U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

# Overview of High-k Scattering Diagnostics on NSTX and NSTX-U

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1. PPPL 2. UW-Madison 3. UC-Davis 4. NFRI

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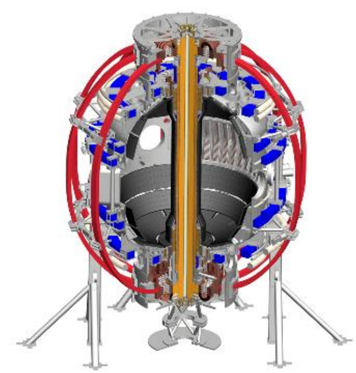
PPPL

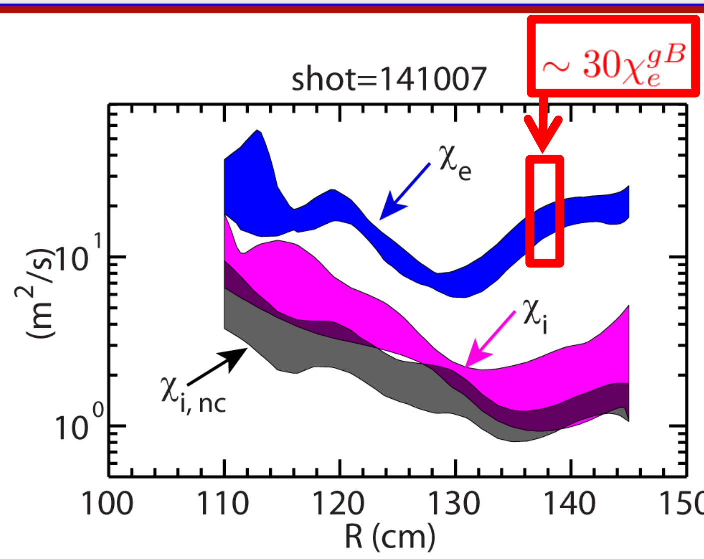


# Outline

- Introduction
  - Why use scattering?
  - How to achieve good radial localization?
- High-$k_r$ microwave scattering diagnostic on NSTX
  - Diagnostic design and capabilities
  - Electron-scale turbulence measurements
- High-$k_\theta$ FIR scattering diagnostic on NSTX-U
  - Design and present status
- Summary

# Measuring Electron Scale Turbulence is Crucial for NSTX and NSTX-U

- Typical transport properties of NSTX NBI-heated H-mode plasmas
  - Neoclassical level of ion thermal transport due to large ExB shear and low aspect ratio
  - Dominant heat loss in the electron channel
- ETG potentially important for NSTX
  - Short wavelength on electron-gyro scale
  - Large growth rate, surviving large ExB shear
  - Can generate larger normalized thermal transport than ITG due to weaker electron-scale zonal flow and secondary instability
- ETG may be important for conventional tokamaks as well
  - e.g. DIII-D advanced hybrid scenarios and high-beta poloidal scenarios



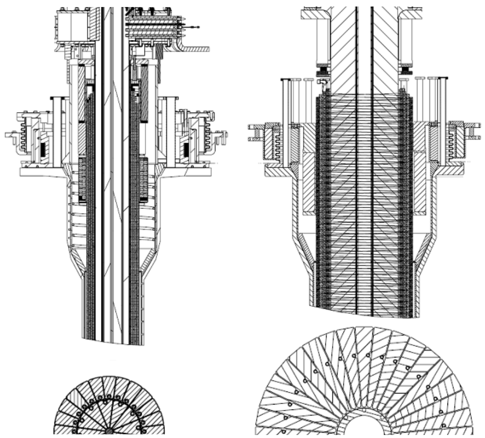

$$\frac{\chi_i^{ITG}}{\chi_i^{gB}} \sim 1 \qquad \frac{\chi_e^{ETG}}{\chi_e^{gB}} \sim 10$$

$$\chi_s^{gB} \equiv \frac{\rho_s^2 v_{Ts}}{L_{Ts}}$$

**Dorland et al., PRL 2000**
**Jenko et al., PoP 2001**
**Nevins et al., PoP, 2006**

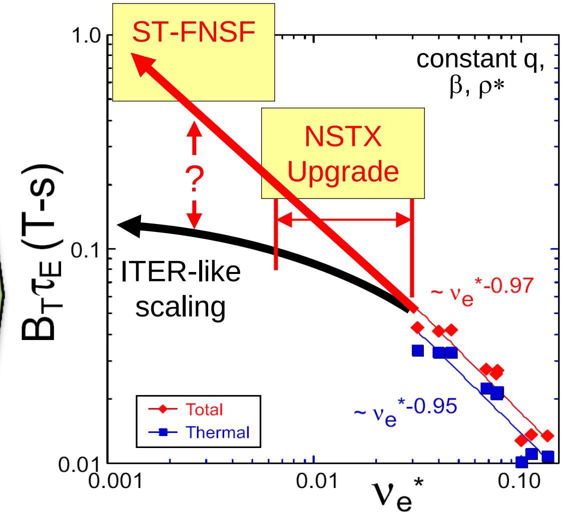
# NSTX Upgrade Allows Exploring Transport and Turbulence in New Parameter Regimes through 2 New Capabilities

Previous center-stack | New center-stack

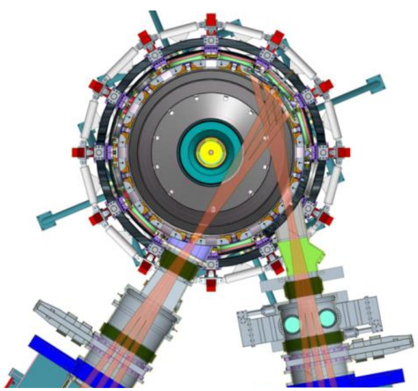


TF OD = 20cm | TF OD = 40cm

- ➢ Reduces $\nu^*$ → ST-FNSF values to understand ST confinement
  - Expect 2x higher T by doubling $B_T$, $I_P$, and NBI heating power
- ➢ Provides 5x longer pulse-length
  - q(r,t) profile equilibration
  - Tests of NBI + BS non-inductive ramp-up and sustainment



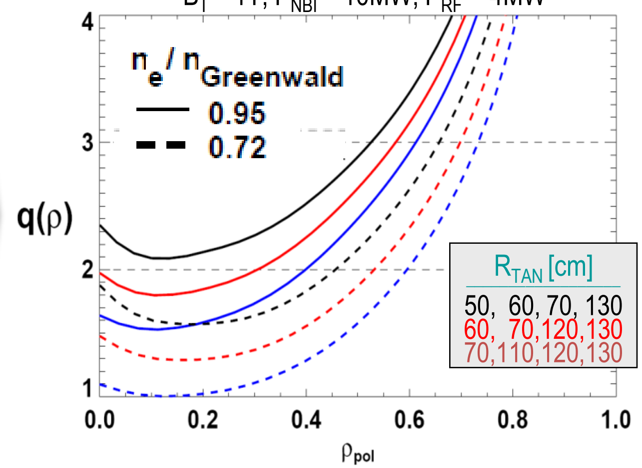

Normalized e-collisionality $\nu_e^* \propto n_e / T_e^2$



Present NBI | New 2nd NBI

- ➢ 2x higher CD efficiency from larger tangency radius $R_{TAN}$
- ➢ 100% non-inductive CD with q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density
  - Plasma position (not shown)

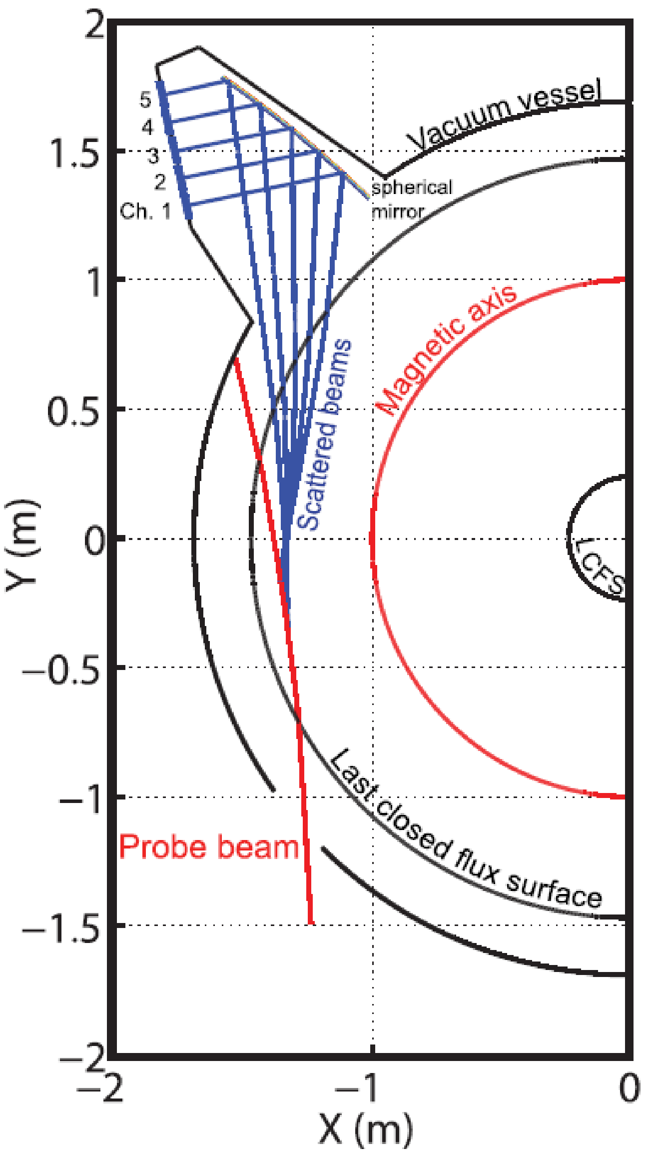
$I_P$=0.95MA, $H_{98y2}$=1.2, $\beta_N$=5, $\beta_T$ = 10%
$B_T$ = 1T, $P_{NBI}$ = 10MW, $P_{RF}$ = 4MW

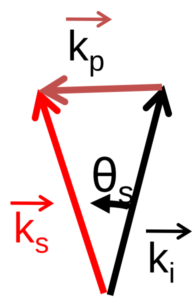


# Measuring Electron-scale Turbulence Presents Challenges to the Diagnosis of Tokamak Turbulence

- Remote sensing required in tokamaks with auxiliary heating
  - Measurements with electromagnetic waves, e.g. imaging or scattering with visible light, Infrared, Far Infrared or mm-waves
- Sub-mm electron gyroradius in present tokamaks
  - Extreme spatial resolution needed in imaging diagnostics, very difficult if not impossible
  - Direct measurements of electron-scale wavenumber spectrum possible with coherent scattering method
    - Good spatial resolution achievable even for $CO_2$ laser scattering
    - More strict validation of numerical codes
    - Absolute calibration hard to achieve

# Tangential Scattering Scheme was Used for the High-$k_r$ Microwave Scattering System on NSTX




- 280 GHz microwave is launched as the probe beam
  - Beam refraction due to density gradient important
  - Ray tracing using a C++ code with MATLAB interface
- Coherent scattering by plasma density fluctuations occurs when the three-wave coupling condition is satisfied:

$$\vec{k}_s = \vec{k}_p + \vec{k}_i$$

- Bragg condition determines $k_p$:

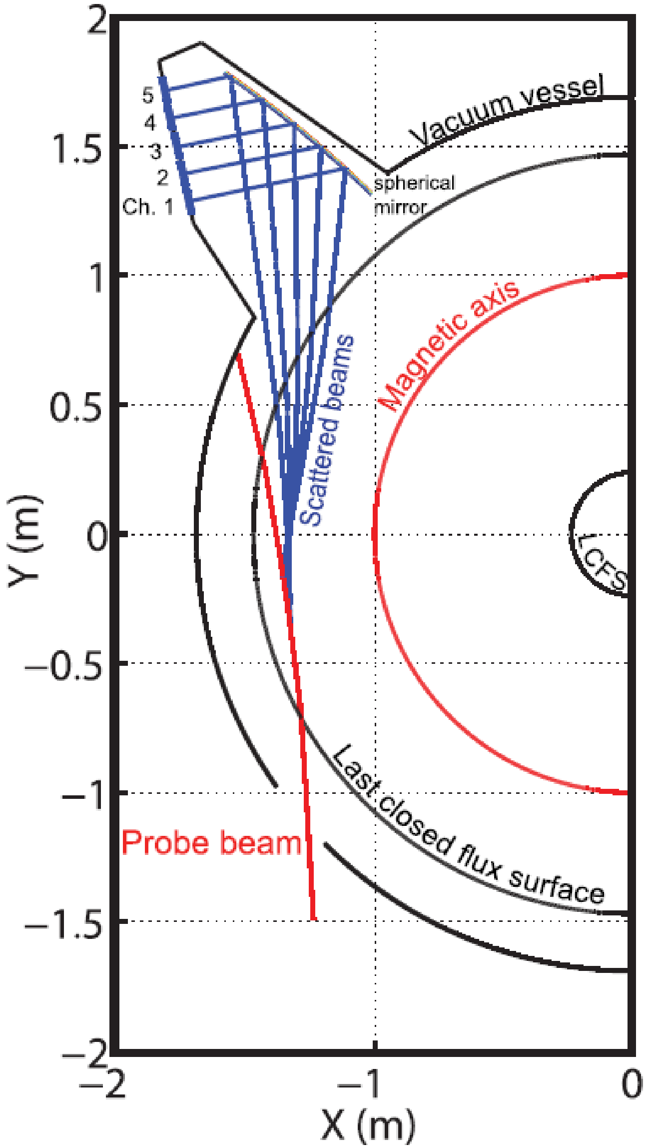
$$k_p=2k_i\sin(\theta_s/2)$$

- The scattering light has a frequency of:

$$\omega_s=\omega_p+\omega_i$$

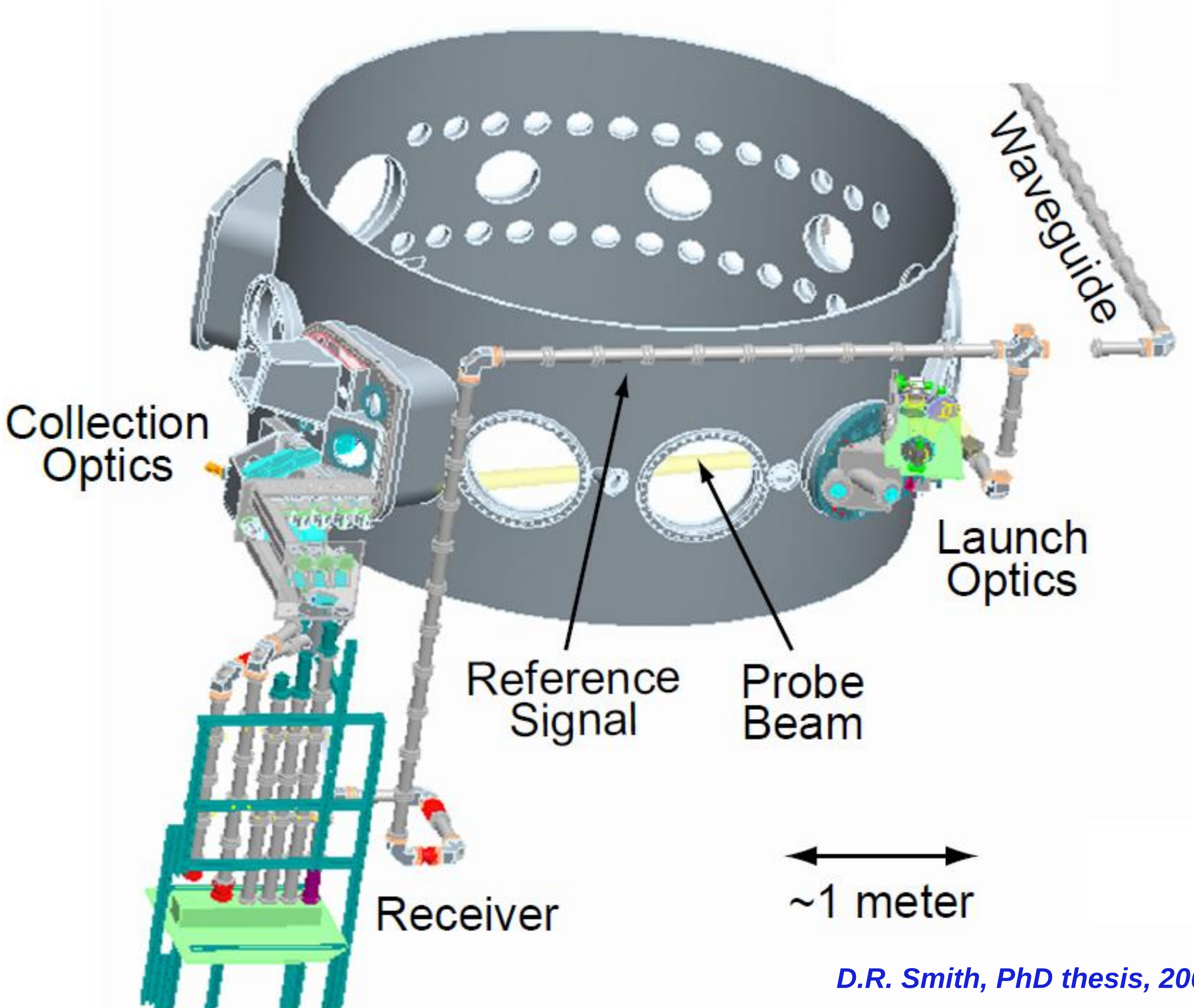
with $\omega_s$ and $\omega_i >> \omega_p$

# Tangential Scattering Scheme was Used for the High-$k_r$ Microwave Scattering System on NSTX




| High-$k_r$ system capabilities | | |
|---|---|---|
| Measured quantity | r/a range | Spatial & temporal resolution |
| Density fluctuation | ~0.2-1 from core to edge (between shot) | $3 \le k_\perp \rho_s \le 12$<br>$\Delta R \sim \pm 2$ cm<br>f~ 5 MHz |

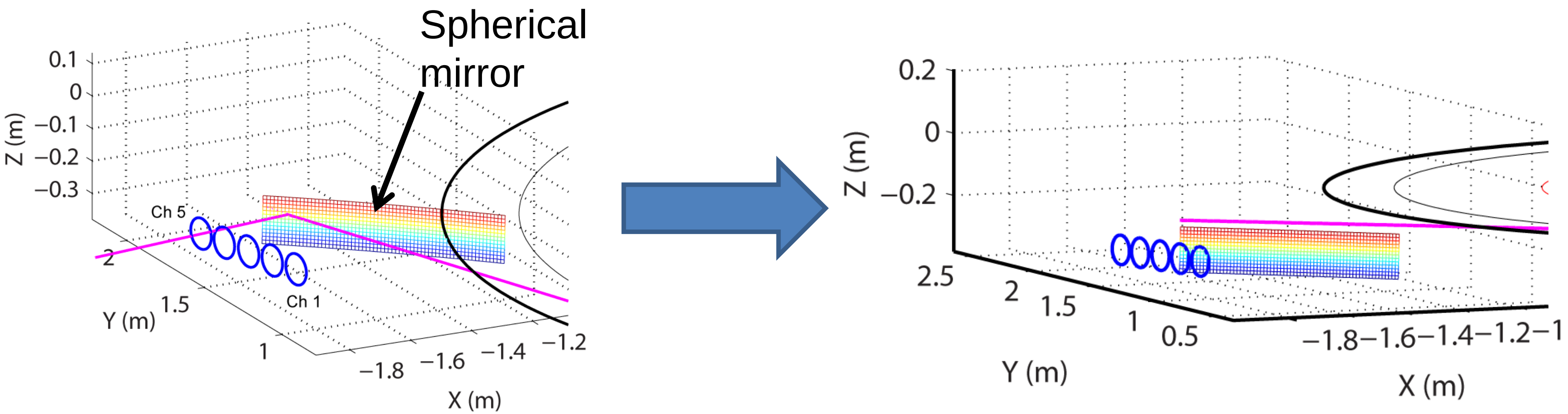
# The High-$k_r$ Microwave Scattering System was a High Priority Diagnostic on NSTX




*D.R. Smith, PhD thesis, 2009*

# The High-$k_r$ Microwave Scattering System was Improved through the Years

- Improved scattering configuration allowing simultaneous operation of all five scattering channels
  - The probe beam hits the spherical mirror and some of the channels have to be fully attenuated to protect detectors
    - Simultaneously utilize at most three out of the five receiving channels
- Launch the probe beam upward preventing it from directly hitting the mirror
  - No channel has to be fully attenuated
  - Stray radiation on all channels is reduced



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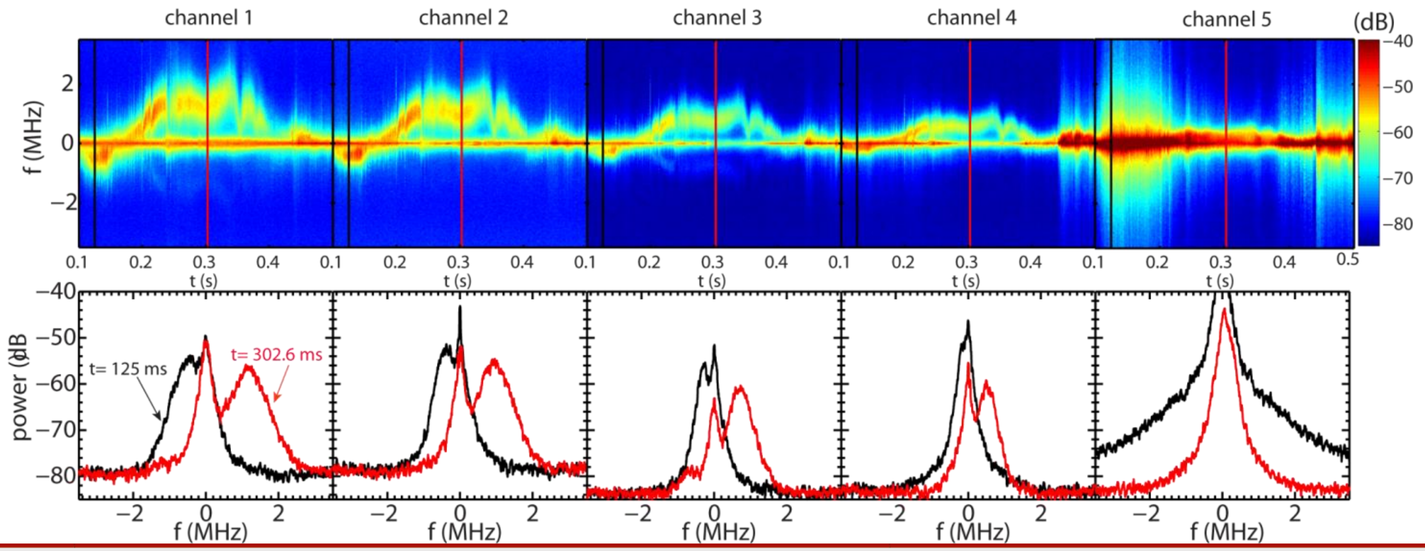
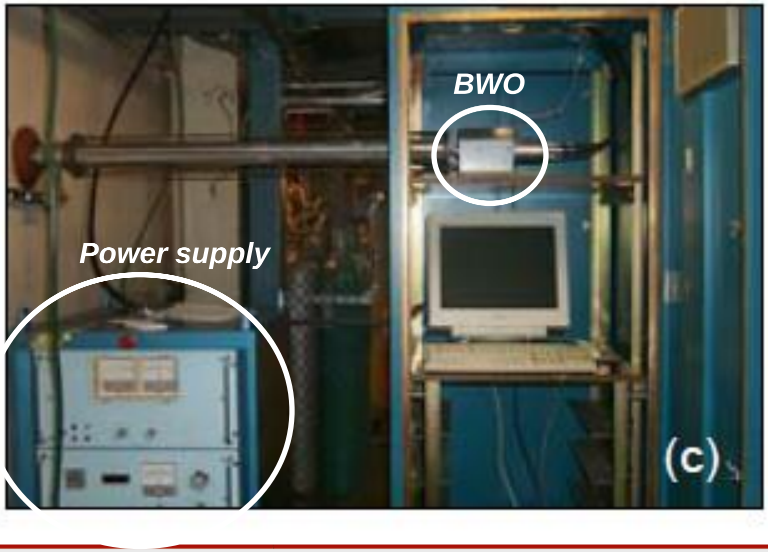
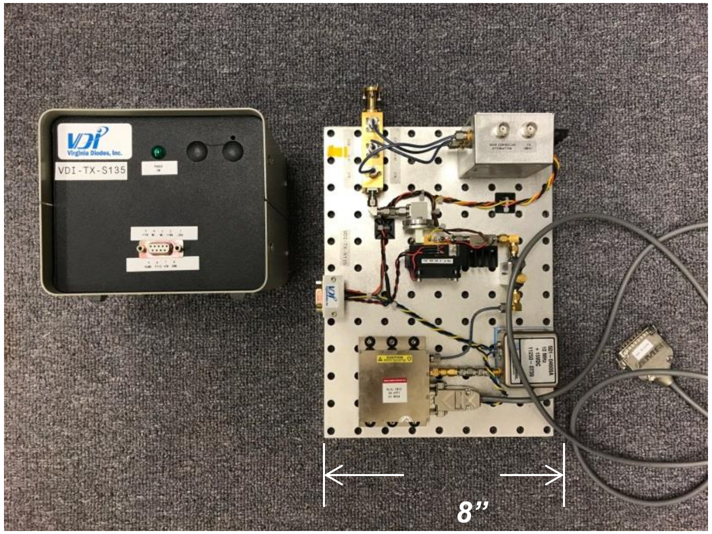


# The High-$k_r$ Microwave Scattering System was Improved through the Years

- Significant improvement in remote control capabilities
  - Between-shot change in probe beam launching angle and receiver aiming angle
  - Radial scan and wavenumber matching
- Microwave source upgraded from a BWO to a solid state source
  - Significantly improved system reliability
  - Much smaller footprint
  - Power reduced from 100 mW to 24 mW, still adequate due to the sensitive mixers

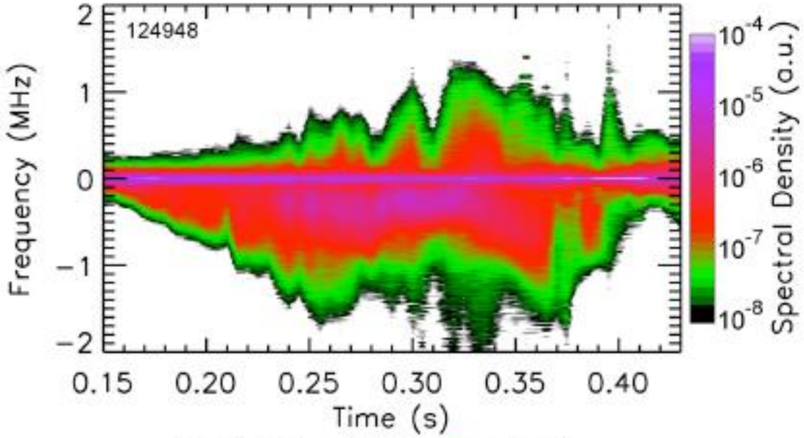


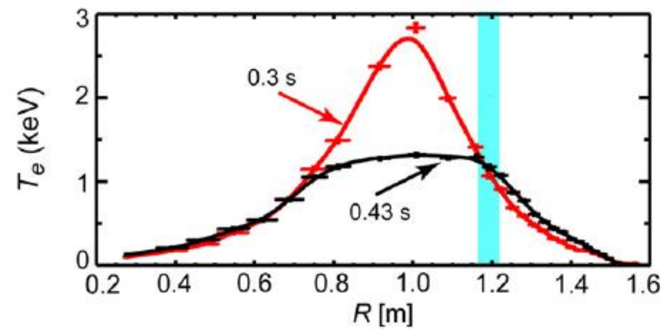



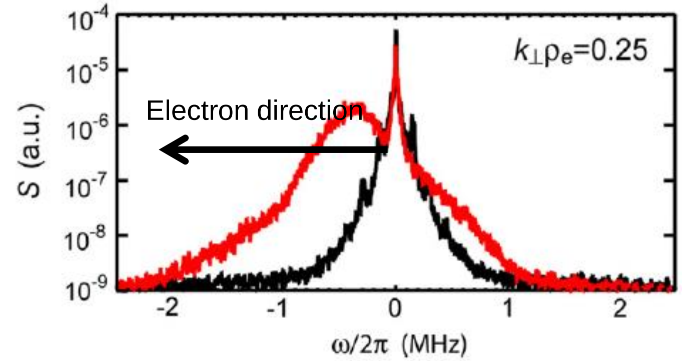
# First Identification of ETG Turbulence in NSTX RF-heated L-mode Plasmas

- The measured high-k turbulence is shown to be driven by electron temperature
  - In RF-heated helium L-mode plasma (1.2 MW, 5.5 kG, 700 kA)
  - Fluctuation propagates in the electron diamagnetic direction
  - Clear reduction in turbulence spectral power at lower electron temperature gradient

$$k_\perp = 14\ cm^{-1}, k_\perp \rho_s = 8 - 10$$



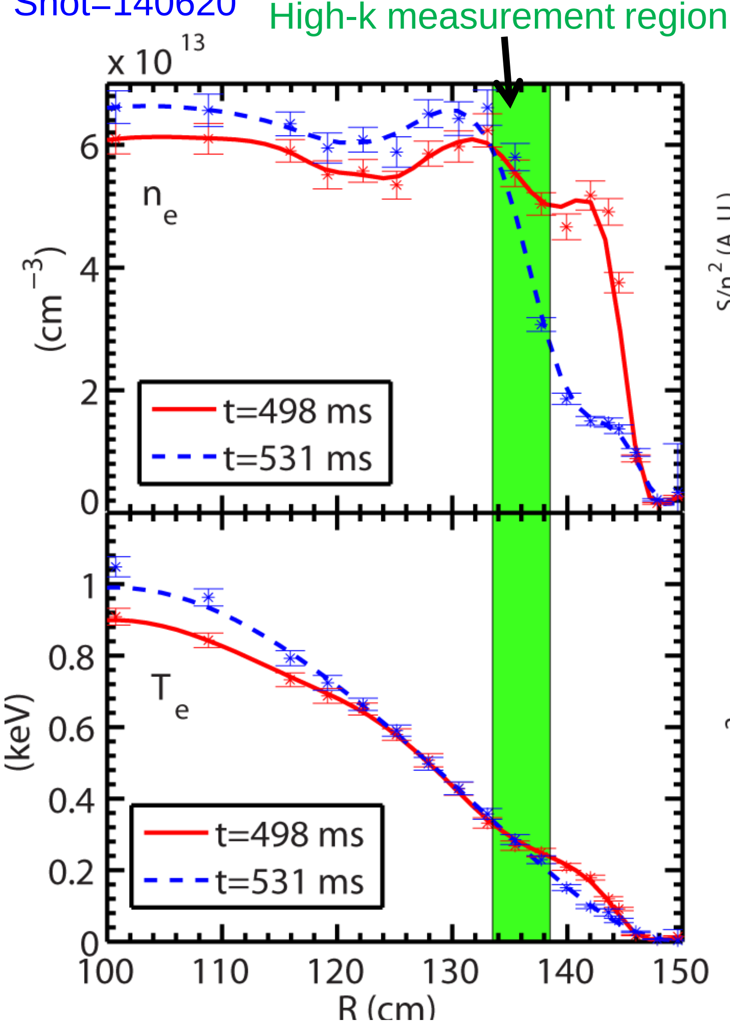



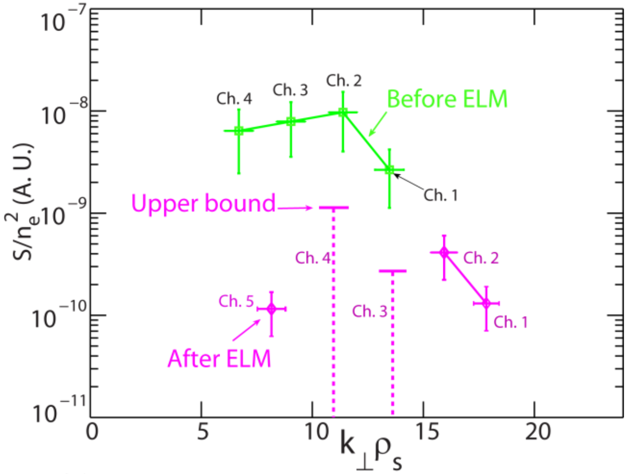



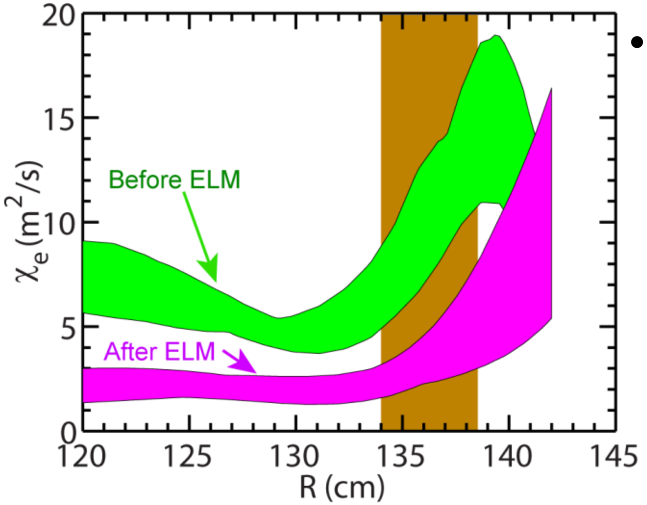

*Mazzucato et al., PRL 2008, NF 2009*

# Density Stabilization of Electron-scale Turbulence

Shot=140620



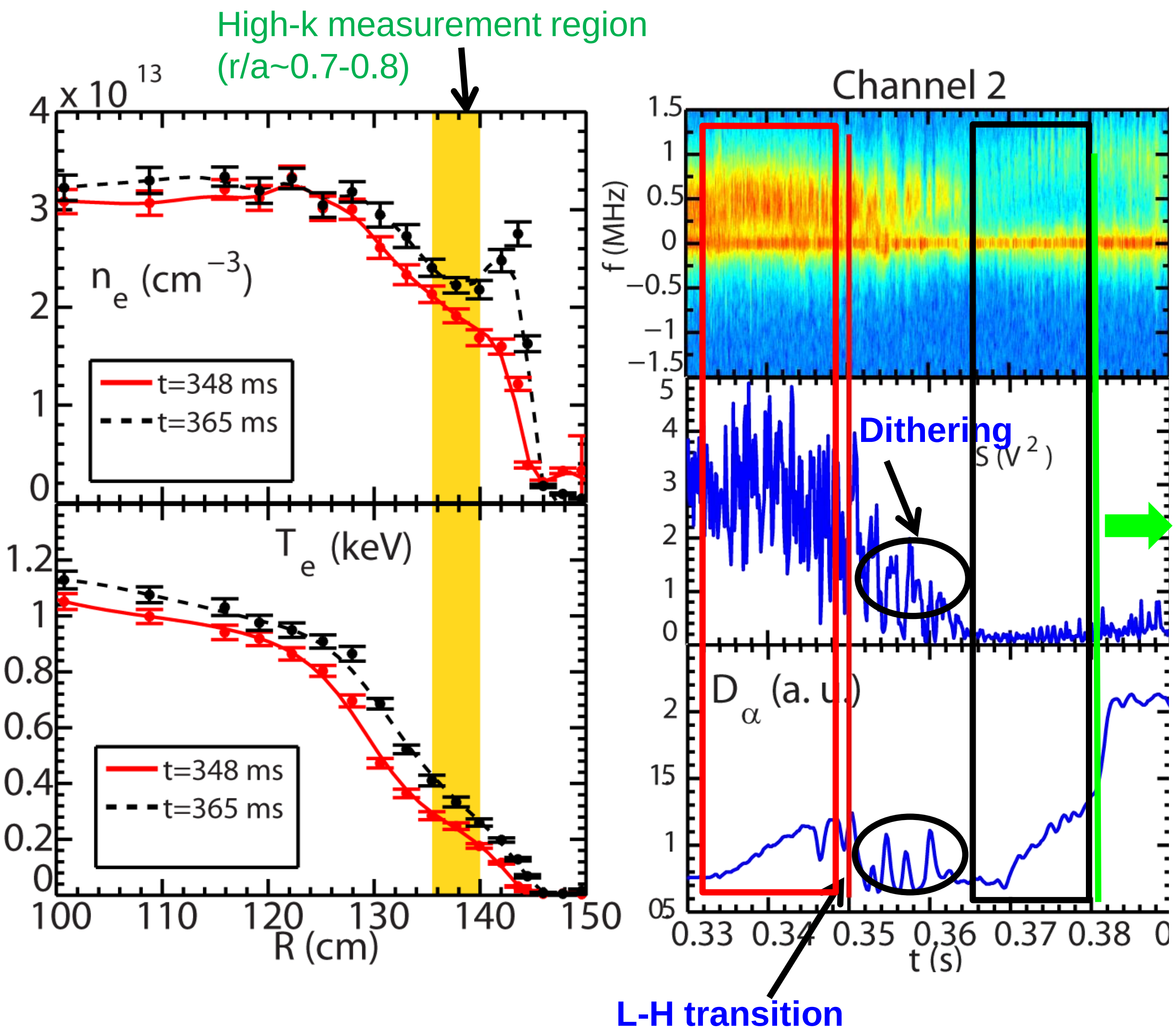




- Significant decrease in spectral power in electron-scale observed for $k_\perp \rho_s \lesssim 10$
- Electron thermal diffusivity is decreased by a factor of ~2 after the ELM event

**Y. Ren et al., PRL 2011, PoP 2012**

# Electron-scale Turbulence Evolution across L-H Transition was Measured

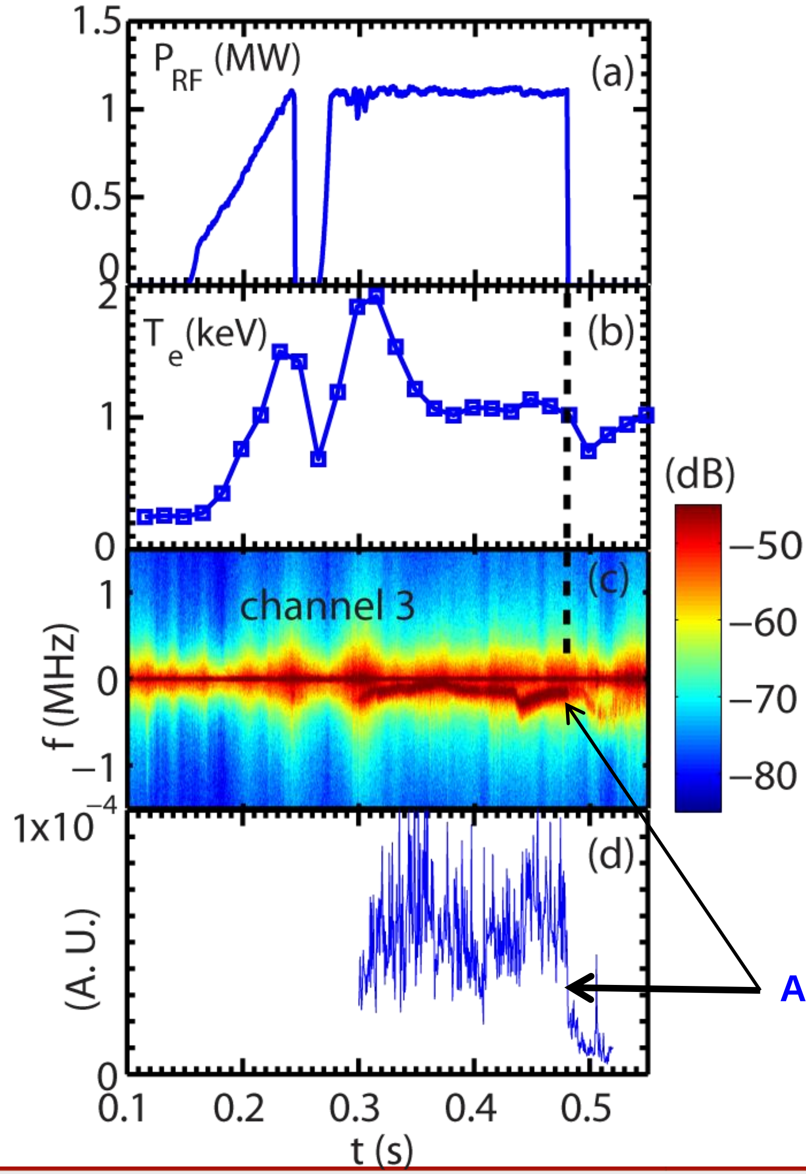



- Clear H-mode density ear appears at t=365 ms, showing the establishment of ETB
  - The density ear due to edge accumulation of carbon impurity
- Quasi-stationary turbulence before the L-H transition
- Dithering in high-k spectral power observed after L-H transition
- Significant suppression of high-k turbulence in 365<t<380 ms
- Some increase in turbulence at t>380 ms

# Fast Response of Electron-scale Turbulence to RF Heating Cessation was Identified

**Shot=140301**

RF-heated L-mode plasma with $B_T$ =5.5 kG and $I_p$=300 kA




- Drop in turbulence frequency spectral power at the time of RF cessation
  - The drop happens in 0.5 to 1 ms, much smaller than $\tau_E \sim 10$ ms
- Electron heat flux decreases by about a factor of 2 after the RF cessation

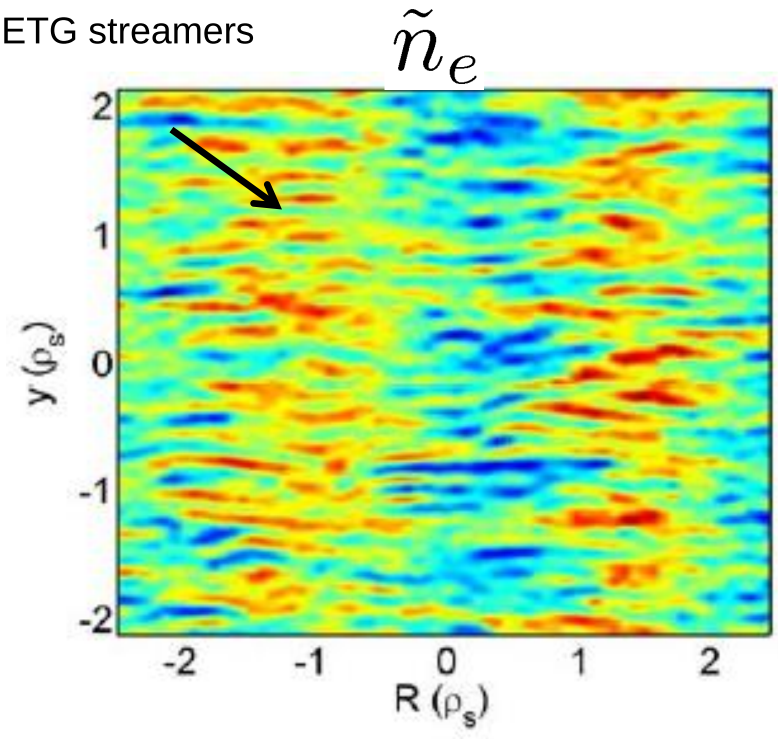
**A sudden drop in spectral power**

**Y. Ren et al., PoP 2015**

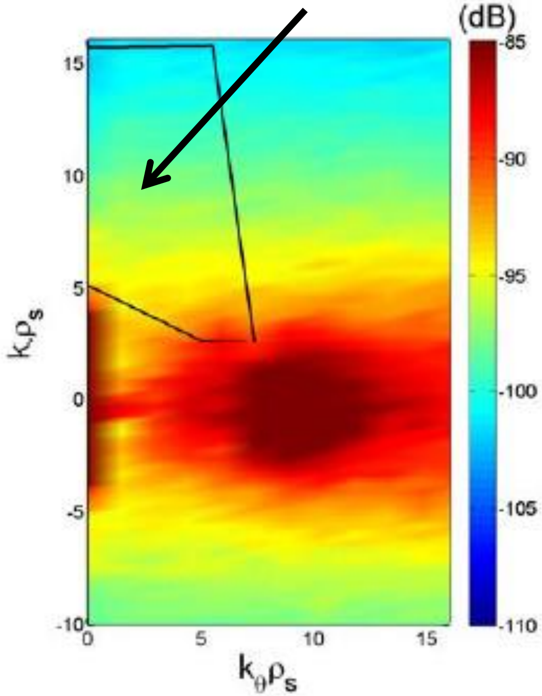
# However, the High-$k_r$ Scattering System Does not Capture the Predicted ETG Spectral Peak

- ETG turbulence develops radially elongated streamers
  - Important for driving anomalous electron thermal transport
  - Corresponding to modes with finite $k_\theta$ and $k_r \sim 0$
- The high-$k_r$ scattering system mainly measures $k_r$ spectrum
  - $k_r\rho_s \sim 4-15$ and $k_\theta\rho_s \sim 1-7$

ETG streamers

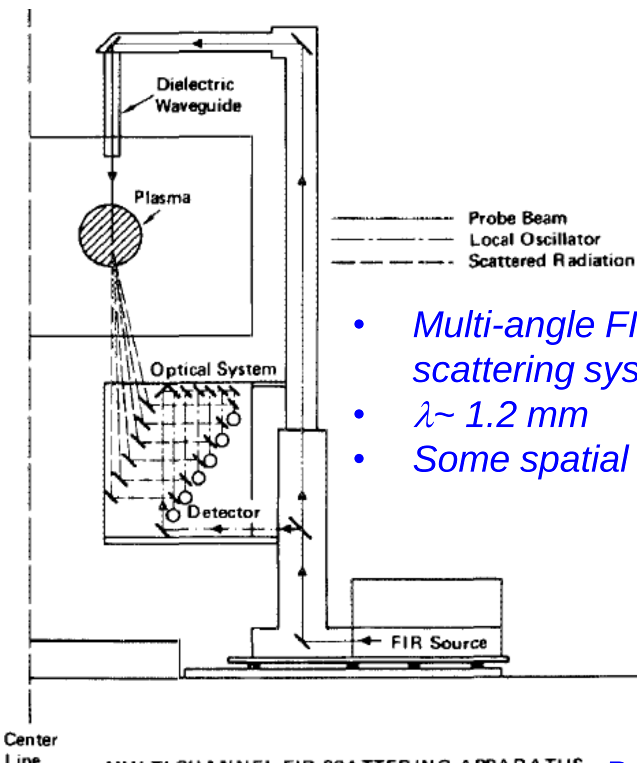



*Spectral coverage of the High-$k_r$ Scattering System*



# Previous Implementations of Measuring $k_\theta$ often Employ Vertical Launching

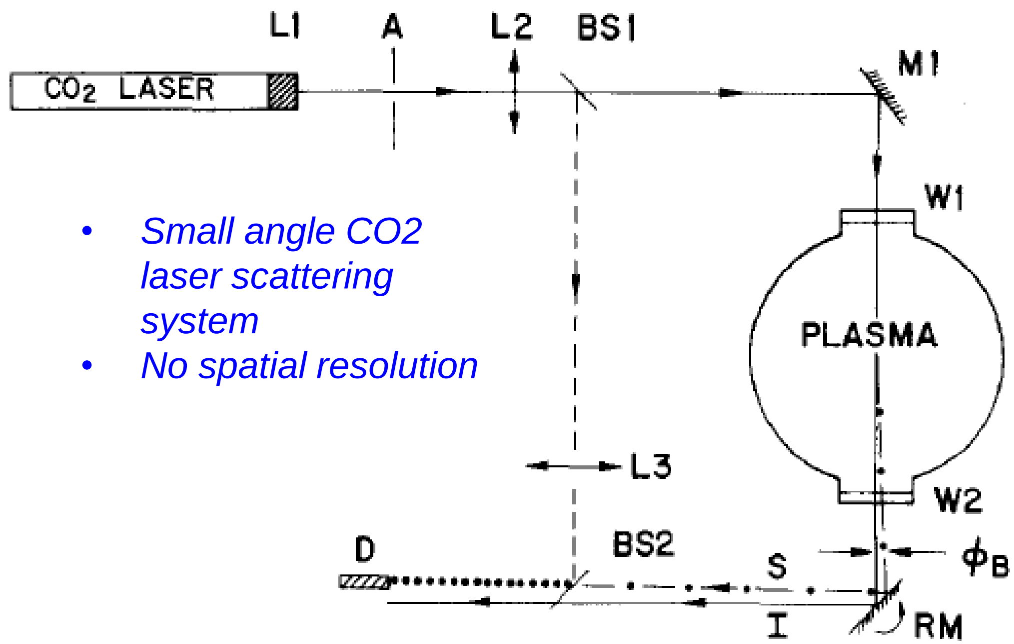
- Measuring $k_\theta$ in the plasma center and $k_r$ at the plasma edge
- No such port access for NSTX-U
- Strongest fluctuations predicted to be at outer mid-plane, where the bad curvature effect is strongest




MULTI CHANNEL FIR SCATTERING APPARATUS

- *Multi-angle FIR scattering system*
- *$\lambda$~ 1.2 mm*
- *Some spatial resolution*

***Park et al., RSI, 1985***

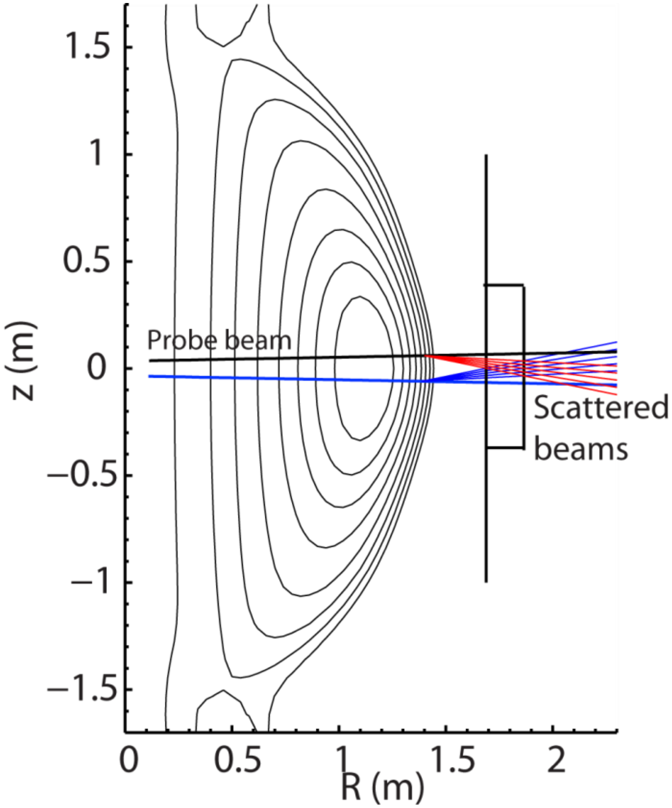


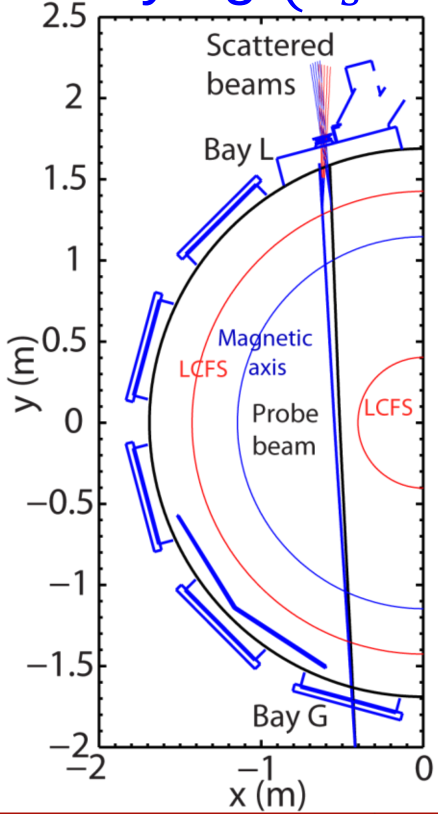

- *Small angle CO2 laser scattering system*
- *No spatial resolution*

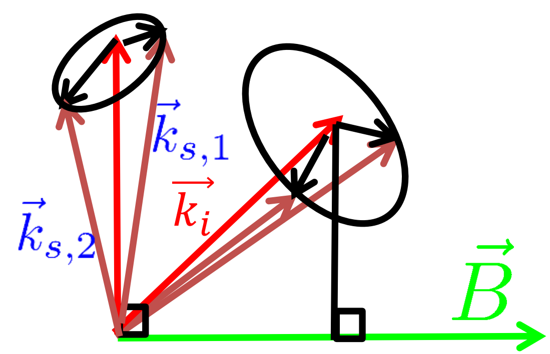
***Slusher and Surko, PoF, 1980***

# The NSTX-U High-$k_\theta$ Scattering System Employs the Perpendicular Scattering Scheme

- Probe beam from Bay G and scattered light received at Bay L
- Two scattering directions at the same flux surface
  - Drift wave turbulence in magnetized plasmas has $\vec{k} \cdot \vec{B} \approx 0$
  - Two scattered beams satisfying $(\overrightarrow{k_s} - \overrightarrow{k_i}) \cdot \vec{B} \approx 0$

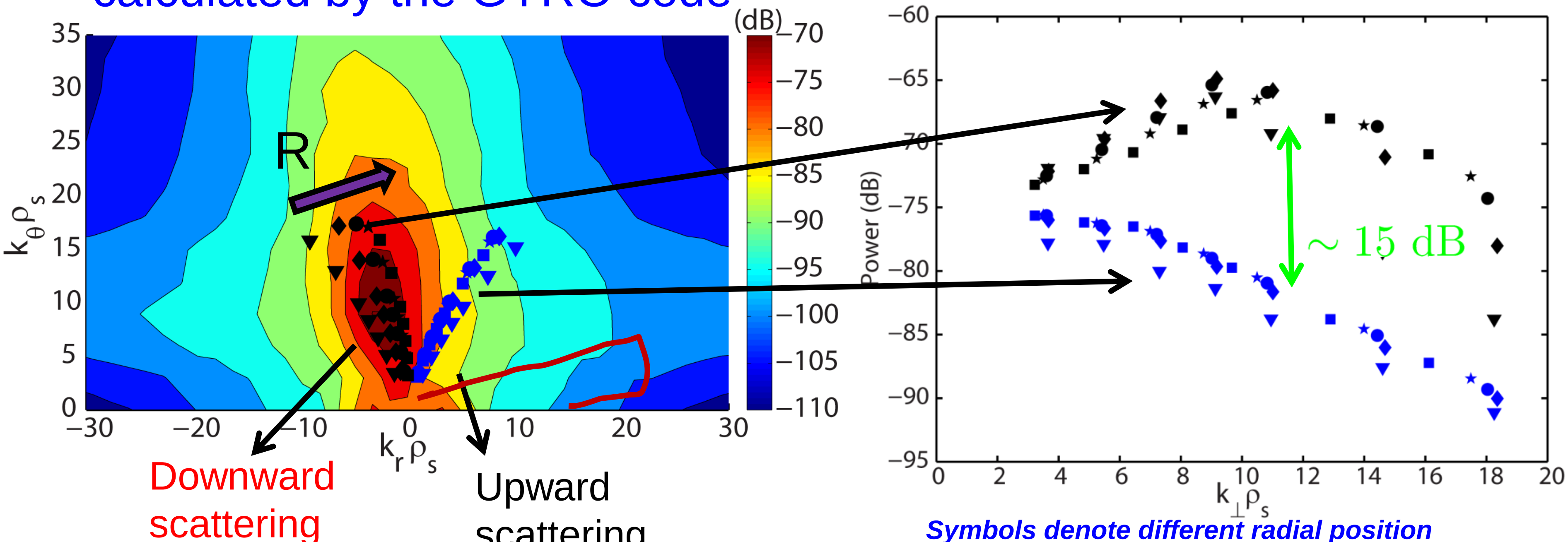


# Two Scattering Schemes Cover Different Regions of the 2D $k_\perp$ Spectrum

- The downward scattering has $k_r<0$, and $k_\theta \approx 3|k_r|$
- The upward scattering has $k_r>0$, and $k_\theta \approx 1.5|k_r|$
- Resolvable spectral power difference between two scattering schemes, ~15-20 dB from a nonlinear ETG simulation
  - Large power difference identifiable in experiment
  - Based on the 2D ETG k spectrum of an NSTX H-mode plasma, calculated by the GYRO code




*Symbols denote different radial position*

# NSTX-U High-$k_\theta$ Scattering System is being Implemented by UC-Davis

FIR Laser System

- 160 W $CO_2$ pump laser
- 88 mW FIR formic acid laser

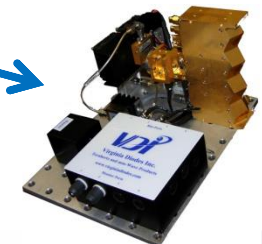
20 m Corrugated Waveguide

Reference Channel

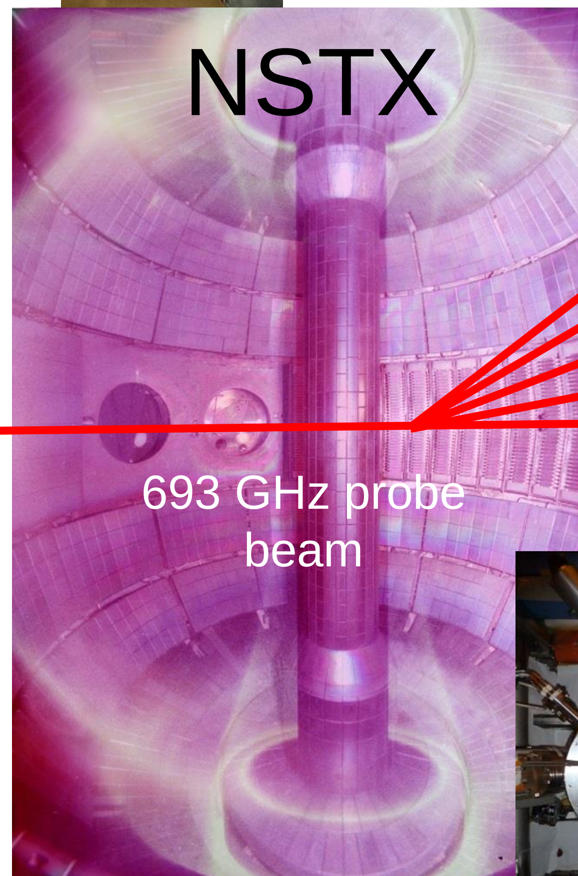
14 GHz LO

x48

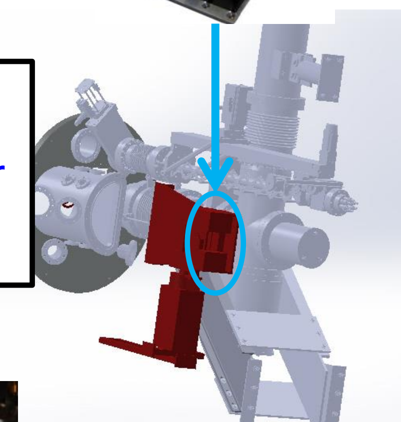
693 GHz subharmonic 4-pixel receiver array



Bay G launch optics

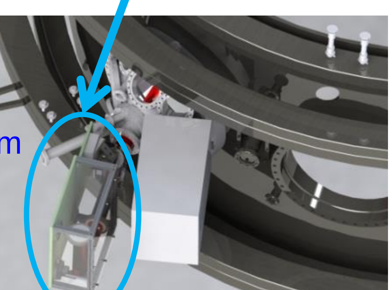



Bay L receiver optics



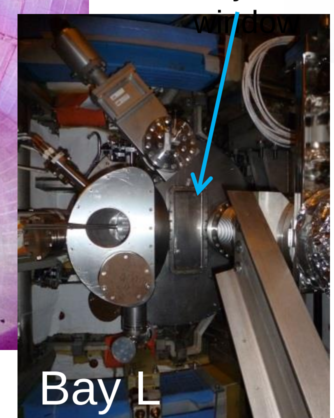
Launch Optics

- Remotely steerable beam ± 2.5°
- HDPE lenses shape beam



Bay G

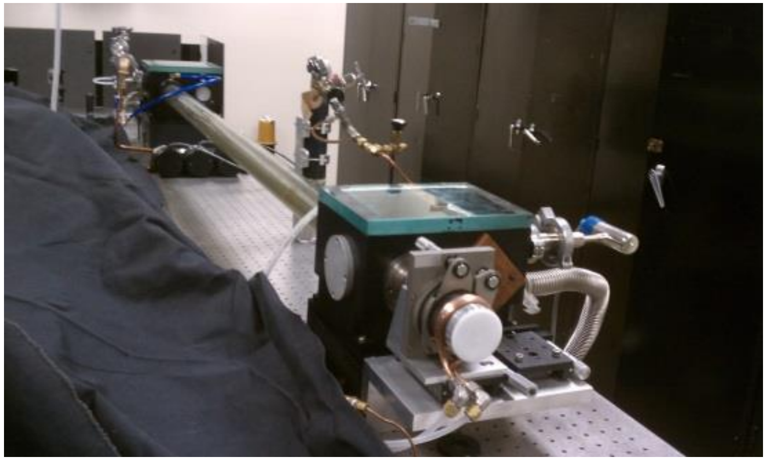
Bay L




- Receiver optics
  - Remotely steerable elements
  - Scattering angles 2° to 15°
  - Bay L 33 cm tall window permits $k_\theta$ detection

# A 693 GHz FIR Formic Acid Laser is Used as the Probe beam

- Optically pumped FIR formic acid laser
- 693 GHz (432 μm)
- 88 mW beam power
- Mesh output coupler provides Gaussian beam profile

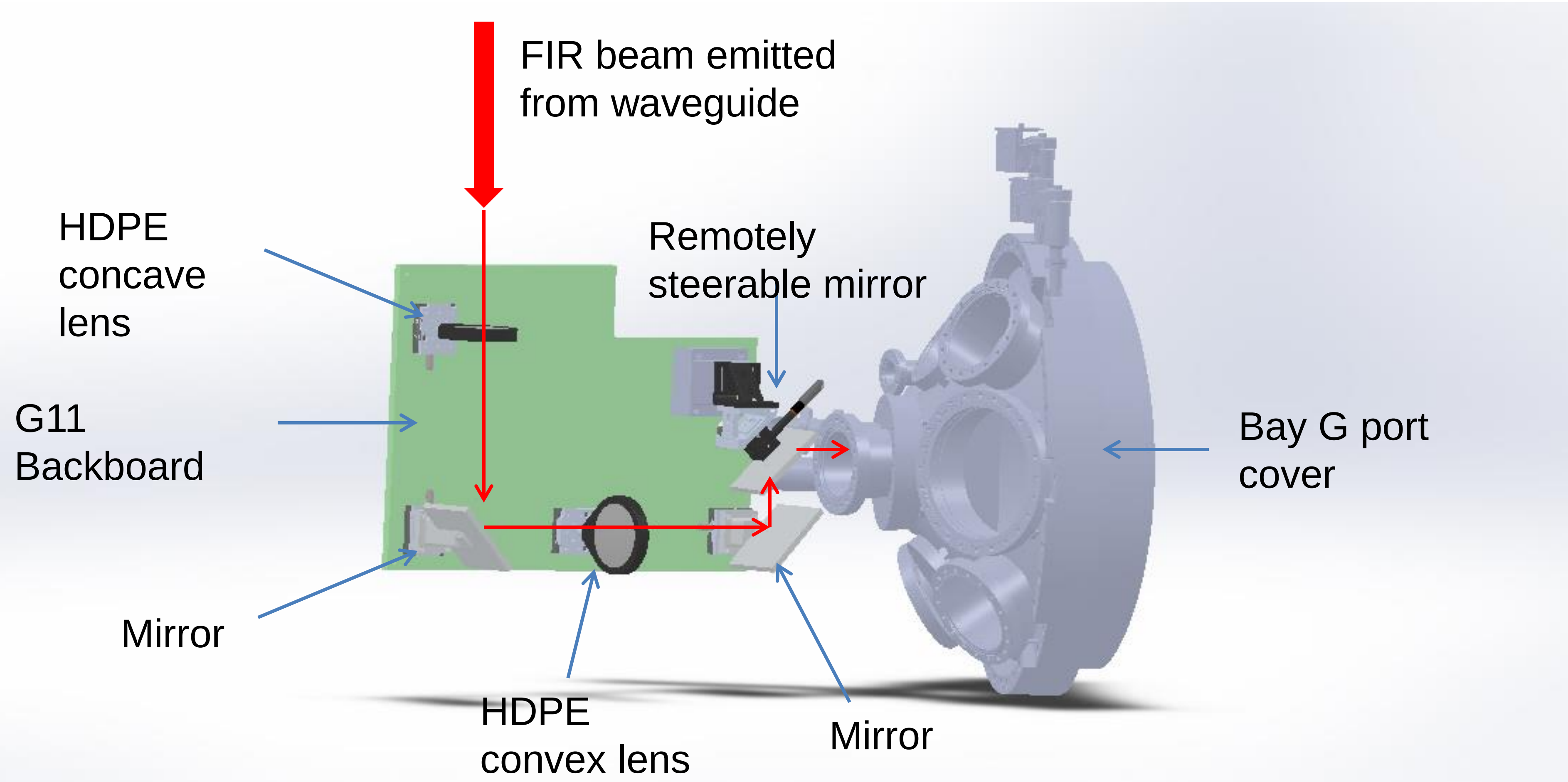


88 mW FIR laser

Edinburgh Instruments PL-6

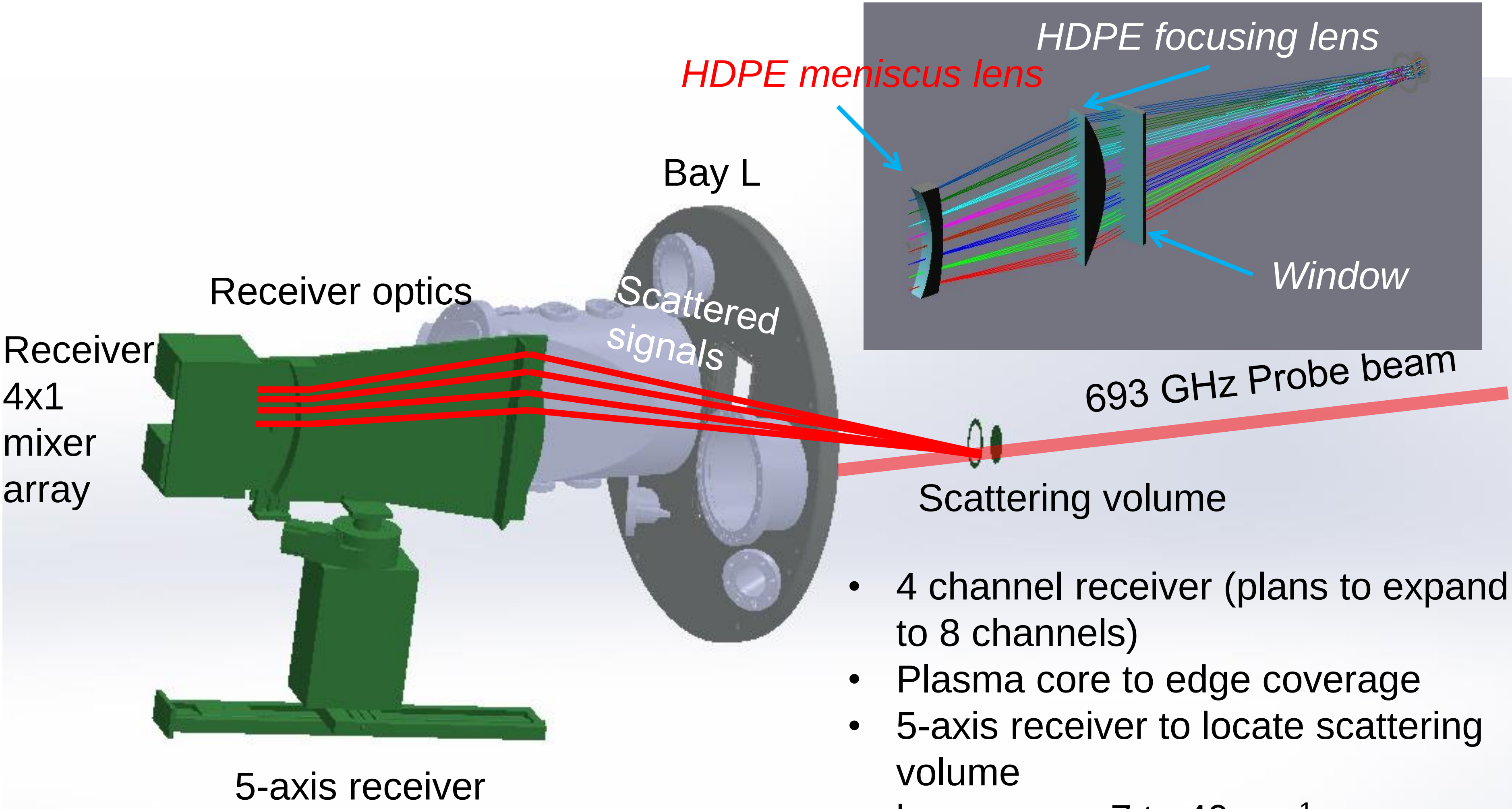
- $CO_2$ Laser
- Grating tunable
- 160 W
- Folded twin tube design
- Solid state 1200 W power supply
- Self contained chilled water circulation

# Remotely Steerable Launching System Provides Upward and Downward Scattering Capability




- 432 µm, Gaussian beam
- Steerable ± 2.25˚ vertical and ± 1.0° horizontal
- Beam waist 520 mm from receiver window

# Four Scattering Channels are Planned Initially




- 4 channel receiver (plans to expand to 8 channels)
- Plasma core to edge coverage
- 5-axis receiver to locate scattering volume
- $k_\theta$ coverage 7 to 40 $cm^{-1}$
- Heterodyne receivers to distinguish the direction of propagation

# Some Considerations of a Spatially-resolved High-k Scattering System on DIII-D

- If employ perpendicular scattering scheme (measuring $k_\theta$ spectrum)
  - DIII-D magnetic shear is too small (compare with NSTX) to provide sufficient help in improving scattering localization
  - Small beam overlap in order to have radial localization
    - mm microwave probably the best bet
  - Large scattering angle-> large exit window required
- If employ tangential scattering scheme
  - Both $k_\theta$ and $k_r$ spectra measurement possible
  - Good radial localization achievable even with $CO_2$ laser scattering
    - Only require small windows for a single radial location
    - Multiple exit windows needed for more radial locations

# Summary

- The high-$k_r$ microwave scattering diagnostic on NSTX was a success
  - Good radial resolution, electron-scale wavenumber coverage and frequency response
  - Provided insight into ETG physics in STs
  - However, measuring $k_r$ not optimal for assessing the relation with transport
- A high-$k_\theta$ FIR scattering diagnostic is being implemented by UC-Davis for NSTX-U
  - Able to measure wavenumber spectral peak of ETG turbulence
  - Featuring two scattering schemes for probing ETG streamers