NSTX

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Investigation of NTM via Reflectometry and Polarimetry on NSTX

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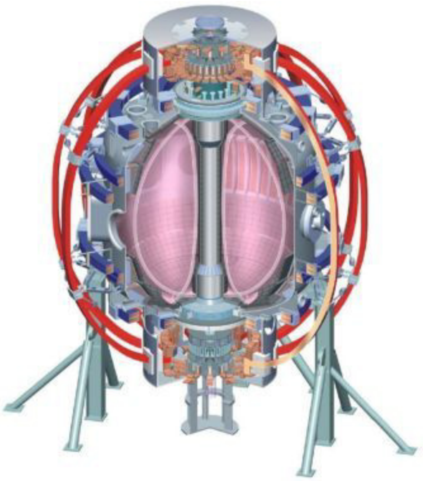
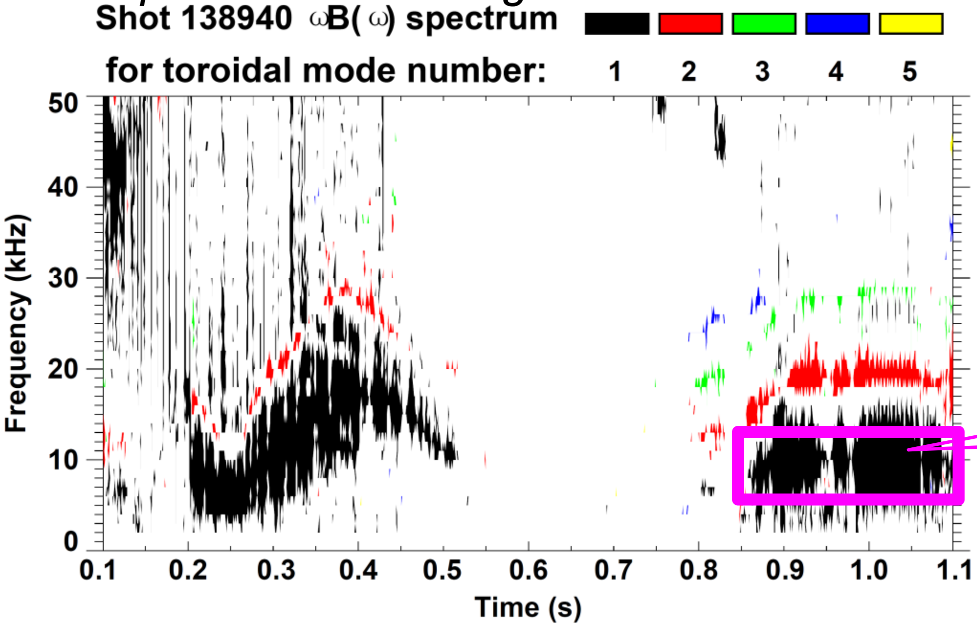


Summary of results

- NSTX is an ideal platform to study Neoclassical Tearing Mode (NTM) physics.
- Reflectometry on NSTX provides measurements with wide radial coverage and high temporal resolution to study NTMs.
  - Temporal evolution of NTM radial structure
  - Turbulence measurements around magnetic islands
- Planned polarimeter on NSTX will directly measure magnetic fluctuations caused by NTM.
  - Modeling for polarimeter development indicates ~0.4° (4°) phase fluctuation response caused by 0.1% (1%) fluctuation.
  - Laboratory test of polarimeter prototype shows multiple reflections degrade phase resolution.
    - Sub-degree phase resolution is expected by introducing optical isolation

NSTX is an ideal platform to study NTM physics

Spectrum from magnetic measurements



2/1 NTM

NSTX plasma parameters:

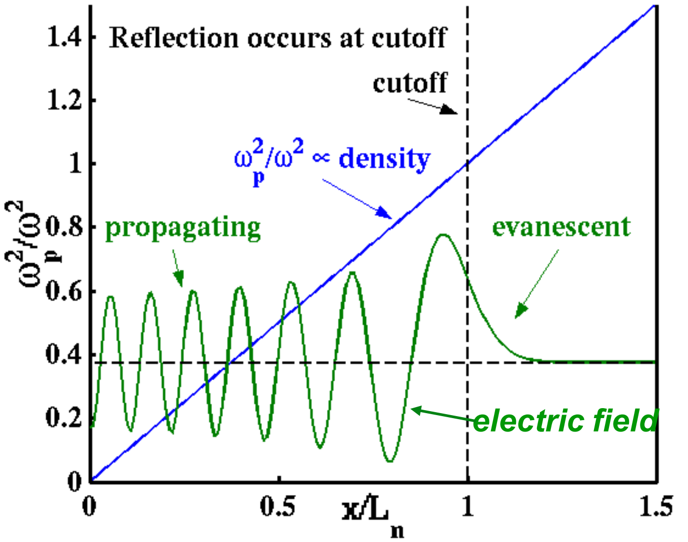
Major Radius:	*R_0 = 1 m*
Minor Radius:	*a = 0.65 m*
Inverse Aspect Ratio:	*$\varepsilon = a/R_0$ = 0.65*
Elongation	*κ = 2*
Triangularity	*δ = 0.35*

- NTM is resistive tearing mode sustained by a helically perturbed bootstrap current.
- NTMs are common on NSTX.
  - NTMs can lead to disruption in a high-β plasma.
  - NSTX has high-β (β_T ~18%) and fully equipped with diagnostics; an ideal platform to study seeding, structure, etc. of NTMs.

Investigation of NTM via reflectometry

Reflectometers measure plasma local density fluctuation

- Microwaves propagate to "cutoff" layer, where density high enough for reflection ($\omega_p = \omega$)
  - Dispersion relation of "Ordinary mode": $\omega^2 = \omega_p^2 + c^2k^2$, ω_p^2 proportional to density ($\omega_p^2 = e^2 n_0/\varepsilon_0 m_e$)
  - $k \to 0$ as $\omega \to \omega_p$, microwaves reflect where $k = 0$

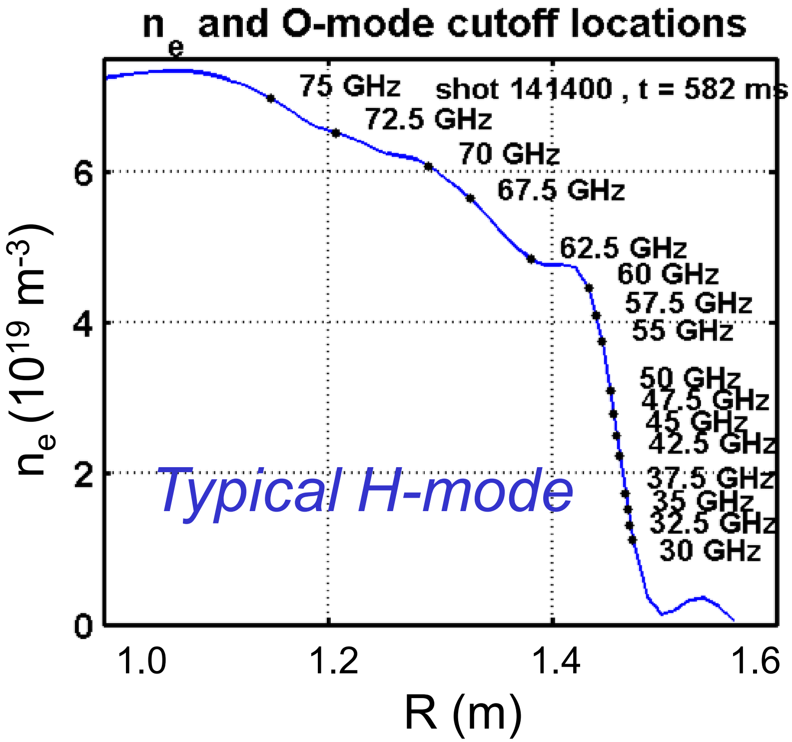

Microwave ("O-mode") propagation

- Reflectometer measures path length changes of microwaves reflected from plasma
  - determined from phase (ϕ) between reflected and launched waves
- Wave propagation controlled by density

$$\phi(f) = 2k_{vac}(f)\int_{R_{co}(f)}^{R_{edge}} \sqrt{1-\frac{n(R)}{n_{co}(f)}}\,dR - \frac{\pi}{2}$$ *(1-D model based on WKB assumption)*

Reflectometer array on NSTX spans broad radial range of plasma

- 16-channel fixed-frequency reflectometer array spans large radial range of NSTX plasma.
  - *f* = 30 – 75 GHz
  - $n_0 = 1 – 7 X10^{19} m^{-3}$ (O-mode)

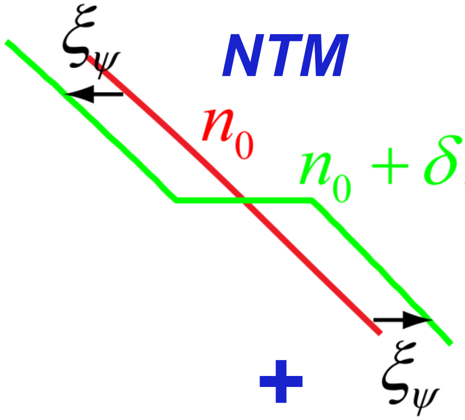


- Temporal evolution of radial mode structure can be measured.
- Possible to measure turbulence around magnetic islands (10 MHz sampling rate)
  - this turbulence affects NTM stability

NTM perturbs density profile

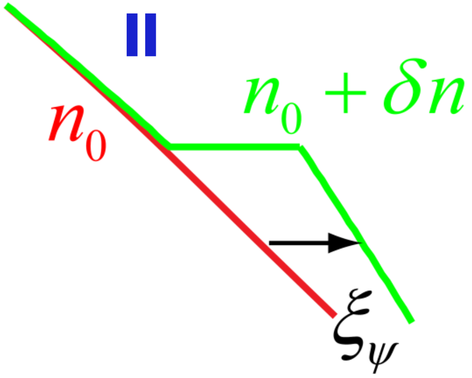
- NTM flattens the density in the islands
  - Displacement inverts around island
  - Sometime NTM is coupled to m/n = 1/1 kink (positive displacement)
    - Kink modifies density displacement
    - Total displacement may not invert if kink is large compared to NTM

- Phase inversion expected between reflectometer channels for islands
  - Possibly no inversion if island coupled to kink



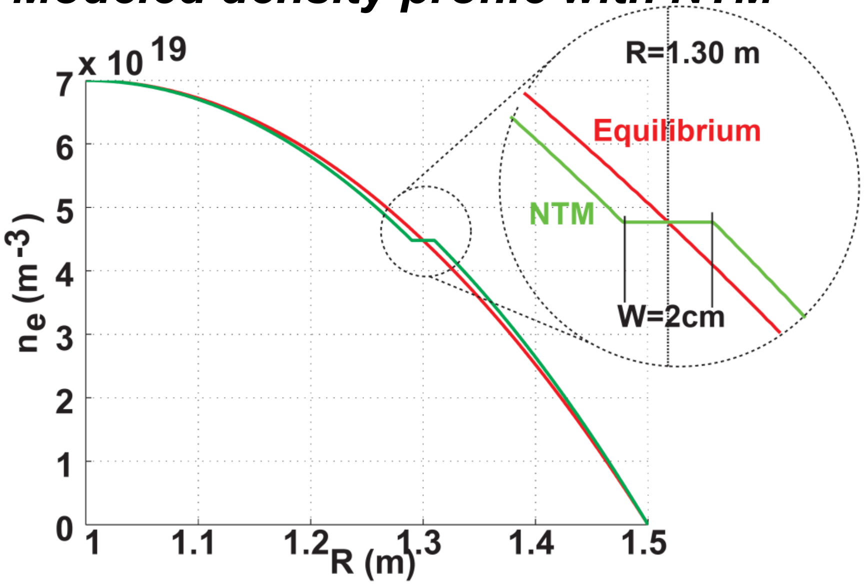
Kink *model*
(S.P. Gerhardt):

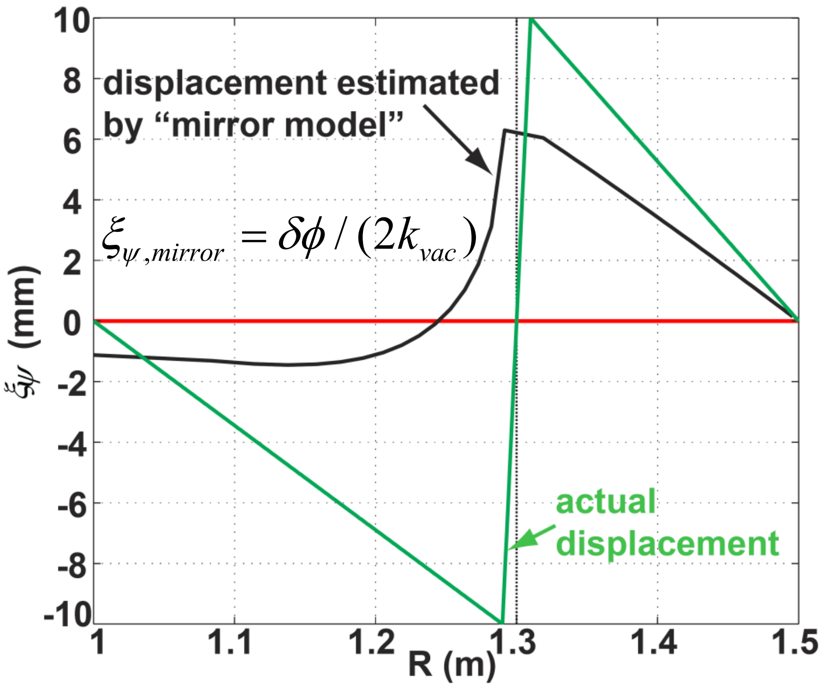
$$\xi_{1,1} = \begin{cases} \xi_0 & r < r_c \\ \xi_0 e^{-[(r-r_c)/r_f]^2} & r > r_c \end{cases}$$



Modeling reflectometry response to NTM shows “mirror model” can approximately give mode structure

Modeled density profile with NTM

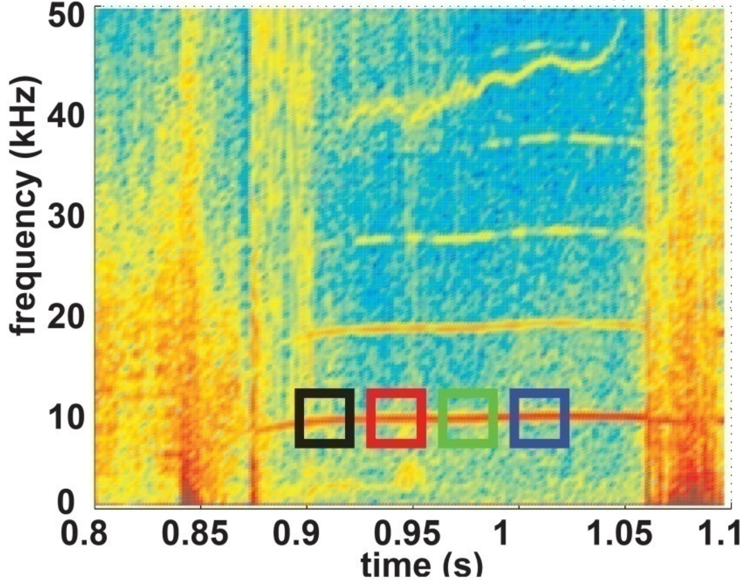




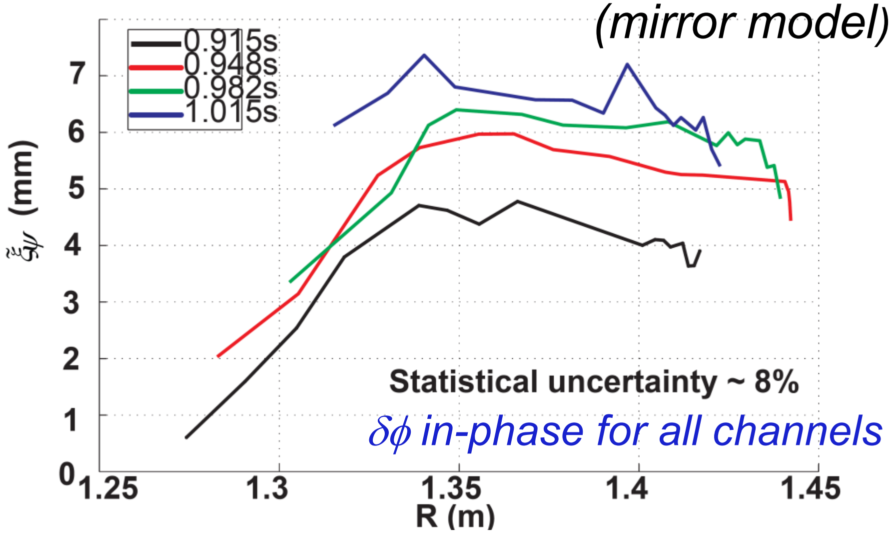
- “Mirror model” assumes phase fluctuation entirely due to displacement of cutoff. $\xi_{\psi,mirror} = \delta\phi / (2k_{vac})$
- Simple model of NTM in plasma (above left) & 1-D WKB approx. $\Rightarrow \delta\phi$
- $\xi_{\psi,mirror}$ roughly approximates ξ_ψ (above right)

NTM mode structure measurement by reflectometry

Phase spectrum of 30 GHz reflectometer
Shot #138940



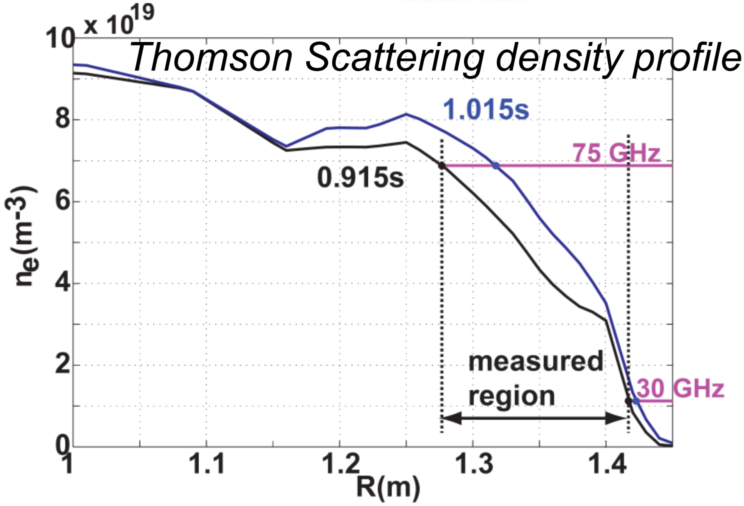
Temporal evolution of displacement
(mirror model)



Statistical uncertainty ~ 8%

$\delta\phi$ in-phase for all channels

Thomson Scattering density profiles

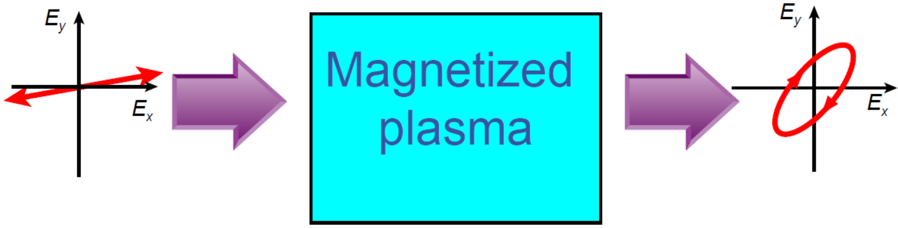


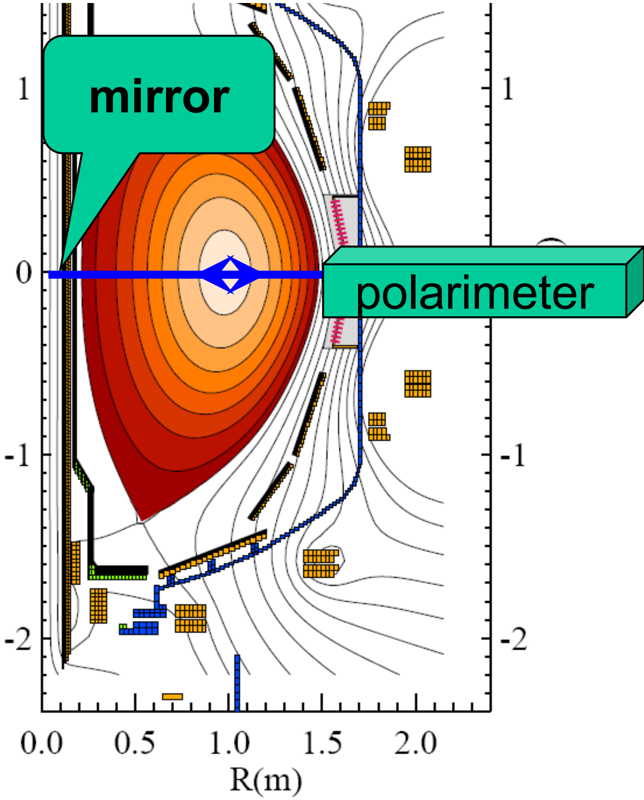
- 2/1 NTM at R ~1.25 m
  - Flat region in density profile at R~1.25 m
  - Equilibrium reconstruction (EFIT02) indicates q=2 at R=1.22 m
- Displacement appears to approach inversion near R ~1.25 m
  - Consistent with identification as NTM

Modeling magnetic islands for polarimeter development

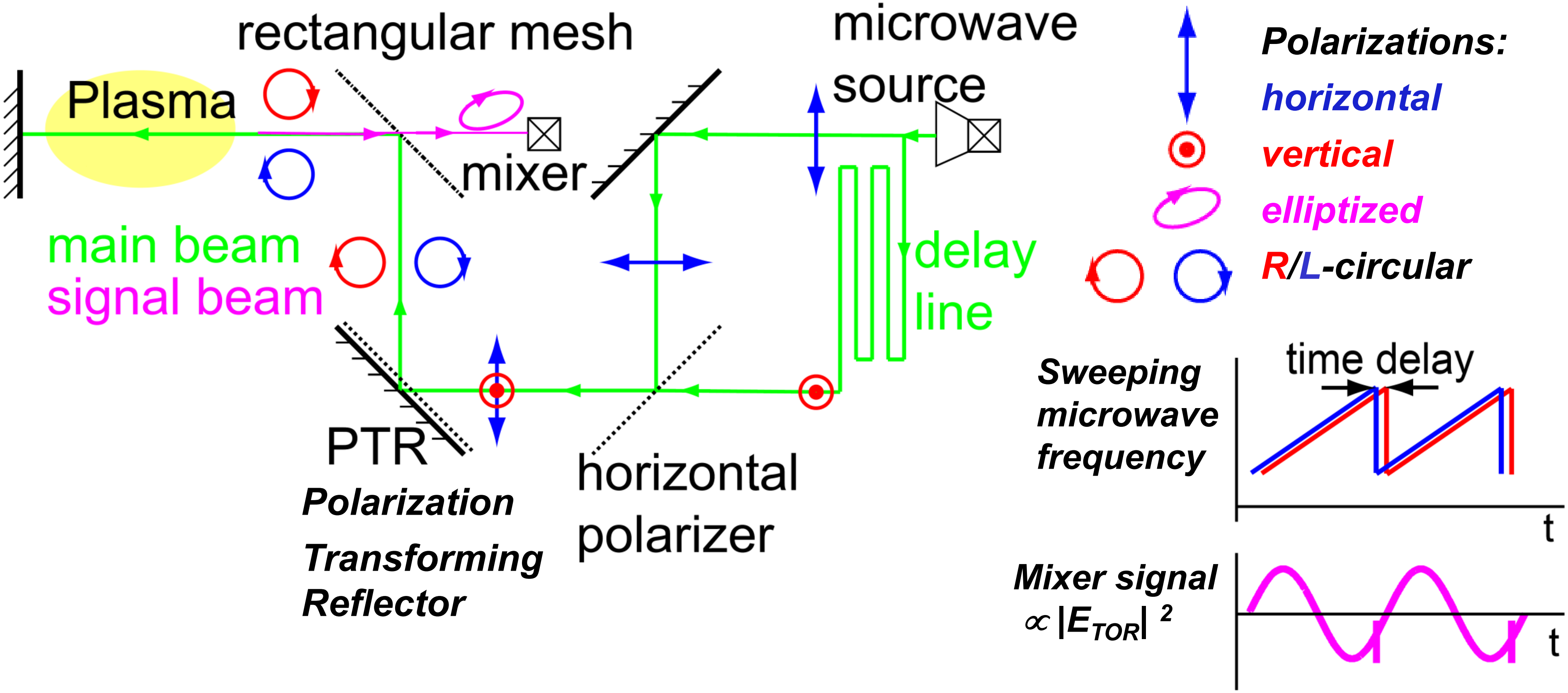
Polarimetry can contribute to NTM studies on NSTX

- Polarimetry measures change of wave polarization caused by magnetized plasma.
- Polarimetry on NSTX can contribute to
  - Equilibrium reconstruction—useful to predict NTM structure
  - Direct measurement of NTM magnetic fluctuations
- Planned polarimeter on NSTX
  - Horizontal retroreflection from Center Stack
  - Vertical scan around midplane
  - *f* = 288 GHz ($\lambda \sim 1$ mm)



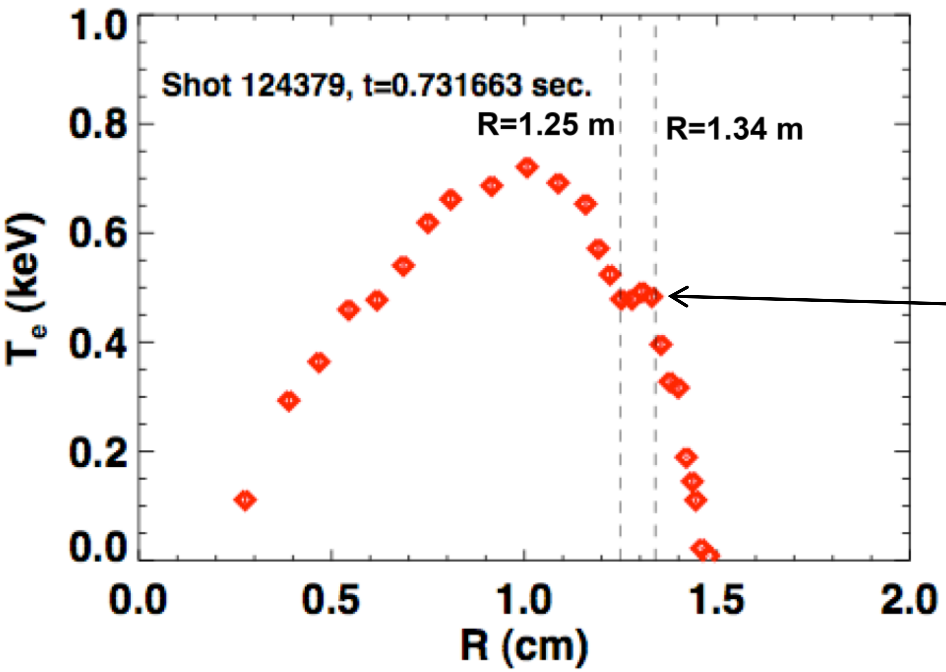


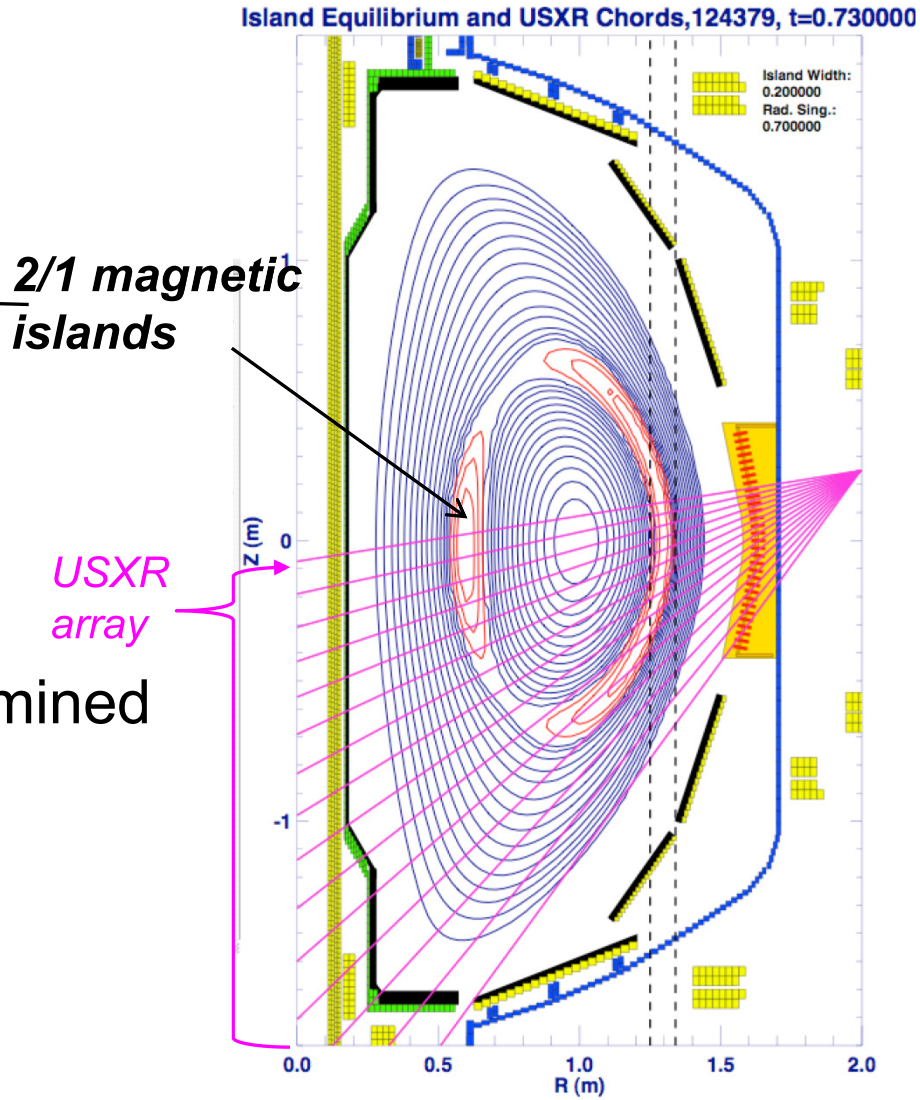
Polarimeter is sensitive to magnetic islands



- Toroidal E component, $|E_{TOR}|$, is detected by mixer.
- Phase of $|E_{TOR}|$ modulation is modified by magnetic islands.
  - Amount of change determined by size and position of islands

Realistic magnetic islands structure used in polarimetry modeling



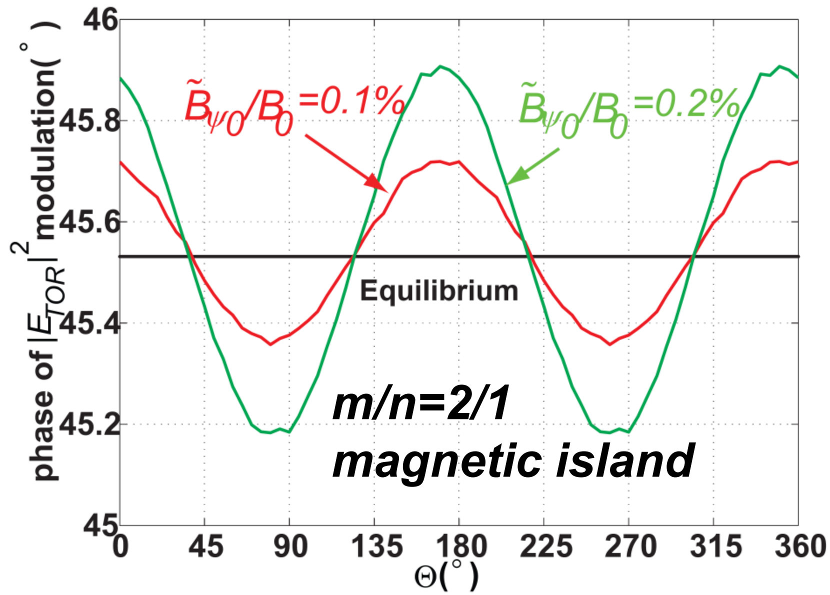


- Magnetic island structure determined using T_e profile and USXR
- On NSTX, typical 2/1 magnetic island
  - Island width w ~ 0.1 m
  - Radial location $\hat{\psi}_{2,1} \sim 0.15$

(Both figures courtesy to S. P. Gerhardt)

Polarimetry modeling shows ~0.4° phase response caused by 0.1% magnetic fluctuation

Equilibrium from shot #133959, t=0.882s



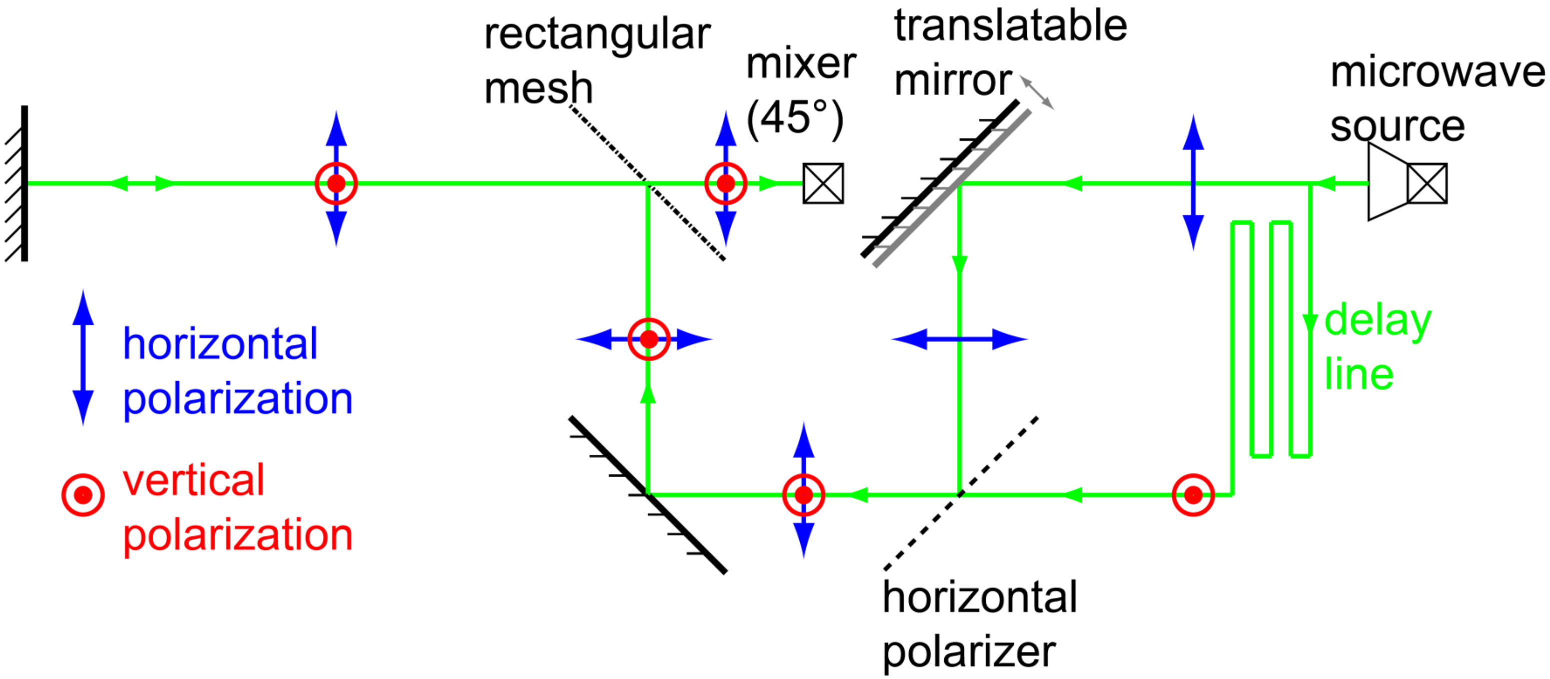
- Model assumes helically perturbed B-field around q=m/n rational surface

$$\tilde{B}_\psi = \tilde{B}_{\psi 0} e^{-\frac{(\hat{\hat{\psi}}-\psi_{m,n})^2}{(w/a)^2}} \cos(m\Theta - n\phi)$$

- *m/n=2/1* island is modeled: (*w~0.1 m*, $\hat{\psi}_{2,1} \sim 0.15$)
  - beam propagates along chord *0.1 m* below midplane
- Phase change of $|E_{TOR}|$ modulation is *~0.4°* with *0.1%* $\tilde{B}_{\psi 0} / B_0$
- Phase change dominated by Faraday rotation
  - Amount of phase change approximately proportional to fluctuation amplitude

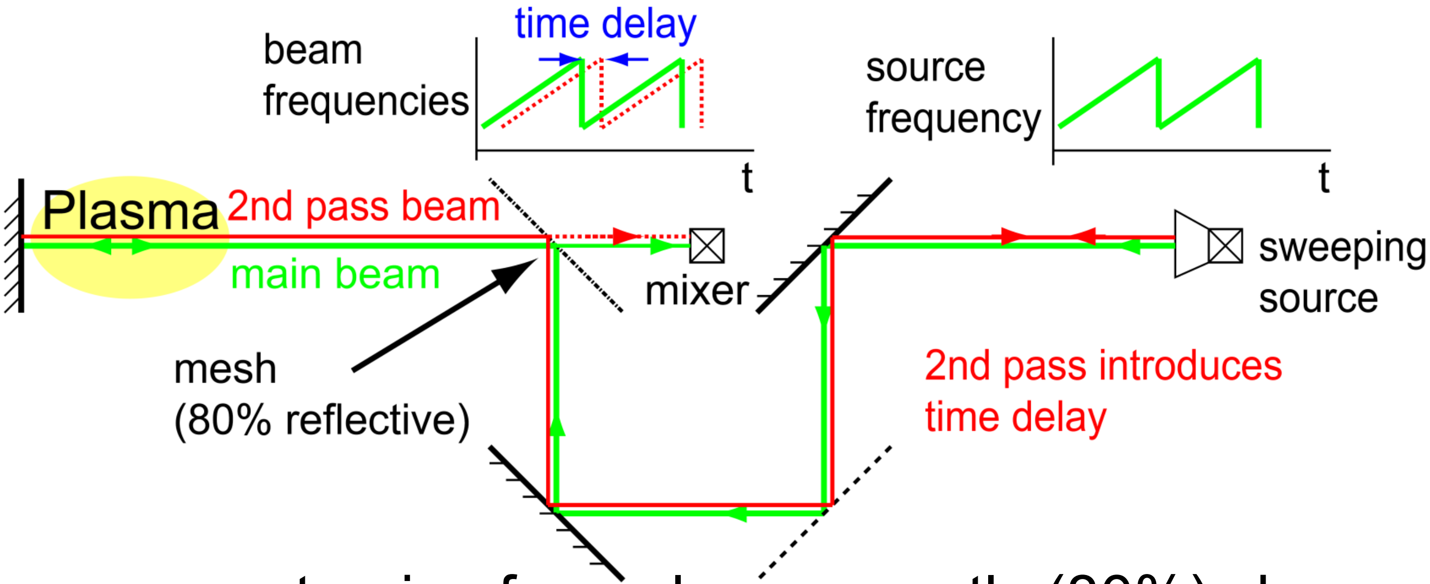
Laboratory test of polarimeter prototype

Polarimeter prototype phase resolution tested in laboratory



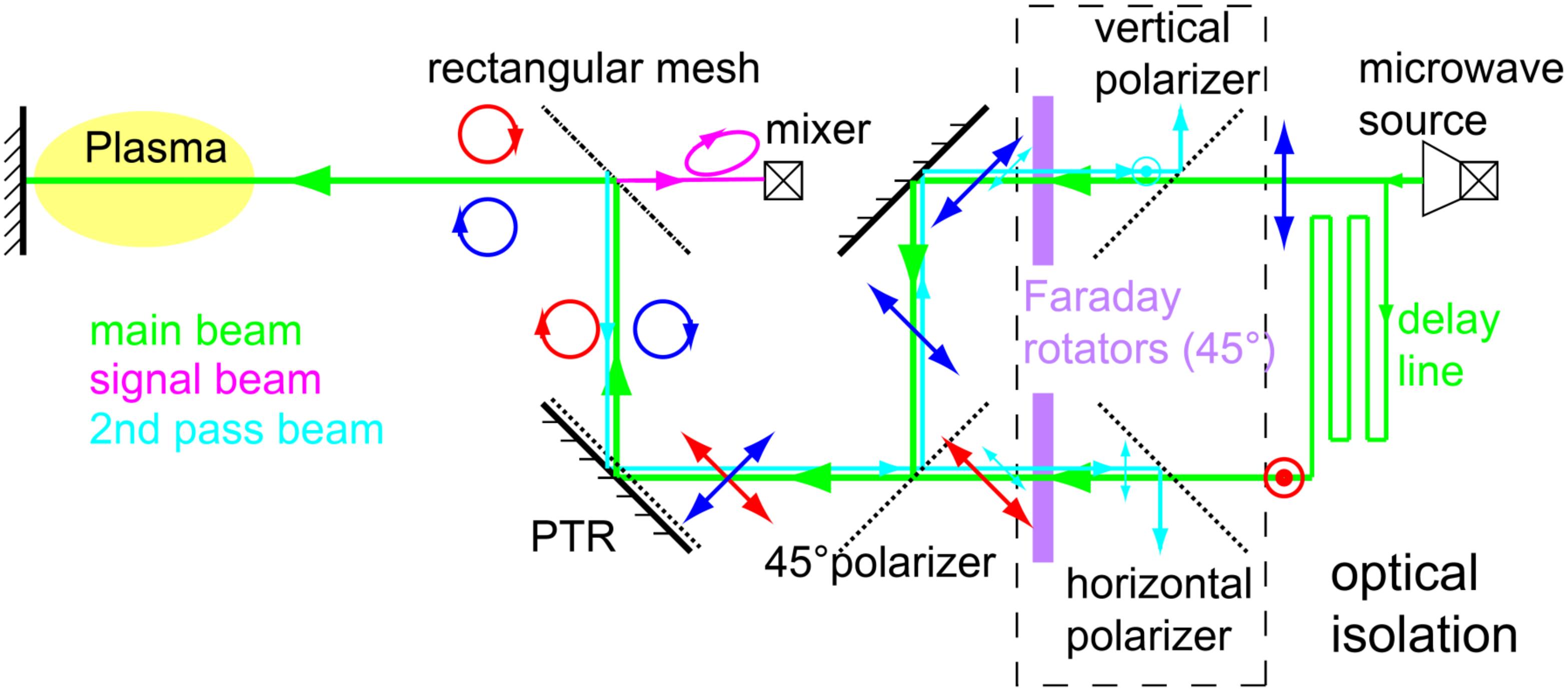
- Prototype configured as heterodyne interferometer
  - Relative phase controlled by translatable mirror
  - Mirror controlled by micrometer (sub-degree phase change)
- Microwave source sweeping frequency up to 1 MHz

Multiple reflections degrade phase resolution



- Microwaves returning from plasma mostly (80%) channeled to source and partially reflected back to plasma (i.e. 2nd pass)
  - 2nd pass beam strongest among multiple reflections
- Interferometry effect is caused by 2nd pass beam
  - Phase of beating signal with main beam very sensitive to path length change (λ~ *1 mm*)
  - Path length changes due to mechanical vibration and plasma turbulence

Optical isolation expected to improve phase resolution



- Multiple reflections can be eliminated by introducing optical isolation.
  - Optical isolator consists of 45° Faraday rotator and polarizer
- Phase sensitivity is expected to be significantly improved.
  - Sub-degree phase resolution is desired

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Future work

- Reflectometry:
  - Improve interpretation of reflectometry measurements
    - Combine with full wave propagation modeling
  - Compare reflectometry measurements with theoretical model of NTMs (e.g. 1/1 kink couples with 2/1 magnetic islands)
  - Integrate reflectometry measurements with other diagnostics (e.g. magnetics, Ultra-Soft X-Ray, etc.) to further study NTMs on NSTX
- Polarimetry:
  - Measurements can contribute to other MHD modes, e.g. Alfvén eigenmodes

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