



MAGNETIC PROBE MEASUREMENTS

on **ANGARA 5-1**

and **PF-3**

FACILITIES

presented by

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Workshop and Expert Meeting on Dense Magnetized Plasmas

ICDMP, Warsaw, December 3 - 4, 2007

PULSED POWER FACILITY ANGARA-5-1



ACTIVITY DIRECTIONS:

- experiments on inertial confinement
 - physics of high energy densities
 - interaction of x-ray radiation with substance
- | | |
|------------------------------|------------|
| number of modules | 8 |
| electric pulse energy | 600 kJ |
| electric pulse duration | 90 ns |
| current through matched load | up to 5 MA |

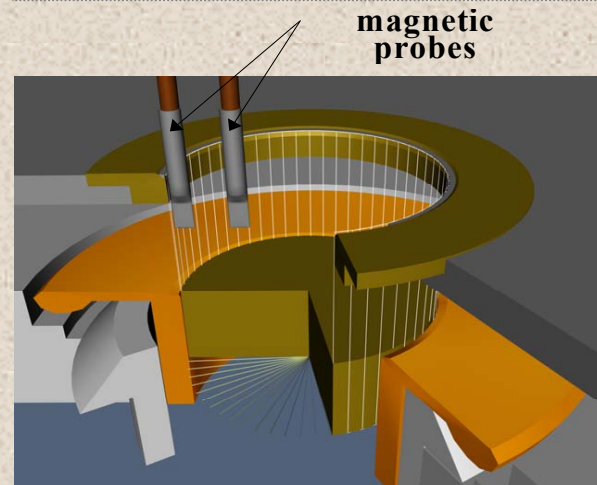
types of loads: gas-puff, foam, dust, z-pinchs

[multiwire arrays](#)

STUDIED LOADS

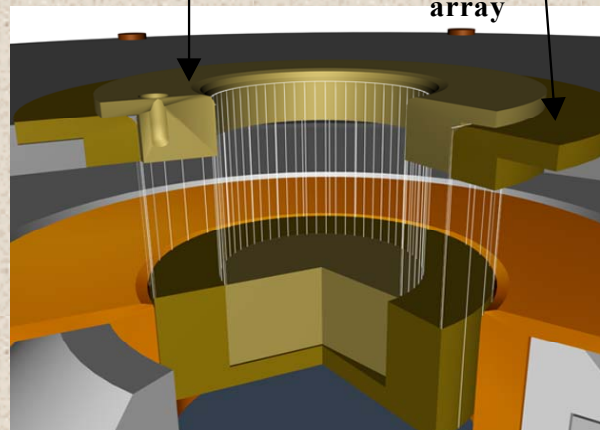
SINGLE WIRE ARRAY

magnetic probes

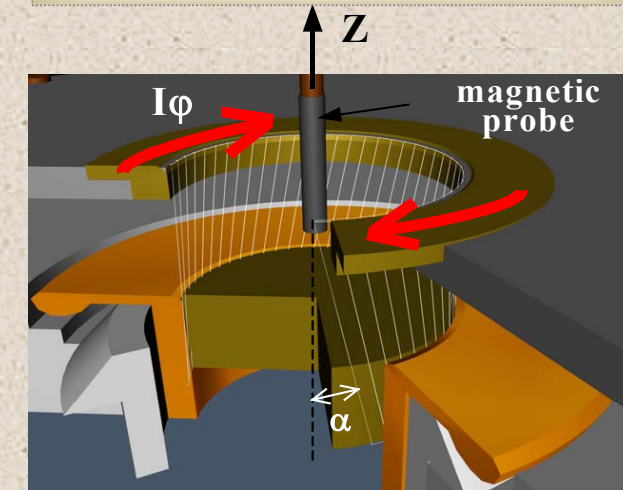


NESTED WIRE ARRAYS

inner array outer array



SCREW WIRE ARRAY



There are various models implosion of wire array –
model of a thin plasma shell
and model of a wire array with the prolonged plasma production +
“a plasma rain storm” (Angara-5-1, Russia)

$\dot{m}(t) = f(t, I, \Delta)$ [$\mu\text{g}/(\text{cm}^2 \cdot \text{s})$] – important parameter, determining distributions of substance and a magnetic field inside a wire array at its compression.



Distributions of a magnetic field and substance inside array should define character of its compression, duration and power of SXR pulse.

??? Questions

- diffusion and skin layer of a current during time implosion ?
- ratio of a full current through Z-pinch and through low-density surrounding plasma ?
- necessity check of theoretical views about wire array implosion

Insufficient knowledge of these ??? Questions

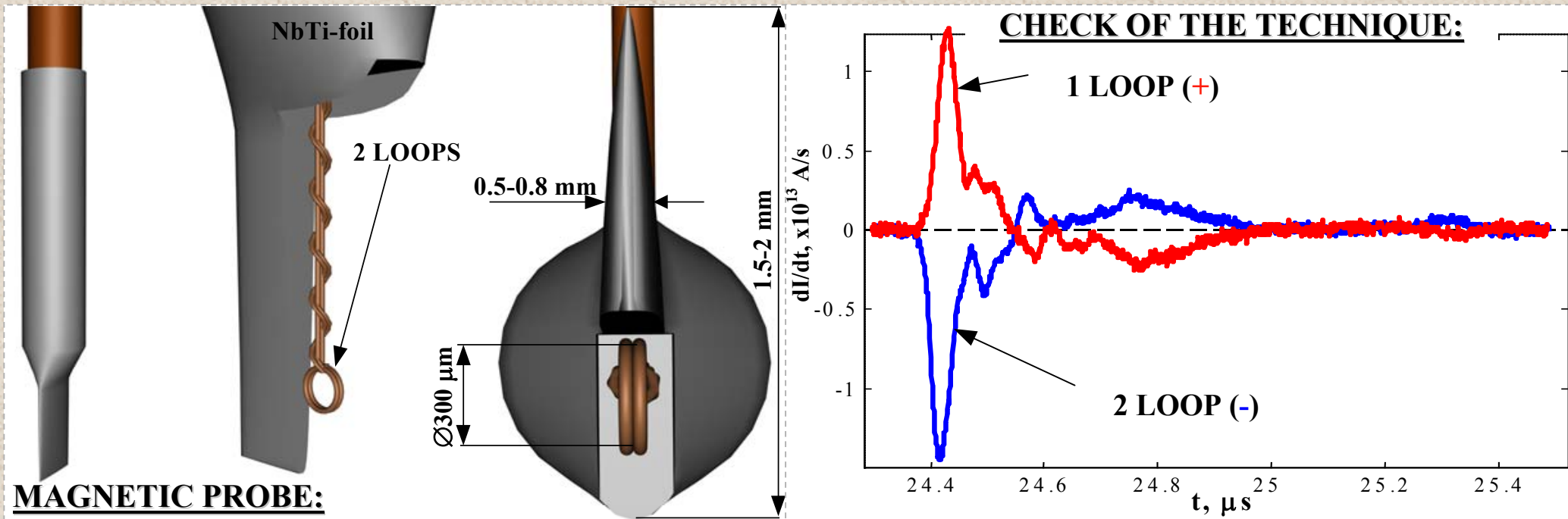


The purpose of research:

experimental research of magnetic fields distributions
during time multiwire array implosion

There are some problems of magnetic fields measurements in plasma with high intensity of radiations and energy release

TECHNIQUE OF MAGNETIC FIELDS MEASUREMENT: (for current measurements)



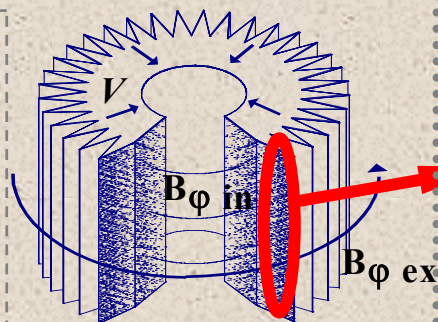
E. Grabovsky, G. Zukakishvili, K. Mitrofanov, et al. In Advanced Diagnostics for Magnetic and Inertial Fusion. Edited by P.E. Stott et al., Academic/Plenum Publishers. 2001, p. 257

- The absolutely calibrated magnetic probes have been designed for the measurements of the plasma current sheath parameters.
- The probes consist of **two loops**, **300 μm** in diameter, in a common screen of NbTi-foil 10-15 μm thickness.
- It provides two signals with different polarity from each probe. It allows to pick out the **pulses having magnetic nature**. \Rightarrow **Probe signal** $U_p \sim dB/dt \Rightarrow B \sim \int U_p(t) dt \Rightarrow I \sim B \cdot r$

$\dot{m}(t)$ — **main characteristic** of the prolonged plasma production:

1-D MHD THEORY:

- formation of the radial plasma stream from wires
- stream of magnetized plasma with azimuthal magnetic field to a center of wire array
- $H^2/8\pi \gg nT$ inside plasma



$$\dot{m}(t) \approx 0.2 \cdot \left(\frac{I(t)_{MA}}{R_{cm}} \right)^{1.8} \frac{\mu g}{cm^2 \cdot ns}$$

1-D theory predict:

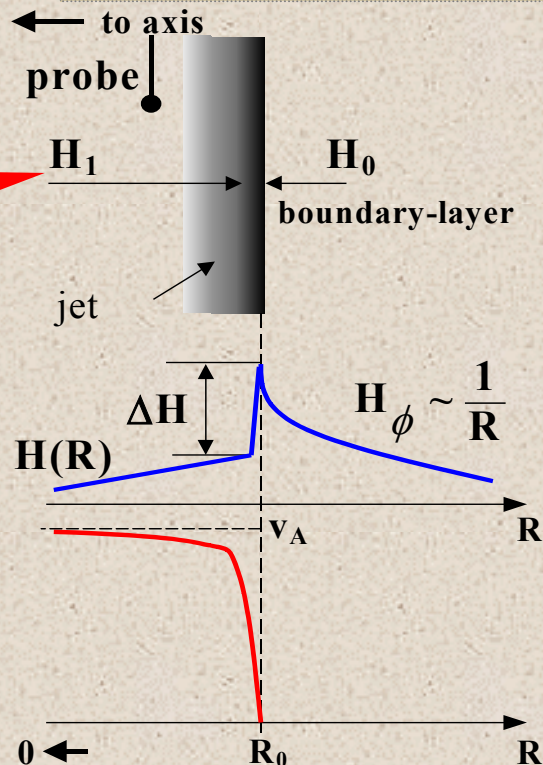
- increase $\dot{m}(t)$ as $\sim I^2$
- occurrence of a precursor on axes of array
- existence jump of magnetic field $\Delta H \approx 40\%$ at initial array radius R



1-D theory to neglect:

- influence of $R-\phi$ and $R-Z$ structures of plasma
- decrease $\dot{m}(t)$ at final stage of implosion

ΔH - JUMP OF MAGNETIC FIELD ON BORDER OF WIRE ARRAY:

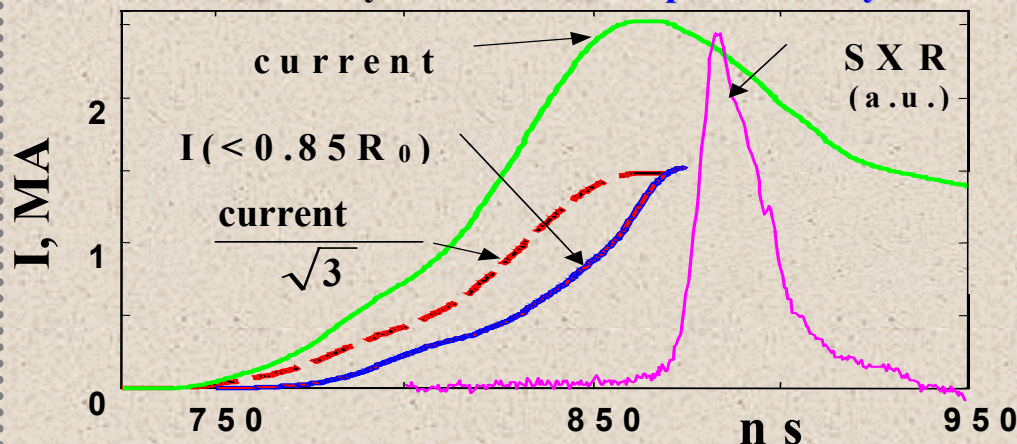


$$\frac{H_0^2}{8\pi} - \frac{H_1^2}{8\pi} = \rho_1 v_1^2$$

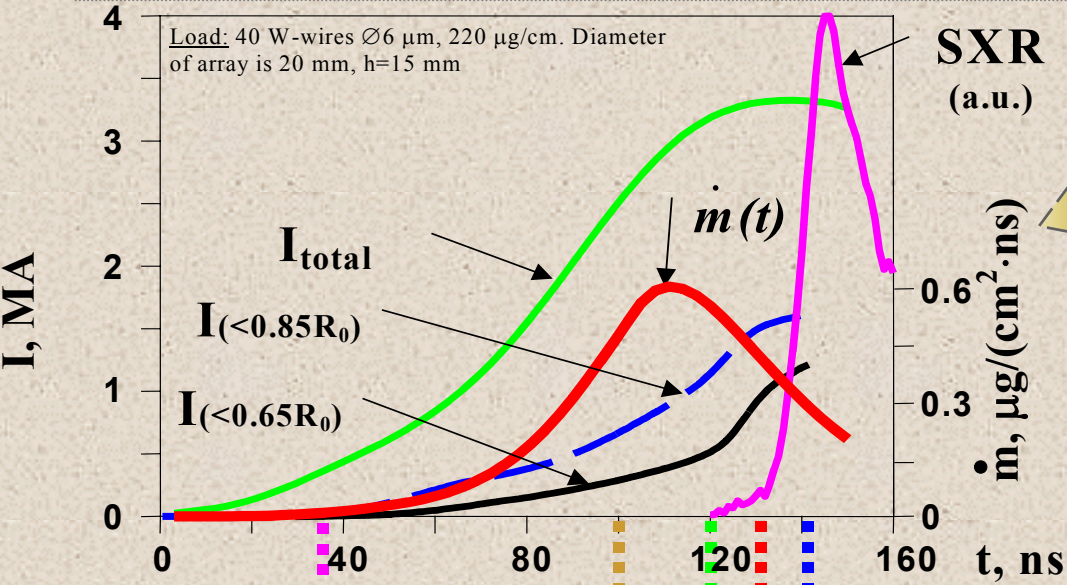
$$v_1 \approx v_A = \sqrt{\frac{H_1^2}{4\pi\rho_1}}$$

$$H_1 \approx \frac{H_0}{\sqrt{3}}$$

while $\Delta H \neq 0$, proceeds plasma production on border of wire array - **is observed experimentally**

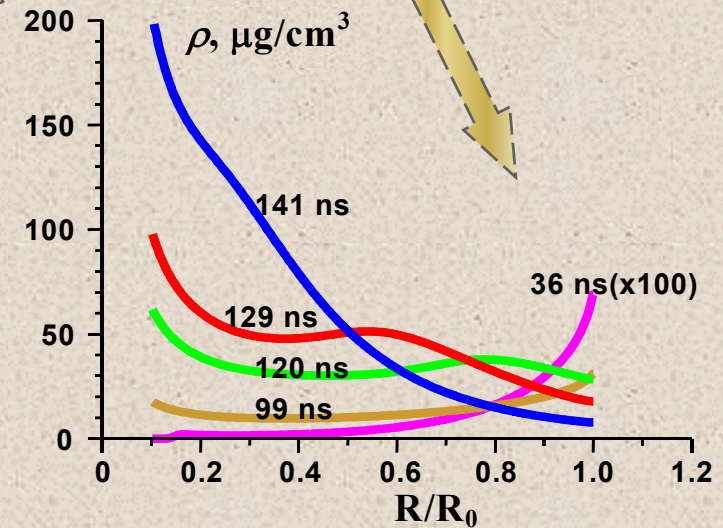
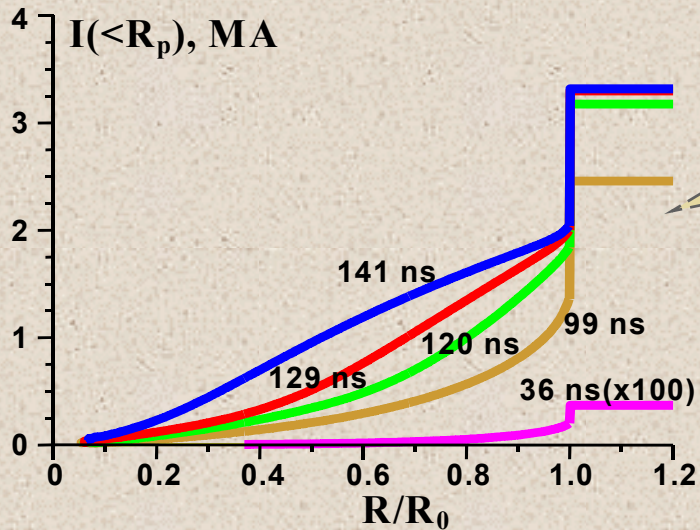


MAGNETIC PROBES - THE SOURCE OF DATA FOR DEFINITION OF $\dot{m}(t)$, CURRENT AND DENSITY DISTRIBUTIONS INSIDE WIRE ARRAY:



1. Selection of dm/dt on concurrence of signals profiles, measured by magnetic probes with profiles, calculated by 1-D MHD code

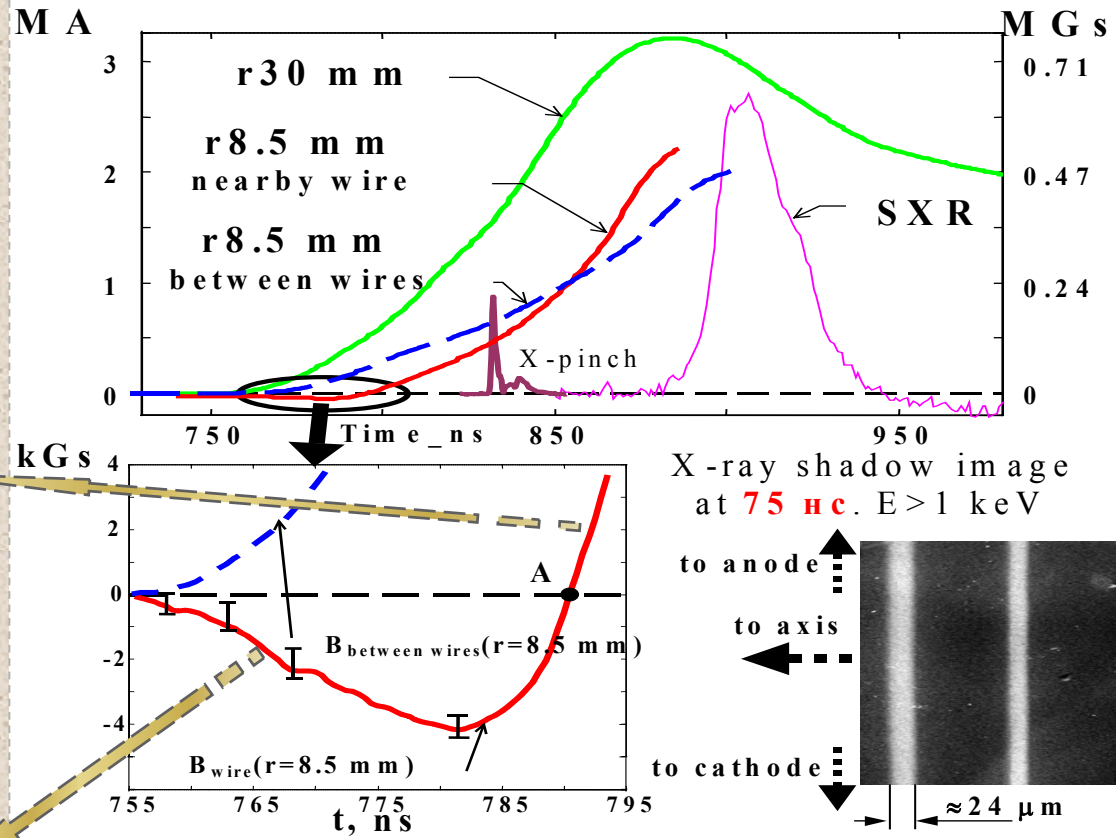
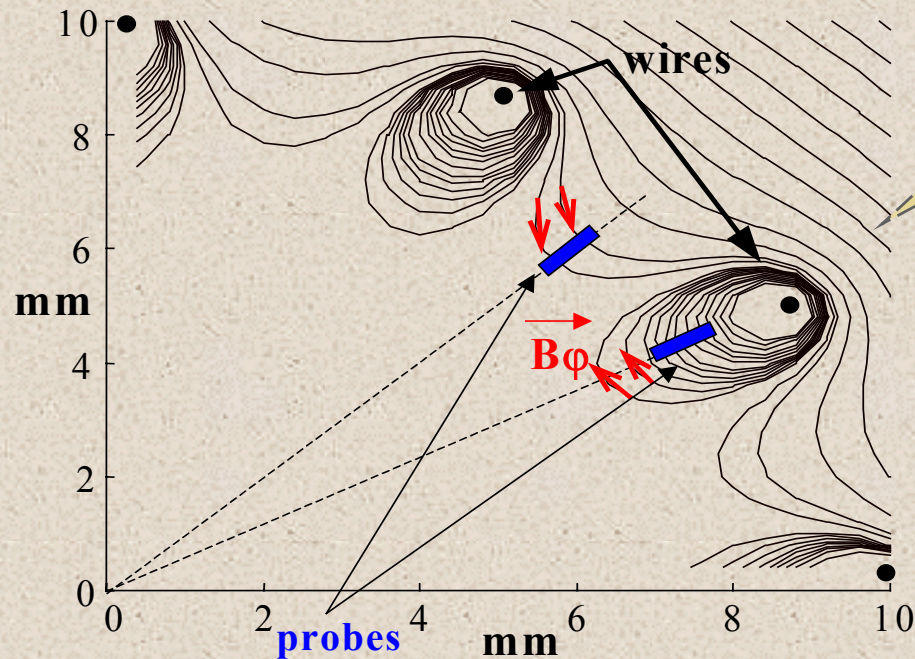
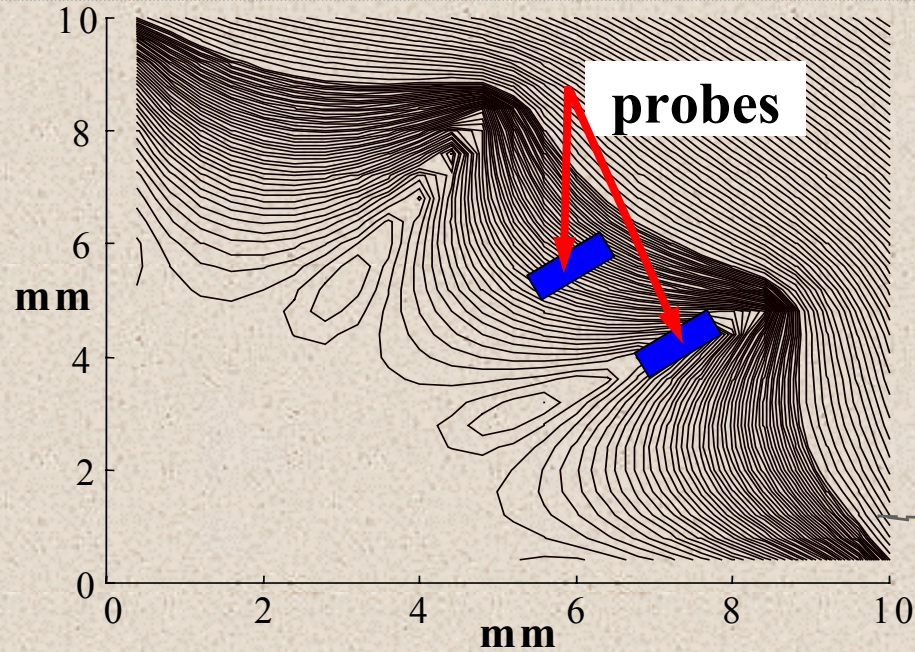
2. Restoration of spatial distributions $I(R,t)$ and $\rho(R,t)$ with use obtained dm/dt



Parameters of “precursor” are determined (at 110 ns):
Current of “precursor” is up to 15% from total current of discharge
Mass of “precursor” is about 1-2% from a mass of wire array

JET CHARACTER PLASMA OUTFLOW FROM WIRES DURING INITIAL STAGE OF IMPLOSION

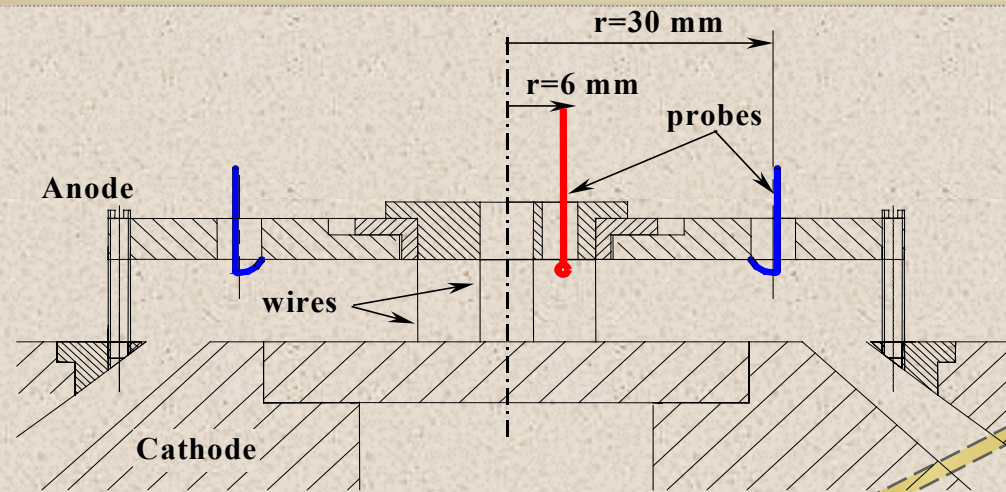
Load: 40 W-wires $\varnothing 8 \mu\text{m}$, $380 \mu\text{g/cm}$. Diameter of array is 20 mm, $h=10 \text{ mm}$



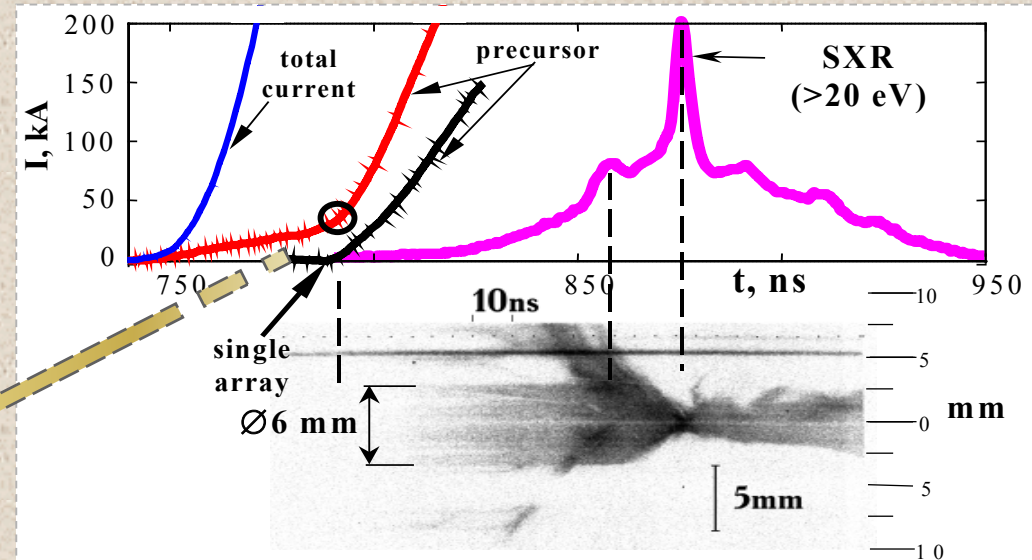
- the separatrix of an azimuthal magnetic field of wire array is displaced to an axis with a speed $V_{\text{separatrix}} \approx (0.4 \pm 0.15) \cdot 10^7 \text{ cm/s}$
- the current moves in plasma jets to the array axis up to 40 ns
- difference of the magnetic field nearby and between wires is not enough after 40 ns of implosion

Measurements of azimuthal magnetic fields in nested wires array

(part of the full current I_{in}/I_0 flowing on inner array at an initial stage of implosion)



Outer array: 40W $\varnothing 5\mu\text{m}$, 169 $\mu\text{g}/\text{cm}$, $\varnothing 20\text{mm}$
 Inner array: 40W $\varnothing 8\mu\text{m}$, 380 $\mu\text{g}/\text{cm}$, $\varnothing 6\text{mm}$
 On axis: agar foam+W, 250 $\mu\text{g}/\text{cm}$, $\varnothing 1.5\text{mm}$



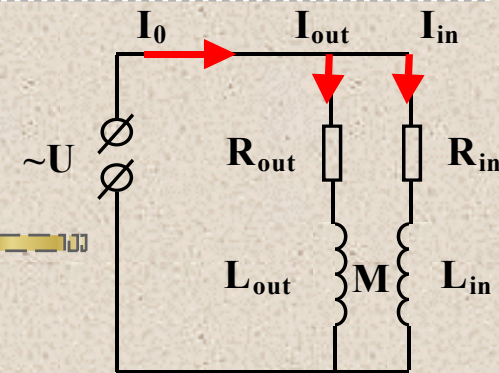
$$\left(\frac{I_{in}}{I_0}\right)_{\text{exp}} \approx 3-5\%$$

agreement with experiment!

$$\frac{I_{in}}{I_0} \approx 3\%$$

- $R_{in}=R_{out}\approx 0$, $L_{out}(t)$, $L_{in}(t) \approx \text{Const}$
- L_{out} , $L_{in}=f(r, N)$ – Grover formula

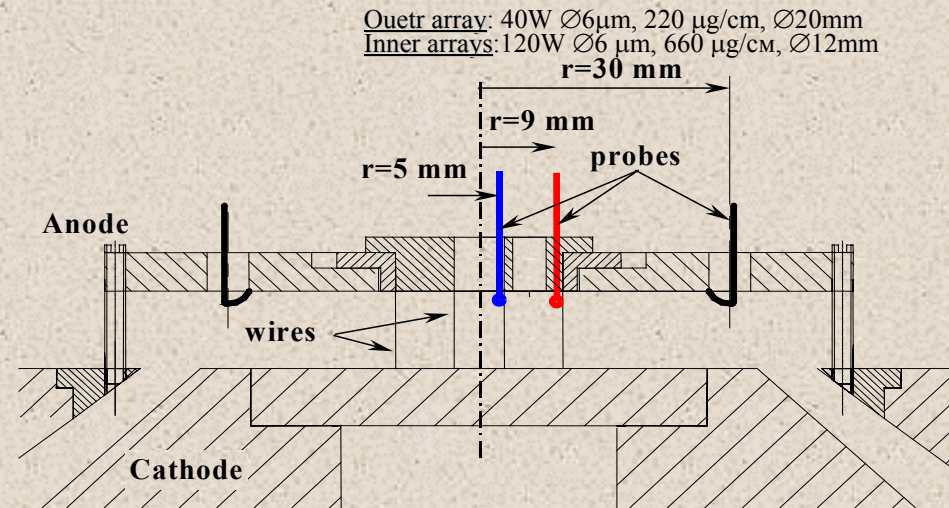
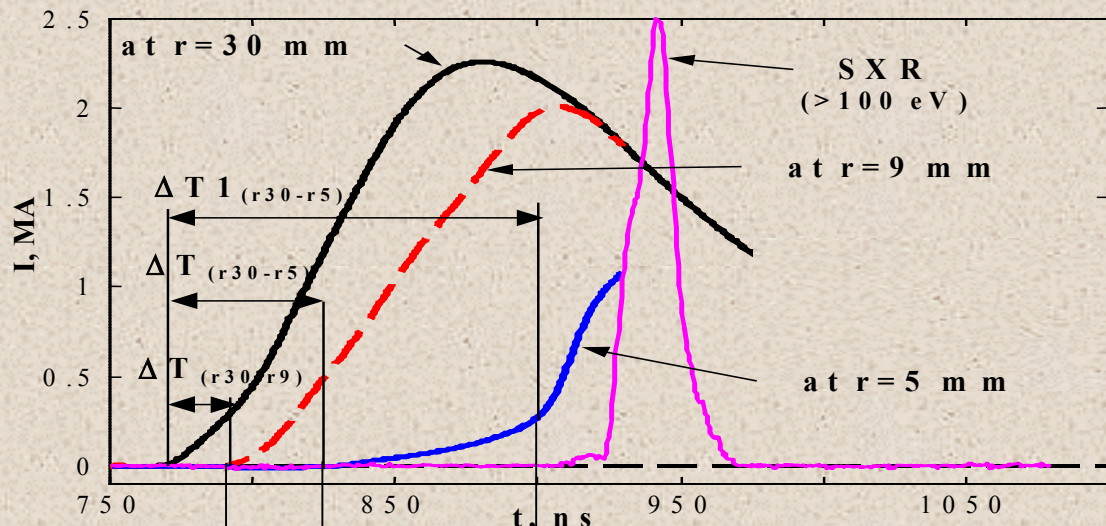
$$\frac{I_{in}}{I_0} = \frac{L_{out} - M}{L_{out} + L_{in} - 2 \cdot M}$$



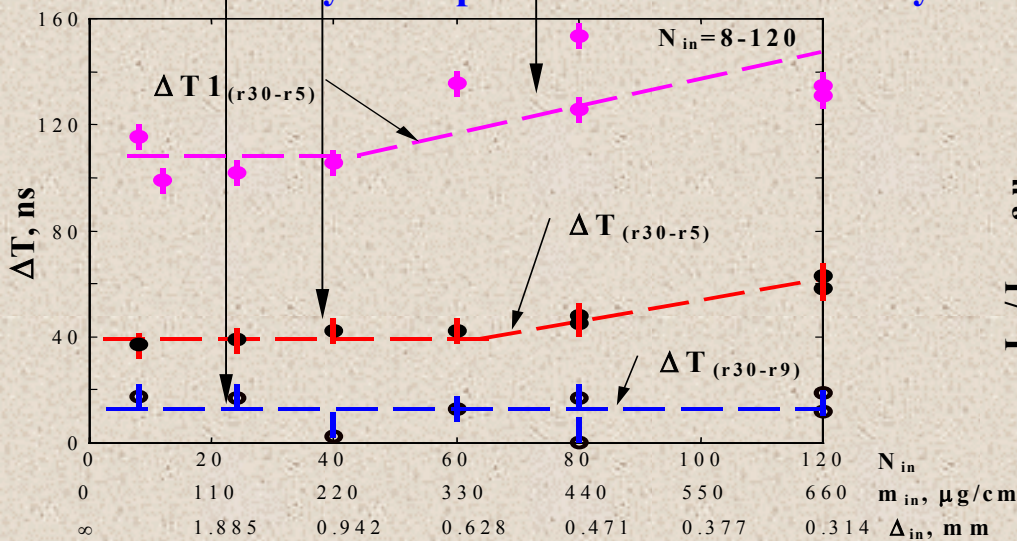
Formation of a plasma corona around wires occurs simultaneously on the majority wires outer and internal arrays

- The current starts to flow simultaneously on outer and internal array. For 40 ns the current of internal array grows **up to 30 kA** (3-5 % of a total current).
- After arrival of the first plasma portions from outer array the glow of internal array on optical streak camera images is observed.
- SXR (>20 eV) is registered during interaction of outer and internal arrays plasmas.

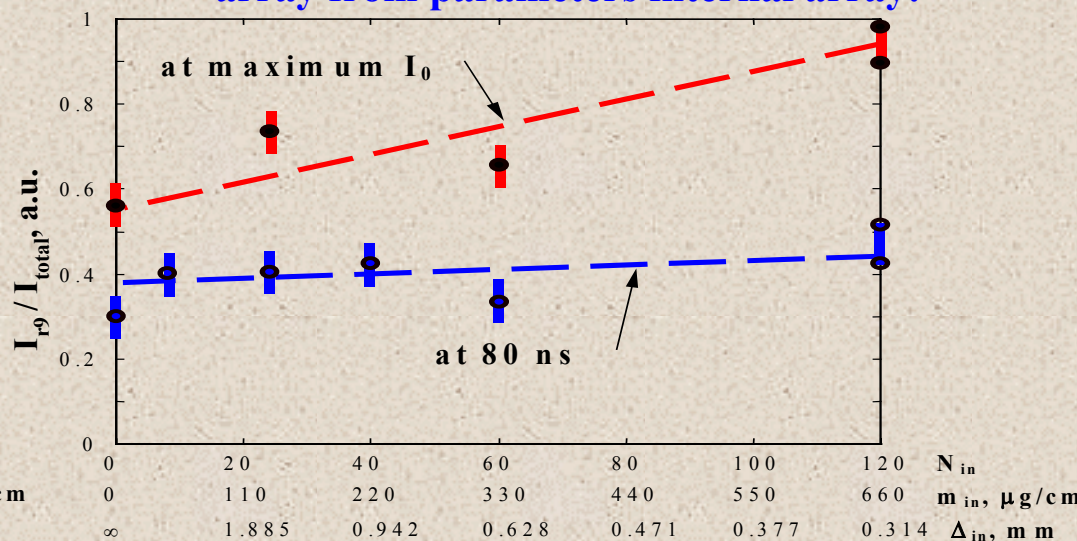
Dependence of internal array on a plasma production and a current dynamics of outer array



Dependence of a penetration delay of a current in internal array from parameters internal array:

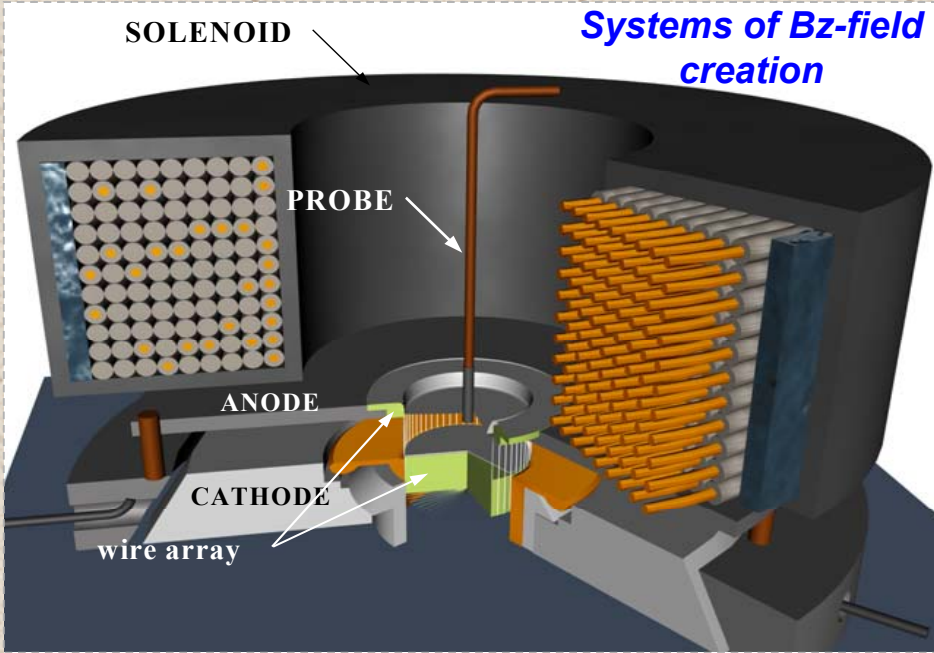


Dependence of the full current part flowing on internal array from parameters internal array:



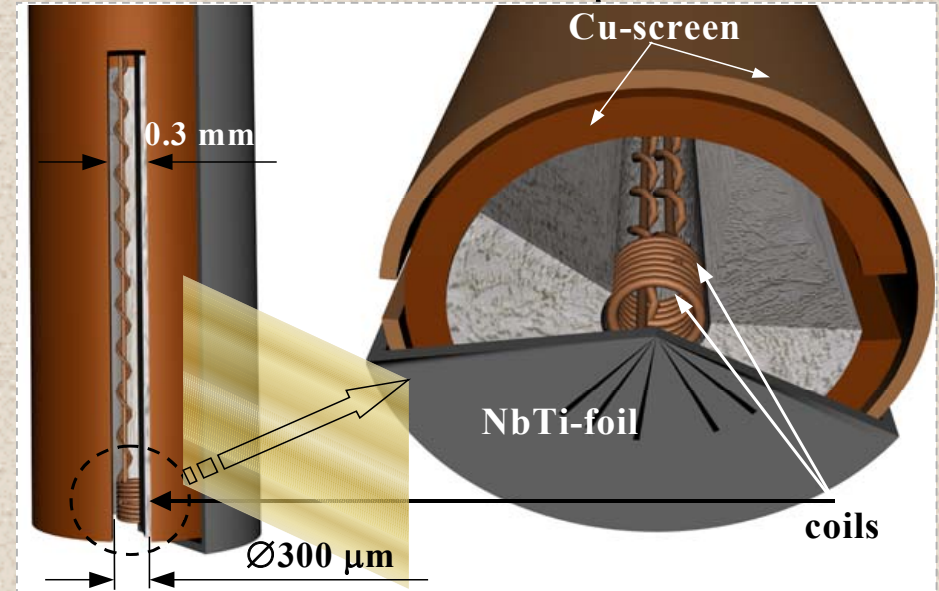
- The delay of a current penetration in internal array grows up to 20-25 ns at reduction of interwire gap in it from 0.6 mm up to 0.3 mm.
- Presence of internal array results in redistribution of a current in volume between arrays, almost at radius of outer array (at $r=9 \text{ mm}$) \Rightarrow dependence a plasma production of outer array. There is a mode subalvenic plasma flow between wire arrays.

Creation and measurement of an axial magnetic fields (for research of r - ϕ structures current plasmas)

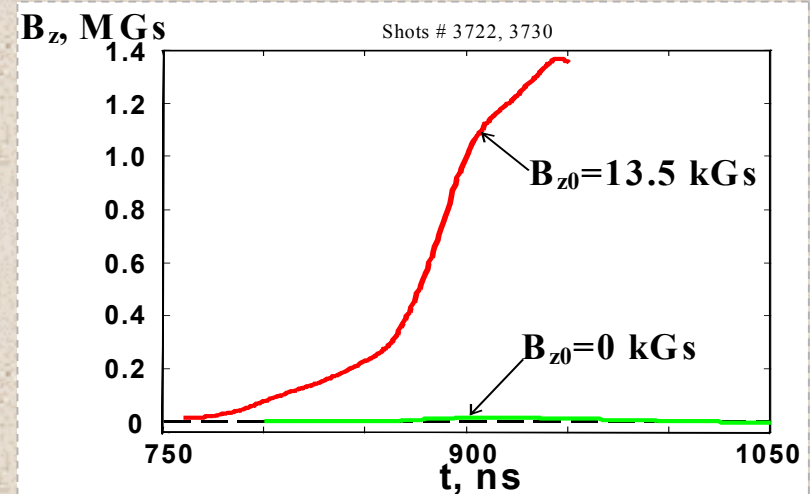


Heterogeneity of a B_z -field in anode-cathode gap $\approx 30\%$

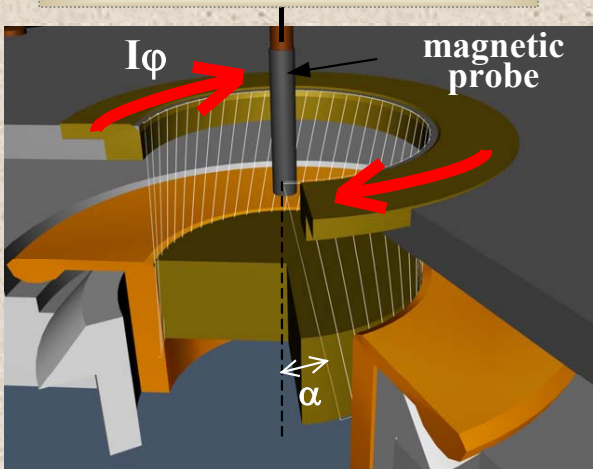
Bz-PROBE:
2 COILS (clockwise/counter clockwise) on 4 TURN $\varnothing 300 \mu\text{m}$



CHECK OF A TECHNIQUE:



SCREW WIRE ARRAY

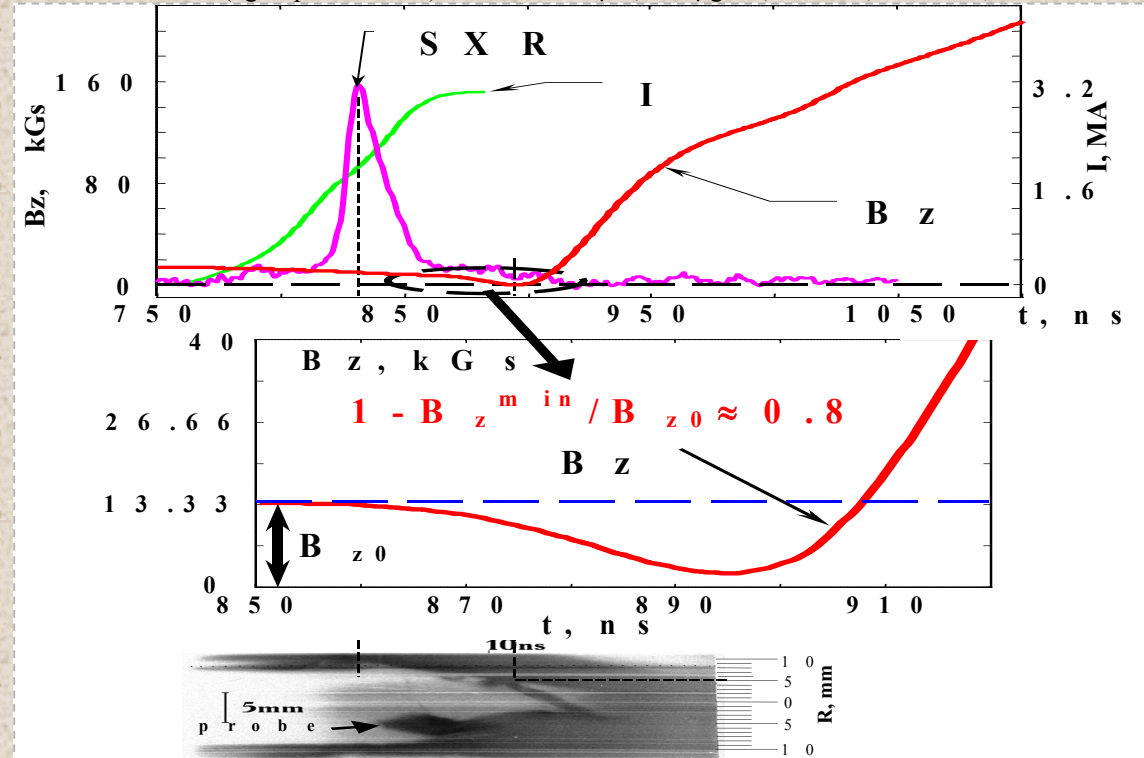
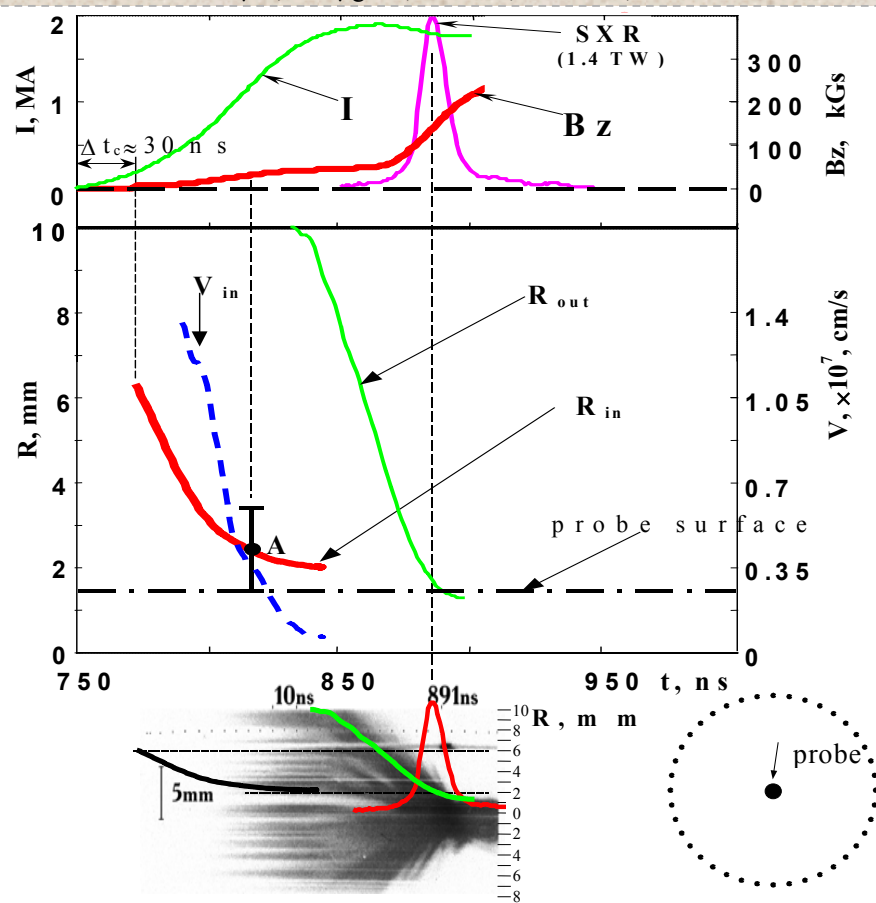


2 METHODS of Φ_z -flux creation

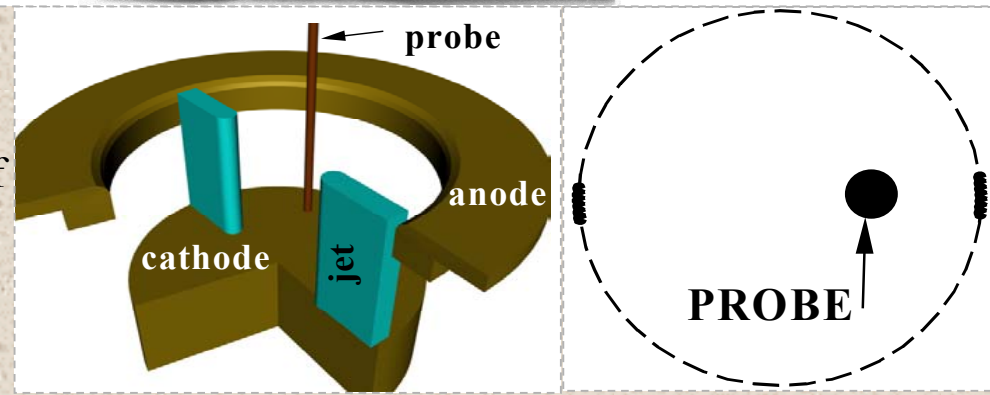
Dynamics of internal border current plasmas at compression of an external axial magnetic flux

Load: 60W-wires $\varnothing 6\mu\text{m}$, 330 $\mu\text{g}/\text{cm}$, $\varnothing 20\text{mm}$, $h=10\text{mm}$, $B_{z0}\approx 5\text{kGs}$

Load: 24(2groups x 12wires) W-wires $\varnothing 10\mu\text{m}$, 300 $\mu\text{g}/\text{cm}$, $\varnothing 20\text{mm}$, $h=10\text{mm}$, $B_{z0}\approx 13.5\text{kGs}$



- Signal from the magnetic probe appears at the 30-th ns of the implosion (Δt_c)
- The upper estimation: precursor plasma mass is less 1% of full wire array mass
- An axial magnetic field is frozen-in to the wire array plasma



2 types of Φ_{z0}



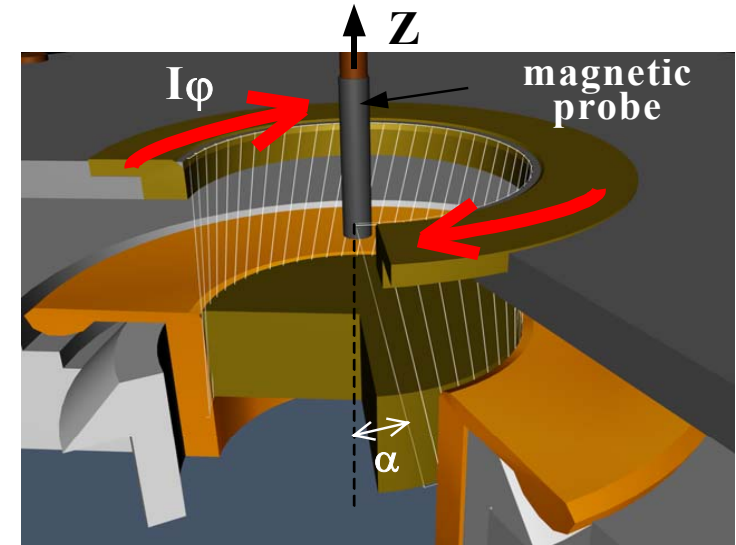
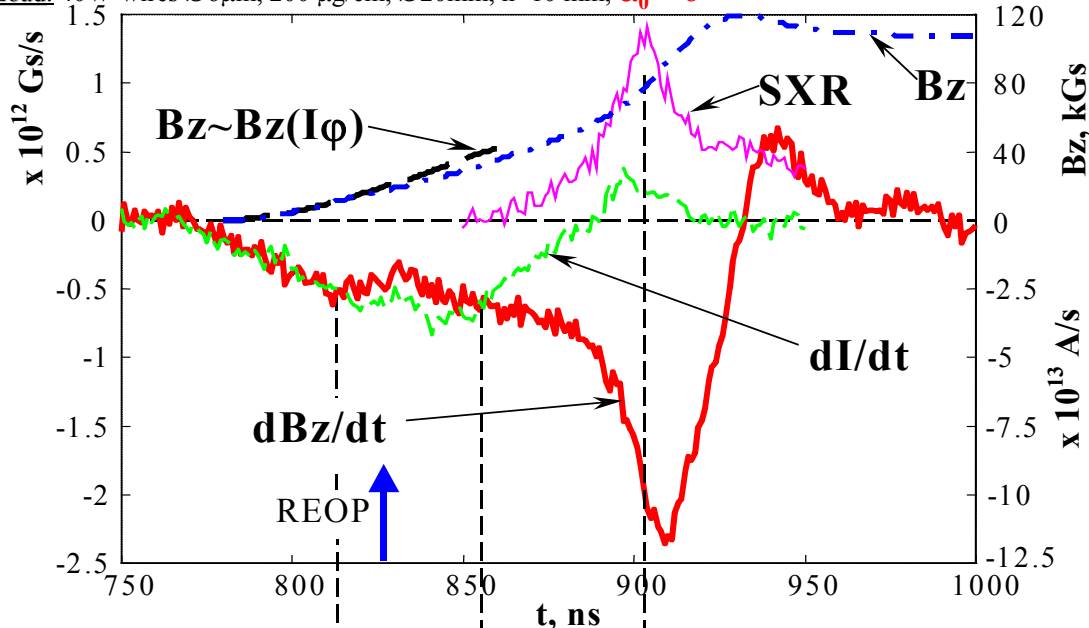
free (outside of plasma)

«frozen-in» to plasma

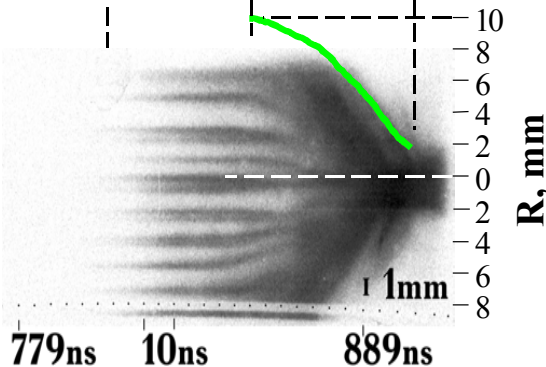
the magnetic field is frozen-in to plasma in the wire region and transferred in plasma jets toward the array axis

Compression of axial magnetic flux by plasma of screw wire array

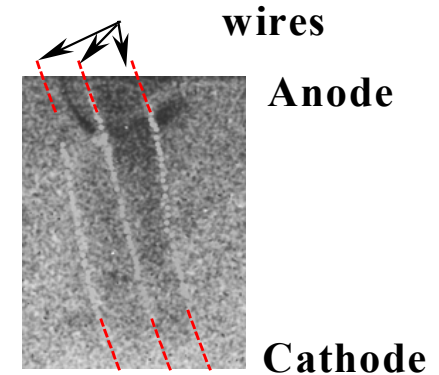
Load: 40W-wires $\varnothing 6\mu\text{m}$, 200 $\mu\text{g}/\text{cm}$, $\varnothing 20\text{mm}$, $h=10\text{ mm}$, $\alpha_0 \approx 6^\circ$



X-ray image at 57 ns
 $E > 200\text{ eV}$

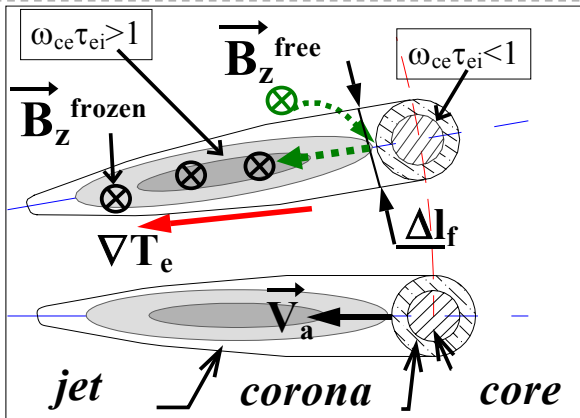


$$I\varphi \sim I_z \cdot \sin(\alpha)$$



- Axial magnetic field is produced by a screw wire array
- $\frac{dB_z}{dt} \sim \frac{dI}{dt} \Rightarrow \alpha \approx \text{Const}$ during 40 ns
- The discharge current first 40 ns flow under same angle under which wires are inclined

A model of an axial magnetic flux compression – “magnetic pump”



The value of the frozen-in to plasma jets axial magnetic flux Φ_{z1} during time interval dt approximately equals:

$$d\Phi_{z1}(t) = B_{z2}(t) \cdot N_f \cdot \Delta l_f \cdot V_a \cdot dt,$$

где $V_a, \Delta l_f, N_f$ - Const.

Conservation law of magnetic flux:

$$\Phi_{z0} = \Phi_{z1}(t) + \Phi_{z2}(t),$$

$\Phi_{z1} = B_{z1}(t) \cdot N_f \cdot \Delta l_f \cdot (R_0 - r(t))$ – the frozen-in to plasma axial magnetic flux,

$\Phi_{z2} = B_{z2}(t) \cdot [\pi \cdot R_0^2 - N_f \cdot \Delta l_f \cdot (R_0 - r(t))]$ – the «free» axial magnetic flux;

The portion of the frozen - in to plasma axial magnetic flux :

$$\frac{\Phi_{z1}(t)}{\Phi_{z0}} = 1 - e^{-\int_0^t \frac{N_f \cdot \Delta l_f \cdot V_a}{(\pi R_0^2 - N_f \cdot \Delta l_f \cdot R_0) + N_f \cdot \Delta l_f \cdot r(\tau)} d\tau} \xrightarrow[\alpha = \frac{\pi R_0^2 - N_f \cdot \Delta l_f \cdot R_0}{N_f \cdot \Delta l_f \cdot V_a}]{r(t)=0} 1 - e^{-\frac{t}{\alpha}}$$

At the following parameters: $R_0 = 1$ cm, $N_f = 40-60$, $\Delta l_f \approx 0.03$ cm, $V_a \approx 1 \cdot 10^7$ cm/s, $r(t) = 0$

$\Phi_{z1}(t_N) / \Phi_{z0} \approx 0.6-0.8$ at $t \approx 80$ -th ns of plasma implosion - *is observed experimentally!*

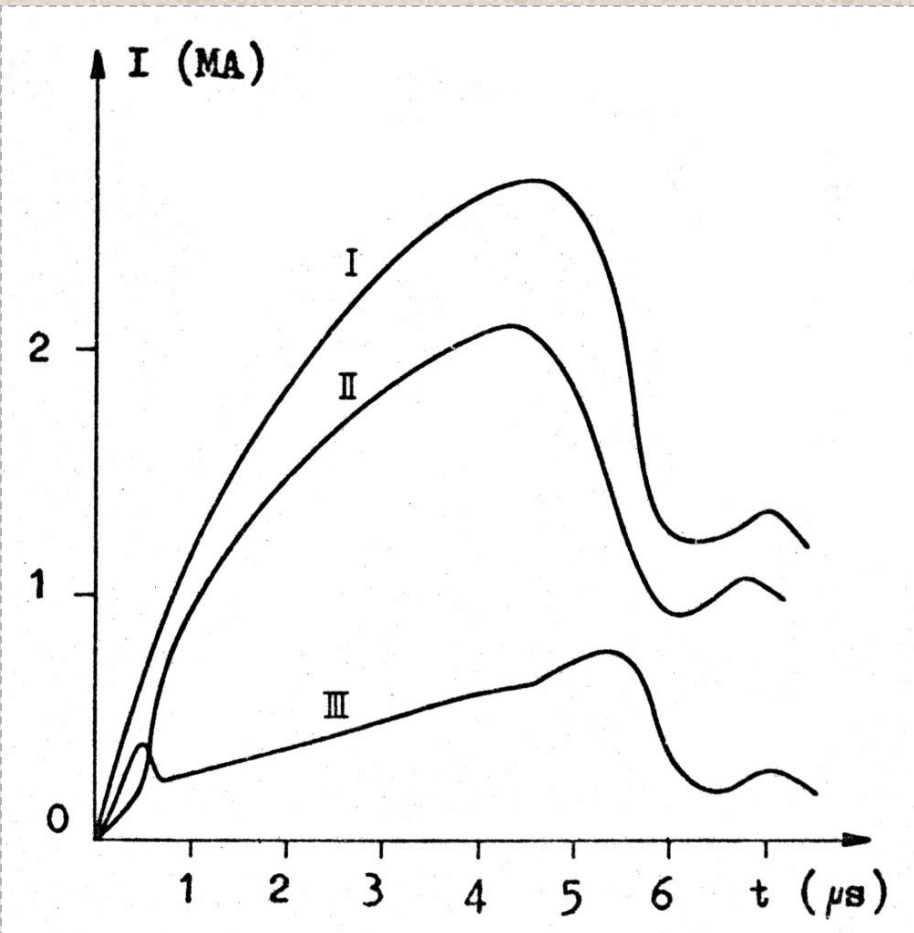
Conditions required for operation of the “magnetic pump”:

- availability of regions with nonmagnetized and magnetized plasmas
- prolonged plasma production and plasma radial motion to the axis

CONCLUSIONS:

- 1) The experimental technique of magnetic fields measurement (by a magnetic probe) in wire array plasma with terawatt X-ray power is developed.
- 2) The researches carried out by this technique have shown difference of compression multiwire arrays from classical model of a "thin" shell. Phenomenon of the prolonged plasma production for implosion of wire arrays is confirmed.
- 3) The current distribution at compression of wires array was obtained. It was shown, that the radial current distribution is much wider than thickness of a skin-layer. Characteristic thickness of a current distribution in a radial direction is comparable to a radius of wire array. In an azimuthal direction the current density is non-uniform - the current during the first 30-40-th ns flow on separate plasma channels along wires.
- 4) The current and mass of "precursor" are equal 3%÷15% of a discharge current and about 1÷2% of full wire array mass.
- 5) The effect of an external axial magnetic flux compression has been used as a diagnostic method for studies of plasma dynamics at the initial stage of wire array implosion. The mechanism of the axial magnetic flux compression, not connected with the formation of the continuous current shell ("the magnetic pump") is offered and experimentally proved.

Problem of neutron yield saturation: what current we measure?



Distributions of the current on the PF in Frascati:

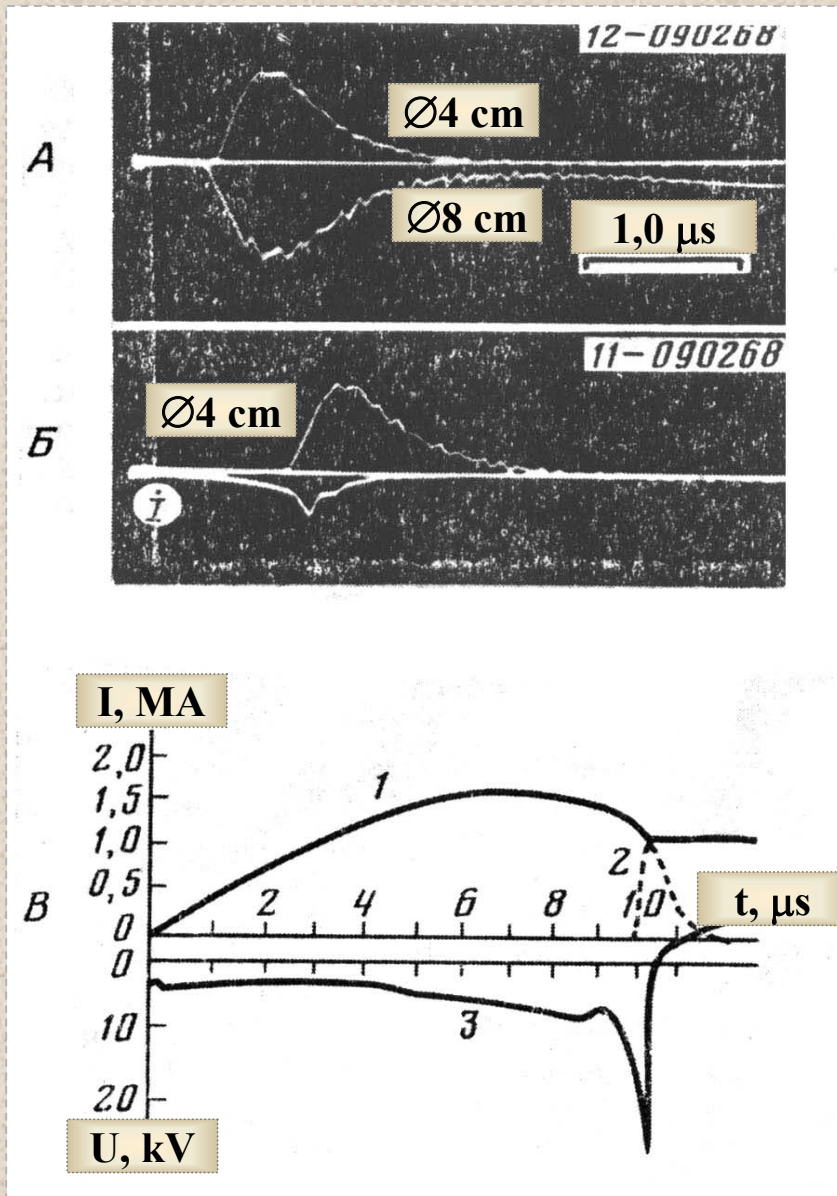
I – total current

II – cathode return current,

III – surface current along isolator

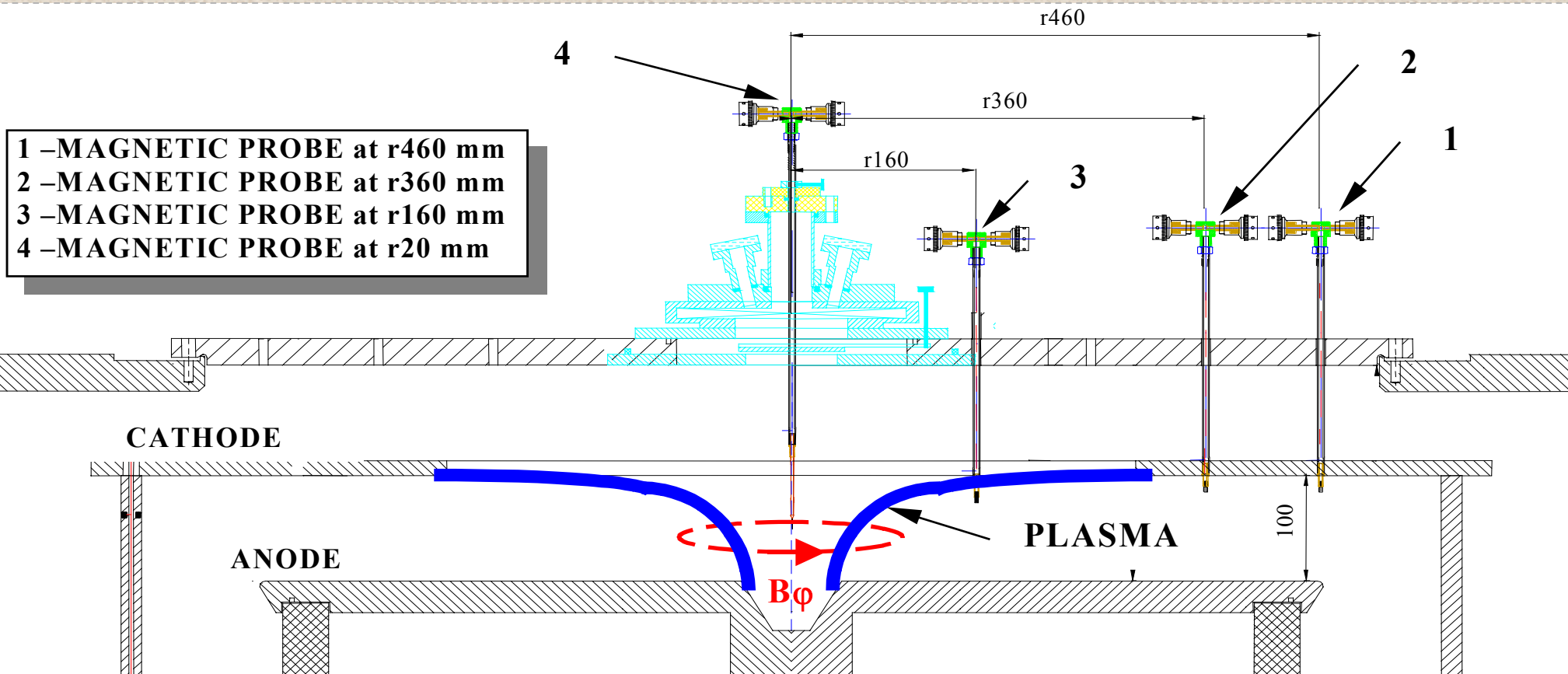
T. Oppenlander, CNEN-Centro di Frascati, Rep.78-6 (1978)

C. Gouylan, et al., 8th Europ. Conf. on Contr. Fus. and Plasma Phys., 1977. Vol.II, p.178



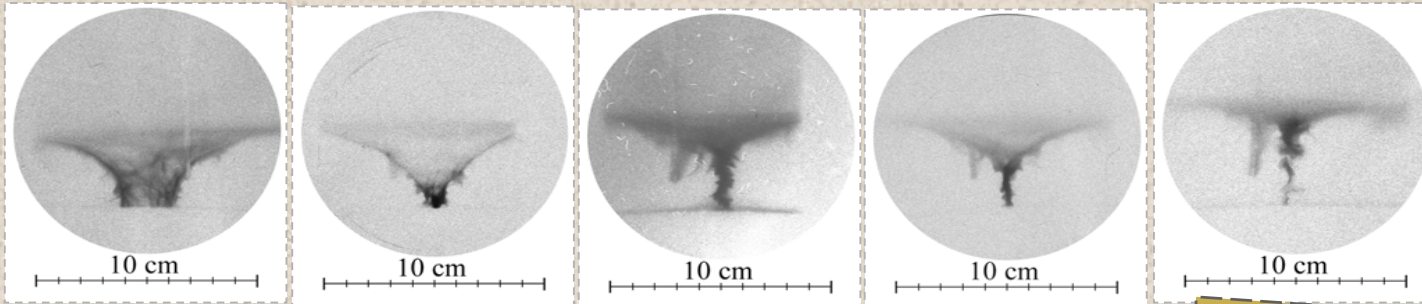
Agafonov V.I., etc. Plasma Phys. And Contr. Nucl. Fus. Res.: Novosibirsk, 1968.- V.2. P.21-37.

EXPERIMENTAL SETUP:



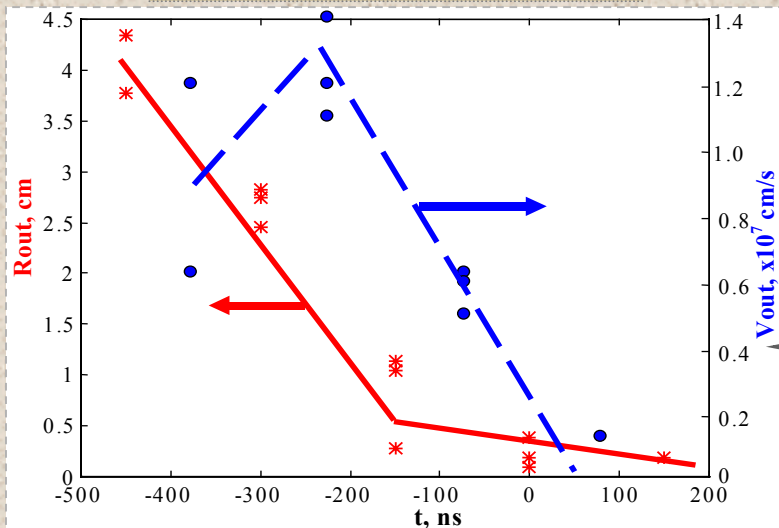
- Special units with vacuum lock has been developed for installing the probes on various distances along the radius and on different height above the anode without vacuum violation in the chamber.
- The measurements with simultaneous use of several probes located at radii $r=460$ mm, $r=160$ mm and $r=20$ mm were carried out. The axis probe was located at the distance 10-20 mm above the anode plane.
- The experiments were performed at the power supply energy $W = 290$ kJ with argon and neon as working gases at the pressure of 1.5 Torr.

STUDIES OF PLASMA SHEATH DYNAMICS WITH OPTICAL FRAME CAMERAS:

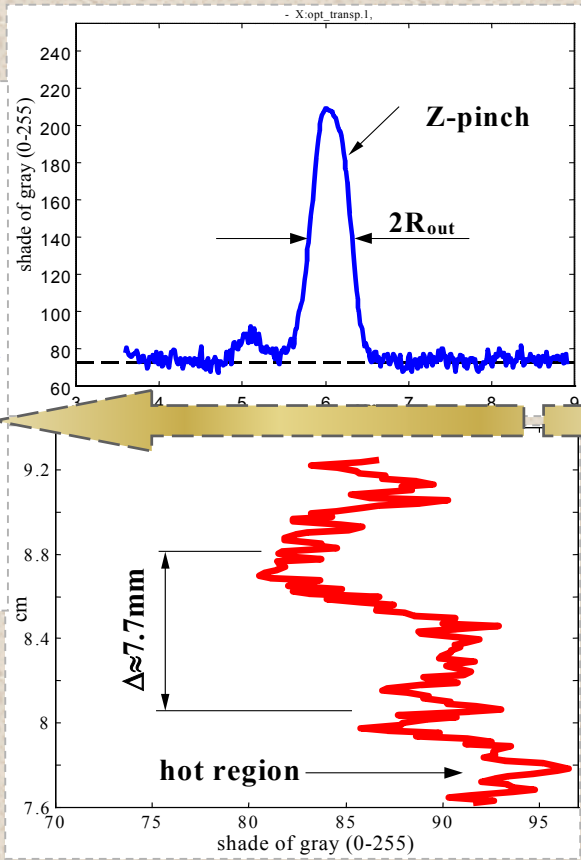


t i m e

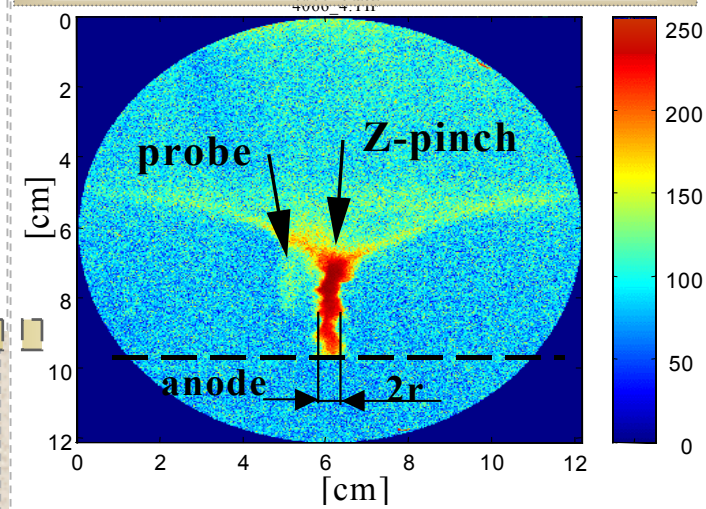
R-t and V-t – graph:



- $R_{out}(t)$ and $V_{out}(t)$ graphs of plasma sheath external border dynamics: the maximal velocity of the sheath is $(1-1.4) \cdot 10^7$ cm/s.
- It is observed two pinch compressions on the facility axis – up to $r_1 \approx 3.8$ mm and up to $r_2 \approx 1.9$ mm

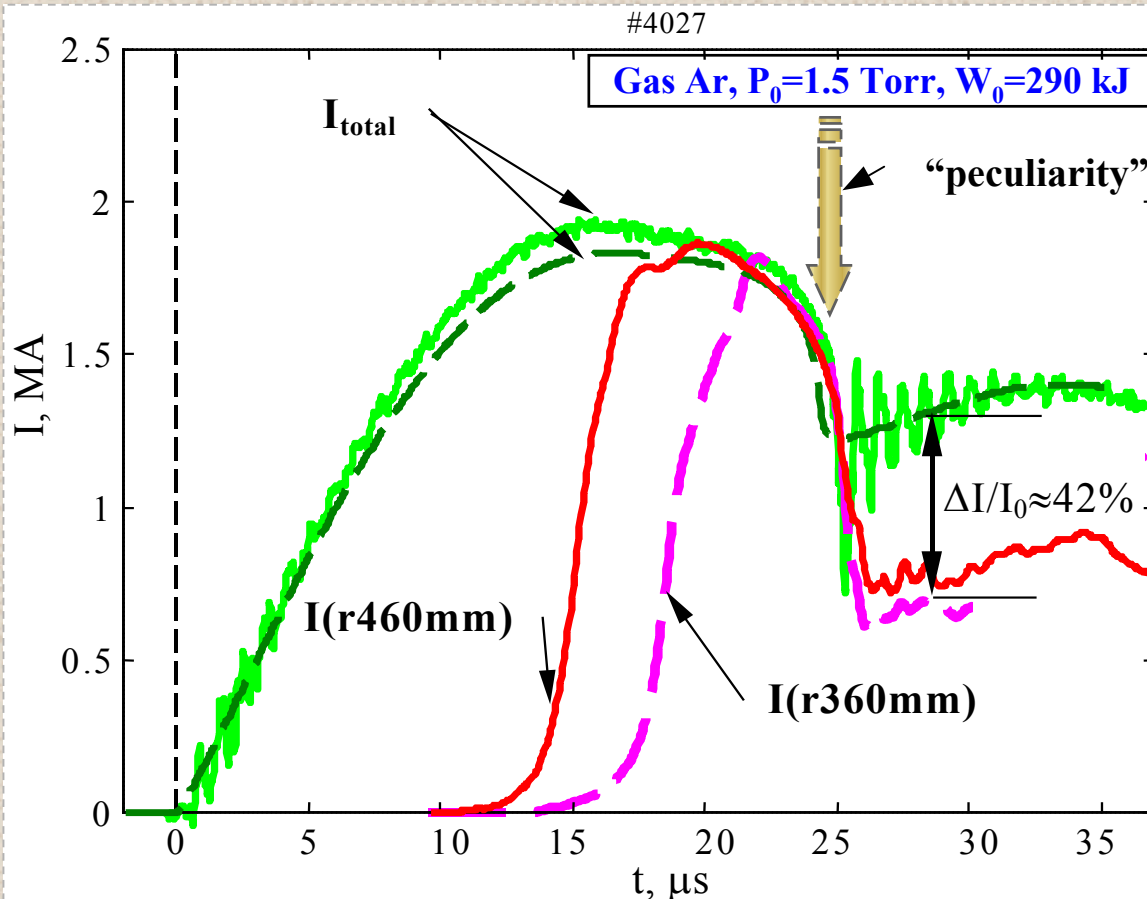


*Digital processing of images:
(in environment MATLAB)*



- 2-D effects - successive transition from noncylindrical to cylindrical Z-pinch are essential.
- Development of instability with modes $m=0,1$ is observed. The period of the instability mode $m=1$ is $\Delta \approx 7.7$ mm
- It is registered $V_z \approx 1.3 \cdot 10^7$ cm/c (phase velocity) $\sim V_r$

STUDIES OF AZIMUTHAL MAGNETIC FIELDS AT "DISTANT" RADII:



DETERMINATION T_e FROM δ_{skin} :

$$\dot{I} \approx I \cdot \left(\frac{V_r}{\delta_{skin}} \right) \Rightarrow \delta_{skin} \Rightarrow T_e$$

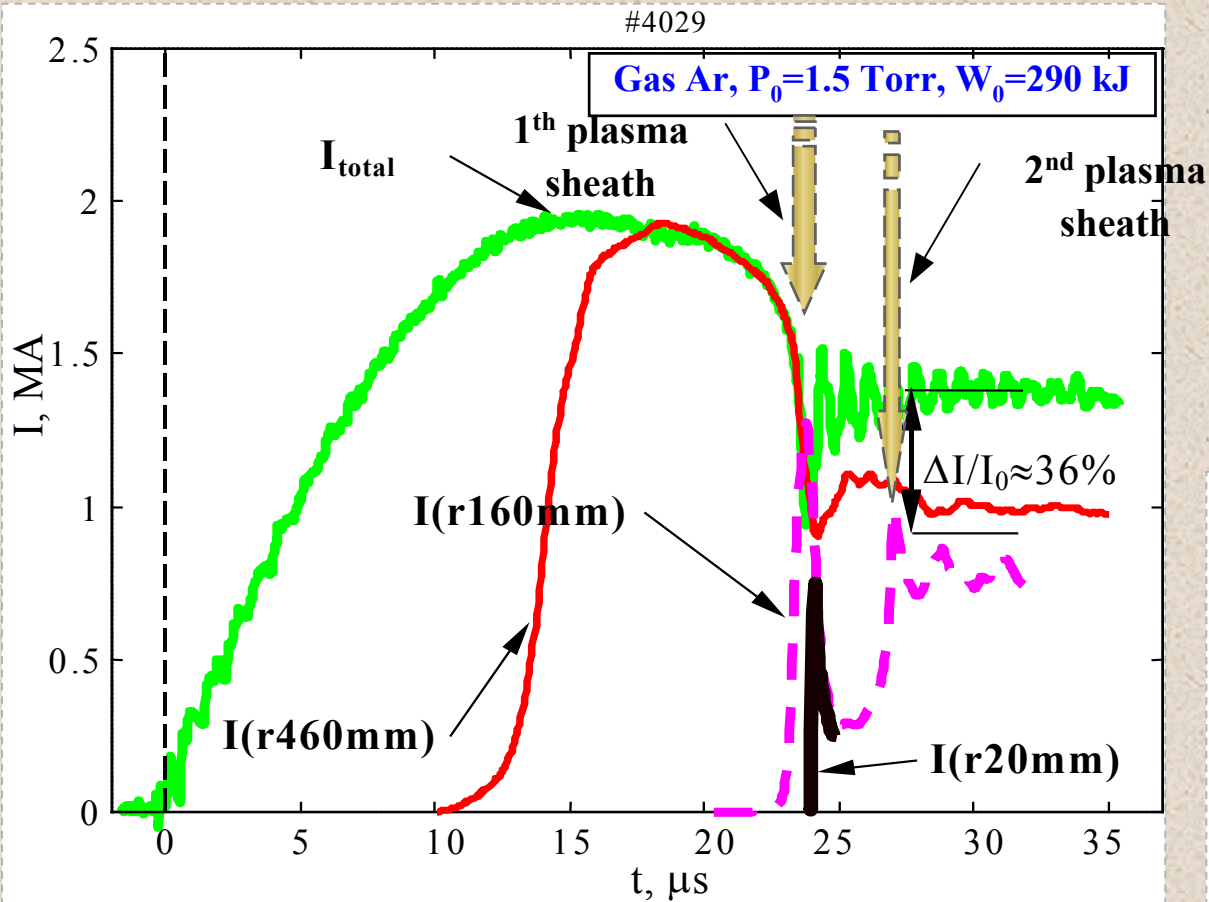
At the approach of plasma Spitzer conductivity:

$$\left\{ \begin{array}{l} \rho = \frac{1}{\sigma} \approx 2.06 \cdot 10^{-4} \cdot z \cdot \ln(\Lambda) \cdot T_e^{-3/2} \text{ [Om} \cdot \text{m]} \\ z \sim \sqrt{T_e}, \quad \ln(\Lambda) \approx 10, \quad T_e - [\text{eV}] \\ \delta_{skin} = \frac{c}{\sqrt{2\pi \cdot \sigma \cdot \omega}} \approx 500 \cdot \sqrt{\rho \cdot t} \text{ [m]} \end{array} \right.$$

where t - characteristic time in sec.

- The derivative of a current increases from $\approx 0.2 \cdot 10^{12}$ A/s (for derivative of total discharge current) up to $\approx (0.75-1) \cdot 10^{12}$ A/s at r460 mm and at r360 mm.
- The time delay between probe signals at radii r460 and r360 mm is $\Delta t \approx 3.2 \mu s$, \Rightarrow radial plasma velocity $V_r = \Delta r / \Delta t \approx 3 \cdot 10^6$ cm/s.
- The estimation of skin-depth of the plasma sheath at the instant of passage of "distant" radii gives $\delta_{skin}(\text{at r460 mm-r360 mm}) \approx (6 \pm 1)$ cm.
- The electron temperature corresponding this δ_{skin} , is $T_e \approx 5-10$ eV.
- After the moment of "peculiarity" $\approx 40\%$ of the current flows outside of the zone with r=460 mm (nearly insulator).

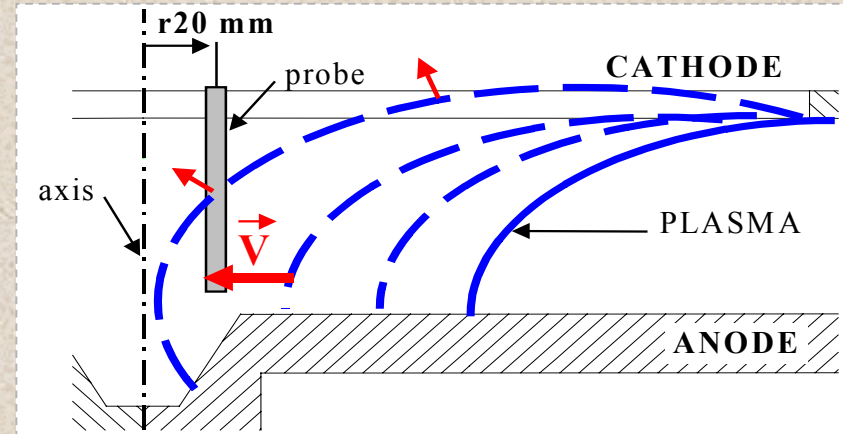
STUDIES OF THE AZIMUTHAL MAGNETIC FIELDS CLOSE TO THE AXIS :



DETERMINATION δ_{skin} FROM MAGNETIC MEASUREMENTS:

$$\dot{I} \approx I \cdot \left(\frac{V_r}{\delta_{skin}} \right) \Rightarrow \delta_{skin}$$

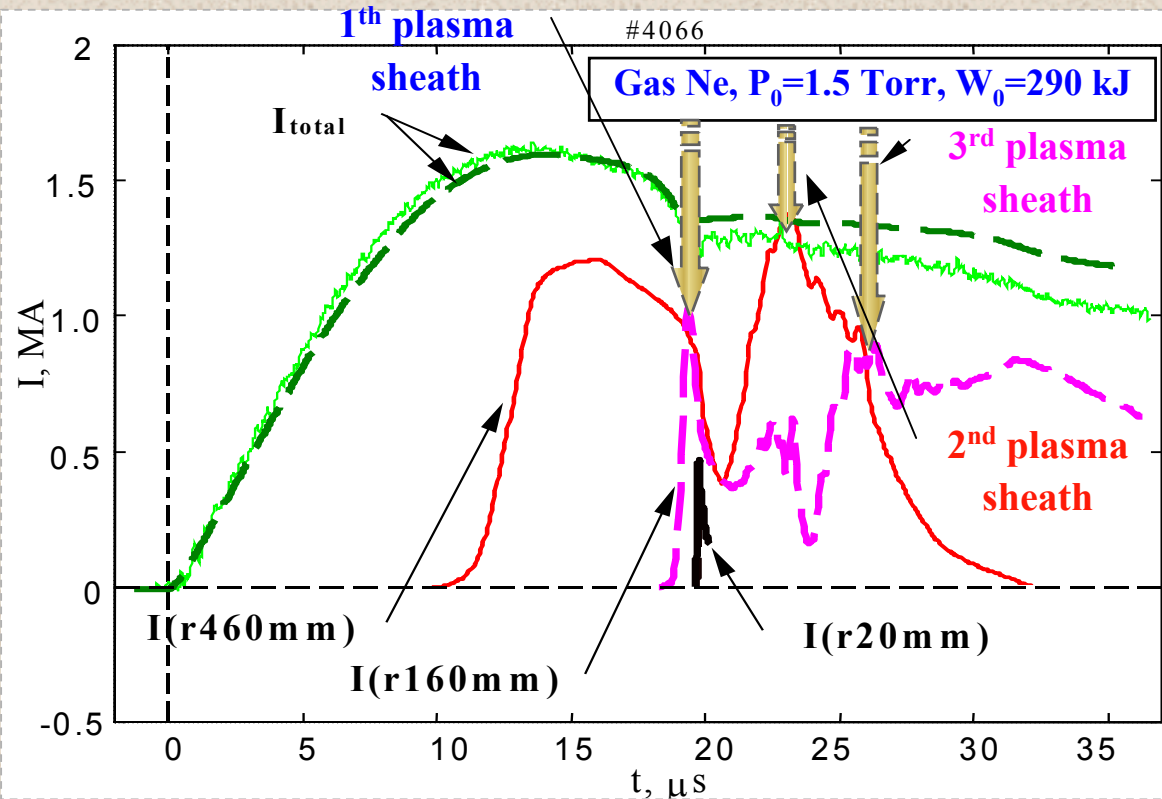
The important role of 2-D effects of plasma compression near PF axis :



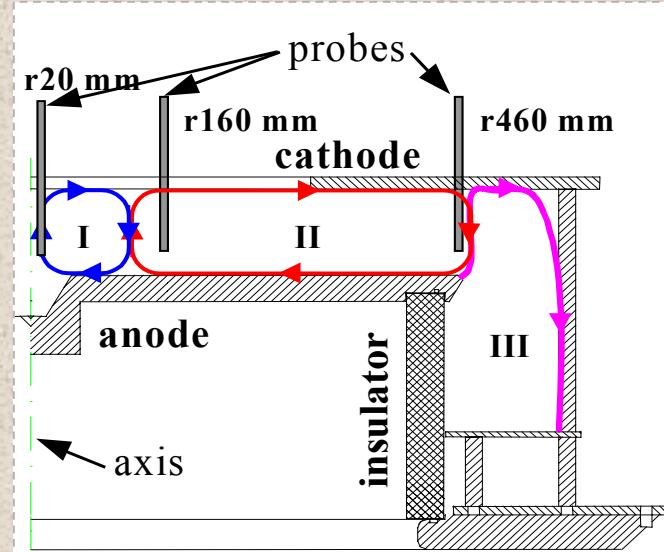
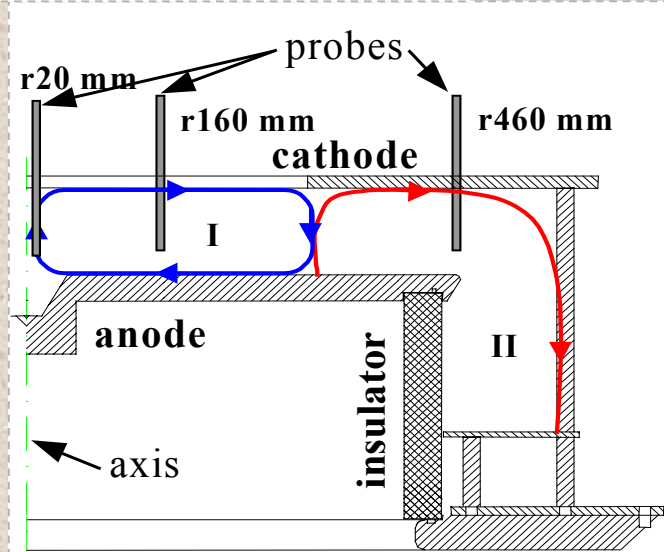
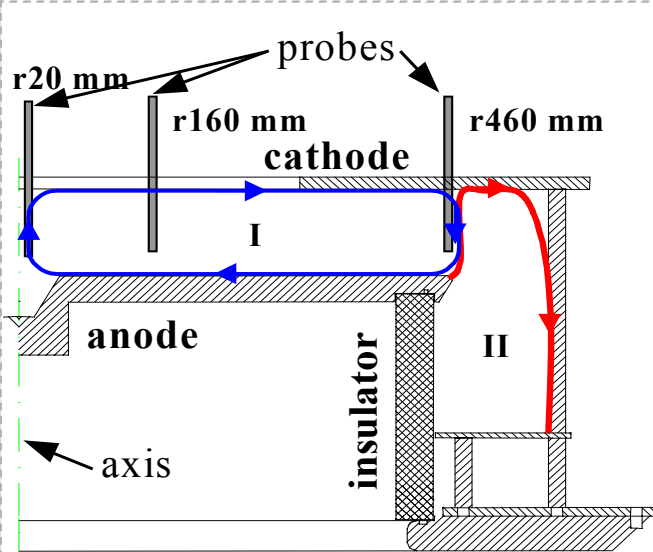
- During plasma sheath movement the current derivative grows in 75 times: from $\approx 0.2 \cdot 10^{12}$ A/s (total discharge circuit) and $\approx (0.9-3) \cdot 10^{12}$ A/s (at $r=460$ mm- $r=360$ mm) up to $\approx 1.5 \cdot 10^{13}$ A/s (at $r=20$ mm) at the final stage of plasma compression to the axis.
- Skin-depth reduces from (6 ± 1) cm at $r=460$ mm- $r=360$ mm up to (3 ± 1) cm inside $r=160$ mm. At the final stage of plasma compression (inside the zone with $r=20$ mm) the skin-depth may be even less than 1 cm.
- The arrival of 2nd current plasma sheath inside zone of $r=160$ mm is observed after “peculiarity”.

STUDIES OF THE AZIMUTHAL MAGNETIC FIELDS NEAR THE PF AXIS:

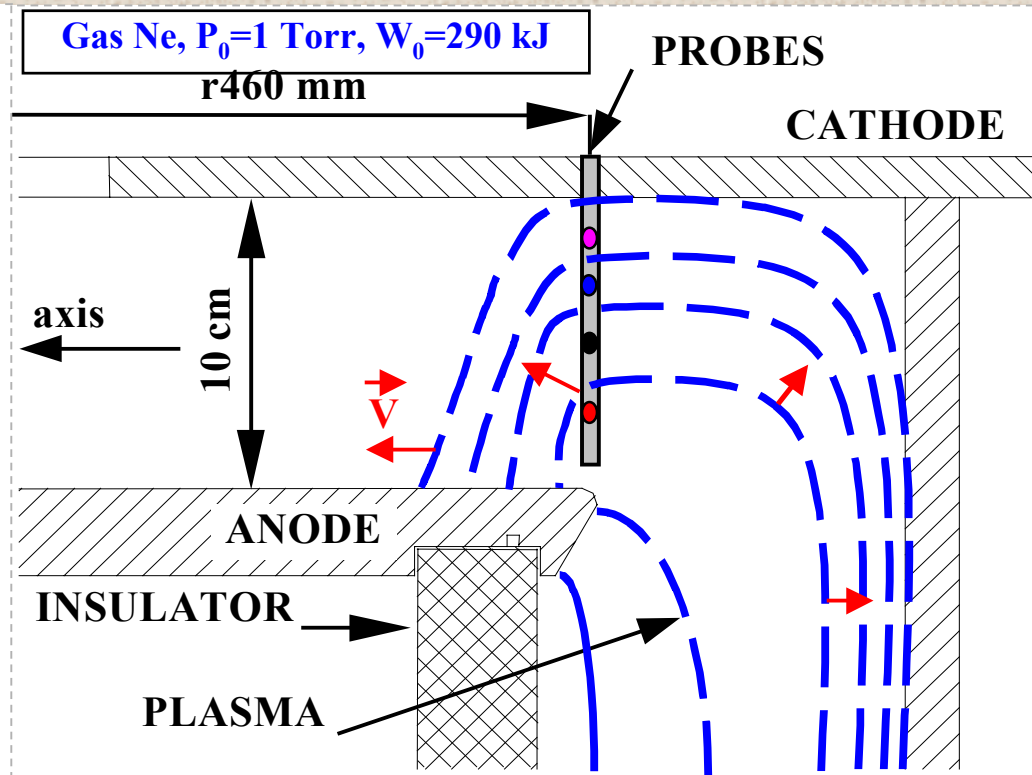
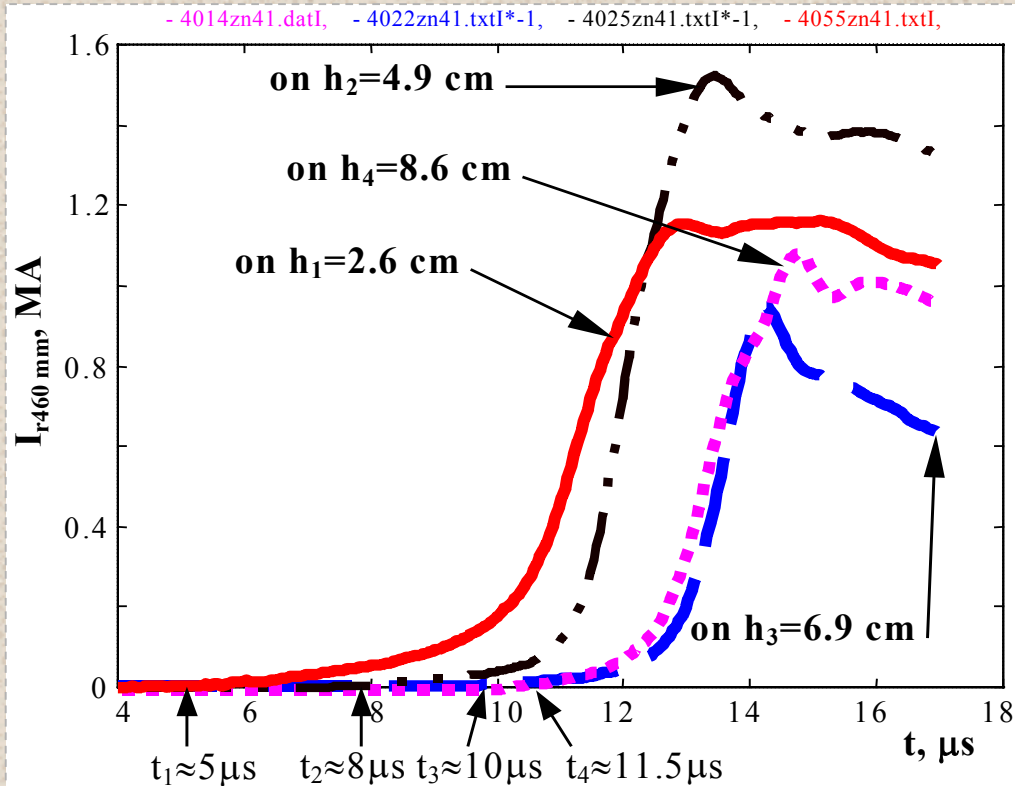
*(formation of separate current loops)
[plasma sheaths]*



- The time of neon sheath compression to the axis on the average is less than time of argon sheath compression in 1.4 times at the same initial conditions.
- Average radial velocity of the neon plasma sheath is 20-30% higher than that for argon plasma – $V_r(\text{at } r460\text{ mm}) \approx 3.4 \cdot 10^6\text{ cm/s}$ and $V_r(\text{at } r20\text{ mm}) \approx 1.3 \cdot 10^7\text{ cm/s}$.
- In case of neon not all current leaves the insulator area from the very beginning of the discharge.
- Magnetic probes at r460 mm and at r160 mm register the currents in different current circuits.

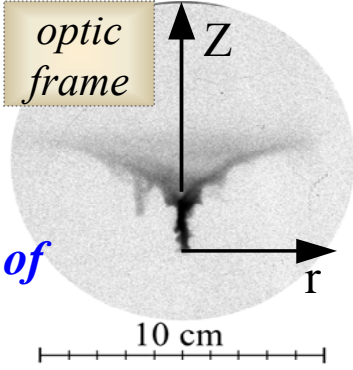


STUDIES OF THE CURRENT SHEATH DYNAMICS ABOVE THE ANODE EDGE:



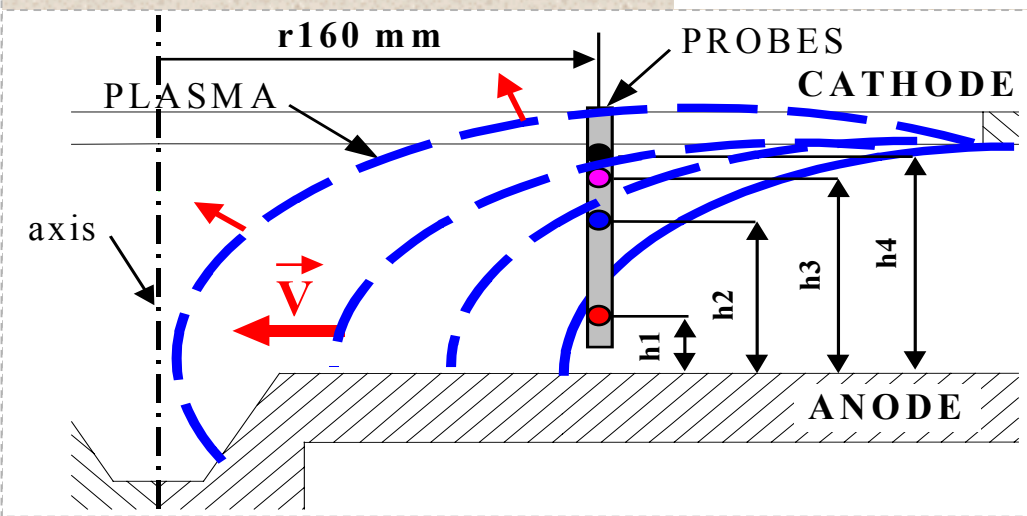
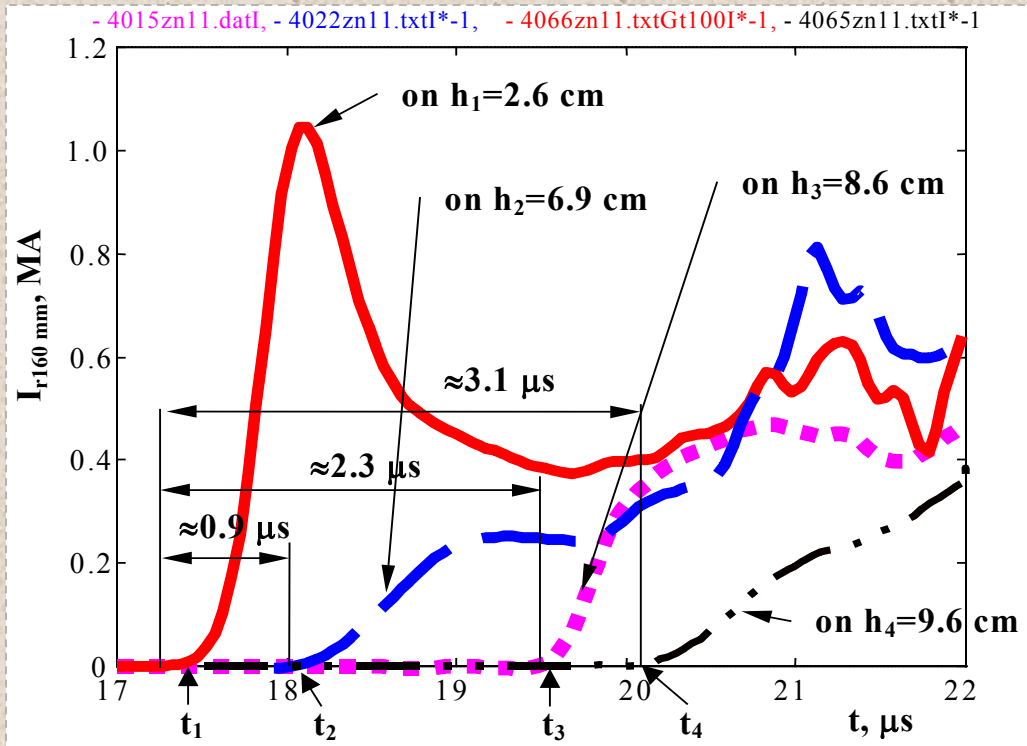
- Dynamics of plasma sheath rising above anode edge at radius $r460 \text{ mm}$ was studied. The question about a height of plasma sheath above anode is very important for *Filippov type PF-systems*.
- The instants of the current-carrying plasma occurrence at the preset heights are registered: $[h_1;t_1]$, $[h_2;t_2]$, $[h_3;t_3]$, $[h_4;t_4]$.
- The estimation of average axial velocity of plasma sheath raising from insulator area to the upper chamber flange (cathode) gives $V_z \approx (1.6 \pm 0.3) \cdot 10^6 \text{ cm/s}$.

STUDIES OF NONCYLINDRICAL SHAPE OF CURRENT PLASMA SHEATH AT ITS MOVEMENT TO THE AXIS



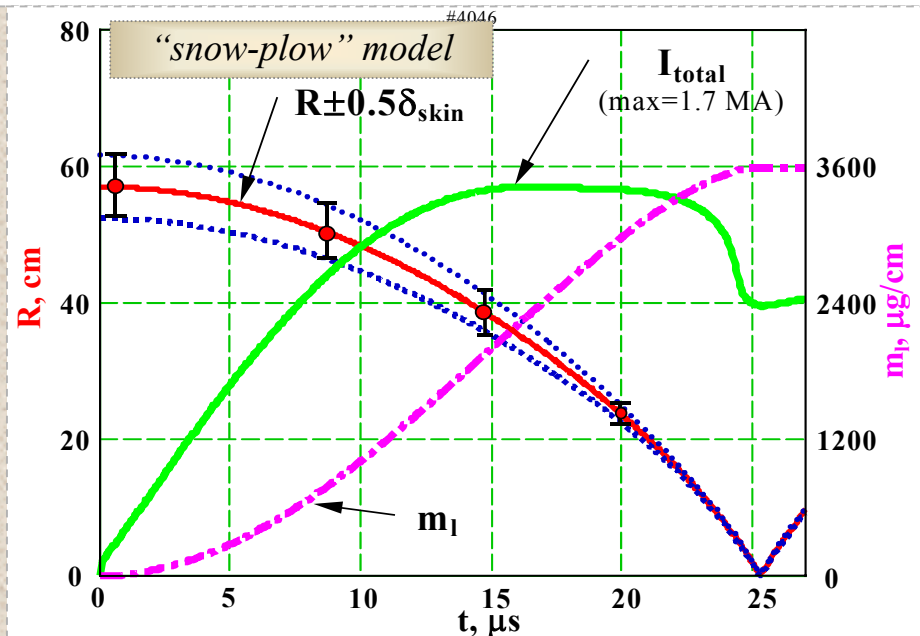
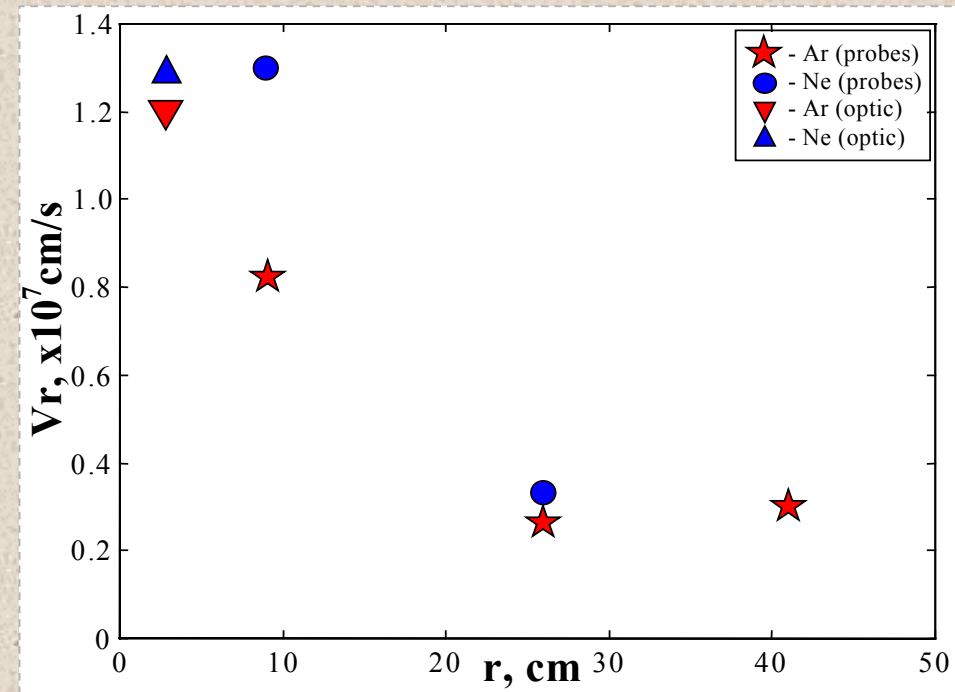
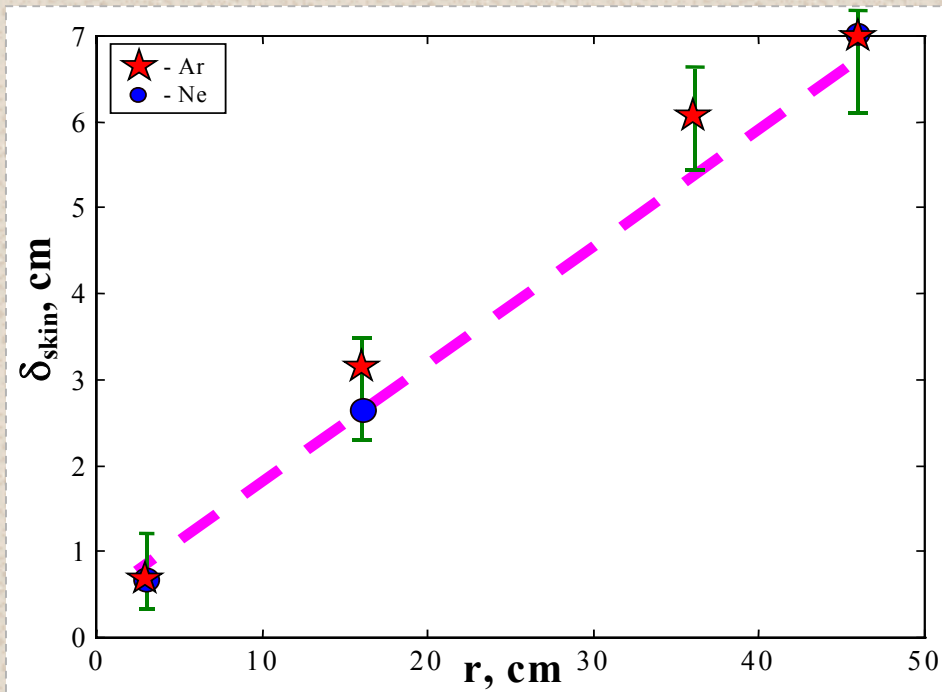
Gas Ne, $P_0=1$ Torr, $W_0=290$ kJ

The important role of 2-D effects of plasma compression !



- The difference in current penetration on different height h in the interelectrode gap at the fixed radius (in our case at $r160$ mm) is registered. This plasma-current sheath has a “funnel” form with a neck inverted to anode.
- The essential difference in current amplitudes on different height of plasma sheath above the anode is observed.
- There is an axial and radial structure of current plasma sheath which can modify at plasma sheath movement to the axis.

SKIN-DEPTH OF PLASMA SHEATH AND DEPENDENCE OF RADIAL SHEATH VELOCITY ON RADIUS:



From the measurements of magnetic fields:

- Reduction of skin-depth of plasma sheath from (6 ± 1) cm (at $r460$ mm- $r360$ mm) up to (3 ± 1) cm (at $r160$ mm) is observed. At final stage of plasma sheath compression at the axis (at $r20$ mm) skin-depth is less than 1 cm.
- The radial velocity of current sheath increases from $\approx (1-3) \cdot 10^6$ cm/s (at $r460$ mm) up to $\approx 1 \cdot 10^7$ cm/s at the final stage of the discharge.

SUMMARY:

The current derivative increases from $\approx 0.2 \cdot 10^{12}$ A/s (in total discharge circuit) and $\approx (0.9-3) \cdot 10^{12}$ A/s (at r460 mm-r360mm) up to $\approx 1.5 \cdot 10^{13}$ A/s (at r20 mm) at the final stage of plasma compression at the axis. Thus, the derivative sharpening is about 75 times.

- Leading front duration of current pulse is decreased from ≈ 5.5 μ s (at r460 mm) up to ≈ 1.5 μ s (at r160 mm) and up to ≈ 120 ns in an axis area of PF facility.**
- The current sheath radial velocity increases from $\approx (1-3) \cdot 10^6$ cm/s (at r460 mm) up to $\geq 1 \cdot 10^7$ cm/s at the final stage of the discharge.**
- The reduction of the plasma skin-depth from (6 ± 1) cm at r=460 mm up to (3 ± 1) cm inside the radius < 160 mm is observed. At the final stage of compression (inside the zone with r=20 mm) the skin-depth is less than 1 cm.**

- The electron temperature at "distant" radii estimated from δ_{skin} is equal $T_e \approx 5-10$ eV.

Thus, measurements of the magnetic fields can be used for estimation of electron temperature at different stages of the discharge.

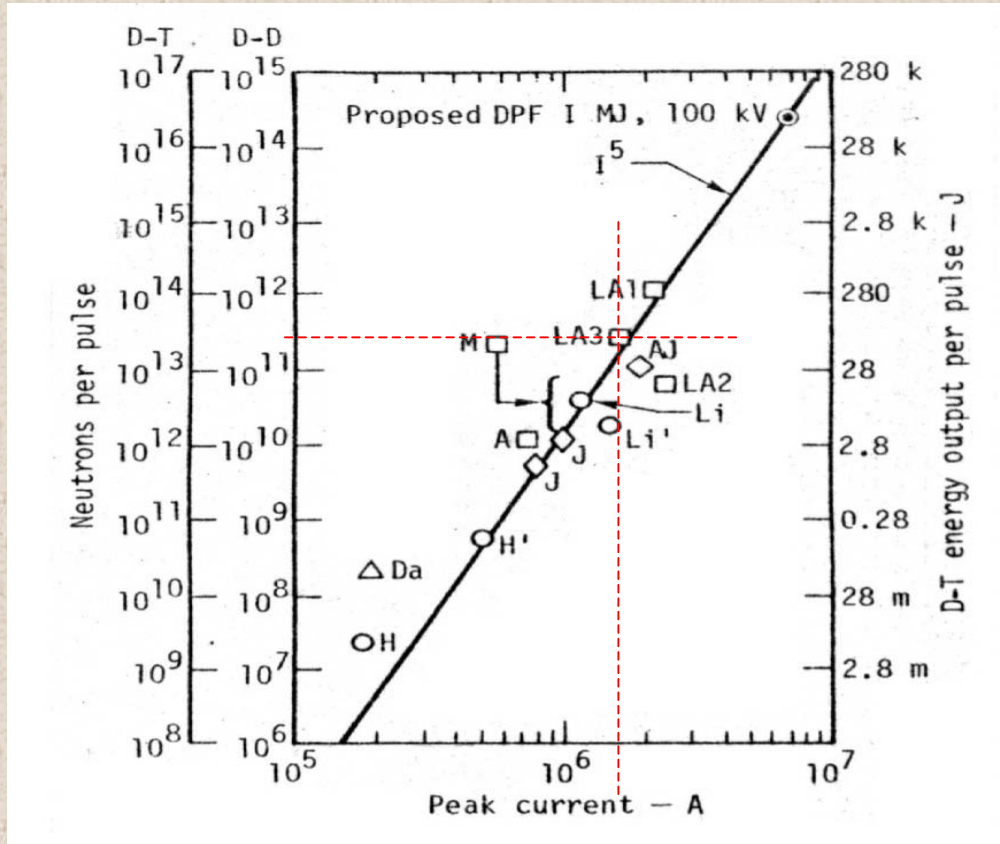
- The existence of shunting breakdowns is registered in the area of the facility insulator at the moment of discharge sharpening at the axis (during the moment of "peculiarity"), in which up to 40% of total discharge current can flow.

The closed current loops, disconnected from the main discharge circuit are formed at the moment of shunting breakdowns. In the case of neon a few such closed current loops can be formed.

Neutron scaling

A “historical” experimental scaling law for neutron yield as a function of the total discharge current (assembled in 1975)

(presented by M.Scholz, IPPLM)



- *Analyzing scaling laws we should know the value of the current really flowing through the pinch.*
- *It is necessary to reconsider scaling laws to avoid the excessive optimism. This scaling should be more realistic.*