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HIGH CURRENT SENSING THROUGH FARADAY ROTATION OF POLARIZED LIGHT OF VARYING WAVELENGTHS IN FIBERS II

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Abstract

Traditionally, large-amplitude, fast-rising currents and magnetic fields has been measured with electro-magnetic probes such as Rogowski coils or B-dot probes. Such probes are observed to work satisfactorily for many experimental configurations but the probe to digitizer signal is affected by cabling and cabling elements. Measurements must frequently be made in the presence of significant electromagnetic interference imposing unacceptable levels of noise on the probe signals. Furthermore, probe measurements on high voltage electrodes may be problematic if the probes are not sufficiently isolated. An alternative method for measuring currents and magnetic fields involves using the Faraday effect on linearly polarized light propagating in single mode fibers.

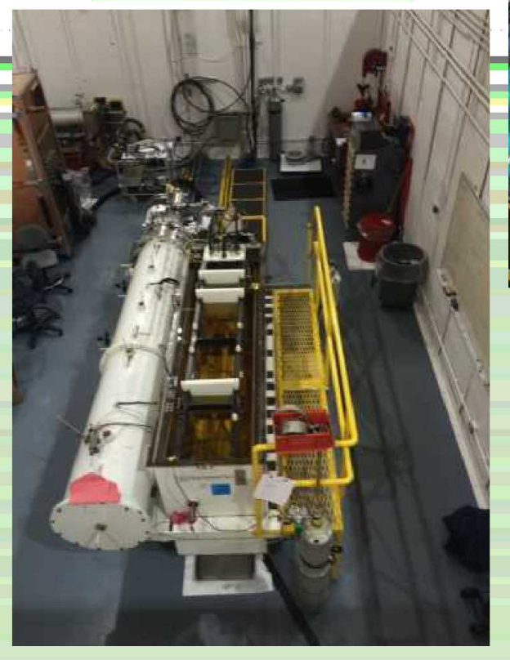
Probes utilizing the Faraday effect have been used for many years. Their operation, whereby the magnetic field strength is proportional to the number of probe output "fringes", is relatively immune to signal cable attenuation losses. Fibers are dielectrics and their electrical insulation reduces breakdown problems near high voltage electrodes. The probe calibration is a material property making in-situ calibrations unnecessary. Previously, the Faraday probe setup required an optical engineer to assemble and align the numerous discreet optical elements (i.e. beam expander, splitter, polarizers and focusing optics). This was time consuming work requiring realignment whenever the assembly was moved. Due to telecommunication advancements, a robust compact Faraday effect optical assembly with fixed alignments is now available at low cost.

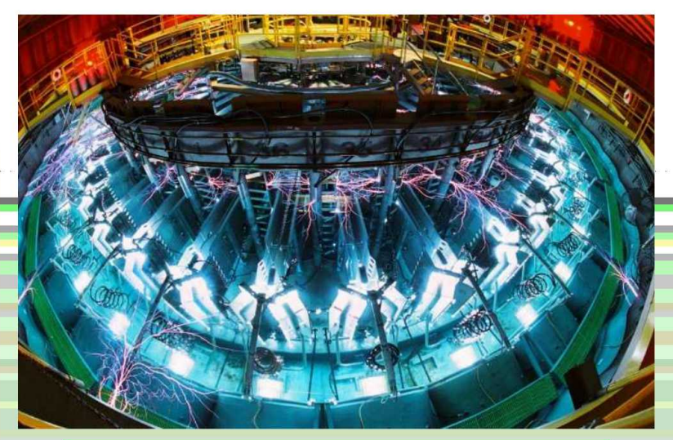
Also, due to these advancements, measurements at many different wavelengths are now possible. Theory predicts the Faraday probe sensitivity is inversely proportional to laser wavelength, thus probes of varying sensitivities can be constructed. The authors previously presented the theory and operation of this type probe at 2017 IEEE-PPC London. However, this paper details four Faraday probes optimized for wavelengths of 450 nm, 532 nm, 632 nm & 850 nm and now includes probe calibration efforts.

Introduction

- Efforts to measure large, pulsed currents are routinely employed in a wide variety of experimental scenarios:
  - Plasma studies
  - Particle beam experiments
  - High power microwave source development
  - Material studies in high magnetic fields
  - Development of pulsed power generators that are used to drive any of these experiments
- The present measurement techniques are observed to work satisfactorily for monitoring currents up to a few MA; for higher currents the measurement sensors can begin to distort in the large magnetic fields that are present
- Measurements must also frequently be made in the presence of significant electromagnetic interference which can impose unacceptable levels of noise on the probe signals
- Methods of making more accurate current measurements are being sought for the high current accelerators at SNL
  - To correlate machine current with particle/radiation output
  - To track accelerator performance changes

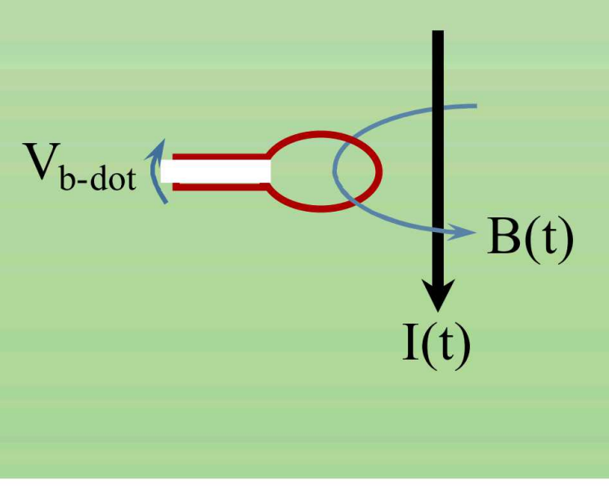

HERMIES III – a modular 20 MV, 600 kA gamma-ray source

Sphinx – a 2 MV, 26 kA high shot rate X-ray source


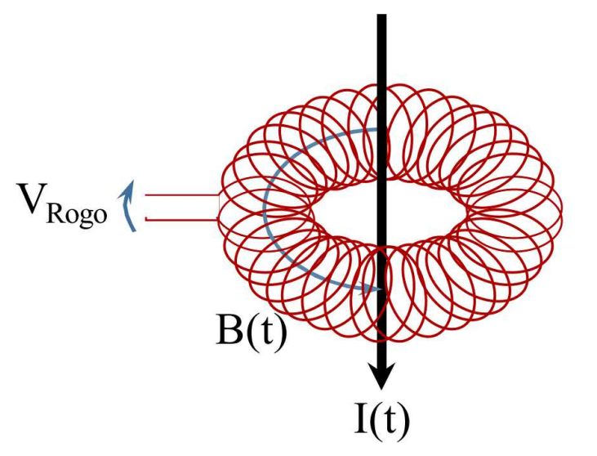

Saturn – a 1.5 MV, 12MA peak variable spectrum X-ray source

Current Measurement Techniques

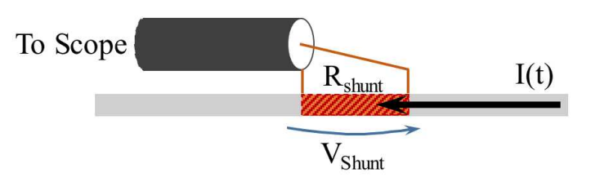
- Measurements of current are often obtained through sensing the magnetic field produced by the current or determining the voltage drop across a resistive element through which the current is flowing
- As noted in Ref. [1], large, fast current pulses have traditionally been measured indirectly with electromagnetic probes such as
  - B-dot probes
    - Simple loop of wire
    - Changing B threading the loop causes electromotive dφ/dt across open ends of the loop



  - Rogowski coils
    - Multi-turn solenoid that encircles the current to be measured
    - Changing B again causes dφ/dt across open ends of the coil



- Current measurements can also be made with current shunts[1]
  - Measurement of potential drop across a known R
  - Requires contact with current-carrying conductor



- Again, electromagnetic probes can work satisfactorily for monitoring currents up to a few MA, but for higher currents these probes can begin to distort in the large magnetic fields
- Because of the physical contact with current carrying components of the experiment, current shunts may introduce unacceptable ground loops
- Reactance of probe circuits can limit probe response to rapidly changing currents, short pulses
- All probes are susceptible to electromagnetic interference, which can impose unacceptable noise levels on probe signals

Faraday Rotation of Polarized Light

- An alternative method for measuring large currents involves using the Faraday effect on linearly polarized light propagating in single mode fibers
- Just as with the B-dot probes and the Rogowski coils, it is the magnetic fields associated with the currents that are measured
  - The Faraday effect is manifested as a rotation of the polarization plane of a light wave traversing a medium when there is a magnetic field along the direction of propagation[2]
  - A rotation arises because the magnetic field induces a circular birefringence in the fiber material, a difference in the refractive indices for the left and right circularly polarized components of the light wave
- The angle of rotation is given by

$$\theta = V' \int_0^L B \cdot dx$$

where V' is the Verdet constant, which depends upon the material and wavelength of the light, B is the magnetic field strength, and L is the path length in the field

- Remembering Ampere's law for closed circuits,

$$I = \frac{1}{\mu_o} \oint B \cdot dx$$

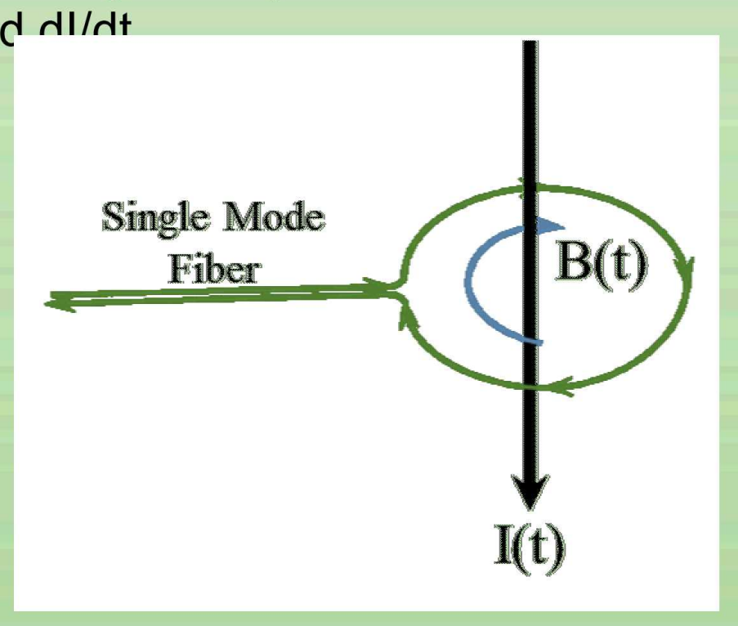
- we then can write

$$I = \frac{\theta}{\mu_o V'}$$

- In pure silica V' has a value of about 4.62 x 10-6 rad/A or 264°/MA for 633-nm-wavelength light
- Using Faraday rotation for current measurements is not a new concept[3-6], but earlier work used longer wavelengths (e.g., 632 nm and 830 nm) for the probe beam
- With advances in laser technology, compact shorter-wavelength visible and even UV lasers are now available

Application of Faraday Rotation

- In a typical probe configuration
  - Linearly polarized light is launched into a single-mode fiber that follows the direction of the magnetic field produced by a pulsed high current
  - Light emerging from the fiber will have a rotating linear polarization state with angular frequency proportional to dB/dt and dI/dt
  - This light is split into two beamlets and one is rotated 45° with respect to the other
  - Both beamlets are converted to electrical signals and analyzed as follows to determine the current measured



To Obtain Current from Measured Signals

- Assume the two detector signals can be expressed by[6]

$$V_{detA} = K_a E_o^2 \cos^2(\theta) \qquad V_{detB} = K_b E_o^2 \cos^2(\theta + 45)$$

where K_x = detector calibration

- With the trigonometric relationships

$$\cos^2(\theta) = \frac{1}{2} + \frac{1}{2}\cos(2\theta) \qquad \cos(2\theta + 90) = -\sin(2\theta)$$

- we can then write

$$V_{detA} = \frac{K_a E_o^2}{2}(1 + \cos(2\theta)) \qquad V_{detB} = \frac{K_b E_o^2}{2}(1 + \cos(2\theta + 90))$$

- Normalizing and solving for cos(q) and sin(q), we obtain

$$\cos(2\theta) = NormV_A = \left(\frac{V_{detA} - \frac{K_a E_o^2}{2}}{\frac{K_a E_o^2}{2}}\right) \qquad \sin(2\theta) = NormV_B = \left(\frac{V_{detB} - \frac{K_b E_o^2}{2}}{-\frac{K_b E_o^2}{2}}\right)$$

- With the relationship

$$2\theta = \tan^{-1}\left(\frac{\sin(2\theta)}{\cos(2\theta)}\right) = \tan^{-1}\left(\frac{NormV_B}{NormV_A}\right)$$

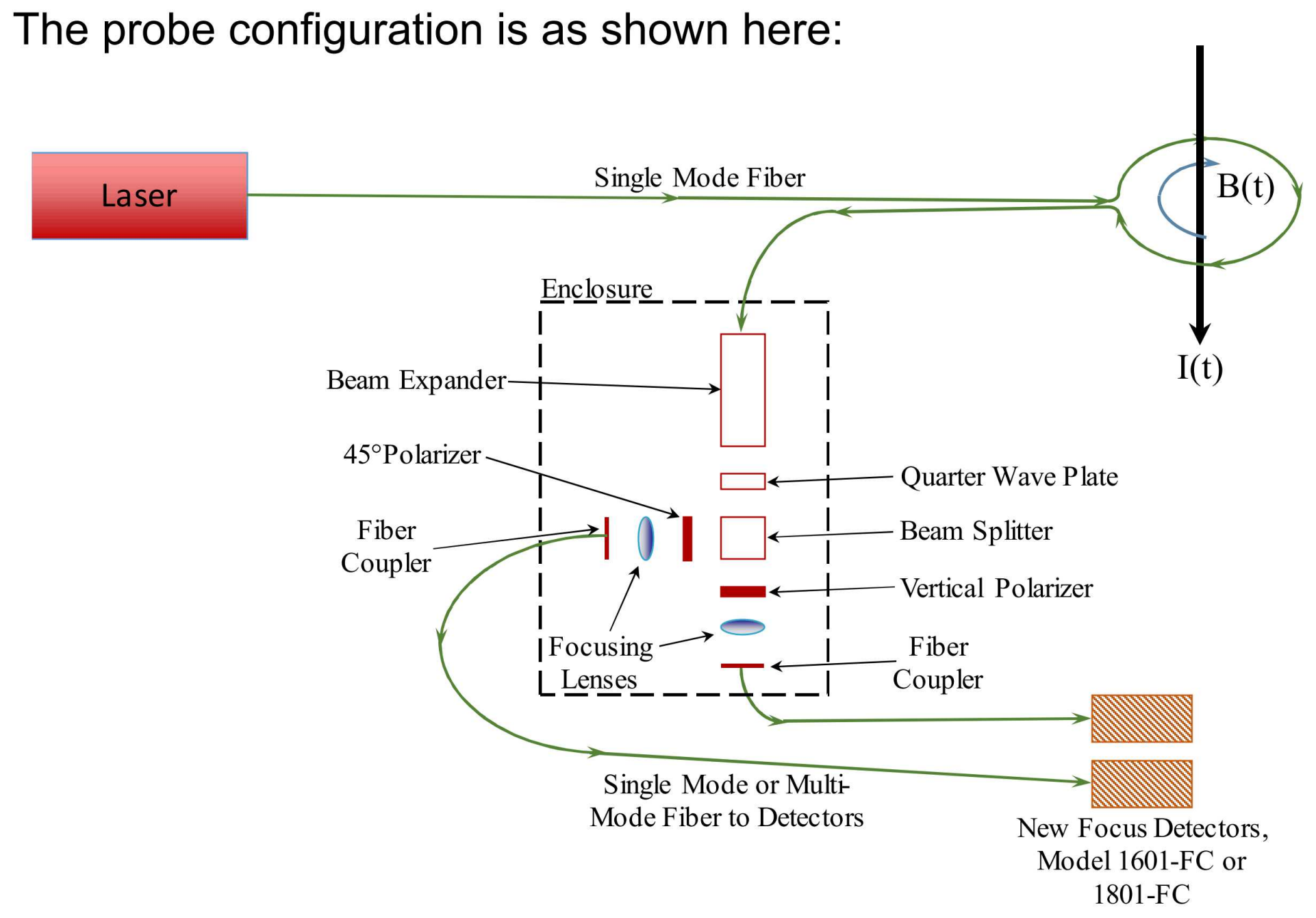
- we can then solve for the current I:

$$I = \frac{\theta}{\mu_o V' N} = \frac{1}{2\mu_o V' N}\tan^{-1}\left(\frac{NormV_B}{NormV_A}\right)$$

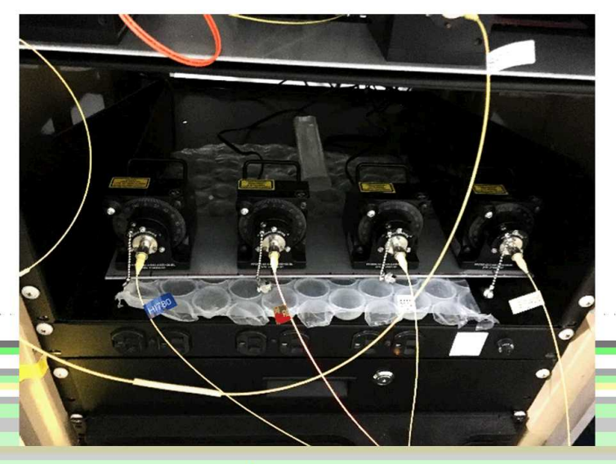
where N = number of times fiber is wrapped around conductor

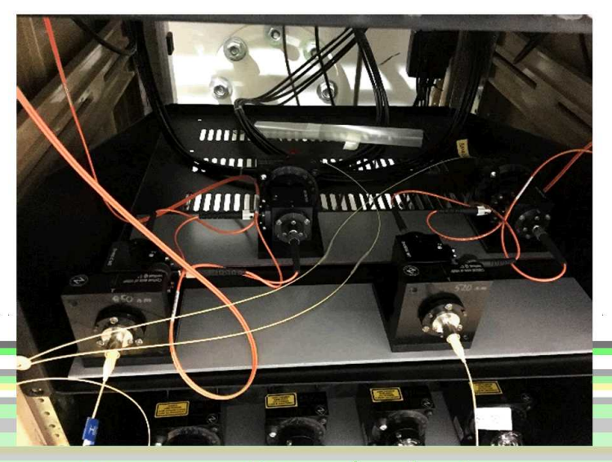
Faraday Rotation Probe Design

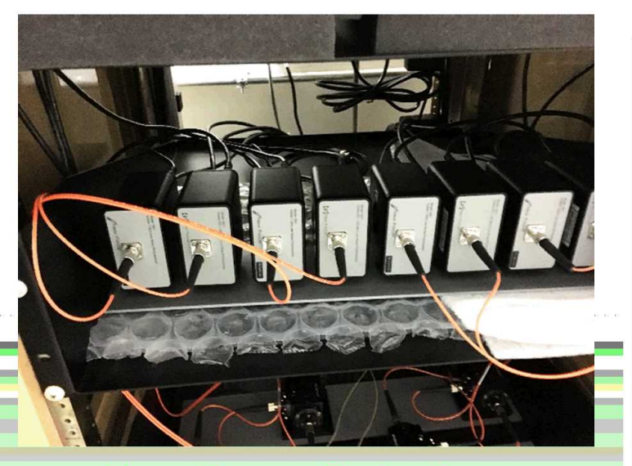
- Majority of optical components come preassembled in an enclosure from Oz Optics
- The probe configuration is as shown here:



- Four complete sets of the lasers, beam splitters, and detectors were purchased to assemble probes for operating at wavelengths of 850 nm, 635 nm, 532 nm, and 450 nm


Lasers

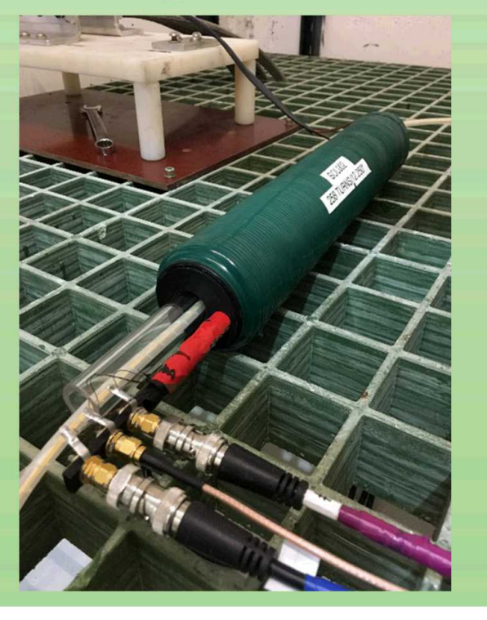

Beam splitter/polarizer assemblies

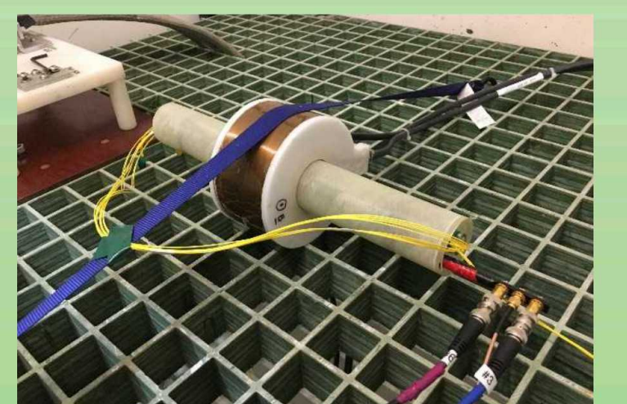

New Focus Detectors

- The probe at 635 nm is very similar to those that have been created by other researchers
  - Its operation and performance provides a baseline for this series of probes
- The other probes should provide measurements more or less sensitive to a given pulsed current
- Four types of single-mode sense fibers were examined:
  - Corning HI780 and RGB
  - ThorLabs S630 and SP405

Observations of Faraday Probe Performance During Tests

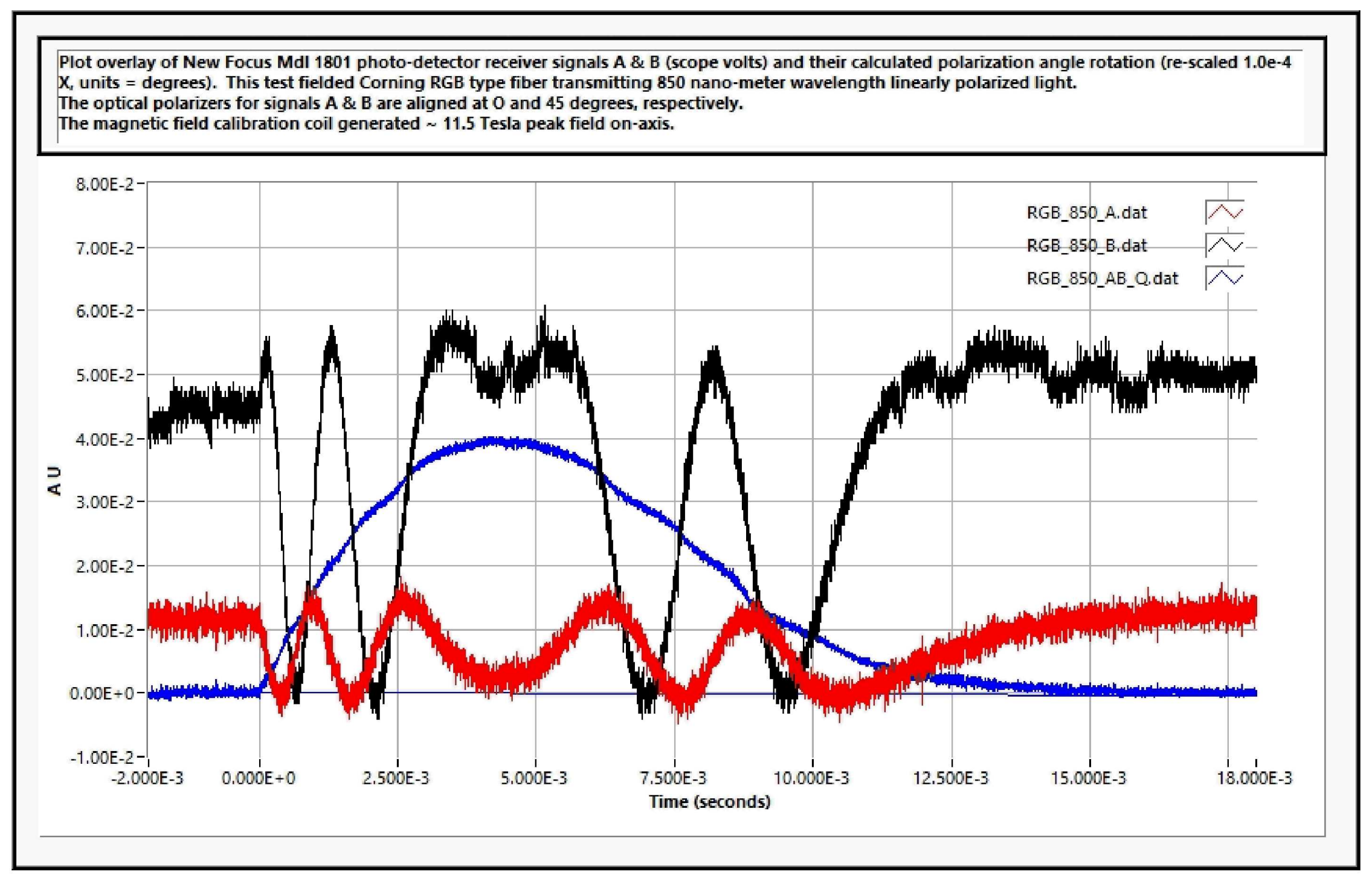
- Tests were performed with the fibers run through a 12.25"-long, 258-turn, 2-layer solenoid (right)
- And with a 3"-long, 230-turn Helmholtz coil (far right)



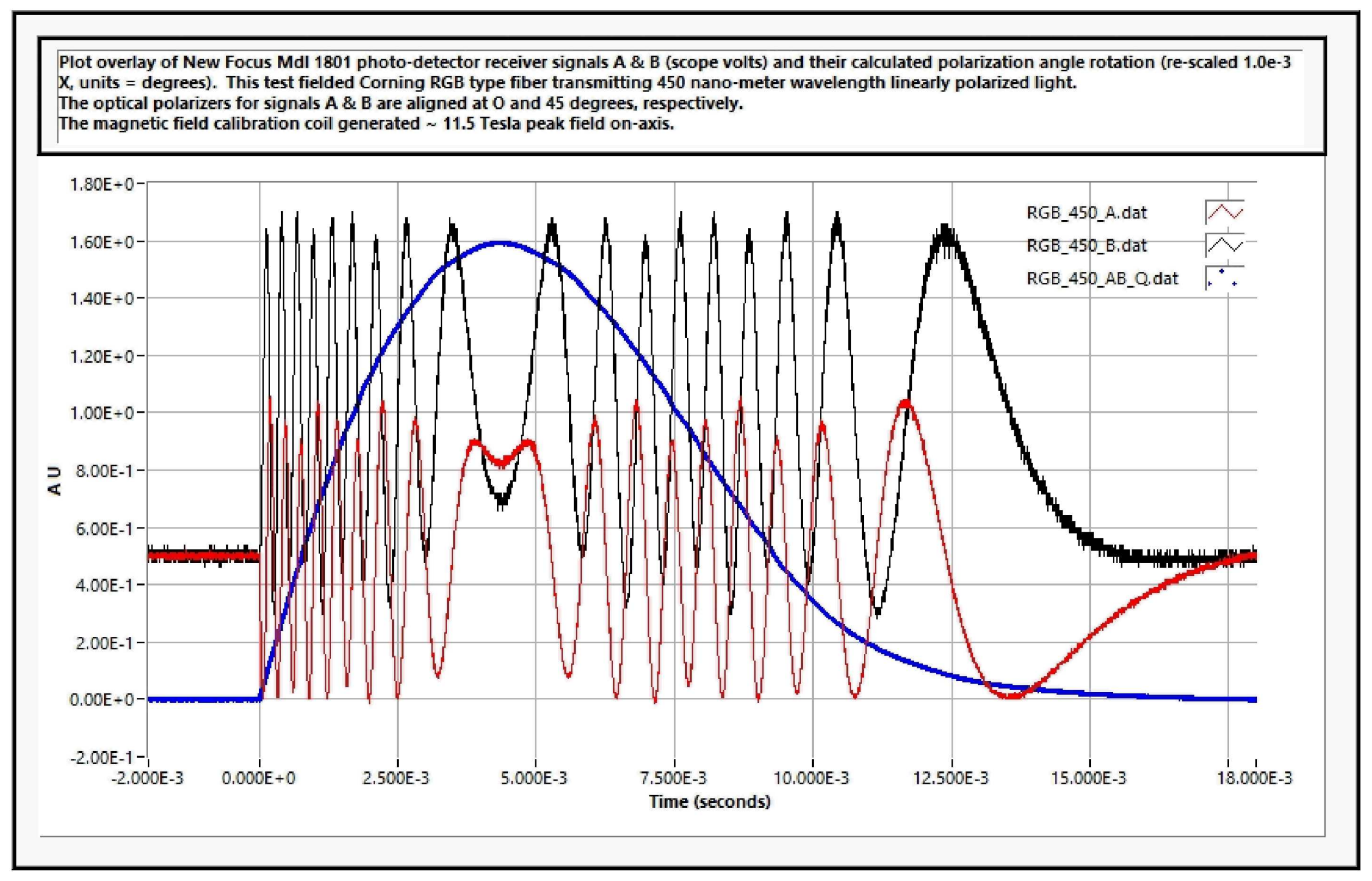


- As expected, the total phase shift increased as wavelength decreased
- The RGB fiber provided good signals (good signal-to-noise ratio) for all wavelengths, whereas the other fibers worked well for some but not all wavelengths

Detector Signals, Total Phase Shift θ for RGB Fiber at 850 nm


Plot overlay of New Focus Mdl 1801 photo-detector receiver signals A & B (scope volts) and their calculated polarization angle rotation (re-scaled 1.0e-4 X, units = degrees). This test fielded Corning RGB type fiber transmitting 850 nano-meter wavelength linearly polarized light.
The optical polarizers for signals A & B are aligned at O and 45 degrees, respectively.
The magnetic field calibration coil generated ~ 11.5 Tesla peak field on-axis.

Detector Signals, Total Phase Shift θ for RGB Fiber at 450 nm


Plot overlay of New Focus Mdl 1801 photo-detector receiver signals A & B (scope volts) and their calculated polarization angle rotation (re-scaled 1.0e-3 X, units = degrees). This test fielded Corning RGB type fiber transmitting 450 nano-meter wavelength linearly polarized light.
The optical polarizers for signals A & B are aligned at O and 45 degrees, respectively.
The magnetic field calibration coil generated ~ 11.5 Tesla peak field on-axis.

Verdet Constants vs. Wavelength Measured for Each Fiber

- Analysis of the recorded data produced Verdet constants for all but one test case (850 nm in the SP405 fiber)
- Verdet constants for the various fibers were all rather close for a given wavelength

Fiber type	850 nm Verdet (rad/(Mamp-turn))	635 nm Verdet (rad/(Mamp-turn))	520 nm Verdet (rad/(Mamp-turn))	450 nm Verdet (rad/(Mamp-turn))
Corning HI780 >780 nm	2.68 (1)	3.61 (2)	6.32 (3)	10.7 (3)
Corning RGB 450-700 nm	2.57 (2)	4.72 (1)	7.16 (1)	10.3 (1)
Thor Labs S630 630-860 nm	2.57 (1)	4.61 (2)	6.89 (5)	7.63 (5)
Thor Labs SP405 400-680 nm	--- (4)	4.66 (2)	6.65 (5)	9.91 (1)

(1) = good signal characteristics
(2) = noisy signals
(3) = very noisy signals
(4) = minimal signal
(5) = large variations in signal maxima and minima

Summary and Future Work

- Faraday rotation current sensing by varying operating wavelength to enhance measurement sensitivity was experimentally demonstrated
- Even though multiple types of optical sense fibers were tested, the RGB fiber performed the best and achieved results far outside of its design specifications
- Next steps:
  - Field the Faraday diagnostic on the Hermes III pulsed power machine
  - Perform a dispersion analysis of the optical fibers and use a numerical calculation method as comparative approach to calculating Verdet constants
  - Explore using shorter (<450 nm) operating wavelengths to enable higher sensitivity measurements

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[1] S. L. Leonard, "Basic Macroscopic Measurements," Plasma Diagnostic Techniques, R. H. Huddleston and S. L. Leonard, eds., Academic Press, San Francisco, 1965.
[2] L. R. Veeser, et al., "Single Mode Fiber Optic Sensor for High Currents," Proceedings of the 4th IEEE International Pulsed Power Conference, 1983, pp. 289-291.
[3] L. Veeser, et. al., "Measurement of Megampere Currents with Optical Fibers", SPIE Vol 380, Los Alamos Conference on Optics 1983, pp. 300-304.
[4] L. Veeser, et. al., "Fiber-optic Sensing of Pulsed Currents", SPIE Vol 648, Photonics 1986, pp. 197-212.
[5] J. L. Stokes, et. al., "Precision Current Measurements on Pegasus II Using Faraday Rotation," Proceedings of the 10th IEEE International Pulsed Power Conference, Vol. 1, 1995, pp. 378-383.
[6] S. K. Coffey, et. al., "Fiber-Optic Systems at the Explosive Pulsed Power Test Facility at AFRL," Proceedings of the 15th IEEE International Pulsed Power Conference, Vol. 1, 2005, pp. 580-583.