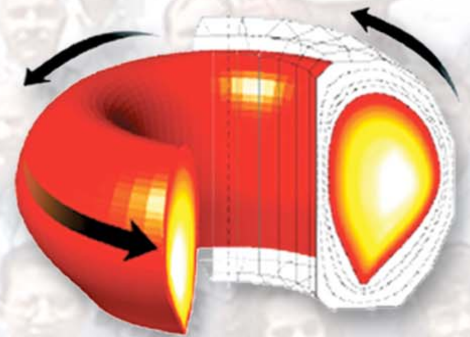
Theory Highlights

by
V.S. Chan



Presented to
DIII–D Program
Advisory Committee

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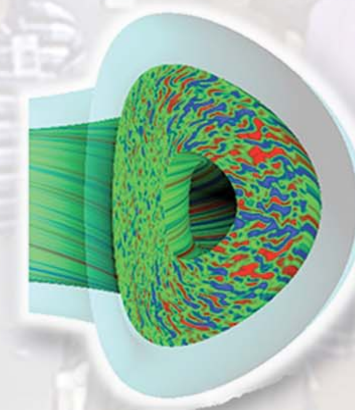


Unraveling the Mysteries in DIII-D Experiments

(1) What causes transport profile corrugations at the minimum q of an NCS plasma?

(2) Why is the sawtooth suppressed in hybrid-mode?

(3) Why does QH-mode have edge harmonic oscillations instead of ELMs?

(4) Does fast wave absorption in beam-heated plasmas weaken significantly with increasing ion-cyclotron harmonics?

(1) Gyrokinetic Simulations Observed Profile Corrugations at Minimum-q of NCS Plasmas

- **The most unexpected result of GYRO simulations has been that plasma equilibrium profiles are not smooth, but develop radial "profile corrugations" at low order rational surfaces like 3/2, 2/1,5/2,3/1.**

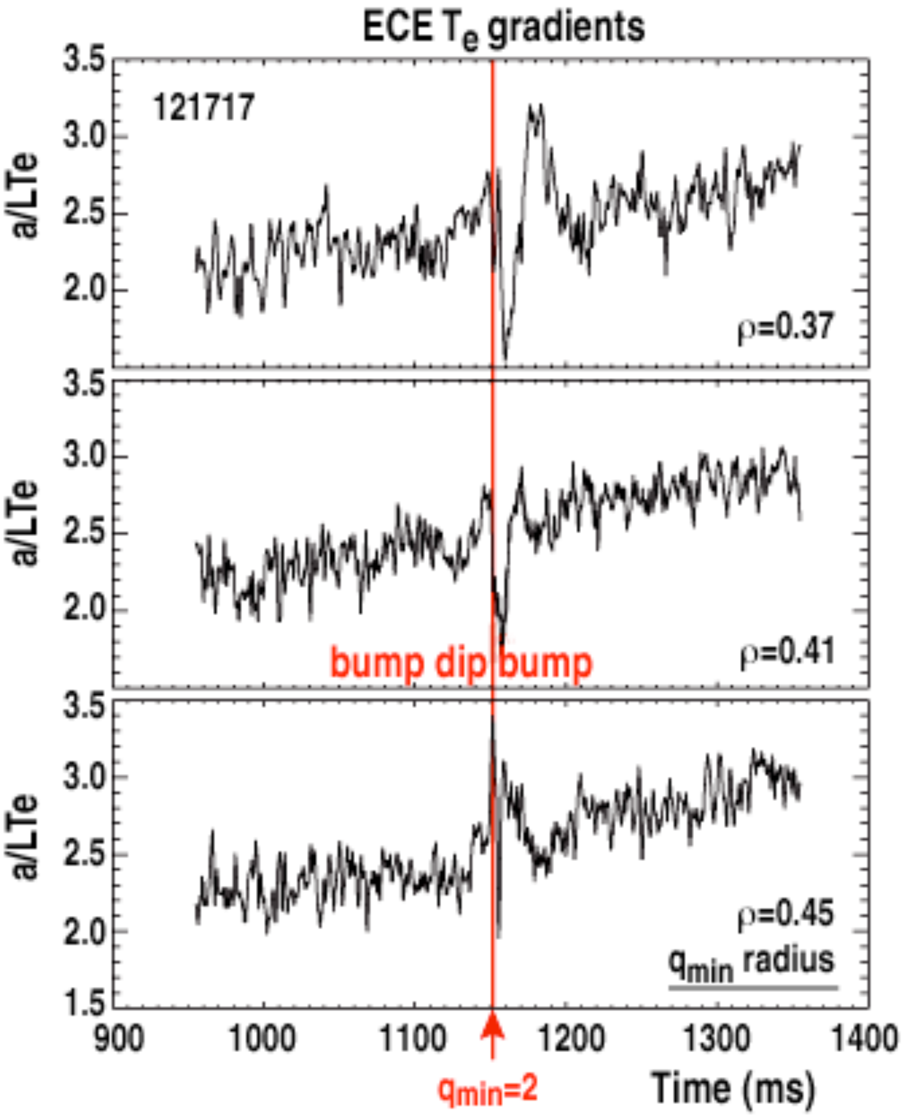
- **The corrugations are on the scale of a few ion gyroradius and most pronounced for electron temperature gradient**

- **The corrugations in GYRO are time and flux surface averages of zonal flows.**

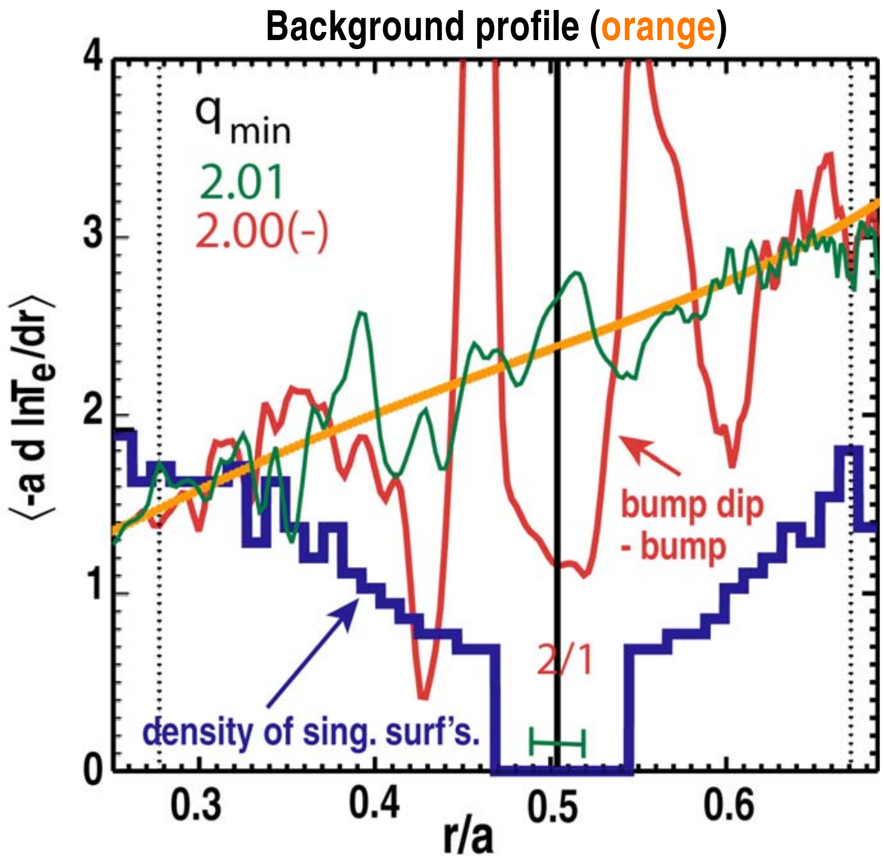
- **The corrugations are small in monotonic - q profiles, but expected to be large in minimum-q (NCS) discharges just as the q-min = 2 surface enters the plasma.**

- **The corrugations have now been seen in DIII-D matching the expected "bump-dip-bump" structure. As such, *this constitutes an indirect measurement of zonal flow and confirms the physical reality of the GYRO profile corrugations*.**

(1) Corrugations Observed at q_{min}=2 are Correlated with Low Singular Surface Density

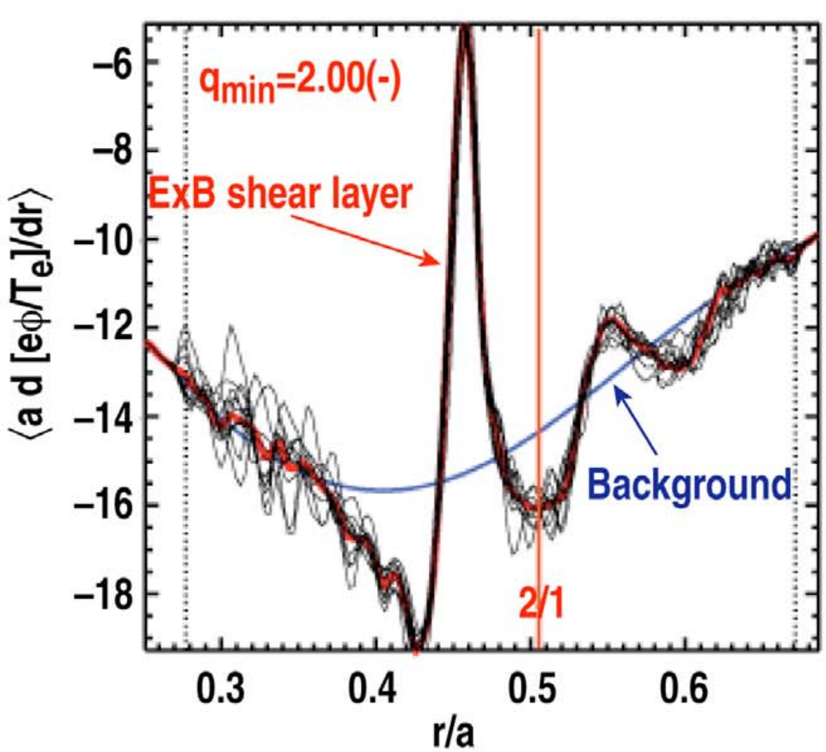


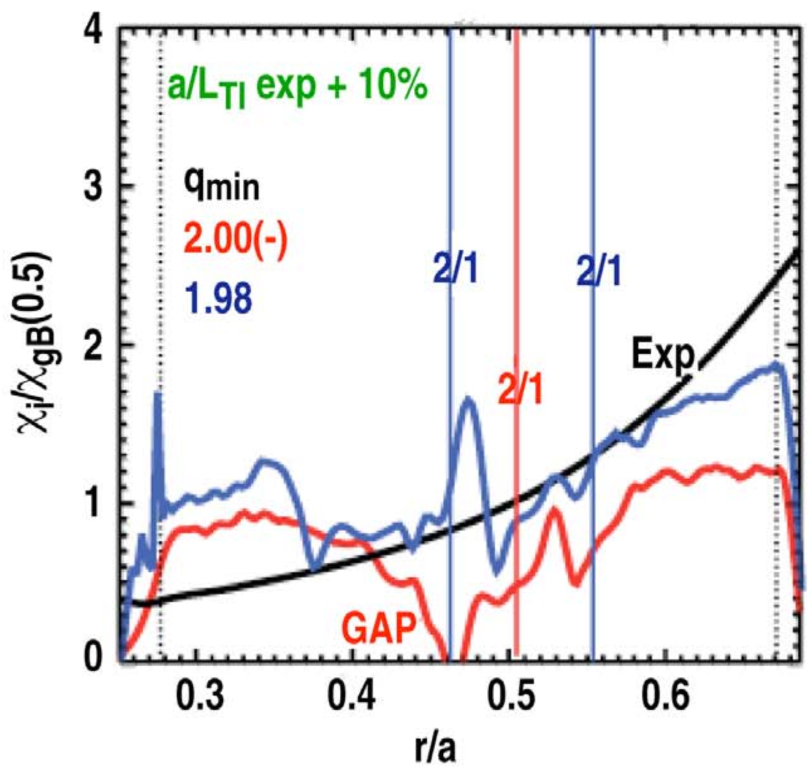
GYRO simulation of ECE a/L_{Te} time trace (zonal flow) has same bump-dip-bump structure at q-min=2.00(-) (RED) but none before at q-min=2.01 (GREEN)



(1) Corresponding Transport Reduction May Trigger ITB Formation

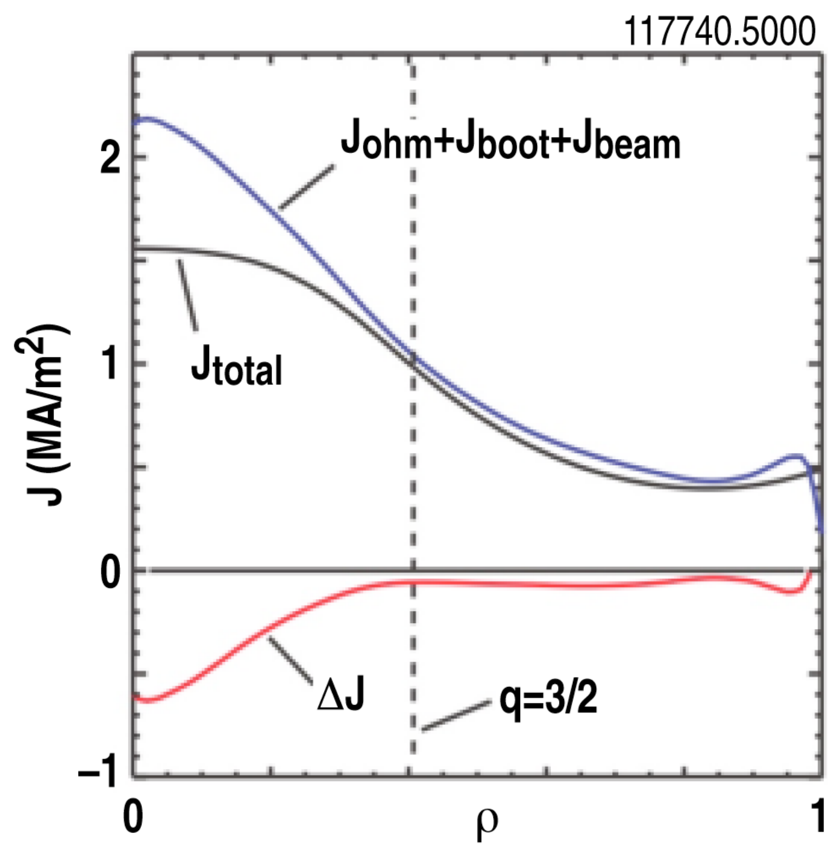
- GYRO simulations are consistent with q-min=2/1 profile corrugation (RED) triggering ITB in ion channel.
- A strong ExB shear layer (lower left) develops at r/a=0.46 making a "gap" in transport power outflow (lower right RED) allowing interior radii to heat up from deposited power.
- As usual GYRO can match DIII-D experimental transport power flow with 10% adjustments in the ion temperature gradient.



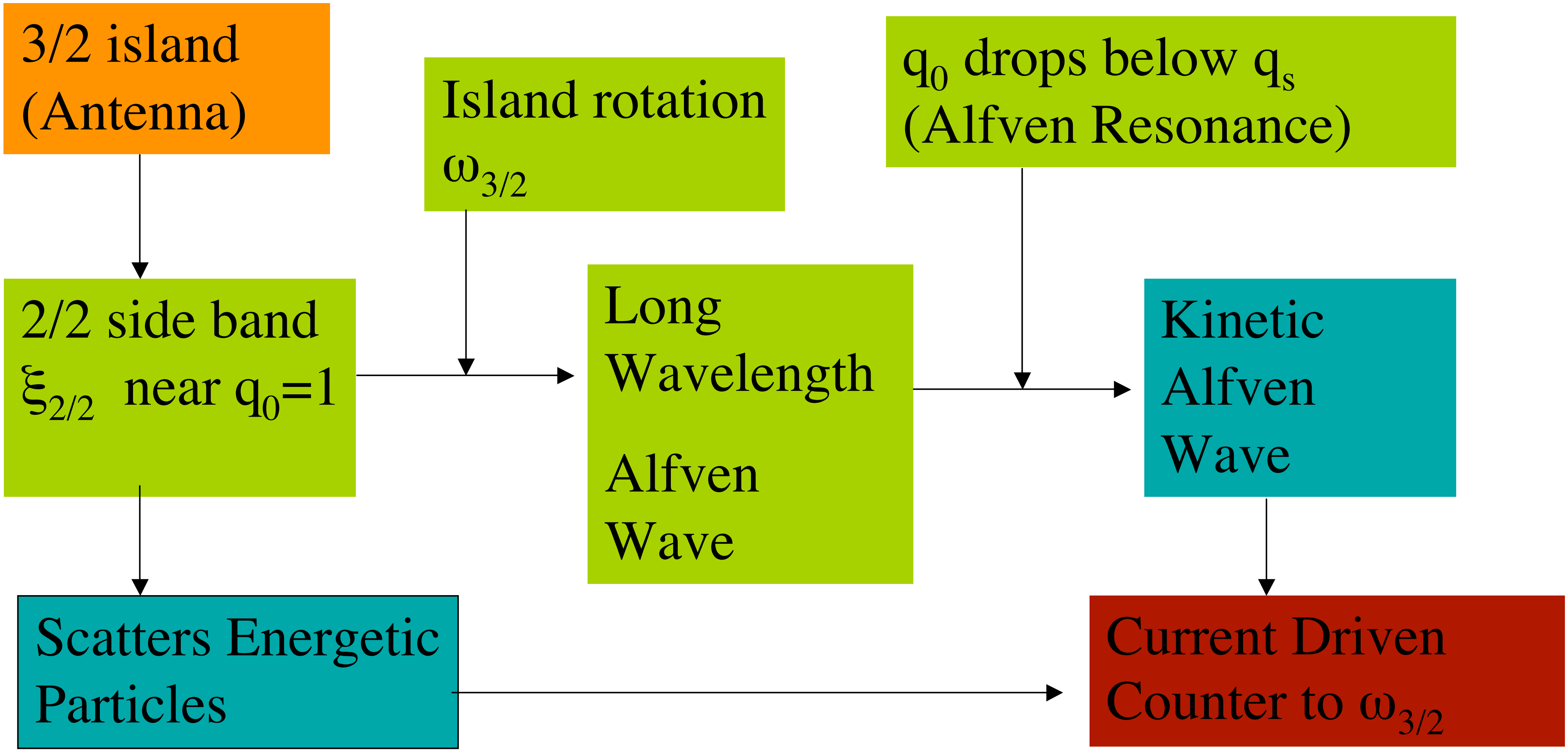


(2) The HYBRID Discharge in DIII-D Has Rotating 3/2 Magnetic Island without Sawteeth

- **Presence of 3/2 magnetic island correlates with absence of sawteeth**
- **Two complementary mechanisms on possible role of 3/2 in sawteeth prevention examined**
- **Rotating 3/2 excites near 2/2 near center which mode converts into kinetic Alfven wave to drive counter current. Operative transiently when central q drops close to 1**
- **3/2 perturbation initiates anomalous transport of energetic ions, reduces central NBI current drive efficiency, less effect on neutron rate**
- **Scaling of the sawteeth prevention to ITER depends on understanding the phenomenon in DIII–D**



(2) Physical Processes in ‘Counter Current Drive’ by the 3/2 Island



(2) Estimate of Total Driven Current is within Range of Experiment

$$I = \pi \kappa r_s^2 J$$

$$J = J_{MHD} f_\perp f_\parallel$$

$$f_\perp = \left(\frac{\rho_i \dfrac{dq}{dr}}{\left(\dfrac{T_e}{T_i} + \dfrac{3}{4}\right) \dfrac{\omega_{3/2}^i}{2n\omega_A}} \right)^{4/3} \left(\frac{T_e}{T_i}\right)^2$$

$$I \propto \frac{\omega_{3/2}^{i,5/3} B^2 \xi_\psi^2}{n^{2/3}} \left(\frac{r_s}{r_{3/2}}\right)^{8/3} \frac{T^{2/3} r_s^{8/3}}{R^{4/3} \rho_m^{2/3}}$$

$$J_{MHD} = \frac{\sqrt{2}\pi^{3/2} \varepsilon_0^2}{e \ln \Lambda} \left[\frac{\omega_{3/2}^{i,3} B^2 \xi_\psi^2}{k_\perp^2} \right]$$

$$f_\parallel = \left| 1 + \frac{\omega_a^e}{\sqrt{2}} Z\left(\frac{\omega_a^e}{\sqrt{2}}\right) \right|^{(-2)} \exp\left(-\frac{\omega_a^{e,2}}{2}\right) (8 + 2\omega_a^e + 1.4\omega_a^{e,3})$$

Numerical Example For DIII-D:

$T_e = 4(kev)$, $T_i = 7(kev)$, $B = 1.7(T)$, $\rho_i = 0.4(cm)$, $\ln \Lambda = 16.7$,

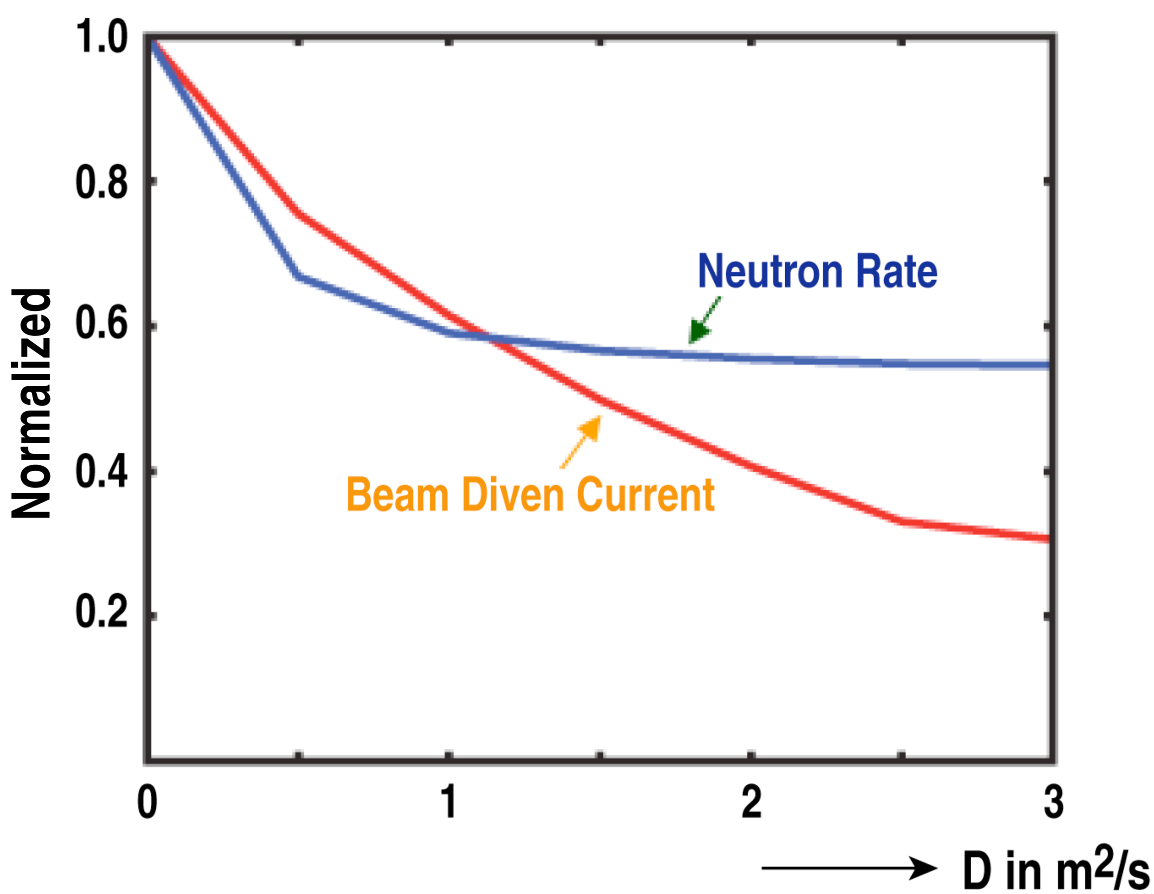
$\omega_{3/2}^i = 1.5 \times 10^4 (rad/s)$, $\omega_{3/2}^e = 4.5 \times 10^4 (rad/s)$, $\omega_A = 2. \times 10^6 (rad/s)$,

$\xi_\psi = r_s/2$, $r_s = 10(cm)$, $r_{3/2} = 30(cm)$, $\kappa = 1.6$, $n = 2$, Parabolic q profile

$J_{MHD} = 4.48 \times 10^4 (Amp/m^2)$, $f_\perp = 1.22$, $f_\parallel = 10$,

$J = 5.48 \times 10^5\ (Amp/m^2) \simeq \Delta J_{EXP}(0)$, $I = 2.75 \times 10^4\ (Amp)$

(2) Additional Anomalous Transport of Beam Ions Adds to the Robustness of the Scenario



- **ONETWO transport simulation with NuBeam Package DIII–D Shot 117740**
  - Beam deposition profile broadened by anomalous transport
  - Need to quantify anomalous transport as due to MHD modes

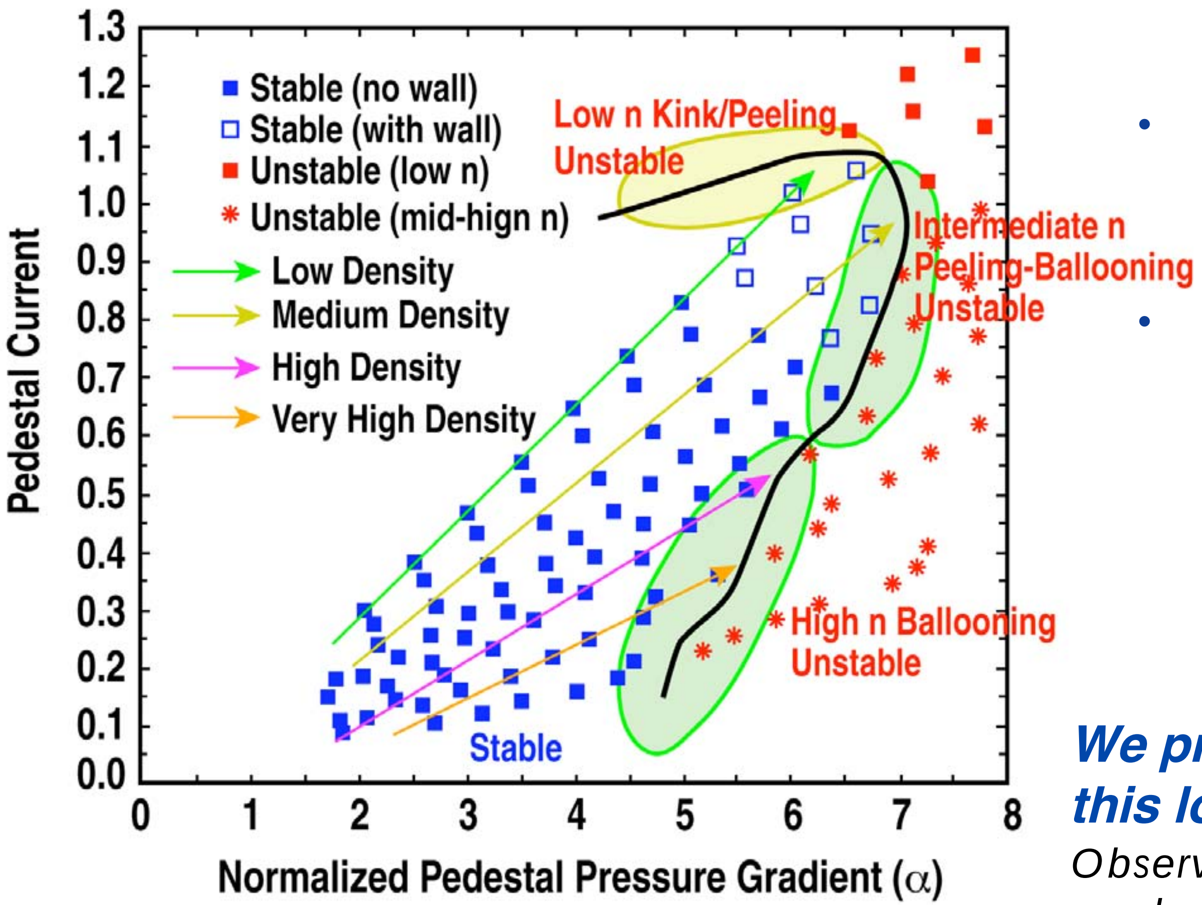
Total beam driven current depends more sensitively on the assumed anomalous transport of the energetic ions than the neutron rate

(3) ELM-free QH & RMP Share Similar Physics

- **Peeling-ballooning model has achieved a degree of success in explaining pedestal constraints, ELM onset and a number of ELM characteristics**
  - Nonlinear explosive growth of one or many filaments, similar to observations
  - Two prong model (conduits and barrier collapse) for ELM losses
- **Propose: QH exists in low-n kink/peeling limited regime**
  - Very low density required with moderate shaping, higher density and pressure possible with strong shaping
    - Agreement with observed QH density range
    - ITER study suggests QH regime for n_{eped}<~4 10^{19} cm^{-3}
- **Flow shear stabilizes edge-localized RWM (and higher *n ballooning*), leaves low-*n* rotationally destabilized kink/peeling mode most unstable**
  - With kinetic corrections, this is the EHO
  - Saturates by damping rotation and providing particle transport
    - Essentially steady state operation in the key edge transport channels
- **Low density RMP ELM free discharges in similar regime**
  - Propose that RMP is playing the role of the EHO -> Controllable, can exist near or well below stability bound

(3) New Theory of ELM-free Operation (QH & RMP) is Based on stability with rotation in low ν^* regime

- **QH mode operation generally requires *strong counter rotation* in the pedestal region and *low density***



Effect of Low Density

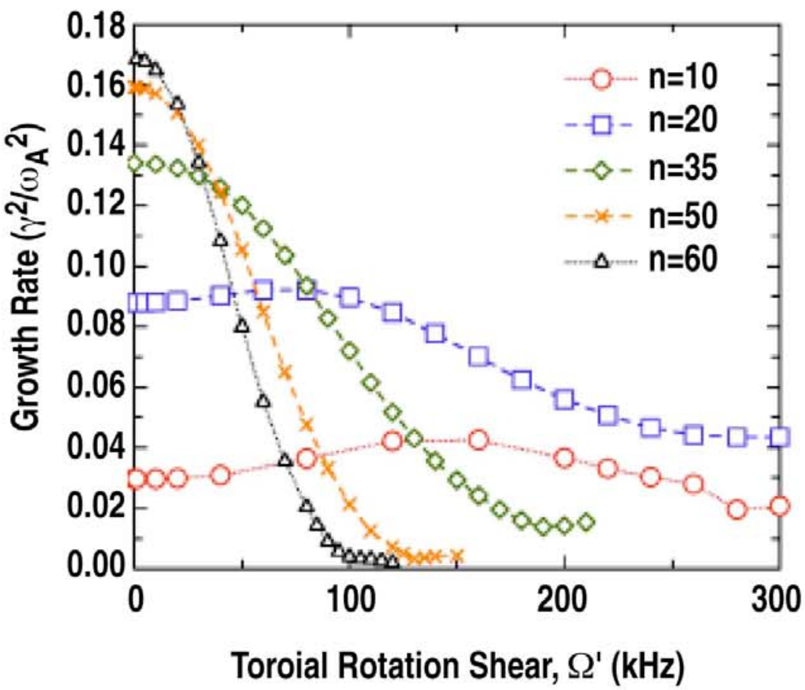
- **The pedestal current is dominated by bootstrap current**
  - Roughly proportional to p'
  - Decreases with collisionality
- **Lower density means more current at a given p'**
  - Moderate to high density discharges limited by P-B or ballooning modes -> ELMs
  - Very low density discharges may hit kink/peeling boundary

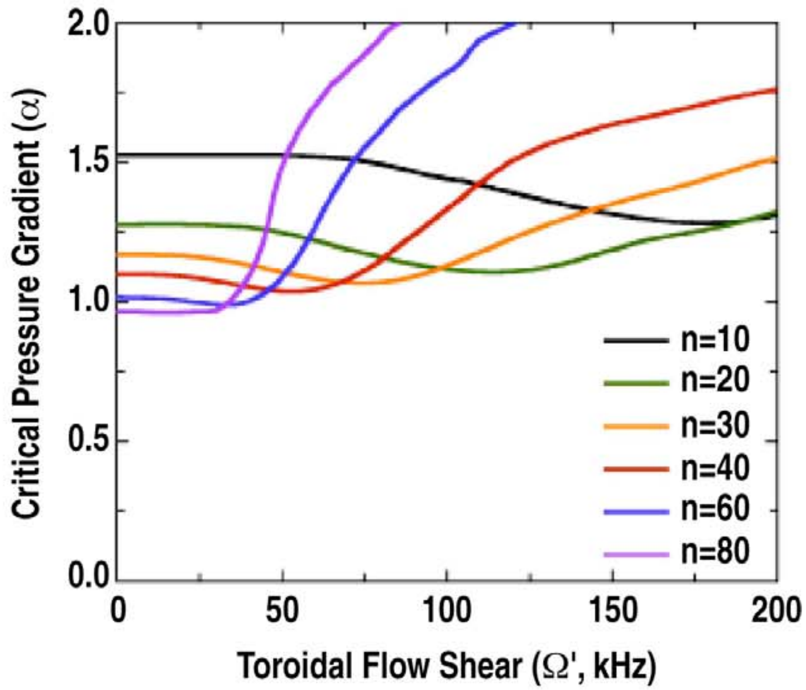
We propose that QH mode exists in this low n limited regime

Observed density requirement for QH, EHO mode structure, and profiles agree with predictions [West 05, Burrell 05]

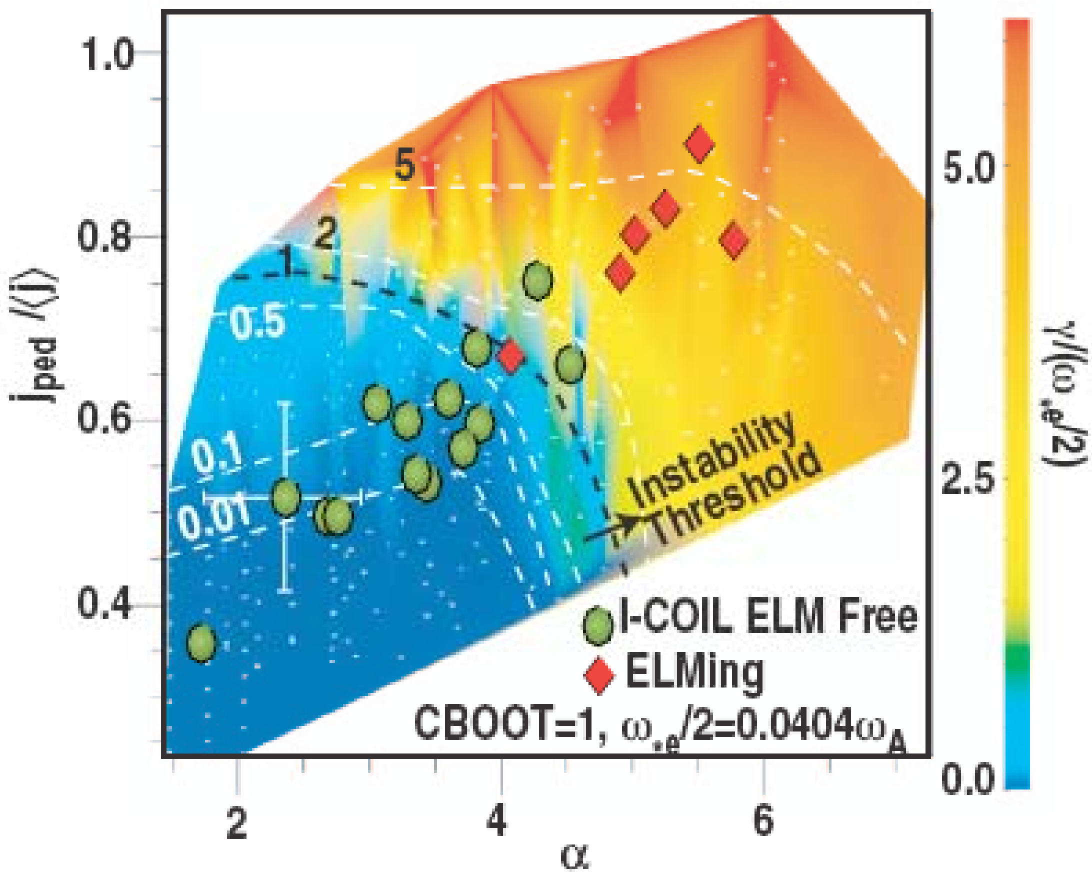
(3) Strong Toroidal Flow Shear in the Edge Region Stabilizes ELMs and Destabilizes Peeling-Kink (EHO) Modes

- **Eigenvalue formulation with rotation and compression derived and included in ELITE**
- **Sheared flow stabilizes "ELRWM" (Edge Localized RWM branch)**
  - Allows plasma to reach ~ideal boundary, trigger rotating low-n mode
- **Sheared flow strongly damps high n, destabilizing at low-n**
  - Most unstable n decreases with increasing rotation
  - ***Rotationally de-stabilized low-n modes are limiting in QH regime***
    - *Modes driven by current and rotation, can saturate by damping their own drive*





(3) RMP ELM-free Discharges are in Similar Regime



- **n=3 Resonant Magnetic Perturbations used to suppress ELMs in low density discharges**
- **ELM-suppressed shots in stable region, nearest kink/peeling boundary**
  - Increasing density causes ELMs to return
- **Propose that RMP plays the role of the EHO here**
  - Particle, Te, rotation steady state
- **While EHO grows only to amplitude needed for steady state, RMP amplitude can be controlled**
  - Able to operate a factor of 2 below stability boundaries

(4) ORBIT-RF Code Includes Important Finite Orbit and RF Physics for Treatment of Non-Maxwellian Ions

- **ORBIT-RF with TORIC4 qualitatively reproduces DIII-D and C-Mod experimental results**

  DIII-D
  - **Reasonable agreement with measured neutron enhancements at $4\Omega_D$ and $8\Omega_D$**

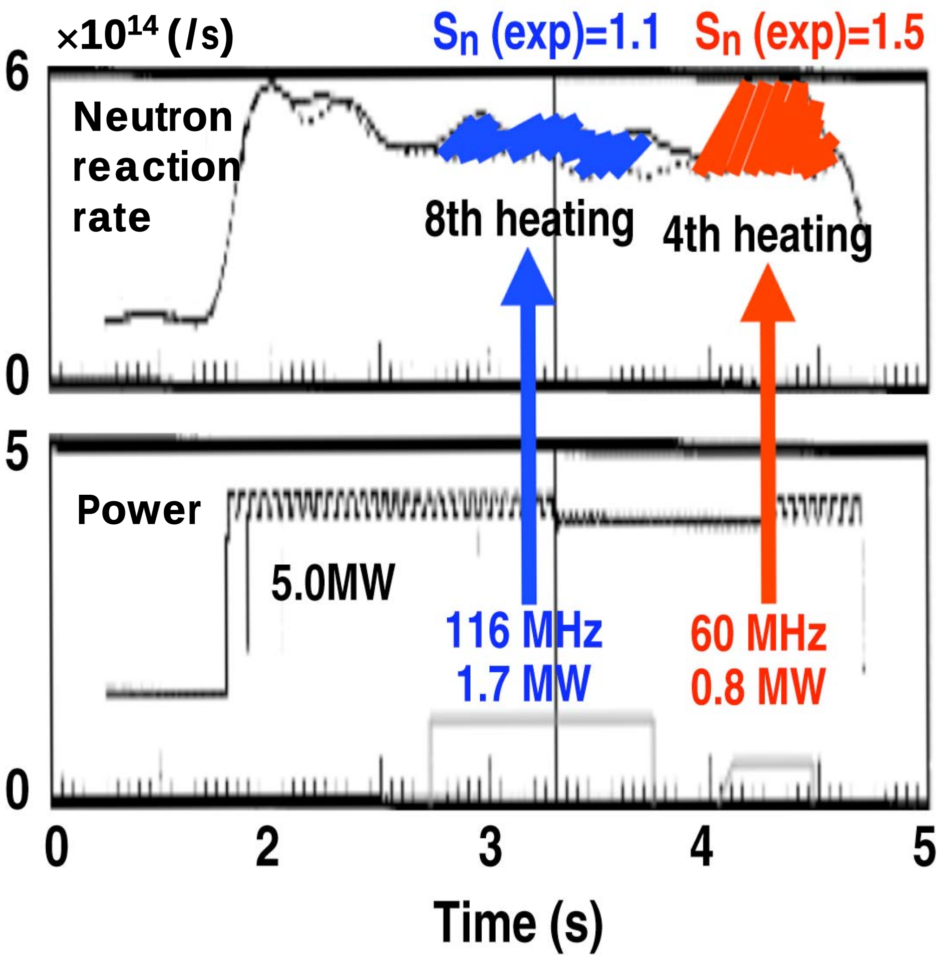
  C-Mod
  - **Good agreement with measured fast ion spectrum**

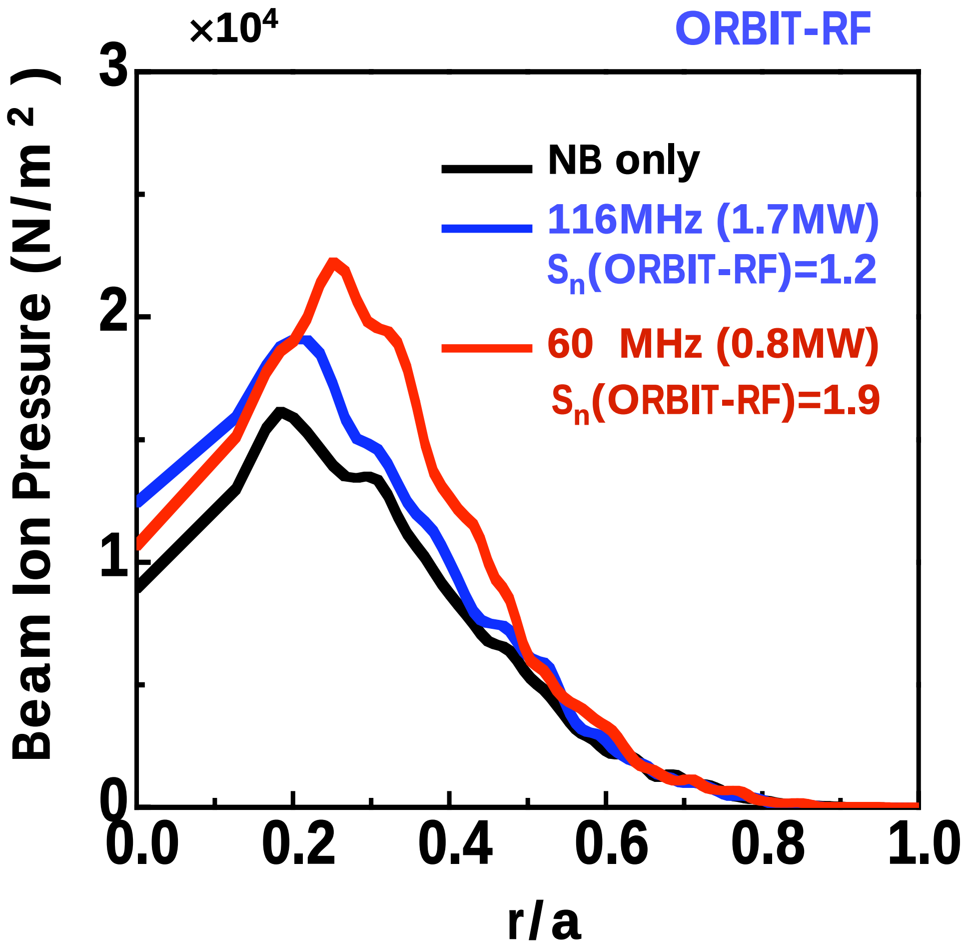
- **The details of beam distribution modified by RF and collisions are important to quantitatively evaluate beam-wave interactions**

- **ORBIT-RF prediction of wave absorption at $4\Omega_D$ and $8\Omega_D$ follows the trend of linear theory using analytical slowing down distribution function**
  - Weak absorption at $8\Omega_D$ differs from AORSA-CQL3D result which does not include finite drift orbits

(4) ORBIT-RF Reproduces Stronger Beam Interactions at $4\Omega_D$ (60 MHz) Than at $8\Omega_D$ (116 MHz) Observed in DIII–D

- **DIII–D high density L-mode**

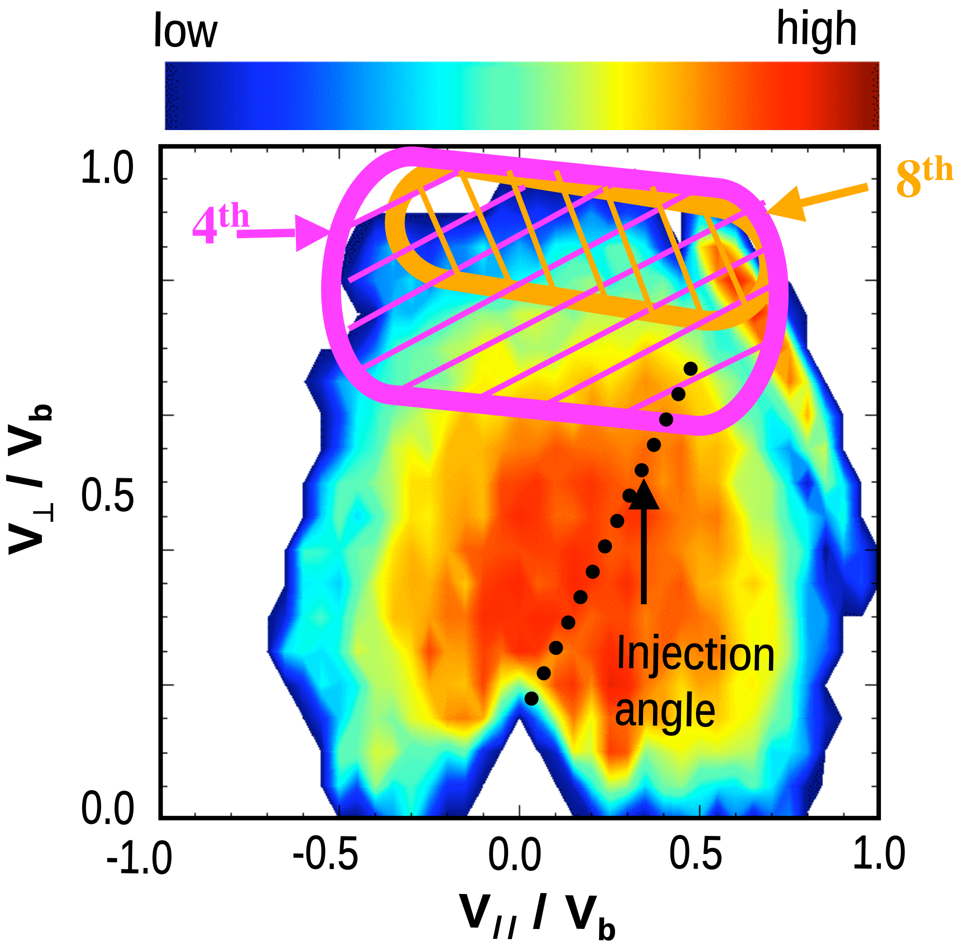




S_n: neutron enhancement factor

(4) Wave Absorption Critically Depends on the Energy and Density of Resonant Fast Ions

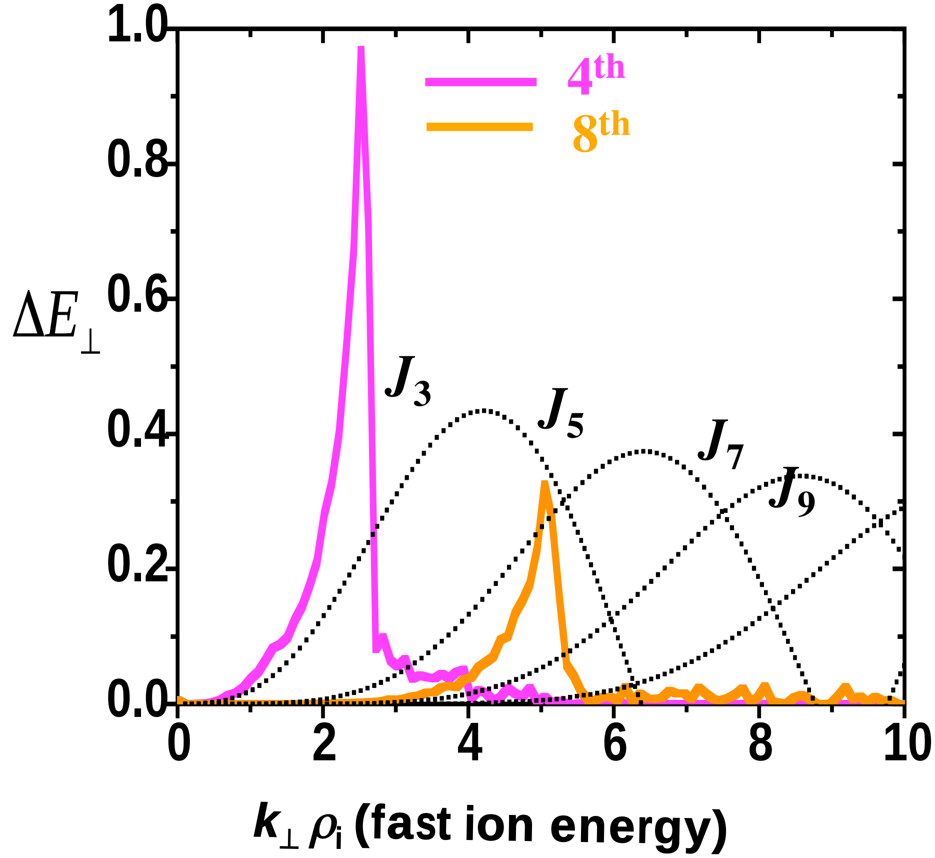
- DIII-D high density L-mode



ORBIT-RF shows 4th harmonic resonant ions occupying a larger phase space

Increase in energy of resonant ions

$$\Delta E_\perp \propto J_{l-1}, J_{l+1}$$



DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

039-06/VSC/jy

Summary

(1) What causes transport profile corrugations at the minimum q of an NCS plasma?

— The corrugations are zonal flows with strong ExB shear that may trigger ITB

(2) Why is the sawtooth suppressed in hybrid-mode?

— 3/2 tearing mode can excite KAW that transiently drives counter current on-axis

(3) Why does QH-mode have edge harmonic oscillations instead of ELMs?

— QH mode operates at low collisionality with high edge pressure gradient that drives strong rotation; ELMS are stabilized but kink-peeling modes (EHO) are destabilized by strong rotational shear

(4) Does fast wave absorption in beam-heated plasmas weaken significantly with increasing ion-cyclotron harmonics?

— 4th harmonic resonant ions have a larger phase space population than 8th harmonic ions, hence stronger FW damping