Physics of Z-pinches

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  – Prof. A. Safranova (UNR)
  – Dr. D. Sinars (Sandia)

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Outline

• Introduction
  • Pulsed-power
  • Exploding wires
  • Wire-Array Z-pinches
  • X-pinches

• Physics Issues Related to plasma initiation and development in Z-pinches and X pinches
The (very) basic idea of Pulsed Power

- Store an amount of electrical energy, $Q$, over time $t_1$
- Release this energy, $Q$, over a much shorter time $t_2$ with efficiency $\eta$
- This results in power (energy/time) amplification:

\[
P_1 = \frac{Q}{t_1} \quad P_2 = \frac{\eta Q}{t_2}
\]

$t_2 \ll t_1 \Rightarrow P_2 \gg P_1$

For example, $t_1=30$ s, $t_2 = 0.3$ µs, $\eta = 0.3$
Power multiplication is $3 \times 10^7$. 
A Mechanical Analog

Pile driver

- Hoist slowly lifts hammer, storing potential energy for tens of seconds
- Gravity converts potential energy to kinetic energy
- Hammer momentum is transmitted to pile in about 100ms
- Power amplification ~ 300
At Cornell, we make use of 2 pulsed power machines for our wire array z-pinch and X-pinch experiments.

**COBRA:** 0.9-1.2 MA, 95 - 235 ns risetime, 200-300 ns fwhm;

4 pulse lines, independent output switches, triggered to vary risetime;

1-3 (or more) pulses per day.

**XP Pulser:** 500 kA, 50 ns risetime, 100 ns pulse;

3-10 pulses per day.
Pulsed Power Technology in General for Z-pinches and X pinches

- Pulsed Power machines used for dense z-pinch experiments (wire arrays and gas-puffs) have peak currents of ~0.2 to 20 MA (Sandia Z-machine, soon to be 26 MA) and up to ~1 μs rise time.
- X-pinches work well on pulsers with as low as 50-100 kA as long as the rate of rise of current is at least ~1 kA/ns.
- There are several ways to generate high voltage, high current pulses, two of which are used in Professor Beg’s lab at UCSD.
- Here we will discuss only the one we use at present at Cornell (Marx Generator).
COBRA Energy Flow

Wire-Cores
ρ ~ 1x10^{22} #/cm^3
T ~ 10eV

Wire-Array
Q_{\text{rad}} ~ 5kJ
ρ_{\text{rad}} ~ 1x10^{21} #/cm^3
τ_{\text{rad}} ~ 5ns

Marx Generator
Q = 53kJ
τ ~ 30s

C = 46nf
Q ~ 29kJ
τ ~ 0.8μs

Power Gain
τ ~ 250ns

Intermediate Storage Capacitor (ISC)

Vacuum Section

Spark-Gap Switches

Laser Triggered Switches

Intermediate Storage Capacitor (ISC)
COBRA Energy Flow
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Exploding Wire Experiments: a few kA per wire

Clayton Myers
Image exploding wire with a laser (shadowgraph).
Exploding wires are more nonuniform in negative polarity. The structures can be understood in terms of electron emission.
Sometimes the structure is really complex (and baffling). The extent of the expansion is determined by the \[
\frac{\text{(deposited energy)}}{\text{(vaporization energy)}}.
\]

(More wire images to come.)
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Wire-array z-pinch basic physics

- Current flows in wires
- They explode and plasma is generated
- Lorentz force \((J_z \times B_\Theta)\) causes radial implosion
- Stagnation of material on axis produces an intense soft x-ray burst
It is the indirect-drive inertial confinement fusion program that drives most of the interest in the physics of wire-array z-pinches.

Z-machine: 20 MA, 100 ns risetime  --> ZR: 26 MA

Radiation-driven inertial confinement fusion z-pinch configuration

Arrays with large numbers of wires
Z-Pinches on COBRA

Typically 8 or 16 wire arrays; shown with 2 X-pinches for x-ray backlighting
X-ray imaging of array wires

- X-pinch backlighting (6µm spatial, <1ns temporal, 3-5keV) of dense cores and coronal plasmas
- Enables measurements of ablation process
  - Expansion rate
  - Plasma density
  - Fine spatial structure
  - Ablation velocity
X-Ray Imaging – Fine Structure

- High resolution, 2-frame imaging enables new observations of W wire-core structure
- Micron-scale gaps grow with time and do not influence core expansion (120° between views)
- Mostly azimuthally symmetric (more on this later)

Shot 554  $T_r = 96\text{ns}$  $I_{\text{peak}} = 1170\text{kA}$
Research Goals

- Understand different elements of wire array z-pinch dynamics through quantitative measurements
  - Wire initiation processes
  - Ablation rate of plasma from wire-cores
  - Plasma density measurements
  - Radial implosion dynamics and related instabilities
- Determine the effects of
  - Current rise time, pulse duration, current per wire, etc.
  - Wire geometry or power-feed geometry
- Use theory and computer simulations to help understand experiments and use high quality experimental data to benchmark codes
- Try to understand when experiments with 4-64 wires are relevant to >200 wire experiments
- Train students on high-energy-density physics exp’ts
There are many options for wire-array parameters

- **Material**: (commonly W or Al; also Cu, St.St., alloys)
- **Wire diameter**: 4-25µm
- **Number of wires**: 4 - 600 (4-64 on COBRA, MAGPIE, ZEBRA)
- **Array dimensions**: (6-16mm diameter) (10-23mm high)
- **Configurations**: Cylindrical array; nested array; linear array
Physics/Applications Questions Addressed

• Sandia’s principal programmatic question: Is there an optimum wire-array configuration for generating x-rays?

• Can we understand the physics of exploding wires and dynamics of wire array z-pinches? This a fundamental question for university groups, but there are others:

• What are the properties of the high-energy-density plasmas produced by wire-array z-pinch implosions?

• Can we use plasma jets produced by wire array z-pinches to help understand some aspects of astrophysical jets and perhaps other astrophysical phenomena?
Dynamics of wire array implosion dynamics

- **Initiation**: metal to WDM ("phase transition")
- **Ablation phase**: mass redistribution
- **Implosion phase**: foot of the X-ray pulse
- **Stagnation phase**: main X-ray pulse
- **Post-stagnation**: tail of the x-ray pulse (not interesting for ICF)

The phenomenology is more complex than simply the implosion of a plasma shell.

Visible light streak camera image of the light from the individual wires, the precursor plasma (on axis), and then the implosion and stagnation.

S.V. Lebedev, Implosion dynamics of wire array Z-pinches. WAW_06, May 1, 2006
Laser Imaging

- Shot 637 “schlieren”
  - 16 x 12.5µm Al
- Images can be taken at anytime during experiment
- Side-on interferometry can give line density
- Axial interferometry being added this summer
- Axial Mode ....
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X-ray Source from X-pinching Plasma

- Start with 2 or more 4-125 µm metal wires in the form of an X
- Explode them with 100 - 1000 kA of current in a ~100 ns pulse, generating an X-shaped plasma
- A ~400 µm long z-pincho forms in the middle and implodes unstably
- A cascade of ever-smaller plasma necks (sausage instability) yields ~ 1 µm hot, dense plasma that emits a sub-ns x-ray burst
- The x-ray burst timing is reproducible to ± 1-2 ns with Mo wires
X pinch scenario

0 nc
Primary pinching

10 nc
Neck cascading

12 nc
Hot spot

20 nc
Neck break

35 nc
Minidiode

37 nc
38 nc
38.5 nc
39 nc
45 nc

Neck cascading

X-pinch before X-ray burst

X-pinch after X-ray burst

Anode
Cathode
1 cm
Radiograph size

I(t)
I(t)
I(t)
I(t)

1 mm
1 mm
1 mm
1 mm
There are many variations of X pinches, too.

For example, this particular laser shadow image is of a 4x4 μm W wire that had a Au coating on it.

Note the gap and the fact that the plasma looks different than it does in an x-ray image.

This image is from Prof. Beg and was obtained with an 80 kA peak current pulser.
Why X pinches?
Not to pump an x-ray laser
Not for x-ray lithography
But they are good for imaging for fun as well as to study the physics of exploding wires and wire arrays.

Point-projection radiographs have µm-scale resolution, implying source sizes of \(~1 \, \mu\text{m}\) or less. The resolution was “too good to be true.” Also, the pulse is short.
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COBRA Operations
2-3 shots/day in a repeating run

• Core diagnostics (same on COBRA and MAGPIE at Imperial College to facilitate comparison)
  – XUV framing camera (4-frame, 3ns gating)
  – Laser imaging (3-frame, 0.2 ns pulses)
  – Visible-light streak camera
  – Various solid-state x-ray detectors
  – X-pinich point-projection x-ray imaging
  – Bolometer

• Other Diagnostics
  – Spatial x-ray streak
  – Spectral x-ray streak
  – 6-frame time-gated X-ray spectral camera
  – Etc.
Implosion Trajectories

- Time at which 50% of initial array mass has been ablated using:
  - lower-bound ablation velocity ($V_{abi} = 24$ km/s)
  - upper-bound ablation velocity ($V_{abi} = 30$ km/s)

$$m_{abi}(t) = \frac{\mu_0}{4\pi R_0 V_{abi}^2} \int_0^t I^2(t') dt'$$
“Delayed” implosion trajectories previously seen on MAGPIE & Z

MAGPIE

\[ \frac{R}{R_0} \] vs. \[ \frac{t}{t_{imp}} \]

- During the first 80% of time the JxB force is not applied to the wire cores, accelerating instead the coronal plasma ("ablation streams")
- Fast acceleration – not all mass participates
- Rate of plasma formation is the most important parameter during the first phase

Z

M. Cuneo et al., PRE 2005
Z-Pinches on COBRA
Gated XUV pinhole images show the z-pin chop implosion
Four-frame, time-gated (3 ns) camera images illustrate the progress of the axially non-uniform snowplow implosion onto the precursor plasma on axis, as well as the “trailing mass.” Trailing mass is also seen in Sandia Radiography images.

Sandia x-ray backlighter
Radiography (300 W wires)

Extreme Ultraviolet images from COBRA
(16 wire, 5.4 µm W array)
Axially non-uniform ablation occurs in all wire arrays

- Mechanism is unknown
- Wavelength depends on wire material
- Wire breakage at some positions triggers implosion
- MHD code calculations can reproduce by introducing artificial perturbations in ablation rate

Ablation rate, and hence ablation velocity, must vary with axial position
Coiled Arrays

A new method to alter ablation and hence implosion dynamics
Hall, Bott, et al, submitted to PRL

Problem is arrays are already 3-D
With coils they’re very 3-D!!! – so why use them?
Coiled Wire changes fundamental ablation wavelength

Usually ~0.5mm wavelength perturbation in ablation, as seen on straight wires

Coiled arrays show ablation at coil wavelength

Tested for 1.4 – 3.7mm

Jets of ablated plasma are aligned with outer radius of the coil wire;
Fastest ablation occurs at the inner radius.

7x 25um Al straight, 1x25um curly
@ 125ns
Substantial axial asymmetry is seen on COBRA and MAGPIE but not on BIN (Lebedev Institute, Moscow)

What is important: wire contacts, power feed geometry, .... ?
X-ray imaging of array wires-reprise

- X-pinch backlighting (6µm spatial, <1ns temporal, 3-5keV) of dense cores and coronal plasmas
- Enables measurements of ablation process
  - Expansion rate
  - Plasma density
  - Fine spatial structure
  - Ablation velocity
Point-projection x-ray imaging of individual wires gives expansion rate and ablation rate, shows symmetry.

Images of W wire cores show nonuniform structure of wire cores (6 - 10 µm resolution).

Compressing axially and expanding radially (see left) enables coronal plasma to be seen: A symmetric dense core; a symmetric dense corona; ablation plasma moving toward the axis; correlation of the prominences in the core with the ablation plasma.
X-Ray Imaging – Plasma Density

- Minimum areal coronal plasma density estimated to be $\sim 60 \mu g/cm^2$
- Assuming corona has $\sim 200 \mu m$ symmetric, radial extent around wire-core, corona volume density is $\sim 5 \times 10^{18} / cm^3$
There is a dense “local” corona

Surrounding the wire, there is a symmetric dense coronal plasma transition from the dense core to the lower density coronal plasma that is swept to the axis.
The local corona is symmetric about the dense wire core.
The Dense core diameter is determined from scanned film images by a series of steps ....
Expansion rate depends on initial wire diameter.

(a) 8 x 12.7 μm W

(b) Core diameter (μm) vs. Time (ns) for different wire diameters:
- 8x7.4
- 8x10.1
- 16x5.1
- 16x7.4
Expansion rate depends on material
The laser thinks the dense corona is considerably bigger than the X pinch.
They measure different “edges”
Many believe that understanding the details of the wire explosion and plasma generation process will be critically important to the quality of a wire array z-pinch implosion (and the peak x-ray power that can be produced for ICF)

X-pinches and X-ray imaging is an important tool for determining what happens to the wires as a function of time during the current pulse
COBRA-STAR: 5 Images per pulse
Images give density profiles at 5 times
10-wire, 12.5 μm W; 12 mm diam; 8 mm high

$t=110 \text{ ns}$

$t=135 \text{ ns}$

$t=160 \text{ ns}$
X-pinch X-ray backlighting of a 10x19.8 µm W wire array, 12 mm diam., 8 mm high gives ion density

The W step wedge on the right implies the density is $\sim 2\times10^{19}/\text{cm}^3$ in the plasma near the axis in frame 3 and $\sim 1\times10^{18}/\text{cm}^3$ in the streams moving toward the axis in both frames 2 and 3. (The image is made by 3-5 keV x-rays [Ti filter].)
Stagnated Plasma on MAGPIE, COBRA and Z all show bright emission points in x-ray self-emission images.

MAGPIE: 1.6 keV Al line radiation

6.15 keV self-emission on Z
Al and Mg spectra recorded by FSSR spectrograph in MAGPIE and COBRA experiments (Al alloy 5056) can give plasma electron temperature vs position.

**MAGPIE**

32x15 µm

**COBRA**

8x12.5 µm
Modeling of time-gated spectra from the SS304/SS304 nested array (shot 461). Spectra imply increased $T_e$ decreased $N_e$ with time (see frames 5 and 6). (UNR)
Precursor plasma column for HED plasma studies.

- The precursor plasma column in wire-array z-pinches transitions from collisionless to collisional plasma conditions as it builds up.
- The initially collisionless cylindrically converging plasma flow eventually forms a dense compact column due to the onset of collisionality, with increasingly strong radiative and ionization energy losses as ablation plasma continues to arrive.
- This “radiative collapse” produces a quasi-stationary (~100ns), ~1 mm plasma cylinder at 50-100eV, and an electron density of $10^{18} - 10^{19}$ cm$^{-3}$ confined by the kinetic pressure of the plasma flow.
- This plasma is attractive for studies of radiative and ionization properties of high-Z plasmas (currently being explored with UCSD through the Outside User Program).
- The ~100 ns confinement time allows LTE conditions to be established and the transition from non-LTE conditions to LTE to be temporally resolved.
Summary and Conclusions - Z-pinches

- Many processes in z-pinch implosions are qualitatively understood and quantitative understanding is being developed.
- We are now concentrating on studies of the plasma initiation process and early dynamics.
- We plan to make “good” quantitative density profile measurements to enable a better understanding.
- Accurate wire core expansion rates are accessible over a time interval.
- Codes must be benchmarked against results, and physics-based models developed to enable predictive capability.
- The precursor plasma is interesting for HED studies.
Back to X-pinch properties and dynamics.

Laser-schlieren images of X-pinches show coronal plasma dynamics, including plasma jets along the axis.

- 4-wire 10 µm tungsten X pinches on the XP pulser
- 200 ps laser pulse
- Times relative to the x-ray burst are (top row) -5.9 ns, -3.4 ns, -0.1 ns, + 4.2 ns, and (bottom row) +8.0 ns, +18.1 ns, + 22.7 ns, 33.4 ns
- Is the gap in the last picture really devoid of plasma?
- Why no gaps earlier since UCSD 2-wire radiographs show gaps in ~ 1 ns?
Comparison of X pinch 3D MHD simulations with experimental results - a good test for 3D MHD codes
It is a really interesting High Energy Density Plasma!

- Atomic physics/x-ray spectroscopy of dense high-Z plasmas
  - Time resolved x-ray spectroscopy implies, for example, $T_e$ up to 2.5 keV and $n_e > 3 \times 10^{23}$ cm$^{-3}$ in Ti X-pinches (Sinars et al, JSQRT, 2003).
  - Can validate computer calculations of atomic energy level differences

- Can study the dynamics of current-driven dense plasmas

- It generates an intense, short pulse x-ray source
  - X-ray bursts last 10-1000 ps (x-ray streak camera)
  - Bursts up to $10^{10}$ W of x-rays > 1.5 keV at 400 kA.

- Many materials have been studied (Mo, W, Nb, Al, Ti, NiCr, Conichrome, Alloy 188, etc.), each with a unique spectrum
High Resolution Imaging with 2-5 keV x-rays

Refraction enhances contrast at boundaries in weakly absorbing objects, e.g., Spider. Exploding W wire yields an absorption image.
Radiographs in Different Energy Bands

2-3 \(\mu m\) resolution

5 mm

40 \(\mu m\)

40 \(\mu m\)
The Middle of an X pinch

“Thermal x-rays” come from necks. Electron-beams generate > 10 keV x-rays 100-500 µm away on the anode side.
Wave Optics Determines Image Character using a Small Source

- Partially Transparent Fiber (8 micron)
- Spherical wave (3Å)
- Near field
- Intermediate region
- Diffraction-dominated
- Refraction-dominated
- Far field
The width of an interference fringe: $w = \left(\frac{\lambda}{h}\right)b$

The image size in point-projection imaging: $v = h(1+b/a)$

{magnification = $(a+b)/a$}

If $v = w$ limits structure resolution, $h^2 = a\lambda$ for $b \gg a$

Examples of required detector resolution

$\lambda = 1\,\text{Å}$

$a = 50, b = 50\,\text{cm}, h = 7\,\mu\text{m}, Mag = 2, \text{detector resolution} = 14\,\mu\text{m}$

$a = 0.5, b = 5\,\text{cm}, h = 1\,\mu\text{m}, Mag = 11, \text{detector resolution} = 10\,\mu\text{m}$
Wave-Optics-Enhanced Point-Projection Radiography Requires a Small Source
(Actual Wave-Optics Calculations for 8 µm B and 3 Å)

Wavelength Spread

Finite source size & Wavelength spread

\[ \Delta \lambda / \lambda \approx 1 \]
Experimental Arrangement
Source size using a wire and fiber

Nb X pinch; 93:1 Experimental magnification
Calculations include source bandwidth

**7.5 µm W wire image**

**8 µm Glass fiber image**

Computed image for 1 ± 0.2 µm size

Computed image for 1 ± 0.2 µm size
Source Size Determination (40 μm Slit)
4 x 20 μm W wire X pinch; M = 6.8 (1.6±0.5 μm)
Source Sizes (Different Wires)

a. $4 \times 20 \, \mu m$
   Mo X pinch (#3349)

b. $4 \times 20 \, \mu m$
   W X pinch (#3402)

c. $4 \times 25 \, \mu m$
   NiCr X pinch (#3356)

d. $4 \times 25 \, \mu m$
   Ti X pinch (#3401)

\begin{align*}
\text{Normalized Intensity (a.u.)} & \\
\text{Slit Distance (\mu m)} & \\
\text{FWHM} & \\
1.2 \, \mu m \pm 0.5 \, \mu m & \\
1.6 \, \mu m \pm 0.6 \, \mu m & \\
2.8 \, \mu m \pm 0.8 \, \mu m & \\
14 \, \mu m \pm 1.5 \, \mu m & \\
\end{align*}
Laboratory Plasma Astrophysics

- Precursor column can be projected above the array using conical array configuration

- To help understand astrophysical phenomena with the help of laboratory experiments requires
  - similarity of dimensionless parameters with hugely different spatial and temporal scales
  - lab experiments benchmark computer codes
Deflection of jet by plasma ablated from CH foil

Jet trajectory is well described by analytical model of Canto & Raga [Astr.Astrphyscs 1995]

Experiment show formation of complex shock structures in the jet and in the wind

Simulations of the experiment with laboratory and astrophysical codes

S.V. Lebedev et al., APS, April 2006
Structure of the Magnetic Tower produced by a radial wire array

Dimensionless parameters from 2-D MHD simulations

Expanding magnetic bubble
Jet pinched by the toroidal magnetic field

Experiment:
X-ray emission (≈300eV)

$\mathbf{n}_i \sim 10^{19} \text{ cm}^{-3}, \ T \sim 200 \text{ eV}$
$I \sim 1 \text{ MA}, \ B \sim 100 \ T$
$\text{Re} > 10^4, \ \lambda/R \sim 10^{-5}, \ \text{Pe} > 10$
$\beta \sim 1, \ \text{Re}_M \sim 10$

S.V. Lbedev et al., APS, April 2006
If there is time ....
8-32 wire W
X-pinches on COBRA
(Dan Sinars, Sandia)

Setup for 32x25 µm W wire test
Cross-Point region has an amazing gap aspect ratio

2-wire 100 µm W on COBRA

Legs are \(\sim 3.2 \text{ mm}\) in diameter!

Where is the current?

\(~ 150 \mu\text{m vertical gap;} ~\)

\(~ 4 \text{ mm horizontal width} ~\)
Experimental setup for time resolved X pinch x-ray source size measurements
Streaked image of the wire grid in x-ray radiation of 4 x 20 µm NiCr X pinch

X-ray Intensity (Arb. units)

Time (ns)

1/3 Current (kA)

PCD

Rogowski

Plastic shell

Glass core

(1)

(2)

(3)

(4)

(5)

B shell

W core

100 µm

T (ps)

Pulse 3626
Time-dependent source size

An x-ray streak camera was used to record enlarged radiographic images of fine opaque and semitransparent objects (wires, fibers, fibers with a metal core) through an entrance slit placed in front of the photocathode. Variation in the intensity distribution of the images through the various objects provides time dependent information on the source size and spectral characteristics. A very brief period has been observed during which the source size remains small (<10µm) but the radiation hardness increases.
Summary of X pinch Plasma Parameters

- The X-pinch x-ray source intensity, geometric structure and spectral parameters have been measured over different energy ranges for many materials (Mo, W, Nb, Al, Ti, NiCr, etc.).
- Location of the bright plasma x-ray source is known in advance to within 150 µm, enabling detailed study of the X-pinch plasma itself.
- Wave optics experiments demonstrate that the x-ray source is 1-10 µm in size depending upon the material.
- Bursts last 10-100 ps (x-ray streak camera), depending upon material.
- Time resolved x-ray spectroscopy indicates, for example, electron temperatures as high as 2.5 keV and electron densities in excess of $3 \times 10^{23} \text{ cm}^{-3}$ in X-pinch plasmas produced from Ti wires.