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Internal magnetic field measurements by laser-based POlarimeter-INTerferometer (POINT) system on EAST

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Abstract: A multi-channel far-infrared laser-based *PO*larimeter-*INT*erferometer (POINT) system utilizing the three-wave technique has been implemented for fully diagnosing the internal magnetic field in the EAST tokamak. Double-pass, horizontal, radially-viewing chords access the plasma via an equatorial port. The laser source consists of three CW formic acid (HCOOH) FIR lasers at nominal wavelength 432.5 μm which are optically pumped by independent infrared CO_2 lasers. Output power is more than 30 mW of per cavity. Novel molybdenum retro-reflectors, can with withstand baking temperature up to 350°C and discharge duration more than 1000 s, are mounted in the inside wall for the double-pass optical arrangement. A Digital Phase Detector with 250 kHz bandwidth, which provide real-time Faraday rotation angle and density phase shift output for plasma control, have been developed for the POINT system. Reliability of both polarimetric and interferometric measurement are obtained in 22 s long pulse H mode discharge and 8 s NBI H mode discharge, indicating the POINT system works for any heating scheme on EAST so far. The electron line-integrated density resolution of POINT is less than $1 \times 10^{16}\,\mathrm{m}^{-2}$ ($< 1°$), and the Faraday rotation angle rms phase noise is $< 0.1°$. With the high temporal ($\sim 1\,\mu$sec) and phase resolution ($< 0.1°$), perturbations associated with the sawtooth cycle and MHD activity have been observed. The current profile, density profile and safety factor (q) profile are reconstructed by using EFIT code from the external magnetic and the validation POINT data. Realtime EFIT with Faraday angle and density phase shift constraints will be implemented in the plasma control system in the future.

Keywords: Polarimeters; Plasma diagnostics - interferometry, spectroscopy and imaging

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Contents

1 Introduction

Achievement of long pulse and steady-state plasma regimes is a major challenge for both ITER and prospective fusion power reactors. Presently-operating devices have produced candidate scenarios for many relevant fusion targets, including the ITER baseline, alternate ITER inductive scenarios, and a variety of high performance steady state regimes. While establishing the optimization and parameters of future reactor operating scenarios has been addressed, a critical step before ITER requires qualification of these high-performance scenarios in long-pulse plasmas (i.e. time scale of many resistive relaxation times and longer than the wall equilibration time). A primary goal of the EAST device is to develop long-pulse high-performance plasmas near the operational (MHD and beta) limits using ITER relevant actuators (NBI and RF current drive and heating) and sensors. The goal of plasma discharge extension to long pulse is important for demonstrating that the current profile relaxes to a steady-state and that no stability boundary is crossed during this evolution that would compromise performance.

Knowledge of the poloidal magnetic field profile, $B_\theta(r)$, along with the associated toroidal current distribution, $J_\phi(r)$ and safety factor $(q(r) = rB_\phi/RB_\theta)$ is essential to the understanding of both tokamak plasma stability and confinement [1, 2]. The stability of the plasma to tearing modes and other magnetohydrodynamic (MHD) events such as the sawtooth perturbation and disruptions are largely determined by the current density profile, which is also a key issue and studied on EAST tokamak [3]. In order to address the critical issues of current profile distribution and temporal evolution, a laser-based Faraday effect polarimetry-interferometry diagnostic is being developed on EAST [4–6], named POlarimeter-INTerferometer (POINT). POINT system, which provides a non-perturbing probe of the core magnetic and current density profiles of high-performance plasmas, will focus on real-time plasma control for up to 100 second discharges in order to extend high-performance plasma regimes to long-pulse with ITER-like scenarios. The realtime output of this system will be used to monitor the fast profile dynamics of electron density, current density and q (safety factor) and ultimately be integrated into the realtime plasma control system. Here it will be critical to assess the utility and explore the limits of line-integrated measurements (density and Faraday effect) for plasma optimization and control.

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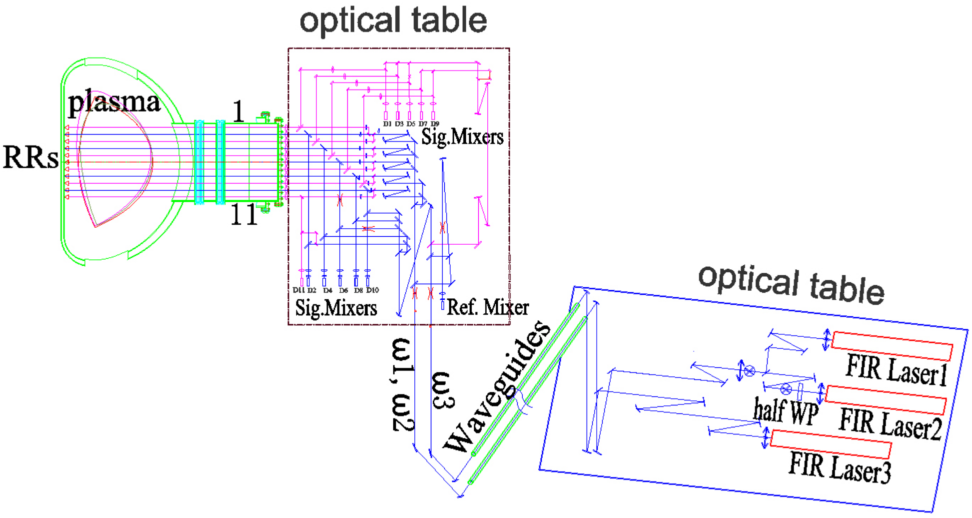

Figure 1. 11 channels optical layout of the EAST POINT system, 5 channels (blue) is installed in 2014 with expansion to 11 channels (with added 6 channels in pink) in 2015.

In this paper, we present initial experimental results from the multi-chord, double-pass, POINT being developed on EAST, during the 2014 experimental campaign, the POINT system has been employed for the first time to measure the electron density, current density and safety factor profiles for long-pulse EAST plasmas. Multi-chord output provides internal plasma constraints to EFIT reconstructions allowing the temporal dynamics of key equilibrium profiles to be determined. Examples are shown for long-pulse plasmas with RF current drive as well as for high-performance H-mode plasmas. Of particular interest are the temporal dynamics of the L to H transition in EAST where current relaxation occurs and MHD modes evolve.

2 EAST polarimeter-interferometer

The three wave polarimeter-interferometer, which may provide poloidal magnetic field distribution with simultaneously measured density distribution, is a popular configuration which was originally proposed by Dodel and Kunz [7]. The three wave configuration has been demonstrated to work successfully on several plasma experiments including RTP, MST, J-TEXT, Alcator C-Mod [8–12]. EAST polarimeter-interferometer, double-pass, horizontal, radially-viewing chords access the plasma via an equatorial port is also based on three-wave technique, has been described detailed in former publication [4–6]. Initially a five-chord system was installed in 2014 and an eleven-chord system is implemented on the core region of EAST plasmas in 2015, which is located at $z = -42.5$, -34, -25.5, -17, -8.5, 0, 8.5, 17, 25.5, 34, 42.5 cm along the vertical direction (0 cm is the plasma center). The initially five-chord is located at $z = -34, -17, 0, 17, 34$ cm along the vertical direction, as blue chords shown in figure 1. The first results of five chords measurement are presented.

Three wave utilized three CW formic acid (HCOOH) FIR lasers at nominal wavelength 432.5 μm, which are optically pumped by independent infrared CO_2 lasers. Output power is more than 30 mW of per cavity. Two lasers, with slight frequency offset (~ 1 MHz), is made collinear with counter-rotating circular polarization in order to determine the Faraday effect by measuring

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their phase difference, ψ_F,

$$\psi_F = 2.62 \times 10^{-13} \lambda^2 \int n_e B_{\|} dl, \tag{2.1}$$

where λ is the wavelength of the beam, dl is the plasma path length, and $B_{\|}$ in Tesla is the magnetic field component along the bearm. The third laser also frequency offset, is used as a reference providing local oscillator (LO) power to each detector so that one can obtain the phase shift caused by the plasma electron density.

$$\varphi = 2.82 \times 10^{-15} \lambda \int n_e dl\,. \tag{2.2}$$

Output power of each FIR cavity can reach a typical average stable power is at around 20 mW for long time operation. Meanwhile, VDI planar-diode Integrated Conical Horn Fundamental Mixers optimized for high sensitivity, typical value is 750 V/W, will be used. It is sufficient to provide good signal quality for the polarimeter/interferometer system.

The triple laser system was placed on the laser table in the laser room in the basement of EAST building, which is just outside the machine hall. The laser room can provide a thermostatic, vibration-free, electromagnetic shielded environment for lasers. Two orthogonal beams are combined here then guided to the optical tower in the machine hall, together with LO beam through two ~ 20 m length waveguides. Optical stability is always an important issue in FIR optical diagnostics. To avoid the vibration caused by the tokamak, a massive stainless steel tower, independent from the EAST machine, is constructed to ensure the stability of beam-processing optics. All optical components will be mounted on one optical board which is installed on the tower. The optical tower is located near the EAST tokamak and besides the diagnostic window for POINT system. It is isolated from the machine and all optics and detectors near the machine are installed on it. The probe beam is split up into individual channels. Probe beams are converted to counter-rotating circular polarization by a quarter waveplate. The probe beams are combined with the LO beam after double pass through plasma along the horizontal direction reflecting by the cube corner retro reflectors in the inner vacuum wall. All intermediate frequency (IF) signals will be processed by an amplifier and filter module and then sent into a high-speed digital phase detector to extract the phase shift information, from which Faraday rotation angle profile and current density profile can be calculated by using EFIT code for EAST.

In the POINT system, the in-vessel retro reflectors are the key components, determining the Gaussian beam propagation size along the laser beam path and the final system accuracy. The retroreflectors are behind the inner-wall tiles and protected by a shutter that is closed during wall conditioning and is opened only when the polarimeter/interferometer system needed. Novel molybdenic retro-reflectors with shutter protection have been mounted on the inner vessel wall in EAST. The retro-reflectors can withstand 350°C baking temperature and 1000 s discharge duration. The accuracy of the retro-reflctors is up to 20 arcsec.

For long term goals include using POINT data, in conjunction with other diagnostic systems, for feedback control in order to maintain stable operation of high-performance tokamak plasmas while avoiding deleterious MHD events such as disruptions and ELMs. Stable Intermediate frequencies (IFs) among the three FIR lasers and real-time output of the electron density and current density are important and necessary. This is especially the case for 1000 s long-pulse discharges in the

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EAST tokamak. A closed-loop control system is developed to stabilize the IFs at a pre-set value based on an automatic control of the cavity length using a piezoe-lectric transducer (PZT). A stable IF signal over a long time period (up to hours) is obtained with the help of this frequency control system. The output IF drift is lower than 0.6% for a 1 hour (3600 seconds) test. Meanwhile, a Digital Phase Detector (DPD), prototype hardware is based on a PCI card that combines a very high speed Field Programmable Gate Array (FPGA), with 250 kHz bandwidth has been developed for use on POINT system. The DPD is used to perform phase demodulation and real-time density calculations, provides real-time Faraday rotation angle and density phase shift output for use in plasma control system. Real-time EFIT with Faraday angle and density phase shift constraints is planned for implementation in the plasma control system in near future. The DPD samples a reference and plasma signal each containing the three frequency bands of information, currently centered at 0.850, 1.275 and 2.125 MHz with about a 100 kHz tolerance. With input signals from the signal and reference mixers, DPD output for each chord corresponds to the plasma density (1.275 MHz) and Faraday-effect (0.85 MHz). This stability is necessary for POINT operation with the long term goal to provide real-time input to the plasma control system.

3 Experimental results

The first results of both polarimetric and interferometric measurement of five-chord POINT are obtained in 2014 experimental campaign. Reliability of both polarimetric and interferometric measurement are obtained in 22 s long pulse H mode discharge with low hybrid wave (LHW) current drive as well as for high-performance H-mode plasmas with neutral beam injection (NBI), as shown in figure 2 and figure 4, indicating density gradient in H mode dose not impact POINT measurement and the POINT system works for any heating scheme on EAST so far. The electron line-integrated density resolution of POINT is less than 1×10^{16} m^{-2} ($< 1°$), and the Faraday rotation angle rms phase noise is $< 0.1°$. With the high temporal (~ 1 μsec) and phase resolution ($< 0.1°$), perturbations associated with the sawtooth cycle and MHD activity have been observed, as shown in figure 3. The time resolution of vertical view HCN laser interferometer system is 10 kHz. The horizontal view POINT interferometer has 1 MHz time response. So POINT system can provide better quality data for plasma control experiments.

A comprehensive method to self-consistently reconstruct the current and profiles with magnetic and POINT measurements by using the equilibrium fitting code EFIT was developed [13]. The current profile, density profile and safety factor (q) profile are reconstructed by using EFIT code from the external magnetic and the validation POINT data. Typical multi-channel polarimeter-interferometer data and inversion analysis are shown in figure 4(b), (c) for a high performance H mode plasma with 2.3 MW NBI, $B_T = 2$ T, $I_p = 500$ kA, central line average density 3.5×10^{19} m^3, elongation = 1.6, $\beta_N = 1.8$ and storage energy = 200 kJ, as shown in figure 4(a). Figure 4(b), (c) show the actual line-integrated density measurements and Faraday rotation measurements are compared with the results computed from EFIT (magnetic equilibrium reconstruction) for five channels. At each chord location, the measurements are consistent with EFIT estimates of line average density and the Faraday effect. This agreement also supports the claim that the toroidal magnetic field is having no deleterious effect on the measurements. Noise seen in the phase both before and after the discharge is related to vibrations and stray B effects. Next, the Faraday

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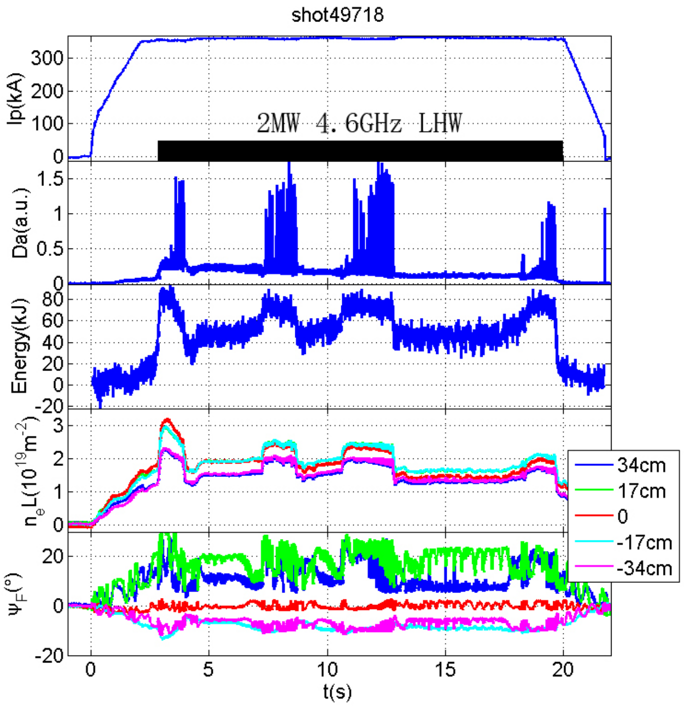

Figure 2. Typical measured waveform from POINT in 2MW 4.6 GHz LHW discharge, shot No. 49718.

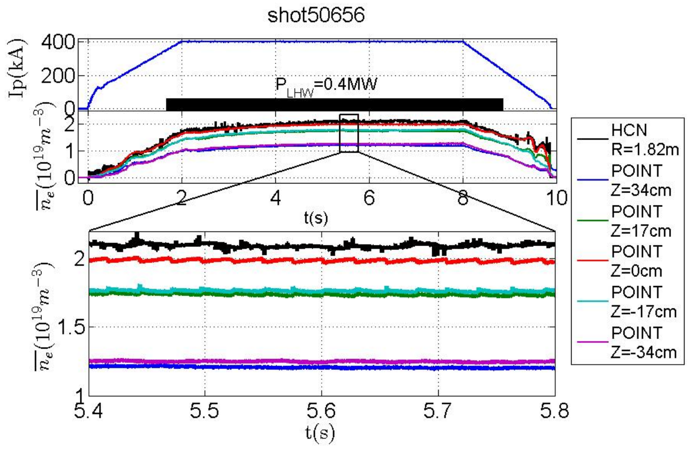

Figure 3. Comparision between HCN interferometer and POINT interferometer. Sawteeth events are clearly observed on density, indicating fast time resolution of POINT system, shot No. 50656.

measurements as a constraint on the magnetic equilibrium reconstruction will show an effect core current profile and q profile.

Two time points, 3.1 s in H mode and 4.6 s in L mode, are chosen for the typical analysis and EFIT plus validation POINT magnetic equilibrium reconstruction. In figure 5(a), (c), measure data points are reprensted by the open rectangle. To obtain the component of the poloidal magnetic field along the laser beam path, the inverse integrated values by EFIT are plotted in dashed line, are spline fit with measurments. The central line average density is about $3.5 \times 10^{19}\,\mathrm{m}^3$ in H

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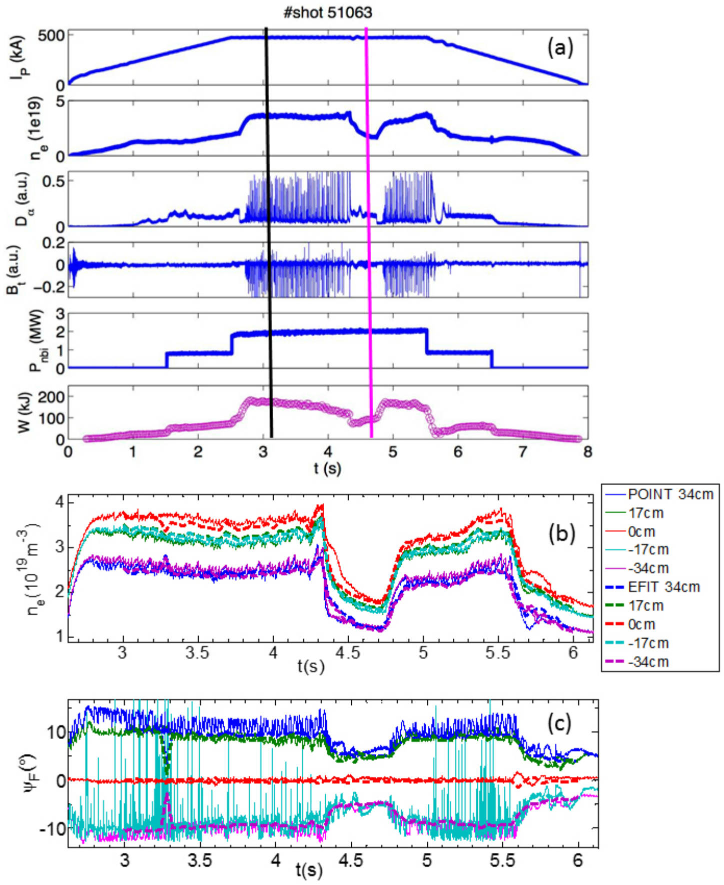

Figure 4. Typical multi-channel POINT data from EAST NBI H mode discharge. Overplotted using dashed lines are results from POINT measurement and EFIT reconstruction. The data from top to bottom are the plasma typical parameter (a), line-averaged density by POINT measurement (solid lines) and inverse integrated analysis by using EFIT reconstructed (dashed lines) (b), line-integrated Faraday rotation angle by POINT measurement (solid lines) and inverse integrated analysis by using EFIT reconstructed (dashed lines) (c).

mode phase and 2×10^{19} m^3 in L mode phase. The maximum value of Faraday rotation angle is about 10° in H mode phase and 5° in L mode phase. The measurements are consistent with EFIT inversed integrated values. The measurements of line average density and the Faraday rotation angle are self-consistent. Identification of the magnetic axis corresponds to the zero crossing of the polarimeter data. The position may be shifted with respect to the vaccum vessel centre depending on the externally applied vertical magnetic field or vertical instability. This serves as a cross check as to the consistency of the computed profiles with respect to the experimental data as well as the time resolution comparision in figure 4(b), (c). Then use the POINT measurements as core constrain to do the magnetic equilibrium reconstruction by EFIT. The electron density profile and current density profile are obtained, as shown in figure 5(b), (d) respectively.

Due to the specific of polarimeter, the constraint mainly affect in core plasma region. Further validation of POINT measurements with $q = 1$ surface position is available. Sawtooth is a Magneto-Hydro-Dynamic (MHD) instability in the core plasma region, which is often observed by ECE and

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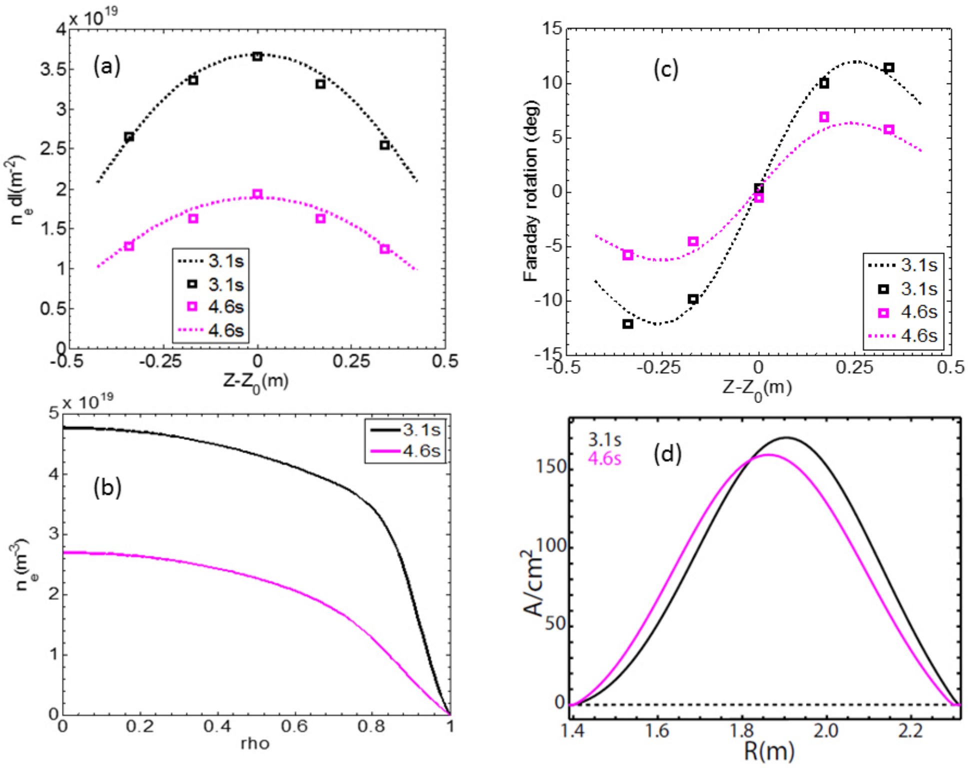

Figure 5. Typical profiles from POINT of EAST NBI H mode discharge. Overplotted line integrated density results from POINT measurement (rectangle) and inverse integrated analysis by using EFIT reconstructed (dotted lines) (a), density profiles by using EFIT reconstructed with POINT data (b), overplotted line integrated Faraday rotation angle results from POINT measurement (rectangle) and inverse integrated analysis by using EFIT reconstructed (dotted lines) (c), current profile by using EFIT reconstructed with POINT data (d).

SXR. The existence of sawteeth are considered associated with $q_{\mathrm{min}} < 1$. And also the radius of $q = 1$ rational surface can be approximated by the inversion radius of sawtooth. As is shown in figure 6, existence of sawtooth is shown in green strip in the time scale, which determined by ECE and SXR diagnostics. The q_{min} should stay below one during the whole sawtooth period. The EFIT magnetic equilibrium reconstruction only with magnetic coil data, the q always more than 1 even if the sawtooth existence phase. After add the POINT data constrains, as shown in the blue open rectangle, the q_{min} less than 1 during the sawtooth existence. So the quality of the current profile reconstruction can be verified with the locations of $q = 1$ rational surface. A $q = 1$ surface is established in the plasma. At 3100 ms and 5000 ms, the inversion radius of sawtooth on 1.8 m (high field side) and 2.04 m (low field side) is observed clearly by ECE. This is in good agreement with the q profile reconstructed by using POINT data, shown in figure 6. Another q profile is overlaid at 5800 ms when sawtooth disappears. Again, the reconstructed q profile shows good agreement with the experimental observation. The minimum q is well above the unity, in consistent with sawtooth suppression. The q_{min} stays below one during the sawtooth period. This technique can provide a useful alternate method that can be used to provide a reasonably accurate determination of the current profiles for the tokamaks without MSE diagnostics. Further, identification of the magnetic

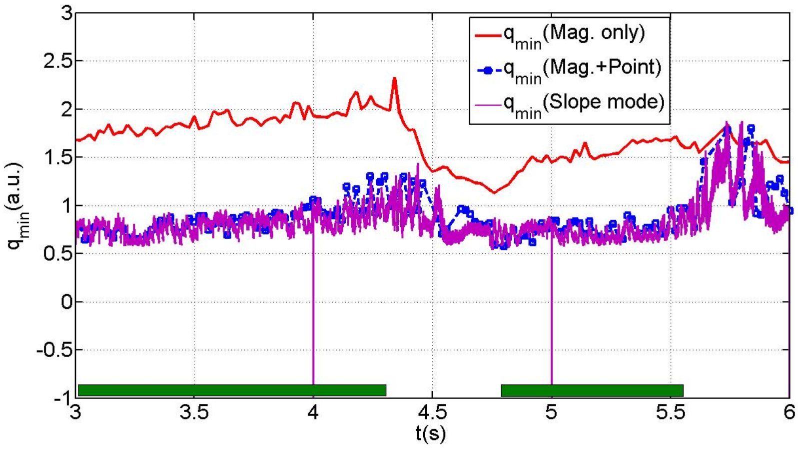

Figure 6. $q_{\min}$ temporal evolution in 51063# by using EFIT reconstructed with only magnetic coils data (red solid line), EFIT reconstructed with magnetic coils data and POINT data (blue dashed line with rectangle) and by using slope model from POINT measurement only (pink solid line with dot).

axis corresponds to the zero crossing of the polarimeter data. For the monotonic q profile, the $q_{\min}$ is equal to q. The q_0 corresponds to the zero crossing of polarimeter data, can be derived from polarimeter data by using the simple slope model, as the pink line shown in figure 6, which also shows good agreement with the EFIT $q_{\min}$ and the $q = 1$ surface by ECE and SXR diagnostics. This validation show the POINT measurments are quite effective data for core plasma constrains.

So the POINT provide a reasonably accurate determination of the current and q profiles for EAST tokamak. It can also be used in conjunction with MSE data and other internal information in future. As shown in figure 7, the current profiles and q profile by using EFIT reconstruction with POINT data demonstrated the current profiles temporal evolution just before H-L back transition. POINT become provide a very useful tool for current and q profiles for EAST tokamak and also for MHD research.

4 Summary and future plans

A five-chord layout has been installed with expansion to 11 chords in 2015 fully diagnose the core region of EAST plasmas. A Digital Phase Detector with 250 kHz bandwidth, which will provide real-time Faraday rotation angle and density phase shift output for use in plasma control, have been developed for use on the POINT system. Reliability of both polarimetric and interferometric measurement are obtained in 22 s long pulse H mode discharge and 8 s high performance H mode discharge, indicating the density gradient in H-mode discharge does not impact POINT measurements and that system works for any heating scheme on EAST so far. The electron line-integrated density resolution of POINT is less than $1 \times 10^{16}\,\mathrm{m}^{-2}$ ($< 1^\circ$), and the Faraday rotation angle rms phase noise is $< 0.1^\circ$. With the high temporal ($\sim 1\,\mu$sec) and phase resolution ($< 0.1^\circ$), perturbations associated with the sawtooth cycle and MHD activity have been observed. The current profile, density profile and safety factor (q) profile are reconstructed by using EFIT code from the external magnetic and the validation POINT data. Fast time response of POINT permits not only measurement current relaxation but also magnetic and density fluctuations associated with MHD

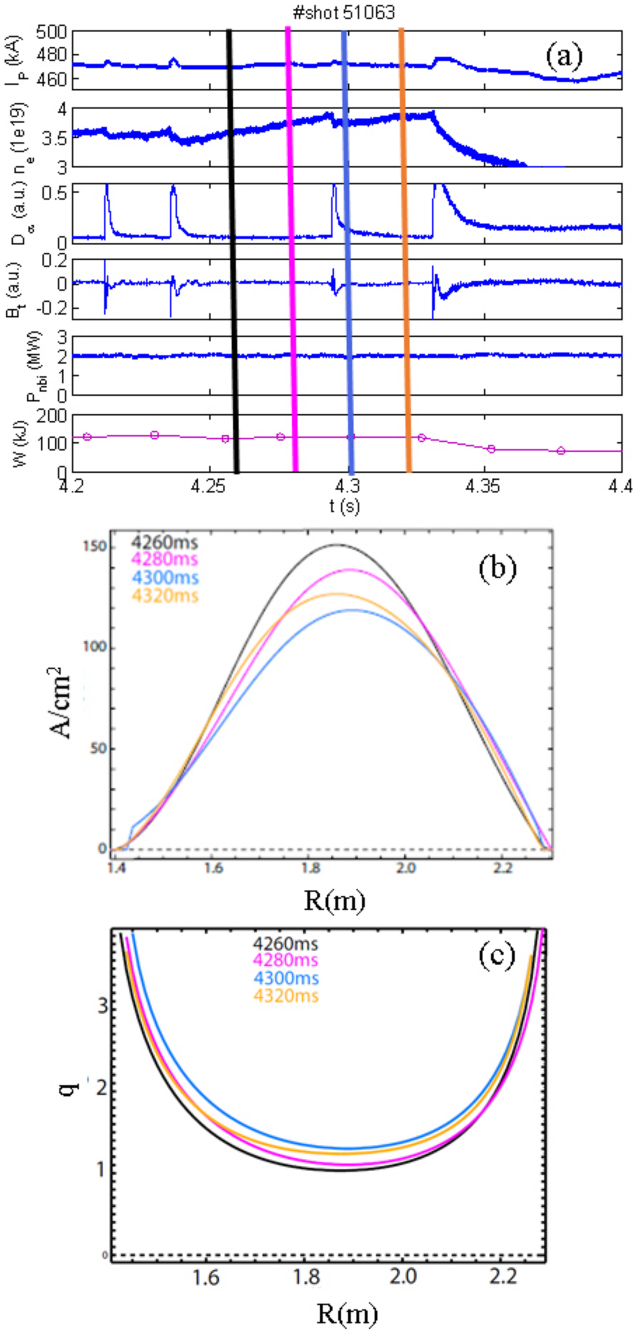

Figure 7. Temporal evolution of current profiles and q profiles before H-L back transition. The data from top to bottom are the plasma typical parameter (a), temporal evolution of current profiles by using EFIT reconstructed with POINT data (b), temporal evolution of q profiles by using EFIT reconstructed with POINT data (c).

effects (tearing modes, NTMs, fast-ion driven modes, etc.) and external magnetic perturbations. Interplay between magnetic fluctuations and current relaxation must be investigated and understood for plasma control optimization. Future plans to upgrade the system and integrate results into

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real-time EFIT (rtEFIT). Long term goals include using POINT data, in conjunction with other diagnostic systems, for feedback control in order to maintain stable operation of high-performance tokamak plasmas while avoiding deleterious MHD events such as disruptions and ELMs in the future.

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