The Dense Z-Pinch Program at the University of Nevada, Reno

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Abstract. A new program of research into the physics of dense z-pinch plasma is being initiated around a high-repetition-rate two-terawatt generator (formerly Zebra/HDZP-II: 2MV, 1.2 MA, 100 ns, 200 kJ, 1.9 Ω final line impedance) transferred to the University of Nevada, Reno Physics Department from Los Alamos National Laboratory. Areas for study include the early-time evolution of a current-driven wire, the plasma turbulence around and between wires, the suppression or reduction of instabilities, the nature of x-ray bright spots, and the tailoring of the x-ray emission spectrum. Novel loads that introduce a stabilizing velocity shear or density profile will be examined, along with configurations that promise to increase the quantity, hardness, stability, and reproducibility of x-ray emission.

A wide variety of diagnostics are being developed, so as to diagnose the plasma thoroughly and make detailed comparisons between experiment, computer simulation, and theory. These include x-ray, soft x-ray, and extreme ultraviolet space- and time-resolved spectroscopy, with polarization measurements; laser interferometry, collective Thomson scattering, Faraday rotation, and laser-induced fluorescence; ion charge spectroscopy with an electrostatic analyzer; and small-angle x-ray diffraction of hard x-rays from the crystal lattice of the solid state load, using a standard x-ray tube and a double crystal monochromator. Quantities to be measured include the ion charge states present in the plasma; the electron density (n_e) and temperature (T_e); the magnetic field (B); the plasma flow speed (v); extreme ultraviolet (2.5 nm < λ < 30.0 nm), soft x-ray (0.3 nm < λ < 2.5 nm), and x-ray (λ < 0.3 nm) emissions; the energy distribution of electrons with particular attention to the direction and relative concentration of suprathermal electrons; the energy and charge-state distribution of ejected multicharged ions; the ablation of neutral gas and the change of state of solid loads; and the amplitude and spectrum of ion wave turbulence.

The plasma z-pinch is one of the most rapidly developing areas of physics and engineering. Driving a giant current through a tiny load is the most efficient and inexpensive method of producing a hot, dense plasma. Much higher confining magnetic fields are generated by a z-pinch plasma than can be externally imposed. Hot, dense plasmas have a wide array of applications, from x-ray sources for biomedical microscopy, defense, and lithography, to the development of thermonuclear fusion; and from the stripping and focusing of ions in accelerators to the production of energetic charged particle beams for the modification of materials. However, the z-pinch would come much closer to achieving its enormous scientific and technological potential if control over the dense, self-compressing plasma were improved. This presents a number of interesting fundamental scientific challenges. First, the dense z-pinch plasma has features that distinguish it strongly from the low-density plasmas that have so far been the primary focus of plasma physics. Particle collisions and radiation transfer are
important in a dense z-pinch plasma, resulting in collective behavior considerably different than those predicted by models developed for collisionless, optically-thin plasma. In the densest regions, multiply-charged ions are strongly coupled, and collective modes likely exist, such as ion sheath waves, that have yet to be confirmed experimentally. Energy gradually stored in metastable excited ionic states can be suddenly released when the ions converge and are collectively collisionally deexcited. Huge magnetic fields influence the atomic processes. Second, the plasma contains strong gradients and evolves rapidly. Different physical mechanisms dominate in different regions as a function of time, and these regimes interact with each other. Complex magnetic field and flow topologies arise when plasmas merge or are twisted by instabilities. Initial conditions and early development can be important. Third, new diagnostics and more detailed experimental observations are needed to accurately measure the complex three-dimensional plasma state, the turbulence and transport driven by the large z-pinch current, and the broad range of z-pinch emissions. Finally, new z-pinch load configurations must be found that increase plasma stability, density, temperature, and reproducibility. Velocity shear, initial density profiles, finite Larmor radius effects, and viscosity could stabilize the z-pinch[1].

To improve our understanding of the z-pinch and devise new schemes that improve its performance, a new program of experimental, theoretical, and computational work is being initiated at the University of Nevada, Reno (UNR). The plasma, atomic, and radiation physics of the z-pinch will be explored with experiments on a high-repetition-rate, 2-terawatt z-pinch [2] (formerly Zebra/HDZP-II) transferred to UNR from Los Alamos National Laboratory. This pulsed power generator, currently being reassembled, will form the core of the Nevada Terawatt Facility. A Center for High Energy Density Science and Technology is being created to facilitate collaborations and coordinate the multi-user facility.

The 2-terawatt pulsed-power generator consists of four major parts (Figure 1). The Marx bank (far right) consists of 32 1.3uF, 100kV capacitors, which can store a total of 200kJ of energy. The bank is coupled to a water-filled, 26mF, 2MV intermediate storage capacitor (the horizontal cylinder in the middle of the device). An SF₆-insulated “rimfire” switch connects the intermediate store to a 50ns, 1.9Ω water-filled vertical transmission line (the vertical cylinder on the left). A self-breaking water switch couples the final feed to the load, located in the vacuum chamber on top of the vertical transmission line. An electrical pulse of up to 1.2MA at 2MV is delivered to the load, with a 100ns rise time.

The z-pinch will be thoroughly diagnosed so as to make detailed comparisons between experiment, theory, and computer simulation. All important plasma parameters will be measured, for the most part with spatial and temporal resolution. An overview of the diagnostics planned is shown in Figure 2. Many x-ray measurements will be performed, both because this is the most feasible way of gaining access to the dense z-pinch plasma, and because x-ray emission is closely correlated with plasma dynamics and is important in determining plasma evolution. A novel two-dimensional x-ray imaging spectrometer will use glass capillaries [3] to multiplex a two-dimensional plasma image (from 0.02 to 100 nm in wavelength) into a spatially-separated array of pixels, to be spectrally dispersed, recorded by a temporally-gated imager, and reconstructed as an image by a computer.
FIGURE 1. Pulsed Power Generator of the Nevada Terawatt Facility (NTF)

- multiband x-ray imaging spectrometer
- x-ray polarization Bragg spectrometers
- aided multilayer grating spectrometer
- laser diagnostics
  - interferometry
  - CTS
  - Faraday rotation
  - induced fluorescence
  - absorption imaging
- GCC multiband 2-D EUV x-ray imaging spectrometer
- soft x-ray microscope
- multichannel pinhole camera with MCPs
- filtered pinhole cameras
- multiple filtered x-ray diodes
- filtered thermoluminescence detectors
- x-ray diffraction diagnostic
  (measurement of transition of ion from solid state)
- gated optical imaging
- ion spectrometer
- ion probe

FIGURE 2. Overview of Diagnostics of the Dense Z-pinch Program at the University of Nevada, Reno.
magnetic field and the anisotropy of the energetic electron distribution will be measured using polarization-sensitive x-ray imaging spectrometers, interpreted by detailed spectral calculations [4]. Quantities to be measured include the ion charge states present in the plasma: the electron density \( n_e \) and temperature \( T_e \); the magnetic field \( (B) \); the plasma flow speed \( (u) \); extreme ultraviolet \((2.5 \text{ nm} < \lambda < 30.0 \text{ nm})\), soft x-ray \((0.3 \text{ nm} < \lambda < 2.5 \text{ nm})\), and x-ray \((\lambda < 0.3 \text{ nm})\) emissions; the energy distribution of electrons with particular attention to the direction and relative concentration of suprathermal electrons; the energy and charge-state distribution of ejected multicharged ions; the ablation of neutral gas and the change of state of solid loads; and the amplitude and spectrum of ion wave turbulence.

The plasma will be carefully modeled with two-dimensional radiation-magneto-hydrodynamic simulation codes (in collaboration with other researchers) [5,6]. In addition, particle-in-cell, Fokker-Planck, and non-local-thermodynamic-equilibrium radiation transport calculations will yield further insight into the interplay between the plasma, atomic, and radiation physics. The effect of collisions and radiation transport on instability thresholds and growth rates will be examined numerically and analytically. Detailed synthetic spectra [4,7] will be computed for the interpretation and analysis of experimental data.

Novel \( z \)-pinch load configurations with the potential for greatly enhanced plasma stability or performance will be explored. With improved stability, the \( z \)-pinch could yield a solution to the challenge of controlled fusion. Similarly, the quantity, hardness, stability, and reproducibility of x-ray emissions could be increased. The effects on plasma instabilities of velocity shear, initial density profile, finite Larmor radius, and other conditions will be investigated. Velocity shear will be produced by injecting high-speed plasma [8] along and around a wire prior to the discharge.

We hope to improve the understanding of hot, dense \( z \)-pinches; develop new \( z \)-pinch diagnostics and loads; and help develop \( z \)-pinch applications.

REFERENCES