2D IMAGING OF THE EDGE TURBULENCE IN RFX-mod

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Introduction

✓ In all magnetic configurations turbulent structures are detected having great influence in confinement properties and plasma-wall interaction

✓ Characterisation of motion and evolution of the edge structures has been done so far with fast CCD cameras and Langmuir probes

✓ The GPI diagnostic has been designed and installed in RFX-mod experiment to obtain *high spatial (2D) and temporal imaging* of turbulence and to follow *edge structures* during the *whole discharge*

✓ A tomographic algorithm has been developed to obtain 2D imaging of edge turbulence from line integrated signals

✓ A new method of analysis is described

The GPID

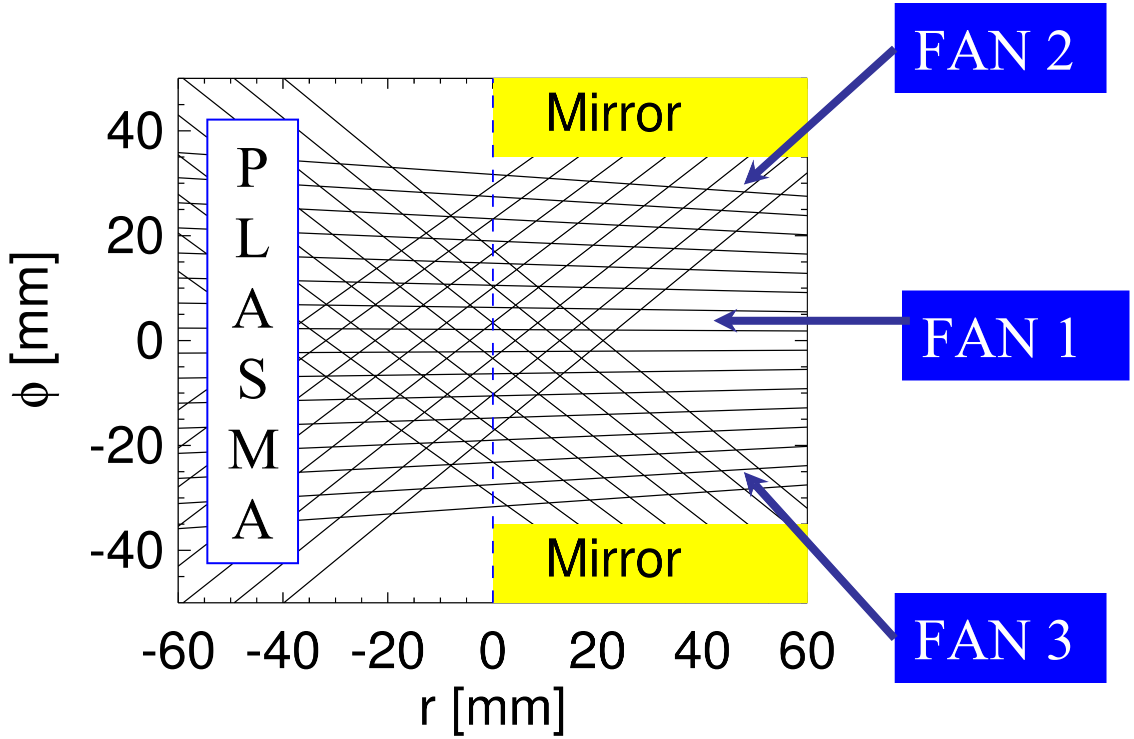
- **G**as **P**uff **I**maging **D**iagnostic: non intrusive optical diagnostic for edge turbulence studies
- Observes the HeI neutral gas puffed in the plasma edge

$$I \propto n_0 f(n_e, T_e) = n_0\, n_e^{\alpha}\, T_e^{\beta}$$

- Characterises the edge turbulence in the plane perpendicular to the main magnetic field
- Studies motion and evolution of edge coherent structures

GPID in RFX-mod

- ✓ 32 chords divided into 3 fans measuring HeI (667,8nm) emission
- ✓ Focus along the line of sight ~ 50mm
- ✓ Spatial resolution 5mm



- ✓ Electronics bandwidth : 2 MHz
- ✓ Sampling rate: 10 MSamples/s throughout the discharge
- ✓ Measures emission integrated along the lines of sight

M.Agostini et al., Rev.Sci.Instrum., 77 10E513 (2006)

*R.Cavazzana et al., Rev.Sci.Instrum.,**75** 4152 (2004)*

Velocity from cross-correlation

- Cross-correlation of spatially distributed measurements
- Time lag, Δt, at which maximum is detected: $\Delta t(\boldsymbol{d}) = \dfrac{\boldsymbol{d} \cdot (\boldsymbol{v}/v)}{v} = \dfrac{\boldsymbol{d} \cdot \boldsymbol{v}}{v^2}$
- which can be re-written as $\Delta t(\boldsymbol{d}) = \boldsymbol{d} \cdot \boldsymbol{w}$

$$\boldsymbol{w} = \boldsymbol{v} / v^2$$

- After linear fit, $\boldsymbol{v}$ is obtained by $\boldsymbol{v} = \boldsymbol{w} / w^2$

- The error is estimated by:

$$\sigma_{\Delta t}^2 = \frac{\sum_i (w d_i - \Delta t_i)^2}{N-1} \qquad w = \left(\sum_i d_i \, \Delta t_i\right) \Big/ \sum_i d_i^2 \quad \text{and} \quad v = 1/w$$

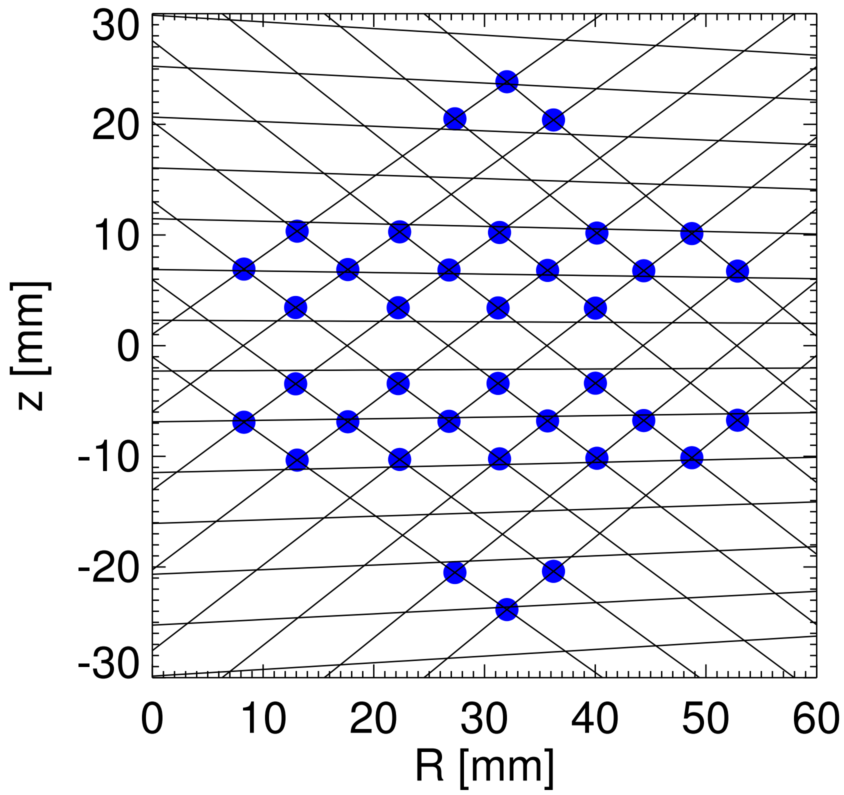
$$\frac{\sigma_v^2}{v^2} = \frac{\sigma_w^2}{w^2} = \sigma_{\Delta t}^2 \frac{\sum_i d_i^2}{\left(\sum_i d_i \, \Delta t_i\right)^2}$$

Back projection

- 3 Lines of Sight intersect in one point [*r**,*z**]

- Emission at point [*r**,*z**] equals product of the three line integrals

$$e(r^*, z^*) = l_1 \cdot l_2 \cdot l_3$$



Inversion Algorithm (1)

- 2D emission in the toroidal- radial plane:

$$e(r,z)=\sum_{kq}\left[C_{kq}\cos\left(\frac{k\pi z}{\Delta z}\right)\cos\left(\frac{q\pi r}{\Delta r}\right)+D_{kq}\sin\left(\frac{k\pi z}{\Delta z}\right)\cos\left(\frac{q\pi r}{\Delta r}\right)+\right.$$

$$\left.+E_{kq}\cos\left(\frac{k\pi z}{\Delta z}\right)\sin\left(\frac{q\pi r}{\Delta r}\right)+F_{kq}\sin\left(\frac{k\pi z}{\Delta z}\right)\sin\left(\frac{q\pi r}{\Delta r}\right)\right]$$

- 32 line integrated signals:

$$l_i=\sum_{kq}\left[C_{kq}\int_{l_i}\cos\left(\frac{k\pi z}{\Delta z}\right)\cos\left(\frac{q\pi r}{\Delta r}\right)+D_{kq}\int_{l_i}\sin\left(\frac{k\pi z}{\Delta z}\right)\cos\left(\frac{q\pi r}{\Delta r}\right)+\right.$$

$$\left.+E_{kq}\int_{l_i}\cos\left(\frac{k\pi z}{\Delta z}\right)\sin\left(\frac{q\pi r}{\Delta r}\right)+F_{kq}\int_{l_i}\sin\left(\frac{k\pi z}{\Delta z}\right)\sin\left(\frac{q\pi r}{\Delta r}\right)\right]$$

- C_{kq}, D_{kq}, E_{kq}, F_{kq}: unknowns to be determined

Inversion Algorithm (2)

$$l_i = \sum_{kq} C_{kq} X_{kqi} + D_{kq} Y_{kqi} + E_{kq} W_{kqi} + F_{kq} Z_{kqi}$$

32 line of sight measurements

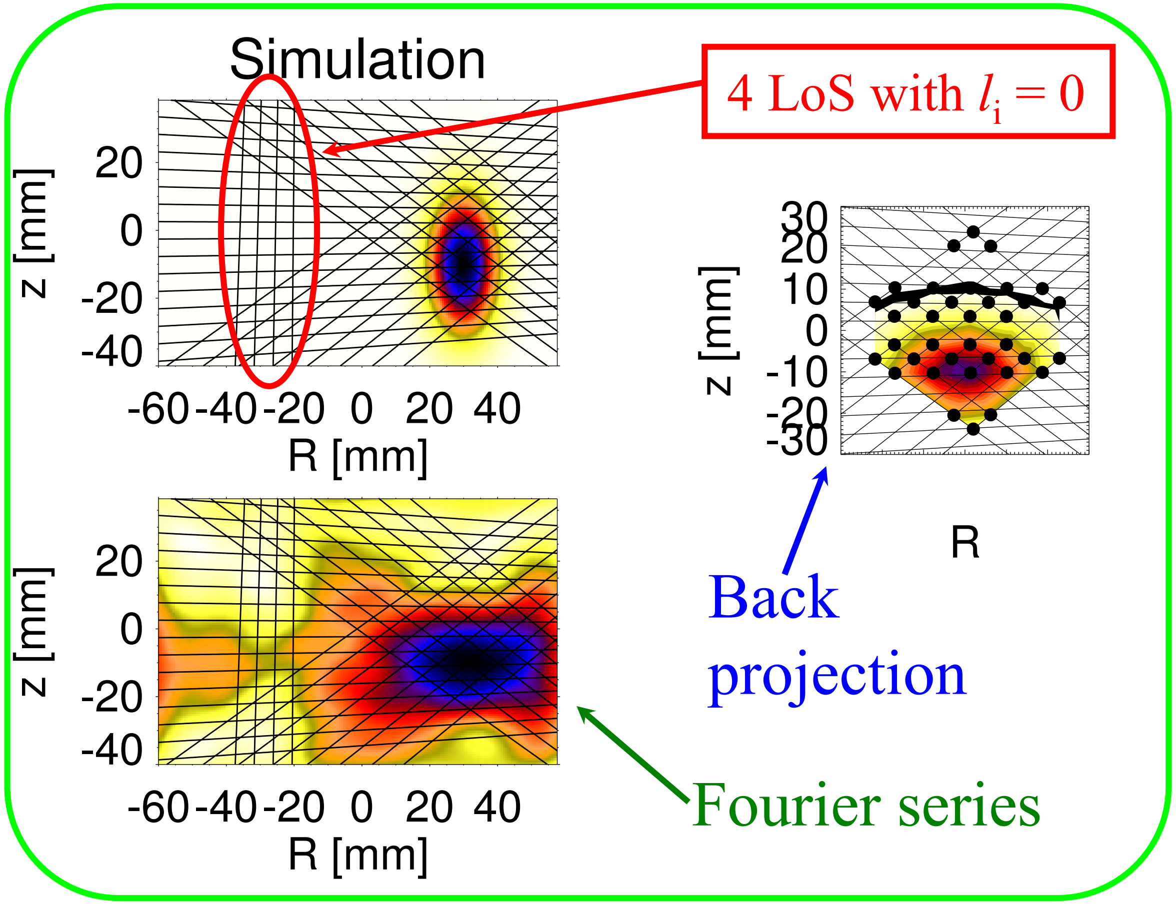
K: wave vector along the toroidal direction: 0 ÷ 5

Q: wave vector along the radial direction: 0 ÷ 3

V.Antoni et al., Phys. Rev. Lett. ***79****, 4814 (1997)*

- The underdetermined linear equations are solved with the **truncated SVD** technique

Simulation

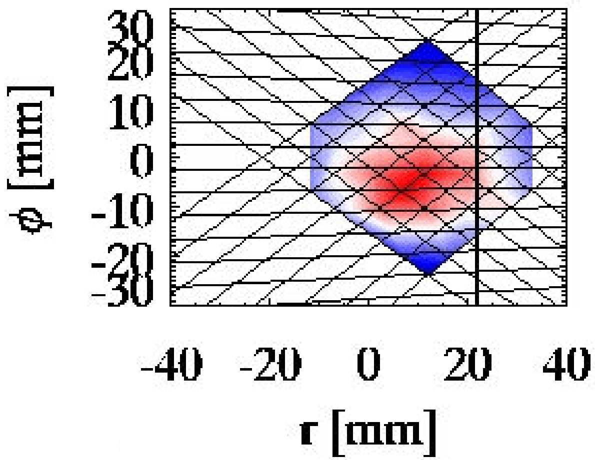


- Simulated Gaussian emitting pattern
- 4 lines of sight with zero signal are added

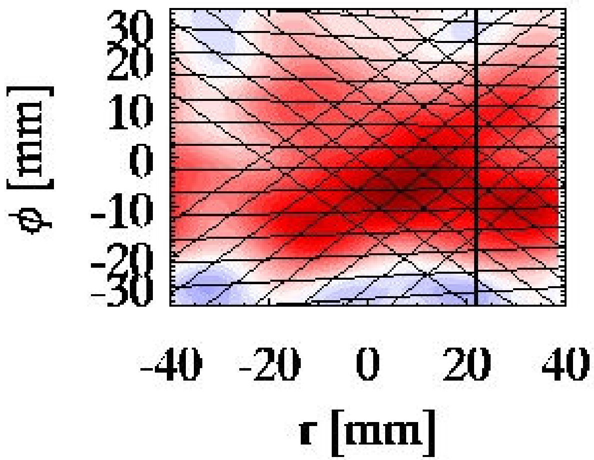
- Reconstruction of the 2D emission with *inversion* and *back-projection*
- High toroidal resolution
- Lower good radial resolution

2D Imaging

Back-projection

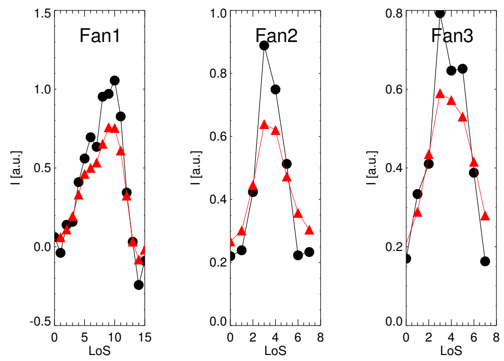


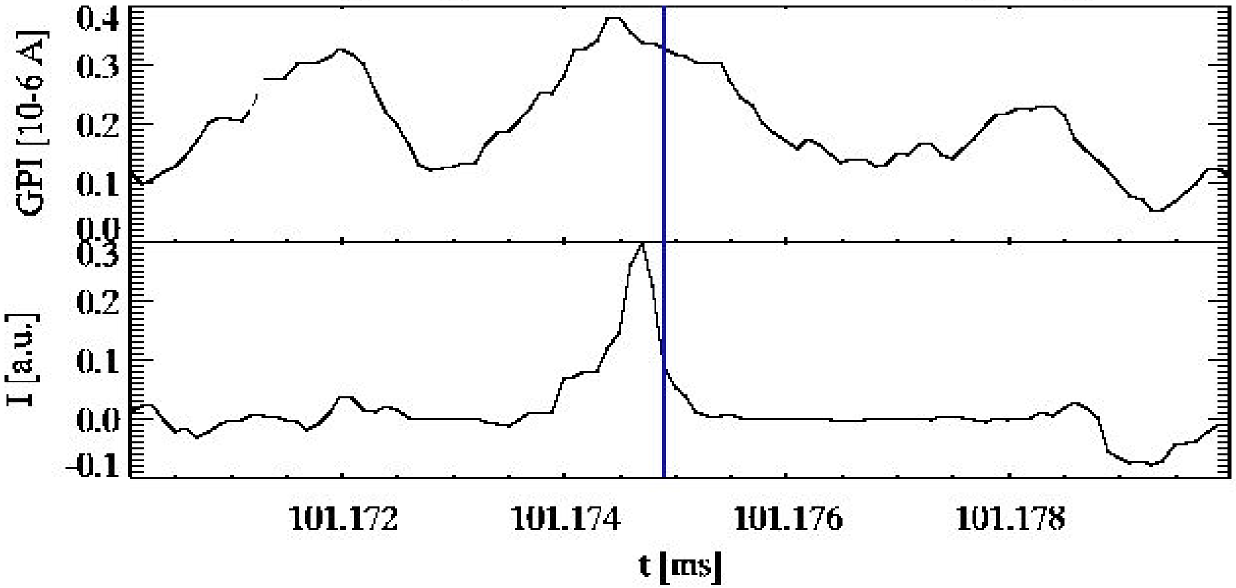
Inversion



#20629: t=101.1749 ms

Line integrals

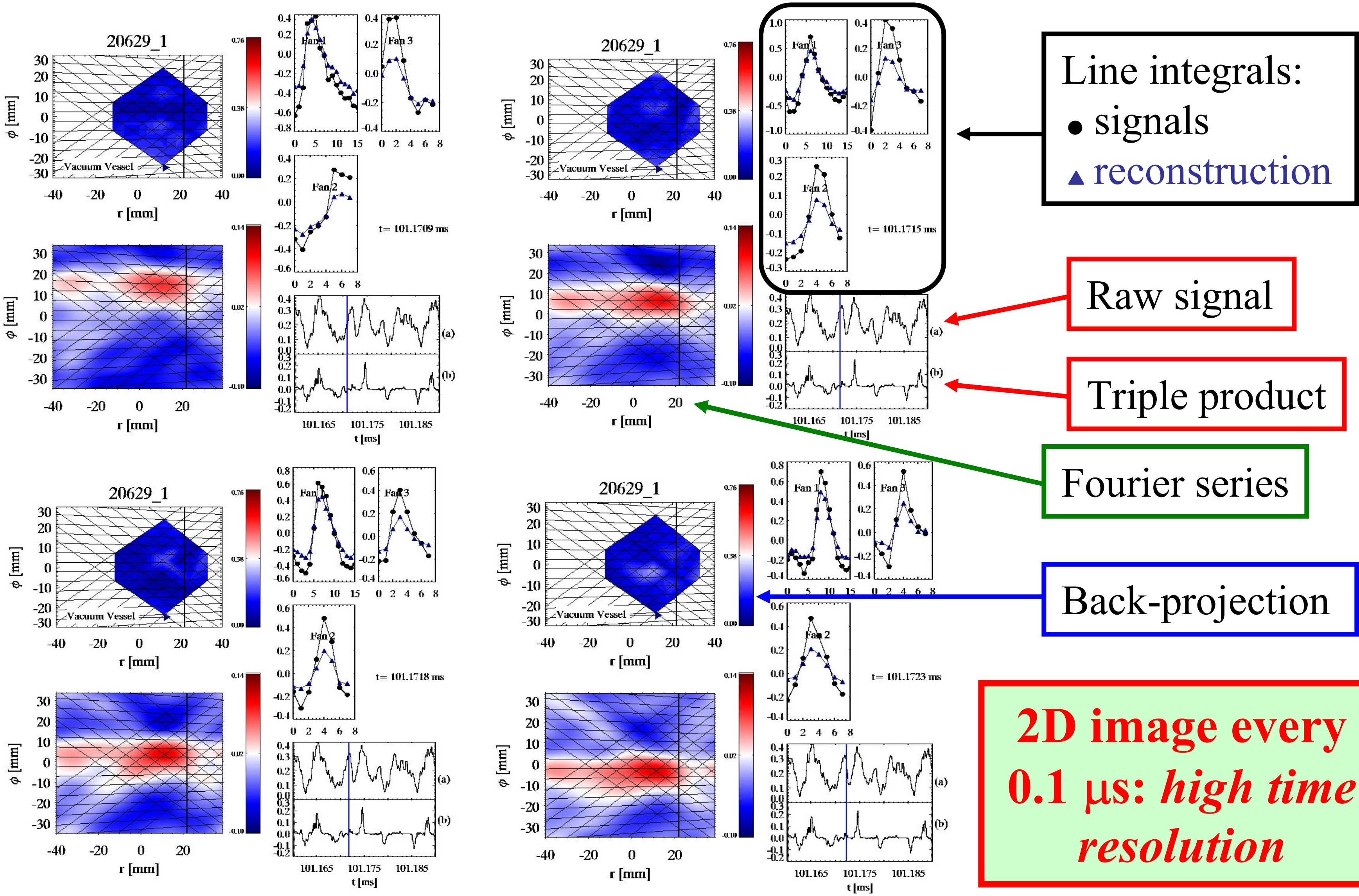




Raw signal

Triple product

2D Evolution



2D image every 0.1 µs: *high time resolution*

Total Mode Energy (1)

- From inversion coefficients time variation of total mode energy:

$$E(t) = \sum_{kq} C_{kq}^2(t) + D_{kq}^2(t) + E_{kq}^2(t) + F_{kq}^2(t)$$

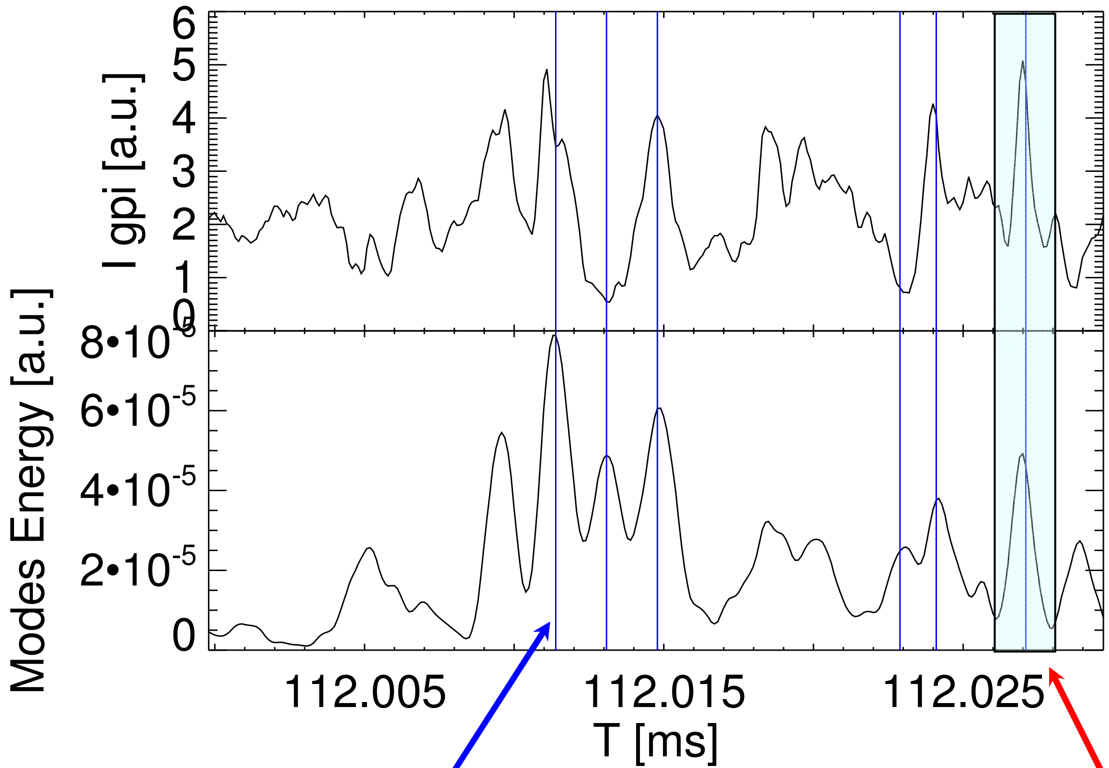
and energy associated to single mode:

$$E_{k*}(t) = \sum_q C_{k*q}^2(t) + D_{k*q}^2(t) + E_{k*q}^2(t) + F_{k*q}^2(t)$$

- In GPI signals intermittent structures are detected by LIM method *[V.Antoni et al., Europhys.Lett.* ***54*** *51 (2001)]*

- Correlation between structures and total energy is studied

Total Mode Energy (2)



- Good correlation between raw data and mode energy
- Intermittent structures in correspondence to energy peaks

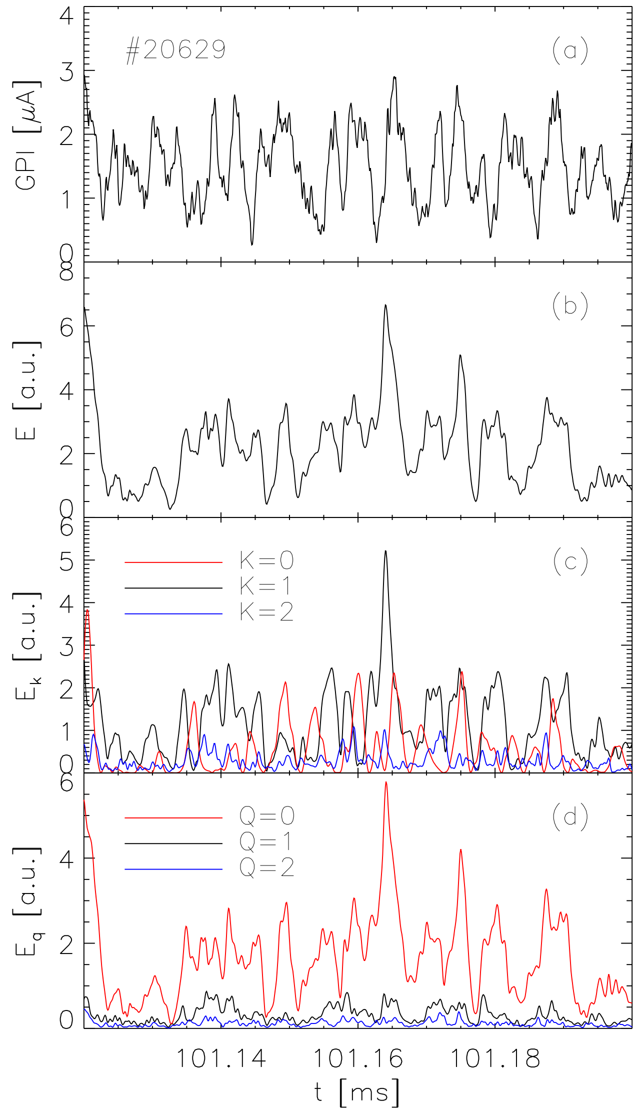
Intermittent structures by LIM method

Inverted structure found

Mode Energy

➢ Total mode energy peaks in correspondence to peaks in the GPI signal, corresponding to reconstructed structures

➢ Dominant toroidal modes are $k = 0$ and $k = 1$;
dominant radial mode is $q = 0$



signal

total mode energy

toroidal mode energy

radial mode energy

Total Mode Phase (1)

- Let's re-write the emissivity:

$$e(r,z) = \sum_{kq}\left[W_{kq}(r)\cos\left(\frac{k\pi z}{\Delta z}\right) + Z_{kq}(r)\sin\left(\frac{k\pi z}{\Delta z}\right)\right]$$

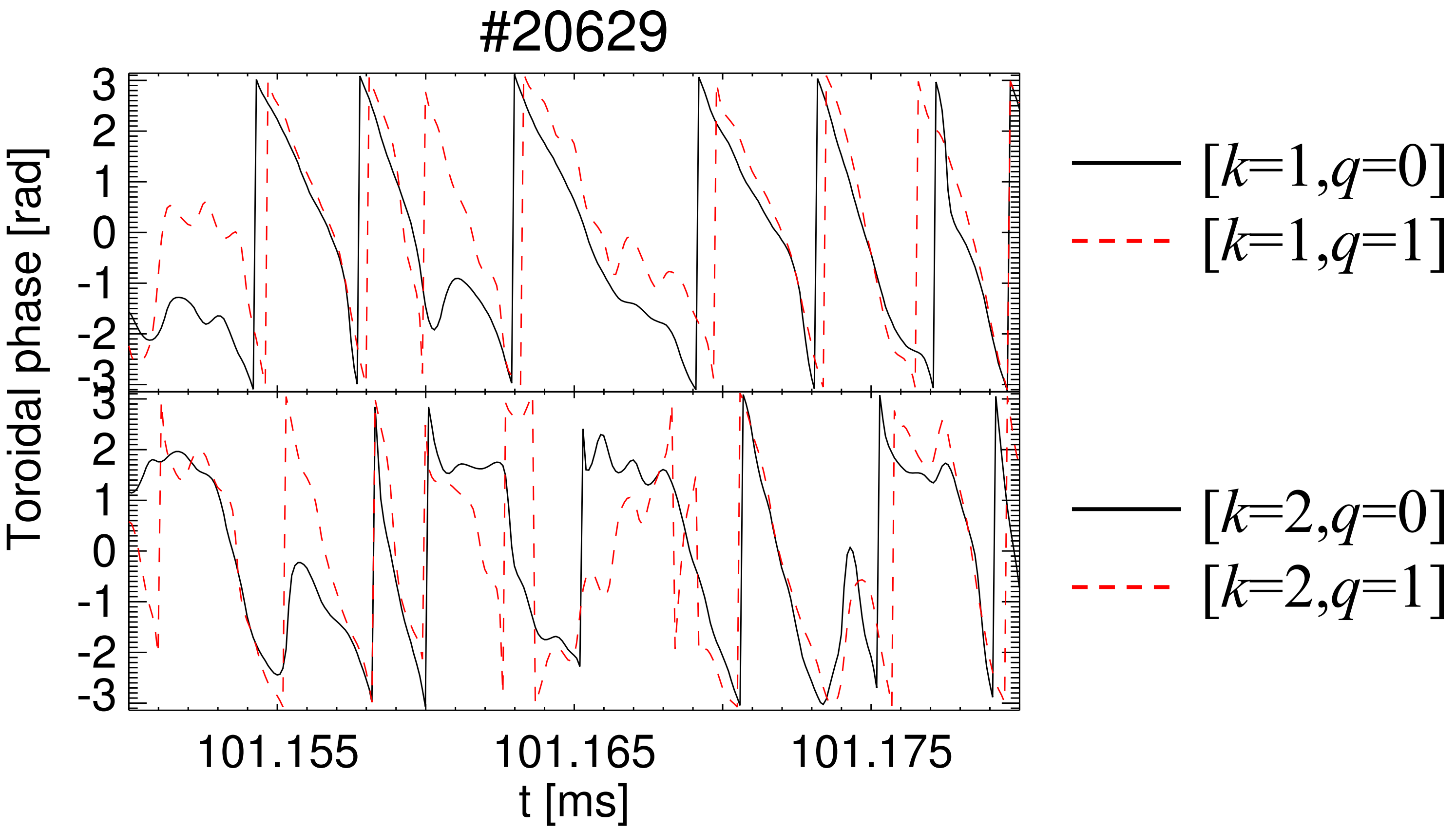
$$W_{kq}(r) = C_{kq}\cos\left(\frac{q\pi r}{\Delta r}\right) + E_{kq}\sin\left(\frac{q\pi r}{\Delta r}\right)$$

$$Z_{kq}(r) = D_{kq}\cos\left(\frac{q\pi r}{\Delta r}\right) + F_{kq}\sin\left(\frac{q\pi r}{\Delta r}\right)$$

- Mode phase can be defined:

$$\tan(\varphi_{k*}) = \left(\sum_q Z_{k*q}(r)\right) / \left(\sum_q W_{k*q}(r)\right)$$

Toroidal Mode Phase (2)

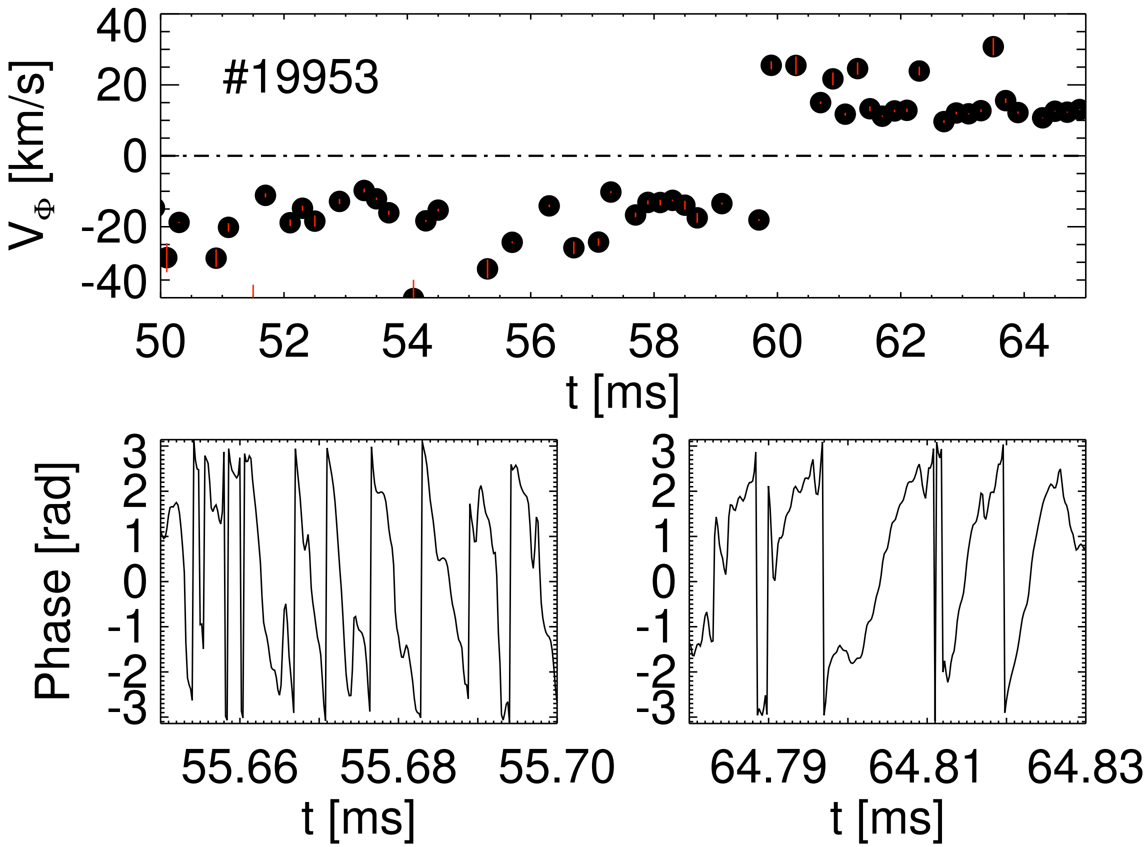


Clear linear dependence of the phase with time

Example of Velocity Inversion

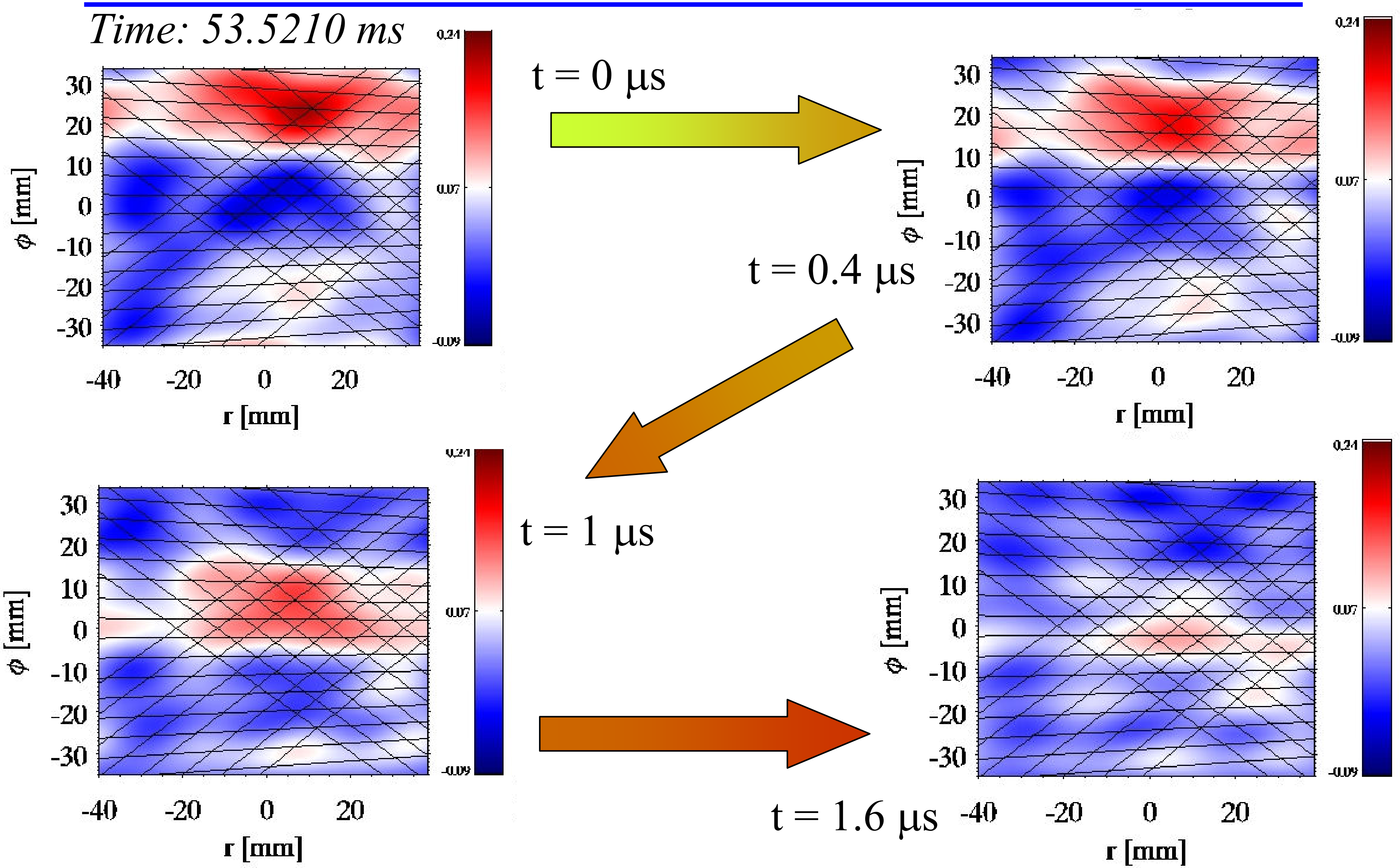
➢ With an externally induced magnetic rotating perturbation inversion of turbulent flow is detected

[Cavazzana et al., EPS 2005]

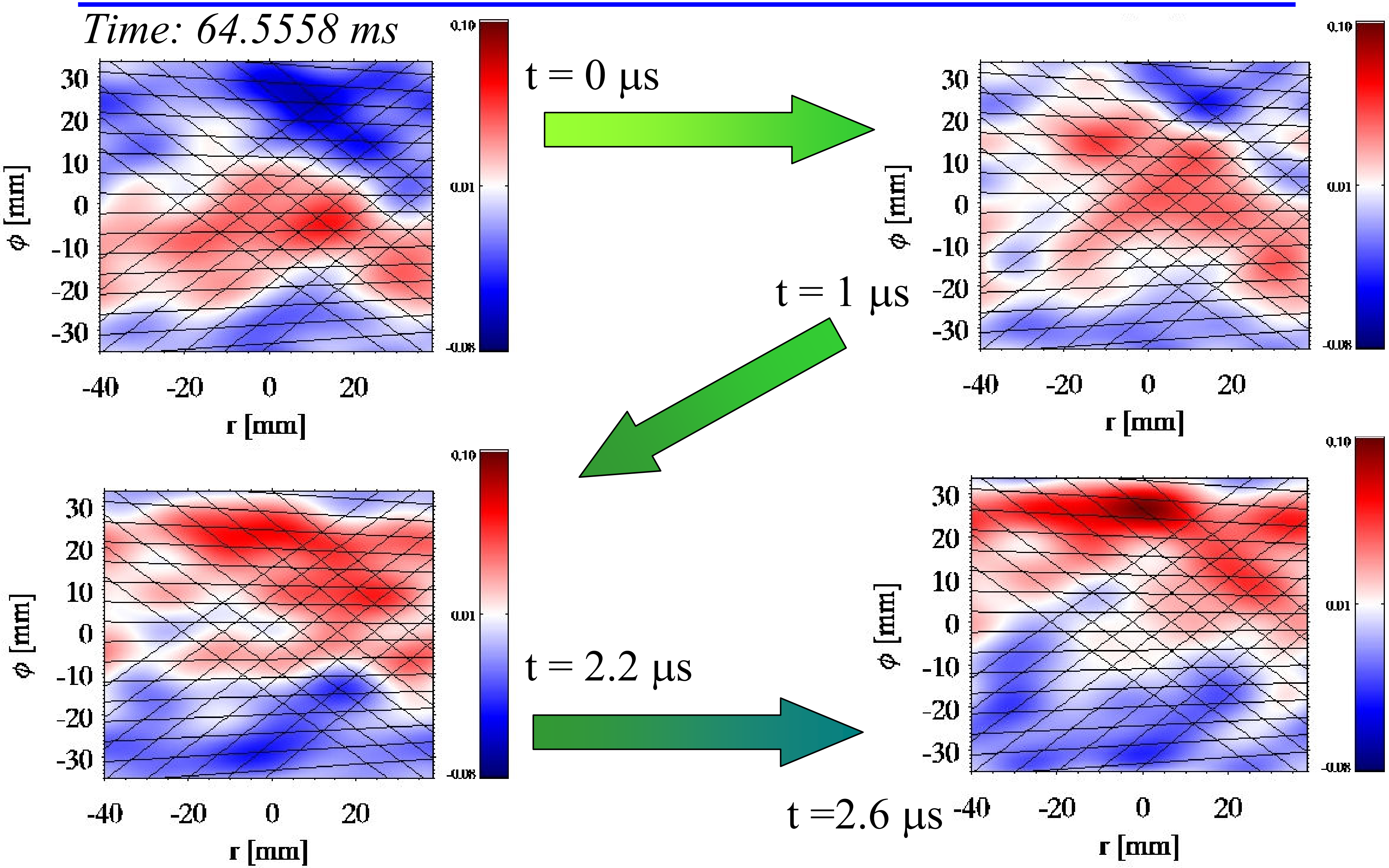


✓ Inversion algorithm and mode analysis are applied to study structures before and after velocity inversion

2D edge structures: normal flow



2D edge structures: opposite flow



Conclusions

- A tomographic inversion method is developed to obtain a *2D imaging* of edge structures in RFX-mod experiment
- Motion and evolution of the structures are studied with *high time resolution (0.1 μs) for all discharges*
- Edge turbulence can be characterised by the *energy and phase of reconstructed modes*
- During inversion of turbulent flow, structures that move in *opposite directions* are detected
- Tomographic reconstruction and analysis of mode energy and phase make GPID *new and powerful method* to investigate turbulent structures