Oblique and Correlation ECE in TCV

exploring micro-instabliities and turbulent structures

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- A direct measurement of a broadened electron cyclotron driven current channel would complement hard X-ray measurements that imply a diffusion of fast particles in TCV.

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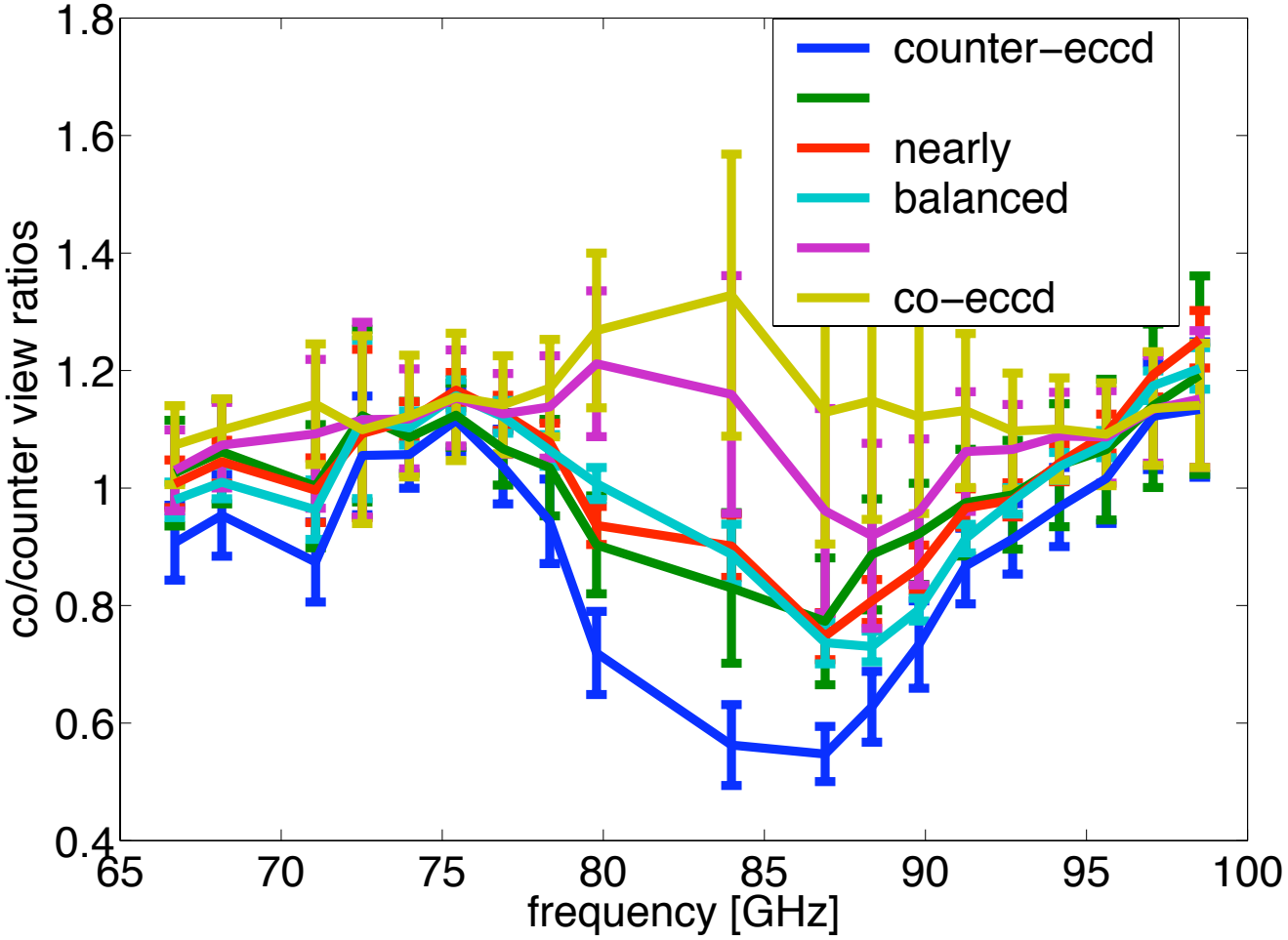
- The width of the channel may then be compared with the spreading by ad hoc diffusion needed in the Fokker-Planck code CQL3D to match the total driven current in plasmas sustained fully by ECCD.

Current channel measurement by oblique ECE

measuring the asymmetry of oblique emission during an ECCD current scan



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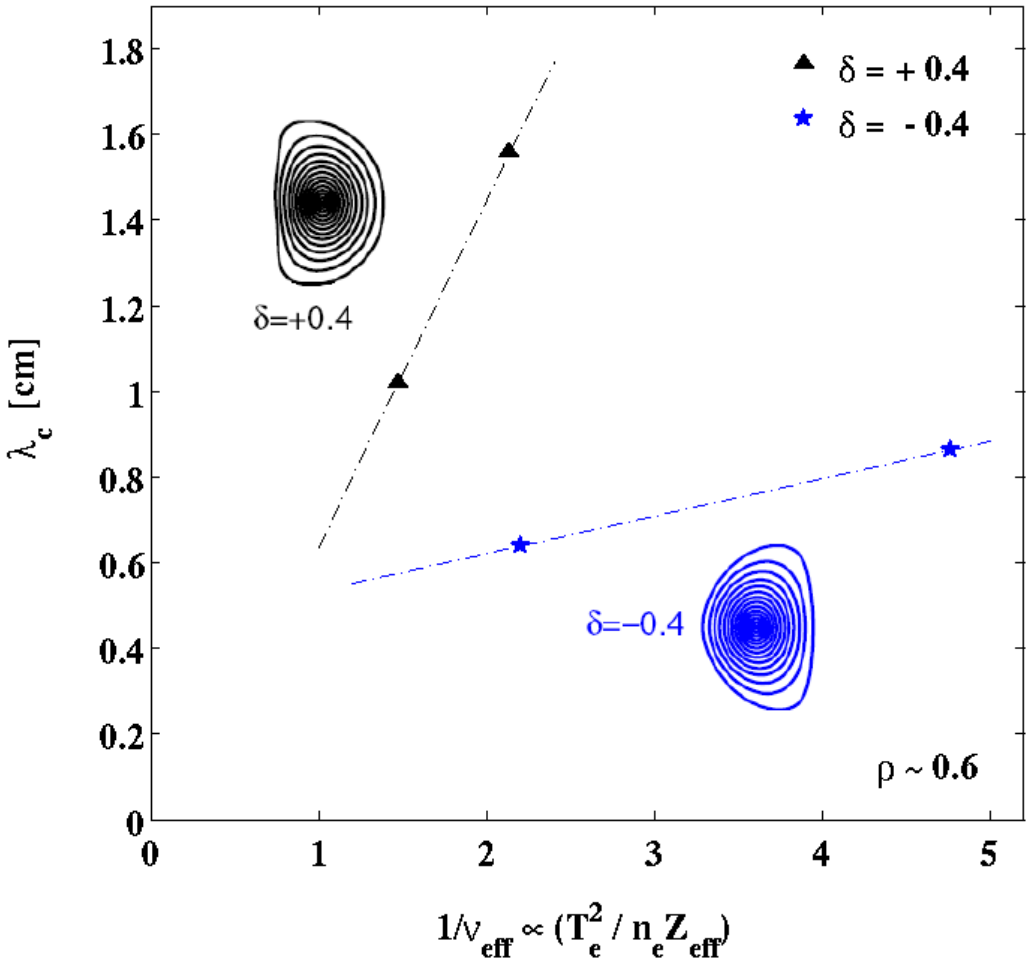
- Macroscopic structures are predicted to be the source of anomalous cross-field transport and their breakup or shrinkage by various effects is believed to be the ultimate reason behind all improved-confinement regimes.
- On TCV when the plasma triangularity is reduced drastically from positive values to negative values, the confinement is significantly improved.
- Measurements of the change in the temperature fluctuations under various plasma configurations may help illuminate the source of the improved energy confinement.

Reduction of correlation length at $\delta < 0$

λ_c dependence on collisionality is also weaker

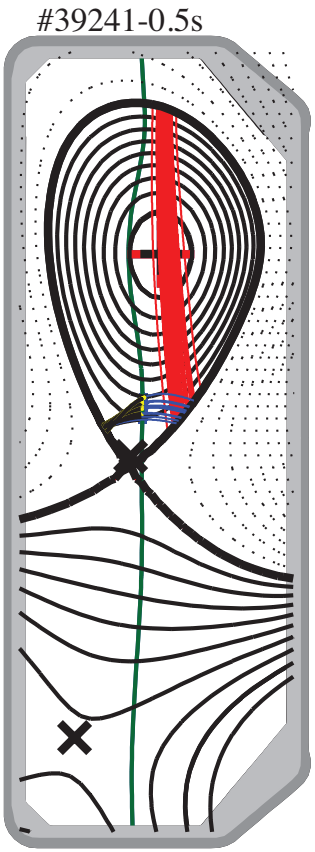


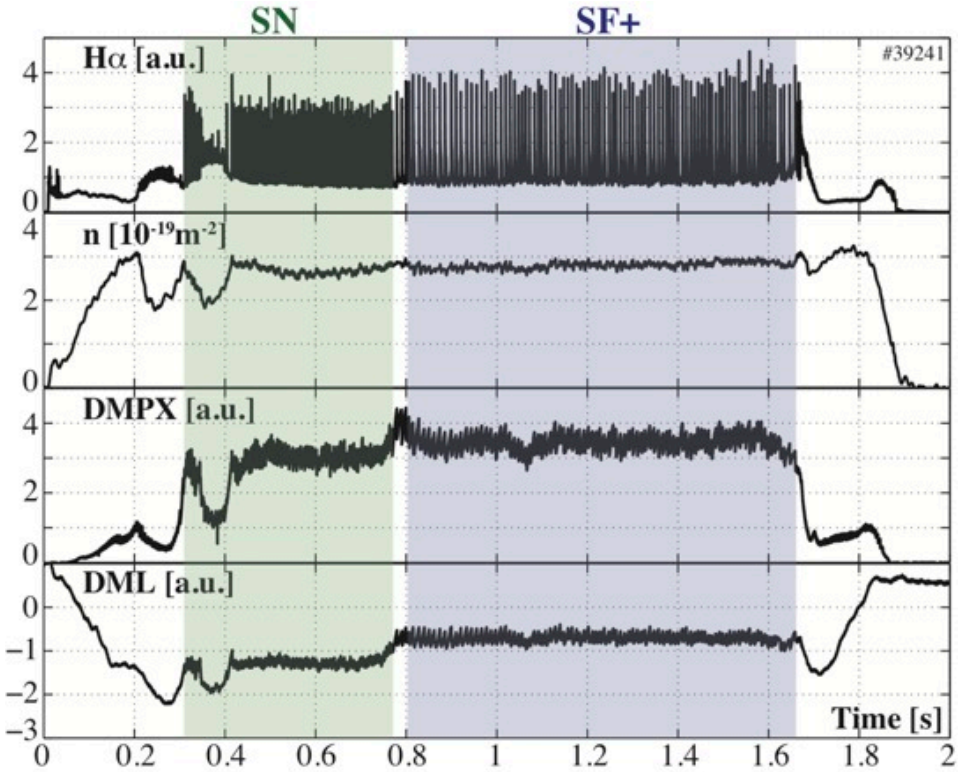
TCV
- Tokamak à Configuration Variable
- EC System

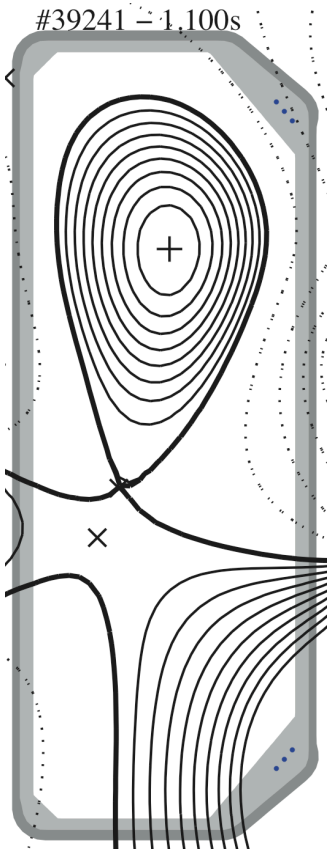
Oblique ECE
- Physics of ECCD and oblique ECE
- Oblique ECE measurments of the current channel
- Summary

Correlation ECE
- Correlation ECE measurements on TCV
- Scan of Plasma Triangularity (delta)
- Summary & Future Investigations

H-mode, Variable Shape, Snowflake Divertor Example [4]



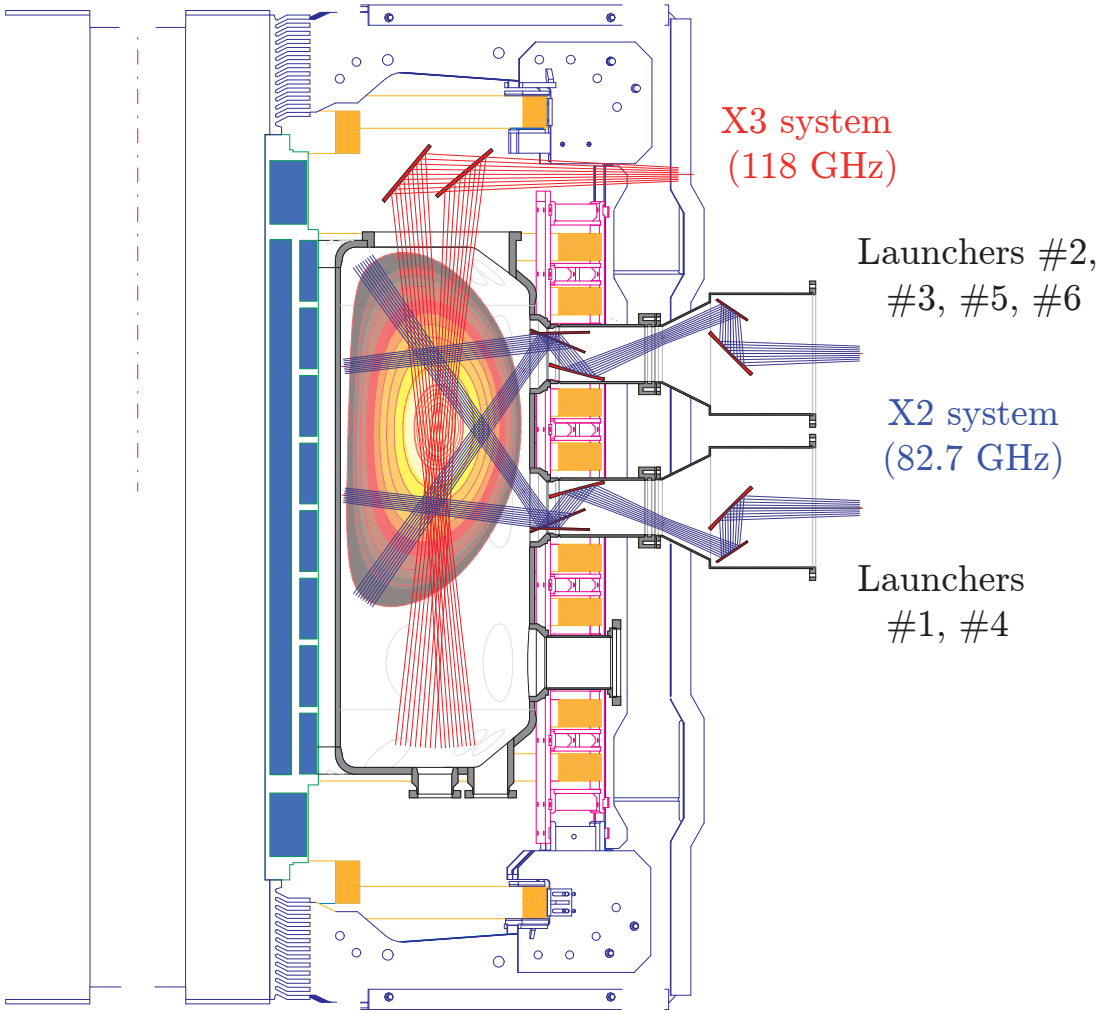


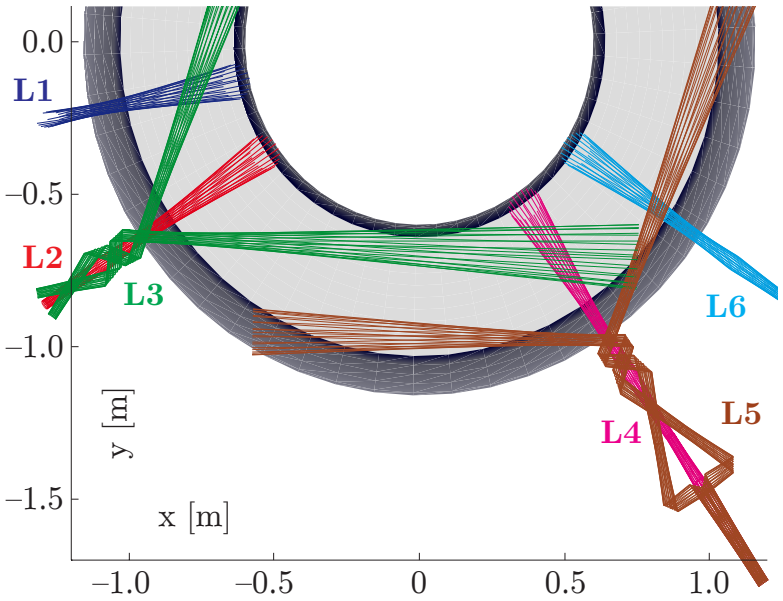


4. F. Piras, Invited Talk at EPS 2010

Plasma Coverage

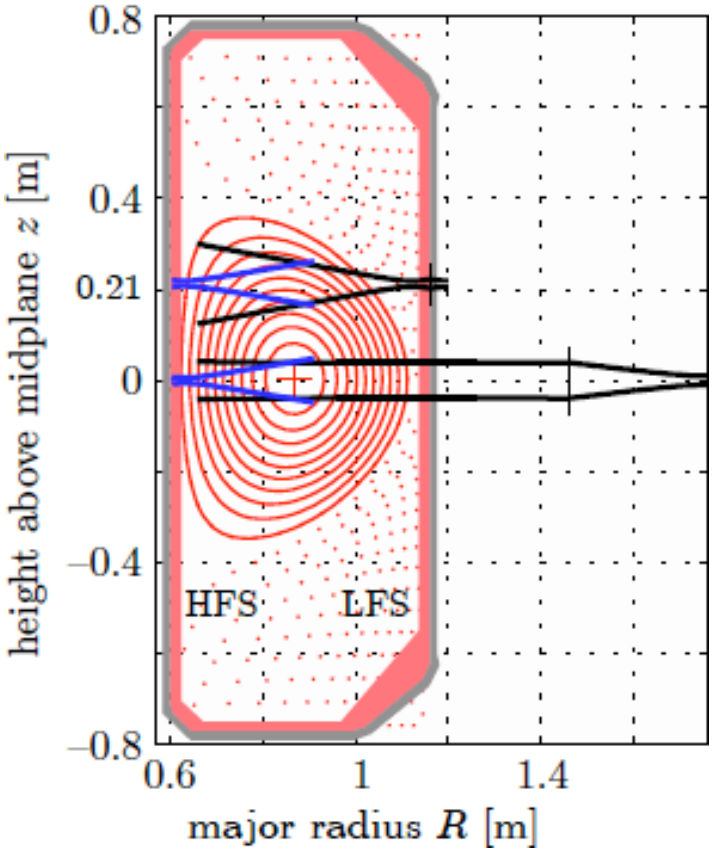
6 X2 & 1 X3 launchers



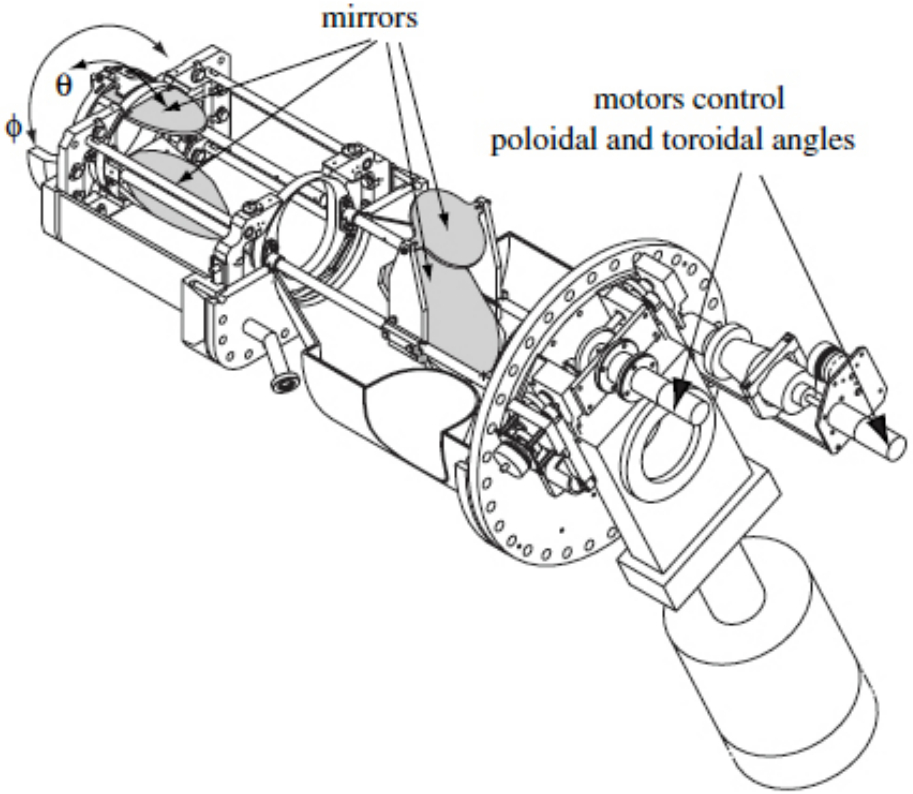


3 clusters of 1.5MW

High and Low Field Side ECE Views



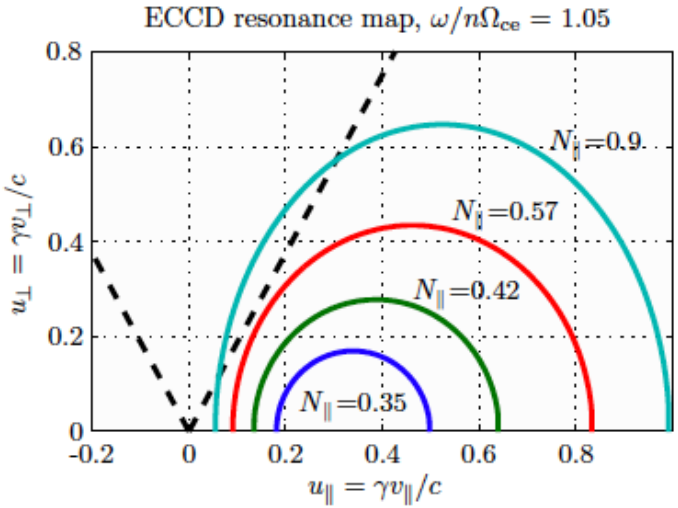
4 ⊥ antennas

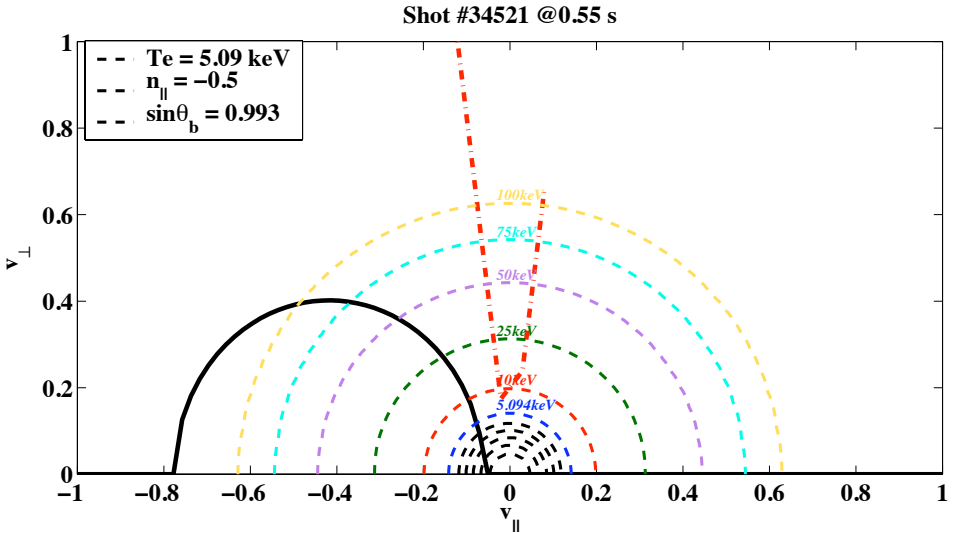


1 sweepable oblique LFS antenna (L7)

Oblique ECE

Absorption of EC waves for ECCD - *electron velocity space*

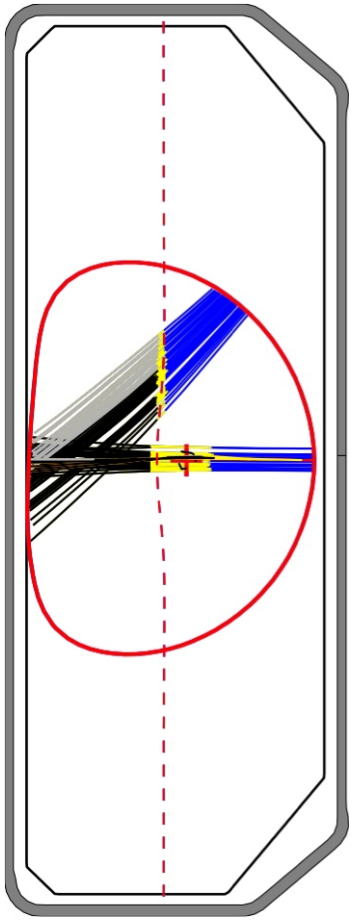




- resonant curves in velocity space depend on toroidal injection angle $\omega = \frac{n\Omega_{ce}}{\gamma - N_\parallel u_\parallel}$
- electron distribution function (EDF) is dominantly distorted to one side of $v_\parallel = 0$, providing ECCD
- co- & counter- ECCD distorts the EDF on opposite sides
- L7 measures the **asymmetry of the EDF** by comparing opposite toroidal views

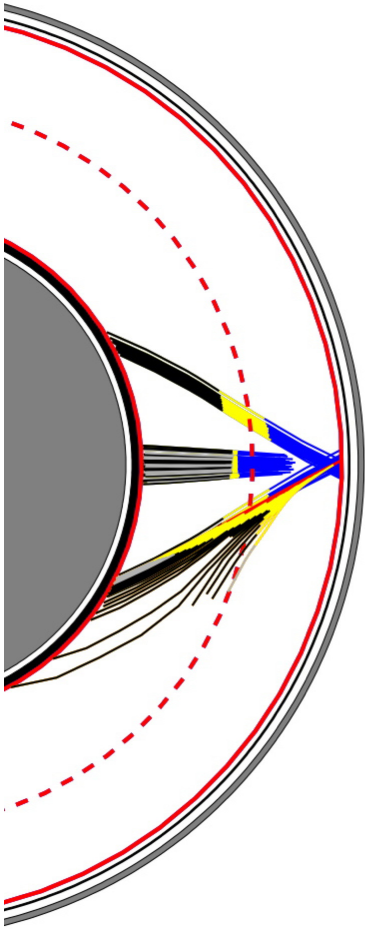
Experimental Setup

poloidal view

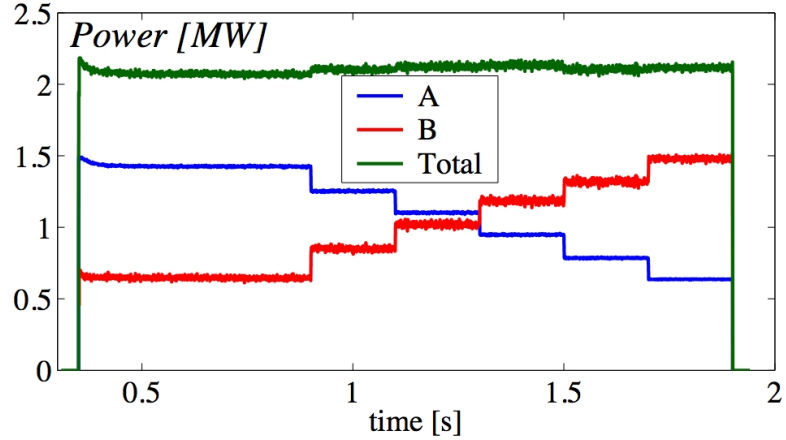


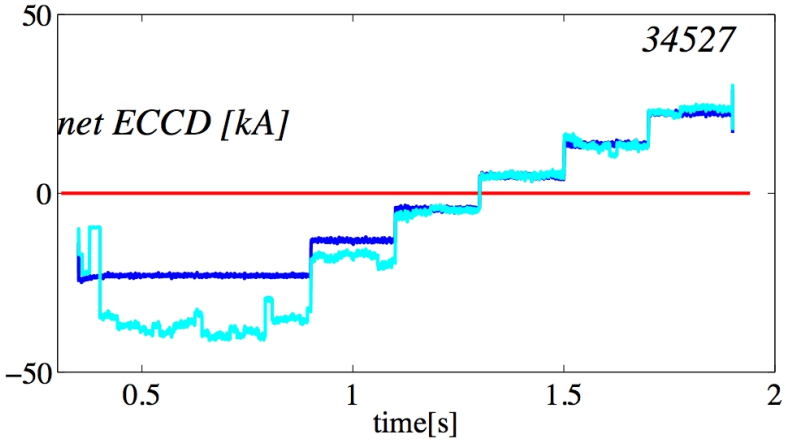
- plasma in front of launchers (L1,4) and the receiver (L7) ($z_{axis} = 0$)
- L1 : CO-ECCD, L4 : CNT-ECCD, *on-axis*
- L2,3 and L5,6 : ECH *off-axis*
- L7 (receiver) for co-viewing
- yellow : absorption regions

top view



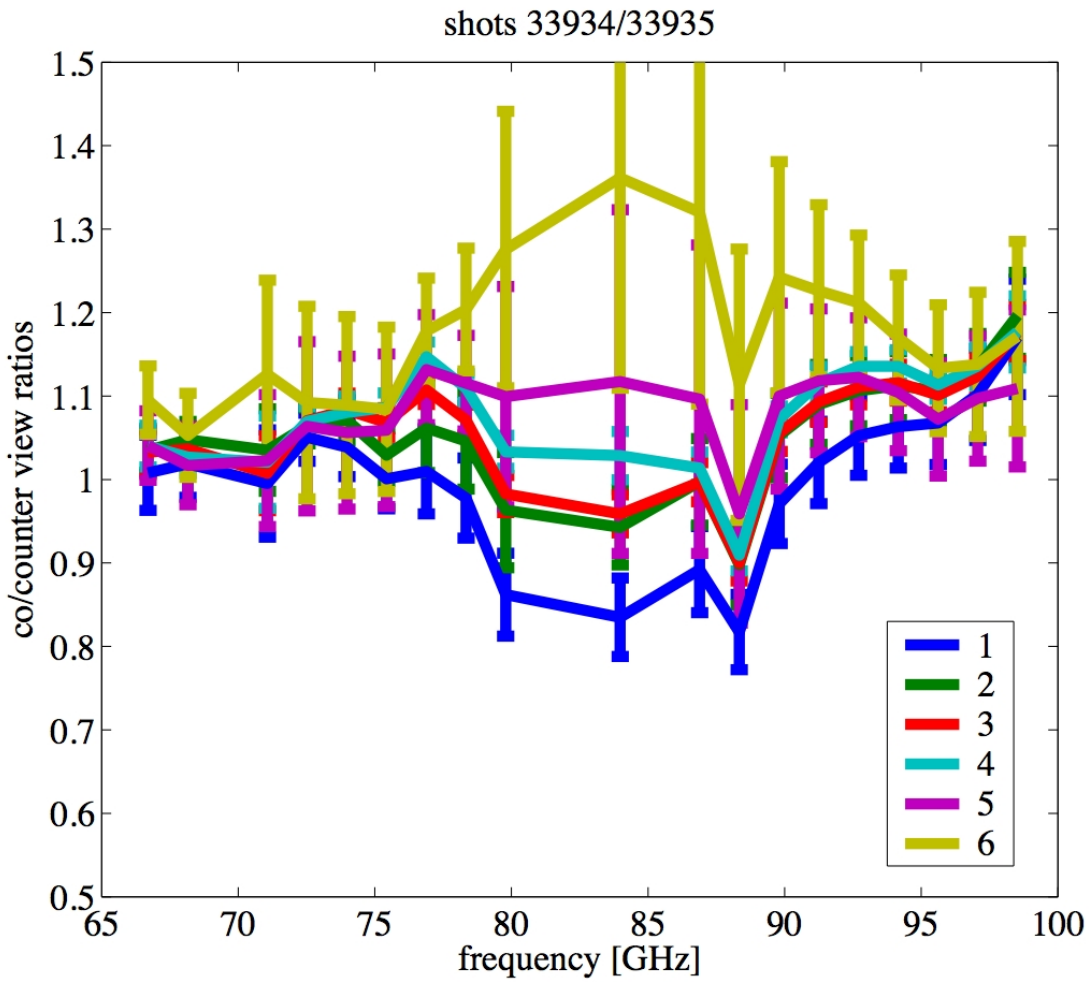
Constant Power and stepped ECCD





- power staircase **up** in L1 and **down** in L4
- yields **constant input power**
- with a scan (counter -> co) of the **net ECCD**
- shots repeated for oblique ECE measurements in both toroidal directions

ECCD current channel detection



- ECE signal averaged during last 180ms of constant ECCD step
- Asymmetry factor : Co-viewing averages divided by Counter-viewing averages
- central plasma region ($\approx 83GHz$) steps from counter (1) to co (6) ECCD

ECE Modeling - NOTECTCV

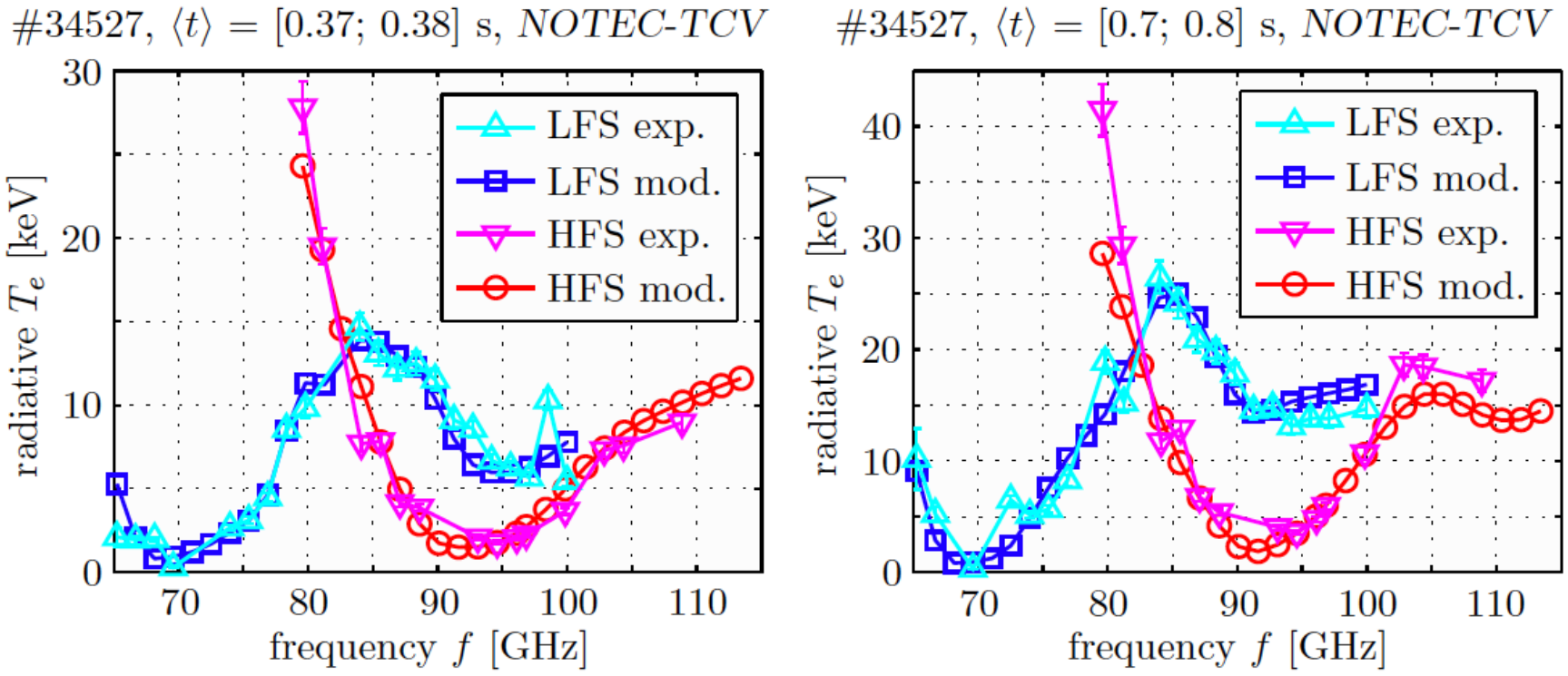
★ $t = 0.37$ **s, early after gyrotron switch-on:**

- bulk: $n_e^{(0)}(0) = 2.3 \times 10^{19}$ m^{-3} (TS, FIR), $T_e^{(0)}(0) = 3.2$ keV (TS, SXR)
- on-axis electron beam: $n_e^{(1)} = 80$ %, $T_{e,\parallel}^{(1)} = 5$ keV, $T_{e,\perp}^{(1)} = 15$ keV, $\rho^{(1)} \in [0; 0.05]$, $\beta^{(1)} = 0.15$
- extended on-axis beam: $n_e^{(2)} = 50$ %, $T_{e,\parallel}^{(2)} = 5$ keV, $T_{e,\perp}^{(2)} = 15$ keV, $\rho^{(2)} \in [0.1; 0.2]$, $\beta^{(2)} = 0.1$
- off-axis hot electrons: $n_e^{(3)} = 2$ %, $T_{e,\parallel}^{(3)} = 4$ keV, $T_{e,\perp}^{(3)} = 35$ keV, $\rho^{(3)} \in [0.2; 0.5]$, $\beta^{(3)} = 0$

★ $t = 0.70$ **s, at steady-state:**

- bulk: $n_e^{(0)}(0) = 1.7 \times 10^{19}$ m^{-3} (TS, FIR), $T_e^{(0)}(0) = 4.8$ keV (TS, SXR)
- on-axis electron beam: $n_e^{(1)} = 9$ %, $T_{e,\parallel}^{(1)} = 5$ keV, $T_{e,\perp}^{(1)} = 25$ keV, $\rho^{(1)} \in [0; 0.1]$, $\beta^{(1)} = 0.4$
- off-axis hot electrons: $n_e^{(2)} = 2$ %, $T_{e,\parallel}^{(2)} = 4$ keV, $T_{e,\perp}^{(2)} = 80$ keV, $\rho^{(2)} \in [0.2; 0.5]$, $\beta^{(2)} = 0$

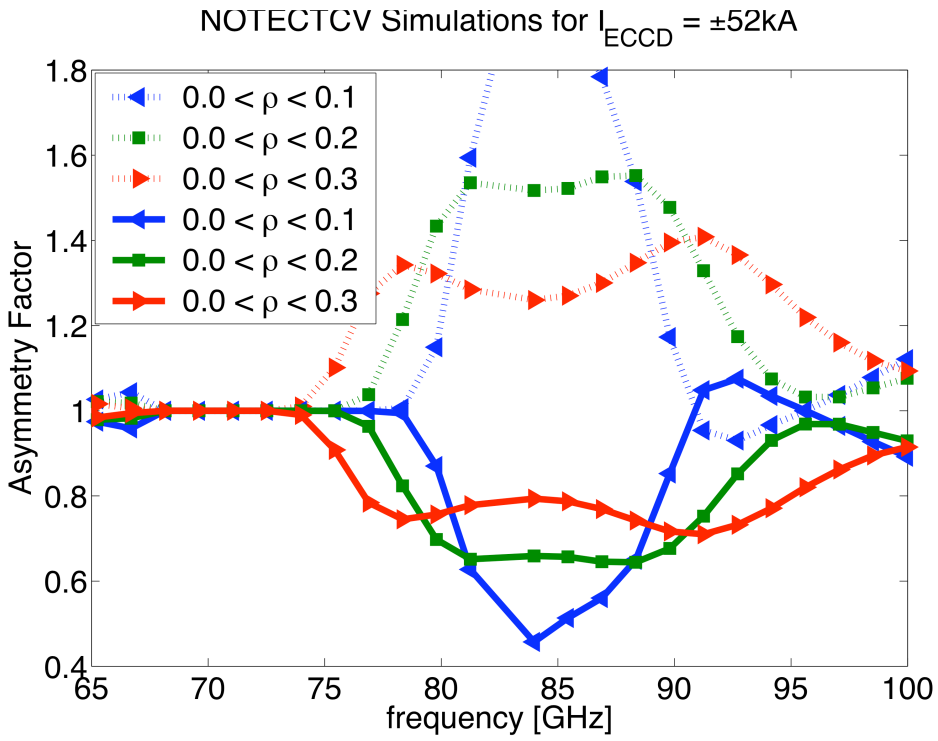
Simulated HFS and LFS ECE



(a) *NOTEC-TCV* at heating onset.

(b) *NOTEC-TCV* at steady-state.

Simulated HFS and LFS ECE



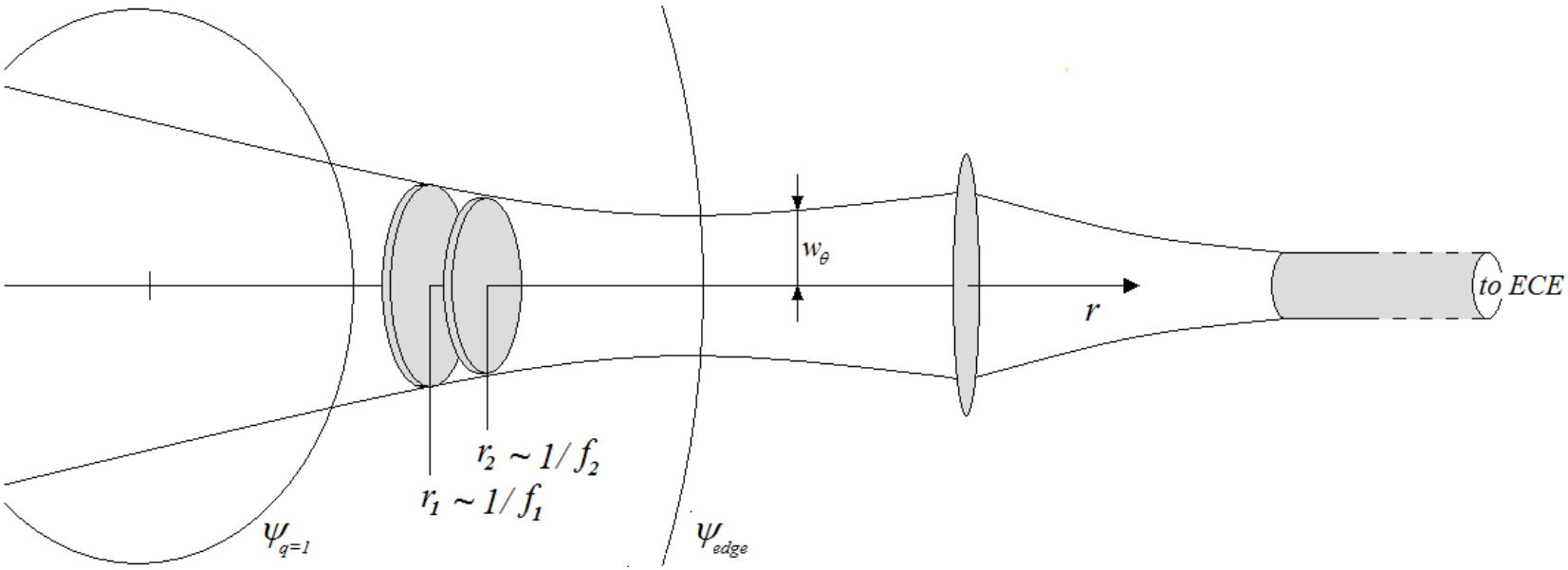
- Radial diffusion is simulated by increasing the width of the current channel
- NOTECTCV co/cnt ratios show the effect of increasing the width
- Narrower widths - close to the TORAY predicted widths - match the measured shape best

EDF asymmetry investigations

- Oblique ECE evidences the EDF Asymmetry during on-axis ECCD,
- Present analysis does not indicate excessive ECCD current-channel broadening from fast electron transport,
- Emission calculation by the GENRAY code based on CQL3D EDFs would provide a more self-consistent result and is being pursued,
- Off-axis ECCD current channel measurements are planned.

Correlation ECE

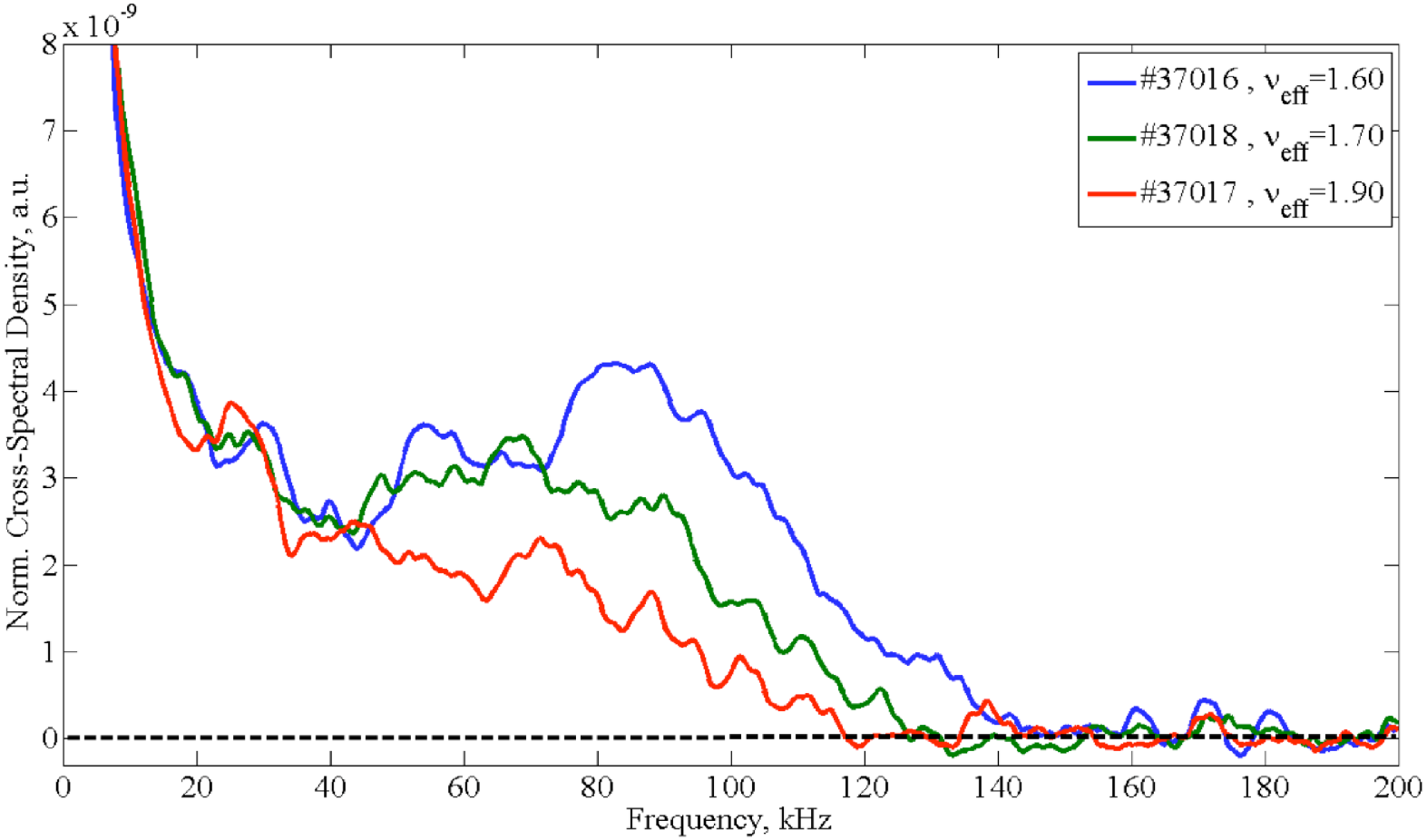
TCV measurement setup



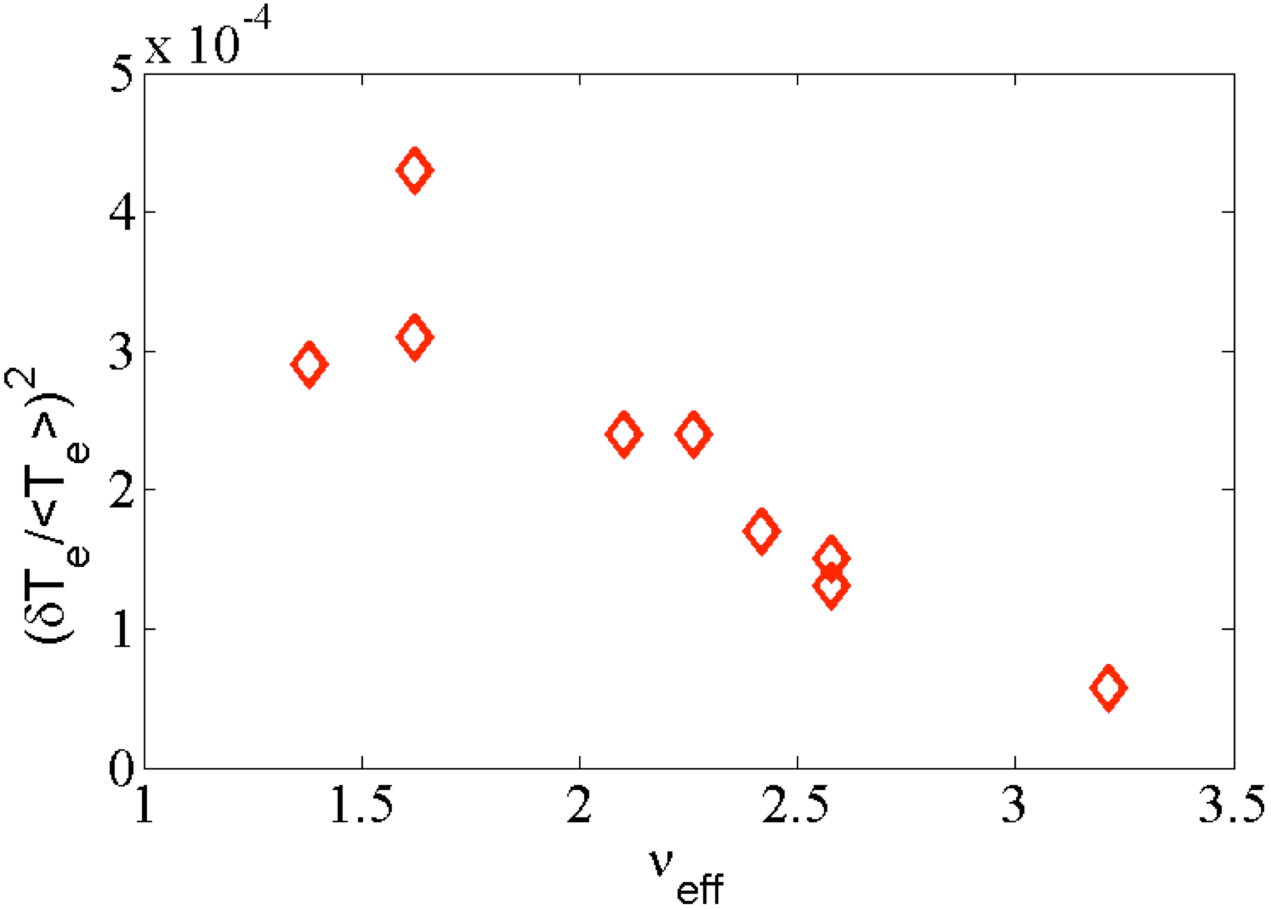
single Gaussian-beam sight-line measurement from 2 narrowband ($100MHz$) tunable (61-89GHz) YIG filters; focused beam resolves to $k_\theta \lesssim 1.4cm^{-1}$

Broadband Fluctuations Decrease as density is increased

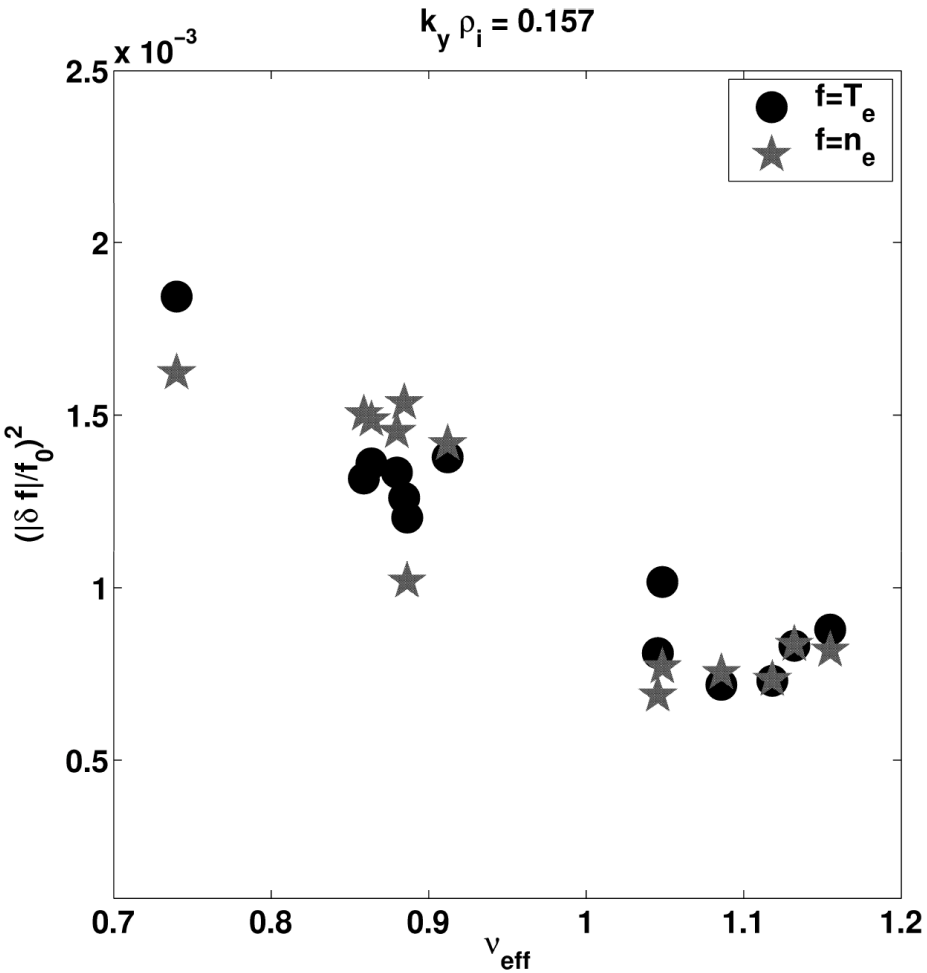
Ohmic L-mode



Measured fluctuation amplitude decreases with collisionality (ν_{eff})...



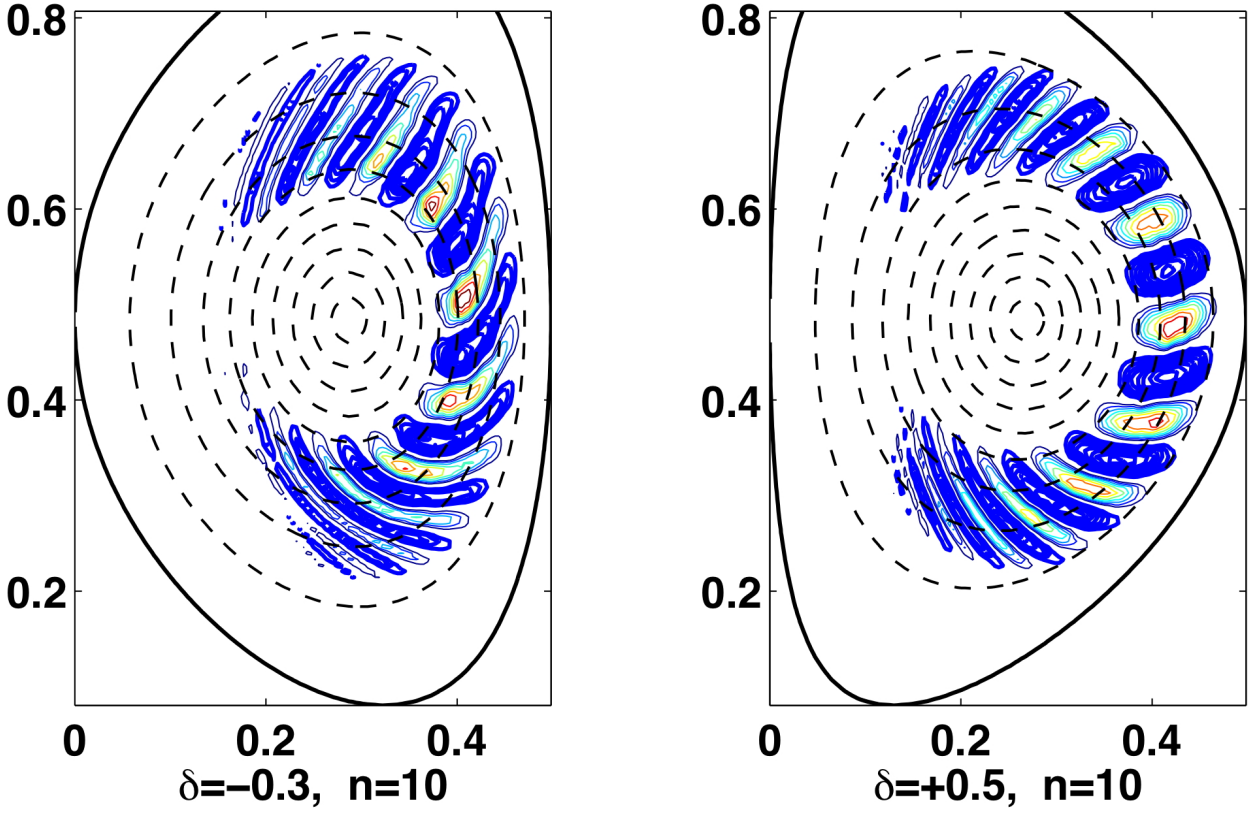
... as do n_e and T_e fluctuations from GS2 code simulations



- optical depth at $\rho_{\sqrt{V}} = 0.55$ is below 3
- measured fluctuations are attributable to both n_e and T_e
- measured frequency is characteristic of Trapped Electron Mode (TEM) turbulence
- TEM growth rates decrease as collisional de-trapping increases

LORB delta scan

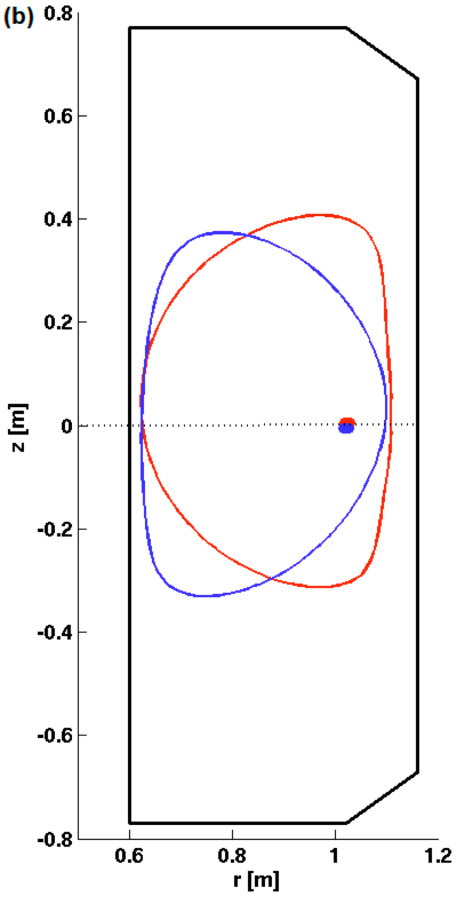
for low collisionality, confinement is higher at negative triangularity, $\delta < 0$

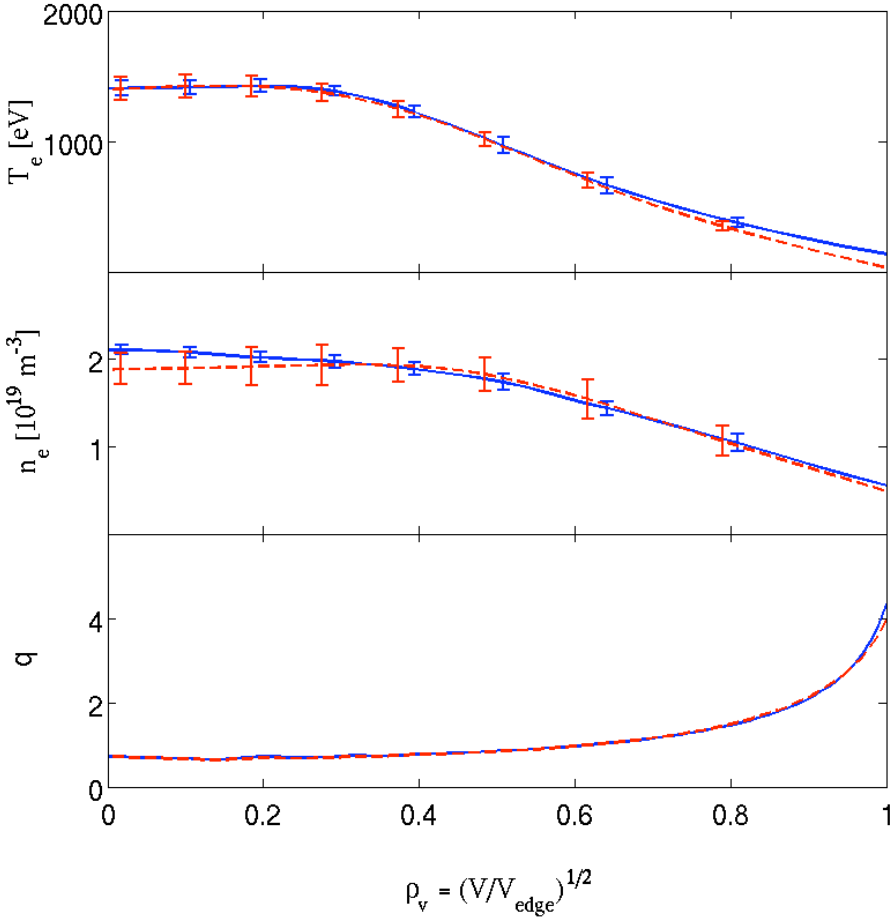


- LORB results : linear global gyro-kinetic code with no collisions
- electrostatic potential contours calculated near mid-radius
- structures have higher shear with $\delta < 0$

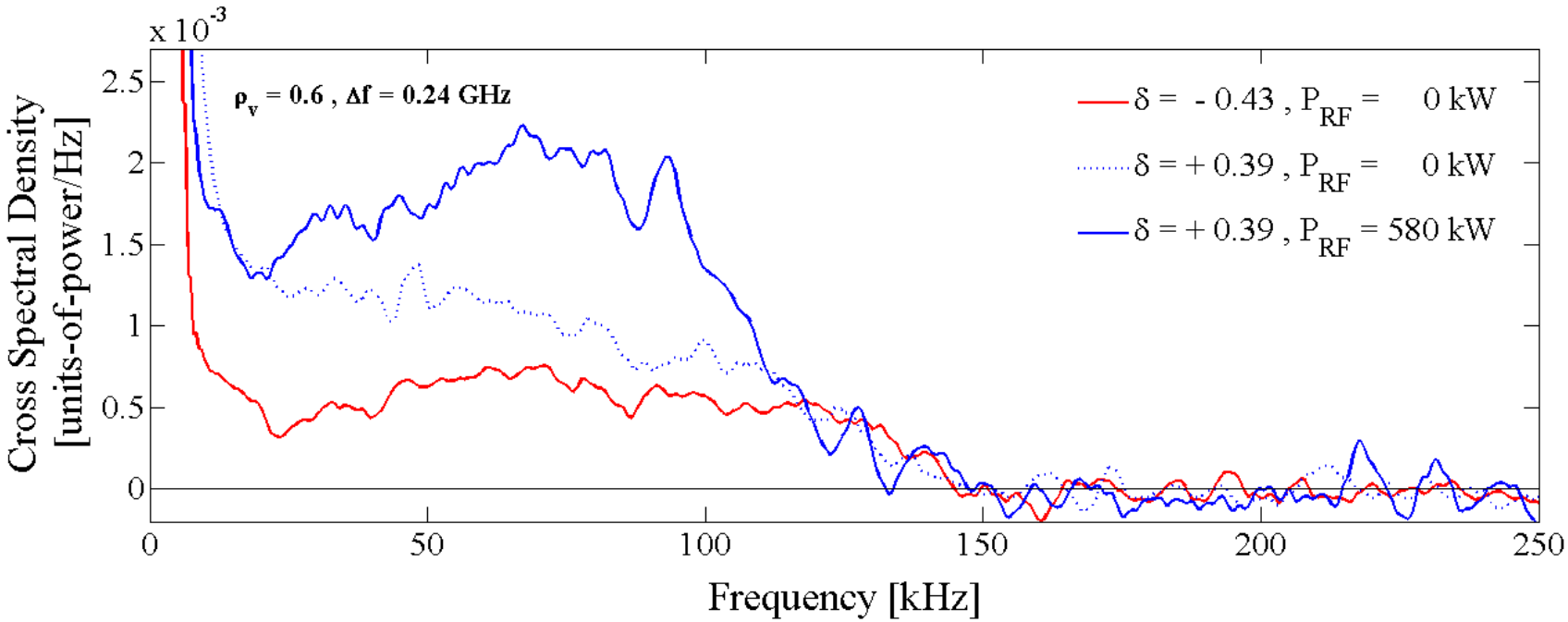
experimental delta scan

matching $\delta = -0.4, 250kW$ Ohmic profiles by adding $580kW$ ECH power in $\delta = +0.4$



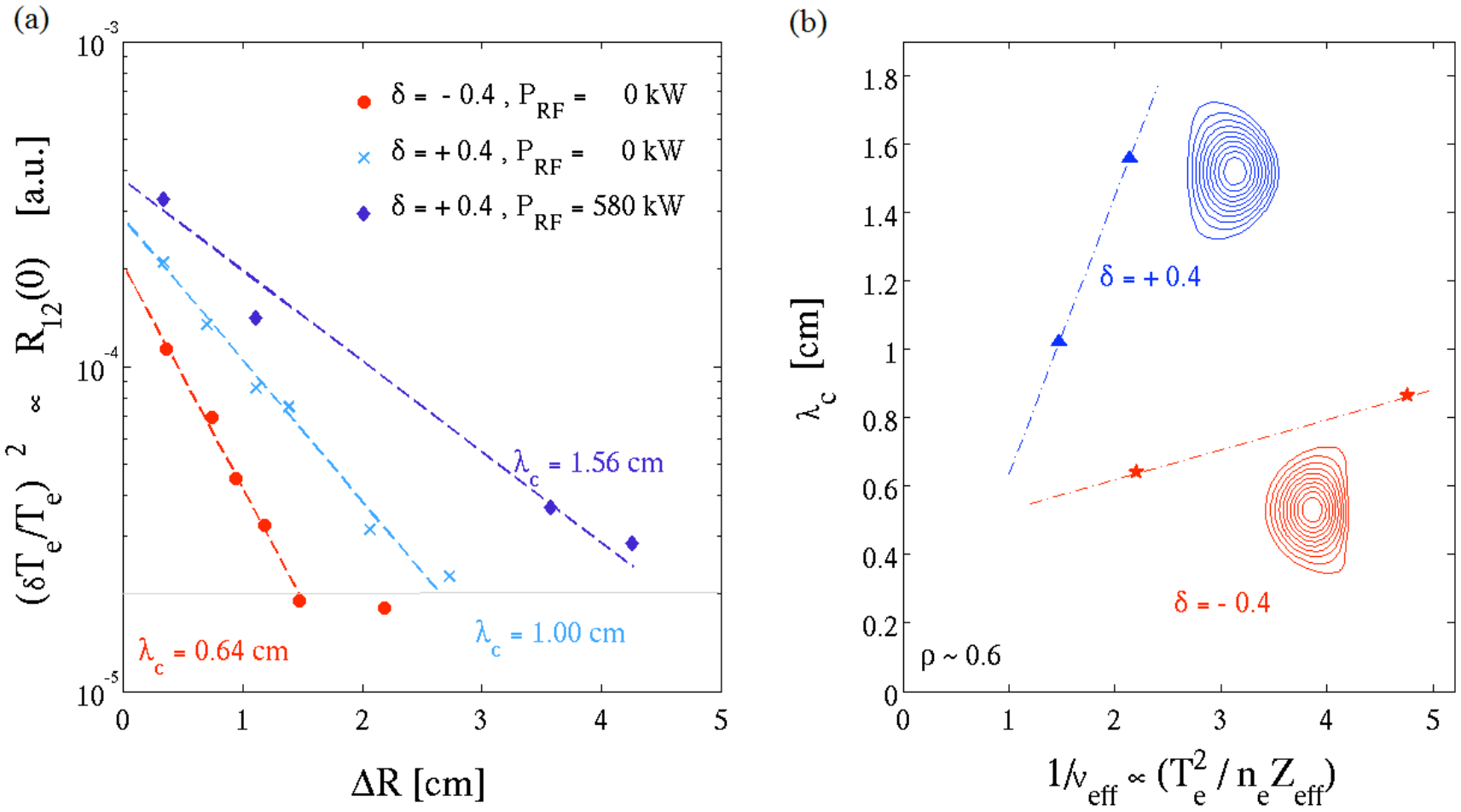


Broadband Fluctuation Characteristics



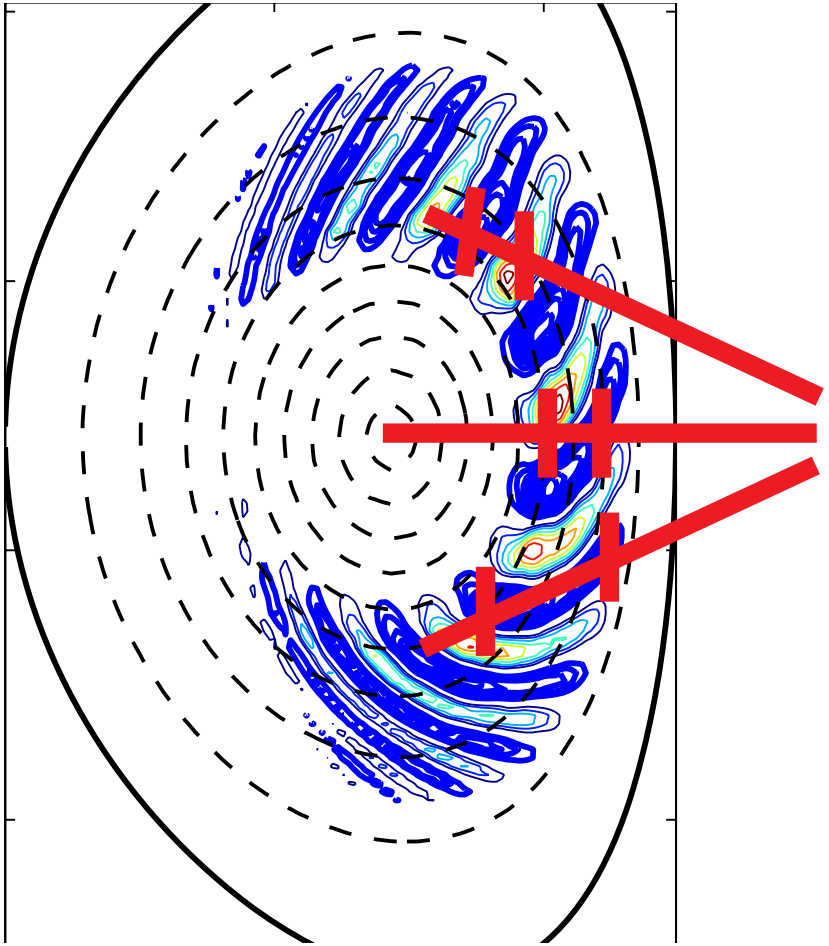
- broadband frequency range is similar at both triangularities
- fluctuation level is lower at $\delta < 0$ than at $\delta > 0$
- fluctuation level is higher when **ECH is added**

Correlation Lengths and Shape



Fluctuation differences with plasma shape

- CorrECE measurements support the prediction that TEM turbulence is a dominant contribution to energy transport in low collisionality TCV plasmas,
- Correlation lengths are significantly longer during ECH, but are drastically shortened at negative triangularity,
- This and the decrease in correlation length with collisionality is consistent with measured changes in heat diffusivity.

Future Investigations

structures viewed at various poloidal angles via the oblique ECE antenna