# Investigation of LC- Plasma Circuit Parameters

G. Dudkin, B. Nechaev, V. Padalko, V. Bystritsky*, Ya. Voznyak**,
V. Veretel'nik***, E. Furman****.

*Federal State Research Facility INP, Tomsk, Russia, 634050, dudkin@npi.tpu.ru*
**Joint Institute of Nuclear Research, Dubna, Russia, 141980*
***Department of Physics and Nuclear Physics, Academy of Metallurgy, Krakow, Poland.*
****Natural Sciences and mathematics, Polytechnical University, Tomsk, Russia, 634050*
*****Research Institute at Polytechnic University, Tomsk, Russia, 634050*

**Abstract – We report on studies of interaction of two plasma flows with opposite E-field polarization which are counter streaming across external B-field. The plasma flows with density of $10^{16}$ cm$^{-3}$ and velocity of $2*10^{7}$ cm/s were generated in ExB fields at the discharge power of 300 MW and current in each discharge of up to 100 kA. The equivalent capacitance of the plasma flows measured was for discharge power of 100 MW, which depended on transverse dielectric permeability of the flows. The speed of depolarization in the process of the flows collision was measured. Based on transitional characteristics of the depolarization process the estimation of the energy and frequency parameters of the LC –plasma circuit formed during collision of the flows was made. The change in time of the plasma flow concentration in the drift channel is given, as well as energy distributions of electrons and ions leaving the collision zone of the flows along the magnetic filed lines.**

## Introduction

In experimental study on dd- reaction in the energy range of 0.5- 3.7 keV (in the center of mass) intense ion flows were used generated in the high power accelerator in the scheme of the direct or inverse Z-pinch. [1 - 4]. It worth to note that the latter that feature high density of energy are characterized by fast non-linear processes and accompanied by intense background radiation (neutron and gamma- quanta). This condition complicates measuring the yield of the nuclear reactions and interpretation of the experimental results. The listed problems stimulated the search for alternative approaches for generation of intense flows of light nuclei of low energies. For instance, paper [5] analyzed possibility of using expended in time ( 10 msk) counter streaming plasma flows. It was supposed that using such flows would decrease the required total energy, and its density in the flows, and respectively- the level of background radiation.

The results on study of forming and interaction of two counter-streaming plasma flows propagating across B-field are given in paper [5]. Based on that results preliminary estimates on main energetic parameters of the discharge in the cross ExB fields were estimated needed to get the plasma flows with defined characteristics. Fig. 1 illustrates the experimental setup

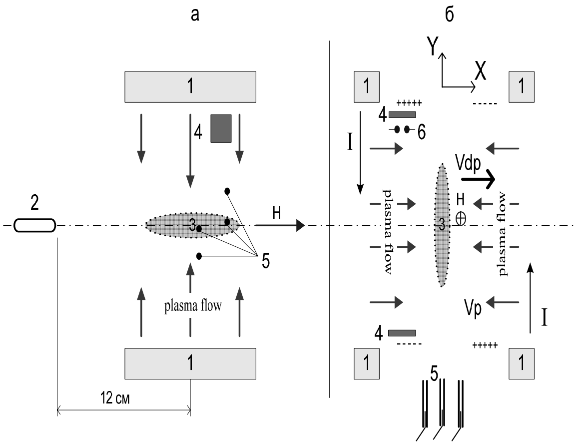

Fig. 1 Scheme of probes location in the setup in two projections: a- view across H-field, b- view along H-field.
1 –electrodes, 2 – electrostatic spectrometer , 3 – zone of collision, 4 –laminate electrodes, 5 – optical detectors, 6 – floating probes. $V_x$, $V_{dp}$ – directions of flow motion and depolarization wave.

The motion of the plasma flows across B-field takes place in the drift channel, formed due to flows polarization [6]. The polarization fields have opposite directions. On formation of the drift channel the flow spends part of its kinetic energy. Thus the total energy in any cross section of the channel is made of electrostatic and kinetic parts [6].

During collisions of the flows, respective depolarization and decay of the drift channels take place. Their restoration requires feeding of the energy from the flows. Experiments showed that collisions of the flows featured quasi periodic character as result of competing processes of decay and restoration of drift channels. [7,8].

Schematically the collision of the flows could be described as follows:
plasma in the flow is characterized by a component of the tensor of dielectric permeance perpendicular to the magnetic field and bulk velocity of flow: $\varepsilon \approx 4\pi M N c^2/H^2$, here M, N – mass of the ion and concentration of ions in the flow respectively. In this case equivalent capacity of the flow is equal to $C \sim \varepsilon l_x l_B/4\pi d$,. It is assumed that the size of the plasma capacitor along magnetic field $l_B$ and the distance between the "plates" of the capacitor (i.e., boundary of the flow) d are fixed. In the same time the plasma capacitance along the flow varies with time as $l_x = V_x t$. Taking that electric energy stored in the flow is equal to $W_e = CU^2/2$, and that potential difference between "plasma" capacitor plates could be defined as $U \approx d V_x B/c$ ( here $V_x$ – is the drift velocity of the ions in the flow) , we get the electrical energy stored in the flow equal to $W_e \approx 0.5 M N V_x^2 l_x l_B d$., which is equal to translational kinetic energy of the flow.

Let us assume that before collision the flows were electrically insulated from each other, and their collision is similar to switching of two oppositely charged capacitors in one circuit (see Fig. 2a).

In the reality we have polarized flows arriving to the collision zone with drift velocity $V_{dr}$. In the same time depolarization wave propagates upstream from the collision zone with the velocity $V_w$ ( in the reference frame of the flow) . In the reference frame of the collision zone (i.e.- of the lab) the velocity of the depolarization wave is equal to $V_{dp} \approx |V_w| - |V_{dr}|$. If $|V_w| = |V_{dr}|$ the process of flows interaction will be continuous, the same as their depolarization , which will be taking place in the zone of flows collision. If $V_{dp} > 0$, a depolarized layer with $V_{dr} \sim 0$ could form during some finite in front of the collision zone. It would result in termination of flows interaction and decoupling of the discharge circuit.

The processes will repeat again - formation of the drift channels in the flows, collisions, propagation of depolarization waves, etc.

The process of flows collision is accompanied by ejection of the plasma jet along the magnetic lines having particle density of several orders higher then the density of the background plasma, characteristic for plasma moving along H-lines spaces beyond the zones of collision [8].

As it follows from the above the character of the flows interaction and the final energy spectrum of the particles after collision depends on dielectric permeance of the plasma flows and their velocity. In its turn the rate of electric energy input in the collision zone depends on inductive and resistive parameters of the plasma capacitors discharge circuit.

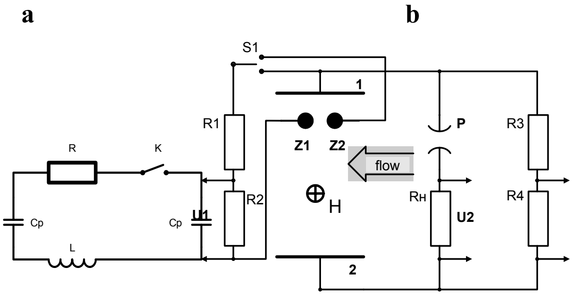

Fig. 2. a – Equivalent scheme of the plasma flows interaction; b- scheme of measuring potential difference between $Z_1$, $Z_2$ ( field $E_x$, Z1- plate 1 ( $E_y$)

In this report we focused on study of energy and frequency characteristics of the discharging processes of the polarized counter- streaming colliding plasma flows ( i.e. equivalent plasma capacitors)

These data were needed for adequate interpretation of experimental results on neutron yields.

## Experimental

One of the flows, formed in the crossed E × H fields, was going through measuring cell. The cell consisted of two copper electrodes with area of $A = 1 \times 1$ cm $^2$ (see position 4 at Fig. 1, 1, 2 at Fig. 2b). The distance between plates $d \approx 2$ cm, which roughly corresponded to the thickness of the flow. At the distance of 5 mm from one of the plates inside of the cell the probes were located ( positions 6 in Fig. 1, Z1, Z2 in Fig. 2b) for measuring the electric fields in X and Y directions ($E_x$ и $E_y$).

The measurements of the equivalent capacitance of plasma flow was done at the distance of ~ 1 cm from the center of the collision zone ( center of the chamber) following the scheme, given in Fig. 2b. Electrodes

( plates ) were connected to micro-sparkgap (P) of the NENGSI 350 02 type. Two electrode sparkgap fired at breakdown voltage (~ 400 V), and electrodes were shunted by discharge circuit resistance of 4 or 40 Ohm To minimize the influence of the inductance of the measuring circuit we used high resistive dividers.. During all measurements the coupling with registering scope (Tektronix 224) was done via optical cables.

The measuring cell could be translated along the flow from the area of discharge, where the flows were formed to the collision zone in the center of the cylindrical ceramic chamber, the length of which was 150 cm and diameter -20 cm. The base of translation was ~ 3 cm.

Experiments were conducted at external magnetic field of $\approx 10^4$G and power level in each of discharges of 100 MW. The maximum current amplitude in each discharge was ≈ 40 кА. Respective energy parameters of the flows satisfied condition $n_i\, m_i\, V_x^2/2 < H^2/8\pi$.

Submitted experimental data correspond to the time interval of 2 ÷3 μs from the от beginning of the discharge current pulses that form the flows. A first collision of flows took place during this time interval.

## Experimental results and discussion.

Fig. 3 displays a sequence of waveforms featuring dynamics of the potential difference between plates 1 – 2 (Fig. 2b). The firing of micro-sparkgap is marked by the index (a) , collision of the flows- as (b). The characteristics of (a) are defined by the parameters of the external circuit, the characteristics of process (b)- by inner. The waveforms were obtained at different positions of the measuring cell in respect to the center of the center of the flows collision zone.

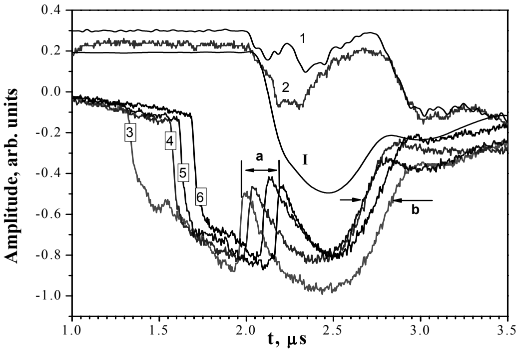

Fig. 3. Waveforms of the potential difference: between Z1 and plate 1 with microsparkgap (1) and w/o it (2); between plates 1 and 2 when measuring cell was moved along the flow from the place of formation flow to the zone of flows collision (3-6) ; (a) – the time delay in time of the firing of microsparkgap; (b) the zone of the flows depolarization process at their collision; I- current in the circuit of microsparkgap

Experiments demonstrated that the level of firing voltage could be controlled pretty accurately by the microsparkgap. This condition provided us with possibility to estimate plasma velocity , using time of flight method, at different distances from the center of the chamber - s, ( Fig.. 3, curve -a), for which potential difference between plates 1 –2 was ~ 400 B (Fig. 2b).

It worth to note that the measured voltage value between the boundaries of the flowis always lesser than that which follows from expression $E_y\, \delta = \delta V_x \times H/c$ , due to some leakage of charges from the boundaries of the flows Respectively $V_{dr} = V_x \approx E_y\, c/H$.

From the set of waveforms using this approach we estimated also the velocity of the depolarization wave of the flows down to some fixed level (Fig. 4, curve-b).

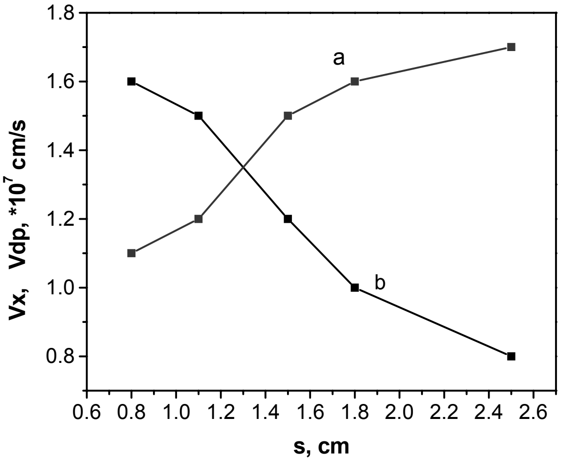

Fig. 4. Velocity of the plasma flow with polarization potential of 400 BV curve – **a),** and velocity of depolarization wave in the flow ( curve **b**) as function of the distance from the center of the flows collision zone

We obtained experiment data on variation of potential difference between the probes Z1 and Z2 as function of controlled currentамплитуде with $R_L \sim 4.2$ Ohm , after firing micro-sparkgap. The data on Hall electric field (Ex) with known values of the transverse current density (across the flow) provide estimation on the plasma concentration ( see Fig.5) in the flow through the measuring cell [9]. . The relation between the current carriers concentration and Hall potential if you know the current value is defined by expression ( in SI units) : $N \approx J_y\, B/e\, E_x$, e – electron charge.

The measurement of the capacitance of the flow, was done on the rising branch of the discharge currents , which formed the flows, and with the load in the micro-sparkgap circuit of $R_L \sim 40$ Ohm. At firing of the microsparkgap initially the voltage difference between one of the probe and the plate dropped . We selected the interval section of < 100 ns from the beginning of the breakdown on the falling voltage curve, where the rate of the potential change was maximal dU/dt → max. From the ratio I = C dU/dt, and measured value of the discharge current we calculated the equivalent capacity of the plasma column with area of 1 cm$^2$ and 2 cm height. The selection of the time interval depends on the velocity of the flow ≥ $10^7$ cm/c, based on the criteria that during this interval the parameters of the flow passing through the measuring cell stay fairly constant.

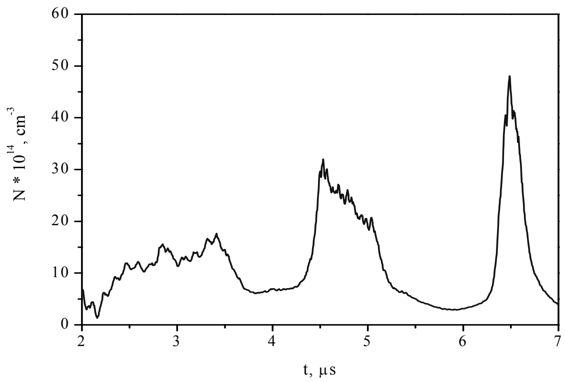

Fig. 5. Modulation of the plasma concentration in the quasi-continuous interacting flows

As a result of processing experimental waveforms we obtained for the current through the microsparkgap $i \approx 3$ A, and $dU/dt \approx 10^8$ V/c. Respectively- $C_e \approx 3\ 10^{-8}$ F, and from $C_e = \varepsilon\, \varepsilon_0\, S/d$, we get: $\varepsilon \approx 3.4\ 10^5$.

The values for N and ε, agree very well with expression, $\varepsilon = 4\pi M N c^2 / H^2$ obtained by independent approach in the same time interval. So, in conditions of constant magnetic field we could justify validity of extrapolation of this ratio for other values of concentration and dielectric permeability.

It follows from the waveforms that the field $E_x$ between one of the probes 6 and the plate 1 ( Fig. 2b) oscillates during collision of the flows with a period of $T \sim 100$ ns. In this case the equivalent discharging capacitance in the interacting flows during one period is equal to $C_p \approx C_e (V_x + V_{dp})\, T\, l_B / S$. Following the expression $T^2 \sim L\, C_p$ we could estimate inductivity of the circuit of the plasma capacitors as - $L \sim 10^{-8}$ Гн. During the process of the flows depolarization ($\Delta t \approx 200 - 300$ ns) the oscillation decrement varied from 1.5 to 4 , which corresponded to change of the circuit resistance from 0.1 to 0.3 Ohm. It indicates that electric energy losses in the collision zone are of resistive character, and in time they are controlled by LC parameters of the discharge circuit.

Based on the experimental data we could estimate energy characteristics of plasma LS circuit.

The total electric and kinetic energies input in the collision zone from both flows during the time interval t is equal to :: $W_e \approx 2C_p U^2/2 \approx C_e(V_x + V_{dp})\, t\, l_b\, U^2/S$ и $W_k \approx 2M\, n_i\, V_x^2\, d\, l_B\, V_x\, t/2$. Assuming $U = 400$ V, $t = 300$ ns, $\langle V_x \rangle \approx \langle V_{dr} \rangle = 1.3\ 10^7$ cm/s, $n_i \sim 2\ 10^{15}$ cm$^{-3}$, $d = 2$ cm, $l_b = 10$ cm, $S \approx 1$ cm$^2$, we get $W_e \approx 2.4$ J, $W_k \approx 8.8$ J. Thus, electric energy makes significant part of the total energy pumped into collision zone , and it must be accounted when analyzing and interpreting results on neutron yield in experiments on collisions of $d^+$ plasma flows . For instance, the process of depolarization of plasma capacitors is accompanied by depolarizing current of $I_{dp} \approx 2\, C_p\, U/t \approx 10^4$ A. Magnetic field of this current has the same direction as the external magnetic field. Its rate could reach $10^{10}$ Gs/s [6]. This fast rising field could result in inducing strong E-fields and distort the ion energy distribution in the collision zone.

Using small size grid particle energy analyser we measured parameters of the plasma jet at the discharge power of 100 MW, ejected from the collision zone. The analyser was placed at the distance of 10 cm from the collision zone and could be moved along and across magnetic field . The following parameters of the jet were obtained:

| | |
|---|---|
| jet duration in time | ≤ 300 нс; |
| size of the jet in direction of the flow flight ( across magnetic field ) | 0.5 cm; |
| jet cross section | ~ 1 cm$^2$ , |
| ion density in the jet at the analyser entrance up to | $10^{16}$ cm$^{-3}$. |

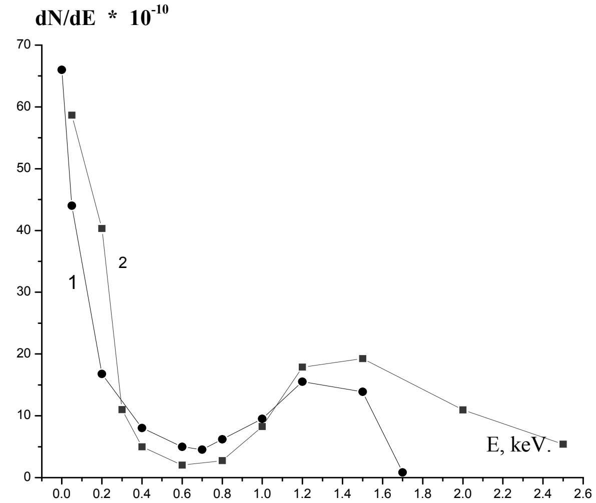

Fig. 7 Differential energy spectra of ions (1) and electrons (2), registered at collectors of grid energy analyzer

Based on the energy distribution of the ions in the jet (Fig.7), that flies along magnetic field, and its parameters, we made estimations of jet energy, generated in the first collision. The balance of energies pumped in the collision zone with their energy leaving along the field lines with plasma jet holds with account of electric energies of the flows. increase (velocity and temperature) resistive losses drop

It is worth to note that with the flows energy, and oscillation frequency of discharge circuit reaches 50 MHz. This frequency approximately corresponds to cyclotron frequency of deuterons in the magnetic field of $10^4$ Gs. In condition of resonance more efficient transfer of electric energy of polarized plasma flows to heating could be possible [10]. BY estimations the density of electric energy in the flows reached 1

J/cm$^3$, with power density input in the collision zone – up to 1 GW/cm$^3$, respectively. Thus , it seems feasible to accumulate electric energy in the plasma flows, propagating across magnetic fields, at the density level characteristic for inductive storages. In the same time the rate of the energy input of this stored energy in the collision zone of the plasma flows corresponds to the rate which is characteristic to the transfer time from the low impedance forming network to the load.

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