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## Faraday rotation measurements by phase-based technique on HL-2A

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**ABSTRACT:** Poloidal magnetic field is a very important physical parameter for the understanding of heating and confinement in tokamak plasmas. One channel of an eight-chord, horizontally-viewing, double-path interferometer system on HL-2A has been modified to include a polarimeter capability in order to measure Faraday rotation. The polarimeter utilizes one phase technique, which is based on a Veron-type HCN laser interferometer and “Dodel and Kunz”-type polarimeter including a rotating grating to shift the frequency of one probing beam by  $\Delta\omega$ , and two counter-rotating circularly-polarized probing beams. The Faraday rotation angle can be directly determined by measuring the plasma birefringence. The implementation of this instrument only needs one HCN laser source and one detector to characterize the rotation. The first experimental results have shown that the Faraday rotation angle of less than  $1^\circ$  can be measured with up to 0.1 ms time resolution.

**KEYWORDS:** Polarimeters; Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics - interferometry, spectroscopy and imaging

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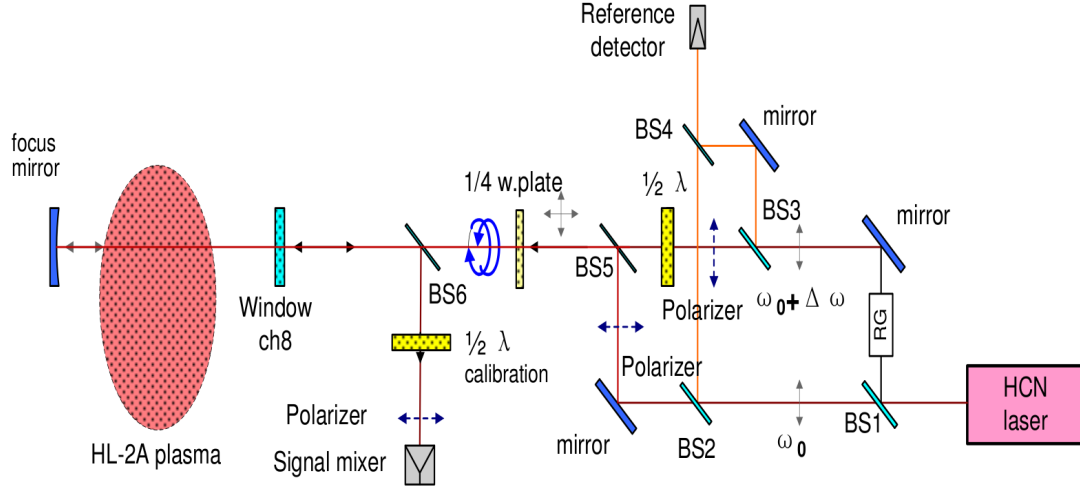
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## 1 Introduction

Fusion device, for example tokamak, is a toroidal system where the plasma is confined by a magnetic field. Plasma current density distribution and poloidal magnetic field profile are very important for study of plasma equilibrium, stability and confinement. In particular, detailed information of poloidal magnetic field is required for understanding negative shear and internal transport barrier confinement mechanism. Among nonperturbing diagnostics developed for poloidal magnetic field measurement, method based on the Faraday rotation effect has been considered as the conventional method and has been proposed for implementation on ITER [1].

The Faraday rotation effect technique was developed based on a rotating polarization ellipse [2] and first successfully implemented on TFR [3]. Then, there are two kinds of techniques had become standard diagnostic on most fusion devices. One is the amplitude measurement of the Faraday rotation angle [4]–[7]. This approach requires two detectors to characterize the rotation for one probing channel, and is sensitive to signal amplitude changes associated with refractive effects. Another approach is triple-laser phase measurement polarimeter [8]–[11]. In this technique, the rotating elliptically polarized wave is replaced by injecting two co-aligned counter-rotating circularly polarized laser beams into the plasma. The two beams, generated by separate FIR laser with slightly offset frequency, experience a different phase delay which can be measured using heterodyne detection techniques.

Motivated by the need for measured information of poloidal magnetic field and current density, the multichannel interferometer system on HL-2A [12] was reconfigured to include one channel polarimeter capability. This approach requires one detector for each chord and entire system requires a single laser radiation source.

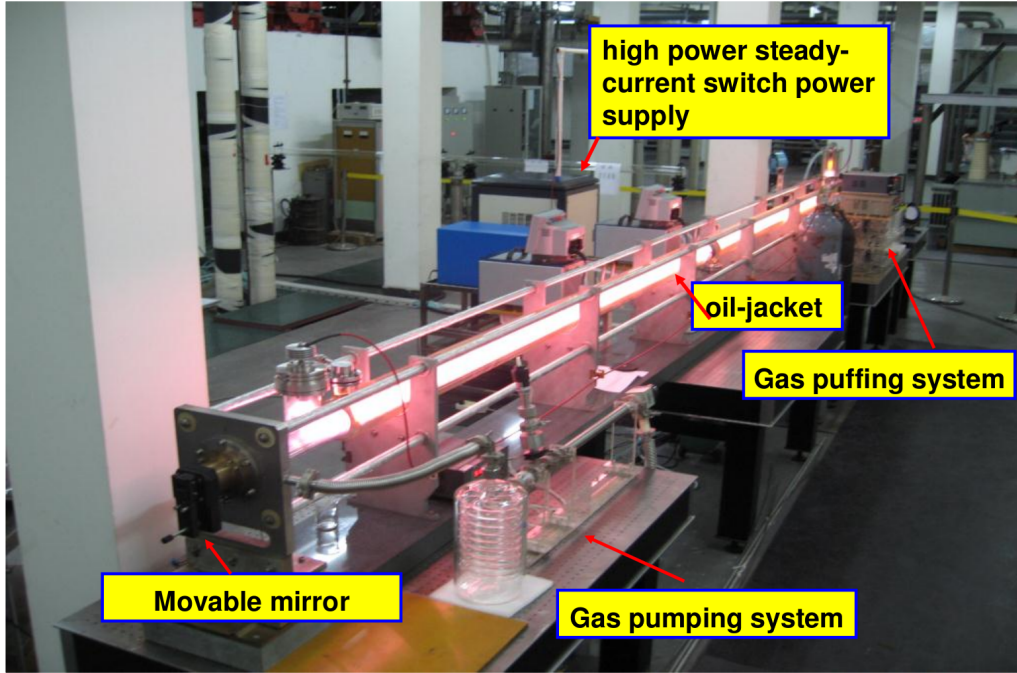


**Figure 1.** Schematic drawing of the polarimeter optical system on HL-2A.

## 2 Experimental arrangements

HL-2A [14] is a mid-size tokamak (major radius  $R = 1.65$  m, minor radius  $a = 0.4$  m) with a closed divertor. It can be operated with plasma current of 150–500 kA, toroidal field of 1.22–2.8 T, average line electron densities of  $1\text{--}5 \times 10^{13} \text{ cm}^{-3}$  and discharge duration of 2–5 s with single-null divertor or limit configuration. On this device, a multi-channel HCN laser interferometer had been installed. Because of triplet multipolar magnetic field coils were set in the divertor chamber, this does not allow vertical probing channel. The eight interferometer chords with vertical spacing 7 cm each other are arranged to view the plasma along horizontal sight lines [12]. In this configuration, the parallel component of  $B$  is related to the poloidal magnetic field. The phase measurement technique that is independent of the amplitude of the signal, requires a rotation grating (diameter 176 mm, number of grooves 1320) in order to produce a second laser beam that is Doppler shifted in frequency by 10 kHz. Recently, to test the feasibility of measurement of Faraday rotation angle by single HCN laser, one channel (ch8) of the eight channel interferometer on HL-2A has been modified to include a polarimetry capability.

The polarimeter is based on a Veron-type HCN laser interferometer [4] and “Dodel and Kunz”-type polarimeter [15] including a rotating grating to shift the frequency of one probing beam by  $\Delta\omega$  and two counter-rotating circularly-polarized probing beams at slightly offset frequency. The two circularly polarized probing beams come from the same laser. The optical measurement principle is schematically shown in figure 1. In this illustration the mirrors are plane reflectors, BS1–BS5 are crystal quartz beam splitters and BS6 is mesh splitter. As crystal quartz beam splitters should spoil the laser line polarization, two polarizers are used to fix the polarized direction before the beams met on the BS6. In this polarimetric experiment two collinear input beams are generated by combining two orthogonal linearly-polarized components, produced by a HCN laser (wavelength  $337 \mu\text{m}$ ), one of which is frequency shifted ( $\sim 10$  kHz) using a rotating grating and has polarization rotated  $90^\circ$  using a  $1/2$  wave plate. The combined beams then pass through a quarter-wave plate thereby generating two counter-rotating circularly-polarized waves. Because of birefringence, each



**Figure 2.** HCN laser system.

beam experiences a different value of the refractive index during propagation through the plasma resulting in a phase delay. This phase difference is equivalent to twice the Faraday effect, which can be directly determined by measuring the mixing product of the two beams and evaluating the phase difference with respect to a reference. The reference and probing mixer signals are digitized and a demodulation algorithm is used to determine the phase using field programmable gate array (FPGA) technique. The electron density profile information can be obtained from the seven-channel HCN laser interferometer, so that the line-integrated poloidal magnetic field at polarimeter chord location can be obtained by formula (2.1).

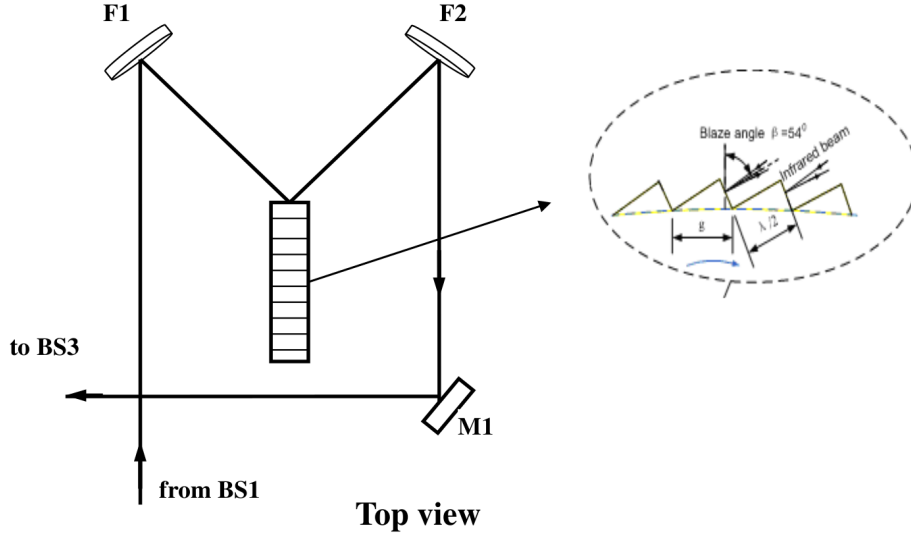
$$\Omega(\omega \gg \omega_p) = \pi/\lambda \int_{Z_1}^{Z_2} (N_+ - N_-) dZ = \frac{\lambda^3 e^3}{8\pi^2 c^3 \epsilon_0 m_e^2} \int_{Z_1}^{Z_2} n_e B_{//} dZ \quad (2.1)$$

where  $\Omega$  is Faraday rotation angle,  $N_+$ ,  $N_-$  refers to the refractive index values of left hand and right hand circularly polarized waves propagated in plasma,  $B_{//}$  is a component of poloidal magnetic field along the probing beam direction,  $\lambda$  is laser wave length,  $(Z_2 - Z_1)$  is a length of probing wave pass through plasma.

### 3 Characteristics of system

#### 3.1 HCN laser with 6 meter long resonant cavity

The HCN laser consists of a resonant cavity of 6 meter long, Pyrex waveguide tube of 68 mm diameter and two plane reflectors (one is mirror, another is mesh) against its ends (see figure 2). The glass tube is surrounded by an oil jacket with temperature about 140°C. The discharge is fed



**Figure 3.** The heterodyne frequency off-set by using a rotating grating.

by a 15 kVA high power steady-current switch power supply. A mixed gas of  $\text{CH}_4$ ,  $\text{N}_2$  and He ( $\text{N}_2 : \text{CH}_4 : \text{He} = 8.8\% : 22.8\% : 68.4\%$ ) is used to obtain the laser oscillation. Meanwhile extra He is added to stabilize the discharge. Because the mixed gas is consumed during discharge, working gas should be puffed into the laser tube continuously. Two flow meters are used to measure and control gas flow rates of mixed gas and He. The output power of the laser is over 300 mW with discharge current of 1.5 A and voltage of 6.7 kV. The laser long term power stability is about 2%.

### 3.2 Rotating grating to produce frequency off-set probing beam

In order to obtain two counter-rotating circularly-polarized probing beams by one HCN laser, a rotating grating (blazed grating) is used to make a measure beam by shifting the frequency of  $\Delta\omega = 2\omega \frac{RW \sin\beta}{c}$ , where  $R$  is the radius of the cylinder grating,  $W$  is grating angular velocity,  $\beta$  the angle of the blaze angle and  $c$  the speed of light. The grating blaze angle is designed of  $54^\circ$ , grating groove width  $g$  of 0.208 mm. Let beam incident at groove surface normal direction (see figure 3), according to the grating equation:

$$2g \sin \alpha = m\lambda \quad (3.1)$$

where  $\alpha$  is the diffraction angle, only  $m = 1$  satisfies this equation. So that the diffracted light central primary maximum is transferred on  $m = 1$ , the diffraction angle is about  $54^\circ$  too. Other diffraction spectra, including  $m = 0$  to be missing. That means the grating just like as a plan reflector. In theory about 80% of the incident laser power is on the return path of  $m = 1$  diffract beam [16]. A concave mirror F1 is employed to set the laser beam waist of  $\phi 10$  mm on the surface of rotating grating. The beam covers about more than 24 grooves; therefore it should avoid any intensity fluctuations of the diffracted beam which could be expected if only a few grooves were involved. On the other hand, this number is small enough and the radius of the cylinder is large enough, so the angle of incidence does not deviate too much from the blaze angle over the whole cross section of the beam, and the curvature of the grating can be neglected. The diffracted beam

is then focused by a mirror F2, identical to F1, in such a way as to give the same divergence and diameter at the recombining beam splitters (BS4 and BS5, see figure 1) as those of another probing beams.

### 3.3 Beam transport with small caliber optical element

In the design and arrangement HL-2A polarimeter optical system, the Gaussian beam theory of propagation has been applied. The diameter of each mirror is generally greater than 2.2 times the beam diameter, which corresponds to a  $1/e$  intensity decrease, in order to have more than 99.9% of the intensity reflected. Because of the HL-2A tokamak mechanical constraint and space limit, the diagnostic windows and optical elements cannot be very large. In order to obtain a reasonable diameter for diagnostic window and the first mirror (the mirror that connects plasma and polarimeter), a spherical focusing mirror has been used mounted on the first wall at the high field side. The beam waist is set at the central of the plasma with diameter of 13 mm. Therefore the size of window can be about 40 mm, and the diameter of the first mirror is about 60 mm.

A Gaussian beam propagation calculation code has been used to simulation the trajectory of the transport of HCN beam by plane and spherical focusing mirror. All optical elements in HL-2A polarimeter can be smaller than 70 mm.

### 3.4 Waveguide mixer

The lower noise room temperature waveguide mixer (Shottky Diode Detector, noise temperature  $< 6000$  K, video responsivity  $\sim 400$  mV/mW) has been used in polarimeter. A circular feed horn waveguide is applied as an antenna to replace the usual corner cube, and a DC-bias used for the diode to achieve the lowest conversion loss. The optical beam receiving efficiency is improved. Compared result of polarimeter beat signal by DLATGS detector and waveguide mixer confirms that the signal with new Shottky mixer becomes very clear and the SNR has been improved about 2–4 times.

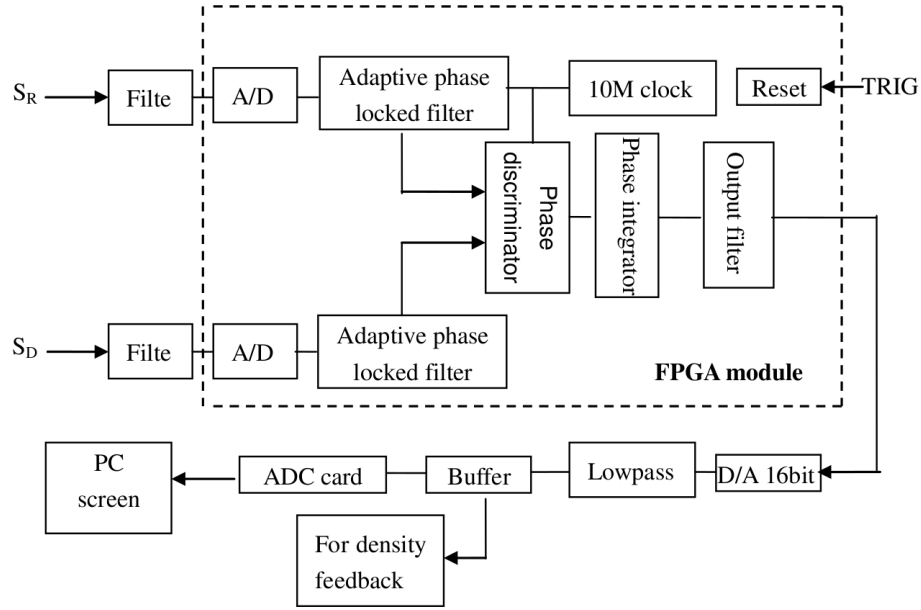
### 3.5 Data acquisition and processing system by FPGA technique

The raw beat signals from mixer are amplified and then sent to the digitizer and data acquisition system. The FPGA technique characterized by high reliability, easy modification and low cost is used to count the zero crossings of the signals in our system (see figure 4). This technique combines with the advantage of software and hardware phase comparator. 10 MHz sampling clock and 16 bit A/D and D/A conversion is applied for time resolution up of  $0.1 \mu\text{s}$ . The delay time of real time phase compared is about 0.2 ms. In parallel with the hardware development, there was a software development as well in order to better deal with the polarimeter data by FFT technique [17].

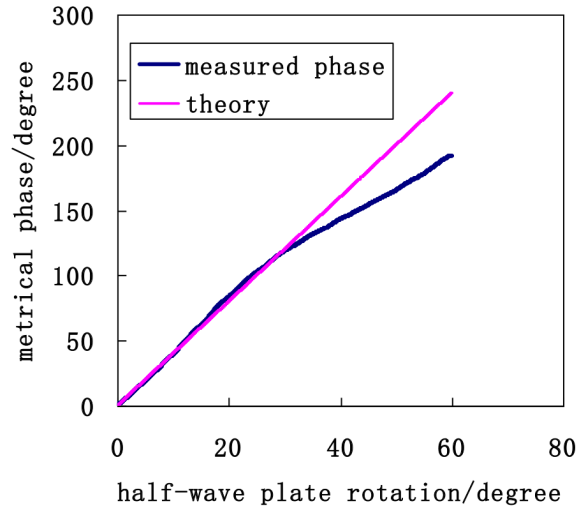
## 4 Initial experimental results

In order to demonstrate the capability of the phase-based technique using an HCN laser polarimeter, the Faraday effect measurement was tested on HL-2A.

Polarimeter is based on the interference of the two probe waves and any non-plasma induced deformation in the beam polarization will contaminate the experimental result. Crystal quartz



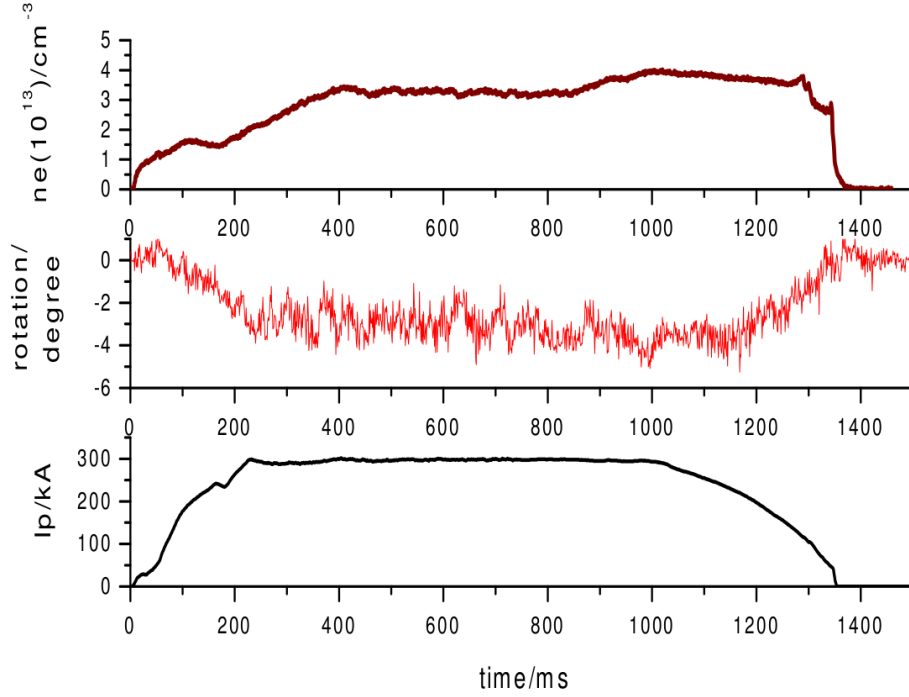
**Figure 4.** Flow diagram of data acquisition system by FPGA module.



**Figure 5.** Calibration curve for the polarimeter on HL-2A.

and wire mesh beam splitters are used to divide and recombine the source beams in the optical arrangement shown. These beam splitters are polarization sensitive and can distort the polarization state of the probe beams and introduce phase delays. Consequently, the polarimetry system requires calibration in order to isolate the phase shift associated with the plasma induced Faraday effect. For instrument calibration, a stepper-motor-driven rotating half-wave plate can be inserted in the probing arm. Because HL-2A polarimeter probing beam double pass the plasma, the calibration system was set in the front of mixer (see figure 1). By comparing the known rotation angle of the quartz to measured polarization rotation angle, the calibration factor can be determined. The calibration result is shown in figure 5. The horizontal axis corresponds to the quartz rotation angle





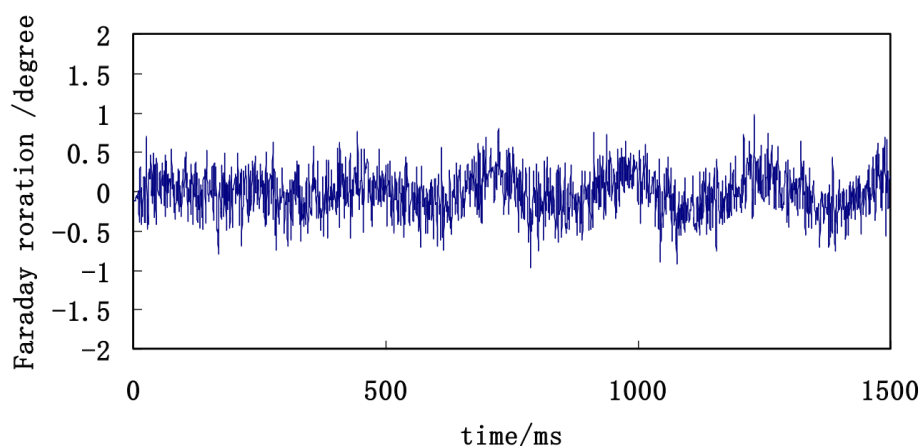
**Figure 6.** Faraday rotation time traces for shot 15471, in which the ECRH has been launched during 400–800 ms. The line-integrated density and the plasma current are given for reference.

while the vertical axis is the measured rotation. The black line denotes the metrical value and red one denotes the theoretical Faraday rotation data. The difference between measured and theoretical value in the range of 30–60 degrees is about 20% which is likely due to anisotropic reflection and transmission properties (mesh and crystal quartzes) distorted the polarization state of the beams. But in the small angle (the range of 0–30 degrees) the difference is about 10%, and on HL-2A the Faraday rotation angle that caused by the plasma current is less than 10 degrees, therefore we adopted the calibration coefficients in the range of 0–30 degrees as system measured calibration coefficient.

An example of the measured Faraday rotation signals during a deuterium diverted discharge with  $I_p = 300$  kA,  $B_t = 2.3$  T, and  $\bar{n}_e = 3.5 \times 10^{13} \text{ cm}^{-3}$  is given in figure 6. In the plasma current flat top the metrical Faraday rotation angle is about 3 degree. It agrees with expectation by EFIT code. An electron-cyclotron-resonance heating (ECRH) wave is launched into plasma from 400–800 ms, leading to a small decrease in density and hence in Faraday rotation, which is due to pump out effect. After 800 ms the ECRH turn off, the density increase and Faraday rotation angle increase too.

Figure 7 shows the polarimeter system background noise during no plasma discharge. We can find that an oscillation with period of  $\sim 270$  ms appeared in the waveform. This stems from a surface imperfection in the rotation grating used to frequency shift the beam. Under the present experimental conditions the Faraday rotation measurement accuracy is of the order of  $1^\circ$  with time resolution of 0.1 ms.

Reduction in polarimeter phase noise in the future can be achieved in HL-2A polarimeter system by employing a new higher quality rotation grating or removing the grating modulation and



**Figure 7.** The polarimeter system noise without plasma.

replacing it with a two FIR laser beams, carefully adjust two probing beam match on collinear, using polarizers instead of crystal quartz beam splitters (for example BS5) to improve the system polarized performance and so on.

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