

# Neutron Production in the Compact Plasma IEC-Devices with Hollow Cathode<sup>1</sup>

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**Abstract – The results of neutron emission rate estimation in the plasma of the hollow cathode high voltage discharge of the compact cylindrical IEC-device with account to electrode size, plasma concentration and discharge tension are presented. The equations revealed for discharge current  $I > 0,01$  A the quadratic dependence of neutron emission rate  $\Phi$  in the “beam/plasma” channel, from discharge current  $I$  similar to the neutron emission rate behavior for “beam/beam” channel. The results are very important for the construction of improved modified IEC-devices.**

## 1. Introduction

Inertial electrostatic confinement (IEC) neutron sources on deuterium are constructively simple, safe and rather intensive ( $10^6$ - $10^8$  n/s) and because of this are the aim of the wide range of researches [1-3]. The theory of IEC systems is intensively working out, and showing that they are perspective for further modification aimed at neutron production intensification. The main ways of the modification are in elaboration of more powerful discharge facilities, optimization of the cathode configuration, implementation of the additional external deuteron and plasma sources.

There are the following channels of neutron production in IEC systems: “beam/plasma” – the fast confined deuterons collide with plasma deuterons, “beam/beam” – the fast deuterons collide with each other on the opposite courses, “plasma/plasma” – thermonuclear reactions in the plasma and “cathode/plasma” – the reactions as the result of the cathode striking by beam deuterons.

According to our estimations neutrons are basically produced in “beam/plasma” channel when gas pressure is  $10^{-1} \div 1$  Pa [4] and the area of their production is situated inside the hollow cathode.

There is a possibility for the additional neutron emission rate intensification by means of cathode configuration optimization, using the properties of the hollow cathode discharge [5]. Discharge plasma is

inhomogeneous in the hollow cathode discharge. It is concentrated in the center of the hollow cathode and concentration is in several times more there than in the suburb.

The cylindrical IEC-device with the cross-section of cathode about 0,05m, filled with deuterium at the pressure about  $10^{-1} \div 1$  Pa is studied. The aim of the work is to calculate the neutron emission rate  $\Phi$  of such device using the assumption about continuous deceleration of the circulating deuterons in the confining flow with accounting of the plasma concentration growth in the central region.

## 2. The model of the hollow cathode discharge

The scheme of the studied IEC-system is shown in Fig.1. The electrode system is consisted of the net cylindrical cathode ( $H$  – the cathode length,  $d$  – the cathode diameter  $H < d$ ) with nets from the butt ends ( $t$  – the transparency of one net,  $t=0,9$ - $0,95$ ) and two anodes, which are situated symmetrically on the axis of the cylinder. The size of the net cell  $h$  is matching the equation  $h=0,2 \div 0,4H$  in order to ensure electrical field penetration inside the cathode [4]. The hollow cathode discharge mode is achieved by the soft pressure regulation.

In the calculations it was assumed that energy losses of deuterons per cycle are smaller than their total energy  $\varepsilon$  at the cycle. Deuterium was considered to be atomic, the deuteron current from plasma to the cathode considered to be saturated (the zoned estimation [6]), the electric field in the cathode potential fall area was considered constant and the analytical estimation of the cross-section energy dependence was taken from [7] for  $\varepsilon < 150$  keV:  $\sigma_n(W) = 140 \varepsilon^{-1} \exp\{-44,4/\varepsilon^{1/2}\}$  barn.

The discharge process in the device is developing as follows. At the first stage the avalanche of electrons is developing between central region and the anodes as a result of high voltage applying  $U \sim 100$  kV. The deuterons, which are produced in the avalanche, are accelerated towards the central region.

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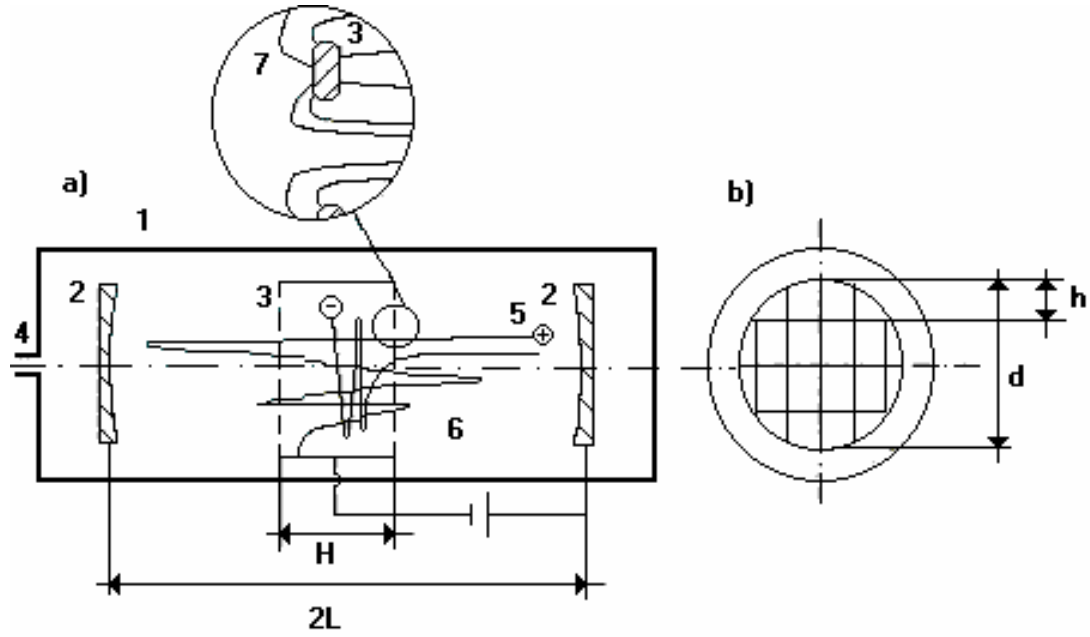


Fig. 1. The scheme of the cylindrical IEC-device (**a**) – longitudinal cross-section, **b**) – transverse cross-section): 1 – chamber, 2 – anodes, 3 – net cathode, from the butt ends of the cathode cylinder, 4 – gas input, 5 – deuterons trajectories, 6 – electrons trajectories, 7 – electric field lines

If gas density and net transparency ensure free path-through, deuterons will be decelerated by the field from the opposite side of cathode and then accelerated towards the central region again. The number of circulating deuterons grows up to the moment when the rate of their production in the avalanche became equal to the integral rate of their deceleration (thermalization) in the central region and the rate of their leaving the flow due to the scattering and direct cathode striking.

Circulating deuterons have different amplitudes due to the energy loss (mainly the recharging processes) on their orbits. In fact, two oppositely directed flows of deuterons with the same energy spectra are appeared.

Those circulating deuterons, which are striking the cathode surface, cause the secondary electron emission from it. Approximately half of the electrons are emitted into the central region and confined there by the electrical field, which is penetrated into the cavity. The confinement of electrons in the central region is sufficient because of the potential wall, which is surrounding the central region everywhere except small size areas near the centers of the net cells. The confinement of electrons in the cathode cavity results the high extent of gas ionization there.

Those deuterons, which are decelerated in the cathode cavity, cause plasma concentration growth in the central region. The extent of plasma concentration growth in the central region is controlled by the intensity of deuterons production in the avalanche. The

growth of the concentration is possible up to the moment when the central region plasma Debye's radius become the order of  $h$ .

Central region plasma density growth causes the reducing of the total transparency of the central region, but it is compensated by the additional deuteron's production in the avalanche due to the additional electron current from the central region plasma.

### 3. Neutron emission rate calculation

Neutron emission rate  $\Phi \approx 2Hn_c\sigma_n Q$ , where  $Q$  – the total deuteron flow from one side of cathode,  $n_c$  – concentration of the central region plasma; and in "beam/plasma" channel may be determined from the energy spectrum  $f(\varepsilon)$  of circulating deuterons according to the following equation:

$$\Phi = 2Hn_c \int_{\varepsilon^*}^{\varepsilon_0} d\varepsilon' \sigma_n(\varepsilon') f(\varepsilon') / \tau(\varepsilon') w(\varepsilon'), \quad (1)$$

where  $f(\varepsilon)$  – the function of beam deuterons spectrum with energy  $\varepsilon$ , which is normalized to the total deuteron flow from one side of cathode  $Q$  like this:

$$Q = \int_{\varepsilon^*}^{\varepsilon_0} d\varepsilon' f(\varepsilon') / \tau(\varepsilon') w(\varepsilon'); \quad (2)$$

$w(\varepsilon)$  – deuteron energy losses on the cycle with energy  $\varepsilon$ ,  $w(\varepsilon) = 4\varepsilon^2 / \xi_0 \varepsilon_0$ ,  $\xi_0 = 1/n_0 \sigma_{tr} L_k$ ,  $n_0$  – initial gas density,  $L_k$  – cathode tension fall zone length, estimated as:  $L_k \sim 0,1(L-H/2)$  [4],  $L$  – the half length of the discharge chamber;  $\sigma_{tr}$  – transport cross-section;  $n_c$  – cen-

tral region plasma density;  $\tau(\varepsilon) = L_k(2m_d\varepsilon)^{1/2}/\varepsilon_0$  – time of deuteron cycle with energy  $\varepsilon$ ;  $m_d$  – deuteron mass;  $\varepsilon^*$  – the minimum energy of circulating deuterons, estimated as:  $\varepsilon^* \sim (h/L_k)\varepsilon_0$ ;  $\varepsilon_0$  – the maximum beam deuteron energy.

The equation for  $f(\varepsilon)$  is obtained provided the deuteron beam is wide as follows:

$$\sum_{j>i} f(\varepsilon_j) \gamma_{ji}(\varepsilon_j) = f(\varepsilon_i) \left\{ \sum_{j<i} \gamma_{ij} + \gamma_t(\varepsilon_i) \right\} \quad (3)$$

where  $\gamma_{ji}(\varepsilon_j)$  – the frequency of deuteron's transitions from the level with energy  $\varepsilon_j$  to the level with energy  $\varepsilon_i$ ,  $\gamma_t(\varepsilon_i)$  – the frequency of deuteron's striking the cathode or scattering to the wall.

It is considered that deuteron's transitions take place only between the nearby levels and  $\omega$  is in many times smaller than  $\varepsilon_i$ . Then:

$$f(\varepsilon_i + \omega(\varepsilon_{i+1})) \gamma_{i+1i} = f(\varepsilon_i) \{ \gamma_{ii-1} + \gamma_t(\varepsilon_i) \}, \quad (4)$$

Accounting  $\gamma_i \sim 1/\tau(\varepsilon)$  and  $\gamma_t \sim s/\tau(\varepsilon)$  ( $s = 1 - t^2 + n_c \sigma H$ ,  $n_c \sigma H \ll 1$ ,  $\sigma$  – deuteron/deuteron cross-section) the resulting equation for the energy spectrum of deuterons is:

$$[f(\varepsilon)/\varepsilon^{1/2}]' - f(\varepsilon)s/\varepsilon^{1/2}\omega(\varepsilon) = 0, \quad (5)$$

Physical interpretation of (5) may be found from the law of the plus charge conservation in the discharge gap. If the (5) is integrated the first member is the rate of the total deuteron's "driftage" towards cathode due to the energy lossess – the difference in the definite point of discharge gap between deuteron's flows directed to the center and outward, the second member is the deuteron's leak from the flow directly to the cathode due to the scattering and cathode striking.

Solving (5) in the range  $\varepsilon^* < \varepsilon < \varepsilon_0$  it may be obtained:

$$f(\varepsilon) = (A\varepsilon^{1/2}) \exp\{-(\xi_0/4)(\varepsilon_0/\varepsilon)\}, \quad (6)$$

where  $A \approx L_k(2m_d)^{1/2} \exp\{\xi_0/4\} Q/\varepsilon_0$  from (2).

The deuteron deceleration rate from the flow into the central region plasma (thermalization) is given by the following equation:

$$D \approx Q \exp\{-s\xi\}, \quad (7)$$

where  $\xi$  – the average number of deuteron oscillations:

$$\xi = \int_{\varepsilon^*}^{\varepsilon_0} d\varepsilon / w(\varepsilon) \approx (\xi_0/4)(\varepsilon_0/\varepsilon^*), \quad (8)$$

Central region plasma density may be determined from the equality of deuteron's deceleration rate  $2D$  and the rate of deuteron's extraction from the central

region plasma to the cathode net from it butt ends  $I_{dL}/e$  as the radial extraction is considered to be negligible.  $I_{dL}$  is ion saturated current from plasma to cathode [6],  $e$  – electron charge, which is estimated as follows:  $I_{dL}/e = (1-t)(\pi d/2)^2 n_c (2\varepsilon_T/m_d)^{1/2}$ , where  $\varepsilon_T$  – central region plasma temperature, which is about 10 eV due to energy losses for irradiation from the central region plasma. It is important in this assumption that the extent of plasma ionization in the central region is about 100%. According to this:

$$n_c = 8 \cdot Q(m_d/2\varepsilon_T)^{1/2} \exp\{-s\xi\} / (\pi d)^2 (1-t) \quad (9)$$

Numerical evaluation for the given parameters reveals that the regime of the central region plasma concentration growth appears when  $I > 0,01$  A.

In order to determine the final dependence of the neutron emission rate  $\Phi$  from the value of the discharge current  $I$  it is necessary to find out the connection between  $Q$  and  $I$ .

In the stable regime  $I$  is the current in the cathode circuit:

$$I = I_{dL} + I_{dg} + I_{cg}, \quad (10)$$

where  $I_{dg} = 2eQs$  – the current of deuterons, hitting the cathode,  $e$  – electron charge,  $I_{cg} = \gamma I_{dg}$  – secondary electron emission current,  $\gamma$  – secondary electron emission coefficient.

Because of ion current from plasma to the net cathode saturation  $I_{dL}$  is connected with  $I_{eL}$  as follows:

$$I_{eL} = \alpha(1-t)^{-1} \mu^{-1} I_{dL}, \quad (11)$$

where  $\alpha$  – some numerical coefficient, depending on the central region plasma surface configuration,  $\mu = (m_e/m_d)^{1/2}$ ,  $m_e$  – electron mass. If the temperatures of ion and electron systems are equal  $\alpha \sim 0,1 - 1$ . Then:

$$I = 2eQ(\gamma+1)s + \alpha^{-1} I_{eL}(1-t)\mu. \quad (12)$$

From the other side the discharge current is the current in anode circuit:

$$I = G(I_{eL} + 2eQ(1-t)\gamma/2), \quad (13)$$

where  $G$  – the coefficient of reinforcement of the discharge gap.

Excluding  $I_{eL}$  from (11) and (12), the dependance of  $Q$  on  $I$  is found:

$$Q = (I/2e) [1 - \alpha^{-1} G^{-1}(1-t)\mu] [s(1+\gamma) - s\mu \alpha^{-1} \gamma/2]^{-1}. \quad (14)$$

Accounting that  $\mu$  is small, finally:

$$Q \approx I \cdot [2es(1+\gamma)]^{-1}. \quad (15)$$

Finally from (1), (6), (8), (9) and (15):

$$\Phi = \frac{1 \cdot 10^9 \text{Hexp}\{-44,4/\varepsilon_0^{1/2} - 2,5s(1-t)\xi_0 h/L\} I^2}{d^2 (1-t)^3 (1+\gamma)^2 (10/\varepsilon_0^{1/2} + 1)} \quad (16)$$

where  $\Phi$  is in n/s,  $I$  is in A,  $\varepsilon_0$  is in keV,  $L$ ,  $H$  and  $h$  is in cm.

From the equation (16) for  $\varepsilon_0=100\text{keV}$ ,  $H=5\text{cm}$  and  $d=5\text{ cm}$ ,  $h=1\text{ cm}$ ,  $L=30\text{cm}$ ,  $\gamma=2$ ,  $1-t=0,02$  it may be found that neutron emission rate  $\Phi=2 \cdot 10^{10} \cdot I^2 [\text{n/s}]$ , where  $I$  is in A.

## Conclusions

The equation for the neutron emission rate of the cylindrical IEC-device in hollow cathode discharge regime is obtained with the dependence on the cathode diameter, length, net cell size and transparency.

The accounting of central region plasma density growth resulted the quadratic dependence of neutron emission rate  $\Phi$  from the discharge current  $I$  ( $I>0,01\text{A}$ ) in “beam/plasma” channel. This is the novel result, because earlier such behaviour was characteristic for the neutron emission rate only in “beam/beam” channel.

The results of calculations shows that IEC-devices with hollow cathode effect are perspective as an inten-

sive neutron sources and the result strongly depends on the cathode transparency.

As neutron emission rate depends also on the parameters of the central region plasma they may be regulated by the definite external factors, for example by laser plasma injection as it was suggested earlier [4].

## References

- [1] Miley G.H., Sved J. Appl. Radiat. Isot. **48**, №10-12, 1557-1561 (1997).
- [2] J.F. Santarius, G.L. Kulcinski, et al. in *Proc. of the 16th ANS Topical Meeting on Fusion Energy*, Madison WI, 2004.
- [3] Miley G.H., Sved J., in *Proc. of the 5th US-Japan Workshop on IEC Fusion*; U W-M, 2002.
- [4] Кузнецов А.Ю., Цыбин А.С., Козловский К.И. в *Материалах Международной научно-технической конференции «Портативные генераторы нейтронов и технологии на их основе»*, М., ВНИИА, 2005, с.184-190.
- [5] Москалев Б.Н., «Разряд с полым катодом», Москва, Наука, 1967.
- [6] Райзер Ю.П., «Физика газового разряда», Москва, Наука. 1992.
- [7] Александрович Э.-Г.В., Соковишин В.А., ПТЭ, **5**, с. 7-25, 1961.