Studies of Conical Plasma Liners: Simulation vs Experiment[1]

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Abstract – The aim of the work is multiparametric studies of cumulation effects in conical wire array Z-pinches. We have carried out MHD-simulation of magnetic compression of plasma liners created by conical multiwire arrays electrical explosion. These simulations reproduced the experiments performed at «ANGARA-5-1» facility (TRINITI). The experimental Z-pinch implosion was implemented with the discharge current 2 to 3 MA and the pulse rise time about 100 ns.

The description of the plasma dynamics at different stages of implosion was reproduced as a result of simulation. Numerical and experimental time profiles of voltage drop at the load and soft X-ray yield power were compared. The effect of the geometry changes upon the implosion process was studied.

Numerical simulation was based on 2D RMHD code MARPLE (IMM RAS) using unstructured triangular grids. The code implements one-fluid two-temperature MHD model. Radiative energy transfer is computed by means of grid-characteristic method. Model of prolonged plasma ablation was applied to simulate plasma source. The governing MHD system of is completed by electrical equation for the full circuit including the generator itself, leading-in systems and the discharge chamber with the plasma in it. Equations of state, transport and kinetic coefficients, opacity and emissivity coefficients are taken from the tables.

Numerical experiments proved the behavior of the discharge to be satisfactory described in general by 2D one-fluid two-temperature RMHD model with prolonged plasma ablation implemented in the code MARPLE. This code calibrated against the conical liners simulations may be further applied to serial computation aimed to optimization of the experimental setup for 3D implosion of plasma.

1. Introduction

The theoretical level of the power engineering problems investigations may be improved drastically at present time due to burst out progress of high performance computing systems enabling more realistic simulations. Modern problems in pulsed-power energetic issue challenge to the computer simulation theory and practice. An essential part of such numerical investigations is devoted to computer simulation of self-constricted discharges, or pinches, resulted from electric explosion of cold matter, e.g., gas-puff jets, foam strings, or metallic wire arrays. The goal is to study the evolution of very intensive transient electric discharges and to perform a multiparametric optimization of future experimental schemes. Numerical experiments cover considerable part of laborious work in planning natural experiments, prediction of experimental schemes efficiency, and experimental data analysis. The team from the Institute for Mathematical Modeling, Russian Ac. Sci. (IMM RAS) in collaboration with colleagues from Kurchatov Institute and Troitsk Institute For Innovation & Fusion Research (TRINITI) and other research centers proposed new computer models of high-speed radiative magnetohydrodynamic processes and developed novel problem statement data representations especially efficient for implementation of complex models. These theoretical and practical studies resulted in creation of application scientific high-temperature hydrodynamics and magneto-hydrodynamics code MARPLE (Magnetically Accelerated Radiative Plasma Explorer).

2. General description of a radiative magneto-hydrodynamics code MARPLE

The code is based on the single-fluid two-temperature magnetohydrodynamic model [1] taking into account radiative energy transfer [2], supplemented with the

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prolonged plasma ablation model [3], the electrical equation for the full circuit (generator, leading-in systems and the discharge chamber with the plasma in it), and computed/experimental database (equations of state, transport and kinetic coefficients, opacity and emissivity coefficients) in the form of tables and analytical dependencies [4]. Different types of 2D symmetry are provided.

Up-to-date numerical methods and software engineering were applied for implementation of the above models and computer simulations. Complex geometry of experimental and industrial facilities as well as spatially non-uniformly scaled physical processes is handled by use of unstructured meshes: triangular/ quadrilateral/ blocked. The MHD system is solved by the generalized TVD Lax-Friedrichs scheme which was developed for the unstructured mesh applications. For the solution of parabolic equations describing the magnetic diffusion and conductive heat transfer, we developed the new finite-volume schemes constructed by analogy with mixed finite-element method. The radiative transport equation is solved by means of semi-analytical characteristic algorithm. The analytical solution along the characteristic direction is constructed by means of the backward-forward angular approximation to the photon distribution function known as the Schwarzschield-Schuster technique [2]. The energy exchange between radiation field and plasma is taken into account via a radiative flux divergence, which is incorporated into the electron plasma component energy balance as a source function. Diverse physical models processing and modification is supported by overall splitting scheme when the physical processes are included consequently.

Flexible software architecture based on C^{++} object-oriented programming provides updating possibility and readability of the code. The developed application software is compatible with different operating systems (MS Windows, Linux, UNIX) and different platforms (PC, powerful workstation, mainframe including parallel processing). In order to ensure teamwork of all the project developers at all the stages – programming, simulations, further accompaniment of the code and its further development – the code construction is based on bloc principle.

MARPLE data preparation tools are developed using the technique based on IC models [5]. MARPLE preprocessor comprises all activities concerning data preparation, namely geometry definition, mesh generation, problem description (boundary conditions, material properties, and so on).

3. Governing system and the boundary conditions

We consider here the case of axially-symmetrical plasma flows. The governing system [1] including the radiative energy transport was written in terms of cylindrical R-Z geometry. The energy balance is described via the relaxation of electron and ion temperatures, Joule heating, and radiative energy source. Correspondingly, the plasma pressure P is calculated as the sum of electron P_e and ion P_i components. We take into account the anisotropy of transport coefficients, i.e., thermal and electric conductivities dependence on the magnetic inductance value and orientation. The problem considered here is described by the MHD-system taking into account two non-zero components of the velocity $V = (u, 0, v)$ and electric field strength $E = (E_r, 0, E_z)$, while the magnetic inductance has only azimuthal component $B = (0, B_\varphi, 0)$. For practical calculations of tungsten wire arrays, we use the EOS and opacity and emissivity data tables compiled using the techniques described in [4] (code TERMOS, Keldysh Institute for Applied Mathematics, RAS).

The zero-normal velocity condition is applied at the electrode surfaces, which are assumed being equipotential. The electric current density is normal to the electrode surface. (No Hall and gradient-dependent terms in the Ohm's law equation were considered.) Both the electron and ion thermal flux at the boundary was zero since the energy exchange between the plasma and the electrode surfaces is negligible.

The boundary magnetic inductance at the external wall is calculated according the Biot-Savar formula via the experimentally measured time dependence of the total electric current through the plasma volume.

4. Voltage drop at the generator load

In order to compute the evolution of the electric current in the discharge chamber circuit correctly the governing MHD system is supplemented with the equation for full electric circuit including the generator itself, the leading-in lines and the discharge chamber with the plasma inside. The discharge chamber volume may be described as a circuit element with variable resistance and inductance. The electrotechnical equation is derived from the electromagnetic induction equation integral formulation and is written for the full current in the overall circuit.

The time dependence of the computed voltage drop at the generator load $U(t)$ is an important criterion for comparison of the experimental and numerical results. For this purpose, the computational scheme for the governing RMHD system solution includes the procedure for calculation of the voltage drop at the generator load. The algorithm is based on the energy balance in the form fist discussed in [5]:

$$\Delta U = \frac{W_p}{I};$$

$$W_p = \frac{d}{dt}\int \frac{H^2}{8\pi} dV + \int \frac{j^2}{\sigma} dV + \frac{1}{c}\int w[j, H]\, dV,$$

where ΔU is the voltage drop, $I(t)$ is the electric current (a given function of time in our present computations), W_p is the power input from the external circuit including the intensity of the magnetic field energy change, the Joul heat power and the ponderomotive force work in plasma.

5. Computer model of plasma ablation

Plasma ablation model generalizing that suggested in [3] was used for simulation of prolonged plasma production. Our model assumes that the wire carcass is stable during the entire plasma production time in full agreement with experimental facts. In 2D plasma, ablation is modeled by a fixed plasma source located on a surface inside the computational domain. The plasma production continues until the complete evaporation of the wire carcass. When the load is balanced with the current pulse growth rate, the ablation is finished soon after the current peak.

The plasma production is included as a step in the overall splitting scheme. Plasma ablation rate is given by the formula

$$\frac{d}{d_t}m = \begin{cases} kB(t)^2 & \text{for } t < t_b \\ \dfrac{kB(t_b)^2}{M_0(1-\alpha)}\left(M_0 - m\right) & \text{for } t \ge t_b \end{cases}, \qquad (1)$$

where t_b is defined by the condition $m(t_b) = \alpha M_0$.

The array full mass M_0, the magnetic induction $B(t)$, and t_b are functions of the plasma source location. In the above formula dm/dt is the plasma ablation rate from the square unit of the ablation surface. This surface in the (r, z) plane is defined by a line equation. According to the experimental data, we assume that the temperature of the evaporated plasma is 10 eV and the ablation velocity is 15 cm/mks. The energy and momentum conservation laws in the vicinity of the source are provided in the finite volume scheme

6. Experiment conditions

One of the possible ways to effect on the soft X-ray yield profile is using axially symmetrical conical wire arrays instead of cylindrical ones. Besides that, such configuration allows supervised experimental study of the prolonged plasma ablation and 3D hydrodynamic effects in the implosion of wire arrays. This work deposits new knowledge into the theoretical development of the quasispherical dynamic hohlraum.

The 3D plasma dynamics is investigated experimentally and numerically. The "ANGARA-5-1" facility generates an electric pulse with a current amplitude of up to 3 MA which causes an implosion of wire array in the Z-pinch mode. The array has a "truncated cone" form and made of tungsten wires 6–8 mkm diameter (see Fig. 1). The angle between the cone axis and the ruling of cone varies in the range 150–490. The experimental data are compared with numerical results via spatial or temporal distributions of the X-ray sources. It is found that the precursor dynamics related to the conic array implosion differs from that of the cylindrical one. Experiments as well as numerical simulations show that the maximum radiation power time depends only on array mass and radius, and generator current. The radiation pulse duration depends on the initial heterogeneity in the liner mass distribution or wire ablation rate.

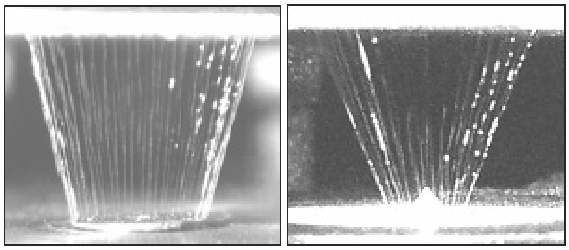

Fig. 1. Conical wire arrays with flat and cone-shaped cathodes

7. Numerical results

We simulated three experiments at Angara-5-1 with conic multiwire arrays and carried out the comparison with the experiments including voltage drop between the electrodes at a certain distance from the axis and the soft X-ray pulse profile. The pictures of two arrays just before the experiments are presented in Fig. 1.

The initial data for simulation were the dimensions and mass of the array and the generator electric current applied (experimental data). They are listed in the Table. The heigth of all arrays was 1.5 cm.

Table. Wire arrays parameters

Experiment	M_0 (mkg)	Cone angle	Cone base diameter	Cathode shape
4482	370	27°	5 cm	flat
4489	370	27°	5 cm	cone
4499	335	15°	6 cm	flat

The parameters of plasma ablation model in Eq. (1) were the same for all simulations, $k = 0.27$ (code units) and $\alpha = 0.5$. These parameters were obtained from calibration of 1D model vs experiments with standalone cylinder liners.

Simulated profiles of the voltage at the outer edge of the domain of simulation and soft X-ray pulses can most directly be compared with the respective experimental data. Fig. 2 shows measured and simulated voltage at the outer edge of the computational domain and time profiles of the soft X-ray pulse as synchronized with the generator current. 2D plots of distributions of plasma parameters (density, temperature and velocity) and magnetic field are also very useful to insight into plasma dynamics in such experiments. Successive stages pinch formation (2D plots for plasma density) obtained during the simulation of the experiment 4482 are presented it Fig. 3.

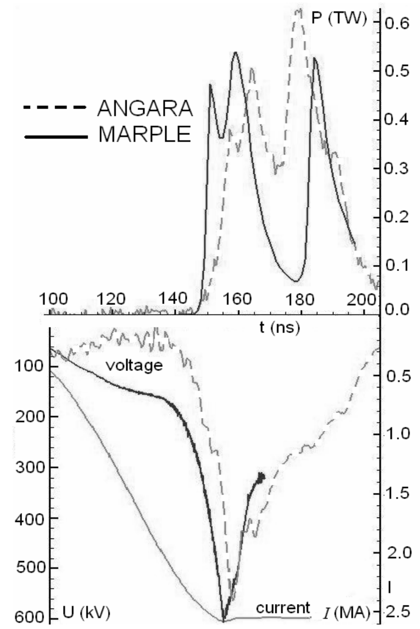

Fig. 2. Voltage (kV) and SXR-pulse (TW) (ANGARA – experiment, MARPLE – simulation)

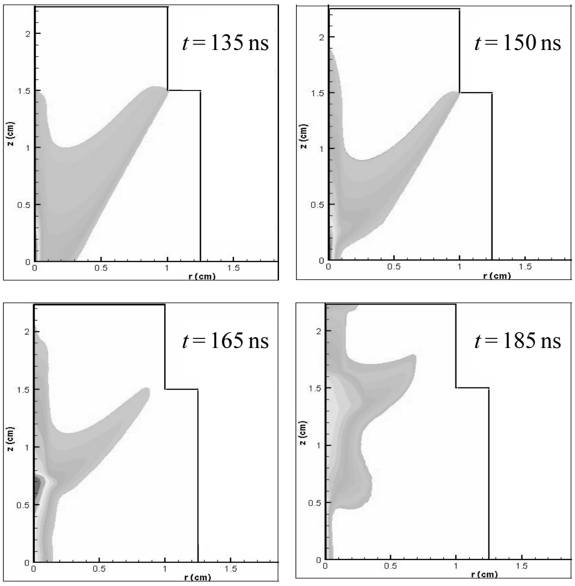

Fig. 3. Pinch shape in 4482 simulation (t = 135 ns – precursor formation; t = 150 ns – SXR prepulse; t = 165 ns – the first SXR pulse, t = 185 ns – the second SXR pulse, radiating zone split)

The 2D RMHD simulations by the MARPLE code reproduced sufficiently well general properties of compression of the conic multiwire arrays including the process of prolonged plasma production. The simulations confirmed the hypothesis that the cone-shaped cathode insertion helps to avoid pinch split. A certain mismatch (less than 10 ns) in time of simulated and measured voltage and X-ray pulses is caused probably by the plasma ablation model inaccuracy.

8. Conclusions

It turns out that the conical liner is an object enriched with a considerable number of various features. Therefore, it suits well for testing the RMHD code and the radiative transport module.

It seems possible to construct sufficiently accurate ablation rate function dm/dt via fitting of numerical results to experimental data.

The present-day code version reproduces accurately the nature of experimental results.

After the revision of the computer model and adjusting it via simulations of experiments with conical liners the code MARPLE may be used for estimation of future quasispherical liner parameters.

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