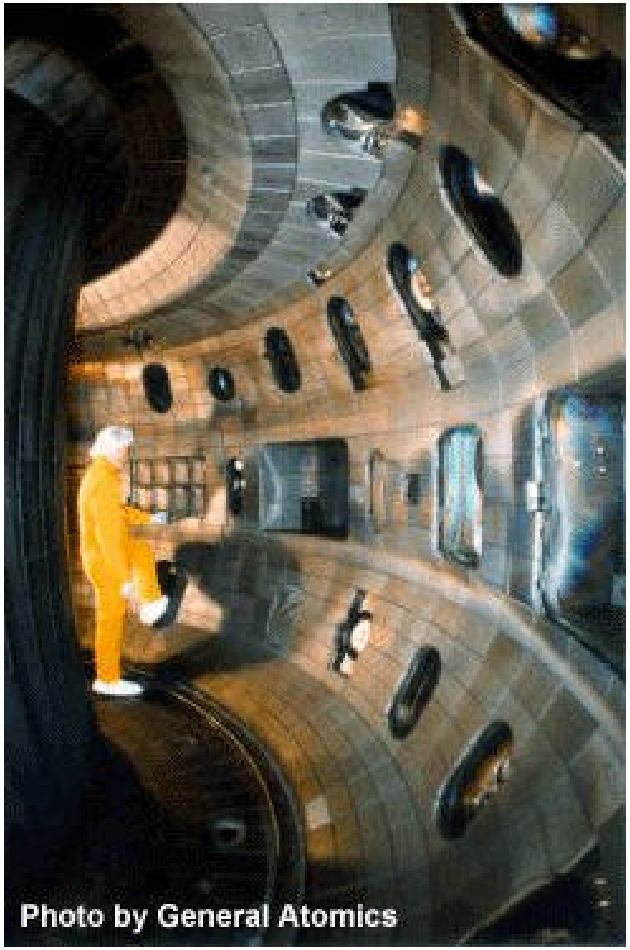
Effect of the electron temperature fluctuations on the turbulent flux measurements in the edge of DIII-D



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Outline of the talk

I. Motivation

- Fluctuation-driven particle and heat fluxes in edge/SOL plasma
- Problems associated with the flux measurements
- Assessment of the possible effect of the temperature fluctuations on the measurements

II. Experimental method on DIII-D

- Fast T_e measurements: Harmonic technique
- Probe head layout
- Different methods of calculating fluxes from probe data

III. Experimental results

- Comparison of the spectral characteristics of n_e, T_e and V_f fluctuations
- Comparison of the poloidal wave number spectra of T_e and V_f fluctuations
- Phase angles between n_e, T_e and V_f fluctuations
- Results of applying temperature corrections to the measured fluctuation-driven fluxes

IV. Discussion and summary

Fluctuation-Driven Particle and Heat Fluxes

- Like many other aspects of SOL physics, mechanisms behind cross-field particle and heat transport are still poorly understood, but it is widely accepted that “anomalous” transport in the edge and SOL is largely driven by electrostatic fluctuations
- Fluctuating poloidal electric field E_θ causes fluctuating radial $E_\theta \times B_j$ drift. Providing the plasma density and temperature fluctuate, the following time-averaged fluxes result:

Particle flux: $$\Gamma_r^{ES} = \frac{1}{B_j}\left\langle \tilde{n}_e \tilde{E}_q \right\rangle$$ **Heat flux:** $$Q_r^{ES} = \frac{3}{2} k \frac{\left\langle \tilde{n}_e \tilde{T}_e \tilde{E}_q \right\rangle}{B_j}$$

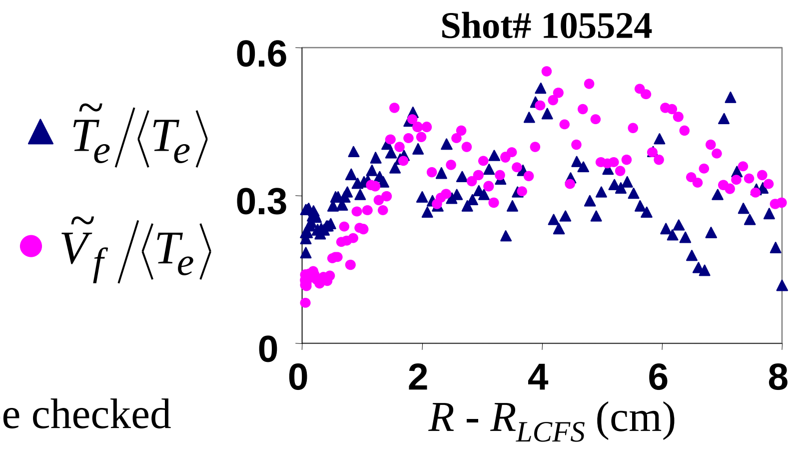
- All plasma parameters needed to calculate those fluxes in the edge and SOL plasmas can be derived from probe data
- So far probes provide **the only available means** to directly measure local fluctuation-driven fluxes and are therefore widely used for that purpose
- However, interpretation is not straightforward and problems exist:
  - * Measured fluxes sometimes exhibit unphysical behavior: heat flux reversal (DIII-D), particle flux continues to increase inside the separatrix into the pedestal (C-Mod)
  - * Fluxes estimated from the probe data near LCFS are typically higher than surface-average values obtained from modeling and particle/energy balance considerations

Possible source of errors: Neglecting T_e fluctuations

- The poloidal electric field (E_q) is commonly estimated from the floating potential (V_f) measurements at two poloidally separated locations.
- A proper estimate of E_q would require using two poloidally separated measurements of the plasma potential $\boldsymbol{V_p = V_f + C(kT_e/e)}$, where $\boldsymbol{C \sim 3}$ for deuterium plasmas. Therefore, a large error can be introduced!
- Effect of T_e fluctuations can be neglected if:
  - * Relative T_e fluctuation level is much smaller than potential fluctuation levels

This is not true in DIII-D

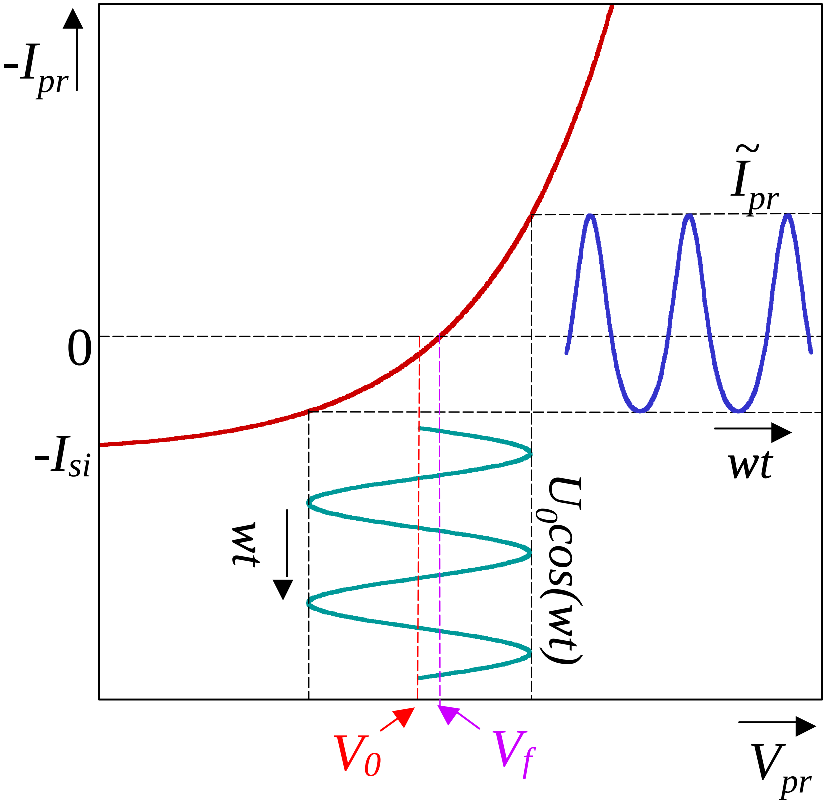
$$\tilde{T}_e/\langle T_e\rangle \approx \tilde{V}_f/\langle T_e\rangle$$



  - * $k_q(\tilde{T}_e) << k_q(\tilde{V}_f)$ - needs to be checked

- **Therefore:**
  - * Fast measurements of the electron temperature are required
  - * Poloidal structure of the temperature fluctuations needs to be studied

Fast T_e measurements: Harmonic technique



- A DC-floating probe is driven by high-frequency sinusoidal voltage $U = U_0 \cos(wt)$
- Due to non-linearity of the probe I-V characteristic harmonics are generated in the current spectrum
- For $eU_0/kT_e < 1$ T_e can be determined from the ratio of the amplitudes of 1st and 2nd harmonics[1,2]

$$\boxed{kT_e \approx \frac{eU_0}{4} \frac{I_w}{I_{2w}}}$$

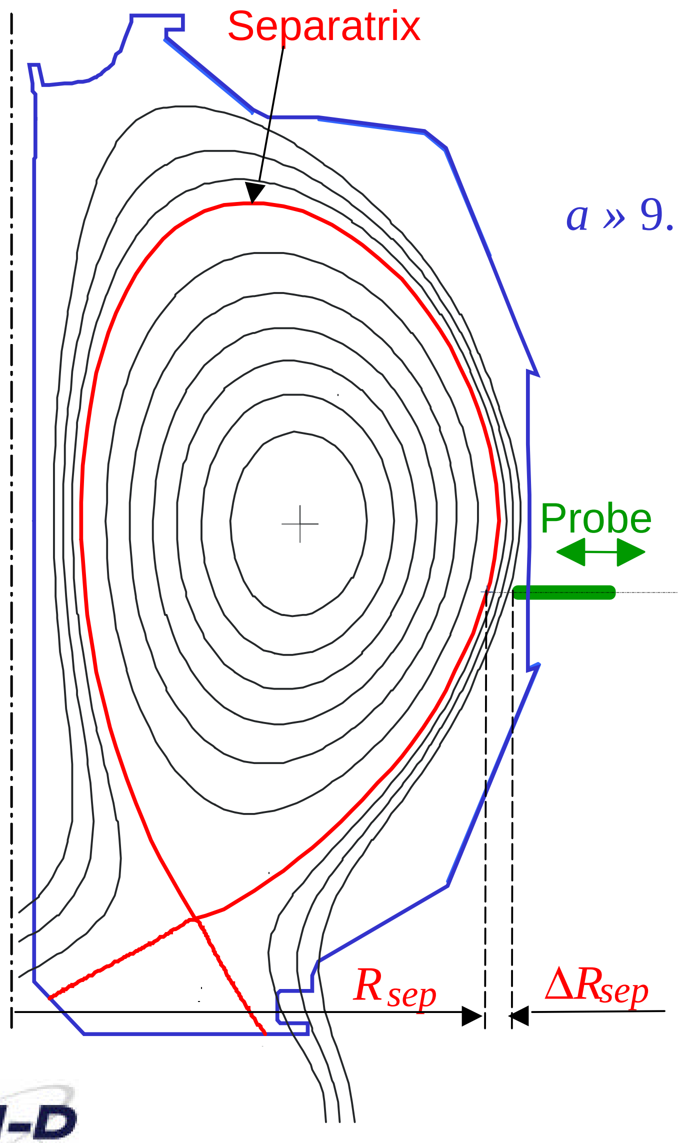
[1] Boedo *et al*, Rev. Sci. Instrum. **70** (1999)

[2] Rudakov *et al*, Rev. Sci. Instrum. **72** (2001)

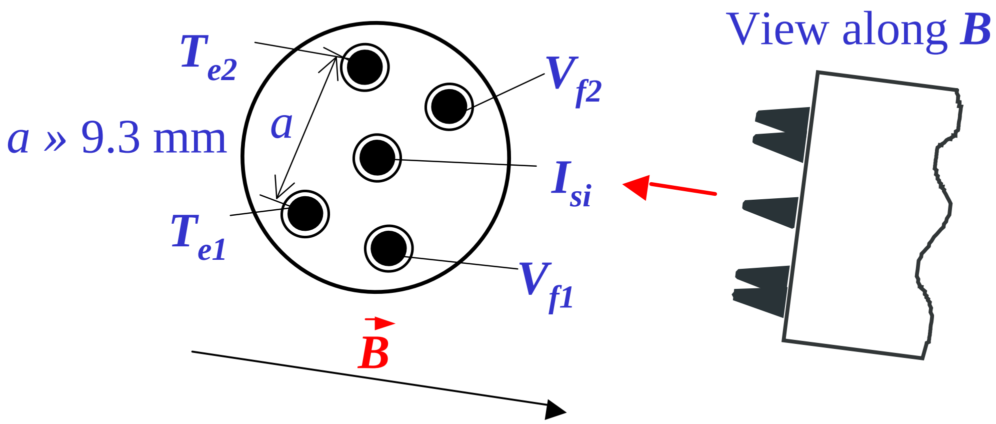
On DIII-D:

- Drive frequency: 400 kHz
- Bandwidth: typical 100 kHz, maximum 200 kHz
- Novel features: fully digital analysis, active voltage feedback

Experimental Arrangement on DIII-D



Probe head layout



- Probe head layout has been modified to include two poloidally separated channels of fast T_e measurements

- The tip arrangement is designed to achieve best possible alignement of T_e and V_f tips without significant shadowing

Calculating turbulent fluxes from probe data

Turbulent fluxes can be calculated in time domain:

$$\Gamma_r^{ES} = \frac{1}{B_j}\left\langle \tilde{n}_e \tilde{E}_q \right\rangle$$

$$Q_r^{ES} = \frac{3}{2}k\frac{\left\langle \tilde{n}_e \tilde{T}_e \tilde{E}_q \right\rangle}{B_j} = \frac{3}{2}kT_e\Gamma_r^{ES} + \frac{3}{2}\frac{n_e}{B_j}\left\langle k\tilde{T}_e \tilde{E}_q \right\rangle = Q_{conv} + Q_{cond}$$

convective **conductive**

or in frequency domain:

$$\Gamma_r^{ES}(w) = \frac{1}{B_j}\int_0^\infty n_e^{rms}(w)E_q^{rms}(w)g_{nE}(w)\cos(a_{nE}(w))dw$$

$$Q_r^{ES}(w) = \frac{3}{2}kT_e\Gamma_r^{ES}(w) + \frac{3}{2}\frac{n_e k}{B_j}\int_0^\infty T_e^{rms}(w)E_q^{rms}(w)g_{TE}(w)\cos(a_{TE}(w))dw$$

convective **conductive**

where:

$X^{rms}(w)$ - RMS fluctuation amplitude

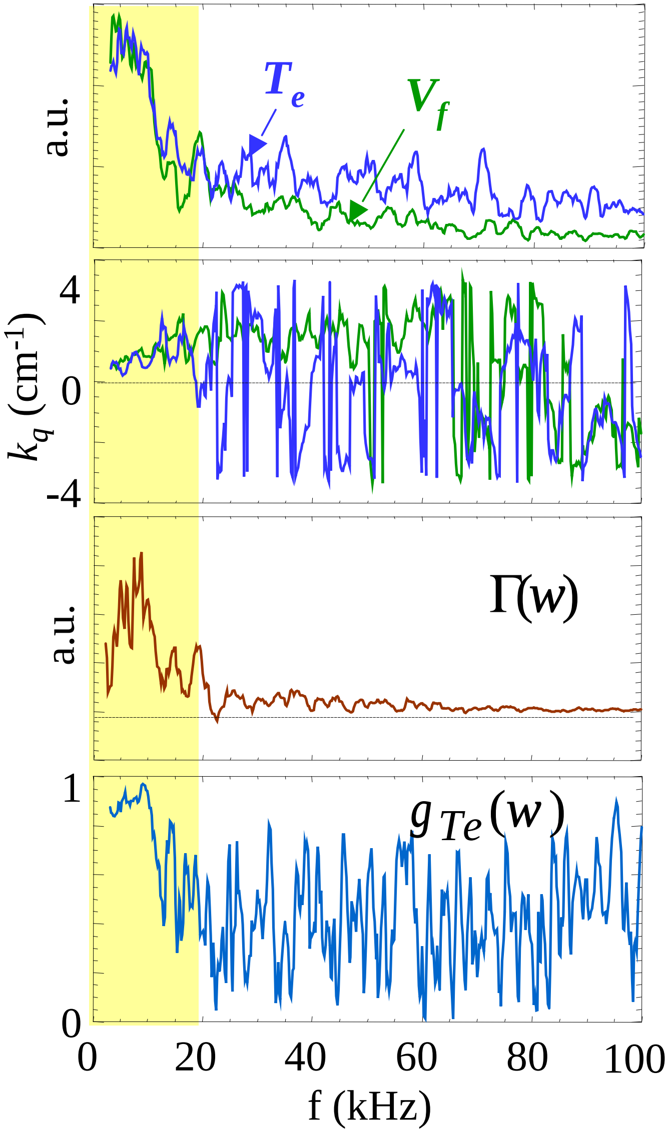
$a_{XX}(w)$ - phase angle between n_e or T_e and E_q

$g_{XX}(w)$ - coherence

Can be obtained from raw signals using FFT

Spectral features of fluctuations in L-mode (near SOL)

- The shapes of T_e and V_f spectra are generally close, but V_f spectra fall off more rapidly with frequency
- Poloidal wave numbers of the temperature fluctuations below 20 kHz are close but not equal to those of V_f fluctuations
- Most of the fluctuation power and of fluctuation-driven flux are concentrated at frequencies below 20 kHz. Fluctuations are most coherent in that range
- For the above conditions we can characterize the relative phasing of the fluctuations by an average phase angle calculated where the coherence and cross-power are maximum



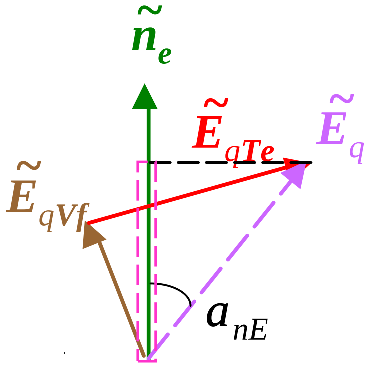
Correcting the fluxes for T_e fluctuations

Net poloidal electric field can be represented as a sum of two components:

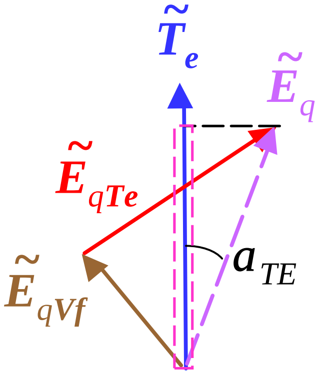
$$E_q = -\nabla_q (V_p) = -\nabla_q (V_f) - 3\nabla_q (kT_e / e) = E_{qVf} + E_{qTe}$$

Net field **V_f contribution ^{o} E_{qVf}** **T_e correction ^{o} E_{qTe}**

It is convenient to illustrate contribution of the two components of E_q to fluxes using phase diagrams (length = amplitude, a = phase angle)



$$\Gamma, Q_{conv} \propto \boxed{\tilde{n}_e \tilde{E}_q \cos(a_{nE})}$$



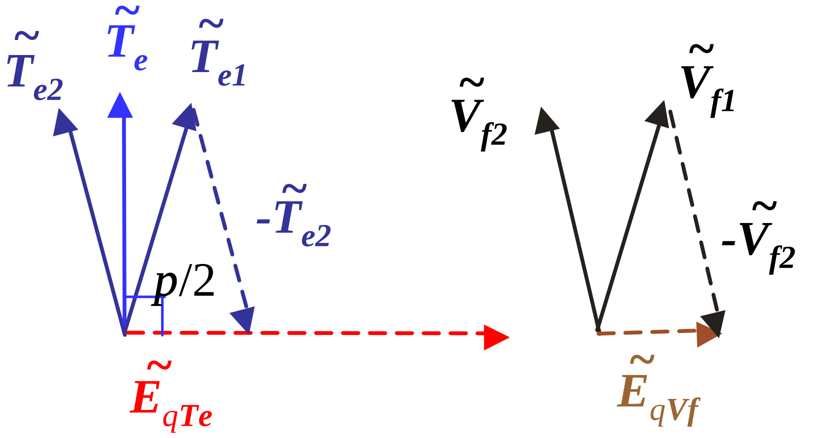
$$Q_{cond} \propto \boxed{\tilde{T}_e \tilde{E}_q \cos(a_{TE})}$$

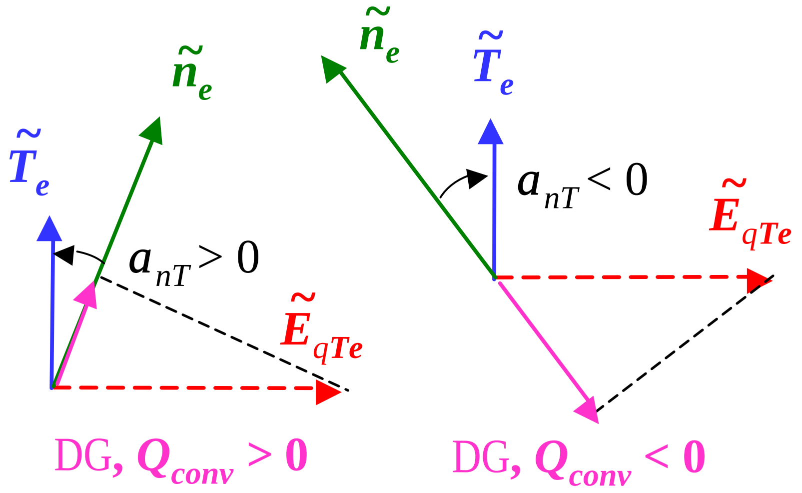
Note: if for any of E_q components a = ±90°, it will cause no flux

T_e correction to fluxes can be large and of either sign

- Since $\tilde{T}_e / T_e \approx e\tilde{V}_f / kT_e$ and $k_q(\tilde{T}_e) \approx k_q(\tilde{V}_f)$ E_{qTe} should be about 3 times larger than E_{qVf}
- Phase angle between T_e and E_{qTe} tends to be around $p/2$, so contribution of E_{qTe} to Q_{cond} should be relatively small
- Contribution of E_{qTe} to Γ and Q_{conv} depends on the phase angle between T_e and n_e. If T_e and n_e are in phase, this contribution is small, otherwise it may be quite large and of either sign

$$\boxed{\Delta\Gamma, Q_{conv} \propto \sin(a_{nT})}$$



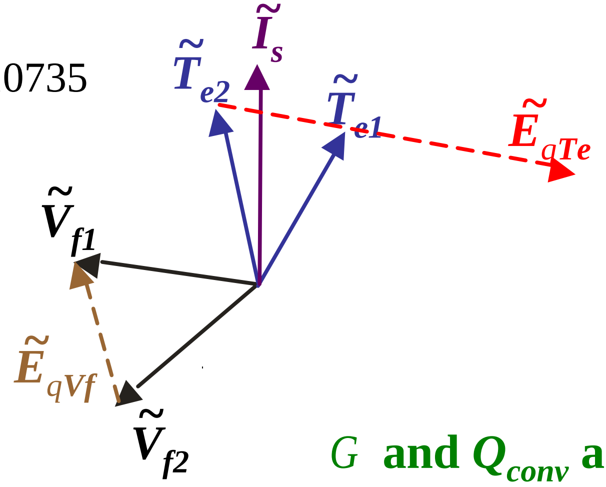


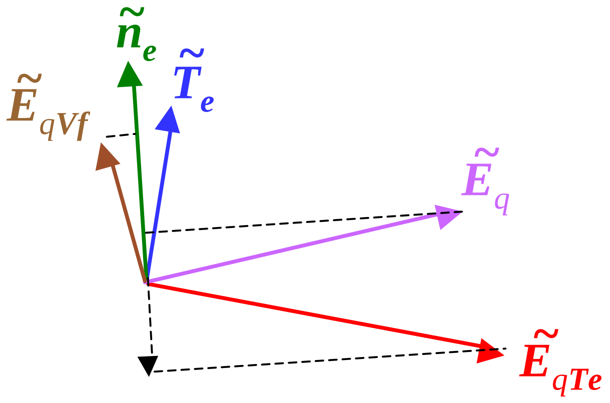
Experimental results: flux correction in L-mode

Measured parameters

Derived parameters

Shot 110735





G **and Q_{conv} are reduced by a factor of ~ 3**

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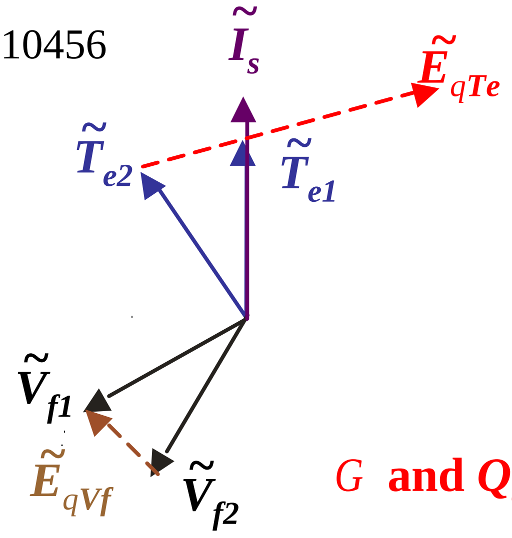
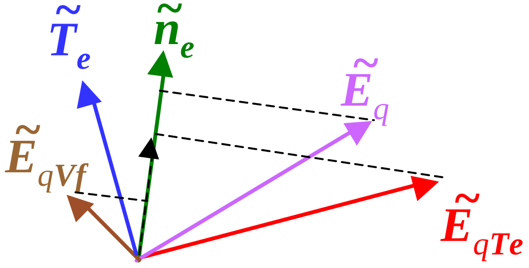
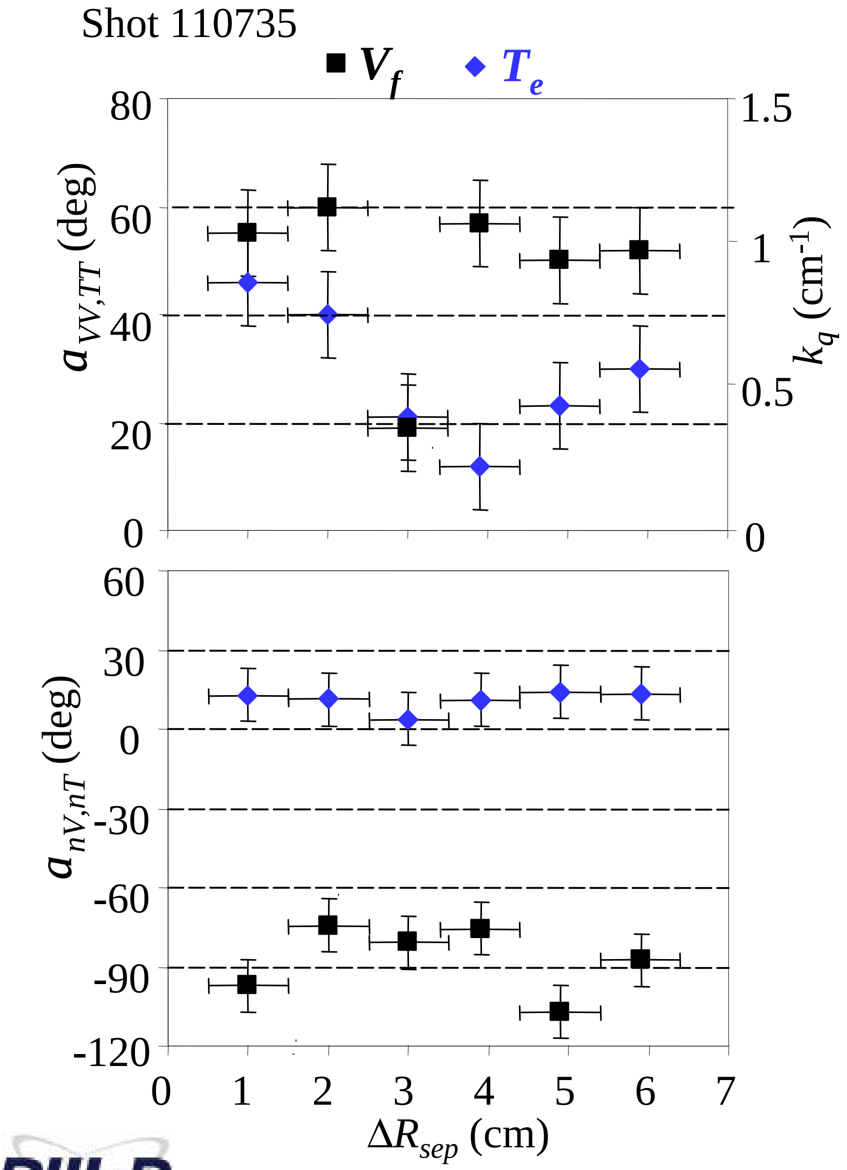




G **and Q_{conv} are increased by a factor of ~ 3**

Experimental results: radial dependence of phase angles



- Poloidal wave numbers of the temperature fluctuations below in near SOL are close to those of V_f fluctuations. In far SOL they differ by a factor of 2 - 3

- Phase angle between T_e and n_e tends to be small, about 15°, while phase angle between V_f and n_e is around 90°.

- Since $\Delta\Gamma$, $Q_{conv} \propto \sin(a)$ and $\sin(a_{nV}) / \sin(a_{nT}) \approx 5$, relative effect of T_e fluctuations is offset in this case, but it can still be large

Summary

- SOL transport is still poorly understood but thought to be largely $E \times B$ fluctuation- driven
- So far electric probes provide the only available means for measuring local fluctuation-driven fluxes in the edge and SOL
- Neglecting electron temperature fluctuations while deriving fluctuation-driven fluxes from the probe data can lead to large errors
- New experimental arrangement on DIII-D provides a unique opportunity to study poloidal structure of the electron temperature fluctuations
- Poloidal wave numbers of the electron temperature fluctuations below 20 kHz in L-mode are close to those of the floating potential fluctuations in near SOL, differ considerably in far SOL
- Depending on the phase angle between density and temperature fluctuations, contribution of the temperature fluctuations to the measured poloidal electric field can be large and lead to significant increase/decrease or even direction reversal of the measured particle and convective heat fluxes
- Conductive heat flux measurement is less affected by T_e contribution to E_q since phase angle between T_e and E_{qTe} tends to be around $p/2$

More experiments in L and H mode are needed!