Title

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ABSTRACT

A compact neutron generator based on D-D or D-T fusion reactions is being developed at the Lawrence Berkeley National Laboratory. The deuterium or tritium ions are produced in a radio-frequency (RF) driven multicusp plasma source. Seven beamlets are extracted and are accelerated to energy of 100 keV by means of a three-electrode electrostatic accelerator column. The ion beam then impinges on a titanium coated copper target where either the 2.4 MeV D-D or 14 MeV D-T neutrons are generated by fusion reaction. The development of the neutron tube is divided into three phases. First, the accelerator column is operated at hydrogen beam intensity of 15 mA. Second phase consists of deuterium beam runs at pulsed, low duty cycle 150 mA operation. The third phase consists of deuterium or tritium operation at 1.5 A beam current. Phase one is completed and the results of hydrogen beam testing are discussed. Low duty cycle 150 mA deuterium operation is being investigated. Neutron flux will be measured. Finally the phase three operation and the advance neutron generator designs are described.

Key words: Neutron Generator, D-D Neutron Source, Multicusp Source

INTRODUCTION

The RF-driven multicusp ion source developed at Lawrence Berkeley National Laboratory has found numerous applications ranging from neutral beam injection systems for fusion reactors to particle accelerators, proton therapy machines and ion implantation systems. Sources such as this are simple to operate, have long lifetime, high gas efficiency and provide high-density plasmas with high yield of monatomic species. These characteristics make the RF driven multicusp source a viable candidate for compact, high-output, neutron generators, utilizing the D-D or D-T fusion reactions. The cross-section of the reaction favors the D-T reaction, giving approximately two orders of magnitude higher neutron yields. See figure 1 for D-T and D-D neutron production cross-sections.

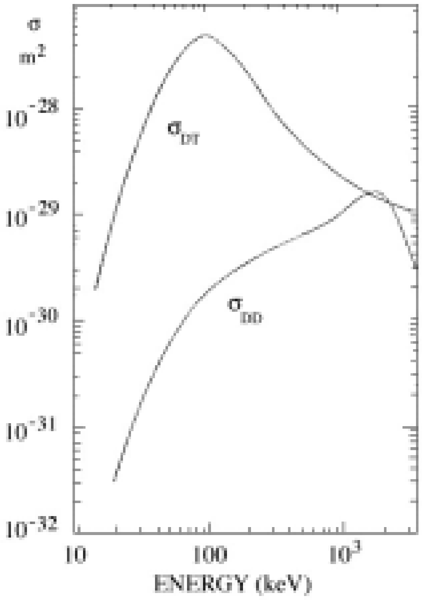

Figure 1. Fusion reaction cross-sections for D-D of D-T reactions

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Various different neutron generators systems are being developed and tested at the Plasma and Ion Source Technology Group in Lawrence Berkeley National Laboratory. The conventional system utilizes multicusp ion source, multiple-hole beam extraction system with three electrodes and titanium-coated target. Beam current and neutron yield measurements will be discussed. Also a smaller, compact generator has been developed. This new neutron generator uses quartz plasma chamber with external antenna, two-electrode, diode accelerator system and titanium target in very compact dimensions. The development of this compact neutron generator will also be mentioned in this presentation.

1. PLASMA GENERATOR DESIGN

In the conventional neutron generator, a 30-cm diameter multicusp ion source is used to generate plasma. The chamber is stainless-steel and is surrounded by columns of samarium-cobalt magnets. The plasma is generated by RF induction discharge. The RF power supply can be driven at 13.56 MHz for CW or low-power pulsed operation up to 5 kW or 2 MHz for high power (up to 90 kW) pulsed operation. The ion source, vacuum tank, vacuum pump and the high voltage feed through of the generator are shown in Fig. 2. The aluminum support structure around the neutron generator is used for lead and polyethylene shielding for the secondary electron induced x-rays and for the neutrons.

The terminating impedance of the plasma typically ranges between 0.5 - 2 Ohms, whereas the coaxial transmission line and the output impedance of the RF-amplifier are both 50 Ohms. An RF-matching network is used to match the plasma and antenna impedance to the output impedance of the RF-amplifier and coaxial transmission line.

Conventional RF-antenna arrangement is used in the plasma generator. The coaxial titanium-quartz tube antenna is housed inside the plasma chamber[1]. Very high hydrogen or deuterium atomic ion species percentage has been achieved (Fig. 3).

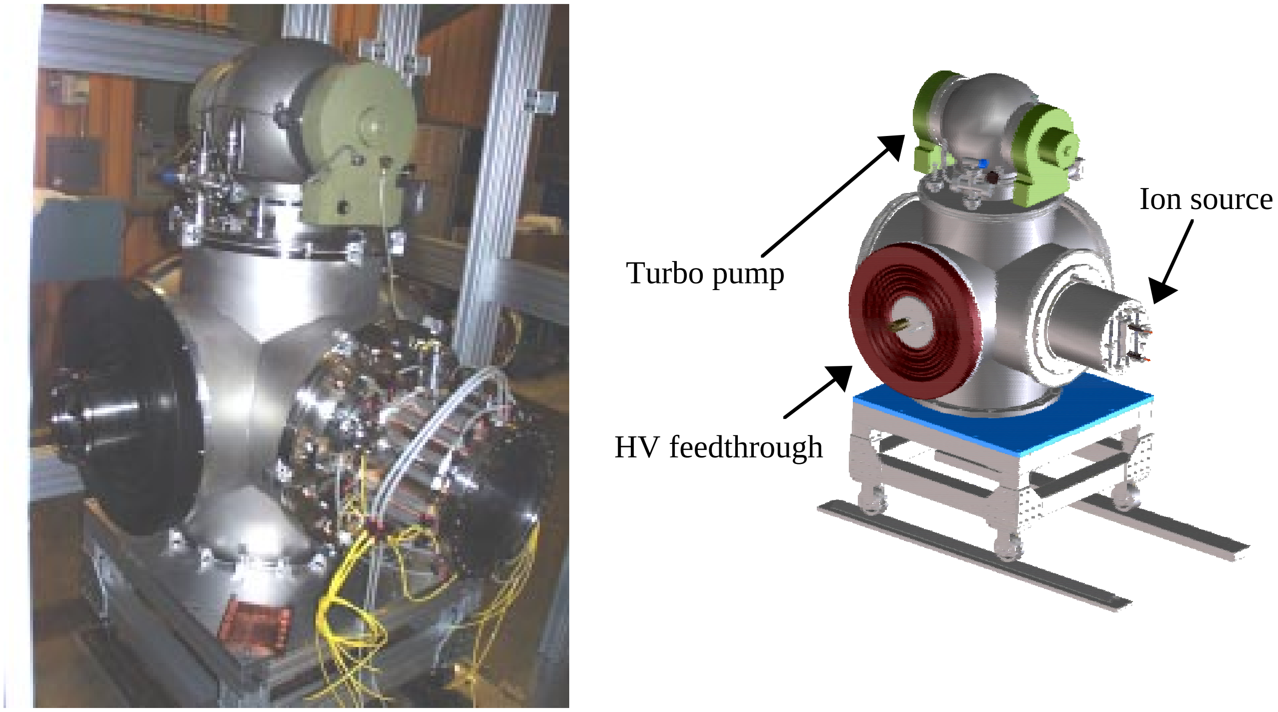

Figure 2. The neutron generator in the test-stand and layout of the set-up. From left, the high voltage feed-through is shown, the turbo vacuum pump unit on top of the vacuum vessel and on the right the 30 cm in diameter, multicusp ion source.

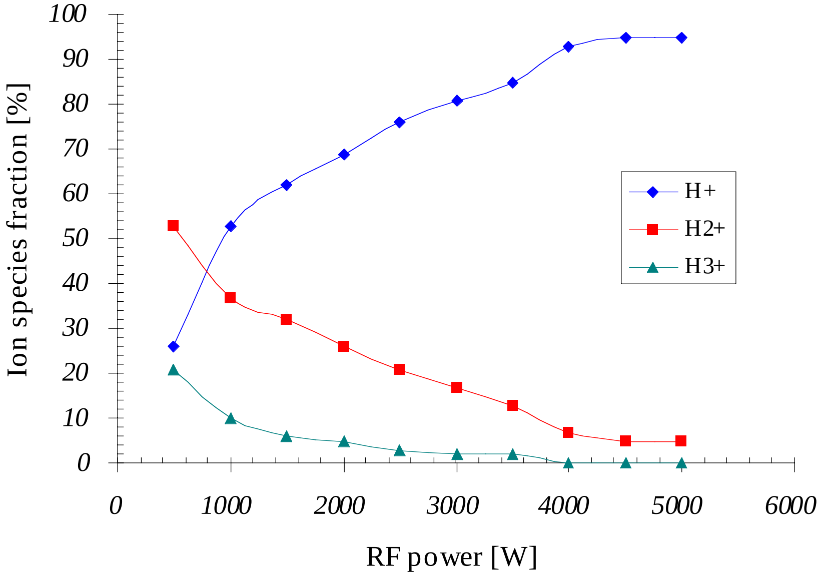

Figure 3. The hydrogen ion species fraction as a function of the RF power. More than 90% pure atomic species can be obtained at power > 4.0 kW.

The high atomic species fraction in the beam is important so that higher neutron yields can be achieved, see Fig. 4. The beam current density as a function of the RF power is shown in Fig. 5. The linear behavior of the obtainable, saturated beam current density as a function of the RF power is typical for RF induction ion sources[2]. The maximum obtainable current density depends also on the volume of the discharge vessel.

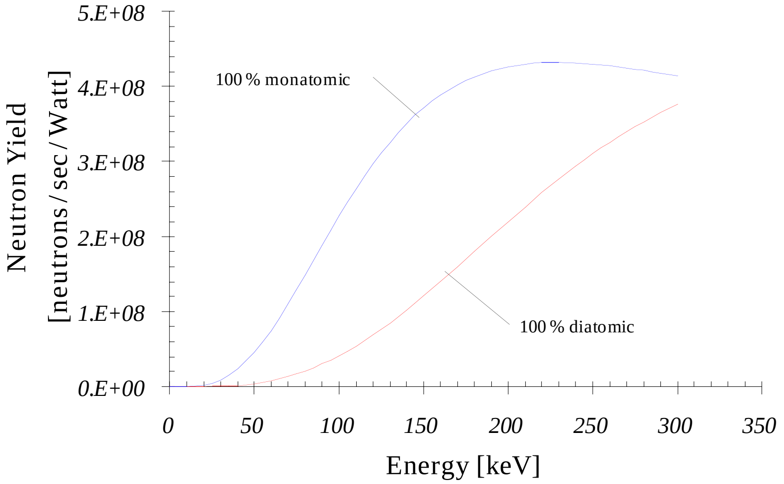

Figure 4. The comparison of neutron yields between monoatomic beam (the upper curve) and the molecular beam (lower curve). Neutron yields simulated using MCNP code.

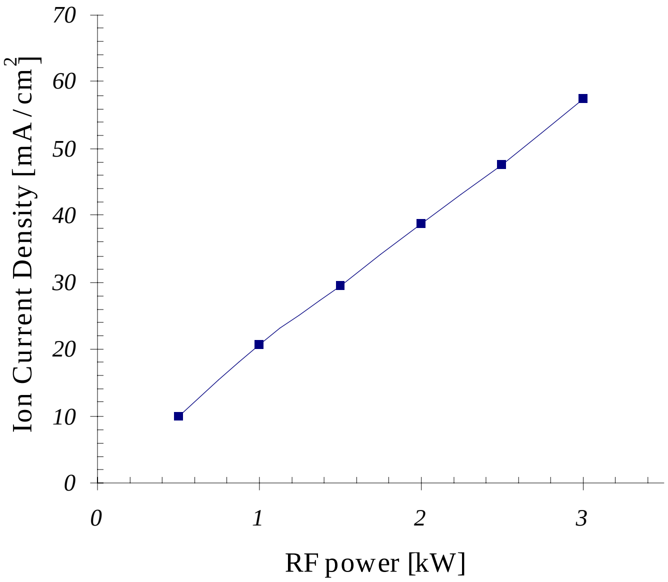

Figure 5. Ion beam current density as a function of the RF power. The source pressure in this measurement was 2 mTorr. The large 30 cm in diameter multicusp source was used.

2. ACCELERATOR DESIGN

The beam extraction/accelerator system was simulated by using the IGUN[3] ion extraction simulation code. The beam is being extracted through a multi-aperture grounded plasma-electrode, extracted by low voltage and then accelerated to full energy with a third electrode. The target is biased at slightly higher voltage to suppress the secondary electrons created by the beam at the target. In this design the ion source is at ground potential and the target is at high negative potential. The design allows the beam trajectories to cross-over, which spreads the beam to larger area. A simulation of the beam behavior in the extraction gap is shown in Fig. 6. For the experiments described in this presentation, a seven hole extractor with combined area of 1 cm^2, was used. The target was placed 50 mm from the third electrode downstream.

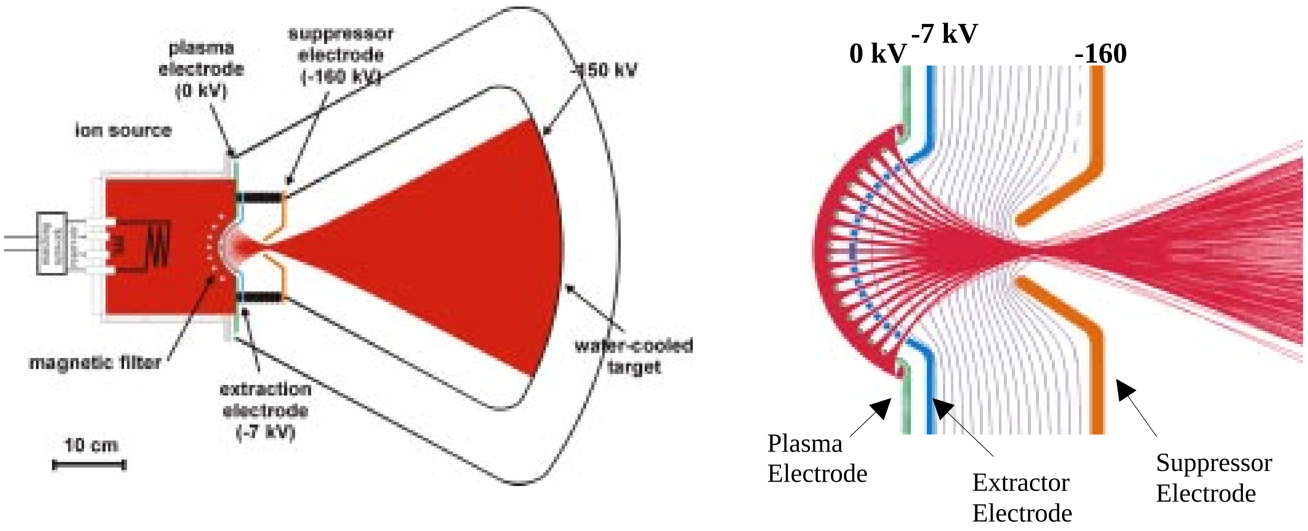

Figure 6. The RF-induction plasma source, beam extractor system, accelerator and target geometry is shown in picture on the left. The IGUN simulation of the extraction area is shown on the right.

3. 2.5 cm-DIAMETER NEUTRON GENERATOR

In addition to the conventional high power neutron generator, a very compact neutron tube (2.5 cm in diameter) is being developed. This tube is designed to operate in a pulsed mode. In this generator the plasma is also produced using RF induction, but the antenna is placed outside the quartz plasma chamber. The accelerator in this tube is a single gap diode structure. A pair of magnets are incorporated in the target to suppress the secondary electron emission. The tube consists of the plasma generator, an externally located RF antenna, the plasma electrode and the titanium coated copper target. The tube is made of quartz which works as a high voltage insulator and a vacuum vessel. The layout of the tube is shown in figure 7. In figure 8, the compact neutron tube is being tested with hydrogen gas at 1 kW of RF discharge power.

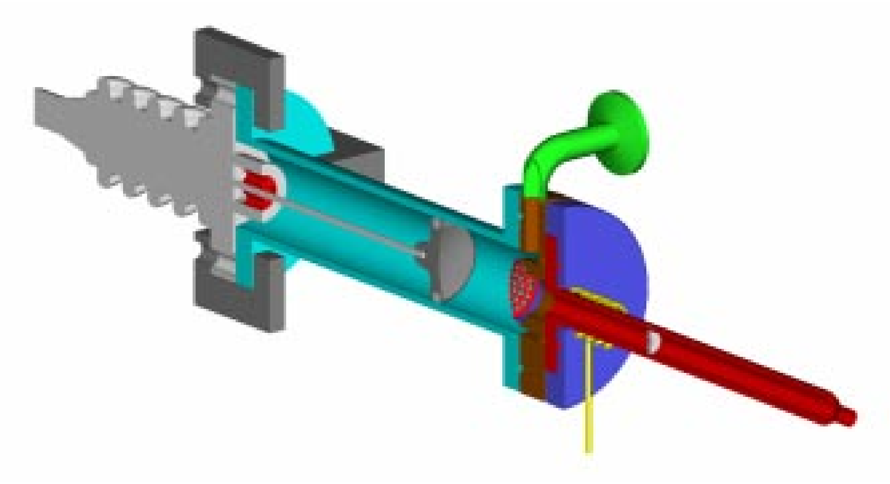

Figure 7. The compact, 2.5 cm neutron generator layout. Plasma is formed in the quartz tube on the right, using external RF induction antenna. The beam is then accelerated toward the titanium coated copper target.

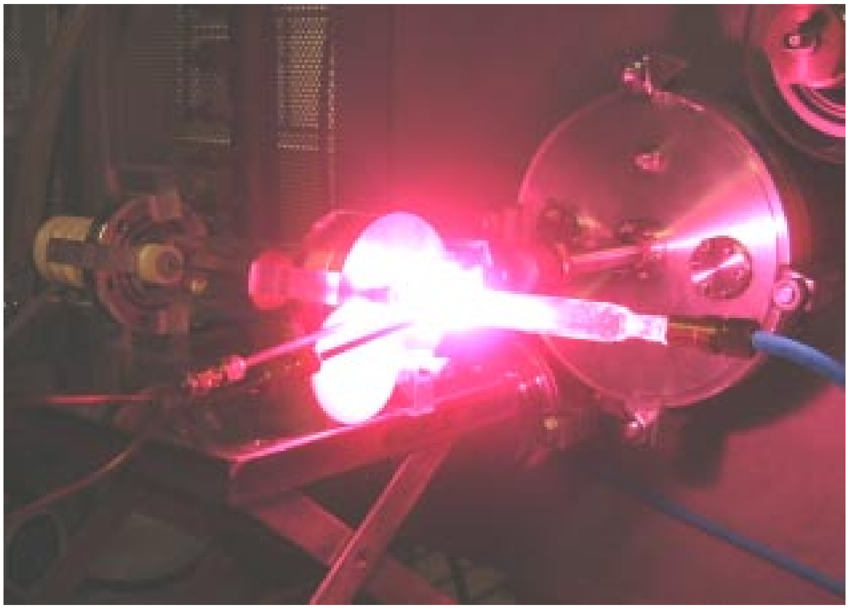

Figure 8. The compact tube under testing using hydrogen gas and 1 kW of discharge power. The high voltage feed-through can be seen on the far left, gas feed on the right.

4. MEASUREMENTS

The larger tube has so far been run at 80 kV acceleration voltage, 5 kW discharge power at 1% duty cycle and 10 mA of deuterium beam. The target was not water cooled during the initial measurements. The measurements were done using ^{3}He-detectors, located inside the lead/polyethylene shielding. The neutron yield was 2-3 x 10^6 n/s, which is about factor of three less than the yield produced at optimum TiD_2 target conditions.

The 2.5 cm tube is under testing. So far the tube has been operated using hydrogen plasma. The ionization efficiency of the hydrogen is very similar to deuterium. Neutron shielding is not needed when high voltage tests are done with hydrogen. The results of the hydrogen beam current measurement are shown in figure 9. Relatively high current density can be obtained because the volume of the ionization chamber is small.

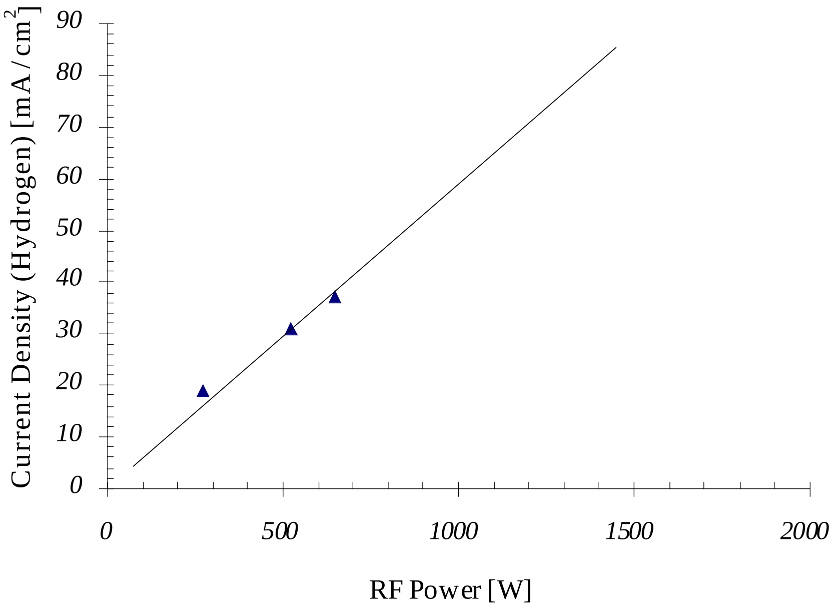

Figure 9. The current density obtained from the one inch neutron generator, using hydrogen gas. 5 mm accelerator gap was used.

The space charge limited current density depends on the gap width and the voltage used according to Child-Langmuir-law:

$$j = 1.72\sqrt{Q/A}\,\frac{U^{3/2}}{d^2}\,. \tag{1}$$

where Q is the charge state and A the mass number of the ion, U the accelerating field and d the acceleration gap. In this formula the $[j]$ = mA/cm^2, $[U]$ = kV and $[d]$ = cm. The extracted current follows this law, which can be seen in the figure 10, where the extracted current density is plotted against the gap width.

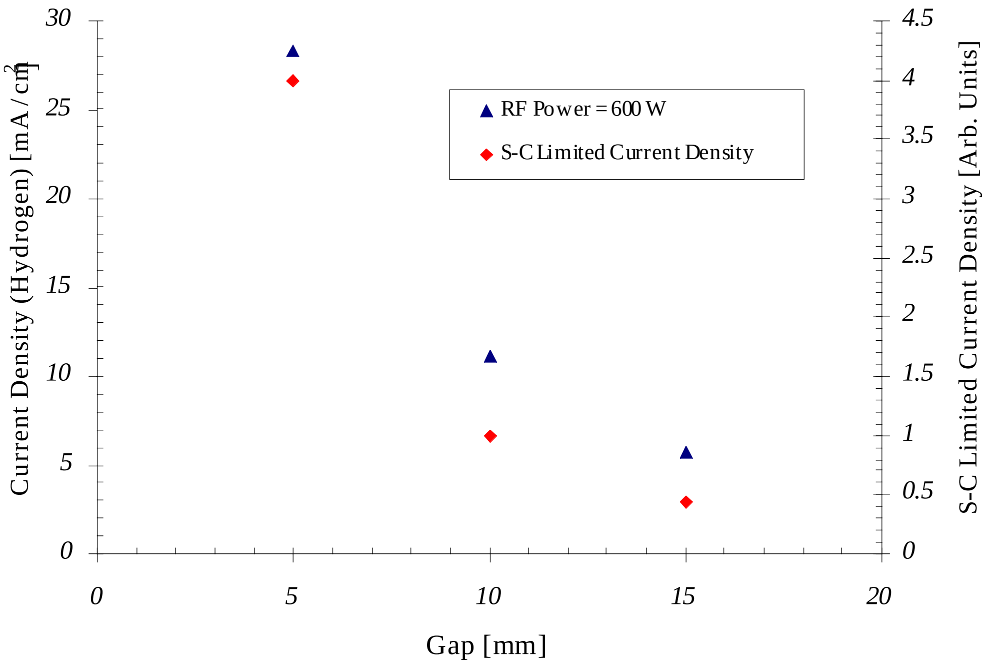

Figure 10. The current density obtained from the one inch tube compared to the space charge limited current density given by Child-Langmuir law at constant acceleration voltage.

The 2.5 cm neutron tube has been successfully operated at 80 kV. In order to obtain similar neutron yield as the large tube operating at phase 1 specifications, the diameter of the round extractor aperture at 5 kW RF power operation can be as small as 2 mm.

5. DISCUSSION

For the large tube, the next development phase is the phase 2 operation. This requires beam intensities of 150 mA. For this, the extraction area has been increased by adding more holes to the plasma and extractor electrode. The 7 holes of the old set-up is changed to 61 holes in the new set-up. This will give approximately a factor of 9 increase in the extracted current. A picture of the new electrode (extractor electrode) is shown in figure 11, where the old seven-hole extractor is displayed with the new 61 hole extractor. First tests should begin at the end of July 2001.

The 2.5-cm-diameter tube neutron measurements will start in the fall 2001. The goal is to achieve neutron yields in the order of 10^{10} n/s.

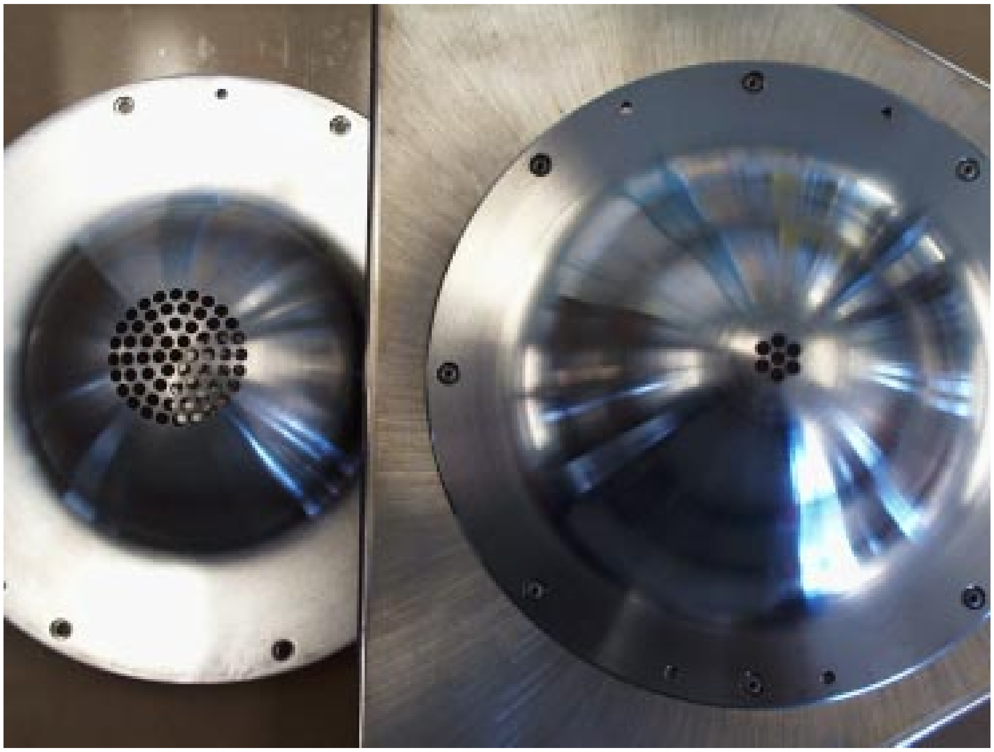

Figure 11. The new 61 hole extractor electrode on the left, the old 7 hole extractor on the right.

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