Ultrahigh charging of small spherical grains by the beam-plasma method for creating a compact neutron source

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4th International Conference on

Photonics & Laser Technology

July 28-29, 2016 Berlin, Germany

Motivation



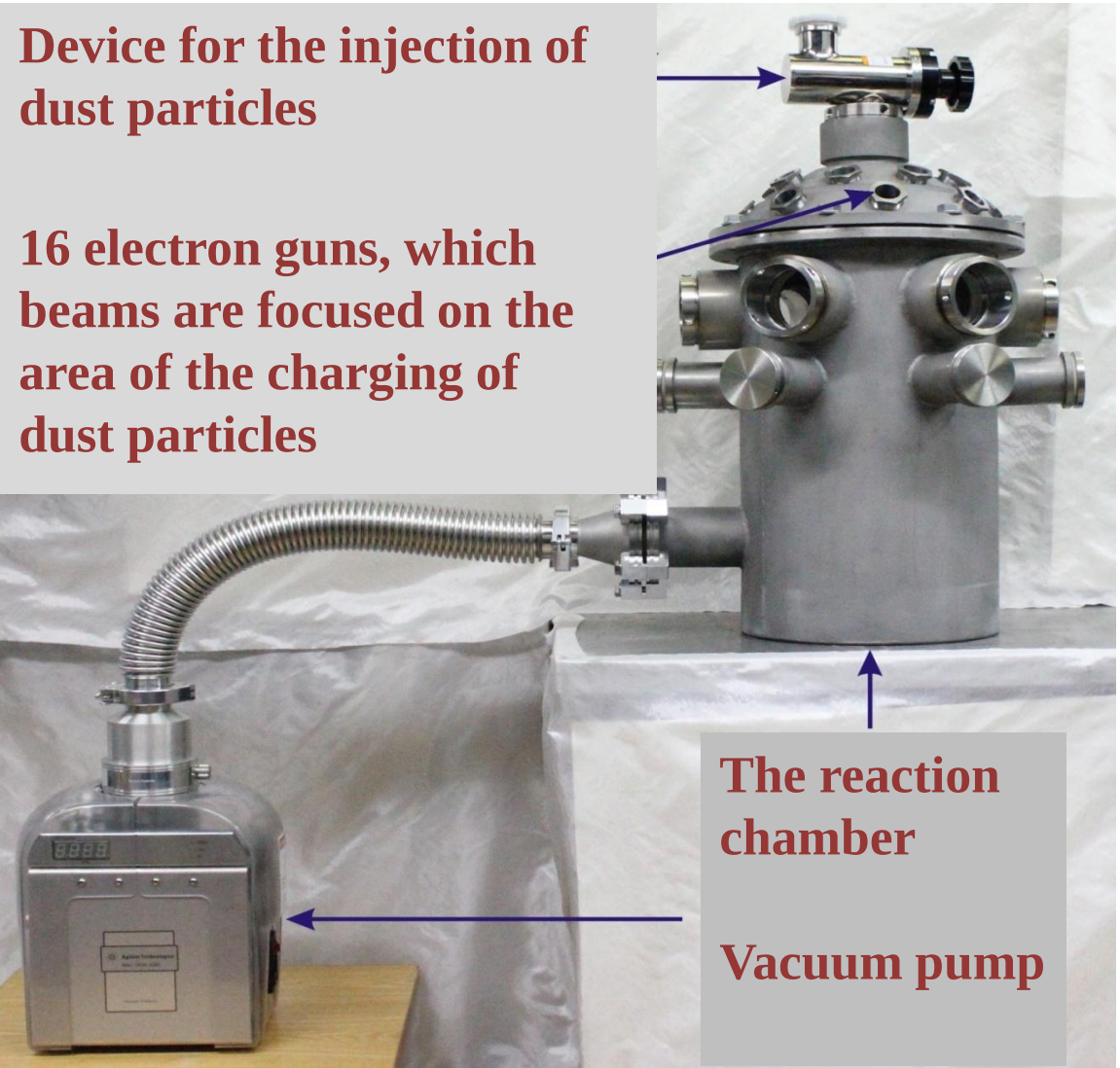
Patient treating room for neutron radiation therapy

Gas discharge neutron sources are popular ones. In fact, they are linear ion accelerators providing the ion energies up to 70–90 keV.

Their main drawback: generation as a by-product of hard X-ray radiation that is very dangerous in medical applications.

Conclusion – there is a necessity to develop new methods of neutron generation without hard X-rays radiation.

Our offer is the neutron generator based on ultra-high charging of dust particles by high-voltage electron beams



The generator can provide a pulsed neutron output intensity of 10^7 n/s and more.

The generator does not emit hard X-ray radiation and therefore can be used in various biomedical applications.

For example, intense neutron irradiation can create short-lived isotopes with half-life of a few tens of minutes for usage in medicine as markers for the diagnosis of internal organs.

Capabilities of the electron gun used in the offered neutron generator

Density of the created plasma in D_2:
$n = 10^{10} – 10^{13}$ cm^{-3}.

Beam pulse duration:
100 ns – 1 μs.

Electrons energy:
up to 25 keV

Electron beam current density:
1 A/cm^2

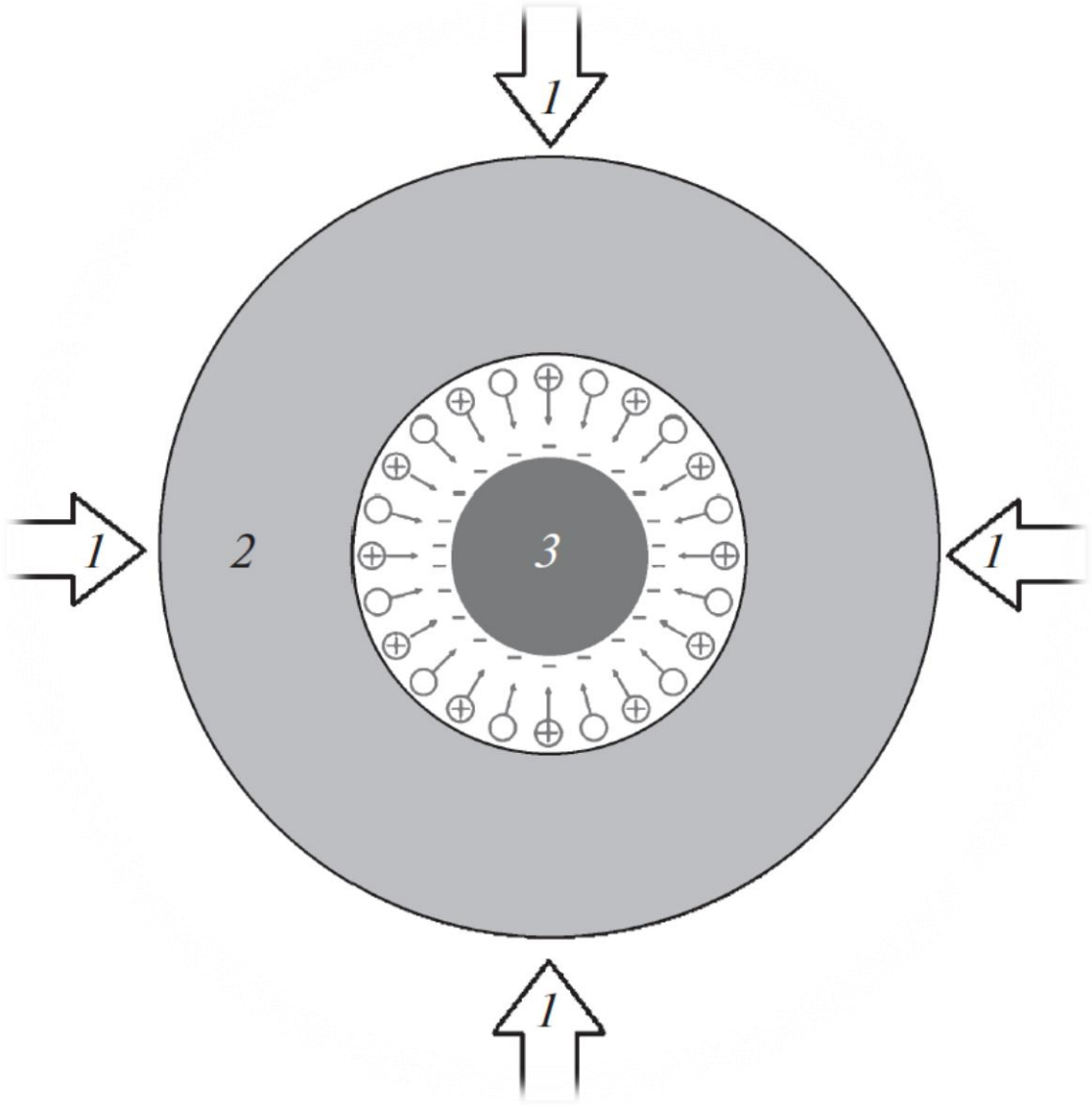
The advantage of the proposed method

The advantages of the proposed method of neutron generation in comparison with normal gas-discharge ion accelerators are:

1) significant increase (by orders of magnitude) of ion flux striking the target;
2) lower voltage leading to absence of the hard x-ray radiation;
3) significant increase (by orders of magnitude) in the effective area of the target due to the usage of a large number of small particles;

In total, the offered generator gives possibility to increase the number of neutrons per single pulse for one or two orders.

Schematic illustration of the process of ultra-high charging of spherical target irradiated by e-beam.



1 – HV electron beams
2 – plasma around target
3 – spherical target

• spherical targets (3) are immersed in plasma (2) ;

•electron beams (1) charge the particle (3) to a high potential;

•plasma ions are accelerated in strong electrical field around the charged particle;

•nuclear reactions occur in the target accompanied with the yield of neutrons.

Nuclear reactions used in the offered generator of neutrons

Neutrons appear in the gas discharge sources as a result of nuclear fusion reactions:

$$\mathbf{D + D \rightarrow {}^{3}He + n} \quad (E_n = 2.45 \text{ MeV}, E_{^3He} = 0.82 \text{ MeV})$$

$$\mathbf{D + T \rightarrow {}^{4}He + n} \quad (E_n = 14.1 \text{ MeV}, E_{^4He} = 3.5 \text{ MeV})$$

The initiation of these reactions requires two conditions:

1) deuterium or tritium ions have to have energies higher than 10 keV;

2) a target has to contain deuterium or tritium.

Numerical model describing the ultra-high charging process

- Poisson's equation:

$$\varepsilon_0 \vec{\nabla} \cdot \left[-\vec{\nabla}\varphi\right] = e(n_i - n_e - n_{eb})$$

$$n_{eb} = \frac{j_{eb}}{e} \frac{1}{\sqrt{2\varepsilon_b/m}}$$

$$\varepsilon_b = \varepsilon_{b0} + \varphi(x)\cdot e, \quad (\boldsymbol{\varepsilon_{b0}}\textbf{=20 – 25 keV})$$

- The balance equations for the ions and electrons

$$\dot{n}_i + \vec{\nabla} \cdot \vec{\Gamma_i} = S_{ionb} + k_i(E/N) n_e N_g - \beta n_e n_i \qquad \vec{\Gamma_i} = n_i \vec{V}_i(E) - D_i \vec{\nabla} n_i$$

$$\dot{n}_e + \vec{\nabla} \cdot \vec{\Gamma_e} = S_{ionb} + k_i(E/N) n_e N_g - \beta n_e n_i \qquad \vec{\Gamma_e} = n_e \vec{V}_e(E) - D_e \vec{\nabla} n_e$$

$$S_{ionb} = \sigma(\varepsilon_b) \frac{j_{eb}}{e} N_g$$

$$V_i(E) = \sqrt{1.4 e E \lambda_i / M_i}$$

Numerical model describing the ultra-high charging process

- The equation for accumulation of the charge on the target:

$$\dot{\rho} = e\Gamma_i - j_{eb}[1 - \gamma(\varepsilon_b)]$$

- *Initial conditions:*

$n_i(x, t = 0) = n_e(x, t = 0) = N_0$ ($N_0 = 3 \cdot 10^{12}$ **cm^{-3}**)

$\rho(t = 0) = 0$ **P = 0.1 Tor**

- *Boundary conditions:*

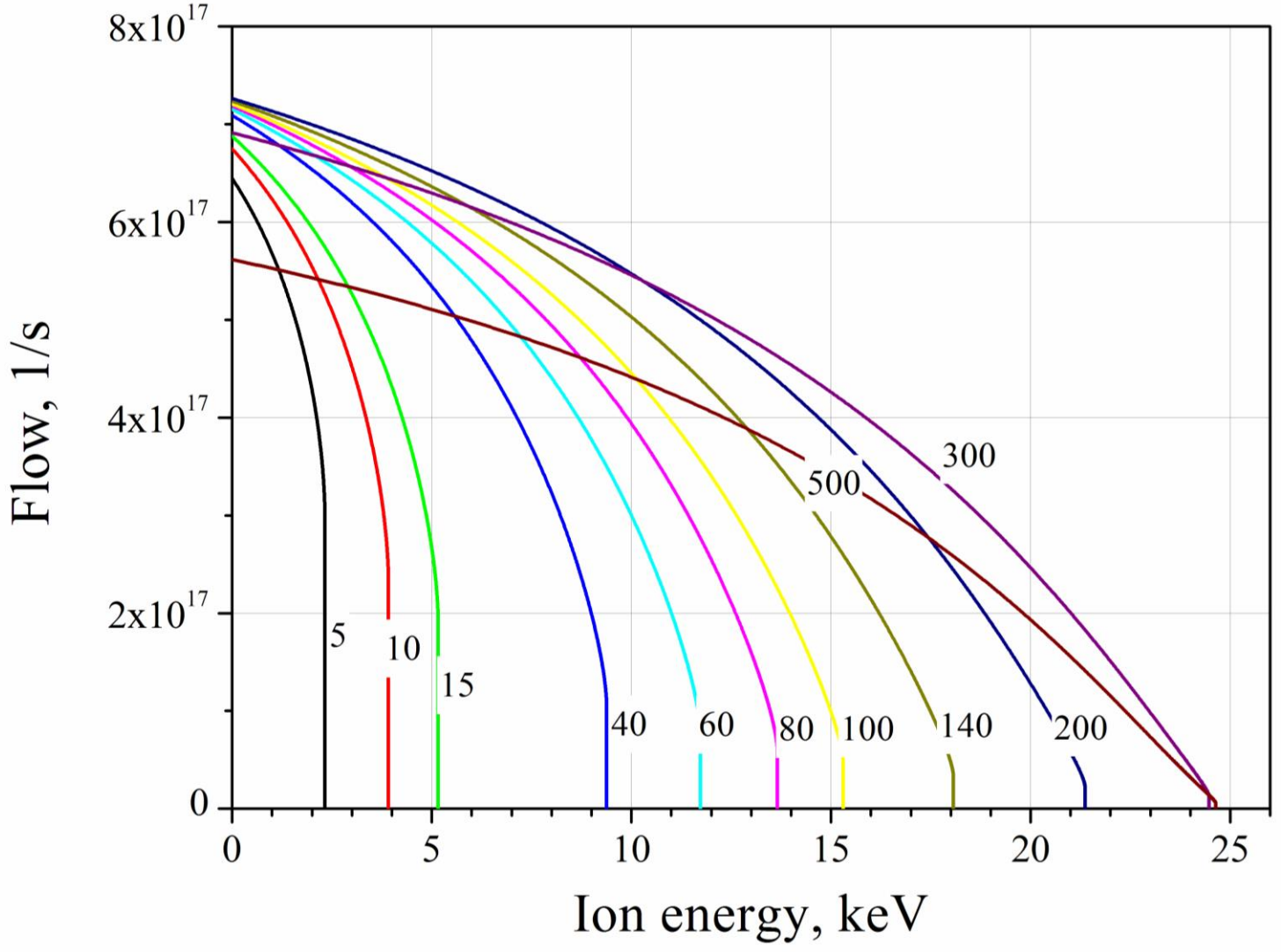
$$-\varphi_x'(x = d_p/2) = \frac{q(t)}{4\pi\varepsilon_0 x^2}$$ – on the surface of a spherical grain

Parameters used in the calculations:

Electron beam: j_{eb} **= 15 A/cm^2,** ε_{b0}**=20 – 25 keV**

Gas pressure: **P = 0.1 Tor**. Pulse duration **500 ns**

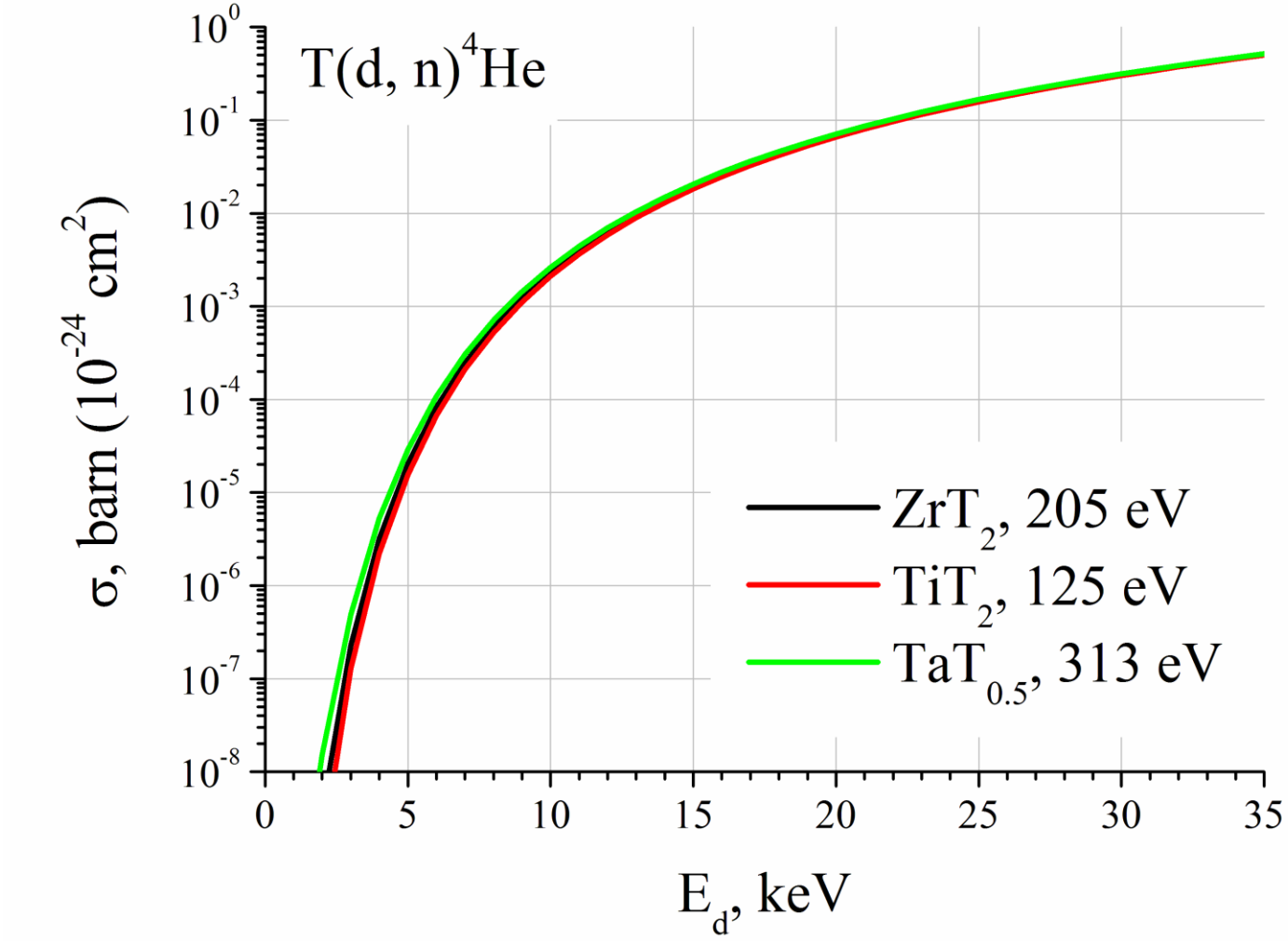
Energy spectra of ions striking the strongly charged target ε_{b0}=25 kV



The figures at the curves denote the time (in ns) passed after beginning of the charging.

Cross sections of nuclear reaction used in calculation

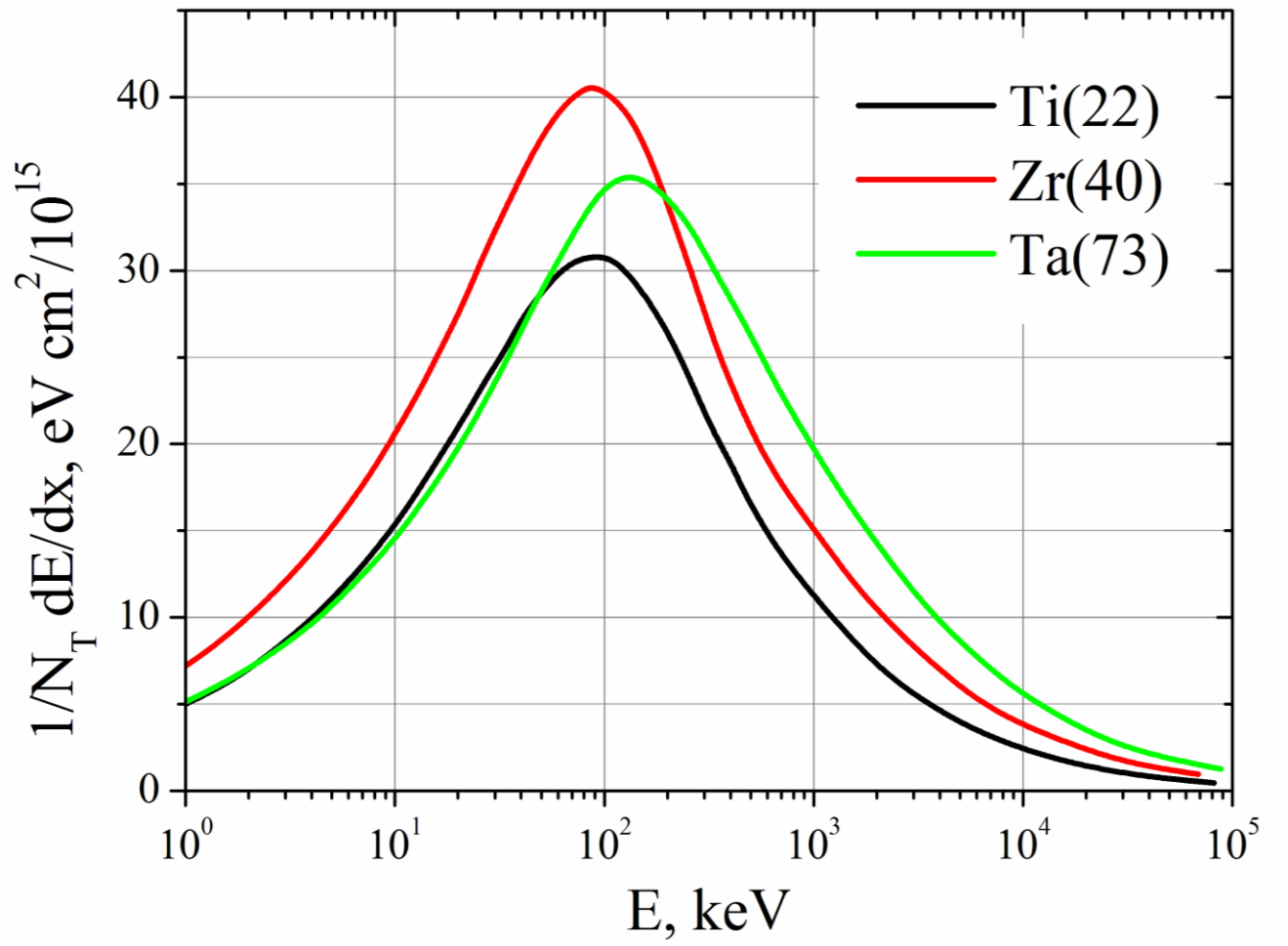
D + T → ^{4}He(3.5 MeV) + *n(14.1 MeV)*



H.-S. Bosch, G.M. Hale /Improved formulas for fusion cross-sections and thermal reactivities // Nuclear Fusion. 1992. V. 32, No. 4. Pp. 611-632.

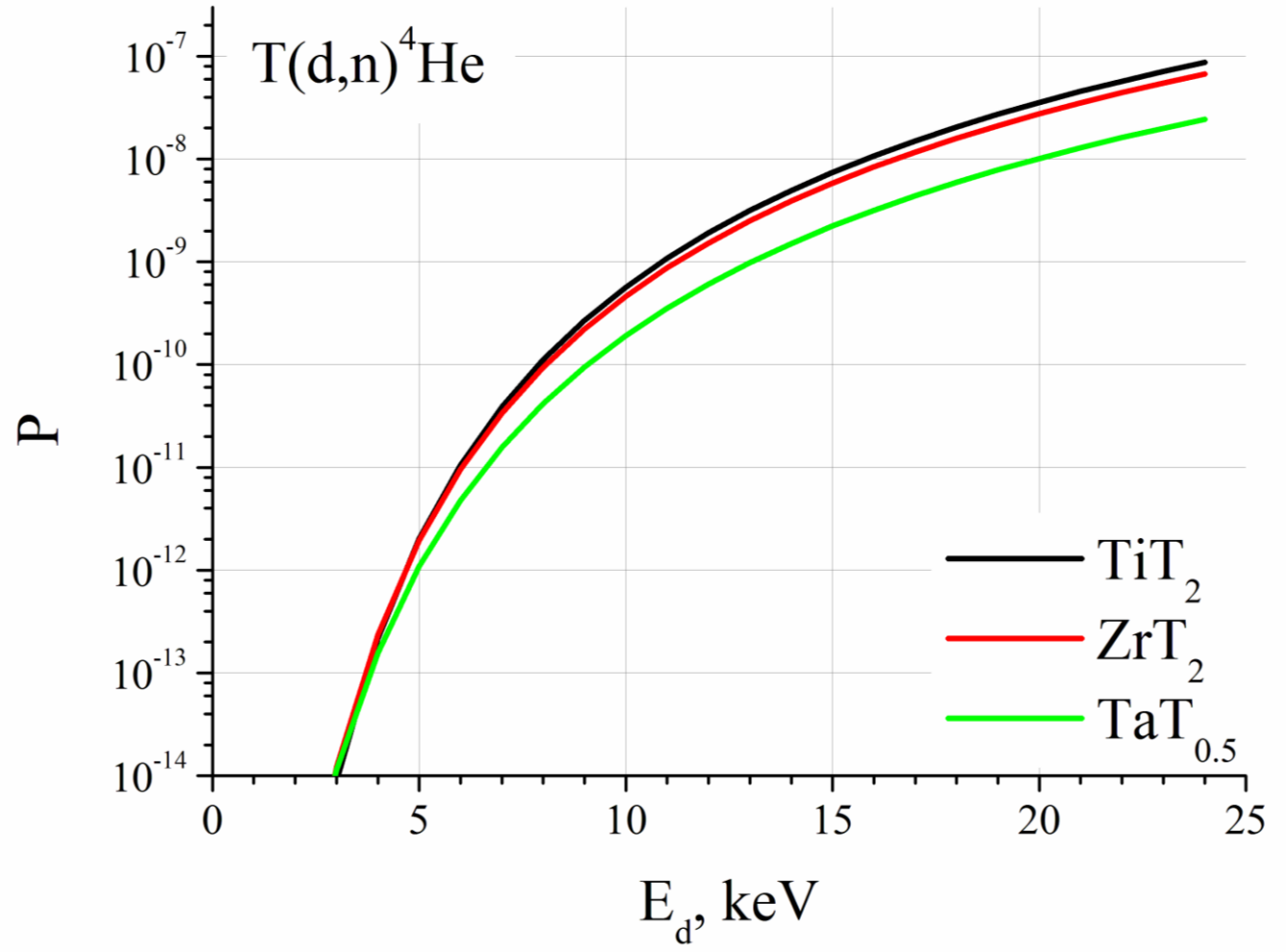
The Stopping of H^+ Ions in Matter

(http://www.srim.org/)



This information was used to calculate the distribution of ion energy at the ion stopping during their penetration into different matter.

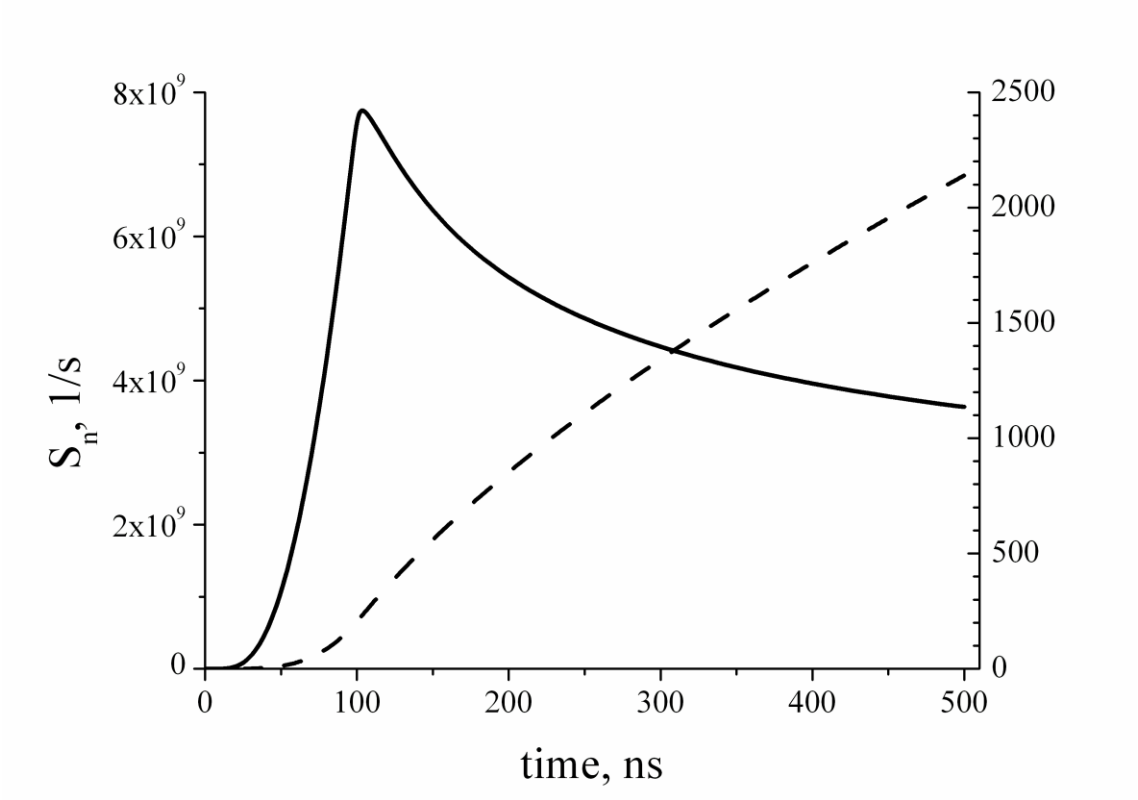
Calculation results on nuclear reaction probability P



Integration of the nuclear reaction cross sections over the path of ions in the target allowed to get the **reaction probability**

Probability of the **D + T** reaction vs nucleus energy.

Time dependence of the neutron production rate under operation conditions of the offered neutron generator



Knowing the dynamics of the energy spectrum of the ion flux onto the target and the energy dependence of the reaction probability, we can find the time dependence of the neutron production rate

Neutron production rate (neutrons per second), ε_{b0}**=20 kV**

The calculated neutron yield from a single grain per pulse.

ε_{b0} = 20 kV, Pulse duration 500 ns.

Nuclear reaction	Target	Neutron yield from a single grain per pulse
$D(d,n)^3He$	TiD_2	11
$D(d,n)^3He$	ZrD_2	8.5
$D(d,n)^3He$	$TaD_{0.5}$	3.2
$T(d,n)^4He$	**TiT_2**	**2140**
$T(d,n)^4He$	ZrT_2	1650
$T(d,n)^4He$	$TaT_{0.5}$	618
$D(t,n)^4He$	TiD_2	294
$D(t,n)^4He$	ZrD_2	235
$D(t,n)^4He$	$TaD_{0.5}$	93.5

Important:

Plasma forming gas D_2 and target material TiT_2 are the most promising for development of the offered neutron generator.

Conclusion

- We offered a new type of gas discharge neutron generator based on ultra-high charging the dust particles immersed in plasma.
- We have done the proper numerical calculations to find out the optimal operation conditions of this generator.
- We showed that the generator working with electron beams of 20-25 keV in a pulsed periodical regime with a frequency of 1 kHz can provide the neutron yield of more than $2 \cdot 10^9$ n/s in the case of irradiation of 1000 spherical targets of 250 microns radius.
- The results will be used for the development of a compact and low-voltage neutron generator without hard X-ray radiation that is very wanted for medical applications.

Thank you for your attention!

Your questions, please.