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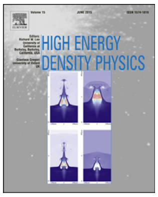

Optimization of an electromagnetic generator for strong shocks in low pressure gas

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ABSTRACT

In this paper, we present the design and optimization of an electromagnetic generator, able to produce strong shocks in noble gases, relevant to astrophysical conditions. It is a powerful accelerating device which ejects a quasi-planar plasma sheath out of a set of coaxial conical electrodes where a pulsed 100-kA current is passing. A simple model is used to optimize the operation parameters. Preliminary experiments show that the generator is capable of launching supersonic shocks in Argon, in the form of a thin plasma layer with the speed of ~1–30 km/s. A three-dimension MHD simulation gives a description consistent with the model and with the observations.

1. Introduction

The study of the processes governing the accretion and ejection of matter are key elements to predict the evolution of Young Stellar Objects (YSOs) and their feedback to the interstellar medium. The observational signature of mass accretion is correlated to the presence of a strong shock which forms when the matter from a circumstellar disk hits the photosphere of the star. In this context, laboratory plasma astrophysics is a powerful tool to study the dynamics of these hypersonic processes [1].

During the last decade, a number of experiments have been conducted to study accretion shocks on large-scale laser facilities. In such experiments, a powerful beam in the ns-regime is focused on a foil ($>10^{14}$ W cm^{-2}) closing a cell filled with a high atomic number gas, at a fraction of a bar. The ablation process induces a shock wave in the foil, which then propagates in the gas at a velocity of several tens of km/s [2]. Numerical simulations can describe these shocks with an improving precision [3]. Complementary to laser experiments, compact pulsed power generators may drive an electromagnetic coaxial plasma gun to create astrophysically relevant shocks in low pressure noble gases [4] with a high availability and a rather modest capital cost. The electromagnetically driven shock waves may have larger scales than those by laser; thus they can be observed rather easily [5].

In this paper, we present the design, calibration and results of a compact electromagnetic plasma generator with the aim to produce supersonic shocks up to ~40 km/s speed at static pressures of few mbar. We consider a coaxial plasma gun operating in a snowplow regime [6], i.e. where the radial electrical discharge is accelerated by the Lorentz force and is accreting gas along its path. The geometry is optimized using a lumped-parameter iterative model [7,8], linking the transient discharge dynamics and quantities like mass and speed of the plasma sheath. The results of this 0-D model will be compared to 3-D MHD simulations performed with the code GORGON which has been used successfully to describe other pulse-power driven plasma experiments [9] as well as laboratory plasma astrophysics experiments [10]. The diagnostics which are currently implemented will be presented to illustrate the model as well as preliminary records of the plasma speed.

2. Device

Our aim is to generate fast moving plasma with a quasi one-dimensional geometry. A surface discharge is a well-known way to initiate a cm-size plasma layer [4–8]. The targeted speed of few cm μs^{-1} imposes a characteristic duration of 1 μs for the acceleration process and for the application of magnetic forces. Finally the accelerator must be connected to a tube where the plasma can propagate in the background gas. The resulting device is described

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in Fig. 1. The pulsed power generator is based on a capacitive storage at the kJ level and a triggered switch, feeding a discharge cell filled with gas at low pressure (0.1–10 mbar) as proposed by Kondo et al. [4]. A transient high voltage (15 kV in 20 ns) is applied to a short gap between a pair of coaxial, conical electrodes, initiating a surface breakdown on a polyacetal plate. Then, the electrical discharge takes place radially in a thin layer of gas between the electrodes and it carries a rapidly rising current (typ. 200 A/ns). The high-intensity current (up to ~ 150 kA) generates a strong azimuthal magnetic field between the electrodes, thus resulting in a magnetic pressure *jXB* which accelerates the annular plasma sheath (Fig. 2). A hot and fast moving plasma is produced, which travels axially between the electrodes. During this motion, the plasma sheath accretes a noticeable part of the background gas, around 40% [6].

Compared with the Mather-type plasma focus [6,8], the plasma sheath considered here is quite planar close to the insulating surface and, later, is less affected by the radial variation of the B-field in the relatively short gap. However the thickness of the plasma sheath increases gradually [8], staying in the mm-range. We employ coaxial conical electrodes, each 42-mm high, with a gap of 2.5 mm at the surface of the polyacetal insulator (Fig. 1). At the bottom level, internal and external radii of electrodes are 12.5 mm and 15 mm respectively. A tube with the internal diameter of 4 mm is connected at the top of external electrode ensuring the free flight of the shock after it leaves the accelerating section. This small-size discharge cell, on top of the table-top generator, is being modeled in the following section.

3. Circuit design and optimization of the electric generator

We optimize the electric generator for various gases, namely Ar and Xe, with the motivation to produce plasma shocks with speeds ~1–30 km/s, i.e. Mach numbers up to 200. For that purpose, we design the electrodes and configure the electrical circuit parameters to produce 1-μs pulses in the gas chamber. The geometry of the electrodes is mentioned above. The half angle of the conical electrode is chosen to be 15° and thus the height of the cone is *h* ~42 mm.

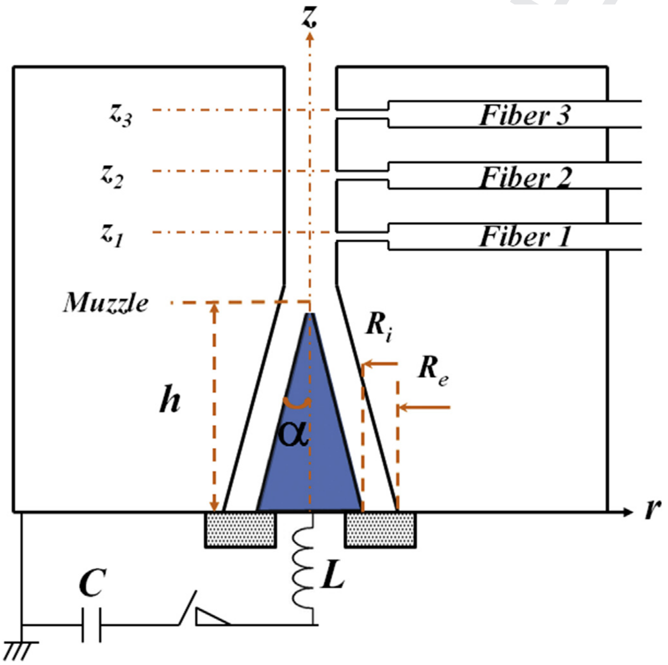

Fig. 1. Sketch of the shock generator showing the pulsed electrical circuit, the set of coaxial conical electrodes with a constant radial gap and the plastic insulator, featured in grey, on which a planar surface discharge is initiated. The installation of three optical fibers, at $z_1 = 62.5$ mm, $z_2 = 70$ mm and $z_3 = 77.5$ mm, allows looking radially at the plasma moving inside the shock tube.

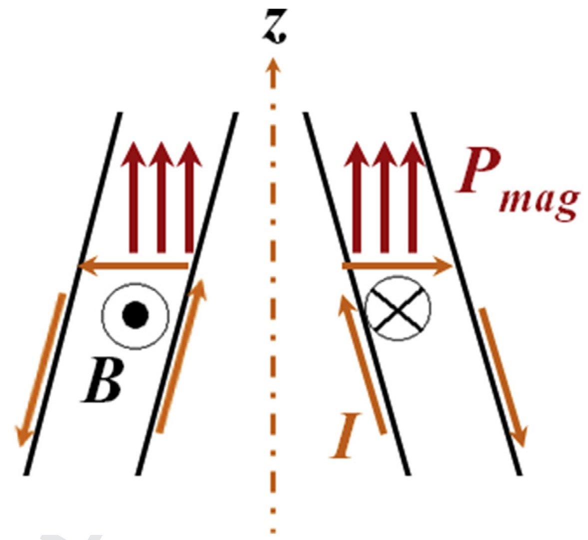

Fig. 2. Schematics of the plasma dynamics inside the coaxial gun: in fast-pulse mode, the electrical current flows in the superficial layers of the two coaxial conical electrodes and through an annular plasma layer. The magnetic pressure *Pmag* pushes the discharge axially.

Eleven ($N = 11$) capacitors, each with capacitance C_0 of 0.6 μF, are connected in parallel, giving an equivalent capacitance of the bank $C = 6.6$ μF. Charging voltage U_0 of the bank is set to 15 kV. Thus, the available electrical energy is 750 J. The circuit resistance is used to be 1 mΩ and damping resistance is set to zero, which yields a total resistance ($R = R_{cir} + R_{damp}/N$) of 1 mΩ, and a pseudo-periodic regime is expected.

Based on the above geometrical and electrical parameters, we have estimated the time evolution of various parameters of the radial discharge layer, namely speed, mass, acceleration etc. at different position along the axis, from $z = 0$ to *h*. For this calculation, we need to solve a set of three equations which give the main current ($-dq/dt$), which is supposed to flow only through the plasma layer, the mass accretion rate (dM/dt) and the velocity *v* of the plasma. These equations together with initial conditions are explained below. The classical RLC circuit equation is written as:

$$Ld^2q\big/dt^2 + R\,dq/dt + q/C = 0 \tag{1}$$

When the *R*, *L* and *C* parameters are time-independent, the circuit Eq. (1) has an analytical solution, a damped sinusoid for the current $I = -dq/dt$, and that was used as a test of the iterative solving process and to confirm the parameters of the external circuit with a short circuit load. The inductance of the external circuit L_0 is computed from the ringing frequency in short circuit (66 nH), which results in a circuit impedance $Z_0 = (L_0/C)$ to be 0.1 Ω. In the plasma gun mode, the sheath carrying the current (cf. Fig. 2) is accelerated by the magnetic pressure, and it behaves as the deformable part of the circuit; then *L* is time-dependent and a numerical solver is necessary for Eq. (1). We used a lumped-parameter model which has proven to describe similar circuits successfully [7,8]. Gonzalez [7] showed that the mass and momentum equations for a current sheath, in the shape of an annular piston moving forward in the axial direction, can be given by

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