

Final Technical Report, DOE Grant DE-FG02-98ER54496
“Physics of High-Energy-Density X Pinch Plasmas”
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I. Introduction

This project was concerned with the physics of X-pinch plasmas immediately before, during and after they emit their < 1 ns soft x-ray (1-10 keV photon energy) burst from a plasma that is 1-10 μm in size. X-pinch plasmas are produced by passing submicrosecond, few hundred kA current pulses through two or more fine (10-100 μm) metal wires that cross and touch in the form of an X. If a single wire is used, the current driven explosion is followed by an unstable, self-magnetic-field-driven implosion that produces “micropinch” at random locations along the wire. However, with an X pinch, the micropinch is reliably produced very close to the wire cross point. Therefore, we can zero-in on the location of the micropinch with our diagnostics and study their properties in great detail. We are also able to make use of the soft x-ray burst from an X pinch for high resolution and high magnification x-ray imaging.

In this report we summarize the accomplishments of our studies of these extremely interesting plasmas. For example, by analyzing the X ray spectra from various X pinches, we have found that X pinches generated from molybdenum (Mo) and titanium (Ti) wires can have temperatures in excess of 1 keV (10,000,000 K), ion densities of $10^{22}/\text{cm}^3$ (more than 10% of the density of the wire material when it is a room temperature solid), but for very short (< 1 ns) times [see publications 10, 11, 13, 15 and 18 in Section IV]. In other studies, Mo and niobium (Nb) X pinches were determined to be only about 1 μm in diameter [see publications 16 and 26]. It is clear from these plasma conditions why X pinches are excellent candidate plasmas for the study of magnetized high energy density plasma properties. This is the direction of our future research with X pinches.

Four graduate student have completed Ph.D.’s under the sponsorship of this grant,

1. Daniel Sinars, “Time Resolved Measurements of the Parameters of Bright Spots in X-pinch Plasmas,” Ph.D., Cornell University, 2001. Dr. Sinars works at Sandia National Laboratories, Albuquerque, New Mexico.
2. Byungmoo Song, “High Resolution Radiography Using the X-pinch X-ray Source,” Ph.D., Cornell University, 2004. Dr. Song works for Intel Corporation in Portland, Oregon.
3. Katherine Chandler, “Spectroscopic Measurements from the X-ray Bursts of Four Wire Manganin X-pinch,” Ph.D., Cornell University, 2006. Dr. Chandler is an Assistant Professor of Physics at Idaho State University.
4. Marc Mitchell, “X-pinch Plasma Dynamics Studied with High Temporal Resolution Diagnostics,” Ph.D., Cornell University, 2007. Dr. Mitchell is a Research Assistant Professor in Physics at Idaho State University.

Another graduate student, Kate Bell, started research on X pinches under the auspices of this grant and is now otherwise sponsored. On average, we have included 1 undergraduate student in our X-pinch research each year. One recent Cornell undergraduate who worked with us on X pinches, Daniel Lundberg, is now an advanced graduate student at Princeton Plasma Physics Laboratory.

There have been at least 32 peer-reviewed publications that were based upon research that was fully or partially sponsored by this grant, plus approximately an additional 20 publications from conferences for which proceedings were published but the papers were not peer-reviewed. Finally, there were approximately 46 presentations at conferences for which there are only abstract references. The peer-reviewed publications are listed at the end of this final report.

In the following section, we summarize the principal research accomplishments made under the sponsorship of this grant. We then summarize some of the non-technical accomplishments of our project, for example, we have worked with several other independent research groups to help them get started in X-pinch research.

II. Summary of X-pinch Research Accomplishments

Figure 1 illustrates the stages of an X pinch up to the moment it emits its short ($< 1\text{ ns}$) intense soft X-ray burst. Prior to the start of this project, we were able to use the X-pinch for X-ray backlighter imaging of exploding wire plasmas and we knew the X-ray source was a small, hot, dense plasma. Overall, the goals of this research project have been to better understand the dynamics of X-pinches, to determine their physical properties quantitatively, and to improve their characteristics as an x-ray source for point-projection imaging. All of these goals have been achieved. Almost all results discussed in this section were obtained on the 500 kA peak current, 50 ns rise time XP pulsed power machine. (See publications 1, 5, 11 or 12 and all four of the theses cited in Section I for descriptions of XP.)

During the evolution of a two- or multi-wire X pinch, it forms a small Z-pinch at the cross point of the wires that is unstable and forms a cascade of smaller and denser necks as a result of the classical “sausage instability” of z-pinch plasmas. In the final phase, a micropinch forms, emits an x-ray burst and disrupts, and a gap opens in the center where the Z-pinch formed. This process is illustrated in Fig. 1. The gap opening is accompanied by few ns duration pulses of higher energy x-ray radiation that results from electrons being accelerated in the gradually increasing gap. Figure 2 continues the images in Fig. 1 to illustrate the explosive disassembly of the X pinch and the evident shock waves as the gap increases.

As a result of the research carried out under the sponsorship of this grant, the properties of X pinches such as those imaged in Figs. 1 and 2 have been determined via a detailed analysis of the X-ray emission spectra. The results show that we generate 1-10 μm scale size, near-solid-density plasmas that reach peak temperatures of 1 keV or more with several different wire materials [publications 3, 6, 7, 10-13, 15, 18 and 22]. For example, X-ray line spectra (including Ne-like and near-neighbor ionization state line emission) emitted by Mo-wire X pinches at peak compression and as they explosively disassemble (see Fig. 2) imply plasma electron densities as high as $10^{22}/\text{cm}^3$ at temperatures $\geq 1\text{ keV}$ that last for

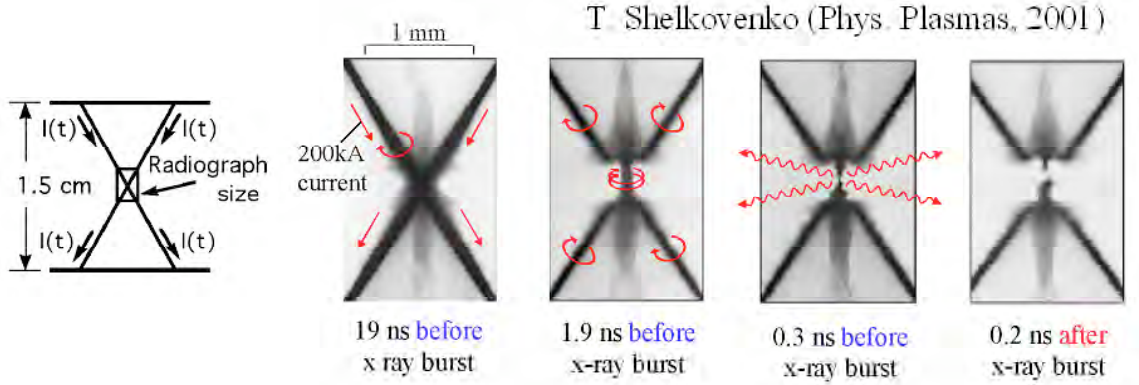


Figure 1. A series of x-ray images of 4 different Mo wire X pinches obtained using x-ray backlighting of the X pinch shown by another X pinch. The times that are given below each image are relative to the time of the soft x-ray burst. The line drawing to the left shows that for most experiments, the X pinch height was 1.5 cm, the crossing angle was about 60 degrees, and the images are of the central 3 mm of height of the X-pinch. The first image shows the wires during the explosion phase of a nominal 200 kA X-pinch, the formation of a cylindrical plasma column and its unstable implosion are shown in the second and third images, and the beginnings of the gap opening up is shown in the fourth image [from publication 3].

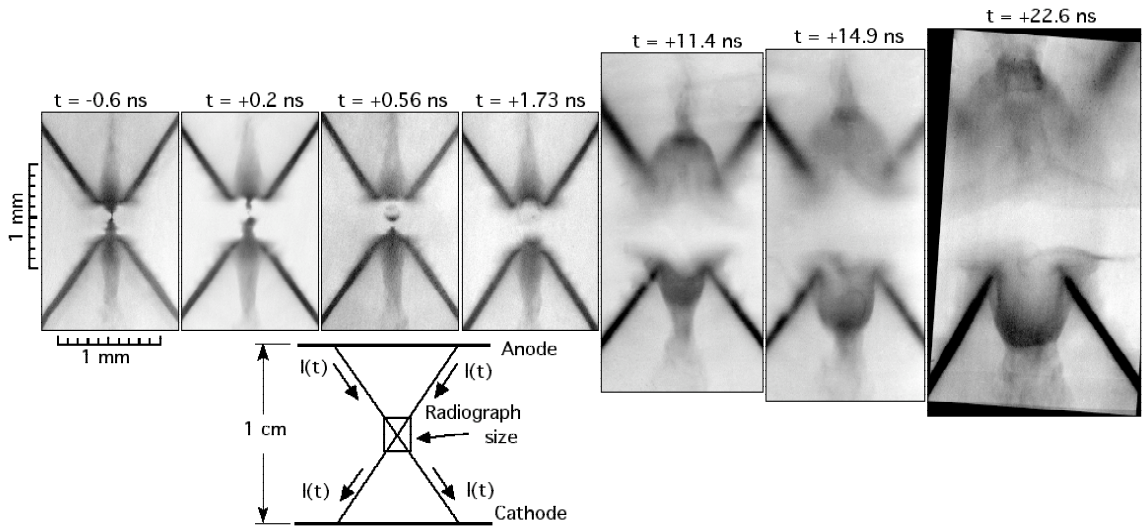


Figure 2. Sequence of X-ray backlighter images of Mo-wire X pinches obtained using other X pinches mounted in parallel as the x-ray source [from publication 3]. The indicated times are relative to the moment of the soft x-ray burst. The first image, a repeat of one in Fig. 1, was obtained before the x-ray burst ($t = 0$). The subsequent images show the progress of the explosive disassembly of the X pinch. Notice the shock wave that appears to propagate away from the original micropinch as time progresses. The schematic diagram at the bottom shows the size of the radiograph for the first four images.

~100 ps [publication 13]. X-ray streak photography shows that the most intense continuum emission in the 3-5 keV range from the micropinches generated by Mo wire X pinches lasts for 30 ps or less (full width at half maximum) [publications 10, 12 and 13] and extends up to 10-12 keV [publication 16]. Molybdenum is atomic number $Z = 42$, and so the presence of Ne-like (and near-neighbor ionization state) emission in line spectra implies the presence of Mo^{+32} (and its neighboring ionization states) in Mo X-pinch plasmas. The apparent source size of the > 2.5 keV continuum from an X pinch is as small as $1\text{ }\mu\text{m}$ based upon imaging the diffraction pattern that results from passing the radiation through a $40\text{ }\mu\text{m}$ slit plus a $12.5\text{ }\mu\text{m}$ Ti foil (filter) [publication 26]; the line radiation source size, however, is a factor of the order of 10 larger [publication 18].

In order to try to determine if there is enough plasma in the main current carrying channel to carry the current as the gap forms immediately after the X-ray burst, we have obtained some schlieren and interferometric images of the X-pinch shortly after that moment using a 0.2 ns, 530 nm (frequency doubled) Nd:YAG laser. These images suggest that there is plasma present over $\sim 1\text{ mm}$ of width in the vicinity of the gap as it is opening. Qualitatively, it appears to be blown outward by the same explosion that is driving the shock wave seen in the last 6 images in Fig. 2, except the plasma density measured with the laser is 1-2 orders of magnitude lower than the plasma seen in the point-projection radiographs. Analysis of the interferograms suggests that the plasma density profile is hollow, similar to a blast wave. This hollow plasma has more than enough charge carriers to carry the full plasma current [Marc Mitchell, Ph.D. thesis cited in Section I, to be published]. However, from the harder x-rays emitted by energetic electrons in the gap as it is opening, we know that there is still a portion of the current being carried within $\sim 100\text{ }\mu\text{m}$ radius of the original axis of the imploding plasma [publication 23].

The dynamics of the implosion phase was investigated in detail together with other research groups that have highly capable magnetohydrodynamic computer simulation capability [publications 2, 10 and 29]. As a result, we now believe that the final stage of the radial implosion in a medium to high atomic number X pinch can be described as radiatively assisted collapse. That is, up until about 2 ns before the X ray burst is emitted (second image in Fig. 1), the implosion is subsonic, and so material can be ejected along the axis as it is imploding radially inward. However, as the sausage instability develops, the rapid local implosion of a plasma neck (third image in Fig. 1) increases the density and the radiation rate (proportional to density-squared) because the implosion speed becomes supersonic and mass cannot escape along the axis fast enough to prevent a build-up. The loss of internal thermal energy to radiation and increased ionization (an energy sink) is not matched by the rate of increase of the line density through increased ionization, a source of radial pressure. As a result, the implosion driven by the increasing magnetic pressure speeds up and drives the plasma to a radius under $1\text{ }\mu\text{m}$, at which point it becomes optically thick to its sub-keV radiation. The trapped radiation rapidly increases the internal thermal energy, but the inward momentum of the magnetically driven plasma implosion continues to compress the plasma. This triggers an explosive disassembly of the extremely hot, dense plasma, which is clearly evident in images 2-6 in Fig. 2. The 2D and 3D computer codes used to model X pinches are no longer valid as soon as a gap begins to open, but since radiation loss and opacity can be turned on and off in a code, unlike in an experiment, it has been shown pretty

conclusively that the only way for the final stage of X pinch implosion to be so rapid and violent, and for the x-ray pulse to have as short a rise time as it does, is if the final implosion phase is supersonic, radiation-loss-assisted, and stopped by the onset of re-absorption of the X-rays emitted in the imploding plasma that is increasing in density faster than the radius is decreasing.

It is noteworthy that we have run a series of experiments in which positive polarity and negative polarity pulses were alternated by reversing the charging voltage of the XP pulsed power machine, but keeping the current pulse the same through the X pinch. Indeed, there is a slight difference in the dynamics of the corona plasmas that form around the wires and between the wires above and below the cross point. However, there appears to be no systematic difference in the plasma dynamics or x-ray burst characteristics at the cross point. Since the high energy density micropinch plasma at the cross point is believed to satisfy all of the conditions of magnetohydrodynamics, at least up until the moment that of x-ray burst emission and the gap begins to open up, we did not expect the direction of the electric field to matter. However, X pinches have surprised us many times before and we were ready for another surprise if it showed up in the experiments.

We have also carried out X-pinch experiments on the new COBRA accelerator, built under the auspices of Cornell's NNSA-sponsored Center for Pulsed Power Driven High Energy Density Plasma Studies (Professor Bruce Kusse, Director and Principal Investigator). The experiments on COBRA ranged in peak current up to 1 MA. Those experiments have contributed to our growing understanding of X pinches and their use for x-ray point projection imaging, but their main value was high resolution point-projection imaging of individual wires in the initial stages of wire-array Z-pinch experiments [see publication 31]. In recent work, it was found possible to vary the timing of 5 individual X pinches and obtain a sequence of 5 high resolution images of the same wire-array Z-pinch on the same pulse. [This work is as yet unpublished, but a manuscript is in preparation, and it is the principal experimental accomplishment written up in the thesis of Jonathan Douglass, "Experimental Study of Tungsten Wire-Array Z-pinch Plasmas Using Time-gated Point-Projection Radiography," Ph.D. 2008, Cornell University.]

III. Accomplishments other than X-pinch Dynamics and Properties

A significant fraction of our research program was devoted to the development of X-ray diagnostics. Using X-pinch as X-ray sources for point-projection radiography of individual wires in wire-array z-pinch has already been noted. However, here we are referring to time integrated and time-resolved diagnostics that give both spatial and spectral information about the X-pinch. Publications 19 - 21, 31 and 32 describe 4 different new X-ray spectroscopic techniques that were developed as part of the present grant.

One of the benefits of an X-pinch is that matching its properties with magnetohydrodynamics computer simulations is an excellent test of the validity of the physics models in the code. Thus, we have had several collaborations develop that used the X-pinch dynamics data as a benchmark for codes [publications 2, 10 and 29]. Likewise, we

have collaborated with groups that have codes for calculating plasma conditions from the details of the X-ray emission spectra [publications 6, 13, 15 and 18].

There is no doubt that the ability to obtain very high resolution images using the X pinch as a point source of radiation is an important outcome of our X-pinch studies under this grant. It enables high resolution imaging of biological objects as well as rapidly changing plasmas [publications 5, 8, 16 and 19]. Early on in this program, we passed on this skill to the wire-array z-pinch group in the Physics Department at Imperial College [publication 4]. We also helped a nascent group at the University of California, San Diego, to initiate a project with Lawrence Livermore National Laboratories to image inertial confinement fusion capsules. There is now discussion of using the technique at Sandia National Laboratories, Albuquerque, in the pulsed-power-based inertial confinement fusion program. Other groups, such as the pulsed-power program in the Physics Department at the University of Nevada, Reno, are now using the X-pinch as a hot dense plasma for use in X-ray spectroscopic studies of high-Z plasmas.

A final outstanding feature of the biological imaging application of X pinches is that it makes attraction of excellent undergraduates for research projects easy. In addition, our imaging capability was featured in the annual report of Cornell's Vice-Provost for Research a few years ago, and a 1 meter version the image shown in Fig. 3 of a common house fly was printed on a large pillow and displayed at Cornell's Mann Library in the Fall of 2007. We hope to continue this "popular use" of the X-pinch along with serious academic studies of its unique high energy density properties in the future.

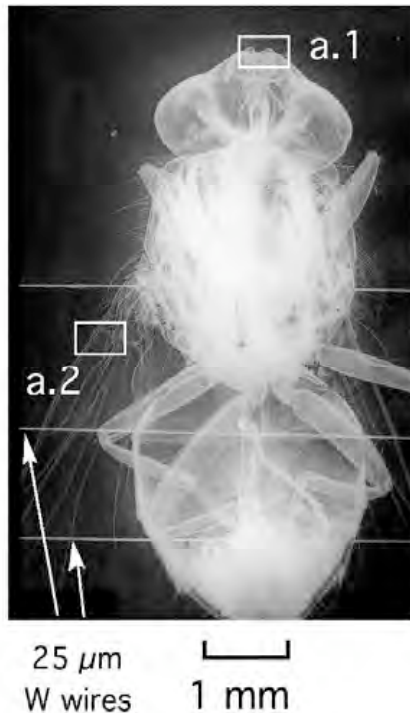
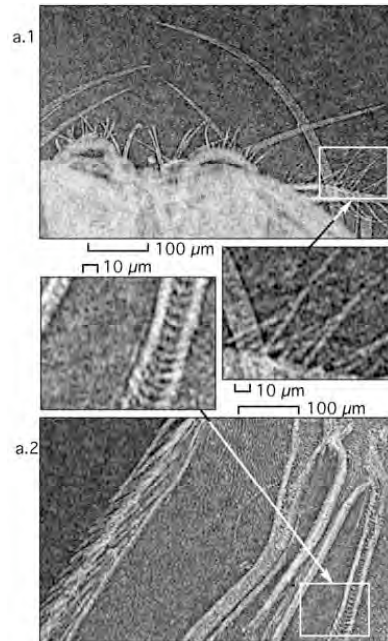


Figure 3. Left: Image of a common house fly obtained using a Mo wire X pinch. Right: Detail from the image showing the extremely good



resolution (about $3\ \mu\text{m}$) obtained in the full image in areas a.1 (top) and a.2 (bottom).

IV. Peer-reviewed Publications

1. "Evolution of the Structure of the Dense Plasma Near the Cross Point in Exploding wire X Pinches," T.A. Shelkovenko, S.A. Pikuz, Y.S. Dimant, A.R. Mingaleev and D.A. Hammer, *Phys. Plasmas* **6**, 2840 (1999).
2. "Microexplosion of a Hot Point in an X-Pinch Constriction", G.V. Ivanenkov, S.A. Pikuz, D.B. Sinars, V. Stepnienski, T.A. Shelkovenko and D.A. Hammer, *Plas. Phys. Reports* **26**, 868 (2000).
3. "Radiographic and Spectroscopic Studies of X-Pinch Plasma Implosion Dynamics and X-Ray Burst Emission Characteristics," T.A. Shelkovenko, D.B. Sinars, S.A. Pikuz, K.M. Chandler and D.A. Hammer, *Phys. Plasmas* **8**, 1305-1318 (2001).
4. "X-Pinch as a Source for X-Ray Radiography," S.A. Pikuz, T.A. Shelkovenko, D.B. Sinars, D.A. Hammer, S.N. Bland and S.V. Lebedev, *Nukleonika* **46**, 115 (2001).
5. "Point Projection Radiography Using an X-Pinch as the Radiation Source", T.A. Shelkovenko, D.B. Sinars, S.A. Pikuz, K.M. Chandler and D.A. Hammer, *Rev. Sci. Instrum.* **72**, 667 (2001).
6. "Spatial, Temporal and Spectral Characteristics of an X-Pinch", S.A. Pikuz, T.A. Shelkovenko, D.B. Sinars, D.A. Hammer, S.V. Lebedev, S.N. Bland, Yu. Skobelev, J. Abdallah, C.J. Fontes, and H.L. Zhang, *J. Quantum Spectroscopy and Radiative Transfer* **71**, 581 (2001).
7. "Temporal Parameters of the X-Pinch X-Ray Source", D.B. Sinars, S.A. Pikuz, T. A. Shelkovenko, K.M. Chandler and D.A. Hammer, *Rev. Sci. Instrum.* **72**, 2948 (2001).
8. "Phase-contrast x-ray radiography using X pinch radiation," S.A. Pikuz, T.A. Shelkovenko, D.B. Sinars, K.M. Chandler and D.A. Hammer, in *Proc. of the SPIE Conference on Applications of X Rays Generated from Lasers and Other Bright Sources II*, G. A. Kyrala and J.-C. J. Gauthier, Editors (SPIE, Bellingham WA, 2001), Pp 234-239.
9. "X pinch: a source of 1-10 keV x-rays," T.A. Shelkovenko, S.A. Pikuz, D.B. Sinars, K.M. Chandler and D.A. Hammer, in *Proc. of the SPIE Conference on Applications of X Rays Generated from Lasers and Other Bright Sources II*, G. A. Kyrala and J.-C. J. Gauthier, Editors (SPIE, Bellingham WA, 2001), Pp 180-187.
10. "High Energy Density Z-Pinch Plasma Conditions with Picosecond Time Resolution", S.A. Pikuz, D.B. Sinars, T.A. Shelkovenko, K.M. Chandler, D.A. Hammer, G.V. Ivanenkov, W. Stepnienski and I. Yu Skobelev, *Phys. Rev. Lett.* **89**, 035003 (2002).
11. "Time-Resolved Spectroscopic Measurements of ~1keV, Dense, Subnanosecond X-Pinch Plasma Bright Spots," T.A. Shelkovenko, S.A. Pikuz, D.B. Sinars, K.M. Chandler and D.A. Hammer, *Phys. Plasmas* **9**, 2165 (2002).
12. "X-Pinch Plasma Development as a Function of Wire Material and Current Pulse Parameters," T.A. Shelkovenko, S.A. Pikuz, D.B. Sinars, K.M. Chandler and D.A. Hammer, *IEEE Trans. Plasma Sci.* **30**, 567-576 (2002).
13. "Time-resolved spectroscopy of Al, Ti, and Mo X pinch radiation using an X-ray streak camera," D.B. Sinars, S.A. Pikuz, T.A. Shelkovenko, K.M. Chandler, D.A.

- Hammer and J.P. Apruzese, *J. Quant. Spectrosc. and Radiat. Transfer* **78**, 61 (2003).
14. "Application of refractive bubbles-in-capillary x-ray lens to X pinch experiments," S.A. Pikuz, V.E. Asadchikov, K.M. Chandler, D.A. Hammer, Yu. I. Dudchik, N.N. Kolchevsky, F.F. Komarov, M.D. Mitchell, A.V. Popov, T.A. Shelkovenko, R.A. Senin, I.A. Suloev and A.V. Vinogradov, *Rev. Sci. Instrum.* **74**, 2247 (2003).
 15. "X-pinch plasma conditions from time-resolved x-ray spectroscopy," T.A. Shelkovenko, S.A. Pikuz, I.Yu. Skobelev, D.B. Sinars, K.M. Chandler, M.D. Mitchell and D.A. Hammer, *Rev. Sci. Instrum.* **74**, 1958 (2003).
 16. "X pinch X-ray radiation above 8 keV for application to high-resolution radiography of biological specimens," Byung Moo Song, T.A. Shelkovenko, S.A. Pikuz, M.D. Mitchell, K.M. Chandler, D.A. Hammer, *IEEE Trans. Nucl. Sci.* **51** (5), 2514 – 2529 (2004).
 17. "Focusing x-ray spectrograph with crossed dispersion," S.A. Pikuz, B.M. Song, T.A. Shelkovenko, K.M. Chandler, M.D. Mitchell and D.A. Hammer, *Rev. Sci. Instrum.* **75**, 3777 (2004).
 18. "Analysis of L-shell line spectra with 50-ps time resolution from Mo X-pinch plasmas," S. B. Hansen, A. S. Shlyaptseva, S. A. Pikuz, T. A. Shelkovenko, D. B. Sinars, K. M. Chandler and D. A. Hammer, *Phys. Rev. E* **70**, 026402 (2004).
 19. "Plasma imaging and spectroscopy diagnostics developed on 100-500-kA pulsed power devices," D.B. Sinars, L. Gregorian, D.A. Hammer, Y. Maron, *Proceedings of the IEEE* **92**, (7), July 2004.
 20. "X-ray imaging of an X-pinch plasma with a bubble compound refractive lens", C. K. Gary, S. A. Pikuz, M. D. Mitchell, K. M. Chandler, T. A. Shelkovenko, D. A. Hammer, and Yu. I. Dudchik, *Rev. Sci. Instrum.* **75**, 3950 (2004).
 21. "Application of the focusing x-ray spectrograph with crossed dispersion to investigations of X pinch plasmas", S. A. Pikuz, B. M. Song, T. A. Shelkovenko, K. M. Chandler, M. D. Mitchell, and D. A. Hammer, *Rev. Sci. Instrum.* **75**, 3777 (2004).
 22. "Spectroscopic analysis of x-ray bursts from nichrome and conichrome X-pinch plasmas," K. M. Chandler, A. S. Shlyaptseva, N. D. Ouart, S. B. Hansen, M. D. Mitchell, S. A. Pikuz, T. A. Shelkovenko, D. A. Hammer, V. L. Kantsyrev, and D. A. Fedin, *Rev. Sci. Instrum.* **75**, 3702 (2004).
 23. "Electron-beam-generated x rays from X pinches," T. A. Shelkovenko, S. A. Pikuz, B. M. Song, K. M. Chandler, M. D. Mitchell, D. A. Hammer, G. V. Ivanenkov, A. R. Mingaleev, and V. M. Romanova, *Phys. Plasmas* **12**, 033102 (2005).
 24. "Time-Dependence of X-pinch Structure in One Test from two Radiographic Images," S. A. Pikuz, T. A. Shelkovenko, D. B. Sinars and D. A. Hammer, *IEEE Trans. Plasma Sci.* **32**, 580-582 (2005).
 25. "Cross Calibration of New X-ray Films Against DEF from 1–8 keV Using the X-pinch X-ray Source," K. M. Chandler, T. A. Shelkovenko, S. A. Pikuz, M. D. Mitchell, D. A. Hammer and J. P. Knauer, *Rev. Sci. Instrum.* **76**, 11311 (2005).
 26. "Determination of the size and structure of an X-pinch x-ray source from the diffraction pattern produced by microfabricated slits," Byung Moo Song, Sergei A. Pikuz, Tatiana A. Shelkovenko, David A. Hammer, *Applied Optics* **44**, 2349 (2005).

27. "Multiwire X pinches at 1 MA Current on the COBRA Pulsed Power Generator," Tatiana A. Shelkovenko, Sergey A. Pikuz, Jon D. Douglass, Ryan D. McBride, John B. Greenly and David A. Hammer, IEEE Trans. Plasma Science, 2336-2341, (2006).
28. "X pinches in dielectric frames," M. D. Mitchell, S. A. Pikuz, T. A. Shelkovenko, D. A. Hammer and K. M. Chandler, IEEE Trans. Plasma Sci., 2342-2348 (2006).
29. "The structural evolution and formation of high-pressure plasmas in X pinches," J.P. Chittenden, A. Ciardi, C.A. Jennings, S.V. Lebedev, D.A. Hammer, S.A. Pikuz and T.A. Shelkovenko, Phys. Rev. Lett. **98**, 025003 (2007).
30. "Structure of the dense cores and ablation plasmas in the initiation phase of tungsten wire-array Z pinches," J. D. Douglass, S. A. Pikuz, T. A. Shelkovenko, D. A. Hammer, S. N. Bland, S. C. Bott, and R. D. McBride, Phys. Plasmas **14**, 12704-1-9 (2007).
31. "The Extreme Luminosity Imaging Conical Spectrograph (ELICS)," S. A. Pikuz, T. A. Shelkovenko, M. D. Mitchell, K. M. Chandler, J. D. Douglass, R. D. McBride, D. P. Jackson and D. A. Hammer, Rev. Sci. Instrum. **78**, (2007).
32. "Wide Band Focusing X-ray Spectrograph with Spatial Resolution," S. A. Pikuz, J. D. Douglass, T. A. Shelkovenko, D. B. Sinars and D. A. Hammer, Rev. Sci. Instrum. **79**, 013106-1-7 (2008).

In addition to these peer-reviewed publications, we presented approximately 20 papers at conferences with published proceeding (5th and 6th International Conferences on Dense Z-pinches, 2002 and 2005, respectively, and the pulsed power conference in 2004).