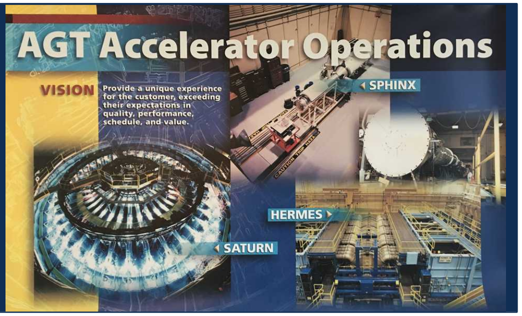
SAND2017-6257C

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



Sean Coffey and Chris Grabowski

2017 IEEE International Pulsed Power Conference

Brighton, UK

June 18-22, 2017

* This work supported by the U.S. Department of Energy.

Abstract

Traditionally, large-amplitude, fast-rising currents and magnetic fields have been measured with electromagnetic 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 so in-situ calibrations are 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 tele-communication 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. This paper details four Faraday probes optimized for wavelengths of 450 nm, 532 nm, 632 nm & 850 nm and includes probe calibration efforts.

Outline of Presentation

- *Introduction*
- Overview of More Traditional Current Diagnostics
- The Principle of Faraday Rotation
- Diagnostic Suite Under Development
- Summary and Conclusions

Measurement of Pulsed High Currents

Sandia National Laboratories

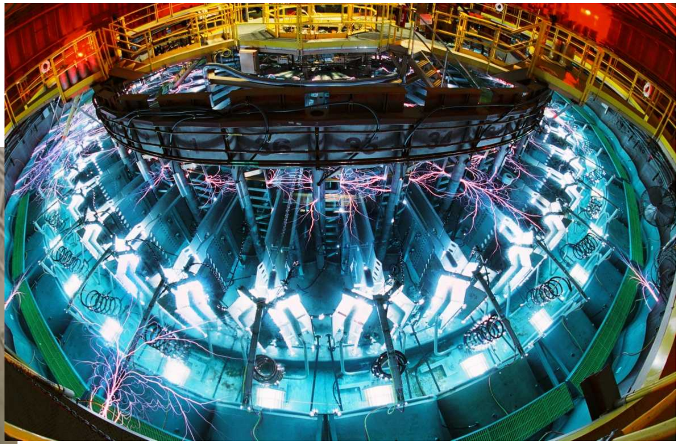
- Efforts to measure large, pulsed currents are routinely employed in a wide variety of experimental scenarios:
  - Plasma studies
  - Particle beam experiments
  - High power microwave source development
  - Material studies in high magnetic fields
  - Development of pulsed power generators that are 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

Motivation for a Current Measurement Using Faraday Rotation

- 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



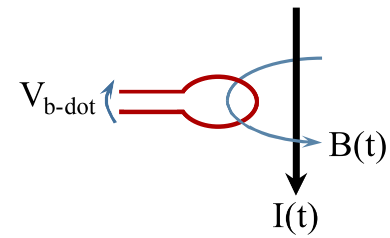
Saturn – a 1.5 MV, 12MA peak variable spectrum X-ray source

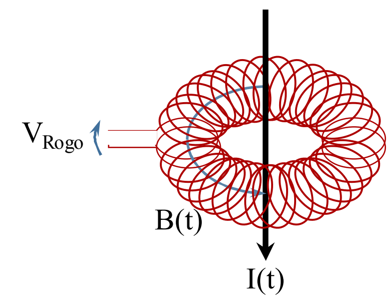
Outline of Presentation

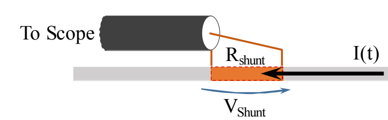
- Introduction
- *Overview of More Traditional Current Diagnostics*
  - *B-dot probes*
  - *Rogowski coils*
  - *Current shunts*
- The Principle of Faraday Rotation
- Diagnostic Suite Under Development
- Summary and Concluding Remarks

Measurement of Pulsed High Currents

- Traditionally, large, fast current pulses have been measured indirectly with electromagnetic probes[1]
  - 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







[1] S. L. Leonard, "Basic Macroscopic Measurements," *Plasma Diagnostic Techniques*, R. H. Huddleston and S. L. Leonard, eds., Academic Press, San Francisco, 1965.

Difficulties with Traditional Probes

- 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

Outline of Presentation

- Introduction
- Overview of More Traditional Current Diagnostics
- *The Principle of Faraday Rotation*
- Diagnostic Suite Under Development
- Summary and Concluding Remarks

Principles of Faraday Rotation

- An alternative method for measuring large currents involves using the Faraday effect on linearly polarized light propagating in single mode fibers
- Strictly speaking, 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

[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.

Principles of Faraday Rotation (cont.)

Sandia National Laboratories

- 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 4.62×10^{-6} rad/A or 264° /MA for 633-nm-wavelength light

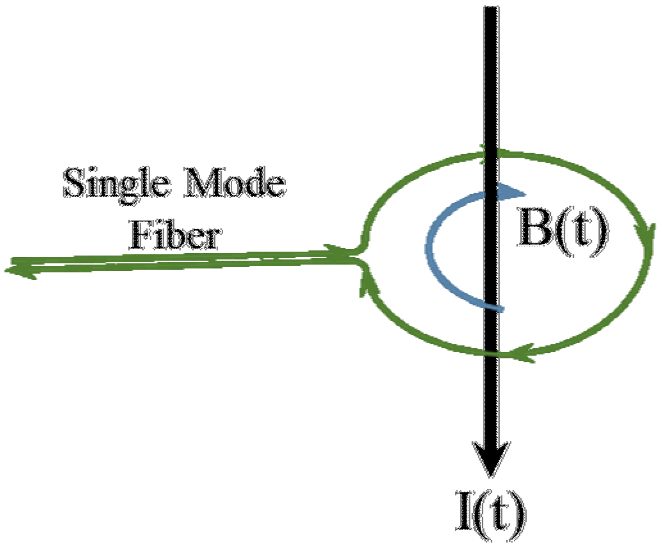
Measurement of Currents

- 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

[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.

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



Analyzing Faraday Rotation Data

- 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

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

- Normalizing and solving for cos(θ) and sin(θ), 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

Applications (cont.)

- Such optical fiber probe involves minimal intrusion into the system → can therefore permit fast-responding current sensing very close to high-voltage, high-current conductors
- Current sensitivity depends upon laser wavelength of the light
  - Probes using longer wavelengths can sense extremely high current pulses
  - Probes using shorter wavelengths can sense lower currents, perhaps down to a few hundred kA
  - For still lower currents, the sensing fiber may be wrapped multiple times around the current-carrying conductor to produce a sufficient signal

Outline of Presentation

- Introduction
- Overview of More Traditional Current Diagnostics
- The Principle of Faraday Rotation
- *Diagnostic Suite Under Development*
- Summary and Concluding Remarks

Faraday Rotation Probes For Saturn, HERMES III, and Sphinx

- A rather wide range of currents is produced by the Saturn, HERMES III, and Sphinx accelerators

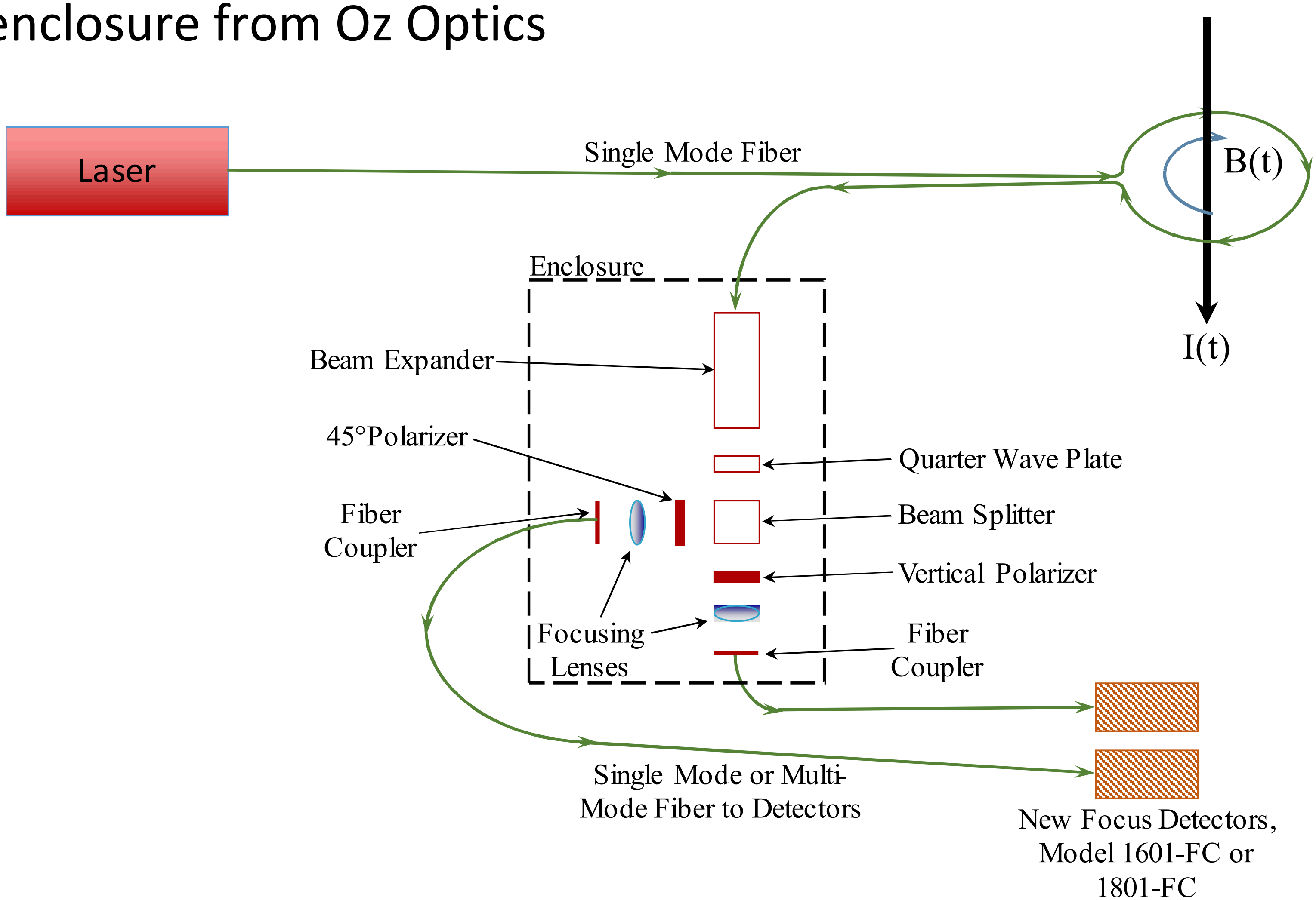
→ A "suite" of Faraday rotation probes is therefore desired to cover this range

  - Longer wavelength probes may be used for the higher-current applications (*e.g.*, Saturn load, where I = 10~12 MA)
  - Probe wavelengths will be reduced for higher sensitivity at lower currents (e.g., HERMES III and SPHINX and individual sections, or "lines", of Saturn, where I <1 MA)
  - A less-sensitive probe (with wavelength >850 nm) may find application in Saturn Next, which is being designed to have currents exceeding 20 MA

- The majority of the optics will be put together in one, compact, factory-assembled package

Faraday Rotation Probe Design

- Majority of optical components come preassembled in an enclosure from Oz Optics



Probes Details

- Lasers and associated optical hardware are being purchased for probes operating at wavelengths of 850 nm, 635 nm, 532 nm, and 450 nm
- The probe at 635 nm is very similar to those that have been created by other researchers
  - Its operation and performance will provide a baseline for this series of probes
- The other probes are then expected to provide measurements more or less sensitive to a given pulsed current

Summary and Concluding Remarks

- Through a relatively simple extension to the existing theory and concept for Faraday rotation current measurement, it is possible to make more sensitive current measurements
- Once the remaining components arrive during the coming months, probes for each wavelength – 850 nm, 635 nm, 532 nm, and 450 nm – will be assembled and calibrated using a pulsed magnetic field calibration stand
- The probes will then all be fielded on the SPHINX accelerator first (with multiple fiber wraps for the less-sensitive probes) before being fielded on HERMES III or Saturn