White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***06/16/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	P
• Plasma self-organization	S
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	X

Title:	
Corresponding Author:	Vladimir V. Ivanov
• Institution:	University of Nevada, Reno
• email:	ivanov@unr.edu
Co-Authors:	A.V. Maximov, University of Rochester, A. M. Covington, University of Nevada, Reno

(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)

- ***Describe the research frontier* and importance of the scientific challenge.**

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Interaction of laser radiation with plasma under the MG external magnetic field

V. V. Ivanov[1], A. V. Maximov[2] , A. M. Covington[1]

[1] *University of Nevada, Reno, NV 89557, USA*

[2] *LLE, University of Rochester, NY 14623, USA*

Describe the research frontier and importance of the scientific challenge

A strong magnetic field can dramatically change the properties of plasmas. Studies of plasmas in the magnetic field are important for basic physics, astrophysics, controlled fusion, and Z-pinch physics. Simulations show that the magnetic field B=3-5 MG can confine fast electrons and provide enhanced heating of laser plasma [1]. Features of parametric instability and absorption of the extraordinary wave in a strong B-field were calculated in [2]. Confinement in the magnetic field plays a key role in the MagLIF fusion conception [3]. Cluster fusion with the magnetic field was suggested in [4]. Implosion of plasma in the magnetic field compressing by the Omega laser, B >30 MG was studied for ICF [5]. However, the experimental investigation of plasmas in the controlled MG magnetic field remains a challenge. Only a small amount of experiments were carried out with plasmas in the B-field >1MG.

Laser produced plasmas have been well investigated up to laser intensities of 10^{20} W/cm^2. However, laser plasma in the external magnetic field has been studied only with B <0.2MG [6]. Self-generated magnetic fields from MG to sub-GG were observed in plasma produced by intensive femtosecond laser pulses [7] but these magnetic fields have never been used in applications. Z pinches can routinely generate MG fields but Z-pinch plasma is hardly reproducible due to strong instabilities and generates a powerful x-ray burst and energetic particles. This makes it difficult to perform controlled studies of magnetized plasmas. Recently, we carried out experiments with laser plasma in the MG magnetic field generated by the 1MA pulsed power machine and discovered new plasma jet features (see details below). These features point to the unexplored field in plasma physics which may bring benefits to basic and applied plasma physics.

Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required

We suggest to study the interaction of the laser radiation with magnetized plasma using a university-scale pulsed power machine as a source of the magnetic field up to 4MG. MG magnetic fields can be produced by the Zebra pulsed power generator at the University of Nevada, Reno (UNR) using a metal rod load 0.7-2mm in diameter [8]. Plasma with a step-like gradient, electron temperature of 10-15eV, and high density appears on the surface of the load and slowly expands during the current pulse. A 50-TW Leopard laser coupled with the Zebra generator at UNR can be used for heating the magnetized plasma. This type of experiments needs both a MA class pulsed power machine and high-intensity laser beam and may be performed at the Nevada Terawatt Facility, UNR and Z machine at Sandia National Laboratories.
A series of shots was carried out recently at the Zebra generator with laser beam intensity of 3×10^{15} W/cm^2 in the 30 µm focal spot (0.8ns, 18J, 1057nm) and the magnetic field B >2MG (see Fig. 1). In these shots we observed a collimated plasma jet, 1-3mm long, propagating back to the laser from the focal spot. Figure 2 compares shadowgrams of laser plasma with and without the magnetic field. Fig. 2(b) shows a collimated jet at 9 ns after the interaction of the laser pulse with Al 1 mm rod load at current of 0.96MA and the magnetic field of 2.8MG. This plasma jet may be linked to the **E**x**B** drift observed at smaller B-filds [6]. Some features may be linked to the electrothermal instability. An interesting detail of the shadowgram in Fig. 2(b) is the formation of the plasma jet on the rear side of the rod load. This rare jet may be produced, for example, by the high-energy electron beam generated in the focal spot. The energy of electrons is in a sub-MeV range if they can pass through almost 1 mm of solid Al. A jet on the rare side is also seen on the Cu load that is 0.8mm in diameter. Dynamics of formation of jets are shown in a two-frame shadowgram in Figure 3 with 6 ns between frames. The enhanced temperature and keV x-ray radiation were found by x-ray spectroscopy in Al plasma at the B-field. We note, that a rare-side plasma jet was observed on the target, 0.24mm thick without the magnetic field but at laser intensity of 10^{19}

W/cm^2 [9]. This rare jet was explained by generation of the MeV electron beam. Collimated jets were also seen in the laser specular reflection direction [10] with intensity of laser radiation on the pre-plasma ~10^{19} W/cm^2. Electrons were accelerated in the specular-reflected laser light and collimated by a self-generated magnetic field. Therefore, plasma jets and MeV electron beams are generated in laser plasma at laser intensity much higher than in our experiments. A mechanism of generation of the MeV beam in our experiments is not clear. A small amount of MeV electrons can be generated at smaller laser intensity [11] but these electrons do not produce plasma jets.

Figure 4 shows a plasma jet at smaller load current, 0.2MA and the same laser intensity. Jets in Fig. 4 are narrower and have a more complicated structure compared to Figures 2 and 3. This may be linked to a different regime of laser-plasma interaction.

Generation of fast electrons in laser produced plasma has never been studied in external MG magnetic fields. We suggest the investigation of laser plasma in the MG magnetic field with the laser intensity in the range of 10^{15} - 10^{19} W/cm^2. The Leopard laser will be used in both a sub-nanosecond and sub-picosecond regimes. The Zebra generator produces a current >1.5MA with a load current multiplier, therefore, the magnetic field up to 4MG can be applied to laser plasmas. The generated electron beam can be investigated by regular methods for particles. The enhanced heating of plasma in the magnetic field can be studied by x-ray K-shell spectroscopy using bent crystals.

Another opportunity for laser - pulsed power facilities is the investigation of parametric effects in the MG magnetic field. A parametric decay of the laser radiation generating $\omega/2$ and $3/2\omega$ harmonics arises in the plasma region near the quarter-critical plasma density. “Red” and “blue” spectral components of parametric harmonics carry a signature of both the plasma temperature and a strong magnetic field**.** Dense magnetized plasma in the magnetic field of 2-4 MG can be provided by metal rod loads at the Zebra generator. Narrowband laser radiation with intensity >10^{14} W/cm^2 for these experiments will be delivered by the Nd:glass Tomcat laser at NTF coupled with the Zebra generator.

Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit

The proposed research project can clarify the formation of plasma jets, the generation of fast electrons, and the heating of laser plasma in MG magnetic fields. We can find answers to several questions. Are plasma jets produced by MeV electron beams? What would be energy of electrons generated by the laser with intensity of 10^{19} W/cm^2 in the MG magnetic field? What are the mechanisms of plasma heating and confinement in the MG field?

Studies of parametric instabilities are important for basic plasma physics but they may also result in the development of the laser diagnostic for measuring magnetic fields B >10 MG in the dense plasma.

The proposed research can impact the fields of plasma physics connected to fusion studies, basic physics, astrophysics, and physics of accelerators if electron beams with energy >100 MeV can be found.

The proposed research can be performed at the university facility and will be used for the training of students in plasma physics.

1. Y. Sentuku, A. Kemp, M. Bakeman et al., J. Phys. IV France **133**, 521 (2006).
2. V. B. Krasovitskii et al., Phys. Plasmas. **14**, 092108 (2007).
3. S. A. Slutz, R. A. Vesey et al., Phys. Rev. Let. **108**, 025003 (2012).
4. T. Ditmire et al., Nature **398**, 489 (1999).
5. M. Hohenberger et al., Phys. Plasmas **19**, 056306 (2012).
6. C. Plechaty, R. Presura, A. Esaulov, Phys. Rev. Let. **111**, 182002 (2013).
7. M. Tatarakis, I. Watts, F. N. Beg et al., Nature **415**, 280 (2002).
8. T. J. Awe, B. S. Bauer et al., Phys. Rev. Let. **104**, 035001 (2010).
9. M. Tatarakis et al., Phys. Rev. Let. **81**, 999 (1998).
10. R. Kodama, K. A. Tanaka et al., Phys. Rev. E **84**, 674 (2000).
11. C. Rousseaux, F. Amiranoff et al., Phys. Fluids B 4, 2589 (1992).

Figures

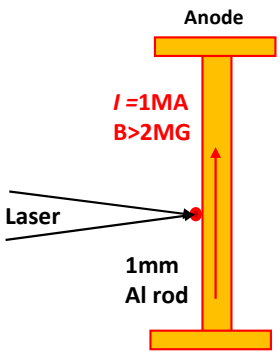

Fig. 1. The experimental setup for investigation of laser produced plasma in the magnetic field.

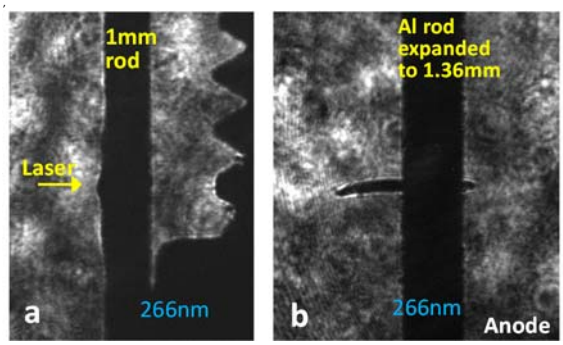

Fig. 2. (a) A shadowgram of laser plasma at 266nm without the magnetic field. (b) A shadowgram of the coupled shot of the Leopard laser with the Zebra generator at 7ns after the laser pulse. Current is I=0.96MA and the estimated B is 2.8MG.

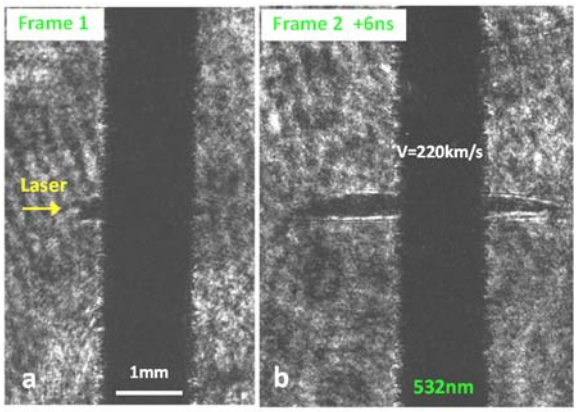

Fig. 3. (a) A two-frame shadowgram at the wavelength of 532nm of the laser plasma in the magnetic field. Shadowgrams are taken at 3.5ns(a) and 9.5ns (b). Current is I=1MA.

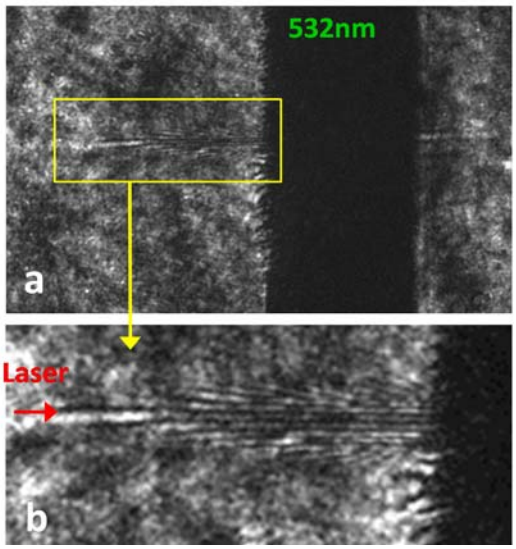

Fig. 4. (a) A shadowgram of plasma at 2.9ns after the laser pulse at current of 0.2MA. (b) A magnified image of the rectangle area.