Summary

For the first time, the current profile in a Reversed Field Pinch is measured with fast time resolution using the technique of polarimetry. The Far Infrared Interferometer system at the Madison Symmetric Torus has been upgraded to measure Faraday rotation with a time resolution of 4 μs. This data, combined with the inverted density profile from the interferometer measurement, enables the determination of the poloidal magnetic field and toroidal current profiles. Presented here is data showing the broadening of the toroidal current profile after a sawtooth crash and the peaking of the profile during Pulsed Poloidal Current Drive (PPCD). Also shown is the measurement of an oscillation in the poloidal field and on axis current during Oscillating Poloidal Current Drive (OPCD). The planned upgrade of the FIR system to measure line integrated density and Faraday rotation simultaneously is discussed as well as the potential to use the current profile data to examine stability of the tearing modes in an RFP.

Measurement of the Current Profile Is Crucial to Understanding Reversed Field Pinch Physics

Knowledge of the parallel current profile is crucial in the Reversed Field Pinch as it determines stability for resistive tearing modes. These tearing modes create magnetic islands centered around their resonant surface. When these islands overlap, (as is often the case in the RFP), the resulting stochastic field lines cause a loss of core confinement.

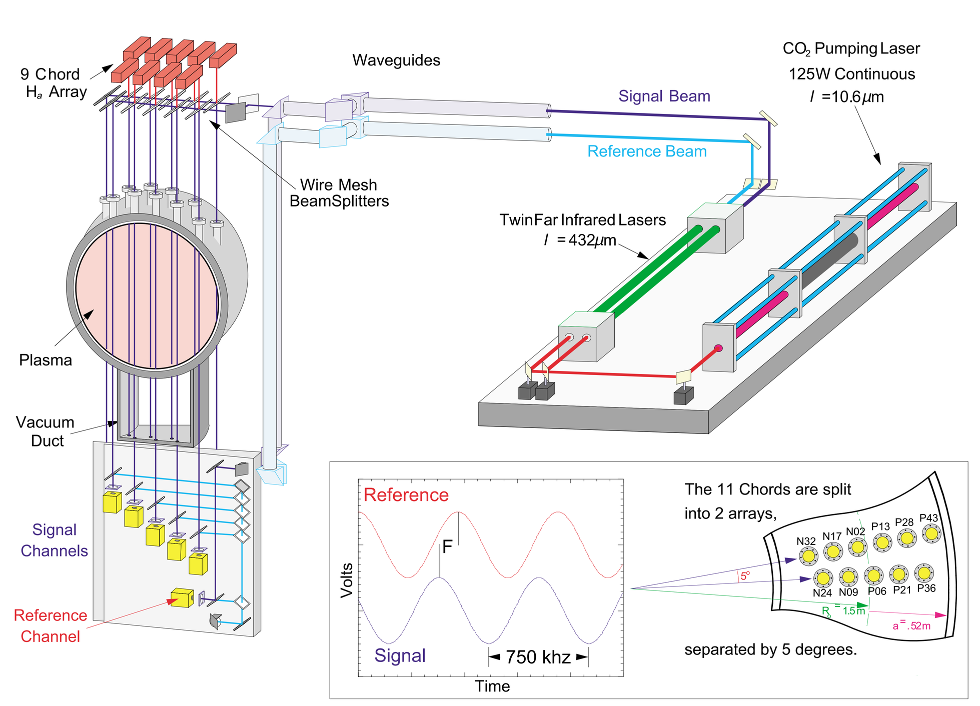
As the current profile becomes more peaked, tearing modes can become unstable. After some critical threshold is passed, a sawtooth relaxation event occurs, the tearing mode amplitudes become large and confinement is degraded. The tearing modes nonlinearly couple and drive dynamo current in the edge. This flattens the current profile, returning to more relaxed state. The current profile begins to peak again due to the peaked temperature profile and the cycle starts again.

During Pulsed Poloidal Current Drive (PPCD), poloidal current is driven in the edge of the plasma in an attempt to keep the plasma near a minimum energy state. This is observed to result in a reduction in tearing mode amplitudes accompanied by an increase in confinement time. This enhanced confinement period can last more than 10 ms. While this phenomenon is well established, it is not well understood.

The increase in confinement seen with PPCD indicates that current profile control can provide a method to reduce tearing mode driven transport. Oscillating Field Current Drive (OFCD) can drive current by injecting helicity into the RFP plasma.

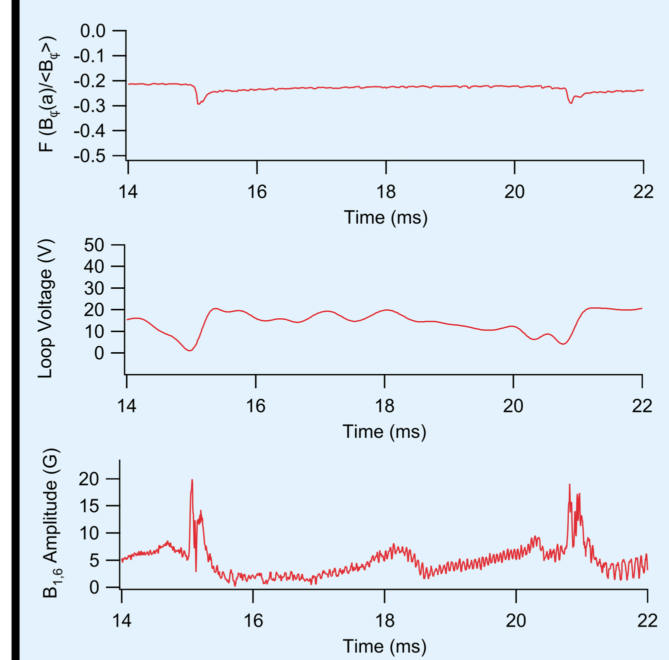
Far Infrared Polarimeter and Interferometer System

The MST Far Infrared Interferometer/Polarimeter system consists of dual FIR laser cavities pumped by a CO_2 laser. The beam is split using wire meshes and directed through 11 chords into the plasma. The two cavities have a difference frequency of 750 kHz. This is typically digitized at a rate of 1 MHz, aliasing the signal down to 250 kHz. This gives a time resolution of ~4 μs.



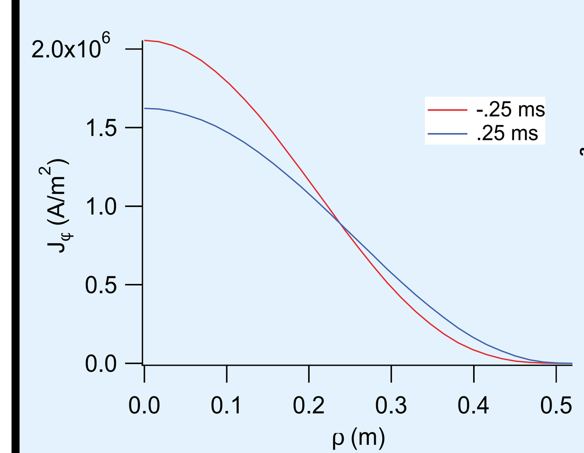
The Current Profile Flattens After a Sawtooth Crash

Fluctuations increase and confinement drops after a sawtooth

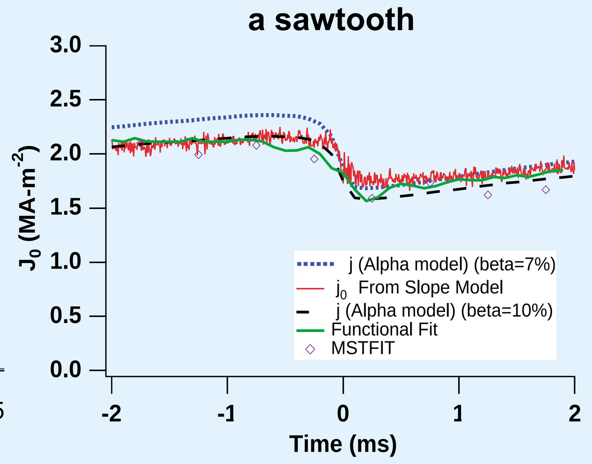


During the sawtooth crash, tearing mode fluctuation amplitude is increased while core confinement is decreased. Dynamo current is driven through nonlinear coupling of the tearing modes. This dynamo current is anti-parallel to the applied toroidal electric field in the core and parallel in the edge.

The toroidal current profile broadens after a sawtooth crash

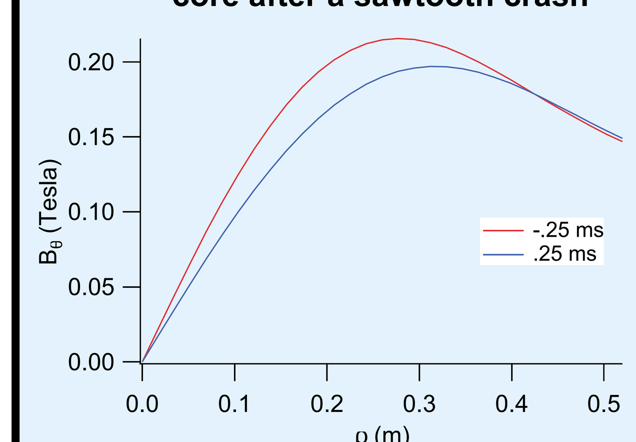


Other models also show a decrease in on axis current after a sawtooth



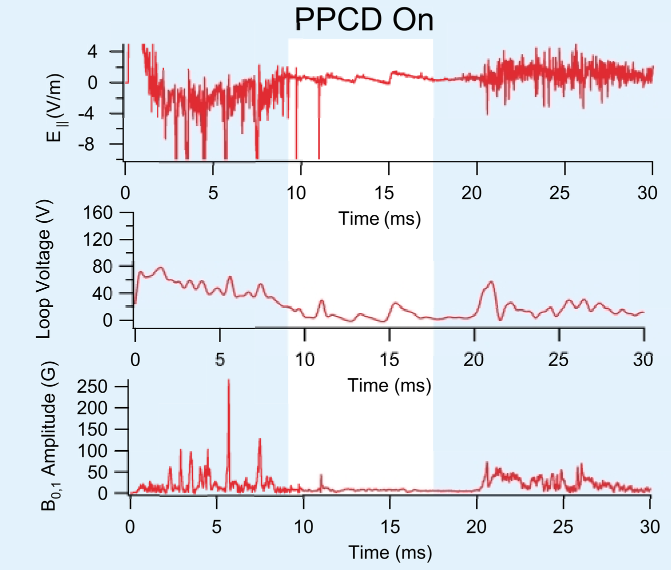
Measurements of the toroidal current profile over a sawtooth crash show that the profile peaks leading up to the crash then broadens afterward. The current on axis drops by 25%. Other models can predict the on axis current. All models agree that the current density drops after the sawtooth crash.

The poloidal field decreases in the core after a sawtooth crash



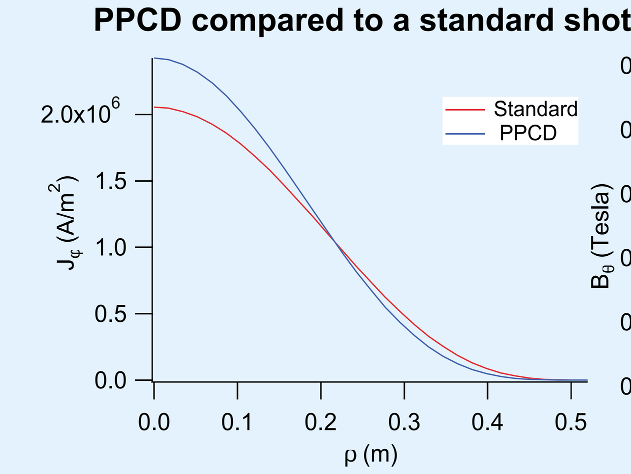
The poloidal magnetic field exhibits a decrease near the core of the plasma after a sawtooth crash. This represents a net loss of poloidal flux.

During Pulsed Poloidal Current Drive, The Current Profile Peaks

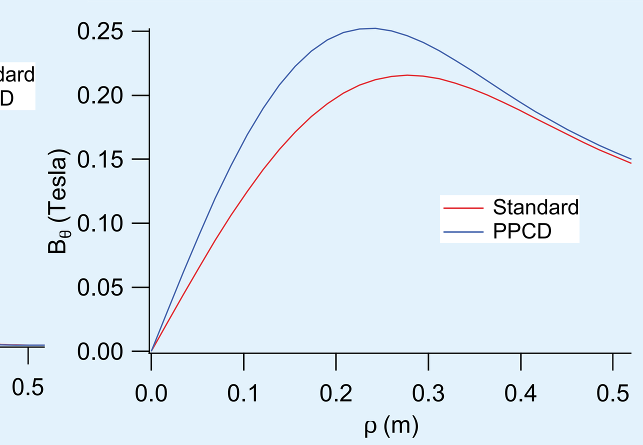


During PPCD, poloidal current is driven in the edge to alleviate the necessity of driving dynamo current. Tearing mode activity is observed to decrease and core confinement can increase by a factor of 9.

Toroidal current profiles peak in PPCD compared to a standard shot

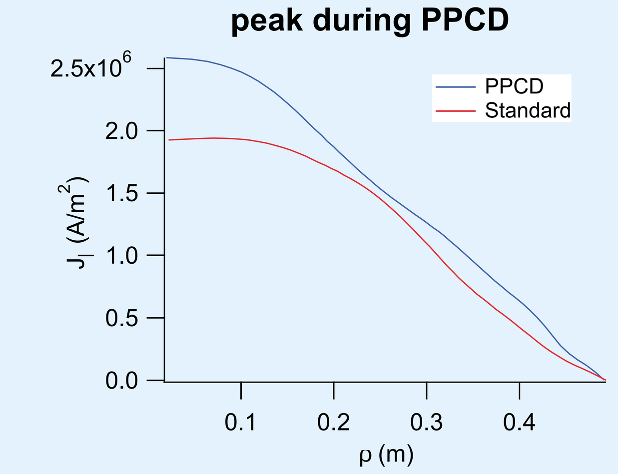


The poloidal magnetic field increases in the core in PPCD



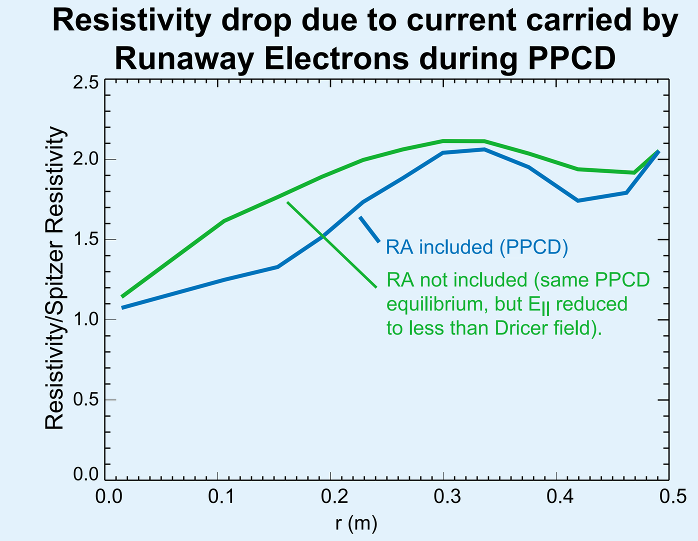
The toroidal current profile peaks during the enhanced confinement period of PPCD. The poloidal field in the core also increases.

Parallel current profiles also peak during PPCD



.The parallel current profile is also observed to increase during PPCD relative to a standard shot. An increase of ~25% over a standard shot in the on axis current is seen.

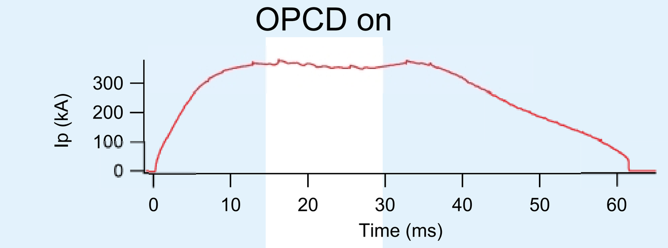
Resistivity drop due to current carried by Runaway Electrons during PPCD



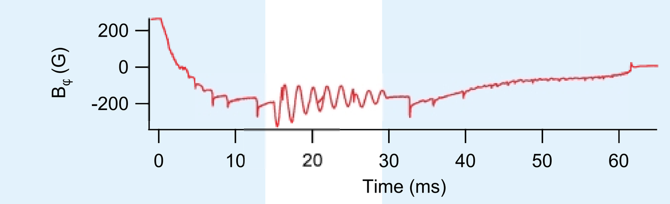
An increase in hard X-ray flux during PPCD is an indication that confinement of fast electrons is improved. Modeling (see poster by O'Connell) suggests that these fast electrons can carry 25% of the current in the core during high confinement periods. This provides a possible contribution to the peaking of the current profile.

Oscillations in the Poloidal Magnetic Field Are Seen During Oscillating Poloidal Current Drive (OPCD)

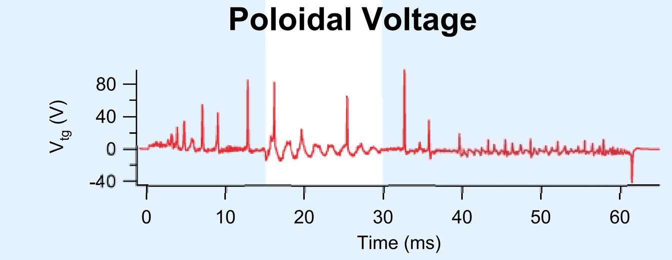
Shot 1010727100 Plasma Current



Edge Toroidal Magnetic Field

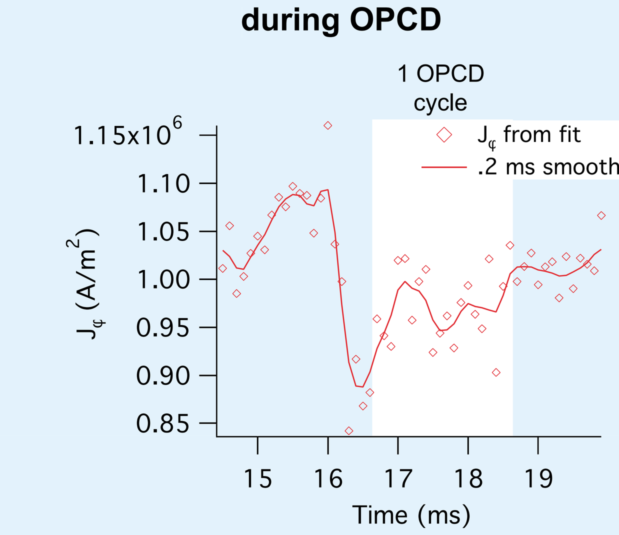


Poloidal Voltage



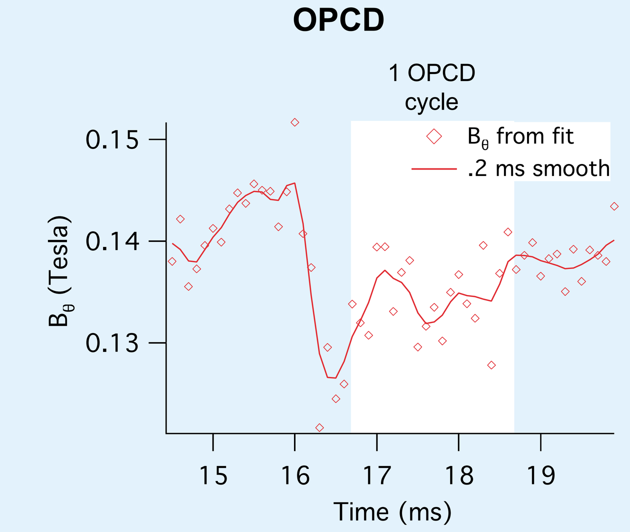
Oscillating field current drive (OFCD) is an attempt to drive current by the application of toroidal and poloidal currents with the correct phase. Preliminary tests on MST have used only the poloidal current component (OPCD).

On axis toroidal current during OPCD



During OPCD the applied current is in the poloidal direction therefore only directly affecting the toroidal field. However, an oscillation at the OPCD frequency (500 Hz) is seen in the on axis current and the poloidal field.

Poloidal Field at r/a ~ .5 during OPCD



Using Nonlinear Techniques, a Current Profile Can Be Found to Fit the Polarimeter Data

A nonlinear fitting routine is used to determine the toroidal current profile. The toroidal current density is assumed to have the form

$$J_\varphi = \alpha_1\left(1-\left(\frac{r}{a}\right)^2\right)^{\alpha_2}$$

where α_1 and α_2 are free parameters and a is the minor radius. Another free parameter determines the location of the magnetic axis. Using other trial functions had no large effect on the shape of the fitted current density profile for standard and PPCD shots. The flux surface geometry is approximated as nested circles with a Shafranov shift which varies quadratically as a function of radius. For a given set of parameters, the poloidal magnetic field in the cylindrical approximation can be determined using Ampere's law

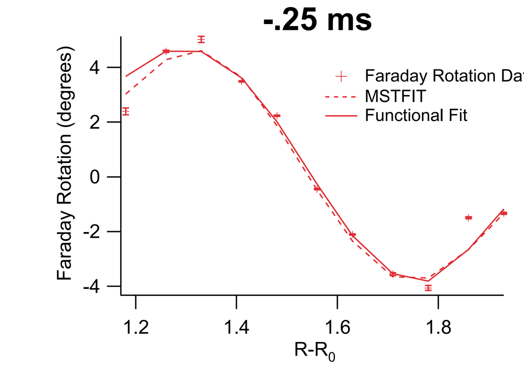
$$\mu_0 J_\varphi(r) = \frac{1}{r}\frac{d[rB_{\theta,cyl}(r)]}{dr}$$

Toroidal curvature effects are included under the large aspect ratio expansion as

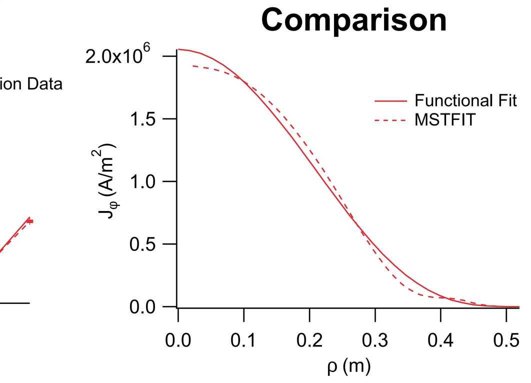
$$B_\theta(r) = B_{\theta,cyl}(r)\left[1-\left(\frac{r}{R_0}+\frac{d\delta(r)}{dr}\right)\cos(\theta)\right]$$

where R_0 is the major radius and δ(r) is the Shafranov shift as a function of radius. The poloidal field profile in conjunction with the density profile can then be used to calculate the Faraday rotation on each chord. The fitting routine then finds the set of parameters which minimizes the deviation from the measured polarimetry data and total toroidal current.

Faraday rotation fit at -.25 ms



Toroidal Current Profile Fit Comparison



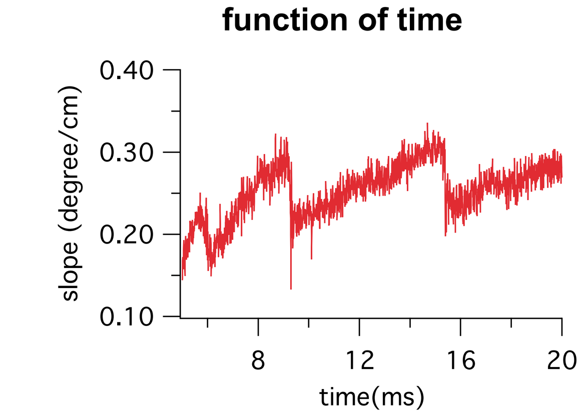
The current profile (and other quantities) can also be determined using MSTFIT, a Grad-Shafranov equilibrium solver. The toroidal current and poloidal field profiles found by each code are similar as seen in the diagrams to the left showing fits from both at .25 ms before a sawtooth crash.

Finally, a third method to determine the on axis current is by computing the slope of the Faraday rotation measurement at the magnetic axis. The current on axis is then given by

$$J(0) = \frac{2}{\mu_0 c_F}\frac{d\Psi}{dx}\frac{1}{\int n_e f(r,\beta)dz}$$

where Ψ is the measured Faraday rotation, c_F is a calibration factor, and f(r,β) is a profile shaping factor. This method can have a good time response as seen in the figure below.

Variation of Faraday Slope as a function of time

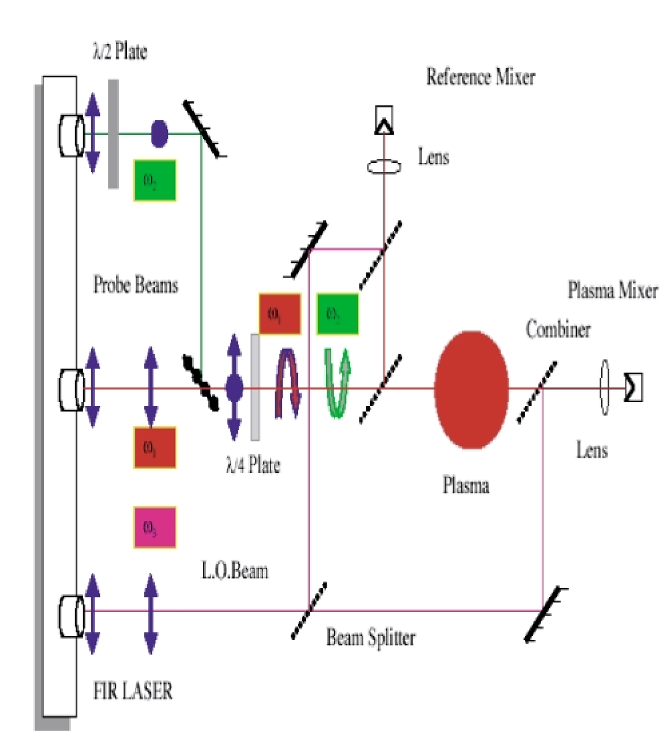


The Polarimetry Upgrade Allows the Measurement of Faraday Rotation With Fast Time Resolution.

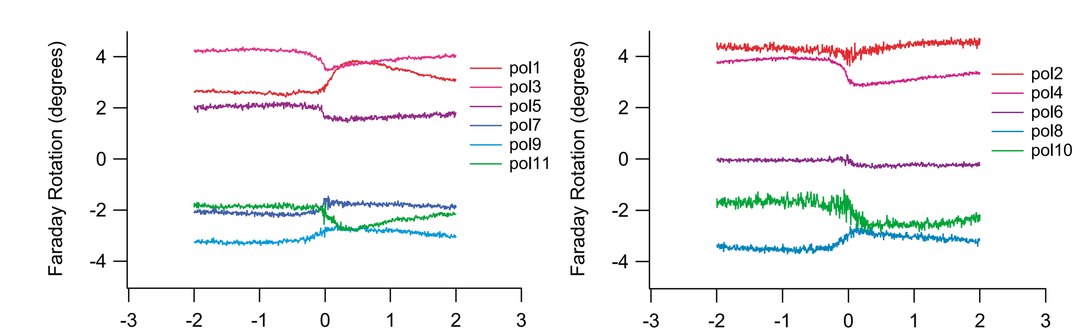
By using two counter rotating, circularly polarized beams to probe the plasma, the Faraday rotation can be measured. The diagram shows how each linearly polarized FIR beam is transformed into a circularly polarized beam by passing through a quarter-wave plate. Since each beam experiences a different index of refraction, there will be a phase shift between them after they propagate through the plasma. This phase shift is proportional to the product of the density and the component of the magnetic field parallel to the FIR beam. With a third beam acting as a reference, the density can be simultaneously determined.

At the present time, only two beams are in place. To obtain both polarimetry and interferometry data, many shots (~100) must be taken in polarimetry mode. Then, the system can be converted to interferometer mode and more shots taken. The data can then be ensemble averaged and used together. Care must be taken to only include similar shots in the ensemble.

Layout of the Polarimeter Upgrade



The fast time response of the Faraday rotation measurement can resolve changes resulting from the sawtooth crash



The fast time response of the polarimeter can be seen in these ensembled Faraday Rotation traces. The time axis is given relative to a sawtooth event. The traces are bandpass filtered with a bandwidth of 20 kHz. The fast changes in the plasma poloidal field and density due to the sawtooth are seen on all chords.

Future Work

By adding a third FIR cavity, a reference beam can be added so that line integrated density can be measured simultaneously with Faraday rotation. This will allow single shot measurements of the toroidal current profile at a fast time resolution.

Measurements of the toroidal and parallel current profiles will allow analysis of the tearing mode stability of the MST plasma. Linear codes (RESTER) and nonlinear (DEBS, NIMROD) are available to perform this analysis. Also, the origin of the current profile shaping in PPCD and its effect on stability can be analyzed.