Internal magnetic field, temperature and density measurements on magnetized HED plasmas using Pulsed Polarimetry

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Report submitted to:

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Subcontract through MSX grant: March 1, 2016 – May31, 2016
(Resources from the UW 62-6377 budget were used for hiring a student to work on MSX, Trevor Hutchinson, providing much needed manpower, this was paid back by extending the work on MSX and Pulsed Polarimetry through May, 2016.)

Reporting Period: April 30, 2014 – May 30, 2016
Annual Progress Report

Accomplishments

What are the major(stated) goals of the project?

The goals were to collaborate with the MSX project and make the MSX platform reliable with a performance where pulsed polarimetry would be capable of adding a useful measurement and then to achieve a first measurement using pulsed polarimetry.

The MSX platform (outside of laser blow off plasmas adjacent to magnetic fields which are low beta) is the only device that can generate high beta magnetized collisionless supercritical shocks, and with a large spatial size of ~10 cm. Creating shocks at high Mach numbers and investigating the dynamics of the shocks was the main goal of the project. The MSX shocks scale to astrophysical magnetized shocks and potentially throw light on the generation of highly energetic particles via a mechanism like the Fermi process.

What are the major(stated) goals of the project?

1. Participate in and improve the Magnetized Shock Experiment (MSX) parameters
2. Study formation of the FRC with regards to n_e and T_e profiles to optimize operations.
3. Diagnostic development: Interferometry and spectroscopy had been added. Imaging, internal magnetic probing, and X-ray detection were needed for showing that shocks and non-thermal particles were being produced.
4. As stated in this year's proposal. Develop pulsed polarimeter capabilities using fiber optics to provide the least intrusive magnetic field measurements for the field strengths that MSX was capable of generating. It was becoming clear that the combined parameters of n_e~10^{23}m^{-3} and B = 5-10T need for an optical pulsed polarimeter were longer term goals for MSX.
5. Produce calibrated data for T_e and n_e measurements using the TS capabilities of Pulsed Polarimeter the program gave the necessary time to do so.
6. Include the measurements in publications and reports of the MSX team. A team consisting of Dr. Thomas Weber and myself.

What was accomplished under these goals?

1. By July 2014, MSX had become a reliable machine, capable of 30 shots a day, with high reproducibility. This was the outcome of a concerted effort by Dr. Thomas Weber and myself with help from Trevor Hutchinson. Decades old problems on FRX-L were addressed and solved. With this capability, MSX(FRX-L) fulfilled its commitment to the MTF project (belatedly) by showing that "Plasma gun assisted FRC formation is viable and extends the range of FRC parameters". Specifically, higher trapped flux and lower density. This was crucial for MSX in reaching the collision-less supercritical shock regime, resulting in a publication. The upstream parameters, as measured by external field probes and interferometry showed that the velocities were sufficient for generating a collisionless supercritical shock.
2. By October 2014: Field measurements of the plasma in the shock region were disappointing. The insertable alumina cladded multi-pickup coil diagnostic built by Trevor showed that the FRC was not maintaining a reversed field after entering the shock chamber due to free expansion. A new, close fitting chamber was needed.
3. November 2014: It was clear that the fields in the formation and shock regions were

too low for the pulsed polarimeter. An optical fiber was laid under the theta coil in the formation section for future use. At APS, FRC formation and performance, internal probing, interferometry and the viability (from existing field measurements) of using fiber optic pulsed polarimetry for magnetic sensing on MSX was presented.

4. October-December 2014. I taught fall qtr at UW, I am only 60% FTE on this grant.
5. Sept 2014 to February 2015 while teaching at UW, the fiber concept was advanced. The historic problems for fiber optic pulsed polarimetry is the limitation of pulse energy (<1µJ) and very low Rayleigh backscatter levels at this energy. The funds allocated for a custom fiber development in the grant were small and only one idea could be pursued to 'enhance' the backscatter of a fiber. It was decided to imprint or write an array of discrete localized fiber Bragg gratings along a fiber with a specific reflection coefficient at 532nm wavelength and spacing of 2.5*mm*, 400/*m* or 2.5mm over 1*m*. The fiber was designed and made in the period Sept 2014 to February, 2015 in parallel with teaching. The fiber was tested and found to greatly enhance the backscatter while faithfully sensing the local magnetic field but the reflection coefficients had large scatter. This was the first fiber of its kind.

   February – May 2015: Returned to LANL, Dr Weber and Dr Alan Lynn, UNM had operated MSX in my absence. Alan and Thom had done extensive imaging of the plasmas in the shock region using visible light. Some dramatic behavior was shown. I felt the new chamber was a high priority as there was little chance of success with the existing chamber producing high parameters. A new chamber was designed, manufactured and installed by April 2015. X-ray detection systems based on thin foils were developed using old LANL PMTs which led to a sophisticated 4 port X-ray detection systems with energy discrimination based on foil metals and thicknesses.

   The new optical fiber was tested at LANL using the 20ps pulse from the pulsed polarimeter laser and detecting backscatter with an old LANL Imacon streak camera. *For the first time*, due the exceptionally high level of back reflection, distributed return light from a fiber was *photographed* as a steak with time resolutions measured in 10's of picoseconds.

   The potential for MSX to produce neutrons as a bright neutron source was also explored during this time with the hopes of achieving funding inside LANL as the DOE HED program had decided MSX would not be supported beyond July 2015.
6. June 2015. I returned to Seattle to vacation. When I returned to LANL there was to be a concerted effort to at least get some data from the Pulsed Polarimeter on the formation stage. The instrument was recalibrated and positioned for this effort. The building compressor had failed for the lab but this seemed to be a temporary set back.
7. July 2015 - **Compressor**. I returned and fixing the building compressor failure was now an urgent matter. Plumbing in our own compressor or bypassing the building compressor with a local smaller unit was not pursued as there was a keen possibility of a major unforeseen mishap with the MJ Marx bank system. With due diligence by the Physics division area supervisor, Julie, Group manager, Dr Glen Wurden, Physics Division Head and so on, the compressor was finally replaced in February of 2016! Replaced by the easily available unused compressor in the adjacent bldg. The procrastination and incredible bureaucracy of LANL stalled MSX for 10 months despite the urgency. Both Thom and I received no-cost extensions of our grants until

January 2016.

8. July- September 2015 – fiber optic pulsed polarimetry(FOPP). With MSX on hold for an indefinite time, I concentrated on fiber optic PP which could be done independently of MSX The equipment needed to adapt the UW pulsed polarimeter and a multi-tesla solenoid was made. The local field internal to a solenoid producing a 2.6T field was measured for the first time using streak camera detection. This was an important new result, as streak cameras provide the highest performance in bandwidth and therefore spatial resolution, in principle down to 100 μm.
9. November 2015, The FOPP results were reported at APS along with the X-ray and new interferometer measurements for MSX, a HeNe interferometer that has essentially unlimited time response, crucial for small spatial and fast time scales of the shock studies on MSX. Dr Weber also was promoted to a LANL staff position assuring MSX could continue under his direction.
10. December 2015- February 2016. I returned to Seattle to vacation and to write the paper on the fiber optic measurements for the High Temperature Plasma Diagnostic conference in Madision,Wi. in June. Dr Weber was also preparing a publication on the new high bandwidth interferometer. A subcontract to support my efforts at MSX beyond February 2016 for 3 months was put into place so I could return.
11. March – May, 2016. I returned to MSX on the 3 month subcontract. The compressor had been replaced and we could continue to operate. From March onward, progress was subject to Thom's work load and getting the machine working after such a long time was slow. The 4 port X-ray diagnostic was built and began to operate. Efforts were made to find an avenue of support for MSX. In May, the effort was progressively being applied to getting fiber optic pulsed polarimeter data before my subcontract was up. The cladded fiber was placed in front of the stagnating magnet in order to measure the compressed shocked up field. No luck. Then the fiber was inserted through the bore of the magnet, extending into the shock region, regardless of the FRC, the bore field was spatially resolved by the fiber, a repeat of the work last summer. A timing scan was done for the arrival of the FRC on the face of the magnet and for the first time, the FRC magnetic profile stagnating on the magnet was observed and measured. A magnetic field profile of a few cm's spatial extent, in front of the magnet with a peak field of 7 Tesla in the direction along the axis of the machine was measured for several shots. This data was taken on Sunday May 29th. We had worked up to the last days of the subcontract to get a plasma result. The HTPD conference was the following week, so there was no time to incorporate these results into the paper, which was also a pressing issue. What this did show, and what was suspected for a while is that the field from the magnet is not well enough concentrated near the bore to impede the FRC and seems to funnel or guide and concentrate the FRC at the magnet bore. This was the first distributed measurement of the magnetic field of a magnetized plasma. It was the first time that I had gotten to see the curve that represents the progressive integral of the spatial magnetic field, a curve that once differentiated, yields the local magnetic field. However not with the optical pulsed polarimeter which requires more of the MSX program than Thom and I could accomplish. I am afraid the project taken as a whole was beyond the resources we had at our disposal.

12. Sept 2016. I attended the HTPD conference in June, using my own resources, as I felt this result must be published by any means. RSI published my paper(co-authored with Thom) on first measurements of the distributed magnetic field using a new custom fiber called a "*backscatter tailored*" optical fiber that allows streak camera detection. In principle, the spatial resolution can be sub-mm and mega-Gauss (100T) fields can be resolved using this technique if fibers can be positioned in the field regions. It is a paradigm shift from magnetic sensing using electrical probes.

What was done? (see above)
What was learned?

FRC formation significantly improved over FRX-L

The plasma gun array provided the necessary ingredient to be able to enter the collisionless Supercritical shock regime as shown in **Fig 1**. The parameter range for FRC formation has been extended downward in density and more significantly, upward in trapped flux. The performance also depends on the velocity of the FRC, velocities of 350km/s were obtained for low density FRCs.

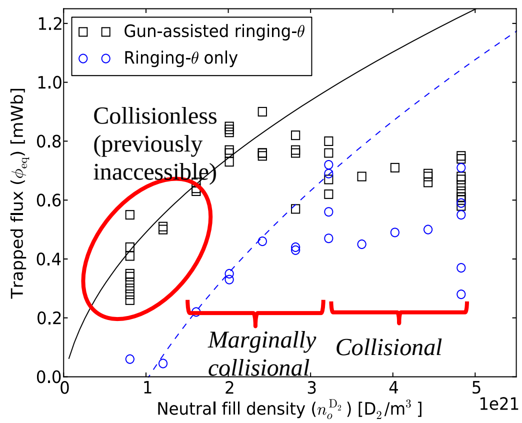

Fig 1 Improved FRC formation on MSX and collisionless regime entered.

Concept of fiber optic sensing on MSX

For magnetic fields that are too low for the pulsed polarimeter, a fiber optic pulsed polarimeter (FOPP) represents the same magnetic sensing geometry across the dipole magnetic field with the least perturbation to the plasma. The fiber is 125μm in diameter and can be cladded with a small diameter refractory tube as shown in **Fig 2**. A near continuous distribution of $B_s(s)$ is obtained with much higher sensitivity than optical pulsed polarimetry Most Important: ***sub-6mm, fine scale structures are detectable.***

In this case, the fiber optic pulsed polarimetry was successfully carried out and the magnetic field distribution measured with the fiber inserted through the bore of the magnet.

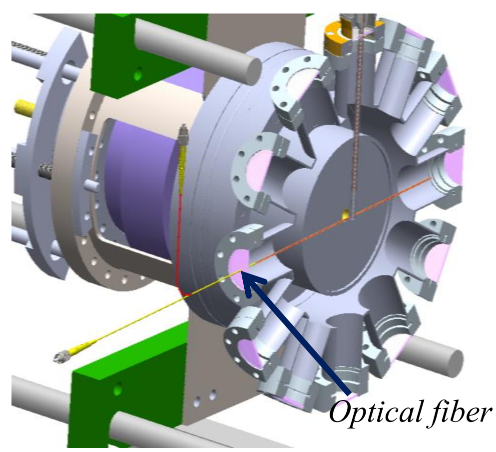

Fig 2 Shock chamber with a fiber sensor across the bow of the magnet.

Pickup coil probe arrays on MSX

Magnetic field probes on MSX near the magnet and illuminated by the FRC impacting the magnet enclosure as shown in **Fig 3**. Probe stems are physically large alumina tubes with o.d.s of 0.25” or larger. Electrical probes have other problems too. More coverage means more probes and bigger structures. Electrical filtering and integrators are needed. They are BW limited. Most importantly, no magnetic structures less than 0.25” are subject to observation.

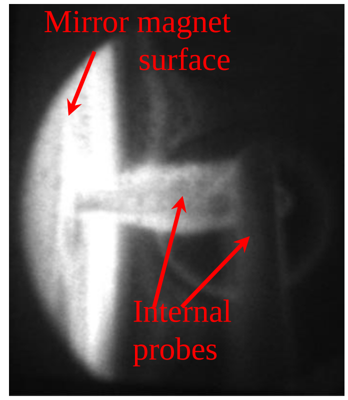

Fig 3 Conventional probe array diagnostics

New Interferometer with high bandwidth

The old heterodyning systems with Bragg cell AOMs were too limited in bandwidth for this project and for any project in the MTF catchment really. A high bandwidth full quadrature interferometer was develop for MSX and successfully captured very fast density phenomena. 300MHz was the limit for the system due to intra-cavity laser oscillations at 400MHz. Data is shown in **Fig 4**.

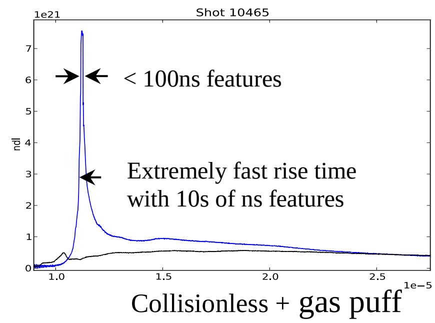

Fig 4 New wide bandwidth HeNe Interferometer

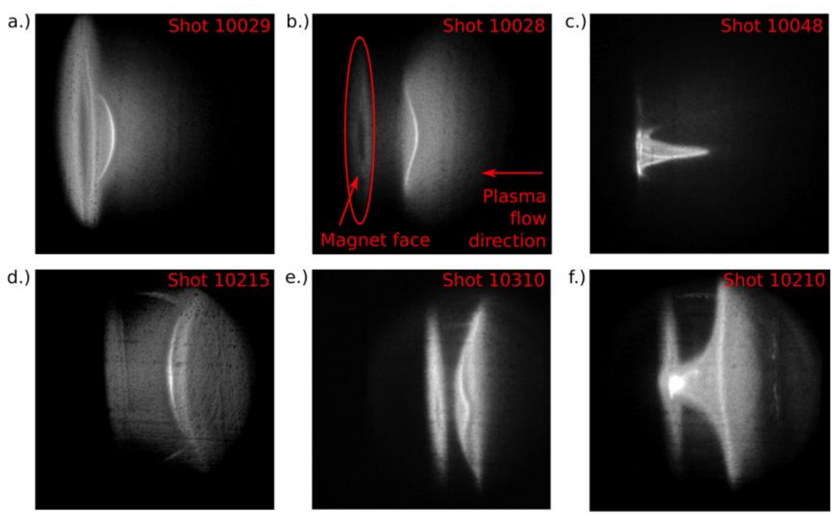

Fig 5 Top row – Mirror field + gas puff: a.) weak, b.) intermediate, c.) strong field. Bottom row – cusp field + gas puff: d.) weak,e.) intermediate, f.) strong.

Some of the interesting shock fronts that were obtained on MSX are shown in **Fig 5.** The images are of emission in the visible , no filtering. The shock front of interest would be invisible and travelling upstream of the magnet. Imaging in the X-ray region would be the ideal diagnostic to have on MSX.

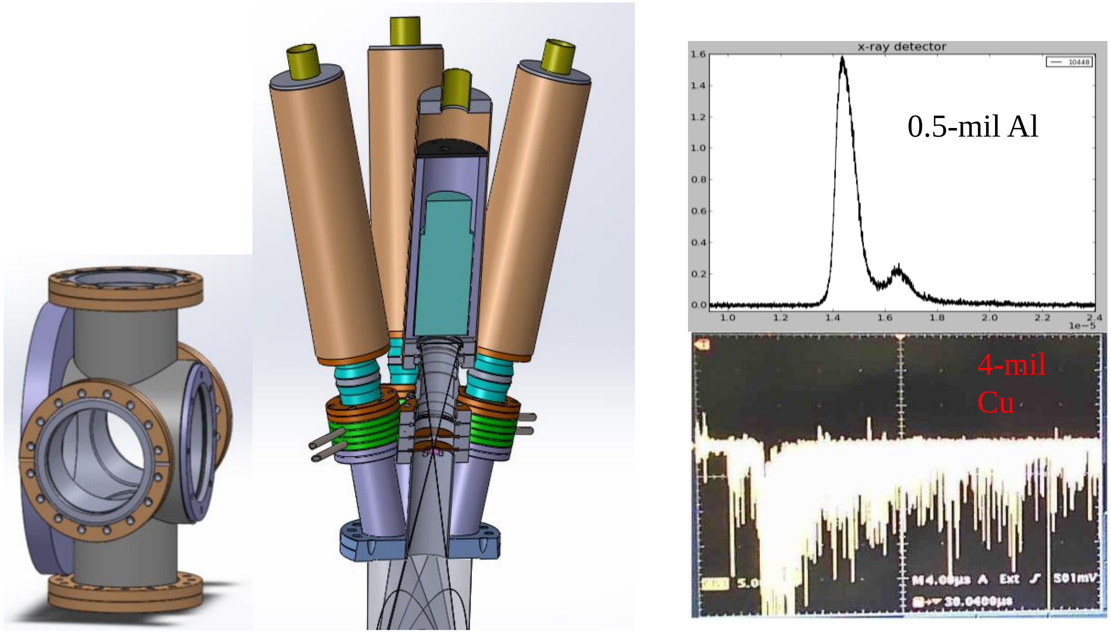

Fig 6 Some of the changes to MSX and diagnostic structures that were implemented on this short time scale, Swks cad drawings show a) the new shock chamber, b) a multi-foil X-ray detection system and c) initial X-ray signals which show copious amounts of hard X-rays.

In **Fig 6**, are shown the modifications to the shock chamber in order to limit the expansion of the FRC. The magnet was also brought closer up to the translation section. Also a large 4 port flange was designed and built to allow symmetric views of the shock region for thin metal film/scintillator/PMT detection systems, providing discrimination between thermal X-ray and non-thermal particle distributions. Some of first Xray signals on MSX are shown which stimulated and justified the need for this diagnostic.

Modelling of the MSX

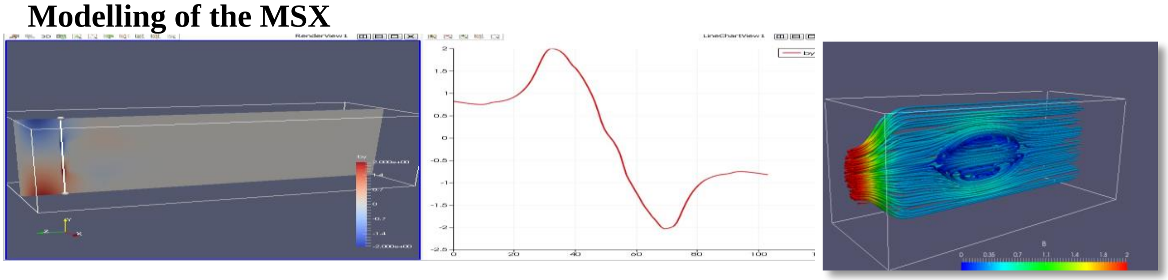

Fig. 7c) Shows simulations of translating FRC impacting the stagnating magnetic field. 7 a,b) are the radially directed magnetic field profile of the FRC in front of the magnet. The MSX geometry is fully represented.

In **Fig 7**, Dr. Omelchenko of Trinum Research, Inc collaborated with MSX and ran simulations of the FRC dynamics with his HYPERS code. Some of the phenomena that was observed was quite well simulated. The magnetic fields that were suggested by the simulations bode well for fiber optic field sensing at +/-2 T fields in the shock.

Fiber Optic Pulsed Polarimetry

Magnetic pickup coils for field sensing are cheap, expedient and simple(always work), they will never leave the tool box of the MFE community. However, the complexity and intensity of confining magnetic fields is becoming more demanding. To meet this demand, fiber optic magnetic sensing is appropriate. Long time scales of MFE and short time scales of HED are accommodated without integrators or filtering or bandwidth limitations. No electrical hazards for HED experiments with fibers. The Faraday effect is linear for an enormous, unbounded range, it would seem, of field strength. Distributed magnetic sensing along a fiber, FOPP, also known as POTDR was introduced by A.J. Rogers in 1984 and has been subject to poor signal and therefore poor spatial resolution >10cm and field resolution ever since. The new so-called *backscatter-tailored* fiber is a genuine breakthrough. Over 30,000 times brighter than fiber Rayleigh scatter and so bright that the eye can see the return signal and most importantly, ultra-fast detectors are able to sense the return light. The implications for magnetic field sensing are manifold. MegaGauss(100T) down to 10s of Gauss are measureable with speed of light bandwidths and spatial resolution of 100 microns using silica and terbium doped fibers.

With such high levels of backscatter, high rep lases of 50MHz (inexpensive fiber lasers) with 10 nJ pulse energies produce enough retrun signal to allow nearly continuous field measurements in both space and time. In HED applications, the streak camera can multiplex several fiber polarimeter outputs with the fibers either spatially displaced, time displace by 10's ns to zero ns or both. Sub-*mm* resolutions are possible since the FBG spacing can be on the order of 100 microns without any degradation in SNR.

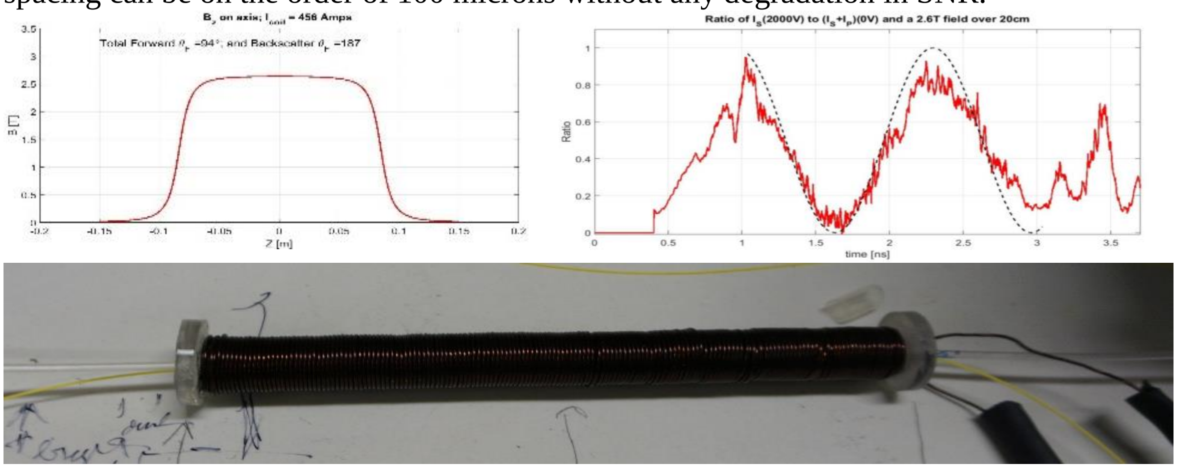

Fig 8 8a) The simulation of the field in the solenoid shown in 8c), 8b) the reconstructed Faraday rotation from the new Backscatter Tailored optical fiber with a dotted trace the expected curve for the 2.6T solenoidal field. The position matches very well indicating the spatial dependence of the field is captured as indicated by the dotted curve, 8c) shows the 20cm long solenoid with the fiber threading the bore.

Fig 8 shows the FOPP results. A very high SNR was achieved, higher than 3000:1 using a streak camera. But there were holes (large attenuations) in the fiber FBG array due to low reflection coefficients for those FBGs. This was the first fiber and the technique for producing a more reliable 'low' reflection has improved since then.

FOPP plasma results on MSX

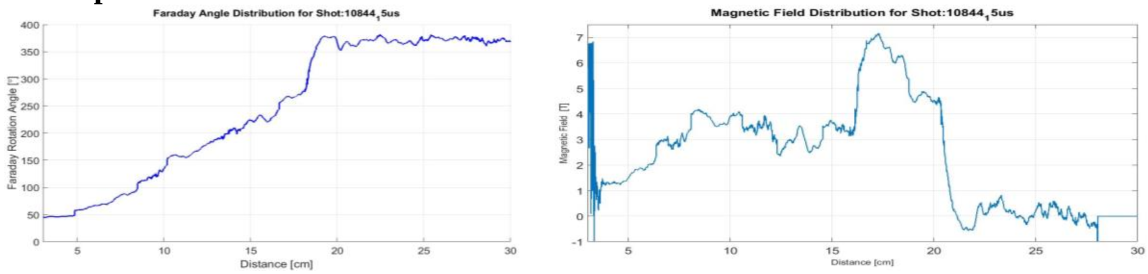

Fig 9 Fiber optic pulsed polarimetry traces for shot 10844 showing a 7T peak field infront of the magnet surface. 9a) progressive Faraday rotation along fiber, 9b) the derivative of 9a) or local B field along the fiber.

On essentially the last day of the subcontract, Sunday, May 29th , Thom and I were successful in getting some distributed field measurements of the FRC plasma with the *backscatter tailored* fiber oriented along the machine axis through the bore of the magnet. The Faraday rotation trace Fig 9a) once unwrapped, shows an integrated Faraday rotation angle monotonically increasing from 50° to a maximum angle of around 400° and then is flat indicating a field amplitude of zero. The angle has a rapid rise at a time in the streak or a distance along the fiber that corresponds to the magnet face. The derivative of 9a) is the local magnetic field shown in Fig 9b) . One can see that the field in the solenoid has a peak field of around 4T and the magnetized object has a peak field of 7T and is about 5 cm long with next to no axial field behind it, upstream of the plasma. This is an encouraging start to FOPP for plasma measurements, more signal processing needs to be done on this data but it already, in a raw form, shows a wealth of detail that has never been observed until now.. Other shots show the same behaviour. Whether this data will be published, I don't know but I hope that it will be.

Facility and support at LANL

As one can see, Thom and I tried very hard to make MSX into a viable experiment facing little support from the lab and a general lack of funding. MSX is a jewel in DOE's program, unique, viable and a current research topic of wide interest to the community. The lab, LANL, is a very difficult environment, having a collaboration with a university, in this case, gave some relief from the high LANL overheads. I will not go into specific problems that I noted at the lab only to say that I hope DOE will support Dr.Weber's efforts to keep FRC research and pulsed power plasma projects alive at LANL. I would not have continued my involvement with MSX, in fact, it would not have been possible to run the experiment, if it weren't for the same effort coming from Thom. He is a highly motivated and competent scientist interested in doing experimental plasma research at the highest level.

Products

Publications

TE Weber, TP Intrator, RJ Smith 2015 *"Plasma-gun-assisted field-reversed configuration formation in a conical θ-pinch",* Phys Plasmas **22**, 042518

R J Smith, T E Weber , 2016,*"Streak camera based FOPP technique for fiber optic magnetic sensing to sub-mm resolution",* Rev Sci Instrum, 87(11):11E725

T E Weber, …, 'MSX Interferometer paper', in progress

T E Weber …, 'Shocks generated by MSX paper' in progress

Presentations

2015 APS-DPP (Savannah)

- R J Smith, *UW, Seattle*, T E Weber, *Los Alamos National Laboratory, NM*, "*Diagnostic Progress and Results on LANL's Magnetized Shock Experiment";*

2014 APS-DPP (New Orleans)

- R J Smith, *UW, Seattle*, T E Weber, S C Hsu, LANL, *Los Alamos*, T M Hutchinson, UNR, *Reno*, S F Taylor, UW, *Wi*. "*Pulsed polarimetry and Magnetic Sensing on the Magnetized Shock Experiment (MSX)*"

Technologies or techniques

The response to the request made in June of 2015 by DOE for the development and deployment of new techniques beyond possible applications in fusion energy is given in Appendix A, written before magnetic measurements using the new fiber had been made.

Magnetic sensing impacts any number of fields in modern society, most outside of MFE or HEDLP but the magnetic field is a driver in these disciplines. FOPP makes it possible to measure small fields in space and time wherever optical fibers can be introduced.

Inventions, patent applications, or licenses

The *backscatter tailored* optical fiber is patent pending. I have not decided whether to proceed to a patent application.

Other products

None

Participants and other collaborating organizations (provide facility and operate the MSX device)

Investigators/Collaborators

- Thomas Weber (Co-PI): LANL (0 FTE)

Post-baccalaureate student

- Trevor Hutchinson: BA Lewis and Clark University, (0.5 FTE)

Impact

What is the impact on the development of the principal discipline(s) of the project?

The development of a key diagnostic technique: Pulsed Polarimetry, providing instantaneous and remote measurements of the internal magnetic field, electron density and temperature, with sub-*cm* spatial resolutions (20 *ps*) optically with no perturbation to the plasma and the development of fiber optic pulsed polarimetry for the measurement of remote field

For MSX, the key development is the unique formation of collision-less supercritical magnetized shocks in a terrestrial environment. The only other experimental situation that is of the same scope is the Earths Bow shock which is much more expensive to probe and diagnose.

What is the impact on other disciplines?

The pulsed polarimeter is well suited to magnetized HED experimental platforms such as Magneto-Inertial confinement (Maglif at Sandia) and Z pinch experiments. The technique can achieve sub-mm spatial resolution using ultra-fast photography using the optical Kerr effect with a 1*ps* time resolution using a visible laser. Fiber pulsed polarimetry (FOPP) is complementary to internal magnetic probing providing quantitative information on the efficiency of the EM drivers in coupling power to the plasma, essentially the Poynting flux is measured. The external field measurements of FOPP complement the internal measurements of optical pulsed polarimetry. However FOPP is an instrument calibrated and working without the plasma, PP is dependent for its success on the merit of the plasmas field and density. It is a diagnostic that improves as the magnetic experiments and devices improve: higher fields and higher densities, both necessary to make fusion energy viable and it will always be so.

These experiments can provide insights into the dynamics of astrophysical systems such as planetary bow shocks and supernova remnants. Members of the heliophysics and astrophysics communities have embraced this effort and have provided appreciated feedback regarding unanswered space physics questions.

What is the impact on the development of other human resources?

The magnetic field, if measured to low levels has a profound bearing on human resources, in my mind. More and more the magnetic field is an object of interest in medicine and physiology. Obviously, magnetic field is synonymous with currents, and so the practical application of sensitive FOPP can be expressed in terms of current strengths and current distributions. Anything electrical is a target for this technology.

What is the impact on physical, institutional, and information resources that form infrastructure?

This research could result in a new DOE diagnostic capability for *non*-perturbative *local* magnetic sensing across the whole MFE and MHED portfolio.

What is the impact on technology transfer?

Pulsed polarimetry is a non-perturbative internal remote sensing technique of the distributed magnetic field in magnetized plasmas and thereby the internal current distribution. The technique is unique to this field in that it excels with higher density and magnetic field strength or higher performance, the direction of thermonuclear fusion in tokamaks. The diagnostic represents an encompassing diagnostic technique of n_e, T_e and B profiles in future fusion reactors like DEMO of a nature that will allow operation, MHD stabilization by local field sensing, and optimization of a burning plasma in the most hostile setting (remote sensing). This application to MSX is a first application of this unique and important technique.

What is the impact on society beyond science and technology?

A need to broaden Lidar techniques to the IR and FIR region is paramount for this field and such an investment, I strongly believe, will pay dividends for FIR astronomy and remote sensing in other fields. FIR Lidar development is needed and long overdue both powerful ultra-short laser (passively pumped by CO2 sources0 and ultra-fast detectors and detector FPAs.

What dollar amount of the award's budget spent in foreign countries?
$0.00

Changes

Changes in approach and reasons for change

Fiber optic magnetic sensing capability has been added, as the initial fields obtained on MSX will be weak. FOPP(under development) on MSX replaces the pulsed polarimeter with regards to characterizing the internal B distributions in the shock until performance demands a non-perturbing technique as PP.

As regards to Lidar TS n_e and T_e measurements using the Pulsed Polarimeter, the approach as detailed in the proposal is being carried out but the progress is at the mercy of the development of the MSX device and program (commissioning magnet March and commission several diagnostics April 2014). The thrust of the program is to form and characterize a supercritical collision-less magnetic shock which to date is absorbing the available manpower, results are just now coming in and a detailed scan of the shock region is presently being carried out.

Actual or anticipated problems or delays and actions or plans to resolve them

There are as yet no anticipated problems in running the Pulsed polarimeter on MSX, but deploying the PP system has less urgency than demonstrating and characterizing a first shock on MSX which is consuming all available manpower and delays in getting first results is deemed more important to the project, that is Trevor and I are needed to accomplish this. When dedicated time was possible for PP to try to measure ne and Te profiles, a problem with the building compressor arose which took 10 months to fix. During that time fiber optic pulsed polarimetry was demonstrated leading to a publication and a measurement of the distributed field of the a magnetized plasma stagnating on the stopping magnet of MSX.

Changes that have a significant impact on expenditures

All of this work was done under budget.

Appendix A: Reply to DOE's solicitation

High energy density laboratory plasmas and inertial fusion energy science and technology

Categories: MHEDLP, MFE and astrophysical plasma research. Present support for this development is the DOE Joint Program in HEDLP.

The novel technique of Pulsed Polarimetry is an FES funded technology development with broader scope than fusion science for magnetic sensing. The technique represents a paradigm shift in magnetic sensing providing near continuous field determination in both space and time, remotely, non-perturbatively and by optical (non-electrical) means. The pulsed polarimetry technique has the potential to contribute to most disciplines in which a magnetic field plays a decisive role.

The pulsed polarimetry technique applies generally to all optically transparent media as the two key ingredients: a scattering mechanism and an optical activity, such as the Faraday effect are universal. The technique has promise to any application where the remote sensing of intense B fields and their distributions are desired by non-electrical, non-intrusive means and often in hostile environments and over finite distances.

Description of the technology and its role in FES:
Pulsed polarimetry originated as a generalization of the TS Lidar technique pioneered at the Joint European Torus. It was realized that the magnetic profile could be added to the measurements of the electron temperature and density profiles. The progressive Faraday rotation along the line-of-sight, present in Thomson backscatter, is used along with the density profile to determine the local magnetic field. The temperature is not directly relevant and for this reason, the technique applies outside of FES.

Knowledge of the magnetic field distribution is key to plasma stability and reacting to changes in plasma performance. A pulsed polarimeter for future tokamaks would provide unprecedented spatio-temporal distributions of Te, ne, and B in a burning plasma without the introduction of electrical probes or retro-reflecting surfaces for polarimetry. The technology for a Lidar instrument (laser sources and detectors within the 50-400um wavelength range) in the FIR region needs investment. Diagnostic options are severely limited for burning plasmas (DEMO) but pulsed polarimetry could provide profiles and the dynamics of key parameters across the plasma with minimal access using the robust far infrared region. The technique improves with higher densities and stronger fields.

What societal benefits, including contributions to other areas of science and technology, have or are likely to result from the development described above? *

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1) FIR Lidar: Pulsed polarimetry presents a profound opportunity for the US to make a major contribution to a future fusion reactor. Spatial distributions of ne, Te and B at high scan rates would provide most of the information needed to optimize and run a fusion reactor. Such a development would at the same time open up a new field of FIR Lidar sensing providing remote sensing in a valuable spectral range that so far lags behind the optical, IR and microwave ranges. Relevance to the basic sciences via environmental atmospheric sensing and FIR astronomy through detector development is

envisioned.

2) Remote monitoring and sensing of structures with intense magnetic fields: For instance, human organs can be imaged using Lidar sensing in the IR, pulsed polarimetry could be of use to imaging tissues subjected to intense magnetic fields, essentially, the local Verdet constant is sensed. Uses are remote sensing for the medical field, superconducting magnet development, HV driver technology (mea-amp, mega-volt terrawatt power sources, electrical discharges(lightning), transmission line and rail gun development, remote detection and monitoring of intense magnetic fields for industry.

3) Fiber optic pulsed polarimetry: The two key elements for pulsed polarimetry in a fiber optic medium are Rayleigh scattering and the Faraday effect. The range of field intensities and the spatio-temporal resolution is dramatically improved using optical fibers over that of measurements in a plasma medium. Fiber Optic Pulsed Polarimetry is also known as Polarization Optical Time Domain Reflectometry (POTDR). Recently, DOE supported work has led to the successful development of specialized fibers that enhance the scattering over Rayleigh by many orders of magnitude. This represents a watershed development in this technique as low Rayleigh scattering levels had posed a severe limitation to FOPP.

The applications of a robust remote, non-electrical, sensing of magnetic fields using optical fibers is manifold throughout a range of disciplines where high B fields are created and used usually in hazardous pulsed HV settings. Relevance to condensed matter in extreme magnetic fields, MFE, HEDLP, superconducting magnet development and basic science are envisioned, wherever the introduction of optical fibers can be tolerated.

In conclusion, magnetic fields of sufficient intensity can be locally determined by optical means in any transparent medium using a Lidar technique known as pulsed polarimetry provided the necessary laser source and detectors are extant. For fiber sensing, the optical and near-IR laser sources and detectors are well developed and high resolution magnetic mapping and imaging over long distances are possible. Pulsed polarimetry presents a unique measurement capability lying outside of conventional magnetic sensing and therefore will find uses wherever a magnetic field plays a decisive role.