mechanisms so that a measure of desired AT features is maintained without external current-profile control. Regimes exhibiting these characteristics are those where the safety factor (q) evolves to a stationary profile with the on-axis and minimum q~1 and those with a deeply hollow current channel and high values of q. Operating scenarios with high fusion performance at low current and where the inductively driven current density achieves a stationary configuration with either small or non-existing sawteeth, may enhance the neutron fluence per pulse on ITER and future burning plasmas. Hollow current profile discharges exhibit high confinement and a strong "box-like" internal transport barrier (ITB). We present results providing evidence for current profile formation and evolution exhibiting features consistent with non-neoclassical anomalous effects or with self-organizing mechanisms. Determination of the underlying physical processes leading to these anomalous effects is important for scaling of current experiments for application in future burning plasmas.

Development of models to describe anomalous current profile evolution

- **Scenarios considered here are alternatives to the usual advanced tokamak (AT) mode.**
  - » AT features maintained to some degree without external current profile control
  - » Considered attractive for burning plasma operation
- **Hybrid mode: anomalous current profile evolution**
  - » Safety factor (q) evolves to a stationary profile with on-axis q (q_0) and the minimum of q (q_{min}) ~ 1
  - » Neoclassical tearing modes (NTM) appear to be important
  - » Some discharges exhibit sawteeth (4,3) and some don't (3,2)
  - » Coupling between large radius and magnetic axis
- **Current holes: self-organization of hollow current profile at high q_0**
  - » High confinement with strong (box-like) internal transport barrier (ITB)
  - » Anomalous neutral-beam effects couple to negative shear q profile

Hyper-resistivity (HR) in Corsica provides a model for anomalous current profile evolution due to fluctuations

- **Hyper-resistivity is an additional term in Ohm's law that provides current diffusion**

  BOOZER, A.H., J. Plasma Phys. 35 (1986) 133.

  » This is added to the flux-diffusion term generally used

  » Corsica simulations solve Ohm's law and the equilibrium at each time step in the simulations

  CROTINGER, J.A., et al., Lawrence Livermore National Lab. Report UCRL-ID-126284, 1997 available from NTIS #PB2005-102154.

- **Two models for the HR-coefficient are present in Corsica:**

  » Berk*-Fowler-LoDestro-Pearlstein (BFLP) - new model based on NTM islands and field-line entanglement**

  * **BERK, H., et al., UCRL-ID-142741 (2001), http://www.osti.gov/bridge**

  ** **RECHESTER, A.B., and ROSENBLUTH, M.N., Phys. Rev. Lett. 40 (1978) 38.**

  » Ward-Jardin model based on q=1 resonance plus analytic form for HR

  WARD, D.J., and JARDIN, S.C., Nucl. Fusion 29 (1989) 905.

  » Models are additive and coupled through the equilibrium evolution

Derivation* of the BFLP Hyper-Resistive term in Corsica

- **Calculate the pondermotive force due to the presence of magnetic islands. We start from the Drift Kinetic Equation for electrons.**

$$\frac{\partial f}{\partial t} + \frac{v_{\parallel}}{B} B \bullet \nabla f + v_D \bullet \nabla f + \frac{B \bullet E}{B} \frac{\partial f}{\partial v_{\parallel}} = C(f)$$

- **Kinetic dynamo: transport due to stationary, tangled magnetic fields.**

$$\frac{v_{\parallel}}{B} \nabla \bullet \tilde{B} \langle \frac{\nu v_{the}^2}{\nu^2 + k_{\parallel}^2 v_{the}^2} \rangle \tilde{B} \bullet \nabla f$$

- **MHD dynamo:**

$$\frac{\langle \tilde{B} \bullet \tilde{E} \rangle}{B} \frac{\partial f}{\partial v_{\parallel}} = -\frac{\nabla \langle \tilde{\phi} \tilde{B} \rangle}{B} \frac{\partial f}{\partial v_{\parallel}}, \text{ with } \tilde{E} = -\nabla \tilde{\phi} + \tilde{E}_{\parallel}^{T}$$

  - The contribution from $\tilde{E}_{\parallel}$ produces transport from stationary fields, whereas the contribution from $\tilde{E}_{\perp}$ is non-stationary transport and "generally small".

- **The remaining kinetic term is non-stationary and "generally small".**

*H. Berk, *et al.*, UCRL-ID-142741 (2001) available at http://www.osti.gov/bridge

The perturbed B in the kinetic dynamo for the BFLP model is obtained from the modified Rutherford island equation

- Assume dynamics are governed by the modified Rutherford equation:

$$\frac{dw}{dt} = 1.22\frac{\eta}{\mu_0}\left(D' + \frac{D_R}{w} + \frac{D_{neo}}{w^2 + \overline{w}^2}\right)$$

- Independent islands only interact through their effect on the equilibrium, with

$$w^2 \equiv w^2{}_{m,n} = \frac{2q^2 R\tilde{B}}{mB_T q_r}$$

- Modified Ohm's law becomes,

$$\left(\frac{\partial\psi}{\partial t}\right)_\phi = \eta\langle J \bullet B\rangle - \frac{\partial}{\partial\phi}\sum_{m,n}\frac{|\tilde{B}\cdot\nabla\phi|^2}{\varepsilon_0\omega_{pe}^2}\left\langle\frac{\nu v_{the}^2}{\nu^2 + k_{||}^2 v_{the}^2}\right\rangle\frac{\partial}{\partial\phi}\frac{\langle J \bullet B\rangle}{\langle B \bullet B\rangle}$$

  where ϕ = toroidal flux and we have been imaginative pulling terms through spatial derivatives to force "helicity conservation"
- The MHD dynamo conserve helicity exactly.
- The simulations to date only include the kinetic dynamo; the other terms are being added.

HEGNA, C.C., Phys. Plasmas **5** (1998) 1767.
LaHAYE, R.J, Phys. Plasmas **13** (2006) 055501.

Overview of hyper-resistive model due to Ward & Jardin

- **Trigger turn-on of HR when q_0 gets to a critical value within some radius**
- **Analytic model used for hyper-resistive coefficient where our simulations use:**

$$C_{HR}(r) = \lambda_0 (1 - r/r_s)^{\alpha}, r \le r_s$$
$$0 \qquad , r > r_s$$

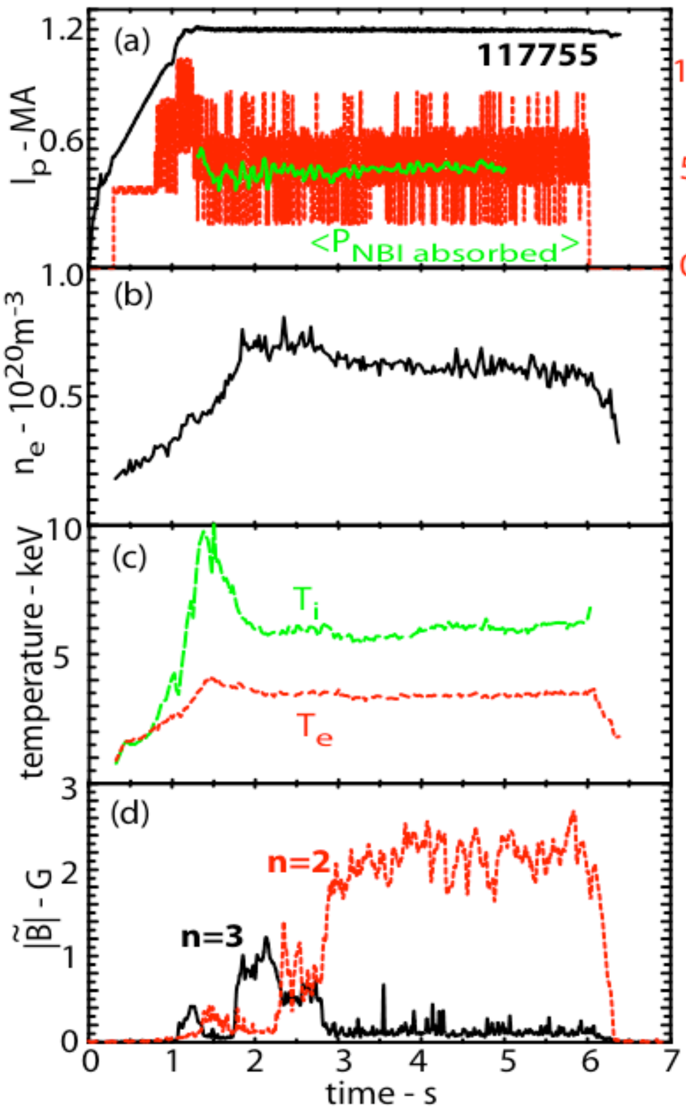
with $\lambda_0=200\eta_0$ for η=resistivity, α=1.2, q_{crit}=.99 and

r_s = location where 1/1 helical flux = 1/1 flux at center

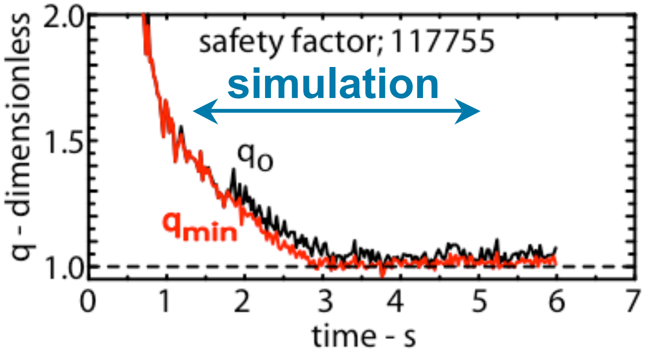
- **Shape of (total) current inside r_s determined by parameters of the functional form chosen plus the presence of other non-inductive current drive**
- **WJ and BFLP coefficients are additive and both can be active**

WARD, D.J., and JARDIN, S.C., Nucl. Fusion 29 (1989) 905.

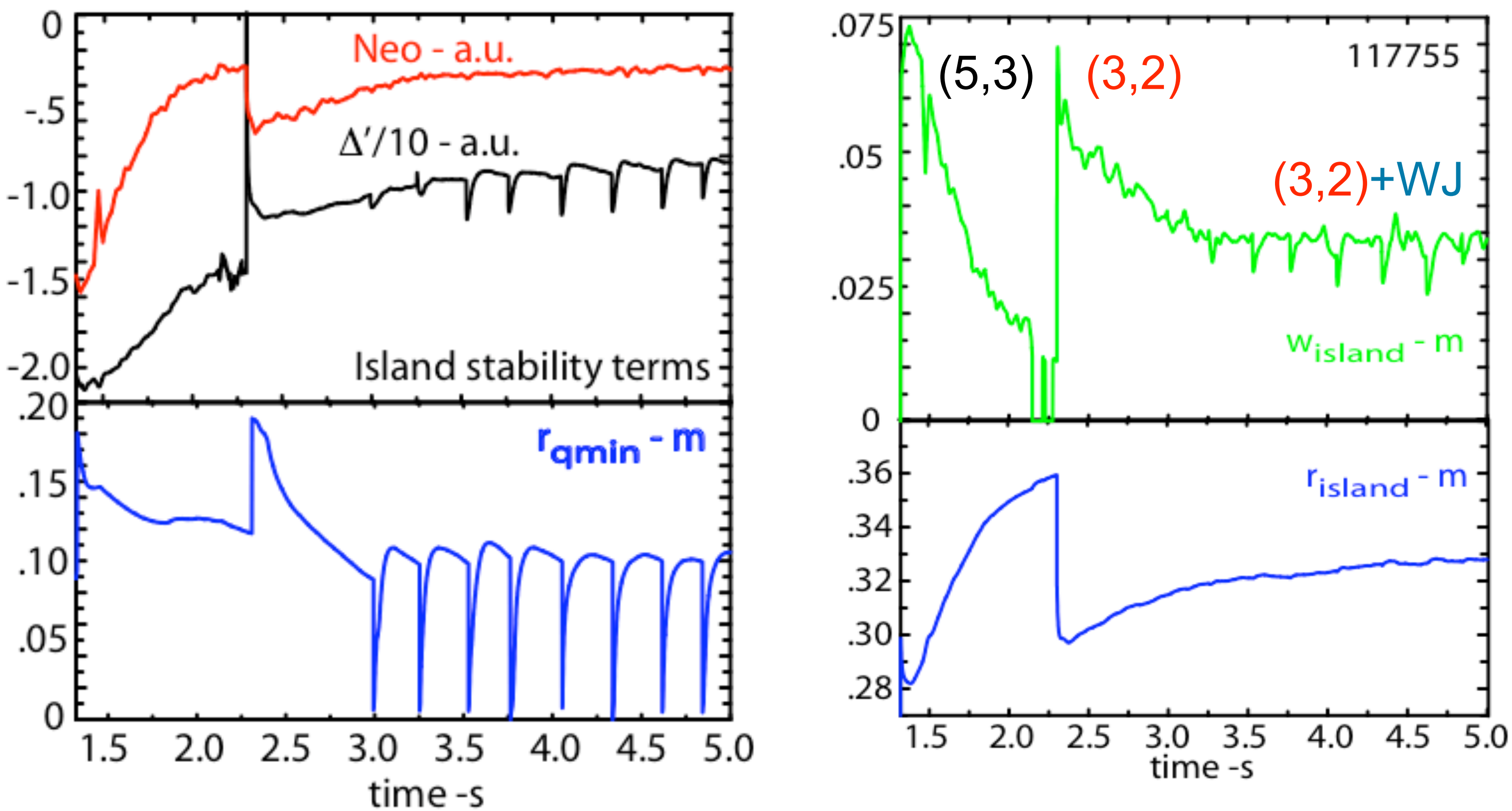
HR simulations presented are for a DIII-D hybrid shot, 117755



- **Representative of many hybrid discharges on DIII-D: B_T=1.7T, β_N~2.7 and H_{L89}~2.5**
- **Parameters:**
  - » (a) Plasma current and neutral-beam power under β-feedback control with Corsica calculated absorbed power in simulations
  - » (b) Electron density
  - » (c) Ion and electron temperatures
  - » (d) n=3 and n=2 edge magnetic fluctuations: (m,n)=(5,3) and (3,2) modes
- **Under NTM activity, the hybrid mode evolves to steady parameters at t > 3s.**

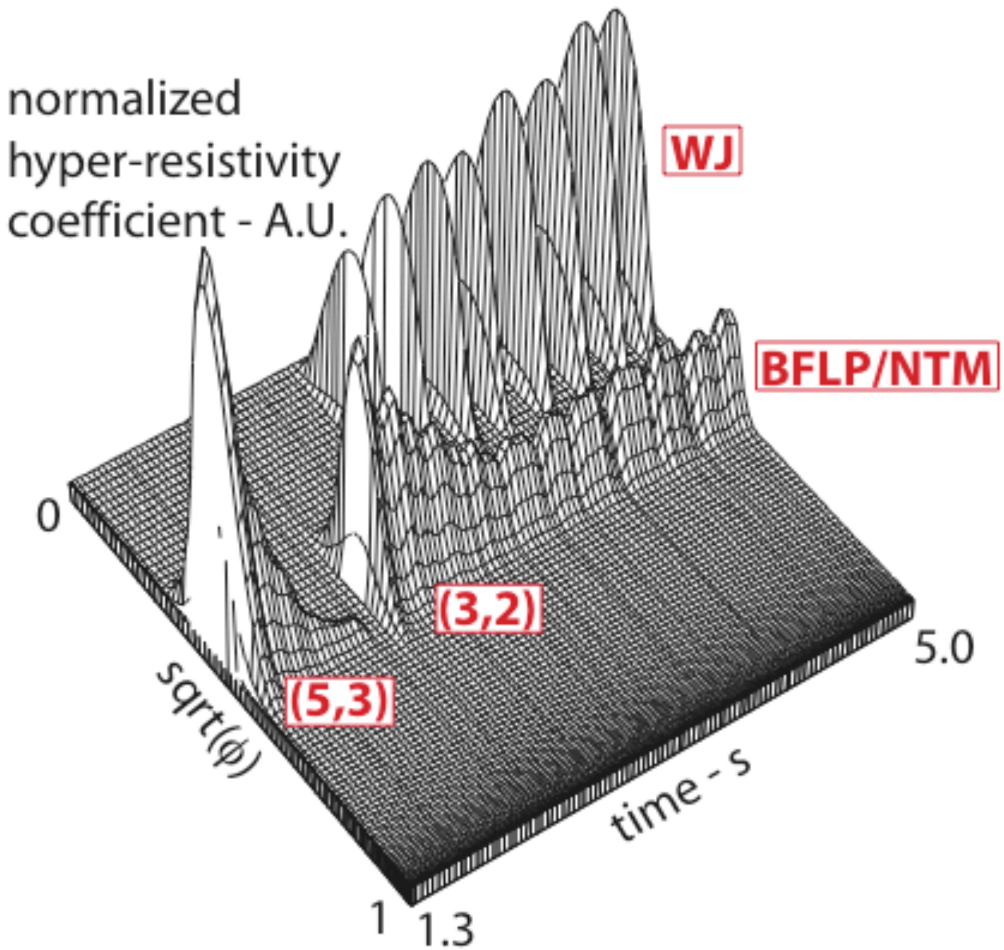


NTM islands destabilized by neo-classical term with Δ' stabilizing provide the drive for BLFP HR coefficient

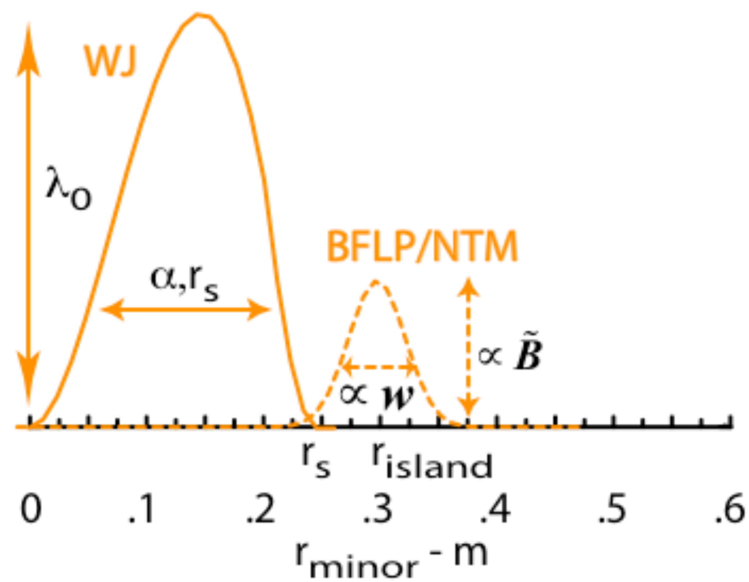


- **Evolution to finite island width and steady radius late in time**
- **R_{qmin} indicates changes in q-profile shape with island evolution**
- **Change in r_{qmin} due to WJ current diffusion feeds back on BFLP via Δ' term and alters island stability late in time**

BFLP provides continuous current diffusion near the NTM while WJ has transient effect near magnetic axis at low q_0



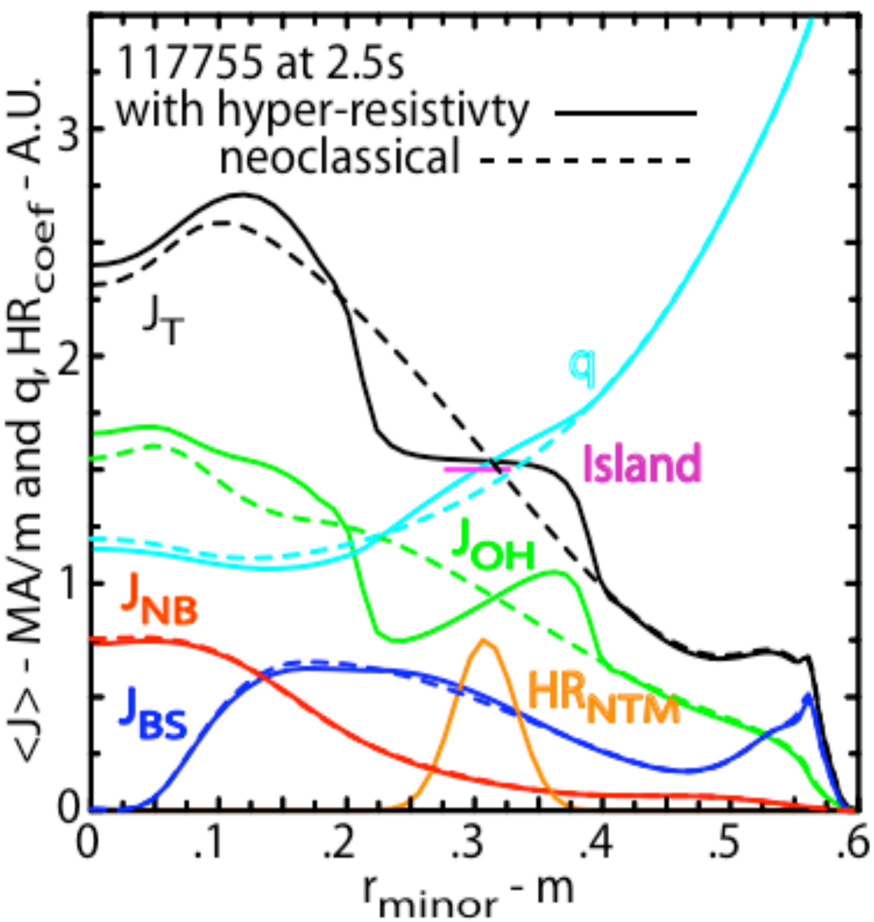
- Hyper-resistive coefficient for BFLP determined from NTM parameters



- WJ coefficient determined by analytic model used.

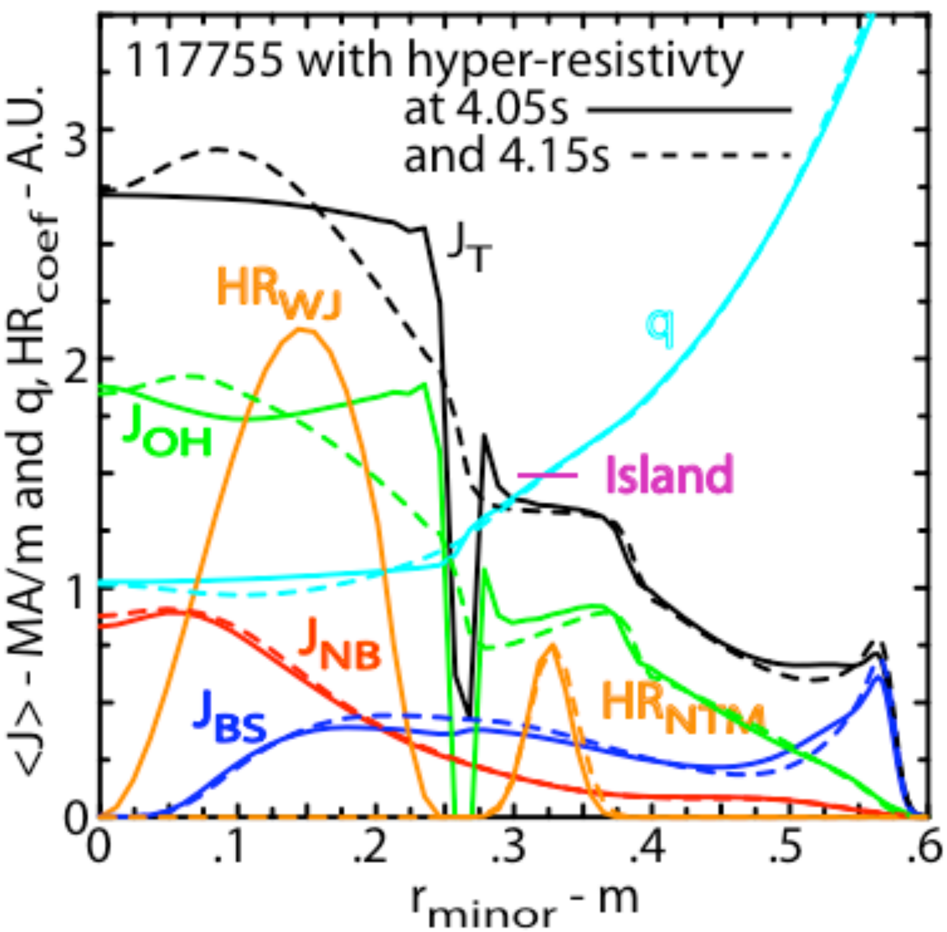
As q_0, q_{min} are dropping due to flux diffusion, the BFLP/NTM model alters q-profile evolution locally

$$\langle J \rangle = \langle J \bullet B \rangle / \langle B/R \rangle$$



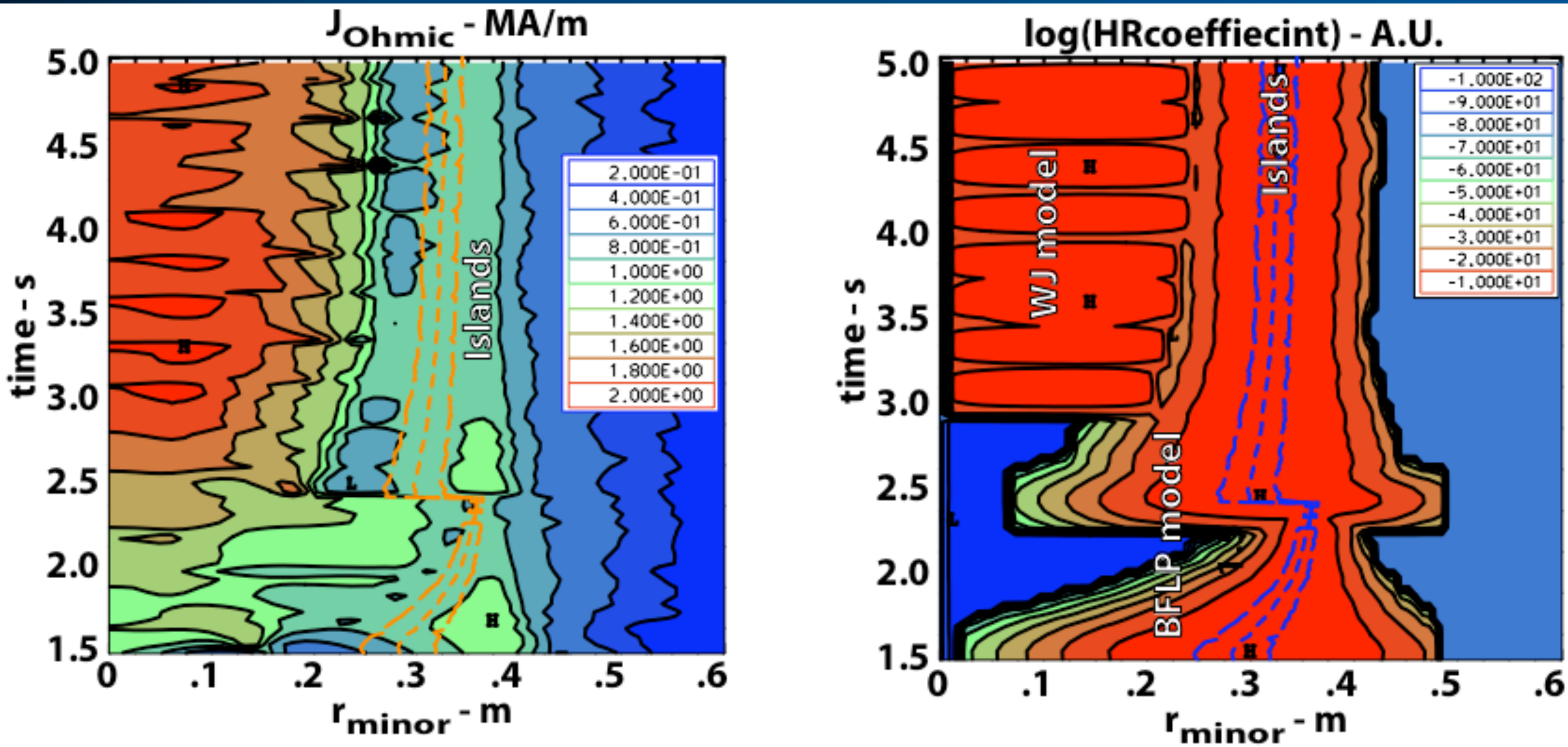
- Comparison of current-density profiles during early evolution
  - J_T = total current
  - J_{OH} = Ohmic current
  - J_{NB} = neutral-beam current from Monte Carlo deposition + orbits
  - J_{BS} = bootstrap current from NCLASS
- Only BLFP is active: (3,2) NTM mode with a 5cm island at R_{minor}~.3m
- J_{OH} locally diffused over island
- Normalized HR_{NTM} coefficient indicates region of HR activity
- J_T, q profiles continuously modified from just outside the island-induced HR activity to the magnetic axis

WJ HR-model transiently modifies the q inside r(q=1) while BFLP(NTM) continues to modify profiles inside the island



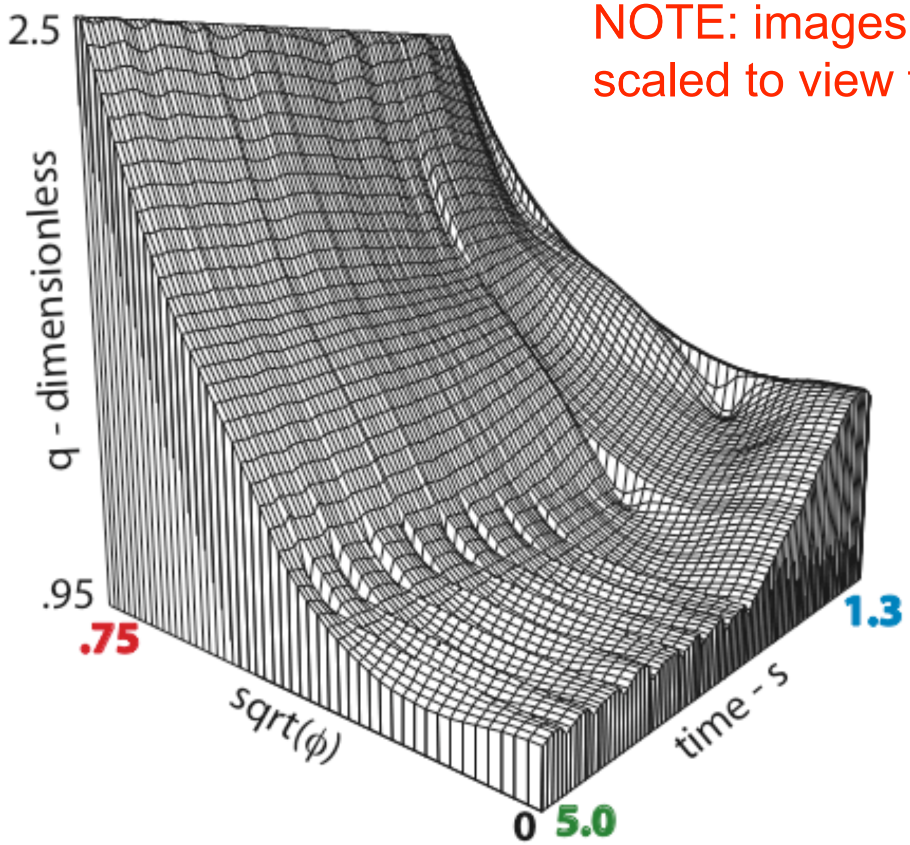
- ——— **current re-distributed out to radius forcing $\phi = \psi$**
  - » Transient HR_{WJ} >> continuous HR_{BFLP}
  - » Current sheet (voltage drop) in J_T, J_{OH} due to helicity conservation
- – – – – – **current rebuilds due to normal flux-diffusion limited by HR current diffusion and non-inductive sources, J_{BS} and J_{NB}**
- **J_{OH} diffusion near island maintained by HR_{BFLP}**
- **BFLP raises q just inside the island and this limits the extent of WJ**

Coupling between axis and island is through the equilibrium (solved each time step in simulations)

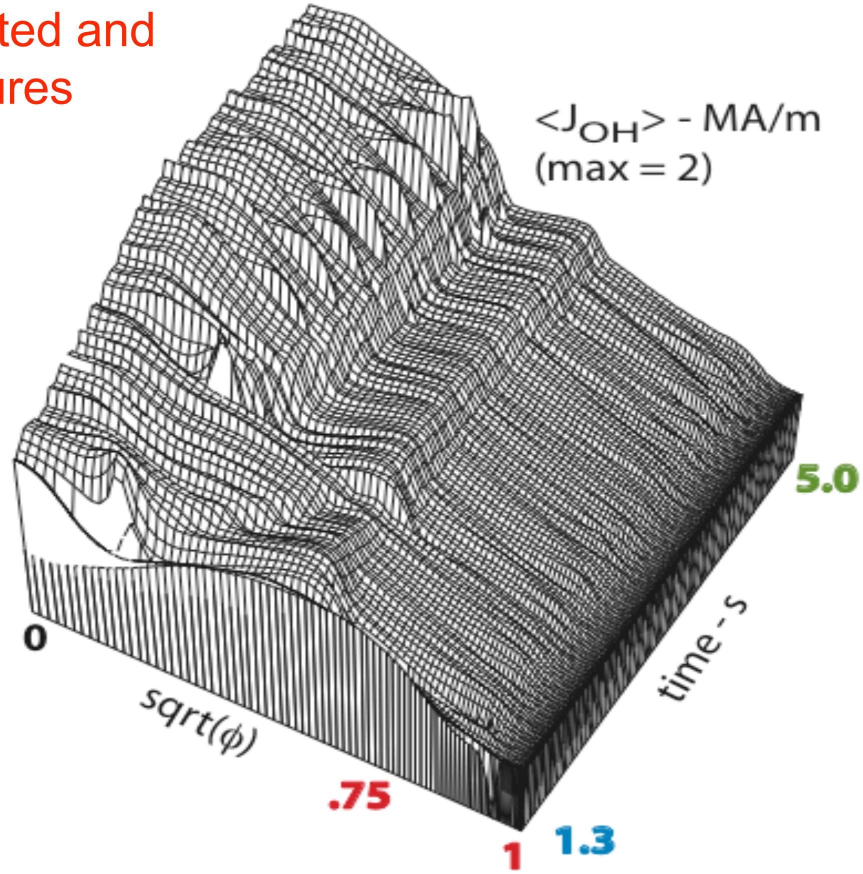


- **Equilibrium solution couples island region and axis - limits radial extent of WJ activity**
- **Region near r_{minor} ~ .25 is the interface between the two HR models.**
- **Current diffusion due to BFLP and WJ interact just inside the island**

Hyper-resistivity strongly alters the evolution of the current and q profiles

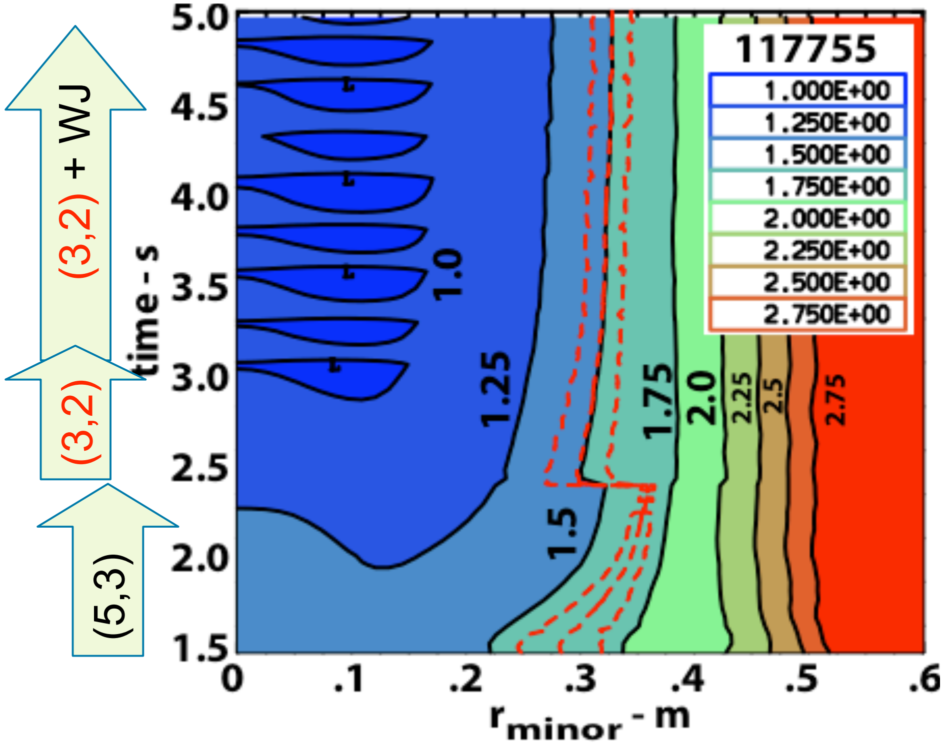


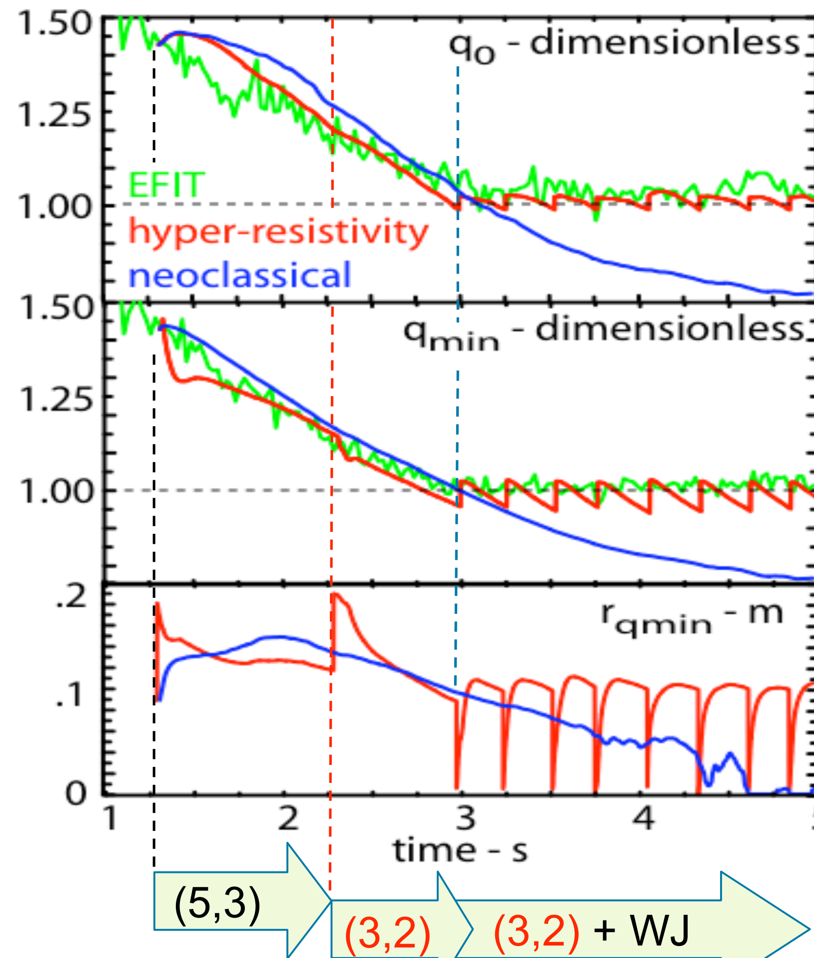
NOTE: images rotated and scaled to view features



- **Early evolution of q strongly modified by current diffusion from BFLP**
- **WJ current diffusion maintains weak negative shear near the axis**
- **Interaction of BFLP and WJ controls q profile late in time**

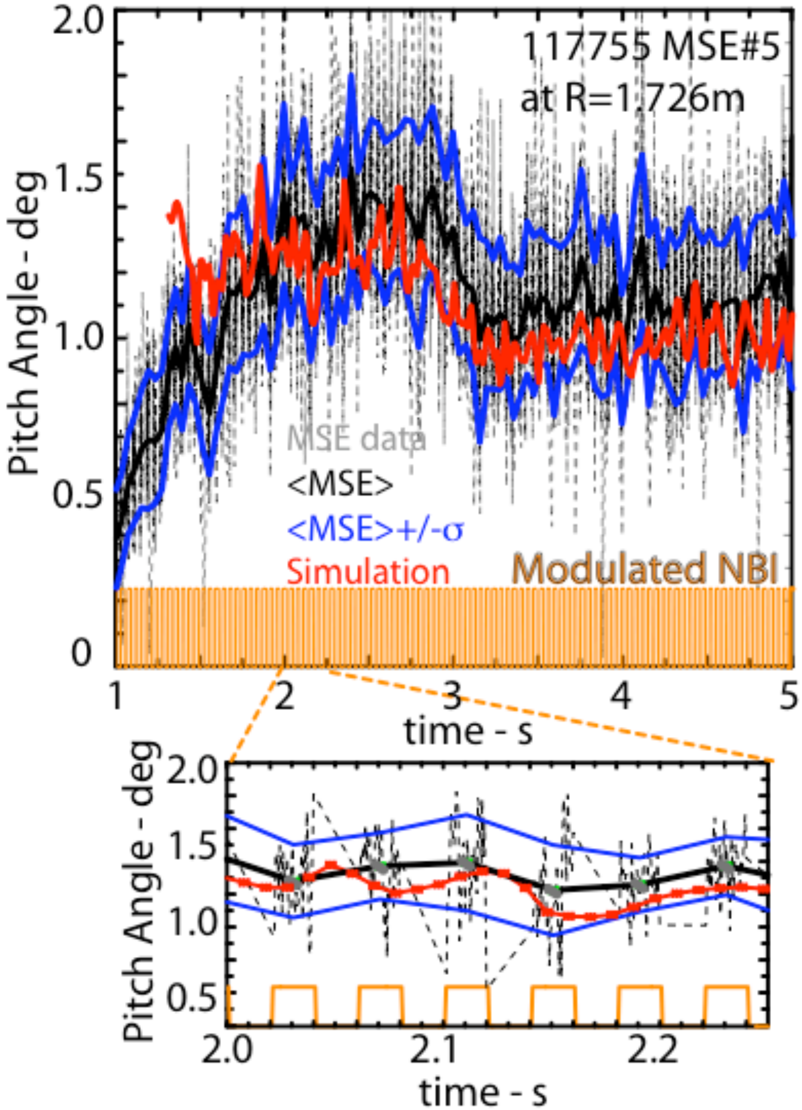
The evolution of the q profile is modified by the hyper-resistivity locally diffusing the current density

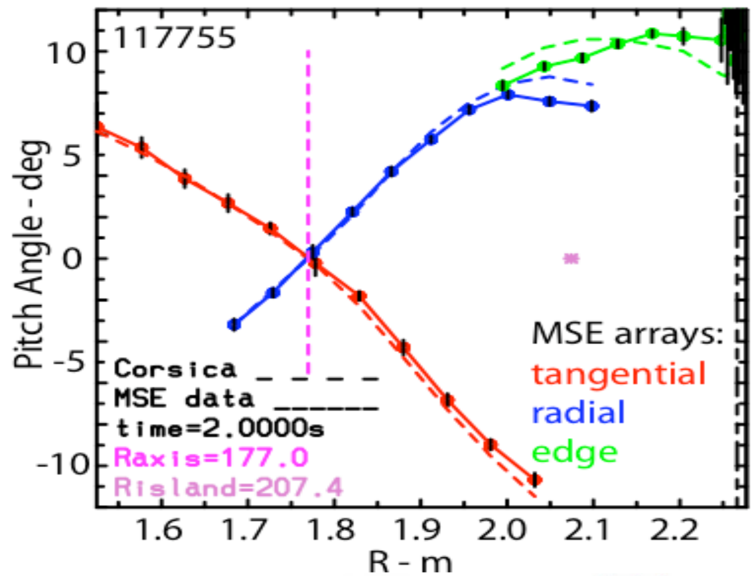


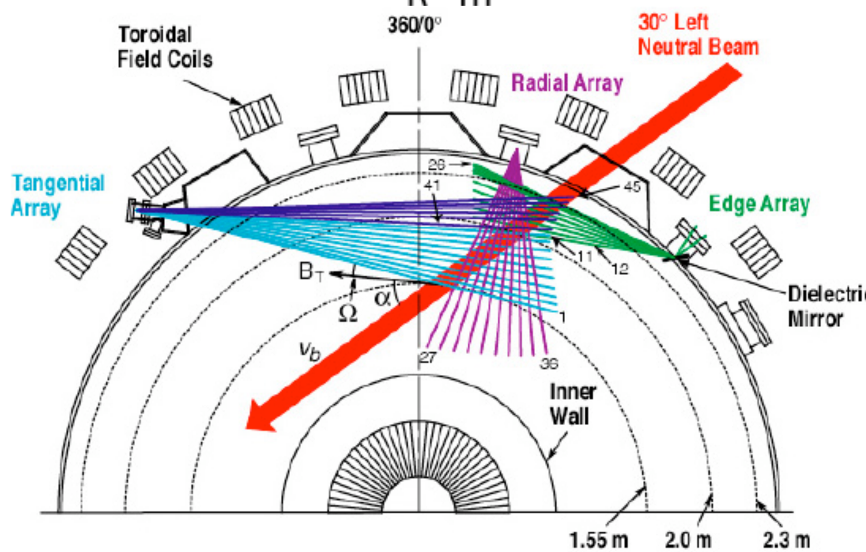


- **q profile contours**
- **Simulation evolution with HR**
  - » Contours > 1 modified by NTM-HR
  - » Contours ~ 1 due to WJ-HR
- **Island evolution: r_{island} +/- $w_{island}/2$**
- **HR evolution agrees with EFIT**
- **R_{qmin} ~ change in profile**

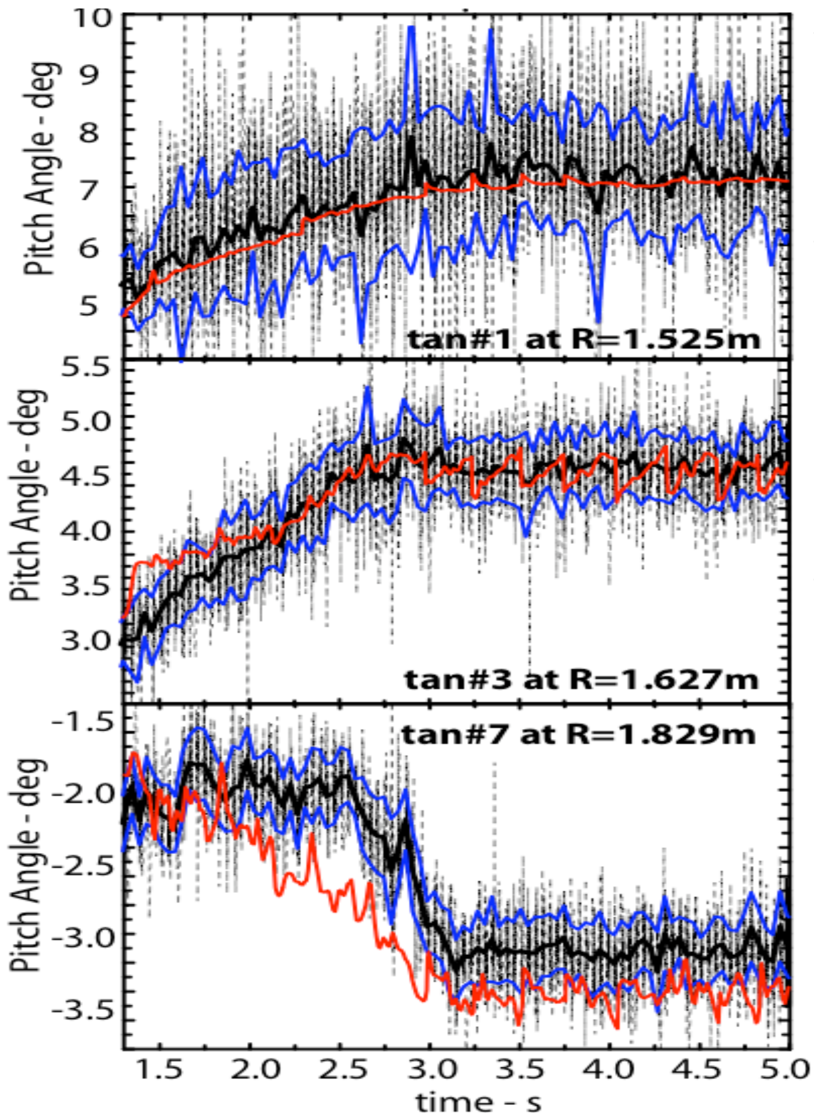
Corsica motional Stark effect (MSE) synthetic diagnostic calculates "pitch angle data" for measurement comparison



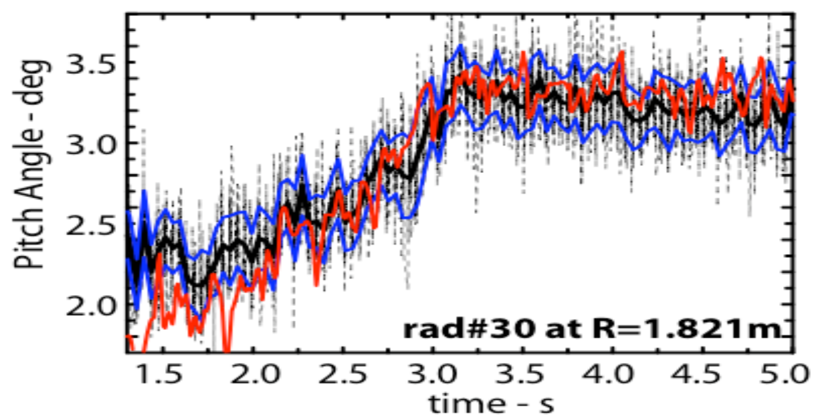




HR evolution with predicted islands consistent with MSE measurements over most of plasma



- **Time-dependence indicates simulated evolution in substantial agreement with experiment**
- **Discrepancy at large radii due to:**
  - » Toroidal rotation effects in MSE data - synthetic data has diamagnetic E_r but toroidal rotation E_r not yet included
  - » Profile fits in pedestal region
- **Tan#7 and Rad#30 view same R but toroidal rotation effects different**

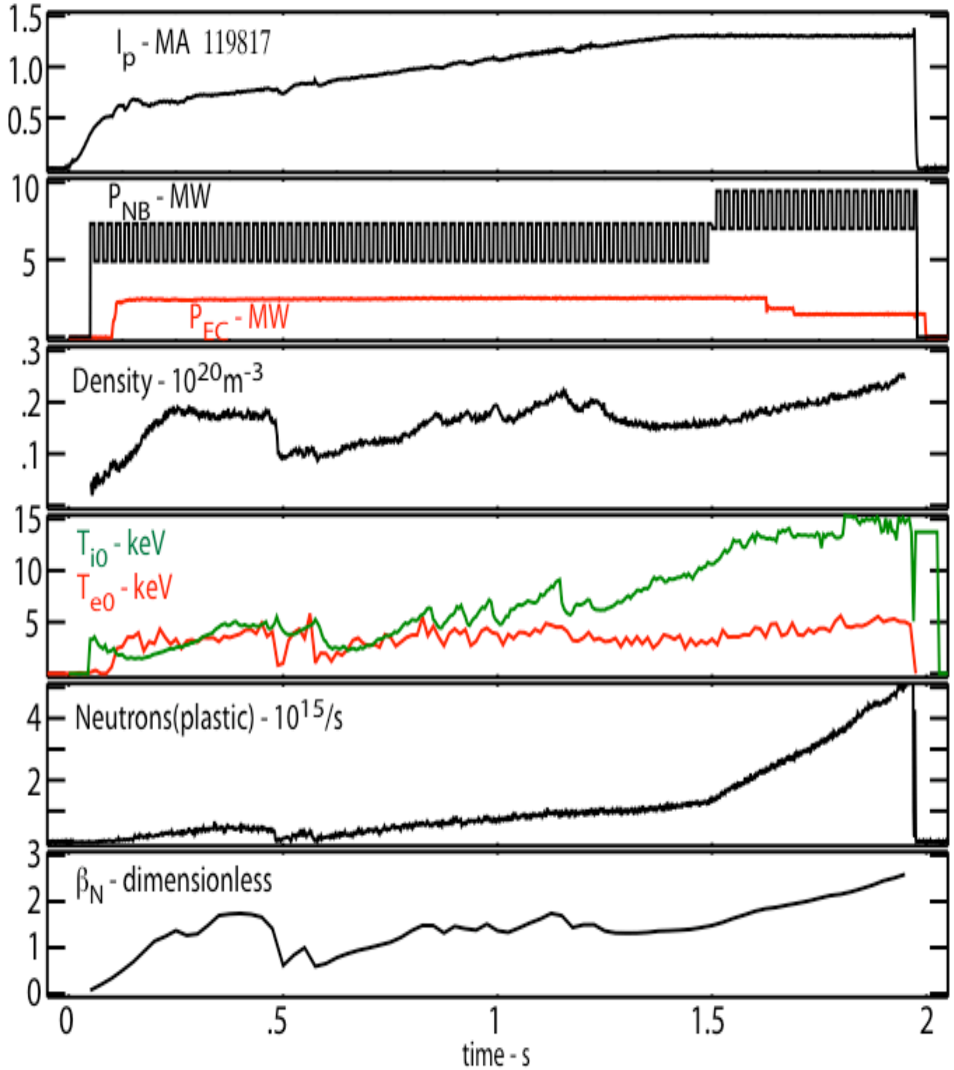


MSE data
<MSE>
<MSE>+/-σ
Simulation

Hyper-resistive modeling of a DIII-D hybrid mode is consistent with the observed evolution

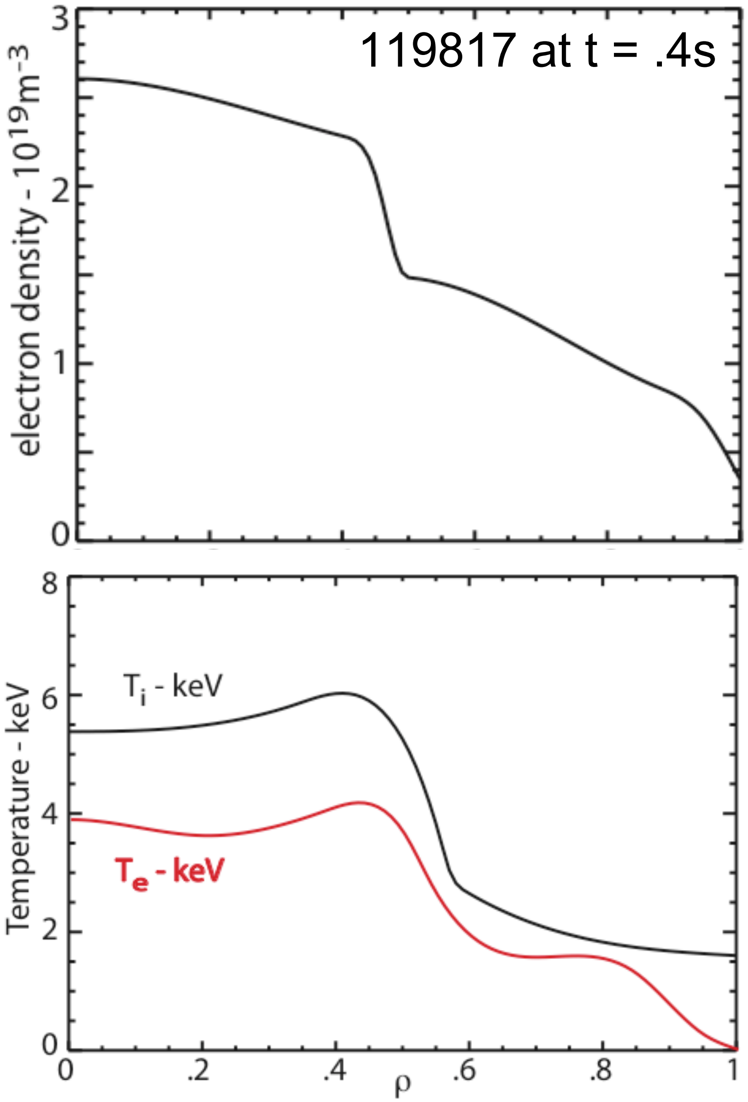
- **Current diffusion from the unstable NTM-drive in the BFLP HR model is sufficiently strong to alter the q-profile evolution for DIII-D parameters - potential to lead to a general model for hybrid modes**
- **Hyper-resistively modified current-profile evolution is consistent with the motional Stark effect measurements**
- **NTM hyper-resistivity alters the current density from just outside the unstable island location to the magnetic axis**
- **Coupling to a 2nd HR model near the magnetic axis is required to achieve the steady q profile conditions when q_0,q_{min} drop to near 1**
  - » The WJ-model used depends on a q=1 resonance to flatten the q-profile near the axis by altering the poloidal, toroidal flux distribution
  - » Future work will explore multiple NTM modes and/or alternative models
- **The BFLP and WJ models couple through the time-dependent equilibrium evolution**
  - » The BFLP limits the radial extent of the WJ activity
  - » The WJ activity couples back to the BFLP by altering NTM stability

Current holes (CH) created with fast current ramps conducive to negative central shear (NCS) formation



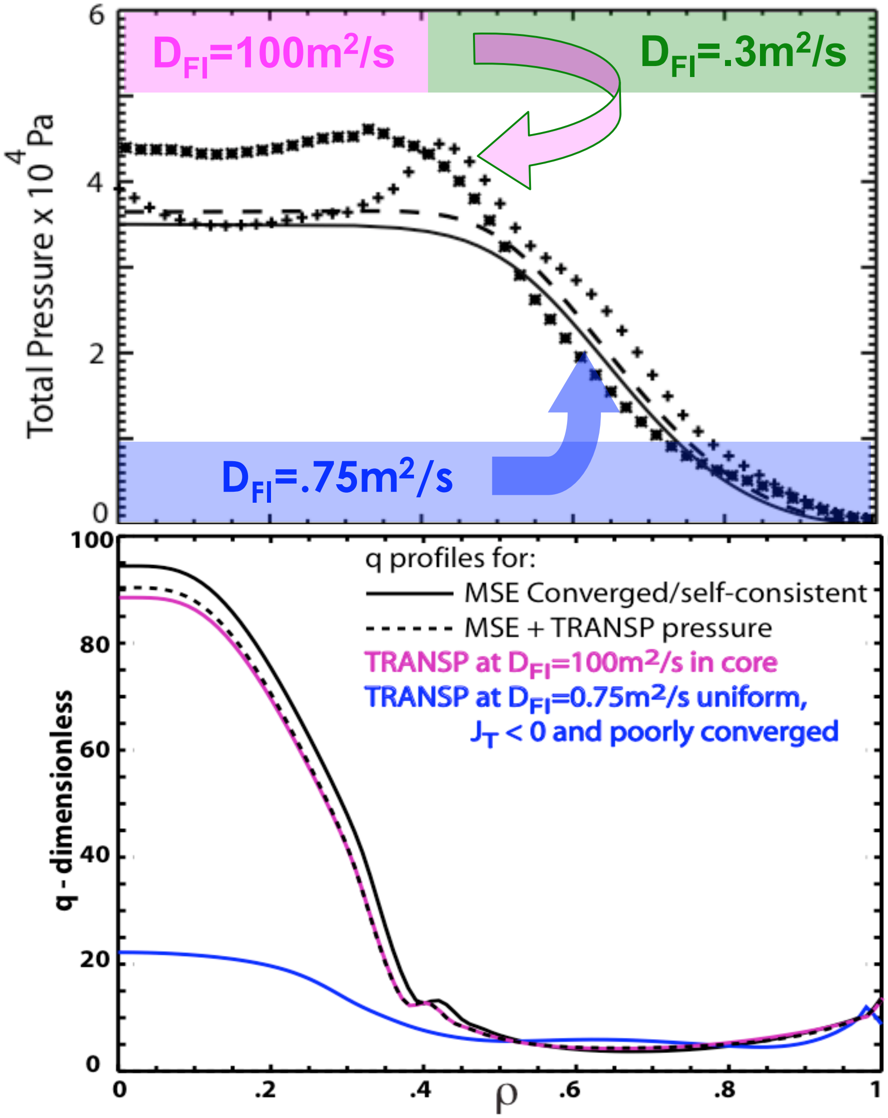
- **Parameters for DIII-D shot 119817 used to explore CH formation and evolution**
  - » High-temperature core, T_e ~ 4keV, slows flux diffusion
  - » Back-EMF from non-inductive current drive further reduces current near axis
- **Maximum current hole width obtained in DIII-D is D_{Hole}=.5m (~half plasma diameter)**
- **Narrower CH-plasmas have been sustained for up to 2.5 s in a six-second long discharge**
  - » ~ current relaxation time
  - » ~ 20 energy-confinement times

CH discharges with NCS tend to form internal transport barriers (ITB) that drive self-organization in the hole



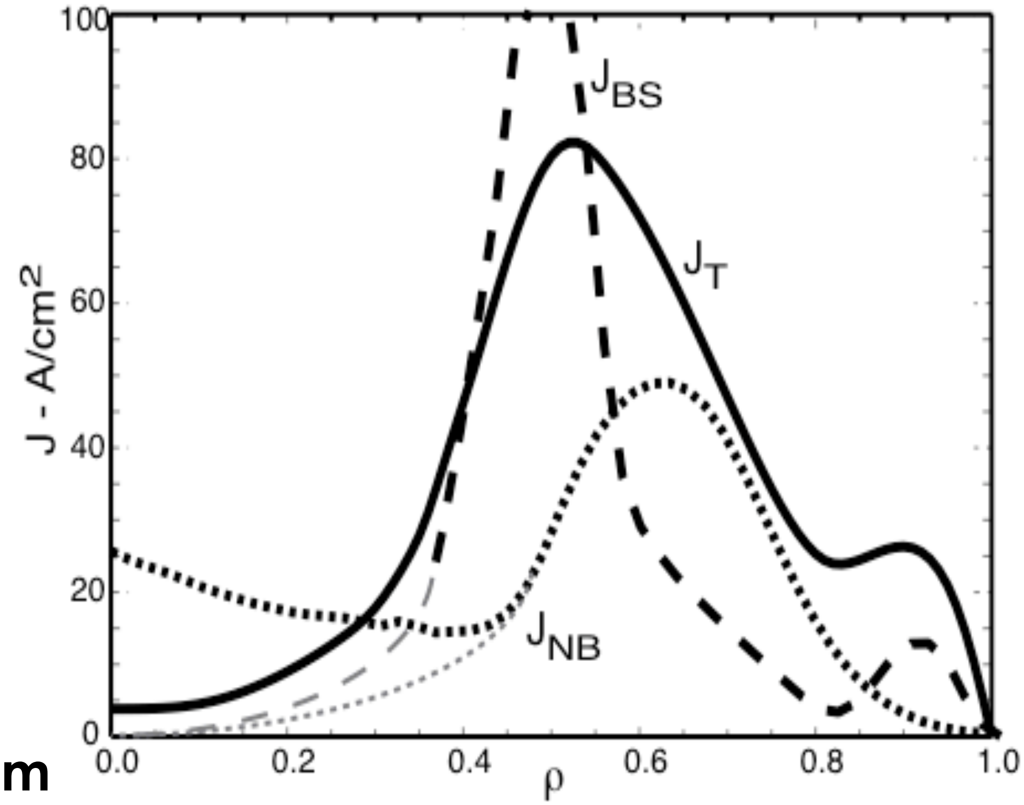
- **B_P~ 0 in core results in flat profiles due to large transport (low confining field in core)**
- **Sharp gradients at edge of hole drive large J_{BS} and good global confinement**
- **Strong NCS consistent with rise of fast-ion instabilities**
  - » Diffuse the fast injected ions
  - » Reinforce steep gradients
- **CH plasma relies on self-organization: self-consistent current, temperature and density profiles that sustain the hole**

Careful equilibrium reconstruction required indicates the the presence of fast-ion diffusion in the core



- ——— **EFIT constrained by MSE and external magnetics**
- **TRANSP-based kinetic equilibria**
  - » * * * Uniform fast-ion diffusion at $D_{FI}=.75m^2/s$ agrees with measured neutron rate but poorly converged
  - » + + + "Very large" D_{FI} in core ~ low χ^2
    - › consistent with neutron rate
    - › maximum pressure for J_{Hole} > 0.
- - - - - **Final, self-consistent EFIT with MSE and large core D_{FI}**
  - » Both MSE and external magnetic measurements are required
  - » Pressure profile from TRANSP
  - » Fit constraints optimized to give best convergence and fit to data

Current distribution consistent with CH equilibrium indicates roles of steep gradients and fast-ion diffusion



- Current profiles for 119817 obtained from TRANSP code.
- Neoclassical package in TRANSP not valid* for low Bp inside the hole.
- Neutral-beam current is also expected to be much lower than calculated by TRANSP.
- Extrapolations of J_{BS} and J_{NB} consistent with final equilibrium are shown in grey - required to keep $J_{OH} \geq 0$ inside the hole
- Current-drive formation is dependent on the self-organization of profiles inside the hole.

* BERGMANN, A., et al., Nucl. Fusion **45** (2005) 1255

Self-organization effects are consistent with the formation and sustaining of current-hole plasmas

- **Self-organization mechanism gives $J_T \sim 0$ inside the CH:**
  - Electron core heating to slow flux diffusion and minimize core J_{OH}
  - NCS creates transport barrier that provides large J_{BS} at edge of the hole
  - Lack of poloidal flux inside the hole results in flat profiles due to poor local confinement and thus J_{BS}~0 inside the hole
  - Equilibrium consistent with strong fast-ion re-distribution results in low J_{NB} in the core and maintains the low pressure gradient
- **Detailed modeling is required to get good equilibria**
  - self-consistent with the neutron flux
  - providing best convergence
  - fit to the measurements, core MSE and edge magnetics
- **Models for both neoclassical bootstrap current and neutral-beam current drive inside the hole require modification due to effects of the low poloidal field**