Simultaneous High-k Scattering and Microwave Imaging Reflectometry on NSTX-U

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Abstract

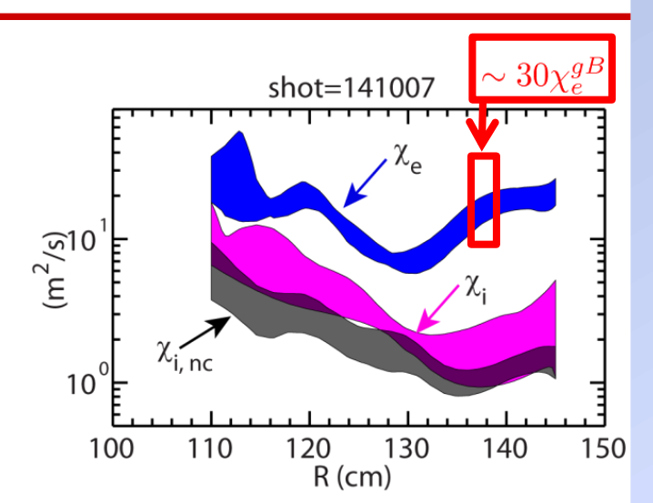
An 8-channel 693 GHz poloidal high-k scattering system is under development, replacing a 5-channel 280 GHz toroidal scattering system, to study high-k density fluctuations on NSTX-U. The far-infrared probe beam is launched from Bay G towards Bay L, where large aperture optics collect radiation at 8 simultaneous scattering angles ranging from 2 to 15° . This yields measurement of poloidal wavenumbers from 7 cm^{-1} to >40 cm^{-1}, while translatable optics allow placement of the scattering volume from r/a = 0.1 out to the pedestal region (r/a ~ 0.99).

A microwave imaging reflectometry (MIR) system will co-exist with the High-k Scattering system on Bay L, with MIR optics positioned above that of the scattering system, to monitor low-k_θ (< 3 cm^{-1}) density fluctuations. Details of the 5×8 channel (5 poloidal, 8 radial) MIR system, spanning frequencies of 51 to 75 GHz, will be presented together with that of the High-k Scattering system.

*Work supported in part by U.S. DOE Grant DE-FG02-99ER54518 and DE-AC02-09CH1146.

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



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

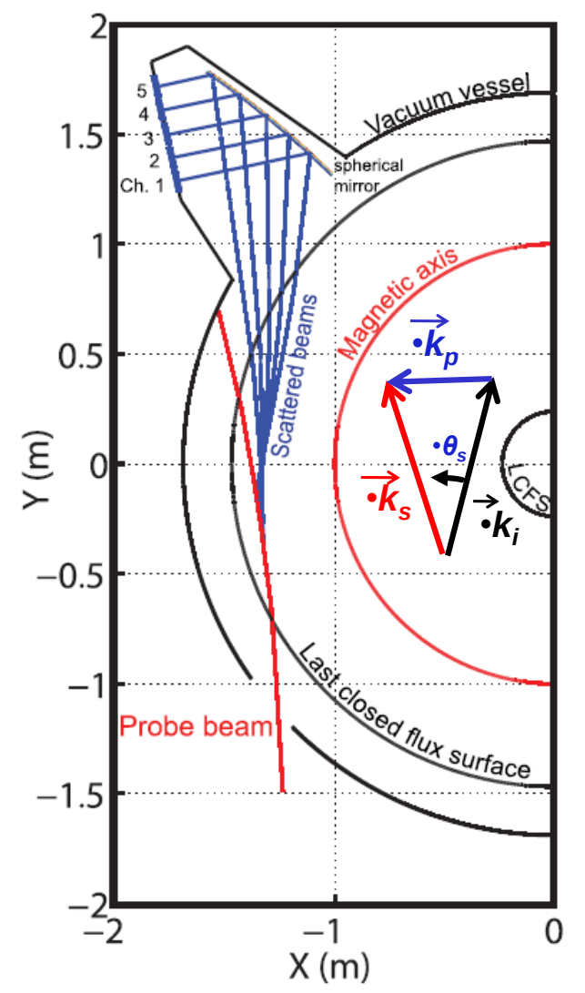
$$\chi_s^{gB} \equiv \frac{\rho_s^2 v_{Ts}}{L_{Ts}}$$

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

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

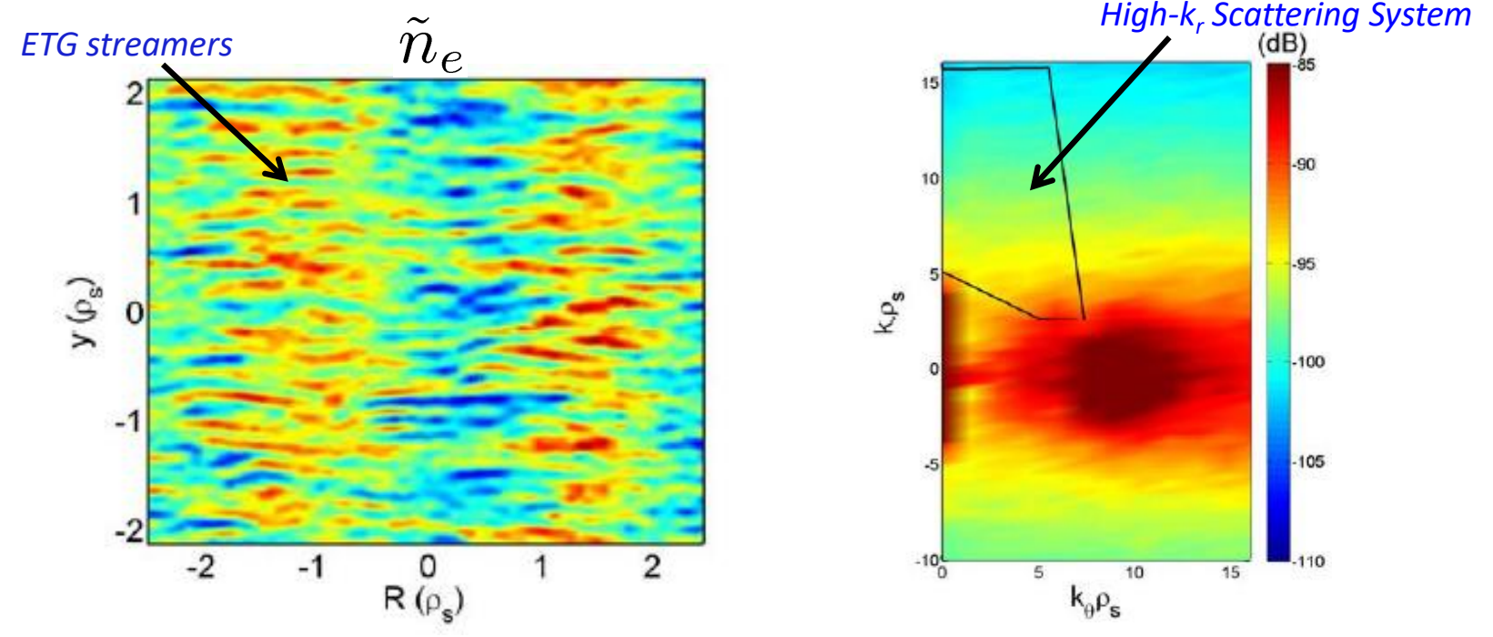
$$\vec{k}_s = \vec{k}_p + \vec{k}_i$$

- Bragg condition determines k_p: $k_p=2k_i\sin(\theta_s/2)$
- Scattered light has a frequency of: $\omega_s=\omega_p+\omega_i$ with ω_s and $\omega_i >> \omega_p$

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

However, the High-k_r Scattering System Did not Capture the Predicted ETG Spectral Peak

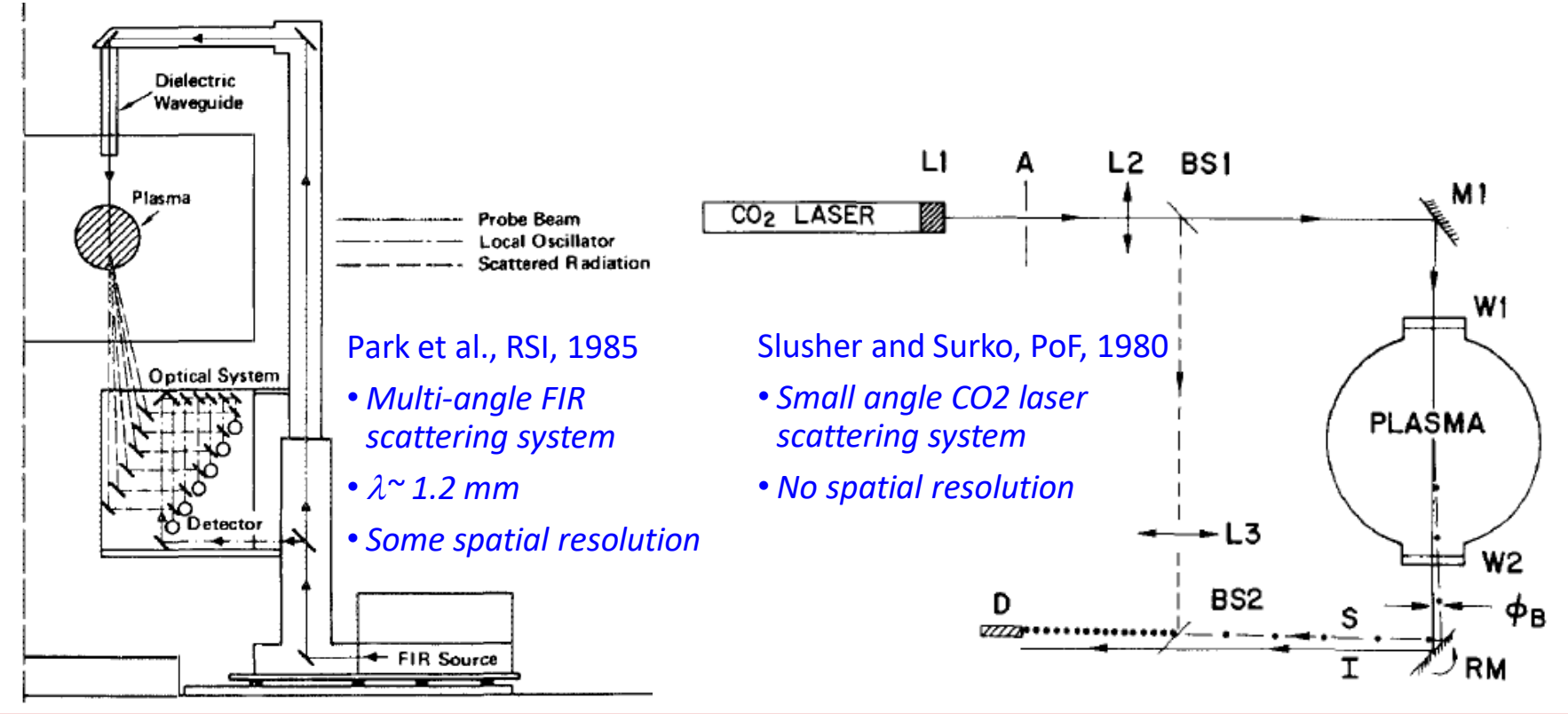
- ETG turbulence develops radially elongated streamers
  - Important for driving anomalous electron thermal transport
  - Corresponding to modes with finite k_θ and k_r ~ 0
- The high-k_r scattering system mainly measures k_r spectrum
  - $k_r\rho_s$ ~ 4 – 15 and $k_\theta\rho_s$ ~ 1 – 7


ETG streamers

Spectral coverage of the High-k_r Scattering System

Previous Implementations of Measuring k_θ often Employ Vertical Launching

- Measuring k_θ 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

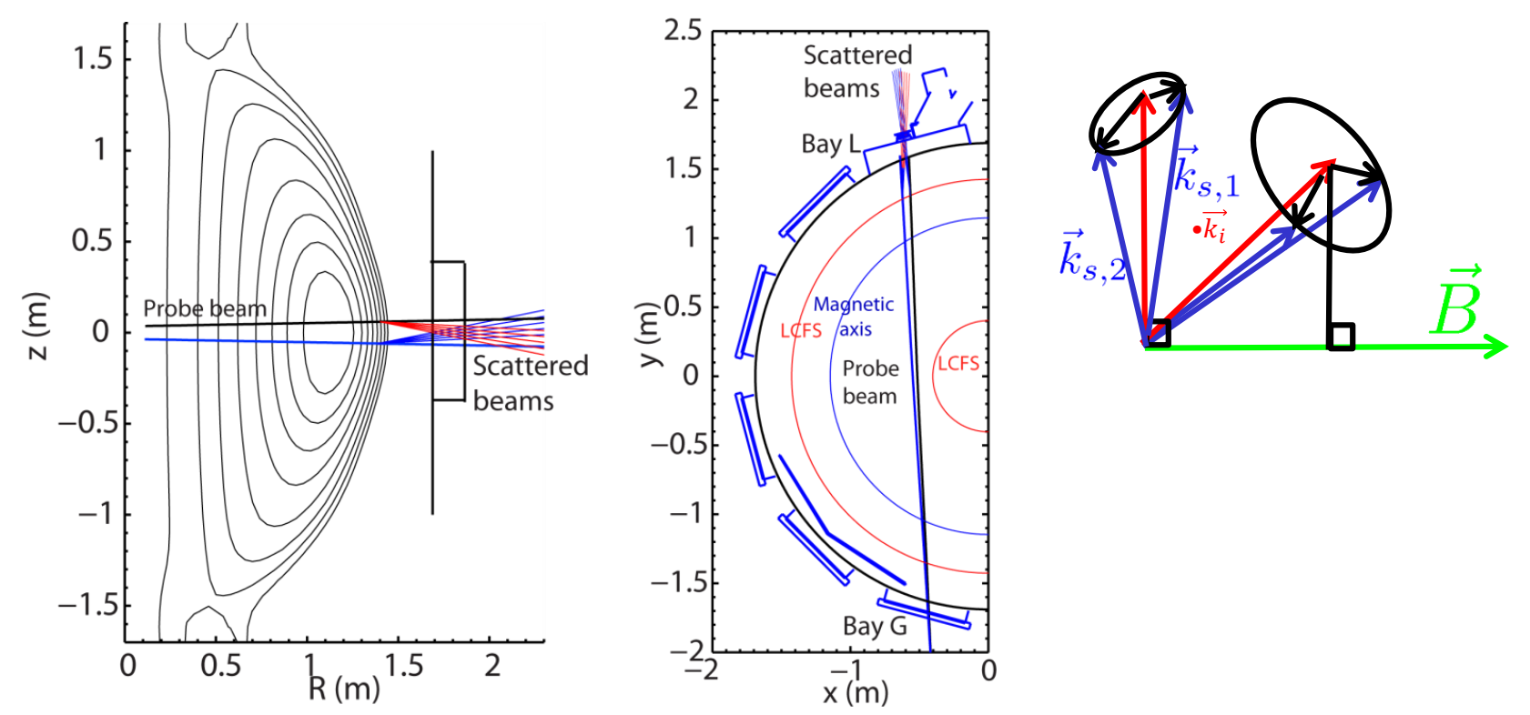


Park et al., RSI, 1985
- *Multi-angle FIR scattering system*
- *λ~ 1.2 mm*
- *Some spatial resolution*

Slusher and Surko, PoF, 1980
- *Small angle CO2 laser scattering system*
- *No spatial resolution*

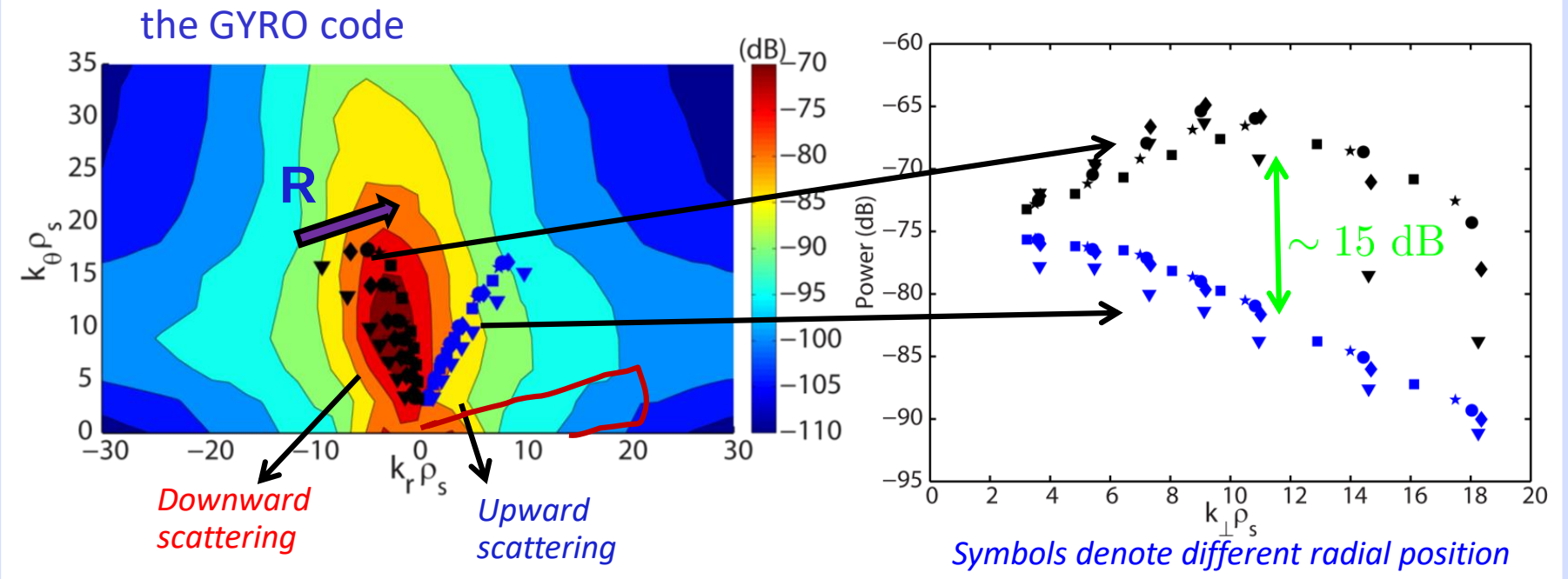
The NSTX-U High-k_θ Scattering System Geometry Employs Perpendicular Scattering

- 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 $\left(\vec{k_s} - \vec{k_i}\right)\cdot\vec{B} \approx 0$



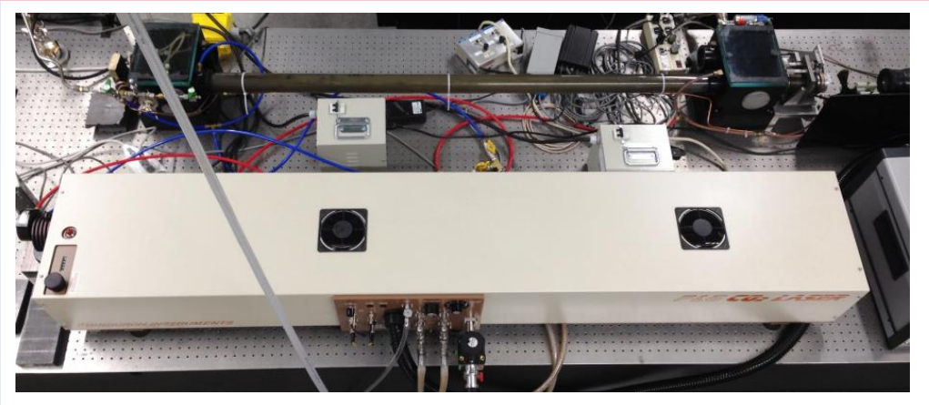
Two Scattering Schemes Cover Different Regions of the 2D $k_\perp$ Spectrum

- The downward scattering has k_r<0, and k_θ≈3|k_r|
- The upward scattering has k_r>0, and k_θ≈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



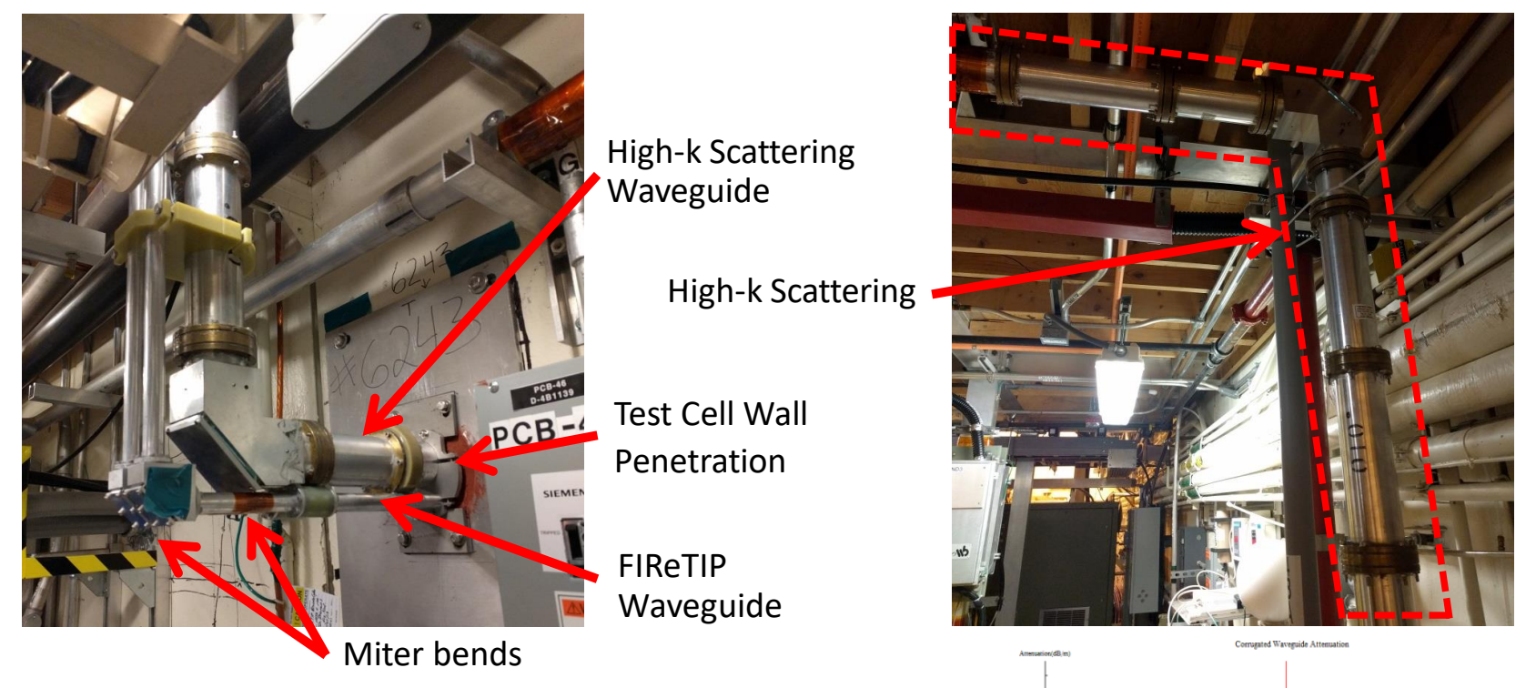
Symbols denote different radial position

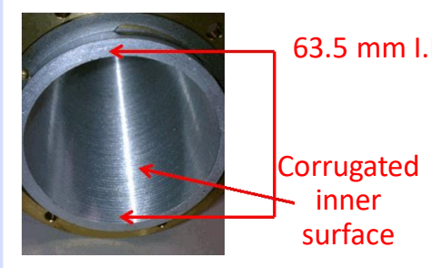
A 693 GHz CO_2-pumped FIR Laser Provides the Scattering Probe Beam



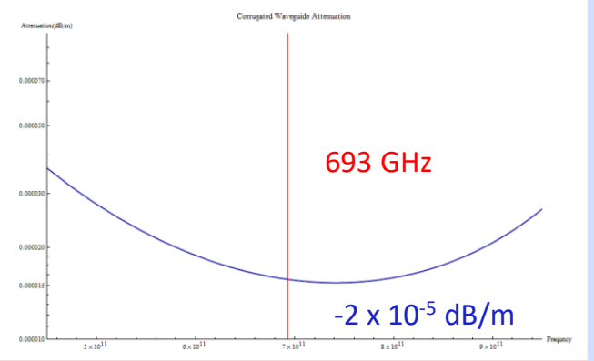
- Edinburgh Instruments PL-6 CO_2 laser (see above) provides 160 W output power
- Optically pumped FIR formic acid laser generates 88 mW at 693 GHz (432 μm)
- Mesh output coupler provides Gaussian beam profile
- CO_2 and FIR lasers (High-k and FIReTIP) to be housed in enclosure area (see right) next to NSTX-U test cell
- Laser paths are fully enclosed in dry air or nitrogen to reduce losses due to absorption by water vapor

Low Loss, Corrugated Waveguide Path to NSTX-U Test Cell

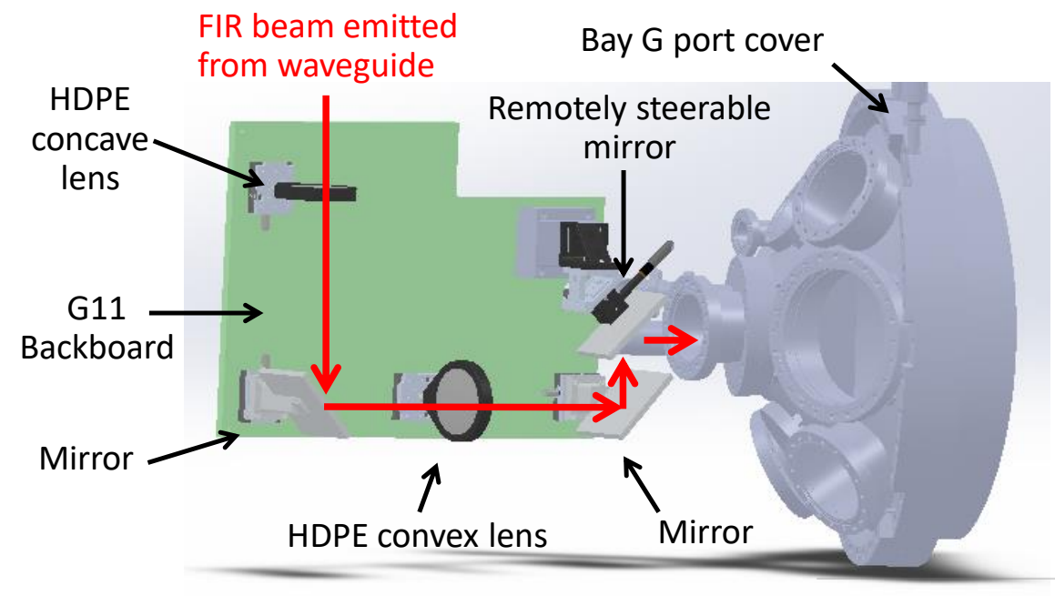




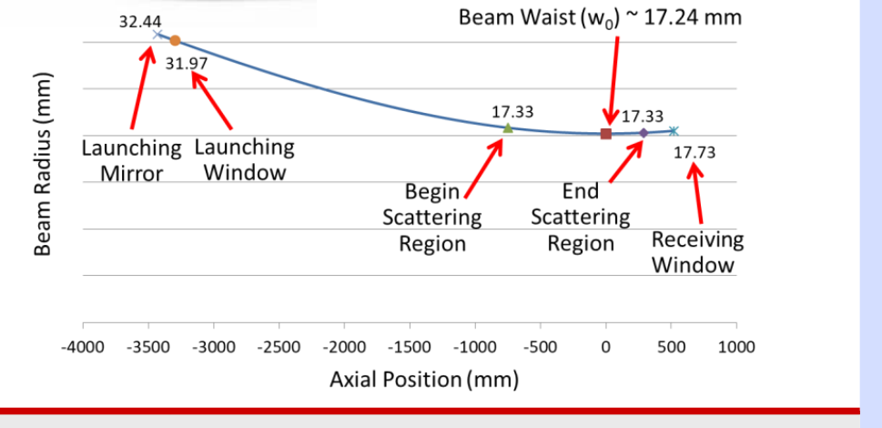
- Probe beam will be delivered to Bay G via overmoded, corrugated waveguide
- ~20 m of waveguide needed to route the probe beam to the vacuum vessel



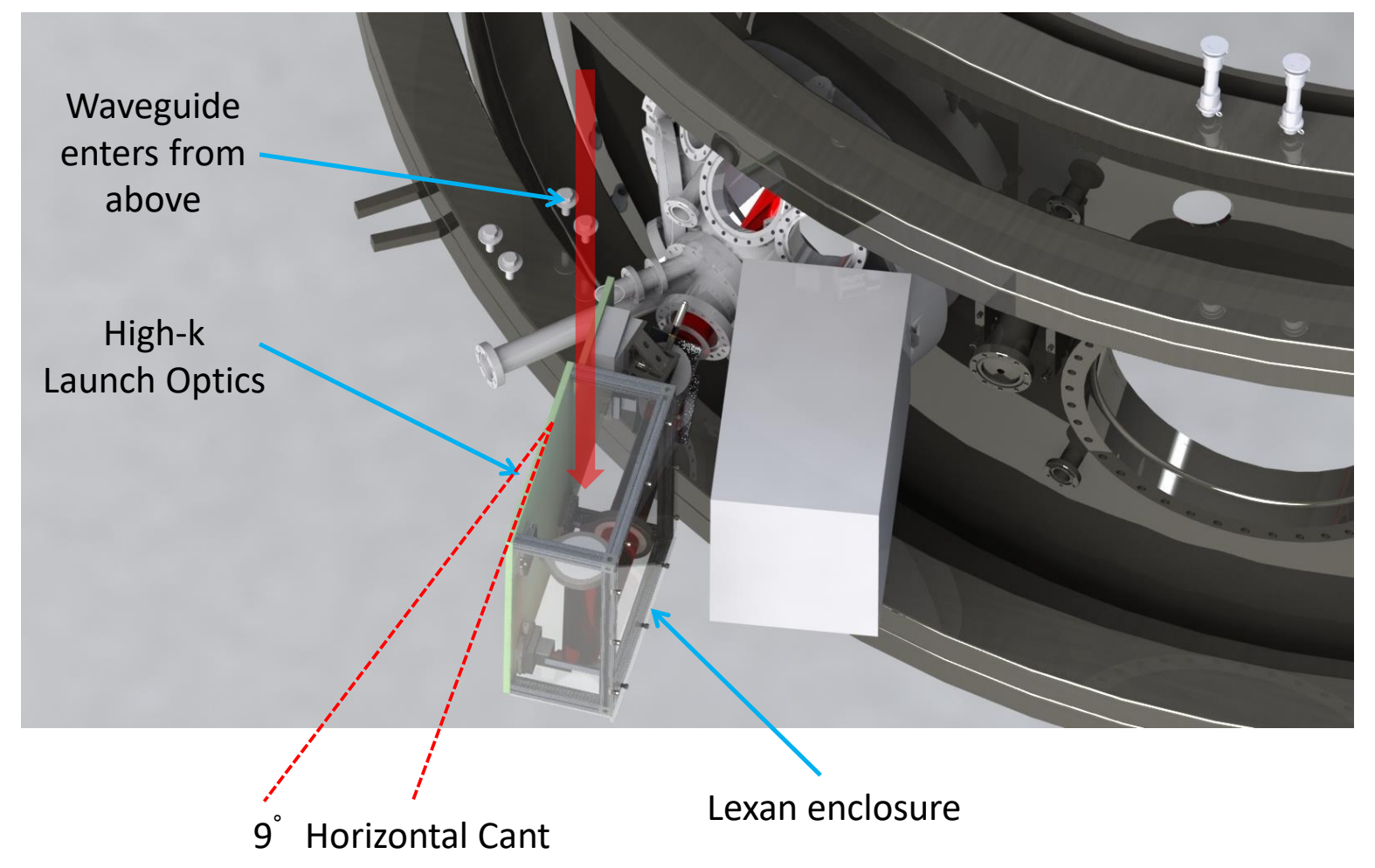
Remotely Steerable Launching System Provides Upward and Downward Scattering Capability



- 432 μm, Gaussian beam
- Steerable ±2.25° vertical and ±1.0° horizontal
- Beam waist of ~18 mm, located 3350 mm from Bay G launch window
- Beam waist 520 mm from Bay L receiver window

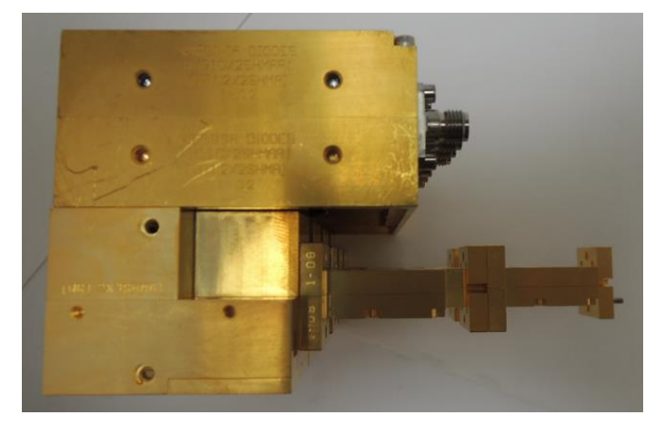


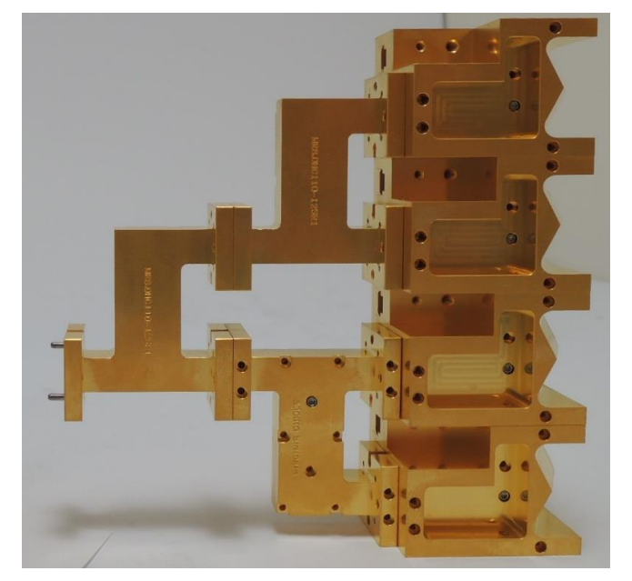
Launch Optics on Bay G: Top View

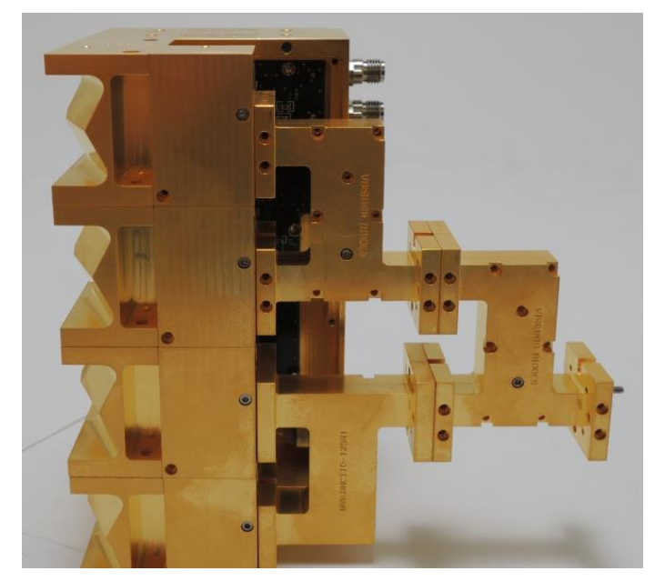


High-k Receiver Employs Dual VDI 4x1 Subharmonic Mixers

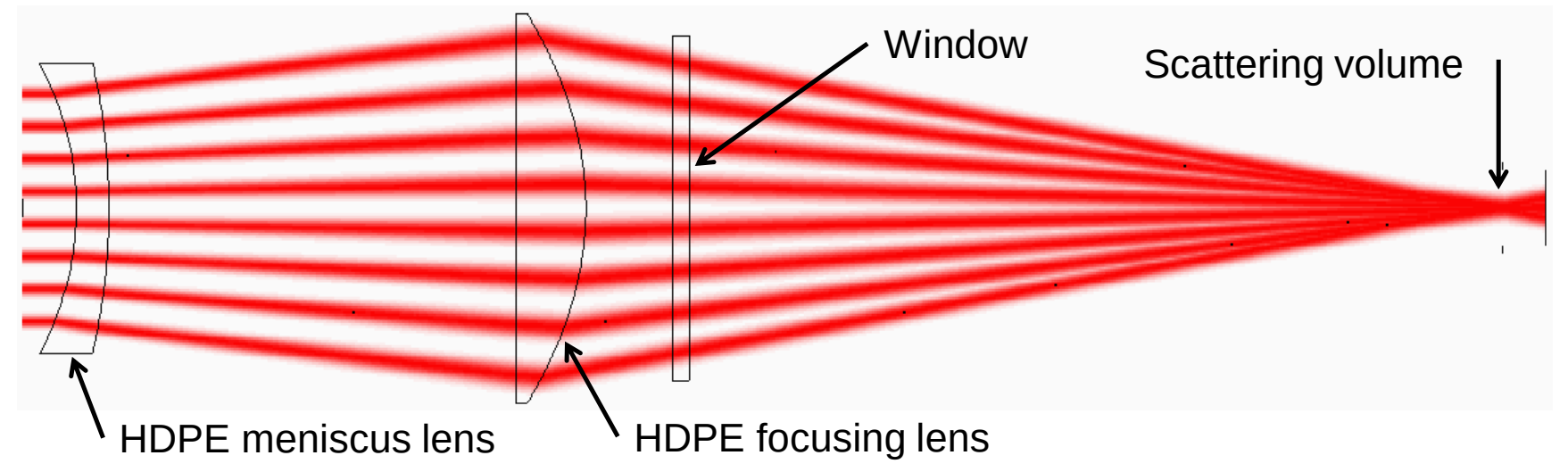
- 4x1 pixel arrays of 693 GHz subharmonic mixers
- Each array is pumped by a high power multiplier that delivers >600 mW at 115.5 GHz
- RF input to each pixel via diagonal horn, in front of which will be placed a small individually adjustable collimating lens
- First array to be delivered in April 2018, and the second array in early 2019

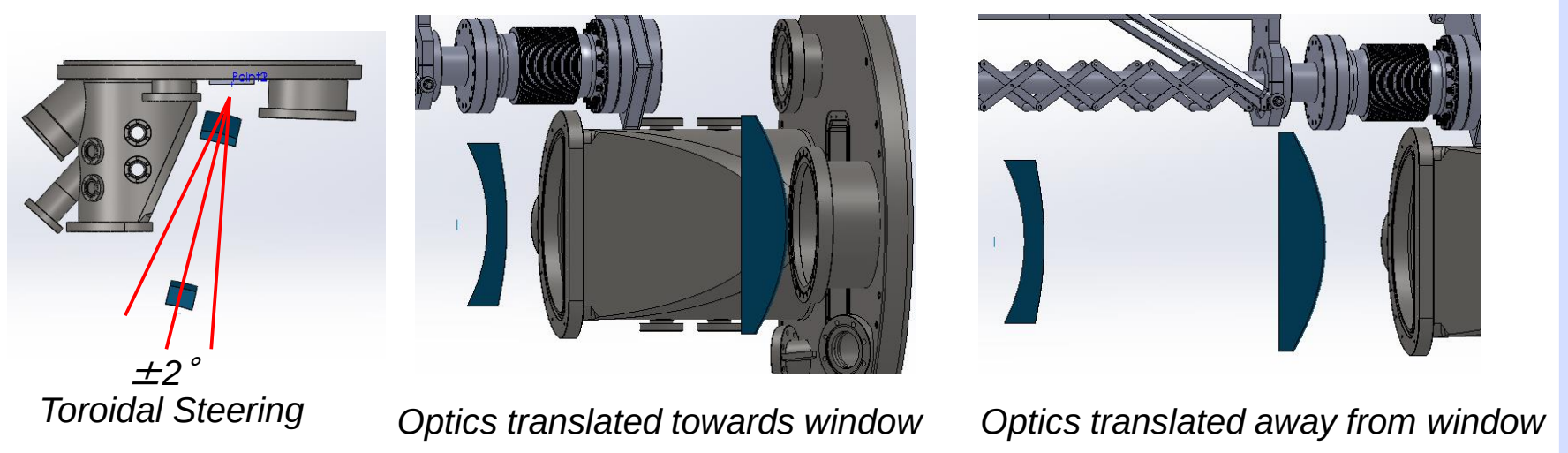






8-Channel Scattering System Optics Designed to Translate/Rotate as a Single Unit

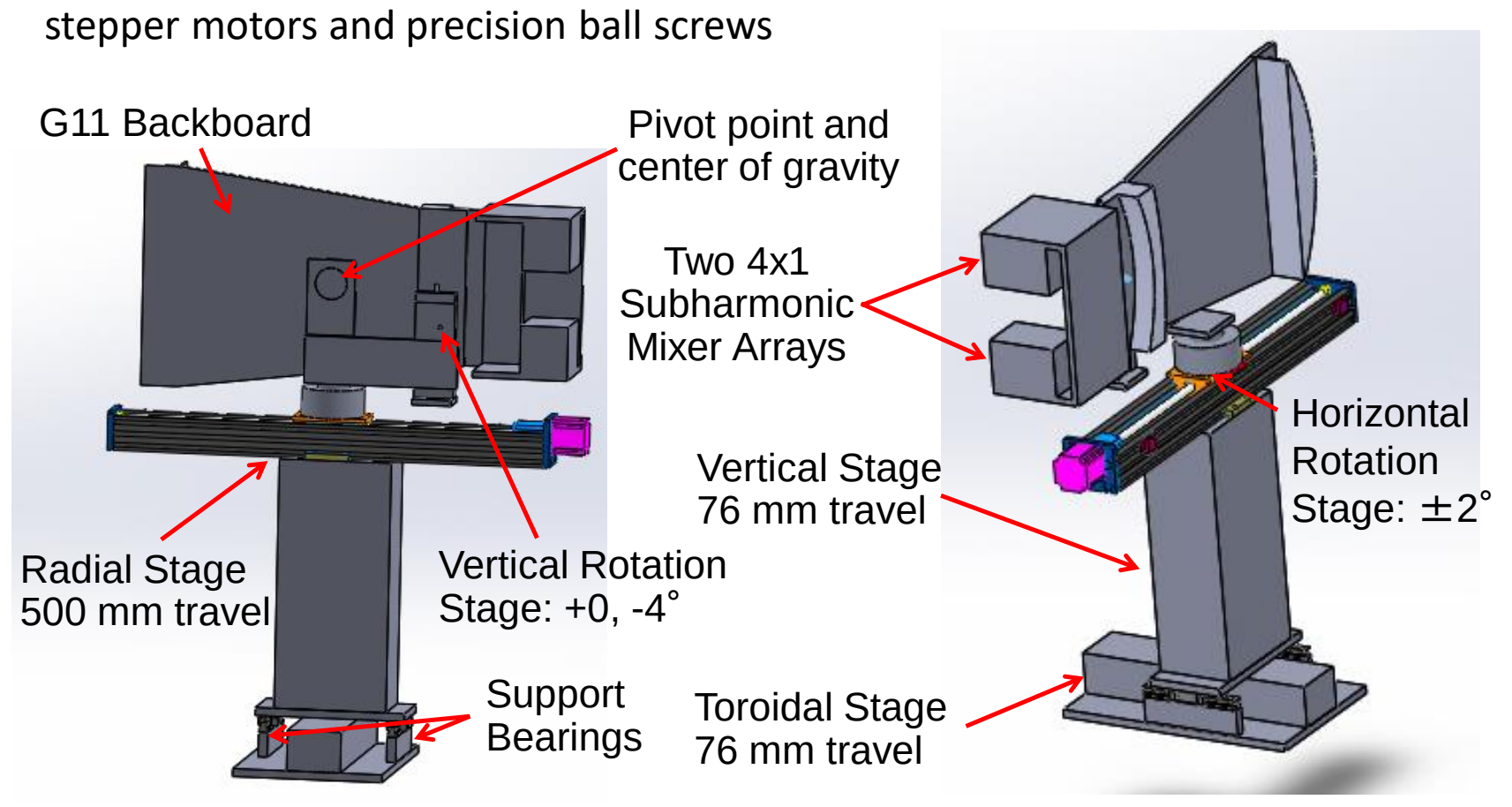




Toroidal Steering *Optics translated towards window* *Optics translated away from window*

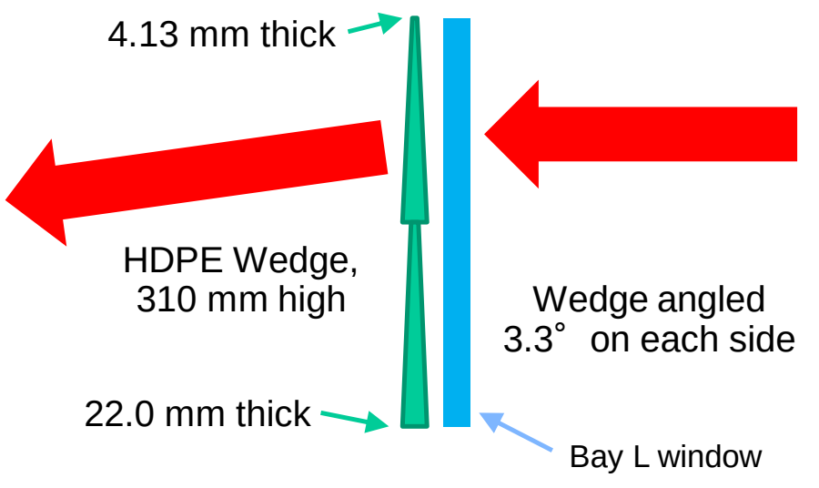
High-k Receiver Mounted on 5 Axis Receiver Carriage

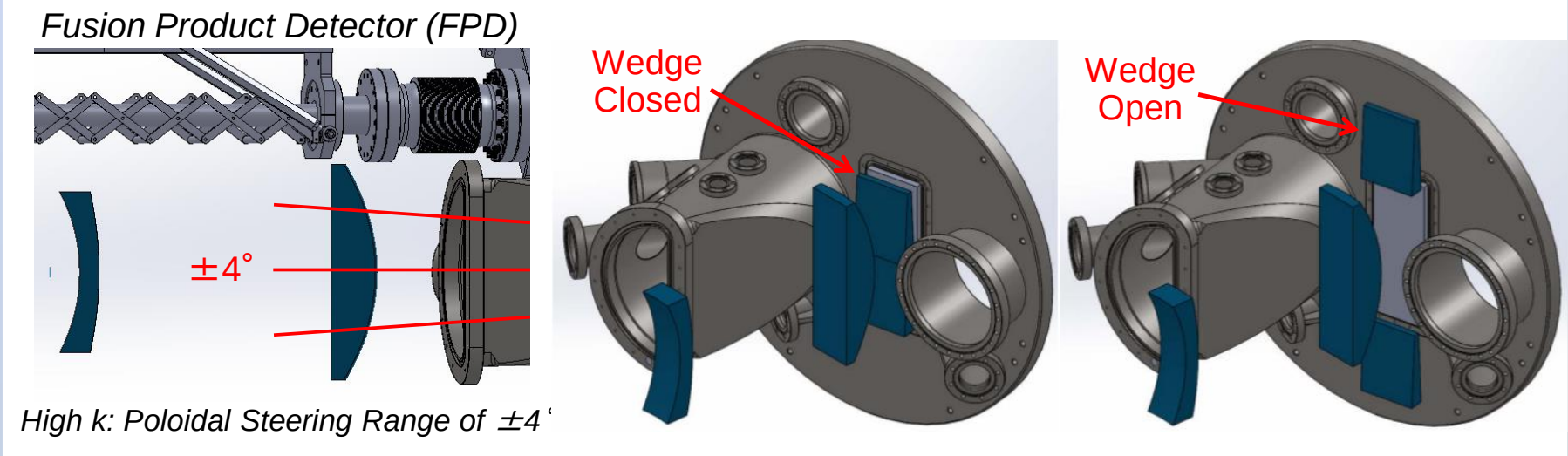
- Receiver optics and subharmonic mixer arrays translate as a single unit
- 5 Axis (linear: X, Y, Z; angular: poloidal, toroidal) control performed by stepper motors and precision ball screws



High-k Scattering Interference with FPD Eliminated by use of Dielectric Wedges

- Fusion Product Detector (FDP) is positioned above the High-k Scattering window
- Desired vertical steering of ±4.0° would place the receiver optics within the FPD when aimed downward (i.e. upwards scattering)
- A 2-part HDPE wedge is placed next to the Bay L window, which tilts the scattered beams by 4.0° when closed

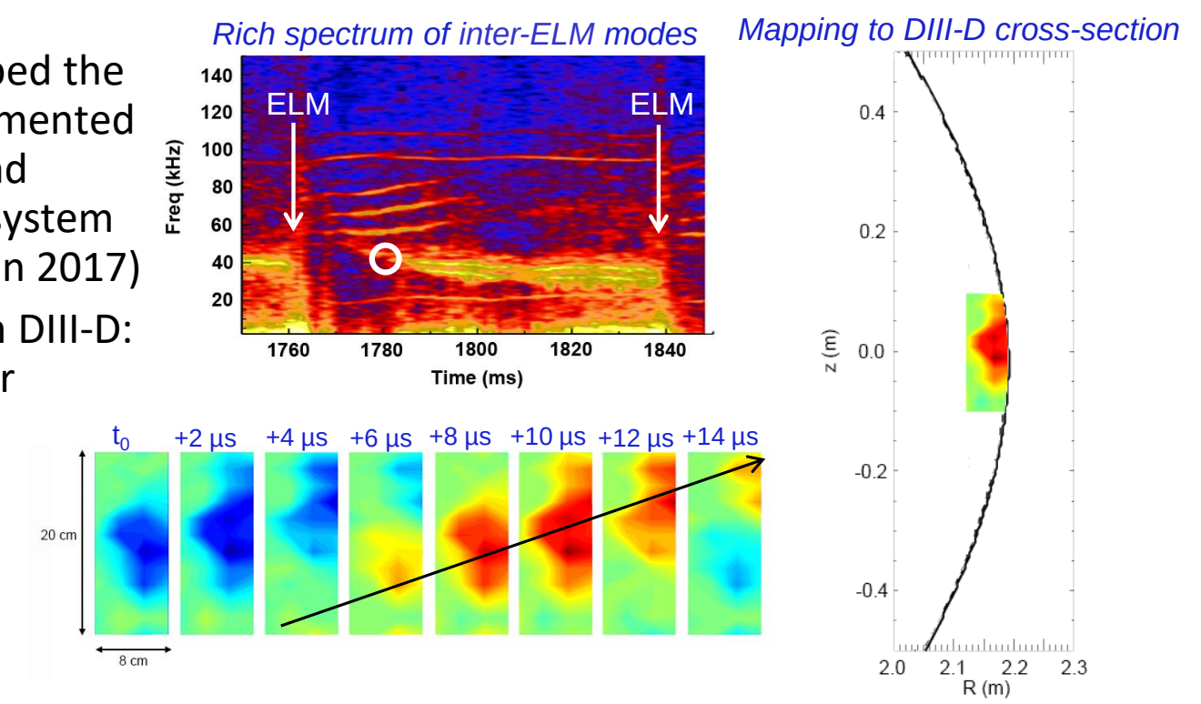




High k: Poloidal Steering Range of ±4°

Microwave Imaging Reflectometry (MIR) to Provide 2D Images of Density Fluctuations in NSTX-U

- **Objective**: 5 (poloidal) x 8 (radial) system to make **localized** measurements of low-k_θ (< 3 cm^{-1}) density fluctuations over a wide extent of the NSTX-U plasma
  - MIR to share same large-aperture window employed by the high-k_θ Thomson scattering system for simultaneous low- and high-k_θ measurements
- **Status**: Optics design underway; operable frequency band determined; preliminary electronics design
- **Experience:** developed the 12 x 4 system implemented on DIII-D in 2013, and developed a 12 x 8 system for EAST (delivered in 2017)
- **Right**: example from DIII-D: type-I ELM precursor


Rich spectrum of inter-ELM modes

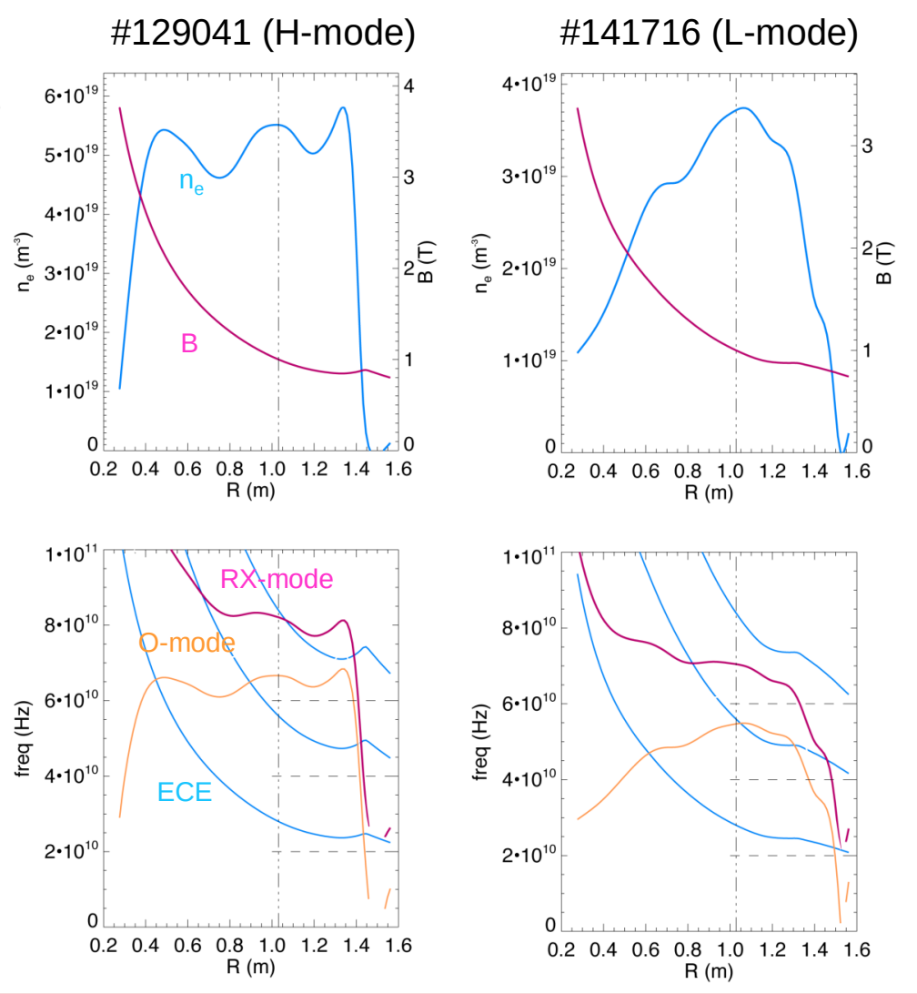
Mapping to DIII-D cross-section

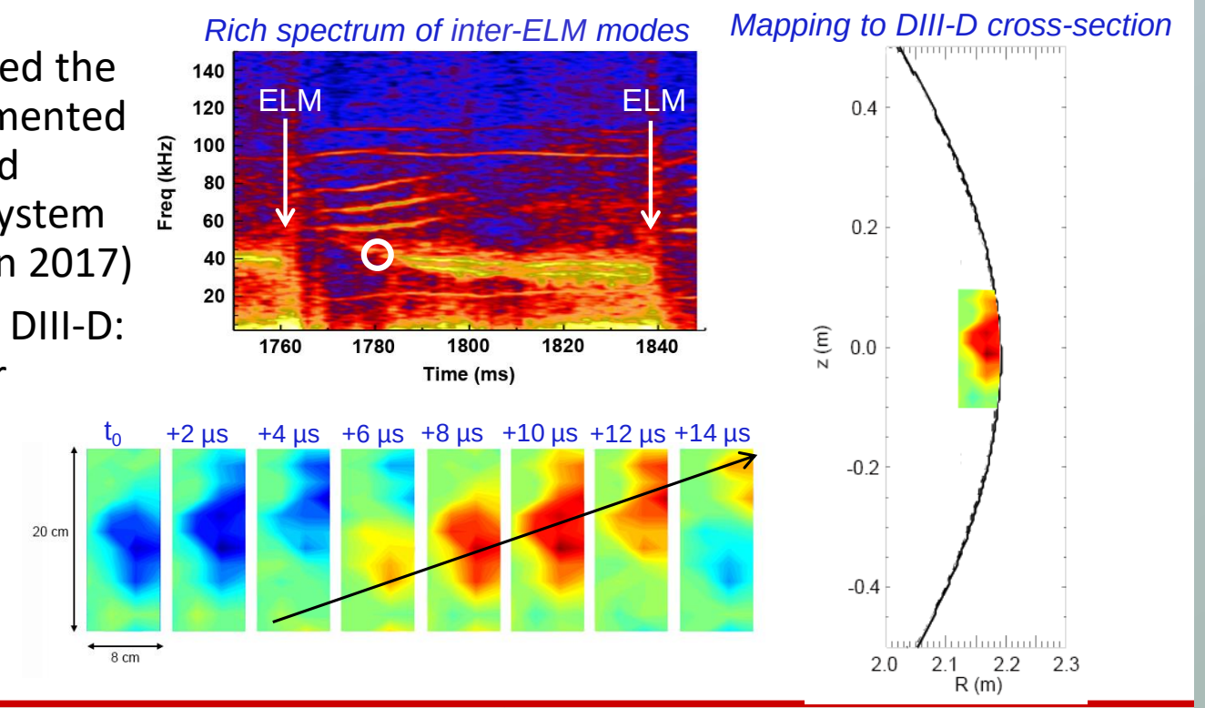
Time-lapse images show poloidal rotation of encircled 58 kHz mode

Microwave Imaging Reflectometry (MIR) on NSTX-U

Objective: 5 (poloidal) x 8 (radial) system to make localized measurements of low-k_θ (< 3 cm^{-1}) density fluctuations in NSTX-U plasmas

- Operating frequency band chosen to maximize radial coverage for variety of plasmas while considering effects of diffraction
- Density and magnetic field EFIT profiles used to representative H-mode and L-mode NSTX discharges
- Magnetic field scaled to be 1 T on axis (consistent with NSTX-U operation)
- Best option: X-mode, 50 – 75 GHz
  - Majority of H-mode pedestal
  - Central core of L-mode
- Accessibility with RX mode is inhibited by 3rd harmonic ECE





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4.13 mm thick
HDPE Wedge, 310 mm high
22.0 mm thick
Wedge angled 3.3° on each side
Bay L window
Fusion Product Detector (FPD)
±4°
Wedge Closed
Wedge Open

High k: Poloidal Steering Range of ±4°

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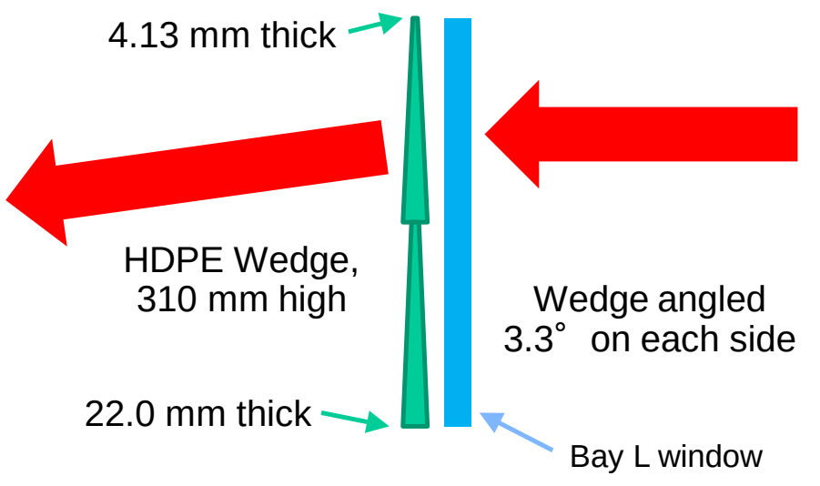

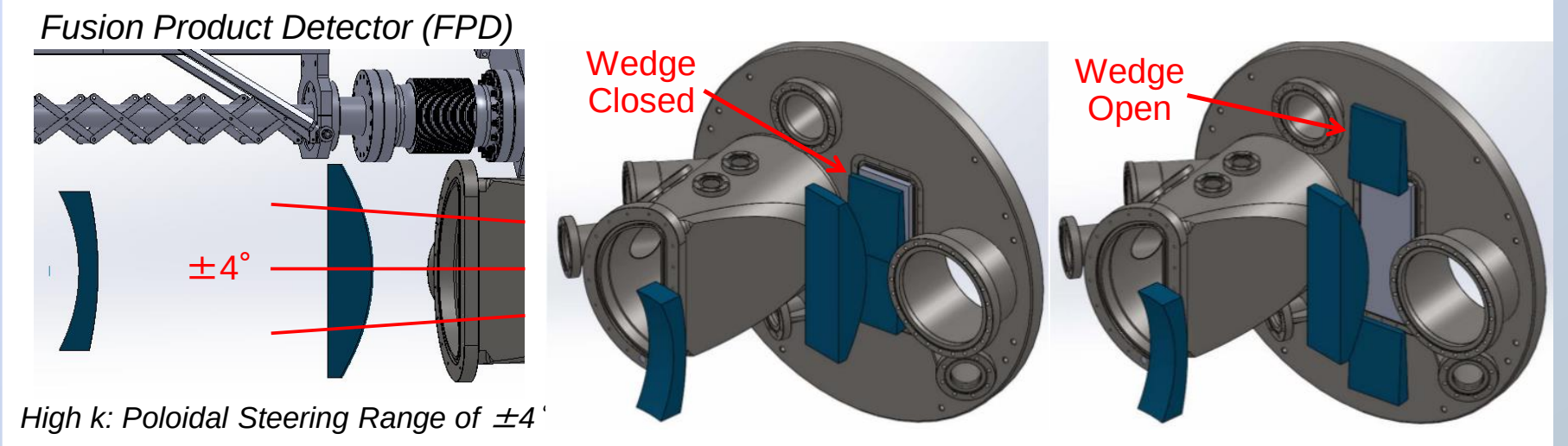

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Rich spectrum of inter-ELM modes

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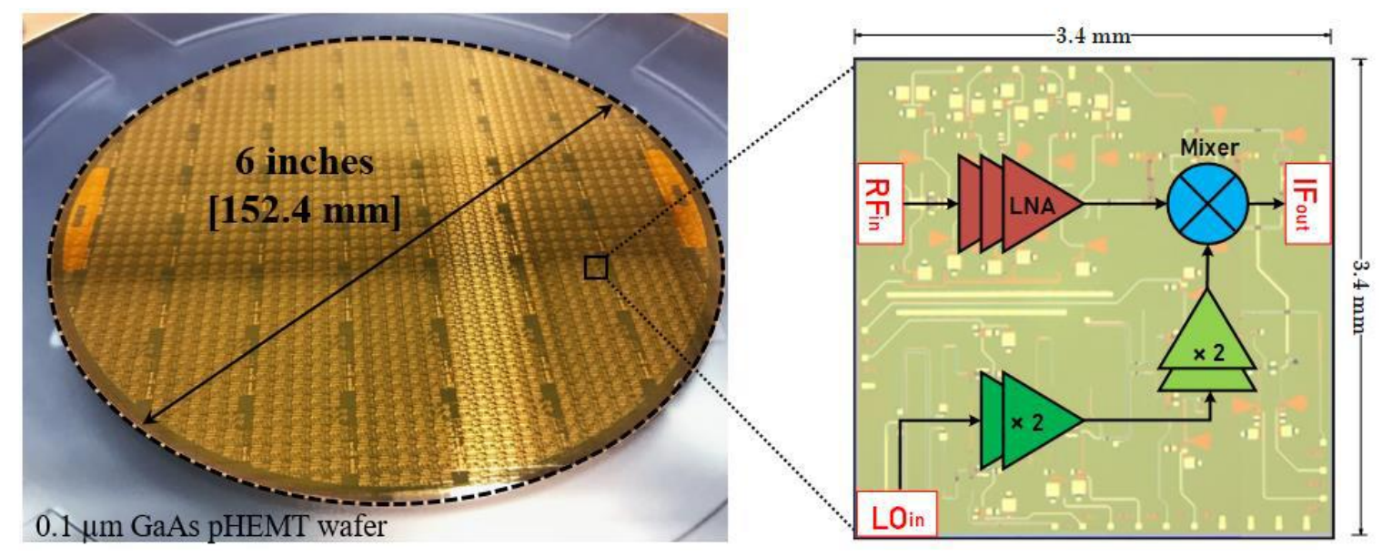
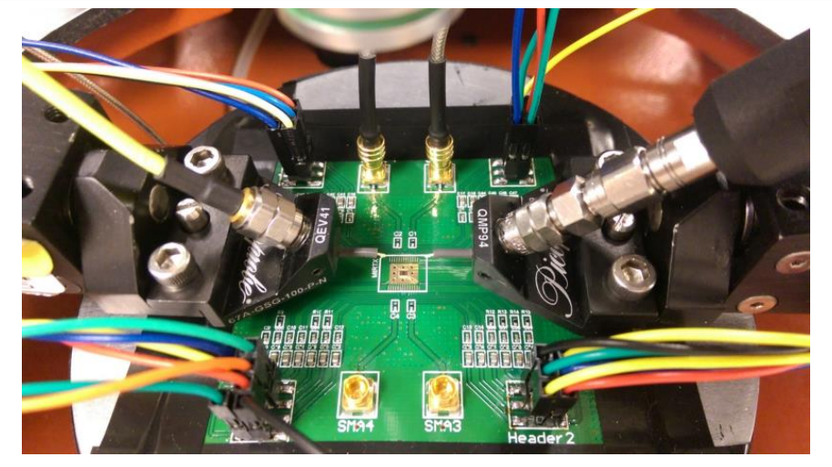
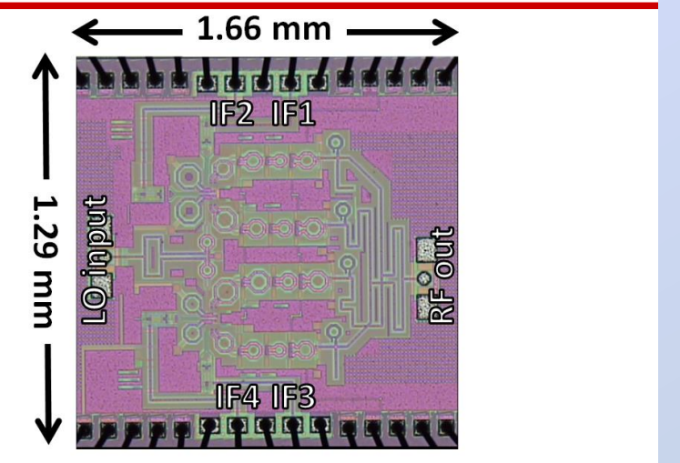
MIR Implementation on NSTX-U Using Next-Generation Diagnostic Technology

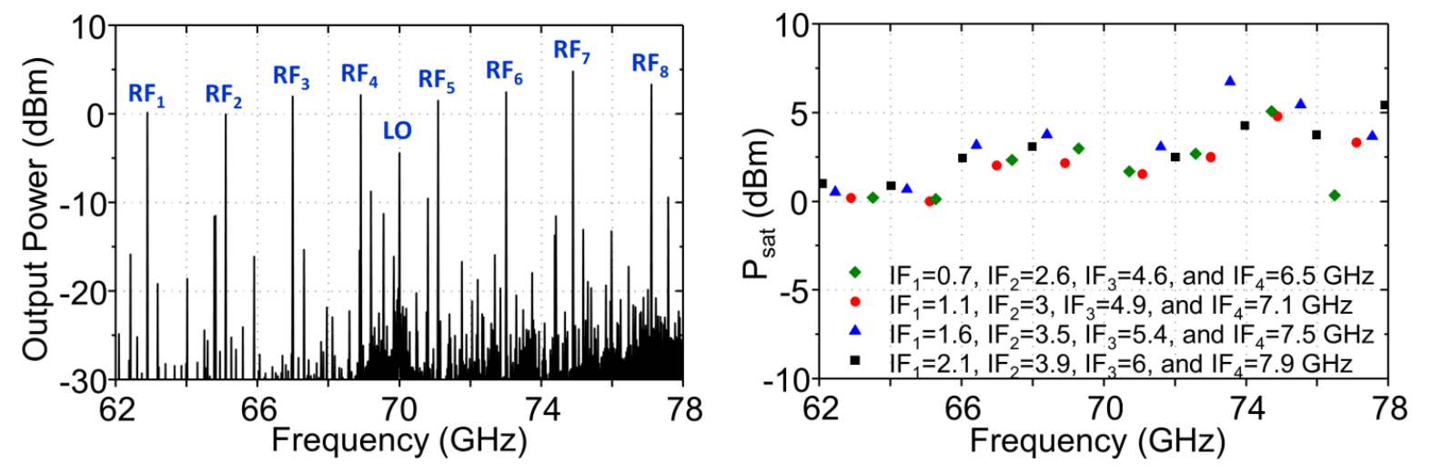
- An 8-frequency CMOS System on Chip (SoC) transmitter has been developed for use on DIII-D and testing in the laboratory. As the frequency range for MIR on NSTX-U is essentially the same as on DIII-D, this same technology can then be implemented on NSTX-U.
- New SoC receivers are also under development for use on DIII-D (see TP11.00153). These broadband receiver ICs provide high sensitivity through the use of on-chip mm-wave low noise amplifiers (LNAs). The built-in frequency multipliers that pump each mixer also eliminate the need for bulky local oscillator (LO) optics.



System on Chip (SoC) Developments for MIR: V-Band CMOS Multi-Frequency Transmitter

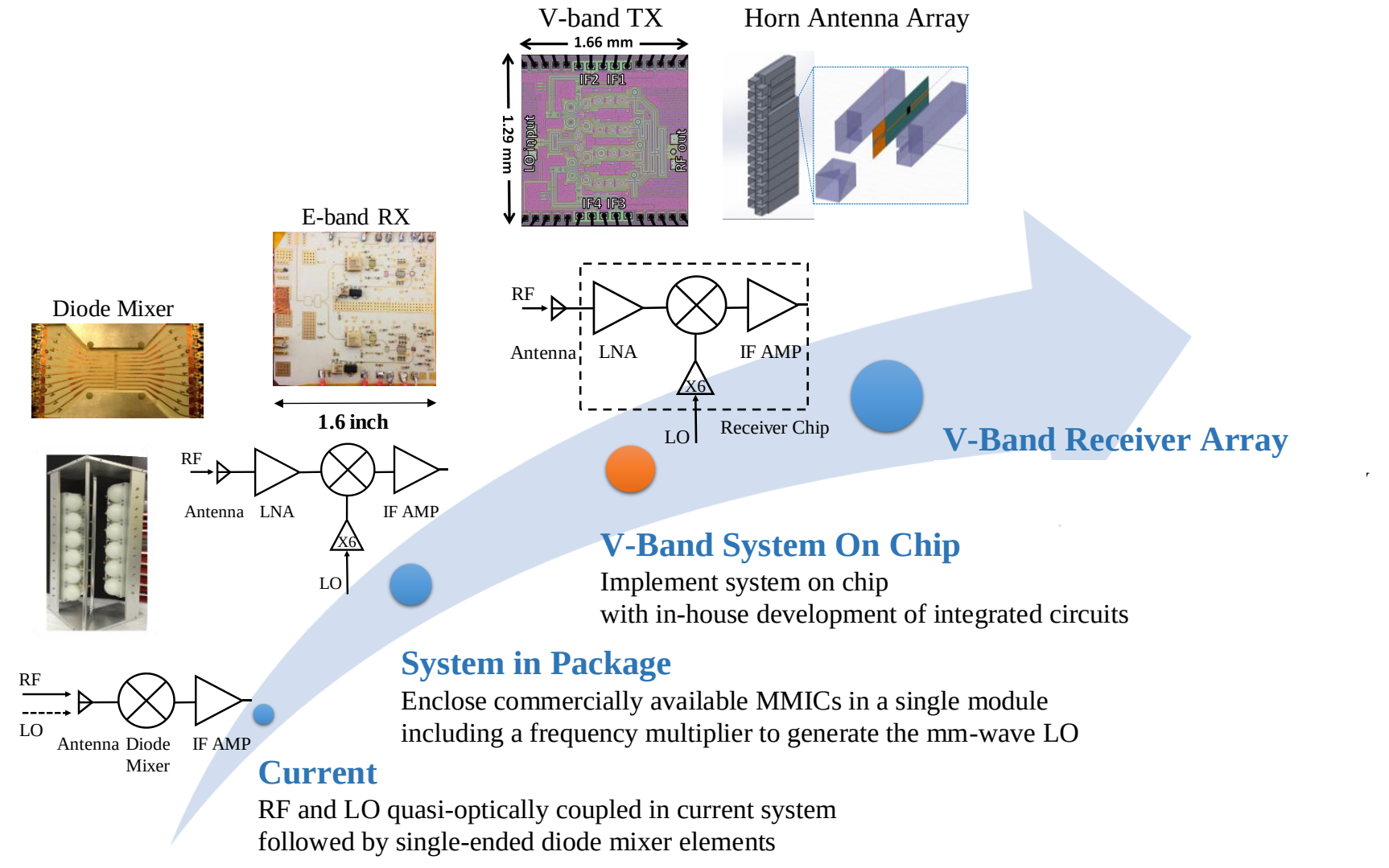






- The measured TX output spectrum.
- The measured TX P_{sat} versus frequency.

System on Chip (SoC) Developments for MIR: Receiver Roadmap



V-Band Receiver Array

V-Band System On Chip
Implement system on chip
with in-house development of integrated circuits

System in Package
Enclose commercially available MMICs in a single module
including a frequency multiplier to generate the mm-wave LO

Current
RF and LO quasi-optically coupled in current system
followed by single-ended diode mixer elements

MIR System to Co-exist with High-k Scattering on Bay L: Share Large Aperture Window

- The High-k Scattering system will be centered on the left-side of the Bay L window, allowing the MIR system to utilize the right-side of the window
- High-k Scattering optics, which are tilted 11.8° to 15.8° toroidally, are pulled back slightly from the window to increase the space available to MIR
- MIR system to operate only with High-k Scattering wedge retracted from port (MIR beams are partially obstructed when the wedge is in place)
- MIR optics to lie parallel to the Thomson Scattering beam dump, i.e. tilted toroidally at -2° with respect to the Bay L window
- Back side of the plasma-facing MIR focuser lens is wedged such that the MIR beams are tilted 5.2° with respect to the MIR optics, correcting for the 2° MIR optics alignment plus another 3.2° needed to orient the MIR beams normal to the plasma