Experimental investigation of plasma turbulence with $k_{\perp}\rho_i >> 1$ in NSTX

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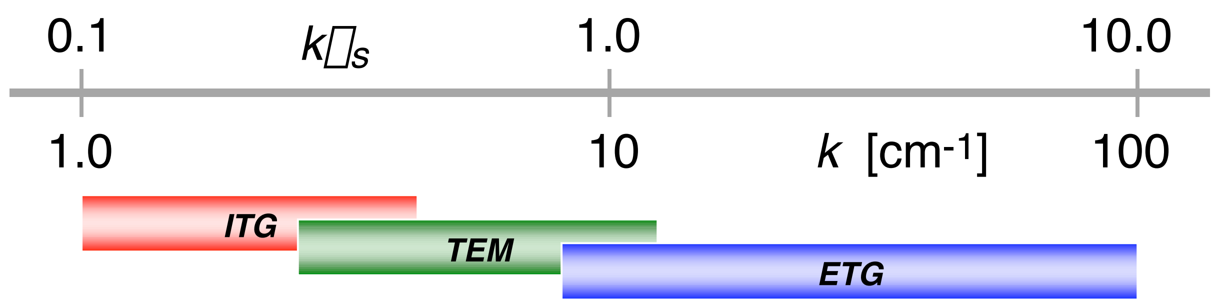
Motivation

- *A longstanding conjecture is that anomalous transport in tokamaks is caused by some type of turbulence.*
- *Two types of instabilities are usually considered: the ion temperature gradient (ITG) and the trapped electron (TEM) modes, characterized by perpendicular wavelengths of the order of ρ_i, and the electron temperature gradient (ETG) mode with perpendicular wavelengths of the order of ρ_e.*



- *During the past two decades, our understanding of plasma transport has improved – but not enough for a comprehensive picture of energy transport in tokamaks.*

Different view from the top

From J. Marburger, NRC BPA Committee, Nov. 18, 2002:

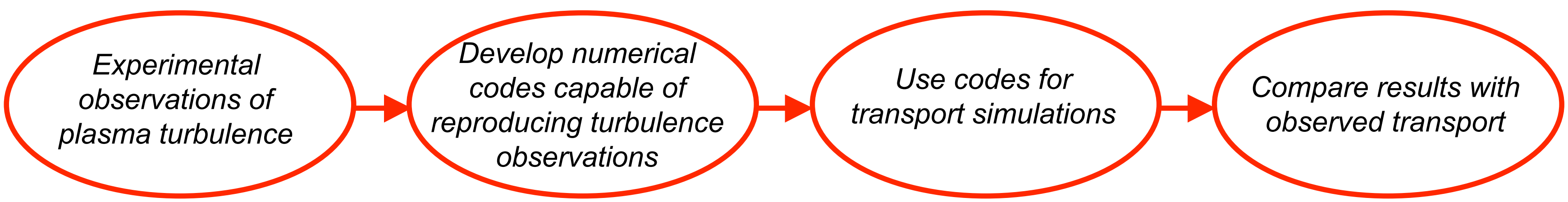
> *"It is fair to say that fusion research today is proceeding with unprecedented theoretical and experimental confidence"*

- *This is contradicted by our incomplete understanding of many fundamental processes, including the very topic of this presentation.*

> *"The ability to predict plasma parameters in realistic simulations, and then test them in detail in actual devices, has changed the character of the entire field substantially"*

- *There are no simulations capable of predicting plasma behavior from first principles. Before predicting the future, we must check experimentally all hidden assumptions and fudge factors.*

Only sensible research program for the study of plasma transport



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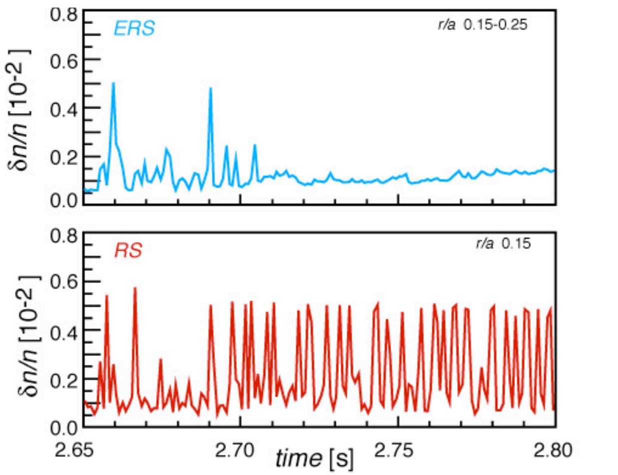
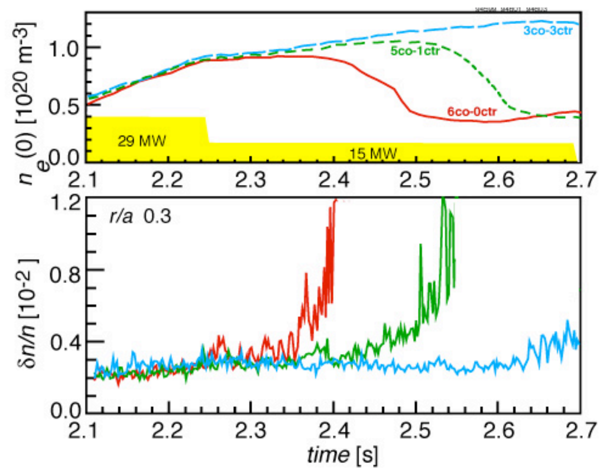
Ion vs. electron transport

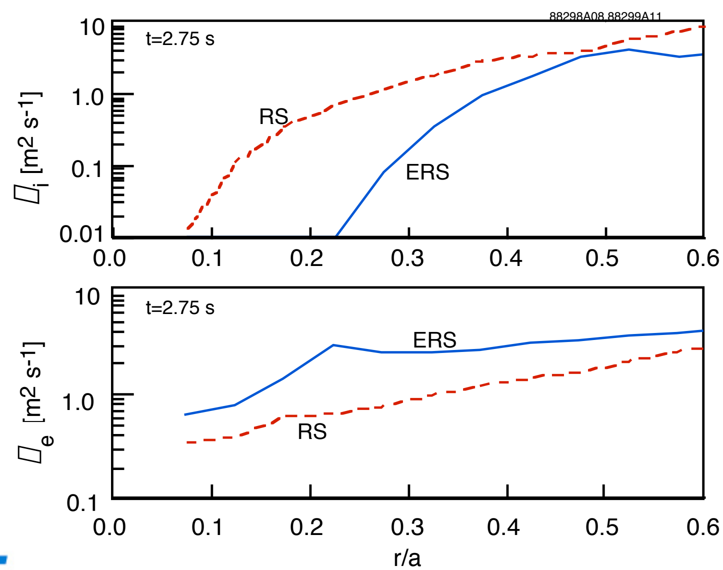
- *Transport of ion energy seems to be controlled by turbulent fluctuations with $k_{\perp}\rho_i < 1$ (ITG). Best evidence from TFTR experiments with reversed shear*



forward-transition coincides with a decrease in fluctuations



back-transition coincides with an increase in fluctuations



- *TFTR observations cannot explain the observed transport of electron energy*

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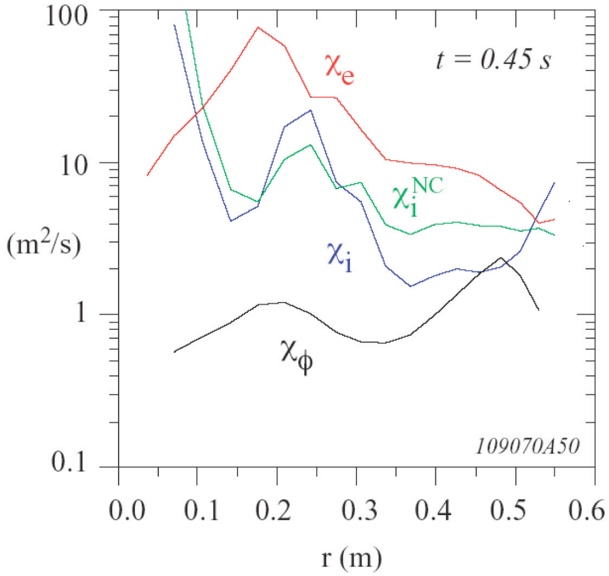
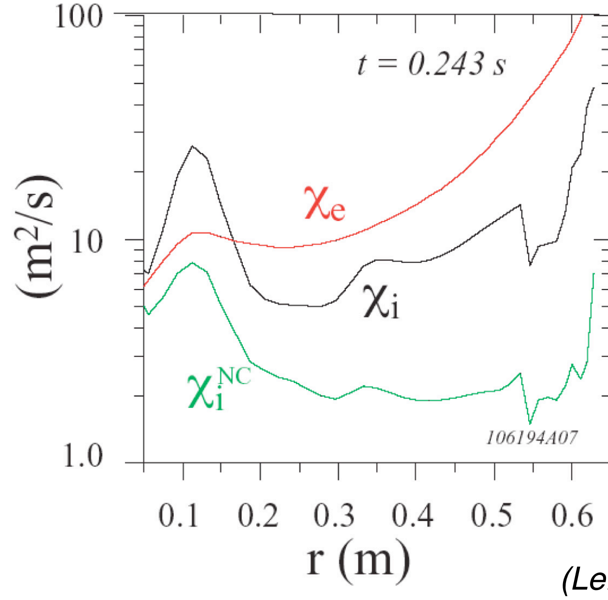
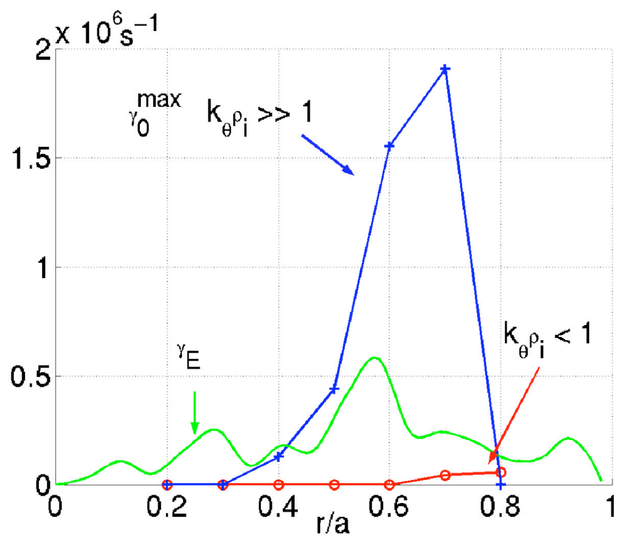
$\chi_e >> \chi_i$ in both NBI and HHFW heated NSTX plasmas





- *This is not surprising since electron transport has been anomalous and worse than ion transport from the very beginning of tokamaks*

(LeBlanc et al.)



- *Recent numerical calculations (Bourdelle et al.) indicate that in NSTX, while instabilities with $k_\theta \rho_i$ <1 are either absent or suppressed by an ExB velocity shear, those with with $k_\theta \rho_i$ >>1 are unstable over most of the plasma cross section.*

Is ETG the cause of anomalous electron transport in NSTX?

This is the question!

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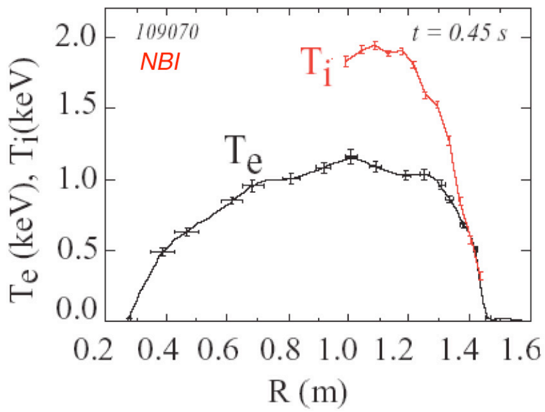
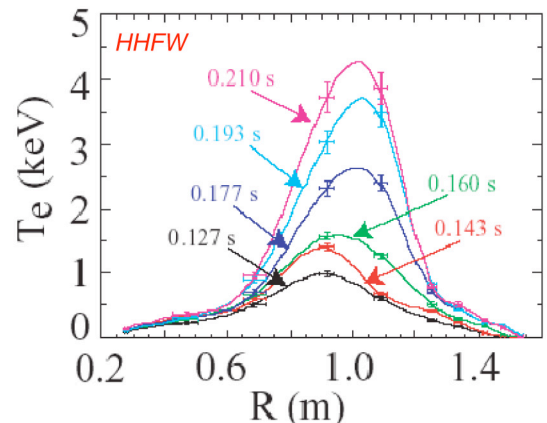
Pros & Cons

Pro: In both ASDEX and ToreSupra, T_e-profiles seem to be limited by a critical gradient length. This suggests that ETG could ply an important role in electron transport.

Con: No such phenomenon was observed in NSTX.





Con: Assuming complete isomorphism between ITG and ETG, we find that $\chi_e/\chi_i \sim (m_e/m_i)^{1/2} \sim 1/60$ for the electrostatic component of the induced transport . The opposite is true for the magnetic component, but some numerical simulations indicate that the latter is negligible – at least for conventional tokamaks (Li & Kishimoto, and Labit & Ottaviani).

Pro: Numerical simulations (Jenko & Dorland) indicate the possible formation of streamers (i.e., structures with long radial correlation lengths) which could enhance χ_e .

Con: In TFTR, electron transport of ERS-plasmas deteriorated is spite of the beneficial effects of reversed shear on the stability of ETG.

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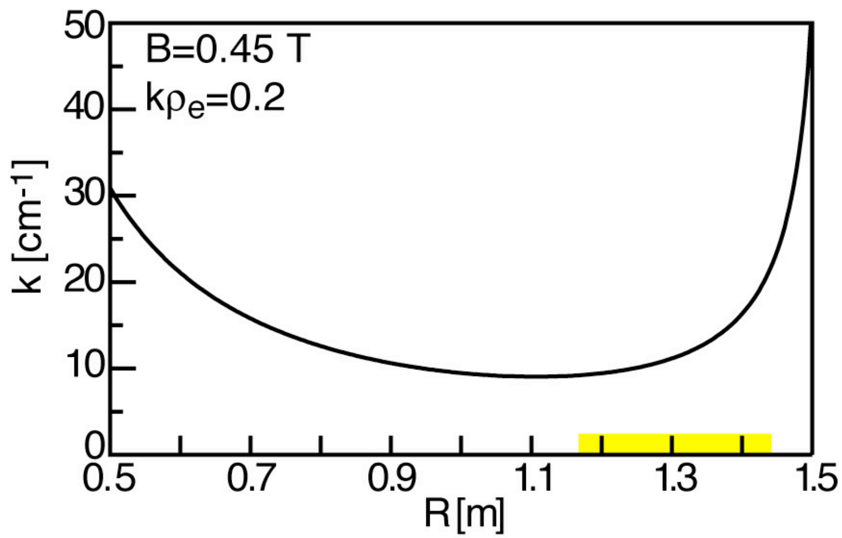
ETG fluctuations in NSTX

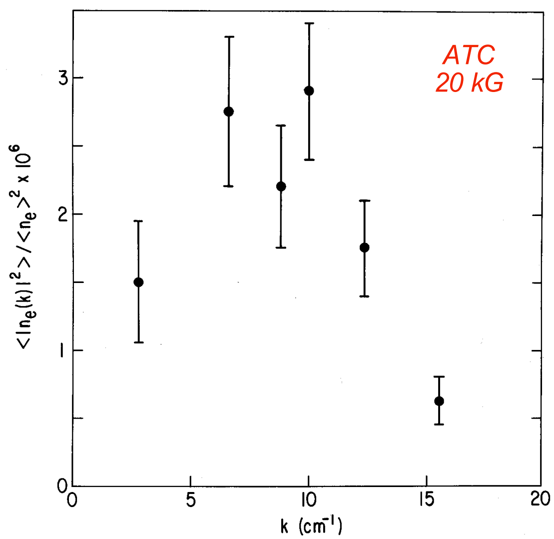
- *The primary goal of this proposal is a direct experimental verification of the importance of ETG turbulence for the transport of electron energy in NSTX.*



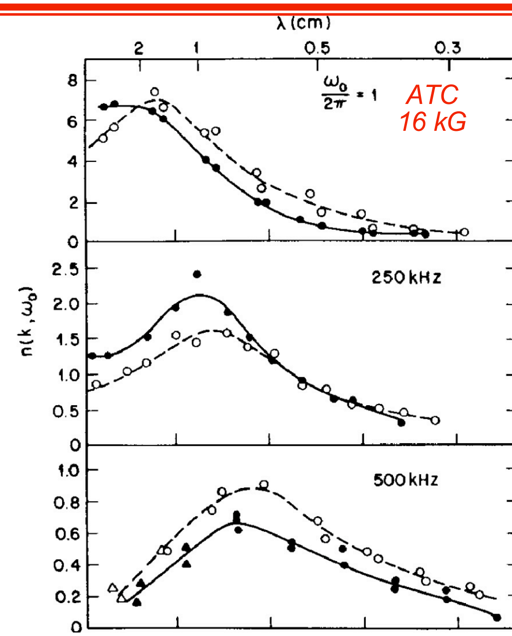
- *The wave number range of ETG fluctuations is inferred from of the observed scale of ITG turbulence.*
- *Coherent scattering of electromagnetic waves is the only feasible method for detection of high-k fluctuations.*

- *Coherent scattering of electromagnetic waves was used for the first detection of turbulent fluctuations in tokamaks.*
- *Existing data are inconclusive about the existence of ETG turbulence in tokamaks.*

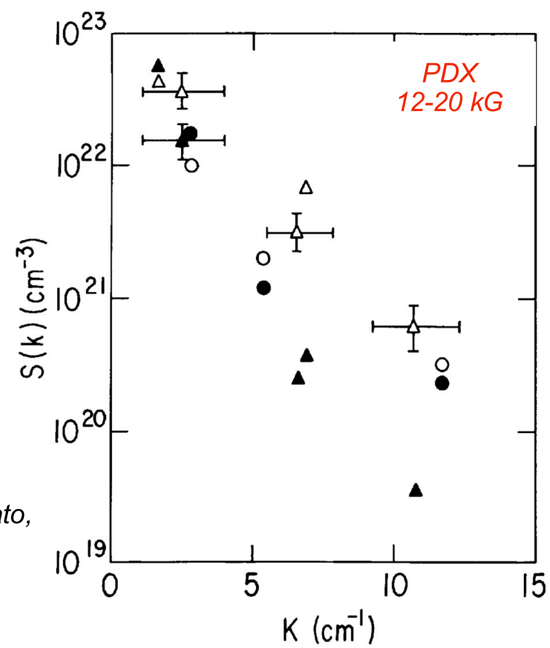
Some observations of high-k fluctuations in low-field tokamaks



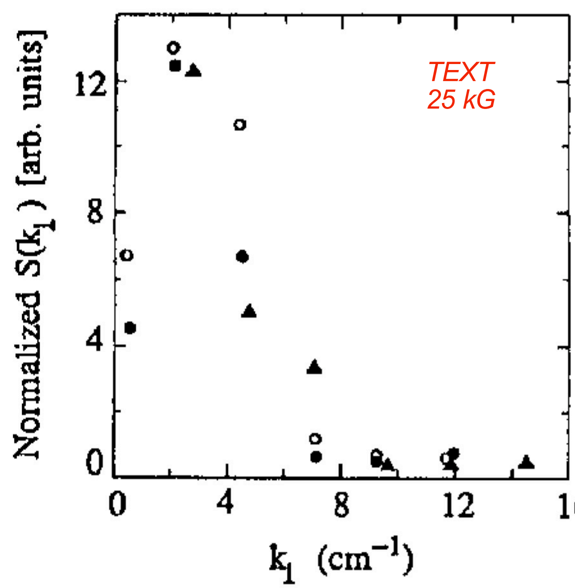
Mazzucato
PRL 26 (1075)



Surko, Slusher
PRL 27 (1976)



Crowley, Mazzucato,
NF 25 (1085)



Brower, et al.
NF 27 (1987)

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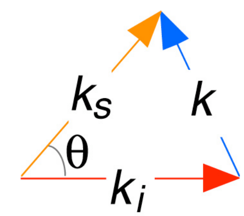
Detection of ETG fluctuations with coherent scattering of em waves

- *Coherent scattering of e.m. waves is characterized by the cross section $\sigma=(e^2/mc^2)^2\, S(\mathbf{k},\omega)$, where $S(\mathbf{k},\omega)$ is the spectral density of fluctuations*

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

- *Frequencies and wave vectors must satisfy energy [$\omega=\omega_s-\omega_i$] and momentum [$\mathbf{k}=\mathbf{k}_s-\mathbf{k}_i$] conservation.*



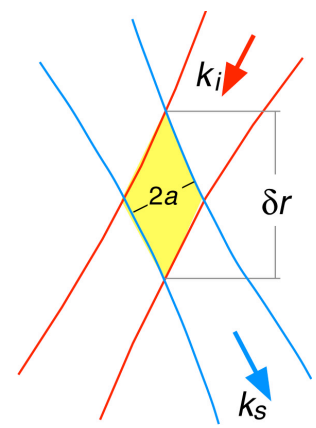
Bragg Condition

- *The wave number resolution is determined by the size of the probing beam. For a Gaussian beam with an amplitude $A=\exp(-r^2/a^2)$, the resolution is δk~$2/a$.*

- *For isotropic fluctuations, the spatial resolution is determined by the common region of radiation patterns of launching and receiving antennae. Example:*

$$\delta r=4k_i a/k=48\text{ cm}$$

for k=10 cm^{-1}, k_i=60 cm^{-1} and a=2 cm. This is not adequate for our goal!



- *Spatial resolution can be substantially better in the case of anisotropic fluctuations.*

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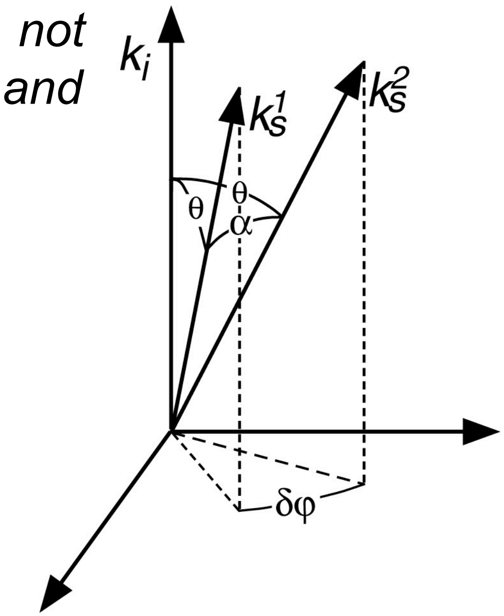
- *Since $k_{\perp} >> k_{||} \sim 1/qR$, the turbulence of interest is not isotropic. Consequently, since the direction of B is not constant, not every point of the common region between launching and receiving beams satisfies the Bragg condition*

$$\frac{k_s^1 \cdot k_s^2}{k_i^2} \equiv \cos(\alpha)$$

$$= \cos^2\theta + \sin^2\theta\cos(\delta\varphi) = 1 - 2\sin^2(\delta\varphi/2)\sin^2\theta$$

$$\alpha^2 \approx 4\sin^2(\delta\varphi/2)\sin^2\theta \approx 4\sin^2(\delta\varphi/2)k/k_i$$

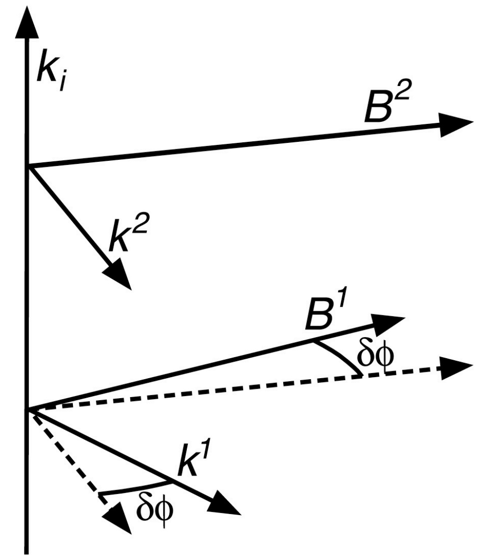


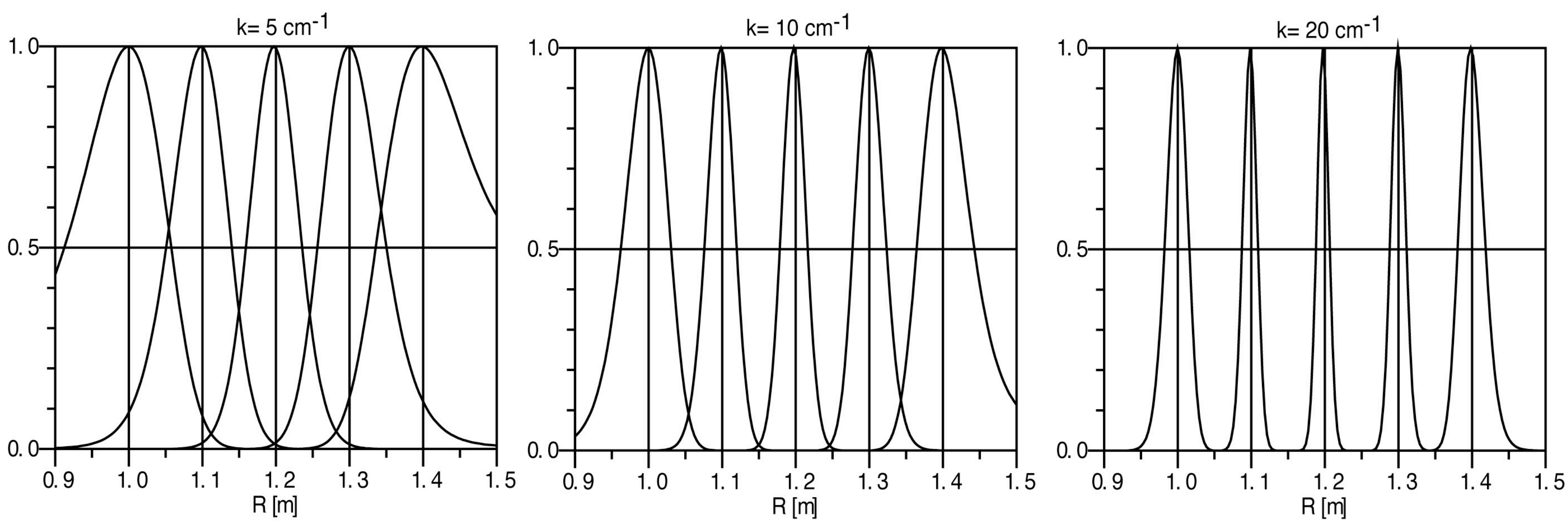
Beam profile in real space	*Beam profile in Fourier space*	*Instrumental function*
$\exp(-r_{\perp}^2/a^2)$	$\exp(-k_{\perp}^2 a^2/4)$	$\exp[-(\sin(\delta\varphi/2)ka)^2]$

- *Spatial resolution improves with fluctuation wave number (k), beam radius (a) and change in direction of magnetic lines (dφ(r)/dr).*

Perpendicular propagation

- *For quasi-perpendicular wave propagation (i.e., for detection of poloidal fluctuations), d□(r)/dr increases with* ***magnetic shear*** *–* ***large in NSTX.***
- *Examples of instrumental functions for B=0.45 T, I=800 kA and a=3 cm.*





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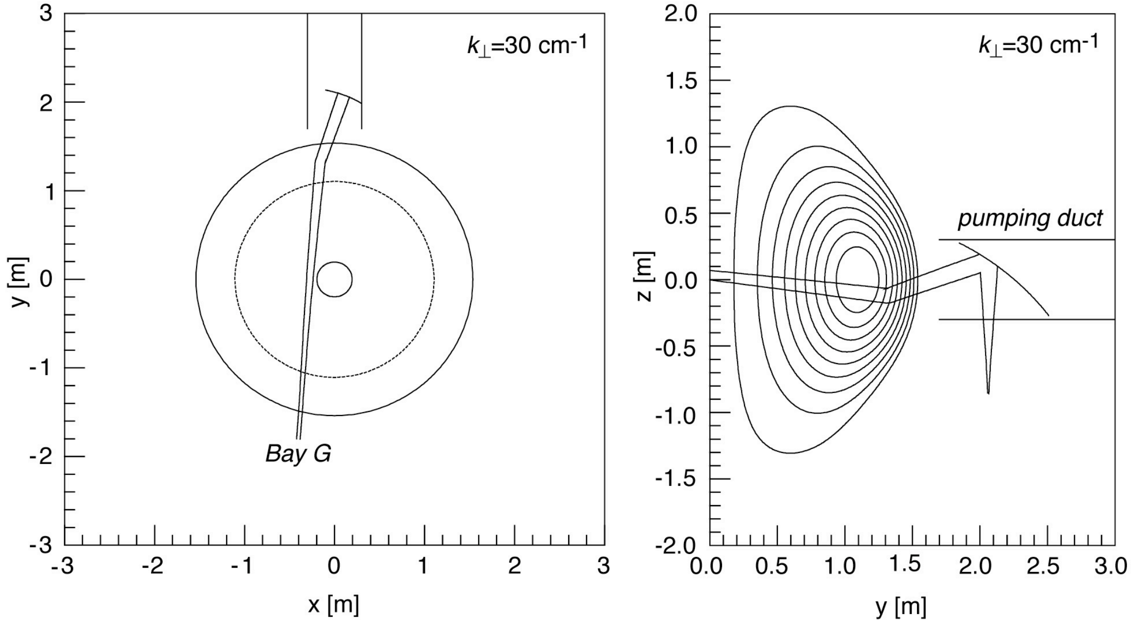
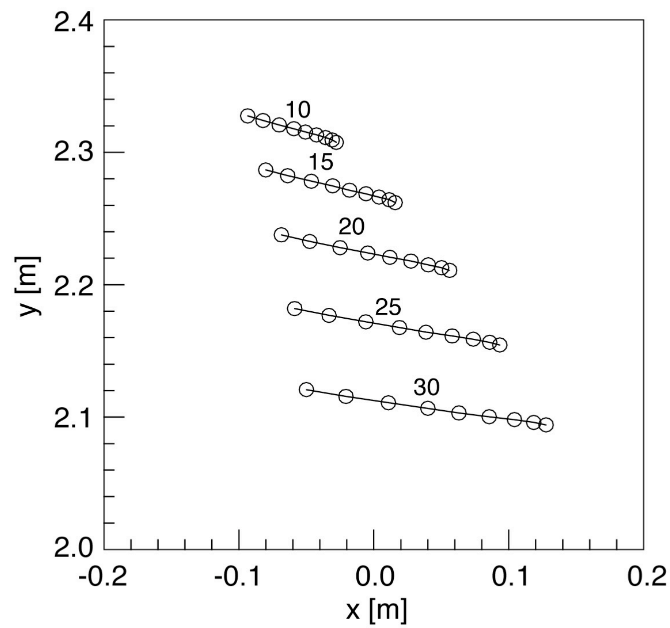
Scattering geometry for detection of poloidal fluctuations



- *Equatorial (left) and poloidal (right) trajectories of rays with 1/e² intensity; probing beam has a frequency of 280 GHz and a minimum waist of 2 cm.*

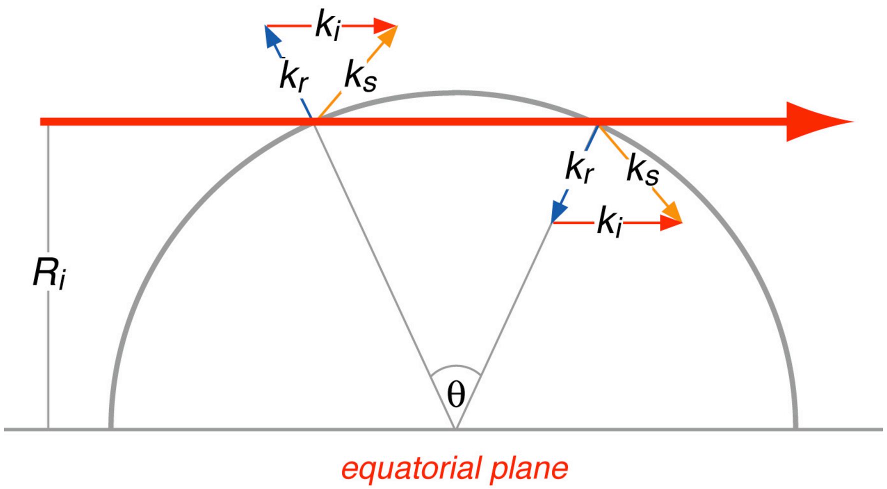
- *Position of scattered beams on the focal plane as the scattering location is moved from R=1.20 m to 1.46 m in steps of 3.25 cm (from left to right in figure); labels are values of $k_{\perp}$, circles represent the waist of received beams.*



Oblique propagation

- *For good radial resolutions, another option is using a probing beam propagating obliquely to the magnetic field. In this case, the instrumental resolution improves because of the toroidal curvature of magnetic field lines.*

Scattering geometry for radial fluctuations



- *Bragg condition: at points of observation, the bisector of* $\mathbf{k}_i$ *and* $\mathbf{k}_s$ *is tangent to the circle of radius* $R_i/\cos(\theta/2)$.

- *Spread in radial locations:* $\Delta R = R_i\left[\left(1 - \left(k_r^{\max}/2k_i\right)^2\right)^{-1/2} - 1\right]$

Example: for $R_i = 1.3$ m, $k_i = 60$ cm^{-1} and $k_r^{\max} = 30$ cm^{-1}

$$\Delta R_i = 4.25 \text{ cm}$$

to which we must add the radius of probing beam (~2 cm) to get the radial resolution.

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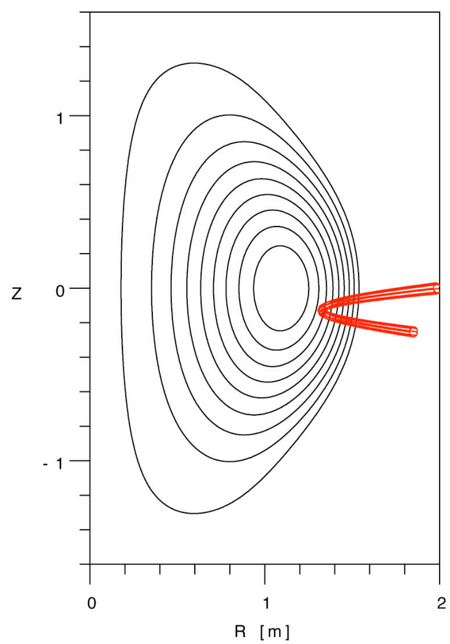
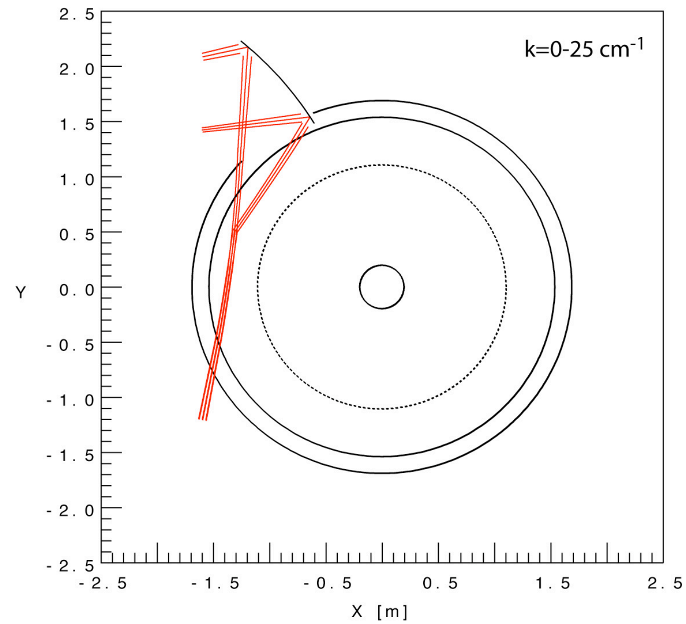
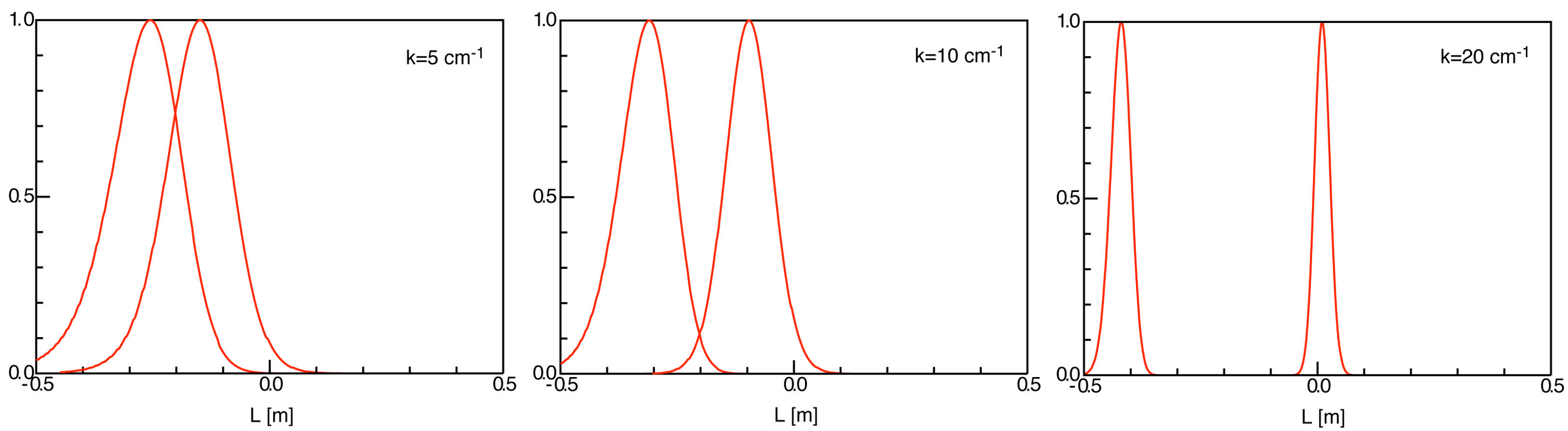
Scattering geometry for detection of radial fluctuations

f=280 GHz
O-mode
beam waist 3 cm
n_o=4x10^{19} m^{-3}







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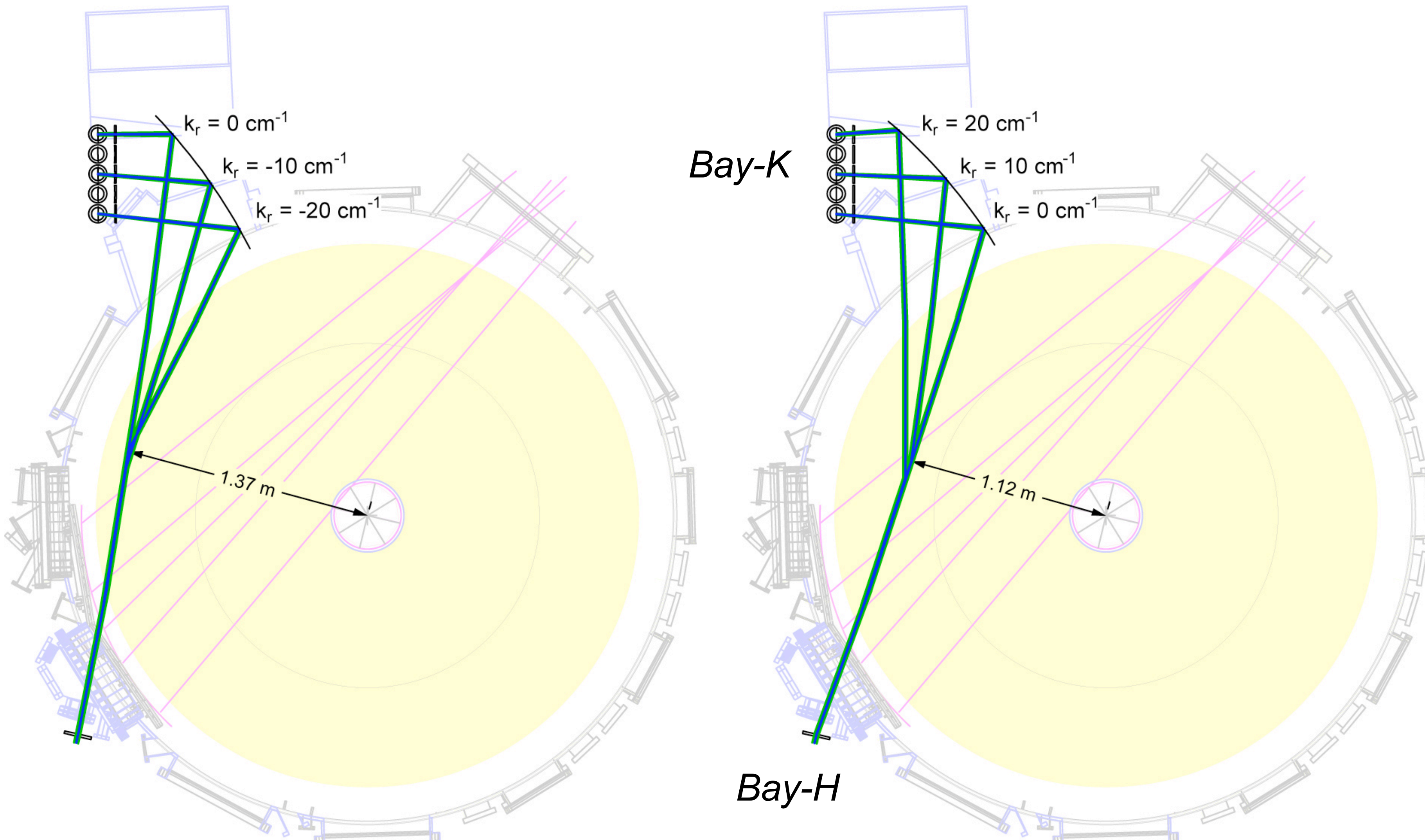
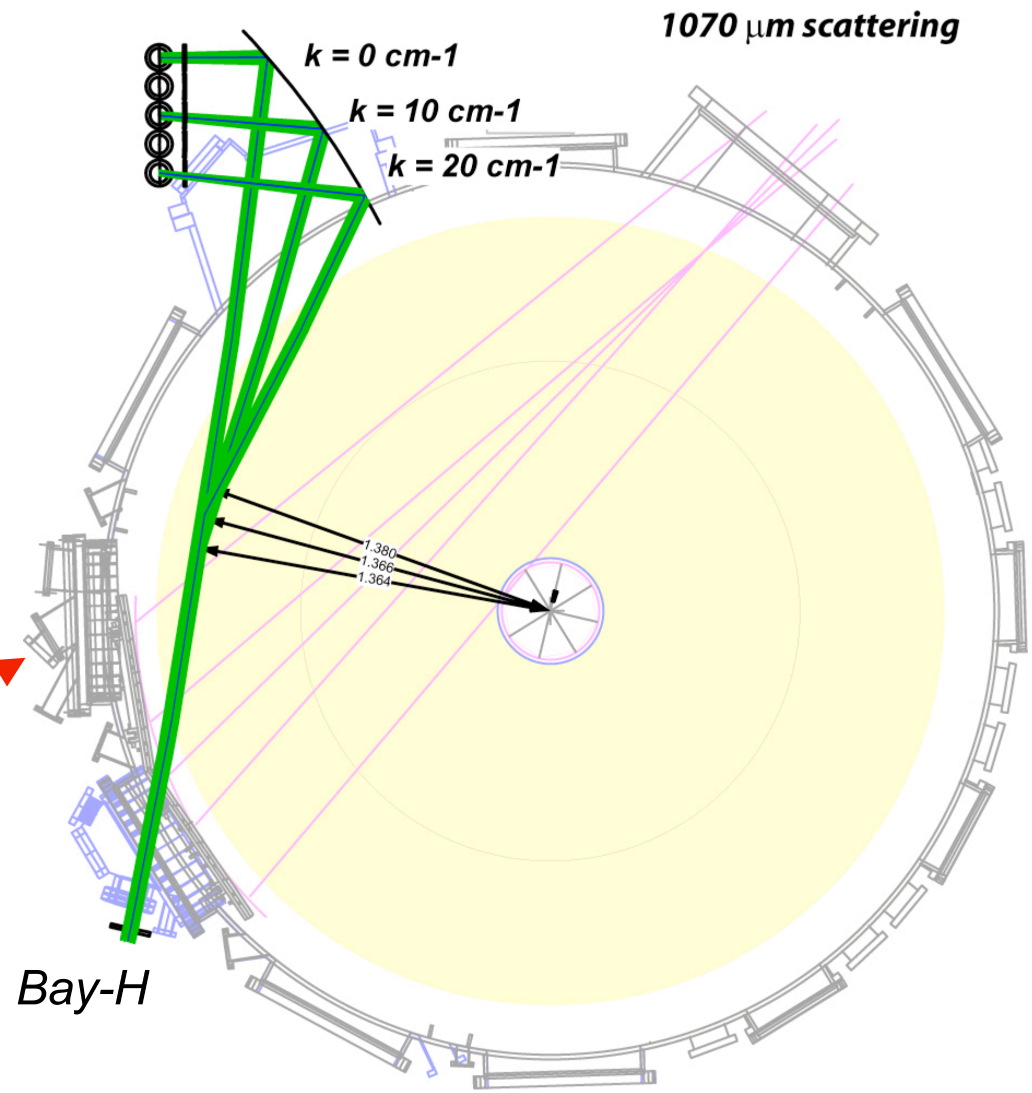
NSTX Implementation

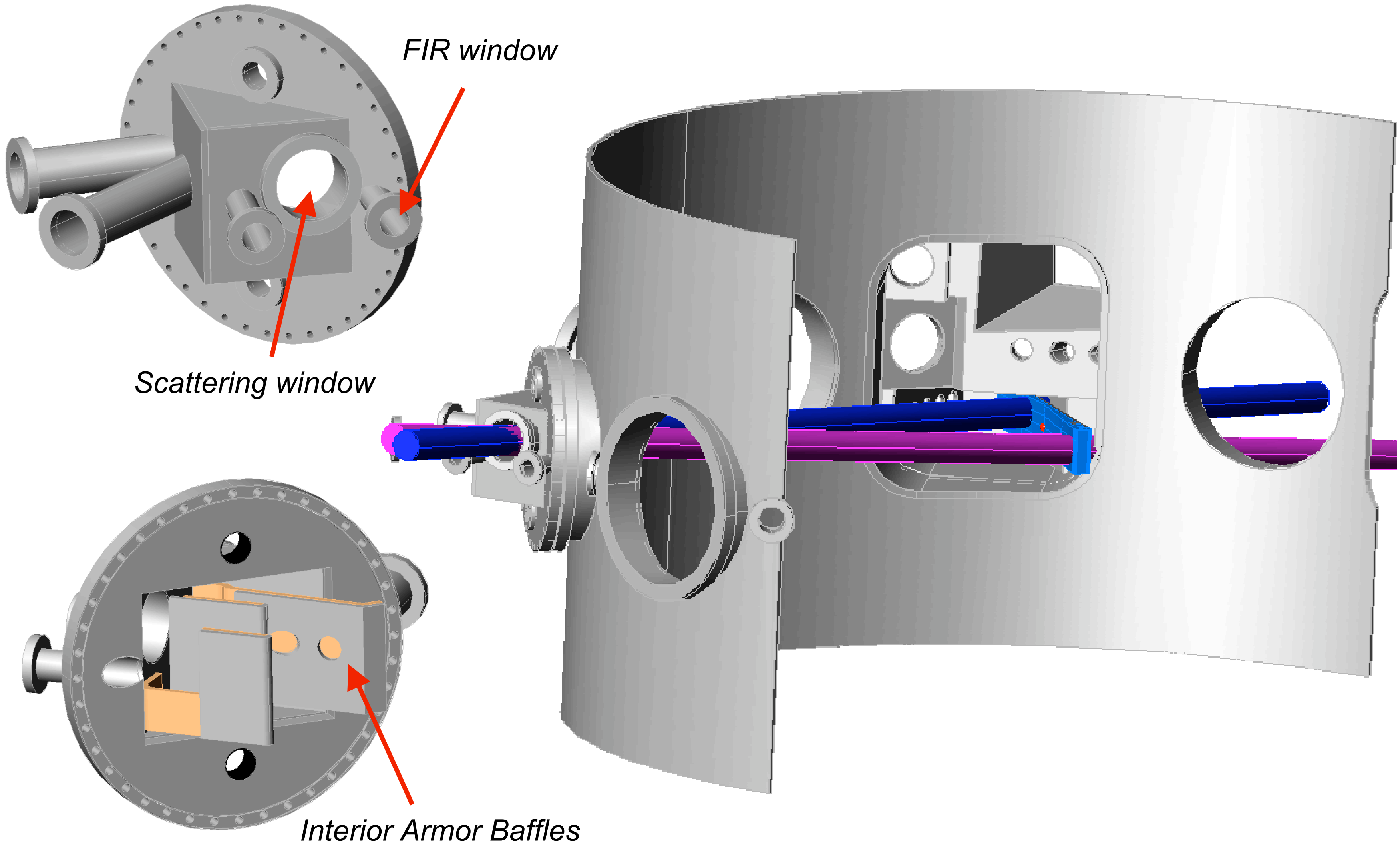


NSTX Implementation

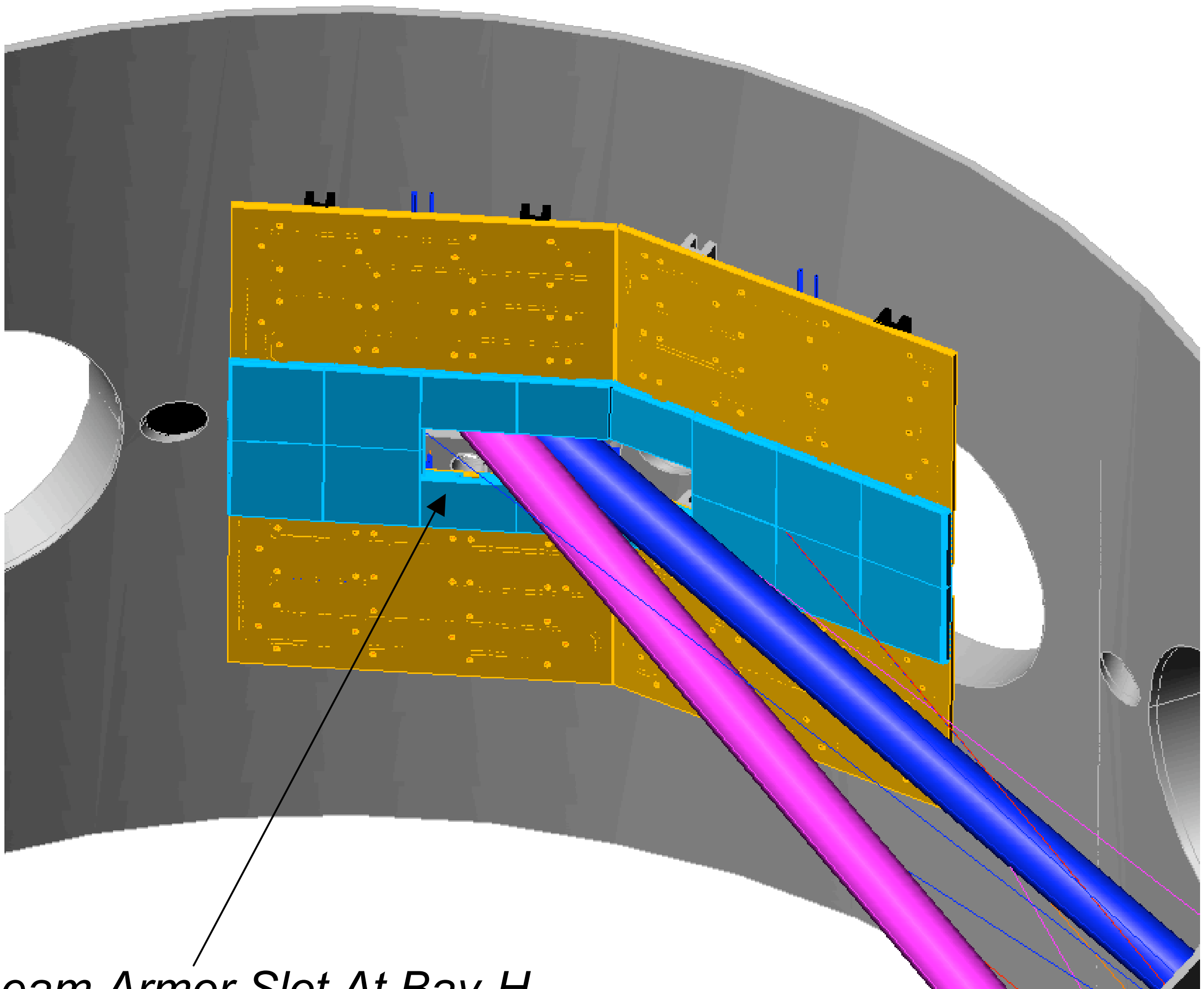


Alternative port for higher k measurements (20-40 cm^{-1})

Launching from Bay-H

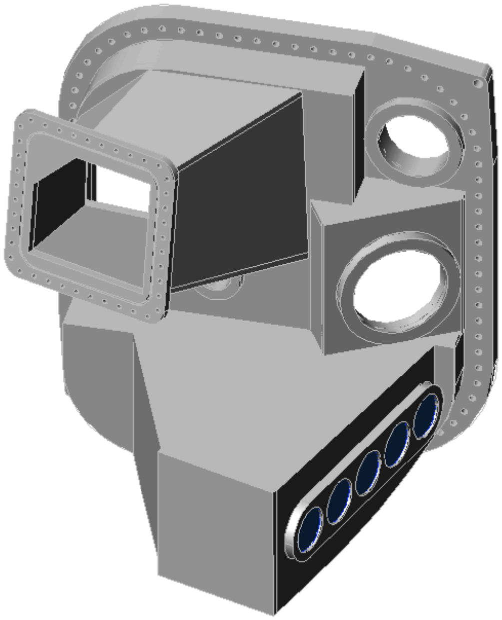


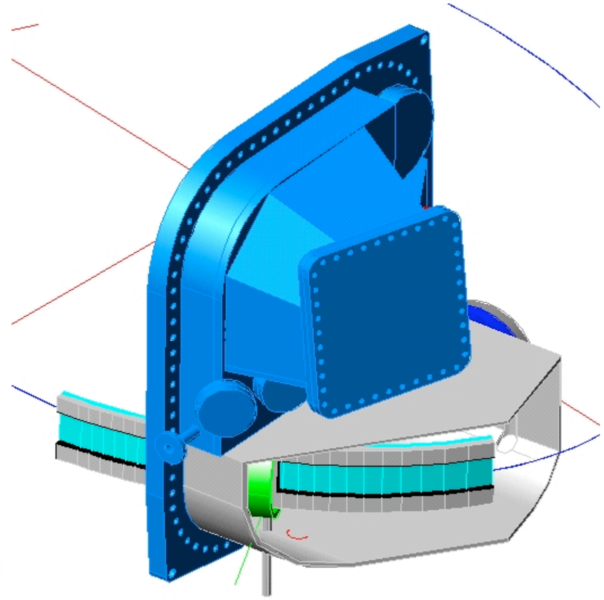
Launching from Bay-H

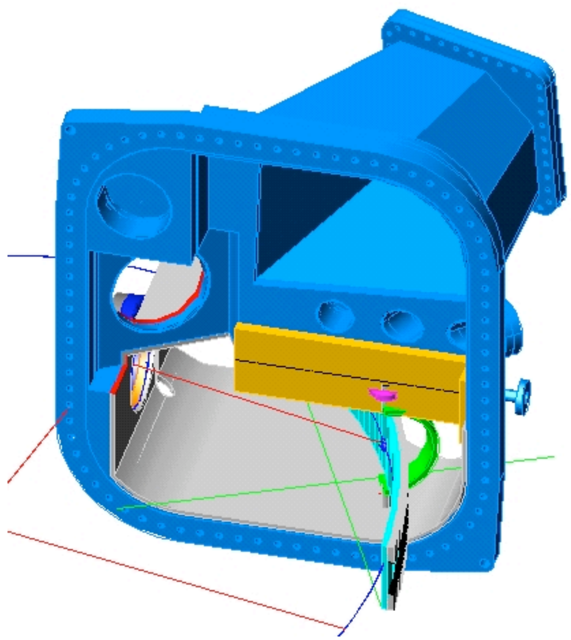


Neutral Beam Armor Slot At Bay-H

Receiving at Bay-K







Minimum detectable fluctuation amplitude

$$\frac{P_{scat}}{P_i} = \left(\frac{e^2}{mc^2}\right)^2 S(k,\omega)\, L\, \lambda$$

$$<\delta n^2> = \frac{<S>}{(2\pi)^3}(\pi k_\perp^2)\frac{2\pi}{L}, \quad \theta = \pi\left(\frac{2}{k_i a}\right)^2$$

$$\frac{P_{scat}}{P_i} = \frac{1}{4}\left(\frac{\omega_p}{\omega_i}\right)^4 k_i^2 L^2 \frac{<\delta n^2>}{n^2}\left(\frac{2}{k_\perp a}\right)^2$$

$n = 2x10^{13}$ cm^{-3}, $<\delta n^2>/n^2 = 10^{-8}$, $k_\perp = 20$ cm^{-1},

$P_i = 0.1$ W, $\omega_i / 2\pi = 280x10^9$ Hz,

$L = 5$ cm, $a = 3$ cm

$$P_{scat} = 1x10^{-11} \text{ W}$$

With total transmission losses of 50%, the signal power is $5x10^{-12}$ *W – larger than the estimated NEP of* $2x10^{-13}$ *W.*

- *Conclusion: the proposed method will be capable of detecting fluctuations much smaller than those expected from the ETG mode ($\delta n/n \sim 1/k_\perp L_{te} \sim 10^{-3}$).*

Conclusions

- *Recent experiments on Tore Supra and ASDEX Upgrade seem to suggest that the ETG mode plays an important role in transport of electron thermal energy – the main loss of energy in NSTX.*
- *The primary goal of this proposal is a direct experimental verification of the importance of ETG driven turbulence for the transport of electron energy in NSTX plasmas.*
- *Turbulent fluctuations with a sub-ρ_i scale – such as those driven by the ETG mode – will be detected with coherent scattering of 1-mm electromagnetic waves.*
- *A unique feature of the proposed method is the ability to measure with high sensitivity and spatial resolution both the poloidal and the radial spectrum of turbulence.*
- *The proposed system will be capable of detecting fluctuations with the scale of ρ_i as well. This will make possible a direct comparison of the observed ETG turbulence – if any – with those turbulent phenomena that are known to dominate the transport of ion energy in tokamaks.*
- *Initial operation will be limited to the measurement of the radial spectrum of fluctuations.*