White Paper for *Frontiers of Plasma Science Panel*

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Title:	The case for magnetized laser-plasma experiments: a white paper
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The case for magnetized laser-plasma experiments: a white paper

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The Research Frontier

The interaction of plasma with magnetic field is a fundamental aspect of plasma physics, yet it is one of the most complex and challenging. Magnetic field introduces a wide range of plasma waves and instabilities, which have yet to be fully explored, and leads to anisotropic transport and viscosity, where even the simplest cases lead to complex theoretical results that have yet to be fully verified experimentally. In turn, plasma modifies magnetic field through fluid flow (smooth and turbulent), electron drift velocity (Hall term), electron heat flow (the electro-thermal effect) and resistive diffusion, even changing the direction and topology of the magnetic field, and plasma can generate its own magnetic field, even in the absence of an initial field. Furthermore, all of these effects are inter-related, for example, magnetic field modifies plasma flow, resistivity and thermal conductivity, leading to a complex, non-linear system.

Magnetized plasma is of interest in many areas of physics, such as cosmic ray acceleration, astrophysical jets, solar flares, planetary cores, planetary magneto-spheres, some industrial plasma processes and in various approaches to fusion as either a means of confinement, compression or reducing thermal losses.

These applications cover a wide range of plasma densities, temperatures and flow velocities, making it difficult to study more than a small subset in laboratory experiments.

The Approach

High-power lasers can produce a very wide range of plasma parameters; densities from below atmospheric to many times greater than solid, temperatures from the eV to the keV range, and flow velocities up to supersonic values. In particular, lasers can attain energy densities unobtainable by other means in the laboratory.

The introduction of a magnetic field generation system to the 60-beam OMEGA laser and to the 4-beam OMEGA-EP laser at the Laboratory for Laser Energetics has led to a wide variety of magnetized plasma experiments being carried out, including record magnetic field compression [1,2], magnetic reconnection [3], collimation of positrons produced at relativistic laser intensities [4], and magnetized inertial fusion [5,6,7]. New experimental proposals continue to arrive from a broad user community through the National Laser User Facility and Laboratory Basic Science programs. Figure 1 shows the number of shot days that have been executed using MIFEDS up to 2014 and the general topics that have been covered. Future plans include studying the dynamo effect, magnetized shocks, modification of kinetic effects, laser-driven MagLIF (magnetized liner inertial fusion), and trapping an electron-positron plasma, which could be studied by Thomson scattering.

The basis of the magnetic field generation is a current generator known as MIFEDS (magneto-inertial fusion electrical discharge system) that fits in a standard diagnostic insertion module known as a TIM (ten inch manipulator). The first MIFEDS was built in 2006 with a grant from the OFES Joint HEDLP program [8]. In 2013 a new, completely redesigned MIFEDS was put into service that is more compact, robust, flexible in orientation, and stores twice the energy [9]. This device is illustrated in figure 2. The new MIFEDS is discharged through copper coils wound on plastic supports produced by a 3D printer, allowing a wide-range of field topologies. Examples of these coils are shown in figure 3. Fields up to 15 T over a volume of 1 cm^3 can be generated.

The Omega laser systems provide an unrivalled combination of laser beams and, importantly, diagnostics to complete a uniquely versatile laboratory for the study of magnetized plasma. Diagnostic capabilities cover neutron emission, charged particle emission, x-ray emission, x-ray backlighting, streaked optical pyrometry, VISAR, proton probing to measure magnetic and electric fields, Thomson

scattering, and optical probing, including simultaneous Faraday rotation and refractometry to measure magnetic field.

The most common user request is for a higher magnetic field, and there are some experiments, such as magnetized plasma jets and collisionless shocks, that require a higher field than currently available.

The limiting factor is energy storage (currently 200 J); it is not possible to store sufficient energy in the confines of a TIM to produce much more than 20 T over a sufficient volume for most experiments. A new approach is required to extend capabilities. Currently, there are two approaches on the horizon.

A feasibility study has been carried out at the LLE for a system with a mobile, external capacitor bank that would feed through a TIM and into the target chamber. It has been estimated that a field of 50 T could be reached. This would be sufficient to magnetize laser-produced plasma jets and collisionless shocks, to reach the limit of laser-driven field compression where magnetic pressure equals plasma pressure, and to extend many other studies of magnetized plasma. Such a system could be working within 2 to 3 years.

The construction of a 10 MA-range pulse power facility connected to the OMEGA-EP laser system is currently under discussion. Such a facility could also be used to provide a magnetized target chamber for OMEGA-EP experiments, providing an alternative to MIFEDS for OMEGA-EP experiments that would give higher fields and higher magnetized volumes. The construction of such a facility would be a long-term project.

Impact and Conclusions

Magnetized laser-plasma experiments provide an excellent means of meeting the challenge of studying a wide range of magnetized plasmas in the laboratory. The insight into magnetized plasma physics that such experiments can provide will impact many areas of scientific investigation, such as astrophysics, planetary physics, solar physics and fusion. In practice, wherever plasma is present so are magnetic fields.

The MIFEDS field generator on the Omega laser system has demonstrated the potential of magnetized laser-plasma experiments [1-7], and could continue to provide exciting new experimental results in the years to come, if maintained and periodically upgraded.

However, to push forward the field frontier in a significant manner will require a new system on a larger scale. There are two options currently envisaged: a TIM based system with a mobile, external capacitor bank and a new pulse power facility connected to OMEGA-EP.

We believe that the MIFEDS system should continue to be maintained and upgraded to provide a versatile laboratory for magnetized plasma experiments, and systems to provide significantly higher magnetic fields (~ 50 T) in the near future should be actively pursued.

References

[1] "*Laser-Driven Magnetic-Flux Compression in High-Energy-Density Plasmas*" O. V. Gotchev *et al*, Phys. Rev. Lett. **103**, 215004 (2009).

[2] "*Compressing magnetic fields with high-energy lasers*" J. P. Knauer *et al*, Phys. Plasmas **17**, 056318 (2010).

[3] "*Magnetic reconnection between colliding magnetized, laser-produced plasma plumes*" G. Fiksel, W. Fox, A. Bhattacharjee, P. Y. Chang, K. Germaschewski, S. X. Hu, and P. M Nilson, *Phys. Rev. Lett.*, **113**, 105003 (2014).

[4] "*Magnetic collimation of relativistic positrons and electrons from high intensity laser–matter interactions*" Hui Chen *et al*, Phys. Plasmas **21**, 040703 (2014).

[5] "*Fusion Yield Enhancement in Magnetized Laser-Driven Implosions*" P. Y. Chang *et al*, Phys. Rev. Lett. **107**, 035006 (2011).

[6] "*Inertial confinement fusion implosions with imposed magnetic field compression using the OMEGA Laser*" M. Hohenberger *et al*, Phys. Plasmas **19**, 056306 (2012).

[7] "*Use of external magnetic fields in hohlraum plasmas to improve laser-coupling*" D. S. Montgomery *et al*, Phys. Plasmas **22**, 010703 (2015).

[8] "*Seeding magnetic fields for laser-driven flux compression in high-energy-density plasmas*" O. V. Gotchev *et al*, Rev. Sci. Instrum. **80**, 043504 (2009).

[9] "*Note: Experimental platform for magnetized high-energy-density plasma studies at the omega laser facility*" G. Fiksel *et al*, Rev. Sci. Instrum. **86**, 016105 (2015).

Figures

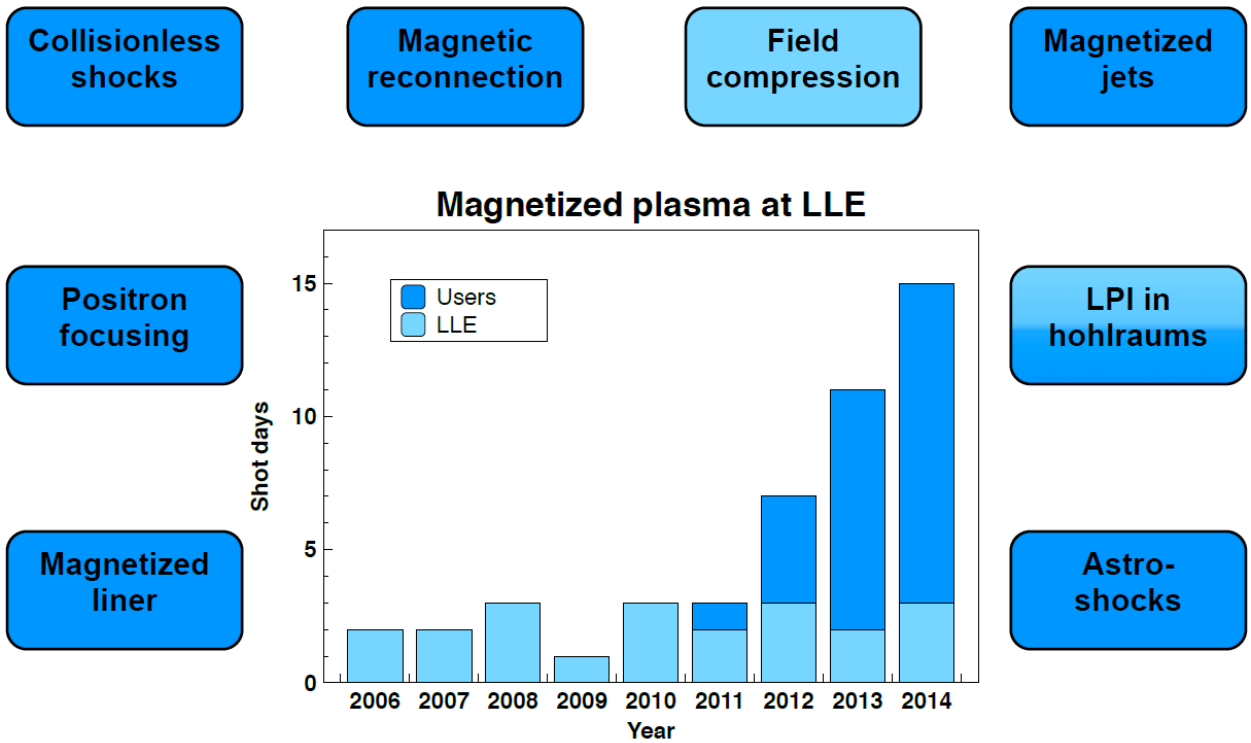

Figure 1: shot days executed using MIFEDS up to 2014 and the general topics they have covered, broken down according to principal investigator (external user, dark blue, LLE, light blue).

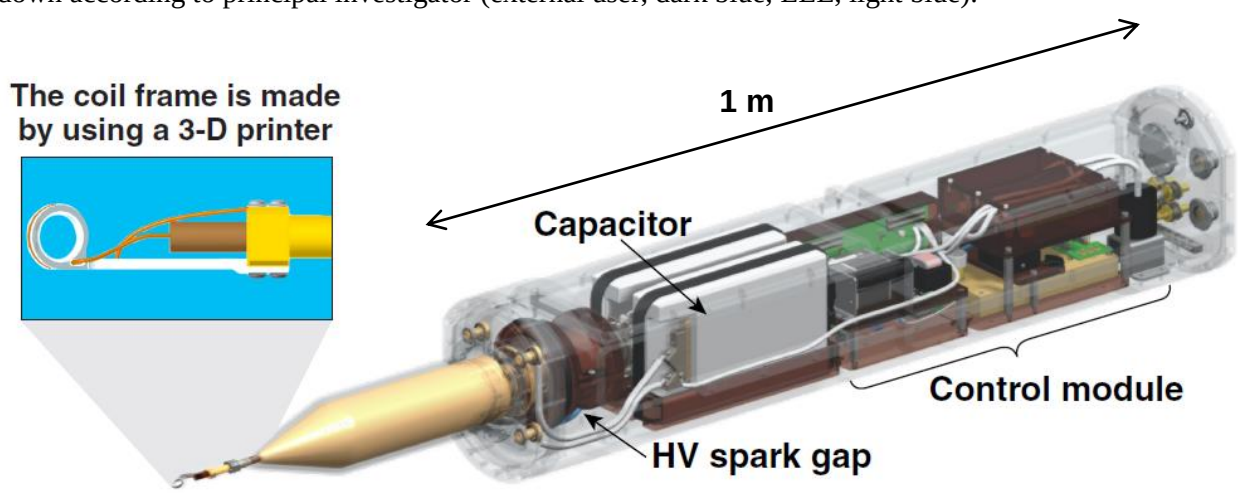

Figure 2: cut-away diagram of the new MIFEDS device.

Figure 3: examples of 3D printed, plastic coil supports.