Z-Pinches in the Western Part of the United States

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References and Special Thanks

• Special Thanks
  • Dr. John Maenchen & Dr. David Johnson, Radiographic Physics Dept. - SNL
  • Dr. Rick Spielman, High Energy Plasma Physics - SNL
  • Dr. Bruno Bauer & Dr. Victor Kantsyrev, Physics, University of Nevada, Reno
  • Dr. Frank Wessel, Physics, University of California, Irvine
  • Dr. H.U. Rahman, Physics, University of California, Riverside
  • Dr. John DeGroot, Physics, University of California, Davis
  • Dr. David Scudder & Dr. Jack Schlachter, Los Alamos National Laboratory
  • Gordon MacLeod & Sheldon Freid, Bechtel Nevada

• Interesting References
Z-Pinch Effect

• Z-Pinch Geometry
  • Plasma column
  • Large current flow along its longitudinal axis

• Mechanism
  • Current generates a large magnetic field
  • Magnetic field in turn interacts with the local current
  • By a Lorentz force ($\mathbf{J} \times \mathbf{B}$), radial confinement or a radial compression
  • Magnetic energy concentrated near plasma surface; efficient

• Instabilities - Currents seek paths of low inductance
  • $\frac{dI}{dt} = \frac{V}{L}$; Coaxial geom. with rigid return -- $L \sim \ln(r_c/r)$

• NOTE: NO External Coils!!! SIMPLICITY!??!
Graphical Picture of the Z-Pinch Effect

Z-Pinch Mechanism

Z-Pinch Coaxial Geometry
Artist’s View of the Radiation from a Z-Pinch
Brief Historical Background

• 1934 Bennett -- (Bennett Pinch - Equilibrium)
  • Plasmas thermal and magnetic pressures are balanced.

• Around 1950; Pinch Exp. for B-Confined Fusion
  • Easy to build & operate but NOT a promising approach
  • Testbed for plasma physics and plasma diagnostic dev.

• Niche in Material Radiation Studies

• Z-Pinch Classifications (Non-Equilibrium Pinch)
  • Shock-Heated Z Pinch
  • Resistive Heated Z Pinch
  • Gas-Embedded Z Pinch
What’s the Problem?

• Early Shock-Heated Pinch Exp. (Snowplow)
  • Low density gas & large pulsed voltage supplied by
    • Inductive storage device
    • Capacitive storage device
  • Required electric field needed ~ 1.6 MV/m
  • Achieved only ~ 0.1 MV/m
  • FLASH OVER Problem - surface becomes ionized by high voltage allowing current to arc & hence short out

• Early Resistively Heated Pinch Experiments
  • Current carrying electrons being slowed by ion collisions
  • Resistance ~ T^{-3/2} ; less effective at high temperatures
  • Simple pinch is unstable
What’s the Problem? (conti.)

• Early Gas Embedded Z Pinch
  • Z-pincho is initiated in a narrow column immersed in a medium of neutral gas (~1960)
    • Inhibit wall impurities in the plasma
    • Suppress some instabilities by inertially coupling the pinch to the ionized corona around the pinch
  • Column expansion was driven by an accretion of neutral gas surrounding the pinch which increased the pinch line density and cooled the plasma (~1982)
    • Suggested solution was to increase the current rise rate
• Summarized Major Problems in Early Days
  • Instabilities -- non-uniform compression for req. time scale
  • State of the art in pulse power not mature
Z-Pinches Throughout the United States
Motivation & Goals Driving Z-Pinch Exp.

• Mid 1960’s to 1990’s
  • Limited power output for fusion race -- $10^{-3}$ TW (mid 1960s)
  • Focus on optimizing subkilo-electron-volt X-ray output
  • (Nuclear weapon) Radiation studies on materials & electronics

• Radiation-Materials & Stockpile Stewardship - Present
  • 1-5 keV Spectral region: radiation-material interaction studies
  • Simulate different stages of a nuclear explosion

• Inertial Confinement Fusion [ICF](Origins ’73) - Present
  • Emphasis - generation of softer X-rays that can be thermalized
    • Pulse power - charged particles (electrons 70s, ions 80s, X-rays 90s)
    • Ablator physics and radiation symmetrization experiments

• Applications in Shock Physics & Astrophysics - Present
Specific Energy Densities

- Explosives: $4 \times 10^3$ J/gm
- Bituminous Coal: $22 \times 10^3$ J/gm
- Natural Gas: $35 \times 10^3$ J/gm
- Crude Oil: $36 \times 10^3$ J/gm
- D-T Fusion: $2 \times 10^{10}$ J/gm
Fusion Process

- Forcing together Deuterium and Tritium nuclei
- Fuse into a form of Helium
- Emits large amount of energy
- Pellet must be squeezed uniformly to high density for a fusion reaction to ignite and burn - **Major Problem**
ICF Uses the Principle of the Hydrogen Bomb

HYDROGEN BOMB

PROPOSED FUSION REACTION CHAMBERS
Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Fuel is compressed by the rocket-like blowoff of the hot surface material.

During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.
Inertial Confinement Fusion (ICF) Requirements

• Ignition Requirements - Laser or Pulse Power
  • 500 TW
  • 2 MJ of X-ray radiation at 3 million degrees
  • 4 ns
  • Pellet size ---
Fusion Experiment Alternatives

• Magnetic Confinement -- Tokamak
  • Magnetic field confines the energy and particles (traps hot deuterium-tritium plasma statistically long enough for fusion)
    • International Thermonuclear Exp. Reactor (ITER) - ~$6 to $10 B
    • Break-even? - Techn. and political diff. (US, Japan, Europe, Russia)

• Inertial Confinement -- Laser Fusion
  • Inertia confines the energy and particles (lasers used to heat the fusion fuel, blow-off results causing the pellet to implode)
    • National Ignition Facility (NIF) - ~$1.2 B
    • Ignition - 0.1% to 0.5 % equivalent efficiency due to laser technology

• Magnetic Insulation - Inertial Confinement -- Z Pinch
  • B-field confines the energy and inertia confines the particles
    • X1 Facility - ~$0.4 B (Note: Z’s equiv. eff. is 15%; X1’s equiv. eff. ?)
    • HIGH YIELD - fusion energy output >> energy input to the system
US Z-Pinch Programs Directed Towards Weapons & ICF R&D Diagnose Intense X-Ray Sources

• DOD & DOE Nuclear Weapons Effects Sim. (NWES)
  • X-rays in the 1 keV and above regime to study transient response and damage due to exo-atmospheric nuclear bursts

• DOE Weapons Physics (WP) and ICF Programs
  • Soft X-rays below 1 keV
    • Radiation transport and trapping
    • Equation of state
    • Opacity properties of high energy density matter

• X-ray Diagnostics
  • Study initiation and evolution of imploding pinches-optimize X-ray performance
  • Material response to X-ray heating
Z-Pinch Advances at Sandia National Lab.

- **Saturn (1996)**
  - Input: 10 MA, 20 TW
  - Out: 40 TW (90 wire array)

- **PBFA Z or Z**
  - Input: 20 MA, 50 TW, 25 TW/cm², few ns
  - Output: ~3MJ, 290 TW
  - 1.8 million deg. (~233 eV)

- **X1 (High yield)**
  - Input: 60 MA, 150 TW, 75 TW/cm², ~10ns
  - Output: 16 MJ, 10³ TW
  - 3 million deg. (~390 eV)
Cartoon Picture of PBFA-Z or Z
PBFA-Z or Z
Building a Wire Array - Close-Up View

- Wire Array - Single/Double
  - ~1/10 th Dia. human hair
  - 0.7 microns thick
  - Array dia. ~ shot glass
- Wire Material
  - Trial & error approach
    - Al, Ti, Cu, W (Tungsten)
  - K Shell Rad. & Rad. Emissivity
- Wire Placement
  - Symmetry - crucial
  - Small interwire spacing - cont. plasma shell
Experimental Setup of Double Nested Wire Arrays
Close-Up View of a Double Nest Wire Array
The Hohlraum - Vacuum Hohlraum

- Radiation chamber - X-ray oven
- Composite - Gold Coated Chamber
  - High Z (atomic number) lined material
- Secondary Hohlraums - Physics Factories
Target Concepts for X1 - Hohlraum Types

- **Dynamic Hohlraum (a)**
  - High Z imploding plasma shell stagnates on an inner low Z cylinder (foam)
  - Plasma stagnates in the low Z
  - Radiation permeates low Z
  - Outer cooler regions of imploding plasma act as a high Z hohlraum wall

- **Static-Walled Hohlraum (b)**
  - Dynamic hohlraum concept
  - Min. capsule preheat at expense of x-ray drive eff.
Temperatures for 90 TW Pinch Power

- Computer Simulation Temp. (eV)
- Nonuniformity: due to sec. hohlraum
- Active Shock Breakout Diagnos.
  - Measure nonuniformity of rad. field
- VISAR - Velocity Interferometry
  - Al/LiF VISAR sample ~ 1.2 Mbars

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Magnetically Insulated Vacuum Transmission Line - MITL

- High E-field vacuum systems emit electrons above ~ 250 kV/cm
- MITLs use the azimuthal magnetic field generated behind the leading edge of the high current power pulse to trap subsequent electrons into high efficiency (low loss) insulated flow
- This technique has been in constant use since the 1960s

Marx 90–120 sec
Intermediate Store 1µs
PFL 200 nsec
Output 60 nsec
Inductive cavities

Graphs showing voltage and time relationships.
Typical Closing Switch
Equipotential Plots for Typical Closing Switches
ARCS AND SPARKS: OPEN SHUTTER PICTURE OF Z
X-Ray Pinhole Images on Nested Shot 180

- Experimental Data
- Pinch Compression
  - 40 to 1
- Tightest pinch achieved on Z
  - 1 mm diameter

1 ns intervals
Why does Z appear to be so Successful? What is its Secret to Success?

- Instability Problems Addressed?
- Pulse Power Problems Addressed?
- Secret to Success
  - MITL - Magnetically Insulated Transmission Lines
  - Extract the energy quickly, form of x-rays, before instabilities destroy the pinch geometry (FAST PINCH Machine)
  - More thin wires in array allows for a more uniform plasma pinch
Nevada Terawatt Facility - University of Nevada, Reno

- High Density Z Pinch - II (HDZP-II)
  - Existed at Los Alamos National Laboratory
  - Moved to Reno in Summer 1998
  - Smaller Pinch - Couple of Terawatts

- Purpose
  - Z studies at Sandia
    - Limited to about 200 shots / yr
    - Difficult to study pinch properties due to tremendous energies/powers generated
  - Will fill a need for short-pulse, high power, low cost z-pinch with good diagnostics and high repetition rate.
High Density Z Pinch - II (HDZP-II)
HDZP-II Uses Three Stages of Pulse Compression

- Pulse power depends on the fast rise time of the current to the load. Induction effects hinder ideal pulse power operations and need to be minimized.
Staged Z-Pinch: University of California, Irvine

- Laboratory Facility Name: ZOT
- Projected to Achieve Break-even Fusion in a Compact Laboratory Device
  - Two Dim codes suggest that ignition and near unity yield is possible in a staged Z-pinchi driven by 50 kJ energy bank
  - Definitive experiments have not been performed to date
- Slow Pinch Machine
  - MHD instability time scales are important
- Low Cost, Low Maintenance Machine
What Is Meant By “Staged”?

- Objective is Stable Energy and Power Compression

- Energy is coupled in stages
  - Pulse power driver
  - Imploding liner pinch
  - “Squeezes” magnetic field lines
  - Heats prepulsed DT fiber target

- Pinch is multi-shell configuration
Stabilization of Linear Pinch End-On Kerr Cell Photos

Unstable pinch

Pinch stabilized with $B_z$ and $B_\Theta$ fields

2-D Illustration of Staged Z-Pinch Facility and Discharge-Load Region
3-D View of Staged Pinch Facility

- Rail-Gap Switches
- Plate Transmission Line
- Capacitor Bank
- Cable Conduit
- Load Region
- Vacuum Pump

NOT SHOWN: Upper Deck & Cryo-Extruder

3 m
Vacuum Load Region

- Underside of Staged Z Device
- Z-Pinch Vacuum Chamber
  - Anode-cathode gap is 15 mm
  - $I_{sc} = 2$ MA
  - Quarter period rise time = 1.8 $\mu$s
- Vacuum Pumps
Upper Deck

- Load Region
- Maxwell Rail Gap Switches
- Plate Transmission Line (1.25 m x 2.0 m)
  - 6.4 mm thick Al plates
  - Insulated 1.8 mm thick mylar film
- Capacitor Banks
  - 2 sets of Cap. banks each consisting of ten 2.5µF, 50 kV Cap.
Cryogenic Extruder

- Deuterium Fibers are Extruded
  - Deuterium freezes at 14 K
  - In vacuum it can “live” at room temperature
  - Transparent to room temperature infrared
  - Fiber diameters ~110 to 130 µm
  - Gravity is used to maintain a vertical orientation of the fiber in the Z pinch chamber
What Are The Key Mechanisms?

- Staging Process
  - Coupling of energy in different stages.
- Non-equilibrium, Transiently Stabilized, Composite Pinch
  - Two plasmas employed.
  - Dynamic magnetic compression inhibits the instability process.
  - Simulations have shown microsecond orders in stability.
  - Compressing the magnetic field increases the implosion time compared to Fast Pinches.
Conclusion

• *Z-Pinches May Be Used As A Testbed For Plasma Experiments and Diagnostics*

• *Z-Pinches Are Now Strong Contenders In The Fusion Race*

• *Z-Pinches Are Useful Tools In The Stockpile Stewardship And Nuclear Weapons Programs*

• *Someday, Compact University ICF Laboratory Reactors May Be Feasible*