Laboratory simulation of jet propagation in ambient medium with Plasma Focus facilities

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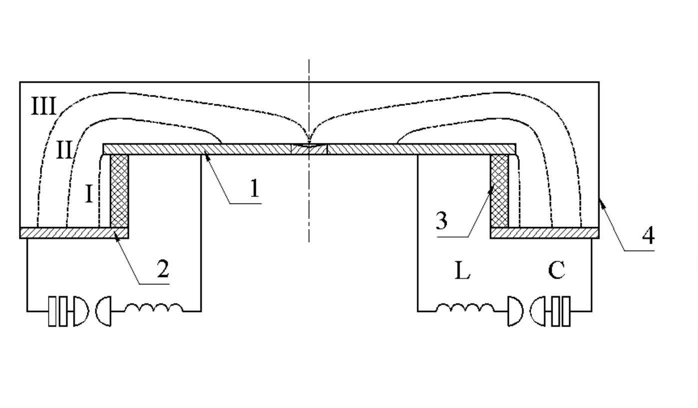
Introduction

- ✓ Laboratory simulations of jets is one of the interesting trends today. Experiments on simulating the young stellar objects emissions with fast Z-pinches , high-power lasers, plasma guns and other devices is well known

(*Bruce A. Remington, R. Paul Drake, Dmitri D. Ryutov, Experimental astrophysics with high power lasers and Z pinches, Reviews of Modern Physics, 78:755, 2006)*.

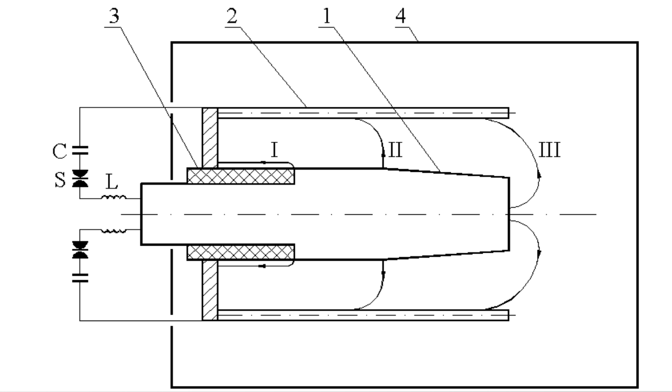
- ✓ We would like to present another device, which, in our opinion, has a number of advantages - "Plasma focus" (PF)
- ✓ The principle of PF operation is also based on the phenomenon of the pinch effect and it known as intensive sources of plasma flows, widely used in various practical applications.
- ✓ In recent years, these flows are also used for modeling of astrophysical jets. It was shown that the basic similarity laws necessary for the modeling of astrophysical jets are fulfilled at these installations, which determines the eligibility of their use in such experiments.
- ✓ In this presentation, we would like to focus on the study of the propagation of these flows over long distances in the external environment, in particular, on the formation of the bow shock

Plasma Focus



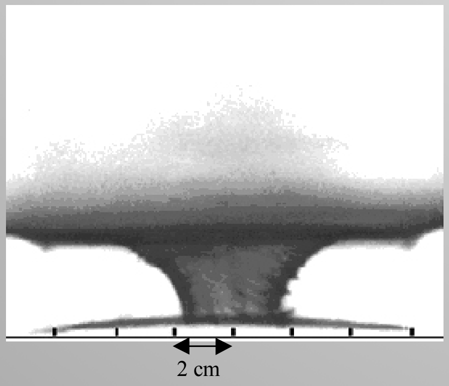
Filippov-type (D/L≥1)

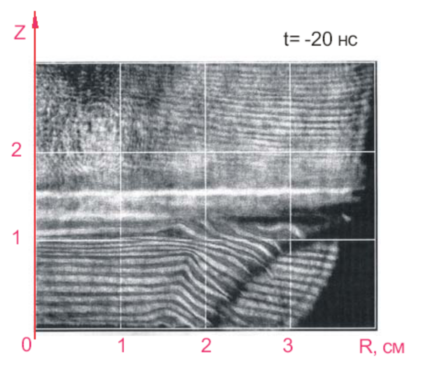
1 – anode, 2 – cathode,
3 – insulator,
4 – vacuum chamber
C – power supply, L – external inductance, S – spark gap
I – break-down phase;
II – run-down phase;
III – dense plasma focus phase

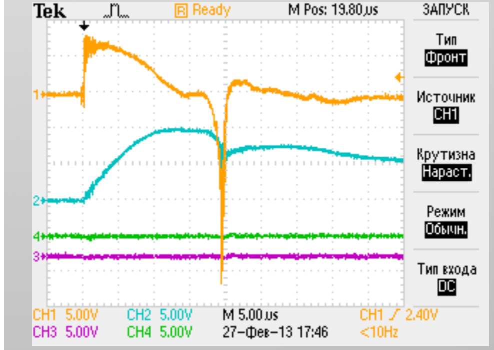


Mather-type (D/L<<1)

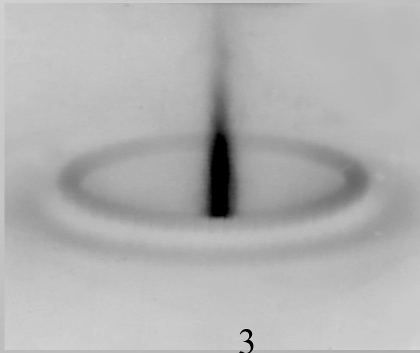
After the preliminary pumping, the chamber is filled with working gas under a pressure of a few Torr. When the spark gap switches on, a high voltage of power supply is applied between the anode and the cathode, which leads to a breakdown of the working gas. The resulting PCS moves under the action of the Amp`ere force toward the system axis, where the plasma pinch occurs. The pinching is accompanied by a drop in the current, and the appearance of a sharp dip in its derivative.







CH1 5.00V CH2 5.00V M 5.00 µs CH1 ⁄ 2.40V
CH3 5.00V CH4 5.00V 27–Фев–13 17:46 <10Hz



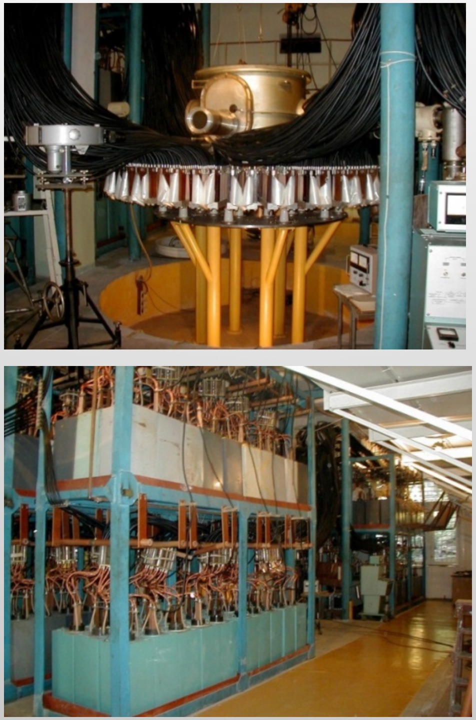
Experimental facilities

The main experiments are carried out on the PF-3 (plasma focus Filippov-type), the world's largest installation of this class.

Some interesting experiments were done on PF-1000 (IFPiLM, Warsaw, Poland) and KPF-4 (SFTI, Sukhum, Abkhazia) facilities. The main purpose of the experiments at these facilities was to study the flow dynamics at profiled initial gas distributions created by pulsed gas injection.

PF-3

(NRC KI)



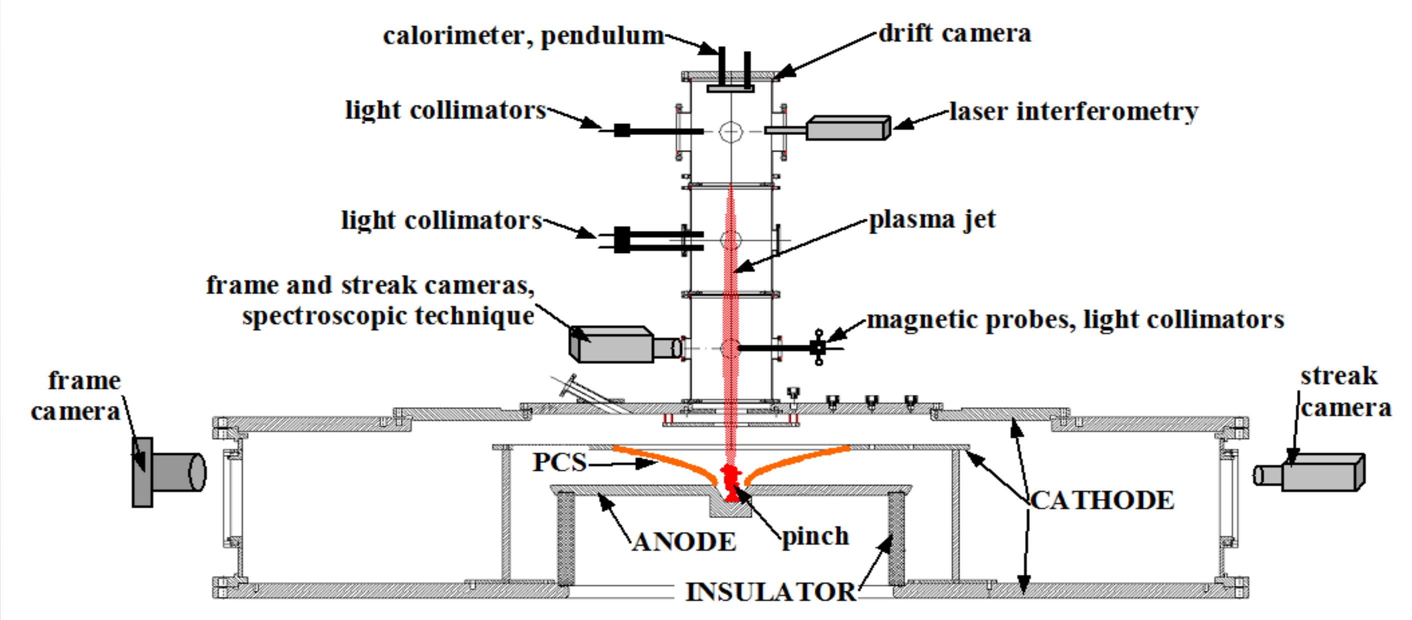
KPF-4 «Phoenix»

(SFTI, Sukhum)

PF-1000

(IFPiLM, Warsaw)

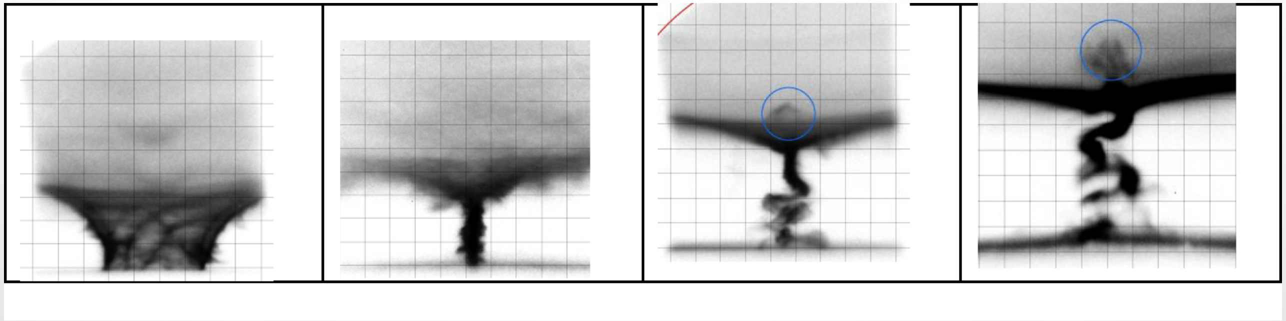
PF-3

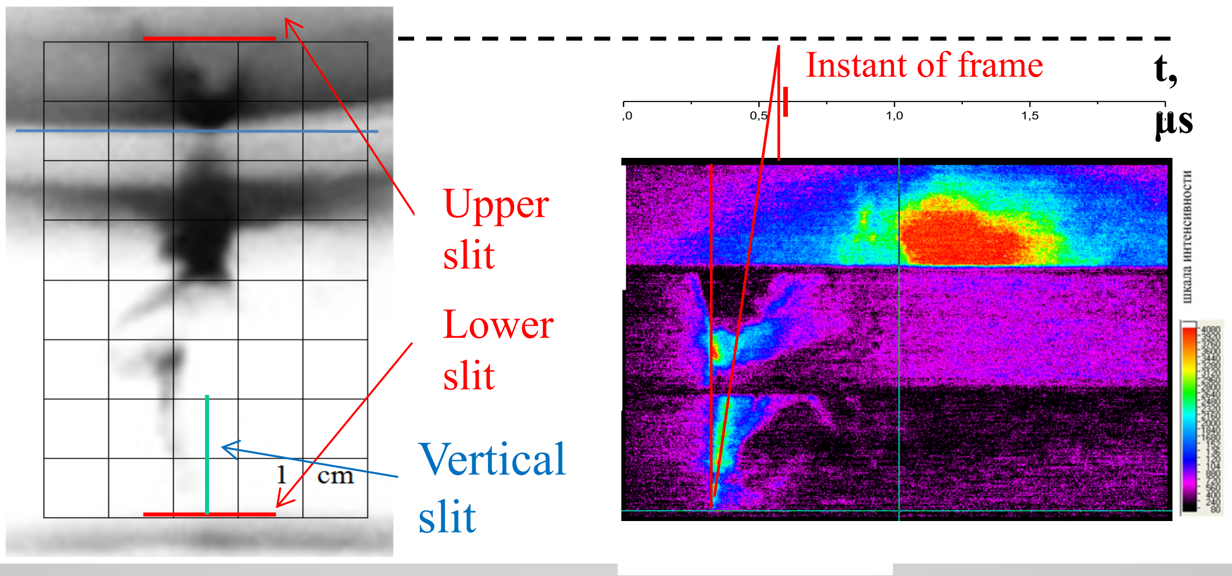


For these purposes, the PF-3 facility has been upgraded. A drift diagnostic chamber was designed which enables measurements of the plasma jet and background plasma parameters in three coordinate planes at the distances of 35, 65, and 95 cm from the point of generation.

The wide set of diagnostic tools was used for studies the jet parameters in different cross sections of the drift chamber, including streak and frame cameras, light collimators, multi-component magnetic probes, ballistic pendulum, calorimeter, spectral diagnostics, etc.

Jet formation

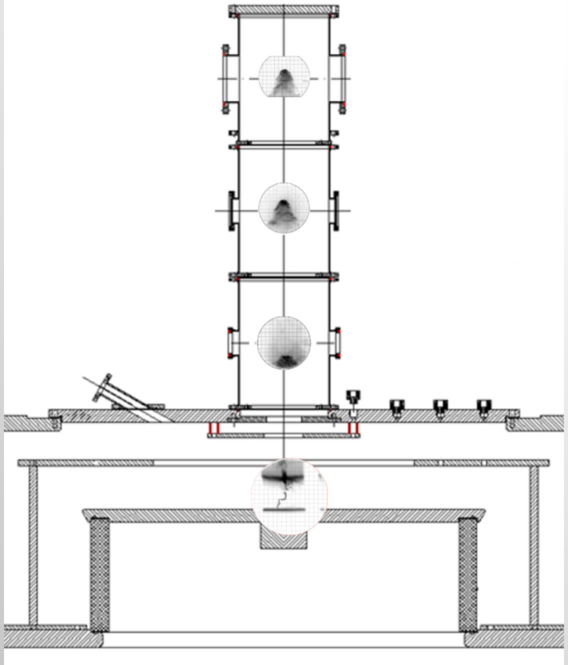


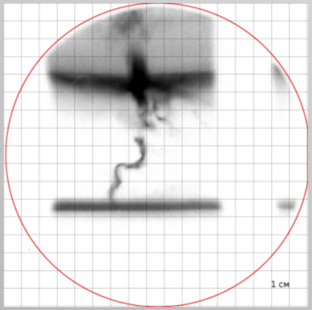


The compact plasma jets moving along the axis occur at the stage of the pinch decay and developing the MHD instabilities. The initial jet velocity, $V_0 \geq 10^7$ cm/s, exceeds the velocity of the current-carrying plasma sheath in the axial direction.

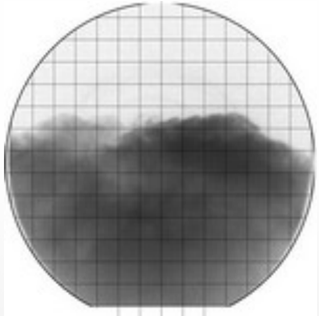
After some point in time, the flow lives its own life, independently of the main plasma sheet and pinch.

Jet spreading, PF-3

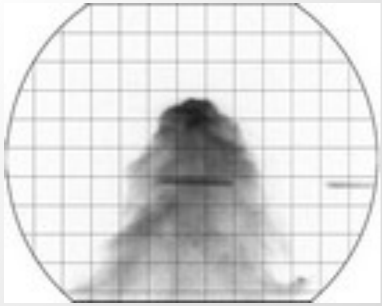




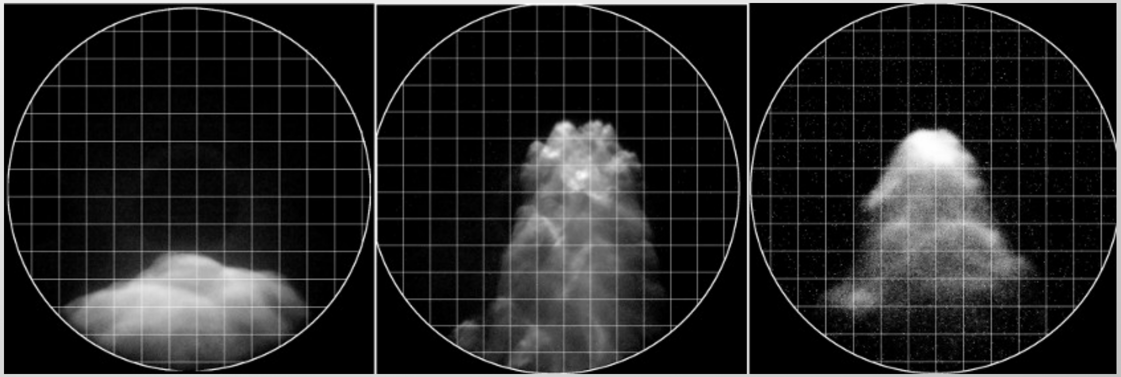
The anode region



H_2, h=95 cm



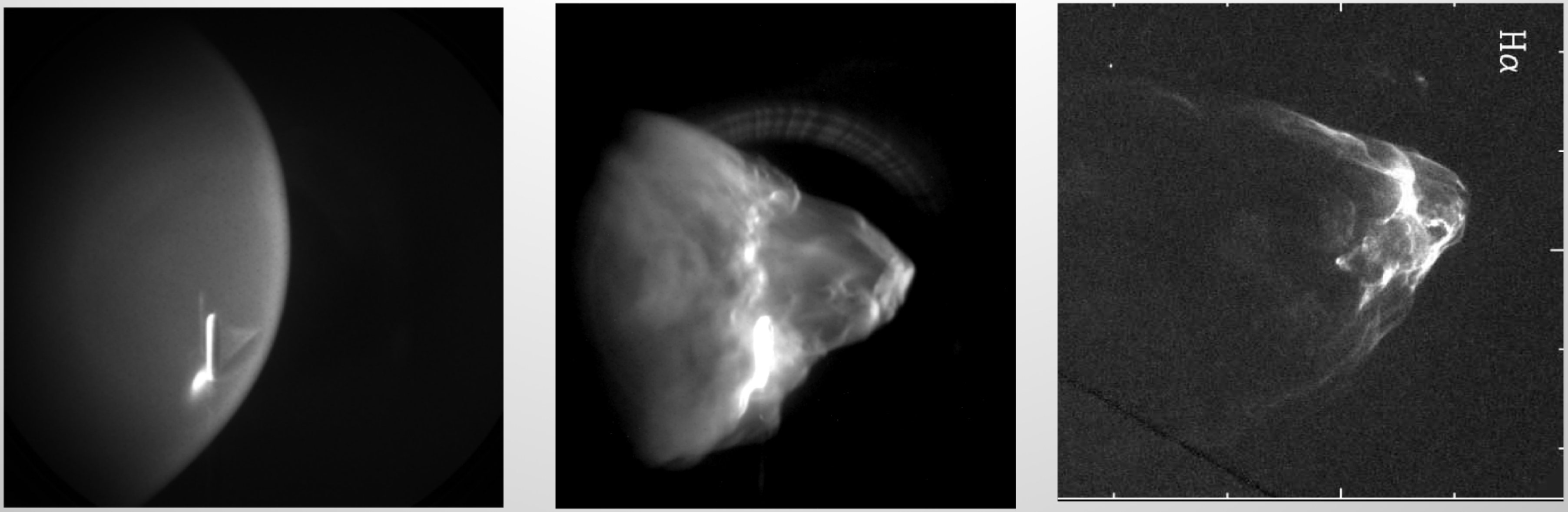
Ar, h=95 cm



а) б) в)

Photos of the plasma flow front at a distance of 35 cm from the anode at a discharge in hydrogen (a) and neon (b), as well as at a discharge in neon at a distance of 65 cm. Scale is 1 cm.

PF-1000, stationary filling

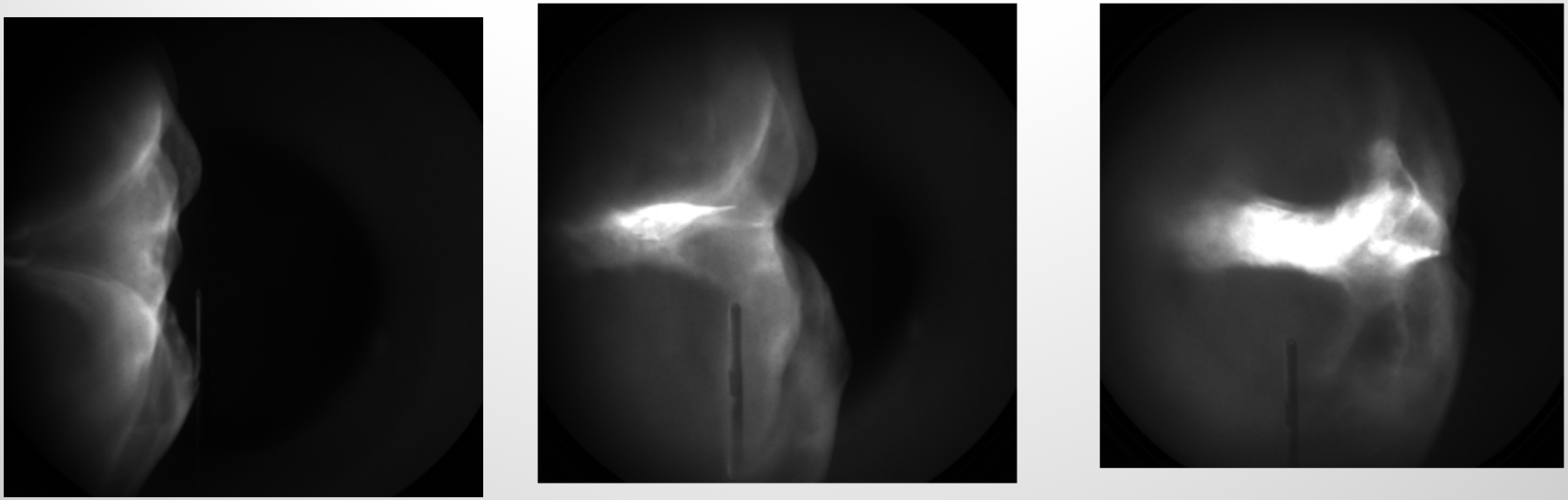


a) b) c)

Photos of the plasma flow at a stationary inlet of (a) deuterium and (b) neon;
(c) HH34 (B.Reipurth, S.Heathcote, J.Morse, P.Hartigan, J.Bally, Astron. J., 123, 362, 2002).

In case of discharges in pure deuterium, only the shockwave front is visible. A similar situation is observed in case of discharges in pure neon. That said, the flow contour becomes conical, which is yet another indicator of the importance of radiation cooling

Stationary filling of deuterium and pulsed injection

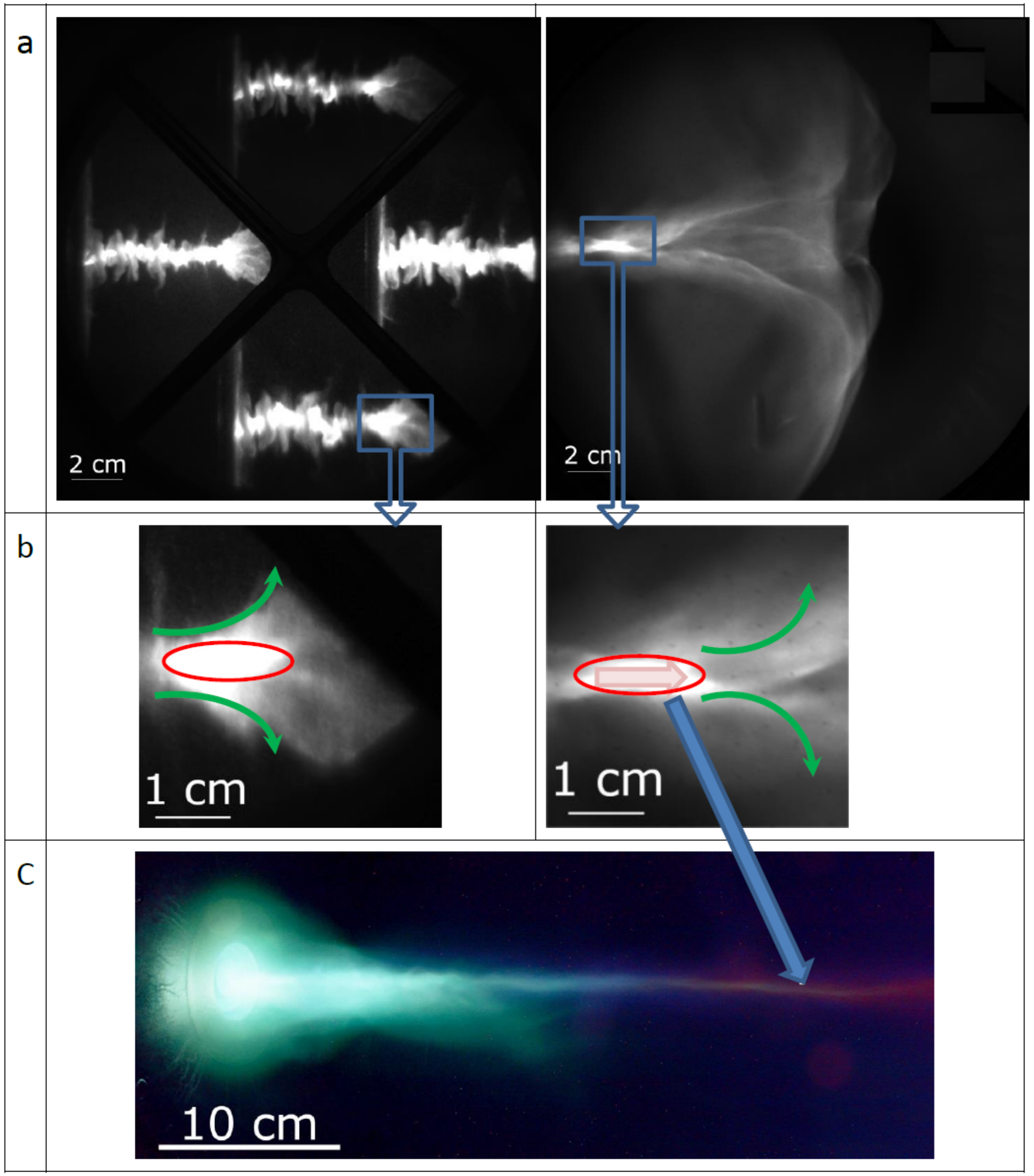


a) b) c)

Photos of plasma flow at pulsed injection of neon (a, b) and deuterium - neon (c) mixture. Direction of flow moving is from left to right

The existence of regions with elemental composition different than in background gas allows us to better understand the flow structure.

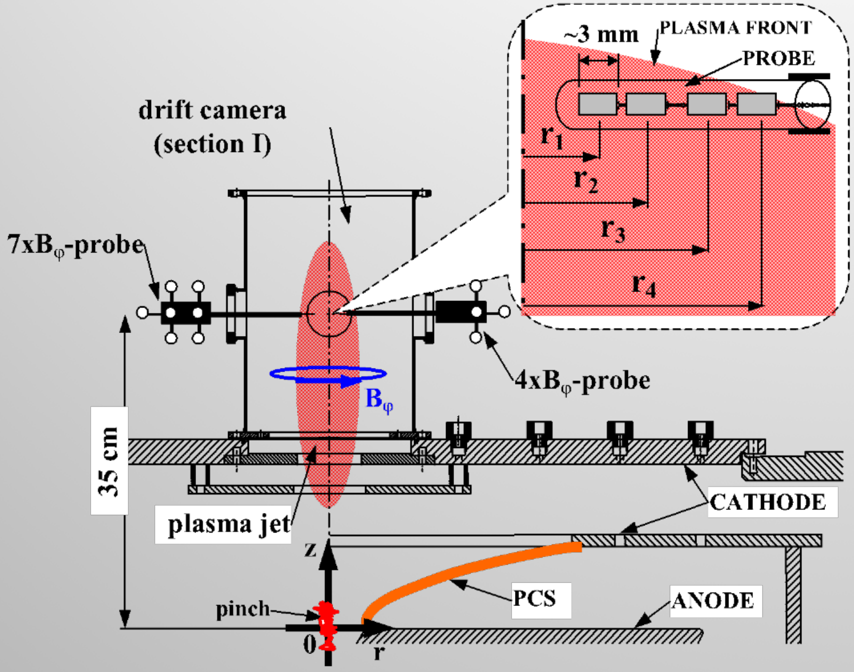
Scenario of jet formation and dynamics

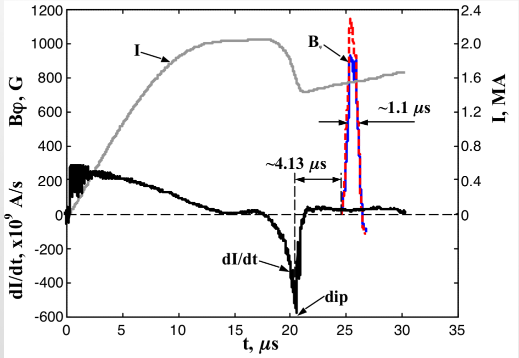


MEASUREMENTS OF MAGNETIC FIELDS IN THE PLASMA FLOW

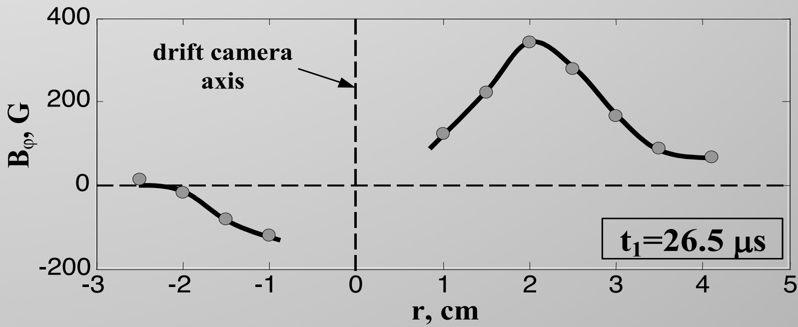
One of the advantages of experiments with the PF is large enough dimension of the jet (several cm), making it possible to apply magnetic probe techniques. This allowed to measure the distribution of magnetic fields in a laboratory jet.

- N-channel[N$\times B_\varphi(r)$] magnetic probe for measurements the radial distribution;
- 4- channel (B_z, B_r, B_φ, optic) probe for measurements of three components of the magnetic fields and optical radiation of plasma (with PM)

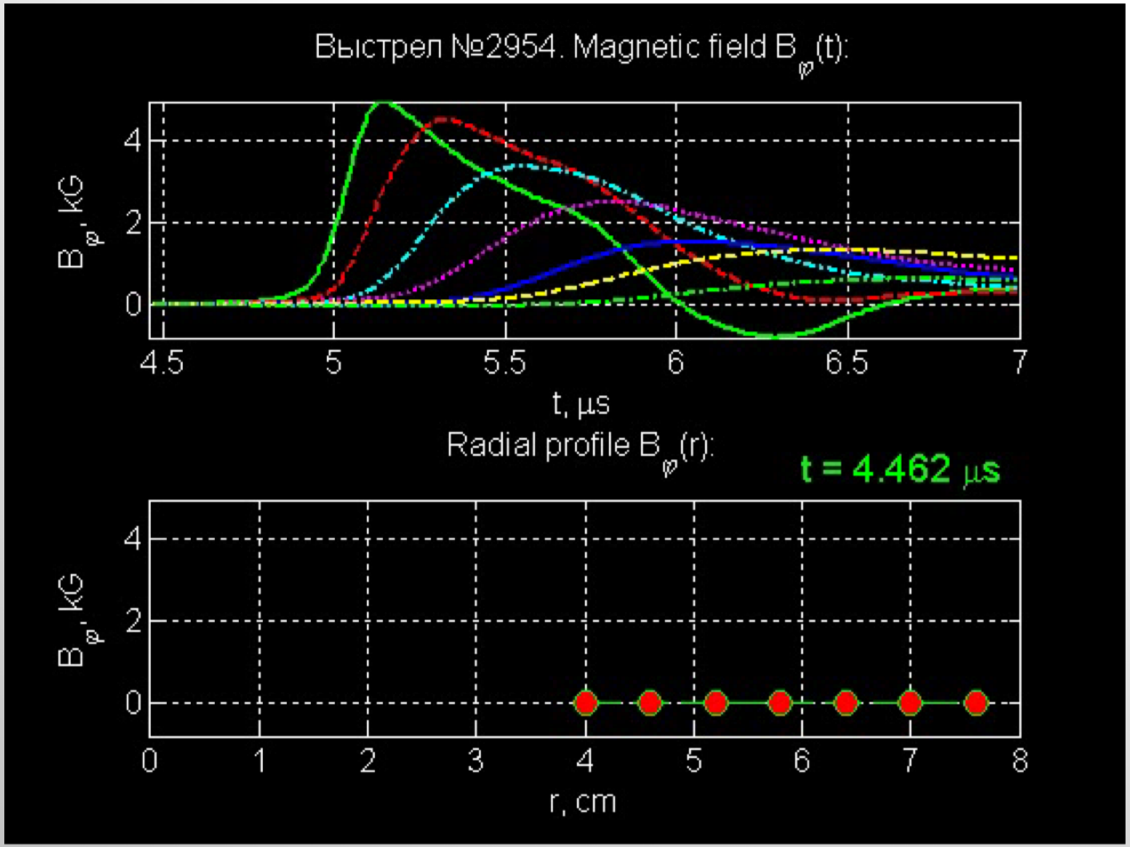


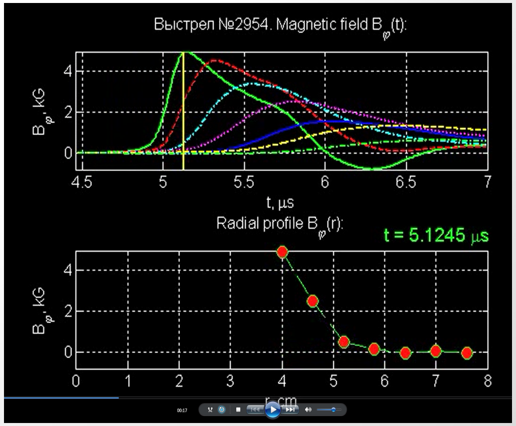


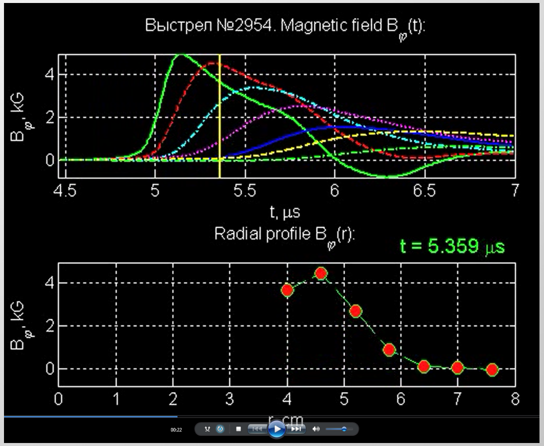
Region with the magnetic field has a finite size, indicating that the magnetic field is trapped by the jet.

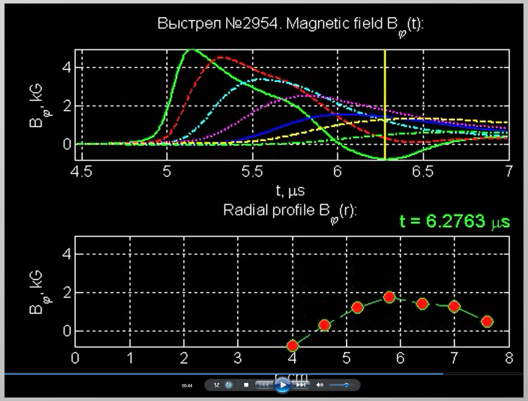


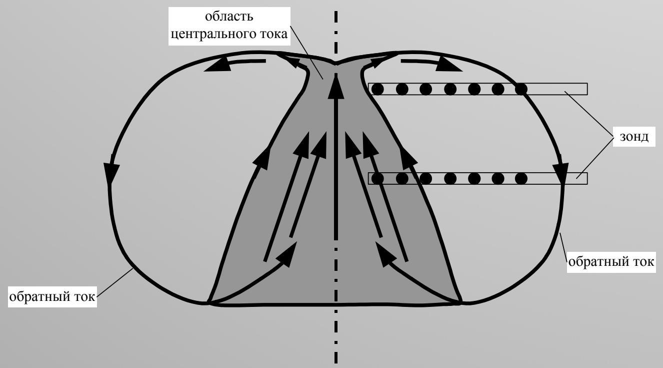
Such distribution can be explained by the axial current in (1-10) kA flowing in the zone near axis with radius of 1-1.5 cm (*K. Mitrofanov et al., JETPh, 2014. V. 119, 910)*


Выстрел №2954. Magnetic field B_φ(t):
B_φ, kG
4
2
0
4.5
5
5.5
6
6.5
7
t, µs
Radial profile B_φ(r):
t = 4.462 µs
B_φ, kG
4
2
0
0
1
2
3
4
5
6
7
8
r, cm


Выстрел №2954. Magnetic field B_φ(t):
B_φ, kG
t, µs
Radial profile B_φ(r):
t = 5.1245 µs
B_φ, kG
r, cm


Выстрел №2954. Magnetic field B_φ(t):
B_φ, kG
t, µs
Radial profile B_φ(r):
t = 5.359 µs
B_φ, kG
r, cm


Выстрел №2954. Magnetic field B_φ(t):
B_φ, kG
t, µs
Radial profile B_φ(r):
t = 6.2763 µs
B_φ, kG
r, cm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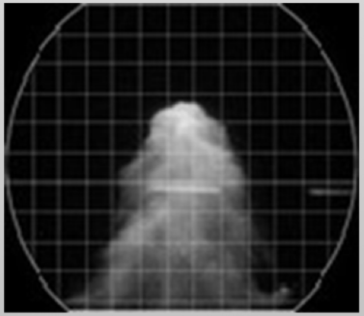
обратный ток
обратный ток



Magnetic probe measurements

Measurements at the periphery of the plasma flow made it possible to determine the radius of the reverse currents. Experiments carried out at different facilities with different gas filling conditions showed the dependence of this radius on two significant factors:

- Radiative cooling
- Background plasma pressure

At the PF-3 installation in experiments with Ne, the jet periphery, where the reverse current flows, lies in the radius range of 6-8 cm. In experiments with hydrogen, the reverse current region was actually not detected. Presumably, in the case of hydrogen, the current is closed on the metal body of the drift chamber with a radius of 10 cm. The minimum size of 3-6 cm was obtained on the KPF-4 with a stationary filling of 2 Torr Ar. At the same time, when working with deuterium (PF-1000 unit) or with the gas-puff of argon (KPF-4 unit), this radius can exceed 20 cm.

The analysis of the whole data set shows that the outer radius corresponds well to the dependence R ~ p-1/2 obtained in the paper Beskin et al. MNRAS 472, 3971–3978 (2017)

Ambient pressure

In cylindrical nonrelativistic jets the transverse force balance equation results in the conservation of total electric current I through the jet (Beskin, 2010). This implies that the electric current flows in a narrow central core and the return current flows along the outer boundary of a jet. As outside the core

$$B_{\varphi} = \frac{2I}{cr_{\perp}} = B_{\rm max}\frac{r_{\rm core}}{r_{\perp}},$$

and the transverse force balance near the jet boundary can be written down as

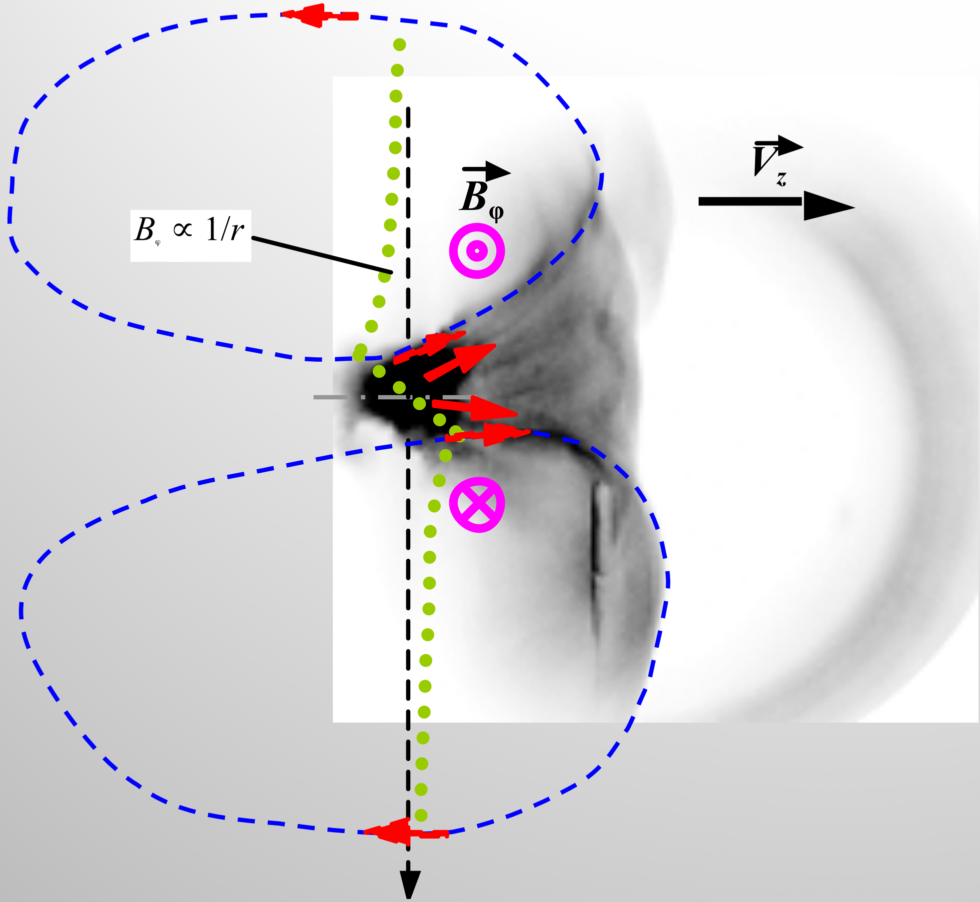
$$\frac{B_{\varphi}^2}{8\pi} = P_{\rm ext}$$

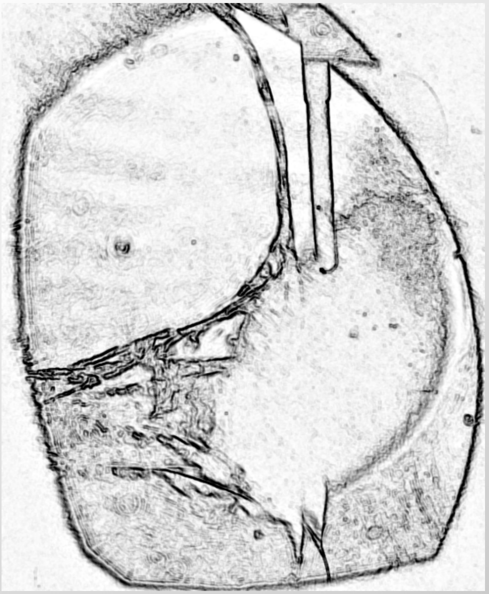
we obtain

$$r_{\rm jet} \approx \left(\frac{I^2}{2\pi c^2 P_{\rm ext}}\right)^{1/2} \sim 5.5\, r_{\rm core}\left(\frac{B_{\rm max}}{1\,{\rm kG}}\right)\left(\frac{P_{\rm ext}}{1\ {\rm Torr}}\right)^{-1/2}$$

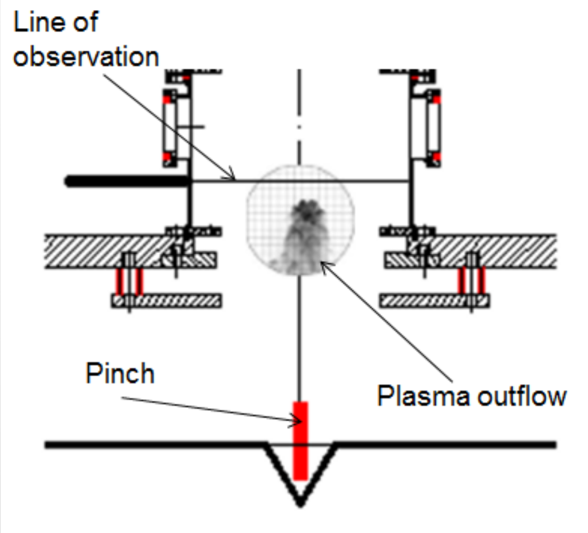
All these three values can be evaluated from experimental data.

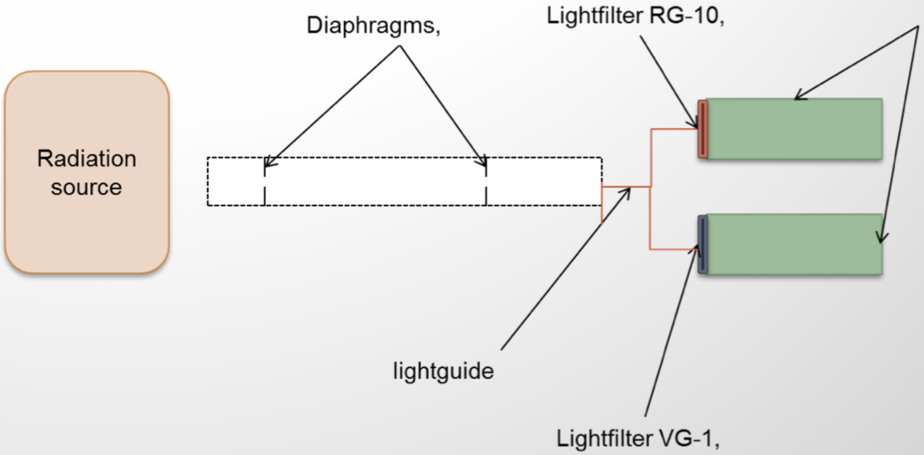
Structure of the plasma flow





Pre-ionization



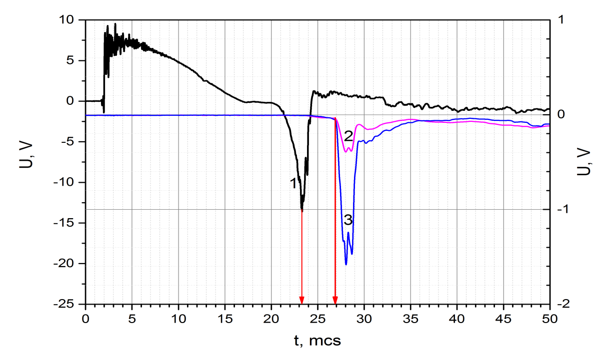

Radiation source

Diaphragms,

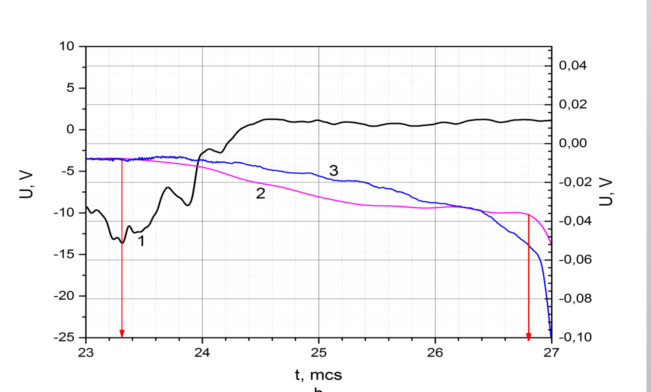
Lightfilter RG-10,

lightguide

Lightfilter VG-1,



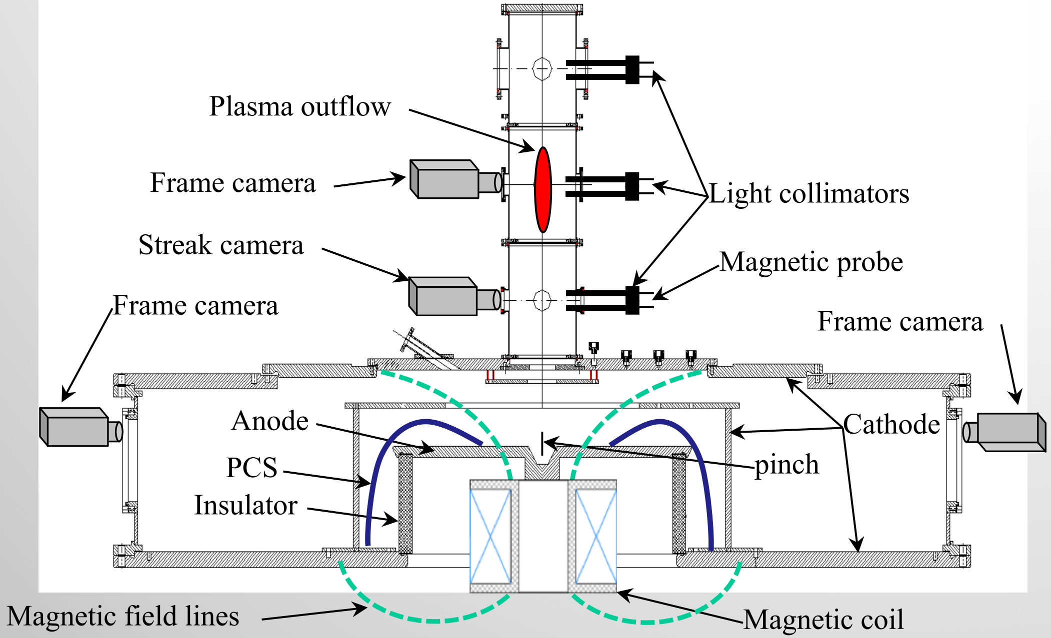
a

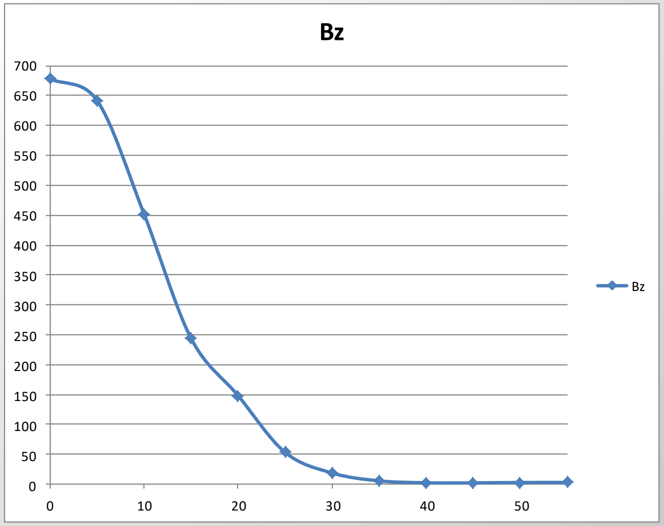


b

It is shown that as the jet moves, it significantly changes parameters of the background medium and, in fact, moves in the plasma. The calculations confirm that the laboratory jet can heat the background plasma to several eV.

Experiments with external magnetic field





We have created a small external longitudinal field in the pinch region. When compressing the sheath and, accordingly, the magnetic flux, the induction of the magnetic field on the axis increases to a value of ~ 10 T. As shown by magnetic probes, this leads to a noticeable increase in the captured field in the flow.

The increase in both the poloidal and toroidal components of the captured magnetic field is shown. This effect may be due to the rotation of the plasma flow.

Conclusions

- Plasma Focus (PF) installations have proven to be effective in simulating outflows from compact astrophysical objects.
- A distinctive feature of the experimental scheme with PF is the ab5ility to study the propagation of plasma flows over long distances, while it is possible to change the parameters of the environment.
- The influence of radiation cooling and magnetic fields on the collimation and stability of the plasma flow is analyzed. The presence of areas different in elemental composition from the background gas allows a better understanding of the flow structure.
- The dependence of the reverse current radius on the background gas pressure is shown
- The effect of background gas pre-ionization by plasma flow radiation is shown.
- An increase in both the poloidal and toroidal components of the captured magnetic field was shown in experiments with the external poloidal field. This effect may be due to the rotation of the plasma flow