Pulsed neutron generators based on the sealed chambers of plasma focus design with D and DT fillings

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Abstract. Development of neutron generators using plasma focus (PF) chambers is being conducted in the All-Russia Scientific Research Institute of Automatics (VNIIA) during more than 25 years. PF is a source of soft and hard x-rays and neutrons 2.5 MeV (D) or 14 MeV (DT). Pulses of x-rays and neutrons have a duration of about several tens of nanoseconds, which defines the scope of such generators—the study of ultrafast processes. VNIIA has developed a series of pulse neutron generators covering the range of outputs $10^7$–$10^{12}$ n/pulse with resources on the order of $10^3$–$10^4$ switches, depending on purposes. Generators have weights in the range of 30–700 kg, which allows referring them to the class of transportable generators. Generators include sealed PF chambers, whose manufacture was mastered by VNIIA vacuum tube production plant. A number of optimized PF chambers, designed for use in generators with a certain yield of neutrons has been developed. The use of gas generator based on gas absorber of hydrogen isotopes, enabled to increase the self-life and resource of PF chambers. Currently, the PF chambers withstand up to 1000 switches and have the safety of not less than 5 years. Using a generator with a gas heater, significantly increased security of PF chambers, because deuterium-tritium mixture is released only during work, other times it is in a bound state in the working element of the gas generator.

1. Introduction
Plasma focus (PF)—one of the most intensive neutron radiation sources. Researches of PF are going on in major laboratories of the world already of about 50 years. Among major Russian institutes, that are carrying out researches of PF in Russia are NRC “Kurchatov Institute”, RFNC-VNIIEF, LPI RAS, and others [1].

PF forms in chambers with specially located electrodes. To perform all the process there are usually used the discharge current of specific amplitude and duration through gaseous environment (usually the chamber space is filled with D or DT mixture). At the same time a short neutron and x-ray pulse of tens of nanoseconds duration is generated.

Principle of operation of neutron generator on the basis PF chamber is illustrated in the figure 1. Generator operation is performed in the following way. Firstly, the electrical breakdown of interelectrode space spreads all over the surface of insulator with current-plasma sheath (CPS) formation. This stage represents current sheath motion along anode. Secondly, stored energy in capacitor is transformed in magnetic energy that, in its turn, is stored in inductances of loop...
and plasma focus chamber. Part of energy, stored in chamber, is condensed in PF and exactly this part of energy determines operational effectiveness of PF unit.

2. VNIIA plasma focus chambers

VNIIA started development and production of PF chambers about 30 years ago. By that time, the need of industrial use of nanosecond pulse neutron generators became evident and it was required to develop PF chambers of sealed-off design. At present, VNIIA makes serial production of 4 types of sealed-off PF chambers (see figure 2), that are designed for operation at output of $3 \times 10^7$ to $1 \times 10^{12}$ n/pulse with neutron energy of 14MeV and of $1 \times 10^6$ to $1 \times 10^{10}$ n/pulse with neutron energy of 2.5MeV.

Neutron pulse duration in PF chambers is not more than 50–60 ns, and at the same time the intensity reaches $10^{18}$ n/sec. PF chamber is also a powerful sources of soft ($\sim$ 1 keV) and hard (up to $\sim$ 100 keV) x-ray radiation with an integral output $\sim$ 10–100 J per pulse with a pulse duration of $\sim$ 9.3 ns (see figure 3).
Mass-spectrometric measurements were used to analyze composition of gas in PF chambers. After measurements the chambers was switched on to record the neutron output. Investigations enabled to conclude that chamber lifetime and safety are limited by the presence of impurities, released from the surface of electrodes and chamber insulator under the effect of plasma sheath when triggered, and in the case of deuterium-tritium filling by impurities, released from electrodes under the effect of $\beta$-particles from radioactive tritium. To reduce the amount of impurities, released into the PF chamber volume, gas generator was introduced [2], which provides a constant composition of the gas mixture in the PF chamber. These measures allowed to increase a lifetime of chamber up to 1000 switches on and a shelf-life of up to 4–5 years.

Electrodes geometry of PF chambers is determined with consideration of CPS motion time (beginning from the moment of discharge up to the pinch moment along the chamber axis) approved with the time when the current inside the loop reaches its maximum. In order to find solution of that problem, “The two-dimensional magnethydrodynamic code for plasma focus calculation” program on the basis of one-liquid magnethydrodynamic (MHD) model was developed. The program allows setting the geometry of PF chamber, determining the filling-in gas, and electrotechnical parameters of loop $L$, $C$, $R$ [3]. The program calculates CPS configuration in time, chamber inductivity, plasma parameters in PF chamber (density, temperature, rate of sheath motion et al.), and also the discharge current and the balance of energies in the loop.

3. VNIIA pulsed neutron generators

VNIIA developed the line of neutron generators with operating currents of 100–1200 kA and with the neutron output of $10^7$–$10^{12}$ n/pulse (see figure 4) [4]. Design solutions, laid as foundation of generators, are protected by patents [5, 6]. Neutron generators with operating currents of 100–300 kA have the inductivity of 40–60 nH, and, at the same time, the inductivity of used PF chambers (that are used as parts of generators) is not more than 10 nH.

ING-104 and ING-105 neutron generators with operating currents of 600–1000 kA have a rather low inductivity of electrical circuit $\sim 15$–20 nH. Due to applications of low-inductive circuitry and parallel connection of discharge modules. PF chambers, especially designed for operation under such kind of currents, have a rather low inductivities $\sim 15$–20 nH, in first hand due to design features. Figure 5 shows the dependence of the neutron yield from the chamber PF filament current gas generator, setting the pressure of deuterium-tritium mixture at different charging voltages on the capacitor bank. These curves show that for each of the charging voltage there is a certain current intensity, which corresponds to the optimal gas pressure in the chamber, at which the neutron yield is maximized.
4. Some applications of generators VNIIA on the basis PF chambers

Short duration (\(\sim 10 \text{ ns}\)) of the neutron and x-ray radiation with a significant output makes generators based on the PF to be the most suitable sources for development of diagnostic methods of fast pulsed single processes with nanosecond time resolution [6]. In carrying out large-scale scientific experiments, portable generators based on PF allow calibration of measuring paths directly in a given geometry of the experiment.

Generators based on the chamber PF can act as a source for pulsed dynamic radiography. Figure 6 demonstrate radiographic images obtained by the image plate (IP) detector with three plates in the x-ray section and four plates in the neutron one [7]. The detector was at the distance of about 20 cm from the chamber center.

The sample presented on the left side of figure 6 was a 50 \(\Omega\) electrical load. Its radiographic images have shown that x-ray influence on neutron images is negligible and that spatial resolution of the images is about 1 mm. Progress in obtaining radiographic images of fast dynamic phenomena is associated with an increase of neutron and x-ray generator output based on chamber PF and efficiency of recording systems.

Questions of application of PF generators in radiology and medicine are described in the
monograph: “The development of methods and apparatus for cancerous growth diagnostics and therapy on the base of neutron and x-ray radiation pulse generators” [8]. In this work, when biotest object were exposed to nanosecond x-ray pulses, dose rates up to $10^9$ Gy/sec have been achieved. In order to achieve the same capacity with the neutron radiation dose it is necessary to create new sources of neutrons based on the Fermi surface energy of the order of 30–100 kJ [8]. Currently VNIIA works on creation of sources of ionizing radiation based on the phenomenon PF.

5. Conclusion

Today in the field of PF VNIIA provides the following activities:

- the technology for serial production of PF chambers of sealed-off design with extended lifetime and shelf-life has been set up;
- a line of industry compact pulse nanosecond neutron generators on the basis of PF, with D/DT filling, with output from $10^5$ to $10^{12}$ n/pulse has been developed;
- different areas of application of nanosecond neutron generators based on PF are being developed.

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