NATIONAL RESEARCH CENTRE
«KURCHATOV INSTITUTE»

Laboratory Simulation of Astrophysical Jets within Facilities of Plasma Focus Type

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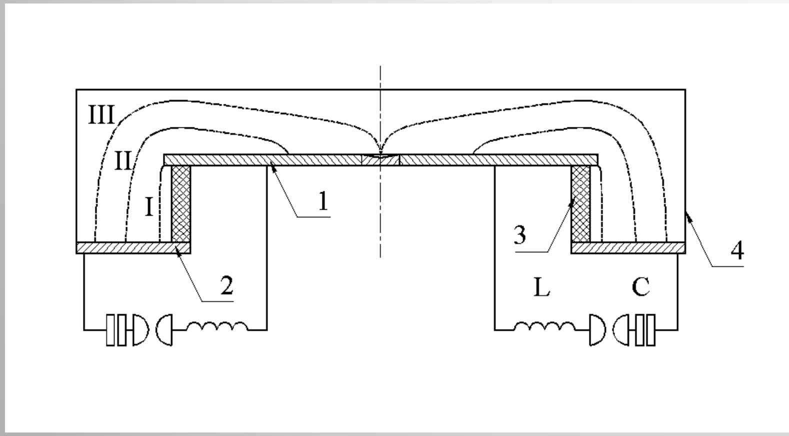
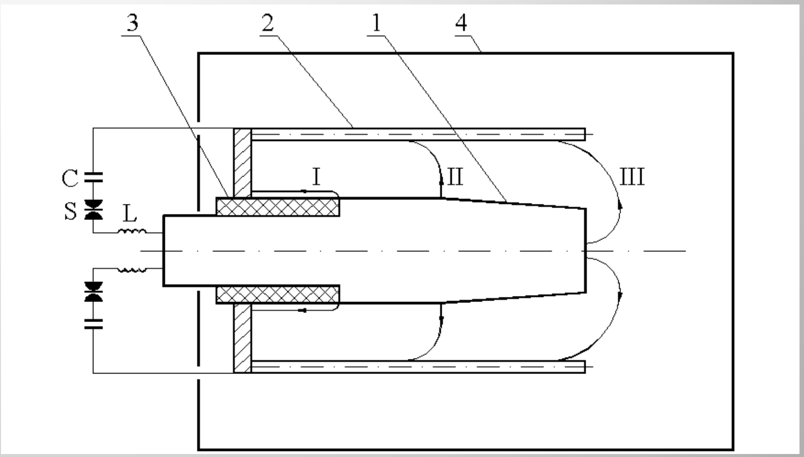
HEPRO VI

Statement of task

- Laboratory simulation is one of the effective tool for studies of the astrophysical jets. Experiments with the similar dimensionless parameters could give us possibility to observe some processes, which are inaccessible for direct studies (*B.A. Remington, R.P. Drake and D.D. Ryutov, RMPh, 2006,78:755)*
- Over the past decades, a new experimental capability emerged due to developing of high-energy density (HED) facilities: high power lasers (*B. Albertazzi et al, SCIENCE, 2014, **346**, 6207)* and dense Z-pinches (Suzuki-Vidal F et al., 2011, Ap&SS, **336**, 41.) These facilities were developed mainly as a result of the inertial confinement fusion (ICF) program, but are also very actively used for laboratory modeling.
- The plasma focus (PF) is one of the representatives of Z-pinches. One of the important features of PF facilities is generation of intense plasma streams which find various applications in science and technology. Such plasma streams are used to study interactions of plasma with solid-surfaces, modifications of materials in order to improve their characteristics, to produce nanostructures, etc.
- An interesting application of pulsed plasma streams, generated by PF discharges, is modelling of various processes in the Space, including the generation and propagation of the astrophysical jets. In our view, the plasma focus has a number of advantages.

PLASMA FOCUS





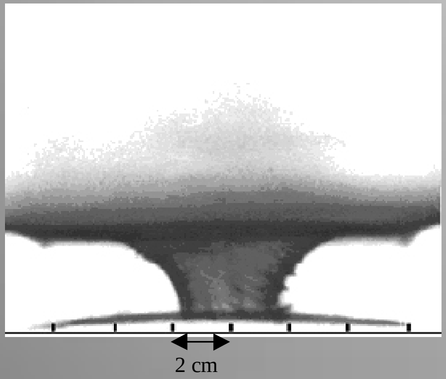
Filippov-type (D/L≥1)

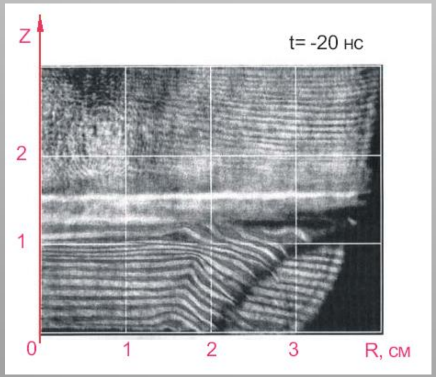
Mather-type (D/L<<1)

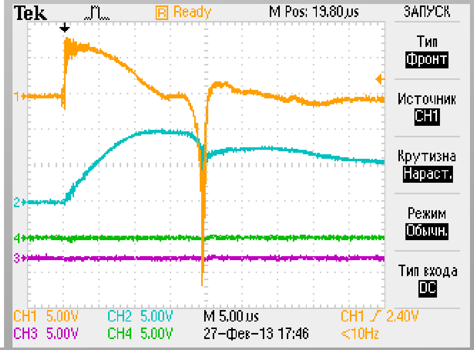
1 – anode, 2 – cathode, 3 – insulator, 4 – vacuum chamber

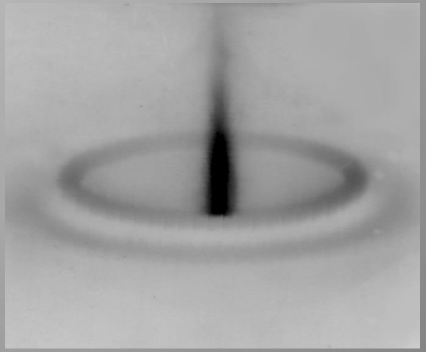
C – power supply, L – external inductance, S – spark gap

I – break-down phase; II – run-down phase; III – dense plasma focus phase









Experimental facilities

Laboratory simulations of YSO jets was initiated in NRC "Kurchatov Institute" by E. P. Velikhov
(*V. Krauz et al.,Physica Scripta. T161 (2014) 014036)*
The main experiments are carried out on the PF-3 (plasma focus Filippov-type),
the world's largest installation of this class.

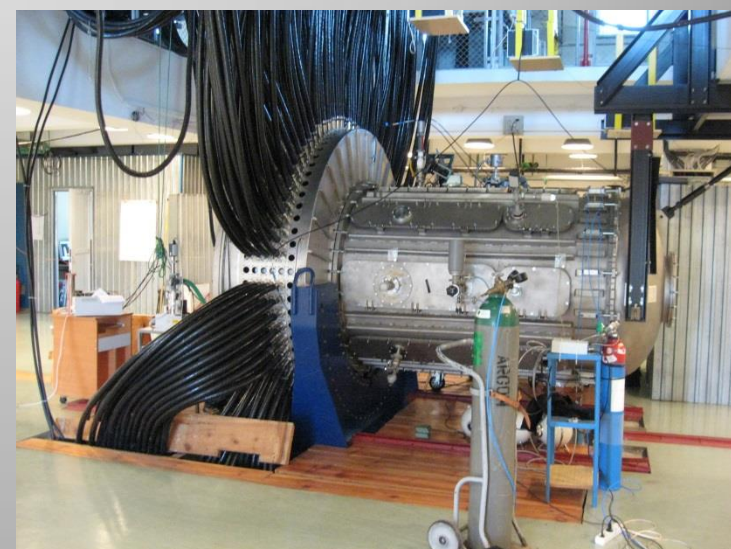
Some interesting experiments were done on PF-1000 (IFPiLM, Warsaw, Poland) and KPF-4 (SFTI, Sukhum, Abkhazia) facilities.

PF-3

(NRC KI)

KPF-4 «Phoenix»

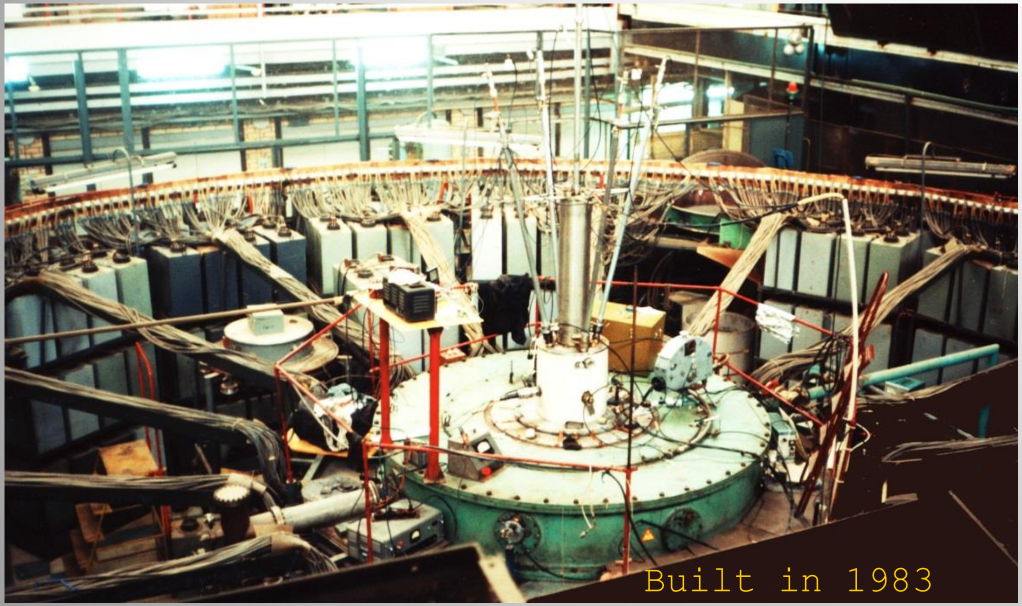
(SFTI, Sukhum)

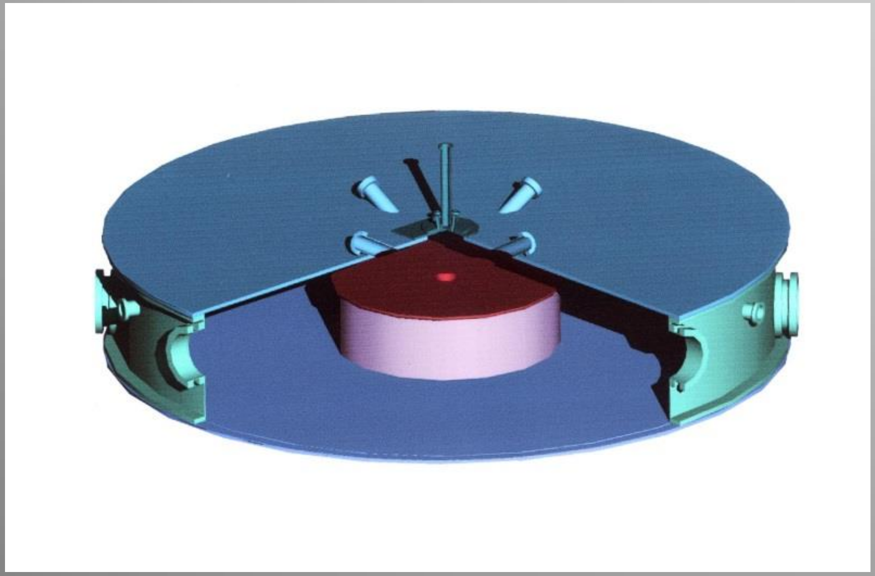


PF-1000

(IFPiLM, Warsaw)

Plasma Focus PF-3





PF-3 facility:

The diameter of the anode and that of the chamber equal 1 m and 2,5 m, respectively

The height of an insulator is 26 cm

The distance between anode and upper cover of discharge chamber (cathode) is 22 cm

Maximal energy stored at the power supply (C_{max}=9,2 mF, V_{max}=25 kV) is 2,8 MJ

Short-circuit current is 19 MA

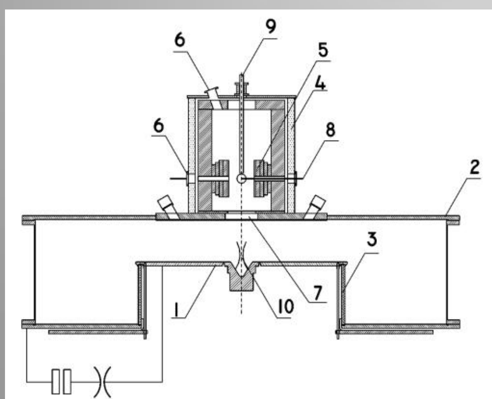
Experiments were done at the W=290-560 kJ and the discharge current 1 – 2 MA.

Working gas are H_2, D_2, He, Ne, Ar, Xe and their mixtures at pressure 1 – 4 Torr

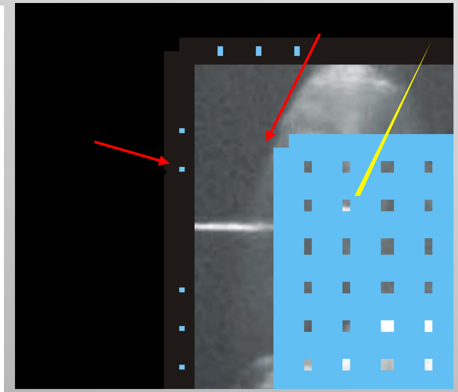
Simulation of the Solar Wind shock wave (Kurchatov Institute and CEA, France)

D.Mourenas et al., Physics of Plasmas (2003) ***10****, 605*

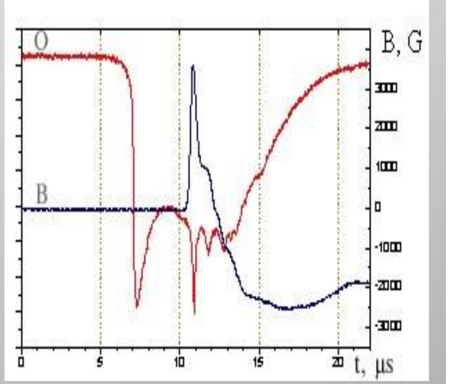
$W \sim 1 MJ$, $I \sim 3$ MA, $P_{Ne} = 0.5 \div 1$ Torr,
$B_0 = 2500$ G, $M_A = 3 \div 10$



1 – anode; 2 – cathode; 3 – insulator; 4 – chamber of interaction; 5 – magnetic poles; 6 – diagnostic ports; 7 – mesh; 8 – magnetic-optical probe; 9 – Faraday cup; 10 - pinch.

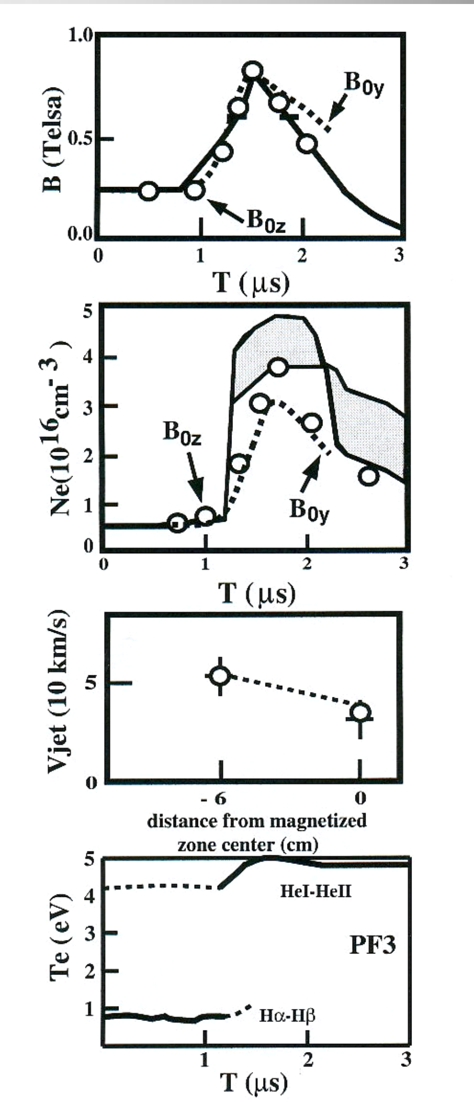


Plasma jet image
τ_{exp}= 10 ns



Traces of the magnetic (B) and optic (O) probes

n_e= (5÷6) 10^{16} cm^{-3}, $T_e \cong 5$ eV

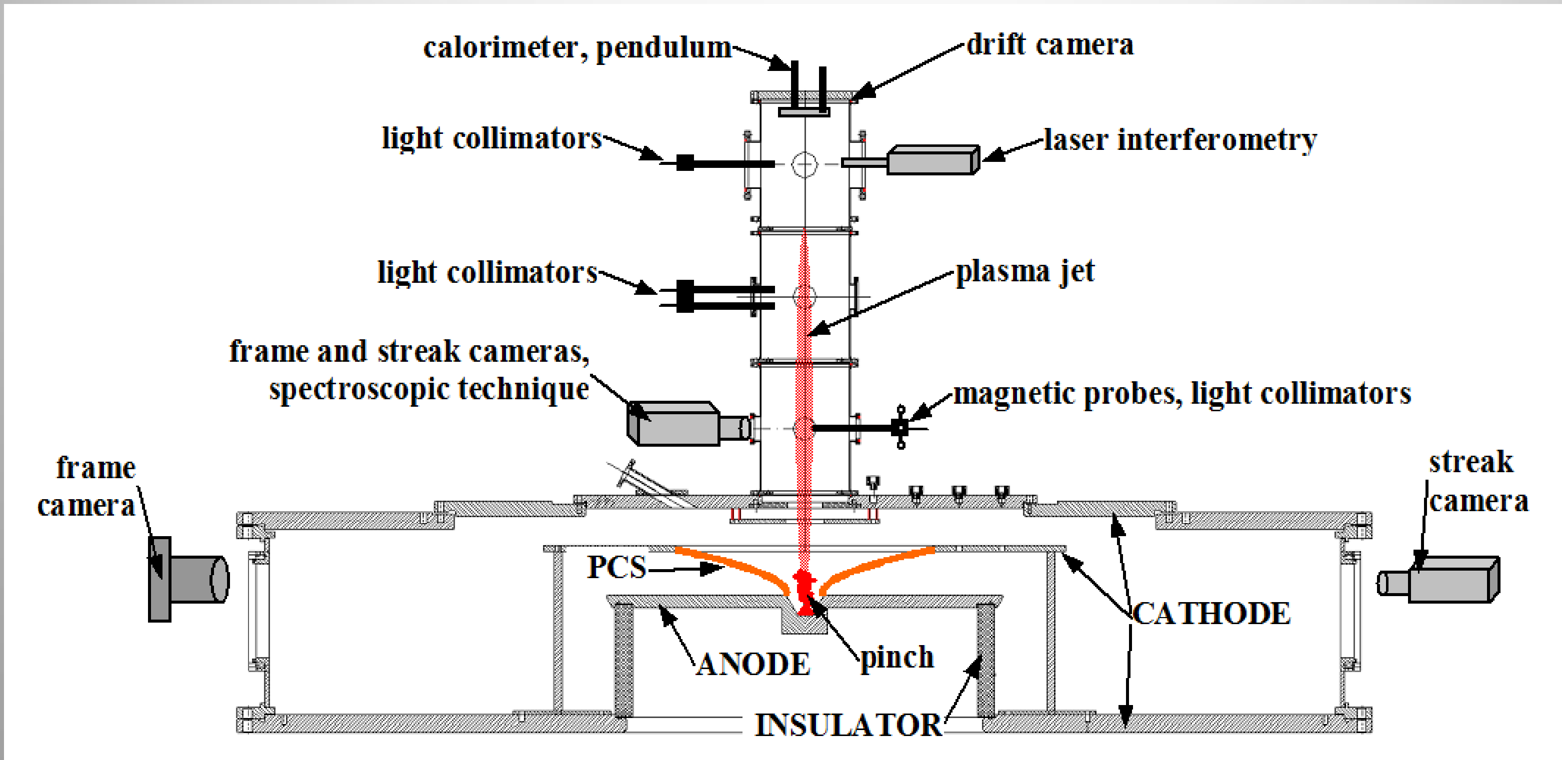


Upgrading of the PF-3

The one of the main advantage of the experimental scheme on the PF facilities is the possibility modeling not only the processes of the jet generation, but also its propagation in the ambient plasma. It allows us to study the very important problem of the jet stability at its propagation to the distances much greater than their cross dimensions (up to 100 cm).

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.

Diagnostics



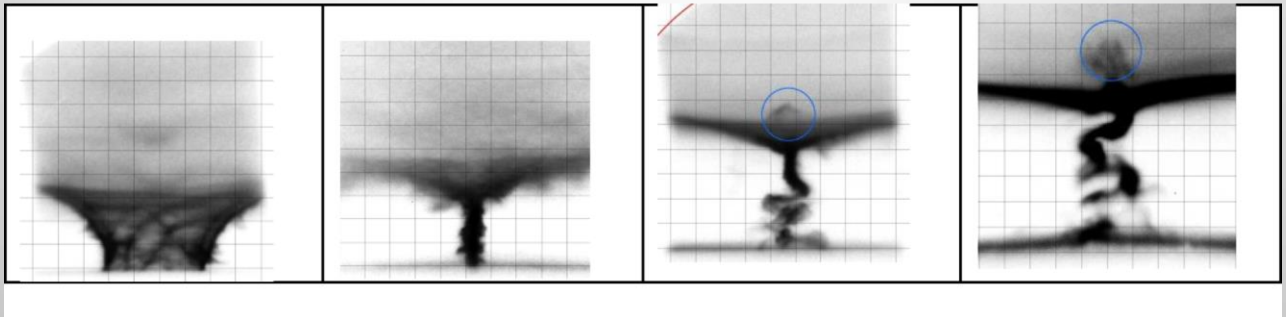
The wide set of diagnostic tools was used for studies the jet parameters in different cross sections of the drift chamber, including streak and frame cameras, light collimators, multi-component magnetic probes, laser diagnostics on the base of nanosecond Nd3+:YAG laser, ballistic pendulum, calorimeter, spectral diagnostics, etc.

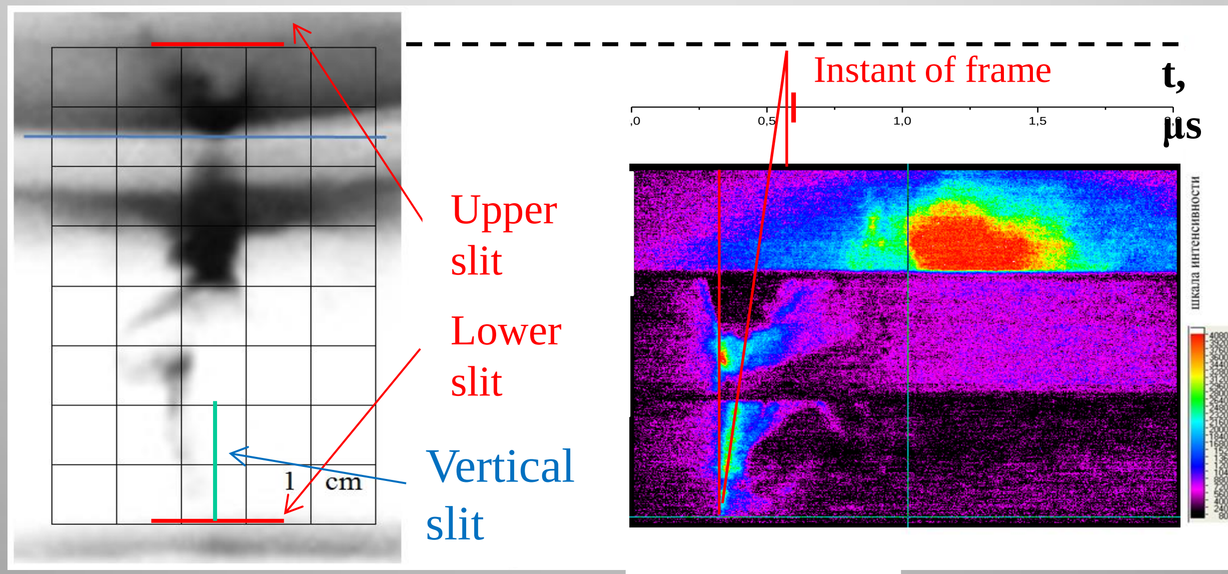
The main tasks

- **The study of the stage of plasma flows formation**
- **Studies of plasma jet parameters and its propagation in the ambient plasma**
- ✓ *Velocity*
- ✓ *Dimensions (divergence)*
- ✓ *Density and temperature of the plasma jet*
- ✓ *Jet energy and momentum*
- ✓ *Density and temperature of the ambient plasma*
- ✓ *Distribution of the magnetic and electric fields*
- ✓ *Damping (deceleration) of the plasma flow, depending on the parameters of the ambient plasma (various gases, gas-puff etc.)*

- **The experiments focused on the simulation of specific options of the astrophysical jets**

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.

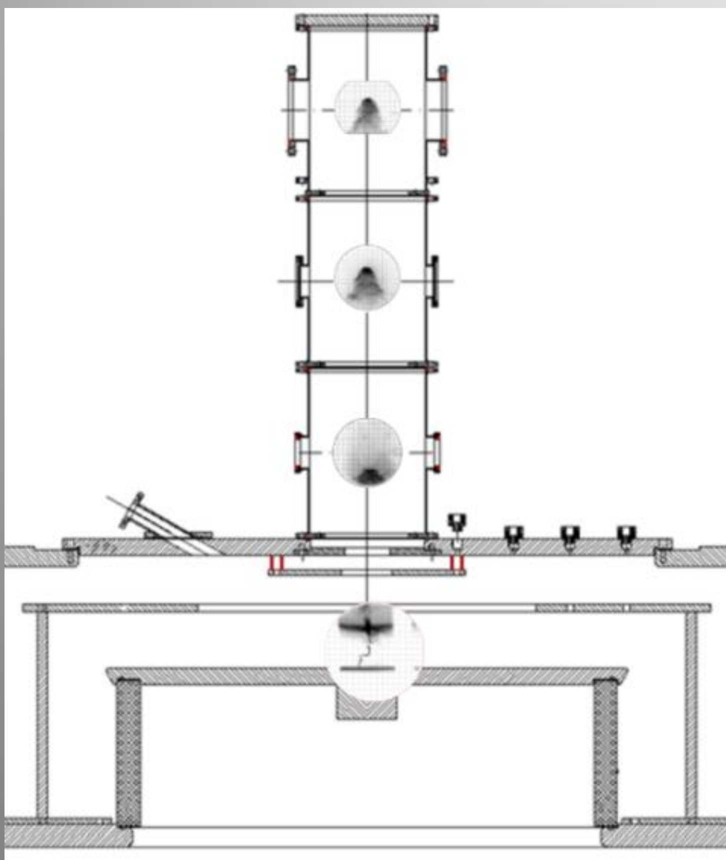
Jet propagation

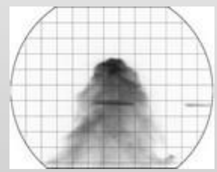
At stationary gas filling the regimes with the formation of compact plasma flows were obtained. The transverse dimension of the flow head does not exceed a few cm at propagation distances up to 100 cm.

Anan'ev S.S., VANT. Ser. Thermonuclear fusion. 2013. ***36****. № 4. 102*

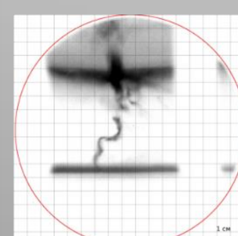
Mitrofanov et al., Astronomy Reports, 2017, ***61****, No. 2, p. 138*

Beskin V.S. et al., Radiophysics and Quantum Electronics, ***59****, No. 11, 2017, 900*

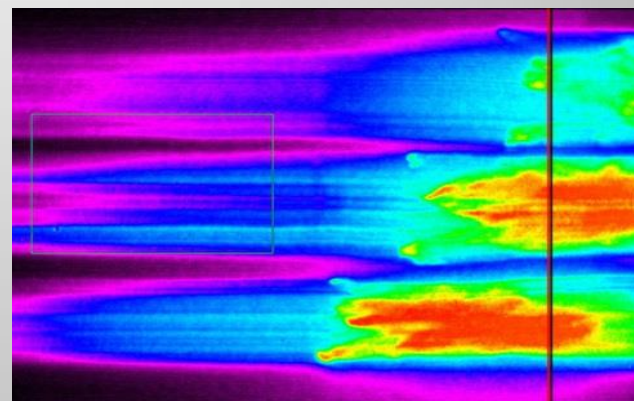




Ar, 95 cm

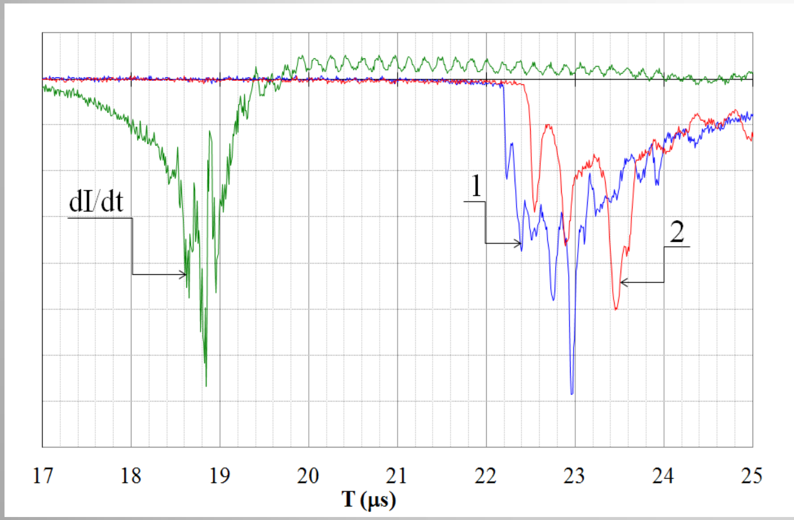


Anode plane

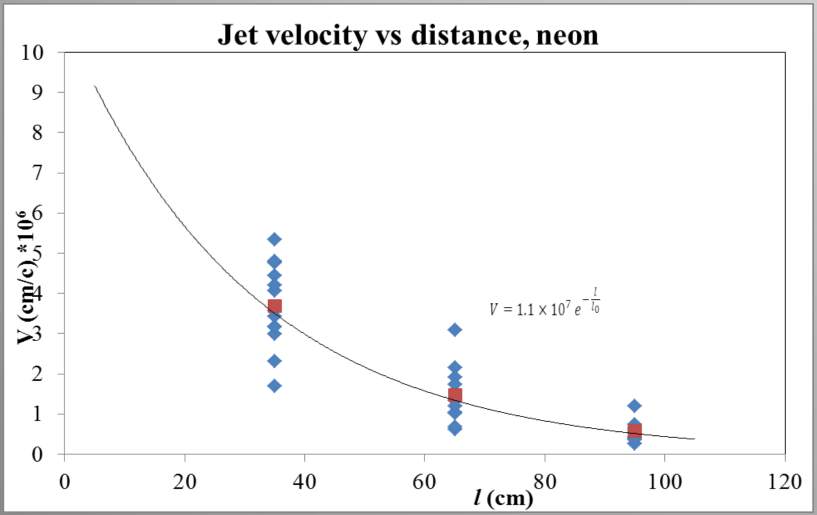


Streak camera images, Ne, 35 cm.
Three horizontal slits are placed with a step of 4 cm.
The analysis of these images indicates the presence of flow rotation

Averaged velocities for different gases and cross sections



Gas	$V_{inst} \cdot 10^6$ (cm/s)			$V_0 \cdot 10^7$ (cm/s)	l_0 (cm)
	V_1 (35 cm)	V_2 (65 cm)	V_3 (95 cm)		
Ne	3.8±1.0	1.5±0.72	0.6±0.26	1.1	30
Ar	4.7±0.4	2.0±0.4	0.7±0.2	1.5	30
He	6.3±0.7	2.6±0.6	1.2±0.2	2.1	34
H_2	5.5±1.0	2.9±0.8	2.1±0.4	0.9	61
H_2+Xe	4.4±0.8	2.5±0.4	1.3±0.3	1.0	47
D_2	6.5±0.9	2.6±0.3	1.9±0.2	1.2	50
D_2+Xe	5.2±0.4	2.1±0.4	0.8±0.2	1.55	31



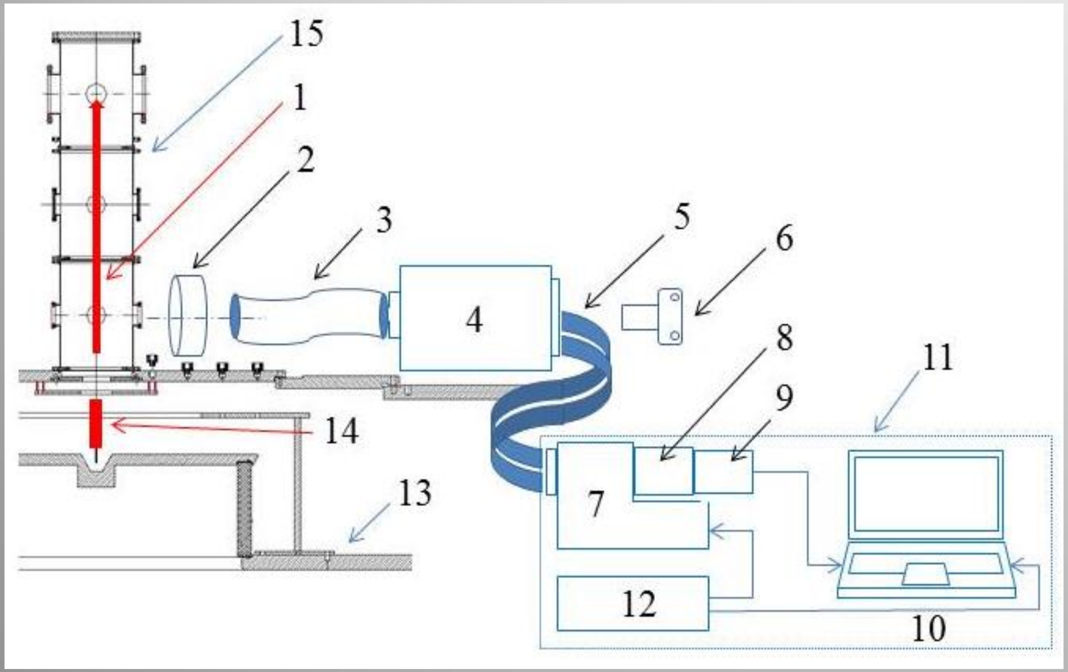
$$V = V_0 \exp(-l/l_0)$$

The presence of the ambient gas significantly affects the flow parameters. It was shown that l_0 strongly depends on the used working gas. It can be explain by the different degree of ambient gas ionization by the pinch emission.

At the same time, the initial velocity weakly depends on the type of gas and corresponds well the velocity determined by the frame cameras at the stage of the jet formation.

Spectroscopic system for plasma parameters measurements

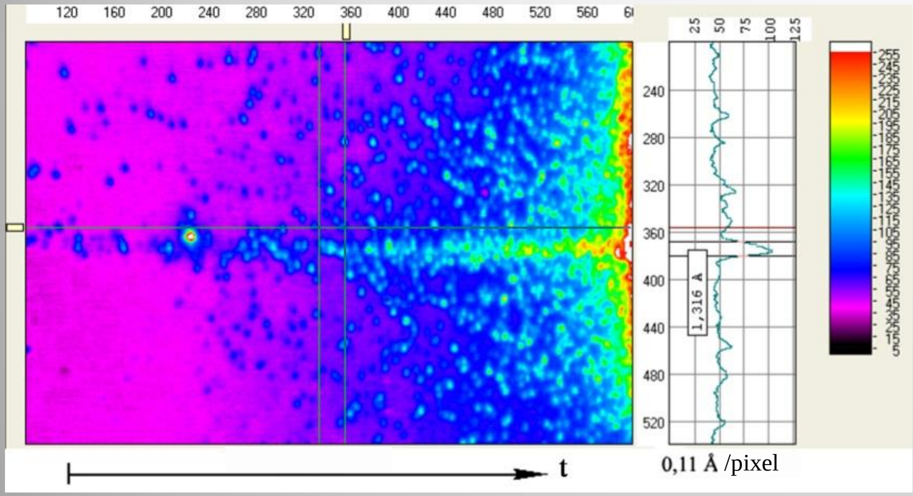
For the study of the plasma parameters the diagnostic set including the spectrograph with high resolution in combination with a time-analyzing streak camera was developed.

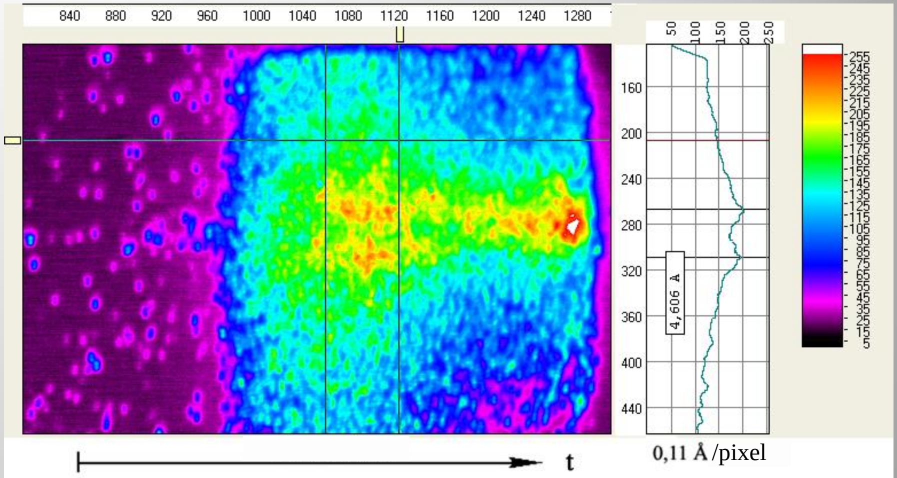


1 - emitting object; 2 - lens; 3 – light guide with a regular arrangement of fibers; 4 -spectrograph; 5 - magnetic holder for fibers, 6 - digital photo camera; 7 – streak-camera; 8 - tube; 9 - CCD; 10 - notebook; 11 - shielding box; 12 - uninterruptible power supply; 13 – PF-3 vacuum chamber; 14 - plasma focus; 15 – drift tube.

The plasma concentration estimated from the Stark broadening of the spectral lines of working gas due to the electric fields of various nature.

Plasma parameters





The background plasma concentration is $N_e \sim (2\text{-}4)\times10^{16}$ cm^{-3}. Maximum value in the helium jet at 35 cm is estimated as 2×10^{17} cm^{-3}. The electron temperature of the helium jet plasma was 4-8 eV. The neon jet plasma is characterized by the maximum concentration value equal to $(2\text{-}4)\times10^{17}$ cm^{-3}. The electronic temperature was $T_e \approx 2\text{-}3$ eV.

At the distance of 65 cm from the focus, the concentration of background neon plasma was outside the limits of spectral equipment registration and was be estimated as $N_i \leq 10^{16}$ cm^{-3}. The maximum value of electron concentration in the jet was $(0.5\text{-}2)\times10^{17}$ cm^{-3}. The electron temperature of the neon jet plasma was $T_e \approx 1$eV.

Obtained data were used for estimation of the main dimensionless parameters.

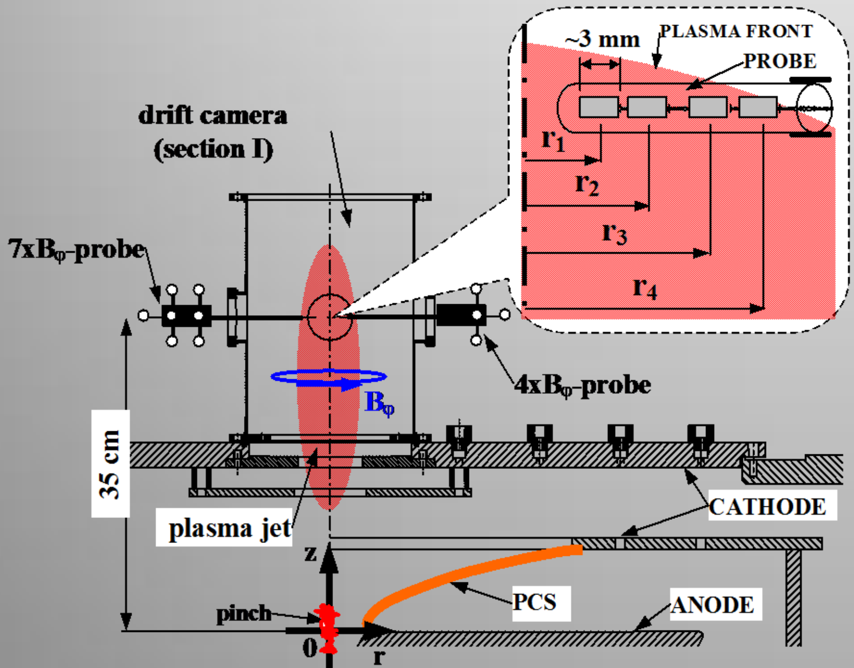
S. S. Anan'ev et al., Plasma Physics Reports, 2016, **42**, 269

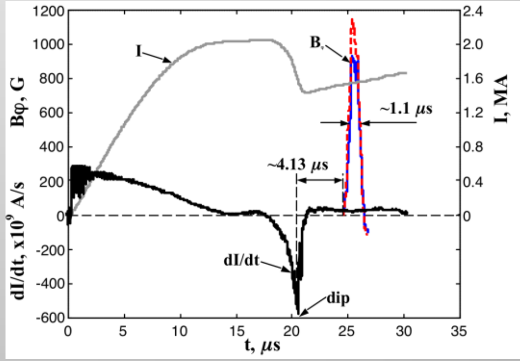
S A Dan'ko et al. PPCF, 59 (2017) 045003

MEASUREMENTS OF MAGNETIC FIELDS IN THE PLASMA FLOW

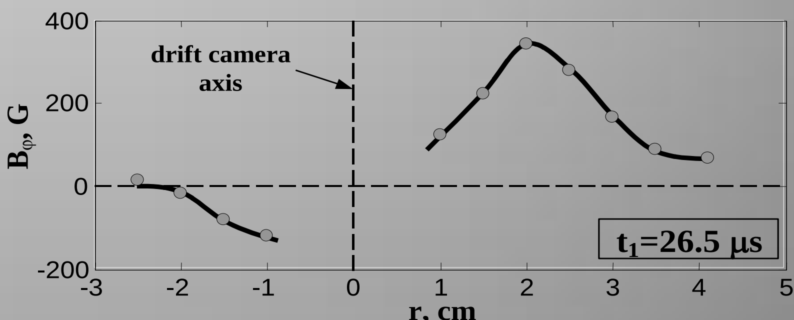
One of the advantages of experiments with the PF is large enough dimension of the jet (several cm), making it possible to apply magnetic probe techniques. This allowed to measure the distribution of magnetic fields in a laboratory jet.

- N-channel[Nx$B_\varphi(r)$] 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)



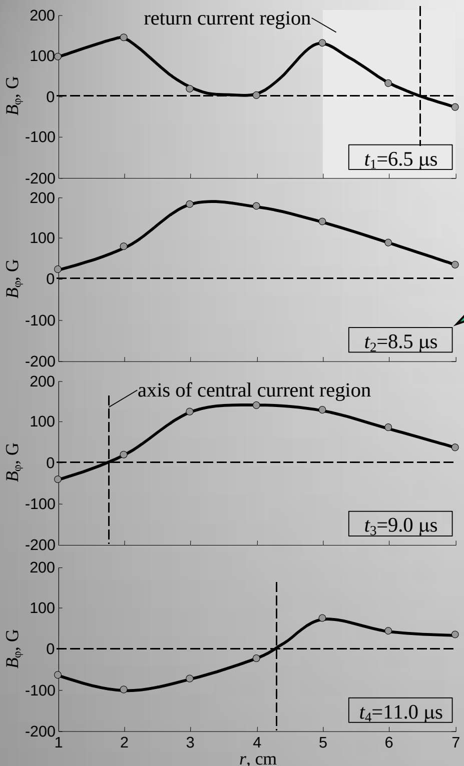


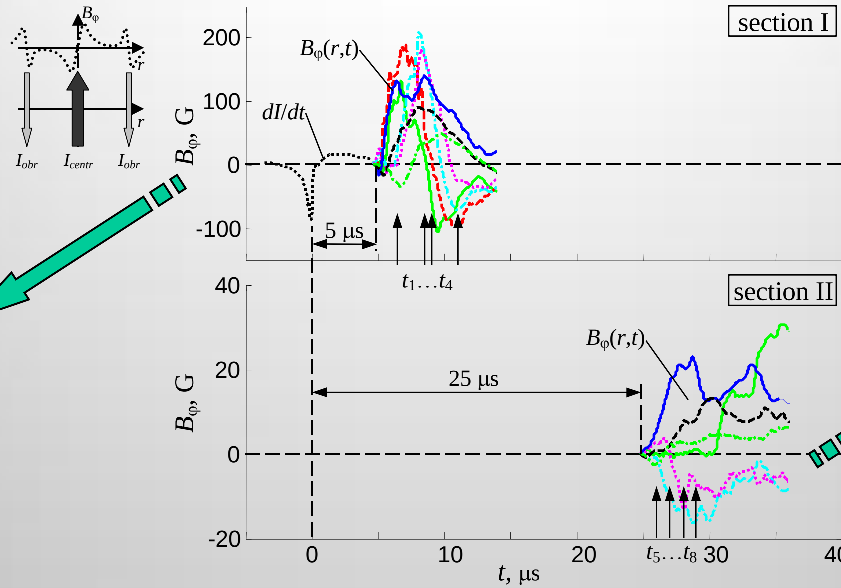
Region with the magnetic field has a finite size, indicating that the magnetic field is trapped by the jet.

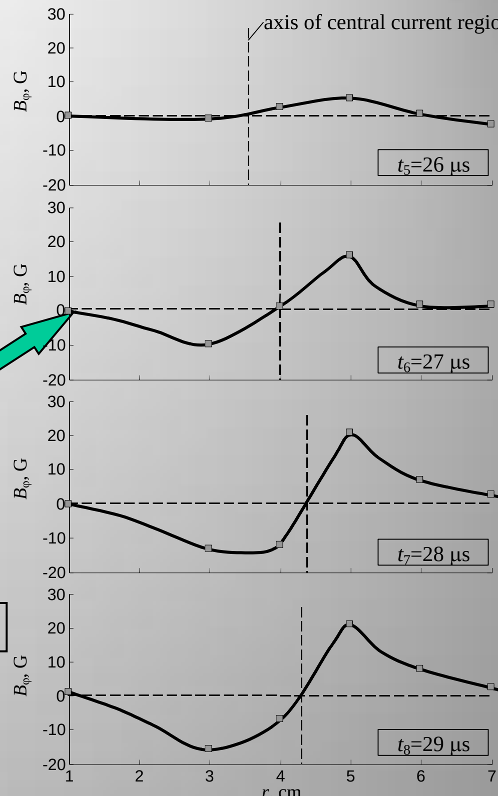


Such distribution can be explained by the axial current in (1-10) kA flowing in the zone near axis with radius of 1-1.5 cm (*K. Mitrofanov et al., JETPh, 2014. V. 119, 910)*

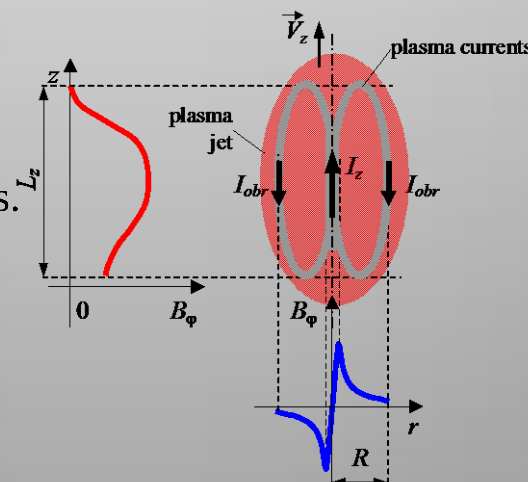
Radial distribution of the magnetic field in the jet, 35 cm and 60 cm from anode (PF3 facility)







Shot #4295, gas Ne, P_0=2.0 tor, U_0=9 kV, W_0=373 kJ

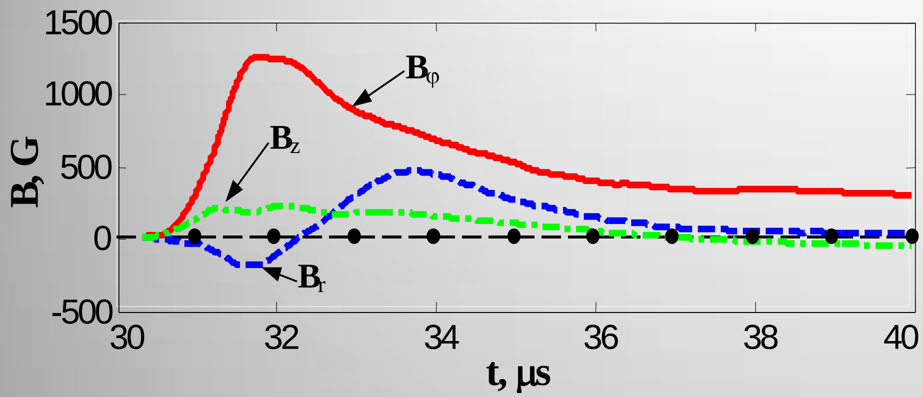


The measurements on the periphery of the plasma jet showed the presence of return currents.

*Mitrofanov et al., Astronomy Reports, 2017, **61**, No. 2, p. 138*

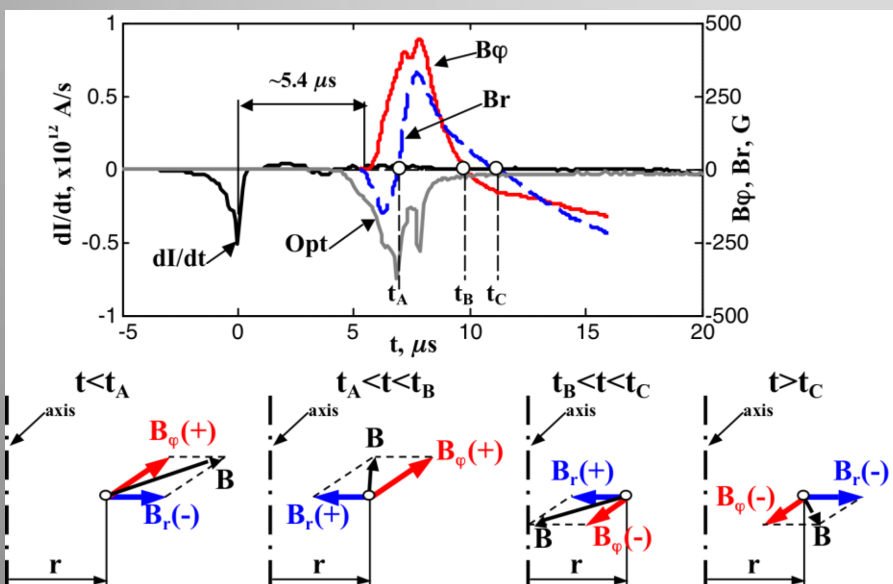
*Beskin V.S. et al., Radiophysics and Quantum Electronics, **59**, No. 11, 2017, 900*

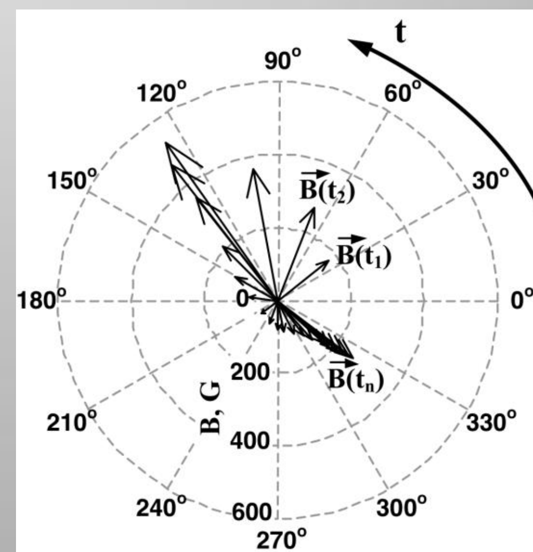
Rotation of the magnetic field vector



K. Mitrofanov et al., JETPh, 2014. V. 119, 910

$$\vec{B} = \vec{B}_r + \vec{B}_\varphi + \vec{B}_z$$



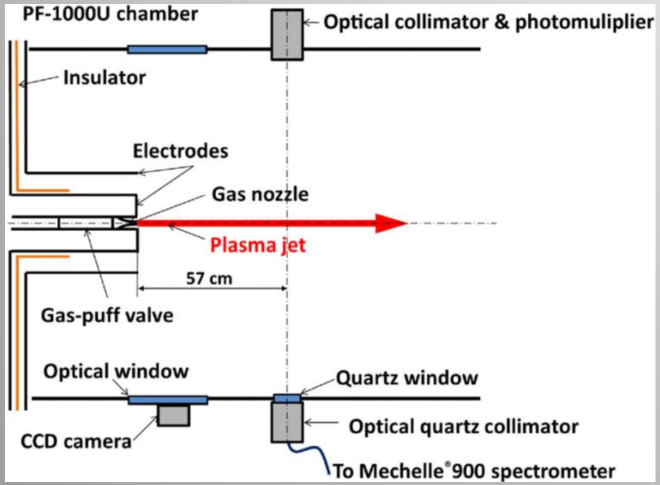


It was shown the rotation of the magnetic field vector, which, in assumption of frozen magnetic field, may be associated with the rotation of the plasma flow.

Experiments on PF-1000

The PF-1000 (IFPiLM, Warsaw,) and KPF-4 (SFTI, Sukhum,) experiments are aimed at creating profiled initial gas distributions.

On the PF-1000, after the initial filling the chamber with deuterium (0.9 Torr), there was applied an additiona injection of a chosen gas (deuterium, helium, neon or their mixtures) along the electrode-axis, which influenced on the pinching and generation of plasma streams and their penetration through the background gas.

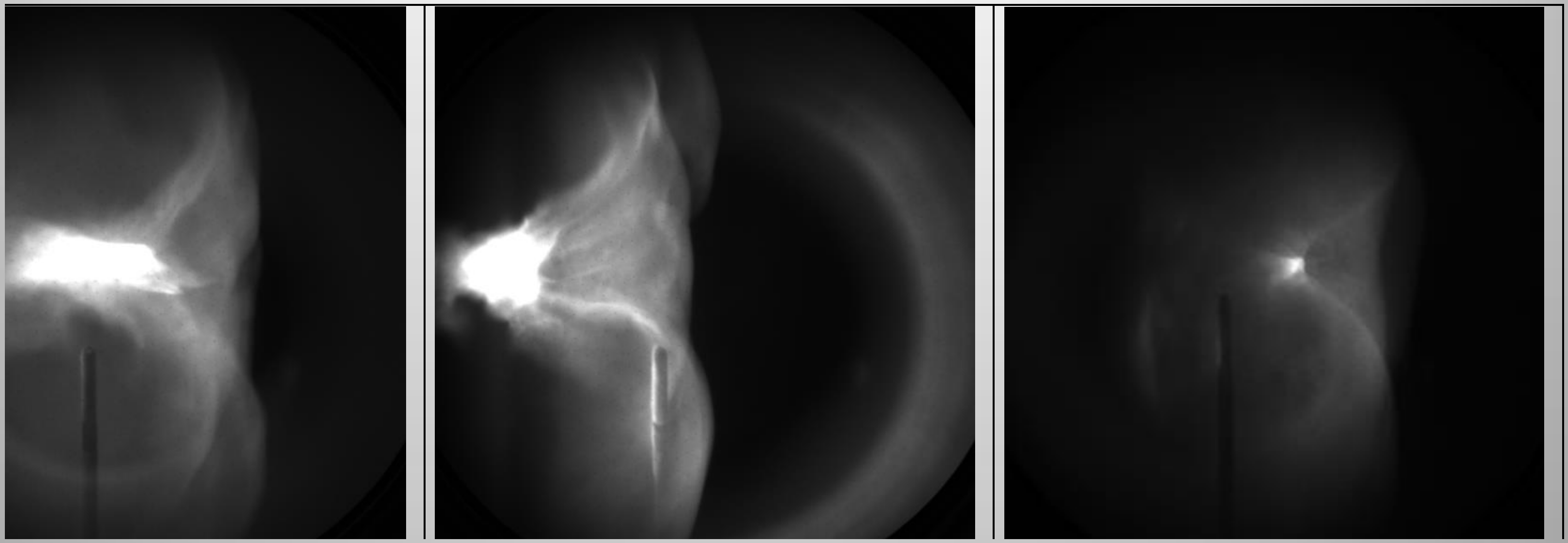


Time-integrated picture of a plasma jet

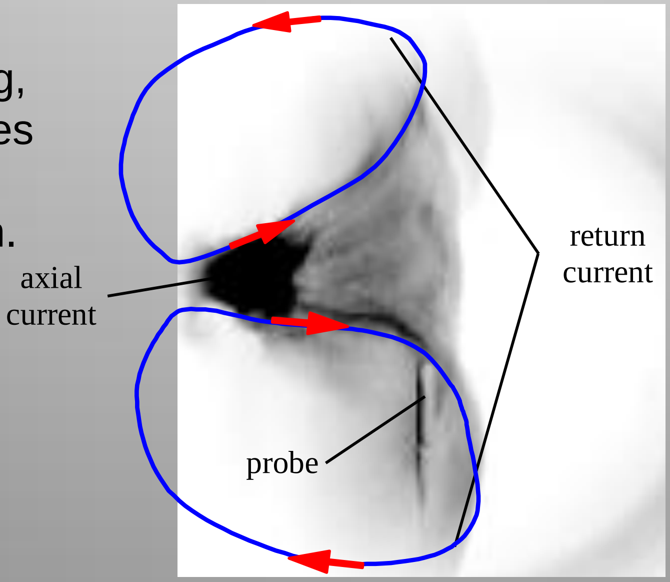
The plasma density was estimated from the Stark broadening at a distance of 27-57 cm from the end of the anode, which amounted to (0.4 – 4.0) x 10^{17} cm^{-3} The electron temperature was estimated as 3-5 eV. The density of ambient plasma is ~ 1.5 x 10^{15} - 10^{16} $см^{-3}$.

(*E. Skladnik-Sadowska, et al., Phys. Plasmas* ***23****, 122902 (2016)*)

Compact plasma objects



At modes with gas-puffing, compact plasma structures were formed with dimensions of several cm.



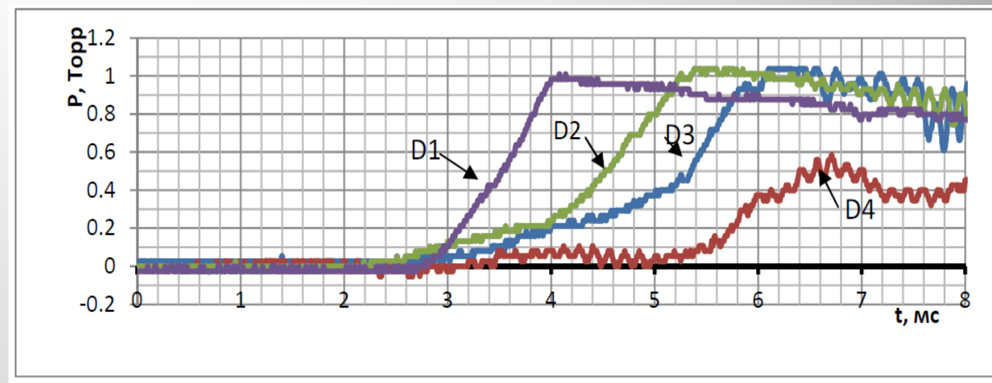
Signals from magnetic probes showed that inside those plasma structures the axial current is flowing.

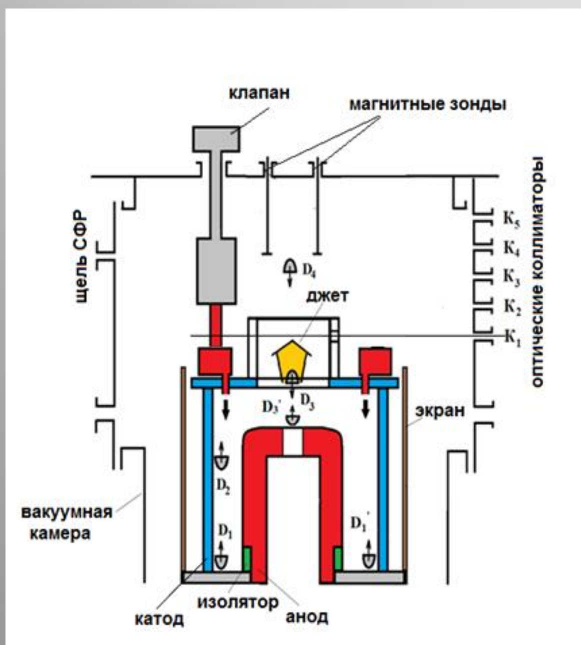
A complicated form of the plasma jet front might be caused by return currents which could flow at a plasma jet periphery.

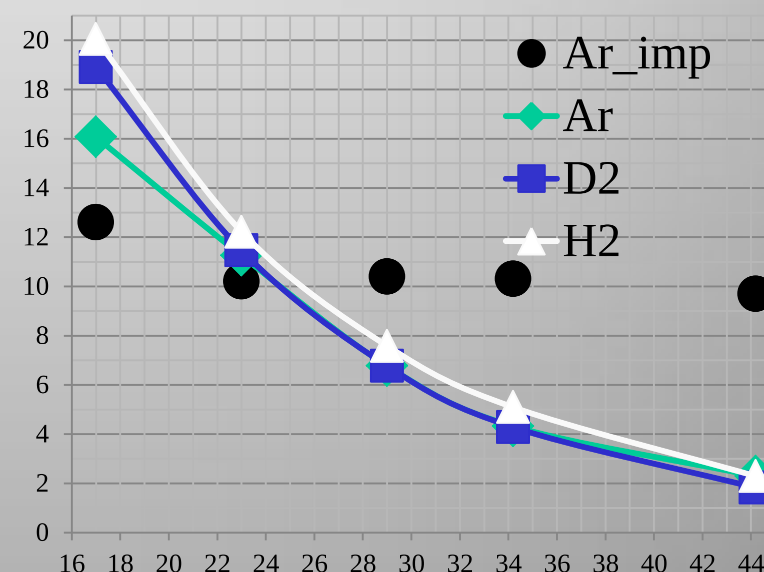
V.I. Krauz et al., Journal of Physics: Conference Series, to be published

KPF-4, gas-puff

The experiments on PF enable us to vary the parameters of the external medium over wide limits, including the so called contrast—the ratio of the density in the jet to the density of the ambient gas.







D_i – electret pressure sensors,
D_i’ – electrodynamic pressure sensor.
D1,D1’ – (-31) cm, D2 - (-11 cm) ,
D3- 15 cm , D4 – 42 cm. 0 см – anode top

V.I. Krauz et al., Journal of Physics: Conf. Series, to be published
*D. Vojtenko et al., Plasma Physics Reports, 2017, **12,** to be published*

Dimensionless Scaling parameters

Achieved parameters of the plasma jet seems very prospective for the simulation the plasma jets in the young stellar objects known as the objects 'Herbig-Haro'.

	YSO		CH, 10^{12} W/cm^{2*}	PF-3 (35 cm above the anode)	PF-1000U (57 cm from the anode top)
Peclet	10^{11}	> 1, convective heat transfer	3.5	>10^{7}	>10^{7}
Reynolds	1.0x10^{13}	>>1 – the viscosity is unimportant	3.7x10^{4}	10^{4} -10^{5}	> 2 x 10^{4}
Magnetic Reynolds	1.0x10^{15}	>1, magnetc field is frosen	~50	~100	50-100
Mach (V_{jet}/V_{cs})	10-50	> 1, the jet is supersonic	~ 1	> 10 (for Ne and Ar)	> 2
$\beta = P_{pl}/P_{magn}$	>>1 near source <<1 from 10s AU		>>1 near source <<1 away	~ 0,35 (for Ne at 35 cm)	
Density contrast ($n_{jet}/n_{ambient}$)	>1			1-10	1-5

Conclusions

- Experimental stands for laboratory simulation of astrophysical jets has been created on the base of plasma focus type facilities.

- The study of plasma ejections in laboratory experiments allows us to understand the structure and the cause of the collimation and stability of the jets. The parameters of plasma flows generated in the PF discharge were studied as they propagate over considerable distances ~ 100 cm

- The close connection among the astrophysical observations, the physical theory, and the laboratory experiment is necessary. The astrophysical observations allow us to snapshot the jet-ejection structure at some time, but prevent us from observing the entire process starting from the jet-initiation time. However, it is impossible to carry out the active space experiment since the state of the medium and other parameters characterizing the astrophysical plasma ejection cannot be changed.

- The repeatability and reproducibility of the laboratory-experiment results are very important from the viewpoint of the problem of stability and stationarity of the jets.

- Achieved parameters of the plasma jet, such as its velocity, $V \geq 10^7$ cm/s, the Mach number, $M \geq 1$, the Reynolds number, $R = 10^4 - 10^5$, the contrast (ratio of the jet density to the density of ambient plasma), $K = 1\text{-}10$, the plasma temperature, $T = 1\text{-}5$ eV, seems very prospective for the simulation the plasma jets in the young stellar objects known as the objects 'Herbig-Haro'.

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Thank you for your attention!