Pulsed polarimetry techniques for fusion plasmas

R J Smith
University of Washington, Box 352250, Seattle, Washington, 98195, US
E-mail: smith@aa.washington.edu

Abstract. Pulsed polarimetry techniques are described for the determination of the local magnetic field distribution, \( B(r) \), in magnetically confined plasmas. Pulsed polarimetry is a non-perturbative Lidar-like technique that exploits both the Thomson scattering and magneto-optic Faraday effects to measure \( B_{\parallel} \) at the position and along the sightline of a polarized light pulse propagating in the plasma. The implementation of pulsed polarimetry on high performance magnetized plasmas of relevance to magnetic fusion falls naturally into three categories based on the size and optical activity of the plasma and present-day laser and detector options: 1) large tokamak plasmas typified by ITER and DEMO, 2) meter-sized high energy density plasmas typified by the Magnetized Target Fusion (MTF) program and 3) cm-sized plasmas typified by wire Z-pinches. Plausible pulsed polarimetry systems are presented for each category along with the current interest in obtaining the local field measurement for the respective programs.

1. Introduction
The confining magnetic field (poloidal field, \( B_\phi \) for tokamaks) is a key parameter in magnetically confined plasmas. A determination of \( B \) is equivalent to measuring \( j \). The magnetic field touches on all facets of plasma performance: stability, dynamics and transport (energy and particle confinement). Despite this significance, a robust non-perturbative \( B \) diagnostic has eluded the plasma physics community. Stellar techniques exist for density, \( n_e \), temperatures, \( T_i \) and \( T_e \), ion flow velocity, \( V_i \), with high spatial resolution, precision and bandwidth. So much so, that for tokamaks, \( B_\theta(r) \) has been reasonably constrained. Conventional polarimetry[1] is the mainstay \( B \) diagnostic. The Motional Stark effect (MSE) diagnostic measures the local magnetic pitch angle.[2] Grad-Shafranov equilibrium solvers reconstruct the magnetic equilibrium in great detail throughout the plasma volume. However, polarimetry measures a non-local sightline averaged \( <n_eB_\parallel> \), not \( B \) directly, MSE requires a dedicated, particle beam and is difficult to implement on next step tokamaks and equilibrium solvers are slow and rely heavily on internal measurements for accuracy. Considering the entire magnetic fusion energy (MFE) program, knowledge of local \( B \) is far from satisfactory. Outside of the tokamak program, the diagnostic choices for constraining \( B \) are disappointingly few. These plasmas can be highly dynamic on \( ns-\mu s \) time scales, with difficult noise problems. Diagnostics must have exceptional bandwidth. One cannot simply ignore these confinement concepts which hold the records in fusion reactivity, broadly known as high energy density (HED) plasmas.

2. The pulsed polarimetry method
Pulsed polarimetry[3] is a non-perturbative Lidar-like remote sensing technique based on both the Faraday and Thomson scattering (TS) effects. The measured polarization azimuth, \( \alpha \), of the backscatter is directly related to \( n_eB_\parallel \). With \( n_e \) independently measured, \( B_\parallel \) is determined. Unlike conventional Lidar, \( \alpha \) is a non-local quantity. Both plasma scattering and plasma dispersion theory at optical frequencies are relevant. For instance, the cold \((T_e=0)\) plasma dispersion theory determines the refractive index for O and X-mode propagation \((k\cdot B=0)\) with \( E \parallel \) and \( \perp \) to \( B \), respectively, and the
circularly polarized modes ($k \cdot B \neq 0$). In this model, $a(l)$, is given by equation (1) for $f (=c/\lambda)$, well above sightline cutoff.

$$\alpha(l) = 2 \times 2.63 \times 10^{-13} \lambda^2 |\langle n_e | B_\parallel | T \rangle | ds \text{ [rad]}$$  

(1)

Which can be inverted to give $B_\parallel(l)$,

$$B_\parallel(l) = \frac{1.9 \times 10^{12}}{\lambda^2 n_e(l)} d\alpha$$

(2)

For incoherent scattering, the scattering level is given by equation (3) with collection solid angle, $\Delta \Omega$, pulse energy, $E_{\text{pulse}}$ and spatial resolution, $\Delta s$. For the coherent regime, $\alpha > 1$, a suitable relation between $n_e(l)$ and $I(l)$ is needed. Finite-$T_e$ effects modify the scattered distribution and introduce depolarizing effects but backscatter faithfully preserves the polarization of the pulse.[4]

$$I(l) = E_{\text{pulse}} r_l^2 \Delta \Omega n_e(l) \Delta s / \tau_{\text{pulse}} \text{ [W]}$$

(3)

If $k \cdot B \neq 0$ or $B_\perp$ is strong, the Cotton Mouton (CM) effect can introduce an ellipticity, $\delta(l)$. If this effect is strong, $\alpha$ may no longer be directly related to $n_e B_\parallel$ and both $a(l)$ and $\delta(l)$ are then needed to resolve $B_\parallel$. In this paper, only direct detection is considered. Measureable quantities are contained in the backscatter’s Stokes vector, $S$. An important property of $S$ for incoherent scattering is additivity: $S = \Sigma S_i$ for any partition of the scattering volume. Individual electron radiators determine $S$.[4]

3. Pulsed Polarimetry techniques for fusion relevant devices

3.1. ITER tokamak (4 m size)

The implementation of pulsed polarimetry on large, low density plasmas is best served with a photodiode detection system. Tokamaks are the most demanding application given the low $n_e$ (weak scattering levels) and $a(L_p)$ must be large ($\sim 1$) to compensate for the low SNR. The FIR range of 50-400 $\mu$m is suitable and familiar, lying above the strong ECE background. FIR laser and detector technologies plausibly allow 30 cm spatial resolution, equivalent to JET’s TS Lidar system for a 4 m device.[5] Plausible pulsed polarimetry sightlines on ITER are shown in figure 1.

To achieve a 30 cm resolution, detector bandwidths of 400 MHz and a $\tau_{\text{pulse}} \sim 300$ ps are required.[3] The LiHe cooled $N_{\text{bn}}$ hot electron bolometers can achieve this. Quantum well (dot) infrared detector (QW(D)IP) technologies are also promising which offer focal plane arrays. Detectors are small, $\sim 1 \text{ cm}$, defeat refraction, allows arbitrary sightlines, removes ambiguities from the presence of both the Faraday and CM effects and allows a $\lambda$ closer to sightline cutoff. The important inboard sightlines become, in principle, accessible as shown in figure 1.

Pulsed polarimetry is also a complete diagnostic. Finite-$T_e$ effects can be corrected using the measured $T_e(l)$ profile. Also, both $B_\parallel$ and $B_\perp$ can be sensed. Diagnostic integration is therefore high.

As regards polarimetry, pulsed polarimetry uniquely spatially resolves $B$, defeats refraction, eliminates retro-reflectors, allows arbitrary sightlines, removes ambiguities from the presence of both the Faraday and CM effects and allows a $\lambda$ closer to sightline cutoff. The important inboard sightlines become, in principle, accessible as shown in figure 1.

As regards interferometry, profile information can only be provided by a multi-chord system or a sophisticated reflectometer. A single mid-plane tangentially viewing pulsed polarimeter measures $n_e(R)$, $T_e(R)$ and potentially the plasma diamagnetism (the distributed Shafranov shift).

3.2. Magnetized target fusion (MTF) plasmas (m-size)

If the required spatial resolution is $\sim 1 \text{ cm}$ or less, photodiodes become problematical with very small detector areas for the required bandwidth. Streak cameras are a better choice with 10 ps, even 1 ps response times. The slit entrance aperture allows 2-d intensity imaging or a spectral ($T_e$) resolution.

The MTF program seeks to reach fusion reactor conditions by compressing a field reversed configuration (FRC) plasma with a metal liner.[6] The plasmas are dynamic on a $\sim 10 \mu$s time scale with $n_e \sim 10^{21-25} \text{ m}^{-3}$, $B \sim 5-500 \text{ T}$, $T_e \sim 0.1-10 \text{ keV}$ and $L_p \sim 30-60 \text{ cm}$. The compression time scale is $\sim 10 \mu$s and energy transport models predict that a fusion $Q > 1$ will be reached under the most pessimistic
Inverse bremsstrahlung is a consideration and would be mistaken for a decreasing principle, two OKE shutters can be used in series. Light leakage is also present in image intensifiers. For $\text{fs}$ polarimetry can be corrected using measured $\Delta$ scattering cell: over 2 collects over 7% of the re-scatter ($2.1 \times 10^7$ $n_{\text{MTF}}$ pulsed polarimeter system. The internal distributions of ($n_e$, $T_e$, $B$) for FRCs are unknown, and transport poorly understood. As $n_e$ increases, the resolution of all parameters improves. The measurement interval is far shorter than $\tau_e \sim 1 \mu s$. A multi-pulse system would resolve the dynamics.

![Figure 1. Pulsed polarimetry sightlines on ITER. Divertor access is possible by extending the pulse path. The mid-plane sightlines provides tangential viewing sightlines out of the poloidal plane.](image1)

![Figure 2. Illustration of a sightline on a FRC. Backscatter is shown with the orientation of the polarization. The spatial resolution is determined by the detector response time.](image2)

3.3. Z-pinch and laser produced plasmas (cm size)

At the extreme range of MTF: $n_e = 3 \times 10^{25} \text{ m}^{-3}$, $B = 500 \, \text{T}$, $L_p \sim 2 \, \text{cm}$, streak camera detection becomes impractical. A high speed photographic method is advocated here.[7] The backscatter is directed through a scattering cell and an ultra-fast shutter based on the optical Kerr effect (OKE) is used to freeze this intensity distribution to be recorded by a CCD camera.

The $s$ and $p$ backscatter components are both imaged from a depth-wise narrow pulse as shown in figure 3. The shutter, consisting of a Kerr cell sandwiched between crossed polarizers, is gated ON by an intense pulse also supplied by the probe laser. The shutter time is given by the longer of the pulse duration or the relaxation time of the medium. The CS$_2$ medium has a 1.8 $\mu s$ relaxation time producing a $\Delta s \sim 270 \, \mu m$ and $\sim 400$ $fs$ times are possible.[8] The method can be used to generate 2-d images with the transverse dimension being a spatial or spectral dimension. A relativistic longitudinal smearing is present. This can be dealt with by pre-distorting the pulse prior to scattering or using narrow-depth pulses prepared with anamorphic optics. Using scattering to visualize scattering incurs a SNR penalty but the penalty is acceptable and the gains in detection performance warrant it.

A plausible laser system for probing the precursor phase of a wire Z pinch plasma ($n_e=1.4 \times 10^{19} \, \text{cm}^{-3}$, $B=20 \, \text{T}$, $T_e=100 \, \text{eV}$) with sub-mm spatial resolution consists of a 10 J pulse at 1057 $nm$ and $\tau_{\text{pulse}}=350$ $fs$. A shutter time of 2 $ps$ provides a $\Delta s<500 \, \mu m$ yielding a $\alpha(\Delta s)$ of 1.2° at $\lambda=528 \, nm$. For a collection half angle, $\theta_{\phi}$, of 3°, the scattering energy level over $\Delta s$ is 4.7 $n$ or $1.2 \times 10^{10} \, \text{ph}$. Considering the scattering cell: over 2/s, $3.1 \times 10^6 \, \text{ph}$ are scattered with an $a_{\text{cell}} = 4 \, \text{cm}^{-1}$. A collection angle of 30° collects over 7% of the re-scatter (2.1$\times 10^7$ ph). The SNR is $4.6 \times 10^3$ allowing angular resolutions to a few 0.01° or a few percent accuracy in $B_0$ from photon statistics. A consideration for this technique is the light leakage when the shutter is OFF. The OFF/ON transmission ratio can be low $\sim 10^3$. In principle, two OKE shutters can be used in series. Light leakage is also present in image intensifiers. Inverse bremsstrahlung is a consideration and would be mistaken for a decreasing $n_e(l)$ but pulsed polarimetry can be corrected using measured $n_e(l)$ and $T_e(l)$ if $Z_{\text{eff}}$ can be estimated.
Figure 3. A schematic for a pulsed polarimeter using an imaging detection system based on an OKE ultra-fast shutter. A 2-d image of an extended scattering volume is obtained for each polarization state. A waning of intensity in one channel would correspond to a waxing of intensity in the other. Background emission is obtained over a longer time interval.

Wire array Z pinches have produced record X-ray levels, ~300 TW[9] and may play a role in magnetic fusion as an X-ray source for inertial confinement (ICF).[10] The dynamics of wire Z pinches by which the plasma is assembled on axis is driven by magnetic force and not fully understood. Instabilities developing in the phase of wire ablation form implosion bubbles and ablation jets with <1 mm spatial scales. Field measurements with sub-mm and sub-ns resolutions are needed.

4. Summary
Pulsed polarimetry provides remote sensing of local $B$, $n_e$, $T_e$ across the full spectrum of magnetically confined plasmas with fusion relevant parameters. Photodiode detection and FIR lasers are amenable to the low density tokamak plasmas which require modest spatial resolution (30 cm) for their ~4 m size; streak camera detection and lasers in the NIR and visible are appropriate to the high density, high field plasmas of the MTF program providing sub-cm resolution for their 30 cm size; and high speed imaging using an ultra-fast shutter to resolve sub-mm features on wire Z pinches.

Pulsed polarimetry is uniquely suited to the measurement needs of future burning tokamaks (DEMO), by alleviating the need for retro-reflectors and fixed sightlines of a conventional polarimeter or the dedicated beam of an MSE diagnostic which also will have difficulty providing inboard measurements. The attributes of high diagnostic integration in one port, advantageous operation in the FIR range with regards to first mirrors, arbitrary sightlines, and robustness to the hostile environment of a burning plasma implied by an optical remote sensing technique typifies pulsed polarimetry.

The pulsed polarimetry technique has seemingly wide applicability to future confinement scenarios at the highest parameter ranges. An instrumental sensitivity $\sim \lambda^2 n_e B L_p$ (line integrated rotation angle over the plasma) guarantees ever better spatial resolution for the more challenging future plasma scenarios. Higher $n_e$ raises the scattering level allowing $\Delta s$ to be reduced at a fixed detection SNR, a stronger magnetic field raises the $n_eB$ product providing comparable sensitivity to $\alpha$ at shorter wavelengths for the reduced $\Delta s$, and the faster dynamics of the future plasma is always accommodated as $\tau_E$ is necessarily longer than $L_p/c$ transit time.

5. Acknowledgements
This work has been supported by the Office of Fusion Energy Sciences.

References
[1] Hutchinson I H 2002 Principles of Plasma Diagnostics (Cambridge University Press, Cambridge) 133-41
[2] Thomas D M et al. 2008 Fusion Sci. Tech. 53(2) 487-527
[3] Smith R J 2008 Rev. Sci. Instrum., 79, 10E703
[4] Segre S E, Zanza V 2000 Phys. of Plasmas, 7, 2677-84
[5] Salzmann H et al. 1988 Rev. Sci. Instrum., 59(8), 1451
[6] Intrator T 2004 Phys of Plasmas, 11(5), 2581
[7] Duguay M A et al. 1971 App. Optics, 10(9), 2162
[8] Yasui T et al. 1998 Nonlinear Optics '98, Materials, Fundamentals and Applications Topical Meeting (Cat. No.98CH36244), 218-20
[9] Deeney C et al. 1998 Phys.Rev. Lett. 81 4883
[10] Sanford T W et al. 1999 Phys. Rev. Lett. 83, 5511