FIR and mm-Wave Density Monitoring, Feedback Control and Fluctuation Diagnostics for NSTX-U

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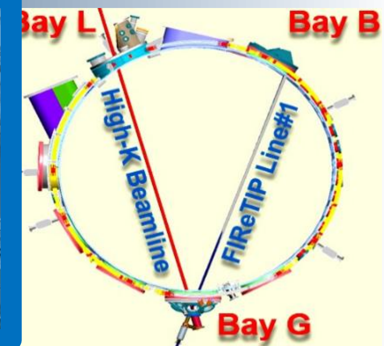


Friday, May 27th, 2016

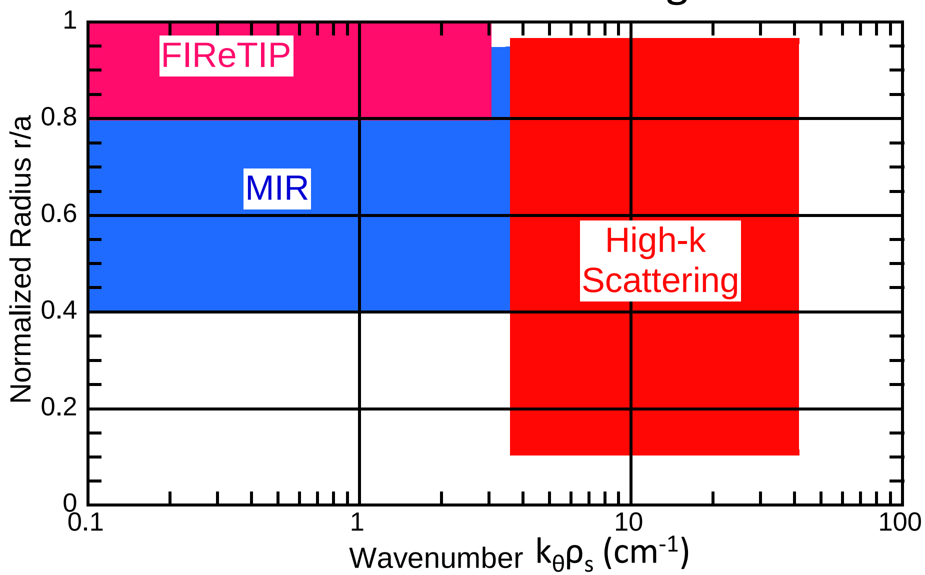
PPPL

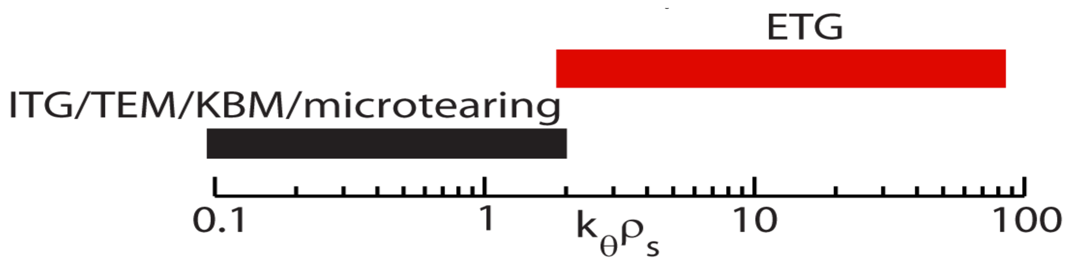
D.M.R.C
Davis MM-Wave Research Center

UCD NSTX-U Microwave Diagnostics

- Three diagnostics for complete coverage of transport physics
    - FIReTIP, low-k turbulence from edge channels
    - High-k Scattering, high-k turbulence from core to edge
    - MIR, MHD activities and low-k turbulence (L-mode core and H-mode pedestal)

Turbulence Coverage

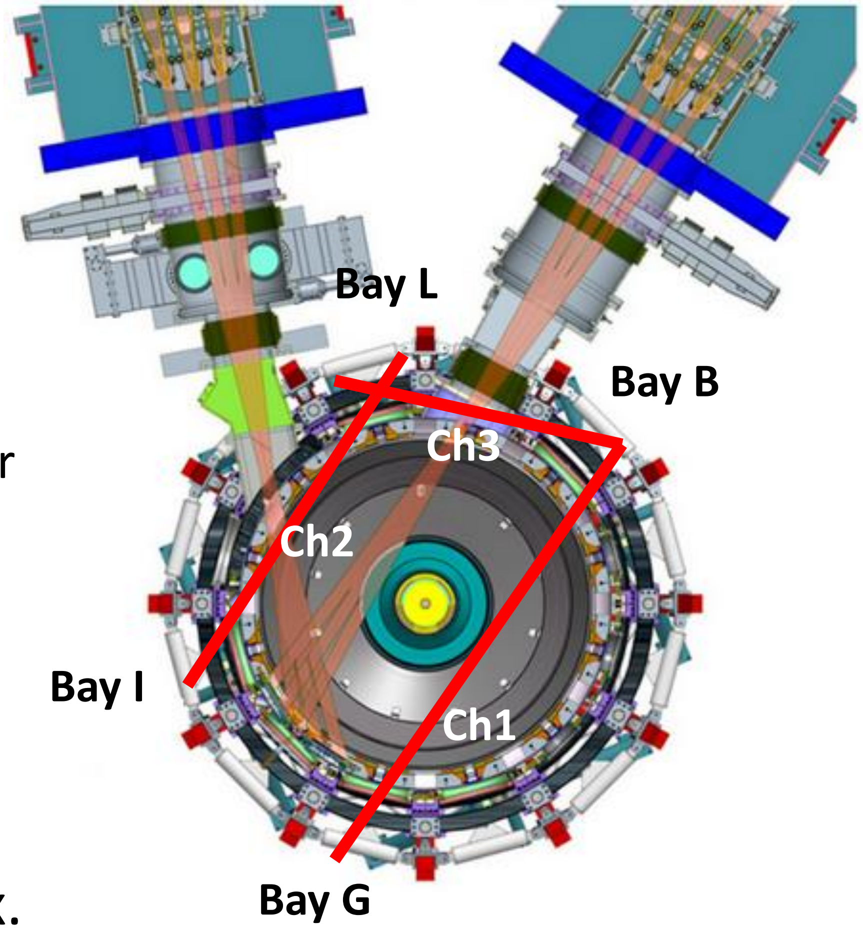




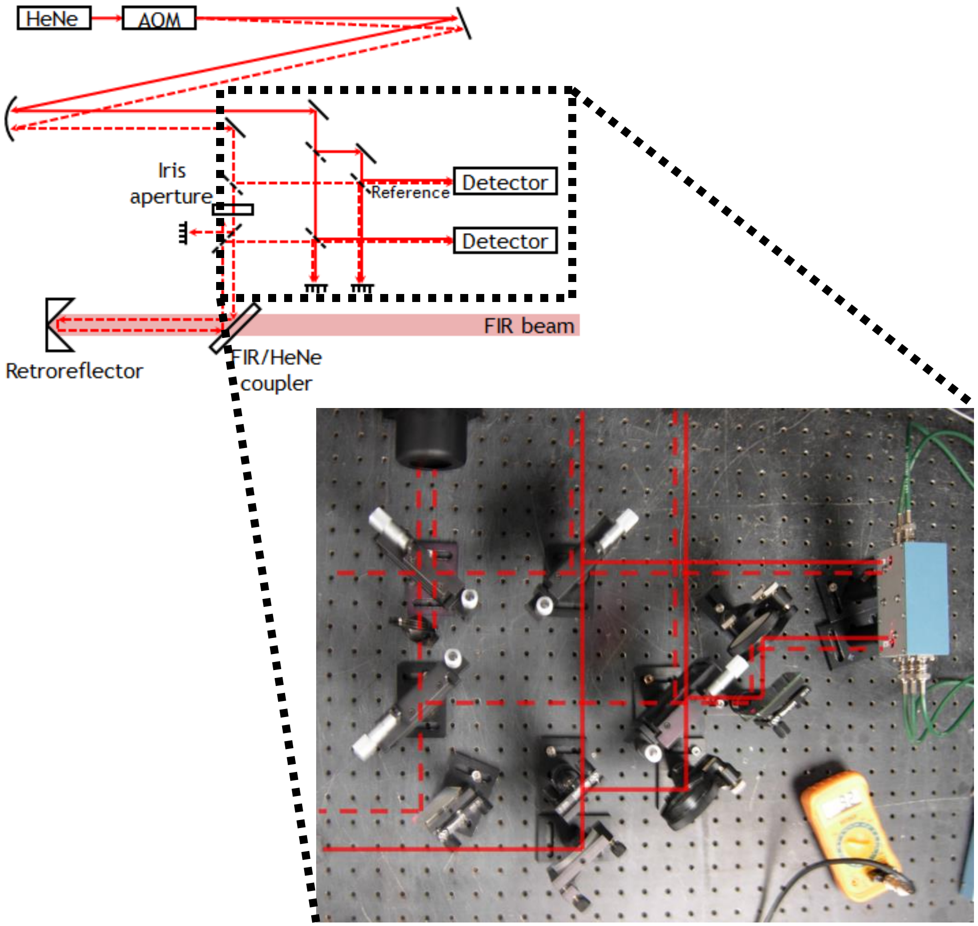
These diagnostics form a complimentary triad for transport physics. Density fluctuation measurements in a broad wavenumber range are possible.

Far InfraRed Tangential Interferometer/Polarimeter

- Line-averaged double-pass core electron density for real-time feedback control in the NSTX-U PCS
- Two-color system
  - 118.8 μm methanol lasers
  - 632.8 nm HeNe laser interferometer
- Initial installation will provide core density feedback on Ch. 1.
  - Ch1, Core density
  - Ch2, Core density fluctuation
  - Ch3, Edge density fluctuation
- High temporal resolution (approx. 5 MHz) possible due to Stark-effect tuned methanol laser



FIReTIP System Goals

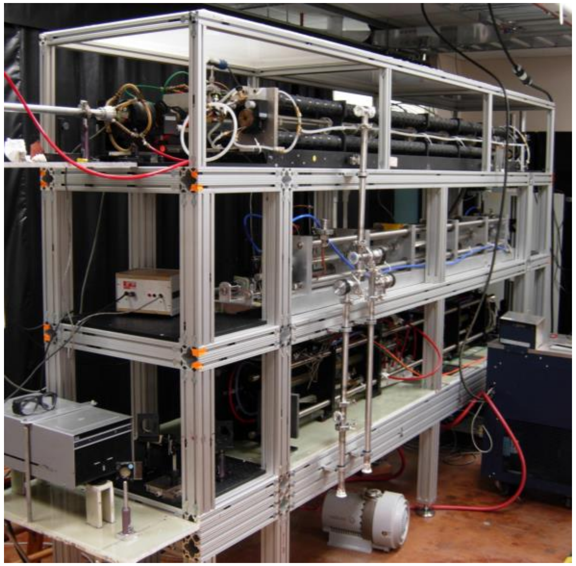


Coaxial heterodyne HeNe laser interferometer will measure mechanical vibrations for real-time phase corrections in FIReTIP (above)

- Provide FIReTIP density feedback capability by the end of the 2015-2016 run period (Ch. 1)
- Real-time hardware/software implemented by run period beginning February 2017
- FIReTIP polarimeter functionality included 2017 (Ch. 1)
- Ch. 2 and 3 added for core and edge density fluctuations 2018

FIReTIP System Status

- FIReTIP laser table & lasers
  - 3 level table houses FIReTIP and High-k lasers in mezzanine area
  - FIReTIP lasers ready & in transit to PPPL (High-k lasers to be shipped at a later date)



- Waveguide
  - PTFE, overmoded, waveguide
  - Approximately -0.15 dB/m
  - Installation pending IP approval

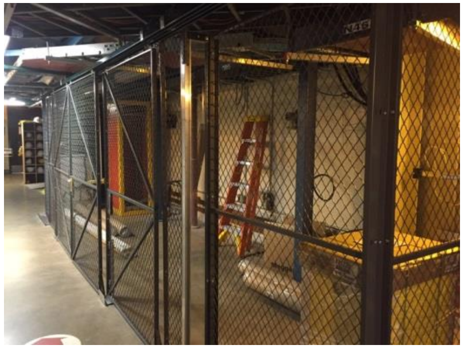
- Front-end optics
  - FIR and HeNe optics, Ch. 1
  - In transit to PPPL

FIReTIP System Status

- Mixer table inside NSTX-U Test Cell
  - 3 level table
    - Top, HeNe system
    - Mid, Ch. 2 & 3 mixers
    - Lower, Ch. 1 and reference mixers
  - Ready & in transit to PPPL

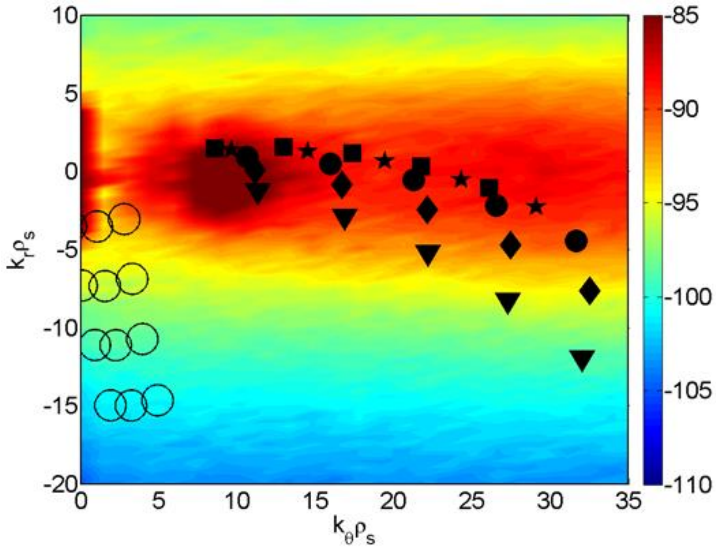
- Electronics
  - PS and battery bank being fabricated
  - All other system electronics completed (FPGA, fringe counter, etc)

- Laser cage outside NSTX-U Test Cell
  - Expansion complete
  - Installation of laser curtains & utilities pending



High-k Scattering Physics

Simulation of ETG mode turbulence
Peak ETG mode predicted to be near
$k_\theta \rho_s \sim 10$, $k_r \rho_s \sim 0$



Black symbols denote 693 GHz poloidal High-k Scattering coverage. Open circles show the limitation of the previous 280 GHz high-k_r scattering system.

$$P_s = \frac{1}{4} r_0^2 |\tilde{n}_e|^2 \lambda_i^2 L^2 P_i$$

Scattered power is proportional to density fluctuation power. The Scattering angle determines the fluctuation wavenumber and the fluctuation frequency through the frequency shift.

- EM waves scatter from density fluctuations
  - Energy and momentum conserved

$$\vec{k}_s = \vec{k}_i + \vec{k} \quad \text{and} \quad \omega_s = \omega_i \pm \omega$$

  - High frequency probe beam

$$\omega_i >> \omega \rightarrow k_i = k_s$$

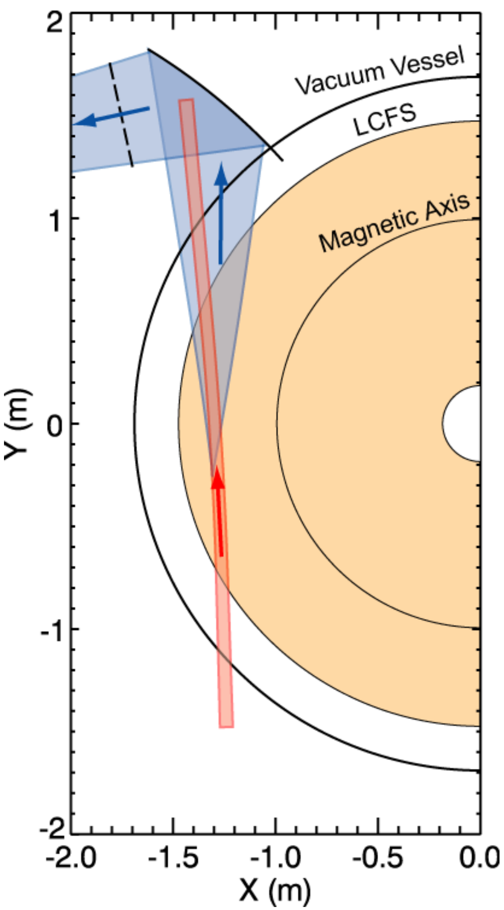
  - Bragg condition

$$k = 2k_i \sin\left(\frac{\theta}{2}\right)$$

  - Need multiple detection channels to construct k-spectrum

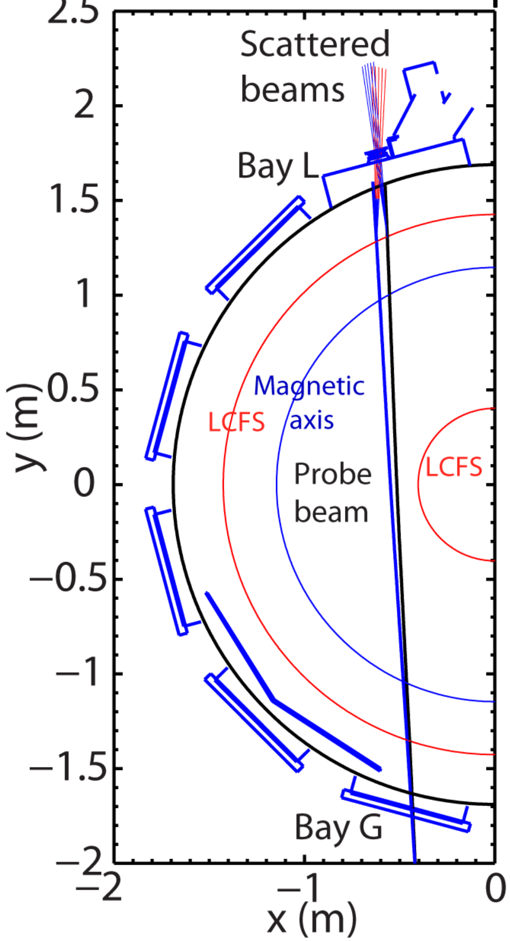
High-k Scattering Systems
NSTX (280 GHz k_r) and NSTX-U (693 GHz k_θ)

- 280 GHz k_r Scattering

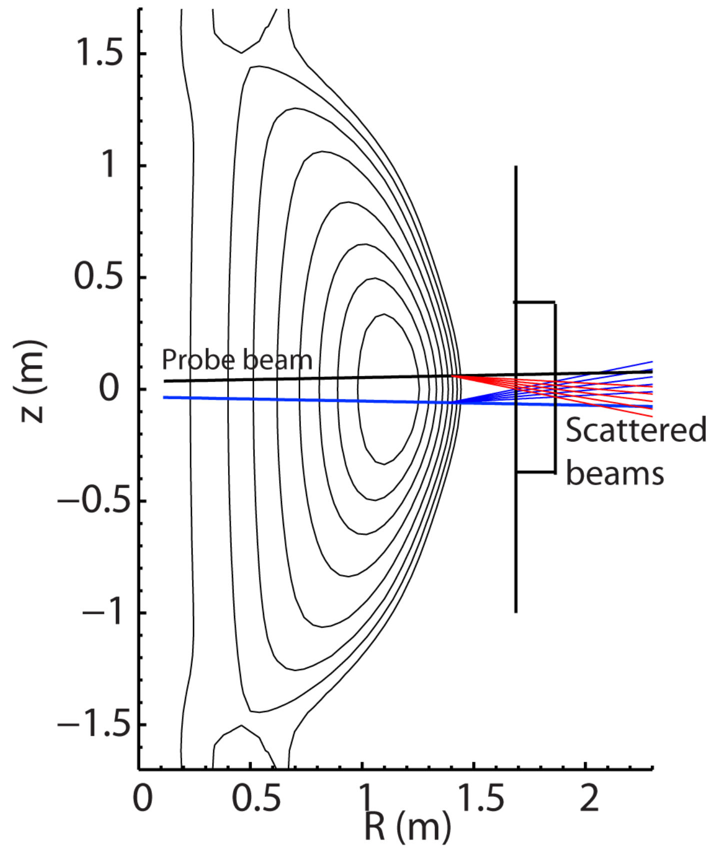


Top View

- 693 GHz k_θ Scattering
- Increased perpendicular wave number coverage from 7 cm^{-1} up to ~40 cm^{-1}



Top View



Side View

NSTX-U High-k Scattering System

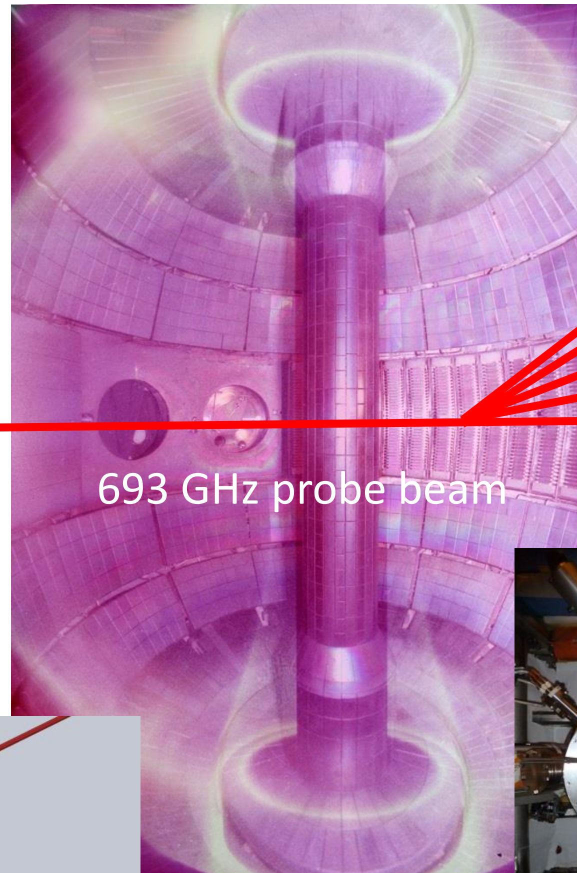
FIR Laser System

- 180 W CO_2 pump laser
- 100 mW FIR formic acid laser

20 m Corrugated Waveguide

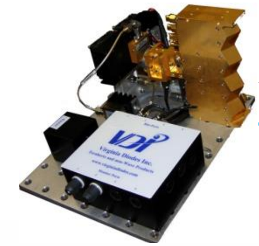
Bay G launch optics

NSTX



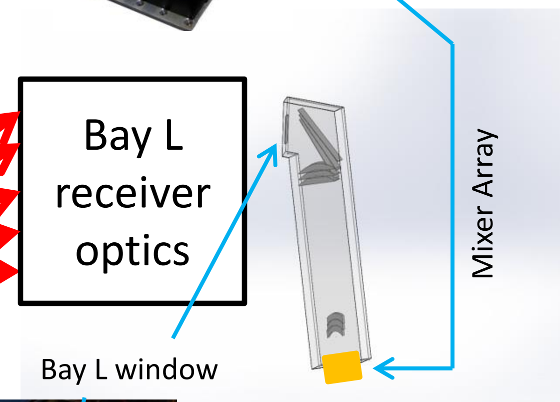
Bay L receiver optics

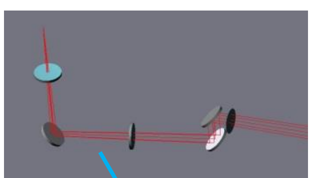
693 GHz subharmonic 4-pixel receiver array

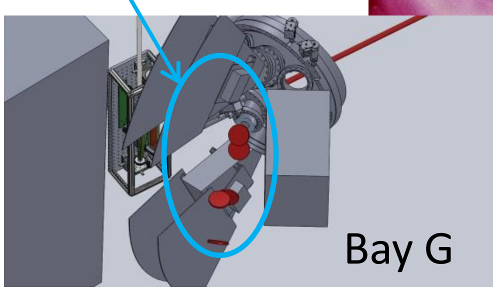


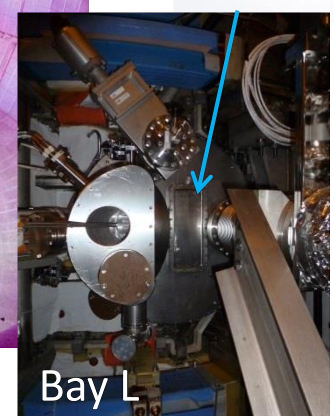
x48

14 GHz LO









Launch Optics

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

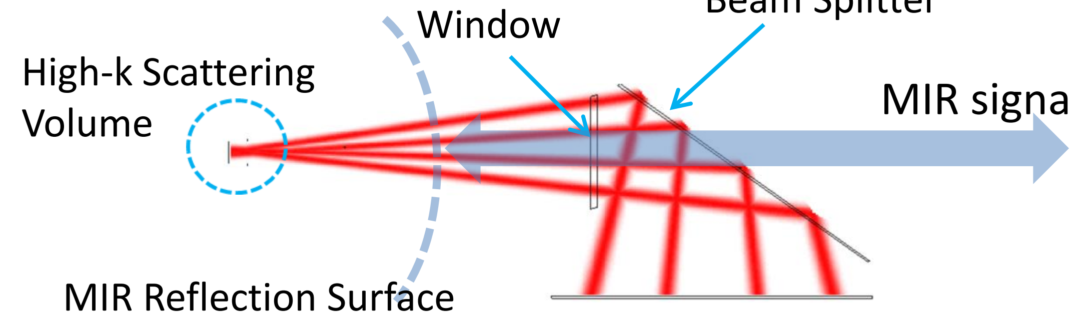
Receiver optics

- Remotely steerable elements
- Scattering angles 2˚ to 15˚
- Bay L 33 cm tall window permits k_θ detection

Continuing High-k Development

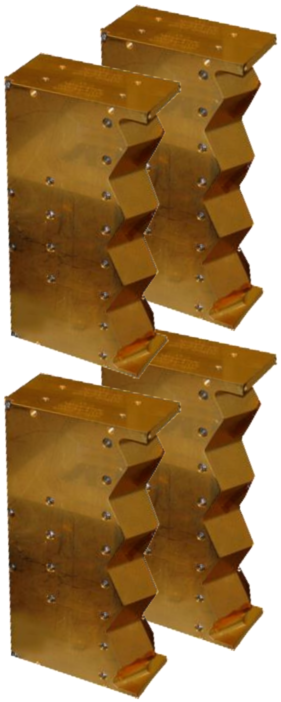
Modular 4 x 1 mixer array is expandable to 8 x 1, and then 8 x 2 pixels.

Microwave Imaging Reflectometry

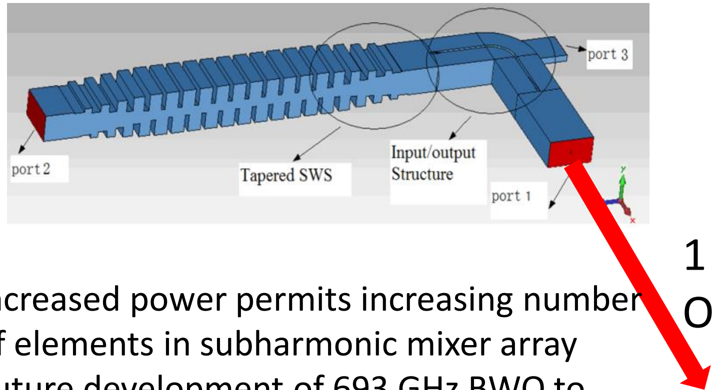


- Replace main reflector with beam splitter
- Reflection at 693 GHz and transmission at 40-80 GHz allows simultaneous High-k and MIR operation

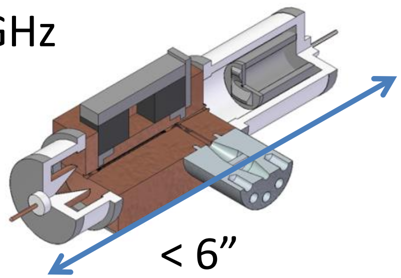
8 x 2 Mixer Array



346 GHz Backward Wave Oscillator



- Increased power permits increasing number of elements in subharmonic mixer array
- Future development of 693 GHz BWO to replace FIR laser system

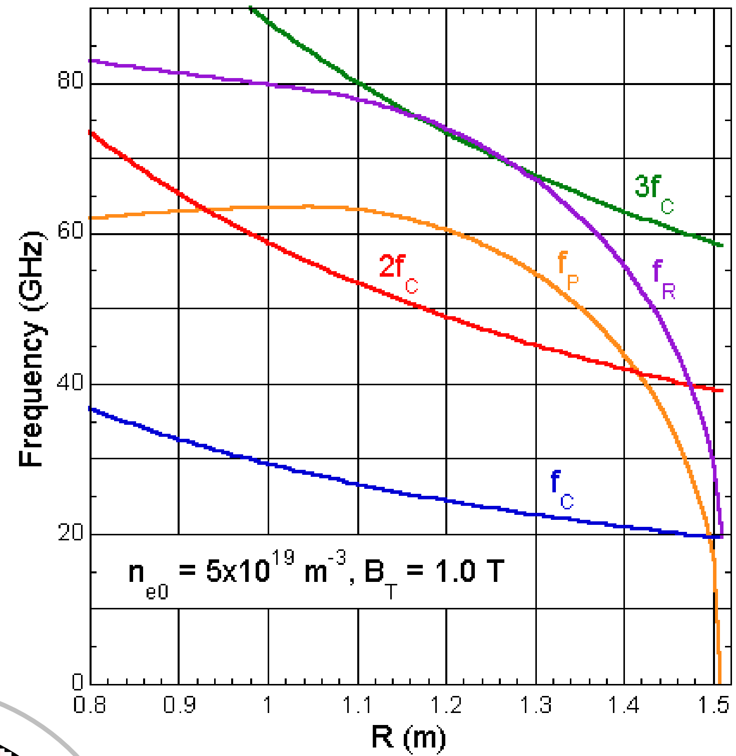


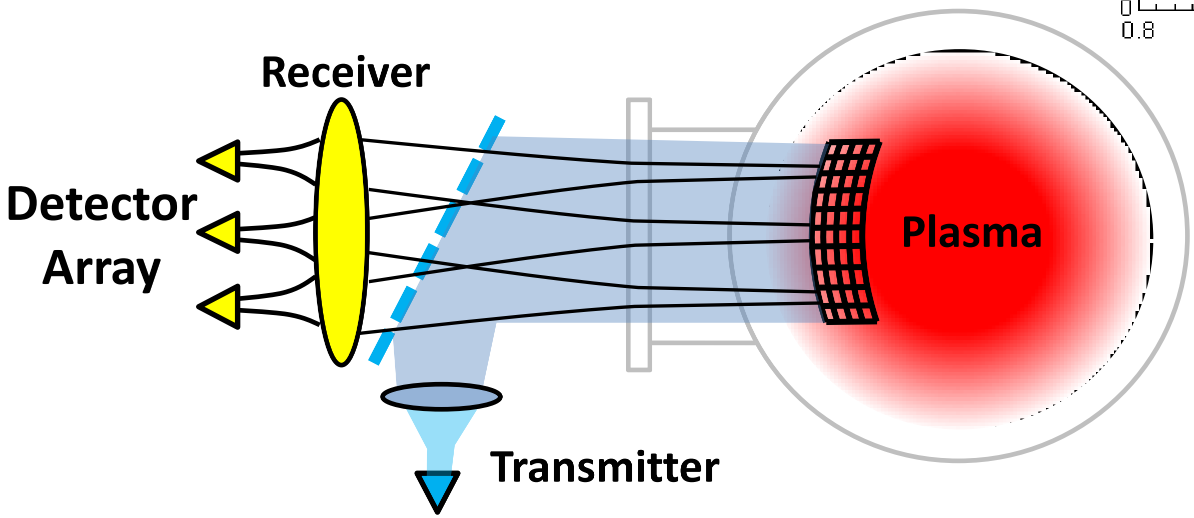
High-k Installation and Operation

- 2016
  - Completion and lab testing of scattering system at UC Davis
  - Installation and calibration at PPPL
- 2017-2019
  - Commissioning and research data 2017
  - Continuing development
    - Additional receiver elements
    - 346 GHz BWO
    - Inclusion of MIR system with High-k receiving window

Microwave Imaging Reflectometry

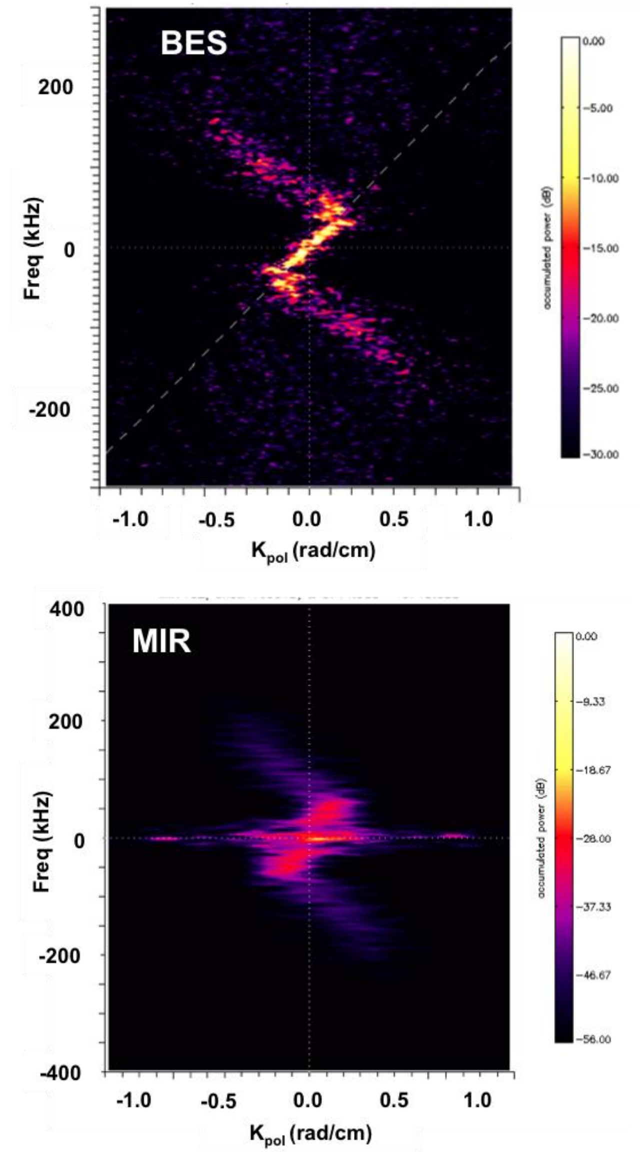
- Higher B_T operation (0.5 T → 1.0 T) allows broader X-mode accessibility
- Scattering window at Bay L has a large clear aperture (34 cm x 12.7 cm) able to accommodate imaging optics
- Co-locate with high-k system port
- MIR not dependent on NBI





MIR measures the spectrum and propagation of ITG-scale density fluctuations on DIII-D

- **2D, localized measurement provides both frequency and poloidal wavenumber**
  - turbulence propagation and dispersion relations
- **Vertical resolution and sensitivity are similar to BES**
  - benchmarked measurement capability
- **Radial resolution in the pedestal is much better than BES**
  - potential to resolve ExB shear profiles and zonal flow evolution

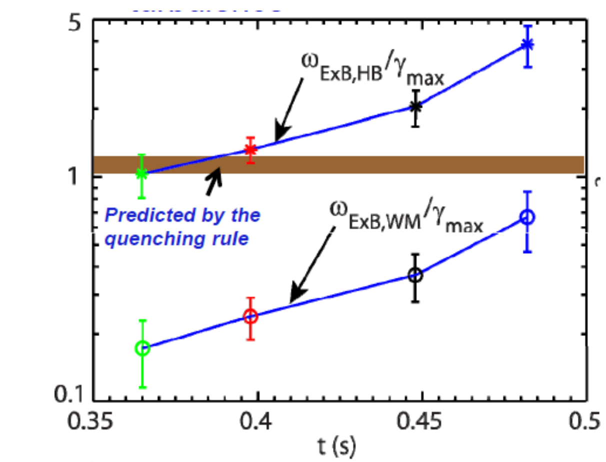


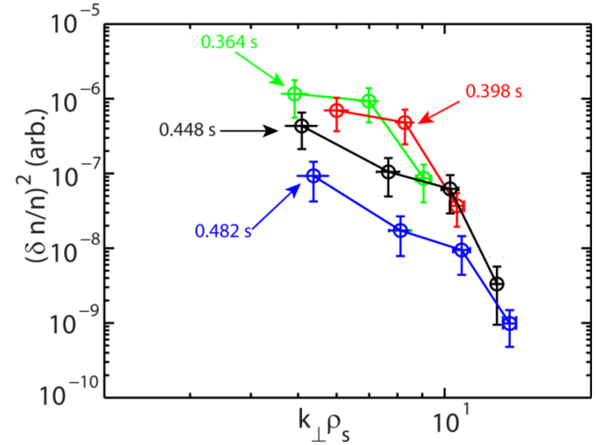
MIR would support multiple NSTX-U research thrusts

- **Thrust TT-2:** Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U
  - Provide core turbulence measurement in L-mode plasmas
- **Thrust BP-1:** Characterize, control, and optimize the H-mode pedestal performance, transport, and stability
  - Measure turbulence change across L-H transition
  - Measure turbulence and MHD activities responsible for transport and stability in pedestal
- **Thrust MS-3:** Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas
  - Measure disruption dynamics and precursor

MIR for NSTX-U core transport studies

- Continuous ExB Shear ramping-up is observed to reduce high-k turbulence in NSTX L-mode plasmas
- Low-k and high-k coupling is important for explaining experiment
- MIR measurement of low-k turbulence could provide such vital information

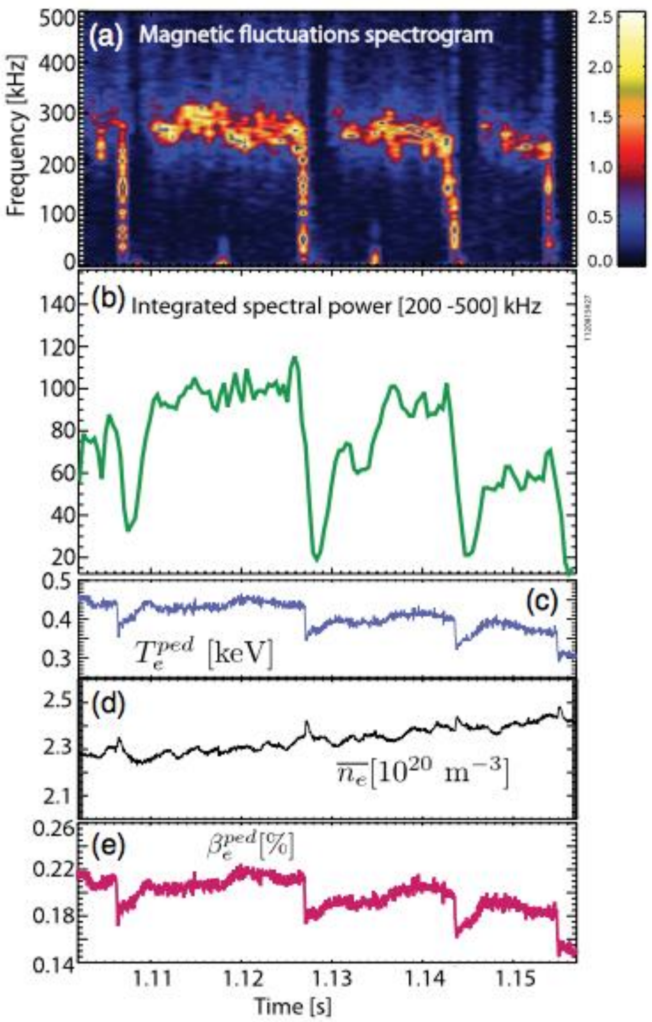




Ren et al., NF 2013

MIR for NSTX-U edge pedestal studies

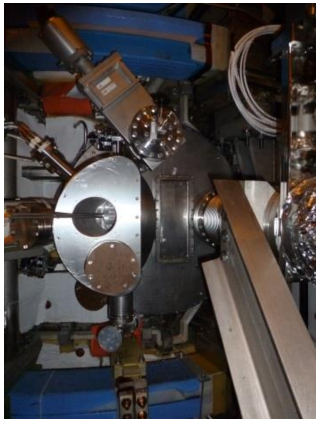
- **L-H transition physics**
  - Zonal flows, density fluctuation level when combined with synthetic diagnostics
  - BES, GPI and MIR in the pedestal will complement each other to give a better turbulence characterization across the L-H transition
- **Characterizations of the inter-ELM fluctuations/instabilities limiting the pedestal**
  - See Diallo PRL 2014 (C-Mod), PoP2015(DIII-D)
  - Determine the poloidal and radial extents of edge fluctuations
- **Onset of ELMs**
  - fast and 2D imaging of density fluctuations can potentially provide an enhanced picture of the ELM onset



Diallo et al., PRL 2014

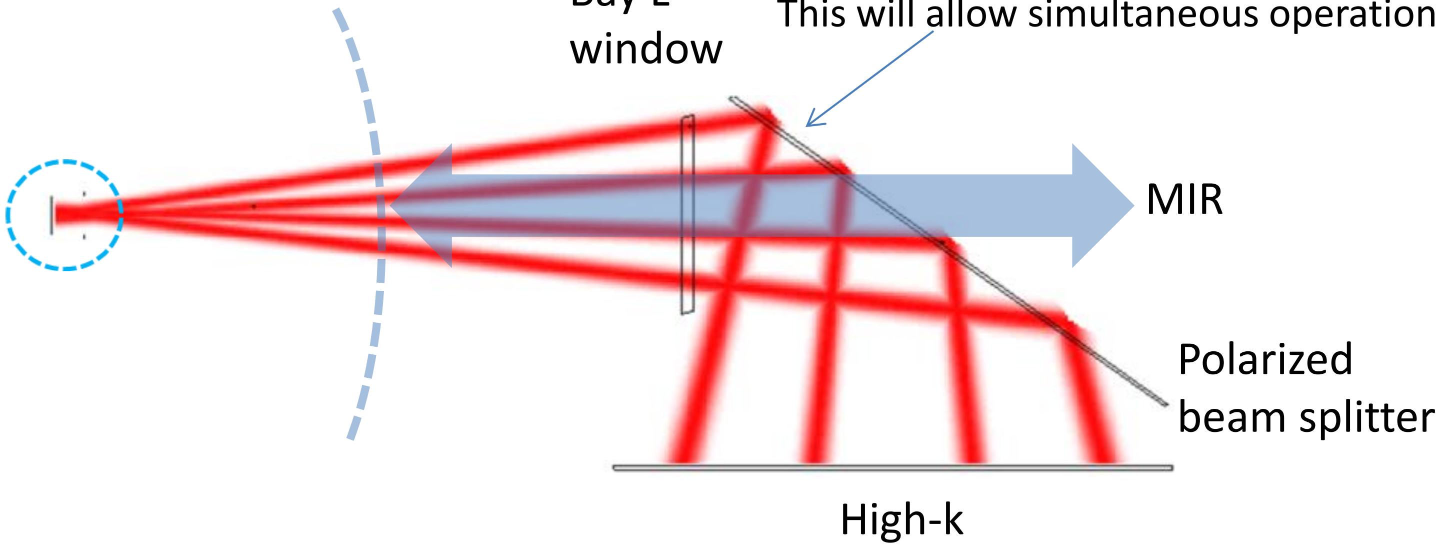
Microwave Imaging Reflectometry Status

- Design of transmit/receive optics for port sharing with High-k Scattering
- Large window at bay L is ideal for MIR inclusion
- System can be expedited by borrowing MIR system from DIII-D. Only the bay L optics need to be fabricated.



Large beam size for MIR signals works well with the high-k receiver window. Both instruments can operate here, although MIR is not committed to bay L.

High-k Scattering and MIR signals are cross polarized, allowing a polarizer to reflect High-k while passing MIR signals. This will allow simultaneous operation.



Current Fund Limited MIR Development Schedule

- Spread over 3-years due to DoE restrictions on maximum amount that could be spent in any one fiscal year and requires borrowing of DIII-D MIR system during maintenance periods

- DIII-D and EAST MIR development experience provides confidence in our ability to develop an independent NSTX-U MIR system by early 2017 with additional funding of □$ 200 k

Table 3. MIR Development Plan

Tasks	Year 1				Year 2				Year 3				Responsible Parties
	1	2	3	4	1	2	3	4	1	2	3	4	
Design MIR optics													UCD
Fabricate MIR optics													UCD
Fabricate MIR array box													UCD
Characterize MIR optics													UCD
Fabricate FIReTIP framework													UCD
Install MIR optics on Bay L													UCD/PPPL
Proof-of-principle operation of MIR													UCD
Purchase/Fabricate MIR electronics													UCD/PPPL

Thank You for Your Attention