Title:	**Two Photon Absorption Laser Induced Fluorescence for Neutral Hydrogen Profile Measurements**
Principal Investigator:	Earl Scime
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Funding Opportunity Announcement:	DE-SC0004736
Final Report Date:	September 23, 2016
Period Covered by Report:	July 15, 2010–July 14, 2016 (initial funds not received until October 2010)
Project Budget:	$599,236 (DoE), WVU ($50,000), General Atomics ($131,000)
Participating National Laboratory:	Oak Ridge National Laboratory

Project Goals and Objectives

The magnitude and spatial dependence of neutral density in magnetic confinement fusion experiments is a key physical parameter, particularly in the plasma edge. Modeling codes require precise measurements of the neutral density to calculate charge-exchange power losses and drag forces on rotating plasmas. However, direct measurements of the neutral density are problematic. In this work, we proposed to construct a laser-based diagnostic capable of providing spatially resolved measurements of the neutral density in the edge of plasma in the DIII-D tokamak. The diagnostic concept is based on two-photon absorption laser induced fluorescence (TALIF). By injecting two beams of 205 nm light (co or counter propagating), ground state hydrogen (or deuterium or tritium) can be excited from the $n = 1$ level to the $n = 3$ level at the location where the two beams intersect. Individually, the beams experience no absorption and therefore have no difficulty penetrating even dense plasmas. After excitation, a fraction of the hydrogen atoms decay from the $n = 3$ level to the $n = 2$ level and emit photons at 656 nm (the H_α line). Calculations based on the results of previous TALIF experiments in magnetic fusion devices indicated that a laser pulse energy of approximately 3 mJ delivered in 5 ns would provide sufficient signal-to-noise for detection of the fluorescence. In collaboration with the DIII-D engineering staff and experts in plasma edge diagnostics for DIII-D from Oak Ridge National Laboratory (ORNL), WVU researchers designed a TALIF system capable of providing spatially resolved measurements of neutral deuterium densities in the DIII-D edge plasma. The laser systems were specified, purchased, and assembled at WVU. The TALIF system was tested on a low power hydrogen discharge at WVU and the plan was to move the instrument to DIII-D for installation in collaboration with ORNL researchers. After budget cuts at DIII-D, the DIII-D facility declined to support installation on their tokamak. Instead, after a no-cost extension, the apparatus was moved to the University of Washington-Seattle and successfully tested on the HIT-SI3 spheromak experiment. As a result of this project, TALIF measurements of the absolutely calibrated neutral density hydrogen and deuterium were obtained in a helicon source and in a spheromak, designs were developed for installation of a TALIF system on a tokamak, and a new, xenon-based calibration scheme was proposed and demonstrated. The xenon-calibration scheme eliminates significant problems that were identified with the standard krypton calibration scheme.

DESCRIPTION OF ACCOMPLISHMENTS AND THEIR SIGNIFICANCE TO THE FIELD

The original goals of this project were to design, build, and test a neutral density diagnostic based on two-photon laser induced fluorescence (TALIF) and then to install the diagnostic on the DIII-D tokamak at General Atomics in La Jolla, California. The project was to proceed in phases. First, design and installation of the lasers at WVU. Then validation of the diagnostic technique on hydrogen and deuterium plasmas in a helicon plasma source, followed by demonstration of absolution calibration for both hydrogen and deuterium using a krypton TALIF technique. In parallel with the diagnostic development at WVU, and based on results developed during the testing of the diagnostic, the diagnostic system would undergo a performance review process followed by a design review process at DIII-D. After completing a successful design review, the TALIF system would then be moved to California and installed on DIII-D. The General Atomics partner would provide environmental controls for the laser systems and access to a port on the DIII-D chamber.

As will be shown below with summaries of the experimental results, the demonstration of absolutely calibration hydrogenic TALIF at WVU proceeded as planned and a number of papers were published with shared the success of the technique with the broader scientific community. A preliminary design review was completed successfully at DIII-D and then a final design review was successfully completed. Unfortunately, at the same time, base funding for the DIII-D program was reduced and the General Atomic leadership decided they could no longer support the infrastructure investments required for TALIF installation on DIII-D. Therefore, the system remained at WVU while the WVU team sought additional partners for a field test of the TALIF system.

In 2014, a new partner was identified – the HIT-SI3 group at the University of Washington-Seattle. HIT-SI3 is a small spheromak experiment designed to study new techniques for helicity injection into toroidal systems. In the winter of 2015, the entire TALIF system was transported by truck from West Virginia to Seattle. The HIT-SI were a success and resulted in a joint publication describing the range of neutral densities in their experiment. During the HIT-SI calibration process, chromatic aberrations due to the different fluorescence wavelengths for the hydrogenic and krypton schemes were identified as a major problem with optimizing the collection optics during the experiments. As a result, a new xenon-based TALIF calibration scheme was developed and demonstrated at WVU. The new xenon scheme fluoresces at nearly the exact same wavelength as hydrogenic TALIF.

New partners continue request the WVU team move the TALIF facility to their experiment to provide calibrated neutral density measurements. These potential partners include the EAST tokamak in China, the HIDRA experiment at the University of Illinois at Champaign-Urbana, and the proto-MPEX experiment at Oak Ridge National Laboratory. As yet, no proposals to begin those partnerships have been funded so the TALIF apparatus remains at WVU where it continues to be employed in a variety of experiments.

Provided below are summaries of the various TALIF-based projects undertaken as part of this project.

A. Hydrogenic TALIF in Helicon Source: Shown below are the TALIF scheme used for hydrogenic TALIF and measurements which demonstrate successful TALIF in hydrogen and deuterium. Note that the isotopes are clearly distinguishable in the combined plot.

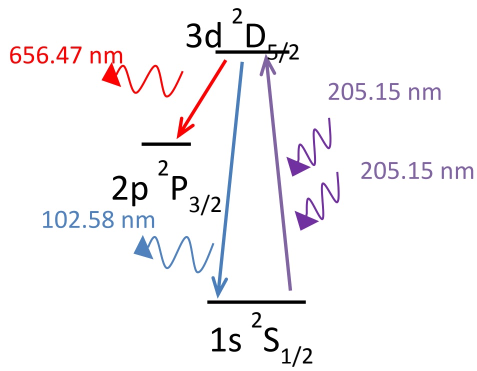

Figure 1. The TALIF scheme used for hydrogen and deuterium.

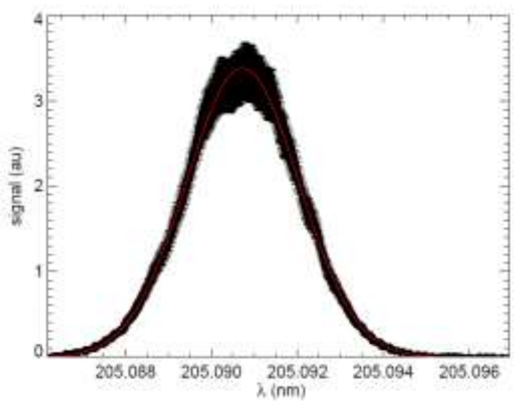

Figure 2. Hydrogen TALIF measurement in the WVU helicon source.

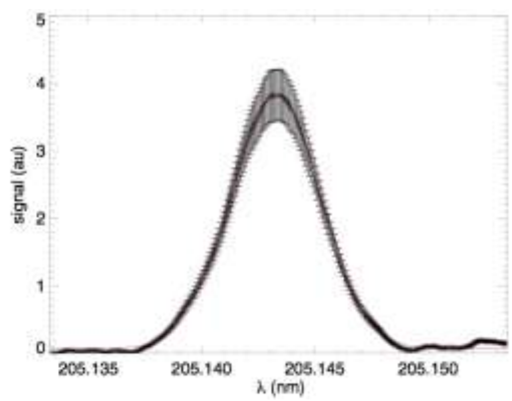

Figure 3. Deuterium TALIF measurement in the WVU helicon source.

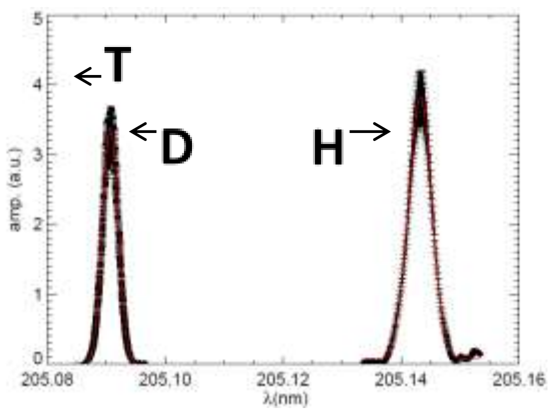

Figure 4. Combined hydrogenic TALIF measurements showing how isotopic abundances are measurement with TALIF.

B. Krypton TALIF in Helicon Source: Shown below is the krypton TALIF scheme and measurements which demonstrate that the neutral density profile in a helicon source is hollow and that the plasma is nearly 100% ionized.

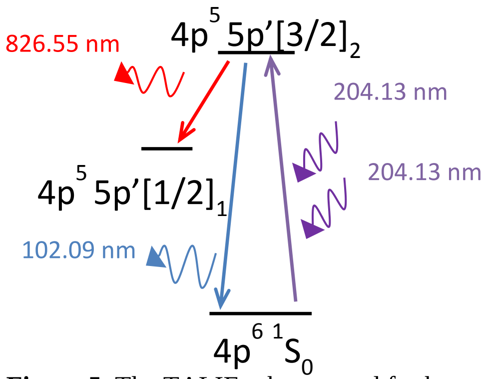

Figure 5. The TALIF scheme used for krypton.

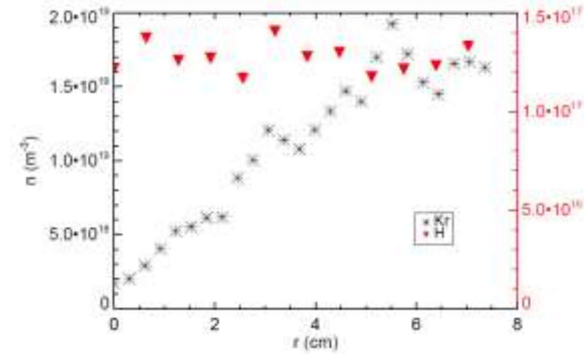

Figure 6. Hydrogen and krypton TALIF measured neutral densities as a function of radial position in the helicon source.

C. Absolutely Calibrated Hydrogenic TALIF in Helicon Source: Absolutely calibrated hydrogen density measurements in the helicon source shown no evidence of strong ionization and the measured profiles were nearly flat across all radii. The TALIF measurements also provided direct measures of the neutral temperature.

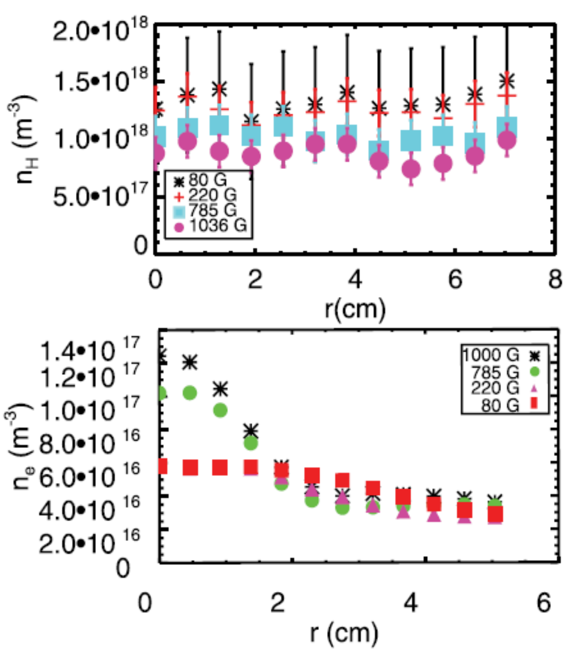

Figure 7. Atomic hydrogen (top) and plasma (bottom) density for a range of magnetic field strengths. At high field, above 785 G, the plasma density profile becomes centrally peaked but the neutral density profile stays flat.

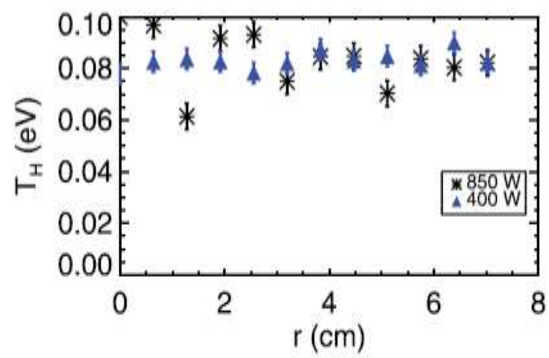

Figure 8. Neutral hydrogen temperatures for two

D. DIII-D Critical Design Review: After successful measurements at WVU, a design for installation of TALIF on DIII-D was proposed, reviewed, and approved.

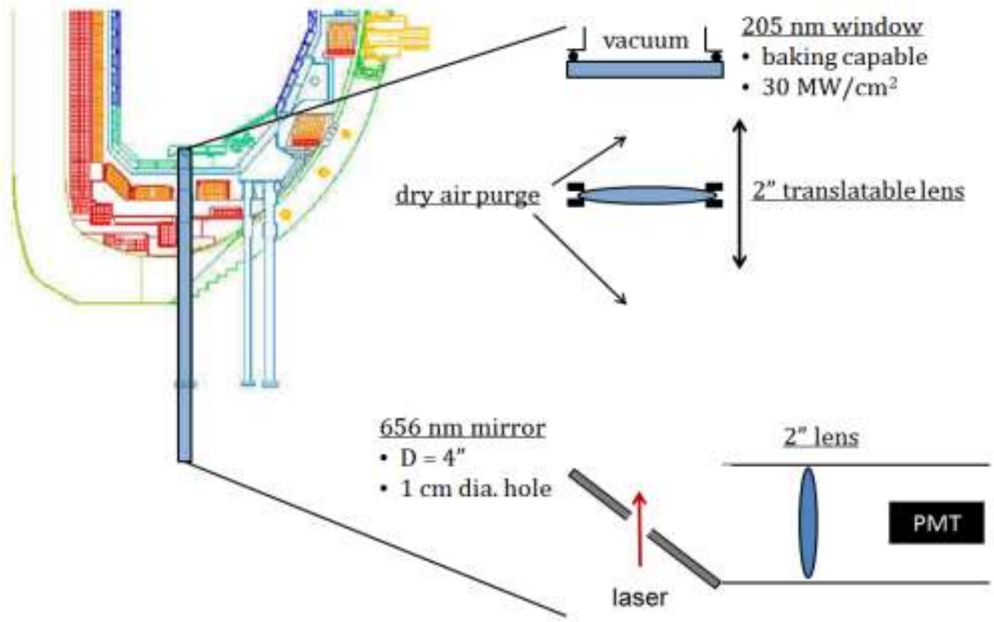

Figure 9. Approved design for TALIF installation on DIII-D tokamak. The laser would have been injected vertically up through a port in the divertor region of the vacuum chamber.

E. HIT-SI TALIF Experiments: Shown below are TALIF measurements obtained at the HIT-SI3 facility.

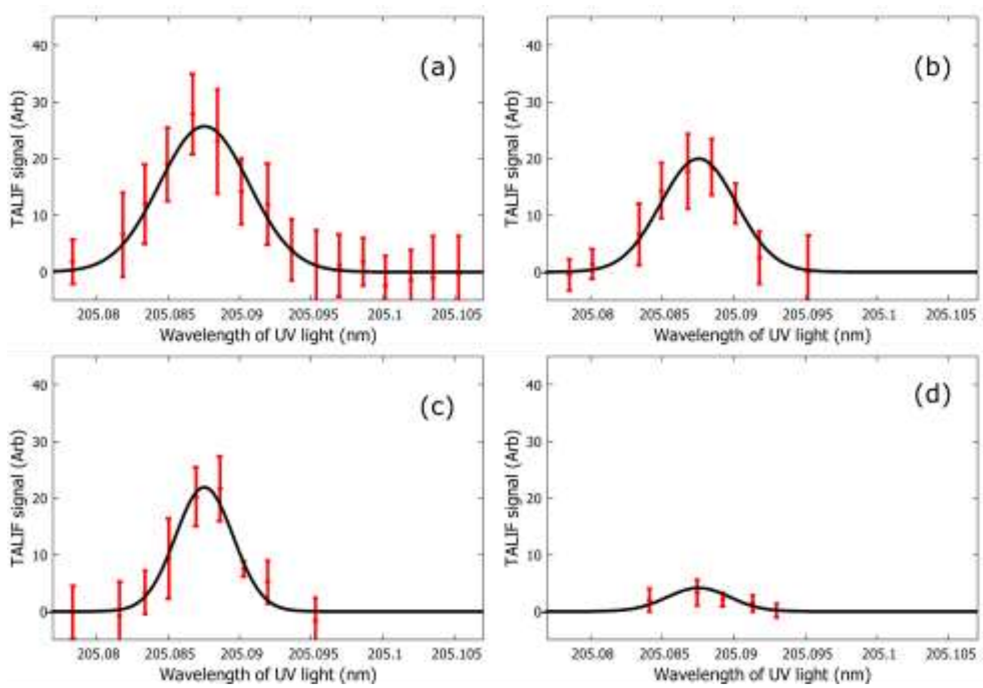

Figure 10. TALIF signal from Deuterium plasmas in the HIT-SI3 spheromak. The error bars come from the standard deviation of the measured data. The black line is a Gaussian fit from which the temperature is determined. Dataset (a) was recorded 18 cm into the chamber at 2.16 ms. Datasets (b)-(d) were recorded 11 cm into the discharge at 2.18, 2.16 and 2.10 ms

F: Xenon TALIF Calibration Scheme: Shown below is the new xenon TALIF scheme proposed and then demonstrated at WVU. Note the pump wavelength is accessible with the current laser system and the fluorescence wavelength is nearly identical to the hydrogenic scheme. Also shown are the krypton and xenon measurements that were used to produce a new relative hydrogen to xenon absorption cross section ratio using the known ratio of krypton to hydrogen.

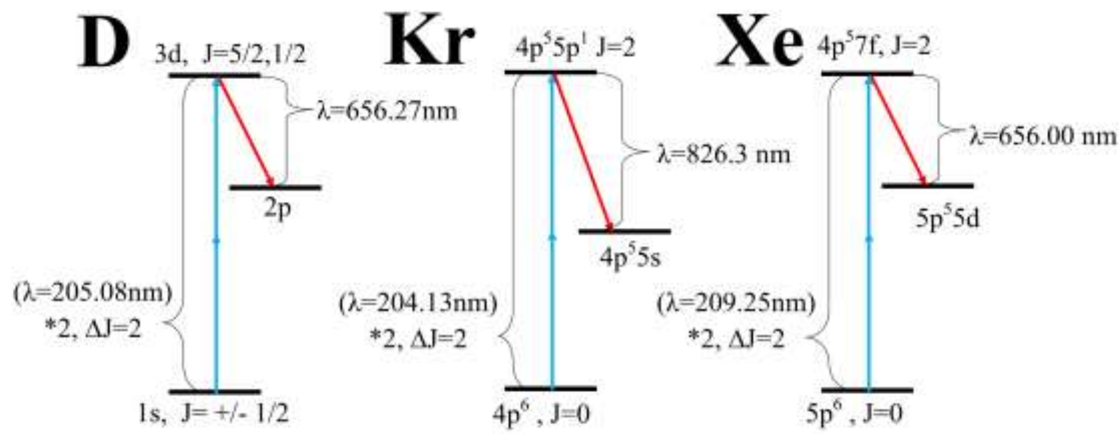

Figure 11. The partial Grotrian diagrams of the deuterium (a), krypton (b), and xenon (c) showing the excitation photons and the emission photons for each TALIF scheme.

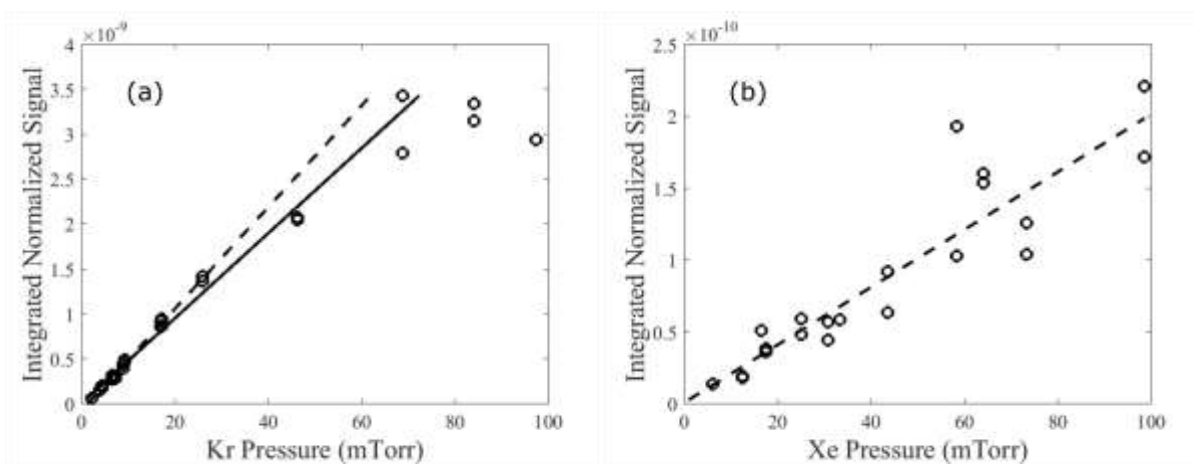

Figure 12. Normalized TALIF signal for (a) xenon and (b) krypton as a function of neutral gas pressure.

G. Significance to the Field: The density sensitivity achieved with TALIF is sufficient, based on comparisons with measurements and simulations of expected background light levels in DIII-D, to have been able to move forward with measurements in DIII-D with reasonable confidence of success. The HIT-SI experiments were successful and yielded neutral hydrogen density values well below the HIT-SI team thought were likely in their discharges. The challenges in optimizing the collection optics did identify problems with the standard krypton calibration scheme due to differences in the focal properties of typical lens at the hydrogen and krypton fluorescence wavelengths. As a result, the WVU team proposed and has now demonstrated a new xenon-based calibration scheme for hydrogen TALIF. The xenon scheme has been published and now is available for use by all other groups. The krypton experiments themselves provided the first comprehensive measurements of neutral density measurements in a helicon source and the profile measurements, in particular, have already had a major impact on the helicon source research community. Other research groups, such as one at Australian National University, have already duplicated the WVU TALIF system design and are engaged in neutral density measurements in stellarators and helicon sources.

PUBLICATIONS*

1. Elliott, D., E. Scime, and Z. Short, "Novel xenon calibration scheme for two-photon absorption laser induced fluorescence of hydrogen," Rev. Sci. Instrum. **87**, 11E504 doi:10.1063/1.4955489 (2016).

2. Elliott, D., D. Sutherland, U. Siddiqui, E. Scime, C. Everson, K. Morgan, A. Hossack, B. Nelson, and T. Jarboe, "Two-photon LIF on the HIT-SI3 experiment: Absolute density and temperature measurements of deuterium neutrals," Rev. Sci. Instrum. **87**, 11E506 doi: 10.1063/1.4955494 (2016).

3. Galante, M., R. M. Magee, and E. Scime, "Two Photon Absorption Laser Induced Fluorescence Measurements of Neutral Density in a Helicon Plasma," Phys. Plasmas **21**, 055704 (2014).

4. Magee R. M., M. E. Galante, J. Carr, Jr., G. Lusk, D. W. McCarren, and E. E. Scime, "Neutral depletion and the helicon density limit,' Phys. Plasma **20**, 123511 (2013).

5. Magee, R.M., M. E. Galante, N. Gulbrandsen, and E. E. Scime, "Direct Measurements of the Ionization Fraction in Krypton Helicon Plasmas," Phys. Plasmas **19**, 123506 (2012).

6. Magee, R. M., M. E. Galante, D. McCarren, E. E. Scime, R. L. Boivin, N. H. Brooks, R. J. Groebner, D. N. Hill, and G. D. Porter, "A Two-Photon Absorption Laser Induced Fluorescence Diagnostic," Rev. Sci. Instrum. **83**, 10D701 (2012).

*Note: Only peer-reviewed journal publications are listed here. Over a dozen conference abstracts were submitted during the period of performance of this project.

PERSONNEL

Name	Role	Percentage of support*
Matthew Galante	Graduate Student	100%
Richard Magee	Postdoc	50%
Earl Scime	Principal Investigator	10%
Gregory Lusk	Undergraduate	5%
Mark Soderholm	Undergraduate	5%
Robert VanDervort	Undergraduate	5%
Dustin McCarren	Graduate Student	16%
John McKee	Graduate Student	16%
Drew Elliott	Graduate Student	0%

* Percentage of support based on fraction of time supported over 3-year period of funding (excluding no-cost extension periods). For example, graduate student Drew Elliott completed the experiments at University of Washington-Seattle that demonstrated the success of the diagnostic system, but did so after the student support for this project expired – so he performed a major portion of the experimental work but was never supported by the project.

CURRENT AND PENDING SUPPORT

Title: Extended Mission: TWINS Mission Analysis
PI: Earl Scime
Source of Funding: Princeton University
Amount of Funding to WVU: $ 30,000
Performance Period: 10/1/16-9/30/17
Dr. Scime's Commitment: 0.0 summer months (staff supervision only)
Dr. Scime's Responsibilities: Analysis of data from TWINS instrument. Preparation of annual reports to be performed during academic year.
Overlap with this DoE EPSCoR Project: None

Title: Experimental Investigation of Spontaneous Double Layers in Expanding Plasmas
PI: Earl Scime
Source of Funding: NSF
Amount of Funding to WVU: $ 671,795
Performance Period: 7/1/2014-6/30/2017
Dr. Scime's Commitment: 1 summer months (in years 2&3)
Dr. Scime's Responsibilities: Preparation of annual reports, supervision of students and postdoc in research. One of three summer months to be dedicated to this activity each year.
Overlap with this DoE EPSCoR Project: This project includes a task that employs the laser system developed for this project for neutral density measurements in the laboratory helicon plasma source.

Title: Low Voltage, Ultra-Compact Plasma Spectrometers for Heliophysics
PI: Earl Scime
Source of Funding: NASA
Amount of Funding to WVU: $ 719,717
Performance Period: 7/1/2014-6/30/2017
Dr. Scime's Commitment: 1 summer months
Dr. Scime's Responsibilities: Preparation of annual reports, supervision of students and postdoc in research. One of three summer months to be dedicated to this activity each year.
Overlap with this DoE EPSCoR Project: None

Title: GOALI: OPTIMIZATION OF ION IMPLANTATION PROCESSES – ENABLING TECHNOLOGY FOR ADVANCED SEMICONDUCTOR FABRICATION
PI: Earl Scime
Source of Funding: NSF
Amount of Funding to WVU: $ 435,000
Performance Period: 07/ 01 / 2016 - 06 / 30 / 2019
Dr. Scime's Commitment: 1.0 summer months in years 2 and 3
Dr. Scime's Responsibilities: Preparation of annual reports, supervision of students and postdoc in research. One of three summer months to be dedicated to this activity each year.
Overlap with this DoE EPSCoR Project: None

<u>Pending Support</u>

Title: Investigating the link between ion injections and storm intensity
PI: Amy Keesee
Source of Funding: NASA Helio Guest Investigator
Amount of Funding to WVU: $437,089
Performance Period: 11/1/2016-10/31/2019
Dr. Scime's Commitment: 0.25 summer months
Dr. Scime's Responsibilities: Analysis of data from the TWINS instrument
Overlap with this DoE EPSCoR Project: None

Title: Low Voltage, Ultra-Compact Plasma Spectrometer: Phase 2
PI: Earl Scime
Source of Funding: NASA
Amount of Funding to WVU: $ 1,034,101.82
Performance Period: 07 / 01 / 2017 - 06 / 30 / 2020
Dr. Scime's Commitment: 1 summer months/year
Dr. Scime's Responsibilities: Preparation of annual reports and supervision of student studies to be performed during academic year. One of three summer months to be dedicated to this activity each year.
Overlap with this DoE EPSCoR Project: None

COST STATUS

This project included both DoE and cost share components. The DoE portion of the budget was $599,236 and the cost share was supplied by WVU ($50,000) and General Atomics ($131,000). The WVU and General Atomics contributions were both for specific equipment items. The General Atomics cost share was used to purchase a high-performance laser wavemeter, laser power meter, and specialty UV-grade optics. The WVU cost share was contributed to the purchase of the pulsed UV laser system – total cost $196,202. The remainder of the DoE budget were completely spent through supporting the postdoc, the graduate students, PI summer support, the undergraduates, experimental supplies, and project-related travel.

No-cost extensions were requested and approved. During the extensions, the project continued with students being support from internal WVU sources and culminated with the successful performance of TALIF measurements at the University of Washington-Seattle's magnetic fusion HIT-SI3 experiment.

Appropriate close-out financial documents are being submitted by WVU to the DoE Chicago office.