NSTX

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Synthetic diagnostics for NSTX simulations

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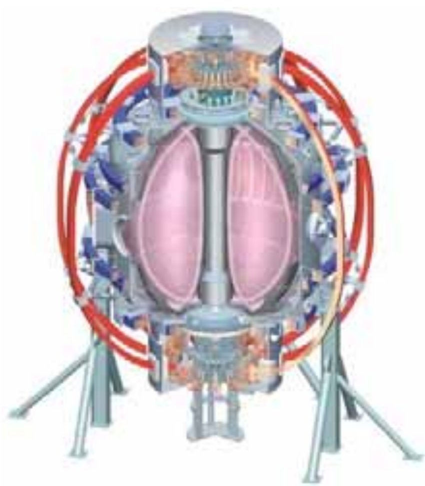
and the NSTX Research Team

November, 30th, 2010



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General (and basic) structure of a synthetic diagnostic

Diagnostic hardware
Magnetic equilibrium
Plasma profiles

→ ① **Simulated diagnostic** → Must reproduce the diagnostic response

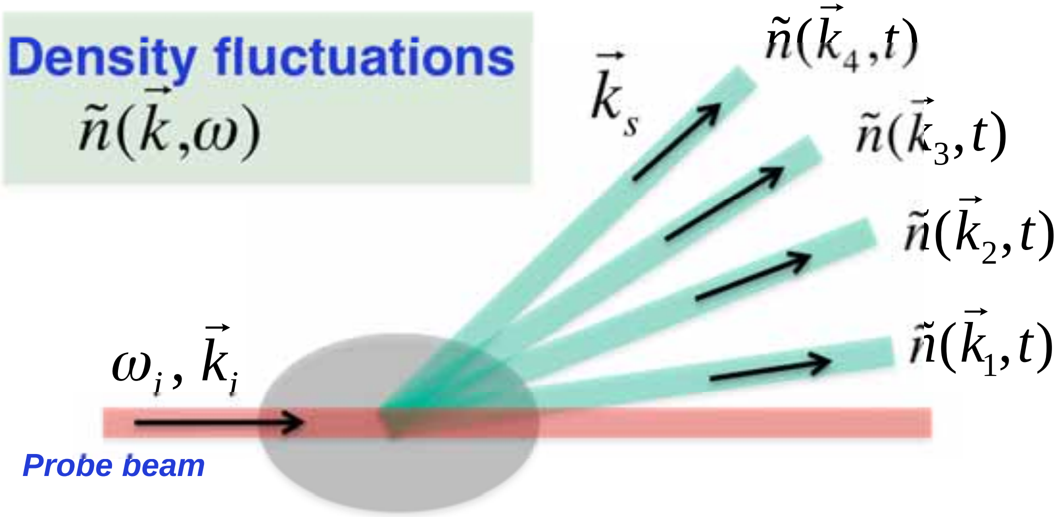
Geometry
(experiment / code)

→ ② **Interface with numerical code** → Filter simulated data for analysis (Point Spread function for BES, Selectivity Function for high-k)

③ **analysis tool (e.g. spectra)** — 1D Fourier Transforms: along θ, r, t

- modular structure
- should be transportable to different numerical codes and adaptable to other diagnostics

The synthetic high-k aims at reproducing the real diagnostic



High-k scattering measures $\{k_\perp\}$

$$\vec{k} = \vec{k}_s - \vec{k}_i$$

$\omega_i >> \omega$ => Small θ_s

$$k = 2k_i \sin(\theta_s/2)$$

$$\mathbf{E}_i(\mathbf{r},t) = \mathbf{E}_i(\mathbf{r}_\perp)\, e^{i(\mathbf{k}_i\cdot\mathbf{r}-\omega_i t)}$$

Fourier Transform of density fluctuations weighted by the beam intensity

$$\mathbf{E}_s(\nu_s) = \frac{r_e}{X} e^{i\mathbf{k}_s\cdot\mathbf{x}}(\hat{s}\hat{s}-\mathbf{1})\cdot\int_{T'} dt' \int_V d^3r'\, \mathbf{E}_i(\mathbf{r}_\perp)\, e^{i(\omega t'-\mathbf{k}\cdot\mathbf{r})}\,\tilde{n}(\mathbf{r}',t')$$

Direction & amplitude of k_s

Amplitude profile of beam (size of the scattering volume)

Present status of the synthetic high-k

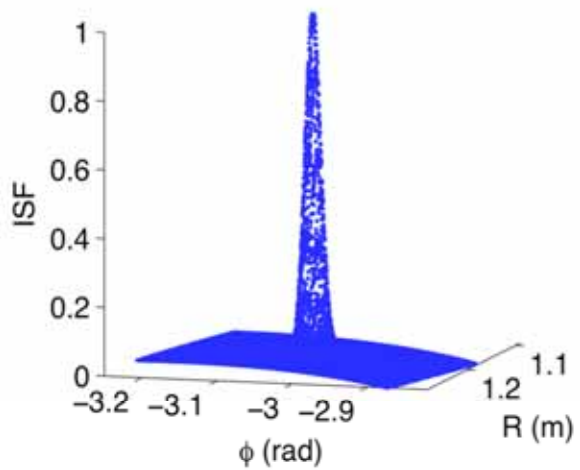
MDS tree

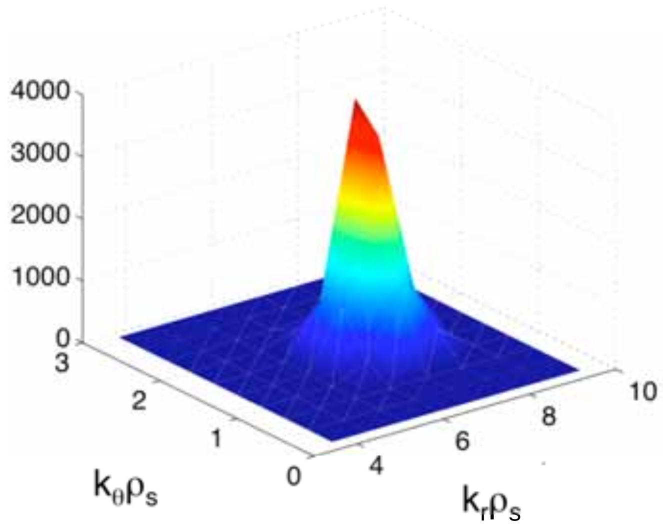
Beam tracing ① ⇨ **Write input files** ⇨

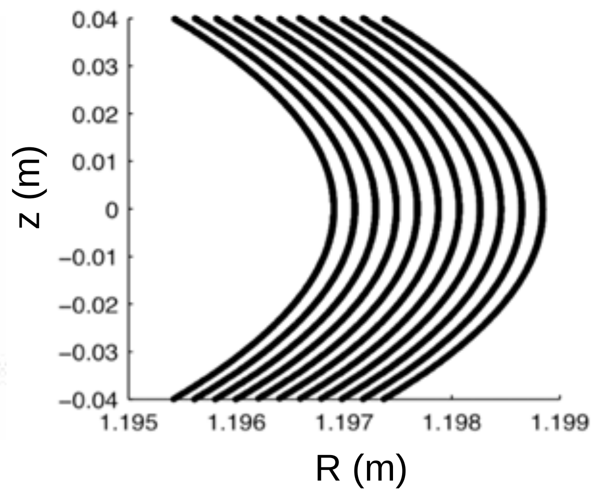
- interface with GYRO
- interface with GTS ②

- Uses EFIT/LRDFIT equilibrium + TS profiles
- run complex ray tracing eqs. for probe+receiving beam
    - localize 3D scattering volume
    - compute the instrumental selectivity function
    - produces a (k_r,k_θ) filter for the simulated spectra

1D FFT: θ, R, t ③



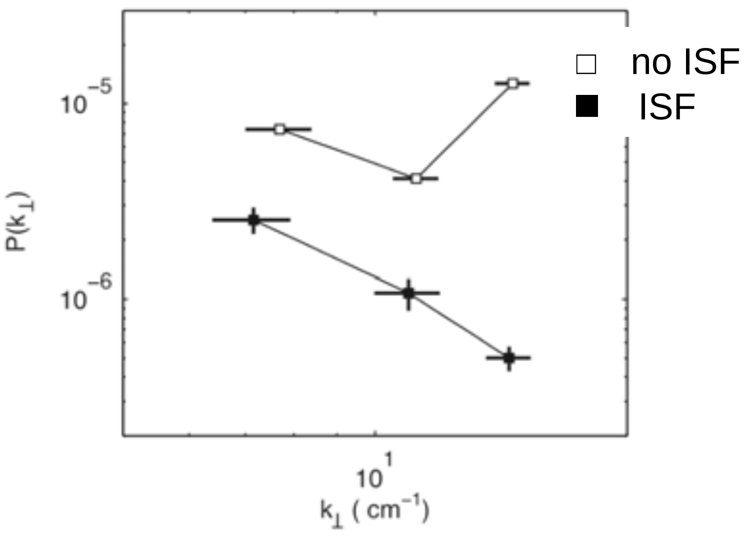




The spectral slope is mainly affected by 2 effects

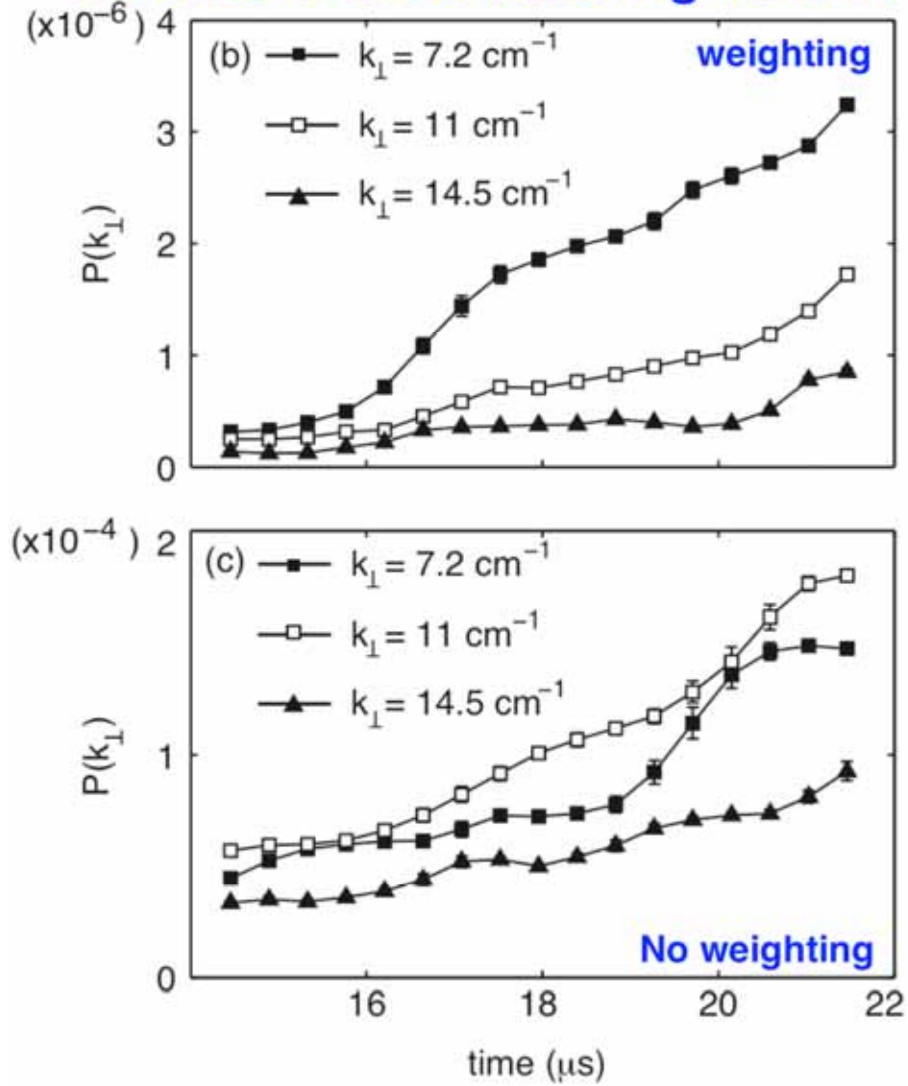
Geometrical effects in the collection efficiency

$k_\perp \sim 7.5\ cm^{-1}$	1
$k_\perp \sim 11\ cm^{-1}$	87%
$k_\perp \sim 15\ cm^{-1}$	65%



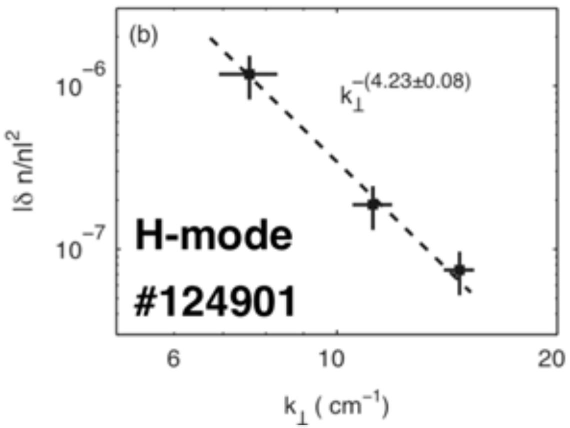
Some contribution to the spectrum slope comes from the experimental setup

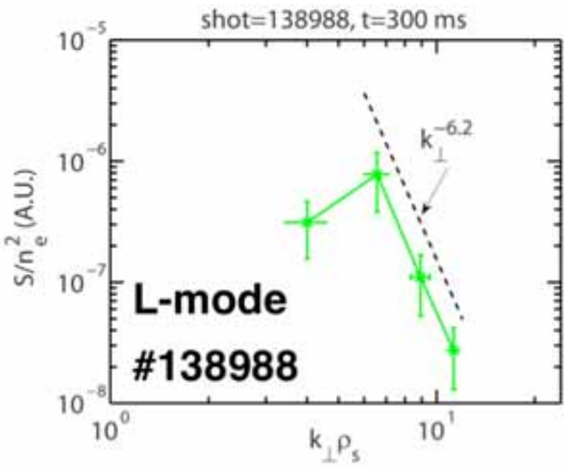
The size of the scattering volume



Geometrical effects are not sufficient to reproduce measurements

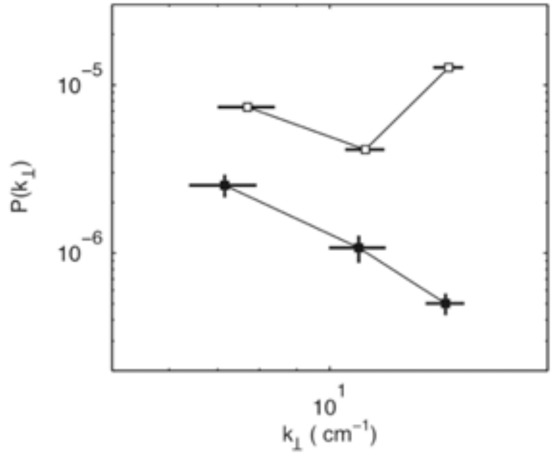
Experiments



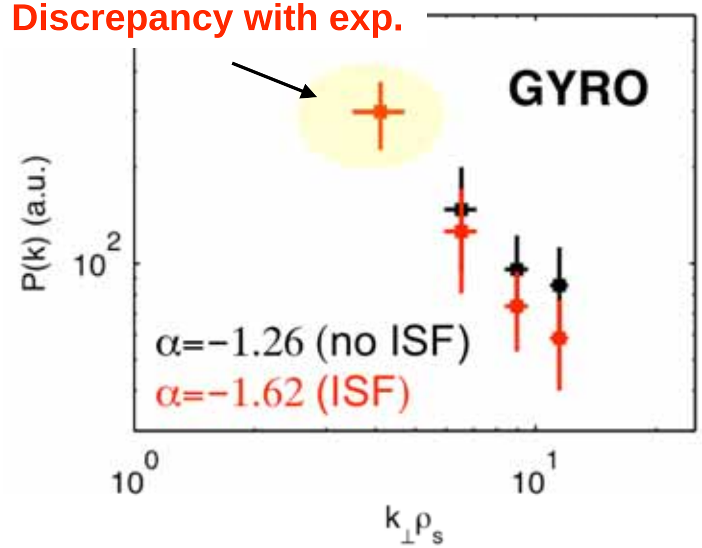


Simulations

GTS



GYRO



Future directions and timescales

1. Benchmark of the synthetic high-k
   - Option 1: energy calibration => not feasible in the short time scale
   - Option 2: design an alternate simple experiment
   - Option 3: simulate a calibration experiment

2. Code verification and validation against experiments
   - Given: the high-k measures in a range of (kr,kq) where ETG spectra are maybe not significant and other instabilities can play a role
   - Can we identify a set of experiments for V&V (it would be useful to have high-k combined with other turbulence diagnostics) ?

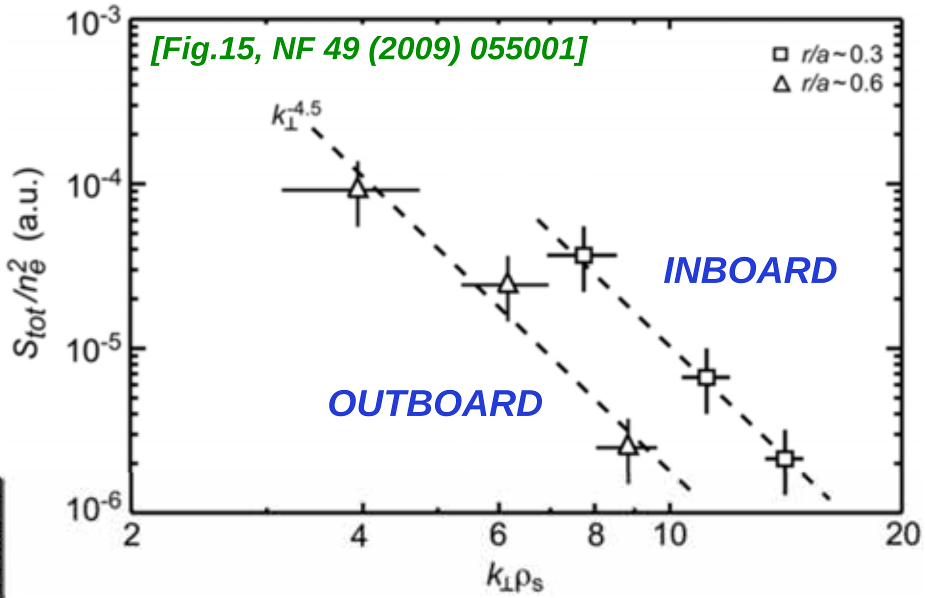
3. Can we use these same simulations to predict the optimal layout for the second-generation high-k ?

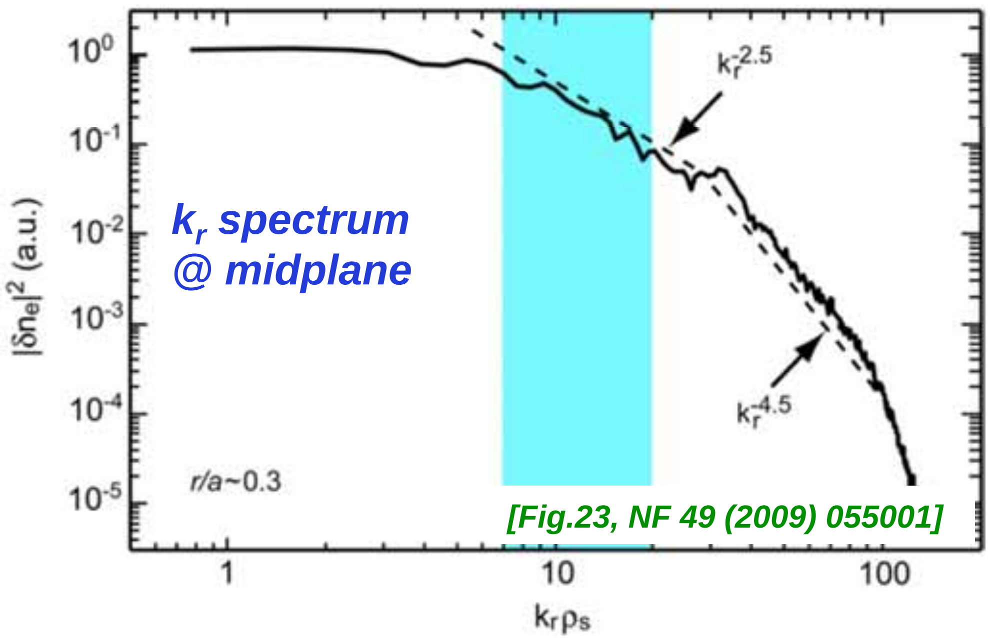
BACKUP SLIDES

A direct comparison may lead to fortuitous agreement

$P_{HK}(k_\perp^j,\omega)$ — ***Discrete in*** $k_\perp$ / ***Good statistics in*** ω

$P_{SIM}(k_r,k_\theta,\omega)$ — ***Wide range in*** (k_r,k_θ) / ***Poor statistics in*** ω





What has been overlooked ?

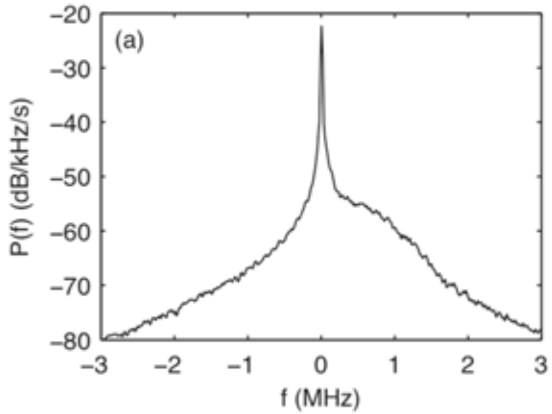
- ***selection of*** (k_r,k_θ)
- ***scattering volume***
- ***instrumental transfer function***

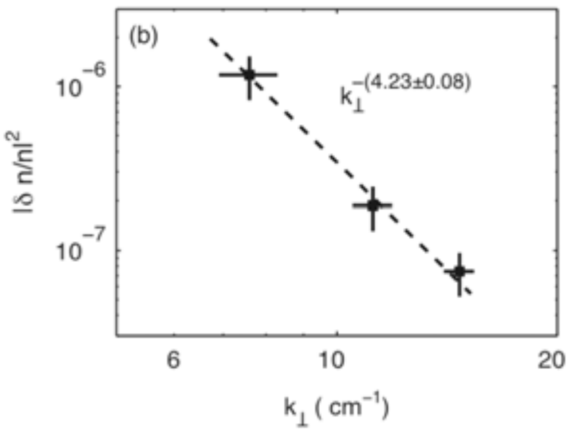
Two cases study: L-mode and H-mode plasma

Turbulence spectra from the high-k scattering diagnostic

#124901 H-mode

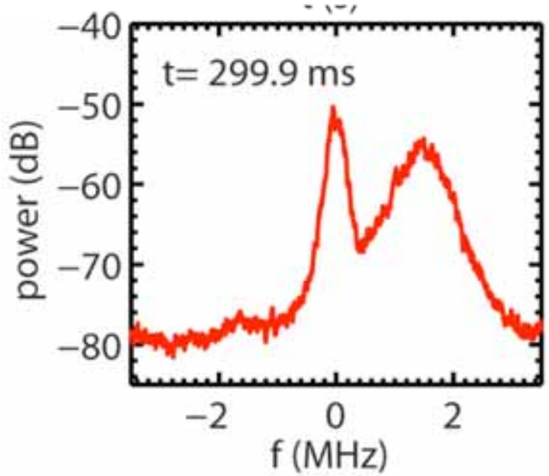
t = 300 ms, Δt=10ms

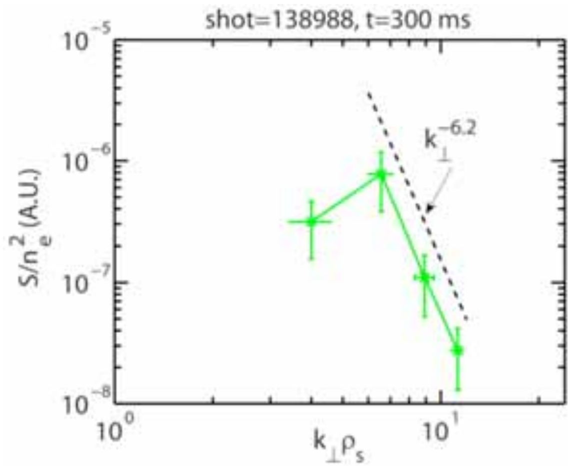




#138988 L-mode

t = 300 ms, Δt=1ms



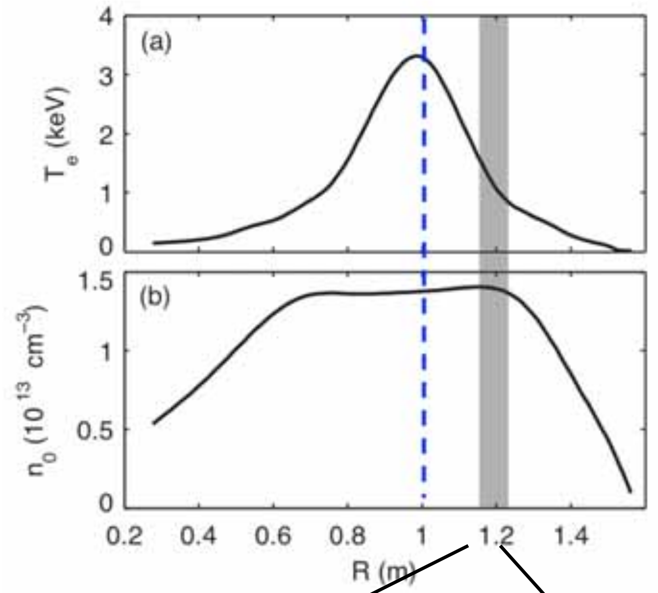


See poster BP9.67
Y. Ren *et al*

Level of fluctuations is similar, but spectra are steeper in L-mode

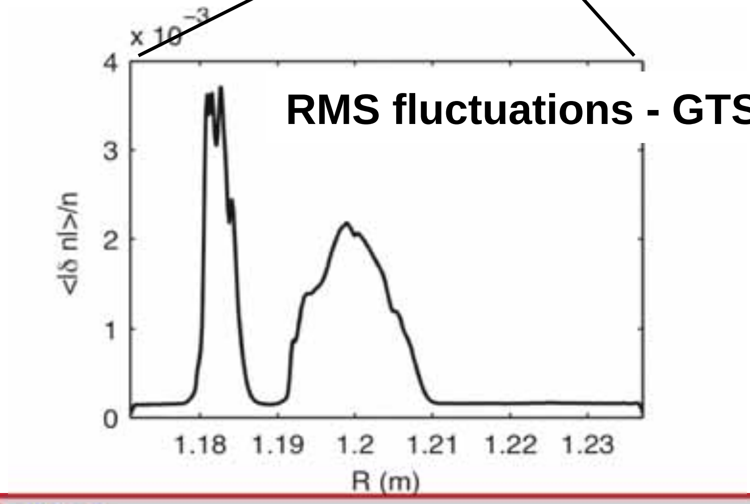
H-mode #124901

Measured profiles



R_m=0.19 m
R_0 =1.01 m
R_M=1.52 m

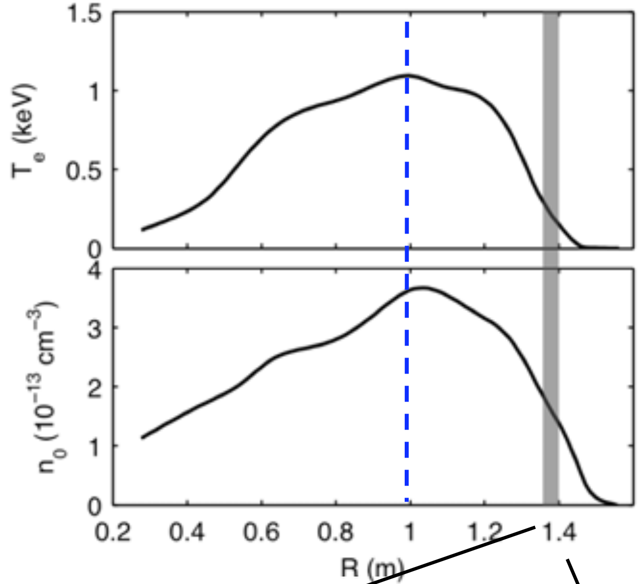
RMS fluctuations - GTS



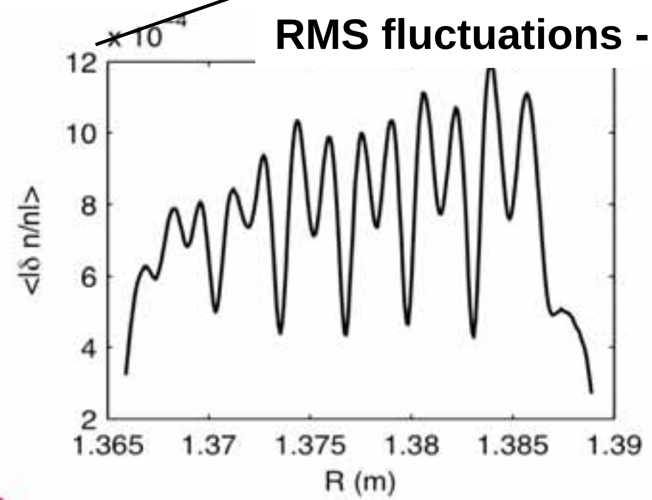
L-mode #138988

Measured profiles

R_m=0.19 m
R_0 =0.99 m
R_M=1.46 m

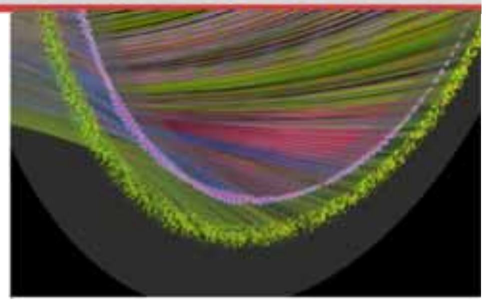


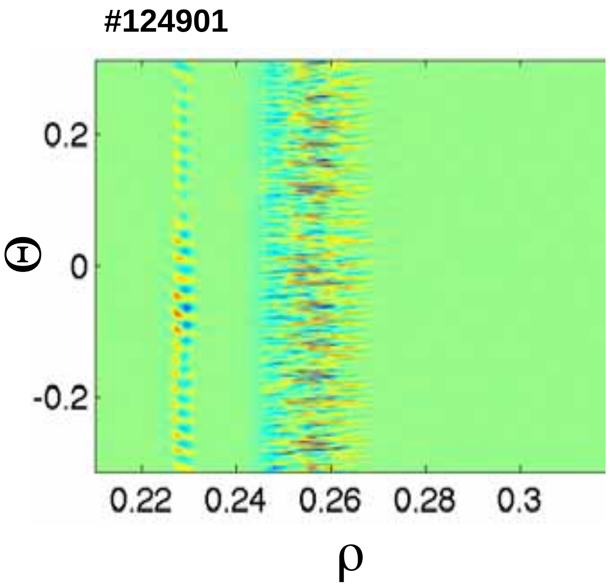
RMS fluctuations - GYRO



Interface with GTS*: spectra are computed in real coordinates

[WX Wang et al, Phys. Plasmas **13** 092505 (2006)]*





<u>Simulation using:</u>
– numerical equilibrium
– experimental parameters
– electrostatic
– adiabatic ions

(ρ,θ) grid not regular

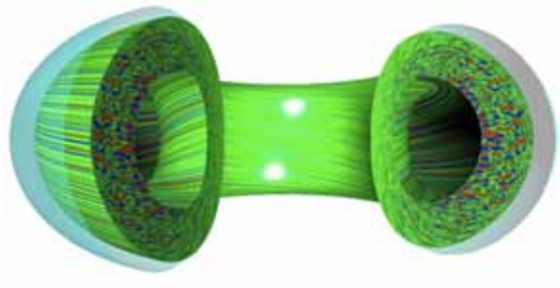
- $\Delta\rho$, $\Delta\theta$ are set by Larmor radius ρ_e
- $\Delta\theta$ is regular on each flux surface, it changes between flux surfaces

64 planes: toroidal separation comparable to scattering volume extension
=> each plane is dealt with independently

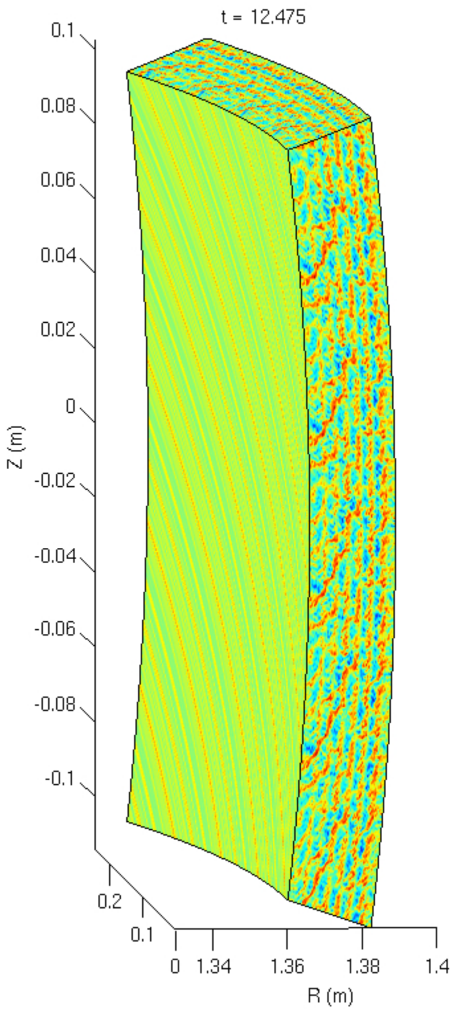
Compute spectra in real coordinates => *k* directly compared with exps

Interface with GYRO*: spectra are computed in flux coordinates

[J. Candy and R. Waltz, Journal Comp. Physics, 186-545 (2003)]*



#138988



<u>Local simulation using:</u>

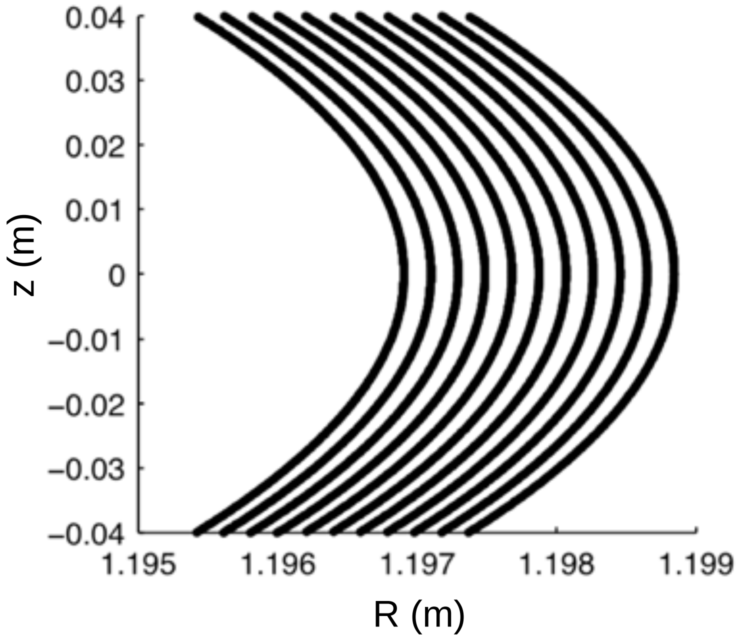
– numerical equilibrium
– experimental parameters
– finite collisionality
– toroidal flow and flow shear
– electrostatic (β_e is small)
– adiabatic ions (will ultimately use kinetic)

(ρ,θ) grid regular => compute spectra in flux coordinates

Periodicity along toroidal direction => need only a finite number of planes (50 for this simulation)

=> need to convert k to physical units to compare with experiments

Interface with GTS: k_θ spectra are computed in real space along a pseudo-polar direction



1. Along each flux surface in real space (R,z) we construct a trajectory :

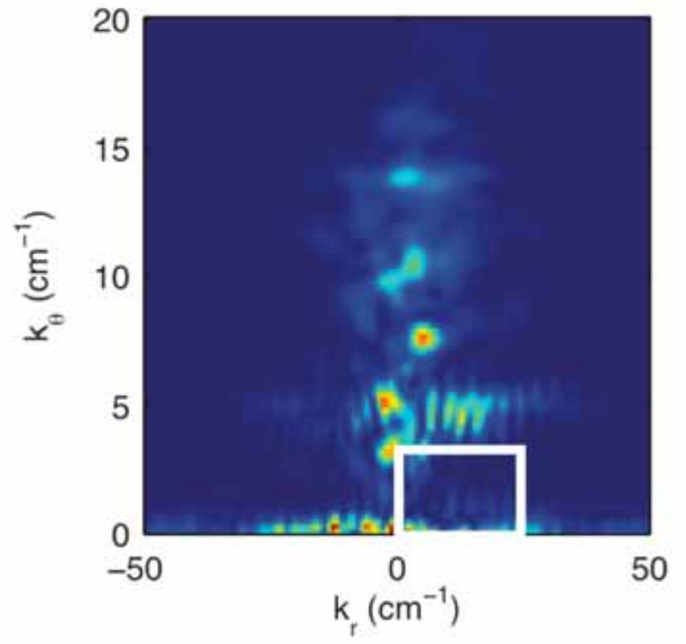
$$ds_j = \sqrt{(R_{j+1} - R_j)^2 + (z_{j+1} - z_j)^2}$$

2. Interpolate density along this trajectory using the same step for all flux surface (to have the same k_N)
3. Compute Fourier Transform using the same number of points (to have the same Δk_θ)

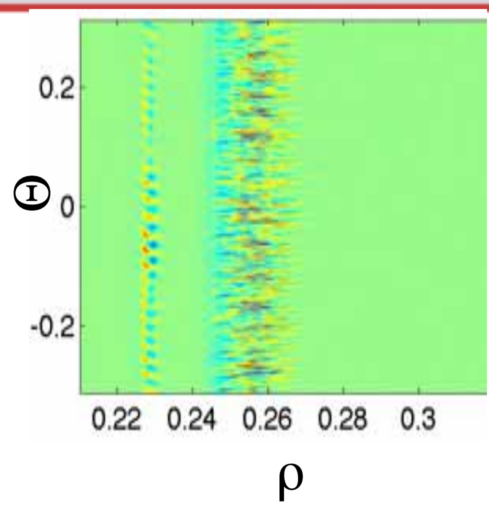
=> The Fourier components depend only on the value of R at midplane $\tilde{n}(R_{mid}, k_\theta, t_i)$

PROBLEM: in order to compute the transform along R, we need to interpolate amplitude and phase of Fourier components

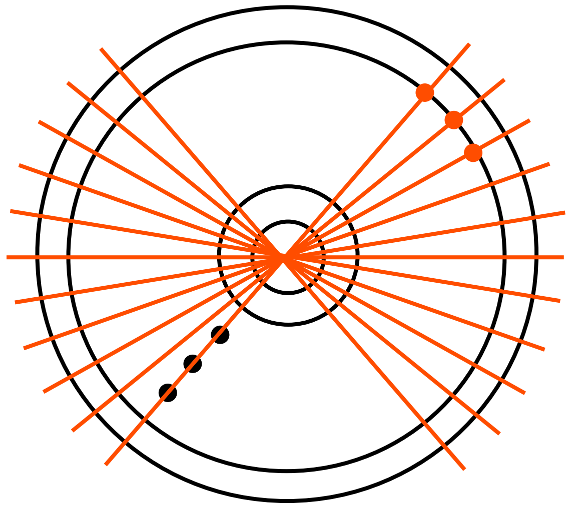
Interface with GTS: density fluctuations are interpolated in flux coordinates



phase interpolation generates artificial structures in k_r, due to phase jumps where density structures are localized.



NEXT STEP UPGRADE



This issue can be overcome by pre-processing density fluctuations in flux coordinates

- ••• interpolate along ρ => uniform ΔR @ midplane
- ••• redistribute data along θ

Block 1: Beam tracing*

* [Nowak and Orefice, Phys. Plasmas **1** 1242 (1994)]

Follow propagation of a Gaussian beam in an anisotropic plasma

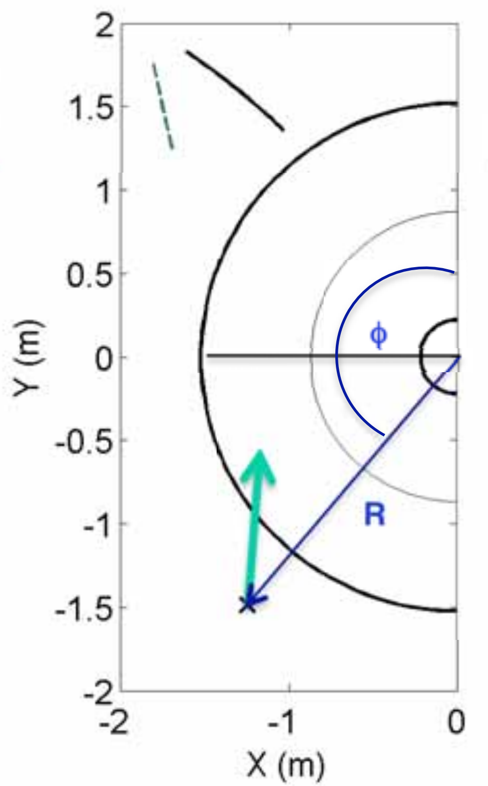
$$\vec{E}_i(\mathbf{r},t) = \mathbf{E}_i(\mathbf{r}_\perp)\, e^{i[k_0 S(\mathbf{r}) - \omega_i t]} \qquad S = R + iI$$

$$\begin{cases} R(x,y,z=0) = 0 \\ I(x,y,z=0) = -\dfrac{x^2+y^2}{k_0 a^2} \end{cases}$$

Initial conditions

$\Re:\quad (\nabla R)^2 - (\nabla I)^2 = N^2$ **=> Leads to** $D(\mathbf{x},\mathbf{k}',\omega)$

$\Im:\quad \nabla R \cdot \nabla I = 0$ **=> Amplitude is constant along rays**



$$\mathbf{k} = \mathbf{k}' + i\mathbf{k}'' = k_0(\nabla R + i\nabla I)$$

$$\begin{cases} \dfrac{d\mathbf{x}}{dt} = -\dfrac{\partial D/\partial \mathbf{k}'}{\partial D/\partial \omega} \\ \dfrac{d\mathbf{k}'}{dt} = \dfrac{\partial D/\partial \mathbf{x}}{\partial D/\partial \omega} \end{cases}$$

Ray tracing equations

Solved in cylindrical geometry (R,φ,z), assuming an equal (and small) time step for all rays

$$D(\mathbf{x},\mathbf{k}',\omega) \equiv (k')^2 - \left(\frac{\omega}{c}\right)^2 [n^2 + (\nabla I)^2] = 0$$

Dispersion relation (Hartree-Fock)

Block 1: Beam tracing*

* [Nowak and Orefice, Phys. Plasmas **1** 1242 (1994)]

The term $(\nabla I)^2$ introduces a 'symmetry breaking' also in axisymmetric configurations => $\partial / \partial \varphi \neq 0$

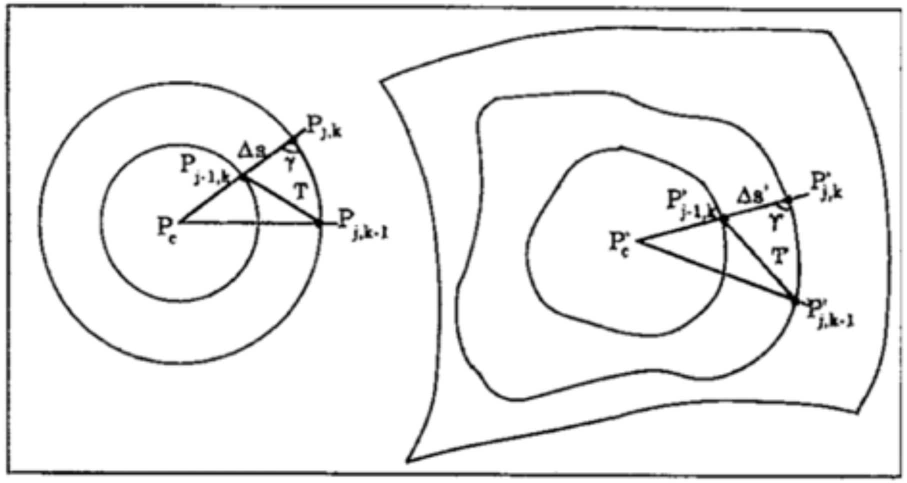
- Compute the components of $\nabla(\nabla I)^2$ using triangulation along directions s_1, s_2, s_3

  From the point $P(x,y,z)=P'_{j,k}$

  s_1, towards $P_1(x_1,y_1,z_1)=P_{j,k}$ (along the ray)

  s_2, towards $P_2(x_2,y_2,z_2)=P'_{j,k-1}$

  s_3, towards $P_3(x_3,y_3,z_3)=P'_{j-1,k}$

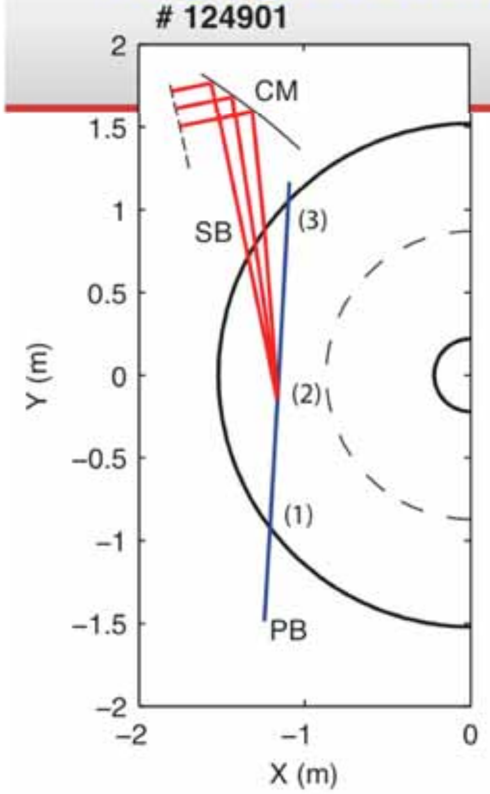


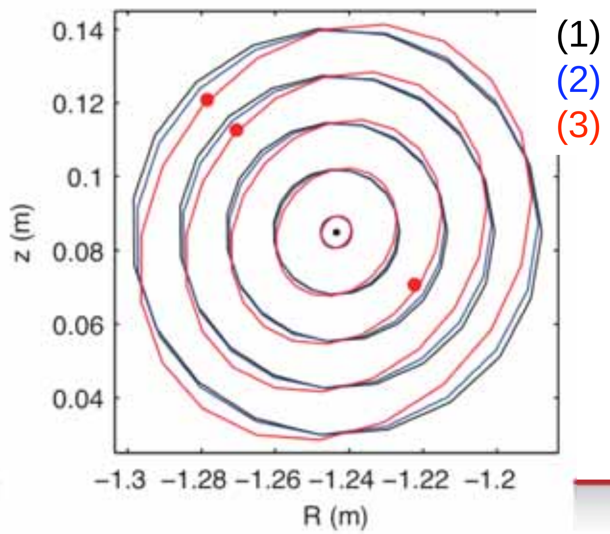
[Fig.2 from Nowak and Orefice, Phys. Plasmas **1** 1242 (1994)]

$$\frac{d(\nabla I)^2}{ds_i} \equiv \frac{[\nabla I(P_i)]^2 - [\nabla I(P)]^2}{ds_i} = \frac{1}{ds_i}\left(d\varphi_i \frac{\partial}{\partial \varphi} + dR_i \frac{\partial}{\partial R} + dz_i \frac{\partial}{\partial z}\right)(\nabla I)^2$$

$$\left|\nabla I(P'_{j,k})\right| = \left|\frac{1}{\sin\gamma(P_{j,k})} \frac{\partial I(P'_{j,k})}{\partial s'}\right| \qquad \frac{\partial I(P'_{j,k})}{\partial s'} = \frac{\Delta s}{\Delta s'} \frac{\partial I(P_{j,k})}{\partial s}$$

Negligible distortion of the wave front at the location of scattering





- No appreciable spreading of the beam at the location of scattering (2) (high frequency beam)

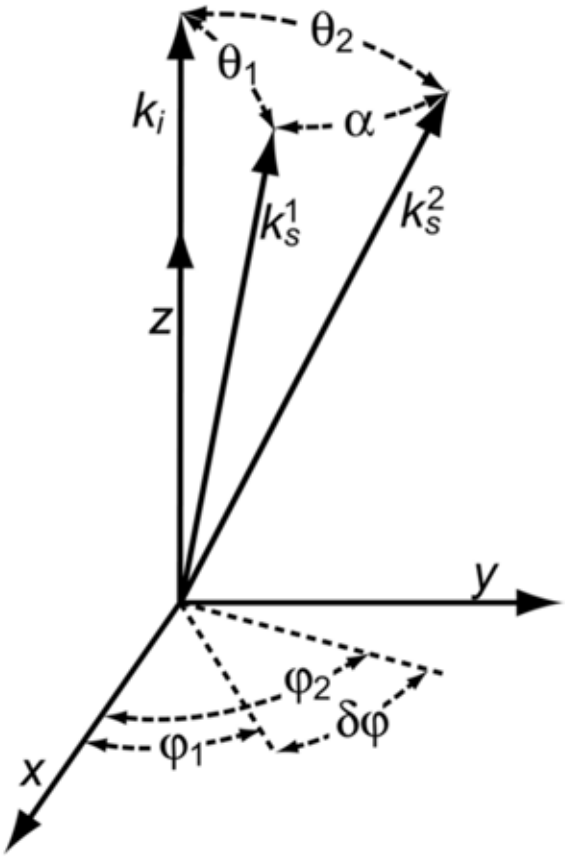
  => Gaussian function used as a weighting function for density fluctuations on the poloidal plane

$$\int_{T'} dt' \int_{V} d^3 r' \, \boxed{\mathbf{E}_i(\mathbf{r}_\perp)} \, e^{i(\omega t' - \mathbf{k}\cdot\mathbf{r})} \, \tilde{n}(\mathbf{r}', t')$$

$\Rightarrow$ full beam equations not necessary for the propagation and distortion of the beam, but important for the reconstruction of the 3D Instrumental Selectivity Function and of the filtering function (k_r,k_θ) for the simulated spectra

The collection efficiency is optimized at tangent injection

*[E. Mazzucato, Phys. Plasmas **10** 753 (2003)]*



$$F = \exp(-\alpha^2/\alpha_0^2) \qquad \alpha_0 = 2/k_i a$$

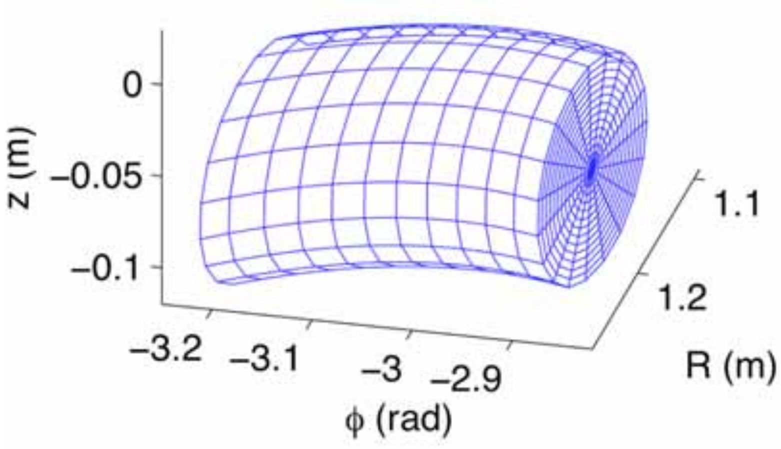
$$\alpha^2 \approx (\theta_2 - \theta_1)^2 + 4\theta_2\theta_1 \sin^2(\delta\varphi/2)$$

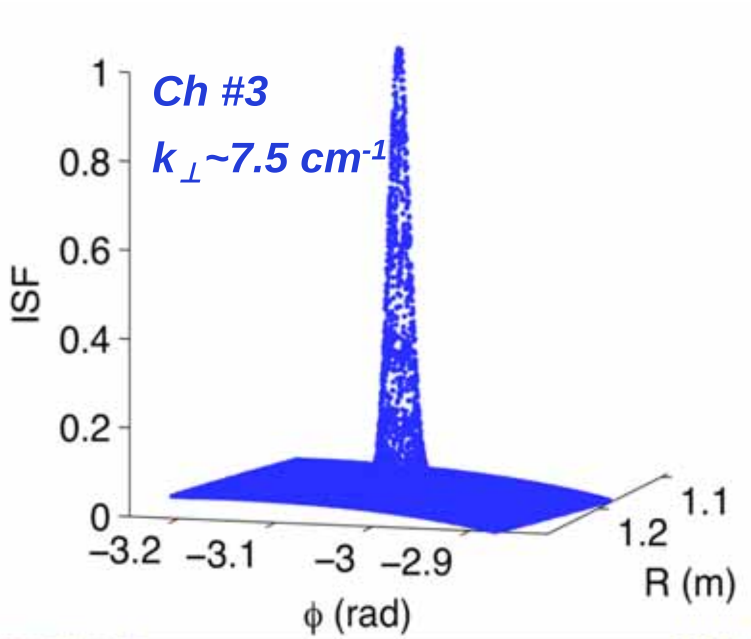
The collection efficiency depends on:

- the scattering angle
- direction of the magnetic field

Max efficiency for scattering along the detector line sight and for tangent injection.

The scattering volume is highly localized in the toroidal direction





1. take a toroidal length $L = \dfrac{2a}{\sin(\theta_s)}$
2. Compute the collection efficiency for all k_i ,θ_s within this volume

The Instrumental Selectivity Function (ISF) is highly localized in ϕ

The resolution in (R,z) is affected by the alignment of incident and scattered beam

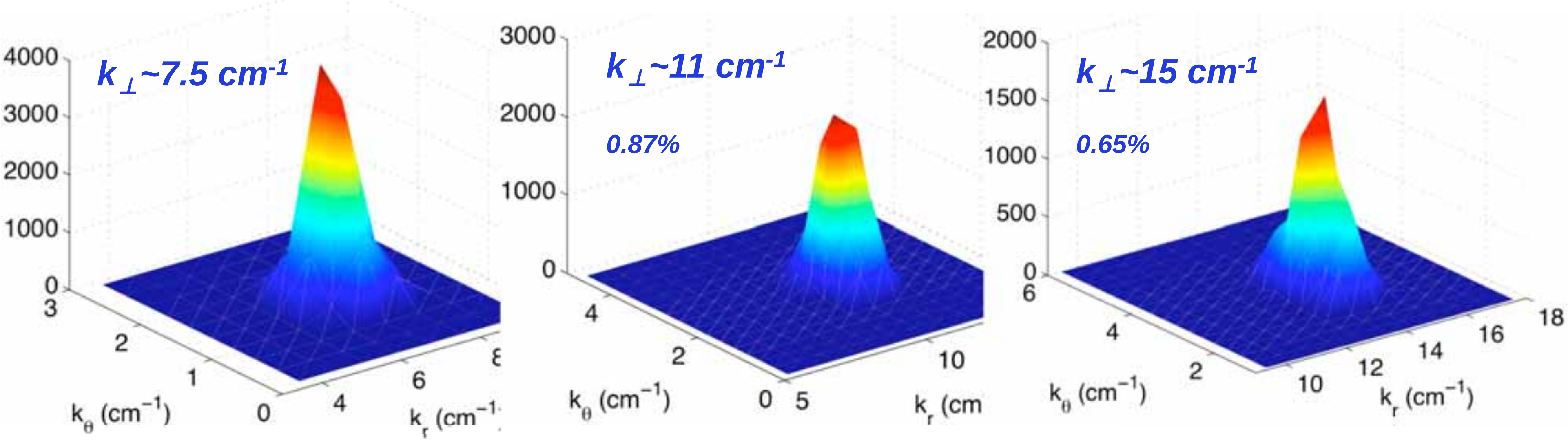
=> Use a function for the receiving window

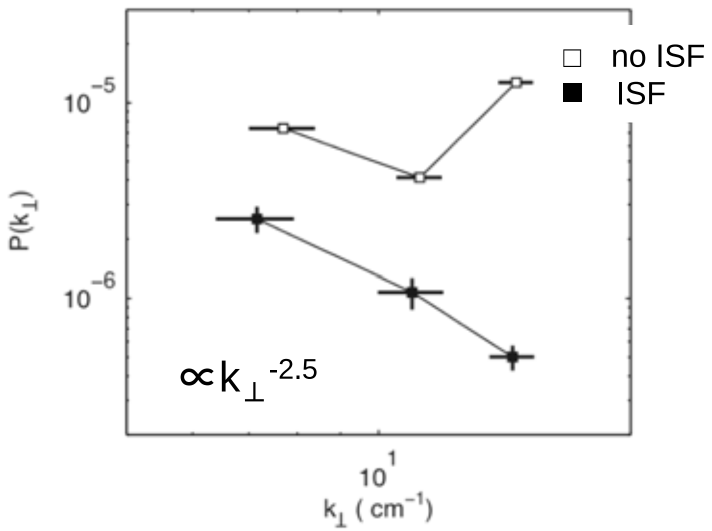
NEXT STEP UPGRADE :

use the 3D extension of the scattering volume for the computation of spectra. Include in the interface for both GTS and GYRO

The collection efficiency is used to reconstruct a (k_r,k_θ) filter for the simulation spectra

NSTX # 124901

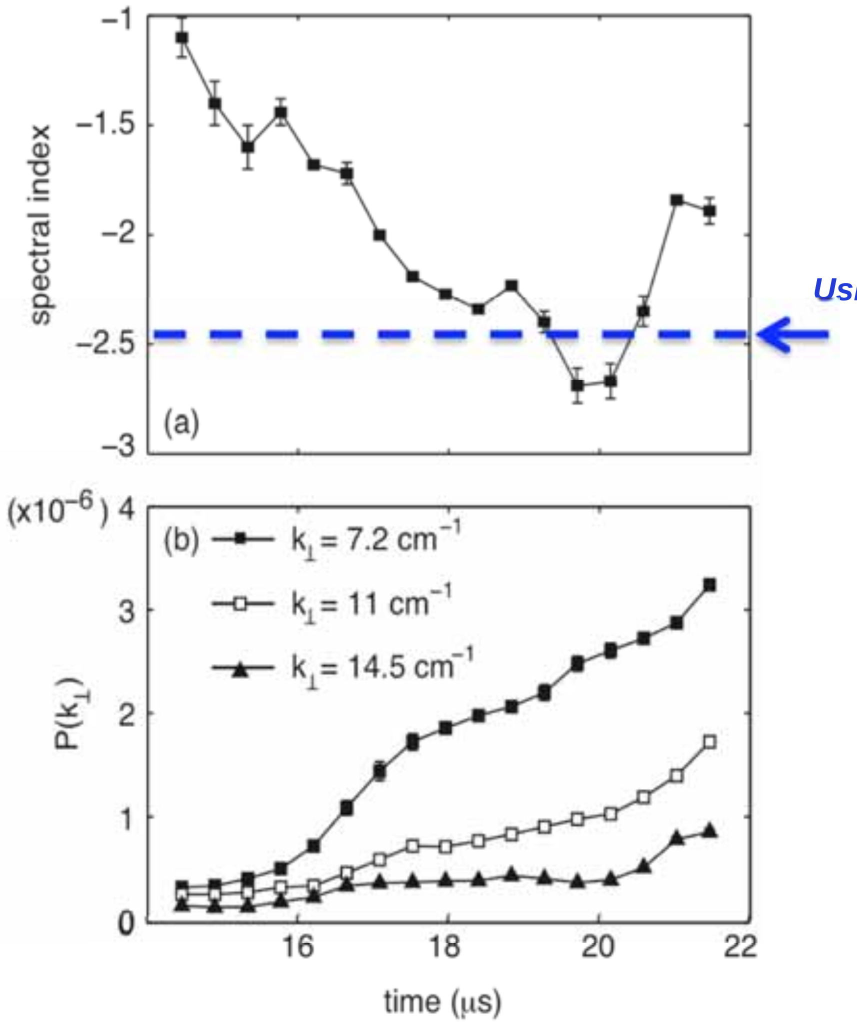




The reconstructed (k_r,k_θ) is important for amplitude correction of both simulated and measured spectra

Simulations must reach stationary phase for a meaningful comparison with experiments

From GTS simulations



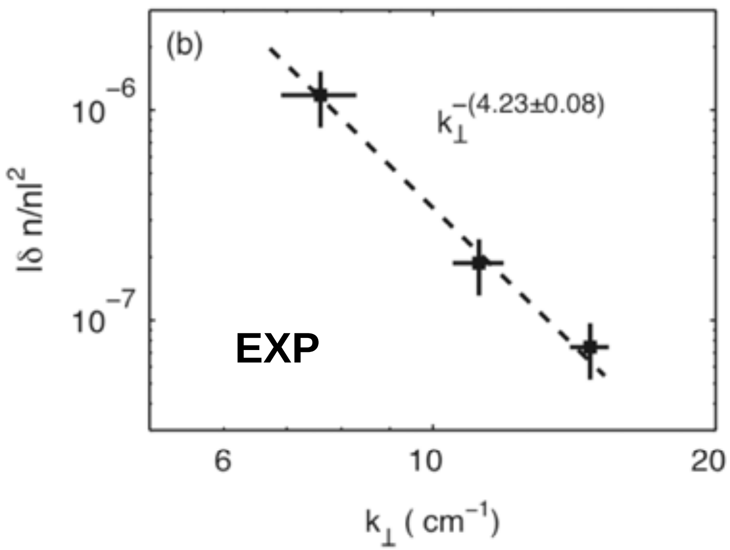
synthetic spectra become steeper (amplitude increases at the smallest $k_{\perp}$)

But still less steep than in experiments

Using $P(k_r)$ computed at midplane

#124901

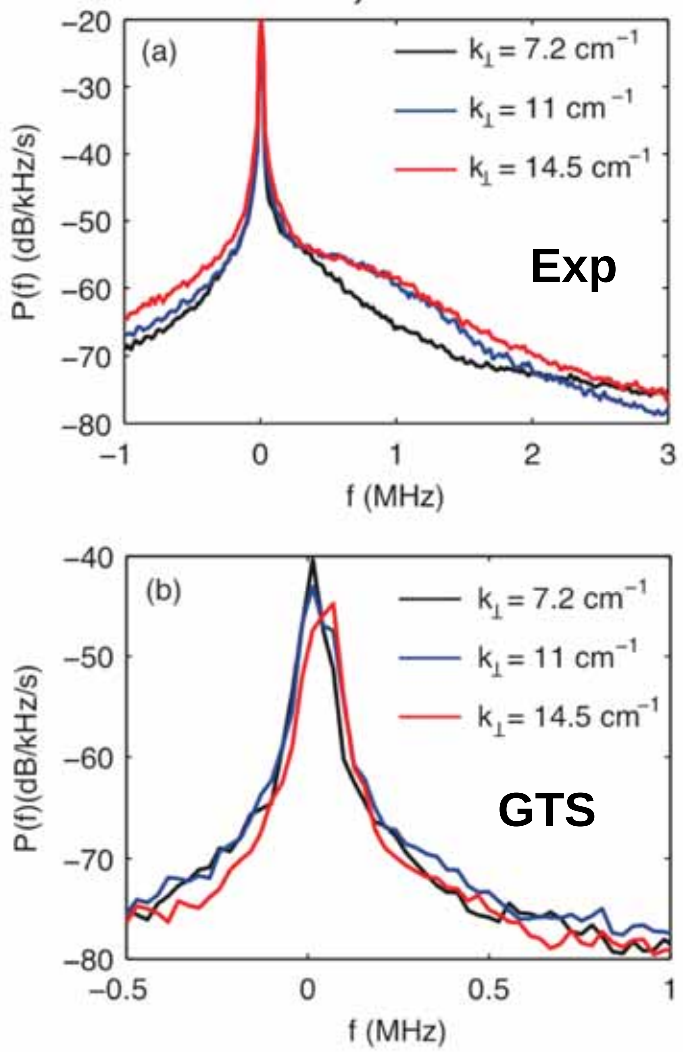
t = 300 ms, Δt=10ms



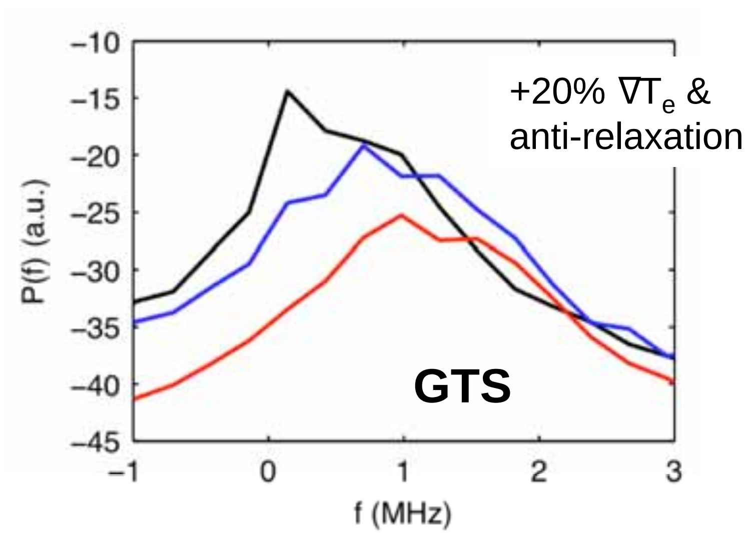
Frequency spectra are broader in experiments

#124901

t = 300 ms, Δt=10ms

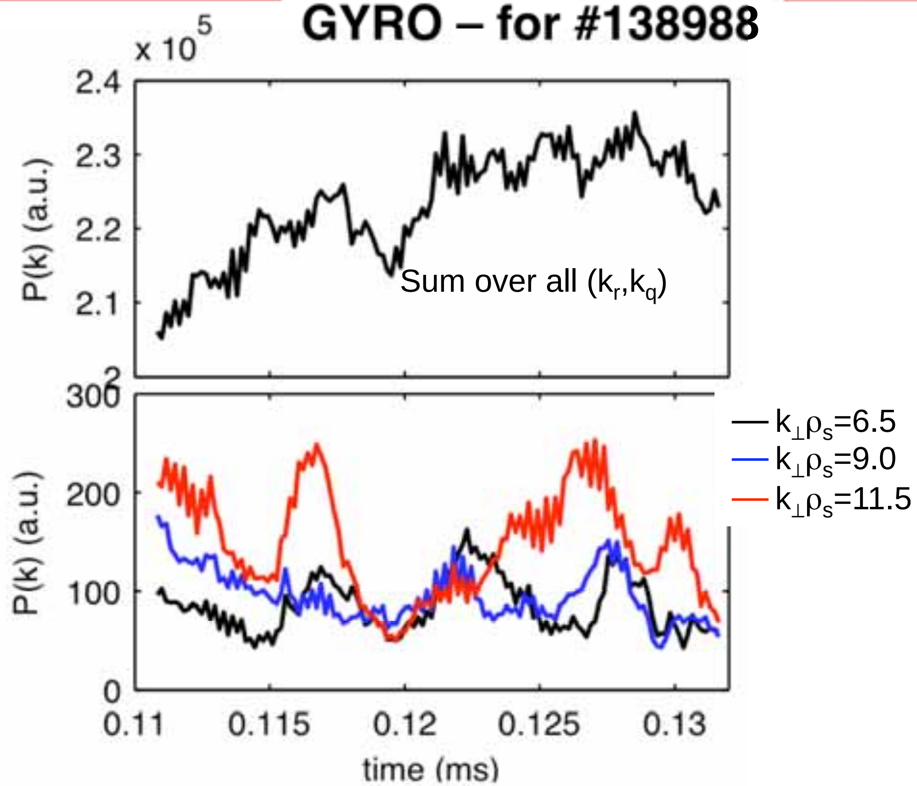


- Peaking frequency is comparable when a Doppler shift of 500 kHz is taken into account (from rotation measurements)
- Simulated spectra are much narrower than measured spectra (left)
- Better match when ∇T_e is increased by 20% and using an ‘anti-relaxation’ algorithm to maintain the gradient drive (below)

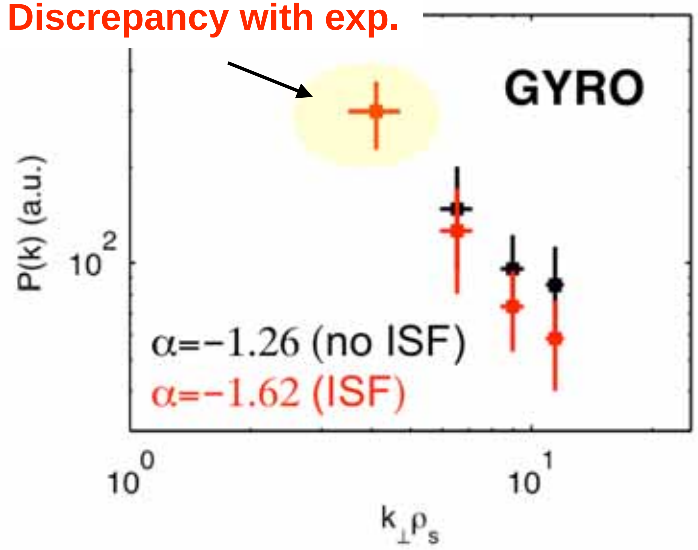


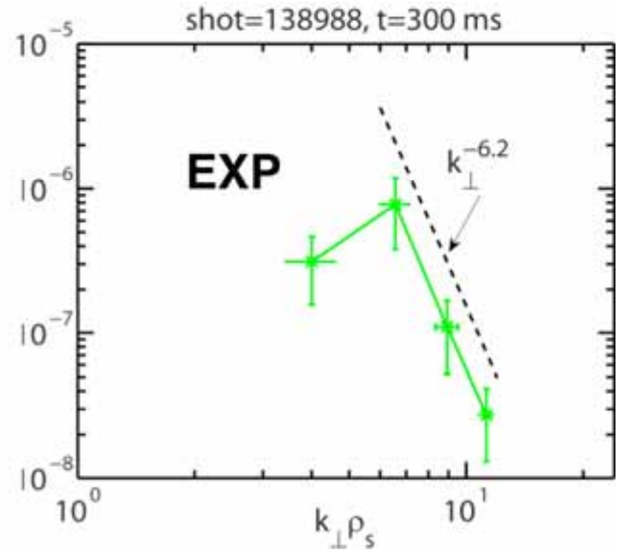
Spectral index less steep than in experiments also in L-mode

GYRO – for #138988



Discrepancy with exp.





- Level of fluctuations appears to be statistically steady
- The ISF does not affect significantly the spectral slope
- the ISF cannot reproduce the dramatic decrease in amplitude at the lowest k
- Predicted ETG transport much smaller than experiment, may not be the dominant mechanism in this L-mode discharge