X-PINCH PLASMA DYNAMICS STUDIED WITH HIGH TEMPORAL RESOLUTION DIAGNOSTICS

A Dissertation Presented to the Faculty of the Graduate School of Cornell University In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by Marc David Mitchell May 2007 © 2007 Marc David Mitchell

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Cornell University 2007

The X-pinch plasma produces extreme material conditions that make it interesting both as a high-energy-density plasma and an x-ray source for imaging. These extreme conditions include high densities (near solid density, 10^{23} ions/cm⁻³ for Mo), high temperatures (above 2.5 keV for Mo), high energy densities (up to 10^{12} J/cm^{3}), high x-ray power densities (up to 10^{22} W/cm³), small source sizes (which can be less than 1 μ m in diameter), and short time scales for the x-ray radiation (less than 100 ps). These extreme conditions are difficult to produce in a laboratory setting and even harder to study. The X-pinch plasma is produced by driving a high current (100-500 kA, 100 ns FWHM pulse for our experiment) through two or more wires that cross at a point forming an "X." A magnetically driven z-pinch forms near the cross point allowing the X-pinch to reliably reproduce the conditions given above. As such, we present a range of experiments designed to study the conditions produced in the Xpinch plasma. Until recently many of the diagnostics used to study the X-pinch have not had the resolution (spatial or temporal) necessary to determine the actual size or duration of the X-pinch x-ray source. We present experimental results showing the temporal extent of the x-ray radiation produced by an X pinch using an x-ray streak camera with better than 10 ps resolution. We also present experiments designed to study the temporal and spatial relationship of the two different radiation sources (thermal and energetic-electron-generated) observed from an X pinch using a filtered

diode array. In addition, we studied the plasma dynamics using both a multi-channel 150 ps, 532 nm (Nd:YAG) laser backlighting system and x-ray radiography (using an X pinch as an x-ray source). We correlate the observed plasma parameters (implosion and explosion rate, neck diameter, axial jet propagation speed, and coronal plasma axial modulation wavelength along the X-pinch legs) to wire material.

BIOGRAPHICAL SKETCH

Marc David Mitchell was born in the small Indiana town of Poseyville in September of 1977. Many of his early interests came from a combination of this small farming community and his parents. His father, being a professor of electrical engineering, was responsible for most of Marc's early fascination with math and science. Marc realized later in life that the math puzzles his father began presenting to him in kindergarten did more that develop his math skills, but ignited his passion for solving problems. The somewhat rural environment of Poseyville never had a shortage of work to be done, and Marc's mother made sure he never spent too much time at idle (as any good mother would). The seemingly endless array of tasks helped form Marc's work ethic from a young age. Of course, as an adolescent, there was also no shortage of complaining. As years past, Marc's father continued to help lay down the path to a future as an experimentalist by fueling his mechanical aptitude and attitude that nothing was insurmountable. Before Marc even reached high school he found himself working on cars, motorcycles, radios and and helping his family construct their future home.

By the time Marc entered North Posey High School he had a clear aptitude for math and science, but with the absence of any kind of advanced placement programs found that he was not being challenged in those subjects. So, like any teenager, he looked for challenges elsewhere. Marc found himself party to numerous athletic and academic teams and in particular was recognized for his achievements on the football field. He filled the rest of his time earning money in the construction business and, of course, spending it on high school romance.

As Marc entered college at the University of Evansville in the fall of 1996, he decided to leave most of his previous distractions behind and focus on academics. Marc considered other schools, but the free tuition as a result of his father's

iii

employment at the university made Evansville an attractive choice. Marc initially concentrated on electrical engineering, but soon he was desperately trying to find ways to break out of his father's shadow. By the end of his sophomore year Marc had added physics as a second major. In Marc's mind the combination of physics and engineering was the perfect match for his desire to understand how things work and his ability for making things work. He graduated from the University of Evansville after four years with a Bachelors of Science in both areas. He was the only member of the class of 2000 to graduate with honors in electrical engineering.

Wishing to continue the marriage of engineering and physics, Marc applied to a handful schools who offered engineering physics programs. After careful review of the opportunities presented to him, he accepted the offer from Cornell University without even visiting the campus. He was drawn to the rare mixture of academic strength and small town setting that Cornell offered. Marc spent the majority of time his first year either fulfilling his requirements as a teaching assistant, working on the endless flow of class work, or trying to find a research area to which he would dedicate the better part of his life. His first introduction into the field of plasma physics was through Professor Bruce Kusse who convinced Marc that he had finally found the right field. Ultimately, Marc joined the plasma physics group but under the direction of Professor David Hammer. Over the next few years Marc got the opportunity to work on a variety of projects from ablation studies of a single wire to X pinches, which would later become the topic of his dissertation. Over the course of his graduate studies he was fortunate to work with some of (maybe "the") worlds best scientists on X pinch plasma physics: Dr. Sergei Pikuz and Dr. Tatiana Shelkovenko. After working on more projects than he can remember he finally defended his dissertation in July of 2006.

iv

Marc got more than just a good education during his graduate career he also met his wife. Katherine Chandler was working in the same research group for the same advisor. Marc and Katherine had an instant rapport, but Marc was hesitant to pursue an office romance. Luckily, Marc quickly came to his senses, and they eventually wed in 2005 after four years together.

By the time Marc defended his dissertation he and his wife had already accepted jobs at Idaho State University, which they started in August of 2006. Katherine finished her Ph.D. in the prior year and now is in her first year as an assistant professor while Marc is working through his first year as a post-doctoral research assistant. Marc and Kathy continue to grow the research they started at Cornell while at the same time branching out into some of the nuclear related research at ISU.

ACKNOWLEDGMENTS

The time I spent at Cornell was a difficult but rewarding time. Thankfully, I had the support of many individuals that kept me heading in the right direction.

I would like to express my gratitude to my advisor Professor David Hammer. His record of graduate students should stand on its own as a testament to the quality of his guidance. Dave allowed me to exercise freedom in my choice of research while at the same time was always available to provide thoughtful suggestions whenever needed. I know his success both as an advisor and scientist will continue.

I would also like to thank Professor Bruce Kusse for introducing me to the field of plasma physics. It was my initial conversations with him that convinced me that plasma physics would be my research emphasis at Cornell. Bruce was also responsible for explaining to me the physics behind many of the diagnostics and pulsed power machines in the laboratory.

I do not have enough thanks for Dr. Sergei Pikuz and Dr. Tatiana Shelkovenko. I have to admit when they first arrived in the laboratory from the P. N. Lebedev Institute in Moscow they were scientific machines. I had a hard time keeping up with the pace of their experiments and their long hours. However, as the years past I realized that they were not only a great asset to the laboratory, but also a great asset to me. Their expertise in X pinches, spectroscopy, x-ray and plasma diagnostics is certainly world class. I hope to continue collaborations with Sergei and Tatiana for a long time to come.

I owe a great dept of gratitude to the wonderful Laboratory of Plasma Studies (LPS) research and support staff. Dr. John Greenly always had a genuine interest in solving any problem that arose. Todd Blanchard was a wizard at turning an idea into a precision experimental device. Alan Dunning kept the lab running safely and efficiently. Harry Wilhelm was a jack-of-all-trades that was always willing to lend a

vi

hand. Joyce Oliver made my life much easier by helping with all the paper work that comes with being a graduate student.

I would like to thank Professor Clifford Pollock, who took time out of his over filled schedule to advise me through my minor in electrical and computer engineering. I would also like to thank Professor Michal Lipson, who filled in for Professor Pollock at my thesis defense.

I enjoy working and talking with the many collaborators I had during my time at Cornell. I particularly enjoyed my interactions with the individuals at Imperial College in London. I learned a great deal from my experiments conducted with Dr. Sergei Lebedev and the mountains of valuable advice from Dr. Simon Bland, Dr. Jerry Chittenden, Dr. Simon Bott, and Dr. David Ampelford. I benefited greatly from my conversations with Dr. Stephanie Hansen, now at Lawrence Livermore National Laboratories, for her extensive insight into plasma spectroscopy.

For several years I was the latest addition to LPS allowing me ample time to learn from the more senior students: Min Hu, Peter Duselis, and my future wife Katherine Chandler. But, I was also very grateful to finally gain some help once new students started to arrive: Jon Douglass, Isaac Blesener, Dan Jackson, and Wasif Syed.

One student that far and away helped me "in the trenches" running experiments more than anyone else was my wife Katherine Chandler. She was constantly helping in any capacity she could, from developing films to loading wires to analyzing spectra. One might expect that she did this because of our relationship, but she did this for every student that passed through during her time at Cornell. Her overwhelming support extended into the home as well. I could not imagine a better partner in the lab or at home.

vii

Finally, I would like to give many thanks to my family and friends whose love and support kept me going for so many years, and whom I miss very much. I would especially like to recognize my parents who guided my through all life's early lessons, and are the most responsible for where I am today.

TABLE OF CONTENTS

BIOG	RAPHI	CAL SKETCH	iii
ACKI	NOWLE	EDGEMENTS	vi
LIST	OF FIG	URES	xi
LIST	OF ABI	BREVIATIONS	XV
LIST	OF SYN	MBOLS	xvii
CHAI	PTER 1:	INTRODUCTION	1
CHAI	PTER 2:	BACKGROUND ON X PINCHES	11
	2.A	Z-pinch and X-pinch plasmas	12
	2.B	Short-lived and long-lived e-beam formation	14
	2.C	Source size measurements of the X pinch	17
	2.D	Temporal duration of radiation	19
	2.E	Measuring the timing of the x-ray burst emission	20
	2.F	Applications of the X pinch	20
	2.F.1	Point-projection and coherence-based phase contrast imaging	22
	2.F.2	X pinches in frames	23
CHAI	PTER 3:	EXPERIMENTAL DESIGN	26
	3.A	Load Parameters	26
	3.B	XP Pulsed Power Generator	26
	3.C	Shearing Interferometer	27
	3.D	X-ray Streak Camera	34
CHAI	PTER 4:	THEORIES RELEVANT TO MICROPINCH FORMATION	37
	4.A	The Bennett pinch relation	39
	4.B	Sausage instability	40
	4.C	Radiative Collapse	43

CHAPTER 5:	RADIATION STRUCTURE OF THE X PINCH	46
5.A	Spatially resolved, time integrated measurements of X pinch	
	radiation	47
5.B	Time resolved measurements using an x-ray streak camera	47
5.C	Spatially and temporally resolved study of energetic electron	
	radiation	61
CHAPTER 6:	RESULTS AND DISCUSSION FROM LASER AND	
	X-RAY IMAGING	64
6.A	Morphology of the X pinch	65
6.B	Expansion of the coronal plasma	68
6.C	Compression of the cross point	69
6.D	Explosion phase	76
6.E	Plasma jet formation	80
6.F	Modulations of the coronal plasma	84
6.G	Experiments with simultaneous x-ray and laser imaging	85
CHAPTER 7:	SUMMARY AND CONCLUSIONS	88
7.A	Radiation structure of the X pinch	88
7.B	Plasma dynamics of the X pinch from laser and x-ray imaging	90
7.C	Future work	92
REFERENCE	S	94

LIST OF FIGURES

Figure 1.1:	Illustration of X-pinch geometries	4
Figure 1.2:	Radiographs of an X pinch showing the processes leading to x-ray	6
	emission	
Figure 1.3:	Radiograph of an exploding wire illustrating the high spatial and	6
	temporal resolution of the X pinch	
Figure 2.1:	Illustration showing the phases of the X pinch	13
Figure 2.2:	Pinhole images showing the spatial radiation structure of an X	16
	pinch	
Figure 2.3:	Slit-step-wedge images of showing the radiation zones of an X	16
	pinch	
Figure 2.4:	Image of a Ni mesh showing the spatial relationship and	18
	resolution of the micropinch and electron beam radiation	
Figure 2.5:	Typical current trace and relative x-ray timing for a Mo X pinch	21
Figure 2.6:	Illustration of X-pinch configurations in frames	25
Figure 3.1:	Typical voltage traces of the intermediate storage capacitor and	28
	pulse forming line along with a typical current trace measured at	
	the load	
Figure 3.2:	Illustration of optical paths for the laser interferometer system	30
Figure 3.3:	Illustration of the air-wedge interferometer	31
Figure 3.4:	Reflectivity of the two air-wedge surfaces as a function of	32
	incidence angle	
Figure 3.5:	Illustration of the x-ray streak camera	36
Figure 3.6:	Example of a time dependent spectrum of a Mo 4-wire 22 μm X	36
	pinch	

Figure 4.1:	Illustration of forces acting on a conducting plasma column	38
Figure 4.2:	Illustration of the $m = 0$ (sausage) instability	41
Figure 5.1:	Illustration of the slit step-wedge camera	48
Figure 5.2:	Images from pinhole and slit step-wedge cameras showing the	49
	time integrated spatial structure of radiation from the X pinch	
Figure 5.3:	Time dependent image of the radiation from a Mo 4-wire 22 μm	51
	X pinch taken with an x-ray streak camera coupled to a	
	spherically bent mica spectrograph (1 mm/ns sweep rate)	
Figure 5.4:	Expansion of image in Fig. 5.3 showing the relation of the	52
	continuum and line radiation	
Figure 5.5:	X-ray streak camera image from a Mo 4-wire 22 μm X pinch at	54
	40 mm/ns sweep rate showing an x-ray burst of about 30 ps	
Figure 5.6:	X-ray streak camera image from a Mo 4-wire 22 μm X pinch at	55
	40 mm/ns sweep rate showing weak bursts of about 50 ps	
Figure 5.7:	Temperature analysis of one of the x-ray bursts from the image	56
	shown in Fig 5.6	
Figure 5.8:	Radiation from a Mo 4-wire 22 μ m X pinch in an 8 ns streak	58
	window showing the temporal relationship of continuum and	
	atomic line radiation	
Figure 5.9:	Plot of intensity as a function of time and wavelength from the	59
	streaked image shown in Fig. 5.4	
Figure 5.10:	Plot of the transmission ratios for the filters used with the SiDs	62
Figure 5.11:	Views of the SiDs used to study the energetic electron radiation	63
	from a Mo 4-wire 22 μm X pinch along with plots of the relative	
	intensity of radiation from each region	

Figure 6.1:	Laser shadow images showing the evolution of a 4-wire 25 μ m Al	66
	X pinch as it progresses in time	
Figure 6.2:	Laser shadow images showing the evolution of a 4-wire 20 μm W	67
	X pinch as it progresses in time	
Figure 6.3:	Plots of coronal plasma expansion rates for a 4-wire 25 μm Al X	70
	pinch	
Figure 6.4:	Plots of coronal plasma expansion rates for a 4-wire 20 μm W X	70
	pinch	
Figure 6.5:	Plot of coronal plasma expansion rate for a 4-wire 25 μm Mo X	71
	pinch	
Figure 6.6:	Plots of neck diameter before x-ray emission for a 4-wire 25 μm	74
	Al X pinch	
Figure 6.7:	Plots of neck diameter before x-ray emission for a 4-wire 20 μm	74
	W X pinch	

- Figure 6.8: Interference image of the cross point region of an Al 4-wire 25 75
 μm X pinch 2.3 ns before x-ray emission
- Figure 6.9: X-ray radiograph of a Mo 2-wire 13 μm X pinch within 0.1 ns of 75 x-ray emission, which shows that the diameter of the neck before x-ray emission can be as small as 2.5 μm
- Figure 6.10: Plots of neck diameter during the explosion phase for a 4-wire 25 77 μ m Al X pinch
- Figure 6.11: Plots of neck diameter during the explosion phase for a 4-wire 20 77 µm W X pinch
- Figure 6.12: Radiograph of the X pinch show that gaps begin to form in the79neck region almost immediately after the first x-ray burst

Figure 6.13:	Comparison of an x-ray radiograph and laser shadow image of an	79
	Al 4-wire 25 µm X pinch at similar times	
Figure 6.14:	Plots of propagation of the plasma jets from the cross point	81
	toward the anode and cathode for an Al 4-wire 25 μm X pinch	
Figure 6.15:	Plots of propagation of the plasma jets from the cross point	81
	toward the anode and cathode for a W 4-wire 20 μm X pinch	
Figure 6.16:	Illustration of half of an X pinch to demonstrate plasma jet	82
	propagation due to "zippering" of the ablated plasma fronts from	
	the X-pinch legs	
Figure 6.17:	Images showing periodic modulations of the coronal plasma	84
	streaming toward axis observed from W wires as part of a wire	
	array and from the legs of an X pinch	
Figure 6.18:	Schematic diagram of optical and x-ray imaging paths	85
Figure 6.19:	Evolution of a Mo 2-wire 13 μ m X pinch captured with X pinch	86
	x-ray backlighting	
Figure 6.20:	Superposition of the laser shadow image and x-ray radiograph for	87
	pulse 4908	

LIST OF ABBREVIATIONS

μF: micrfarad
μm: micrometer (or micron)
Å: Angstrom
A-K: anode-cathode
Al: aluminum
Be: beryllium
CCD: charge-coupled device
cm: centimeter
Cr: chromium
Cu: copper
e-beam: electron beam
eV: electronvolt
FFT: fast Fourier transform
FWHM: full-width at half-maximum
He: helium
ICF: inertial confinement fusion
ISC: intermediate storage capacitor
kA: kiloamp
keV: kiloelectronvolt
kJ: kilojoule
MA: megaamp
MHD: magnetohydrodynamic
MJ: megajoule
mJ: millijoule

mks: meter, kilogram, second units

mm: millimeter

Mn: manganese

Mo: molybdenum

My: mylar

Nd:YAG: neodymium-doped yttrium aluminum garnet

Ne: neon

nF: nanofarad

Ni: nickel

ns: nanosecond

PCD: photoconducting detector

PdV: work done by change in volume (V) at constant pressure (P)

PFL: pulse forming line

Pp: polypropylene

ps: picosecond

SBS: stimulated Brillouin scattering

SF₆: sulfur hexafluoride

SiD: silicon diode

SSW: slit-step-wedge

Ti: titanium

TW: terawatt

UV: ultraviolet

W: tungsten

LIST OF SYMBOLS

- $\int n_e dl$: line integrated electron density (or areal electron density)
- A: mass fraction
- *B*: magnetic field
- B_{θ} : azimuthal componet of magnetic field
- c: speed of light $(3 \times 10^8 \text{ m/s})$
- *d*: distance
- *e*: electron charge
- $F_{kinetic}$: kinetic force
- $F_{magnetic}$: magnetic force
- *I*: current
- *i*: imaginary number
- *I_{PB}*: Pease-Braginskii current
- *j*: current density
- *k*: wave number
- *k*_{*B*}: Boltzmann constant
- $\ln \Lambda$: Coulomb logarithm
- m_e : electron mass
- m_i : ion mass
- N: total number of particles
- n_e : electron density
- n_i : ion density

 P_b : bremsstrahlung radiated power per unit length

 $p_{kinetic}$: kinetic (thermal) pressure

 $p_{magnetic}$: magnetic pressure

- P_{Ω} : ohmic power per unit length
- Q_b : power loss from bremsstrahlung per volume
- r: radius
- S: collection of constant terms equal to 1.69×10^{-4} in mks units
- t: time
- T_e : electron temperature
- T_i : ion temperature
- *v*: volume
- Z: ionazation state
- Z_{eff} : effective ion charge
- $\Delta \Phi$: phase shift
- ε_0 : permittivity of free space
- θ : angle
- λ : wavelength
- μ_0 : permeability of free space
- *π*: pi (3.14159...)
- ρ : mass density
- ρ_0 : solid mass density
- σ : conductivity
- σ_0 : collection of constant terms equal to 1.03×10^{-4} in mks units
- Φ : phase
- ω : frequency (angular)
- ω_{pe} : plasma frequency (angular)

CHAPTER 1

INTRODUCTION

The concept of the z-pinch stretches back as far as 1790 when Martinus van Marum utilized 100 Leyden jars to explode a one meter long wire with around 1 kJ of energy [Haines *et al.* 2000]. Since then we have come to understand a great deal about the physics governing z-pinches, but, as we will soon see, we still have much more to learn. There are many different configurations for z-pinches, but fundamentally they are all the same. Essentially, a z-pinch is a plasma column with a current following along its axis, the z axis. The current flowing in the column creates a radial force inward on the moving charged particles, forcing them in toward the axis. Acting against this inward force, is the thermal pressure from the hot plasma column. (The physical concepts of the z-pinch are discussed further in Chapter 2.) Physicists have found that by using the right balance of current, temperature, and mass we can cause a z-pinch to implode and release an intense burst of x-rays. A z-pinch is now the world's most powerful and efficient soft x-ray source [Spielman *et al.* 1998].

Of the many types of z-pinches, it is the wire-array z-pinch that is the world's most powerful x-ray source, and thus it is of interest to the Inertial Confinement Fusion (ICF) community as a radiation source for indirect drive ICF concepts [Haan *et al.* 1995]. ICF research featuring a z-pinch compression driver is the main initiative behind the Z machine at Sandia National Laboratories. The Z machine is a 100 ns, 20 MA pulsed power driver for plasma radiation sources [Matzen 1997, Spielman *et al.* 1998]. Experiments with tungsten wire-array z pinches on the Z facility can produce up to 280 TW and 1.8 MJ of soft x rays in the 100-10,000 eV range. However, the succession of physical mechanisms that produce these short, intense bursts of x-ray radiation is still not well understood. The next larger (26 MA) wire-array z-pinch

generator is under construction, and an understanding of the physics of x-ray production is necessary in order to use it most effectively for ICF research. A better understanding of the radiation mechanisms in a z-pinch opens the door for increasing x-ray power and yield as well as the tailoring of the x-ray pulse shape, which is critical for ICF.

Despite the possible explanations of kinetic energy, PdV work, and ohmic heating for radiation production, the precise timing, structure and energy of the x-ray pulse produced in a wire array z-pinch are hard to pin down, both experimentally and theoretically. Experiments have shown that wire array implosions proceed as a complex process of steady ablation from the wires, plasma collection on axis, and finally much of the residual mass is swept toward the axis, commonly referred to as a "snowplow" implosion, where it stagnates and radiates the x-ray pulse [Lebedev *et al.* 2002].

Still further complexity comes with the "trailing mass" phenomenon that is often observed during the snowplow implosion. Trailing mass is observed when the snowplow implosion does not involve 100% of the original wire-array mass. In fact, up to 40% of the array material remains near the original wire positions during the first implosion [Hall *et al.* 2006]. Moreover, the current carried towards the axis during an implosion may switch back out to flow through this "trailing mass" at some point during the stagnation phase. This is sometimes called a "current restrike" [Hall *et al.* 2006] and can produce another implosion, resulting in the trailing mass being swept inwards onto the stagnated plasma of the first implosion.

A significant role player in these implosion processes is the susceptibility of the plasma to a number of instabilities, such as a Rayleigh-Taylor instability in the imploding sheath, as well as Magnetohydrodynamic (MHD) instabilities (further discussed in Chapter 2) in the stagnating plasma, creating even further complexities in

understanding x-ray production. Previous observations of "bright spots" from which x-rays are emitted in wire array experiments have been attributed to instabilities or electron beam formation [Deeney *et al.* 1991], which have also been observed in experiments involving single wire z-pinches. More recently, however, wire array experiments done at Imperial College have shown that if MHD instabilities are responsible for the development of bright spots in wire arrays, it is not the instability mechanism that produces bright spots in single wire z-pinches [Hall *et al.* 2006]. A more detailed discussion of the instabilities that impact single wire z-pinches can be found in Chapter 4.

Although in the case of the single wire z-pinch, the mechanism of bright spot formation is different than in wire array z-pinches, single wire z-pinch experiments have continued at university laboratories in an attempt to understand that phenomenon. Results of these experiments have shown that instabilities give rise to multiple small, localized plasma constrictions or micropinches (bright spots), from which soft X-rays are emitted. Temporal and spatial studies of these micropinches proved difficult, however, due to the unpredictable behavior of the time and location of the micropinch formation, which occurs randomly along the wire-initiated plasma. A necessary condition in order to study these bright sources with high temporal and spatial accuracy was the localization of the x-ray source itself. The development of the X-pinch plasma (described in more detail in Chapter 2) was, for this reason, first introduced in 1981 by Ulshmid *et al.* at the P.N. Lebedev Physical Institute in Moscow, Russia [Zakharov *et al.* 1982].

An X-pinch is a variant of the single wire z-pinch and is made by arranging two or more wires to touch-cross at the center, in the form of an "X" (see Fig. 1.1). A current pulse from a pulsed power device (in our case, ~450 kA peak current,



Figure 1.1: Drawings of a two-wire and a multi-wire X-pinch are shown together with two X-pinches in parallel as they would be loaded between an anode and cathode of a pulsed power generator. The anode-cathode gap is typically 1.5 cm in experiments at Cornell.

100 ns full-width at half-maximum [FWHM], 40-50 ns rise time) is passed through the wires creating a plasma along the surface of the wire, commonly referred to as "coronal plasma." The currents in all the wires of an n-wire X-pinch combine at the cross-point (the current doubles for two-wire X-pinches) and the magnetic pressure increases as n^2 (quadruples for two-wire X-pinch) relative to that in a single wire. The magnetic field is strong enough to confine the plasma formed in the cross point region during the current-induced wire explosion, and a small z-pinch is formed, resembling a 100-400 µm long single wire z-pinch. As the magnetic field continues to compress the plasma column, or mini z-pinch, the column undergoes instabilities that cause an implosion of the plasma into small regions of high temperature and density, often referred to as micropinches. It is from these regions that one or more sub-nanosecond soft x-ray bursts (1 – 10 keV) are emitted [Kalantar 1993, Shelkovenko et al. 1999, Shelkovenko et al. 2001a, Shelkovenko et al. 2001b]. Figure 1.2 depicts a two-wire X-pinch as current is being applied, before and after x-ray emission. The picture shows the current heating the wires and creating plasma along the surface of the wires that expands as it is heated by the current. Also illustrated is the formation of the mini z-pinch at the cross point region of the X-pinch. A more detailed description of the Xpinch implosion process is presented in Chapter 2.

The reproducible times of bright spot formation (to within +/-1 - 3 ns) occurring within a very small region of space (to within +/-0.1 mm) in the X-pinch, allows X-ray spectroscopic measurements to be made with the use of high-resolution diagnostic instrumentation. Moreover, the characteristics of the x-ray emission of the X-pinch have led to a significant amount of study concentrated in developing the Xpinch as a reliable laboratory radiographic tool [Shelkovenko *et al.* 2001b]. Not only does the small source size make the X-pinch ideal for point-projection radiography, but the fast time-scale of the x-ray burst emission has made the X-pinch an ideal



Figure 1.2: A radiograph of a two-wire X pinch before and after x-ray emission. A column of plasma, or "mini z-pinch", is formed due to the higher magnetic field strength in the central cross-point region. The plasma column is further compressed until it unstably implodes into small regions of high density and temperature, called "micropinches." It is from these micropinches that x-rays are emitted [Shelkovenko *et al.* 2001b].



11.5 µm W with 2.2 µm Polyimide Coating

200 µm

Figure 1.3: Radiograph obtained with an X pinch of a single exploding wire made from 11.5 μ m W with a 2.2 μ m polyimide insulator. Observed here is the non uniform expansion (a) at the contact near the cathode, (b) in the central region, and (c) the more expanded region. Also observed is a striated structure inside the expanded core as well as the thin insulator [Sinars *et al.* 2001].

source for radiography of rapidly evolving objects as well. Consequently, X-pinches have been used to radiograph the time evolution of single wire explosions, where expansion times have been obtained for many materials [Chandler *et al.* 2001], and to image the small-scale structure of the wire core and coronal plasma, as shown in Fig. 1.3 [Sinars *et al.* 2001]. Furthermore, X pinches have also been able to provide quantitative areal density measurements of wire array z-pinches [Hu *et al.* 2002] and other high-density plasmas. Since the intermediate stage between X-pinch wire explosion and x-ray burst emission is a z-pinch configuration, it is reasonable to expect that the bright spot characteristics of each emission point in a single exploding wire z-pinch are similar to those for X-pinch bright spots with the same wire material, making X-ray spectroscopy of the X-pinch applicable to studies of the z-pinch with a comparable current.

X pinches have been successfully developed as point sources of soft x rays for radiography [Kalantar 1993, Shelkovenko *et al.* 1999, Kalantar *et al.* 1995, Pikuz *et al.* 1997]. However, the physical mechanisms responsible for the short bursts of radiation are only partially understood, and the plasma conditions at the moment of burst emission are not well known. Computer simulations have brought us closer to understanding the MHD conditions that lead to x-ray emission. However, many questions still remain about the final moments before and during x-ray emission itself [Ivanenkov *et al.* 2000, Ivanenkov *et al.* 2002] and [Chittenden *et al.* 2007]. An understanding of the plasma dynamics at the cross-point region of the X-pinch could help the understanding of some of the mysteries behind the physics of the wire-array z-pinch. In addition, from a basic physics perspective, the X-pinch could provide experimental data on highly stripped ionic emission line wavelengths and spectral line profiles at electron densities up to 10^{24} cm⁻³ for Al [Abdallah *et al.* 1996] and Ti [Sinars *et al.* 2003] and where atomic physics modeling is still being developed.

The goal of this dissertation is to contribute to the understanding of X-pinch plasma dynamics, namely, the physics behind the micropinch formation and x-ray burst emission. More specifically, in this dissertation I will address the following questions:

- 1. What is the duration of the micropinch radiation, and what mechanisms allow this short time scale radiation?
- 2. When does the energetic electron radiation begin relative to the micropinch radiation, and where is its source location as a function of time?
- 3. What roles do the plasma dynamics (plasma expansion rate, neck compression and expansion rates, jet formation, axial modulations) play in the X pinch?

In the past we have tried to answer some of these questions, and have come up with a few core hypotheses:

- 1. Micropinch radiation lasts for less than 1 nanosecond (quickly turned on by rapid temperature increase and off by density decrease).
- 2. Energetic electron radiation starts after the micropinch (once lower density gaps begin to form) and progresses from the center to the anode.
- Coronal plasma expansion rates and neck compression rates are linked to the time of x-ray emission and are dominated by the energy deposited in the plasma per unit mass.

We will now, in this dissertation, discuss experiments designed to test these hypotheses. We have included additional observations made possible by the laser imaging. Namely, we observed similar axial modulations of the coronal plasma similar to those seen in wire-array z-pinch experiments. Also, we present an image showing the relative position of the dense wire core and surround coronal plasma. In the following chapter (Chapter 2), I will discuss the background of the Xpinch, how plasma is formed in more detail, and our present understanding of how the physical processes involved lead to the production of x-ray radiation. Also, the results of previous experiments and what has been done experimentally up until this thesis, will also be discussed. I will then discuss, in Chapter 3, the pulsed power device used to conduct all experiments described in this dissertation, as well as the experimental setup for the experiments conducted.

Presented in Chapter 4 is the basic physics of a z-pinch, namely, the balance between thermal and magnetic pressure, and how this relates to the compression of the X-pinch neck. The Bennett pinch relation, radiative collapse, and sausage instabilities are also presented as current theories believed to be responsible for micropinch formation and x-ray production.

In Chapter 5, the radiation structure of the X-pinch is discussed along with experiments involving an x-ray streak camera and the results of those measurements. Measurments taken from PCDs (photoconducting devices), Si-diodes, and a Si-diode array will also be shown. An in depth discussion of the study of energetic electron radiation will also be presented and the experiments conducted to observe the energetic electron radiation will also be described.

Laser imaging is addressed in Chapter 6, including a description of the evolution of coronal plasma formation, as well expansion rates of coronal plasma, both obtained with this diagnostic. The density of early time coronal plasma is discussed, as is the formation of the plasma jet along the axis of the X-pinch (see Fig. 1.2). Also shown are observations of the X pinch near the time of emission of x-rays and at late times. We also present results of experiments designed to capture images of the dense wire core with x-ray radiography, and the less dense coronal plasma by laser imaging at the same time.

Finally, a summary of the experimental results and a discussion and directions for future experiments are presented in Chapter 7.

CHAPTER 2

BACKGROUND ON X PINCHES

The wire array z-pinch is an intense source of x-rays which plays an important role in Inertial Confinement Fusion (ICF) [Sanford *et al.* 2000]. By varying the wire material, wire diameter, and array diameter, optimization of the x-ray yield is studied, as is the conversion of kinetic energy to x-ray radiation. Also, yield scaling with current may be determined. In addition to ICF studies, the intense sources of x-rays such as high power wire array z-pinch may be used to create an environment suitable for nuclear weapons effects testing. Unfortunately, the large wire number arrays that produce high yield cannot be studied on the modest scale pulsed power generators at universities; much more powerful generators are needed.

Consequently, several university laboratories have concentrated their efforts on studying the plasma dynamics of single wire z-pinches and X pinches. Although the dynamics of single wire explosions are significantly different from wire arrays, there are some advantages to studying this more simple case. For example, the results of single wire experiments have revealed wire expansion rates and have given insight into material properties that may influence x-ray yield in wire arrays. Also, the study of X pinches have led to the development of the X pinch as an x-ray backlighting diagnostic, and have further led to questions involving the plasma dynamics of x-ray production, not only for X-pinch applications, but also from a fundamental physics perspective. As such, the X-pinch has developed into an interesting and very useful topic of study for many in the plasma physics community. Both z-pinches and X pinches have fundamental similarities in plasma formation and x-ray production, and both are described in great detail in the following sections.

2.A Z-pinch and X-pinch plasmas

One way to form a Z-pinch is to use a single wire as the load of a pulsed power device. The high current that is delivered to the wire in a short time (~100 ns) causes the wire to heat and devolve gas from the surface, leading to plasma formation along the surface of the wire. The plasma first expands due to the plasma pressure, which increases with increasing current. At the same time, the current induces a magnetic field which applies a force on each moving charge carrier in the plasma that acts against the plasma pressure and eventually exceeds it. This causes the plasma to undergo an m = 0 (azimuthally symmetric) sausage instability in the imploding plasma column, causing axial variation in plasma radius and number density, resulting in one or more localized "pinches." The pinch region of small radius with high temperature and density is often referred to as a micropinch. From the micropinch an intense x-ray burst is emitted and is therefore also commonly known as a bright spot.

A closer look at the three stages that occur during the formation of X-pinch plasmas can be seen in the schematic "movie" of X-pinch plasma development shown in Fig. 2.1. In the first stage, current passes through the wires, heating them and causing them to expand. A rapidly expanding coronal plasma on the surface of the wire surrounds a more dense, cold wire core, where the majority of the mass remains. The dense core is highly resistive and so the majority of the current flows in the surface coronal plasma. Therefore, the rate of energy deposition in the core is very slow, and so is its ablation rate [Sinars *et al.* 2001]. At the cross point region, the magnetic field is greater than at the legs, which serves to confine the plasma resulting in a 150 μ m - 300 μ m long cylindrical column (see Fig. 2.1). This region is also called the "minidiode," in which electron beams may be produced later in the development of the X-pinch. Jet-like plasma structures can also be seen above and below the minidiode at regions of minimum magnetic field.



Figure 2.1: Illustration showing the phases of the X pinch. (a) The top set of drawings shows the cold wires at 0 ns, and then the wires at 10 ns, 12 ns, 20 ns, and 45 ns after the start of the current pulse. As the wires are heated, they expand as plasma forms along the wires' surface. At around 45 ns after the start of the current pulse, the increased magnetic field pressure present at the cross-point of the X pinch due to the larger current in the cross-point region causes a plasma column or "neck" to form. (b) The second set of drawings, the wires continue to expand as more current continues to drive the X pinch. The plasma column in the cross-point region begins to undergo instabilities at around 50 ns after the start of the current pulse, and within 0.5 ns, the column collapses in on itself at one or more spots along the column (often referred to as "hot spots" or micropinches). A burst of x-rays is emitted from each of the hotspots, and shortly after x-ray emission a small gap opens up, across which electrons are accelerated. (c) The bottom drawings are enlarged pictures of the neck illustrating the instabilities that the plasma column undergoes to form the hotspot(s).

The second stage begins with the implosion of the plasma column, including strong sausage (m = 0) instabilities. The plasma column is compressed into a series of smaller and smaller necks (see Fig. 2.1c), where densities can reach near solid density and temperatures are ~1 keV for Mo wires [Hansen *et al.* 2004]. The plasma column implodes on itself on a timescale of a few nanoseconds. The x-ray bursts are emitted from regions as small as 1 μ m.

After the emission of x-ray bursts from bright spots, rapidly propagating shock waves are seen in x-ray backlighter images [Pikuz *et al.* 2002] and a gap forms in the minidiode region in which the density of the plasma is no longer detectable through radiography or optical interferometry (> $10^{18} - 10^{19}$ cm⁻³). Current continues to be conducted during this phase, and electron beam generated radiation is observed, implying that electrons are accelerated across the gap and then radiate as they collide with more dense regions. Evidence for this is the emission of K-alpha line radiation, i.e., inner shell transition radiation from weakly ionized, relatively cold plasma. Figure 2.1b shows the gap formation and the region of energetic electron formation.

2.B Short-lived and long-lived e-beam formation

More recent experiments have revealed that there are two different sources of radiation greater than 8 keV in the X-pinch: radiation from the micropinch and harder radiation from the electron beam source [Shelkovenko *et al.* 2005]. The harder radiation reaches photon energies up to 100 keV and comes from a larger source (~100 μ m) that is slightly displaced from the region where the soft x-rays are emitted and lasts for several nanoseconds. This harder radiation comes from the interaction of the energetic electrons with the ~100 μ m plasma that acts as the anode side of the minidiode. These harder x-ray sources proved to be useful in radiographic imaging of thicker biological samples that could not be penetrated using the soft, 1 - 10 keV x-ray

radiation. Images of a several millimeter thick chicken wing, including bone, and a live tropical fish that was about 1 cm thick, have been taken with at least a 30 μ m resolution [Song *et al.* 2004].

The electron beam source, which produces the harder radiation, is emitted from the immediate vicinity of a gap that is observed in the imploded plasma column, immediately after the thermal x-ray burst is emitted. Energetic electrons are accelerated across that gap, as evidenced by the generation of nonthermal x-ray radiation in the 10 - 100 keV energy range from a 0.1 - 1 mm source. The energy distribution of the 10 - 100 keV x-rays depends on the details of a particular test [Shelkovenko *et al.* 2001b]. Results of studies of the characteristics of the energetic electron-produced x-ray source show that it is slightly displaced from the thermal burst location. Also, studies show that its time duration ranges from 2 to 20 ns, which is a function of the energy range and it is considerably larger than the thermal x-ray source [Kantsyrev *et al.* 2004].

The intensity of the electron-beam-generated spectral lines depends on the Xpinch wire material, mass, current through the X pinch, and the details of the experimental configuration. An important feature in the radiation from Ti X pinches, for example, is the set of satellite spectral lines near the resonance line of He-like ions that indicates the presence of Ti atoms that are ionized only into the L shell.

The pinhole images in Fig. 2.2a show that both Al and NiCr X pinches emit radiation with energy > 20 keV (4.5 mm Al filter) from a 1 mm source. Four-wire Mo and W X pinches yield pinhole images through a 1.6 mm Cu filter (Fig. 2.2b) indicating that high Z wire X pinches can emit > 60 keV x rays. All of these pinhole images show that all four-wire X pinches studied emit radiation with energy greater than 20 keV, from a source that is 1 mm or less.



Figure 2.2: Pinhole images from (a) an Al 4-wire 50 μ m X pinch and a NiCr 4-wire 25 μ m Xpinch show that both Al and NiCr emit radiation with E > 20 keV. 4-wire X pinches using higher Z materials like W and Mo (b) show radiation above 60 keV as seen though a 1.6 mm Cu filter. These high energy radiation regions appear to be about 1 mm or less.



Figure: 2.3: Images captured with a Slit-Step-Wedge (SSW) camera show two distinct radiation source regions: a bright micron scale 7 - 12 keV source from the micropinch and a lager 0.1 - 0.5 mm source of > 8 keV radiation from energetic electrons. For this shot the sources were separated by about 0.5 mm.
The harder x-ray source size and structure were studied with the SSW camera and images of various objects. As illustrated in Fig. 2.3, experiments show two distinct source regions for x-rays: a micron scale 7 - 12 keV x-ray source and a higher energy source with 0.1 - 0.5 mm scale size. Figure 2.4 shows the x-ray image of a Ni mesh (40 μ m wire diameter with 800 μ m between the wires) that was imaged with three times magnification in which the presence of two x-ray sources separated by 150 μ m in the cathode-anode direction is clearly seen. One source is 5 μ m or less in size while the other is 100 μ m. Results of experiments that show the presence of several small micropinches and one or several larger sources resulting from electron beams are presented and discussed in Chapter 5.

2.C Source size measurements of the X pinch

Previous experiments using a time-integrated filtered pinhole camera reveal source sizes for greater than 2.5 keV radiation from Al X pinches to be less than 10 μ m in diameter [Kalantar 1993]. More recently, experiments looking at the diffraction pattern of an image and comparing it to calculations using different source sizes to find a best fit, led to estimations of source size as small as 1 μ m for Mo and Nb X-pinches [Song *et al.* 2005].

The small source size $(1 - 10 \,\mu\text{m})$ of the X-pinch has made it ideal for use as a source for point-projection radiography. One of the earliest applications of this process was used to radiograph another X-pinch [Kalantar 1993]. X-pinches have also been used to study single wire explosions [Shelkovenko *et al.* 2001a]. By varying the wire material, wire size, and filters in front of the film, the wavelengths for imaging can be optimized for the type of imaging required.



Figure 2.4: An image of a Ni wire mesh at 3 times magnification shows the spatial relationship of the 2 radiation sources. The small (~ 1 μ m) micropinch source gives a sharp image of the Ni mesh (~ 5 μ m resolution). The larger (~100 μ m) source from energetic electron radiation gives a blurred, displaced image of the Ni mesh. The two sources were displaced by about 150 μ m. The image was obtained with a W 4-wire 20 μ m X pinch.

2.D Temporal duration of radiation

The temporal parameters of the X-pinch x-ray source have been determined with experiments involving the use of a direct x-ray streak camera. These experiments involved testing the duration of x-ray bursts from Al, Ti, NiCr, Mo, and W X-pinches. Tests showed the time variation of the > 1 keV radiation emission from Mo X-pinches on a time scale as short as 10 ps [Sinars *et al.* 2001].

Further experiments have been conducted to give insight into the properties of the X-pinch plasma during the x-ray bursts using x-ray spectroscopy. Spectroscopic analysis of K-shell line emission has determined electron temperatures near 1 keV and ion densities from 10¹⁹ cm⁻³ up to perhaps 10²³ cm⁻³ for Al and Ti X pinch plasmas driven by about 400 kA peak current [Sinars *et al.* 2003]. There have been recent studies in which L-shell spectroscopic models have been applied to study time-integrated and time-resolved Mo spectra from 450 kA and 1 MA X-pinch plasmas [Hansen *et al.* 2003]. More recently, L-shell and K-shell line emission have been studied for Manganin (CuMn) four-wire X-pinches from x-ray streak camera data on a time scale as short as 10 ps. Estimations have been made of the electron temperature of the plasma of ~200 eV from L-shell Cu spectra and ~2 keV from K-shell Cu spectra and K-shell Mn spectra [Chandler 2005]. An observation of the relative timing of the L-shell and K-shell line radiation, as well as the relative timing of the continuum radiation has been made, allowing tentative conclusions to be drawn on the formation of this radiation [Chandler 2005].

Even though previous results from X-pinch experimentation have brought us closer to understanding X-pinch physics, there are still questions left unanswered due to the fast timescale of x-ray production by the X-pinch. The emission of x-ray bursts from an X-pinch happens on a time scale of tens to hundreds of picoseconds, creating a challenging situation for diagnostic tools.

2.E Measuring the timing of the x-ray burst emission

The timing of the emission of the x-ray bursts in the 1 - 10 keV range depends on the wire material and diameter as well as the current. For a given current pulse, the plasma formed around the cross-point during the explosion of the X-pinch needs time to implode to the axis in order to form a dense, hot plasma. Given the same size wires and current pulse, the initial x-ray bursts occur within 2 ns of each other (for Mo Xpinches). The timing of these bursts is determined by the signals from photoconducting detectors (PCDs) relative to the start of the current pulse. PCDs generate electrical signals in response to incident x-ray radiation by acting like a resistor. With a fixed applied bias voltage, the incident x-ray flux generates a current through the device that produces a voltage drop. For small signals, the effect on the bias voltage is minimal, but if the measured voltage drop reaches half of the applied voltage, the output current is reduced by a factor of two. This saturation compresses the data and increases the dynamic range, allowing PCDs to be used over a wide range of incident powers from 10 - 10^4 W/cm². Figure 2.5 shows a typical current pulse through the load of the XP Pulser together with a PCD trace to show the relative timing of the x-ray burst emission.

2.F Applications of the X pinch

Conventional x-ray tubes that rely on electron-beams are the source of x-rays in traditional radiography. Although x-ray tubes can cover a wide range of energies, source sizes with collimation, intensities, and pulse duration for many applications, the efficiency of these tubes is less than 0.1% up to about 20 keV [Flugge *et al.* 1957]. Also, the minimum duration of x-ray bursts from pulsed tubes is about 0.1 µs which is two orders of magnitude more than the minimum duration of the electron-beamgenerated x-ray bursts in an X pinch. Furthermore, for x-rays below 20 keV in an



Figure 2.5: Current trace through a typical two-wire Mo X-pinch load. In this case, the first x-ray burst occurred at the peak of the current pulse, and the subsequent bursts are less intense.

x-ray tube, it is difficult to achieve both a small ($\leq 100 \ \mu m$) scale focal spot size and high intensity with sub-microsecond duration x-ray bursts. By contrast, the X-pinch produces intense bursts of 10–20 keV energy x-rays, with a few nanoseconds pulse duration, which are generated by electron beams that immediately follow the thermal burst(s). Moreover, the micropinch (thermal) x-ray sources are even smaller size and shorter duration, as has already been discussed.

2.F.1 Point-projection and coherence-based phase-contrast imaging

Given a point source, and an object at a distance away from the source, the object can be imaged by placing a detector behind the object. The small source size and low energy of the micropinch radiation enables its use for imaging weakly-absorbing objects with excellent spatial resolution by a method called coherence-enhanced imaging (often called phase-contrast imaging). The principle of the method is described as follows:

If the radiation source is highly coherent spatially and the detector is located at a suitable distance behind the object, the x-rays emerging from the sample at their various angles will propagate through free space until they reach the detector. One will observe a fringe pattern as a result of a combination of refraction, diffraction, absorption, and interference effects.

At very small distances, the image is formed by absorption contrast, in which there is only a shadow of the more absorbing components of the object. At greater distances, a boundary contrast enhancement appears as a result of interference at the boundary of refracted x-rays and with unaffected x-rays. This is a result of the spatial coherence of the x-rays and can lead to a change of intensity up to 100%. Therefore, the boundaries of different parts of the object become clearly visible even for a nearly

transparent object. This method has been demonstrated successfully using polychromatic radiation from a laboratory x-ray tube source.

The relaxed requirements on the spectral (temporal) coherence of the radiation are essential to implementing coherence-based phase contrast imaging using an X pinch as a source of radiation. A wavelength band selected by a metal foil filter creates a sufficient spectral coherence of the radiation, while the spatial coherence is rather good taking into account the size of the X-pinch source (a few microns or less). Furthermore, the divergence of the x-rays from an extremely small point source can enable a high optical magnification and increased image resolution, depending on the imaging geometry.

X-pinch point projection radiography is very useful in the energy range of 3 -15 keV since X pinches made with commonly available and relatively easily handled wire materials, produce intense and very small radiation sources over this energy range.

2.F.2 X pinches in frames

Although the harder x-ray source from the energetic electron beams proves useful for imaging relatively thick biological samples, the multiple bright spots from electron beams can create multiple displaced images. In order to advance the field of X-pinch radiography it is necessary to increase the rate at which X-pinch pulses can be produced beyond that which can be achieved by loading wires in the cathode-anode gap by hand and then pumping the system down to its operating pressure of 10⁻⁴ Torr. One possible solution includes the use of a chain of preloaded dielectric frames with one or several X pinches in series, as shown in Fig. 2.6 [Mitchell *et al.* 2006a]. This would enable the load to be changed in vacuum. The proposed X-pinch configurations were also predicted to reduce the effects of two problems encountered

with X-pinch point projection radiography. First, as already noted, many X-pinches develop multiple bright spots, creating multiple displaced images. Second, we commonly have intense background radiation connected with energetic electrons generated as part of the pinching and explosive disassembly phases [Shelkovenko *et al.* 2005]. These problems can render images from some tests unusable, thereby reducing the rate of collecting useful X-pinch images. Furthermore, there is also the possibility that reproducible loading of holders would produce more reproducible timing of X-pinch x-ray bursts, which is useful when imaging dynamic systems such as rapidly evolving plasmas. In addition, more reproducible timing would enable the best possible temporal resolution with time-dependent x-ray spectra obtained using an x-ray streak camera. We found it possible to eliminate all of the above problems with a fiberglass frame configuration that suppresses conduction of current on the surface of the frame early in the current pulse, while allowing conduction of the frame later in the current pulse in order to eliminate further pinching in the exploding wire plasma.



Figure 2.6: X-pinch configurations in frames are illustrated, including (a) a single X pinch, (b) four X pinches in series, and (c) two X pinches in series using a dielectric frame and plastic threads.

CHAPTER 3

EXPERIMENTAL DESIGN

3.A Load parameters

The X pinches studied in this thesis were driven with Cornell's XP pulsed power generator. The X pinches were loaded into the 15 mm anode-cathode (A-K) gap and pulsed with 200-500 kA with 40 ns rise time. Most X pinches were centrally located within 4 25 mm diameter return current posts placed at a 40 mm radius. Connections of the X pinch to the anode and cathode were made by stringing the wires though small holes in the anode and cathode and hanging small weights on the wires to keep them tensioned.

3.B XP pulsed power generator

All of the experiments shown were carried out on Cornell's XP pulsed power generator. The XP pulser is a low impedance generator that is capable of delivering up to 600 kA to the load with a 40-50 ns rise time and about a 100 ns FWHM. The XP generator uses a four stage current amplification process to create the desired pulse shape. The energy delivered to the load is initially stored in a Marx generator followed by an intermediate storage capacitor and pulse forming line for pulse shaping and finally a water-vacuum interface to deliver the current to the load.

The Marx generator consists of ten 1.8 μ F capacitors typically charged to 42 kV each for a total of about 16 kJ. In general, a Marx generator is designed to produce a high voltage pulse by charging a number of capacitors in parallel and discharging them in series. This is accomplished by first charging the capacitors with a network of resistors intended to give a relatively long charging time constant (typically seconds). Once the capacitors reach the desired voltage a series of spark gap switches

connecting the capacitors are triggered. Once closed, the spark gaps give the system a discharge time constant much shorter than the charging time constant. This allows the capacitors to discharge in series with a total voltage that is equal to the sum of the voltages on all of the capacitors. The output pulse of the Marx generator is further processed to achieve the fast rise time desired.

The next stage is the intermediate storage capacitor, which consists of four coaxial cylinders with a total capacitance of 80 nF. The intermediate storage capacitor is connected to the pulse forming line by an SF₆ filled self-breaking spark gap switch. The pulse forming line is three water filled coaxial cylinders with a total capacitance of 34 nF. This section is connected to the load region through 8 parallel water gaps. Characteristic voltage traces for the intermediate storage capacitor and pulse forming line are shown in Fig. 3.1a. The peak current delivered to the load is 450-600 kA (depending on the impedance of the load) with about 100 ns FWHM (Fig. 3.1b).

3.C Shearing air wedge interferometer

The laser images presented here were obtained using a frequency-doubled Nd:YAG laser produced by EKSPLA (model SL312). This laser system uses an SBS (stimulated Brillouin scattering) cell to compress the natural pulse width (~5 ns) of the solid state laser to 150 ps. This short pulse length is important for studying X pinch plasmas since much of the interesting physics happens on a sub-nanosecond time scale. The maximum energy output of the laser at $\lambda = 532$ nm is about 120 mJ. However, the laser was operated at about 80 mJ output for most experiments, with only about 4 mJ per each of the three beam lines getting to the load to form an image. It is important that the time-integrated intensity of the laser be greater than the total time-integrated radiated intensity from the X pinch in the $\lambda = 532 \pm 5$ nm band, because images were recorded by CCD cameras that were not time-gated.



Figure 3.1: Examples of (a) typical voltage traces from the intermediate storage capacitor (ISC) and pulse forming line (PFL) along with (b) a typical current trace (taken from shot 4730) showing half of the total current to be about 280 kA at peak, 100 ns FWHM, and 40 ns rise time. The red trace has the higher frequencies filtered out using a fast Fourier transform (FFT).

a.

b.

For most shots we were able to obtain laser images at three different times by splitting the main beam and using three independent beam paths (see Fig. 3.2). The output from the laser was expanded from 0.5 cm diameter to about 4 cm and then split into 3 beams using a glass wedge. The beam intensity of each of the reflected paths (from the front and back surface of the glass wedge) was about 5% of the original beam (~4 mJ). The transmitted beam passed through a neutral density filter to bring it down to approximately the same intensity as the other two. After splitting, the path length of each beam was set in order to control the relative timing of the beams with respect to each other. Each of the three beams passed through the experiment at a slightly different angle (about 1° between beams) so that they could be independently manipulated after the experiment. Finally, each beam was split again to form both shadow and interference images side-by-side on film using an air wedge shearing interferometer [Pikuz *et al.* 2001].

The shearing interferometer is a simple, inexpensive configuration for studying electron densities in the X pinch plasma. The shearing interferometer has been around for some time [Schirmann *et al.* 1970], but was first implemented using the reflection of two glass-air interfaces by Sarkisov in 1996. In our experiments, we are using a modified version of the air wedge interferometer using two right angle prisms proposed by Pikuz *et al.* in 2001. A shearing interferometer is designed to take an incoming beam and split it in such a way as to interfere with itself. The splitting of the incoming beam is accomplished by reflecting the beam off two partially reflective surfaces formed by two glass-air interfaces (see Fig. 3.3a). These interfaces (the hypotenuses of the right angle prisms) are tilted with respect to each other in order to steer the beams. The angle of the resulting "air wedge" is determined by the experimental geometry, but is set as to achieve the proper overlap of the reference and object parts of the original beam (see Fig. 3.3b).



Figure 3.2: Illustration of optical paths of the laser interferometer. The beam is split and the three independent optical paths are manipulated to control the relative timing of the beams (set to about 10 ns between beams). Each beam passes through the experiment at slightly different angles so that they can be independently manipulated. Each beam is split by the air wedge in such a way that it can interfere with itself.

In order to obtain high contrast interference fringes, it is important to have nearly equal intensities for the two beams forming the interference image. For the glass-air-glass interfaces found in the air wedge this can be achieved at two angular regions of reflection (see Fig. 3.4). The first angular region is near normal, which has low reflectivity (< 5%) for each beam. This low reflectivity would require imaging beam to have a very high intensity. The other angular region is near 40 degrees and has a higher reflectivity (about 20%), but is much more sensitive to deviation. The airwedge using right angle prisms is designed to use the later angular region for maximum reflectivity.



Figure 3.3: Illustration of the air-wedge interferometer. (a) Two reflecting surfaces are formed by the hypotenuse of two right angle prisms. A slight angle is formed between the two beams in order it steer the beams. (b) The incoming laser beam is focused near the air gap and the two reflecting surfaces give two virtual point sources that are overlapped in such a way to form an interference image. For this type of interferometer it is important to have part of the beam pass through an unperturbed region of space at the object.



Angle of Incidence (degrees)

Figure 3.4: Reflectivity of the two air-wedge surfaces. In order to achieve high contrast interference fringes the intensity of the two beams must be nearly equal. This is true for the air wedge near normal (0 degree) incidence. However, at about 40 degree angle of incidence the intensity of the two beams is not only matched, but is also near 20% reflectivity (almost a factor of 5 greater than normal incidence).

The interference images obtained give us information about the line integrated density of the electrons ($\int n_e dl$). This is found from the phase shift ($\Delta \Phi$) of the fringes from their unperturbed position. The relation is found by

$$\left|\int n_{e}dl\right| = \frac{4\pi c^{2}\varepsilon_{0}m_{e}}{\lambda e^{2}}\Delta\Phi$$
(3.1)

where ε_0 is the permittivity of free space, m_e is electron mass, λ is the wavelength of the laser light (532 nm), and *e* is the electron's charge [Hutchinson 2002]. The smallest detectible phase shift is about one-tenth of a fringe or $\Delta \Phi = 0.1 \times 2\pi$. The

means the lowest detectible line integrated election density is about $\int n_e dl = 4.2 \times 10^{16}$ cm⁻².

The upper bound on detectable electron density is found because the laser frequency (ω) must be above the ω_{pe} plasma frequency (ω_{pe}).

$$\omega^2 \ge \omega_{pe}^2 = \frac{n_e e^2}{\varepsilon_0 m_e}$$
(3.2)

This means the laser beam is completely reflected at

$$n_e \ge n_c = \frac{\omega^2 \mathcal{E}_0 m_e}{e^2} \approx 4 \times 10^{21} cm^{-3}$$
 (3.3)

where n_c is called the critical density. However, in reality we cannot probe densities this high. Refraction of the incident laser beam due to the shape and density distribution of the plasma cause the maximum detectable density to be much lower. It can be shown that for a cylindrically shaped plasma with a parabolic density distribution that the angular deviation (θ) of the beam is [Hutchinson 2002]

$$\theta \approx \frac{n_0}{n_c} \tag{3.4}$$

where n_0 is the electron density on axis for the parabolic distribution. Using n_0 as an upper bound on the detectable densities and an acceptance angle of about 2 degrees (from the optical geometry), we find that we are able to measure electron densities

$$n_e \le 0.03 n_c \approx 1.2 \times 10^{20} \, cm^{-3} \tag{3.5}$$

This quantity will be used as an upper bound for the density edge seen in the shadow images.

The resolution of the imaging system is limited in part by the resolution of the digital camera used to capture the images. Each pixel equates to about $10 \,\mu\text{m}$ at the

object. However, the diffraction limited resolution of the system is estimated to be at least 10 μ m, so we use 10 μ m as the lower limit on resolution.

3.D X-ray streak camera

The x-ray streak camera is a device that allows temporally resolved information on x-ray emission. The streak camera produces an image that has time along one axis and spatial information (that can be truly a spatial image or a spectral image) along the other axis. The entrance slit defines the spatial direction. For our experiment the streak camera was coupled to a spectrograph to produce time dependent spectra of X-pinch radiation.

The first stage of the x-ray streak camera converts x-rays into electrons when incident radiation strikes the photocathode, which converts the x-rays into electrons via the photoelectric effect. The electrons are then accelerated by an anode mesh toward the end plane of the streak camera (see Fig. 3.5). On the way, they are deflected by voltage on a pair of plates which can be set to apply a nearly linearly-varying time-dependent voltage. This voltage changes the position of the arrival location of the photoelectrons on a phosphor screen. The phosphor screen exposes film or similar detector (after passing through an image intensifier to increase the intensity). The result of these processes is a focused image that is streaked across the film nearly linearly with time. Therefore, the position of the image on the film varies with time, as illustrated in Fig. 3.5.

By coupling the streak camera to a spherically bent mica crystal spectrograph, we are able to obtain time-dependent spectra by dispersing the spectrum in the long direction of the entrance slit. The spectrograph records wavelength perpendicular to the time-axis of the streak camera. Each bright region in "streaked" spectra on the

film represents a separate x-ray burst that occurs at a different time within the X pinch, as seen in the example in Fig. 3.6.

A spherically bent crystal spectrograph acts like a spherical mirror for x-rays. However, the x-ray reflection occurs off of multiple crystal planes. The reflected xrays from these crystal planes constructively interfere if the Bragg condition is satisfied,

$$2d\sin\theta = m\lambda \tag{3.6}$$

where *d* is the distance between crystal planes, θ is the angle between the incoming incident x-rays and the crystal planes, *m* is an integer, and λ is the wavelength of the incident radiation.



Figure 3.5: Illustration of the x-ray streak camera. Incoming x-rays are converted to electrons at the photocathode and are accelerated by the anode mesh. The path of the electrons that are then bent by the linearly varying voltage applied to the sweep plates. A bias voltage is used to control the start position of the streak. The electrons are incident on a phosphor screen that converts the electrons to optical light to expose film.



Figure 3.6: Example of a time dependent spectrum of a Mo 4-wire $22 \mu m X$ pinch taken with an x-ray streak camera coupled to a spherically bent mica spectrograph.

CHAPTER 4

THEORIES RELEVANT TO MICROPINCH FORMATION

The formation of micropinches or bright spots in a single wire z-pinch and X pinch is due to a struggle of pressure balance between the thermal pressure from the expanding plasma column, and the $\mathbf{j} \times \mathbf{B}$ force of the magnetic field induced by the applied current. Consider a uniform column of plasma of radius *r* as shown in Fig. 4.1. The pressure outside of the column is due to the induced magnetic field:

$$p_{magnetic} = \frac{B^2}{2\mu_0} = \frac{\mu_0 I_0^2}{8\pi^2 r^2}$$
(4.1)

where B is the magnetic field, μ_0 is the permeability of free space, and I_0 is the current through the wire. The magnetic pressure is being acted against by the pressure inside the column due to the thermal or kinetic pressure that occurs as the plasma continues to be heated by the applied current:

$$p_{kinetic} = n_e k_B T_e + n_i k_B T_i \tag{4.2}$$

where n_e is the electron density in the plasma, n_i is the ion density, k_B is the Boltzmann constant, and T_e and T_i are the electron and ion temperatures respectively.

The column of plasma is also susceptible to the m = 0 (azimuthally symmetric) sausage instability [Book *et al.* 1976], resulting in non-uniformities along the wire. In addition to the thermal and magnetic field pressures, there is also radiation escaping from the plasma, or radiative loss, which, in turn, cools the plasma column, thus



Figure 4.1: A drawing of the plasma column with applied current along in the zdirection (vertical axis). The current induces an azimuthal magnetic field that creates a force perpendicular to the direction of current flow. The thermal or kinetic pressure of the expanding plasma column acts against this force, creating a struggle for pressure balance.

lowering the thermal pressure. The result of the combination of the sausage instability and radiative loss is the collapse of the plasma column due to the magnetic field pressure exceeding that of the thermal pressure in specific (but unpredictable) points along the plasma column. These processes are further discussed below.

4.A The Bennett pinch relation

The Bennett Pinch relation describes the approximate current needed for the uniform plasma column to be in equilibrium. The derivation begins with the equilibrium condition of a neutral column of plasma, i.e., $n_e = Zn_i$. From equations 4.1 and 4.2 we get

$$\int_{0}^{r_{0}} 2\pi r p_{magnetic} dr = \frac{\mu_{0} I_{0}^{2}}{8\pi}$$

$$\int_{volume} p_{kinetic} dv = N k_{B} T_{e,i}$$
(4.3)

where *N* is the total number of charge carriers and $T_{e,i}$ are the electron and ion temperatures respectively, assuming that they are equal. This results in the Bennett equilibrium current for a stable plasma column:

$$I_0 = \left[\frac{8\pi Nk_B T}{\mu_0}\right]^{\frac{1}{2}}$$
(4.4)

So, in order to compress the uniform plasma column, the Bennett current, I_0 , must be exceeded.

For *n*-wire X pinches, if the total current is *I*, then the current through each wire is *I/n*. Furthermore, if I_0 is Bennett current at the cross point, then from equation 4.4 the Bennett current in each individual wire is $I_{0-wire} = I_0 / n^{1/2}$ (assuming uniform plasma density). At the time that the Bennett current, I_0 , is reached at the cross point the current in each of the wires will be I_0 / n . Since $I_0 / n^{1/2} > I_0 / n$ for n > 1, the Bennett current will always be exceeded at the cross point before the rest of the X pinch. This is how the X-pinch results in a localized region of soft x-ray emission near the cross point.

4.B Sausage instability

As discussed in Chapter 2, instabilities in the plasma column or mini z-pinch of the X pinch are at least partially responsible for the formation of micropinches and the emission of x-ray bursts. Specifically, it is the m = 0 or sausage instability that we have observed in radiographs of both single wire z-pinch and X-pinch experiments. An example of this is shown in Fig. 4.2. The basic idea behind the sausage instability is that a current-carrying cylindrical plasma in equilibrium should exhibit an instability. This is caused by the onset of any perturbation on the plasma column that disrupts the pressure balance on the plasma column. Consider a uniform column of plasma with radius r_0 , and current, I_0 , flowing in the axial direction. The balance of magnetic field pressure to the kinetic pressure of the column at the boundary radius is

$$p_{magnetic} = \frac{B^2}{2\mu_0} = \frac{\mu_0 I_0^2}{8\pi^2 r_0^2} = p_{kinetic} = n_e k_B T_e + n_i k_B T_i, \qquad (4.5)$$

and in cylindrical coordinates:



Figure 4.2: The m = 0 (sausage) instability causes the smaller diameter regions of a plasma column to be compressed faster that the surrounding regions. This process helps the X pinch achieve the small, dense plasma neck that forms near the cross point of the wires.

$$\nabla p_{magnetic} = \frac{1}{r} \frac{\partial}{\partial r} (r p_{magnetic}) = -\frac{\mu_0 I_0^2}{8\pi^2 r^3}$$
(4.6)

$$\nabla p_{kinetic} = -(m_e n_e + m_i n_i) \frac{dv}{dt}$$

Assuming that $m_e n_e \ll m_i n_i$ we get

$$\nabla p_{magnetic} = \nabla p_{kinetic} = -\frac{\mu_0 I_0^2}{8\pi^2 r^3} = -m_i n_i \frac{dv}{dt} \,. \tag{4.7}$$

If the assumption that any variation or perturbation along the wire is of the form $e^{i(kz-\omega t)}$ (azimuthally symmetric) and has a wavelength $\lambda = 2\pi/k$ such that $r(z, t) = re^{i(kz-\omega t)}$, the term on the right can be expressed as:

$$m_i n_i \frac{dv}{dt} = \rho \frac{d^2 r}{dt^2} = -\rho \omega^2 r$$
(4.8)

and so from equation 4.7, it follows that:

$$-\frac{\mu_0 I_0^2}{8\pi^2 r^3} = -\rho \omega^2 r$$
(4.9)

where ρ is the mass density of the expanded column of plasma. Expressing this in terms of the solid density (ρ_0) of the wire (if the wire were to expand uniformly), times

the square of the ratio of the plasma and wire radii (r and r_0 respectively) times the fraction of material that participates (A):

$$\rho = \rho_0 \frac{r_0^2}{r^2} A \,. \tag{4.10}$$

Rewriting equation 4.9 we have

$$r = \left(\frac{\mu_0}{8\pi^2 A\rho_0}\right)^{\frac{1}{2}} \frac{I_0}{\omega r_0}.$$
(4.11)

Given that everything on the right side of the equation is not a function of z except ω , we see that where r is minimum (due to the e^{ikz} perturbation) the rate of change of the plasma column (ω) is maximum. This causes the small diameter regions of the plasma to decrease in diameter faster that the surrounding regions. This self sustaining process is key to creating the dense neck in the X pinch. This approximation breaks down of course when the density becomes high enough that the plasma is opaque to the escaping radiation cooling the plasma.

4.C Radiative Collapse

Along with the pressure balance in the plasma column, there is an additional balance that occurs between the radiation power loss and the rate of ohmic heating. The ohmic heating rate per unit length of the plasma column is

$$P_{\Omega} = 2\pi \int_{0}^{r_{0}} r(j^{2}/\sigma) dr, \qquad (4.14)$$

where j is the current density in the plasma and σ is the conductivity of the plasma. For simplicity if we assume constant current density and Spitzer conductivity,

$$j(r) = j_0 = \frac{I}{\pi r_0^2}$$
(4.15)

$$\sigma = \frac{\sigma_0 T^{3/2}}{Z_{eff} \ln \Lambda}$$

where σ_0 is a collection of constant terms equal to 1.03×10^{-4} in mks units. Z_{eff} is the effective ion charge and ln Λ is the Coulomb logarithm, which is a very slowly varying function of the plasma parameters and for most laboratory plasmas assumes values between 7 and 20 [Roth 1986]. If we also assume that most of the radiation losses from the plasma are due to bremsstrahlung (Q_b), the radiated power per unit length is given by

$$P_{b} = 2\pi \int_{0}^{r_{0}} Q_{b} r dr , \qquad (4.16)$$

where

$$Q_b = SZ_{eff} n_e^2 T^{1/2} \,.$$

Again *S* is a collection of constant terms equal to 1.69×10^{-4} in mks units. If the plasma is optically thin to the bremsstrahlung radiation, then the power balance is

given by $P_{\Omega} = P_b$. Using equation 4.4 to get rid of the temperature and density dependence this balance yields the Pease-Braginskii current (I_{PB}) for a fully ionized plasma

$$I_{PB} = 0.433 (\ln \Lambda)^{1/2} \approx 1.4 \, MA. \tag{4.17}$$

For a more rigorous derivation see Robson 1989. Above the Pease-Braginskii current the radiation losses exceed the ohmic heating and the outward thermal pressure is overwhelmed by the magnetic field. This is not the exact condition in X-pinch plasmas, but it shows that we are in a current regime that has a substantial amount of radiation loss. This helps contribute to the pinching of the plasma neck of the X pinch. Further investigation reveals that this current is considerably modified in the presence of highly-charged ions, so the above result would be for a hydrogen plasma. The modified Pease-Braginskii current for high *Z* plasmas would be far less, but takes on a complicated form [Negus *et al.* 1978].

CHAPTER 5

RADIATION STRUCTURE OF THE X PINCH

The X pinch has several radiation characteristics that make it a useful diagnostic tool and interesting high energy density plasma. We have reported that the X pinch emits an intense burst of x-rays from a micropinch that last less than a nanosecond, often followed by energetic electron radiation. The experiments outlined in this chapter were designed to test the core hypotheses that:

- Micropinch radiation lasts for less than 1 ns and starts from a rapid temperature rise of the plasma.
- 2. Energetic electron radiation starts after the micropinch (once lower density gaps begin to form) and progresses from the center to the anode.

Experiments in the past suggest that micropinch radiation is sub-nanosecond, but the duration of micropinch radiation was beyond the resolution of the diagnostics used [Sinars *et al.* 2003]. We now, with the use of a high speed x-ray streak camera, will show the temporal structure of micropinch radiation. In addition, we usually assert that energetic electron radiation is starts as gaps begin to form in the plasma neck after the micropinch. Although energetic electron radiation has been studied using collimated diagnostics to look at the temporal radiation structure of specific region of the X pinch [Kantsyrev *et al.* 2004], this hypothesis has not been tested until now with a diagnostic that possesses both temporal and spatial resolution and has the ability to compare different spatial regions from a single shot.

We present results from experiments designed to study the time-dependent radiation structure of the X pinch using higher temporal resolution than obtained in the past using an x-ray streak camera and an array of filtered silicon diodes. Better temporal resolution should give us a better understanding of what is happening in the

X pinch. We start with time-integrated measurements to obtain information about spatial structure.

5.A Spatially resolved, time integrated measurement of X pinch radiation

Pinhole cameras and slit step-wedge (SSW) cameras (Fig. 5.1) give us spatially resolved, time integrated information about the radiation from the X pinch. They show intense radiation from the small micropinch source in addition to the large source from energetic electron radiation (Fig. 5.2). Figure 5.2 is provided simply to give a visual reference of the relative size and location of the different x-ray sources in the X pinch. The pinhole images directly show a small central spot from the micropinch. They also show the large energetic electron source extending toward the anode. The SSW camera gives us spatial resolution in one dimension, by the use of a slit, taking advantage of the fact that the central part of the X pinch has very little radial extent. The slit is oriented perpendicular to the z-axis to give us spatial resolution along the z-direction. The various filter thickness in the SSW give us an idea the photon energies radiated from different locations along the z-axis. As with a pinhole camera, the SSW camera shows a narrow intense spot from the micropinch in the center with more diffuse radiation from energetic electrons.

5.B Time resolved measurements using an x-ray streak camera

As described in chapter 3 an x-ray streak camera is a device that allows us to obtain temporal information about radiation from the X pinch. For these experiments the streak camera was coupled to a spherically bent mica crystal spectrograph. By coupling a spectrograph to the streak camera we are able to obtain spectral information as a function of time. Studies of X pinch radiation using x-ray streak cameras have



Slit-Step-Wedge Camera

Figure 5.1: Illustration of the slit step-wedge (SSW) camera. This camera gives spatial resolution along the z-axis. The various filter thickness gives information about the photon energy from locations along the z-axis.



Figure 5.2: Typical images produce by the pinhole and SSW cameras. These images illustrate the relative size and location of different radiation sources in the X pinch. Both the pinhole and SSW images show and intense small spot of radiation in the center from the micropinch and a larger radiation source from energetic electrons extending toward the anode.

been reported by several authors [Chandler 2005, Pikuz *et al.* 2002, and Sinars *et al.* 2003]. However, very little information exists using the faster sweep speeds (< 1 ns window) of the streak camera to give the best possible temporal resolution. Streaked images of X pinch radiation at fast streak speed have proven difficult to collect because of the complication of accurately timing the streak window to the x-ray burst of an X pinch. The X pinch inherently has a few nanosecond jitter in the timing of the initial x-ray burst. In addition, most pulsed power devices have several nanoseconds of jitter for switching out the final pulse forming sections (~ 5 ns jitter for the XP pulser). The combination of these jitters in addition to the trigger jitter of the streak camera due to noise makes capturing a sub-nanosecond radiation burst in a < 1 ns window very difficult. However, the use of a low trigger delay x-ray streak camera recently developed by Kentech has enabled us to capture X-pinch radiation at high speed by allowing us to trigger from UV radiation produced by the X pinch early in the radiation pulse. Triggering from the UV radiation by use of an x-ray diode (XRD) eliminates the jitter of the pulsed power device.

We present in Fig. 5.3 a streaked image of the radiation produced by a Mo 4wire 22 μ m X pinch obtained with a 40 ns time window, in order to show the long time scale radiation characteristics of the Mo X pinch. The image shows the intense continuum radiation from the micropinch followed immediately by (or possibly simultaneous with) Ne-like Mo line radiation from the expanding neck. Spectral analysis of time dependent x-ray emission of an X pinch by Hansen *et al.* in 2004, suggests that the line radiation comes from an expanding region that is larger than the source of continuum radiation. The expanded images in Fig. 5.4 show that at this streak speed the continuum radiation from the micropinches appears to be on the order of 1 ns. The line radiation, however, seems to last much longer (about 10 ns). The subsequent bursts of continuum emission in Fig. 5.4 are from additional



Figure 5.3: Time dependent image of Mo 4-wire $22 \ \mu m \ X$ pinch taken with an x-ray streak camera coupled to a spherically bent mica spectrograph. The 1 mm/ns sweep rate (40 ns streak window) shows the long time scale radiation structure.



Figure 5.4: Expansion of the image in Fig 5.3 shows the (a) ~ 1 ns continuum radiation from the micropinch and (b) the longer time scale line radiation. There are multiple short (~ 1 ns) x-ray bursts from multiple micropinches, but the line radiation does not appear turn on and off so quickly.
micropinches that form in neighboring regions of space or result from energetic electron radiation.

Now if we turn our attention to Fig. 5.5 we see similar radiation characteristics but captured in a 1 ns time window. In Fig. 5.5 we see that the continuum radiation lasts just a few tens of picoseconds. The limiting factor in the resolution is the width of the focus of the x-rays on the photocathode by the spherically bent crystal (about $300 \pm 100 \,\mu$ m), which translates to about 8 ps at speed 6 (1 ns window in Fig. 5.5-6) and about 300 ps at speed 3 (40 ns window in Fig. 5.3-4). The first radiation burst seen in Fig. 5.5a was not captured in the linear part of the sweep (see chapter 3 for more details). However, the second burst, shown expanded in Fig. 5.5b indicates that the continuum radiation lasted for about 30 ps. We also see some line radiation, which lasts only a few picoseconds longer than the continuum. Figure 5.6 shows the longer time scale line radiation that occurs after the continuum (on a different pulse), demonstrating that the line radiation is turning on and off (about 500 ps duration in the Fig. 5.6). This pulsing of the line radiation is likely due to weak pinching of the plasma that does not produce bright continuum.

We see from these results that the duration of the micropinch radiation is still comparable to the resolution of the streak camera especially for the x-ray burst shown in Fig. 5.5b that only lasted for 30 ps. This short time scale along with the bright continuum makes analysis of the temperature over the extent of the x-ray burst difficult. However, we can use the 500 ps x-ray burst from Fig. 5.6 to look at the temperature profile for the burst. Even though this is not one of the initial intense x-ray bursts, it can still reveal information about the radiation mechanism of a micropinch. Figure 5.7 shows temperature at four different times in the x-ray burst found using the Gabreal model developed by Chandler in 2005. We see that the temperature does appear to increase in the early part of the x-ray burst. This supports



Figure 5.5: Time dependent image from a Mo 4-wire $22 \mu m X$ pinch (a) obtained with a 40 mm/ns sweep rate (1 ns streak window) shows that in fact the continuum radiation from the micropinch lasts much less than 1 ns. The expanded image (b) shows the radiation lasts for about 30 ps.



Figure 5.6: Time dependent image of Mo 4-wire $22 \ \mu m X$ pinch obtained with a 40 mm/ns sweep rate (1 ns streak window) shows that the line radiation is turning on and off (probably from weak pinching that does not produce bright continuum). However, the duration is longer than the more intense x-ray burst seen in Fig. 5.5 (about 500 ps in the image above).



Figure 5.7: Temperature was found using the Gabreal model at four different times during the x-ray burst shown in Fig. 5.6. We see that the temperature increases in the early stages of the x-ray burst suggesting that the x-ray burst is initiated by an increase in the plasma temperature.

the hypothesis that micropinch radiation starts from the increase of plasma temperature as the opacity increases. The increased opacity is of course from the increased density from the pinch process. Despite the fact that the x-ray burst in Fig. 5.7 is from a weak pinch after the main x-ray burst, it is likely that the radiation from the initial micropinch works in a similar manner. The initial x-ray burst would of course be more intense since the total ion number is greater, since nearly all of the particles in the neck would be participating in the initial burst but not necessarily subsequent ones.

Now let us look at the relationship of the continuum and line radiation in more detail. For this we choose the Mo 4-wire 22 µm X pinch from pulse 4520 seen in Fig. 5.8a because it was the fastest swept image we obtained that shows all of the continuum and line radiation. The temporal resolution for this shot, which used an 8 ns streak window, was about 60 ps. The graphs in Fig. 5.8a show the intensity profile at discrete times. We see that during the first ~200 ps there appear to be 2 bursts and the continuum radiation is falling off only slightly (reflected by the average intensity in the graphs). At the same time the line radiation (identified by the letters A-G) is increasing in intensity slightly. Over the course of the next 500 ps the continuum radiation drops off dramatically while the line radiation continues to increase. The intensity of each one of these lines along with the continuum is plotted as a function of time in Fig. 5.8b. The plots show that the rising edge of the initial burst is dominated by continuum radiation. By the time the continuum reaches the first peak line radiation begins to emerge. The ratio of the line radiation to the continuum continues to grow as time progresses. In Fig. 5.9 the intensity profile is plotted again in 3-D as a function of time and wavelength to help visualize the radiation structure.



Figure 5.8: Radiation from a Mo 4-wire $22 \ \mu m \ X$ pinch in an 8 ns streak window (a) shows the relationship of continuum and Mo Ne-like line radiation. (b) The relative intensity of each line is plotted as a function of time compared to the continuum. The graphs show that continuum radiation dominates at early times but give way to the line radiation at later times.



Figure 5.9: Plot of intensity as a function of time and wavelength from the streaked image shown in Fig. 5.8 to help visualize the radiation sturcture. The designations A-G in the figure denote Ne-like Mo resonance lines.

The radiation structures seen in figures 5.3-9 give us information about the dynamics of the micropinch. It is likely that the initial continuum radiation is a combination of both thermal and energetic electron bremsstralung radiation. As the plasma neck is being compressed the plasma is being radiatively cooled because it is optically thin in MHD computer simulations [Chittenden et al. 2007]. However, as the density in the neck continues to rise as the plasma becomes optically thick to the lower energy portion of the radiation, and the temperature begins to rise dramatically. In a short period of time the plasma column becomes hot and dense enough to rapidly ionize to the Ne-like state (32 times ionized for Mo). This triggers bremsstrahlung, line radiation and free-bound continuum, as well as black body continuum where the plasma column is optically thick. The dramatic increase in temperature also causes the neck to expand explosively as the kinetic pressure overwhelms the magnetic pressure. As the neck expands the continuum radiation begins to fall off since its intensity is highly dependent on both temperature and density. The intensity of the continuum radiation at this point is most likely dominated by bremsstralung radiation from the bulk plasma. The fact that the line radiation continues to increase as the continuum decreases suggests the plasma maintains (or possibly increases) its high temperature as the column is expanding as a result of ohmic heating and dissipation of stored magnetic energy.

The micropinch radiation is commonly followed by energetic electron radiation as low density gaps form in the exploding plasma neck. This energetic electron radiation is also primarily from bremsstralung radiation as the electrons accelerated by the electric field through the low density neck collide with the more dense regions. The energetic electron radiation usually contains higher energy photons than the micropinch radiation since the electrons gain more kinetic energy as they are accelerated though the low density regions [Shelkovenko *et al.* 2005].

5.C Spatially and temporally resolved study of energetic electron radiation

In order to study energetic electron radiation in more detail we devised an experiment using an array of filtered silicon diodes (SiD). Each SiD was filtered using 60 µm of Al and 50 µm of mylar (see transmission curves in Fig. 5.10) and collimated to look at a 0.4 mm section of a Mo 4-wire 22 µm X pinch along the z-axis (Fig. 5.11). Diamond photoconducting detectors (PCD) were also used to see the softer radiation emitted by the micropinch. We see from the plots of relative intensity in Fig. 5.11a that one or two bursts of soft (1 keV < E < 5 keV) radiation were emitted by micropinches. This soft radiation is followed almost immediately by "short lived" energetic electron radiation in the central section of the pinch. This short lived radiation is a result of small gaps that open immediately after the micropinch radiates [Shelkovenko et al. 2005]. These smaller gaps quickly (within 5 ns) give way to larger gaps killing this radiation. Once larger gaps develop, higher energy "long lived" energetic electron radiation emerges first in the central region and then propagates toward the anode. Figure 5.11b is provided to give an easier comparison of the relative timing of each signal. We found that this long lived radiation was most intense in the region neighboring the center.

We see for the first time that energetic electron radiation starts after the softer micropinch radiation but only in the central region. This supports the hypothesis that the "short lived" energetic electron radiation is from small gaps that form in the neck region as it explodes after the micropinch. We also see that the "long lived" energetic electron radiation starts in the central region and propagates toward the anode supporting the hypothesis that this radiation starts once larger gaps form and continue to expand.

The small peak at the end (at 120 ns) is a result of energetic electrons that passed through a hole in the anode and collided with the back of the experiment

chamber. The collimation did not block this post anode region. We do not know when the electrons were generated so we cannot find their average energy. However, the signal does provide a useful check for the comparison of the relative sensitivity and timing of the different diodes.



Figure 5.10: Plot of the transmission ratios for the filters used with the SiDs.



Figure 5.11: (a) Views of the SiDs used to study the energetic electron radiation from a Mo 4-wire 22 μ m X pinch along with plots of the relative intensity of radiation from each region. (b) The intensity of each detector is plotted on the same graph for easier comparison of the relative timing.

CHAPTER 6

RESULTS AND DISCUSSION FROM LASER AND X-RAY IMAGING

The X pinch has been studied as an x-ray source for some time now, but we still cannot consistently predict its radiation characteristics. If we wish to accurately predict X-pinch behavior we must better understand the physics governing x-ray production. This is no simple task and no one diagnostic can give us all of the information we need to accomplish this task. Here, we present results from experiments designed to take us a few steps closer to understanding the X pinch.

The experiments in this chapter were designed to test the following hypotheses:

- Coronal plasma expansion rates and neck compression rates are linked to the time of x-ray emission and are dominated by the energy deposited in the plasma per unit mass.
- The micropinch radiation quickly "shuts off" from the rapid decrease in density as the neck explodes after the micropinch.

In addition, we will attempt to answer the following questions:

- 1. Is there plasma surrounding the neck at the time of maximum compression?
- 2. Do the plasma jets affect the radiation mechanisms of the X pinch?
- 3. Do the axial modulations seen in the coronal plasma of the X pinch match those seen in wire-array z-pinch experiments?
- 4. What is the relative position of the dense wire core in the surrounding coronal plasma?

In addition to answering these main questions the following experiments were also designed to give us a more complete picture of how the plasma evolves during the life of the X pinch.

6.A Morphology of the X pinch

One crucial piece to understanding the X pinch is to know how the plasma forms and evolves in time. To this end, we have assembled a full battery of images from current start to beyond x-ray production using a 150 ps pulse width laser. The short pulse width of the laser is important since some of the interesting physics of the X pinch happens on a sub-nanosecond time scale. In addition, this diagnostic gives us unique information compared to the X-pinch radiographic images. The X-pinch radiographs show impressive detail [Pikuz *et al.* 2005], but the time relative to the start of the current that we are able to produce an x-ray burst limits the time scale over which we can take pictures. Also, by taking multiple pictures with the laser in each shot we are able to see the dynamics of the X pinch without depending upon shot-toshot reproducibility. Since there is inherently some jitter in timing of some of the events in the X pinch, finding certain quantities like expansion rates of the coronal plasma is much less uncertain if calculated from a single shot.

We see by inspecting the laser backlit shadow images (Fig. 6.1) the morphology of the X pinch coronal plasma as it progresses through the major stages of the pinch sequence. Figure 6.1 shows a series of laser shadow images taken of a 4wire 25 μ m Al X pinch as it progresses in time. These images illustrate the three major stages of coronal plasma development: coronal plasma expansion, m = 0 compression of the cross region, and the explosion phase after the initial x-ray burst.

If we compare the images of an Al X pinch in Fig. 6.1 to the images taken of a 4-wire 20 μ m W X pinch (Fig. 6.2) we can immediately see some of the differences in plasma evolution. We see that the plasma from the Al X pinch expands at a greater rate. We can also see the neck region in the W X pinch takes much longer to evolve, leading to later x-ray emission. In addition, we see that even though the plasma jets forming on axis are propagating away from the center at approximately the same rate



Figure 6.1: Laser shadow images showing the evolution of a 4-wire 25 μ m Al X pinch as it progresses in time.



Figure 6.2: Laser shadow images showing the evolution of a 4-wire 20 μm W X pinch as it progresses in time.

for both materials, the jet is far more developed at the time the W X pinch radiates its thermal x-ray burst.

6.B Expansion of the coronal plasma

We found expansion rates for the coronal plasma surrounding the legs of the X pinch using both shadow and interference images obtained with the air wedge interferometer. The shadow and interference images show different expansion rates because we see different electron density thresholds. As discusses in chapter 3, the laser light is completely reflected by the plasma for electron volume densities above 4×10^{21} cm⁻³. However, with the interference images we can detect lower densities. Given a detection threshold of $\Delta \Phi = 0.1 \times 2\pi$ phase shift, we are able to see line integrated electron densities greater than 4.2×10^{16} cm⁻². This line density is what we will be defining as the plasma edge from the interferograms. Defining a density boundary for the shadow images is a bit more difficult. Refraction due to the density gradients in the plasma plays a role in forming the shadow images in addition to absorption. Therefore, the shadow images are presented for two main reasons. First, they give us an easy way to visualize the shape of the plasma. Second, it gives us an upper bound of the expansion rates for the 1×10^{20} cm⁻³ electron density boundary (see chapter 3).

The expansion rate of the coronal plasma early in time for a 4-wire 25 μ m Al X pinch was found to be 36 μ m/ns from the inerference images and 32 μ m/ns from the laser shadow images (see Fig. 6.3). These numbers are consistent with coronal plasma expansion rates for Al found by Kalantar in 1993. We can look at the coronal plasma expansion rate only early in time because it is difficult to measure coronal plasma expansion much past 30 ns into the current pulse. This is due to the fact that once the global magnetic field becomes large enough, the ablated plasma begins to move

toward the axis, at which time we no longer have the symmetry needed to find the diameter of the plasma columns. This plasma motion will ultimately lead to the build up of plasma on axis. This is what we have called the plasma jet, but is actually more analogous to the precursor plasma that builds up on axis in wire array z-pinch experiments (more on this in section 6.E).

We have also found coronal plasma expansion rates for W to be 11 μ m/ns from the interference images and 10 μ m/ns from the shadow images (see Fig. 6.4). The W X pinches used for these experiments were 4-wire 20 μ m X pinches. This lower expansion rate compared to Al ultimately leads to a later neck formation and x-ray burst.

The coronal plasma expansion rate for Mo 4-wire 25 μ m X pinches was found to be 13 μ m/ns from the shadow images (Fig. 6.5). We were not able to find an expansion rate for Mo from the interference images because the ablated plasma from the wires started moving toward axis very early in time. Ultimately, as we will see later, this more rapid movement of the plasma toward axis will result in a much faster propagation of the plasma jet. It is unclear, however, how this earlier plasma motion away from the legs affects the radiation structure of Mo X pinches, if at all.

The time of x-ray emission seems to be tied to expansion rate. High expansion rate materials like Al radiate earlier than lower expansion rate materials like Mo and W. This will be discussed further in section 6.C.

6.C Compression of the cross point

As discussed in earlier chapters, the compression of the cross point region is the primary mechanism leading up to x-ray emission. The neck goes though three distinct phases over the course of the current pulse.



Figure 6.3: Plots of coronal plasma expansion rates for a 4-wire 25 μ m Al X pinch from (a) interferometry and (b) shadography. The shadow images show an expansion rate of 32 μ m/ns where the interference images show 36 μ m/ns. Measurements were taken about half way between the cross point and the cathode.



Expansion rate of coronal plasma (W)

Figure 6.4: Plots of coronal plasma expansion rates for a 4-wire 20 μ m W X pinch from (a) interferometry and (b) shadography. The shadow images show an average expansion rate of 12 μ m/ns where the interference images show 14 μ m/ns. Measurements were taken about half way between the cross point and the cathode.



Expansion rate of coronal plasma (Mo)

Figure 6.5: Plot of coronal plasma expansion rate for a 4-wire 25 μ m Mo X pinch from shadography. The shadow images show an expansion rate of 13 μ m/ns. Measurements were taken about half way between the cross point and the cathode.

The first is expansion of the coronal plasma. Just like the legs of the X pinch, the cross region begins to expand as current flows in the wires. The expansion is due to the increased temperature resulting from ohmic heating. However, the magnetic field produced by the current eventually overwhelms the kinetic pressure and the neck enters a compression phase.

In the compression phase the magnetic field maximum that exists near the cross point causes an m = 0 instability to develop. As the m = 0 instability progresses all of the material is not being driven toward the axis. Some of the material is squeezed out of the center along the axis, adding to and/or starting the plasma jets on axis [Chittenden *et al.* 2007]. This transport of material away from the center will ultimately aid in producing the micron size plasma column. A more detailed

discussion of neck compression can be found in chapter 4. Ultimately, at maximum compression, a burst of x-rays is emitted followed by the explosion phase of the neck region.

The graphs in Fig. 6.6 and 6.7 show how the diameter of the neck region evolves for Al and W X-pinches respectively. Al 4-wire 25 μ m X pinches show expansion until about 17 ns, at which time the diameter of the z-pinch at the cross point is about 0.4 mm. Next, the neck continues to compress until x-ray emission at about 30 ns. Resolution and timing prevent us from finding the minimum radius of the neck. The minimum spatial resolution of the laser imaging system is a several tens microns (1 pixel = 10 μ m in the digital camera). The time of peak compression is also difficult to capture since the final stages of compression last far less than a nanosecond.

We see many of the same features with the W 4-wire 20 μ m X pinches, but on a longer time scale (Fig. 6.7). W shows a maximum diameter of between 0.4 and 0.5 mm at 28 ns. X-ray emission comes at about 47 ns. The longer time scale of neck development for W and the lower expansion rate for W reported in section 6.B seems to be tied to the lower energy deposited in the plasma per unit mass. We did not measure the energy deposited, but much research has been done to study the energy deposited for a give current pulse as a function of wire material [Chandler *et al.* 2002]. We found that material with the highest energy deposited per unit mass (Al) had the highest expansion rates of the coronal plasma and fastest compression time.

If we closely inspect an interference image of the Al 4-wire 25 μ m X pinch 2.3 ns before x-ray emission (Fig. 6.8) we see that there is no detectable material outside of the dense plasma neck. We see no fringe shifts outside of the 0.1 mm radius neck, and the fringes disappear inside of the dense neck. This sharp boundary implies a very high density gradient. The interferometer is not sensitive to line densities below 4 ×

 10^{16} cm⁻², which translates to about 4×10^{18} cm⁻³ for the given scale length of 0.1 mm. This density is certainly high enough to conduct the majority of the current. However, the sharp density gradient (beyond measure by the interferometer) implies there is little material just below the detection threshold. If there is lower density plasma surrounding the neck it is probably a couple orders of magnitude or more below the detection threshold. This means that the pinch has swept the majority (possibly all) of the surrounding material into the small diameter neck, which in turn implies that the majority of the current appears to be flowing through this neck.

Furthermore, since the interference images show that the plasma in the neck region is very dense (electron volume densities above 1×10^{20} cm⁻³ and the ion volume densities within 1 to 2 orders of magnitude depending on the average ionization state) we should be able to see all of the material in the neck regions with the x-ray radiographs. The x-ray radiographs show similar sharp density boundaries in the neck region as the interferograms. This again implies that the majority of the mass is contained within the small diameter neck. Fortunately, we were able to capture a radiograph of a Mo 2-wire 13 µm X pinch within 0.1 ns of x-ray emission (Fig. 6.9). This radiograph shows a minimum neck diameter of 2.5 µm. Nearly all of the current may well be flowing through this very small diameter neck.



Figure 6.6: Plots of neck diameter before x-ray emission for a 4-wire 25 μ m Al X pinch from (a) interferometry and (b) shadography. Both graphs show maximum diameter around 17 ns. The data shown is up to the time of maximum compression around 30 ns.



Figure 6.7: Plots of neck diameter before x-ray emission for a 4-wire 20 μ m W X pinch from (a) interferometry and (b) shadography. Both graphs show maximum diameter around 28 ns. The data shown is up to the time of maximum compression around 47 ns.



Figure 6.8: Interference images of the cross point regions show that there is no detectable material outside of the small diameter neck. This sample image is of an Al 4-wire 25 μ m X pinch 2.3 ns before x-ray emission. There is no fringe shift outside of the 0.1 mm diameter neck and the lines disappear inside the dense neck.



Figure 6.9: This x-ray radiograph of a Mo 2-wire 13 μ m X pinch within 0.1 ns of x-ray emission shows that the diameter of the neck before x-ray emission can be as small as 2.5 μ m.

6.D Explosion phase

Immediately after the X pinch reaches maximum compression and the micropinch radiation is emitted the neck region of the X pinch explodes. The plasma in the neck region rapidly expands quickly decreasing the density of the plasma. We believe this rapid expansion is tied to the same mechanism that triggers the micropinch radiation. As stated in the chapters 4 and 5 we believe that the temperature of the plasma in the neck rises rapidly once the density become sufficiently high to limit radiative cooling. The resulting dense, hot plasma is believed to be the source of the micropinch radiation. If the plasma temperature does indeed rise sharply it could now be hot enough that the kinetic pressure overwhelms the magnetic pressure, stopping the neck implosion and causing it to explode instead. Is the drop in density from the exploding neck sufficiently fast to explain how the micropinch radiation "turns off" so quickly?

We calculated the expansion rates of the neck region for Al and W (Fig. 6.10 and 6.11 respectively) by tracking the diameter of the neck after x-ray emission. For each material we did not have many shots that we could use to calculate expansion rate. For each individual shot the expansion rate appeared to be very linear, but there was enough shot-to-shot variation in the diameter of the neck at a given time that we only used shots with all three laser images after the x-ray burst to find expansion rates. We saw that the expansion rate for the Al 4-wire 25 μ m X pinch in Fig. 6.10 was about 300 μ m/ns (slightly more from the interference image and slight less from the shadow image). The expansion rate for the W 4-wire 20 μ m X pinch in Fig. 6.11 was found to be about 90 μ m/ns.

Since the expansion rates were nearly linear, let us assume for now that the necks expand at the same rate immediately after the x-ray burst. The minimum diameter for Al in Fig. 6.6 was about 100 μ m (2.3 ns before x-ray emission). If we



Figure 6.10: Shortly after the neck region of the X pinch reaches maximum compression it begins to rapidly expand or explode. We see from both (a) the interference images and (b) the shadow images that for W the neck expands at about $300 \,\mu\text{m/ns}$.



Figure 6.11: The (a) interference images and (b) shadow images for W show that the neck expands about 90 μ m/ns after maximum compression.

use this diameter as an upper bound of the diameter of neck at the time of x-ray emission and the expansion rate of 300 μ m/ns than the density in the neck would drop by at least a factor of 1/16 in the first nanosecond after the x-ray burst. Since the intensity of the radiation is proportional to the density squared [Hansen 2003] the intensity would decrease by a factor of 1/256 in the first nanosecond. But, as we saw in Fig. 6.9 the diameter of the neck can be as small as a few microns. If we were to use a neck diameter of about 10 μ m then the intensity of the radiation would drop two more orders of magnitude in the first nanosecond. We can see from these calculations that the density drop from the expanding neck is more than sufficient to "turn off" the micropinch radiation in less than a nanosecond.

The 90 μ m/ns expansion rate for W of course means that the x-ray intensity would not decrease as rapidly, but it is still sufficient to kill the radiation on a similar time scale, assuming an initial radius at x-ray-burst-time of a few ns.

It is during the explosion phase that we begin to see energetic electron radiation from the cross point region. Previous work suggests that the energetic electron beam radiation starts when small gaps begin to form in the neck region after the micropinch [Shelkovenko *et al.* 2005]. Radiographs show gaps forming in the neck almost immediately after the x-ray burst (Fig. 6.12). However, we now see from the laser images (sensitive to lower densities) that plasma remains in the central region until much later in time (figures 6.1 and 6.2). This means that the gaps that create the energetic electron radiation are actually lower density regions that increase the mean free path of the electrons.

Figure 6.13 is presented to give a better comparison of the gaps observed using x-ray radiography and laser backlighting. Both images are of an Al 4-wire 25 μ m X pinch (from different shots). The radiograph in Fig. 6.13 shows that a 0.5 mm gap has formed 11.0 ns after the x-ray pulse while the laser shadow image shows the a gap just



Figure 6.12: Radiograph of the X pinch show that gaps begin to form in the neck region almost immediately after the first x-ray burst.



Figure 6.13: Comparison of an x-ray radiograph and laser shadow image of an Al 4wire 25 μ m X pinch at similar times. The radiograph shows about a 0.5 mm gap 11.0 ns after the x-ray burst while the laser shadow image is just starting to show a gap forming 14.3 ns after the x-ray burst. In general the laser images show that there is material in the neck region much longer than seen in the radiographs.

starting to open. By this time in the current pulse the energetic electron radiation is often still strongly radiating (see Fig. 5.11).

6.E Plasma jet formation

The geometry of the X pinch gives rise to plasma jets that form on axis. The mass in these jets comes from two different processes that occur in the X pinch. Some of the mass comes from the cross point region. As the magnetic field compresses the plasma near the cross point, some of the mass escapes along the z-axis. Computer simulations suggest that most of the original mass from the cross point region ends up being ejected axially before the main x-ray burst [Chittenden *et al.* 2007]. This axial transport of mass allows the plasma column to be compressed down to only a few microns at the beginning of x-ray emission (because the total number of particles N in the Bennett condition is reduced).

Another process leading to jet formation is the build up of ablated plasma from the legs onto the z-axis. This is analogous to the precursor plasma in wire array experiments [Bott *et al.* 2006]. The global magnetic field (centered on the z-axis) exerts a force on the charged particles carrying current in the legs of the X pinch. This $\mathbf{j} \times \mathbf{B}$ force accelerates the coronal plasma particles perpendicular to the leg of the X pinch. This plasma builds up on axis at the magnetic field null.

We found that the propagation speeds of these jets were similar for Al and W despite the fact that they have very different coronal plasma expansion rates. The propagation speeds were found from the length of the jet extending from the cross point to the lowest detectable boundary on axis (electron line density about 4×10^{16} cm⁻² from interferometry and volume density below 1×10^{20} cm⁻³ from shadowgraphy). The propagation speed of the jet from the cross point toward the anode for Al 4-wire 25 µm X pinches was found to be 170 µm/ns from the



Figure 6.14: Plots of propagation of the plasma jets from the cross point toward the (a) anode and (b) cathode for an Al 4-wire $25 \mu m X$ pinch.



Figure 6.15: Plots of propagation of the plasma jets from the cross point toward the (a) anode and (b) cathode for a W 4-wire 20 μ m X pinch.

interference images and 140 μ m/ns from the shadow images (Fig. 6.14a). The propagation speed for the anode jet in W 4-wire 20 μ m X pinches was slightly greater at 180 μ m/ns and 160 μ m/ns from the interference and shadow images respectively (Fig. 6.15a).

This propagation speed does not actually reflect the speed at which particles in the jet are moving. Rather, this propagation speed is the speed at which the detectible edge of the electron areal density is moving along the axis. To help visualize what is going on let us first imagine the X pinch as two "V" shaped sections joined at their vertices (one on the anode side and one on the cathode side). Now looking at only one of the V's as in Fig. 6.16 we can imagine the ablated plasma front heading toward the z-axis from both sides. As these front meet on axis they "zipper" together forming the plasma jet. In this way it is possible for the detectible density front in the jet to be moving faster than the axial velocity of the particles in the jet.



Figure 6.16: This illustration shows one half of an X pinch to demonstrate plasma jet propagation due to "zippering" of the ablated plasma fronts from the X-pinch legs.

We actually saw more variation between the propagation speeds of the plasma jets toward the anode and cathode than we did between Al and W X pinches. Figure 6.14b shows that the velocity of the cathode jets for Al were found to be $150 \,\mu$ m/ns

(interference) and 140 μ m/ns (shadow). W showed a cathode jet speed of 160 μ m/ns from interferometry and 140 μ m/ns from shadowgraphy (Fig. 6.15b).

The speeds of the cathode jets were found to be less than the speeds of the anode jets for both materials. Assuming that most of the material in the jet is coming from the legs of the X pinch, it is not surprising that the anode jet propagates faster. Many single wire and X pinch experiments have shown that the expansion rate on the anode side is greater that the cathode side [Sarkisov *et al.* 2002]. If the anode side is ablating material more quickly, than the anode jet should accumulate material faster than the cathode jet.

Another interesting thing to note from Fig. 6.14 and 6.15 is that even though Al and W showed similar jet propagation speeds, Al radiated its first x-ray burst before the jets connected the A-K gap whereas W radiated after the jets connected the A-K gap. This connection of the A-K gap by the jets may help contribute the energetic electron radiation commonly seen in W X pinches. This is certainly not the only contributing factor to the generation of energetic electron radiation (discussed in detail in chapter 5), but the lower inductance of the X pinch due to the added current path could help drive more electrons across the minidiode formed after the initial x-ray burst.

We found from the interference pictures that the electron density exceeds 10¹⁹ cm⁻³ on axis by 30 ns into the current pulse for the X pinches in our experiments. As discussed in chapter 3 the interference images give us a line integrated electron density from the phase shift in the interference fringes. Using this information and assuming cylindrical symmetry we were able to extract electron volume density using Abel inversion.

6.F Modulations of the coronal plasma

Periodic axial modulations of the plasma streaming toward the axis have been observed in experiments with both X pinches and wire array z-pinches (Fig. 6.17). The period of these modulations seems to be material dependent, but not greatly dependent on magnetic field strength or geometry. In previous single wire ablation experiments performed at Cornell [Mitchell *et al.* 2006b], as well as in cylindrical wire-array z-pinch experiments at Imperial College [Lebedev *et al.* 2004] and Sandia National Laboratories [Jones *et al.* 2005] modulation wavelengths have been reported that are the same for each wire material. Now we have found that the wavelength of the periodic modulation of the coronal plasma from the legs of an X pinch is also consistent with the numbers reported the publications above. The wavelength found in the present experiments for Al, W, and Mo were 0.50 ± 0.09 mm, 0.29 ± 0.07 mm, and 0.37 ± 0.07 mm respectively.



Figure 6.17: Periodic modulations of the coronal plasma streaming toward axis observed from W wires as (a) part of a wire array and (b) from the legs of an X pinch.

6.G Experiments with simultaneous x-ray and laser imaging

We present here experiments designed to capture simultaneous images of a Mo 2-wire 13 μ m X pinch from the x-ray radiography and laser backlighting. This was achieved by loading the X pinch to be imaged in the return path of the current and loading 2 parallel X pinches in the main current path. The two backlighting X pinches were placed in such a way to preserve the optical path of the laser (Fig. 6.18)



Figure 6.18: Schematic diagram of optical and x-ray imaging paths.

The synchronization of the x-ray and laser images is limited to the time that we can produce x-ray bursts from the X pinches. As such we were only able to capture a small number of images at nearly the same time. All of the x-ray radiographs captured are presented in Fig. 6.19. The images show the evolution of the dense wire cores from the beginning of neck compression and jet formation through well after x-ray emission. Out of these images we were only able to capture one laser image within a



Figure 6.19: Evolution of a Mo 2-wire 13 μ m X pinch captured with X pinch x-ray backlighting. Each image shows the central 4 mm of the X pinch.

small time of the x-ray image from the same shot. The laser image is shown superimposed on the x-ray image in Fig. 6.20. In this image we can see how the dense core is positioned in the expanded coronal plasma. The wire core remains in a stable position while the ablated plasma is rocketed away.



Figure 6.20: Superposition of the laser shadow image and x-ray radiograph for pulse 4908. The radiograph was captured 1.1 ns before x-ray emission and the laser image was captured 1.9 ns before x-ray emission.

CHAPTER 7

SUMMARY AND CONCLUSIONS

In this thesis we have presented experiments designed to study the dynamics and radiation structure of the X pinch using high temporal resolution diagnostics. We were able to answer or at least provide additional insight to many of the questions posed at the onset of this research.

7.A Radiation structure of the X pinch

Question 1: What is the duration of the micropinch radiation, and what mechanisms allow this short time scale radiation?

Hypothesis 1: Micropinch radiation lasts for less than 1 nanosecond (quickly turned on by rapid temperature increase and off by density decrease).

We used a low delay x-ray streak camera to obtain time dependant spectra of X pinch radiation with better than 10 ps time resolution. These are the first experiments with temporal resolution this good. The results showed that the Mo 4-wire 22 μ m X pinches studies radiated only a few tens of picosecond of continuum/line radiation from an early micropinch. This early micropinch radiation was follow by subsequent weaker bursts lasting about 50 ps.

The weaker pinches did not show continuum radiation, possibly either due to smaller density or less total mass. However, these weaker pinches helped provide insight into the micropinch mechanisms. Because the weaker pinches did not show bright continuum the temperature was easier to analyze over the course of the pinch. Using the Gabreal model we found that the temperature was rising in the early part of the x-ray burst. The temperature remained high for the remainder of the x-ray burst. The supports the hypothesis that micropinch radiation is triggered by the rapid
increase in temperature as the plasma become opaque to the radiation acting to cool the plasma.

To examine if the micropinch radiation turns off quickly due to rapid decrease of the density of the plasma we studied the dynamics of the plasma after the x-ray burst. We were not able to directly observe the density in the neck region as it was too high for the laser interferometer. However, by looking at the expansion rate of the neck after the x-ray burst and extrapolating that expansion rate to the time immediately after x-ray emission we estimated that the density was dropping sufficiently fast enough to kill the intensity in less than a nanosecond. Therefore, the micropinch could well be turned on by a rapid increase in plasma temperature and turned off by the rapid decrease of plasma density.

Question 2: When does the energetic electron radiation begin relative to the micropinch radiation, and where is its source location as a function of time? *Hypothesis 2:* Energetic electron radiation starts after the micropinch (once lower density gaps begin to form) and progresses from the center to the anode.

The energetic electron radiation was studied with spatial and temporal resolution with the use a filtered array of collimated SiD's. The results of these experiments showed that the micropinch radiation is followed immediately by "short lived" energetic electron radiation from the cross point region. This short lived radiation lasts up to about 5 ns. The short lived radiation most likely emanates from small gaps that form in the neck [Shelkovenko *et al.* 2005] as the micropinch region(s) explodes. This short lived radiation is likely terminated as the dense regions in the neck dissipate leaving only a single large gap across the central region. The formation of this larger gap gives rise to "long lived" energetic electron radiation. The long lived radiation appears first in the central region but grows in intensity toward the

anode (as the gap expands). The most intense radiation was found to come from the region neighboring the central region and lasts more than 50 ns.

7.B Plasma dynamics of the X pinch from laser and x-ray imaging

Question 3: What roles do the plasma dynamics (plasma expansion rate, neck compression and expansion rates, jet formation, axial modulations) play in the X pinch?

Hypothesis 3a: Coronal plasma expansion rates and neck compression rates are linked to the time of x-ray emission and are dominated by the energy deposited in the plasma per unit mass.

We studied the X-pinch plasma dynamics in order to better understand the conditions leading up to x-ray emission. The low density coronal plasma (electron density > 10^{17} cm⁻³) was studied using a 150 ps pulse width Nd:YAG laser operating at 532 nm. Images were produced using a shearing air-wedge interferometer. We reported expansion rates of the coronal plasma that forms around the legs for Al, W, and Mo X pinches. We also reported neck compression rates for the same X pinches. We correlated these observations to the time of x-ray emission. We found that material with the highest energy deposited per unit mass had the highest expansion rates of the coronal plasma. We did not measure the energy deposited, but much research has been done to study the energy deposited for a give current pulse as a function of wire material [Chandler *et al.* 2002]. The higher expansion rate material also had a more rapid compression of the neck region (again related to the lower mass).

Hypothesis 3b: Energetic electron radiation comes from acceleration of electrons across gaps that form as the neck region explodes.

Observations of gaps in the neck region have been made using x-ray radiography [Shelkovenko *et al.* 2005]. These observations led to the hypothesis given above. However, we now see with the help of the laser produced images (sensitive to lower densities than the x-ray radiographs) that plasma exists in the central region for a much longer period of time. This has forced us to redefine the gaps as lower density regions with sufficiently high mean free paths to allow the acceleration of energetic electrons. Gaps seen with the laser images do not appear until about 15 ns after they are first observed using x-ray radiography.

Hypothesis 3c: Plasma jet formation is dominated by mass ablation rate and should be greater for materials with high expansion rates.

We also used the laser images to study jet formation in X pinches. We found that the propagation speed of the jets for Al and W were very similar despite the fact the Al shows greater expansion rates for the coronal plasma. However, Mo showed a propagation speed about 25% higher than Al and W. Therefore, the ablation rate for Mo is higher than both Al and W even though Al has a higher expansion rate and W has a lower expansion rate. This means that ablation rates and expansion rates are not correlated. In addition, since W radiates later in the current pulse the jets were found to connect the anode-cathode (A-K) gap before x-ray emission whereas jets did not connect the A-K gap before x-ray emission for Al. This may affect the radiation characteristics of the energetic electron radiation, but further experiments are required.

Observation 3d: Axial modulation of the coronal plasma in X pinches match those observed in wire-array z-pinch experiments.

X pinches show similar axial modulation in the coronal plasma as seen in wire array experiments z-pinch experiments [Lebedev *et al.* 2004, Mitchell *et al.* 2006b].

The wavelengths of these modulations were measured and compared to values reported for wire arrays. The values of 0.50 ± 0.09 mm for Al, 0.29 ± 0.07 mm for W, and 0.37 ± 0.07 mm for Mo are within the error reported for wire arrays. This agreement suggests that the wavelength is dominated by material properties and not the magnetic feed topography.

Observation 3e: Spatial relationship of the coronal plasma and the dense wire cores.

We conducted experiments using simultaneous x-ray radiograph and laser imaging. These images give us the first glimpse as to where the dense wire cores are located in the coronal plasma. This helps use determine how the coronal plasma is moving and can be useful for comparison to computer models.

7.C Future work

Many opportunities exist to expand this research and improve our understanding of X pinch dynamics.

First, the data presented in this thesis are only a small sampling of possible configurations of X pinches that could be studied. If we can collect more data on various wire materials, wire diameters, current shapes, and X pinch geometries we may better understand what factors dominate X pinch dynamics. Also more data and analysis are needed for time dependent spectra from X pinches. Although beyond the scope of this thesis, it is possible to estimate the temperature and density of the radiating plasmas by fitting the spectra to known models.

Better values of coronal plasma density would greatly increase our understanding of X pinch dynamics. We were limited in our experiment by the 532 nm wavelength of the laser light. The densities and density gradients were too high during much of the current pulse for the laser to penetrate the plasma. If an

interferometer with a shorter wavelength were use we could penetrate denser regions of the coronal plasma. This would be very helpful for computer modeling of the Xpinch, which is now being pursued.

Finally, much work is needed to develop the X pinch as a practical laboratory and bio-medical imaging source. The X pinch shows great promise as a high resolution (both temporal and spatial) imaging source. However, in order to make the X pinch useful to a broader customer base it must be reliable and well characterized. The X pinch needs to be optimized to get the best imaging characteristics out of the small amount to energy. This would relax the requirement on the pulsed power source and allow more compact designs. We must also continue research to find ways to control the radiation characteristics and increase the repetition rate on x-ray pulses as with the research of X pinches in dielectric frames [Mitchell *et al.* 2006a].

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