Some pioneering research in laboratory simulation of scaled astrophysical phenomena by Russian physicists

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Abstract. The review about the problems of astrophysical phenomena pioneering researching by Russian recognized physicists – S.Anisimov, I.V.Minin, O.V.Minin, V.F.Minin and A.Velikovich - is carried out. For the first time, a mode of hypercumulative collapse of a conical cavity was proposed for the formation of an ultra-high-speed plasma jet. The description of “cumulative plasma jets” is presented. The main parameters of the cumulative plasma jet and the results of laboratory studies on the creation of a hypercumulative plasma jet are described. It was shown that the proposed mechanism allows one to obtain record characteristics of such a jet, which have not been surpassed so far. Test data description of the numerical simulation of the interaction between plungers and a conic cavity on the explosive initiation of the D-D reaction with the aid of aluminum plungers is discussed. The mechanisms of the plunger surface acceleration are described. The generation of the Mach configuration of shock waves in the target was also used for the explosive production of wurtzite with a record yield of the mass of the synthesized material and to focusing of the shock waves in water using plane diffractive optics.

1. Introduction
Laboratory simulation of scaled astrophysical phenomena by matching dimensionless scaling parameters [1] has been the topic of a large number of research such as the formation of jets ejected from Young Stellar Objects [2]. Plasma jets are often associated with black holes [3] and may be generated during the core-collapse of massive stars [4]. The plasma jets are also often seen propagating away from the star at speeds of the order of 100-200 km/s, with lengths up to 0.1 parsec [5]. And the jets are seen to terminate in regions of optical emission produced by bow shock [5, 6].

The paper is structured as follows: the chronology of pioneering scientific results of Russian physicists in the field of pulse plasma jet formation under laser interaction with conical targets; Discussion of hypercumulation methods as applied to the formation of a plasma jet, providing record characteristics in terms of velocity, mass and momentum; Formation of the Mach configuration of shock waves under loading of a conical target for the formation of super-high pressures; Explosive loading of the target for graphite-to-diamond transformation under Mach wave interaction is also discussed. The conclusions derived from the results of the study are presented.

2. Scientific results of Russian physicists
Sergei Anisimov et al. [7] from Landau Institute for Theoretical Physics, Russian Academy of Sciences, was the first who have suggested to study the laboratory scale “cumulative plasma jets” created using lasers. The formation of plasma jets was based on the classical theory of collapsing shaped charge liner by explosives [8-10] in which the variation of the cone angle provides control over the mass and velocity of the jet. Later, the formation of laser-generated plasma jets using a foam filled cone have been studying in [11-16] by A. Velikovich et al. (Dr. Alexander Velikovich receives the 2015 IEEE Plasma Science and Applications Award for advancing the theory of plasma shocks, now he is with the U.S. Naval Research Laboratory). But monochromatic x-ray side-lighting of the jets show [16] that the plasma jet mass was less than 10% of the cone liner mass, jet velocity was 8–12 km/s, and jet ion density was 2x10^{20} ions/cm^3 with the lifetime of the plasma jets about 80 ns.

Such limited parameters were caused by restrictions on the formation of a cumulative jet, which are not surmountable in the classical method by hydrodynamic mechanism [17]. Necessary exactly conditions of the cumulative jet absence at non-stationary collapse of the cumulative hole were specified in [18,19]. It has been for the first time shown that Walsh criterion [9,17] is inapplicable for the axis symmetry case. In axis symmetry case, the flow with the shock wave attached to the axis of symmetry shall never realize, which means cumulative jets form at all times. Depending on the speed and angler of collision, solid, partially dispersed or totally dispersed jets (macro-particles flow) may form. So the conclusions about “cumulative jet” limiting velocity and its parameters made in [8-10, 17] are not valid in common case.

On the other hand, for the first time by Russian physicists Profs. I.V. Minin and O.V. Minin (under the scientific leaderships of Prof. V.F.Minin) were shown, that in process of realization of so-called hypercumulation conditions for cumulative jet formation without complete stagnation point involving formation of the inner zone of constant pressure (dead zone), the flow mass is always greater than slug mass [20-23].

The pioneering research of creation of laboratory so-called hypercumulative plasma jet from hollow cones collapsed onto their axes by pressure generated via laser ablation of their outer surfaces with parameters of jet which are not achievable in the classical cumulation were for the first time published in 1990 [24] by I.V Minin, O.V. Minin et al. A first series of simulation experiments [23, 25-26] was carried out for simulation of the formation of the plasma hypercumulative jet in the conditions typical of the problems of the laser thermonuclear fusion and astronomical phenomenon. The wide-range semi-empirical tabulated equation of state was used in simulation for description of the dependence of pressure on density and specific internal energy [27].

It could be mentioned that in [28] it was noted that the 1984 article [27] includes extensive technical investigations that were initiated two years prior to publication and this investigations were made under the leadership of Prof. V. F. Minin, who developing parallel computing capabilities at the time (at the Applied Physics Institute, Novosibirsk) and experimentally discovered the effect of cumulative jet formation from the collapsing bubble in water under the incident shock wave in 1958. Moreover, in [28] it was concluded that “Two-dimensional computer simulations have been used by Soviet researchers for about the past five years to optimize the "Mach shock wave generator" which uses a conical configuration to achieve 16 km/s. This technique has also been used for equation-of-state studies. A strength of the Soviet program has been the close collaboration between researchers at the Applied Physics Institute, Novosibirsk (V. F. Minin), which has the expertise in two- and three-dimensional hydrocodes necessary for these calculations, and researchers at the Chemical Physics Institute, who apply these capabilities in equation-of-state experiments”. A US scientist who visited the Applied Physics Institute in Novosibirsk in 1990 was given a demonstration on the state of development of parallel processing computing for solving large hydrodynamic problems. This demonstration used Soviet computers (produced with Soviet-made electronic chips) to achieve high-speed computing without the need for a supercomputer, with computational times equivalent to a Cray supercomputer. The PIC methodology mentioned above readily adapts to massively parallel architectures [28].
The extremal parameters of the plasma jet from aluminum liner were the following: at the time moment 1.6 ns the pressure was 8400 GPa, the speed of the jet was 115 km/s (Figure 1). It could be noted that it was (1990) the first simulations of hypercumulative plasma jet by laser ablation with real equation of state in the World - these results remain unsurpassed to today. Moreover, solution of this problem using equations of ideal gas state for the substance constituting a liner and plasma jet were shown to lead to inadequate description of the process. The comparison with the parameters of the jet formed from the "ordinary" conical target from simulations and experiment [7] showed that the increase of the plasma jet speed in the suggested configuration is 25-30 % and the increase of jet pulse is more than 90 times [24-26]. Thus the properties of a plasma jet in hypercumulative regime can be controlled by judicious choices of the conical target geometry, materials and laser parameters. It could be noted that the method of hypercumulative plasma jet creation by laser beam action on a thin metallic conical foil may considered as a new fast igniter scheme for realization of inertial confinement fusion [29].

Figure 1. Hypercumulative plasma jet formation by laser ablation of a conical target at 2 mks. Adapted from [24].

Computational simulation of hydrodynamic equations with wide-range equations of states taken into account were used to investigate peculiarities of the substance flow in conic thermonuclear targets by V.F. Minin et al. [28,30-33]. The obtained results make it possible to account for the process of plasma generation with thermonuclear parameters inside conic targets at explosive and laser casting of their coating. A stable high explosive-driven (HE) generator based on the irregular collision of conical shocks were simulated and investigated for the first time in [33, 28]. Combination of non-regular shock collisions with cumulation allows to generate about twenty Mb shocks in copper plasmas (Figure 2), which is close to the pressure typical for the nuclear explosions [34]. These devices utilize the effect of geometric cumulation under conditions of irregular (Mach) reflection of conically convergent shock waves and are characterized by an additional concentration of energy during the shock wave convergence to the axis of symmetry and, at the same time, by an increased stability of flow as compared to the spherical convergence of shock waves [23]. It could be noted that the results
of pioneering simulations of Mach collisions in such a geometry in the Institute of Applied Physics (Novosibirsk) by prof. Minin V.F. et al. [28,30-33] was shown in [34] but without specifying the authors of the simulation [35].

![Shock Wave Diagram](image)

**Figure 2.** Non-regular shock collisions in copper with March configuration (left: simulation experiment, right: experimental Mach configuration (T.Neal, LASL, Los-Alamos)). Adapted from [32].

The laser action on thick conical targets was used for the quasi-spherical shock compression of thermonuclear plasma (a conic targets were first proposed by Winterberg in 1968 for generating high-temperature plasmas to realise controlled thermonuclear fusion). The pioneering work on numerical simulation of the interaction between plungers and a conic cavity on the explosive initiation of the D-D reaction with the aid of aluminium plungers was published by V.F. Minin et al in 1987 [30] (see Figure 3). It was discovered that the acceleration of the surface of the plunger is provided by the action of two main mechanisms. The first of these is the shock wave, in which the regime of irregular Mach reflection of a conical shock wave coming from the surface of the initial contact of the plunger and the target is realized on the axis of symmetry. The second acceleration mechanism is the compression mechanism, in which the high pressure zones are unloaded, which arise due to the radial convergence of the plunger material to the axis of symmetry under the action of the cavity walls in the target [30-32]. It means that in the case of thicker flyer plate, the gaseous deuterium placed in the target will be compressed and heated quasi-adiabatically. In the case of thinner flyer plate, a cumulative effect becomes prevailing. It means that the junction of circular jet streams initiates a shock wave in the gas, and the collapse of the wave leads to plasma formation with thermonuclear synthesis conditions [34]. In experiments [30], the average velocity of the material ejected from the opening at the apex of a conic target was measured in vacuum. For 2-mm thick aluminium plunger with an initial velocity of 5.4 km/s the localized plasma velocity at a distance of 20 mm from the target edge was equal to 16.5 km/s with numerical prediction of this problem of 17.5 km/s.
Based on these researches, a mechanism for the formation of a compact plasma bunch at the exit of a conical target was proposed and its characteristics determined [36]. The possibility of hyper-velocity cumulative jets generation employing laser compression of conic shells and the possibility of employing these jets for thermonuclear fuel targets ignition were discussed in [37]. The use of Mach waves [38] (Figure 4) and conic targets for the explosive graphite-to-diamond transformation [39] were also proposed. These researches with highly concentrated energy flows open up new possibilities for studying the physical properties of materials at extremely high conditions.

Figure 3. Interaction of the thick and thin flyer plate with lead conical target - a cross-section of the conical target with the cone angle of 28 deg. under the action of an aluminum flyer plate at different times ($t$, in ns). The dashed line indicates the spallation region. Simulation experiment. Adapted from [30].
The focusing of the shock waves in water into an arbitrary region of space using plane diffractive optics in a regime when the acoustic approximation is not valid for the first time described in the pioneering work by Minins [40].

Figure 4. Left: The design of container and scheme of shock wave loading: 1 – explosive, 2 – BN, 3 – steel, 4 – reflected shock wave, 5 – loading shock wave, M – Mach wave. Right: Container after and before explosive loading. This Russian technology provides the transition coefficient up to 95% at the direct first explosion stage and in many cases avoiding of chemical processes. Adapted from [38].

3. Conclusion

The use of the Mach configuration of converging shock waves opens up new possibilities in the physics of high energy densities. For the generation of a high-speed plasma jet under laboratory conditions, the hypercumulation method is promising, which potentially allows one to obtain record characteristics of plasma jets. For generating extremely high pressures in order to study the properties of materials, the Mach configuration of shock waves in a conical target is also extremely promising. In particular, this configuration allows the syntheses of superhard materials with high mass yield without the use of chemical purification. Note that in this area of physics the Russian renowned scientists mentioned in the paper above have made a great contributions and found practical applications of their ideas.

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