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Quasi-spherical superfast Z-pinch implosion for pellet irradiation

Valentin P. Smirnov,
Eugeny V. Grabovskii,
Sergey V. Zakharov

Abstract. New simulation results of the quasi-spherical implosion induced by a 40 MA current pulse are discussed. Results on a quasi-spherical wire array production and some experimental observations of an implosion are presented.

Key words: Z-pinch • Z-pinch implosion

V. P. Smirnov✉, E. V. Grabovskii
Joint Institute for High Temperatures, Russian Academy of Sciences (JIHT RAS),
13/2 Izhorskaya Str., 125412, Moscow, Russia,
Tel.: +7 495 485 9333, Fax: +7 495 485 7990,
E-mail: vsmirnov@ihed.ras.ru

S. V. Zakharov
Joint Institute for High Temperatures, Russian Academy of Sciences (JIHT RAS),
13/2 Izhorskaya Str., 125412, Moscow, Russia
and EPRA,
Villebon sur Yvette, France

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Introduction

Experiments on the Angara-5-1 (TRINITI, Russia) [9, 13] and Z-machine (SNL, USA) [3, 8] have shown the attractiveness of liners Z-pinches as drivers for an ignition of a thermonuclear target with an indirect irradiation. In the last years developments of pulsed power generators have achieved a level close to the pellet ignition threshold $Q > 10$. Though the parameters of the planned facilities are close to satisfy the ignition requirements or even surpass it, the search for a more effective use of the kinetic energy of imploding liner pinch has not lost its attractiveness.

The transition from a cylindrical liner to a quasi--spherical one is the most natural way to solve this problem. The quasi-spherical compression of liners with direct use of the kinetic energy for an implosion of the target shell was analyzed in a number of studies [4, 5, 10]. The enhanced instability of the quasi-spherical liner implosion is a serious of issues of a direct compression scheme [4]. Therefore, in Ref. [10] a scheme of the quasi-spherical liner with an indirect exposure of the target was proposed. This paper presents the results of recent calculations of quasi-spherical liners with a current of 40 MA, and the first model experiments with a quasi-spherical wire-array installation performed at Angara-5-1 with a current up to 3 MA.

The quasi-spherical liner implosion under 40 MA current pulse

The implosion of an initially spherical shell in a sector $\theta_0 < \theta < \pi - \theta_0$ evolves spherically if its mass surface density has an angular distribution $m(\theta) \propto \sin^{-2} \theta$. Simple analysis shows that due to the axial cumulation under identical conditions (current, compression ratio) the kinetic energy surface density in a quasi-spherical implosion [10]: $\{(m_{\text{sph}}\dot{R}^2/2) \propto \gamma\ (I^2/c^2)[(R_0 - R)]/R^2\}$ is higher than the value in a cylindrical implosion [7]: $\{(m_{\text{cyl}}\dot{R}^2/2) \propto \gamma\ (I^2/c^2)\ \{\ln[(R_0 - R)]/R^2\}\}$, where $m_{\text{sph}}, m_{\text{cyl}}$ is the surface mass density for a spherical and cylindrical implosion respectively; $R(t)$ is the radius of a liner and $R_0 = R_{t=0}$; $\gamma(\theta_0)$ is a geometrical factor (e.g. $\gamma(\pi/4) = 1.24$). The external liner accelerated by the magnetic field pressure collides with an internal one. During the high speed impact between the external and internal liners, a shock wave [13] produces a radiation flux. This radiation penetrates liners and reaches the cavity where a capsule can be placed. The radiation is thermalized there and interacts with the capsule finally releasing through the external liner surface. The radiation intensity σT^4 (T is the radiation temperature) inside the liners exceeds the radiation flux density at the external liner surface by a factor of $\sigma T^4_{in} = \sigma T^4_{out}[(l_{out}/l_{in}) + \alpha(R_{out}/R_{in})(\Delta R/l_{in})]$, where R_{in} and R_{out} are radii of an internal and external surfaces of the external liner; $T_{in} = T_R = R_{in}$ and $T_{out} = T_R = R_{out}$ are the radiation temperatures inside and outside; $\Delta R = R_{out} - R_{in}$ is the liner thickness; $\alpha \approx 1.5$ and l_{in} and l_{out} are Rosseland paths in an inner and outer layers of the external liner with the temperatures T_{in} and T_{out}, respectively. The radiation energy confinement in the spherical case is more effective than in the cylindrical [7] by a factor of $(\Delta R/R_{in})/\ln(R_{out}/R_{in})$. In the framework of this simple model the change from a cylindrical to a spherical implosion is estimated to give a gain four to five times of the flux magnitude irradiating the capsule. Also, a higher symmetry of the radiation flux on the capsule is expected due to the absence of colder bottoms in the spherical case.

The quasi-spherical implosion is more sensitive with respect to the magnetic Rayleigh-Tailor instability [2]. To reduce the long-wavelength instability modes a nested double-shell external liner may be used [12]. The mass distribution of the inner shell of the external liner should be profiled to eliminate the regular predictable part of long-wavelength perturbations of the outer shell, which have been developed to the moment of the impact of the shells due to initial mass anisotropy and sphericity [12].

Radiation-magnetohydrodynamic (RMHD) computer modelling with the code Z* is used to estimate the effects of the plasma instability of the quasi-spherical liners and to determine more accurately parameters of the liners and the radiation flux illuminating the capsule. The new generation of the 2-3D radiation-magnetohydrodynamic (RMHD) code Z* has been developed on the basis of the RMHD code ZETA [1,

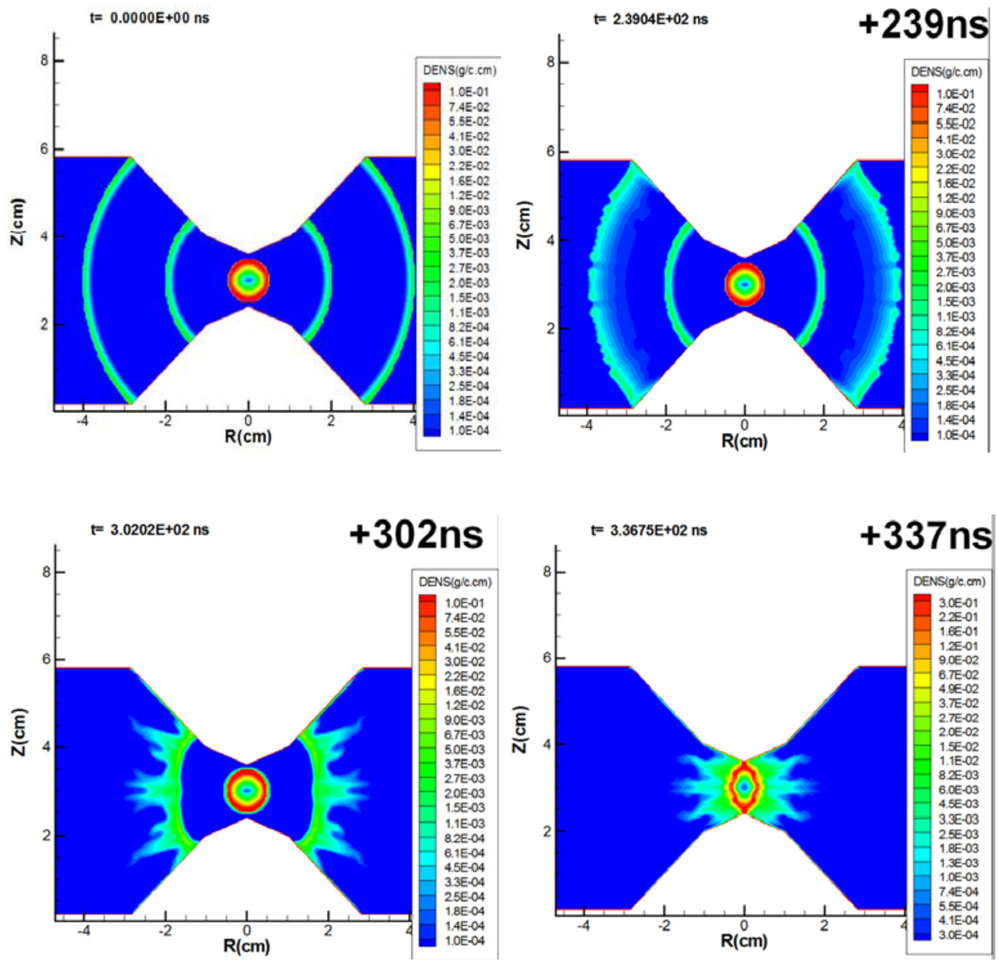

Fig. 1. Density evolution of the quasi-spherical liners in axial section views with the nested double-shell external liner, spherical internal liner (the capsule inside is not shown) between electrodes at the initial moment 0 ns, and at three stages of the process: implosion of the external liner at 239 ns; merging of the outer and inner shells of the nested external liner at 302 ns and during the collision of the liners at the maximum of radiation intensity in the cavity at 337 ns.

11]. Z* includes the magnetohydrodynamic radiation transfer, ionization and other plasma processes in the magnetic implosion of radiative liners with the spectral radiation properties and the equation of state data [6] of the plasma in non-LTE. Ions and electrons in the plasma are treated differently with separate equations of state exchange with energy by means of collisions. This is important for a correct description of intense shock waves in a high-Z element plasma.

The layout shown in Fig. 1 was chosen after several preliminary optimization calculations as a variant for analysis of the implosion dynamics and the radiation generation. Electrodes have the beam angle 90°, $45° < \theta < 135°$.

To reduce the effect of instability the nested double--shell external liner was chosen. The outer quasi-spherical shell of the external nested liner has the radius $R_{11} = 4$ cm and the mass of $M_{11} = 40$ mg. The inner quasi-spherical shell has $R_{12} = 2$ cm and $M_{12} = 10$ mg. The internal liner is spherical with the radius $R_2 = 4.8$ mm, thickness of 0.3 mm and mass of $M_2 = 30$ mg. To maintain a good electrical contact and to keep the room for the internal liner with a capsule the electrodes at $R < 1.2$ cm are inclined from the radial direction. A quasi-spherical implosion of liners with a 40 MA electric generator at 200 ns pulse duration was considered.

The liner shells are supposed to be made from a foam enriched with tungsten. Homogeneous preionization of initially low density, non-conductive liners is supposed to provide enough conductive electrons without destruction of the mass structure. The outer spherical shell has an angular distribution of the mass $m(\theta) \propto \sin^{-2}\theta$. The inner spherical shell of the nested external liner has a twice less radius with the average linear mass density twice less than the outer one. The angular mass distribution of the inner shell corresponds on the average, to $m(\theta) \propto \sin^{-2}\theta$ with an additional mass redistribution chosen from preliminary simulations to compensate the long-wave perturbations caused by the initial sphericity and inhomogeneous mass distribution of the external shell. The spherical internal liner is made mostly from an X-ray semitransparent material with a high-Z dopant. A spherical thermonuclear capsule should be placed in the center of the cavity of the internal liner (to simplify simulations the capsule was not introduced into the modelling system). Implosion dynamics of the quasi-spherical liners with the evolution of MHD instabilities taken into account with random ~ 5% initial perturbation is examined and presented in Fig. 1. The current pulse has a small prepulse and starts at 130 ns reaching the maximum of 38.4 MA at 325 ns (see, Fig. 2).

During the acceleration by the magnetic field pressure of the passing electric current to the moment of 295 ns of the collision between the outer and inner shells of the nested external liner, the outer shell of the nested external liner accumulates 3 MJ of kinetic energy. The effect of instabilities on the outer shell of the nested external liner arising during the implosion of the liners is seen in Fig. 1. To the moment of merging the mass redistribution is defined mainly by these big “regular inhomogeneities” rather than by small random fluctuations. After the impact of the outer shell of the nested external liner with the inner shell with specially

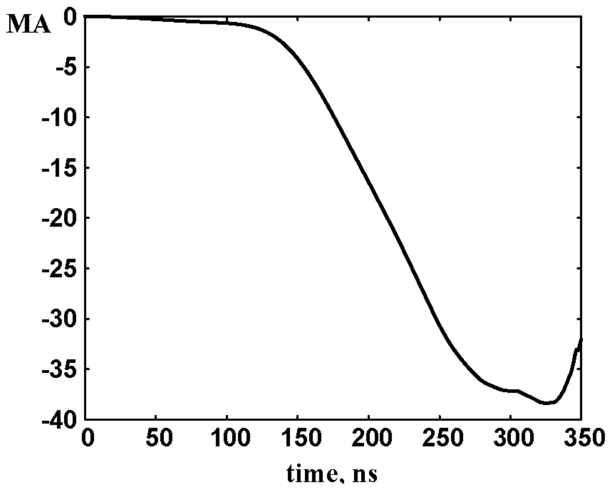

Fig. 2. The current pulse through the quasi-spherical liners shown with 130 ns prepulse.

redistributed mass to repair the distortions produced by the instability, the perturbations are reduced [12].

After the merging of shells, the external liner accelerates and accumulates 5.5 MJ of kinetic energy to the moment of 330 ns. At that moment, the thermal radiation generated by the shock wave penetrates inside the cavity (see, Fig. 3, below). The radiation intensity inside the cavity near the center rapidly increases and, at

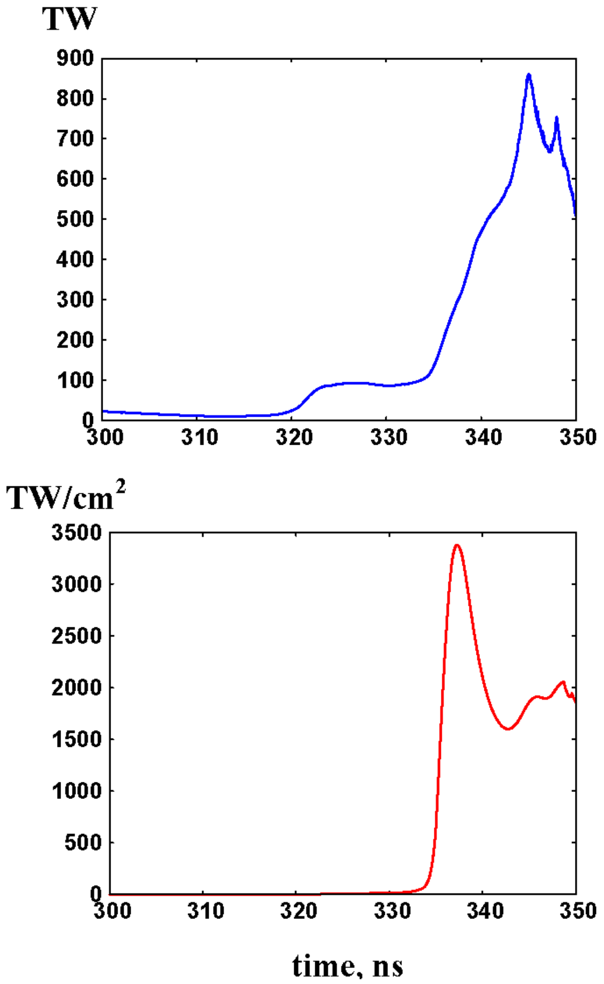

Fig. 3. The calculated radiation power from DL/DH (on top), and illumination intensity in the centre of the cavity (below) vs. time.

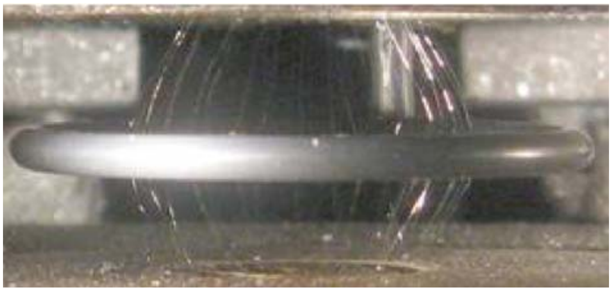

Fig. 4. Electrostatically shaped quasi-spherical wire array with the ring intermediate electrode.

the moment of 335.6 ns, it reaches the half of its amplitude, at 337 ns – a maximum value of 3380 TW/cm^2 and then it decreases to the half value at 341.5 ns. That intensity in the cavity exceeds the radiation intensity obtained in the dynamic hohlraum experiments on Z-machine [8] by an order of magnitude and corresponds to the brightness temperature of $T_{in} \approx 425$ eV. The radiative transfer smoothes the radiation distribution in the cavity. Afterwards, the implosion continues and the cavity collapses. The radiation output from the Z-pinch reaches a maximum of 859 TW at the moment of pinching 345 ns (see, Fig. 3, on top).

The active phase of illumination of the capsule in the cavity lasts 6–8 ns, which is expected to be sufficient for the capsule ablation and implosion under the irradiation. The capsule illumination exposure at the moment when the cavity collapses reaches $\varepsilon \approx 20$ MJ/cm^2. Such illumination intensity considerably surpasses the ignition threshold of the thermonuclear capsule.

Modelling experiments with a quasi-spherical liner

Profiling of the mass along the shell of a quasi-spherical liner is a difficult technological problem, especially for currents less than 10 MA. The new liner production approach for currents exceeding 10 MA is to be published soon in the Russian journal "Plasma Physics Reports". It is proposed to use a wire array (Fig. 4) for experiments with the current of 3 MA. If the length of the wires exceeds the gap between electrodes they can be stretched by the external electric field resulting in the barrel shape of a multi-wire array. To create this field the magnetically insulated electrode system is placed in the gap with the potentials applied externally. The leakage current to these electrodes should be suppressed by a magnetic insulation. The analysis of wire force balance have shown that the array shape can be made to be close to the spherical one by the correct choice of the number of electrodes and their potentials. The mass distribution along the wire can be provided by a shaped plasma deposition. The technology of profiling the wire mass is under development.

In the first experiments with simple electrode geometry the wire array consisted of 30÷606 μm W wires with a height of 15 mm. Its mass was 250–350 μg. The tapered pads on the electrodes were placed inside the wire array with a diameter of ~ 20 mm to improve the contact with the axially imploding plasma. The current of 2.5–3.5 MA with 100 ns rise time passed typically along the liner. The implosion of the wires plasma towards the axis that occurred during current flow was registered by a 4-frame camera with nanosecond time resolution. The radiation was detected by X-ray vacuum diodes with different filters and cathodes and by a spectrograph in the range up to 500 eV. Figure 5 shows the form of the compressed plasma at the moment of maximum radiation obtained with different filters.

The spectral transmission of the applied filters is also presented. Analysis of the pattern clearly shows a higher temperature in the central region of the imploded plasma. The comparison of the radiation spectra and intensities from the central region and in the vicinity

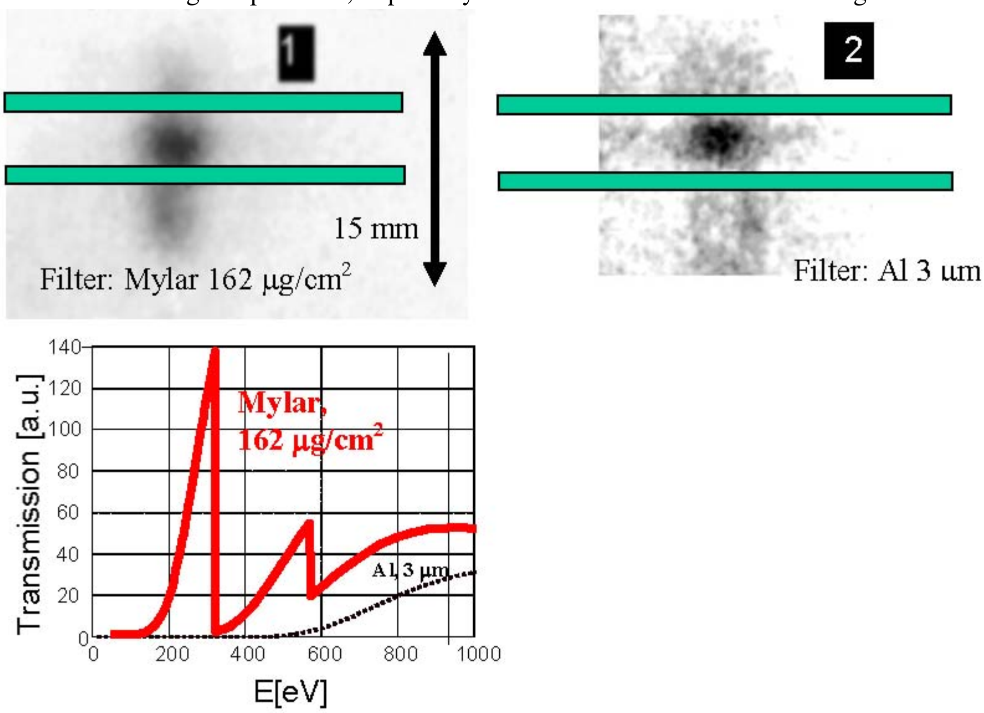

Fig. 5. Frame camera shots with nanosecond time resolution of the plasma at the time of maximum radiation obtained with different filters and the spectral transmission of the applied filters.

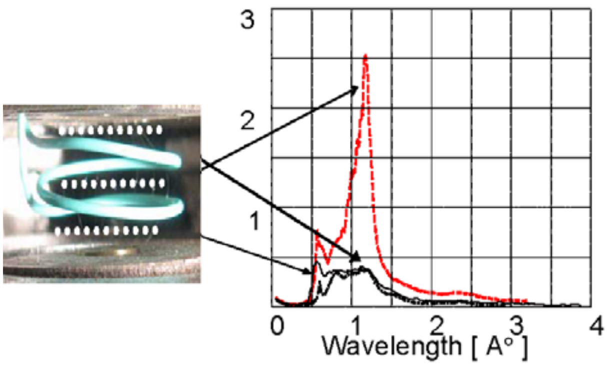

Fig. 6. Comparison of the time-integrated spectral intensities of radiation from the central region (red) and in the vicinity of polar regions (black).

of the polar region of the imploded liner leads to the same conclusion (see, Fig. 6).

The processing of the data allowed us to compare the volume and the surface radiation power from the compressed quasi-spherical liner with that obtained from cylindrical liners in the same conditions, which are: height, diameter, weight and the current. For the cylindrical liner, the bulk radiation flux density was 6.9 TW/cm^3 and the surface radiation flux density was 0.85 TW/cm^2. For the quasi-spherical one, they were of 35.4 TW/cm^3 and 1.8 TW/cm^2, respectively. The provided data are clearly in favour of the possibility to achieve enhanced concentration of energy and power in the case of radiating quasi-spherical liners.

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