ESTIMATION OF THE MASS DENSITY PROFILE OF AN ALUMINUM METAL-PUFF Z PINCH ON THE GIT-12 GENERATOR

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ESTIMATION OF THE MASS DENSITY PROFILE

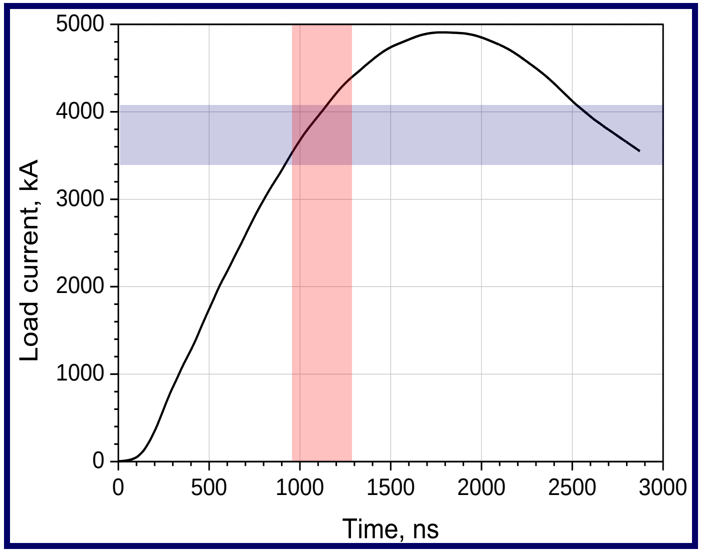
Compression of a Z pinch is provided by the self-magnetic field pressure that arises at the outer boundary of the pinch current sheath. The final density and temperature of the pinch plasma largely depend on the compression stability and uniformity. Usually, when a plasma is accelerated by a magnetic field, MHD instabilities develop, the most dangerous of which is Rayleigh–Taylor (RT) instability.

Instabilities can be suppressed in several ways:

- The amplitude of the initial perturbations can be reduced at the stage of Z pinch formation by using an originally completely ionized gas-puff Z pinch, such as a metal-puff Z pinch.
- Another way is to provide a more uniform delivery of energy from the current generator to the load with the use of an outer plasma shell.
- **One of the most effective methods for suppressing RT instability is to provide a nonuniform radial distribution of the pinch mass (tailored density profile)**

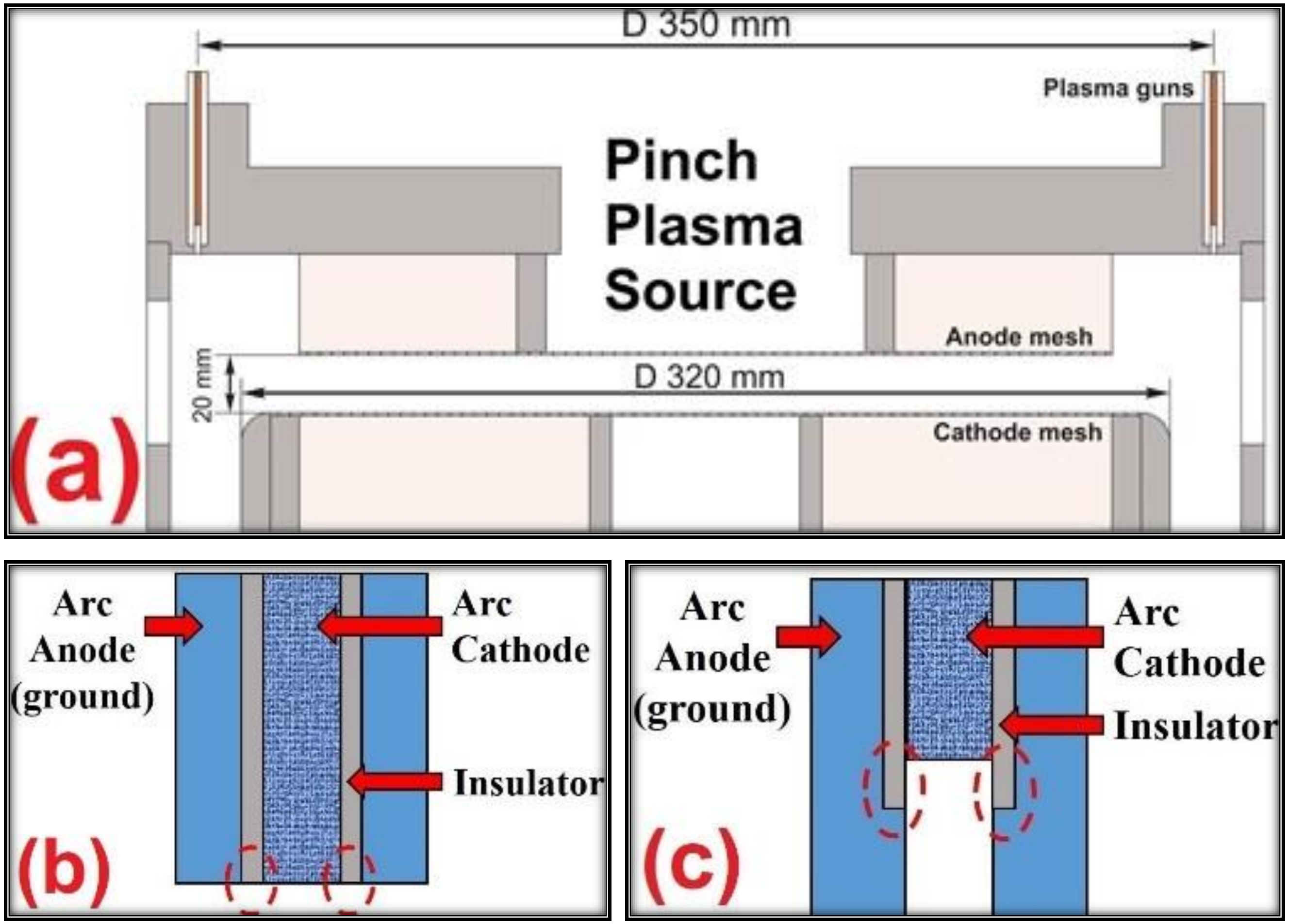
On this basis, it is of great interest to estimate the mass density profile of a metal-puff Z pinch. To reconstruct the initial density profile of an aluminum metal-puff Z pinch, the following experimental data were used: current and voltage waveforms, signals of magnetic probes, and images obtained using optical diagnostics. The density profile was calculated using the zero-dimensional snow plow model.

GENERATOR GIT-12



- **IHCE SB RAS, Tomsk**
- **Charging voltage – 50 kV**
- **Stored energy – 2.6 MJ**
- **Operation with POS: 2.5 MA, 250 ns, 20 kA/ns**
- **Operation w/o POS: 4.7 MA, 1.7 ms, 3 kA/ns**
- **In these experiments: mode without the POS was used.**

EXPERIMENTAL LOAD



The load unit of the GIT-12 generator is shown schematically (see a). In the experiments, we used two design versions of the load unit: the vacuum arc operated in the plane of the anode (isotropic plasma flow, see b); and the vacuum arc was submerged into the anode (collimated plasma flow, see c).

DIAGNOSTIC SETUP

XRD 1: Cu photocathode, filtered by Kimfoil 2 μ + Al 0.2 μ + Polypropylene 30 μ

XRD 2: Cu photocathode, filtered by Al 8 μ + Kimfoil 2 μ + Al 0.2 μ + Mylar 6 μ

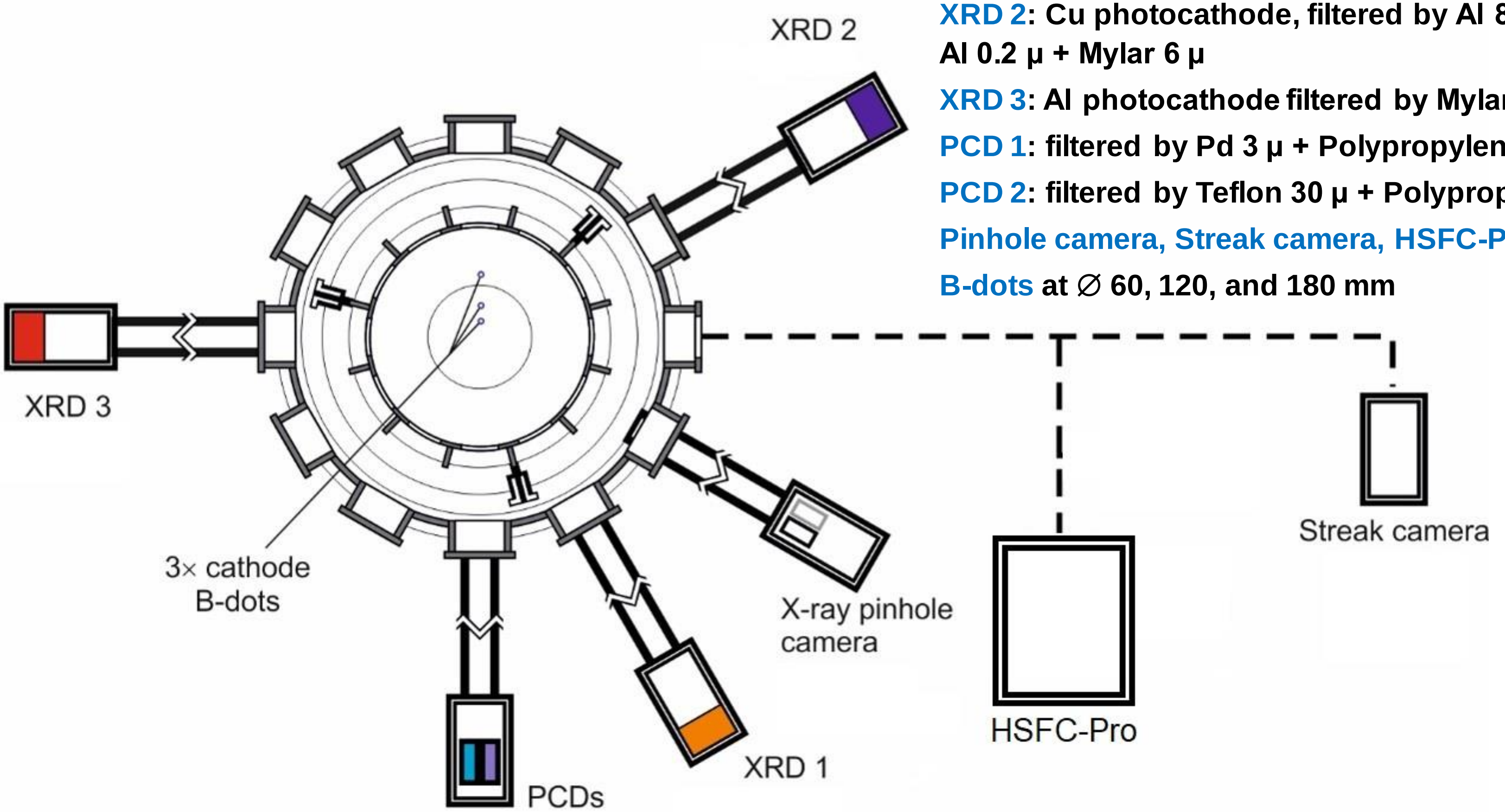
XRD 3: Al photocathode filtered by Mylar 3 μ

PCD 1: filtered by Pd 3 μ + Polypropylene 20 μ

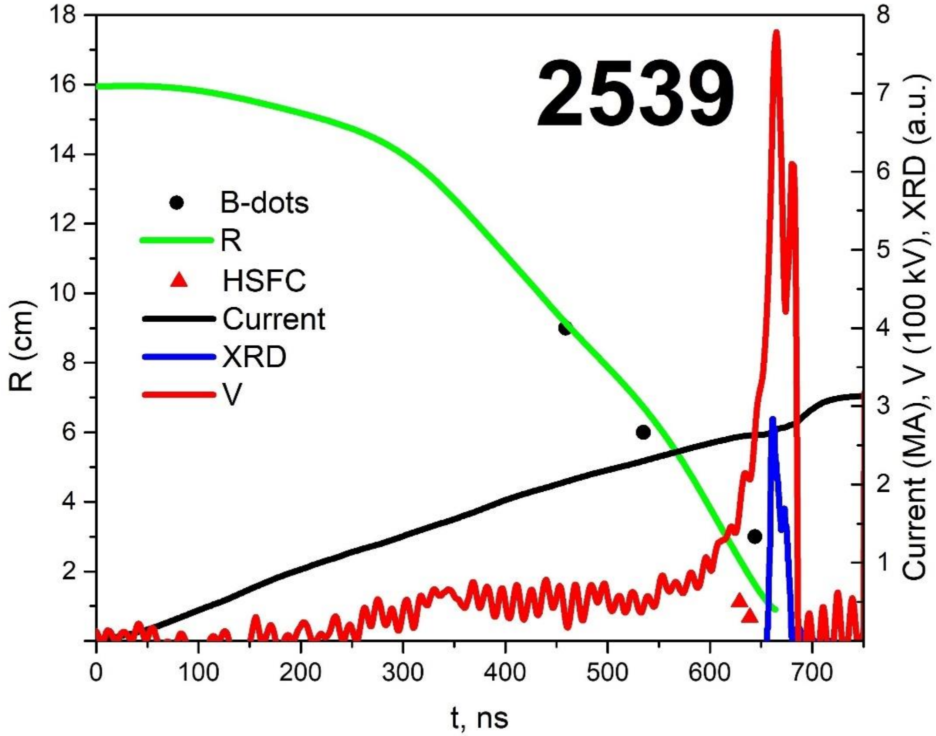
PCD 2: filtered by Teflon 30 μ + Polypropylene 20 μ

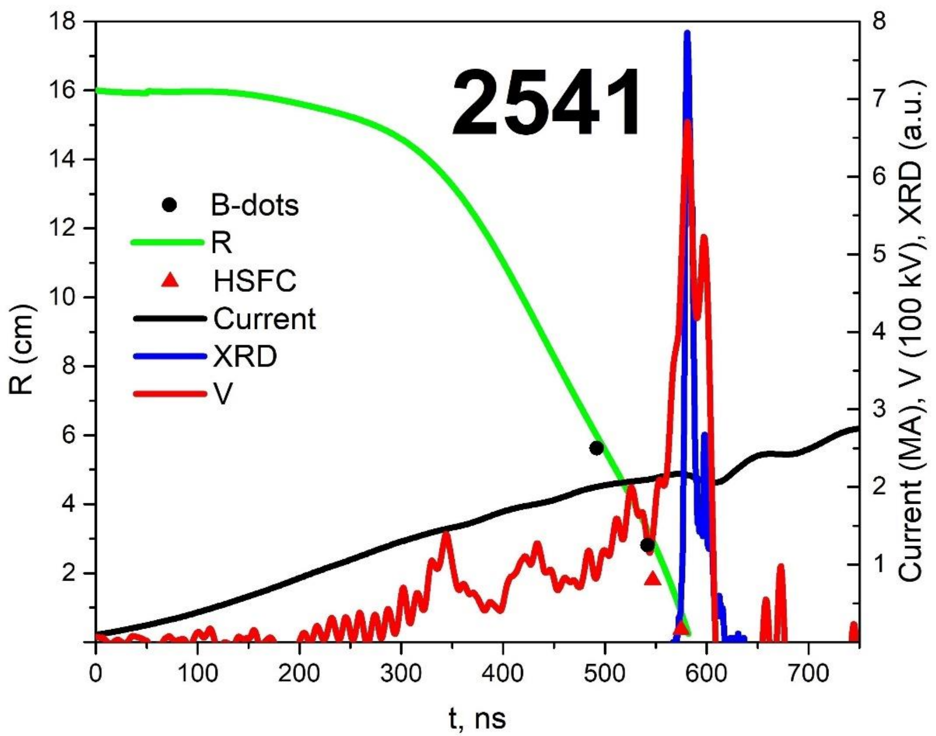
Pinhole camera, Streak camera, HSFC-Pro frame camera

B-dots at ∅ 60, 120, and 180 mm



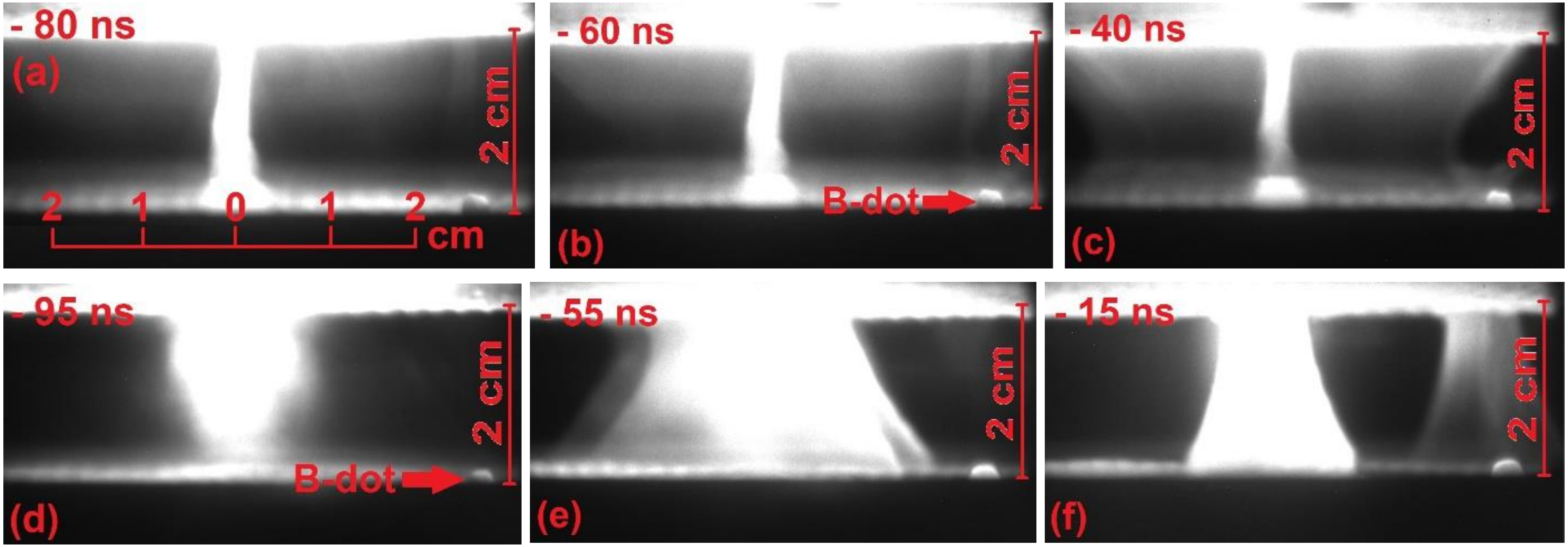
ESTIMATION OF THE CURRENT SHEATH RADIUS





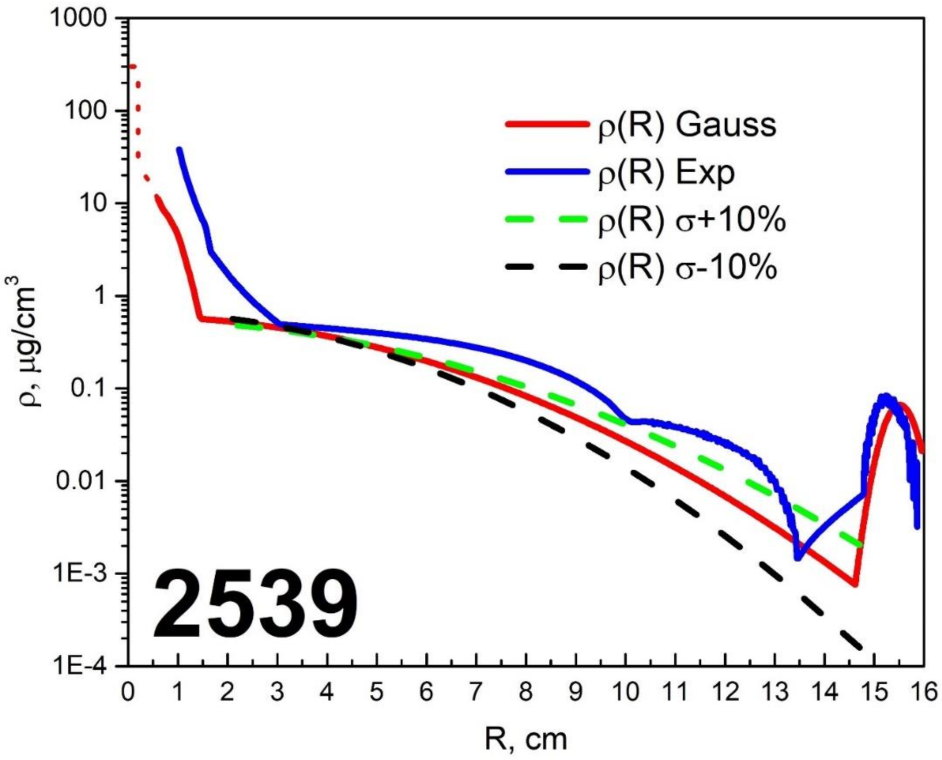
- **Data for shot 2539 (isotropic plasma flow) and shot 2541 (collimated plasma flow)**
- **As follows from the plots shown in figure, the data obtained from the B-dot probe signals and HSFC camera images for shots are consistent in general with the current sheath radius estimated based on the pinch inductance**

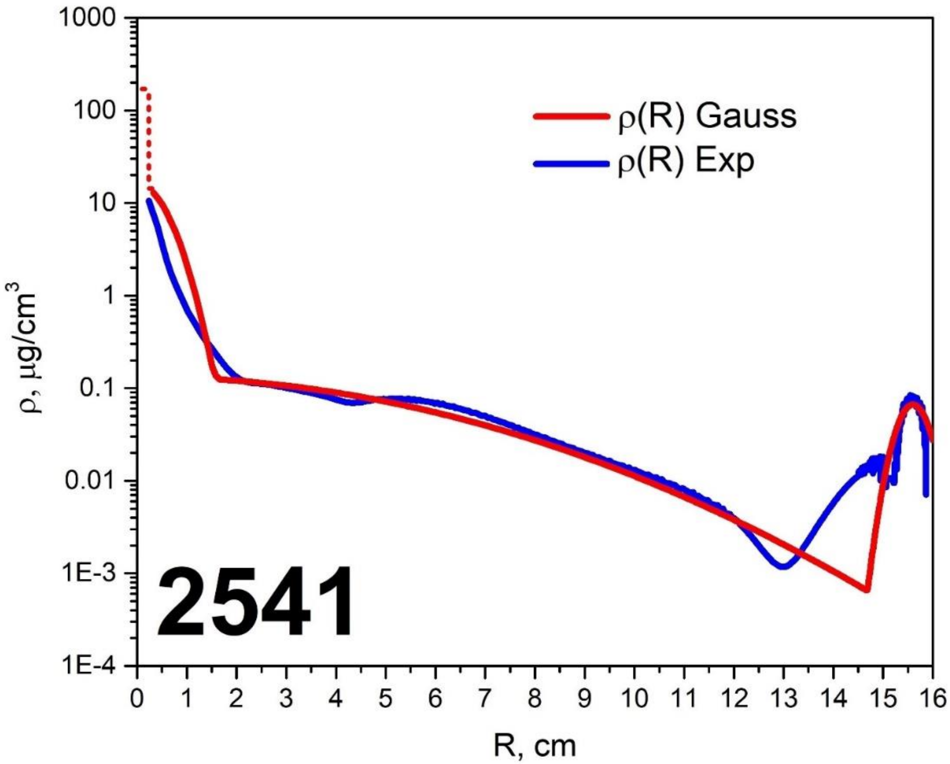
IMPLOSION DYNAMICS



Images of an Al plasma jet taken with a 3 ns HSCF Pro optical camera in shot 2539 (isotropic plasma flow, a-c) and shot 2541 (collimated plasma flow, d-f). The time shifts relative to the K-shell peak are given in the upper left of each image

RECONSTRUCTION OF THE INITIAL DENSITY PROFILE OF AL METALL-PUFF Z-PINCH





- To reconstruct the initial density profile of a pinch, we used experimental data obtained using electrophysical diagnostics and results of calculations based on the snow plow model
- Density profile can be approximated by Gauss functions with different constants:

$$\rho(R) = \sum_i \frac{\rho_i}{\sigma_i\sqrt{2\pi}} \exp\left(-\frac{R_{pinch}^2}{2\sigma_i^2}\right)$$

CONCLUSION

- **The resulting density profile can be approximated by a function describing the uniform central plasma jet and Gaussians with different constants**
- **The density profile in the region nearest to the central jet, described by a Gauss function, is mainly formed due to the contribution of the aluminum anode ions**
- **The density profile in the adjacent region is probably determined by the contribution of the material evaporated from the surface of the insulator near which the vacuum arc operates**
- **The peripheral density profile is provided by the operation of plasma guns arranged in a circle of diameter 35 cm**
- **The obtained mass density profile of a metal-puff Z pinch is close to the tailored density profile proposed in to suppress RT instability in imploding pinches**

ESTIMATION OF THE CURRENT SHEATH RADIUS

When the generator current $I(t)$ flows through an imploding pinch, a current sheath with an external radius $R_{\text{pinch}}(t)$ is formed at the pinch outer boundary. Measurements of the pinch current derivative dI/dt and voltage $V(t)$ in the load unit region make it possible to estimate the imploding plasma radius at any time during the pinch implosion. Knowing the inductance of the circuit segment from the site of measuring the voltage $V(t)$ to the load, L_0 (for the experiments at hand, L_0 = 19.6 nH), we can find the pinch voltage $V_{\text{pinch}}(t)$ as:

$$V_{\text{pinch}}(t) = V(t) - L_0 \frac{dI}{dt}$$

Next, with the known pinch voltage and generator current, we can find the pinch inductance $L_{\text{pinch}}(t)$ as:

$$L_{\text{pinch}}(t) = \frac{1}{I(t)} \int_0^t V_{\text{pinch}}(t) dt$$

The pinch inductance, in the approximation of cylindrical geometry, is rigidly related to its dimensions; therefore, for the geometry in which the experiments were performed, we can describe the inductance of the current sheath by the relation:

$$L_{\text{pinch}}(t) = \frac{\mu_0}{2\pi} l \times ln(\frac{R_r}{R_{\text{pinch}}(t)})$$

where $R_{\text{pinch}}(t)$ is the current sheath radius, R_r is the reverse conductor radius (18.5 cm), l is the pinch length (2 cm), and μ_0 = $4\pi\cdot10^{-7}$ H/m is the permeability. Hence, $R_{\text{pinch}}(t)$ can be expressed from previous formula as:

$$R_{\text{pinch}}(t) = R_r \exp(-\frac{2\pi L_{\text{pinch}}(t)}{l\mu_0})$$

RECONSTRUCTION OF THE INITIAL DENSITY PROFILE OF AL METALL-PUFF Z-PINCH

When the radius of the current sheath is known, the initial density profile of the pinch plasma, ρ(R), can be calculated using the snow plow model. The basic equation of the model can be derived from the law of conservation of momentum. The force acting on a cylindrical pinch is determined by the magnetic pressure. Hence, for a pinch of mass m(t) accelerated under the action of the magnetic pressure from the side of the current carried by the pinch, I(t), equation we can write as:

$$\frac{d(m(t)v(t))}{dt} = -\frac{\mu_0}{4\pi}\frac{I^2(t)}{R_{\text{pinch}}(t)}$$

The variation in mass of a cylindrical pinch (law of conservation of mass) can be described as:

$$\frac{dm(t)}{dt} = -2\pi\rho(R)v(t)R_{\text{pinch}}(t)$$

where $\rho(R)$ is the initial density distribution. The pinch compression velocity is described by the equation:

$$\frac{dR_{\text{pinch}}(t)}{dt} = v(t)$$

These equations, after some manipulation, give:

$$\frac{dm(t)}{dt} = -\frac{\mu_0}{4\pi}\frac{I^2(t)}{R_{\text{pinch}}(t)v(t)} - \frac{m(t)}{v(t)}\frac{dv(t)}{dt}$$

As the current sheath radius $R_{\text{pinch}}(t)$ and its derivative ($v(t) = dR_{\text{pinch}}/dt$) were determined earlier and the current $I(t)$ is measured in experiment, last equation contains only one unknown variable, namely, $m(t)$. Hence, integrating last equation, we can obtain the time-varying pinch mass and, then, using mass conservation equation, the initial density profile of the pinch, ρ(R).