Collisionality dependence of the energy transfer to zonal flows at the stellarator TJ-K

B. Schmid[1], P. Manz[2,3], M. Ramisch[1], U. Stroth[2,3]

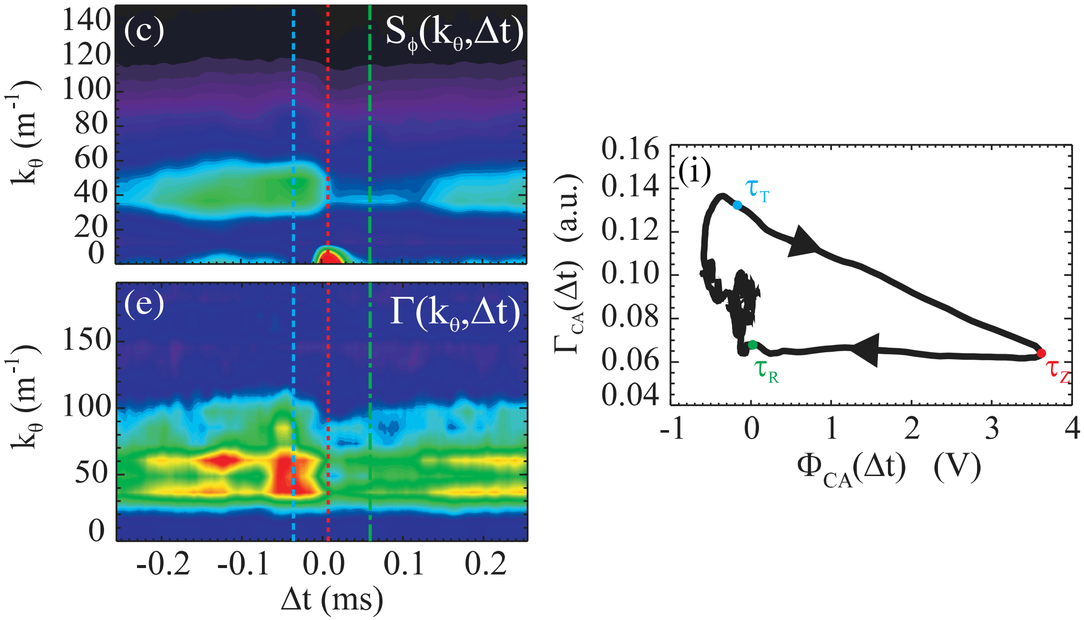
[1] IGVP, Universität Stuttgart, 70569 Stuttgart, Germany

[2] Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany

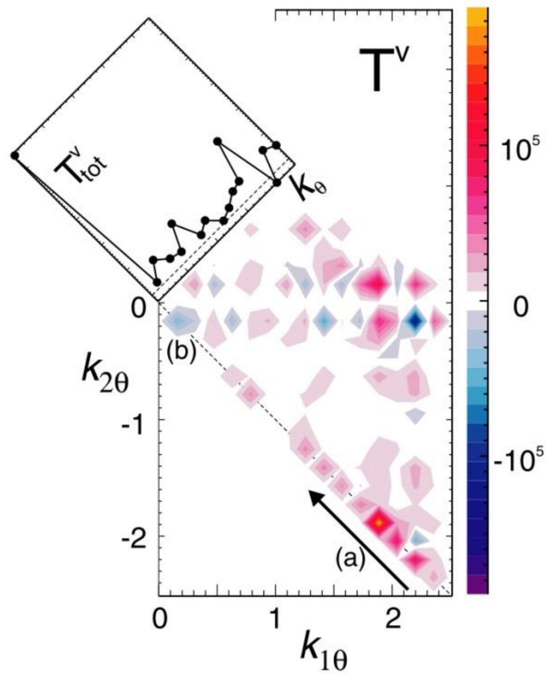
[3] Physik-Department E28, Technische Universität München, 85747 Garching, Germany

EFTSOMP-Workshop, Lisbon, 29. June 2015

Turbulent transport and energy transfer



[G.Birkenmeier et al, PRL 110 (2013)]



[P.Manz et al, PRL 103 (2009)]

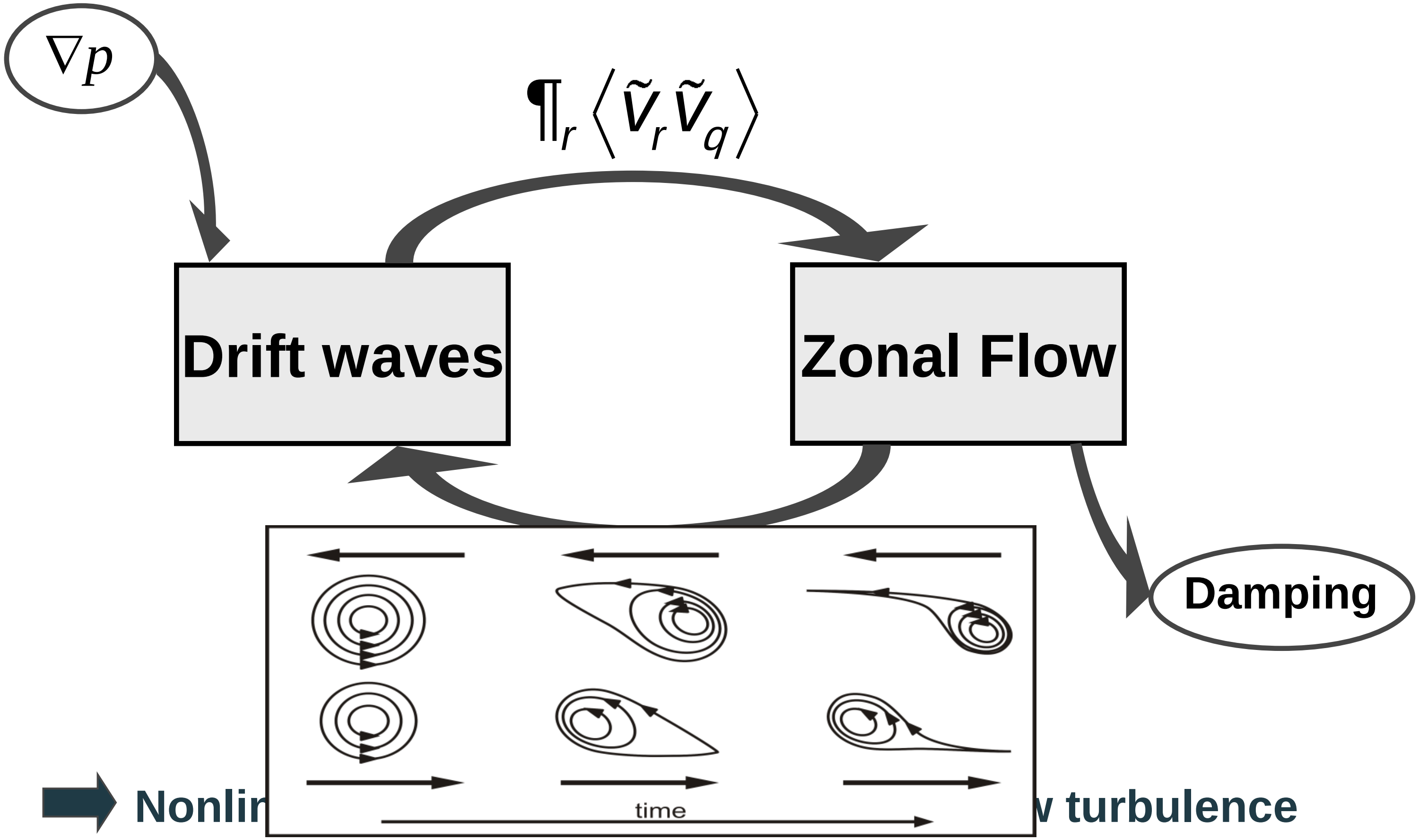
Outline of experimental results

Drift wave – zonal flow coupling

Energy transfer to the zonal flow

Zonal flow scaling with collisionality

Drift wave – zonal flow interaction

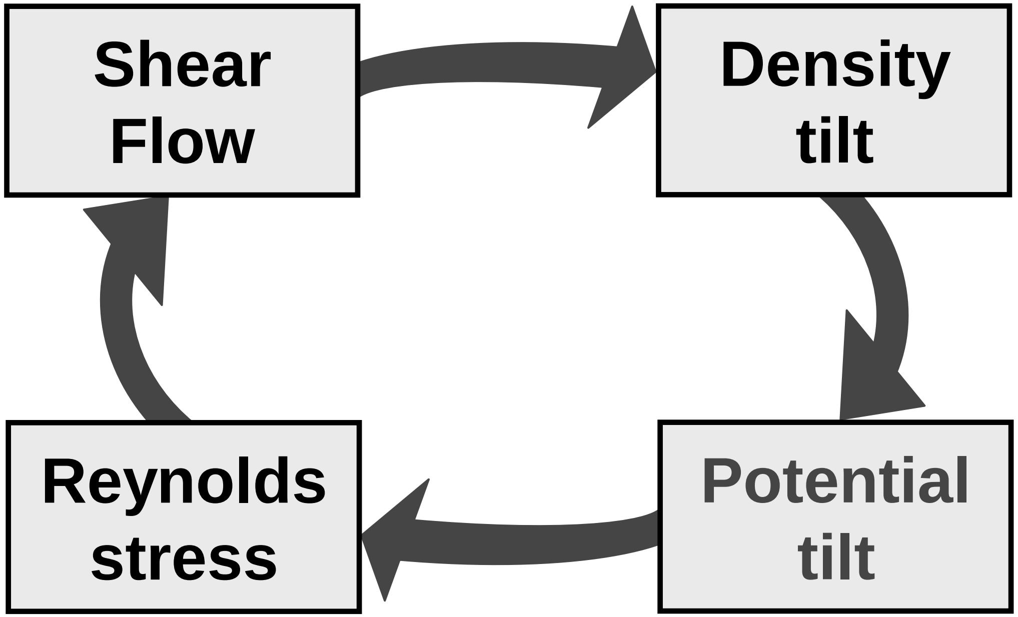


[P.Manz et al, PRL 103 (2009)]

➡ **Nonlin… v turbulence**

Reynolds-stress drive

$$\frac{\partial}{\partial t}\left\langle v_\theta \right\rangle = -\frac{\partial}{\partial r}\left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle$$



$$\partial_t n + \{\phi, n\} + \kappa_n \partial_y \phi = C^{-1}(\phi - n)$$

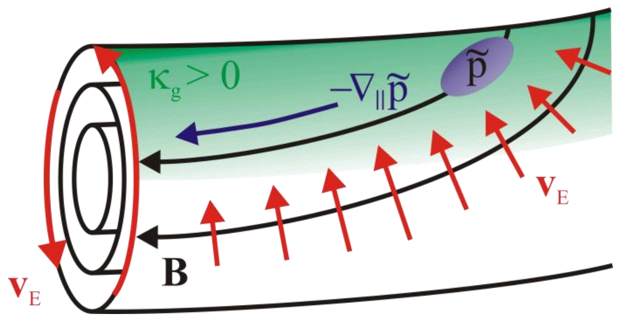
$$\partial_t \Omega + \{\phi, \Omega\} = C^{-1}(\phi - n)$$

Geodesic transfer effect

$$\frac{\partial}{\partial t}\langle v_\theta\rangle = -\frac{\partial}{\partial r}\langle \tilde{v}_r \tilde{v}_\theta\rangle - \omega_B \langle p_e \sin s\rangle$$

Drift waves → (Reynolds-Stress) → Zonal Flow → (Geodesic Transfer) → GAM

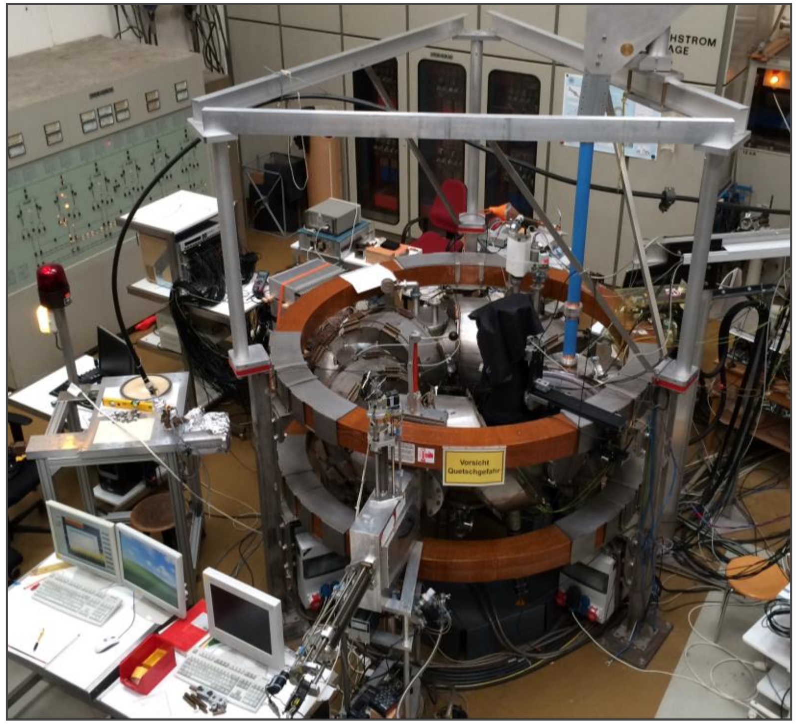
$$\nabla \mathbf{v}_E \propto -\frac{\kappa_g}{B}$$



[G.Birkenmeier, Dissertation (2012)]

Stellarator TJ-K

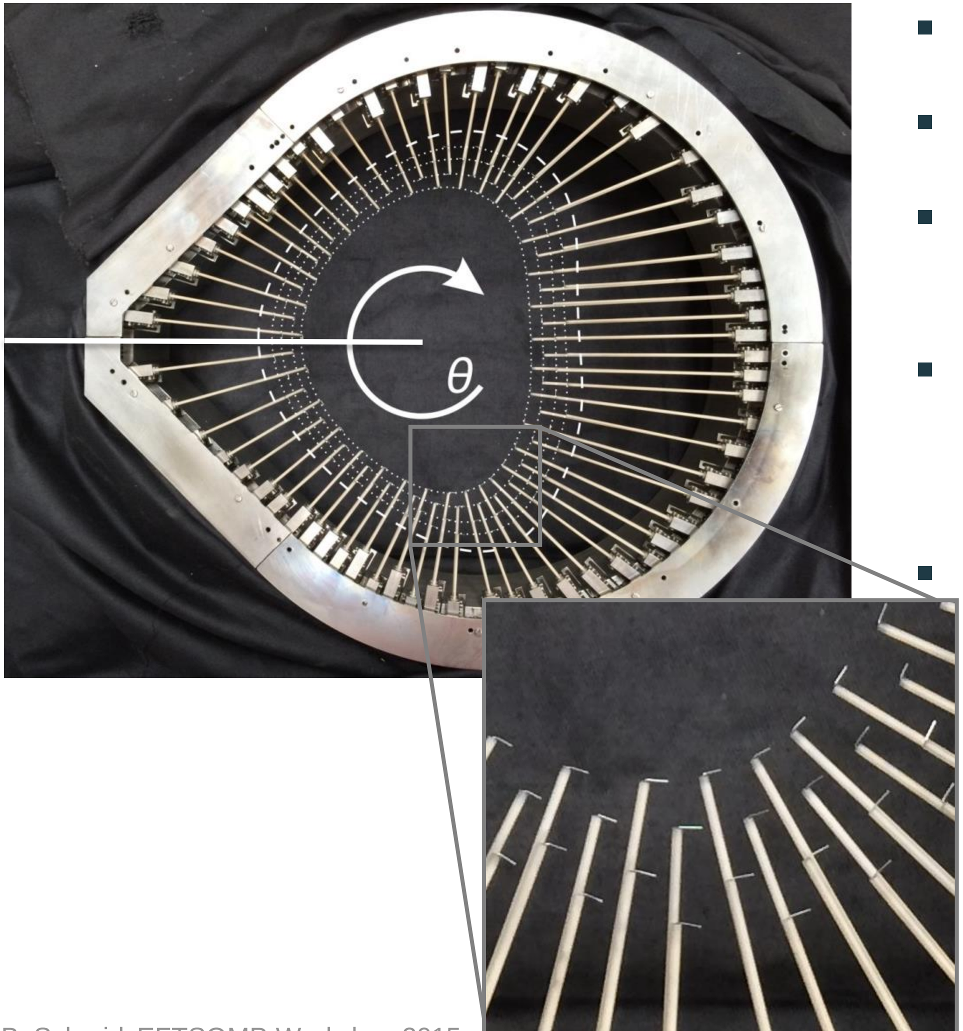
- Major plasma radius: $R = 0.6\,\mathrm{m}$
- Minor plasma radius: $a = 0.1\,\mathrm{m}$
- Magnetic field: $B = 50 - 300\,\mathrm{mT}$
- Microwave heating: 3 kW at 2.45 GHz
  2 kW at 8.0 GHz
- Pulse duration: up to 45 min
- Gas: H_2, D_2, He, Ne, Ar
- Electron temperature: $T_e \approx 10\,\mathrm{eV}$
- Ion temperature: $T_i \leq 1\,\mathrm{eV}$
- Electron density: $n_e \approx 2 \cdot 10^{17}\,\mathrm{m}^{-3}$
- Iota: 0.13 – 0.4



➡ **Whole confinement region accessible to Langmuir-probes**

➡ **Discharges dimensionally similar to fusion edge plasmas**

Poloidal Reynolds-stress array



- 128 shielded Langmuir probes
- 32 probes on each of four flux surfaces
- Ion-saturation current $I_{i,sat}$ and floating potential Φ_{fl} with 1 MHz sampling rate
- Determination of the vorticity

$$\Omega = \nabla_\perp^2 \frac{\phi}{B}$$

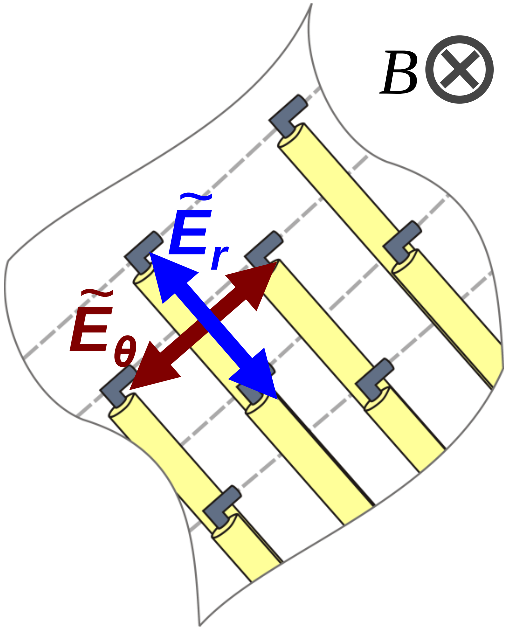
- Direct determination of the radial Reynolds-stress gradient

$$\partial_r \left\langle \tilde{v}_r \tilde{v}_\theta \right\rangle$$

Reynolds-stress measurement

Fluctuations:

- Ion-saturation current: $\tilde{I}_{i,sat} \sim \tilde{n}$
- Floating potential: $\tilde{\phi}_{fl} \sim \tilde{\phi}_p$



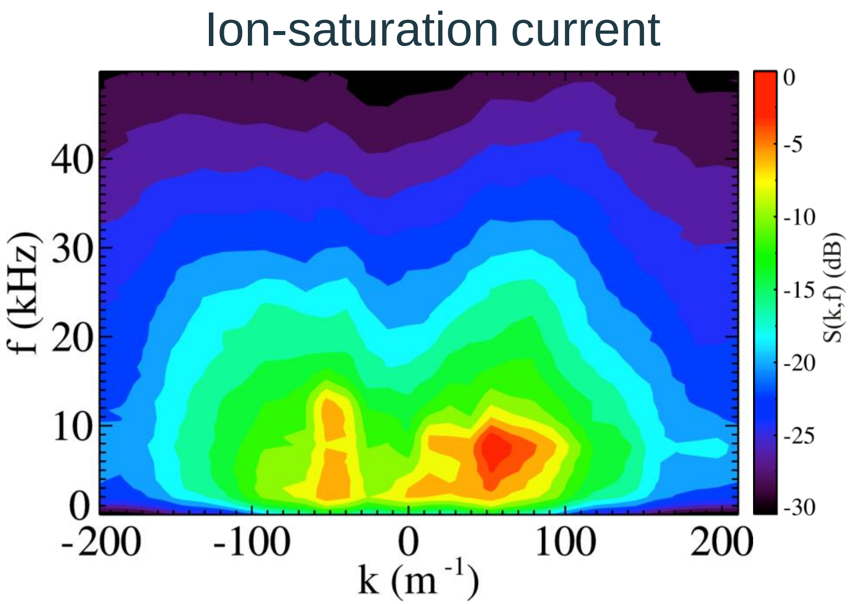
$$v^{E\times B} = \frac{E\times B}{B^2} \Rightarrow \begin{matrix} v_r \sim E_\theta \\ v_\theta \sim E_r \end{matrix}$$

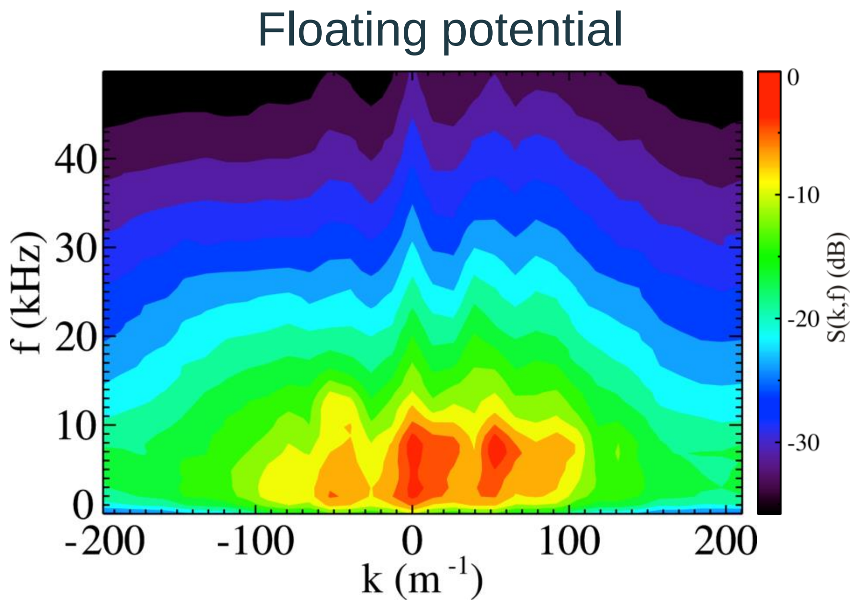
- Reynolds-stress:

$$R_S = \langle \tilde{v}_r \tilde{v}_\theta \rangle$$

$$R_S \sim \langle \tilde{E}_\theta \tilde{E}_r \rangle$$

kf - spectra

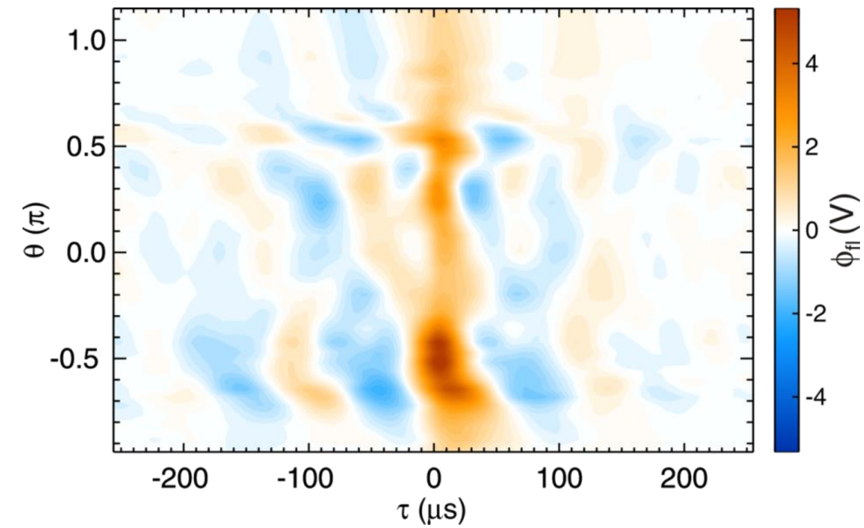




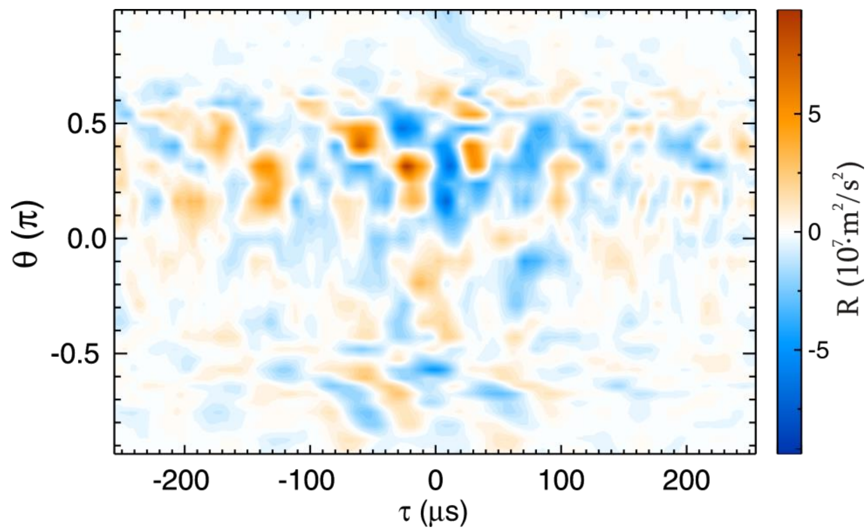
➡ **Prominent m = 0 - mode in the potential**

Zonal potential and Reynolds stress

- Time evolution of the potential $\tilde{\Phi}$ on a flux surface
- Zonal maximum around the trigger time-point $\tau \approx 0\,\mu s$



- Reynolds-stress $R = \langle \tilde{v}_r \tilde{v}_\theta \rangle_t$ on a flux surface
- Triggered on flux-surface averaged potential $\langle \tilde{\Phi} \rangle$



Drift wave - zonal flow interaction

- For a constant biphase relation the quadratic crossbicoherence takes non-zero values

$$b^2_{n,n,\phi}(k_1,k_2) = \frac{\left|\left\langle \hat{n}(k_1,t)\hat{n}(k_2,t)\hat{\phi}^*(k_1+k_2,t)\right\rangle\right|^2}{\left\langle\left|\hat{n}(k_1,t)\hat{n}(k_2,t)\right|^2\right\rangle\left\langle\left|\hat{\phi}(k_1+k_2,t)\right|^2\right\rangle}$$

  where the resonance condition is

$$k_3 = k_1 + k_2$$

- The integrated quadratic bicoherence shows the overall coupling to the k_3 mode

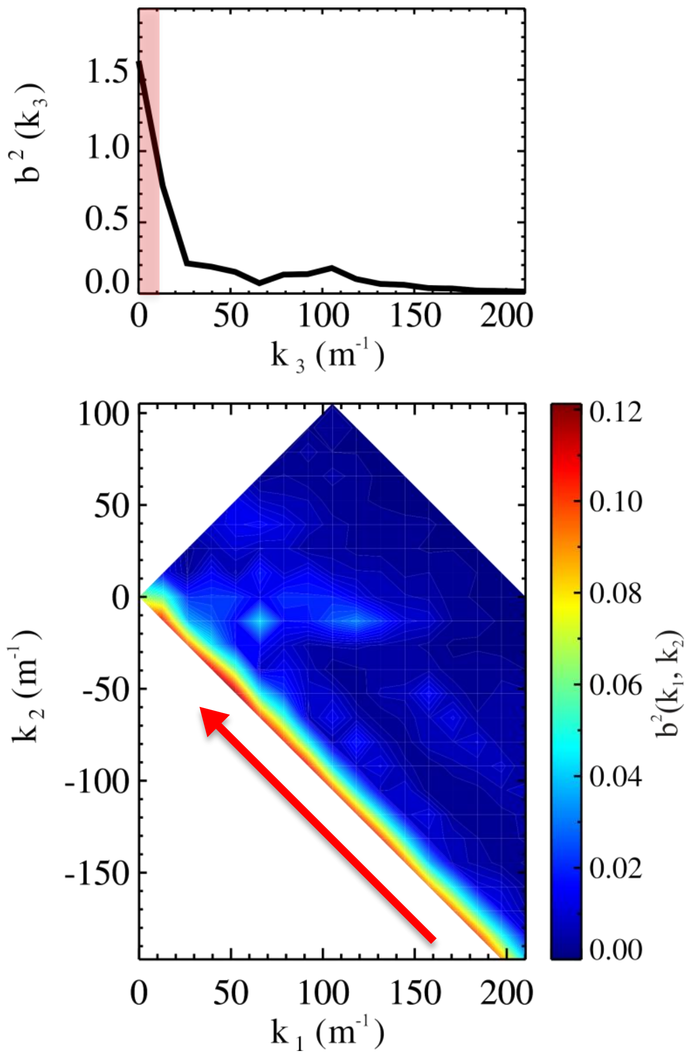
$$b^2_{n,n,\phi}(k_3) = \sum_{k_1,k_2} b^2_{n,n,\phi}(k_1,k_2)\,\delta_{k_1+k_2,k_3}$$

Drift wave - zonal flow coupling

- $b^2_{n,n,\phi}(k_1,k_2)$ and $b^2_{n,n,\phi}(k_3)$ conditional averaged on zonal potential $\langle\tilde{\Phi}\rangle$ with nearly 373k realizations

- Various density modes couple to the zonal flow (k_3 = 0)

- Sign for non-local inverse cascade assumed for drift wave - zonal flow interaction



Time resolved bicoherence

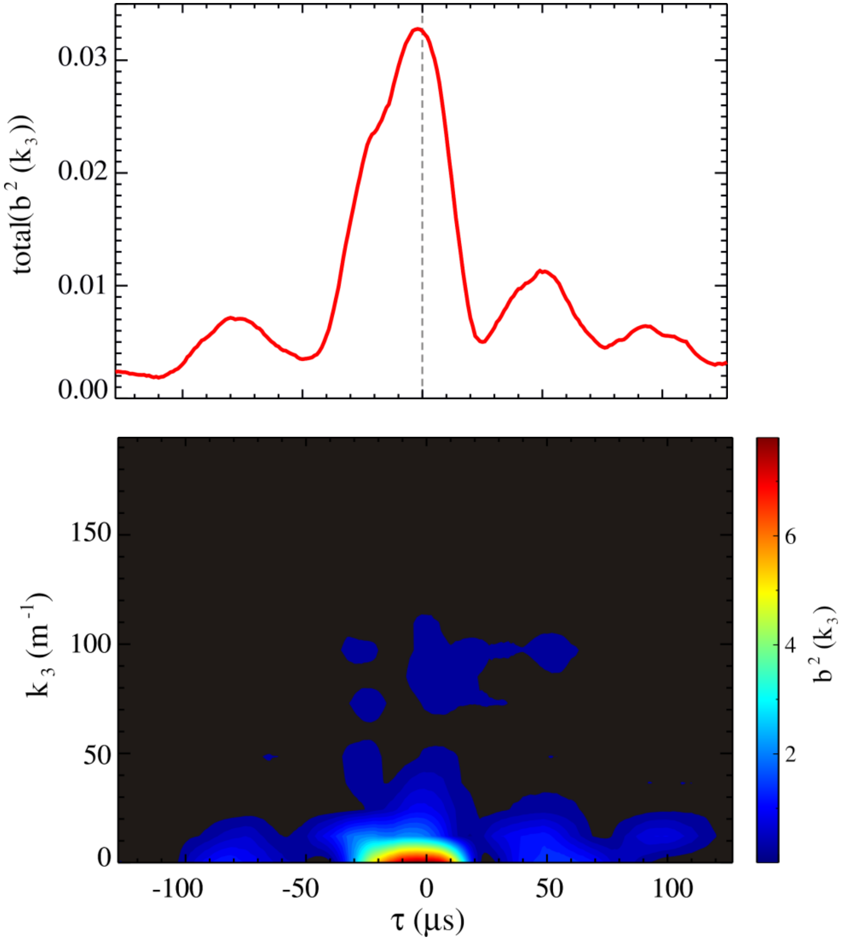
- Time resolved for 256 µs around the zonal-flow occurrence

- Averaged total quadratic bicoherence

$$\sum_{k_3} b^2(k_3) \Big/ \sum_{k_3}$$

- Integrated quadratic bicoherence $b^2(k_3)$

- Strong three-wave coupling around trigger time-point $\tau \approx 0$ µs



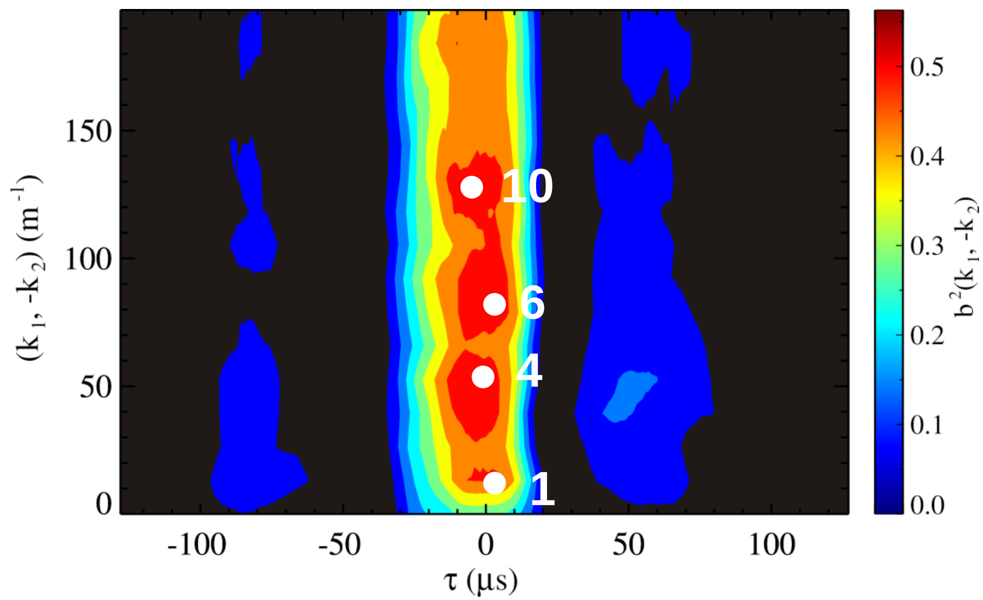
Time resolved drift wave – zonal flow coupling

- Time evolution of all modes which satisfy the resonance condition

$$k_1 + k_2 = 0$$

- Strong coupling around the trigger condition

- Large contributions for density modes with poloidal mode number *m* of 1, 4, 6 and 10



Calculation of the energy transfer with Kim method

- Nonlinear wave-coupling equation

$$\frac{\partial \varphi(k,t)}{\partial t} = \Lambda_k^L(k)\varphi(k,t) + \frac{1}{2}\sum_{k=k_1+k_2} \Lambda_k^Q(k_1,k_2)\varphi(k_1,t)\varphi(k_2,t)$$

- Spectral power transfer equation

$$\frac{\partial}{\partial t} P_k = 2\gamma_k P_k + \sum_{k=k_1+k_2} T_k(k_1,k_2)$$

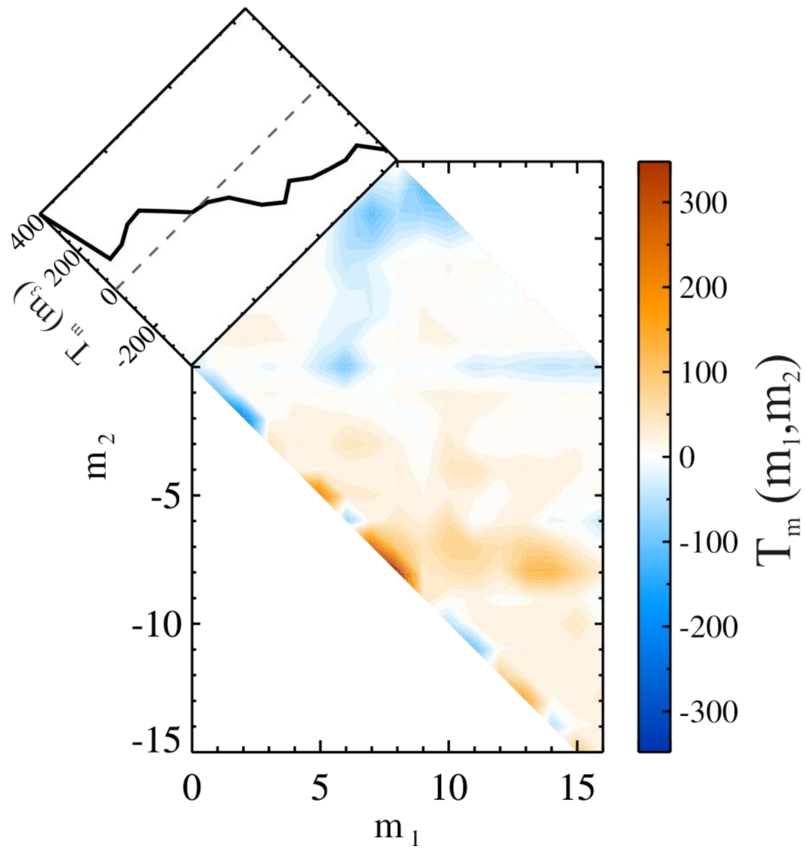
- Nonlinear spectral power transfer function

$$T_k(k_1,k_2) = \mathrm{Re}\left(\Lambda_k^Q(k_1,k_2)\left\langle \varphi(k_1,t)\varphi(k_2,t)\varphi(k,t)^* \right\rangle\right)$$

[J.S.Kim et al, PoP 3 (1996)]

Energy transfer into the zonal flow

- $\varphi(k_1)=n(k_1),\ \varphi(k_2)=n(k_2)$ and $\varphi(k)=\phi(k)$ used for the nonlinear power transfer function T_k
- Conditional averaged on zonal potential $\langle\tilde{\Phi}\rangle$
- Energy transfer to the $m_3 = 0$ potential mode



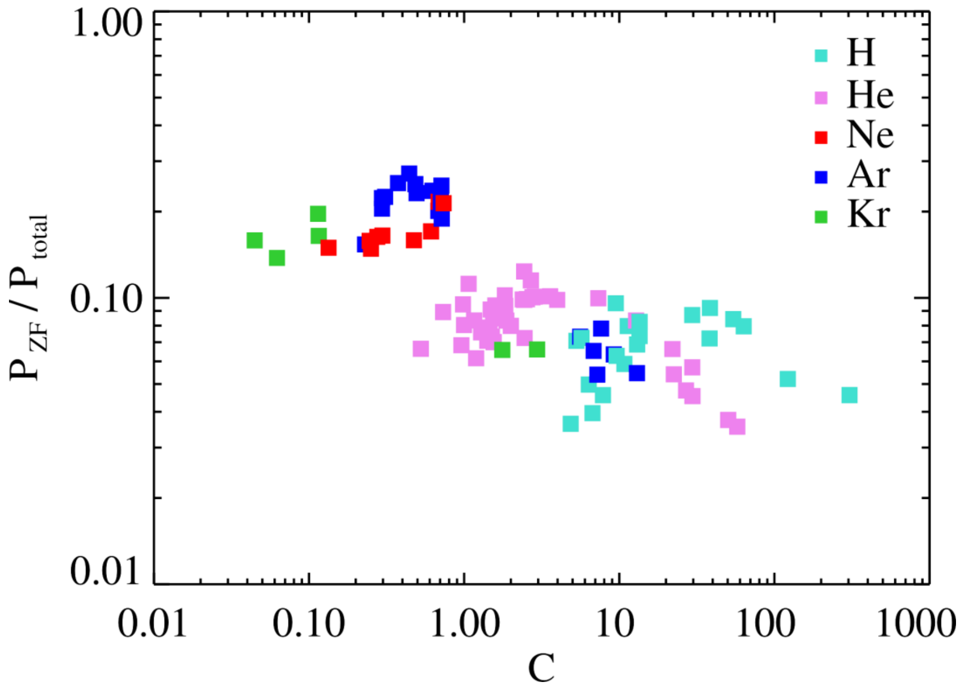
Zonal flow scaling with collisionality

- Collisionality

$$C = \frac{\hat{\nu}_e}{\hat{k}_\parallel^2}$$

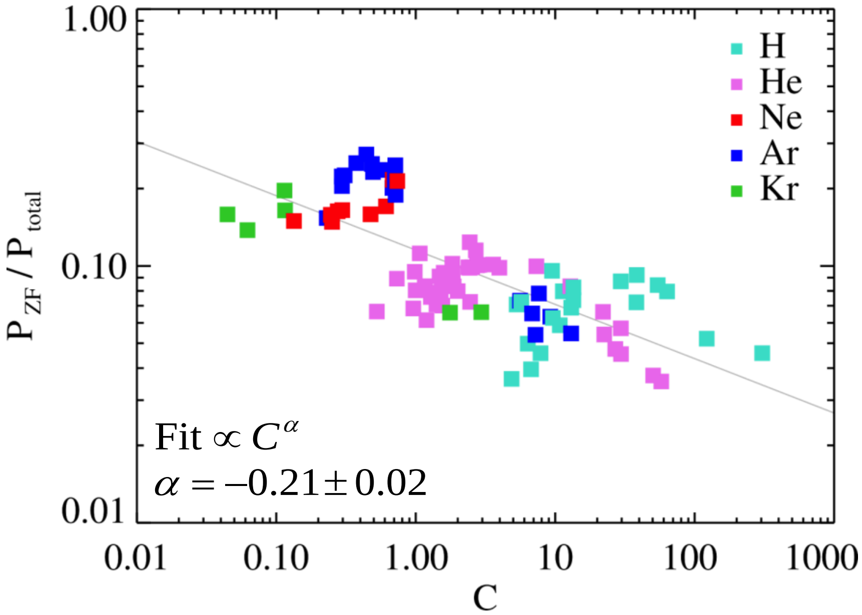
- Normalized electron collision frequency $\hat{\nu}_e$
- Normalized parallel wavenumber $\hat{k}_\parallel$

Relative spectral zonal flow power P_{ZF} / P_{total}

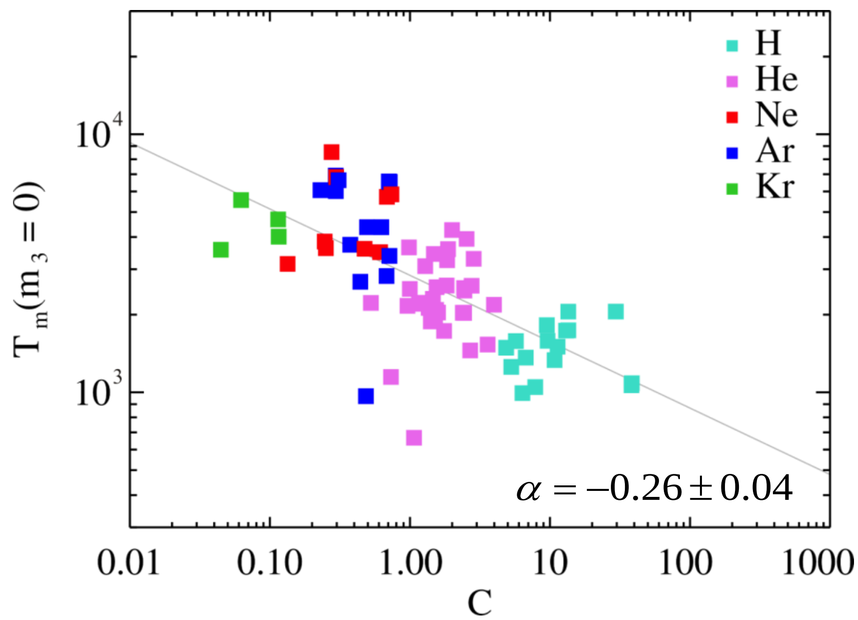


Energy transfer to the m=0 potential mode

Relative spectral zonal flow power P_{ZF}/P_{total}



Energy transfer to the zonal flow $T_m(m_3=0)$



Pseudo-Reynolds stress

- Reynolds stress from potential fluctuations

$$R_\phi = \langle \tilde{v}_x \tilde{v}_y \rangle \sim \left\langle \frac{\partial \tilde{\phi}}{\partial y} \frac{\partial \tilde{\phi}}{\partial x} \right\rangle$$

- Pseudo-Reynolds stress from density fluctuations

$$R_n = \left\langle \frac{\partial \tilde{n}}{\partial y} \frac{\partial \tilde{n}}{\partial x} \right\rangle$$

$$n = \phi - C \underbrace{\left(\partial_t n + \{\phi, n\} + \kappa_n \partial_y \phi\right)}_{A}$$

$$R_n = R_\phi - C\{A, \phi\} + C^2 \partial_x A \partial_y A$$

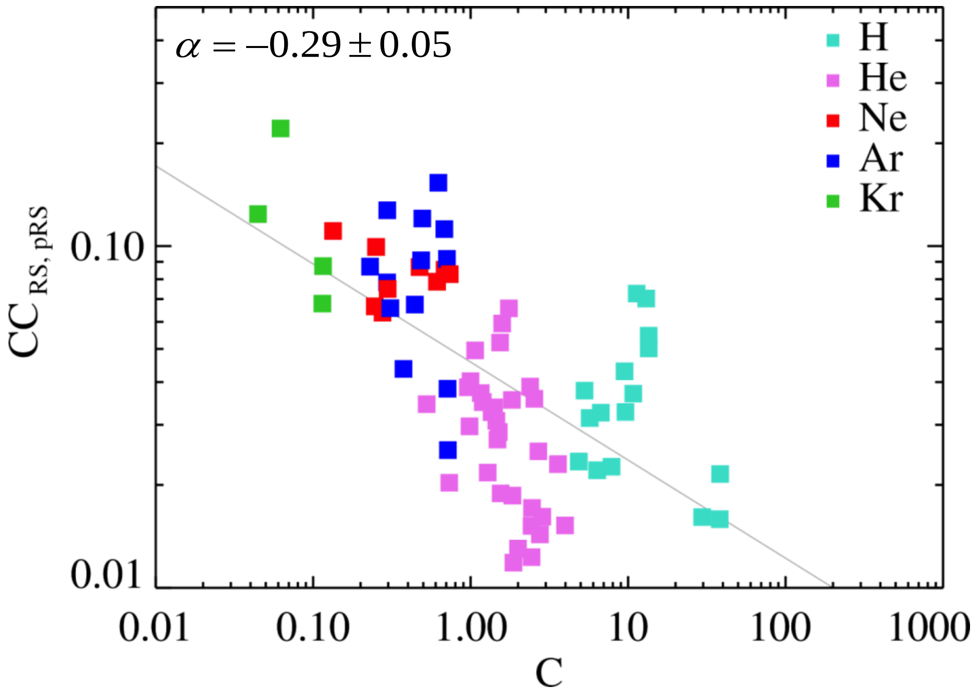
- Calculation of the Reynolds stress- and pseudo Reynolds stress drive

$$-\frac{\partial}{\partial r} R$$

[S.B.Korsholm et al, PPCF 43 (2001)]

Coupling of density and potential

Correlation between Reynolds stress- and pseudo Reynolds stress drive

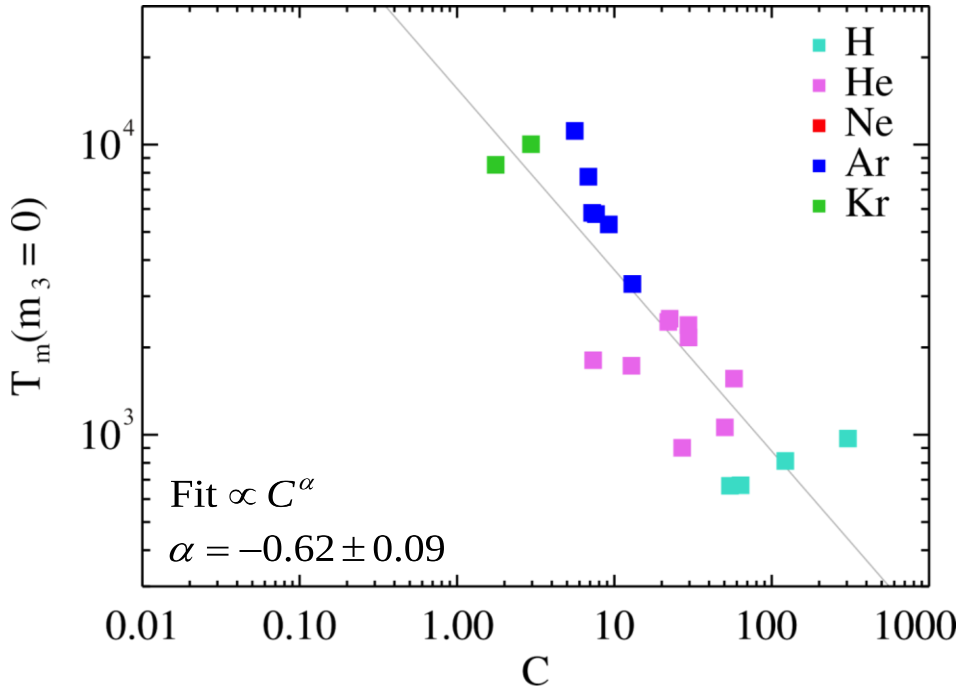


➡ Increased coupling for lower collisionality

Energy transfer at high magnetic field

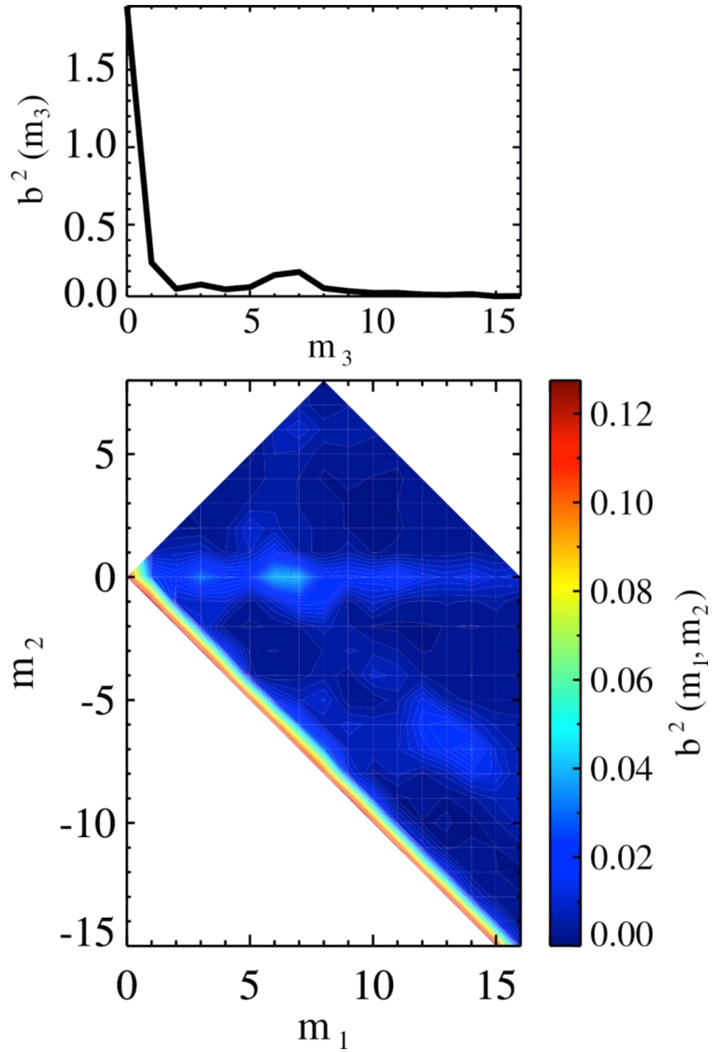
- Energy transfer to the zonal flow $T_m(m_3=0)$ at high magnetic field $B \sim 300\,\mathrm{mT}$

- Stronger increase as for measurements at low magnetic field



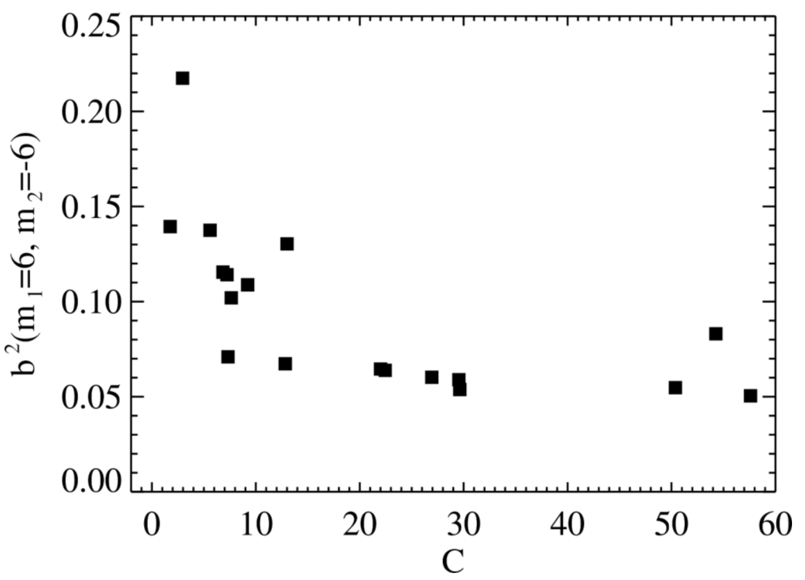
Coupling to the m=6 density mode

- $b^2_{n,n,\phi}(m_1, m_2)$ and $b^2_{n,n,\phi}(m_3)$ conditional averaged on zonal potential $\langle\tilde{\Phi}\rangle$
- Coupling to m=6 density mode
- Distinct coupling for high magnetic field



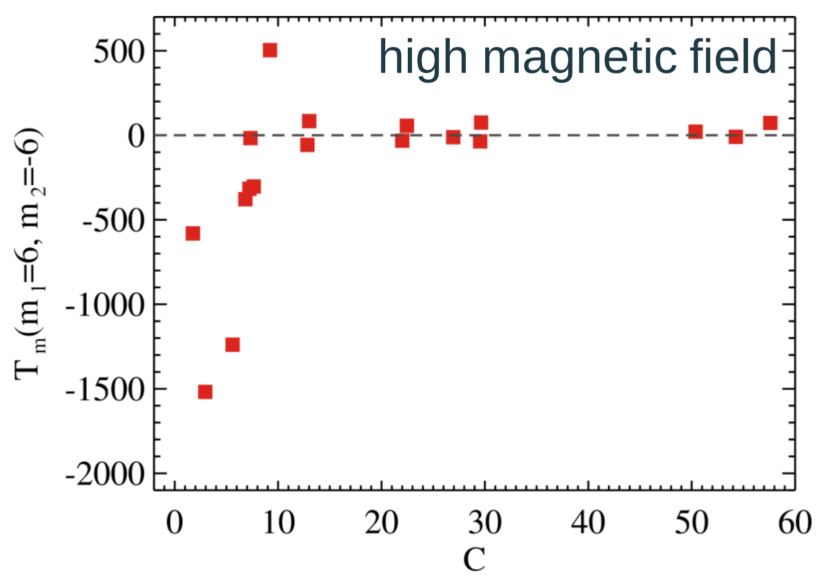
Energy transfer to the m=6 density mode

Crossbicoherence of m=6 mode



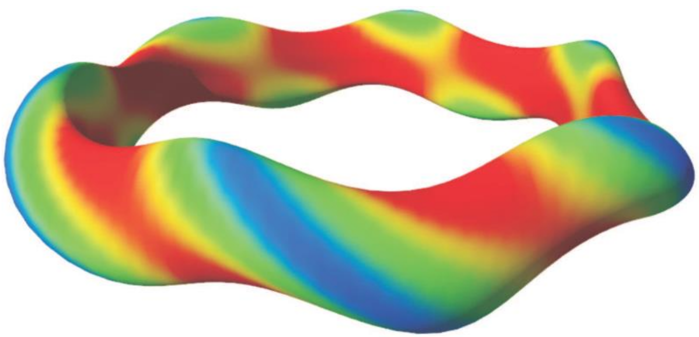
Energy transfer to the m=6 mode

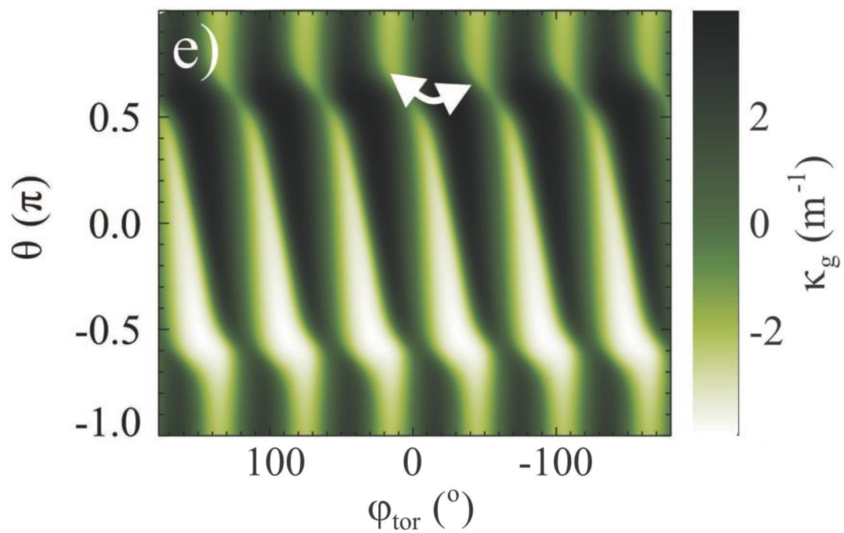
$T_m(m_1=6, m_2=-6)$



Magnetic field with sixfold symmetry

Magnetic field strength |B| and geodesic curvature κ_g on a flux surface

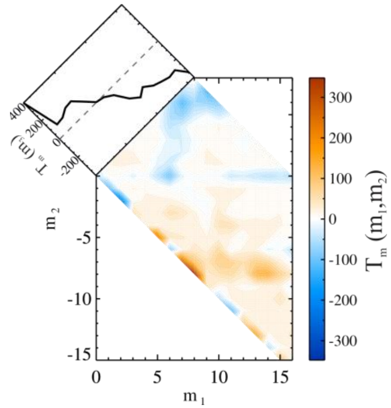


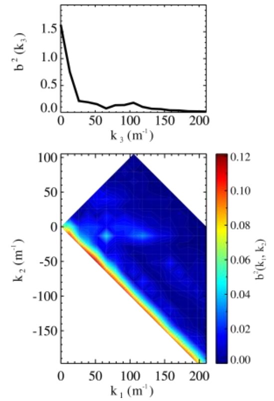


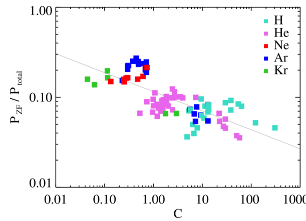
[G.Birkenmeier, Dissertation (2012)]

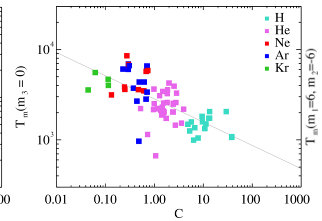
Summary

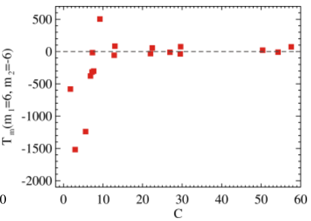
- Time resolved nonlinear drift wave – zonal flow coupling in k-space
- Energy transfer to the zonal flow calculated with Kim method
- Increased energy transfer to the zonal flow and to the m = 6 density mode for lower collisionality
- Increased crosscorrelation between Reynolds stress- and pseudo Reynolds stress drive indicates stronger coupling

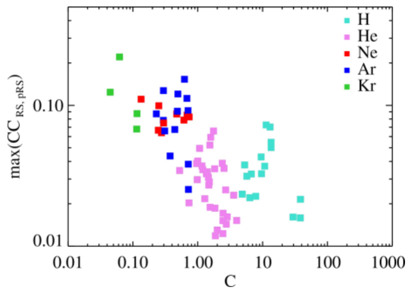




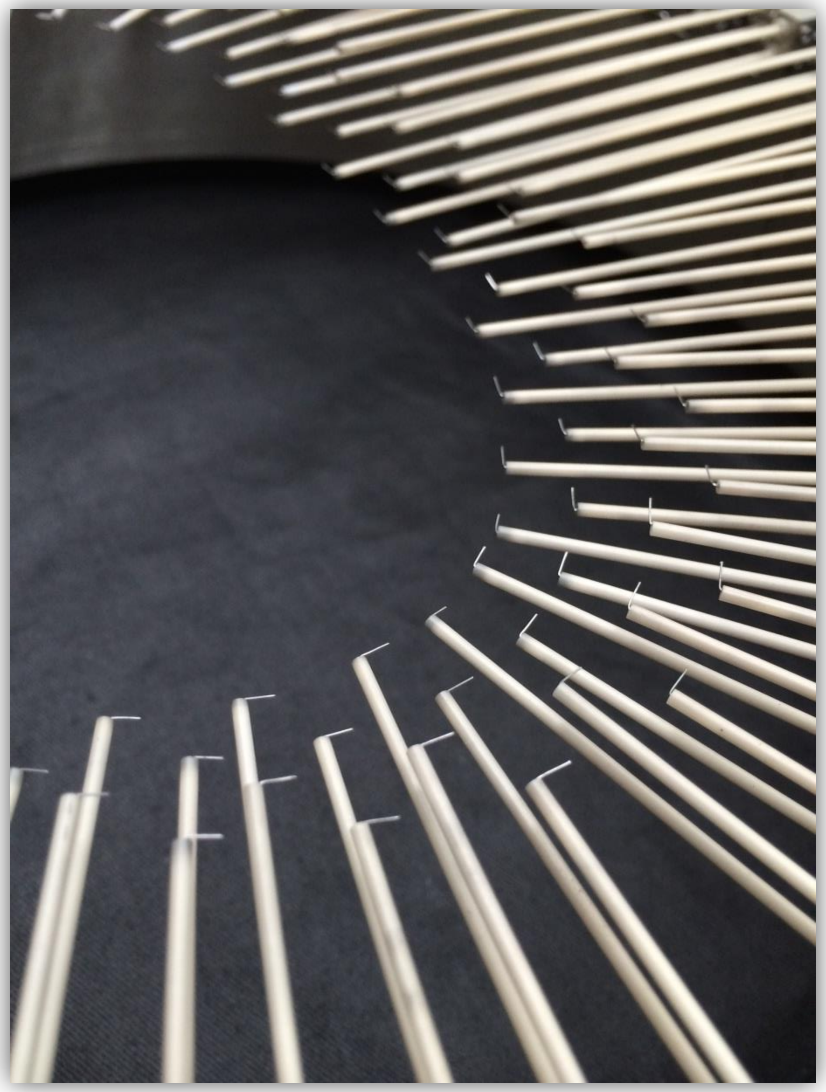








Thank you for your attention!



Zonal flow drive

- Zonal-flow drive equation:

$$\frac{\partial}{\partial t}\langle v_\theta \rangle = -\frac{\partial}{\partial r}\langle \tilde{v}_r \tilde{v}_\theta \rangle$$

- The Reynolds-stress drive is maximal before the trigger time-point

- The flow velocity follows the Reynolds-stress drive phase shifted