Фасад главного здания института
Main building of the institute

Channeling effect in polycrystalline deuterium-saturated CVD diamond target bombarded by deuterium ion beam

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Plan of presentation

1. Introduction
2. Brief review of previous works on the study of DD-reactions at low energies.
3. Characteristics of ion accelerator HELIS
4. Results of HELIS experiments on DD-reaction enhancement and stimulation
5. CVD-diamond sample preparation
6. Results of HELIS experiments on anisotropy of DD-reaction yield in CVD-diamond
7. Discussion and conclusion

Introduction

The HELIS facility at the LPI operates with continuous ion beams with currents up to 50 mA and energies up to 50 keV. This multi-purpose accelerator addresses the wide spectrum of physics experiments, like e.g. light nuclei collisions at energies of several keV, investigation of elementary and collective processes in ion-beam plasma and studies of the beam-target interactions using different materials with modification of the properties of the latter through ion-beam spattering of the thin-film coatings. Nowadays at HELIS we are investigated the interactions of the deuterium beam with deuterium- enriched targets

In this talk, the recent results obtained at the HELIS facility are presented. The neutron yield in the DD-reaction at the deuterium-enriched CVD diamond is measured as a function of the beam incident angle. The neutrons originating in the reaction

$$d+d \rightarrow n\ (2.45\ \mathrm{MeV}) + {}^{3}\mathrm{He}\ \ (0.8\ \mathrm{MeV})$$

are identified using the multichannel neutron detector with ^{3}He-counters.

Some previous works on the study of DD-reactions at low energies

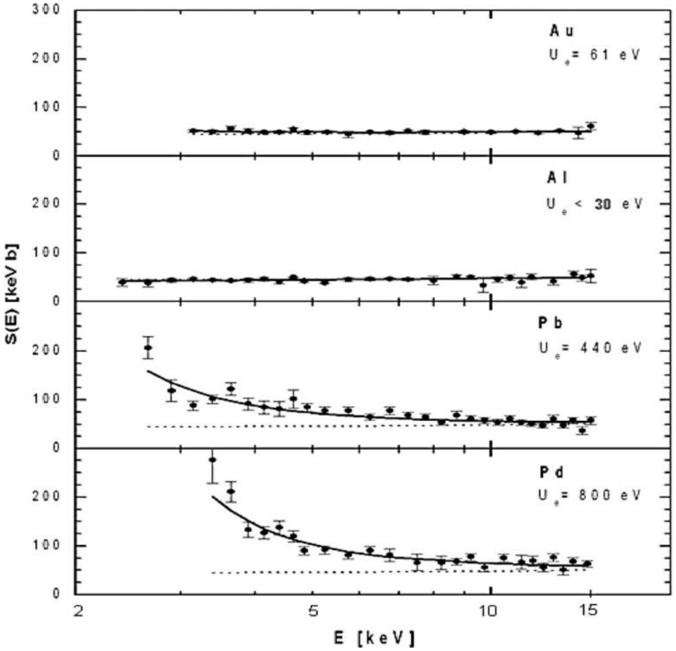
- 1. F. Raiola, P. Migliardi, L. Gang, et al. Electron screening in d(d,p)t for deuterated metals and the periodic table// Physics Letters. 2002. B547. 193.
- 2. H. Yuki, J. Kasagi, A.G. Lipson et al. Anomalous enhancement of DD reaction in Pd and Au/Pd/PdO heterostructure targets under low-energy deuteron bombardment // JETP Lett. 1998. 68. 785.
- 3. A.G. Lipson, A.S. Roussetski, A.B. Karabut, G.H. Miley, DD Reaction Enhancement and X-ray Generation in a High-Current Pulsed Glow Discharge in Deuterium with Titanium Cathode at 0.8–2.45 kV // JETP (2005)100, 1175
- 4. A. V. Bagulya, O. D. Dalkarov, M. A. Negodaev, A. S. Rusetskii, A. P. Chubenko, Bulletin of the Lebedev Physics Institute, 2012, Vol. 39, No. 9, pp. 247–253.
- 5. A. V. Bagulya, O. D. Dalkarov, M. A. Negodaev, A. S. Rusetskii, A. P. Chubenko, Bulletin of the Lebedev Physics Institute, 2012, Vol. 39, No. 12, pp. 325–329.
- 6. A.V. Bagulya, O.D. Dalkarov, M.A. Negodaev, A.S. Rusetskii, A.P. Chubenko, A.L. Shchepetov, Bulletin of the Lebedev Physics Institute, 2013, Vol. 40, No. 10, pp. 282–284.
- 7. A.V. Bagulya, O.D. Dalkarov, M.A. Negodaev, A.S. Rusetskii, A.P. Chubenko, A.L. Shchepetov, Bulletin of the Lebedev Physics Institute, 2013, Vol. 40, No. 11, pp. 305–309.

- All these works were not associated with the effects of channeling!

The LUNA Collaboration

1. **Electron screening in d(d,t)p for deuterated metals and the periodic table**
   Physics Letters B 547 (2002) 193
   F. Raiola, P. Migliardi, L. Gang, C. Bonomo, G. Gyürky, R. Bonetti, C. Broggini, N.E.Christensen, P. Corvisiero, J. Cruz, A. D'Onofrio, Z. Fülöp, G. Gervino, L. Gialanella, A.P. Jesus, M. Junker,K. Langanke, P. Prati, V. Roca, C. Rolfs, M. Romano, E. Somorjai, F. Strieder, A. Svane, F. Terrasi, J. Winter

1. **Enhanced electron screening in d(d,t)p for deuterated metals**
   European Physical Journal A19 (2004) 283
   F. Raiola, L. Gang, C. Bonomo, G. Gyürky, M. Aliotta, H.-W. Becker, R. Bonetti, C. Broggini, P. Corvisiero, A. D'Onofrio, Z. Fülöp, G. Gervino, L. Gialanella, M. Junker, P. Prati, V. Roca, C. Rolfs, M. Romano, E. Somorjai, F. Strieder, F. Terrasi, G. Fiorentini, K. Langanke, J. Winter

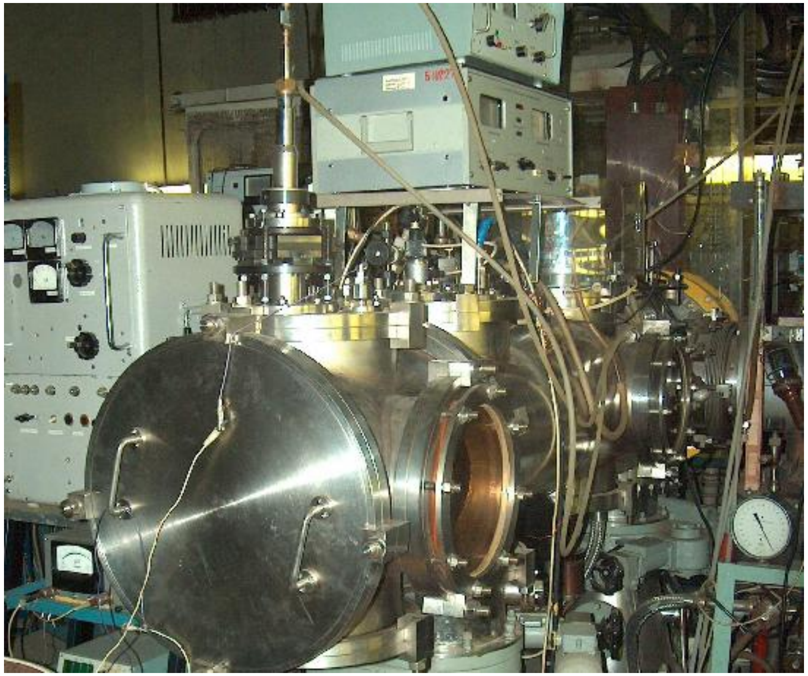


The electron screening effect in the d(d, p)t reaction has been studied for 29 deuterated metals and 5 deuterated insulators/semiconductors. As compared to measurements performed with a gaseous D_2 target, a large effect has been observed in the metals V, Nb, Ta, Cr, Mo, W , Mn, Re, Fe, Ru, Co, Rh, Ir, Ni, Pd, Pt , Zn, Cd, Sn, Pb. An explanation of this apparently novel feature of the periodic table is missing.

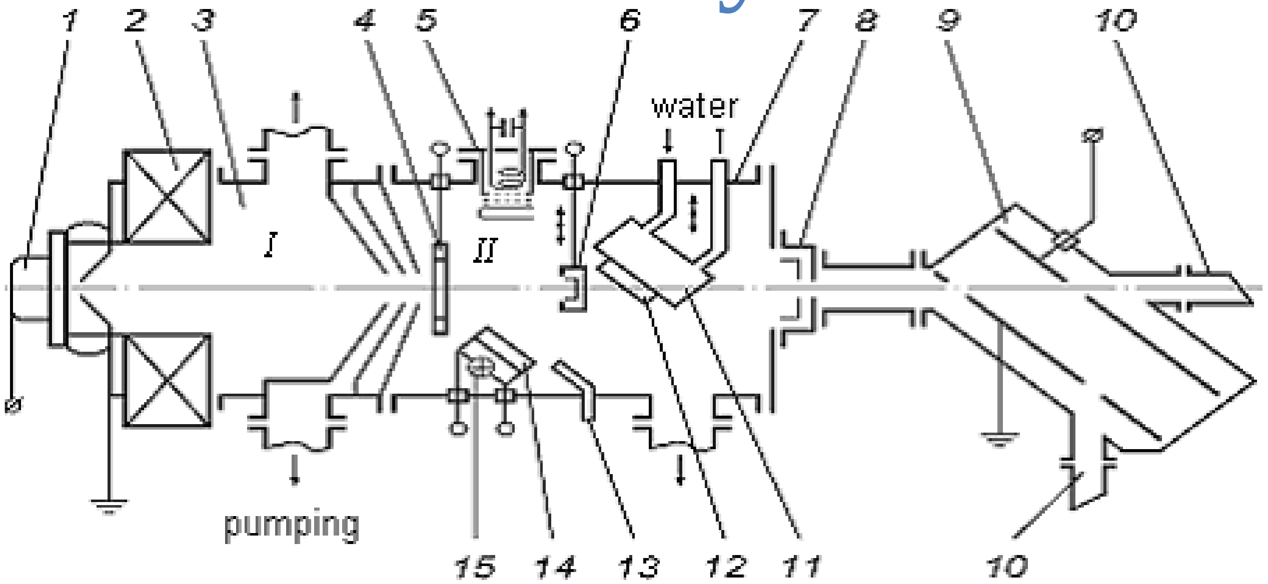
HELIS facility represents ion accelerator of different gases to energy < 50 keV and includes:

- ion source (the actual accelerator) with equipment, providing his power supply;
- beam focusing system;
- vacuum system;
- diagnostic apparatus for measuring current and ion beam energy.

Beam current (at 50 keV)	≤50 mA
Energy range	10 -:- 50 keV
Energy spread	10 -:-100 eV
Normalised emittance	$2 \cdot 10^{-5}$ -:- $5 \cdot 10^{-5}$cm·rad



A schematic diagram of the HELIS facility



HELIS facility: 1 – ion source (duoplasmatron); 2 – electromagnetic lens; 3 – three-stage chamber of differential pumping; 4 – non contact current meter; 5 – auxiliary ion source; 6 - Faraday cage; 7 – chamber of targets; 8 – the device for calorimetric definition of a current of an ion beam; 9 – electrostatic analyzer; 10 – Faraday cage; 11 – water-cooled holder of the target; 12 - target; 13 – feeder of gas in an vacuum chamber; 14 - substrate; 15 – heater of substrates.

Thick target DD-reaction yield

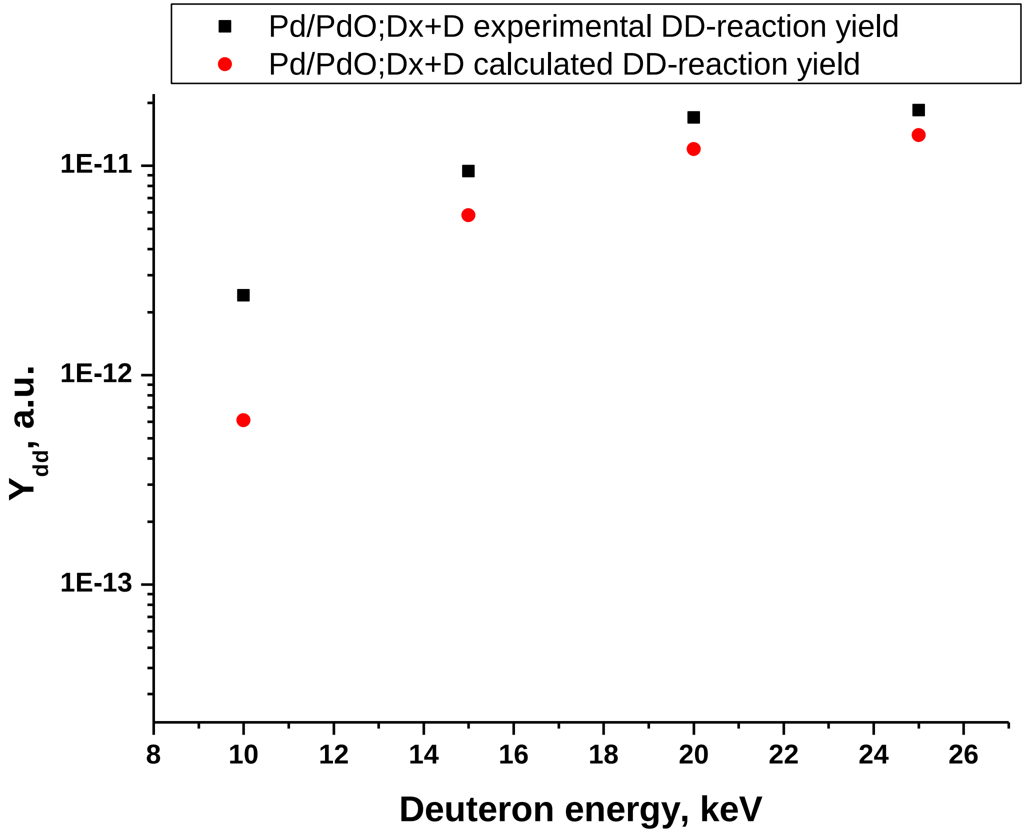
$$Y_{DD\ a.u.} = Y_{DD}/J_d = N_{eff}(T) \times \int_0^{E_d} f(E)\sigma_{DD}(E)(dx/dE)dE$$

$$Y_b = N_{eff}(T) \times \int_0^{E_d} \sigma_{DD}(E)(dx/dE)dE$$

Here Y_{DD} – DD-reaction intensity, J_d – deuteron current; $N_{eff}(T)$ – effective concentration of bounded D in metal at temperature T, captured at depth x: ($N_{eff}(T) = N_0 \exp(-\varepsilon_d \Delta T/k_B T T_0)$, where N_0 – D concentration at $T_0 = 290$ K, ε_d – deuteron activation energy; σ_{DD} – is the «bare» DD-cross-section; dE/dx – is the stopping power in target calculated with Monte-Carlo code SRIM (J.F. Ziegler and J.P. Biersack, code SRIM 2003).

$f(E) = Y_{exp}(E)/Y_b(E) = \exp[\pi\eta(E)U_e/E]$ – enhancement factor; where $Y_{exp}(E)$ is the experimental yield of DD-protons; $Y_b(E)$ is the yield at the same energy, determined according to the Bosch&Halle extrapolation; and $2\pi\eta = 31.29Z^2(\mu/E)^{1/2}$ is the Sommerfeld parameter (where Z is the deuteron charge, μ and E are the reduced deuteron mass and energy, respectively). U_e - screening potential.

HELIS experimental data on DD-reaction yield in deuterated target Pd/PdO:Dx.

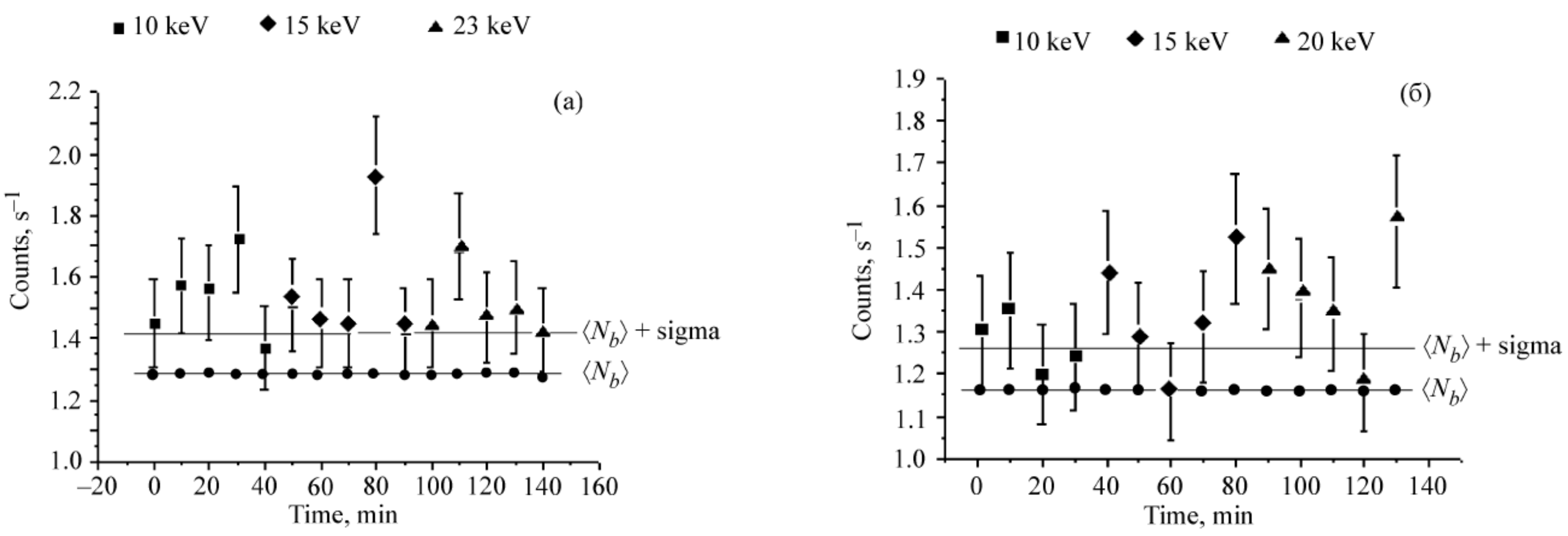


deuteron energy, E_d, keV	10	15	20	25
enhancement factor, f	3.98	1.62	1.4	1.31

U_e = 630 eV

Pd/PdO:Dx screening potential.

HELIS experimental data on stimulation of DD-reaction yield in deuterated target Ti/TiO$_2$:D$_x$ by H+ (a) and Ne+ (b) beams (■,♦,▲). Average background measured with Cu target (●)


a)

b)

$n_n \sim 10^2\ s^{-1}$ into 4π sr – DD-neutron flux stimulated by ion beam

Anisotropy of DD-reaction yield

In our previous investigations of DD-reaction in the crystal targets (Pd, Ti), an anisotropy was observed: the neutron flux along the beam direction was higher than that in the transverse direction.

Particularly large anisotropy is observed using a polycrystalline CVD diamond target.

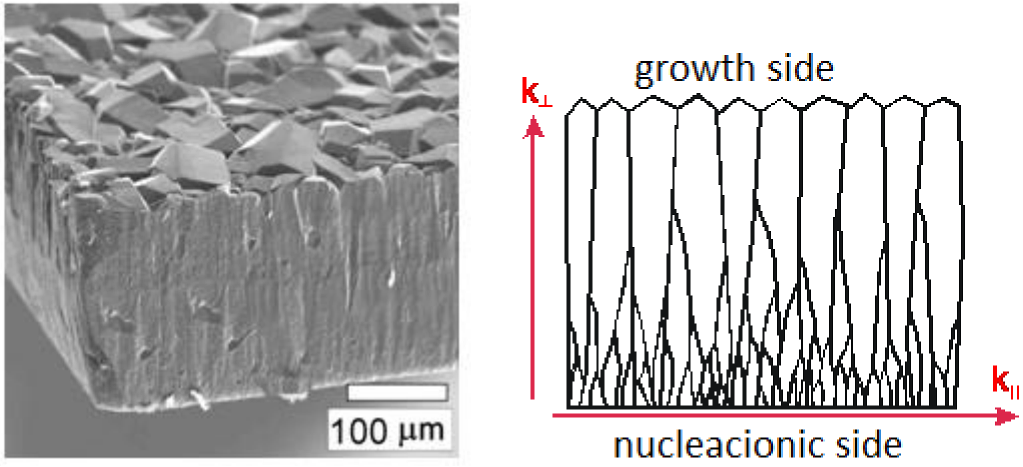
Water-cooled solid target holders allow to change the position of the target in the ion beam

The target of the polycrystalline diamond (CVD-diamond)

Photo diamond film grown on a silicon substrate with a diameter 57 mm.

Photo of the target manufactured of the CVD-diamond without the silicon substrate with a diameter of 18 mm.

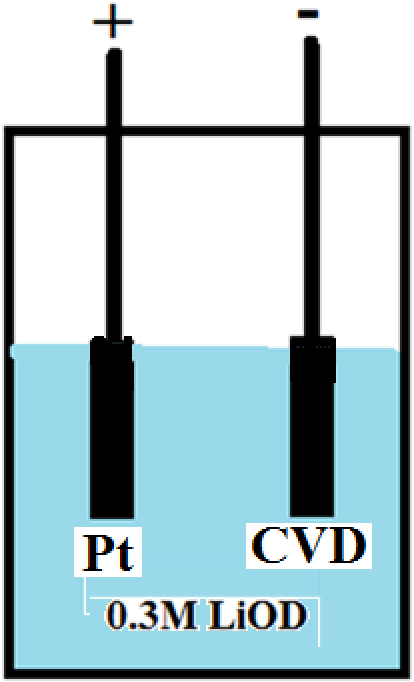
The target of the polycrystalline diamond (CVD-diamond)



The structure of the polycrystalline diamond film in cross section.

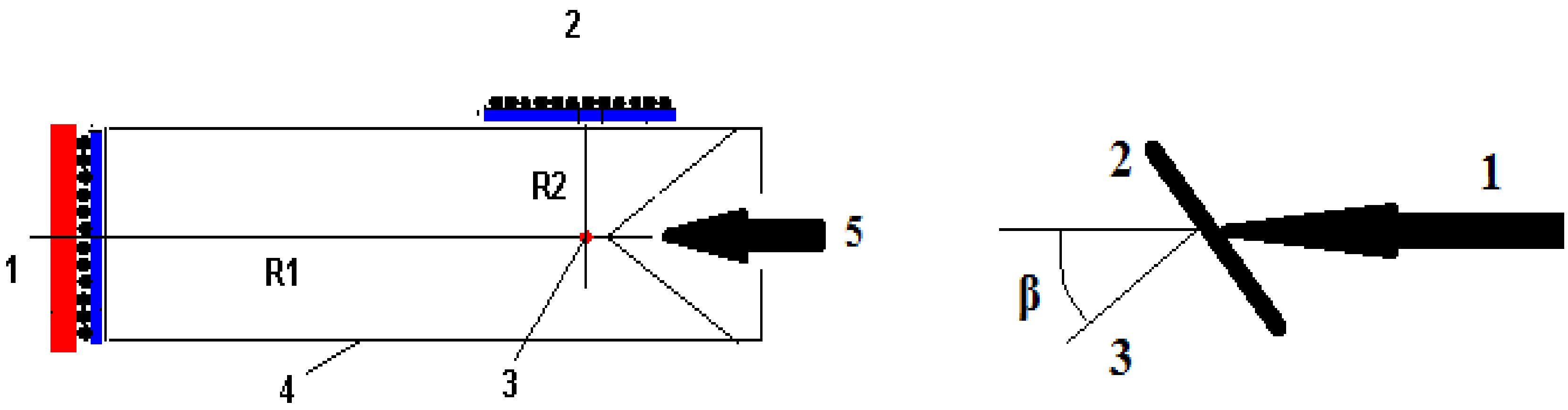
Laboratory microwave plasma chemical reactor STS-100 for growing diamond plates.

Saturation of the polycrystalline diamond with deuterium



The CVD-diamond was saturated with deuterium through electrolysis in a 0.3M solution of LiOD in D_2O, using the diamond samples as a cathode together with a Pt anode. The voltage of 50 V was applied with the current density of 20-30 mA/cm^2. A penetration of the CVD diamond by about 10^{20} deuterium atoms could be concluded from the measurements of the electrolysis current and of the sample mass increase.

Left panel: the ^{3}He detector setup at HELIS, representing the first (1) and the second (2) ^{3}He-counter groups with radii R=85 cm and R=38 cm, respectively. The target is placed at (3) inside the HELIS beam pipe (4). The ion beam direction is indicated by (5). Right panel: The beam direction is indicated by (1), the target is shown by (2), the normal to the target surface (3).

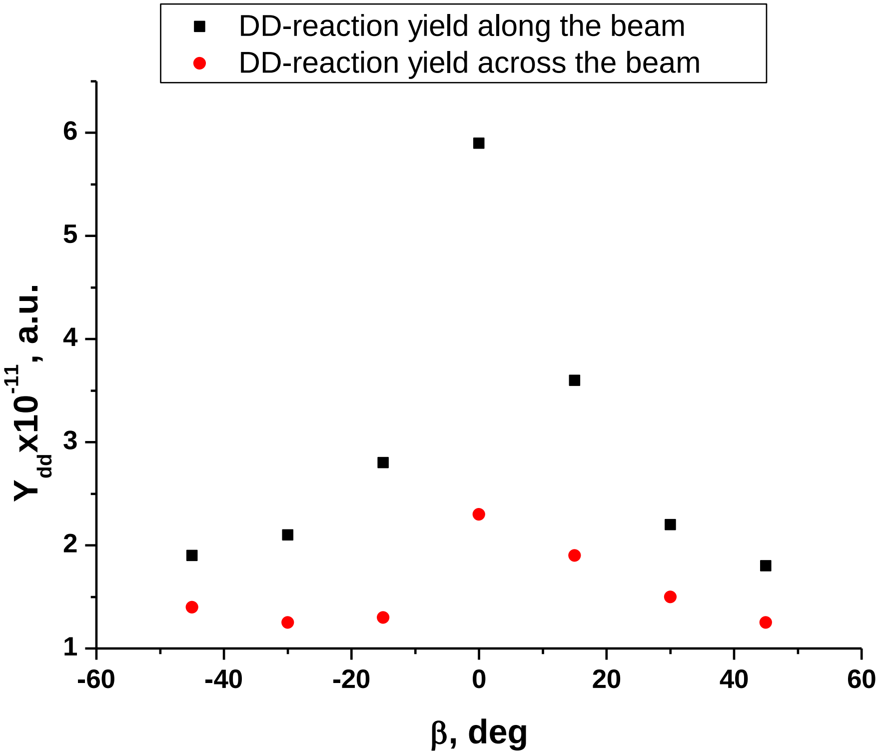


The relative yield of the DD reaction $Y_{dd} = n_n/(S\times I_d)$,

where n_n - longitudinal or transverse neutron flux, S - irradiated area of the target and I_d - the ion beam current.

The neutron yield obtained with the CVD-diamond sample as a function of the angle between the beam and the target plane norm, measured longitudinally (black squares) and transverse (red diamonds) directions with respect to the ion beam.

Ion beam with the energy of E_d=20 keV and the current of 50-60 μA.



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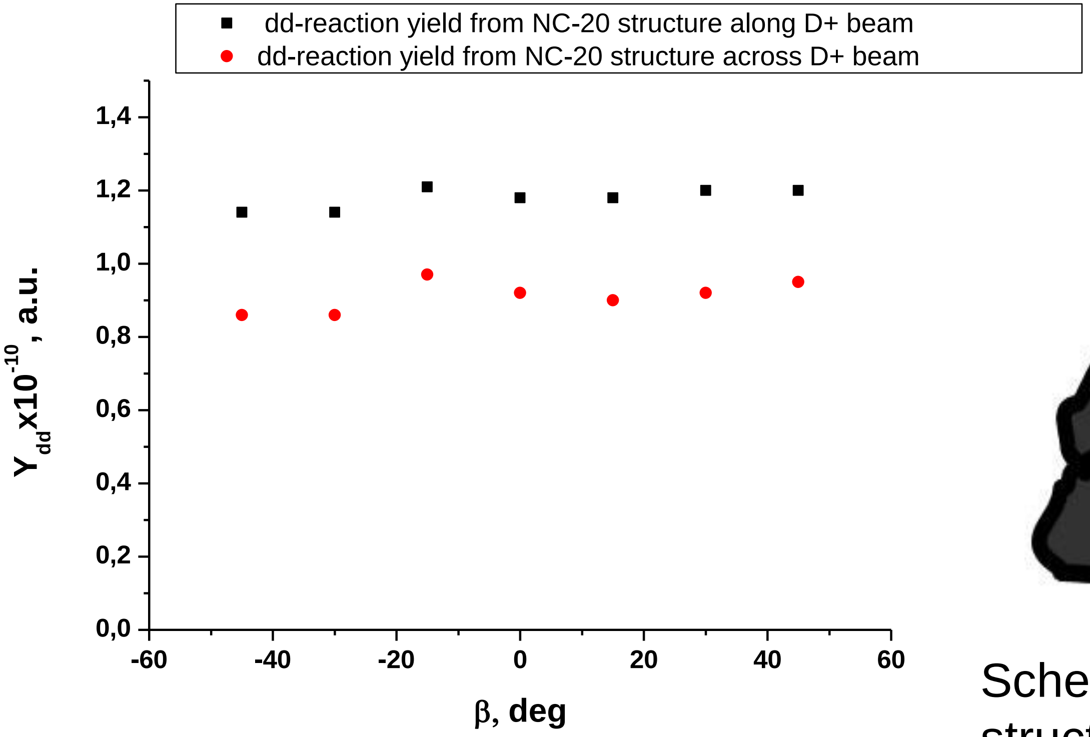
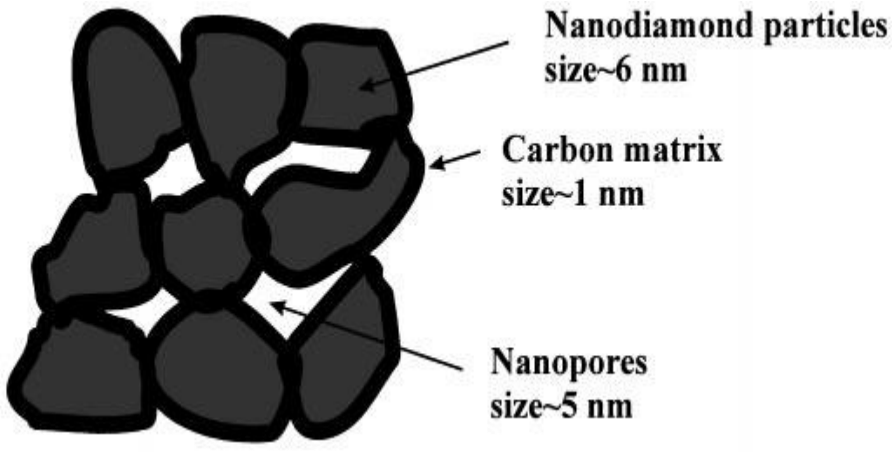
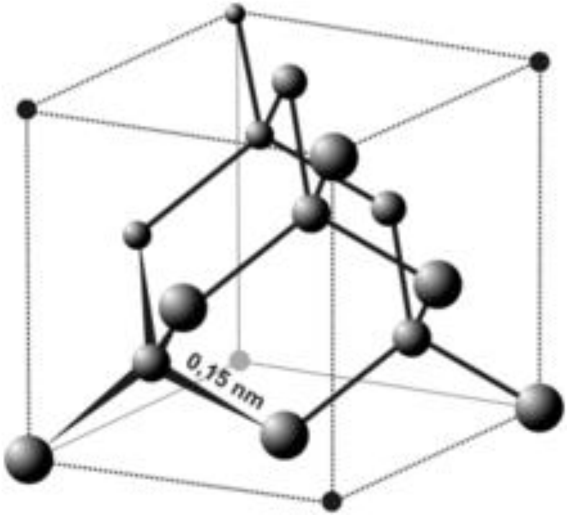
The neutron yield obtained with the diamond composite material (NC-20) as a function of the angle between the beam and the target plane norm, measured longitudinally (black squares) and transverse (red diamonds) directions with respect to the ion beam. NC-20 (80% of diamond, 20% of graphite) is composite material with isotropic structure. Ion beam with the energy of E_d=25 keV and the current of 20 μA.

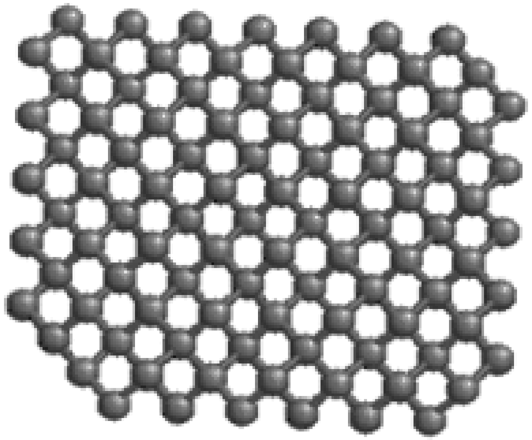


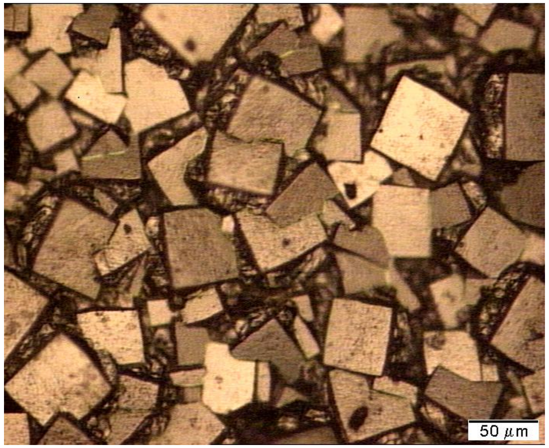


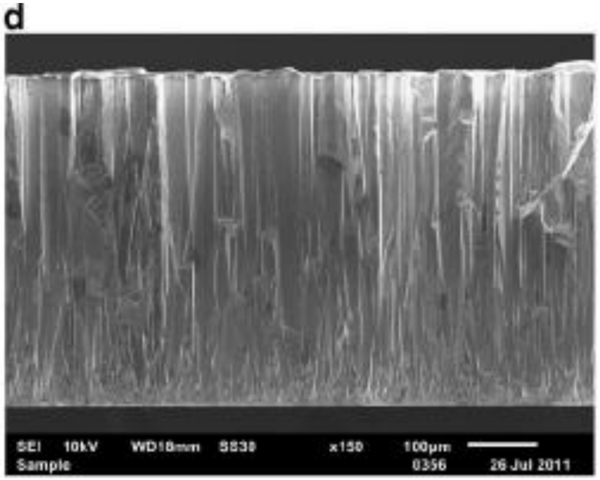
Schematic presentation of nanocomposite structure.

Schematic representation of the diamond crystal lattice









Structures of the growth and fracture CVD diamond surface, obtained with SEM

Discussion

Possible reasons for the increasing of DD-reaction yield

1. Screening effects of deuterium nuclei in the crystal structure;
2. Collective processes associated with high concentration of deuterium in the certain directions;
3. The effects of channeling, leading to an increase in the effective range of ions in the direction of the channel

Conclusion

1) It is observed, that the crystalline structure and the orientation of the sample with respect to the beam has an impact on the neutron yield. The highest yield is recorded with the target, oriented perpendicular to the beam.

2) Such a strong angular dependence of the neutron yield could indicate a presence of narrow channels in the CVD-diamond sample, where the bulk of deuterium, trapped during the electrolysis, is concentrated. These channels could be created by the grain boundaries, which are almost vertical in the vicinity of the growth side.

3) Another reason could be the channeling of ions in the oriented crystallites. Large neutron yield at the angle β=0 can be explained by increased effective range of the deuterium ions inside the channels with respect to that in the diamond.

Thank you for your attention!