The influence of the load’s geometrical characteristics on the generation of the electro-thermo-mechanical instability in a single wire Z-pinch

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Abstract. The Z-pincher plasma device is a type of plasma confinement system that uses electrical current to generate a magnetic field which compresses a current-carrying wire. In a previous proof-of-principle study, we demonstrated that in the interaction of a single wire with a pulsed current, the generated Electro-Thermo-Mechanical (ETM) instability in the solid phase acts as a seeding mechanism for the later developed instabilities observed in the plasma phase. In this study, the influence of the geometrical characteristics, such as length and thickness of the loadwire, on the generation of the ETM instability are investigated. Finite element multiphysics-multiphase simulations starting from the solid state are coupled with Magneto-Hydro-Dynamics (MHD) simulations to study the solid to plasma phase transition and the matter’s dynamics. The numerical results of the wire expansion dynamics prior to plasma formation are validated by experimental results from a modified Fraunhofer diffraction diagnostic, while in the plasma phase the simulated plasma dynamics is validated by shadowgraphic and interferometric experimental results. The numerical and experimental results demonstrate a satisfactory agreement for the wire expansion dynamics and the growth rate of the developed instabilities, for varying wire thickness and length.

1. Introduction

The study on plasma instabilities is a research object of fundamental importance in an international level, since in most plasma applications their existence is undesirable [1,2] and the need for their suppression is necessary. The understanding of the natural mechanisms that generate instabilities is of critical importance in magnetic inertial fusion or inertial confinement fusion to heat conductive targets that interact with either high-power pulsed currents or high-power laser pulses [3,4]. Characteristic cases of conductive targets that interact with strong pulsed currents and magnetic fields are: the Z-pinch plasma confinement system [5], Z-pinch wire arrays [6], X-pinch plasma confinement system [7] and the conductive cylindric liners with fusion fuel contained in them, where implosion phenomena occur [8].

We have recently demonstrated that the effective study of plasma dynamics requires the incorporation of the intrinsic real physical characteristics of the solid target. The study was conducted
in a single wire Z-pinch configuration, which was selected since it has been extensively studied with well understood plasma dynamics and known plasma instabilities [9]. We studied for the first time the heating of the cylindrical target through computational simulations and experiments, from its solid to plasma phase, by considering the phase changes of matter. The agreement of the results between the physical model and the experiments has shown that the incorporation of the real physical properties of the solid target is catalytic for the understanding of the instabilities that develop in the target prior to plasma formation and constitute a precursor for the generation of the plasma magnetohydrodynamic (MHD) instabilities. We have named this instability, prior to plasma formation, electrothermomechanical (ETM) instability.

The current research focuses on the influence of the geometrical characteristics, such as length and thickness of the load-wire, on the generation of the ETM instability. Finite element multiphysics-multiphase simulations starting from the solid state are coupled with Magneto-Hydro-Dynamics (MHD) simulations to study the solid to plasma phase transition and the matter’s dynamics. The numerical results of the wire expansion dynamics prior to plasma formation are validated by experimental results from a modified Fraunhofer diffraction diagnostic, while in the plasma phase the simulated plasma dynamics is validated by shadowgraphic and interferometric experimental results. Copper and silver wires are considered for this study. The numerical and experimental results demonstrate a satisfactory agreement for the wire expansion dynamics and the growth rate of the developed instabilities, for varying wire thickness and length.

2. Numerical modeling
3D finite element multiphysics-multiphase simulations starting from the solid state are performed using the LS-DYNA multiphysics solvers [10]. The FEM model considers the phase changes from thermoelastic to plasma phase, while a transient 3D multiphysics coupled electromagnetic thermomechanical hydrodynamic analysis takes place. Three solvers are employed for the numerical solution of the physical problem: Electromagnetic, Thermal and Mechanical. Maxwell’s equations, which are based on the Eddy current approach, are solved using finite elements for the wire. The surrounding vacuum is modeled with boundary elements coupled with the finite elements. When the electromagnetic fields have been computed, the Lorentz force \( \mathbf{F} = \mathbf{j} \times \mathbf{B} \), where \( \mathbf{j} \) is the current density and \( \mathbf{B} \) the magnetic field, is evaluated at the nodes and added to the mechanical solver, which computes the deformation of the wire. The new geometry is then used to compute the evolution of the EM fields in a Lagrangian way. In addition, the joule heating power term \( \mathbf{j}^2 / \sigma \) is added to the thermal solver to update temperature, where \( \sigma \) is the electrical conductivity. The thermomechanical response of the exploded material considers both the hydrodynamic behavior of the material, using a specific EOS and the elastoplastic material’s behavior, using a dedicated strength material model. The electrical conductivity vs. temperature and density is computed using the Burgess EOS. The current waveform, measured during the experiments, is used to drive the expansion of the metal wire, while the ends of the wire are at ambient temperature.

Temperature-dependent properties of thermal properties, such as thermal expansion, thermal conductivity and specific heat, of mechanical properties (Young’s Modulus) as well as the latent heat of melting and vaporization are considered. The FEM results of density and temperature distribution, when plasma is formed based on temperature-based criteria [9], are coupled as initial conditions to a resistive open source MHD code, considering a single fluid approximation, to study the plasma evolution and dynamics.

3. Experimental methodology
The experiments are performed by utilizing the pulsed power Z-pinch plasma device that exists at the facilities of IPPL. A high current rate of \( \sim 1 \) kA/ns is provided to a typical load reaching a peak current of \( \sim 40 \) kA in 60 ns. The load in the Z-pinch configuration is a single straight wire placed between anode-cathode electrodes and remains under vacuum (\( 10^{-4} \) mbar) to avoid the environmental influence on the generation and plasma dynamics. The experimental study of the electrical wire explosion is implemented by various laser probing diagnostics utilizing the second harmonic (532 nm) of a Q-switched, SBS-
compressed, Nd:YAG laser of 150 ps pulse duration. This laser pulse duration enables the capability of sub-ns time resolved optical probing measurements, which are required for the very fast evolving phenomena that occur during the wire explosion. For the study of the wire expansion evolution before the plasma formation a method to measure the wire thickness based on Fraunhofer diffraction is used [9,11]. For the study of the plasma generation and plasma dynamics of the wires optical probing techniques such as shadowgraphy, schlieren and interferometric imaging are used [9].

4. Results and discussion

Copper and silver wires with diameter in the range between 250 and 300 μm and a length between 5 and 15 mm were examined in this study. Four different test cases are considered; for a Cu wire having: (a) a length of 15 mm and diameter 300 μm, (b) a length of 5 mm and diameter 300 μm and (c) a length of 15 mm and diameter 250 μm and for a Ag wire (d) with a length of 15 mm and diameter 250 μm.

For the Cu wire with 300 μm diameter the outer part of the wire enters in the melting and gas regime at 90 ns and 140 ns respectively, while plasma is initially formed at 200 ns from the current start. The different length of the wire does not influence the expansion rate from solid to plasma phase, therefore cases (a) and (b) follow the same behavior. For the Cu 250 μm diameter wire, case (c) the melting and gas phases are initiated at 80 and 125 ns from current start, while plasma is formed at 160 ns. For the Ag 250 μm diameter wire, case (d) the melting and gas phases are initiated at 70 and 110 ns from current start, while plasma is formed at 140 ns. In figure 1 are depicted results of the wire expansion in relation to time for the cases (a), (c) and (d). The case (a) is also validated by experimental results of the Fraunhofer diffraction technique. For this case, an average radial expansion rate of 53 m/s results from experimental measurements, while a radial expansion rate of 50 m/s is computed in the simulations 140 ns from current start. For the same temporal moment, an average radial expansion rate of 65 m/s is computed for the 250 μm Cu wire and respectively 74 m/s for the Ag wire.

![Figure 1. Wire expansion as a function of time](image-url)
Regarding the influence of the length and the thickness of the wire on the dominant average wavelength of the developed ETM instability, figure 2 shows simulation results of the density of the outer part of the wire as a function of the length of the wire, at the time instant when plasma is initially formed. The cases (a), (b), (c) are considered for a Cu wire. The dominant average axial wavelength for the ETM instability is 228 μm for (a), 162 μm for (b) and 230 μm for (c). It can be assumed that the reduction of the wire length reduces the average wavelength of the ETM instability, while the wire’s thickness variation affects slightly the average wavelength.

![Figure 2. Mass plasma density of the outer part of the wire as a function of the Cu wire length](image)

In the plasma phase, 30 ns after the initiation of plasma formation, the dominant average wavelength for the test case (a) is computed to be 555 μm, for case (b) 500 μm, for case (c) 625 μm and for case (d) 600 μm. For the same time period, the average growth rate of the plasma instability is calculated to be $3.1\times10^7$ s$^{-1}$ for cases (a) and (b), $3.3\times10^7$ s$^{-1}$ for case (c) and $3.6\times10^7$ s$^{-1}$ for case (d). The experimental results are in good agreement with the corresponding produced by simulations. It can be concluded that the growth rate of the developed instability is invariant of the wire diameter and length. Figure 3 presents a typical density distribution of a 250 μm diameter wire (case c), 30 ns after plasma initiation. The dominant average wavelength for the simulation is computed to be 625 μm, while for the experimental shadowgraphic result is measured to be 600 μm.
5. Summary
This study explores the influence of the load’s geometrical characteristics on the generation of the ETM instability in a single wire Z-pinch. Multiphysics-multiphase simulations, along with experimental measurements for the different phases of state are carried out. It can be concluded that the reduction of the wire length reduces the average wavelength of the ETM instability, while the wire’s thickness variation affects slightly the average wavelength and the growth rate of the developed instability is invariant of the wire diameter and length. Further simulations and experiments regarding the influence of coated wires on the generation of the ETM instability will be carried out.

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