*Localized detection of short-scale turbulence in ITER with scattering of CO_2 lasers**

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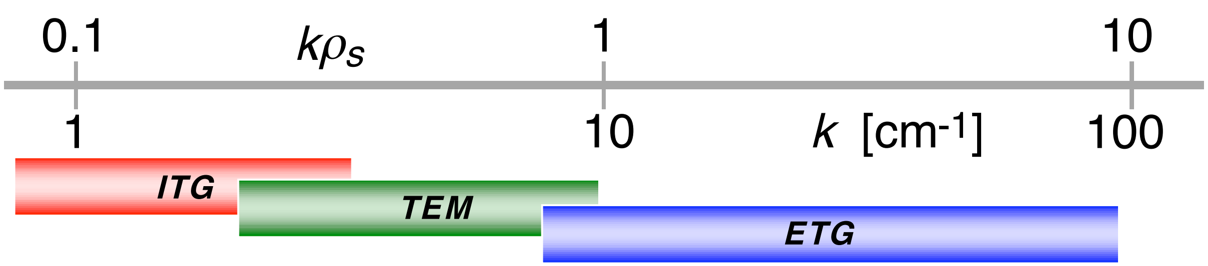
Motivation

- *The direct impact of plasma confinement on the feasibility of fusion reactors makes the investigation of plasma transport one of the most important tasks for ITER*

- *Since both theory and experiments suggest that the main cause of anomalous transport in tokamaks is the existence of a short-scale turbulence, the study of the latter is of paramount importance for ITER.*

- *Three types of instabilities are usually considered: the ion temperature gradient (ITG) mode and the trapped electron (TEM) mode, both with wavelengths of the order of ρ_i, and the electron temperature gradient (ETG) mode with wavelength of the order of ρ_e.*



- *Coherent scattering of CO_2 lasers is the only method capable of detecting the full range of possible fluctuations in ITER. Major advantages are:*
    - *availability of high-power single mode lasers*
    - *negligible wave refraction*
    - *modest requirements for plasma accessibility*

Detection of turbulent fluctuations with coherent scattering of em waves

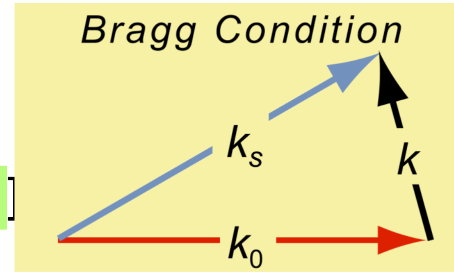
- *Coherent scattering of em waves can be characterized by the cross section*

$$\sigma = (e^2/mc^2)^2 S(\vec{k},\omega)$$

where $S(\vec{k},\omega)$ *is the spectral density of fluctuations*

$$<\delta n^2> = \frac{1}{(2\pi)^4}\int S(k,\omega)d\vec{k}d\omega$$

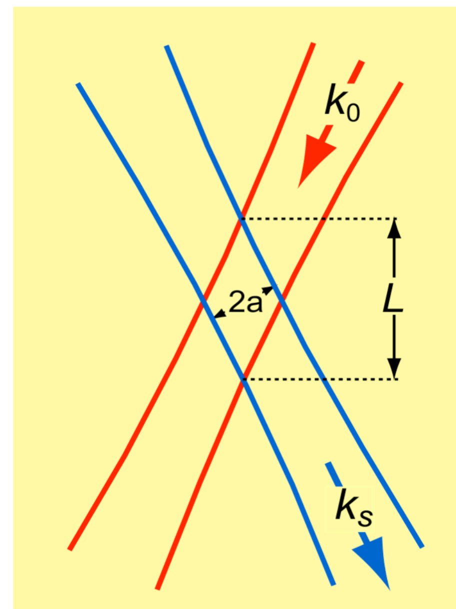
- *Frequencies and wave vectors must satisfy energy [* $\omega=\omega_s-\omega_0$ *] and momentum [* $\vec{k}=\vec{k}_s-\vec{k}_0$ *] conservation (Bragg condition)*



- *Wave number resolution is determined by the size of the probing beam. For a Gaussian beam with amplitude* $A=\exp(-r^2/a^2)$*, it is given by* $\Delta_k=2/a$

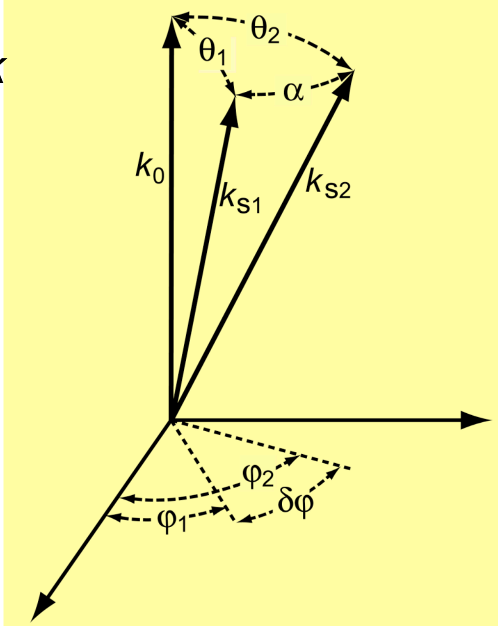
- *For isotropic fluctuations, the spatial resolution of scattering measurements is determined by the common region between launching and receiving radiation patterns.* *Example:* k=8 cm^{-1}, k_0 =6.3x10^3 cm^{-1} (CO_2), a=2 cm

$$L=4k_0a/k=60 \text{ m}$$



- *The size of the scattering region can be much smaller for anisotropic fluctuations*

Instrumental selectivity function for turbulent fluctuations of tokamaks



- *The short-scale turbulence of tokamak is not isotropic since $k_\perp >> k_{||} \sim 1/qR$. Consequently, changes in direction of magnetic field lines can modify the instrumental selectivity function by detuning the scattering receiver*

$$\frac{\vec{k}_{s1} \cdot \vec{k}_{s2}}{k_0^2} \equiv \cos(\alpha) = \cos(\theta_2 - \theta_1) - 2\sin\theta_1 \sin\theta_2 \sin^2(\delta\varphi/2)$$

$$\alpha^2 \approx (\theta_2 - \theta_1)^2 + 4\theta_1\theta_2 \sin^2(\delta\varphi/2) \approx \frac{1}{k_0^2}[(k_2 - k_1)^2 + 4k_1k_2 \sin^2(\delta\varphi/2)]$$

where $k_1 \approx k_0\theta_1$ and $k_2 \approx k_0\theta_2$ (Bragg condition).

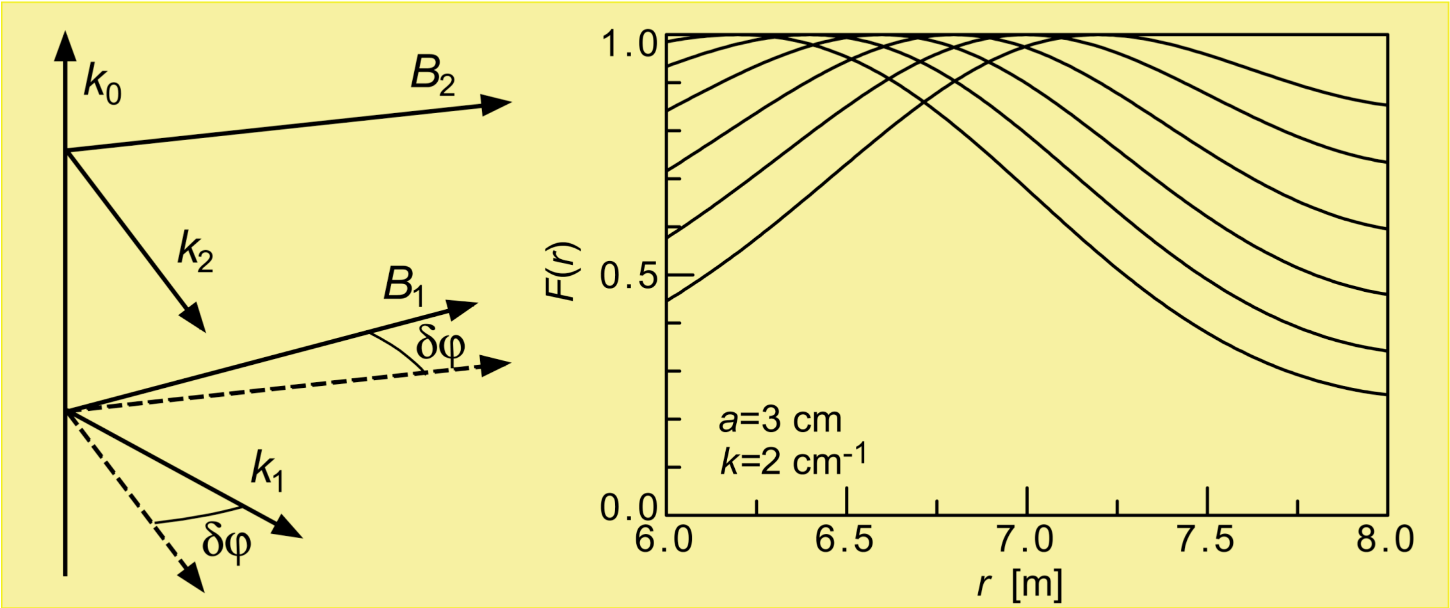
Beam profile in physical space	*Beam profile in Fourier space*	*Instrumental selectivity function*
$\exp(-r_\perp^2 / a^2)$	$\exp(-\kappa_\perp^2/\Delta_k^2)$	$F = \exp[-(\alpha k_0 / \Delta_k)^2]$

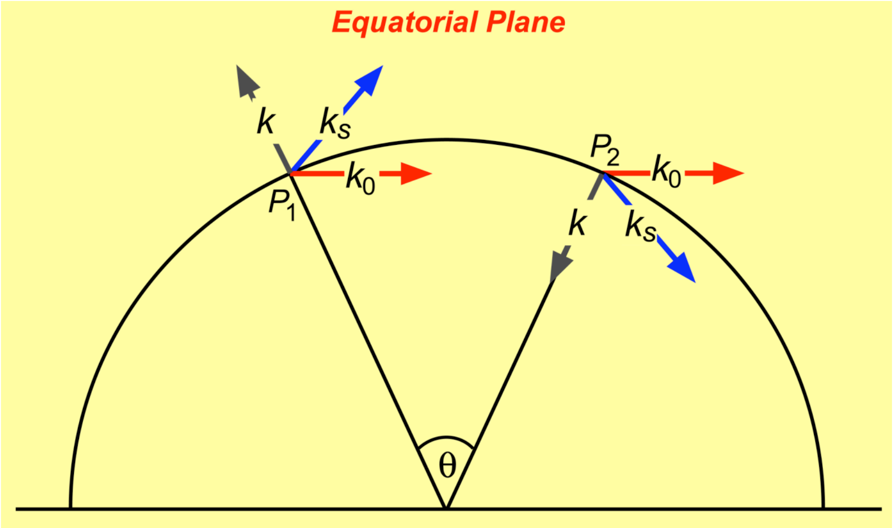
$$F = \exp[-((k_2 - k_1)^2 + 4k_1k_2 \sin^2(\delta\varphi/2))/\Delta_k^2]$$

- *Spatial resolution improves with wave number fluctuations, beam radius and $\delta\varphi$ (i.e., change in direction of field lines within the scattering region)*

Role of poloidal magnetic field

- *When the probing beam propagates perpendicularly to $\vec{B}$, φ coincides with the pitch angle of the field lines. The radial resolution is* $\delta r \approx 2\Delta_k / k < d\varphi / dr >$ *– bad for ITER*





- *When the probing beam propagates at an oblique angle with $\vec{B}$, φ becomes a function of both the pitch angle and the toroidal curvature of magnetic lines*
- *It can be obtained from $\vec{k} \cdot \vec{B} = 0$, i.e,*

$$(\vec{k}_s - k_0) \cdot \vec{B} = 0$$

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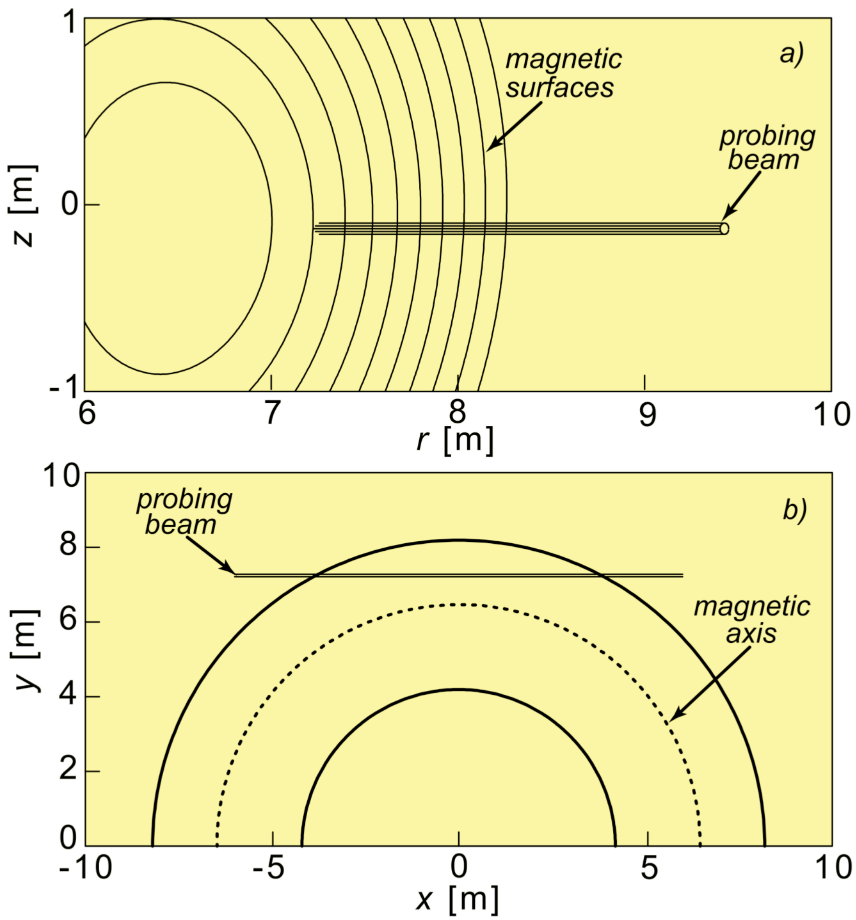
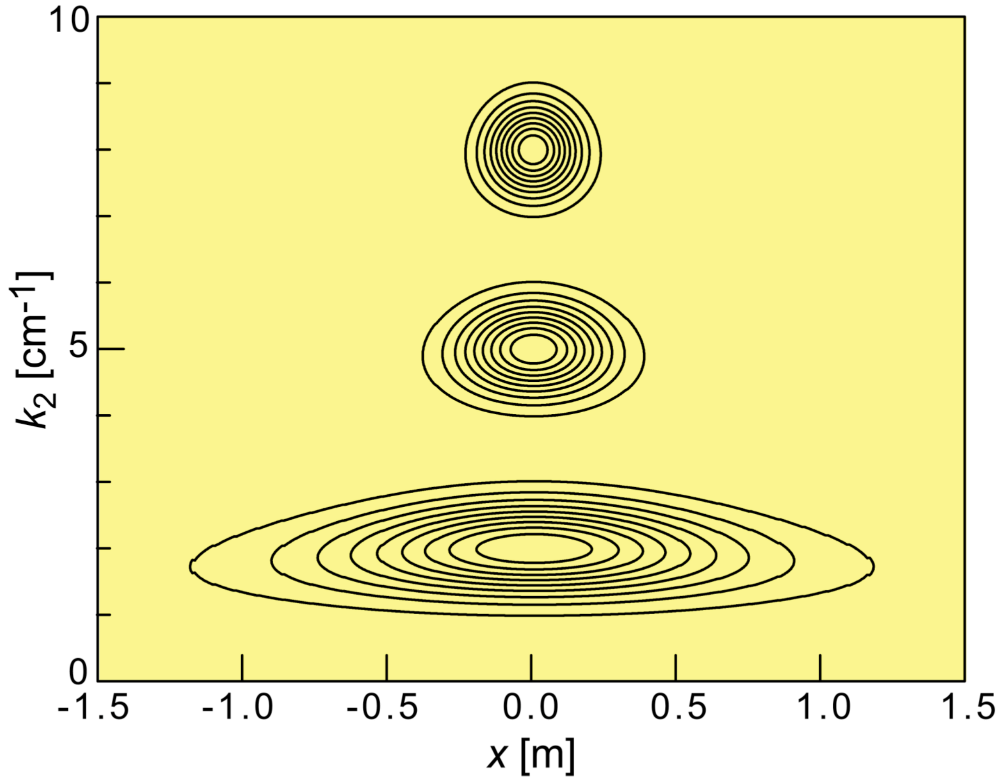
Size of scattering regions depends on wave number of fluctuations



- Poloidal (a) and toroidal (b) trajectories of a CO_2 Gaussian beam with a=3 cm, propagating on the mid-plane of an ITER-like plasma



- Contour plots of $F(k_2,x)$ (nine levels equally spaced from 0.1 to 0.9) for k_1=2, 5 and 8 cm^{-1}(from bottom to top).
- The scattering region is located near the point where the angle between the probing beam and the magnetic line is minimum

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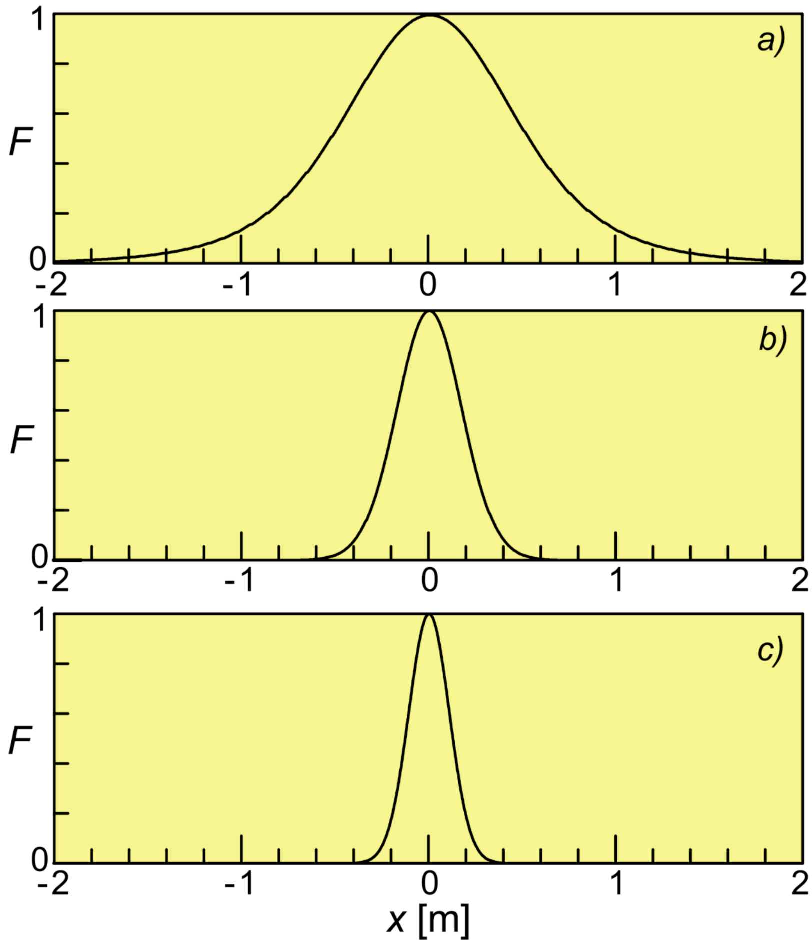
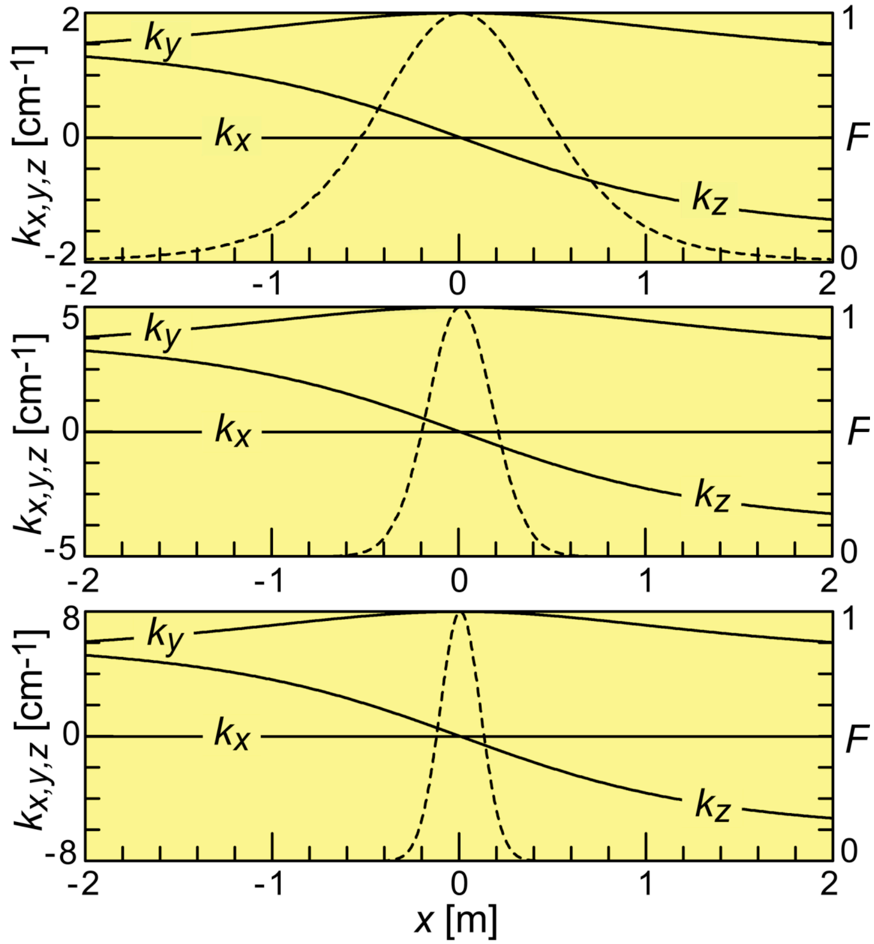
Wave vectors of detected fluctuations are mostly in the radial direction

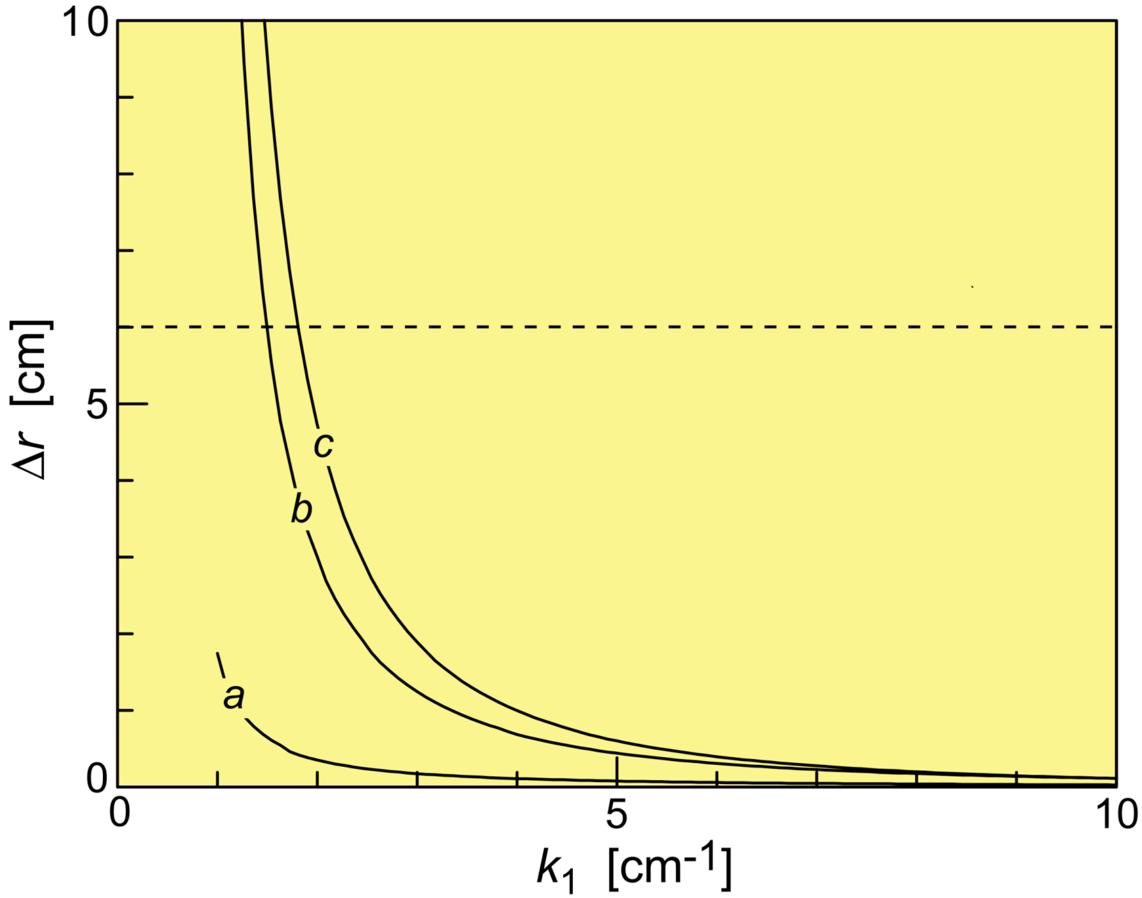


- *Instrumental selectivity function for* $k_1 = k_2 = 2\ \mathrm{cm}^{-1}$ *(a),* $5\ \mathrm{cm}^{-1}$ *(b),* $8\ \mathrm{cm}^{-1}$ *(c)*



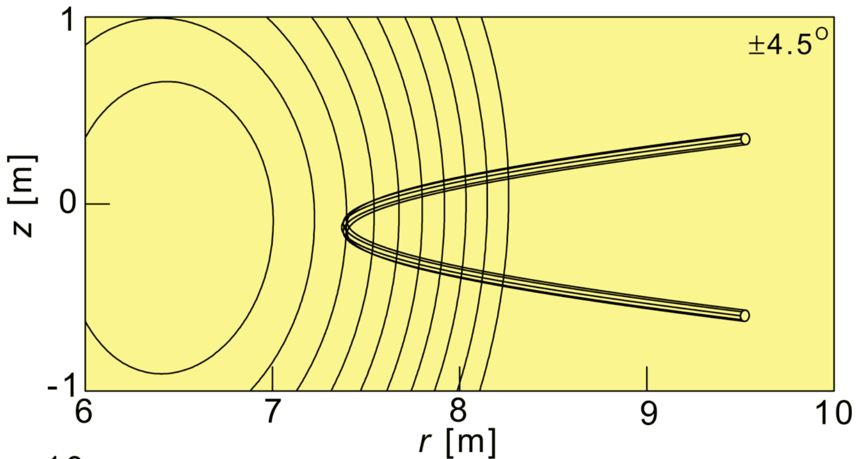
- *Wave vector components of detected fluctuations*

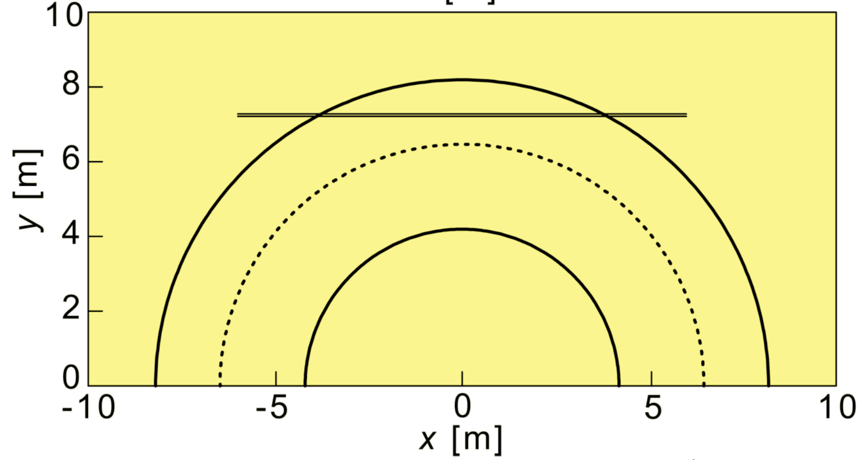
Radial resolution deteriorates with increasing plasma radius

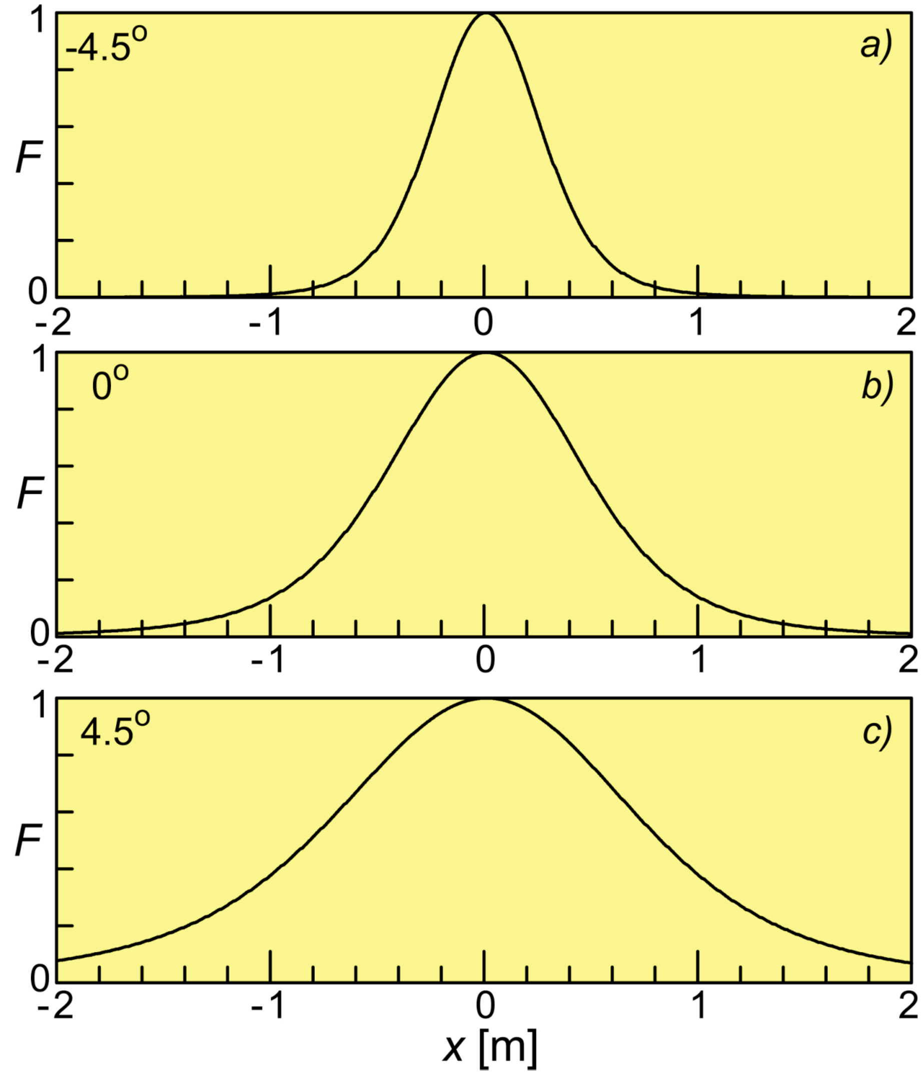


- *Radial footprint of the portion of the beam central ray where F >1/e. Minimum distance of the ray from the magnetic axis is* 0.15 *(a),* 0.5 *(b) and* 0.7 *(c) (in normalized units to the plasma minor radius). Dashed line represents the beam diameter (2a).*

Spatial resolution improves with decreasing angles between probing beam and magnetic lines







- *Selectivity functions for* k_1=2 cm^{-1} *and three launching directions (angles are with the x-axis).*
- *At the peak of F, the angle between the probing beam and the magnetic line is* 8.6° *(a),* 13.9° *(b) and* 18.2° *(c)*

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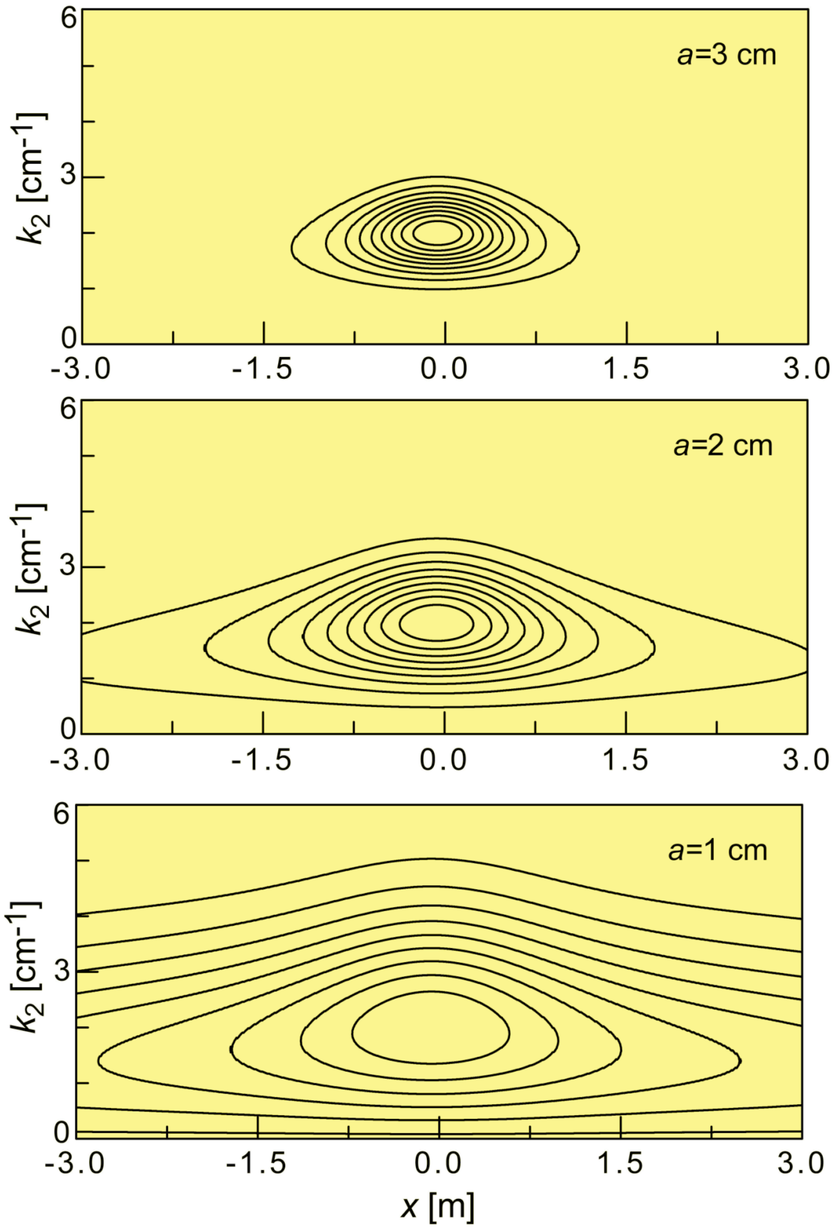
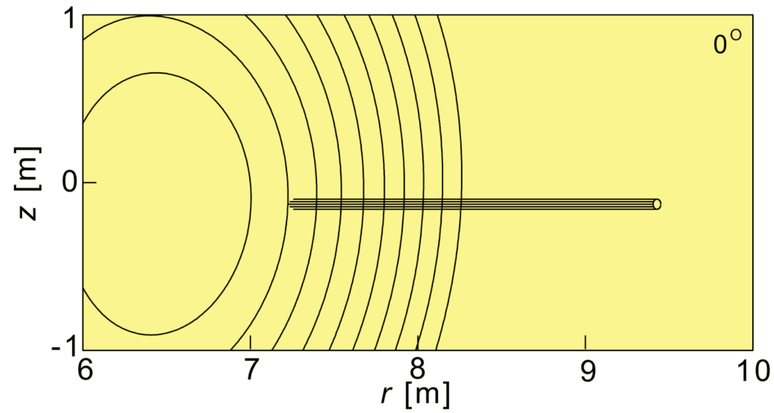
Spatial resolution deteriorates very quickly with increasing beam radius



- *Contour plots of $F(k_2,x)$ for k_1=2 cm^{-1} and a launching angle of 0^o*



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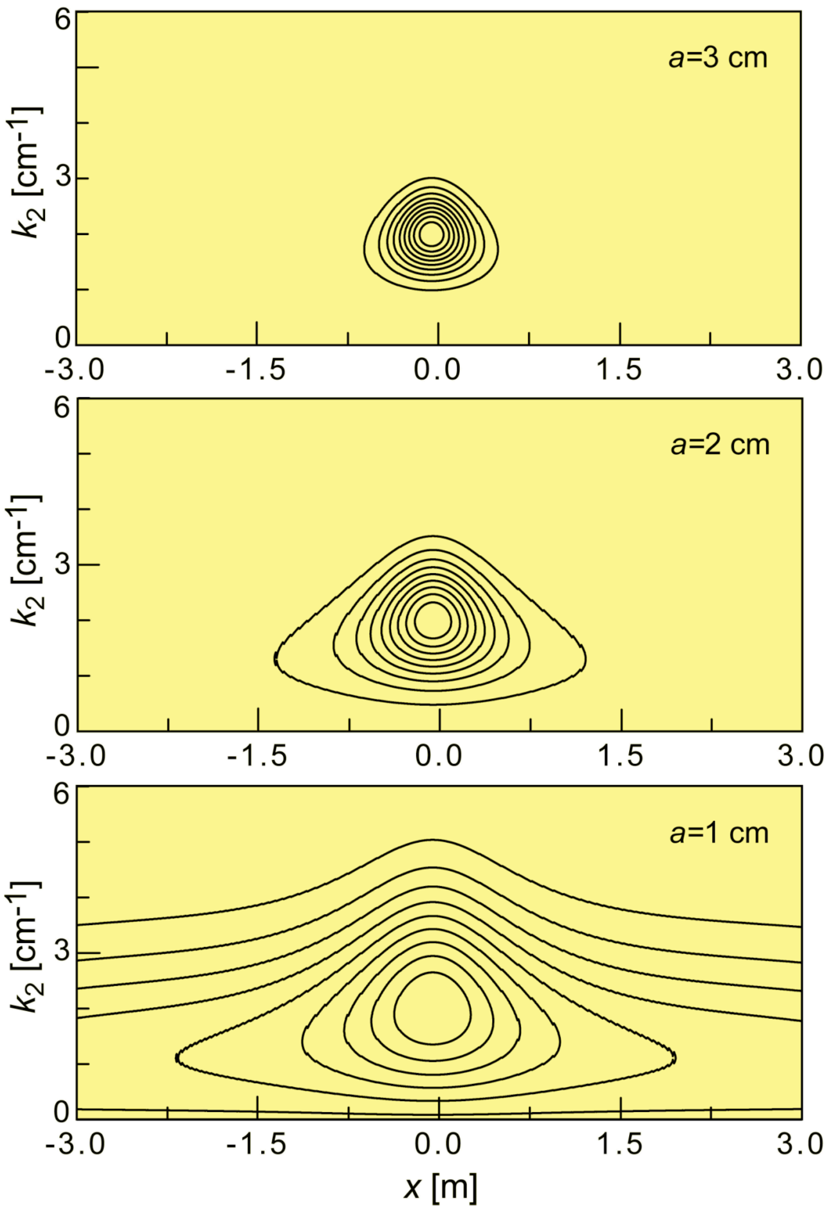
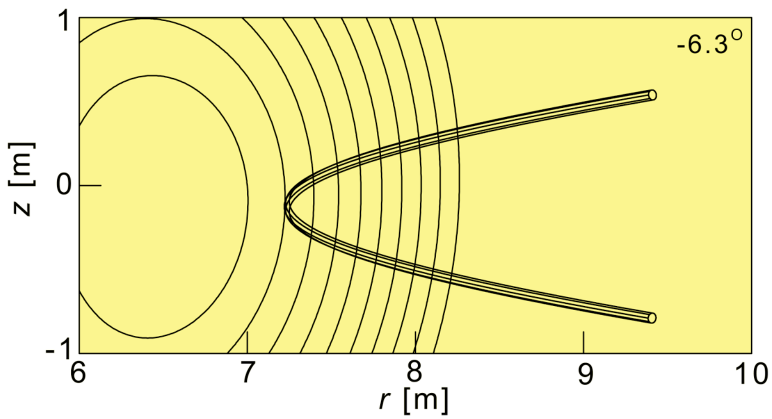
Spatial resolution can be improved by adjusting the launching angle
Remains unsatisfactory for a=1 cm



- *Contour plots of $F(k_2,x)$ for* k_1=2 cm^{-1} *and a launching angle of* -6.3^o



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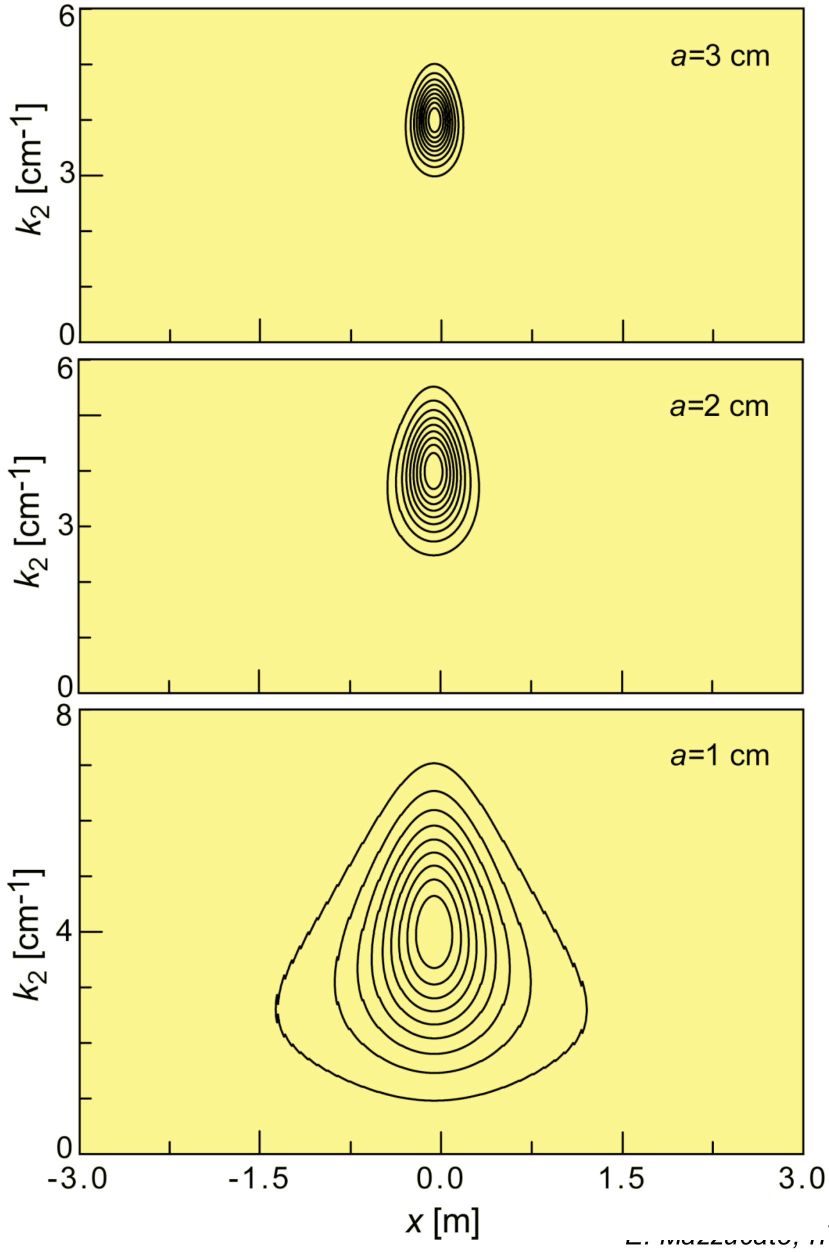
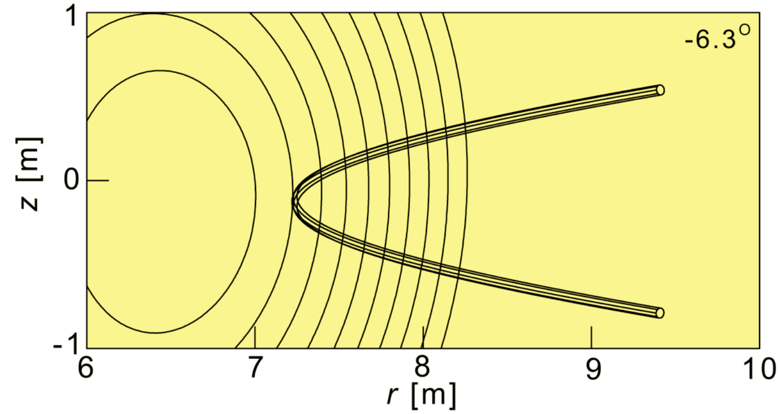


- *Contour plots of $F(k_2,x)$ for k_1=4 cm^{-1} and a launching angle of -6.3°*



Conclusion

- *Coherent scattering of CO_2 lasers could be used for localized measurements of short-scale turbulent fluctuations in ITER*
- *Requires Gaussian beams with 1/e-radii of at least* 2-3 cm *(i.e., circular ports with a clearance of* 8-12 cm*)*
- *Needs assessment of spurious effects from machine vibrations*

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NSTX Implementation