Project Final Report
Award #DE-FG02-05ER54842
8/15/2005 to 8/14/2008
(submitted July 14, 2013)

“High Energy Density Physics and applications with a state-of-the art compact x-pinch”

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Executive Summary:

Recent advances in technology has made possible to create matter with extremely high energy density (energy densities and pressure exceeding 10^{11} J/m³ and 1 Mbar respectively). The field is new and complex. *The basic question for high energy density physics (HEDP) is how does matter behave under extreme conditions of temperature, pressure, density and electromagnetic radiation?* The conditions for studying HEDP are normally produced using high intensity short pulse laser, x-rays, particle beams and pulsed power z-pinch. Most of these installations occupy a large laboratory floor space and require a team consisting of a large number of scientists and engineers. This limits the number of experiments that can be performed to explore and understand the complex physics. A novel way of studying HEDP is with a compact x-pinch in university scale laboratory. The x-pinch is a configuration in which a pulsed current is passed through two or more wires placed between the electrodes making the shape of the letter ‘X’. Extreme conditions of magnetic field (> 200 MGauss for less than 1 ns), temperature (1 keV) and density ($\sim 10^{22}$ cm⁻³) are produced at the cross-point, where two wires make contact. Further, supersonic jets are produced on either side of the cross-point. The physics of the formation of the plasma at the cross-point is complex. *It is not clear what role radiation plays in the formation of high energy density plasma ($>> 10^{11}$ J/m³) at the cross-point. Nor it is understood how the supersonic jets are formed.* Present numerical codes do not contain complex physics that can take into account some of these aspects. Indeed, a comprehensive experimental study could answer some of the questions, which are relevant to wide-ranging fields such as *inertial confinement fusion, astrophysical plasmas, high intensity laser plasma interactions and radiation physics.*

The main aim of the proposal was to increase the fundamental understanding of high energy density physics and particularly address the key issues associated with x-pinch, which include radiation transport, energetic particle transport, supersonic jet formation, using state-of-the-art compact pulsed power drivers. All the **primary objectives** of the proposed work were met. These objectives include:

- Understanding of the fundamental physics of hot and dense plasma formation, implosion to less than 1 μ m size due to the radiation enhanced collapse and energetic electron heating,
- Study of the jet formation mechanism, which is of interest due to the astrophysical jets and deposition of energy by energetic electrons in jets,
- Characterization of an x-pinch as a point x-ray source for the phase contrast radiography of beryllium cryogenic targets for the National Ignition Facility (NIF) experiments.

The work carried out included a strong educational component involving both undergraduate and graduate students. Several undergraduate students from University of California San Diego participated in this project. A post-doctoral fellow, Dr. Simon Bott and two graduate students, David Haas and Erik Shipton contributed to every aspect of this project.

The success of the project can be judged from the fact that fifteen peer-reviewed papers were published in high quality journals. In addition several presentations were made to a number of scientific meetings.

A. Introduction

The study and investigation of high energy density physics (energy densities and pressure exceeding 10^{11} J/m³ and 1 Mbar respectively) is a new field of physics and has been described as an exciting physics frontier by two National Academy reports [1,2]. *The question of fundamental interest is how extreme conditions of temperature, pressure, density and radiation affect matter* [1,2]. This question is relevant to several other fields of physics including inertial confinement fusion studies [3], astrophysical plasmas [4], radiation physics [5] and short pulse high intensity laser plasma interactions [6]. Experiments to study HEDP are normally carried out using large-scale pulsed power generators, high power lasers [7-10] and charged particle beams [11,12]. Indeed, these facilities are not wide spread, thus restricting studies of this interesting field.

A novel way to produce hot and dense plasma (up to $T_e \sim 1$ keV, $n_e \sim 10^{22}$ cm⁻³ and $h\nu \sim 1$ -10 keV [13]) for HEDP studies in the university laboratory is with x-pinch driven by a **compact** pulsed power generator. In the x-pinch, a large current is pulsed through two wires, which are arranged in the form of an “X” between the electrodes. At the cross-point where the two wires make contact i.e. at a predetermined position – the currents of the wires combine to produce hot and dense plasma in a localized position. Furthermore, ultrahigh magnetic fields of the order of 200 MGauss are produced at the cross-point (assuming 100 kA current and spot size of 1 μ m). The magnetic pressure is a factor of 4 larger at the cross point than in the individual wires. The dense spot emits copious amount of intense x-rays in a short pulse (typically less than 100 ps). During the plasma formation process, jets are formed at the cross point extending towards both electrodes. At the termination of the x-ray pulse, a gap is formed in the plasma at the cross-point, which normally gives rise to the energetic electron and ion beams.

The physics of bright spot formation has been of a fundamental interest for well over three decades initially due to the bright spots (in literature bright spots are referred as hot spots or micro-pinch too) observed in plasma focus devices [14], vacuum spark gaps [15] and z-pinch [16].

However, it is not clear from experiments performed so far at various laboratories of what role energetic electrons and radiation play in heating the plasma at the cross point in x-pinch? In addition, how the supersonic jets are formed? Present 2D magneto-hydrodynamic codes are not capable of simulating complex physics associated with these plasmas. Clearly, a comprehensive series of experiments could provide significant insights into the above-discussed issues.

B. Project Findings:

In this project, we have carried out a series of experiments to investigate the following topics:

- Understanding of the fundamental physics of hot and dense plasma formation, implosion to less than 1 μ m size due to the radiation enhanced collapse and energetic electron heating,
- Study of the jet formation mechanism, which is of interest due to the astrophysical jets and deposition of energy by energetic electrons in jets,
- Characterization of an x-pinch as a point x-ray source for the phase contrast radiography of beryllium cryogenic targets for the National Ignition Facility (NIF) experiments.

1. Jet Formation and Relevance to Astrophysical Jets:

In this work x-pinchs consisting of aluminum and molybdenum mounted at different angles (120° and 83°) were studied. Coronal-plasma streaming, which is perpendicular to the wires toward the mid-plane of the x-pinch, was observed to form jets moving toward the electrodes on the either side of the cross point. The jet velocity of $\sim 10^6$ cm/s was similar for both molybdenum and aluminum wires and was slightly larger for the narrow angle (83°). The jets were observed to show kink ($m = I$) instability at late times, after the jets had come into contact with the electrodes. This is due to a transfer of current to the jet. The experimental results agree qualitatively with three-dimensional resistive MHD simulations, which include radiation. The results are shown in Fig. 1. This work was extended where it was shown that the supersonic jets produced in x-pinchs are indeed relevant to astrophysical jets as described below.

Fig. 1. Series of X-ray framing photographs for (a) $2 \times 25 \mu\text{m}$ aluminum and (b) $2 \times 13 \mu\text{m}$ molybdenum x-pinchs. Images were recorded with $2.5 \mu\text{m}$ plastic + $12 \mu\text{m}$ Be filter. Images are taken from different discharges. The timing of each frame corresponds to the start of the current. A comparison of X-ray time-integrated images is shown in (c).

A low-current x-pinch was used to study supersonic jet propagation. The current was significantly lower than the current used in the above-described experiments. X-pinchs comprised of four $7.5 \mu\text{m}$ diameter tungsten wires were driven by an 80 kA, 50 ns current pulse

from a compact pulser. Coronal plasma surrounding the wire cores was accelerated perpendicular to their surface due to the global $\mathbf{J} \times \mathbf{B}$ force, and traveled toward the axis of the x-pinch to form an axially propagating jet. These jets moved towards the electrodes and, late in time (~ 150 ns), were observed to propagate well above the anode with a velocity of $3.3 \pm 0.6 \times 10^4$ m/s. Tungsten jets remained collimated at distances of up to 16 mm from the cross point, and an estimate of the local sound speed gives a Mach number of ~ 6 (see Fig. 2). This is the first demonstration that supersonic plasma jets can be produced using x-pinchs with such a small, low current pulser. Experimental data compares well to three-dimensional simulations using the GORGON resistive MHD code, and possible scaling to astrophysical jets.

Fig. 2. Schematic of the x-pinch (a) showing an enlarged view of the plasma flow convergence region (b). (c) shows anode setup indicating the placement of the wire limb blocks and the redefined convergence region. Finally (d) displays a series of areal electron density images showing the evolution of the plasma jet above the anode.

2. Compact Point X-ray source for Phase Contrast Imaging of Inertial Confinement Fusion Capsules:

In this work, various wire materials including tungsten, molybdenum, and aluminum were employed. Results with plastic capsules 1 mm diameter, 20 μm thick wall with 80 μm foam inside the capsule show phase contrast effects at the edges of the wall due to the foam, which mimics the ice inside the shell. A plastic covered foam shell is shown in Fig. 3. The capsule was kept between two layers of CH with 4 μm thickness each. An additional 25 μm aluminum filter in front of the capsule was used to protect it from low energy x-ray flux. The filter in front of film was 10 μm copper. The 80 μm thick foam was ~ 100 mg/cm³. The phase contrast generated inside the foam edge may be seen in Fig. 3b. The sharpness of the image reveals a source less than 2 μm in size and x-ray diodes show a pulse length of 10 ns. The x-ray pulse from an X -pinch is sufficiently short to avoid the motional blurring due to cryogenic system vibrations, which is not possible with low flux sources.

Fig. 3. A) X radiograph of a 1 mm diameter shell with 80 μm dense plastic foam under 20 μm of fully dense CH plastic. A 10 μm Cu filter suppressed low energy x-ray emission from the x-pinch; this image is primarily from 5–9 keV radiation. B) Plot shows a boxed region in a).

3. Radiation Effects in X-pinches:

As described above, a low current generator was used for these experiments. Molybdenum wires with and without gold coating were employed to study the effect of high atomic number material coating on the low-density ($<10^{18} \text{ cm}^{-3}$) coronal plasma dynamics. A comparison of images from XUV frames and optical probing shows that the low density coronal plasma from the wires initially converges at the mid-plane immediately above and below the cross-point. A central jet is formed which moves with a velocity of $6 \times 10^4 \text{ ms}^{-1}$ towards both electrodes forming a z-pinch column before the current maximum. A marked change in the low density coronal plasma dynamics was observed when molybdenum wires coated with $\sim 0.09 \mu\text{m}$ of gold were used. Figure 4 shows a set of XUV framing and optical probing images of the Au coated Mo wires. Initially the coronal plasma on either side of the wires uniformly expands. The $m=0$ instability in the coronal plasma formed along the wires (the ‘legs’ of the x-pinch) can be seen as small bright-spots in emission, which are not observed in uncoated molybdenum wire x-pinches. The processes forming the jet structure were delayed relative to bare Mo x-pinches, and the time-resolved x-ray emission also showed differences. An $m=0$ instability was observed in the coronal plasma along the x-pinch legs, which were consistent with x-ray PIN diode signals in which x-ray pulses were observed before x-ray emission from hot-spot formation at cross point. These early time x-ray pulses were not observed with pure molybdenum x-pinches. These observations indicate that a thin layer of gold coating significantly changes the coronal plasma behavior.

Figure 4. (a) A sequence of XUV images and (b) a series of schlieren images taken for two wire x-pinchs formed from gold-coated molybdenum wires.

C. Educational Component:

The work carried out included a strong educational component involving both undergraduate and graduate students. Several undergraduate students from University of California San Diego and other universities from the United States participated in this project. There were a number of undergraduate students involved in this project. The majority of these undergraduate students decided to pursue graduate studies after finishing their bachelor degrees. The undergraduate students who participated in this project were: Yosef Ishaq, Utaku Ueda, and Gilbert Collins. The graduate students involved in this project were David Haas and Erik Shipton. Post doctoral fellow, Dr. Simon Bott contributed to the running of this project.

The success of the project can be judged from the fact that fifteen peer-reviewed papers were published in high quality journals. In addition several presentations were made to a number of scientific meetings.

D. Summary:

In summary, we have successfully carried out all the tasks defined in the project and addressed key issues concerning High Energy Density Physics using x-pinch driven by pulsed power generator. These issues include jet formation mechanism and its relevance to astrophysical jets, characterization of an x-pinch as a point x-ray source for the phase contrast radiography of beryllium cryogenic targets for the National Ignition Facility (NIF) experiments, and radiation effect on x-pinch plasmas.

E. Refereed Journal Publications

1. **"Effect of wire number on x-pinch discharges"**J.S. Green, S.N. Bland, M. Collett, A.E. Dangor, K. Krushelnick, F.N. Beg and I. Ross, Applied Physics Letters, **88**, 261501 (2006).
2. **"Dynamics of cylindrically converging precursor plasma flow in wire-array Z-pinch experiments,"**S.C. Bott, S.V. Lebedev, D.J. Ampleford, S.N. Bland, J.P. Chittenden, A. Ciardi, M.G. Haines, C. Jennings, M. Sherlock, G. Hall, J. Rapley, F.N. Beg and J. Palmer, Phy. Rev. E, **74**, 046403 (2006).
3. **"Jet Formation and Current Transfer in X-Pinches,"**F.N. Beg, A. Ciardi, I. Ross, Y. Zhu, A.E. Dangor and K. Krushelnick, IEEE Transactions on Plasma Science, **34** (5), 2325-2329 (2006).
4. **"Compact X-pinch based point x-ray source for phase contrast imaging of inertial confinement fusion capsules,"**F. N. Beg, R.B. Stephens and H.-W. Xu, D. Haas, S. Eddinger, G. Tynan and E. Shipton, B. DeBono, K. Wagschal, Applied Physics Letters, **89**, 101502 (2006).
5. **"Three-channel x-ray crystal spectrometer for diagnosing high energy density plasmas,"**E. Baronova, B. Bucher, D. Haas and D. Fedin, A. Stepanenko, F.N. Beg, Rev. Scien. Instr., **77** (10), 103104 (2006).
6. **"Study of energy transfer in tabletop X-pinch driven by a water line"** F.N. Beg, T. Zhang, D. Fedin, B. Beagen, E. Chua, J.Y. Lee, R.S. Rawat, P. Lee, Physica Scripta, **76**, 134, (2007).
7. **"Comparison of sensitivities of Moire deflectometry and interferometry to measure electron densities in Z-pinch plasmas,"**J. Ruiz-Camacho, F. N. Beg and P. Lee, J. Physics D: Applied Physics, **40**, p2026 (2007).
8. **"Dynamics of low-density coronal plasma in low current X-pinchs,"** D.M. Haas, S.C. Bott, F.N. Beg, T. Zhang, V. Vikhrev, B. Bucker, D. Fedin, E. Baranova, Y. Eshaq, S.I. Krashenninikov, Plasma Phys. Control. Fusion, **49**, p1151 (2007).
9. **"High Resolution Laser Schlieren Imaging of Coronal Plasma Evolution in 80 kA X-pinchs,"**S. C. Bott, D. M. Haas, U. Ueda, Y. Eshaq, R. Madden, G. Collins, and F. N. Beg, IEEE Trans. Plasma. Sci, **36**, 1274 (2008).
10. **"Cross-point coronal plasma dynamics in two- and four-wire x-pinchs,"** R. E. Madden, S. C. Bott, D. Haas, Y. Eshaq, U. Ueda, G. Collins and F. N. Beg, Phys. Plasmas, **15**, 112701 (2008).
11. **"Quantitative Measurements of Wire Ablation in Tungsten X-pinchs at 80 kA,"** S. C. Bott, D. M. Haas, Y. Eshaq, U. Ueda, S. V. Lebedev, J.P. Chittenden, J. B. A. Palmer, S. N. Bland, G. N. Hall, D.J. Ampleford, and F. N. Beg, IEEE Trans. Plasma. Sci., **36**, 2759 (2008).
12. **"Study of the effect of current rise time on the formation of the precursor column**

- in cylindrical wire array Z pinches at 1 MA,"** S. C. Bott, D. M. Haas, Y. Eshaq, U. Ueda, F. N. Beg, D. A. Hammer, B. Kusse, J. Greenly, T. A. Shelkovenko, S. A. Pikuz, I. C. Blesener, R. D. McBride, J. D. Douglass, K. Bell, P. Knapp, J. P. Chittenden, S. V. Lebedev, S. N. Bland, G. N. Hall, F. A. Suzuki Vidal, A. Marocchino, A. Harvey-Thomson, M. G. Haines, J. B. A. Palmer, A. Esaulov, and D. J. Ampleford, *Phys. Plasmas*, **16**, 072701 (2009).
13. **"Investigation of Carbon X-Pinches as a Source for Point-Projection Radiography,"** R. E. Madden, S. C. Bott, G Collins IV and F. N. Beg, *IEEE Trans. Plasma. Sci.*, **37**, 433 (2009).
 14. **"Ablation Studies of Low-Number Wire Arrays at 200 kA Using A Linear Transformer Driver,"** Simon C. Bott, David M. Haas, Yossof Eshaq, Utako Ueda, Robert E. Madden, Gilbert W. Collins, IV, and Farhat N. Beg, *IEEE Trans. Plasma Sci.*, **38**, 567 (2010).
 15. **"Supersonic Jet Formation and Propagation in X-Pinches,"** D. M. Haas, S. C. Bott, J. Kim, D. A. Mariscal, R. E. Madden, Y. Eshaq, U. Ueda, G. Collins IV, K. Gunasekera, F. N. Beg, J. P. Chittenden, N. Niasse and C. A. Jennings *Astrophys. Space Sci.* DOI 10.1007/s10509-011-0599-8 (2011).

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