Investigation of accelerating ion triode with magnetic insulation for neutron generation

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Investigation of accelerating ion triode with magnetic insulation for neutron generation

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Abstract. Vacuum accelerating tube (AT) for neutron generation with the secondary electron emission suppressed by helical line pulse magnetic field which allocated inside accelerating gap in front of hollow conical cathode is discussed. The central anode was covered by the hollow cathode. This technical solution of AT is an ion triode in which helical line serve as a grid. Computer simulation results of longitudinal magnetic field distributional along the axis are presented.

1. Introduction
Laser-plasma deuteron source was used in ion triode to increase AT resource (up to $10^8$ pulses), which is determined by target mass and target mass spraying per laser pulse (~5.10$^{-12}$ kg). The magnetic field in triode is considered as superposition of helical line field and field of oppositely directed azimuthal induction current in the cathode electrode (the “magnetic condenser” effect). Cathode has a form of truncated cone with height $L$ and pitch angle $\alpha$ of cone generator to axis. The magnetic field of helical current with $M$ coils simulated by a number of thin currents rings inscribed in the cone perpendicular to it axis with equal steps and calculated according to the method, described in [2].

2. Model of the vacuum accelerating tube with magnetic insulation
To increase efficiency of neutron production at AT along with accelerating voltage gain a number of various methods to suppress secondary electron emission from cathode are used. Among them two scheme with magnetic isolation may be used: permanent magnetic field with azimuthal symmetry and pulse magnetic fields of helical inductive coil. The value of critical magnetic field induction at accelerating gap near the cathode must be $0.2 \div 0.6$ T for the cathode diameter $0.05 \div 0.1$ m and accelerating voltage $100 \div 500$ kV.

Experimental investigation of deuteron acceleration and neutron generation with secondary electron emission from the cathode suppressed by magnetic field was fulfilled on working sectional vacuum AT models, described in [3,4]. On the base of experimental data analyzes two advanced AT models were educed, which corresponds to technical solution [5,6]. The construction of those AT are presented at Fig. 1 and Fig. 2. Accelerating ion triode made in coaxial electrode geometry with interior anode on which laser plasma is produced and external hollow cathode. Cathode has the cylindrical or cone surface form and cover laser-plasma anode. In the case of pulsemagnetic isolation cone helical inductive coils installed near the inner cathode surface to produce pulse magnetic field for magnetic
The main peculiarity of technical solution discussed is using of laser-plasma source of deuterons. Together with laser beam scanner which scan target surface it allows to improve AT lifetime. For adequate AT parameters: target size $\sim 10^{-7} \text{m}^3$, laser target density $\sim 5 \cdot 10^3 \text{kg/m}^3$ (TiD), the number of ion source pulses is $\sim 10^8$. That is why AT lifetime will be determined only by process of tritium replacement with deuterium on neutron-forming target. To obtain laser plasma Nd:YAG laser (wave length $\lambda = 1060 \text{nm}$) which produce pulses with energy 0.85 J and pulse duration $\sim 10$ ns. AT on Fig.1 and Fig. 2 may be used with a vacuumarc deuteronsource. The number of this source operations is about $\sim 10^6$, and it determine this type AT lifetime. The conducted analysis shown that the main limitations deals withirregularity of source electrode materials burning which saturated with deuterium, unpredictable electrode spot moving, strong outgassing and electrode distraction.

3. Isolation magnetic field configuration

The efficiency of magnetic isolation was investigated first on the pulse ion diode with permanent magnet, made of a material based on NdFeB compounds, comprised a hollowcylinder with outer diameter 8 cm, inner diameter 4.5 cm, and height 4 cm. Experimental results with magnetic field induction value $B=0.4 \text{T}$ and laser energy irradiation $W=0.1 \text{J}$ show possibility of electron current partial suppression. However, this magnet type has typical magnetic field configuration whenpower lines closed on poles which leads to break down for accelerating voltages acceding 300 kV. For magnetic isolation with the help of helical line pulse magnetic field longitudinal component destroyed not so critical. That is why the upper limit of accelerating voltage value 450 kV was achieved.
Let us discuss in detail AT with pulse magnetic isolation shown on figure 2. The magnetic field will be considered as superposition of $M$ thin rings with cylindrical center coordinates

$$\{0, t(m) = h_1 + (m-1)(L - h_1 - h_2)/(M - 1)\}$$

and radius

$$a(m, \alpha) = r_3 - (m - 1)\text{tga}(L - h_1 - h_2)/(M - 1)$$

(m-ring number), with current value $I$, and current $M\cdot I$ in opposite direction on the cathode surface, which form a truncated conewith height $L$ and pitch angle $\alpha$ of cone generator to axis.

The parameters $h_{1,2}$ determinering longitudinal location with respect to cathode. This rings system simulate helical with $M$ coils allocated inside AT. Magnetic field modeling was fulfilled with the method, described in [2].

Components of alone ring magnetic field induction may be described as

$$b_r(r, z, \alpha, m) = \lambda G[a(m, \alpha), r, z - t(m)]; b_z(r, z, \alpha, m) = \lambda H[a(m, \alpha), r, z - t(m)]$$

where

$$G(a, r, z) = \left\{E[f(a, r, z)] \frac{a^2 + r^2 + z^2}{(a-r)^2 + z^2} - K[f(a, r, z)] \right\} \frac{z}{\sqrt{r^2 + \delta^2} \sqrt{(a+r)^2 + z^2}};$$

$$H(a, r, z) = \left\{E[f(a, r, z)] \frac{a^2 - r^2 - z^2}{(a-r)^2 + z^2} + K[f(a, r, z)] \right\} \frac{1}{\sqrt{(a+r)^2 + z^2}}; \lambda = \frac{\mu_0 I}{2\pi};$$

$$f(a, r, z) = \frac{4ar}{(a+r)^2 + z^2}.$$

Functions $K(x)$ and $E(x)$ – total elliptic integrals first and second kind accordingly. For the cathode field components we have the following approximate expression:

$$B_{kr}(r, z, \alpha) \approx \frac{\lambda}{N} \sum_{n=1}^{N} G(b(n, \alpha), r, z - t_k(n)) B_{kr}(r, z, \alpha) \approx \frac{\lambda}{N} \sum_{n=1}^{N} H(b(n, \alpha), r, z - t_k(n)),$$

where

$$b(n, \alpha) = r_3 - (2n-1)\text{tga}L / 2N, \quad t_k(n) = (2n-1)L / 2N$$

Those expressions were obtained by numerical calculation cone surface integral of Biot-Savarts formula, $N$ – number of quadrature formula nodes. Using superposition principle and suggesting that power input 6 (Fig. 2) is under positive potential, we obtain the final expression for the magnetic field induction components in AT with magnetic insulation:

$$B_r(r, z, \alpha) \approx -\sum_{m=1}^{M} b_r(r, z, \alpha, m) + B_{kr}(r, z, \alpha) \quad B_z(r, z, \alpha) \approx -\sum_{m=1}^{M} b_z(r, z, \alpha, m) + B_{kz}(r, z, \alpha)$$

4. Computer simulation

Computer code on the base of the above algorithm has been written. Our experience of constructing and working with pulse neutron generators with AT let us conclude that all this deivces consist of diode with azimuthal symmetry and longitudinal or transverse acceleration of heavy hydrogen nuclides [7].There sizes are in the range of $\sim(10^{-2} - 10^{-1})$ m. Therefore, those values were used for computer simulation.

Fig. 3 shows typical longitudinal magnetic field distributions on the axis $B_z(0, z, \alpha)$. 

Fig. 4 shows distributions of longitudinal magnetic field projection on cathode surface between the cathode and helical electrode using next relation:

\[ B_z(z, \alpha) = \cos \alpha B_z \left( \frac{r_S + r_k}{2} - ztg\alpha, z, \alpha \right) - \sin \alpha B_z \left( \frac{r_S + r_k}{2} - ztg\alpha, z, \alpha \right) \]

Computer simulation shows that best results may be achieved for AT with \( tga \leq r_k/L \). This condition is in a good agreement with experimental results [4].

According [8] total suppression of electron current obtained if magnetic field induction accede the critical value from the following expression:

\[ B_{cr} = \frac{2r_p}{r_k^2 - r_p^2} \left( \frac{m}{e} U(2 + \frac{eU}{mc^2}) \right) = 10^3 \frac{2r_pI_0}{r_k^2 - r_p^2} \sqrt{\frac{eU}{mc^2}} \left( 2 + \frac{eU}{mc^2} \right)^{1/2}, T \]
where

\[ I_0 = \frac{4\pi e_0 mc^3}{e} \approx 17 \text{, kA} \]

- Alphen current, \( m \) is the electron mass, \( U \) is the maximum voltage across the diode gap, \( r_k \) is the radius of the cathode (target) of the accelerating tube, \( r_p \) is the maximum radius of the plasma anode, and \( e_0 \) is the electric constant. Further computer simulation shows possibility to use following approximate expression for the critical current value:

\[ I_0 L_p (r_s - L \tan \alpha)^2 \frac{eU}{2\pi M(r_s + r_s - L \tan \alpha)(r_s^2 - r_s^2)} \sqrt{\frac{eU}{mc^2}} \left( 2 + \frac{eU}{mc^2} \right) \cdot \]

5. Conclusion

On the base of experimental data simulation of magnetic field configuration from helical inductor in accelerating triode with laser-plasma source was fulfilled. Analyse of longitudinal magnetic field distributions on the axis \( B_z(0, z, \alpha) \) allows to find the condition \( \tan \alpha \leq r_s / L \) for optimal AT mode. Then for AT with laser power 0.5 – 1 J the transverse and longitudinal sizes of accelerating ion triode may be reduced up to 0.08 m.

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