



# Development of a Synthetic Diagnostic for Beam Emission Spectroscopy Fluctuation Measurements at W7-X

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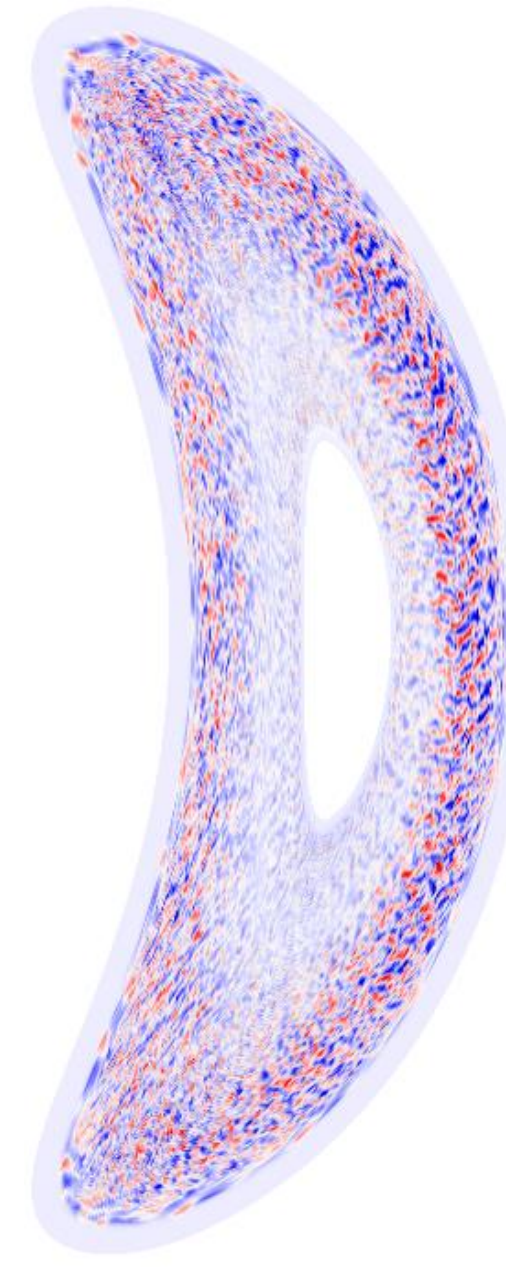
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## Motivation and Overview

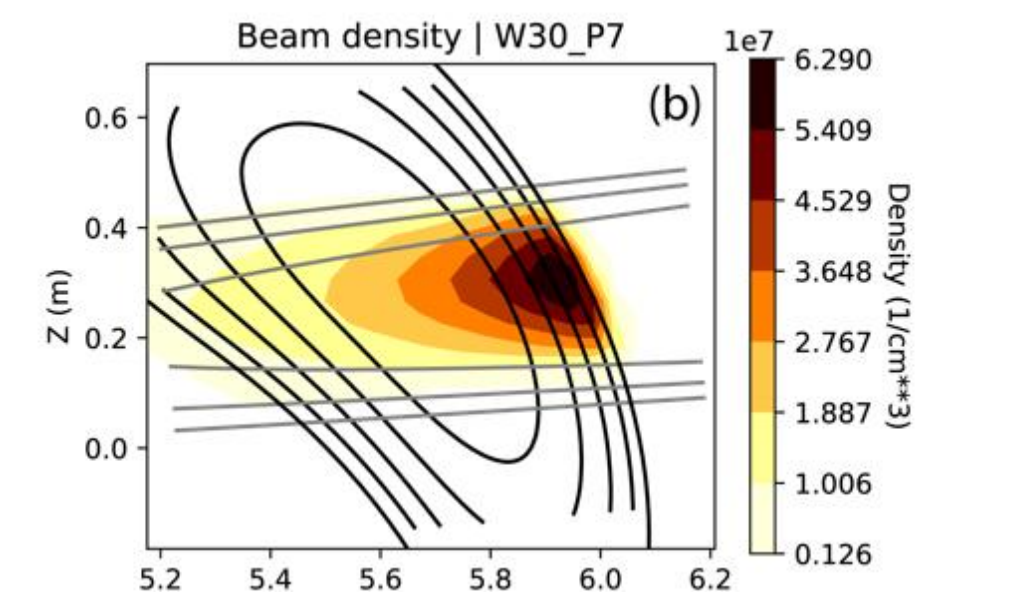
- Turbulent transport dominates neoclassical transport in ion-scale at W7-X [1]
- Beam Emission Spectroscopy (BES) is a 2D turbulence diagnostic
  - Spatial localization through neutral beam
  - Long-wavelength density fluctuations
  - Doppler-shifted beam  $D_\alpha$  emission
  - Turbulence velocimetry with high temporal resolution
- A synthetic diagnostic is needed for direct comparisons with experimental measurements
  - The BES synthetic diagnostic uses density fluctuations ( $\delta n$ ) from GENE-3D gyrokinetic simulation data



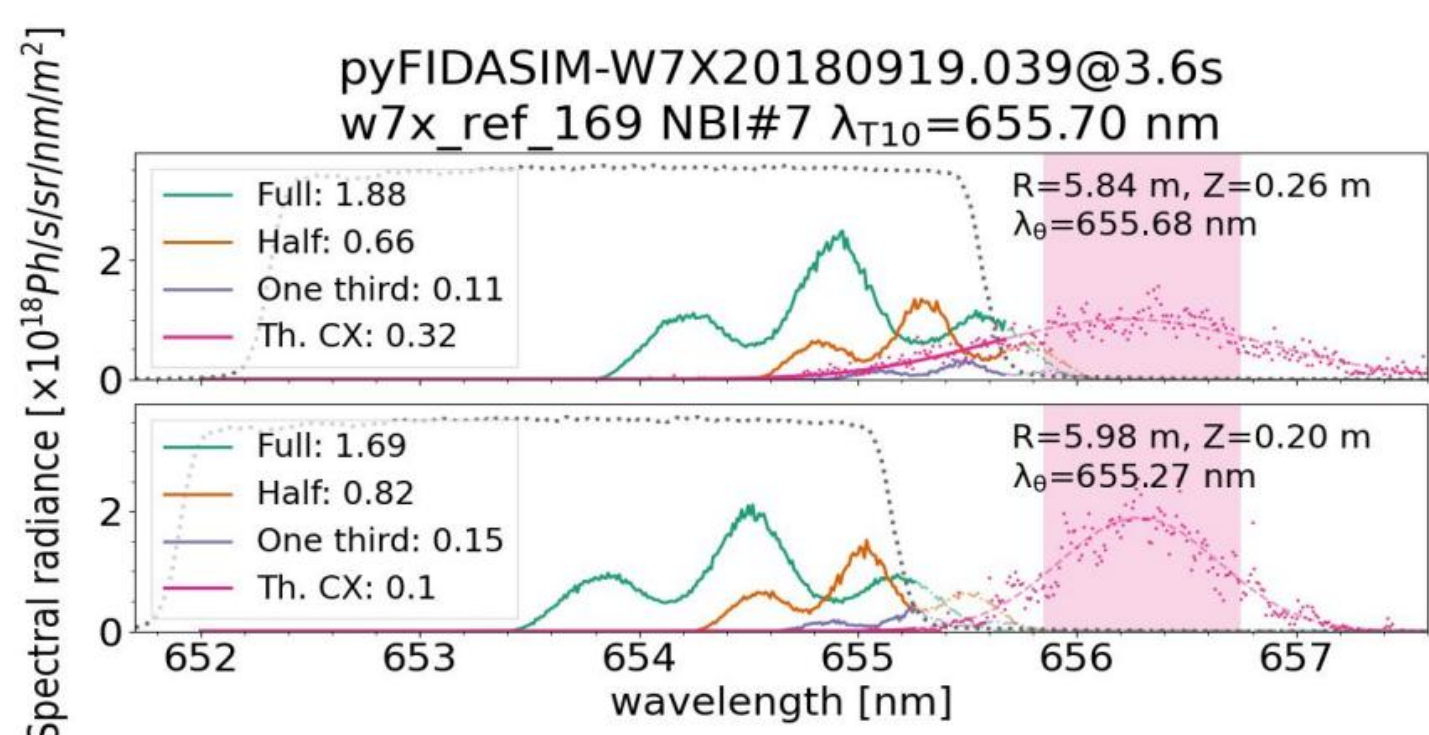
GENE-3D density fluctuations

## W7-X BES Specifications

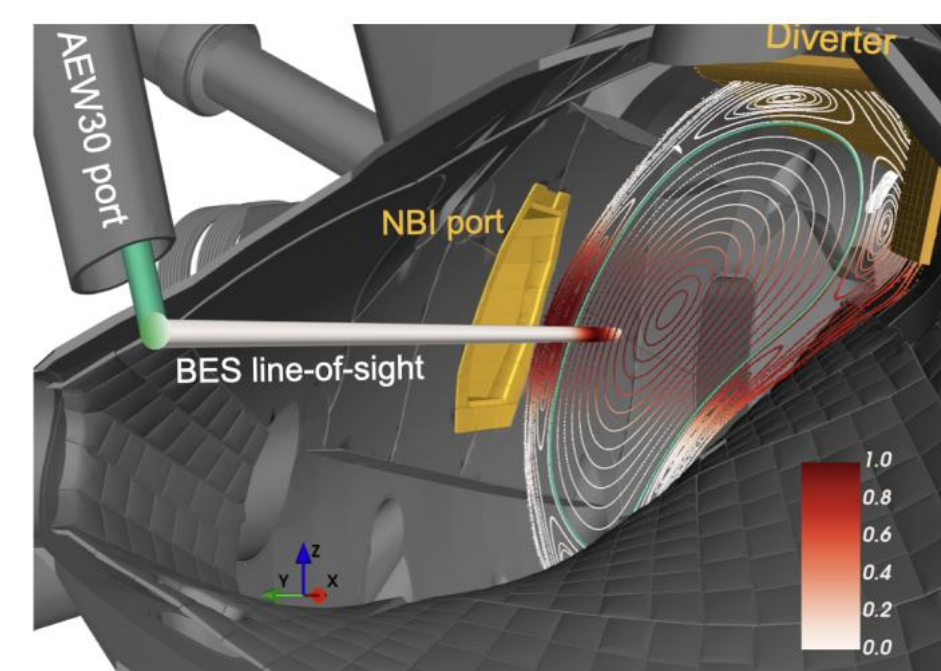
- Outer midplane ( $\rho \sim 0.5$  to  $1$ )
- $k_\perp \rho_i \leq 0.4$  for  $r/a = 0.75$
- 8x8 sightline grid with 1.56 cm spacing
- $\tilde{n}_e/n_e \geq 0.5\%$
- bandwidth of 1 MHz
- NBI Source 7



(top) Beam Density calculated with pyFIDASIM [3]



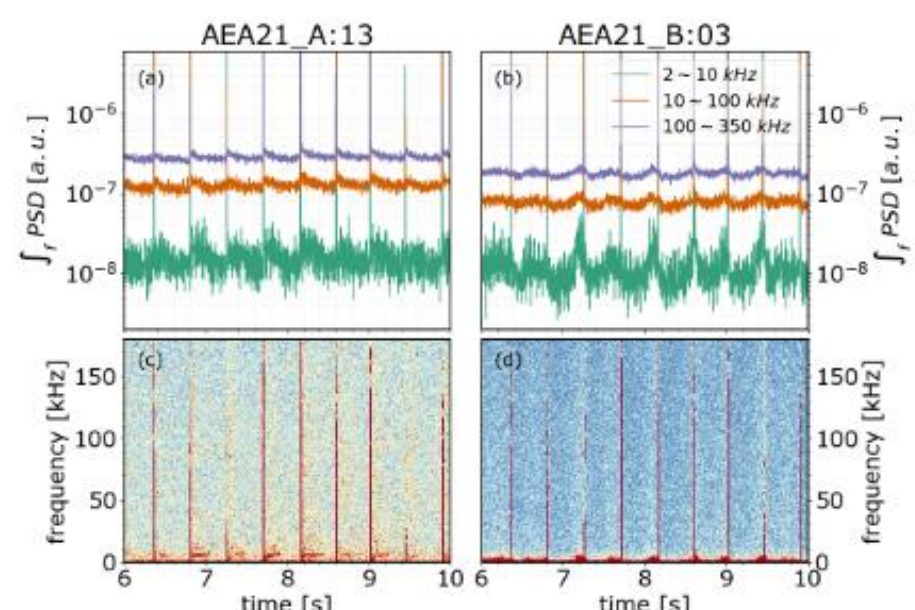
Optical Passband at 656 nm



AEW30 port (108.9 deg): Good field alignment [3]

## Detector Performance Verified with Charge Exchange Measurements

- Preliminary carbon density fluctuation measurements made using CX fibers (C-VI emission line: 529 nm)
- The analysis below was performed by scientist X. Han. A paper on this work has been submitted and is currently under review [2]
- The BES detector will be installed for the upcoming OP2.4 W7-X campaign using a 654 nm filter for the  $D_\alpha$  line



- Low frequency mode ( $< 10$  kHz) observed after pellet injection (c), while the mode is seen in the SOL (d) only after the mode disappears in (c)

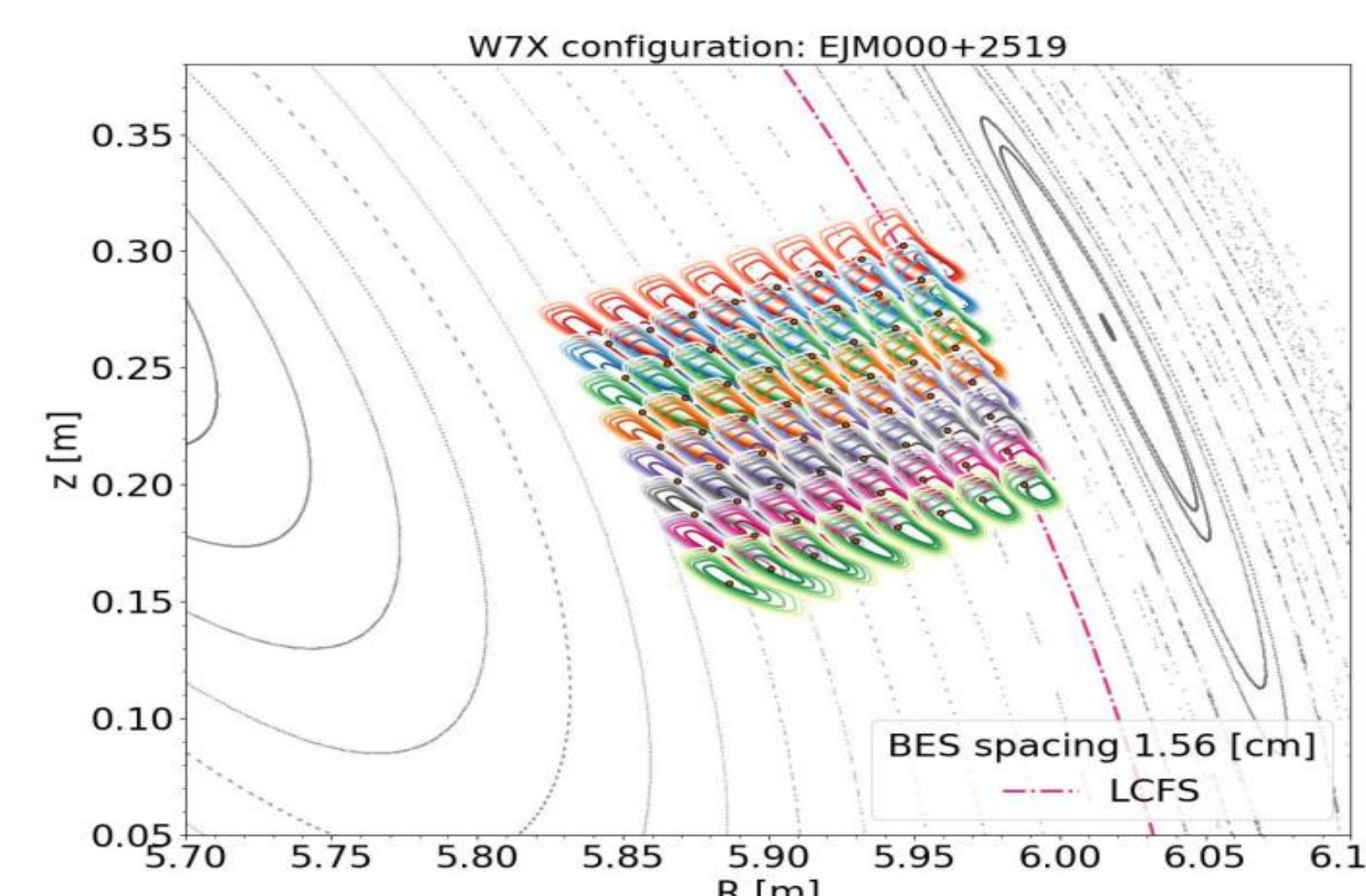


W7-X BES system with 64 channels (input fibers at the top of the image) [2]

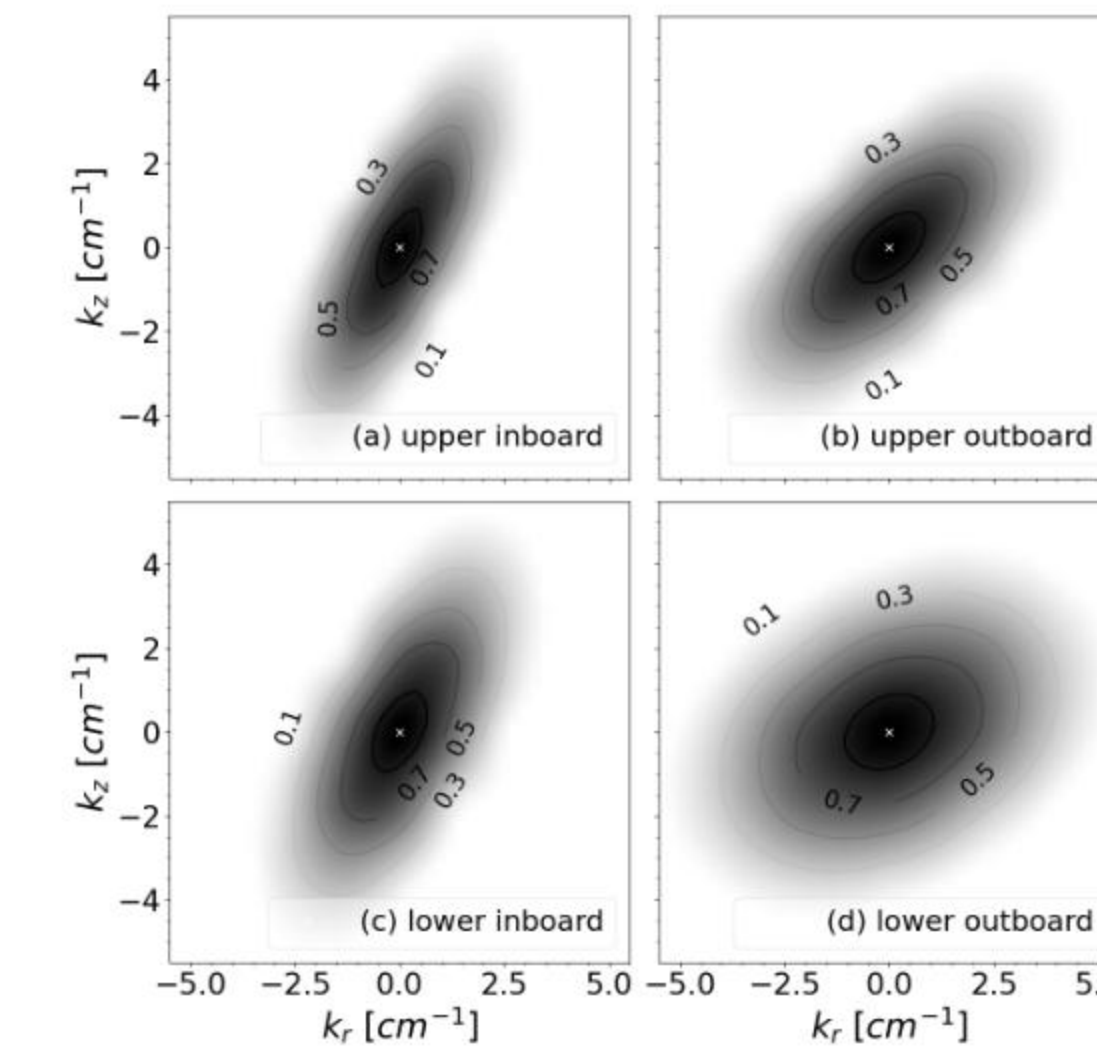
## Point Spread Function for k-space Sensitivities

- A PSF (Point Spread Function) characterizes the “blurring” (spatial smearing) of an object imaged by a detector system. The PSF specifically describes how a single point on an object is mapped on the image seen by the detector

- For this diagnostic, PSFs [3] consider effects due to
  - Finite lifetime effect
  - Viewing geometry
  - NBI Beam Density
  - Magnetic Field Geometry



(left) PSF contours: Top-Innermost channel is elongated due to magnetic field misalignment [4]



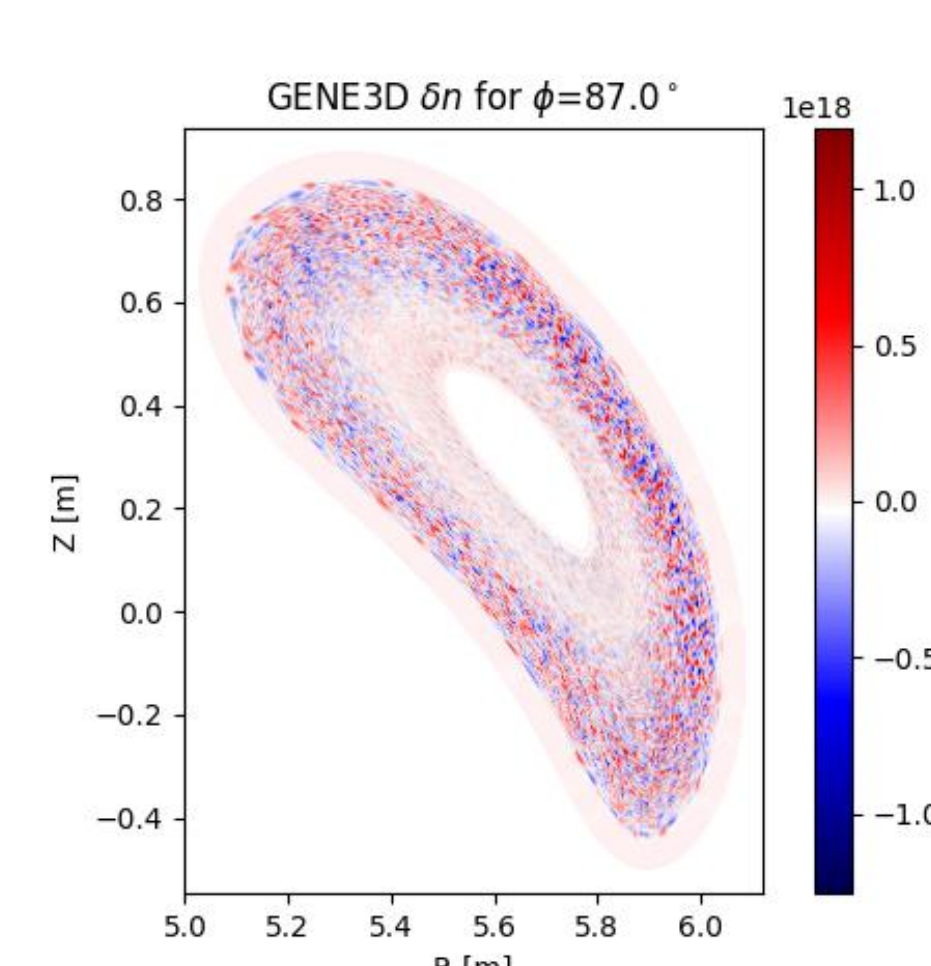
- (right) Spatial Transfer Function (STF) contours calculated by taking the FFT of the PSF
- Useful for estimating wavenumber sensitivity [4]

## Modelling BES response to GENE3D Simulations with a Synthetic Diagnostic

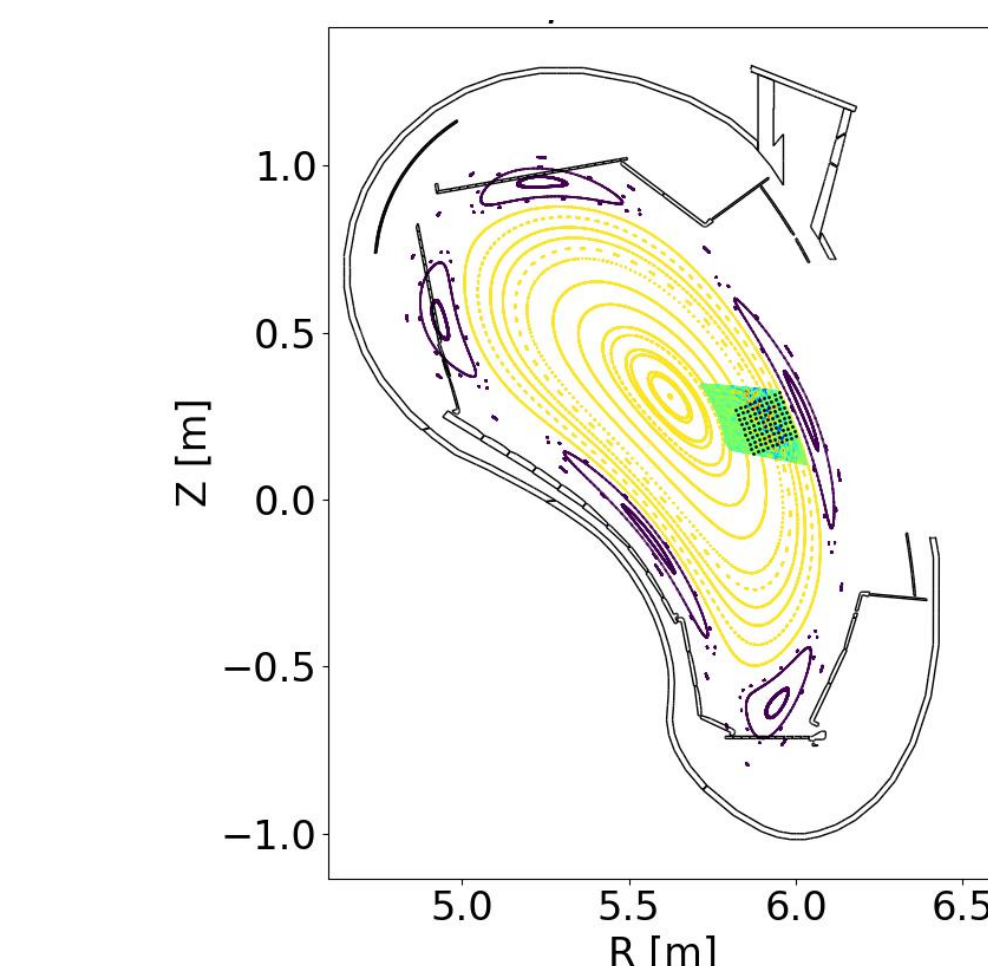
- The following integral is performed for multiple 2D imaging planes along the finite volume formed by the intersection of the LOS and beam to find the synthetic density fluctuation signal,  $\delta n_{syn}$ , for one imaging plane

$$\delta n_{syn}(R_0, Z_0, t) = \frac{\int \int dR dZ \delta n_{GENE}(R, Z, t) \psi(R - R_0, Z - Z_0)}{\int \int dR dZ \psi(R - R_0, Z - Z_0)}$$

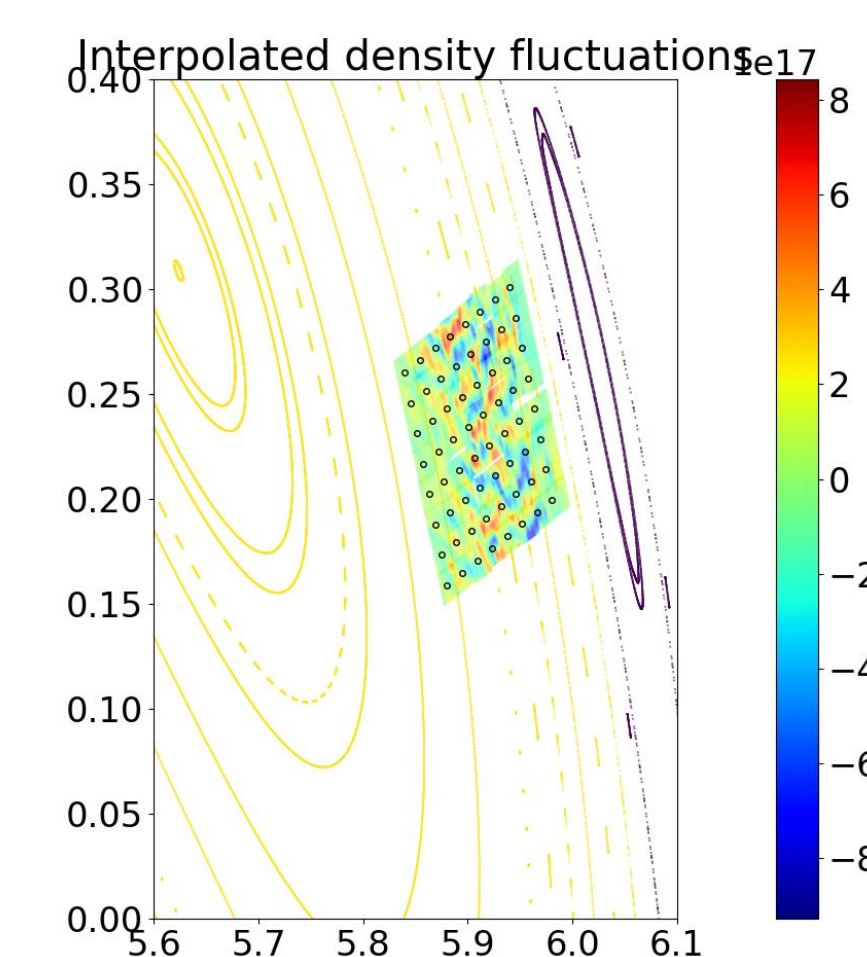
- $\psi(R - R_0, Z - Z_0)$  is the PSF located at a specific offset from the center of the BES sightline (dots in first and third figures below)
- After multiple 2D integrals are done, they are averaged using the beam density to obtain the final processed synthetic signal



One toroidal slice showing GENE3D density fluctuations

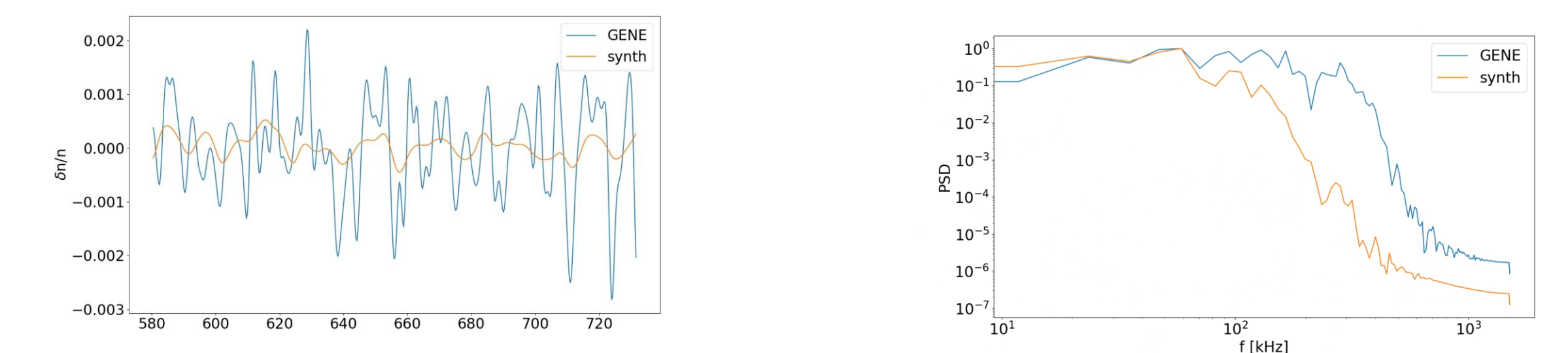


One toroidal slice/imaging plane. Poincare plot displayed as yellow contours. Dots indicate BES sightline grid.

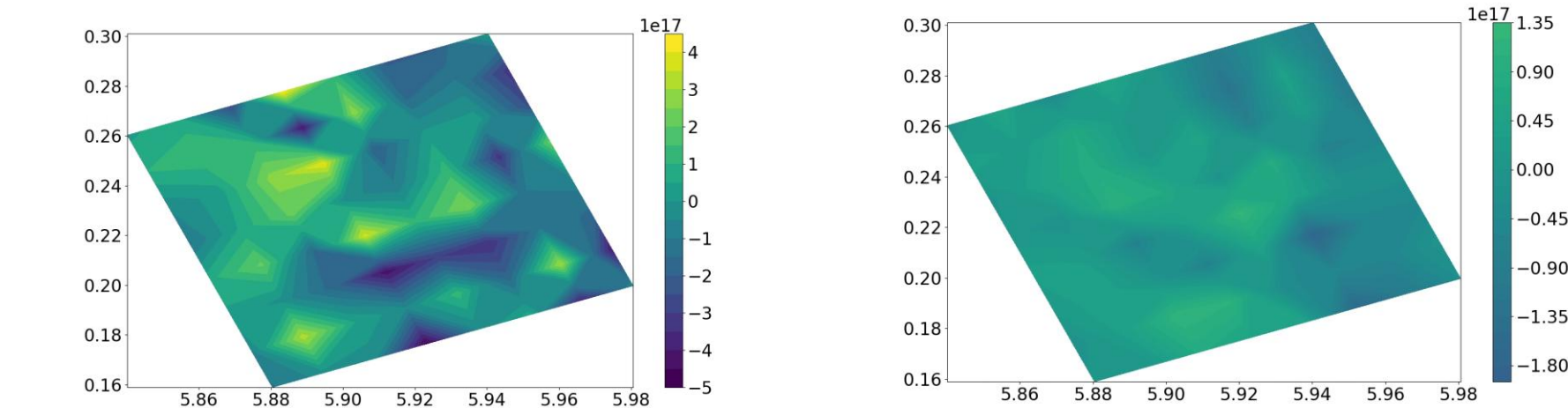


Closer view of density fluctuations and sightline grid (white dots).

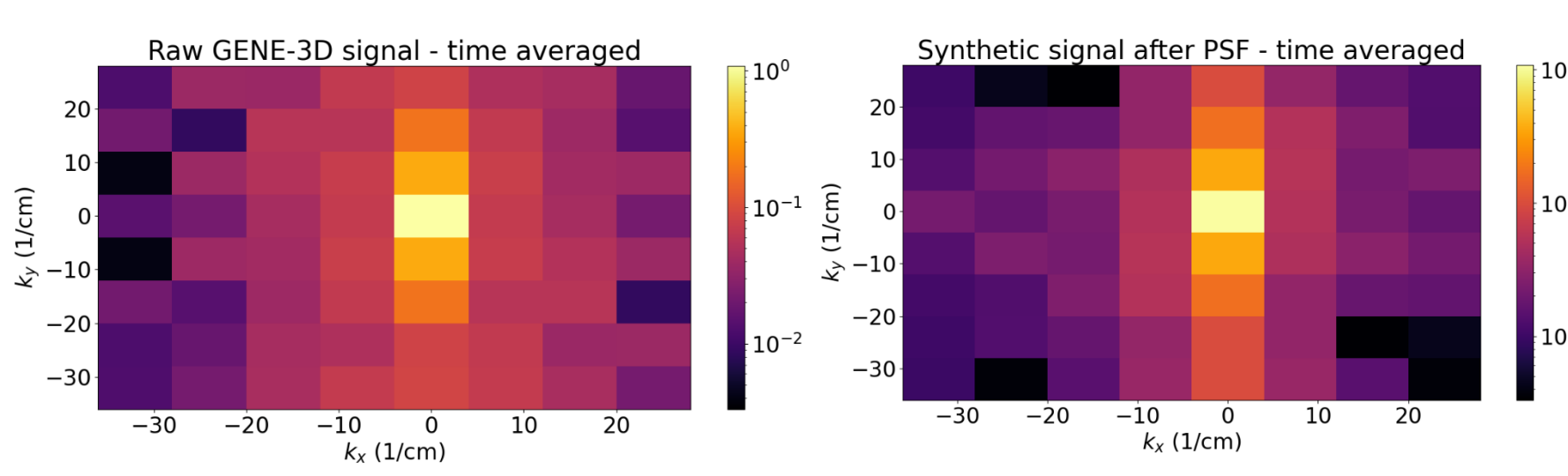
## Synthetic Diagnostic Reveals Frequency Response and k-space Sensitivity to GENE-3D Simulation Data



- For one LOS (upper inboard):
  - (left) time trace comparison between raw density fluctuations and synthetic signal
  - (right) autopower spectrum of raw and synthetic signal. Higher frequency fluctuations are lower in the synthetic signal.



- $\delta n$  on 8x8 sightline grid for raw GENE-3D output (left) and processed synthetic signal (right)



- K-space spectra of 8x8 lines of sight
- Higher k features decrease after applying PSF

## Summary and Future Work

- The W7-X BES system will be commissioned for OP2.4 in 2026

Future work includes:

- Comparing synthetic signals with experimental results
  - Bispectral analysis
  - Cross Correlation & Cross Coherence comparisons
  - Velocimetry comparisons

## References

- C. Beidler, et al, Nature 2021
- X. Han, et al. W7X Paper Rehearsal Presentation 2025
- D. Smith, et al., RSI 2022
- X. Han et al 2024 JINST 19 P11004
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EUROfusion

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