Electrostatic instabilities, turbulence and fast ion interactions in a simple magnetized plasma

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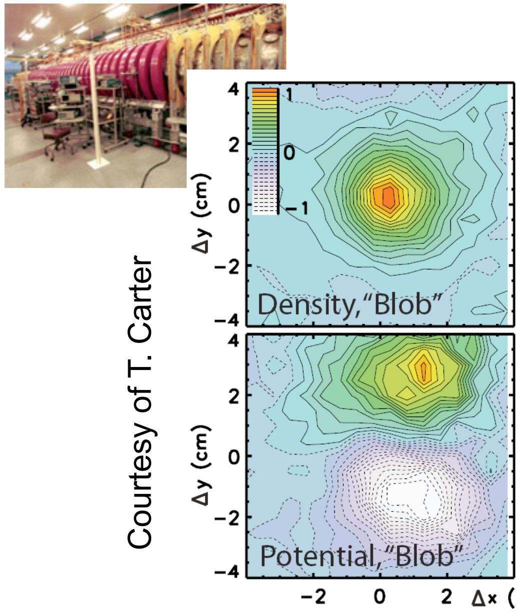
An important *basic* problem for fusion

Intermittent transport in edge plasma

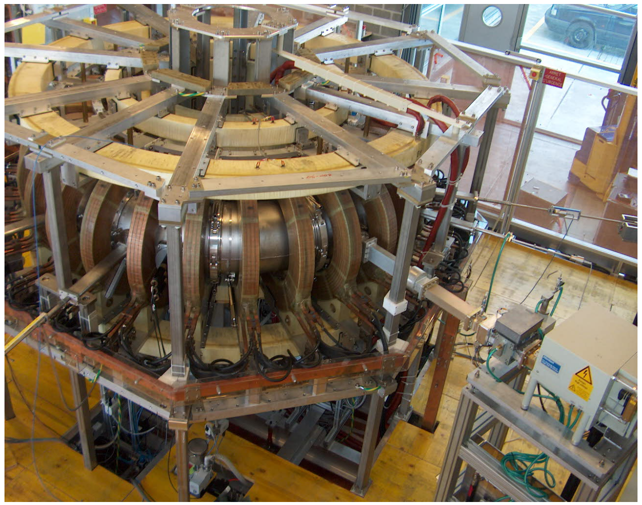
→ plasma-wall interactions, divertor efficiency, confinement

→ observed in many devices and configurations

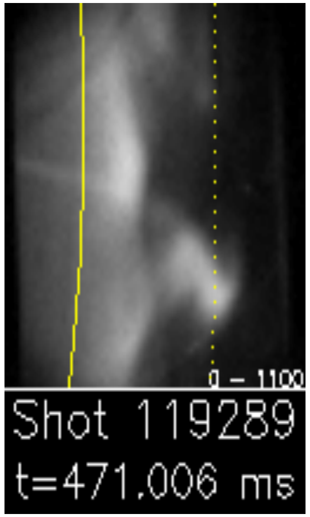
LAPD



TORPEX

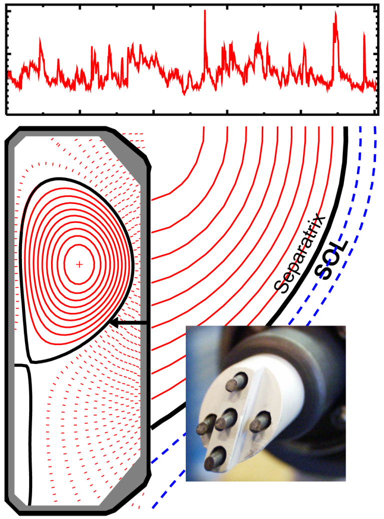


NSTX L-mode



Courtesy of R. Maqueda

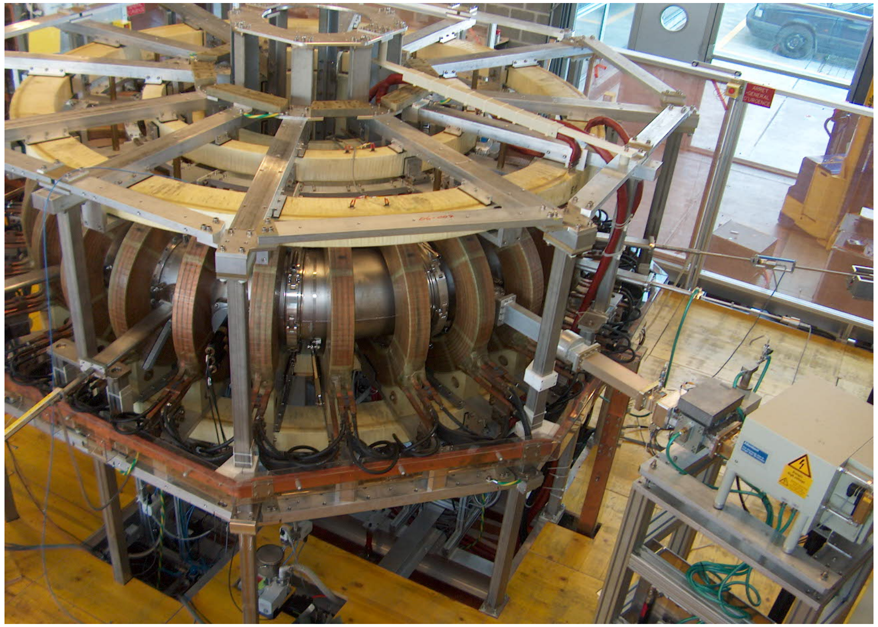
TCV L-mode

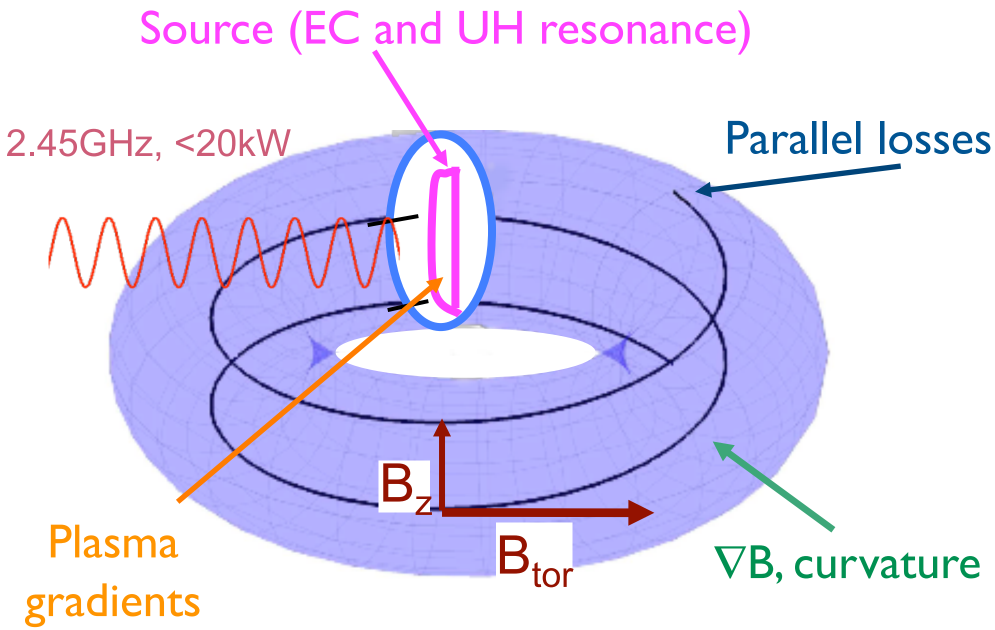


Linear devices… **complexity** **…tokamak devices…**

Linear devices	Complexity	Tokamak devices
Open field lines	Open field lines	Topology change edge/SOL
	∇B, curvature	∇ B, curvature
	→ *Model validation*	Rotational Transform

The TORPEX device – simple paradigm of tokamak SOL





- Plasma produced by EC-waves
- Open field lines - no plasma current
- Extensive diagnostic coverage for turbulence and plasma response
- ∇B, curvature, pressure gradients

R = 1 m; a = 0.2 m

H_2, D, He, Ne, Ar plasmas

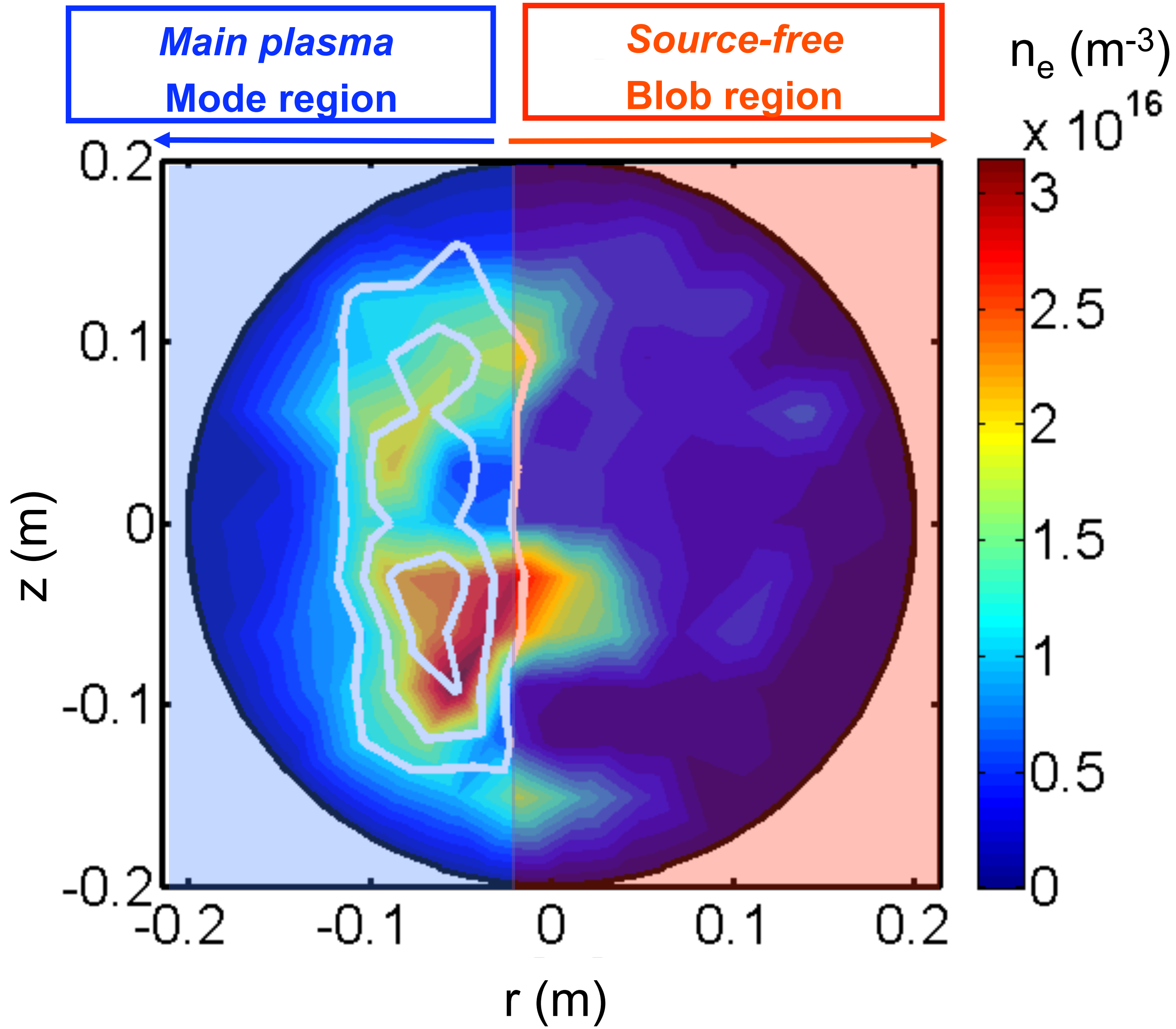
B_{tor} ≤100 mT; B_z ≤10 mT; $\rho_s/a \sim 0.02$

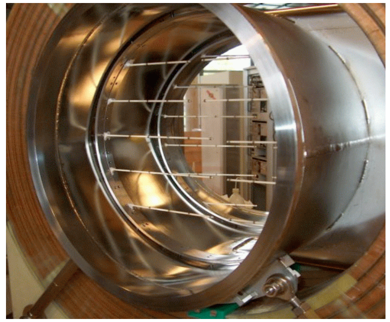
T_e = 2–20 eV; n_e = 0.1–5x10^{16} m^{-3}

→ Complete characterization of turbulence in conditions relevant to tokamak SOL

A. Fasoli et al., PoP (2006)

Target plasma

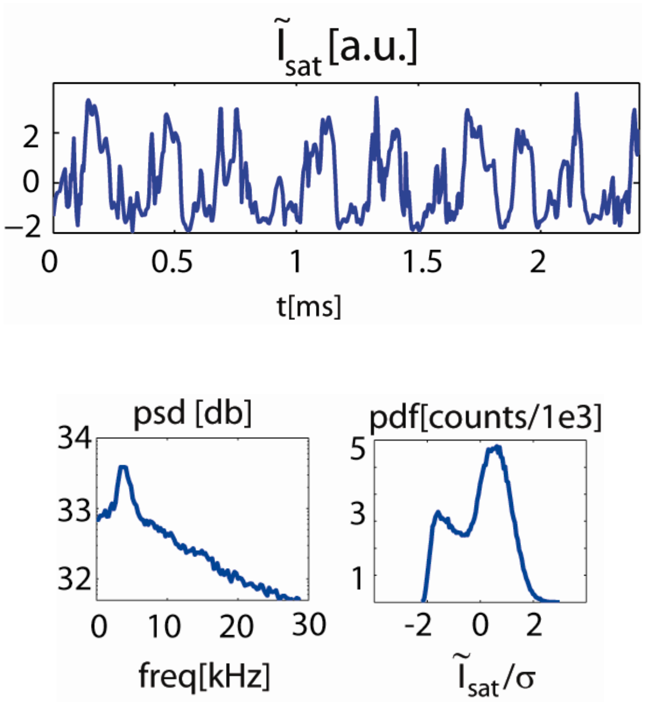




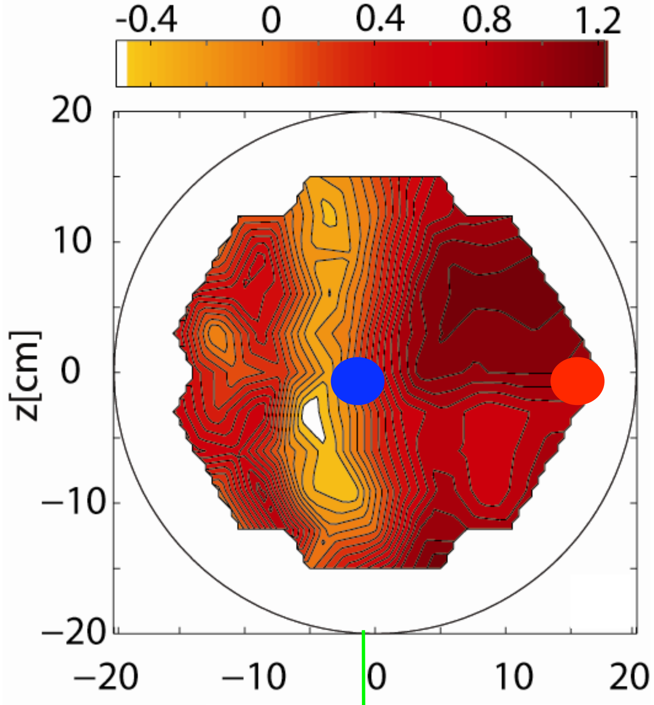
- H_2 plasma
  - P_{rf} = 400 W
  - B_{tor0}=76mT; B_z=2.1mT
  - p_{gas}= 6.0 x 10^{-5} mbar
- Elongated profiles with strongly sheared v_{ExB}

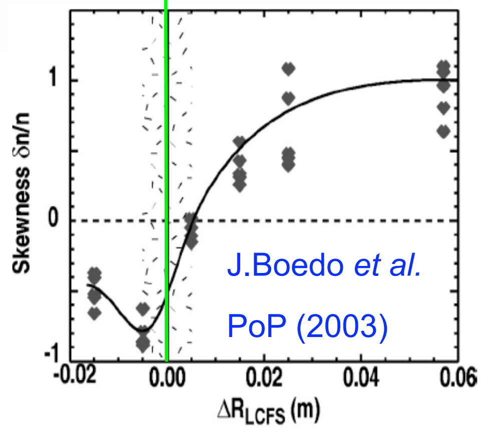
Statistical and spectral properties of density fluctuations

Mode region

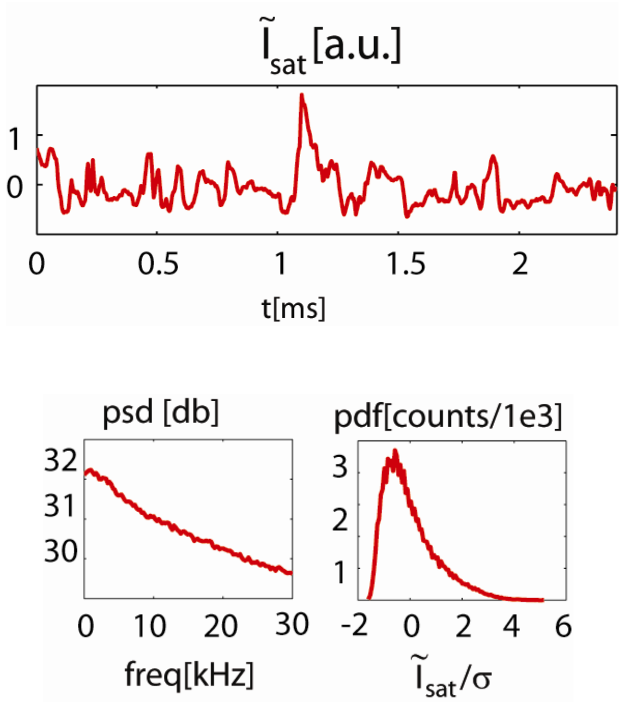


Skewness of I_{sat} signals





Blob region



- Quasi-coherent oscillations
- Mode ~4kHz
- Double-humped pdf

- Intermittent events
- Broad-band spectra
- Positively-skewed pdf

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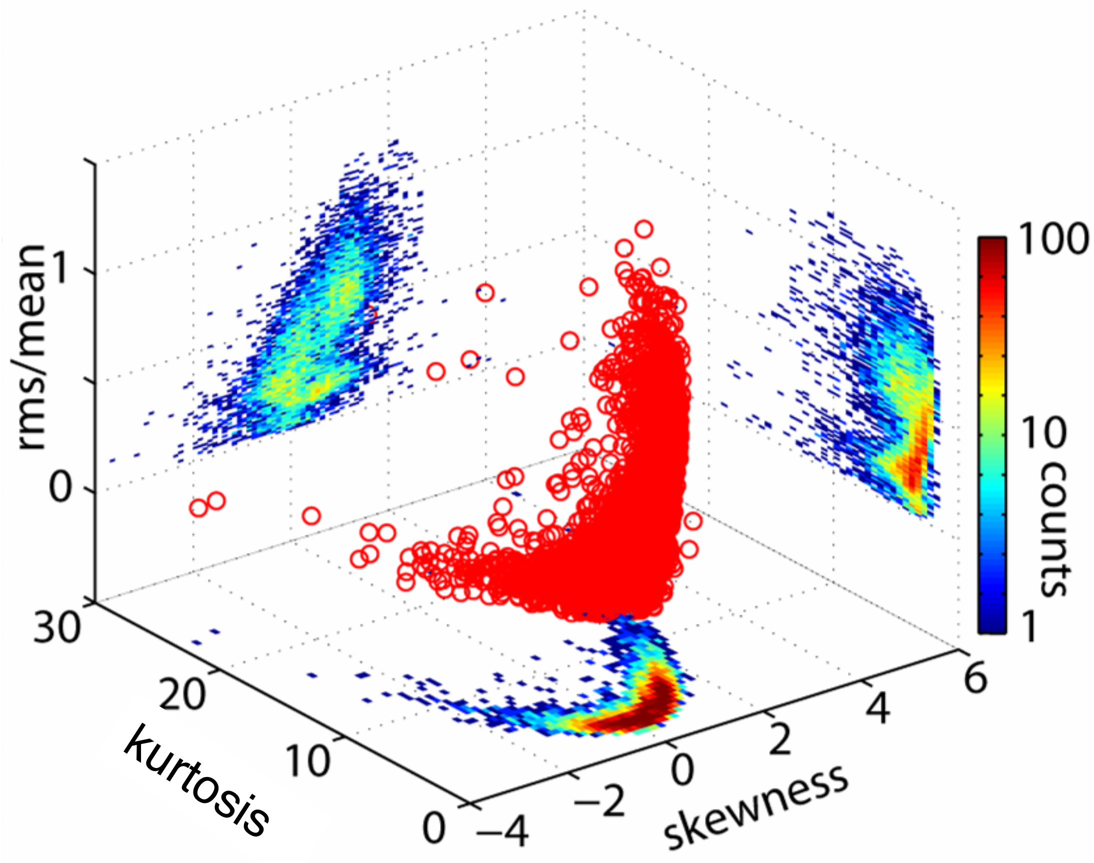
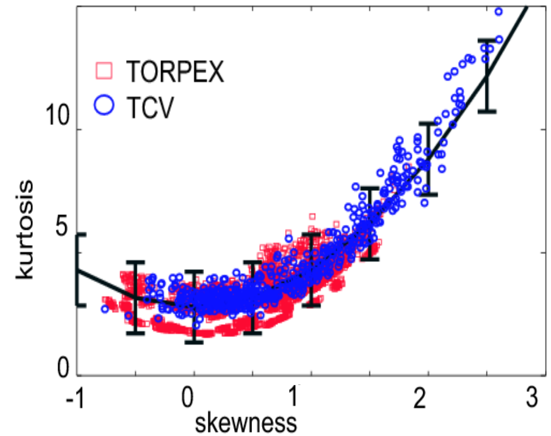
Universality in fluctuations



- ~10000 signals of I_{sat}
  - H_2, He, Ar; pressure and B_z scans
- 1% < $\delta n_e/n_e$ < 95%
- ~800 signals from TCV edge / SOL plasmas (L-mode) give similar results



- Unique PDF: Beta distribution
- Unique relation Kurtosis vs. Skewness: **$K = 1.5\ S^2 + 2.8$**
  - Common to a variety of fluctuation phenomena with convection, e.g. surface T waves in ocean

B. Labit *et al.*, PRL (2007); PPCF (2007)

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Questions addressed

- What kind of modes are responsible for the turbulence ?
- How are macroscopic structures (blobs) generated ?
- How do blobs propagate? Can their dynamics be influenced/controlled ?
- What are the consequences, in terms of
  - Plasma flow/rotation?
  - Transport for non-thermal plasma particles (fast ions) ?
- How can these results be used to validate theoretical models ?

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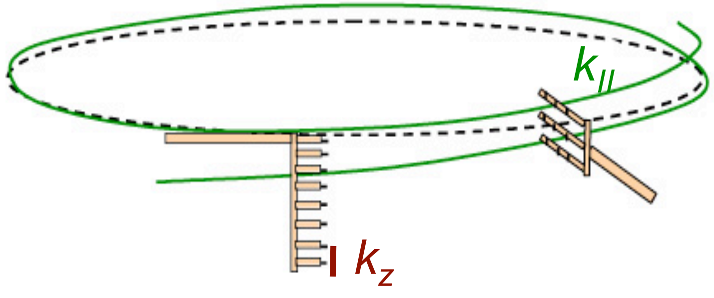
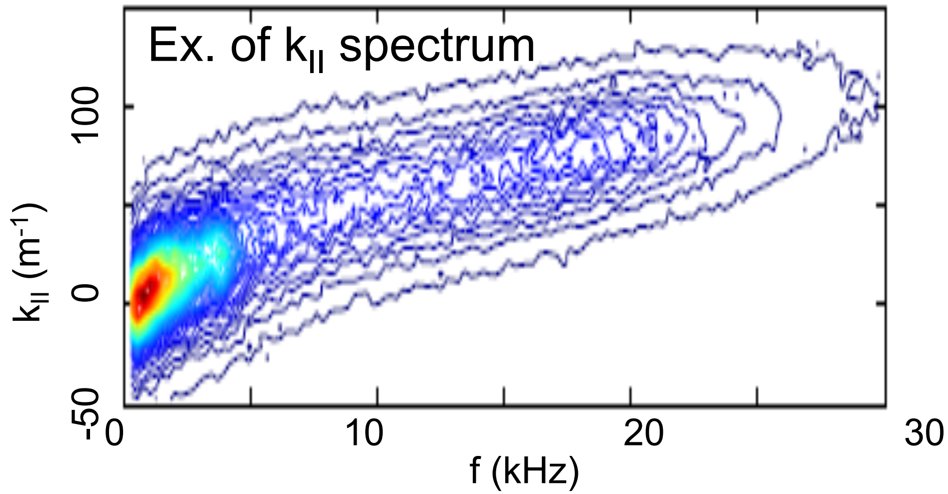
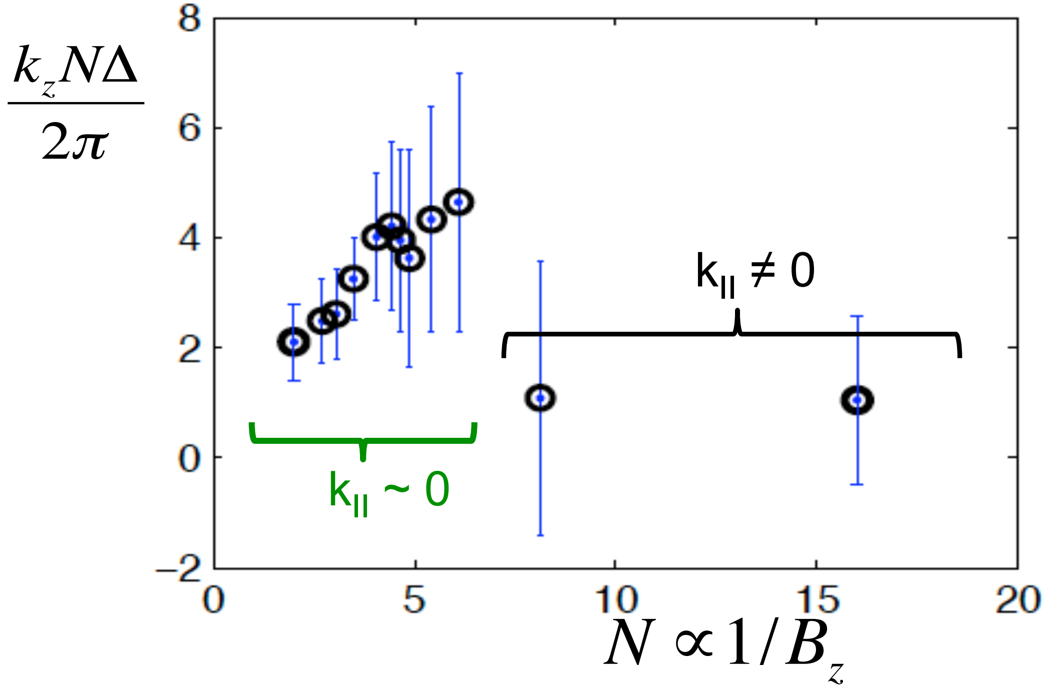
Nature of instabilities: measured dispersion relation

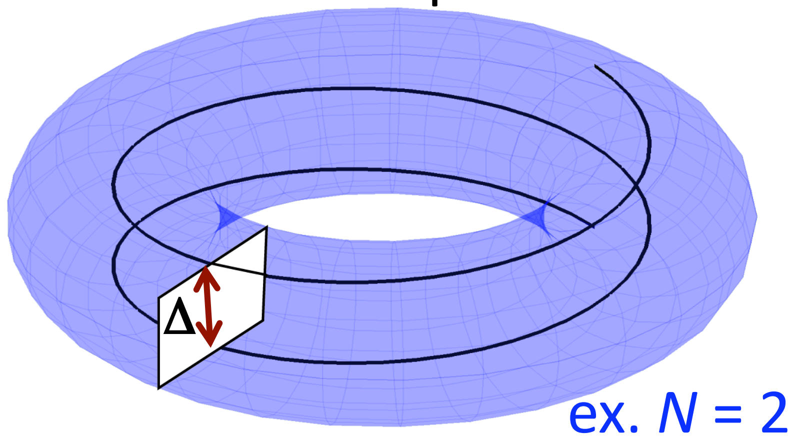
Statistical analysis of 2-points correlations





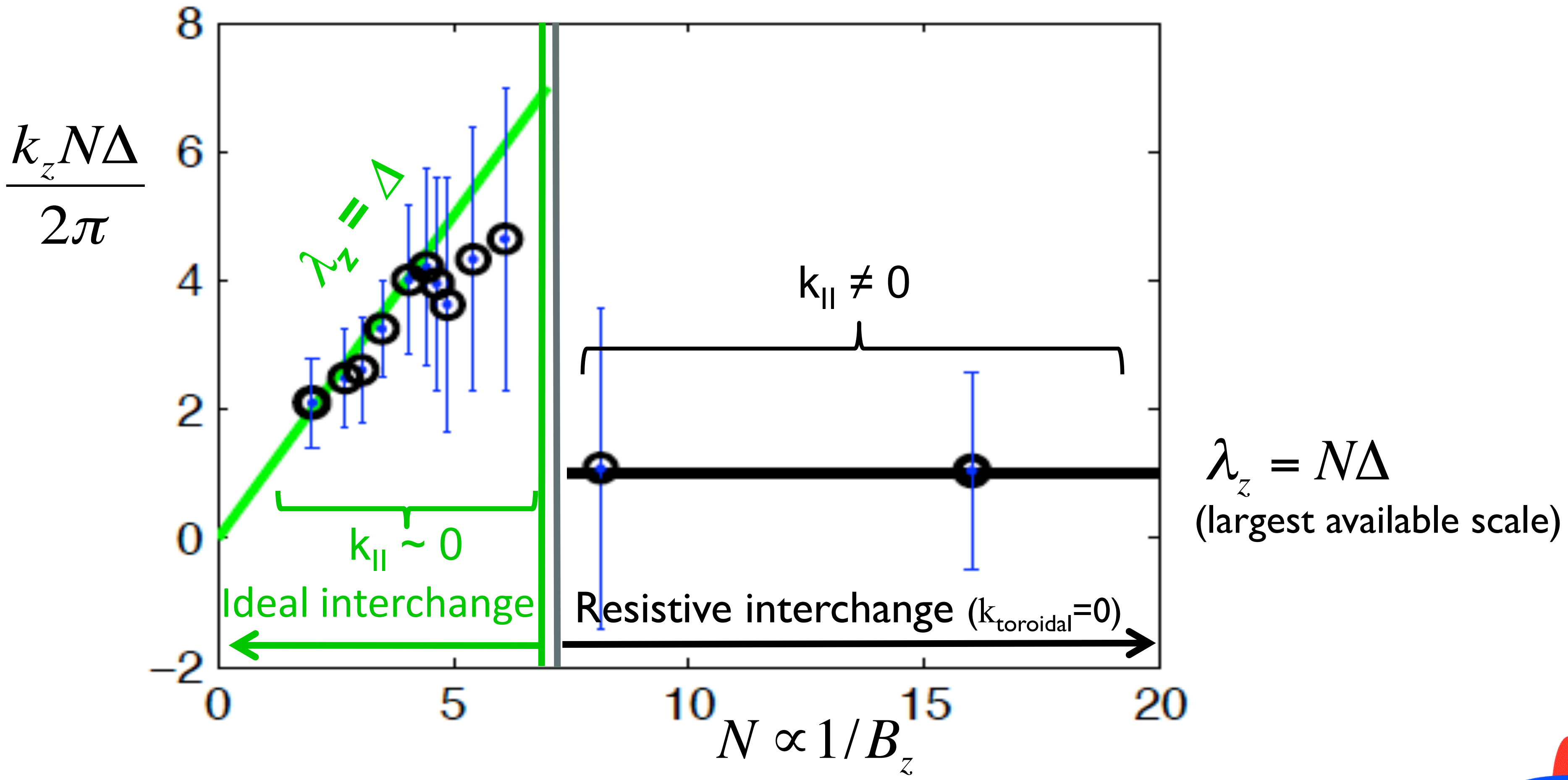


N = number of field line turns
Δ = vertical distance between field line return points



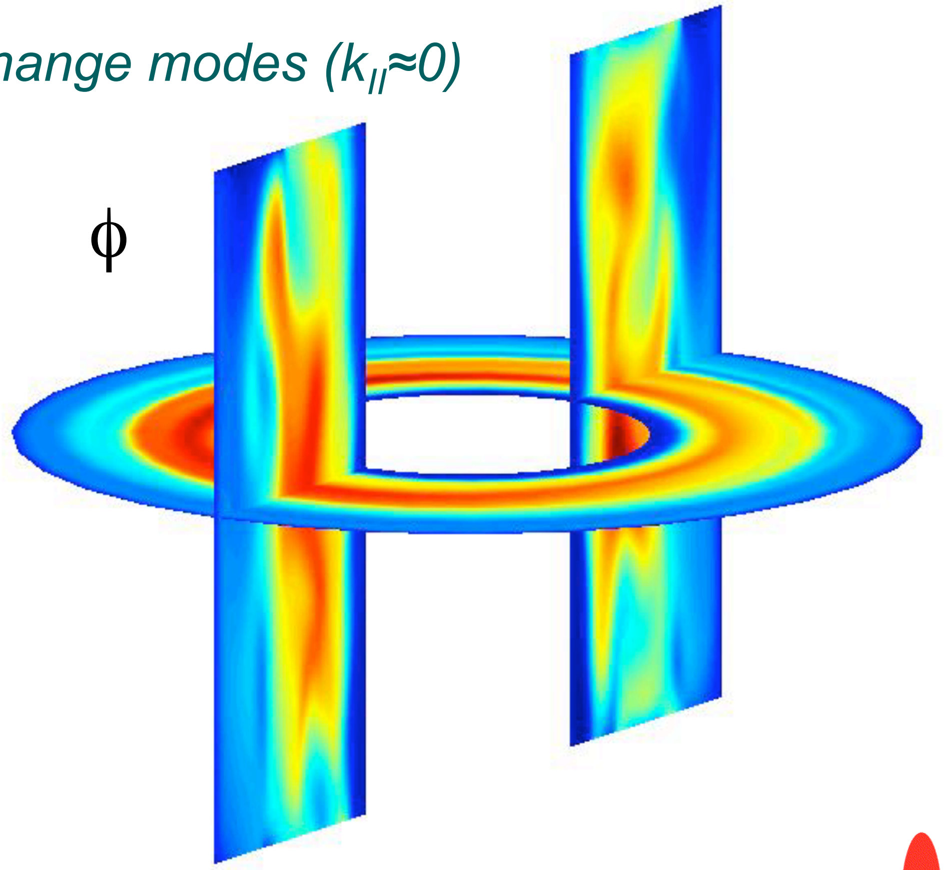
Interpretation of meas. dispersion relation – fluid model

Collisional Plasma → **Braginskii model** → $\rho_i << L$, $\beta << 1$, $\omega << \Omega_{ci}$ → **Electrostatic drift-reduced Braginskii eqs. for n, T_e, vorticity**



- What kind of modes are responsible for the turbulence?
  - Pure interchange, resistive interchange or drift waves, depending on pressure gradient and vertical magnetic field
  - *We will concentrate on pure interchange modes ($k_{//}$≈0)*

3D global simulation
N=2



F.M.Poli, *et al.*, PoP (2006); PoP (2007); PoP (2008); PhD Thesis

A.Diallo *et al.*, PoP (2007)

L.Federspiel *et al.*, PoP (2009); Master Thesis

P.Ricci *et al.*, PoP (2009); PRL (2008); PRL (2010)

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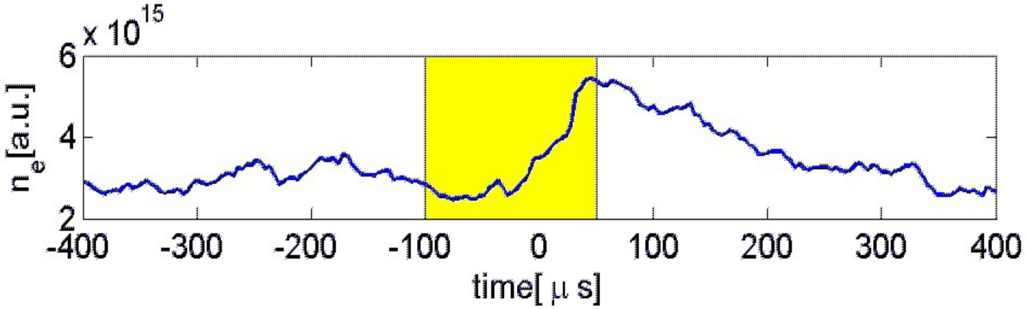
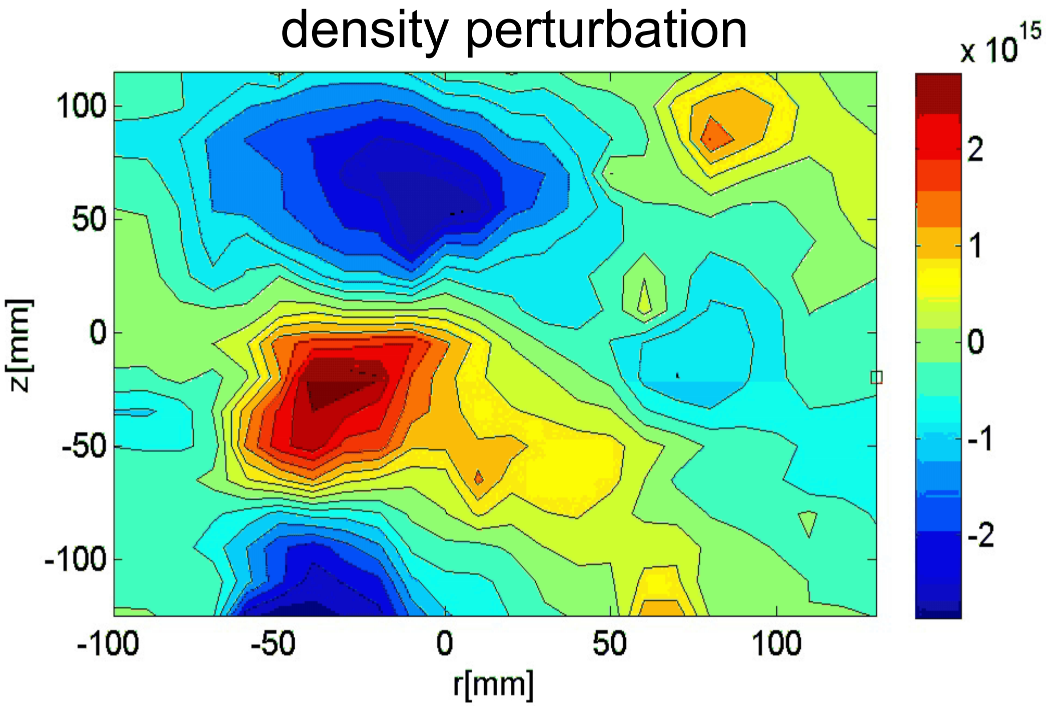
Dynamics of blob ejection





S.H.Müller, *et al.*, PoP (2007); PhD Thesis
I.Furno *et al.*, PRL (2008); PoP (2008)
C.Theiler *et al.*, PoP (2008); A.Diallo *et al.*, PRL (2008)

- Time resolved 2D profiles of n_e, T_e, ϕ_{pl} from conditional sampling
- Coherent structures move with v_{ExB}
- Radially elongated structures form from positive cells
- ExB flow shear breaks off the structures and forms blobs
  - Structures form in ~100 μs ~ estimated shearing time

$$\frac{1}{\tau_{sh}} = \frac{k_z L_r}{2\pi} \frac{\partial V_{ExB,z}}{\partial r} \sim (100\mu s)^{-1}$$

H. Biglari *et al.*, PF B (1990)

- Energy is transferred from shear flow to blobs

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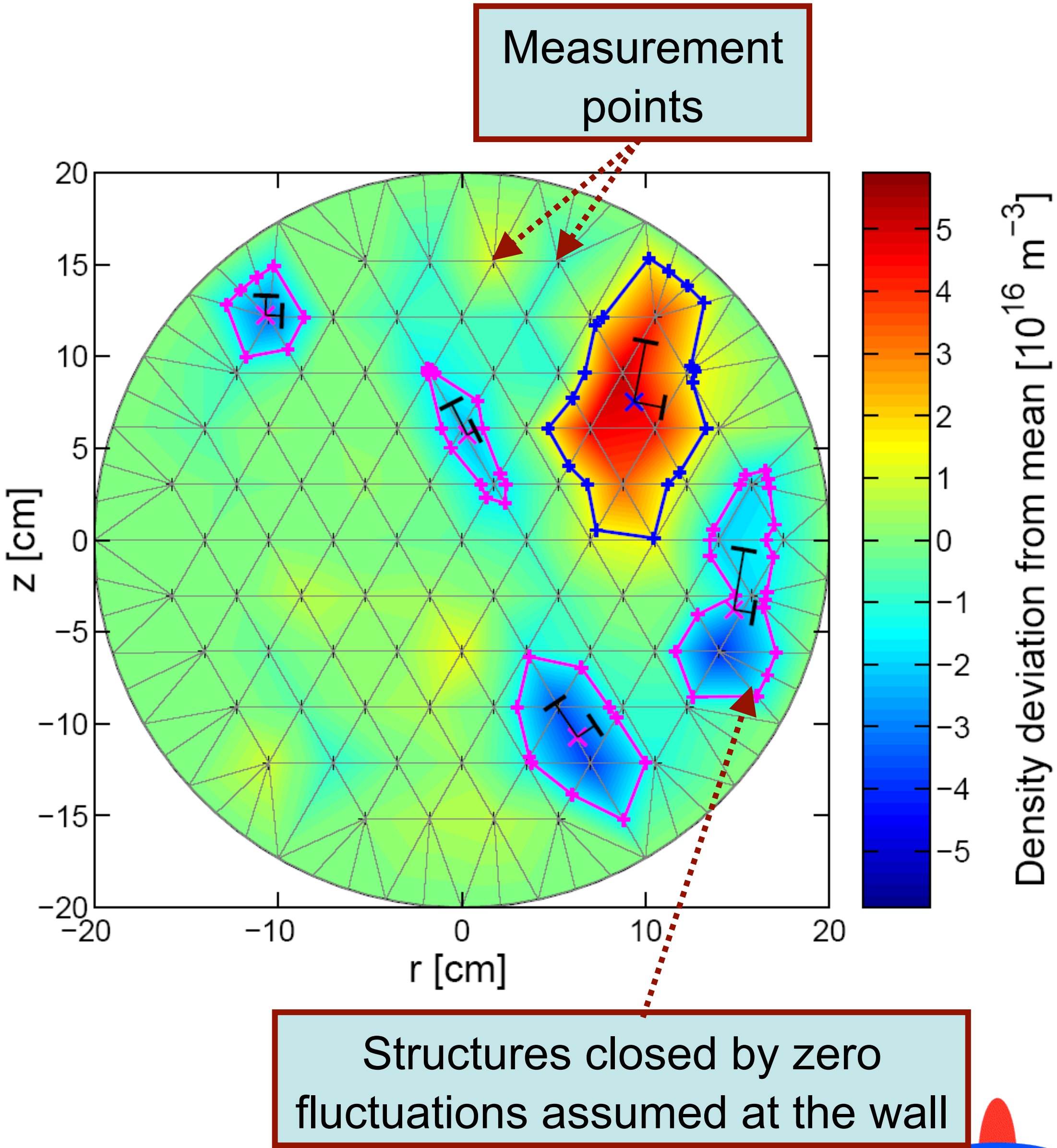
Analysis of spatiotemporal structures

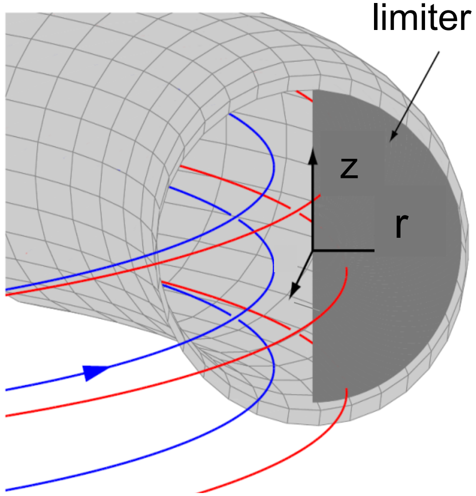
- "Structures": regions where signal exceeds threshold value
  - E.g. $|\delta n| > \sigma_{tot}(n)$
- Threshold intersection contours for each time frame
  - Linear interpolation on triangulated mesh
  - Assume zero fluctuations at wall
- Approach
  - Define *structure observables*
  - Characterize *all structures*
  - Statistical analysis in terms of structure observables



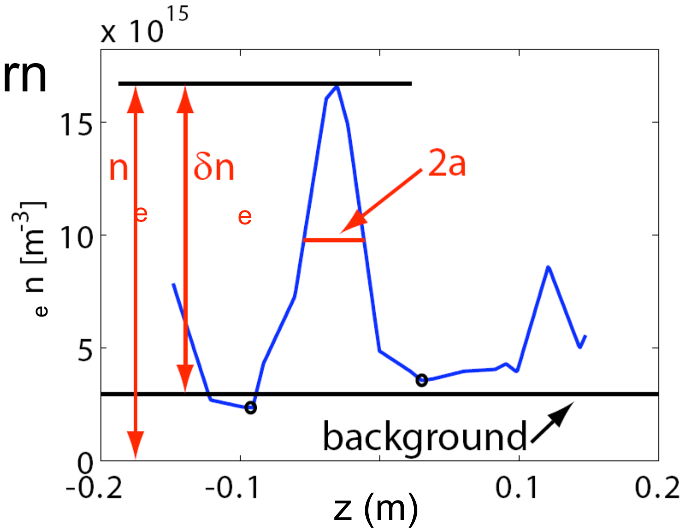
S. H. Müller *et al.*, PoP 2006; PhD Thesis

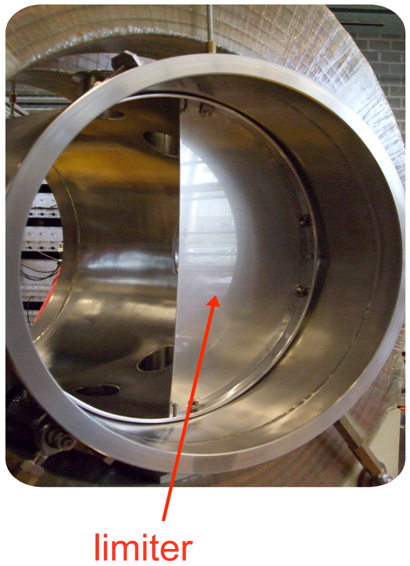
Motion of filaments/blobs in simple geometry

- Steel limiter on low-field side, defining region with
  - Constant curvature along field lines and connection length (~2πR)
  - Near-perpendicular incidence of B-field lines, no magnetic shear



- Blobs identified by pattern recognition, providing
  - Radial velocity v
  - Vertical size a
  - Density δn_e, n_e





C. Theiler *et al.*, PRL 2009; PhD Thesis

Joint probability of blob velocity – size

Generalization of 2D blob models and scaling laws

- Blob motion determined by balance between ExB and mechanisms compensating curvature-driven charge separation

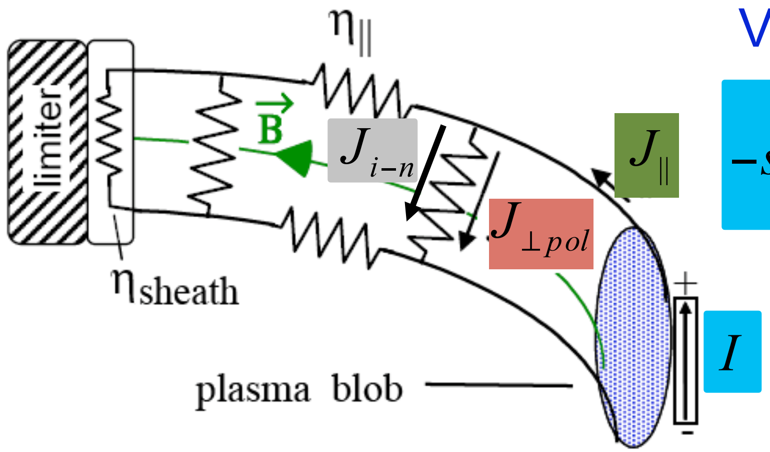


Fig. from Krasheninnikov et al.

Vorticity equation

$$-sign(B_z)\frac{2c_s^2 m_i}{RB}\frac{\partial n_e}{\partial z} = \frac{n_e m_i}{B^2}\frac{D}{Dt}\nabla^2\phi - \frac{n_e e^2 c_s}{T_e L}\tilde{\phi} + \frac{n_e m_i}{B^2}\nu_{in}\nabla^2\phi$$

$$\tilde{v}_{blob} = \frac{\sqrt{2\tilde{a}}}{1 + \sqrt{2\tilde{a}}^{\,5/2} + \tilde{\eta}\sqrt{\tilde{a}}}\frac{\delta n_e}{n_e}$$

Normalizations

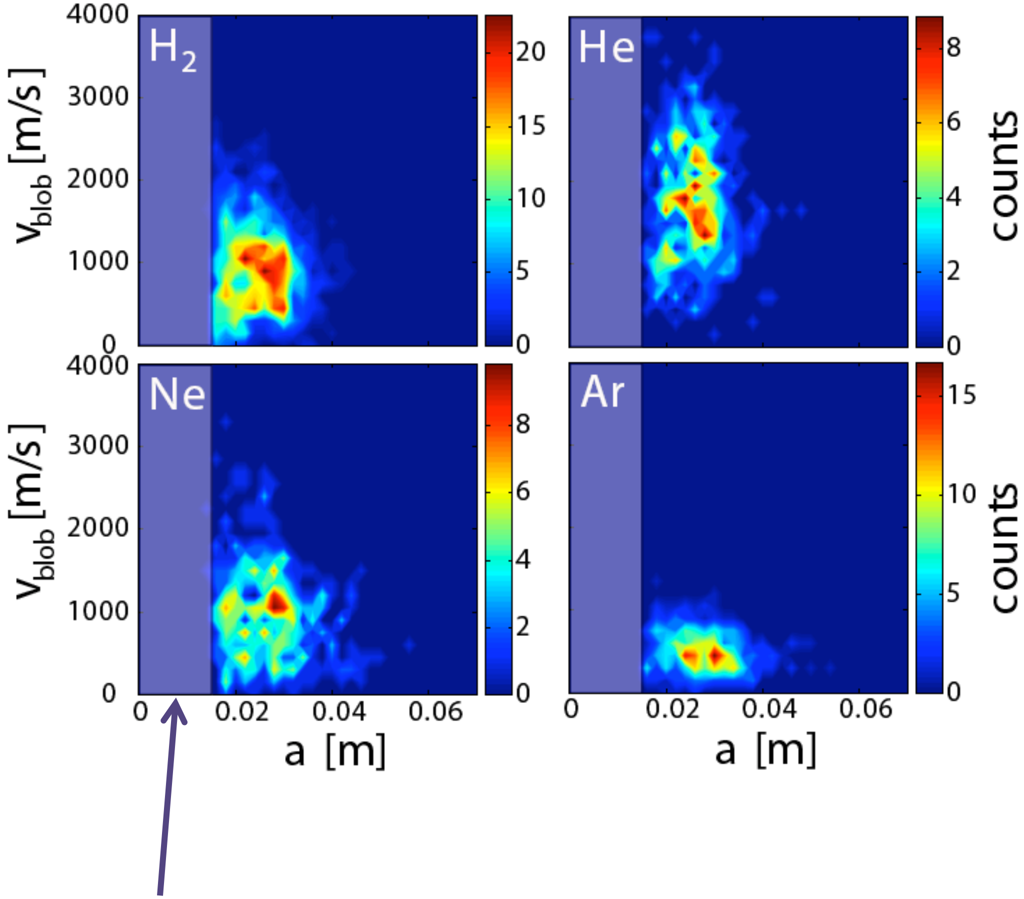
$$velocity = \left(\frac{2L\rho_s^2}{R^3}\right)^{1/5} c_s$$

$$size = \left(\frac{4L^2}{\rho_s R}\right)^{1/5} \rho_s$$

[1]S.I.Krasheninnikov, PLA 2001; [2]O.E.Garcia *et al*., PoP 2005; [3]J.R Myra and D.A.D'Ippolito, PoP 2005;[4]N.Katz et al., PRL 2008

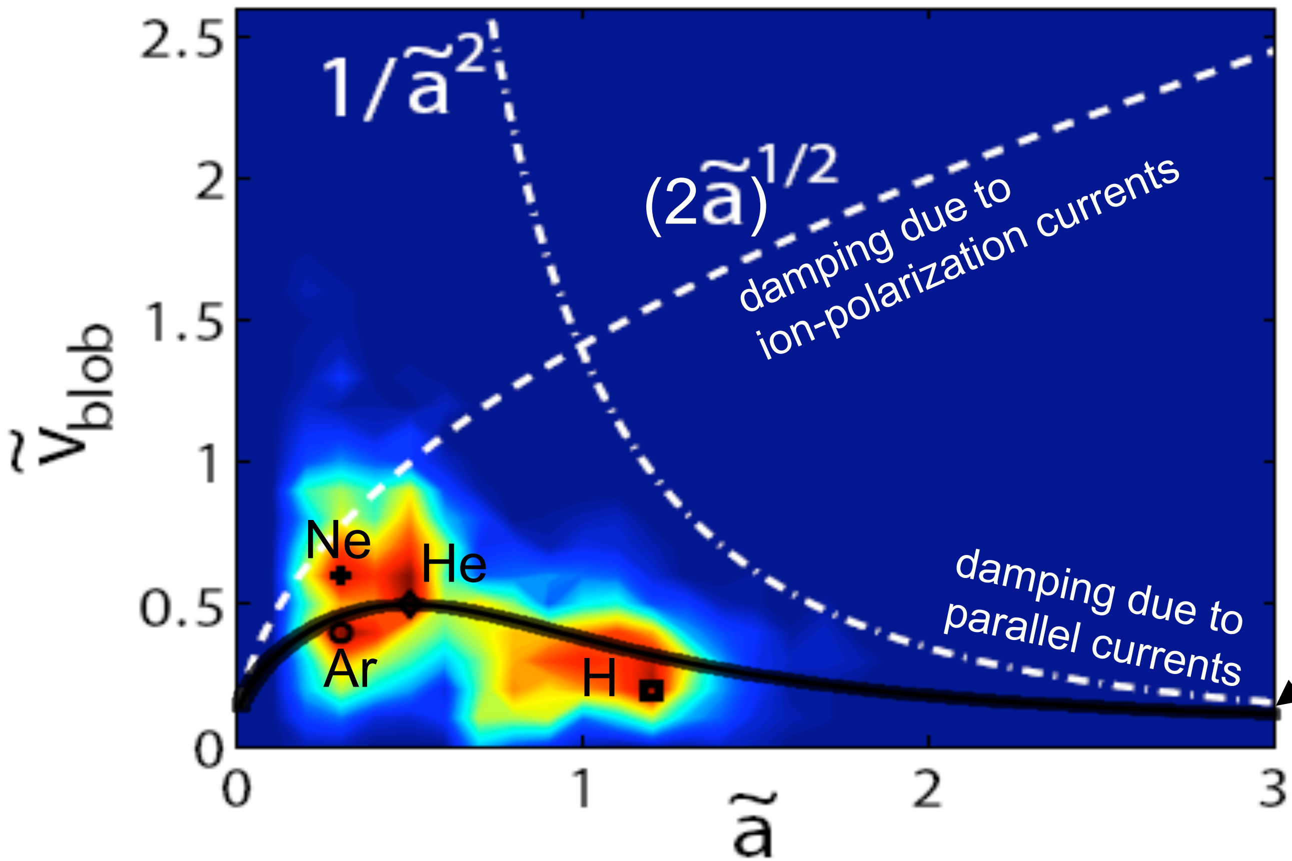
Joint probability of blob velocity – size

- Similar sizes in all gases
- Similar values of $\delta n/n$
- Mean velocity of blobs over their entire trajectory
- Significant differences in the typical velocity, ranging from 500 m/s (Ar) to 2000 m/s (He)



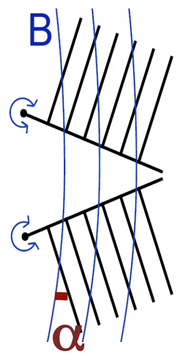
Range of blob sizes below diagnostic resolution

Agreement with generalized 2D blob model



Generalized model including parallel and cross-field currents, ion-neutral collisions

- Parallel electron current should depend on angle α between B-field lines and wall R.H.Cohen and D.D.Ryutov, PoP 1995; CPP 2006
- Idea for blob control: limiter with perpendicular tiltable plates



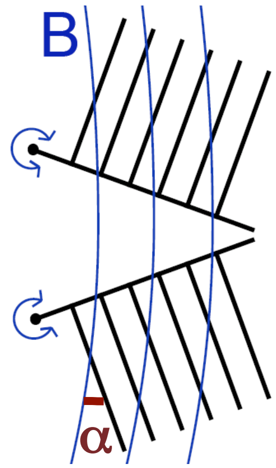
C. Theiler *et al.*, PRL 2009; PhD Thesis

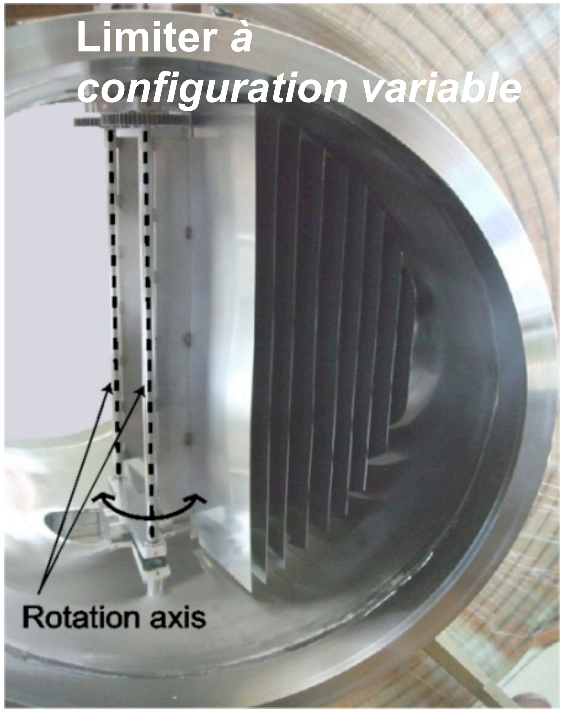
Control of blob velocity via wall tilt

Design

- By pivoting the limiter around a vertical axis, we can achieve $|\alpha| \sim 10^{o}$

Schematic top view





Preliminary results

- No significant difference in blob dynamics for different values of α

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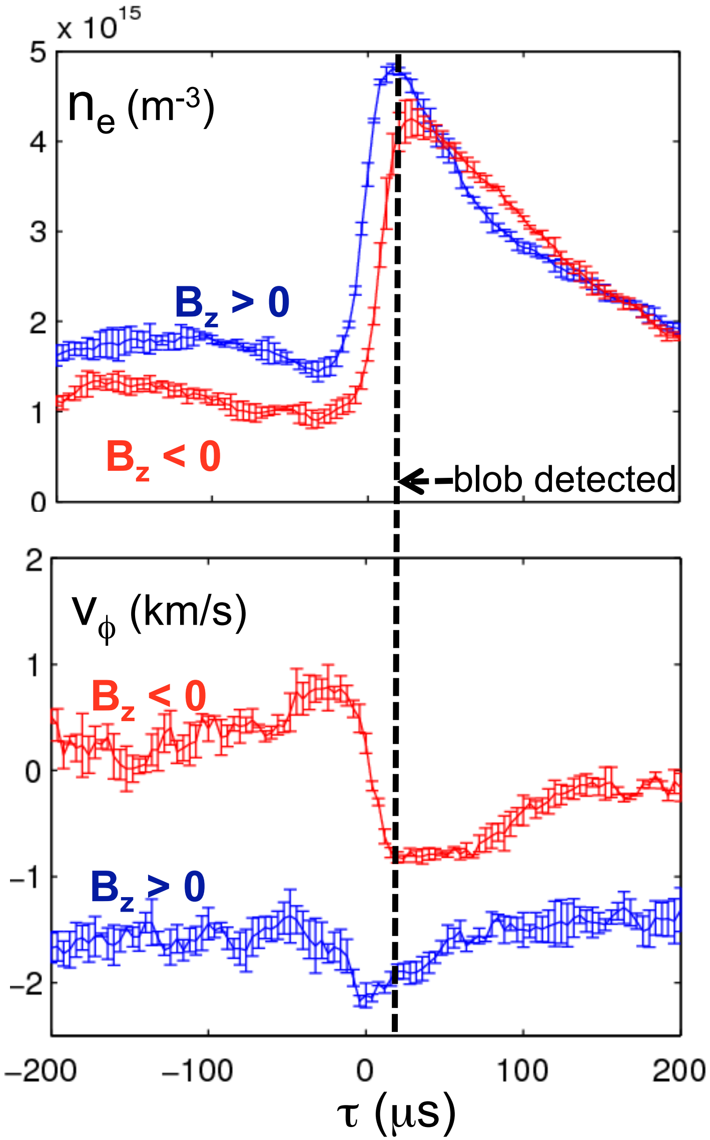
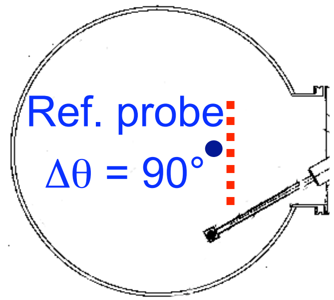
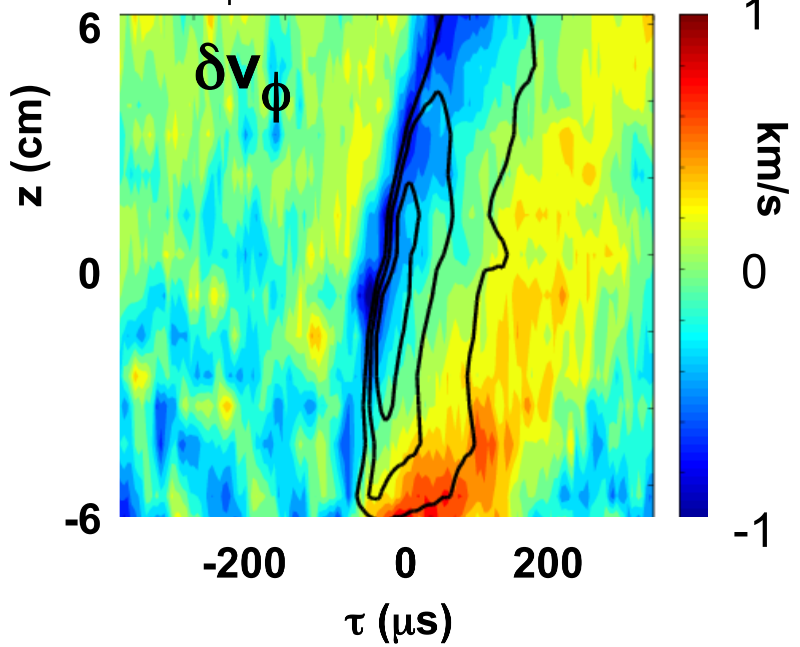
Effect of blobs on plasma flow / toroidal rotation



- Measured with Mach probe along vertical chord in blob region
- When blob passes by, change in toroidal rotation is detected



- Time resolved profile shows positive and negative fluctuations of v_ϕ



B. Labit *et al.*, RSI (2008)

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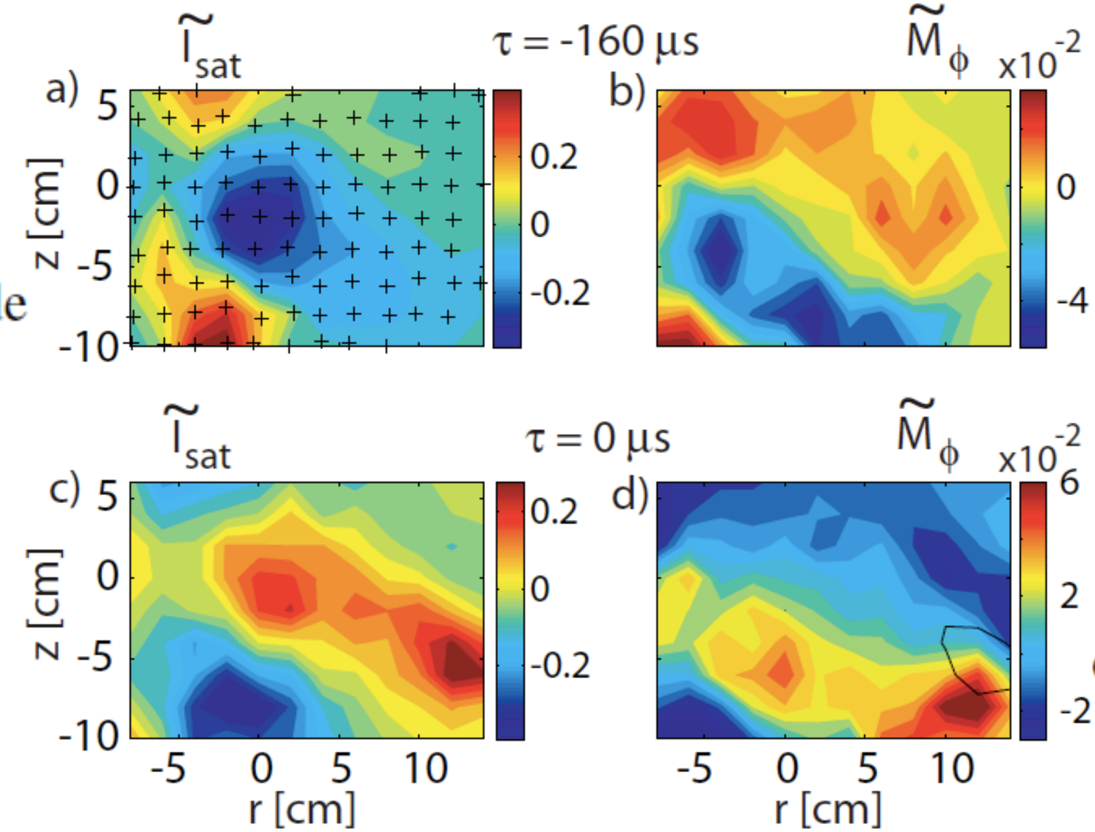
Effect of blobs on plasma flow / rotation
2D time resolved (CAS) profiles

$B_z > 0$

interchange mode



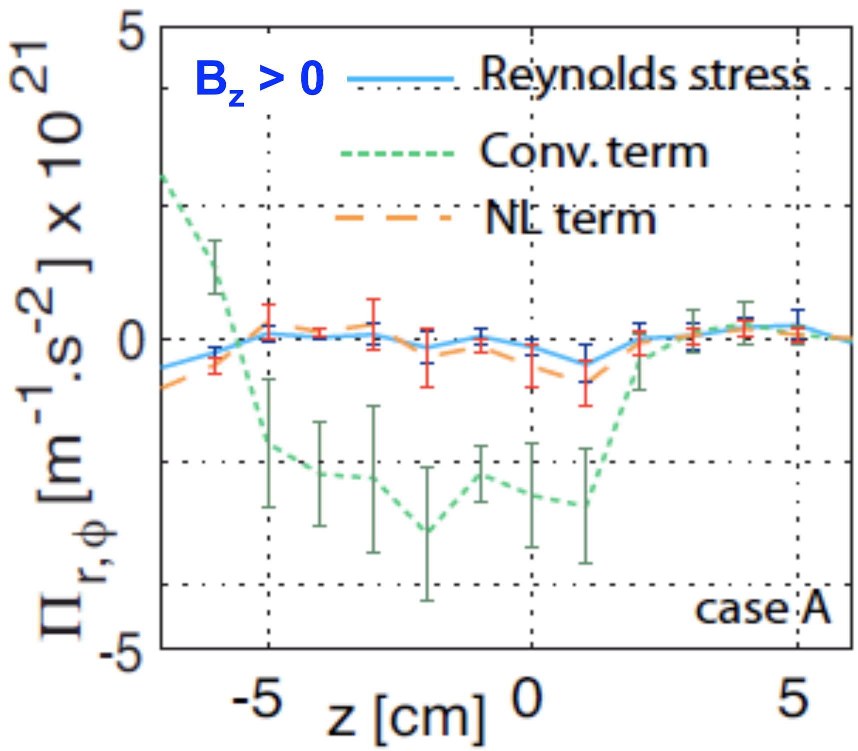
$\angle(I_{sat}, M_\phi) \simeq \pi/2$

same phase difference observed in the mode region

- For B_z<0 monopolar (rather than dipolar) structure for M_ϕ, with $\angle(I_{sat}, M_\phi) = \pi$
- The phase between δI_{sat} density and δM_ϕ is ~constant along blob trajectory
- Nonlocal effects – need 2D coverage

B. Labit *et al.*, submitted to PoP

Mechanism(s) behind generation of toroidal momentum

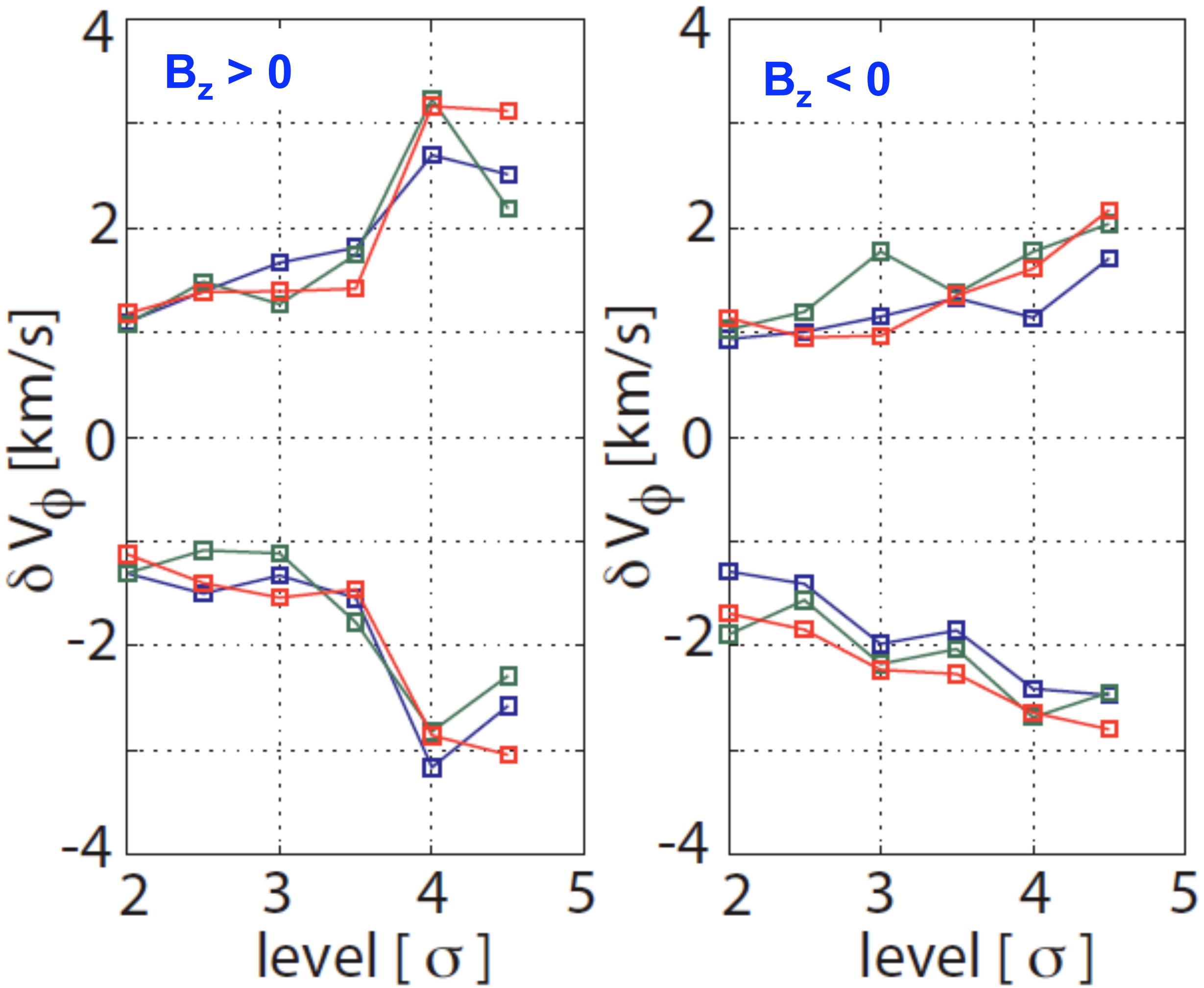


- Convective term dominate over nonlinear term and toroidal Reynolds' stress

$$\Pi_{r,\phi} = \langle n^0\rangle\langle v_r^1 V_\phi^1\rangle + \langle v_r^1 n^1\rangle\langle V_\phi^0\rangle + \langle n^1 v_r^1 V_\phi^1\rangle$$

B. Labit *et al.*, submitted to PoP

Scaling of blob induced flow with blob amplitude



- Same trend for opposite B_z signs, though time averaged profiles are very different
- Symmetry in fluctuations of v_ϕ (skewness ~0)

- Toroidal velocity blobs or holes are associated with density blobs

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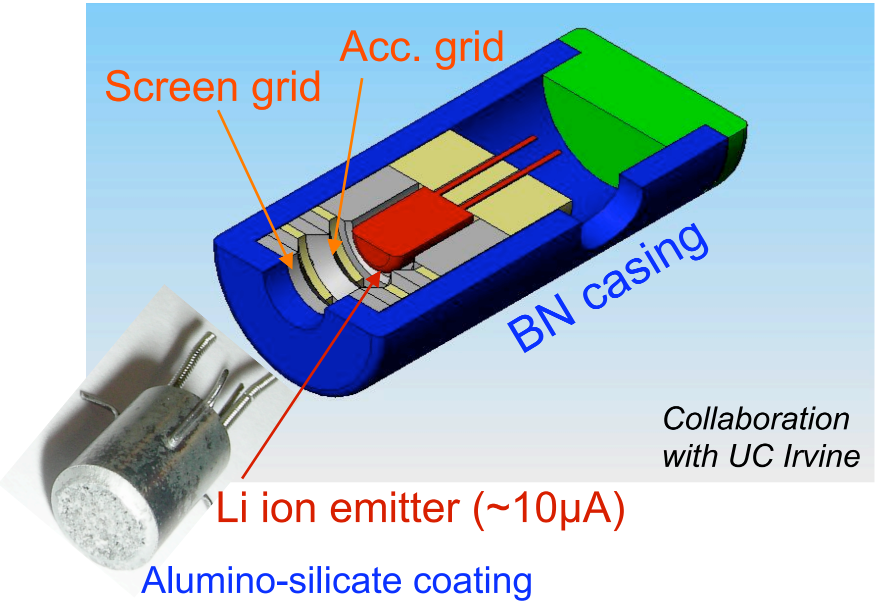
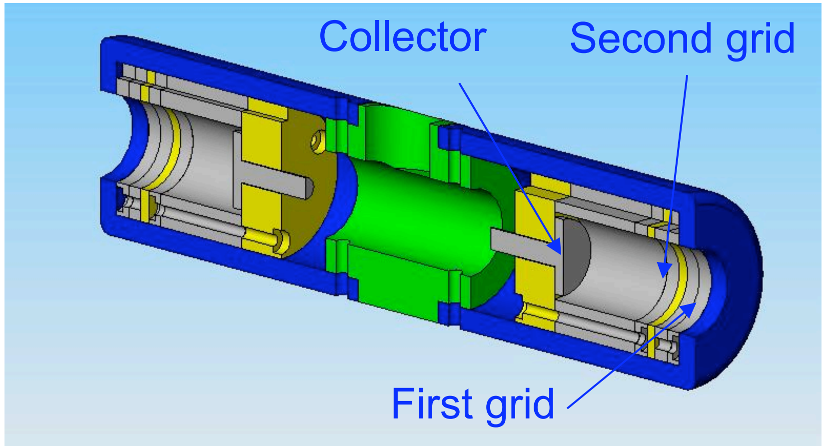
The TORPEX fast ion source and detector

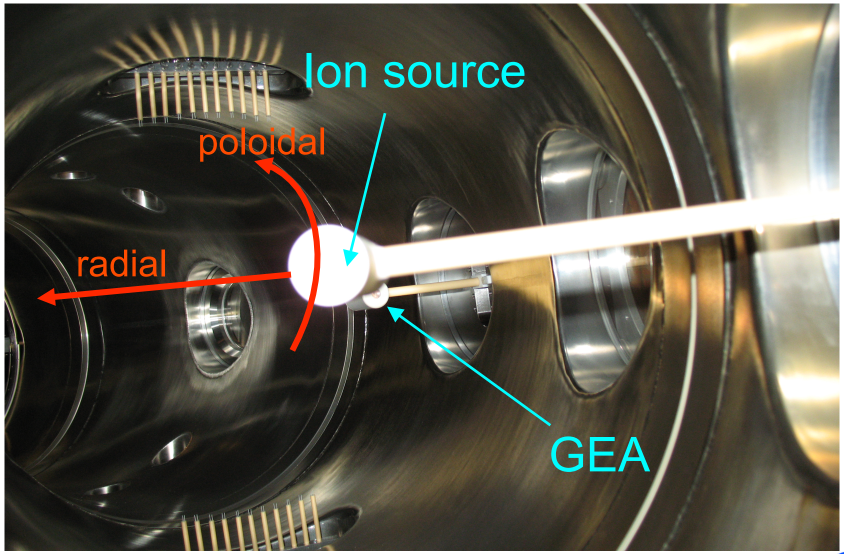
- Double grid for small beam divergence
- 0.1-1kV modulated (~1kHz) power supply



- Two identical Gridded Energy Analysers for noise reduction

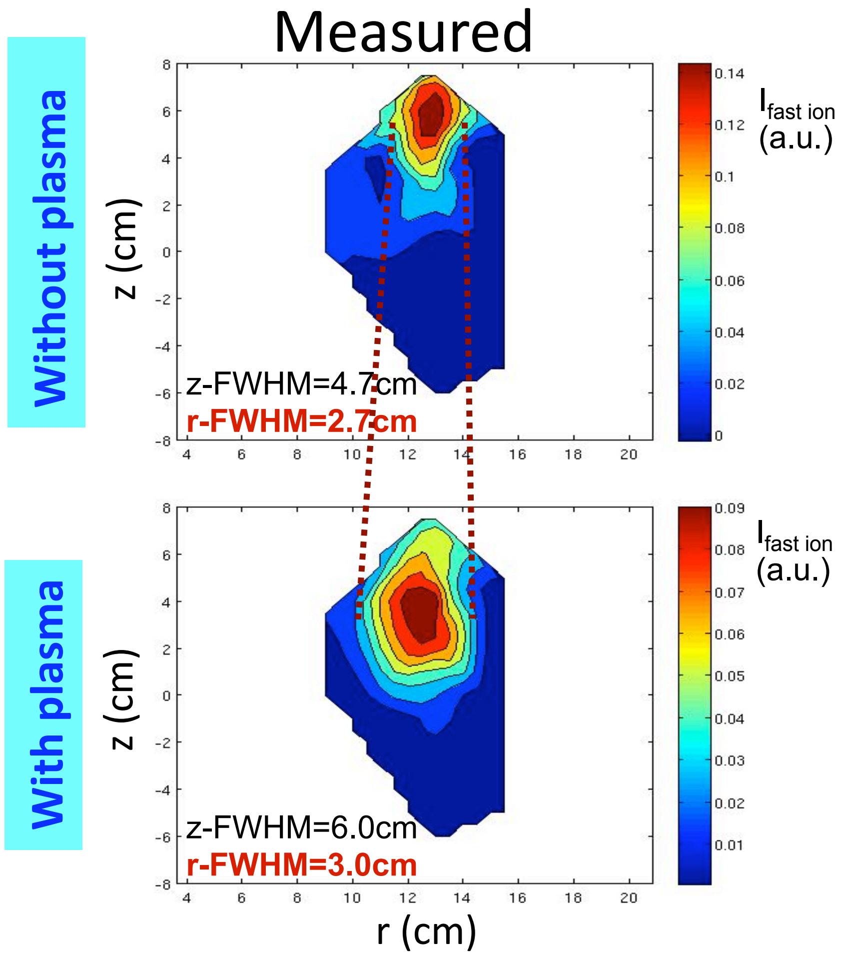


- Ion source and GEA on 2D movable system
- Toroidal separation = 25cm
- Fast ions injected at 300eV in blob region



G. Plyushchev *et al.*, RSI (2006); PhD Thesis

Fast ion current profiles – 300eV, blob region

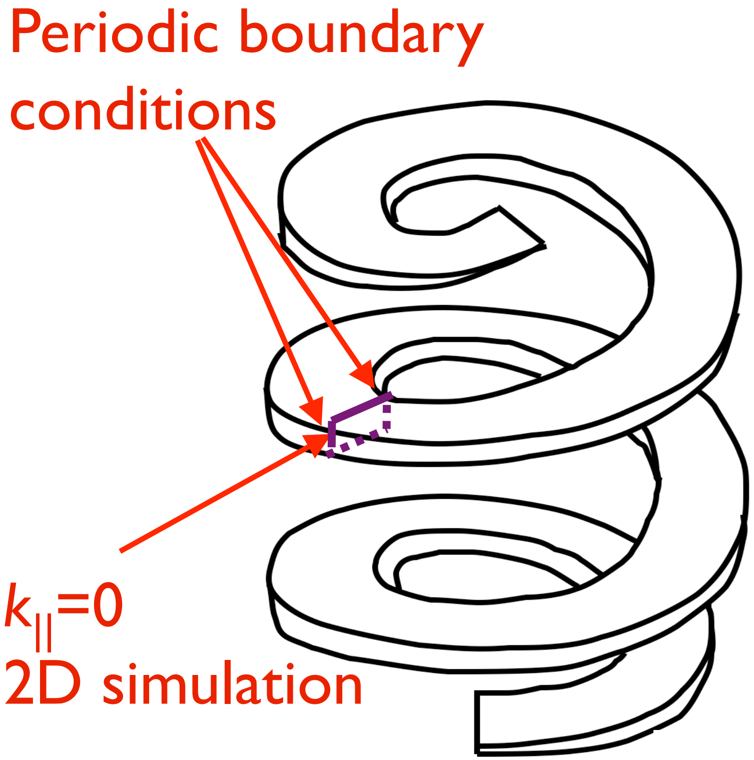


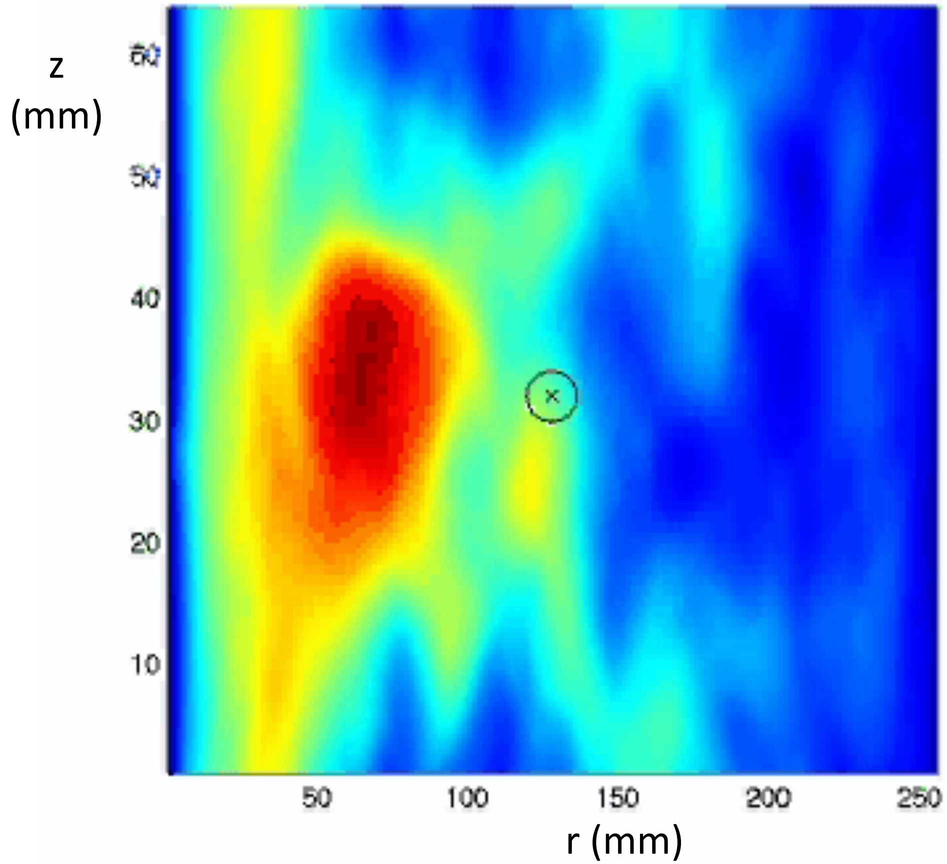
- Small but systematic radial broadening detected in the presence of plasma
- Need comparison with theory to assess its origin - effect of turbulence?

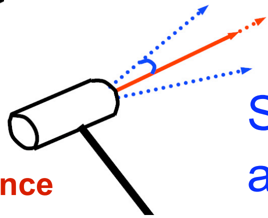
G. Plyushchev *et al.*, paper in preparation; PhD Thesis

Simulated fast ion motion in turbulent E-field

- Motion of tracer particles in turbulence calculated by 2D fluid simulations





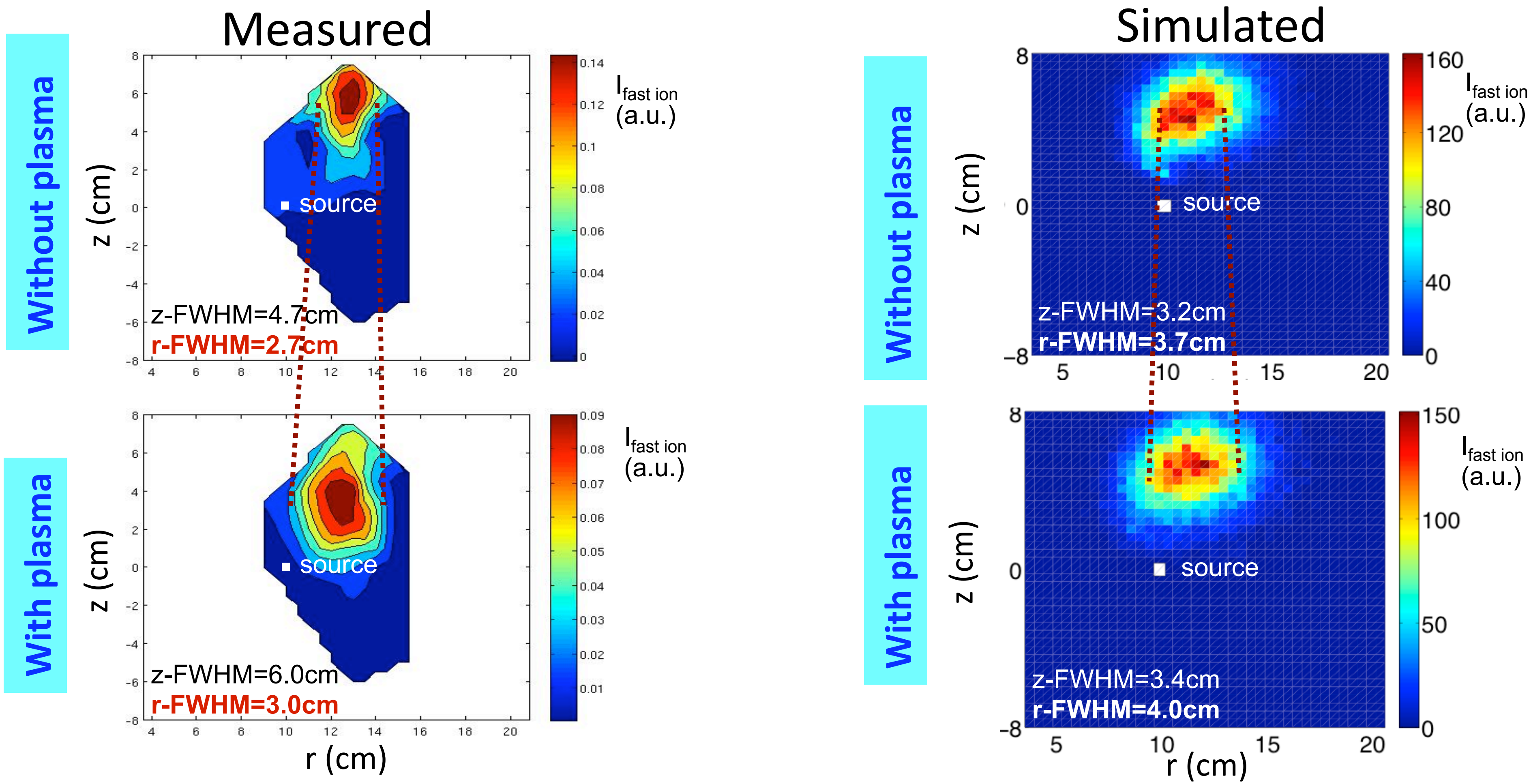


Source with spread in energies ($\Delta E/E$=5%) and in angular distribution (4.5°)

A.Burckel, Master Thesis

See K.Gustafson's poster, this Conference

Fast ion current profiles – 300eV, blob region



- Simulation qualitatively explains the shape of the experimental profiles
  - Spread in initial energies determines vertical profiles
  - Radial broadening due to turbulence (blobs)

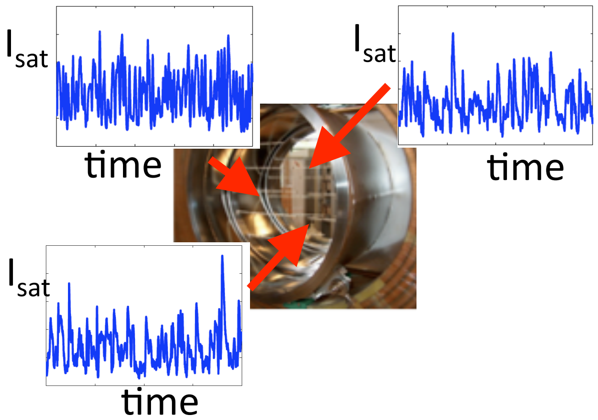
G. Plyushchev *et al.*, paper in preparation; PhD Thesis

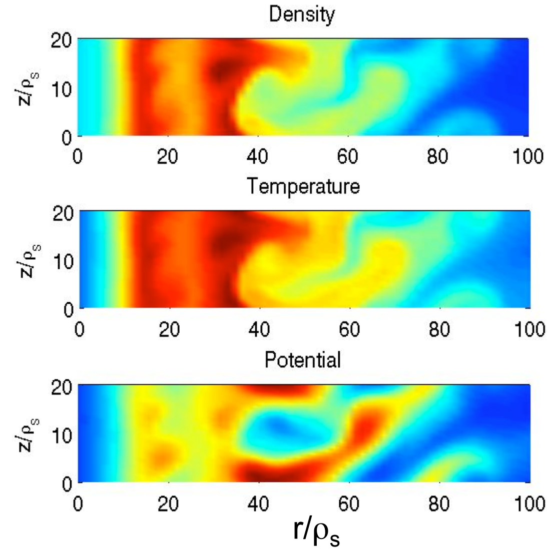
Questions addressed

- ❑ What kind of modes are responsible for the turbulence ?
- ❑ How are macroscopic structures (blobs) generated ?
- ❑ How do blobs propagate? Can their dynamics be influenced/controlled ?
- ❑ What are the consequences, in terms of
  - Plasma flow/rotation?
  - Transport for non-thermal plasma particles (fast ions) ?
- ❑ How can these results be used to validate theoretical models ?

Model validation – observables and metric

- Definition of observables





- Primacy hierarchy
  - **0^{th} level:** I_{sat}^{exp}, T_e^{model},… ; **1^{st} level:** I_{sat}^{model}, n_e^{exp}, blob size^{exp} , blob velocity^{exp},…; **2^{nd} level:** T_e^{exp}, blob size^{model}, blob velocity^{model}, Γ_{blobs}^{exp} …. ; **3^{rd} level:** Γ_{blobs}^{model},…

- Ex. of global metric $\chi=\Sigma_i R_i S_i H_i / (\Sigma_i S_i H_i)$ i=1,2….number of observables

R_i: Agreement/ disagreement

S_i: Sensitivity/weight

H_i: 1/[1 + hierarchy level$_i^{exp}$+hierarchy level$_i^{model}$]

$$S_i = \exp\left\{ -\frac{<\Delta obs_i^{model}> + <\Delta obs_i^{exp}>}{<obs_i^{model}> + <obs_i^{exp}>} \right\}$$

P. W.Terry *et al.*, PoP (2008)

P. Ricci *et al.*, PoP (2009)

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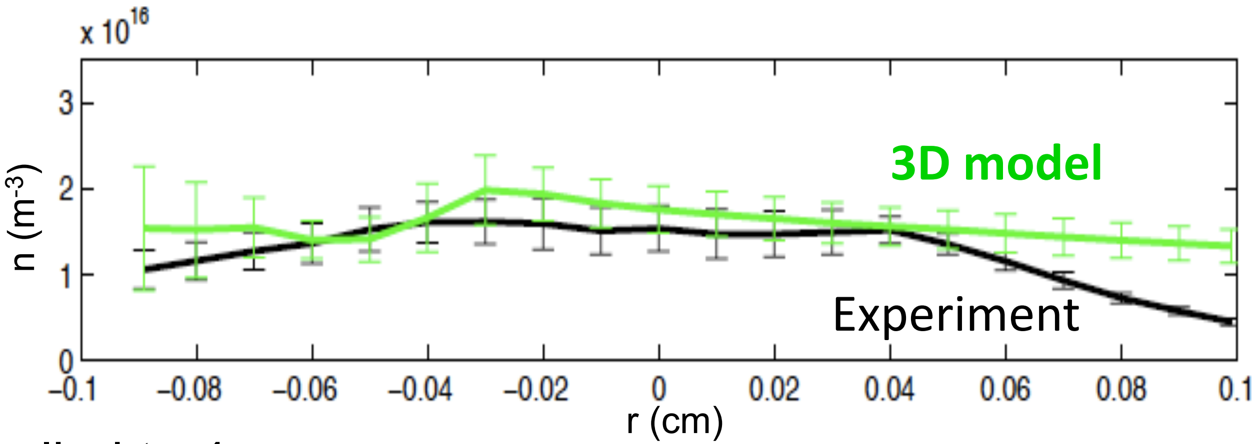
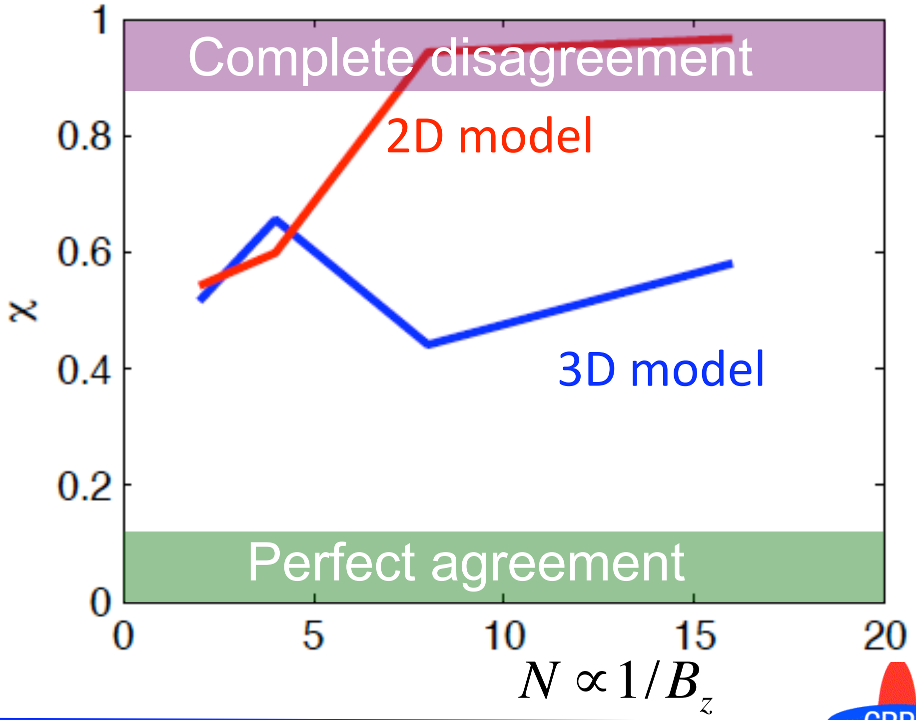
Model validation – ex. of application of metric

- Quantitative comparison of individual observables
  Ex. average density profile at z = 0cm, for N = 8



- 2D and 3D fluid models applied to 4 configurations (varying *N*, i.e. B_z)
- 11 observables (all with $H_i = 0.5$)
  - n(r), T(r), Φ(r), skewness(r), kurtosis(r), δn(r), I_{sat}(r)
  - fluctuation pdf, psd, k_z spectrum, k_{tor} at location of max. mode amplitude



- 3D model clearly necessary for *N* > 5 ($k_{||} \neq 0$ and profiles not slab-like)

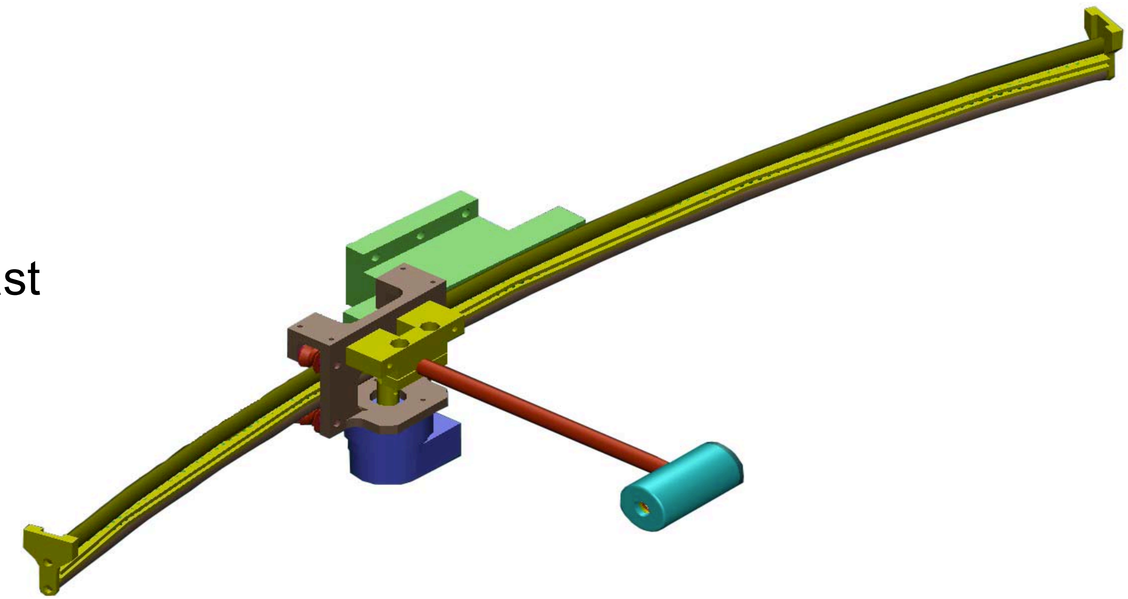
P. Ricci *et al.*, paper in preparation

Summary and outlook

- Results from the TORPEX simple toroidal plasma device enable *quantitative model validation* for intermittent transport in edge plasmas and related wave-particle interaction phenomena

- Blob physics
  - Control of blob dynamics with various limiter configurations, blob e.m. effects
- Fast ion interaction with turbulence/blobs: transport mechanisms

Toroidally movable fast ion source under development



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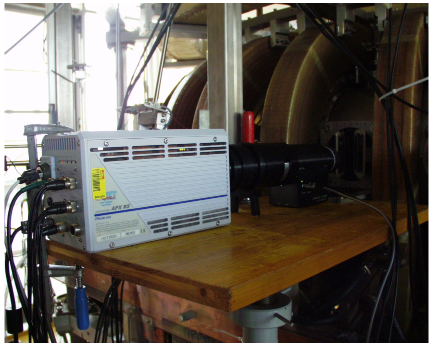
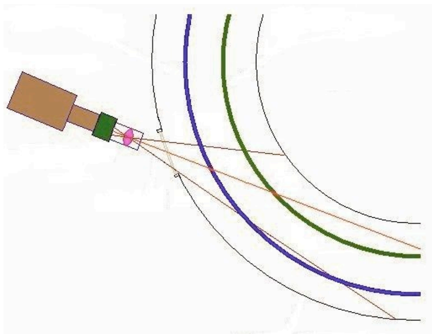
- Change magnetic topology, in particular for fast ion physics studies
- Non-perturbative, high-resolution plasma imaging (fast camera with intensifier and/or gas puffing)

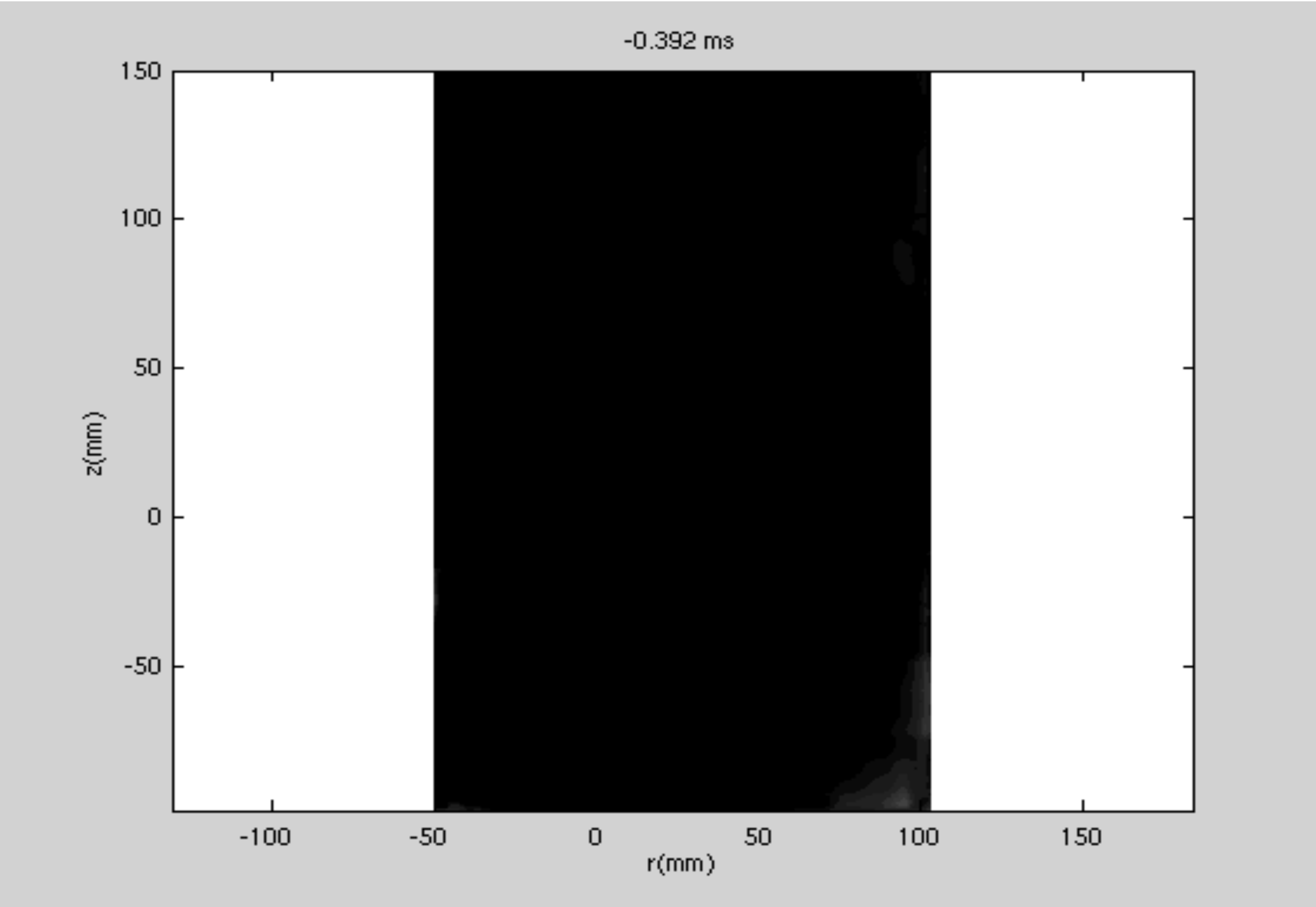
Plasma imaging using intensified fast framing camera

- Inverted camera images confirm the presence of modes and turbulent structures of different scales

50kframes/s
2μs gate
190x140 pixels



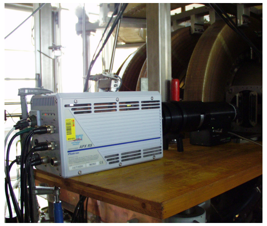




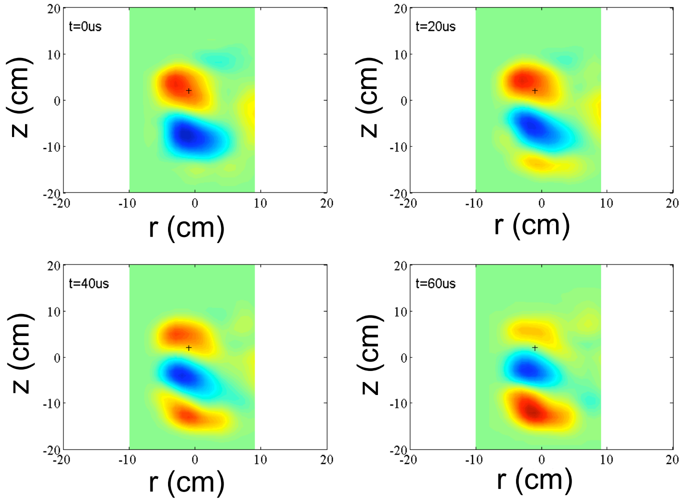
D. Iraji *et al.*, RSI (2008)

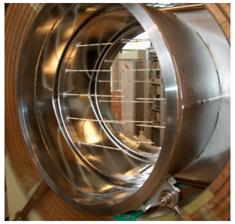
Plasma imaging using intensified fast framing camera

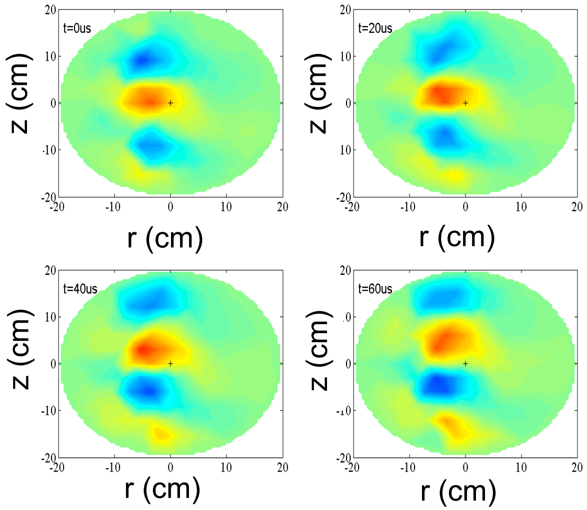
- Conditionally sampled light emissivity profiles show interchange mode (~3.5kHz) with same properties as probe array



D. Iraji *et al.*, paper in preparation: PhD Thesis







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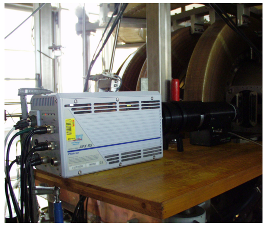

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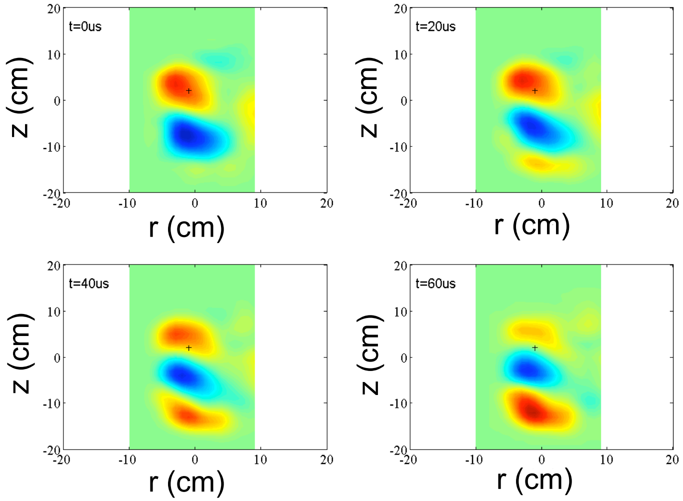
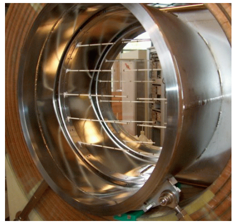
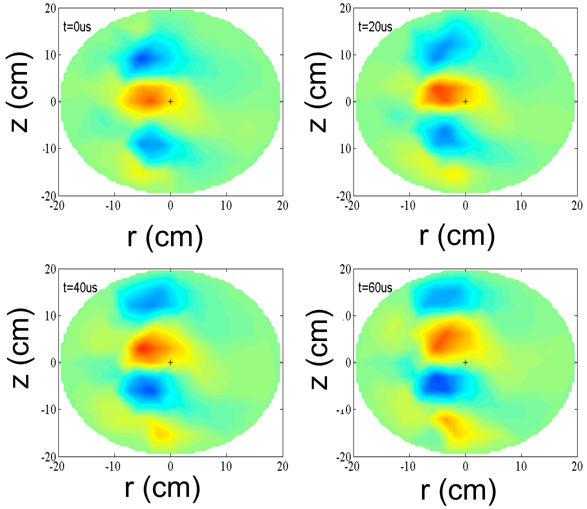
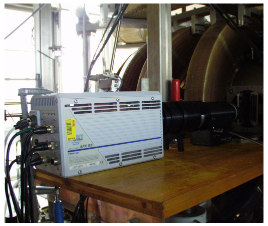
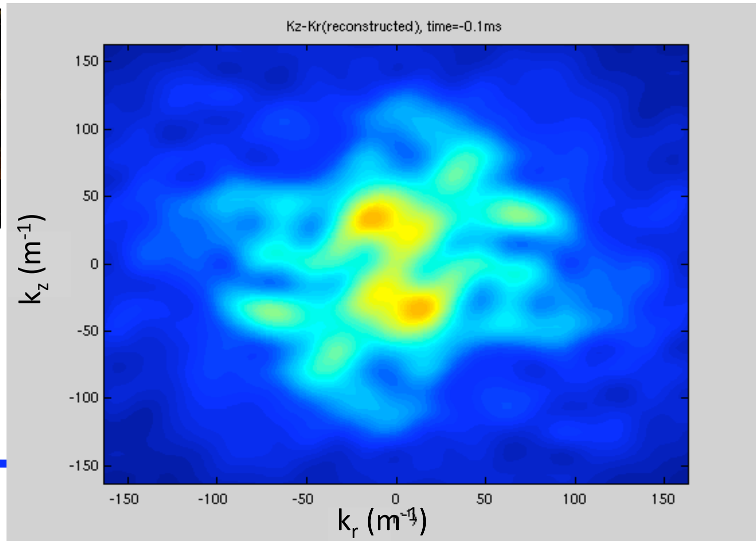


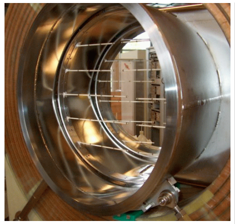


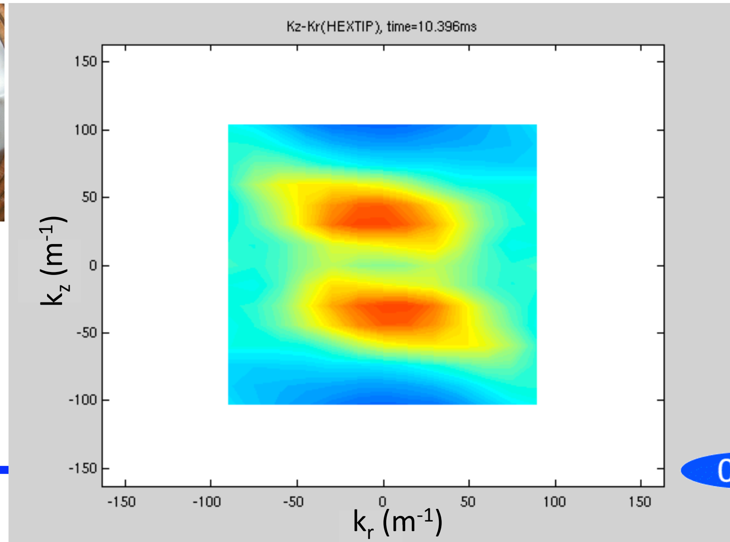


- k_r-k_z spectra show same mode but also additional small scale features









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