

PAPER • OPEN ACCESS

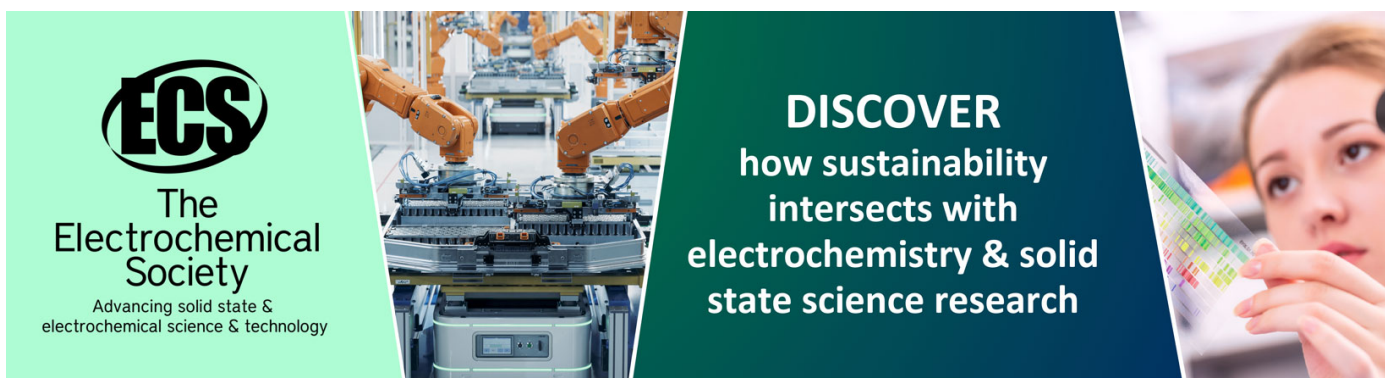
Spatiotemporal and spectral characteristics of X-ray radiation emitted by the Z-pinch during the current implosion of quasispherical multiwire arrays

To cite this article: A N Gritsuk 2017 *J. Phys.: Conf. Ser.* **941** 012007

View the [article online](#) for updates and enhancements.

You may also like

- [Impact ignition as a track to laser fusion](#)
M. Murakami, H. Nagatomo, T. Johzaki et al.
- [Energy gain of wetted-foam implosions with auxiliary heating for inertial fusion studies](#)
R W Paddock, T S Li, E Kim et al.
- [Modeling and projecting implosion performance for the National Ignition Facility](#)
D.S. Clark, C.R. Weber, A.L. Kritcher et al.



ECS
The Electrochemical Society
Advancing solid state & electrochemical science & technology

DISCOVER
how sustainability intersects with electrochemistry & solid state science research

Spatiotemporal and spectral characteristics of X-ray radiation emitted by the Z-pinch during the current implosion of quasi-spherical multiwire arrays

A N Gritsuk

SRC RF TRINITI, Troitsk, Moscow, Russia

E-mail: griar@triniti.ru

Abstract. For the first time, a quasi-spherical current implosion has been experimentally realized on a multimegaampere facility with the peak current of up to 4 MA and a soft X-ray source has been created with high radiation power density on its surface of up to 3 TW/cm². An increase in the energy density at the centre of the source of soft X-ray radiation (SXR) was experimentally observed upon compression of quasi-spherical arrays with the linear-mass profiling. In this case, the average power density on the surface of the SXR source is three times higher than for implosions of cylindrical arrays of the same mass and close values of the discharge current. Obtained experimental data are compared with the results of modelling the current implosion of multi-wire arrays performed with the help of a three-dimensional radiation-magneto-hydrodynamic code.

1. Introduction

To create high density of energy in a substance, the spatial concentration of energy flows generated by powerful energy sources – energy drivers – is used. One such driver is a radiating Z-pinch discharge as the source of a powerful X-ray source. The development of the technology of electric generators of high pulse power made it possible to construct units with a current of up to 26 MA [1]. Further increase in peak currents is associated with significant technical difficulties; therefore, it is extremely important to search for options for more efficient energy concentration, one of which is the three-dimensional compression of spherical arrays.

The transition to spherical arrays will allow us to concentrate the flux of the kinetic energy not only along the radius, but also along the axis of the facility. This will increase the power flow from the driver and make it more symmetrical on the target surface. An additional gain in the concentration of the kinetic energy of the array and the retention of radiation will make it possible to lower the requirements for electrical parameters of the next-generation facilities in the future.

The magnetic field of the current flowing along the load is determined by the distance to the axis of the load and has cylindrical symmetry. The pressure of this field creates a radial acceleration of the load. To maintain the constancy of the acceleration, at all points of the surface of the load its mass must be redistributed so that the sections closer to the axis are heavier, since the pressure of the magnetic field is greater on them. It follows from the equation of the 0-dimensional model of current implosion that for the realization of spherical compression, the angular dependence of the mass per unit surface is chosen in the form $m_s \propto \sin^{-2} \theta$ [2], where θ is the poloidal angle (Figure 1).



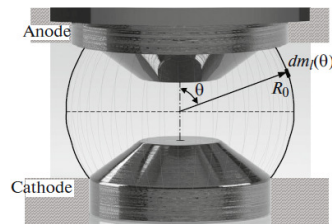


Figure 1. Quasi-spherical multiwire array (QSWA) with conical electrodes. A section of a wire with linear mass $dm_l(\theta)$ is shown, located at the initial radius of the assembly R_0 at a poloidal angle θ .

In this case, the array will compress while remaining spherical, despite different magnetic pressure at different distances from the array's axis. This will allow to concentrate the array's material in the center and improve the parameters of the X-ray pulse due to the simultaneous arrival of plasma into the center of the quasi-spherical array.

Comparison of the kinetic energy density for a quasi-spherical array with the similar value for a cylindrical array shows that with all other conditions being equal (current amplitude and compression ratio), kinetic energy density for a quasi-spherical implosion, due to axial cumulation, exceeds the corresponding value for the cylindrical one by as many times as $(R_0 - R)/R$ is greater than $\ln(R_0/R)$ [2].

2. Results

2.1. Experimental Layout

A new method for creating a quasi-spherical multiwire array was developed at the Angara-5-1 facility in 2009 [3]. Parameters of the shape of a spherical surface are determined by the influence of a radial electrostatic field on the wire array. A special ring-shaped electrode is used to create an electric field that affects the array wires. It is located outside the multiwire array coaxially with it in the middle of the anode-cathode gap of the target array. The electric field between the wires and the ring electrode is created by supplying voltage from an additional high-voltage (-10 kV) source. Electrostatic attraction between the ring-shaped electrode and the grounded wires of the array leads to the formation of a stretched quasi-spherical array. Its diameter is determined by the diameters on the electrodes and the length of the wires in the initial state. Such a design makes it possible to form quasi-spherical loads of any diameter.

To create the necessary distribution of mass along the wires of the array, an additional mass of material was deposited on separate parts of a tungsten wire or kapron fiber array. The width of the strip of additional deposited mass near the electrodes is 4.5 mm with constant linear density. This was carried out in a universal vacuum unit VUP-4 by the method of thermal evaporation [4]. To deposit additional mass, materials in a wide range of atomic numbers from 13 to 83 were used: aluminum, tin, indium and bismuth.

The homogeneity of the deposition of additional mass to the surface of the array wires was controlled with the help of optical and electron microscopes, as well as a REMMA-202 spectrograph analyzer with a LiF crystal on control samples [4].

2.2. Experimental results and discussion

The experiments carried out at the Angara-5-1 facility showed that with the implosion of quasi-spherical wire arrays three-dimensional compression of the array material by a magnetic field was indeed experimentally obtained, both radially and axially. To realize a quasi-spherical implosion, it is necessary to profile the mass of the array in accordance with the formula $m_r \propto \sin^2 \theta$, compensation of the zippering effect and cone electrode inserts to prevent plasma compression and pinch formation far from the center of the array. A series of experiments was performed with loads confirming the necessity of these conditions [5].

The results of measuring the space-time parameters of the radiation source during the implosion of quasi-spherical metallized fiber arrays (QMFA) in one of the shots are shown in Figure 2. Characteristic time-integral images of the pinch during the implosion of QMFA are shown in the three ranges of photon energy in Figures 2a, 2b, 2c, in which the initial position of the array and the position of the anode and cathode before the onset of implosion are indicated by dashed lines. These images demonstrate that radiating plasma objects are formed in the center of the inter-electrode gap when the QMFA is compressed with cone electrodes. The spatial configuration of these objects is close in shape to the spherical surface. The formation of such compact radiating objects, symmetrical relative to the liner axis, between the anode and the cathode of the array indicates a three-dimensional compression of the liner material during implosion of QMFA.

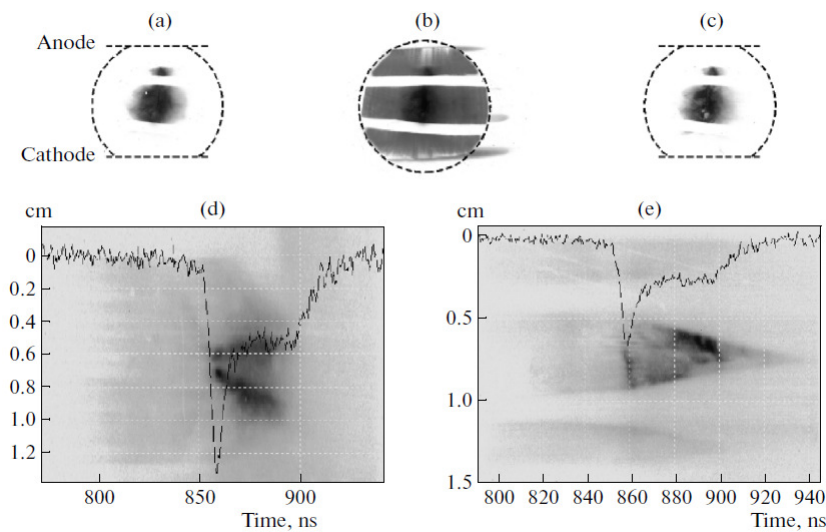


Figure 2. Time-integrated and optical streak images in shot No. 5094: QMFA, 40 kapron fibers ($\varnothing 25 \mu\text{m}$) profiled In–Bi deposition, conical electrodes, total weight of 270 μg , anode-cathode distance 15 mm; a) filter: lavsan - 316 $\mu\text{g} / \text{cm}^2$ ($> 120 \text{ eV}$); b) without a filter; c) filter Al 3 μm ($> 600 \text{ eV}$); d) radial and (e) axial optical streak images of the imploding array synchronized with the SXR pulse with photon energies above 120 eV.

Weak optical radiation from the plasma of the equatorial part of the array converging towards the center is seen from the radial streak (Figure 2d). Then, at the time of the peak of the X-ray pulse ($> 120 \text{ eV}$), the burst of the glow is observed when the plasma arrives at the center from all areas of the array. After compression, its expansion is observed from the radial streak. On the axial optic streak (Figure 2e), the glow appears at the center of the array only at the peak of the X-ray pulse. In the image of Figure 2d, the contours of the shadows of the stretching electrostatic electrode are visible.

The compactness of compression is manifested in an increase in the power flux from the surface of the pinch. Figure 3a and Figure 3b show the time-integrated X-ray images of a pinch in X-ray radiation with a photon energy above 120 eV obtained by implosion with the current of 2.5 MA amplitude, tungsten wire array (W-CWA) in shot No. 5091 and QMFA in shot No. 5094, respectively.

The diameter of the emitting region during the implosion of the W-CWA from the image of Figure 3a is equal to $d_{\text{CWA}} = 5 \text{ mm}$. With the array height $H = 15 \text{ mm}$, the surface area of the pinch is 2.36 cm^2 . The X-ray power in shot No. 5091 is $W_{\text{CWA}} = 1.22 \text{ TW}$ at the current of 2.5 MA, so the X-ray power density per unit surface of the source is 0.52 TW/cm^2 . In the case of QMFA, the diameter of the radiating region in the image in Figure 3b is equal to $D_{\text{QMFA}} = 3 \text{ mm}$. The surface of the compressed plasma is 0.28 cm^2 . The X-ray power in the shot is $W_{\text{QMFA}} = 0.4 \text{ TW}$ at 2.5 MA current, therefore, the X-ray power, referred to the surface area of the X-ray source, in this case is 1.43 TW/cm^2 .

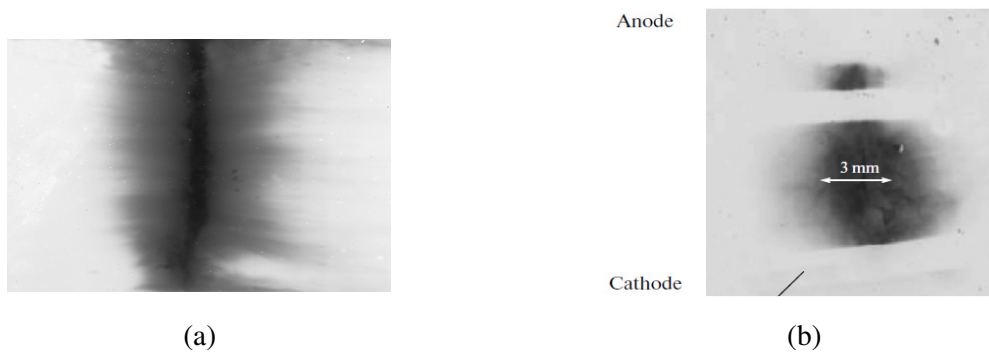


Figure 3. Time-integrated X-ray images of a pinch with photon energy of more than 120 eV (filter lavsan $316 \mu\text{g}/\text{cm}^2$) obtained by implosion of W-CWA and QMFA with close values of the total mass of the arrays: a) shot No. 5091, W-CWA, 40 W wires $\varnothing 6 \mu\text{m}$, initial diameter of array was 20 mm, total weight $330 \mu\text{g}$; b) shot No. 5094, QMFA, 40 kapon fibers ($\varnothing 25 \mu\text{m}$) with In-Bi layers for profiling linear mass and conical electrodes, total mass $270 \mu\text{g}$, 3 mm long segment (white arrow) for scale.

Thus, it was found that the average power flux on the surface of the source of X-ray radiation based on QMFA is almost 3 times greater than the corresponding value for W-CWA during the implosion of arrays of the QMFA and CWA type with approximately the same total mass and discharge current. The measured value of the ratio of the average radiation power fluxes corresponds to a simulation of a similar value in [2].

Three-dimensional RMHD modeling of quasi-spherical compression of wire arrays was carried out using the MARPLE-3D code (Keldysh Institute of Applied Mathematics, Russian Academy of Sciences). The numerical calculations of quasi-spherical wire arrays with spatial profiling of the linear mass are in good agreement with the presented experimental data.

A method for measuring the spectrum with spatial resolution perpendicular to and along the axis of multiwire arrays was used to study the spatial characteristics of the plasma radiation of compressed substance. This made it possible to obtain spectra of both the central part of the Z-pinch and the trailing mass. For this purpose, we used a time-integrated grazing incidence spectrometer GIS with a spatial resolution along the radius and height of the array in the wavelength range (20-400) Å. The spatial resolution of the object was 1 mm for the photon energy of 30 eV and, correspondingly, $250 \mu\text{m}$ for photon energy of the order of 400 eV.

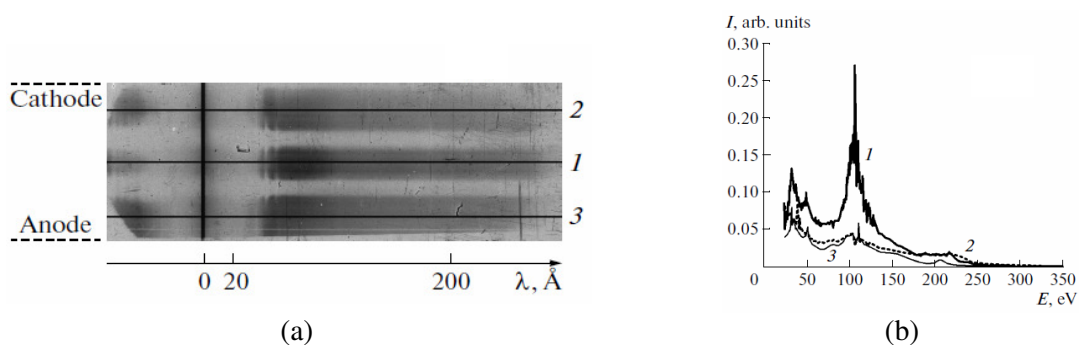


Figure 4. Shot no. 4961, a quasi-spherical array with W wires (total mass of $435 \mu\text{g}$). a) SXR spectra recorded with axial resolution and b) emission spectra measured in the directions shown by the horizontal lines in a).

Figure 4b shows the Z-pinch emission intensity distributions at different heights between the anode and the cathode in an image of the spectrum with axial resolution, obtained along lines 1, 2, 3 in Figure 4a. A characteristic feature of the spectral dependence on the wavelength of photons is that in the emission spectrum of the central part of the array (1), a peak in the intensity of X-ray radiation is observed in the photon energy range 100-150 eV (Figure 4b). Note that this intensity maximum is especially pronounced for arrays with spatial profiling of linear mass of the array.

In contrast to quasi-spherical arrays, peak intensity in the range 100-150 eV is absent during the implosion of cylindrical arrays. The formation of this intensity peak in the pinch spectrum in the middle of the inter-electrode gap indicates a redistribution of energy in the spectrum of the radiation source due to the axial motion of the substance during the current compression of W-CWA.

Conducted studies demonstrated the feasibility of the quasi-spherical implosion in terawatt-class facilities. In the experiments on the implosion of QSWA with profiled linear masses and conical electrodes intense and compact quasi-spherical plasma sources of SXR emission has been achieved. An increase in the average power flux density of such a source has been observed experimentally for the first time. The average power flux density in this source is more than 3 times higher than the corresponding value for the radiation source formed at the implosion of a cylindrical wire array with the same total weight. The next stage of the work will be optimization of the parameters of the QSWA to improve the quality of three-dimensional energy cumulation and to achieve significantly higher pulse powers of the Z-pinch X-ray radiation during quasi-spherical implosion.

This work was supported by the Rosatom Science Foundation under Project № 16-12-10487 and in part by the Russian Foundation for Basic Research under Project 16-02-00084, 16-02-00112, 16-02-00491 and 17-02-00167.

References

- [1] Jones M C *et al* 2014 *Rev. Scien. Instr.* **85** 083501
- [2] Smirnov V, Zakharov S and Grabovskii E 2005 *JETP Lett.* **81** 442
- [3] Grabovskii E, Gritsuk A, Smirnov V, Aleksandrov V, Oleinik G, Frolov I, Laukhin Ya, Gribov A, Samokhin, Sasorov P, Mitrofanov K, and Medovshchikov 2009 *JETP Lett.* **89** 315
- [4] Aleksandrov V, Volkov G, Grabovski E, Gribov A, Gritsuk A, Mitrofanov K, Oleinik G, Frolov I, Barsuk V, Medovshchikov S, and Sasorov P 2012 *Plasma Phys. Rep.* **38** 315
- [5] Aleksandrov V, Gasilov Grabovski E, Gritsuk, Laukhin Ya, Mitrofanov R, Oleinik G, Ol'khovskaya O, Sasorov P, Smirnov V, Frolov I, and Shevel'ko A 2014 *Plasma Phys. Rep.* **40** 939