Faraday Rotation Diagnostic for (Axial) Current Density and (Core) Magnetic Fluctuation Measurements in NSTX

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Goal

1. Propose a high-speed Faraday Rotation diagnostic for NSTX to measure:

- current density on axis: $J_{\phi}(0,t) \Rightarrow [q(0,t)]$
  core constraint on EFIT
- core magnetic fluctuations

Previously proposed for 2002, positive review but not funded due to insufficient funds

2. $J_{\phi}(0,t)$ can be determined in real-time and used directly for feedback (information on plasma shape required, constrain rtEFIT)

3. Fast-time response [$\Delta t \sim 1\ \mu s$] can be exploited to measure internal magnetic field fluctuations, e.g., MHD modes, NTM, AE's, turbulence, etc.

$$\tilde{B}(\omega, k) \propto \tilde{J}$$

Poloidal-View Faraday Rotation for NSTX

Due to limited machine access, we propose a limited system which consists of

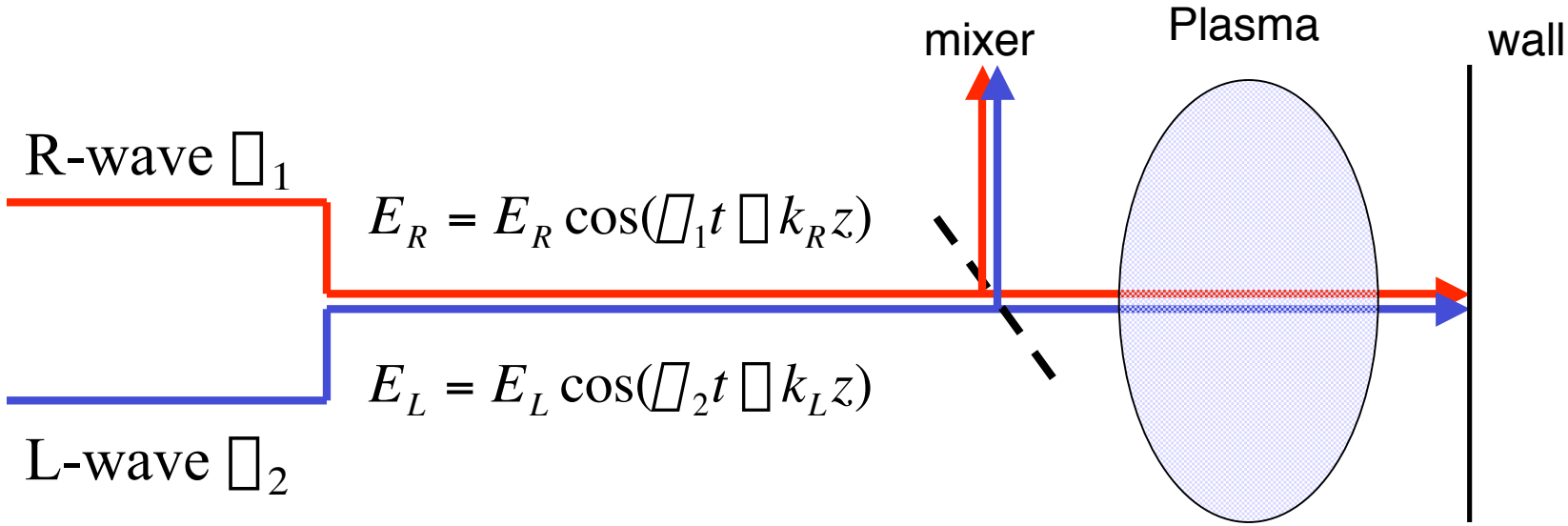
- 3-5 chords located near magnetic axis
- chords will be positioned above, below and on the midplane
- use existing 8(6)” port [Port G, 1 mm interferometer]
- or, use center of Port J, larger vertical extension [~25 cm], guarantees access to magnetic axis (also future expansion)

Faraday rotation technique will be the same as that currently operating on MST RFP with $\Delta t < 1$ μs, $\Delta\Delta$ <1 mrad.

Source (1mm solid-state or 432 μm FIR laser) will be double passed

- reflect from tile on inside wall (center stack)
- initial tests at 1 mm (interferometer) look promising

Faraday Rotation Measurement Method



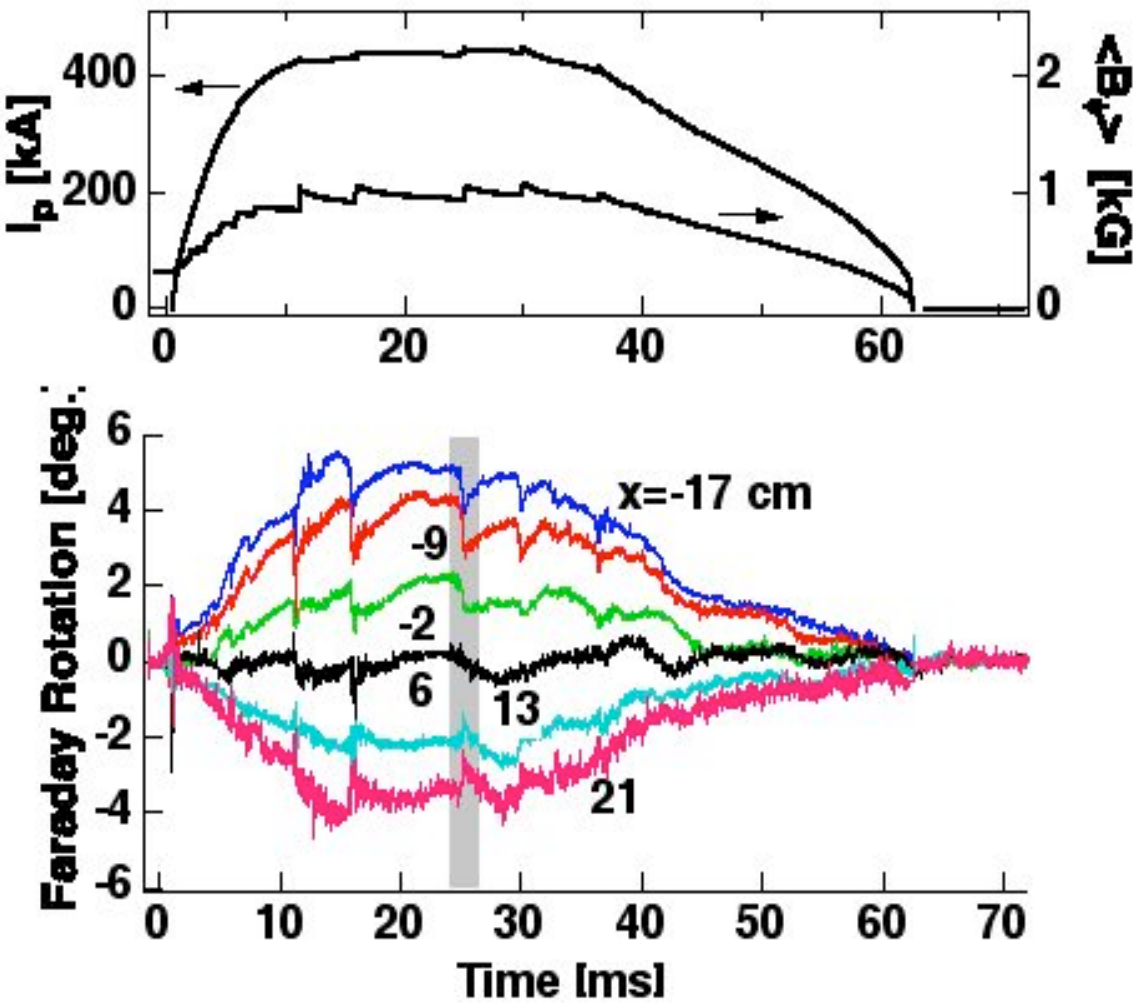
$$j \sim (E_R + E_L)^2$$

$$\sim E_R E_L \cos[(\omega_1 - \omega_2)t - (k_R - k_L)z] + \ldots$$

$$\omega_1 \sim \omega_2 >> \omega_{pe}, \omega_{ce} >> |\omega_1 - \omega_2|$$

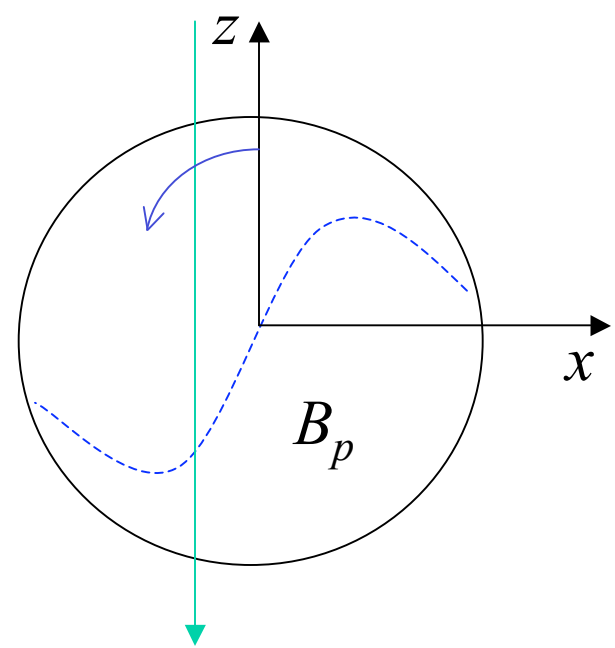
$$k_L - k_R = \frac{\omega}{c}(N_L - N_R) = \frac{\omega^2_{pe}\omega_{ce}}{c\omega^2} \sim n_e B_z$$

Faraday Rotation Time History



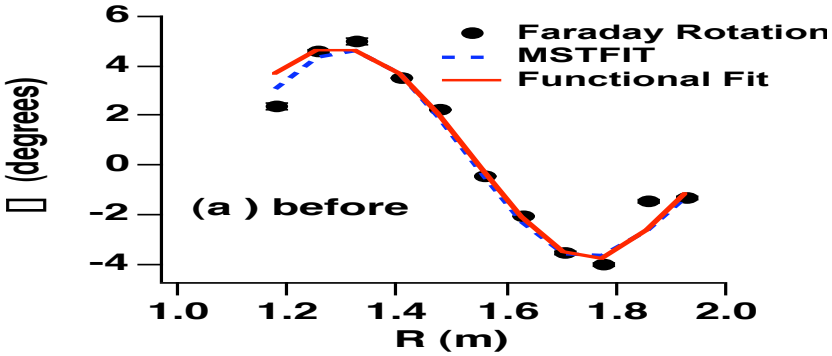
$$\Delta\phi = c_F \int n_e B_z \, dz$$

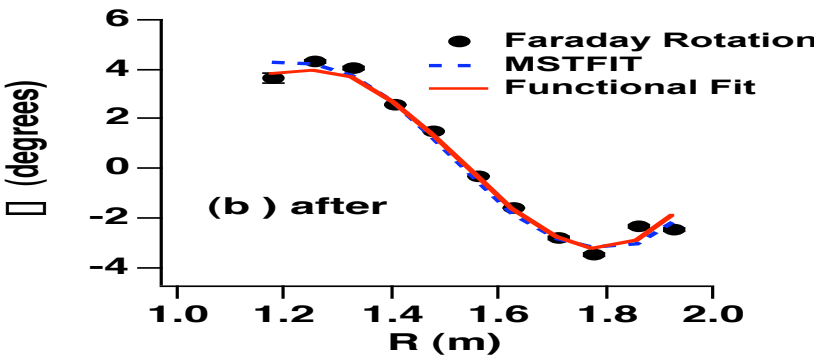
$$= c_F \int n_e \vec{B} \bullet d\vec{l}$$

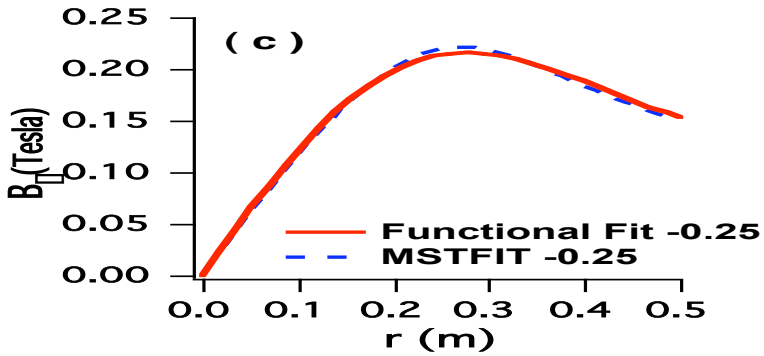


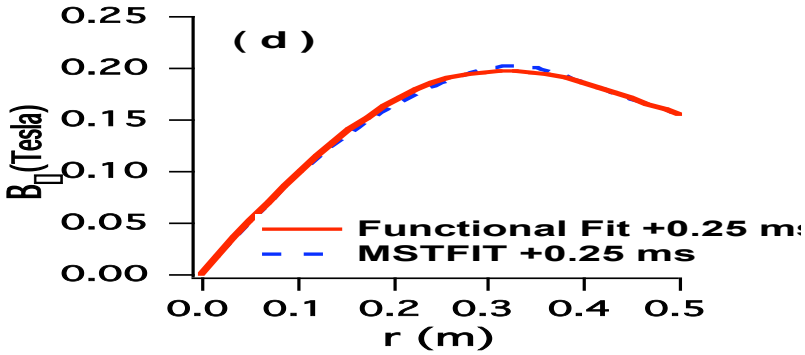
X = -17 cm

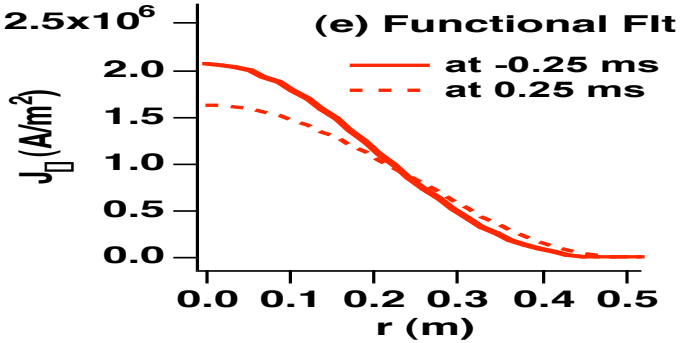
Magnetic Field and Current Density Profiles

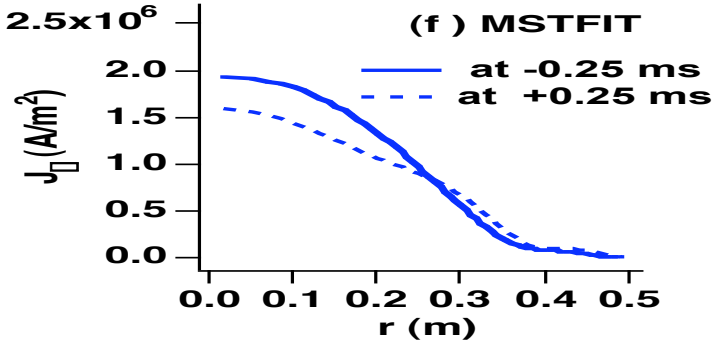






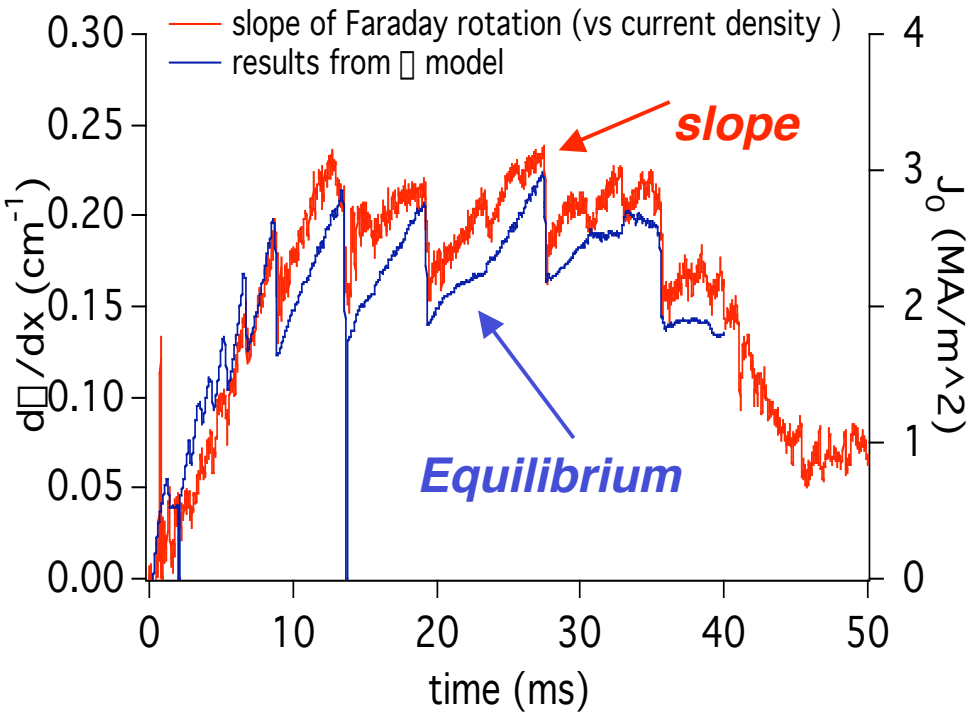


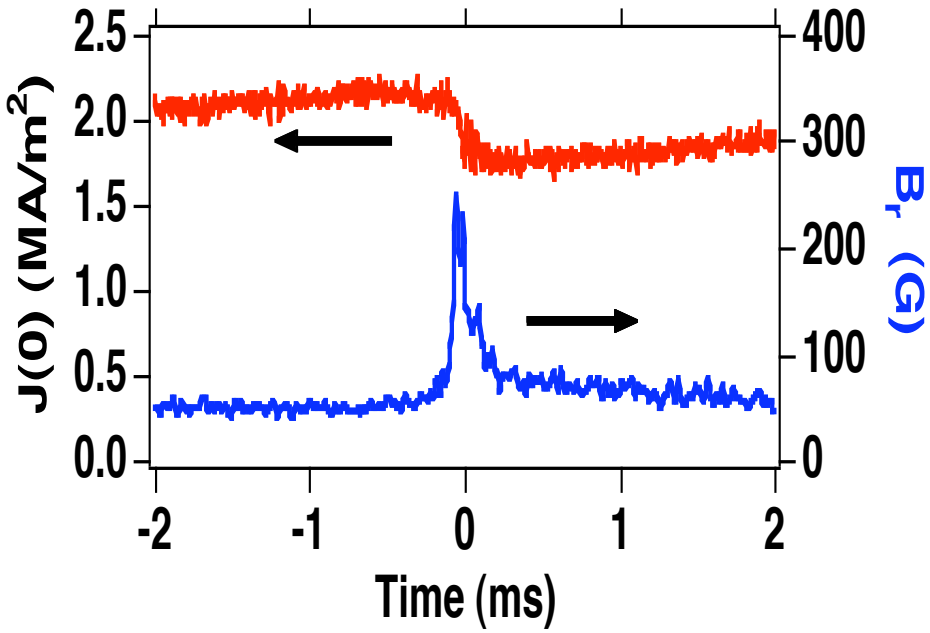




Faraday Slope is Proportional to J(0)

Measure current density fluctuations!



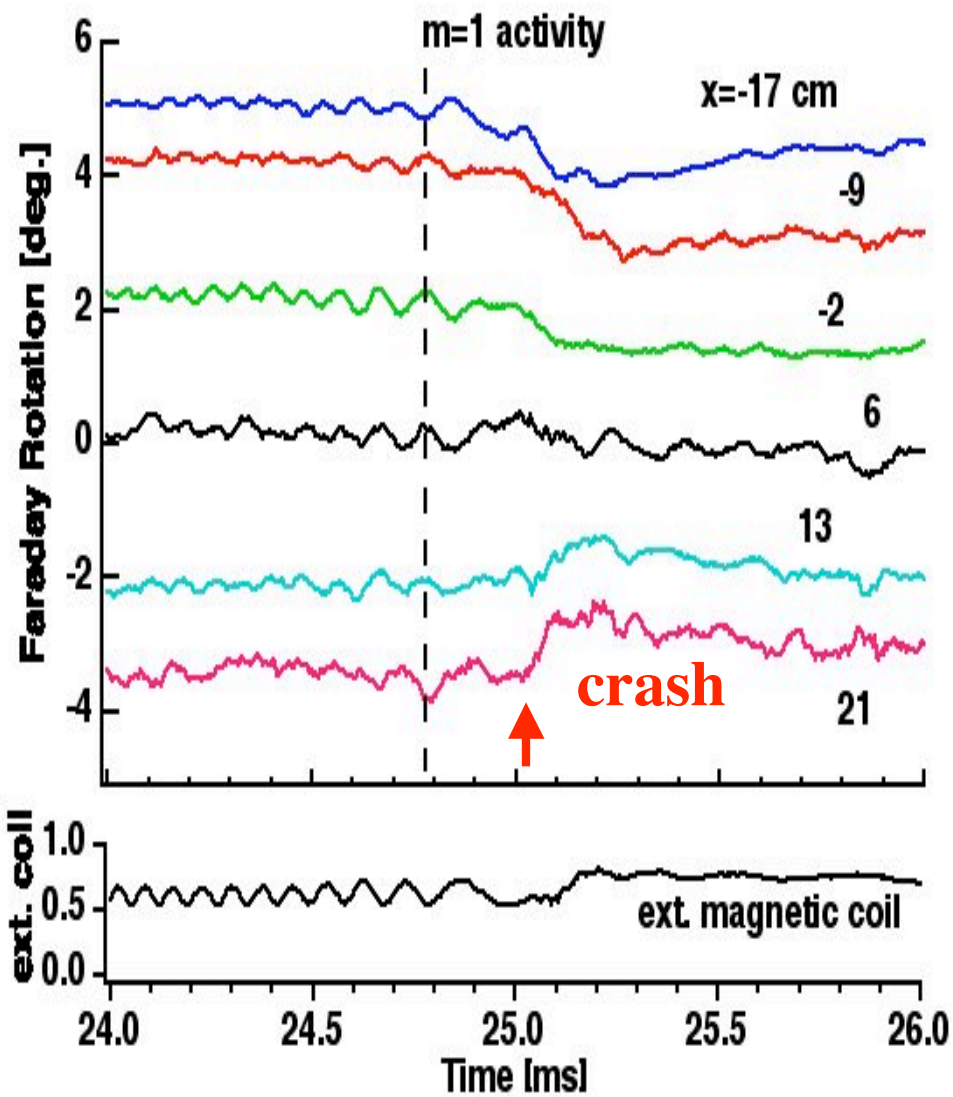


For NSTX, information on plasma shape is required to obtain J(0)

$$J(0) = \frac{2}{\square_0 c_F} \boxed{\frac{d\square}{dx}} \frac{1}{\square n_e f(r,\square) dz}$$

Brower, Ding et al. PRL (2002)

Faraday Rotation and Magnetic Fluctuations



Ding, Brower et al. PRL (2003)

Faraday Rotation : $\square = c_F \square n\vec{B} \bullet d\vec{l}$

$\square = \square_0 + \square\square, \ \vec{B} = \vec{B}_0 + \square\vec{B}, \ n = n_0 + \square n$

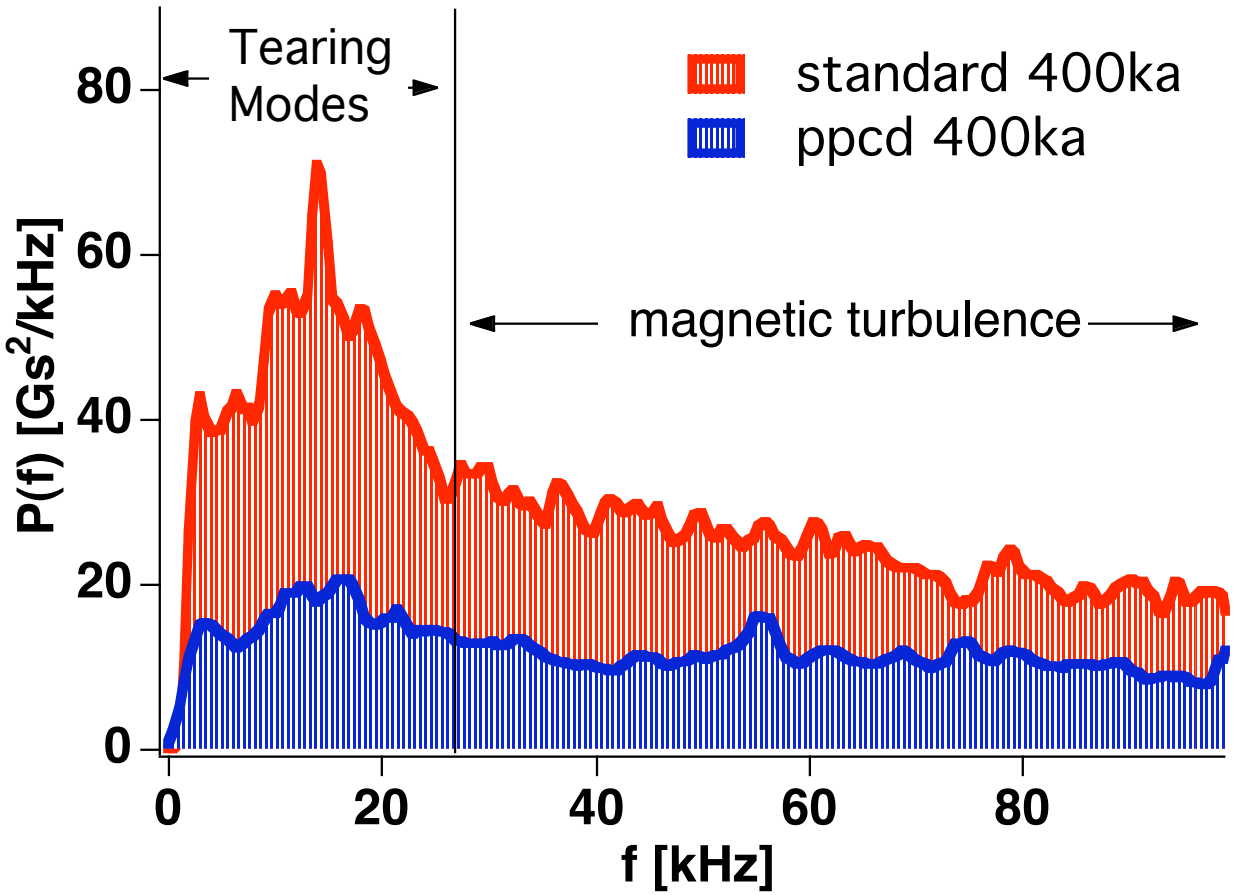
$\square\square = c_F \square n_0 \square\vec{B} \bullet d\vec{l} + c_F \square\square n\vec{B}_0 \bullet d\vec{l}$

($\vec{B}_0 \square \ d\vec{l}$ and $\square\square n \ dl \ \square \ 0$ for central chords)

$$\square\square \ \square \ c_F \square n_0 \square\vec{B} \bullet d\vec{l}$$

$$\overline{B}_r = 33 \text{ [Gauss]}$$

Magnetic Fluctuations Reduced during PPCD



- Magnetic fluctuations have been observed in MST up to 300 kHz

- excellent time and phase resolution

Current Fluctuation Measurement Method

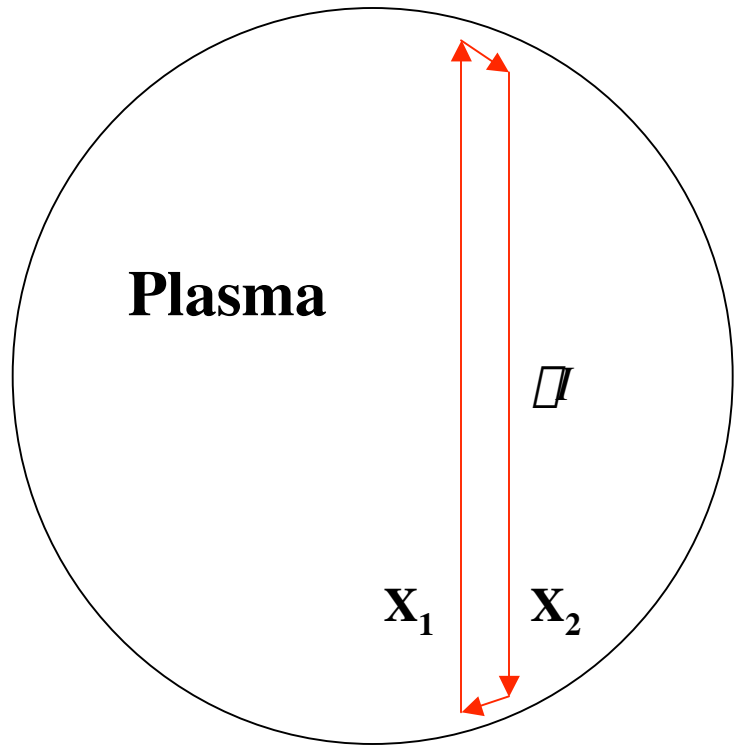
Ampere's Law : $\oint_L \delta\vec{B} \bullet d\vec{l} = \mu_0 \delta I$

Faraday Rotation Fluctuation :

$$\delta\theta = c_F \int n_0 \delta\vec{B} \bullet d\vec{l} \approx c_F \bar{n}_0 \int \delta\vec{B} \bullet d\vec{l}$$

$$\oint_L \delta\vec{B} \bullet d\vec{l} \approx \left[\int \delta B_z dz \right]_{x1} - \left[\int \delta B_z dz \right]_{x2}$$

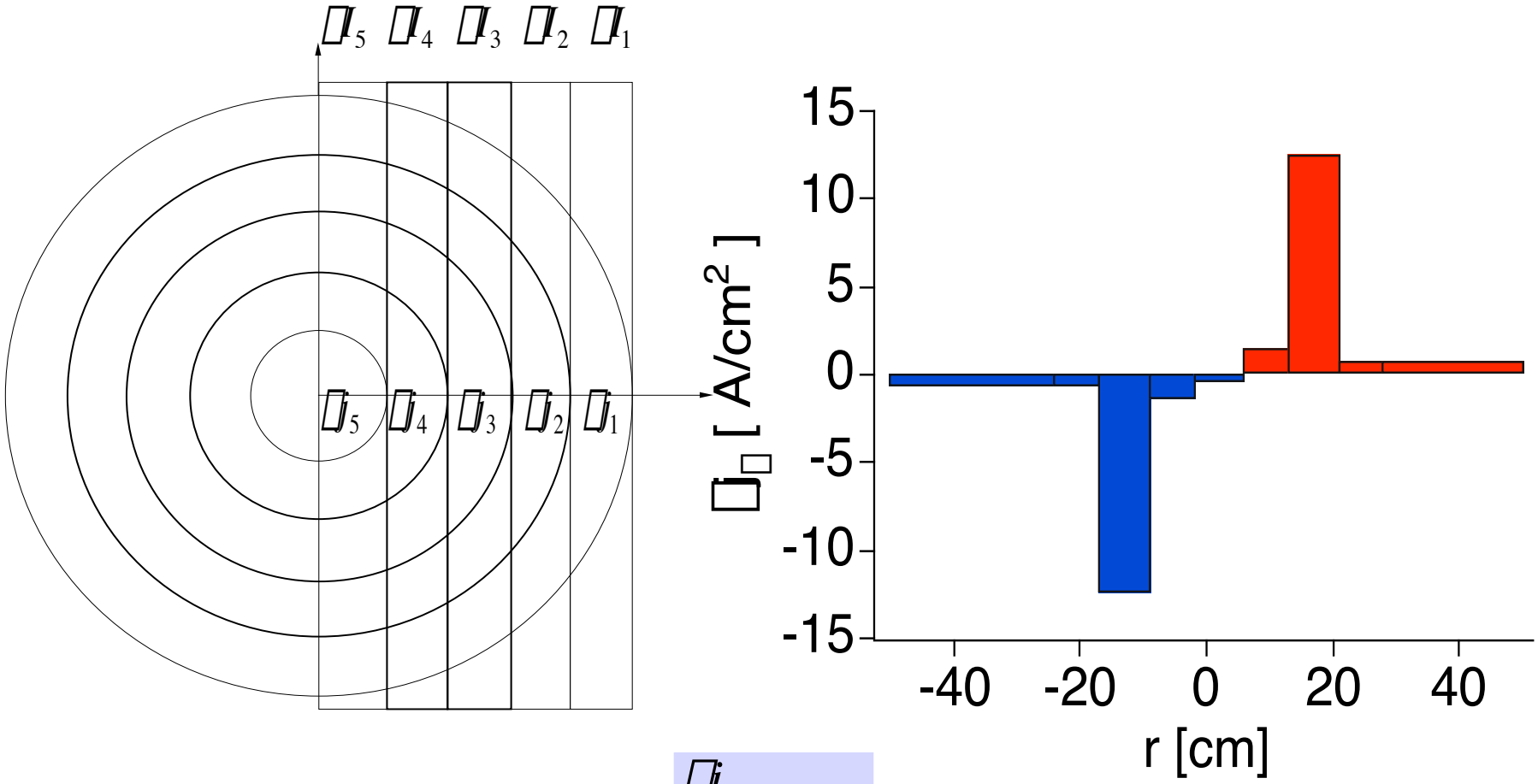
$$\approx \mu_0 \delta I_{\square} = \frac{\delta\theta_1 - \delta\theta_2}{c_F \bar{n}_0}$$



Loop between polarimeter chords is equivalent to a Rogowski coil measurement

Ding, Brower et al. PRL (2003)

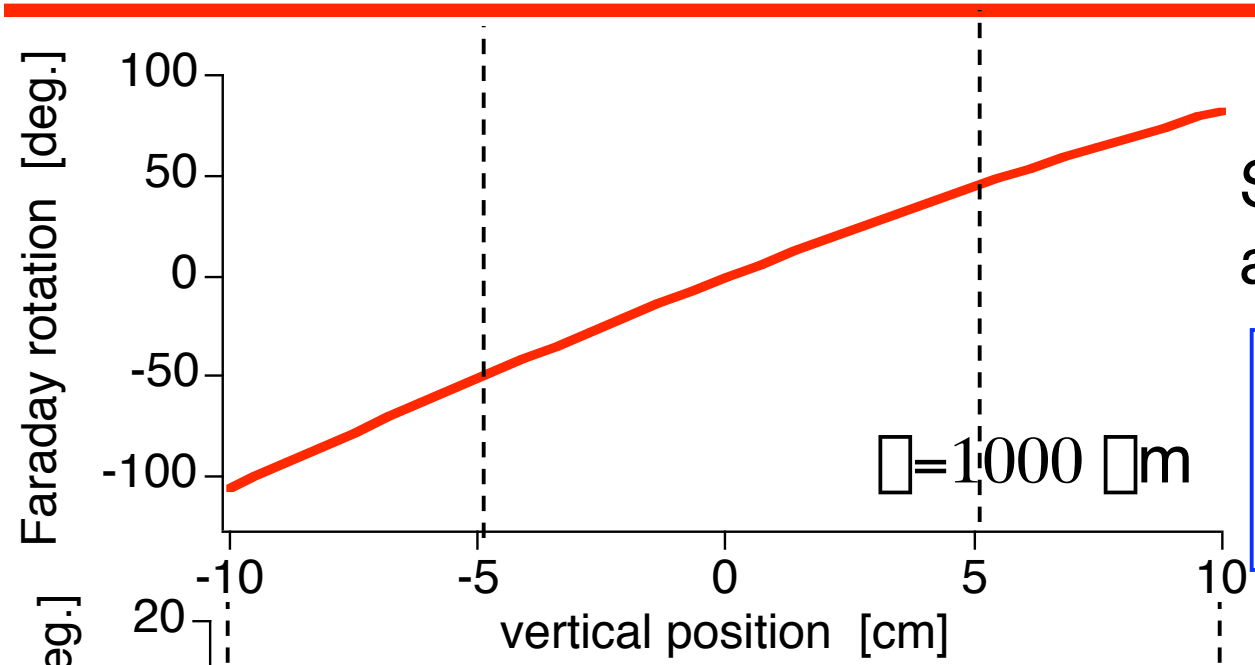
Measured Current Density Fluctuation Profile



$$\frac{\delta j_{\theta}}{J_0} \sim 6\%$$

Current density fluctuation is spatially localized in core

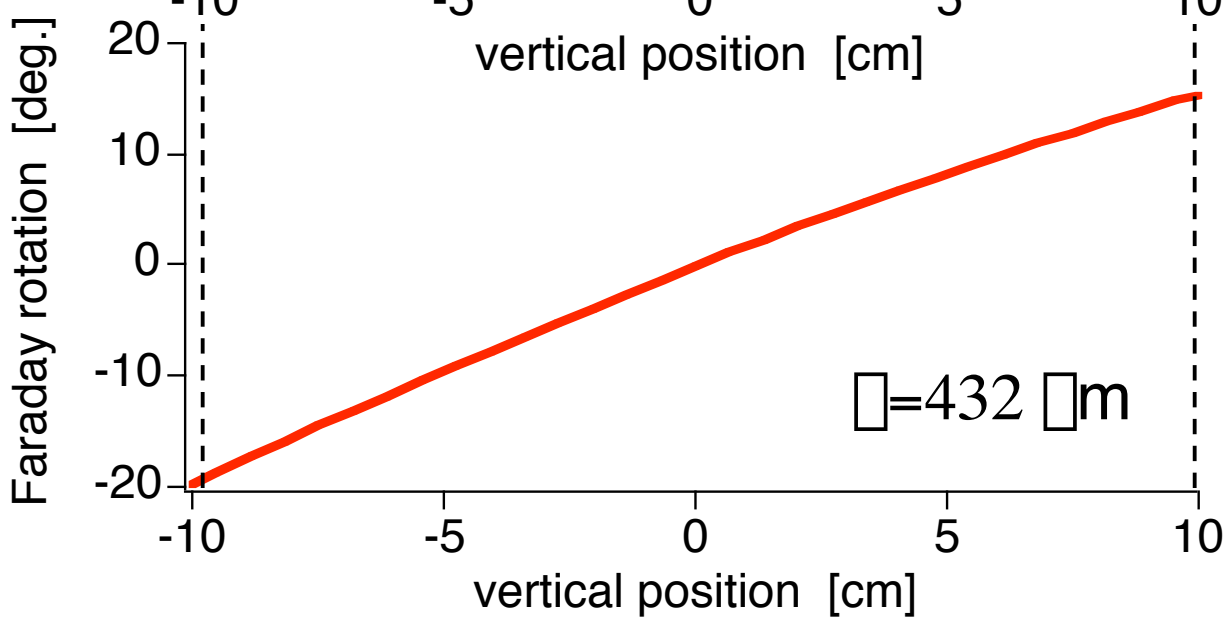
Anticipated Rotation Angles



Solid-State Source at 1 mm

$n_{eo}=7\times10^{19}$ cm^{-3}

$I_p=1$ MA



FIR laser source at 0.432 mm

$$\theta \sim \lambda^2 \int n_e B_z \, dz$$

Faraday Diagnostic Development Path

1. Using 1 mm source:
   ~ Accelerate development to provide Faraday rotation data this upcoming run period
   ~ $25k hardware (second 1mm source) + $100k/yr dedicated research scientist

- Applicable to NSTX plasmas with $n_e \sim 2 \times 10^{19}$ m^{-3} e.g. rf current drive plasmas
- System can be configured for Faraday rotation or density measurement.

2. Using 432 μm FIR laser source:
   ~ 2 year time scale
   ~ $150k hardware (3-wave laser) + $100k/yr dedicated research scientist

- Suitable for wide range of NSTX operating conditions
- Simultaneous Faraday and density measurement.

Faraday Rotation on NSTX

Limited-view Faraday rotation diagnostic can be built for NSTX to measure:

1. Current density on axis: $J_{\square}(0,t)$ [need info. on shape]

- ***provides strong internal constraint on EFIT***
- real-time feedback on Faraday signals would be possible

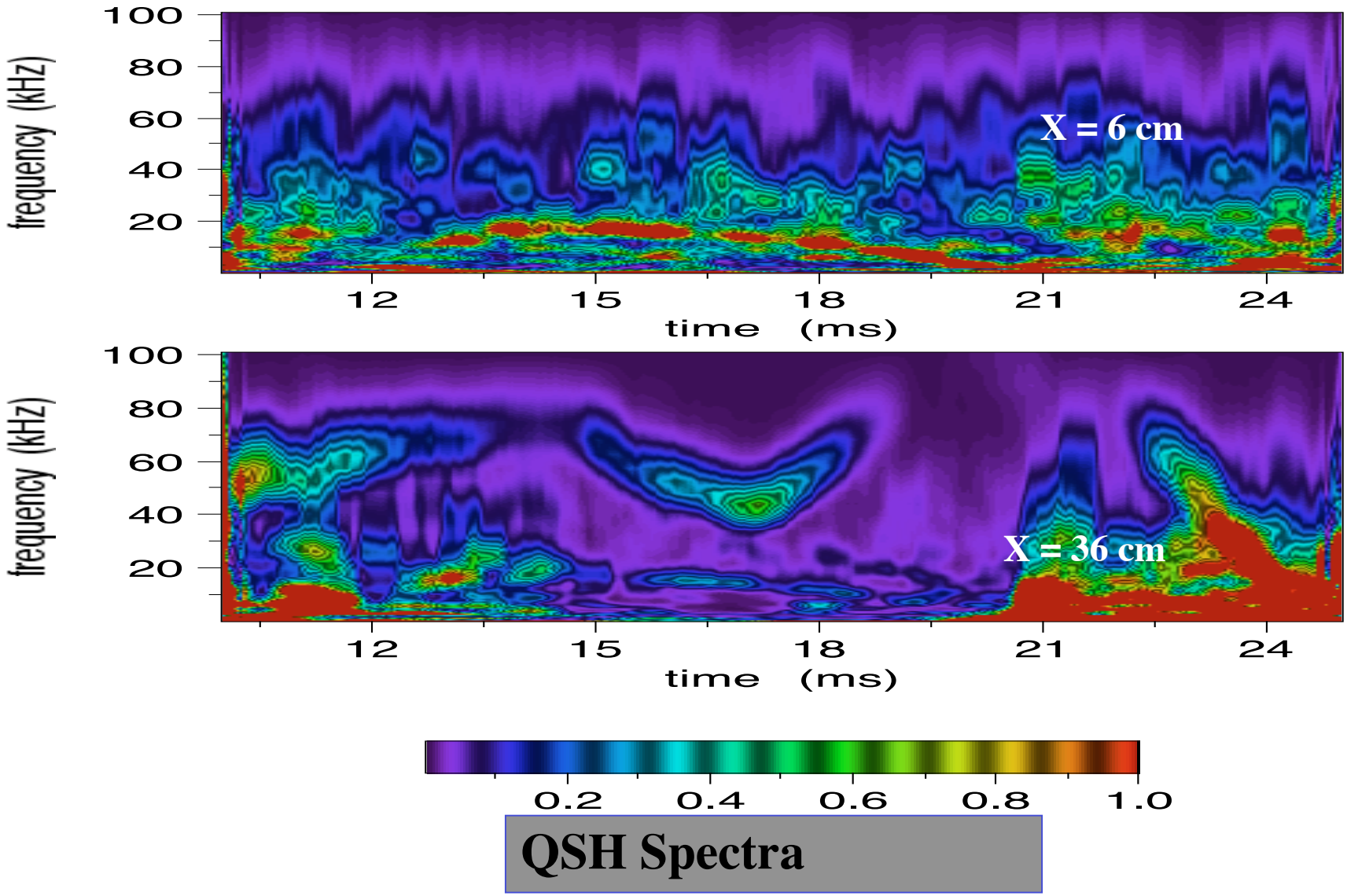
2. Internal magnetic field fluctuations [MHD, AE's, and turbulence]

System would have

1. Time response: $\square t \sim 1\ \square s$

2. Phase resoluton: $\square\square \sim 1$ mrad

Magnetic Fluctuation Temporal Evolution



QSH Spectra

1 mm (~300 GHz) interferometer test

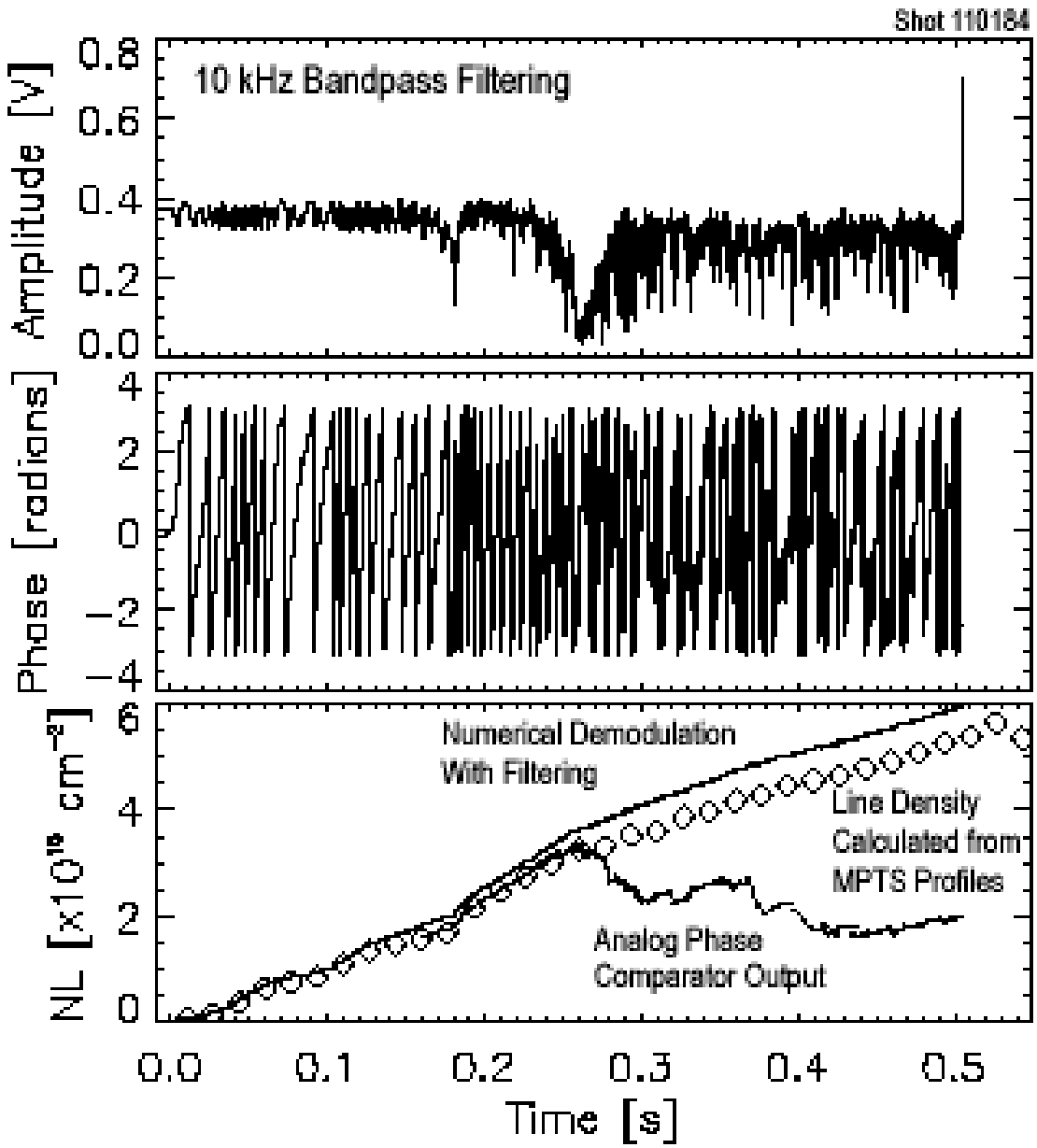
- Reflecting 1 mm source off center-stack seems to work

- Interferometer results seem reasonable

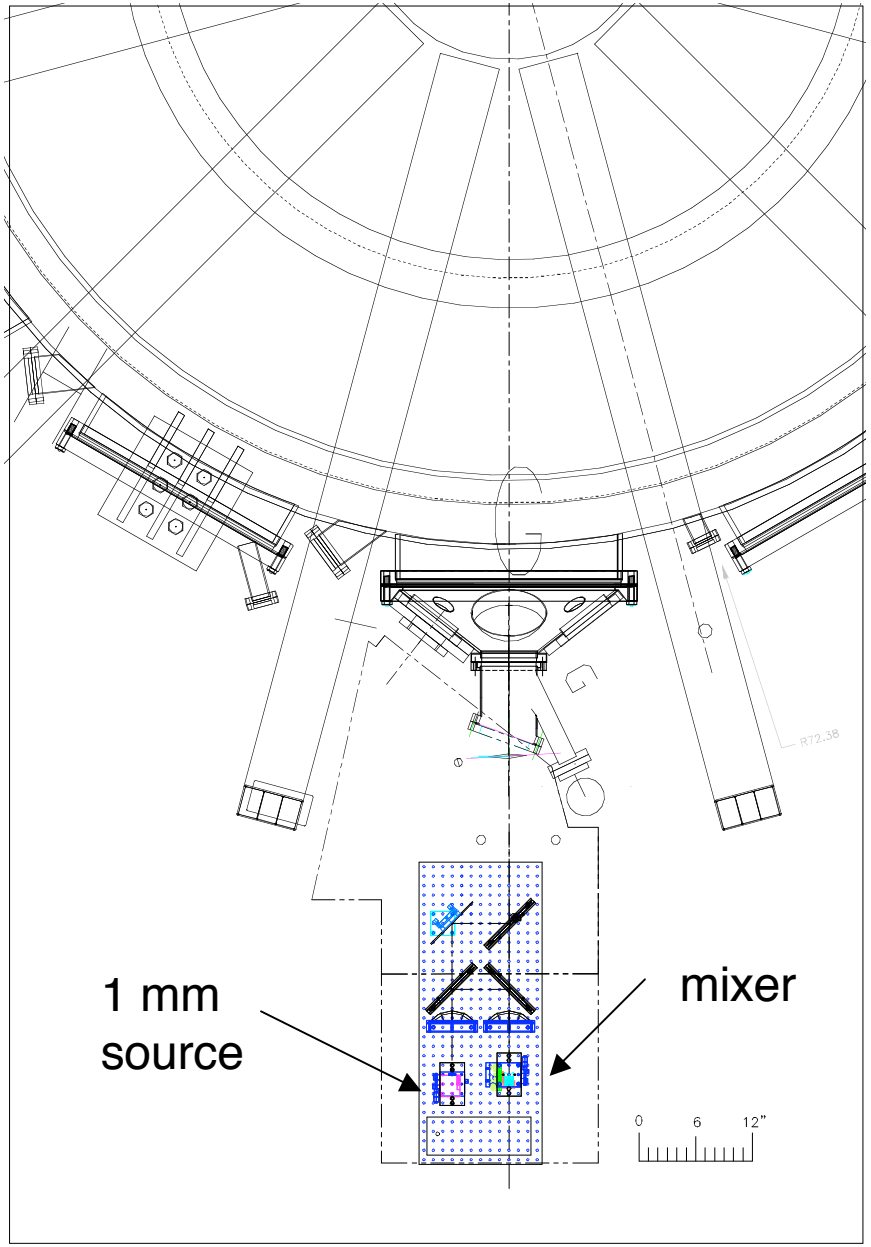
- Lose signal for high density operation (refraction)

- Very limited testing

- Further tests will be made during next NSTX run phase

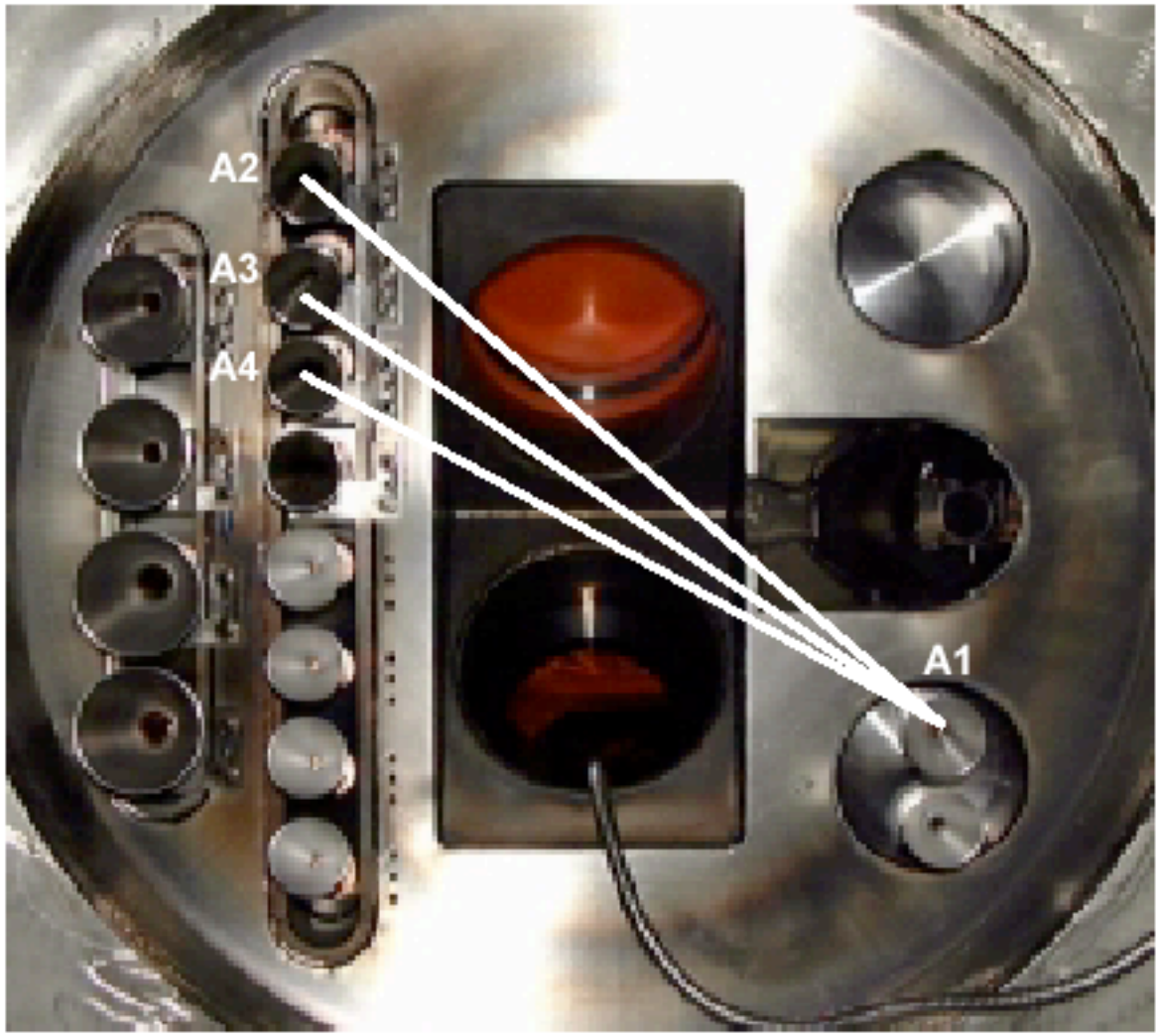


Proposed NSTX layout



Poloidal-View Faraday Rotation for NSTX

Port J



Current Density J(0) Measurement Method

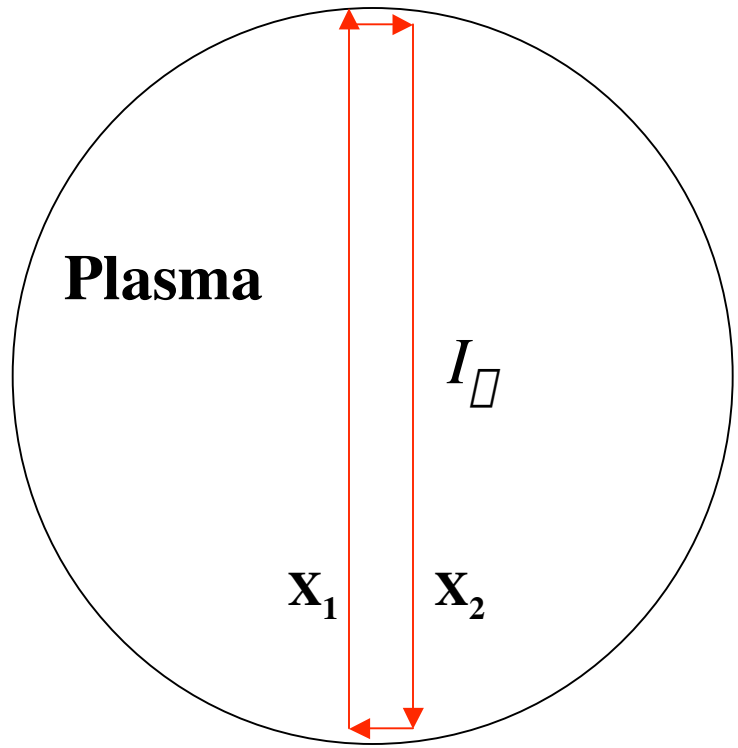
Ampere's Law: $\oint_L \vec{B} \bullet d\vec{l} = \mu_0 I$

Faraday Rotation:

$$\Delta = c_F \int n_0 \vec{B} \bullet d\vec{l} \approx c_F \bar{n}_0 \int \vec{B} \bullet d\vec{l}$$

$$\oint_L \vec{B} \bullet d\vec{l} \approx \left[\int B_z dz\right]_{x1} - \left[\int B_z dz\right]_{x2}$$

$$\mu_0 I_{\square} = \frac{\Delta_1 - \Delta_2}{c_F \bar{n}_0}$$



Loop between polarimeter chords is equivalent to a Rogowski coil measurement

Motivation

1. Knowledge (measurement) of internal magnetic field structure is required to understand ST performance, especially critical for

- stability and confinement
- high β operation
- non-inductive current drive (HHFW, bootstrap current)
- AT scenarios

2. Faraday rotation has been used for many years on many devices to measure $B_{\parallel}(r,t) \Rightarrow J_{\parallel}(r,t)$

3. Recent diagnostic advancements made in Faraday rotation measurements [$\Delta t \sim 1\ \mu s$, $\Delta\theta \sim 1$ mrad] have been exploited (on MST) to measure

- J(r,t) profile evolution through sawtooth cycle (crash)
- internal magnetic field and current density fluctuations (amplitude, spatial distribution)