Study of the reactions between light nuclei at ultralow energies using high power plasma accelerators

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Interest

- verifying the charge symmetry in strong interactions at ultralow energies
- obtaining information on exchange meson currents
- verifying correctness of the description of few-body systems on the basis of modern concepts of nuclear interaction between constituent nucleons
- obtaining information on the size of electron screening of interacting nuclei to explain on existing deficit of light nuclei (except ^{4}He) in stars and the Galaxy
- to test applicability of the standard model to the description of all processes occurring in the Sun

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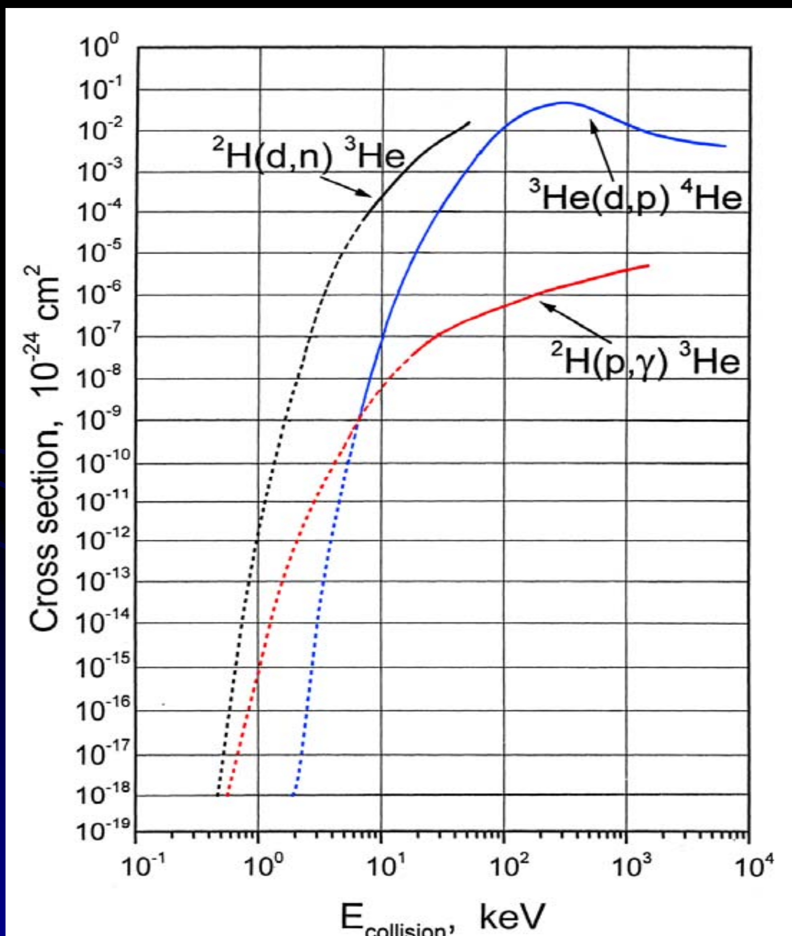
Aim of present research

Measurement of astrophysical S-factors and effective cross sections of the *pd*, *dd*, d^3He and reactions in the ultralow energy region (1-12 keV)



$$p + d \rightarrow {}^3\mathrm{He} + \gamma \ (5.5 \ \mathrm{MeV})$$

$$d + d \begin{array}{l} \rightarrow {}^3\mathrm{He} + n \ (2.46 \ \mathrm{MeV}) \\ \rightarrow p \ (3.03 \ \mathrm{MeV}) + t \ (1.01 \ \mathrm{MeV}) \end{array}$$

$$d + {}^3\mathrm{He} \rightarrow p \ (14.64 \ \mathrm{MeV}) + \alpha \ (3.5 \ \mathrm{MeV})$$

Measurement method

Experimental determination of the astrophysical S-factor and effective cross section of the *dd*, *pd* and d^3He reactions:

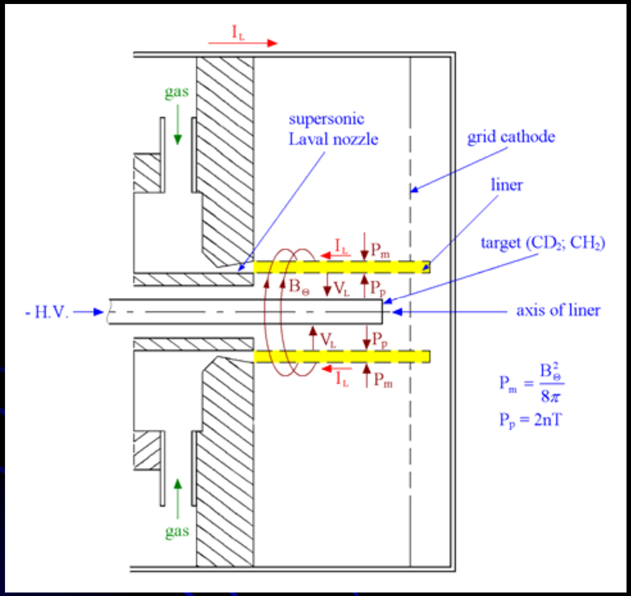
$$S_{kd}(\bar{E}_d) = \frac{N_i^{\exp}}{N_p n_t \varepsilon_i \int\limits_0^\infty f(E_k)dE_k \int\limits_0^\infty \frac{e^{-2\pi\eta}}{E_k'(E_k, x')} dx'} \qquad \sigma_{kd}(E_{kd}) = \frac{S(E_{kd})}{E_{kd}} \cdot e^{-2\pi\eta}$$

$$\eta(E) = Z_1 Z_2 e^{-31.29(\mu/E')^{1/2}} \qquad \tilde{\sigma}_{kd} = N_i^{\exp} / N_d n_t \varepsilon_i \tilde{l} \qquad k = p, d, {}^3\text{He}$$

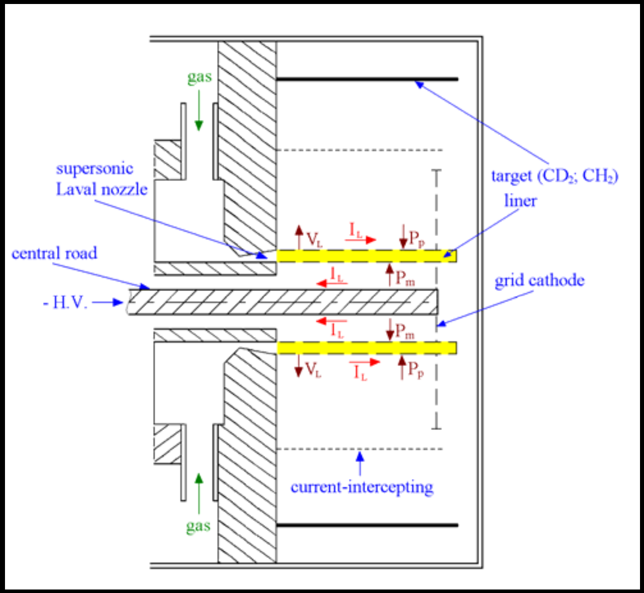
$N_i^{\exp}$ – yield of the detected particles (i = *n*, *γ*, *α*), N_p – number of particles hit in the target (*p* = *p*, *d*, ^{3}He), Z_1, Z_2 and μ – charges and reduced mass of the colliding particles, n_t – density of the target, ε_γ – efficiency of the reaction products detection , E' – energies of colliding particles after passage of a target layer of thickness x', $\bar{E}$– average energy of the of colliding particles, $f(E)$ – energy distribution of the particles hitting the target, $\tilde{l}$ – effective target thickness defined from the expression $N_i(\tilde{l}) = 0.9 N_i^{tot}$ (N_i^{tot} – yield of products from the *dd*, *pd* and d^3He reaction in the case of an the infinitely thick target).

Difficulties

- nuclear reaction cross sections for such energy region (1-12 keV) are very small $\sigma \approx 10^{-43}$-10^{-32} cm^2
- intensities of accelerated *p*, *d*, ^{3}He beams using classical accelerators are too low new experimental methods: using a high-intensity radially liner plasma flow in the direct Z-pinch configurations (plasma is accelerated toward to the axis of liner (1993) or in the “inverse” Z-pinch configurations (plasma is accelerated away from the axis of liner(2000))



direct Z-pinch



“inverse” Z-pinch

$$M(\mathrm{g/cm}) = 2\cdot 10^{10}\cdot I(\mathrm{MA})\cdot \ln(R/r)\cdot V^2(\mathrm{cm/s})$$

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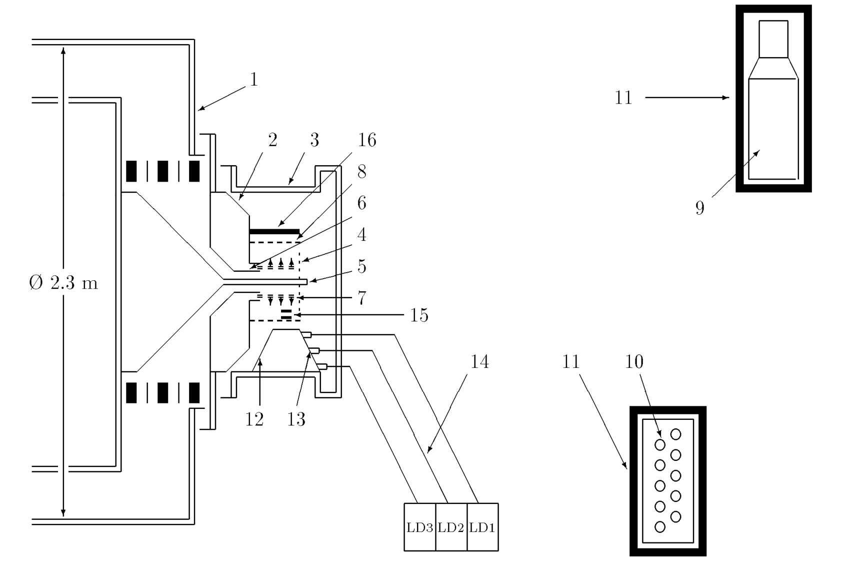
Experimental setup



1 – high-current pulse generator; 2 – load unit of accelerator; 3 – diagnostic chamber; 4 – grid cathode; 5 – inverse current conductor; 6 – supersonic Laval nozzle; 7 – liner; 8 – current-intercepting rods; 9 – scintillation detector;

10 – thermal neutron detector; 11 – Pb shielding; 12 – light-cover cone;

13 – collimators; 14 – optical fibers; 15 – magnetic dB/dt probes; 16 – solid CD_2 target; LD1, LD2 and LD3 – optical radiation detectors

Neutron counters: plastic scintillators (d=100 mm, h=200 mm; 100×100×750 mm^3); thermal neutron detectors placed in paraffin moderator (it consisted of 10 proportional BF_3 or ^3He counters)

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Institute of high-current electronic RAS (Tomsk, Russia) plasma accelerators

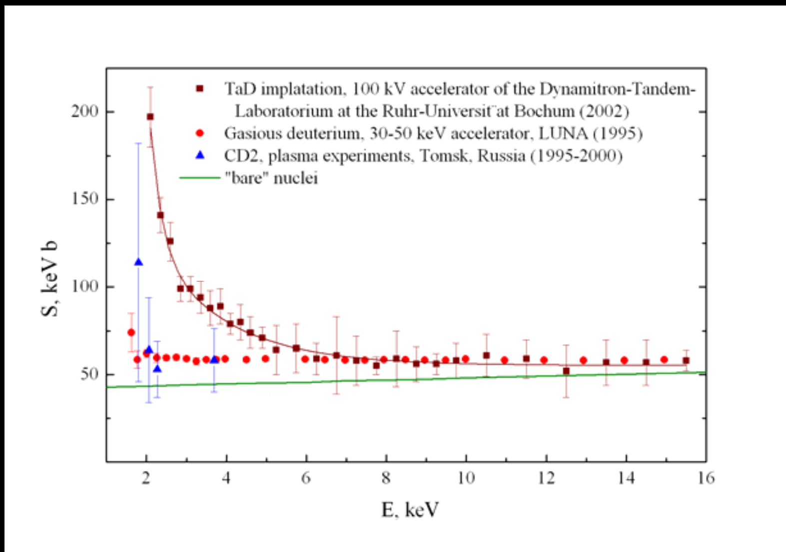
SGM HCEI

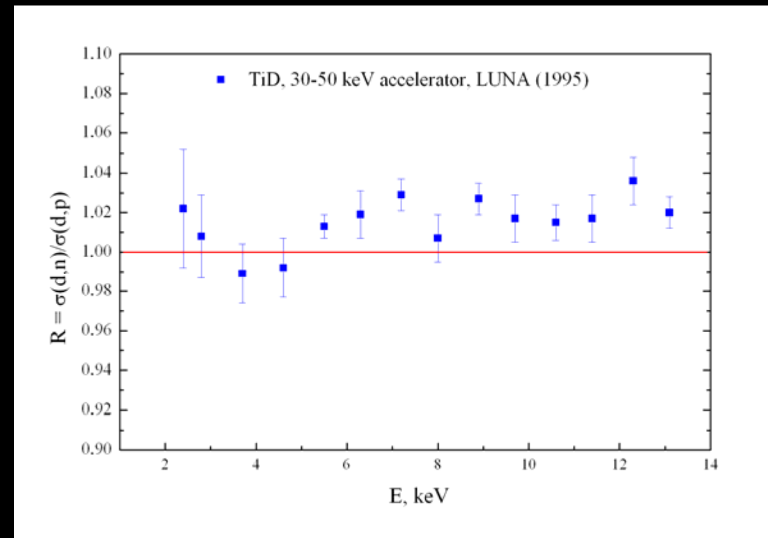
$I \approx 950$ кА, $\tau = 80$ ns

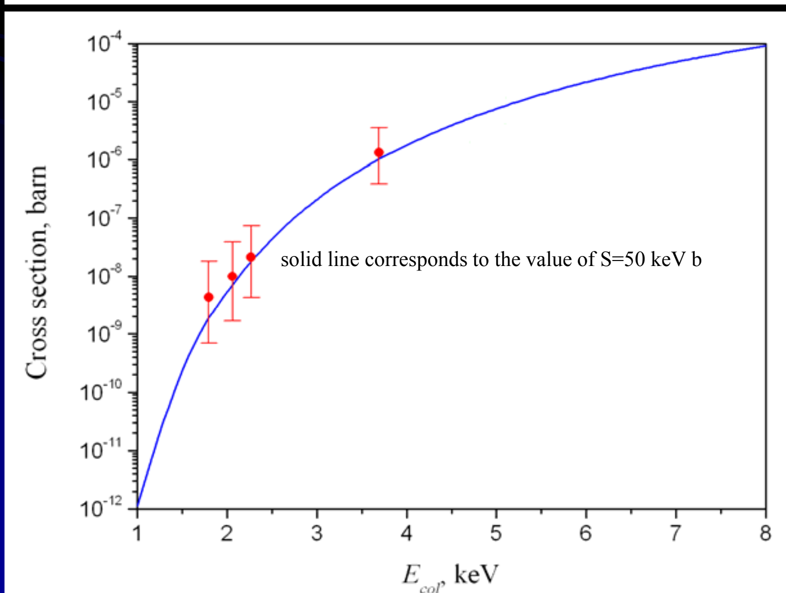
MIG

$I \geq 1.7$ MA, $\tau = 80$ ns

Results of dd-reaction study (up to 2002)
Z pinch technology



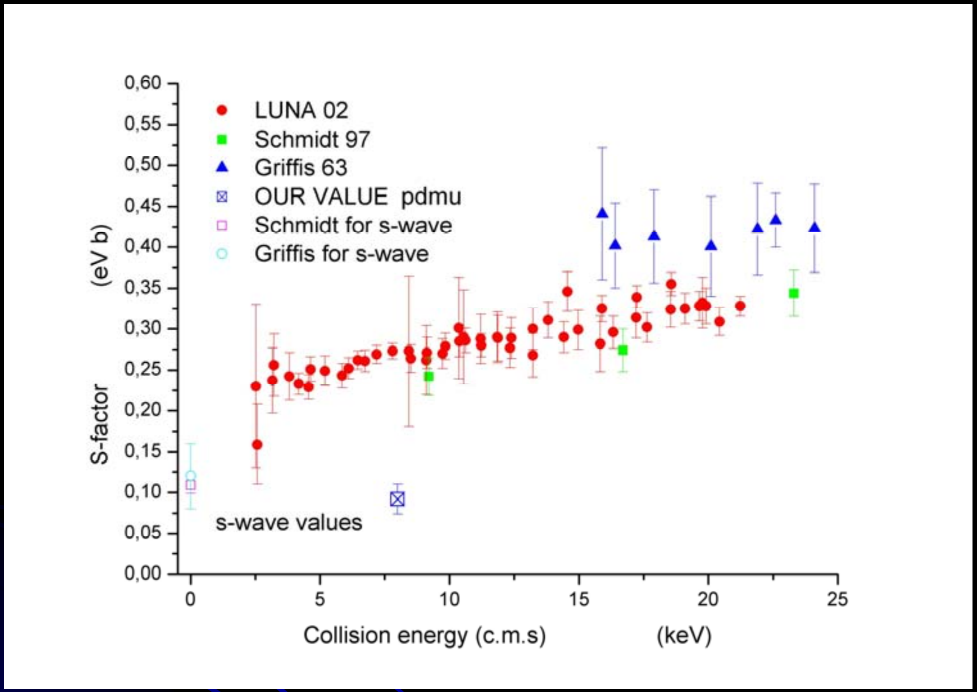




$$\overline{E}_{dd} = 1.8, 2.06, 2.27, 3.69 \text{ keV}$$

$$S_{dd} = 114 \pm 68; 64 \pm 30; 53 \pm 16; 58.2 \pm 18.1 \text{ keV} \cdot \text{b}$$

pd reaction study (2005)
"inverse" Z pinch technology



$$\overline{E}_{pd} = 10.2\ \text{keV}$$

$$\widetilde{\sigma}_{pd}^{\exp}(2.7\ \text{keV} \le E_{pd} \le 16.7\ \text{keV}) \le 4 \times 10^{-33}\ \text{cm}^2$$

$$\overline{S}_{pd}^{\exp}(\overline{E}_{pd} = 10.2\ \text{keV}) \le 2.5 \times 10^{-7}\ \text{MeV b}$$

$$\sigma_{pd}^{cal}(\overline{E}_{pd} = 10.2\ \text{keV}) = 3.9 \times 10^{-33}\ \text{cm}^2$$

$$\overline{S}_{pd}^{cal}(\overline{E}_{pd} = 10.2\ \text{keV}) = 1.2 \times 10^{-7}\ \text{MeV b}$$

$$\overline{S}_{pd}(pd\mu) = 0.092 \pm 0.018\ \text{eV} \cdot \text{b (new value)}$$

$$\overline{S}_{pd}(pd\mu) = 0.128 \pm 0.008\ \text{eV} \cdot \text{b(old value)}$$

Gamma-detectors: plastic cintillator (ø 160×210 mm 2 pieces; ø 50×50 mm);

Problems with Z-pinch

- Absence of reproducibility of the experimental conditions from "shot" to "shot" - imposes certain restrictions on accuracy of measurement of parameters of the investigated processes

This circumstance stimulated the development of two alternative methods for formation of intense charged-particles beams in the ultralow energy region:

- using the pulsed ion source with the closed Hall current (plasma Hall accelerator)
- generation of two opposite plasma flows counter propagating across magnetic field

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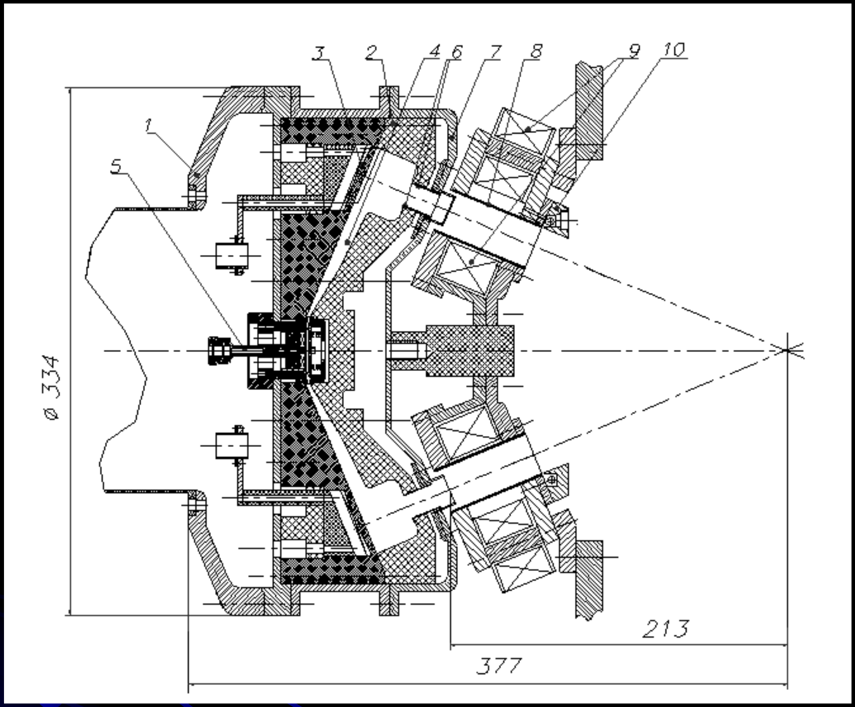
Hall ion source



1 – anode holder, 2 – insulator, 3 – shock coil,
4 – Laval nozzle, 5 – pulse gas valve,
6 – first-step anode, 7 – second-step anode,
8 – conic cathodes, 9 – electromagnet,
10 – Rogovsky belt

- B = 1.6 kGs in the middle of the ring gap
- average diameter of the second anode – 170 mm
- square of emitted surface – 95 cm^2
- voltage of shock coil – 20 kV
- duration of plasma pulse – 1÷50 μs
- rise time of plasma pulse – 200 ns
- amplitude unstability in the high voltage pulse – 0.5 %
- current – 200 A
- generator of accelerated voltage – 2÷20 kV

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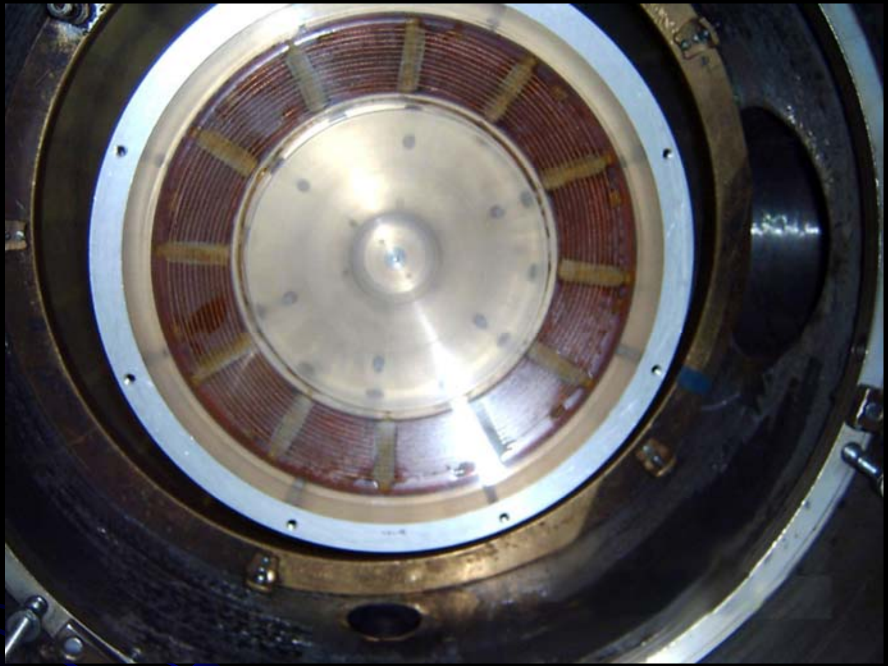
Basic units of the ion source



Induction plasma source installed in the vacuum chamber of the accelerator

Electromagnet of the Hall ion source. The electromagnet is intended for generating a transverse isolating magnetic field in the accelerating gap.

Characteristics of Hall ion source

- Hall plasma source uses an electrodeless induction discharge with pulsed gas bleed-in
- wide range of plasma parameters covers ion level required emission according to the experimental conditions (≤ 1 A/cm^2)
- replacement of the filling gas allows a desired flux of ions to be formed rather simply
- maximum volume of the bleeded-in gas at the atmosphere pressure is 0.3 cm^3
- plasma density is - $(1\text{-}2)\cdot 10^{13}$ cm^{-3}, which corresponds to the ion saturation current ~ (1-3) A/cm^2

<u>Conclusion:</u>

Hall ion source is very effective for high intensity plasma flux formation

Plasma Hall accelerator

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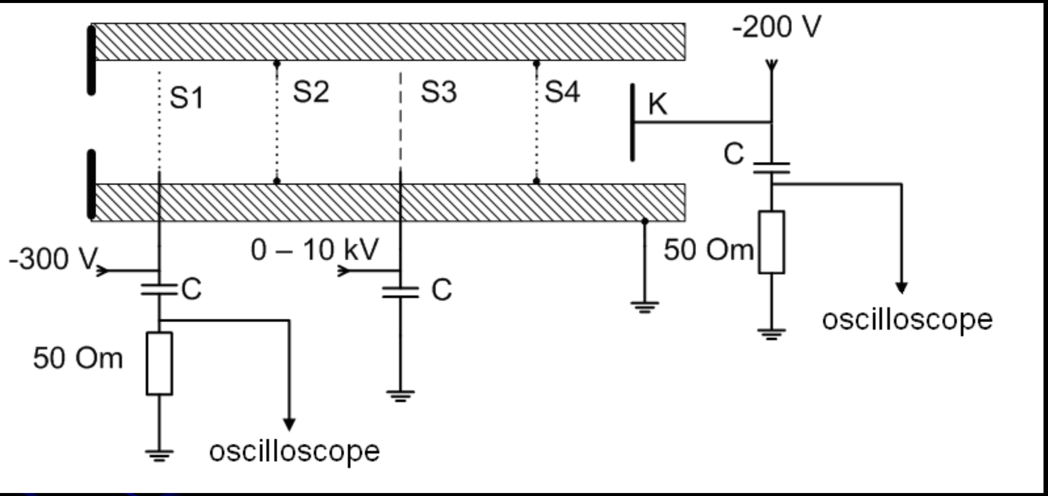
Diagnostics equipment

Electrostatic multigrid spectrometer of charge particles

Purpose:

measurement of energy distribution of ions generated by the Hall accelerator



- Target (CD_2,TiD, TaD, D_2 O) – fore-part of spectrometer flange
- V(S1) = -300 V
- S2, S4 – grounded grids
- V(S3) = 0÷10 kV
- V(collector) = -200 V
- Grid diameter ≈ 50 mm

- distance between grids ≈ 4 mm;
- total area of entrance apertures of spectrometer S ~ 1 cm^2;
- total grid transparency K = 7.2 %;
- transparency of S1 grid ~ 28 %;
- ion density of the input: N ≈ Q /($e \cdot S \cdot K$)

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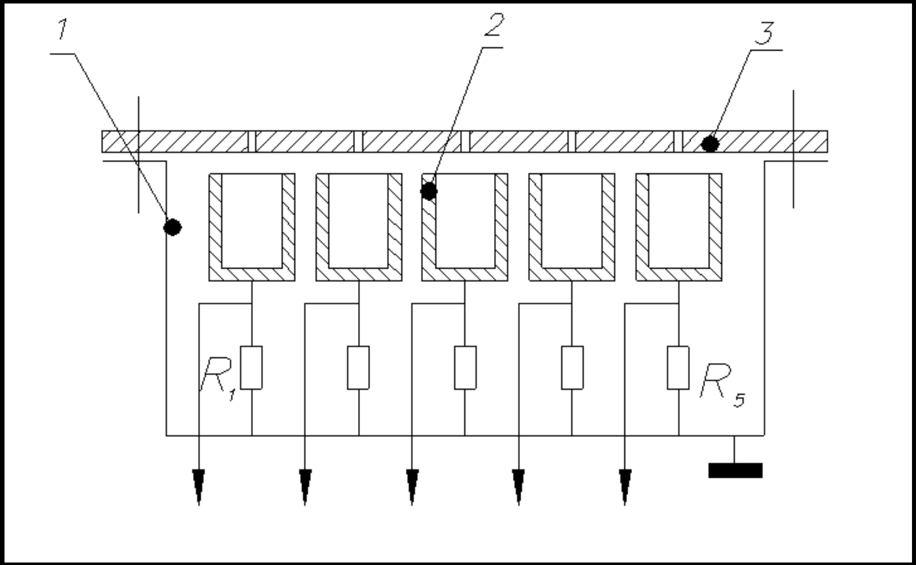
Diagnostics equipment
Collimated Faraday cup arrays

Current density in various ion beam sections – collimated Faraday cup arrays



1 – case, 2 – ion collectors,
3 – collimating plate,
R1-R5 – load resistors.

- CFC collector – a hollow cup 5-10 mm deep
- suppression of secondary electron emission from the collector – transverse magnetic field 2-3 Kgs (samarium-cobalt magnets)
- measurement of plasma density – double and face probes located along the axis of the plasma gun
- maximum plasma density at a distance of 5 cm from the end face of the plasma gun is ~10^{13} cm^{-3} at the ion velosity ~ $5 \cdot 10^6$ cm/s
- ion currents – Rogowski belt

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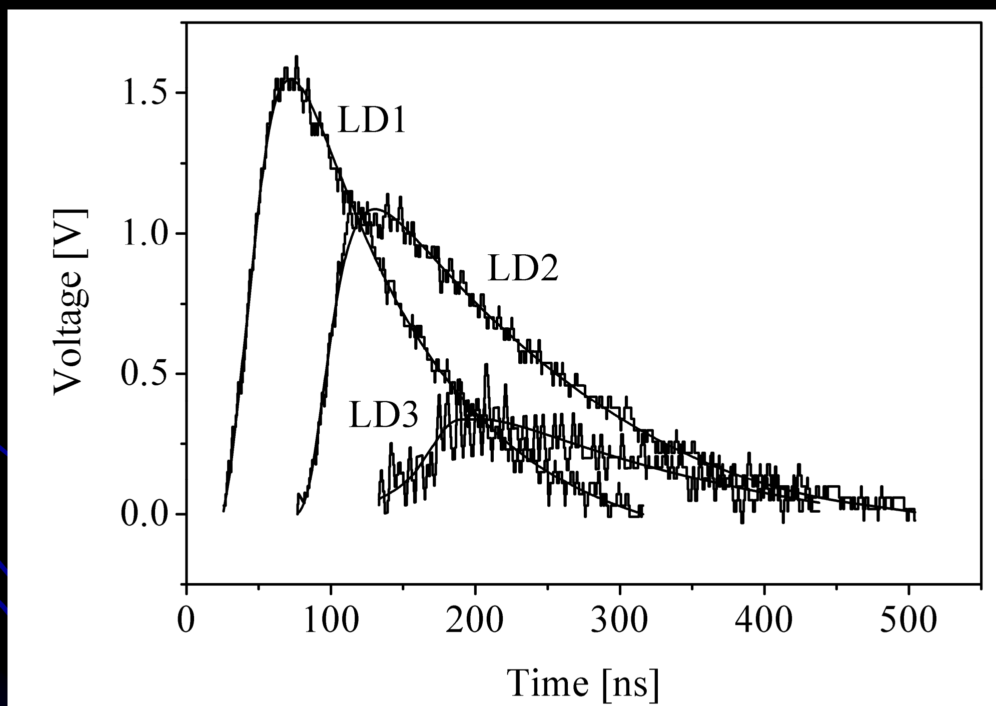
Diagnostics equipment

Plasma optical radiation detectors

Diagnostics based on radiation measurements of the excited neutrals H^* in the H_a-, H_β-wavelength regions in the plasma flow ions. Three optical radiation detectors (LD1-LD3): collimator 40 mm long, a 1 mm diameter by 7 m long quartz fiber, a H_α-, H_β-filters and a PMT. The distance between LD1 and LD2 and between LD2 and LD3 was 50-100 mm.



Conclusion

- Developed and built are:
  a) Hall ion accelerator (model) with conic focusing, induction plasma source, and pulsed gas bleed-in
  b) power supplies for the Hall accelerator
  c) pulse generator of the accelerating voltage with a current up to 200 A and independent adjustment of voltage amplitude up to 20 кV and pulse duration up to 50 μs.
- Electrophysical diagnostics complex for measurement of Hall accelerator parameters.
- Methods for measurement of energy distribution of ions in a plasma flow: 3-channel system for detection of optical radiation; electrostatic multigrid spectrometer of charged particles.
- Arrays of collimated Faraday cups for measurement of current density in various ion beam sections.

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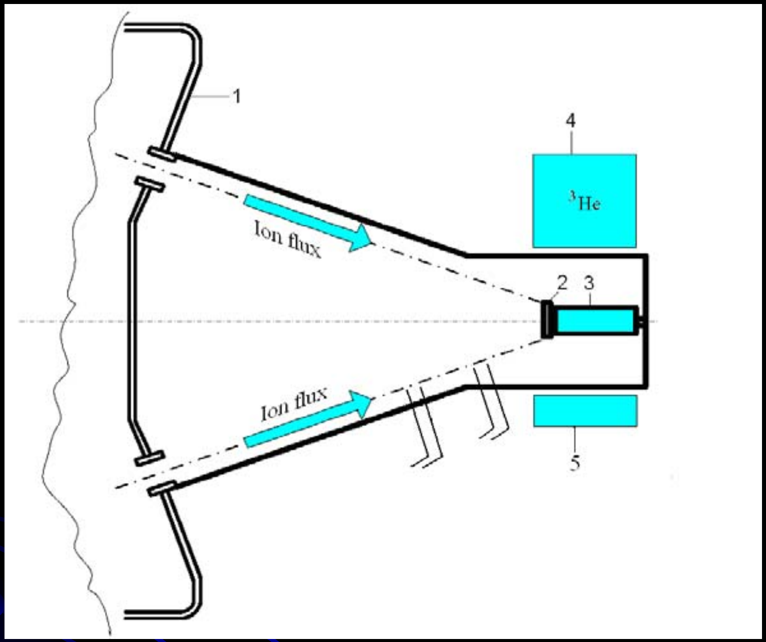
Study of the dd-reaction in the astrophysical energy region using the plasma Hall accelerator



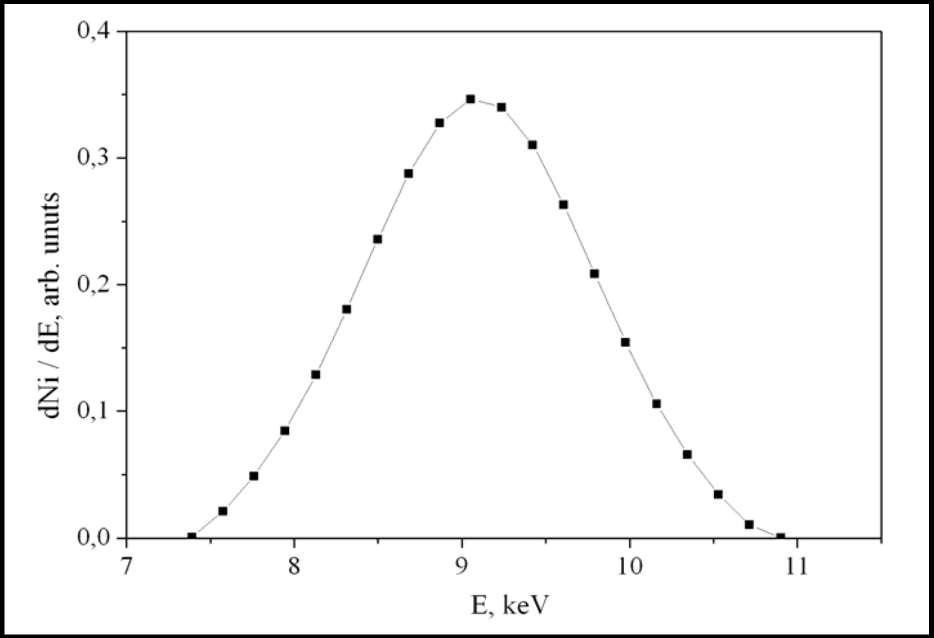
1 – Hall ion source plasma accelerator,

2 – deuterium target (CD_2, TaD, TiD, D_2O)

3 – electrostatic multigrid spectrometer,

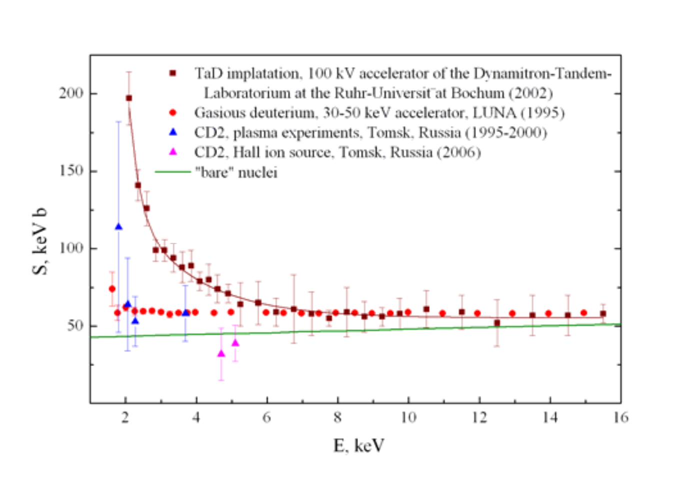
4 – ^{3}He detector of thermal neutrons

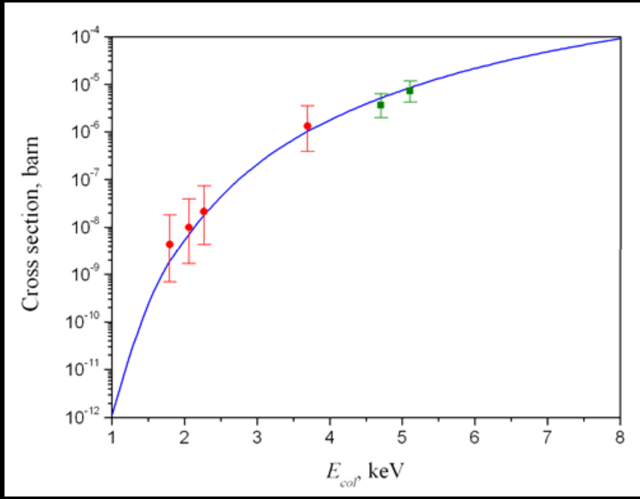
5 – plastic detector



Deuteron energy distribution

Preliminary results





$$\bar{S}\,(4.7\ \text{keV}) = (31.9 \pm 16.9 \pm 3.2)\ \text{keV}\cdot\text{b}$$

$$\tilde{\sigma}_{dd}(4.3 < E_{coll} < 5.1\ \text{keV}) = (3.2 \pm 1.7 \pm 0.3)\cdot 10^{-31}\ \text{cm}^2$$

$$\bar{S}\,(5.1\ \text{keV}) = (38.9 \pm 11.7 \pm 3.1)\ \text{keV}\cdot\text{b}$$

$$\tilde{\sigma}_{dd}(4.7 < E_{coll} < 5.5\ \text{keV}) = (6.6 \pm 2.0 \pm 0.5)\cdot 10^{-31}\ \text{cm}^2$$

Conclusion

- The experimental results obtained with the plasma Hall accelerator indicate that, the developed technique holds promise for detailed study of reaction mechanisms between light nuclei in the region of ultralow energies
- There is a difference between results of the *dd*-experiments with CD_2 and TaD (TiD) targets

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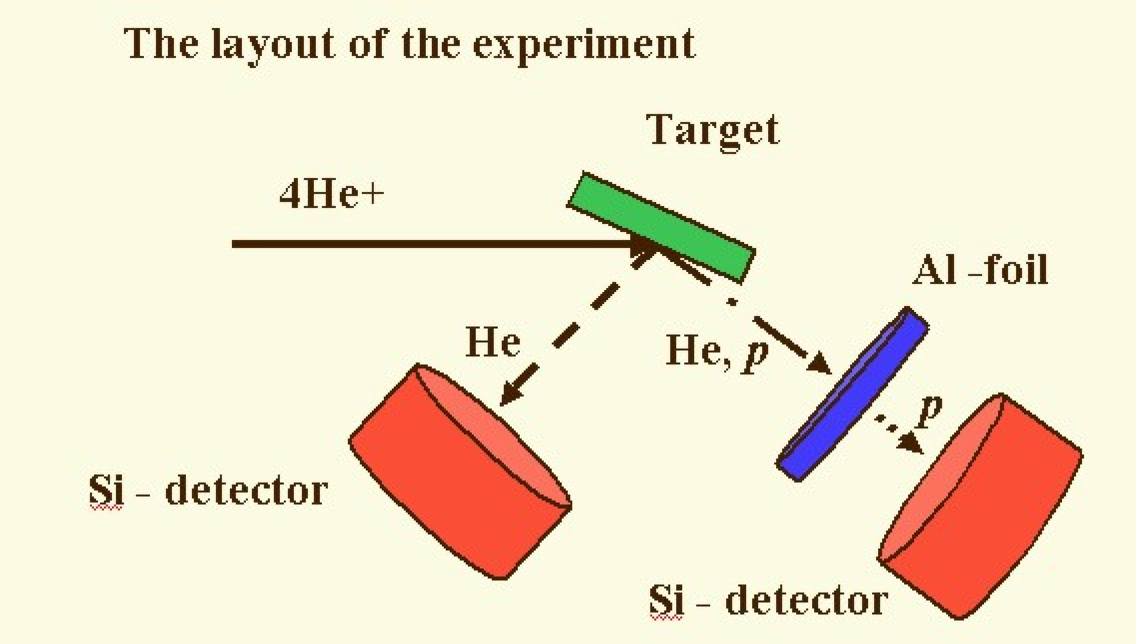
Electron screening

- The electron clouds act as screening potential: this leads to higher cross section, **σ_s *(E)*,** than would be the case fore bare nuclei, $\sigma_b(E)$.
- The enhancement factor: $f_{lab}(E) = \sigma_s(E)/\sigma_b(E) \cong \exp(\pi\eta U_e/E)$, U_e is the electron screening energy ($U_e \cong Z_1 Z_2 e^2/R_a$, with R_a **,** an atomic radius**).**
- If $E/U_e \geq 1000$ – shielding effects are negligible.
- If $E/U_e \leq 100$, relatively small enhancements from electron screening can cause significant errors in the extrapolation of cross sections to lower energies.
- The observed enhancement of the cross section are in all cases is larger than could be accounted for from available atomic physical models.

For testing of the screening effect it is necessary to perform the experiments with different types of the targets (TaD, TiD, ZrD, CD_2, D_2, D_2O)

Distributions of the deuterium (hydrogen) concentration



Van de Graaf accelerator

Method of measurement: elastic recoil detection and Rutherford back scattering

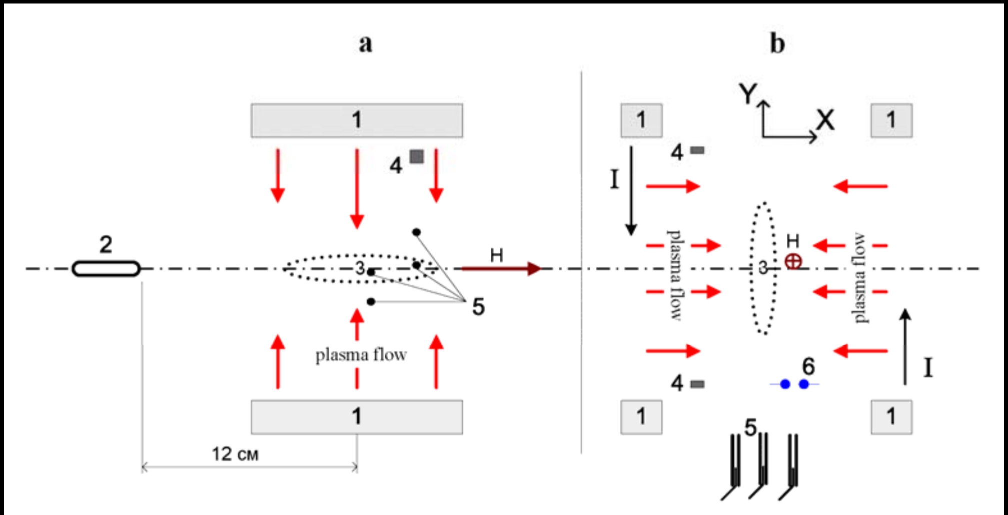
The depth profiles of the deuterium for various type of targets were measured on the set- up located on the electrostatic generator EG-5 JINR: the beam of $^{4}He^{+}$ ions with energy 2.30 MeV and the intensity $\sim 10^{12}$ s^{-1} was used.

The sample, recoil particle detector and the detector of the backscattered $^{4}He^{+}$ ions where established at angle 15^{0}, 30^{0} and 135^{0} to the axis of the $^{4}He^{+}$ ions beam, respectively.

Two spectra have been measured: the spectrum of nuclear recoils (protons, deuterons) and the spectrum of the Ratherford backscattered $^{4}He^{+}$ ions.

Generation and interaction of two opposite plasma flows counter propagating across magnetic field

Idea: interaction of two counter streaming plasma flows, propagating across B-field, as two oppositely charged plasma capacitors , moving toward each other (discharge in the cross E×B fields)



Schematic of experimental setup: a – view along B-field; b – side view normal to B-field

1. discharge HV electrodes, 2. spectrometer, 3. region of plasma flows collision, 4. voltage plate electrodes, 5. light detector's collimators, 6. floating probes

ceramic chamber: d_{in} = 18 cm, l =1 50 cm; solenoidal B-field with end mirrors of 1.4 : 1 ratio; in the middleplane – H ≈ 1 T; two parallel pairs of high discharge high voltage electrodes at 10 cm distance between them; gap – 2 cm, the electrodes' length in the direction of B-field – 14 cm; diameter of chamber ~ 40 cm; density of plasma flow ~ 10^{16} cm^{-3}.

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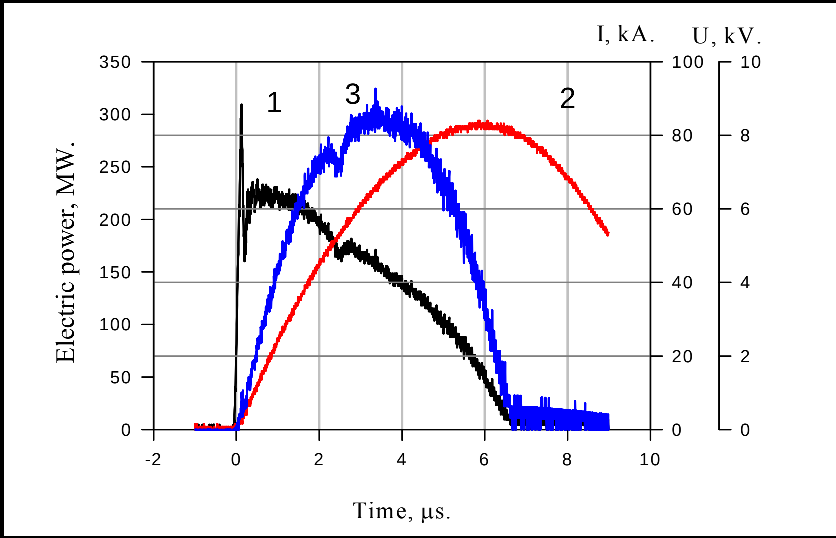
General view of experimental setup

- length of the experimental chamber – 150 cm
- diameter – 20 cm
- accumulated energy in the capacitor storage (30 μF) for discharge electrodes – 25 kJ
- accumulated energy in the capacitor storage (0.05 F) – 0.5 MJ

Energetic Characteristics of the discharge



1. applied voltage waveforms, 2. discharge current, 3. power

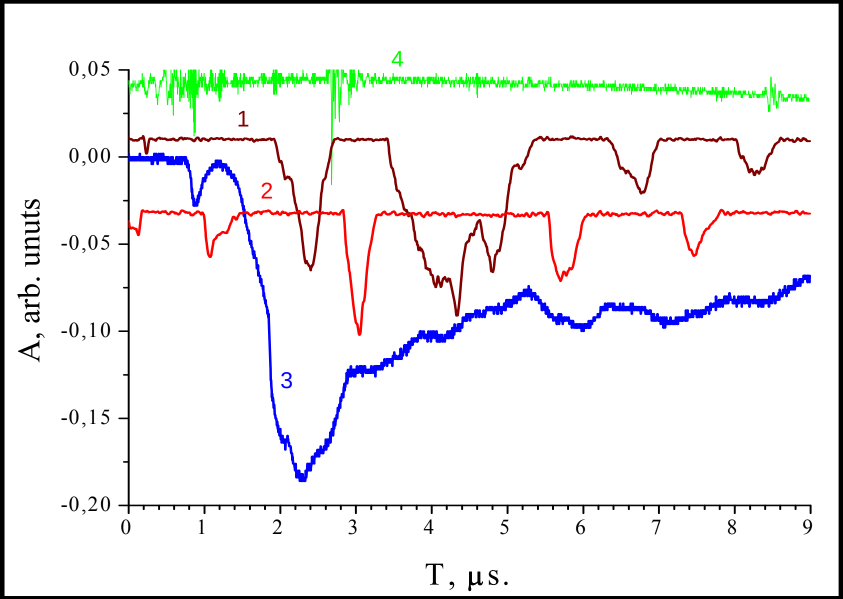
Based on the calorimetric measurements:

- Plasma flow cross section size (in horizontal and vertical planes) – 10×3 cm
- Plasma density – 10^{15} cm^{-3}
- Density of energy – 1 J/cm^3
- Transfer ratio efficiency from the energy deposited in the discharge to the plasma flows – 0.5
- Average speed across 1T B-field – $3 \cdot 10^7$ cm/s

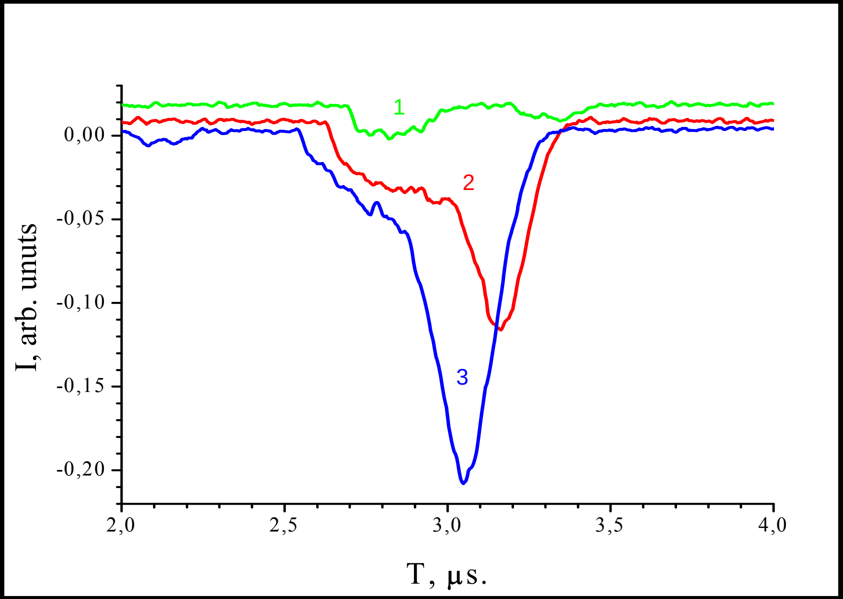
Formation of the drift channel

- Motion of the plasma flows across B-field – in the drift channel (due of flows polarization with oppositive directions)
- During collisions of the flows – depolarization and decay of the drift channels
- Flow spends part of its kinetic energy – formation drift channel
- Collisions of the flows feature quasi - periodic character as result of competing processes of decay and restoration of drift channels
- First effective collision – 2.5-3.0 μs after start of discharged pulses

Experimental results



Waveforms of the: electron (1) and ion (2) currents from the spectrometer collector; (3) potential difference between electrodes #1 at figure of setup; (4) signal from neutron detector



Waveforms of the collector current at different bias voltage of the grid 1 – 1.5 keV; 2 – 1.0 keV; 3 – 0.6 keV

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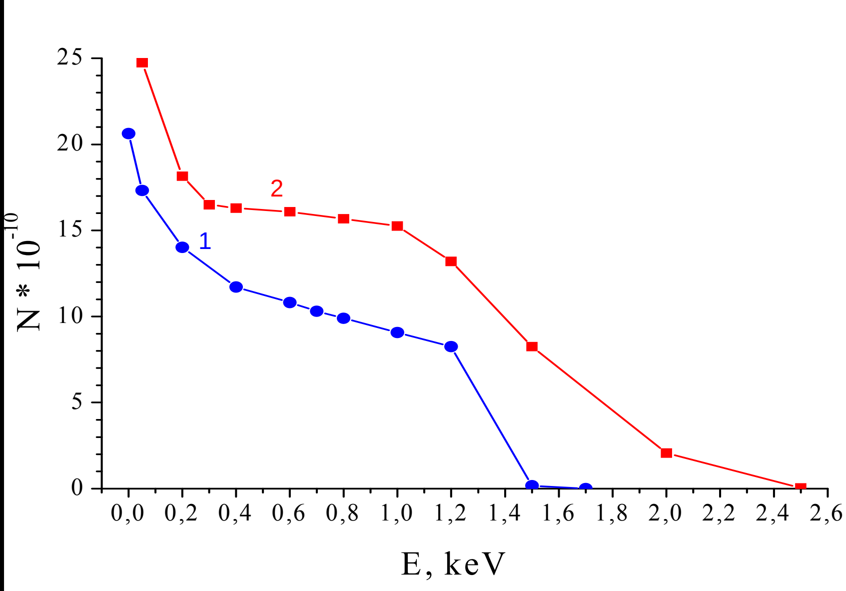
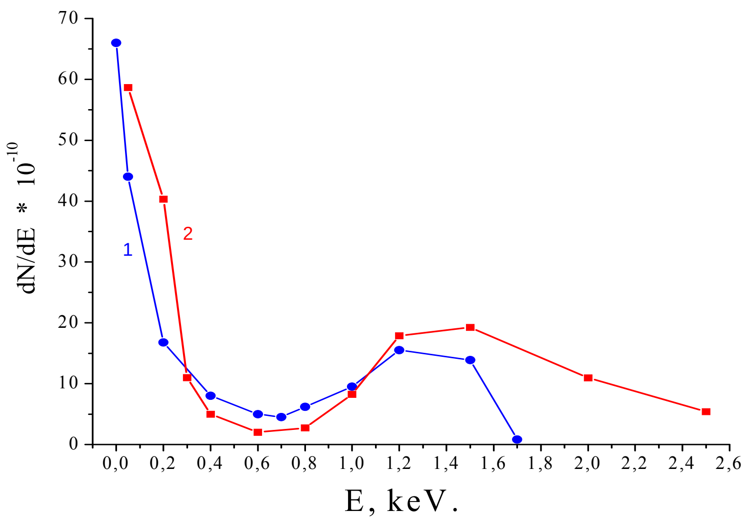
Experimental results



Integral spectra of ions (1) and electrons (2)



Energetic distribution of deutrons (1) and electrons (2) in the jet at the spectrometer entrance

Conclusion

- The size of the collision region of the flows in direction of their propagation was < 0.5 cm.
- The plasma flow from the collision region along B-field lines featured pulsating character when $1/(\varepsilon\mu)0.5 > V_d$
- When the frequency of pulsation was near to Larmor frequency of the deuterons the collision of plasma flows was accompanied by powerful X-ray and neutron bursts
- The quantity of deutrons in the jet and their spectrum is likely to satisfy requirements for study *dd* process in the keV energy range
- To get more clear picture of the processes in the collision region we plan to measure the ion/electron spectra in the drift flow in the pre-collision zone
- It is planned to study on evolution of the spectral distribution of ions in the jet with distance from the collision region to the spectrometer.

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Plans

In nearest three years we plan:

- to improve the characteristics of the Hall accelerator and diagnostics equipment
- to measure *dd*, *pd* and d^3He reactions in energy region 1-12 keV with using the Hall accelerator and different types of the targets (testing of the screening effect)
- to study more detail the processes of formation and interaction of two opposite plasma flows for receiving the final answer – is it possible to use this method for investigations of nuclear reactions at ultralow energies with high accuracy?

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