

Neutrons and Neutron Generators

Steve Hansen

I. INTRODUCTION

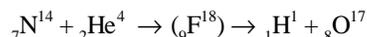
This article was originally intended as a brief introduction to the article by Richard Hull on the Farnsworth/Hirsch “fusor.” However, as there has been some interest by a number of subscribers in neutron generators, I decided to provide a somewhat more lengthy tutorial on the reactions that produce neutrons, some practical applications of neutrons, and a few of the various types of devices that have or are being used to produce neutrons. Closer to home, my first major vacuum project (this was around 1968) was to be a neutron generator. It consisted of a 500 kV van de Graaff machine with a five-foot accelerator tube. I got to the point of producing an electron beam. Frankly, it was a bit wobbly and quite scary. That’s when I decided that plasma devices would be more fun.

II. HISTORICAL BACKGROUND

In 1897, J.J. Thomson determined that the electron was a negatively charged particle with mass. The structure of the atom was beginning to be understood as a neutral entity consisting of some number of these low-mass electrons with a corresponding number of higher mass protons with equal but opposite charges.

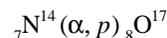
Rutherford, in 1919, was investigating the range of alpha particles (fast helium nuclei produced by radioactive elements) in air when he noted the infrequent production of a particle that could traverse a much longer distance. It turned out that some of the alpha particles were interacting with the nitrogen molecules in the air-filled environment of his scintillation chamber, causing the disintegration of the nitrogen along with the release of a proton. This was the first observation of transmutation.

Properly stated, the reaction that Rutherford observed is:



where the subscript preceding the element’s name is the atomic number, the superscript is the atomic mass. In the reaction, an unstable intermediate isotope of fluorine is formed which quickly decays to oxygen with the release

of the proton. The reaction may also be stated in an abbreviated form as:



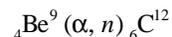
With protons and transmutation now part of the vocabulary, the next major discoveries were those of the neutron, the positron, artificial radioactivity and the transmutation of elements by machine-generated high energy particles. All of this happened in the period of 1930 to 1932. Deuterium (${}_1\text{H}^2$) was also discovered in this period.

It had been noted by Bothe in 1930 that beryllium (${}_4\text{Be}^9$), when bombarded by alpha particles, gave off a highly penetrating radiation which was then called “beryllium rays.” These were thought to be akin to gamma (γ) rays. In 1932 James Chadwick identified these emanations as neutral (uncharged) particles, each with a mass about the same as that of the proton. The lack of charge explained the penetrating properties of these particles.

In his experiment, Chadwick used naturally produced alpha particles to transmute beryllium into carbon. The neutron producing reaction is:



or, in shorthand:



For reference, when 1 gm (1 curie) of radium, an alpha particle emitter, is mixed with a few grams of powdered beryllium, about 10^7 fast (high energy, 5.76 MeV) neutrons are emitted every second.

OK, this was a major discovery but it doesn’t involve an ounce of vacuum. (Figure that expression out!) While all of this other stuff was going on, vacuum got thrown into the mix when J.D. Cockcroft and E. Walton built the first real atom smasher. One part of their apparatus consisted of a voltage multiplying rectifier (the now familiar and ubiquitous Cockcroft-Walton multiplier), one version of which produced an output voltage of about 800 kV, unloaded. The other part was an evacuated glass tube with an ion source at the top end, one intermediate accelerating electrode, and a target chamber at the lower

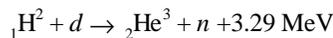
end. With a gas being fed into the ion source, the accelerator would produce a beam of charged particles with an energy corresponding to the loaded multiplier voltage, about 700 keV.

Cockroft and Walton performed their history making experiments with hydrogen and the accelerator, therefore, produced a beam of protons. The pair used lithium as the target material. What they observed was a release of alpha particles:

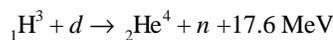


The Q is the kinetic energy of the alpha particles in excess of the kinetic energy of the incident proton and, for this reaction, is slightly more than 8.6 MeV per alpha or 17.3 MeV total. (Depending upon the particular reaction, Q can also be negative. This was the case in the reaction observed by Rutherford.) Cockroft and Walton also found that incident energies as low as 20 keV could initiate this reaction, although the yield was very small at these low proton energies.

At about the same time the team of Urey, Murphy and Brickwedde succeeded in concentrating the suspected heavy isotope of hydrogen, which was named deuterium (${}_1\text{H}^2$ or simply D). Later on a heavier, radioactive isotope of hydrogen was discovered, tritium (${}_1\text{H}^3$ or T). These isotopes of hydrogen were found to have substantial use in accelerators used as neutron sources. For example, bombarding a deuterated target (initially frozen "heavy water," D_2O , later with the gas molecules "bound" in a solid target material) with deuterium ions will produce copious quantities of neutrons with a Q of +3.29 MeV. By bombarding a tritiated target with deuterons, the neutron producing reaction has a Q of +17.6 MeV. Both of these reactions will proceed at fairly low energies and neutron generators using these materials usually operate at potentials of 50 to 150 kV. The deuterium-deuteron reaction, $\text{D}(d,n)$, is:



Since two particles are produced, the Q gets shared. The neutrons that are produced have an energy of about 2.5 MeV. The tritium-deuteron reaction, $\text{T}(d,n)$, is:



The neutrons produced have an energy of about 14 MeV.

These remain the principle reactions for neutron production. A typical laboratory-scale neutron generator is shown in Figure 1. These will occupy a small room and can be used to produce neutrons fluxes in the range of 10^{11} neutrons/sec. There are a wide variety of other reactions with protons or deuterons bombarding targets composed of various light elements. In addition to alpha particle and neutron production, some reactions will produce gamma radiation. A few of these reactions will be mentioned later. Next we will look at some practical applications of neutrons and some compact devices for the production of neutrons.

III. SHIELDING NEUTRON SOURCES

Like all forms of radiation, neutrons have dangerous as well as beneficial properties. In this section we'll look at some considerations with regard to the shielding of neutron sources. *Please note*, there is nothing quantitative in this section. If you have any desire to create and play with neutrons, get some expert advice with regard to hazards and protection.

The properties of neutrons makes efficient shielding a more complicated affair than, for example, shielding from x-rays. Neutrons have to be slowed down and captured.

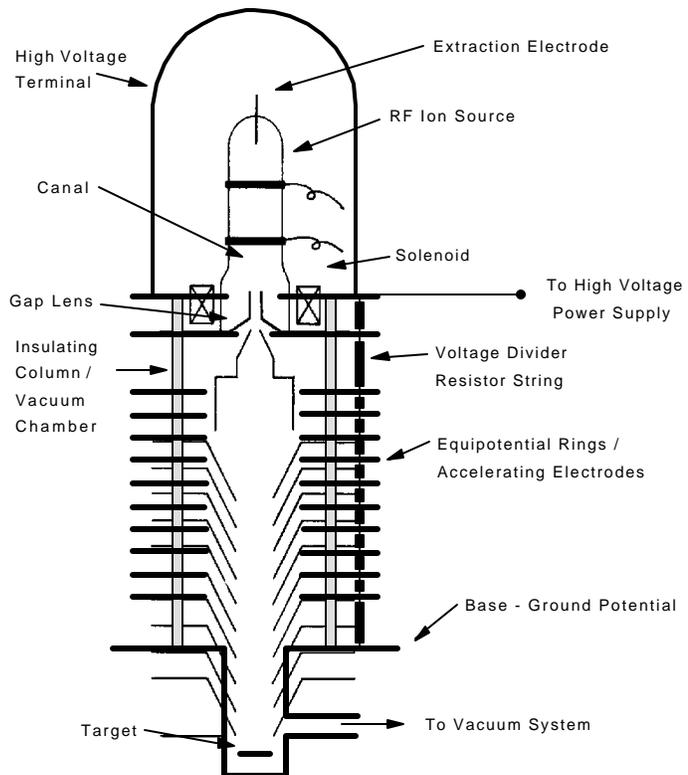


Figure 1 - Potential Drop Neutron Generator

But this process results in additional forms of radiation being produced and these have to be addressed as well.

Fast neutrons, the high energy particles that emerge from an accelerator target or from a reactor, are slowed down, or moderated, to lower energies by placing a suitable material in the path of the neutrons. Hydrogen rich substances are quite efficient at doing this as neutrons will lose more energy per collision with light atoms than with more massive substances. Efficient moderators include water, plastics and paraffin. This is one reason why nuclear reactors are immersed in tanks of water.

This process slows down the neutrons to energies that may only be a fraction of an eV. Neutrons with energies of less than 1 eV are called thermal neutrons.

Since humans are mostly water, if you are standing in the way of a beam of neutrons, you will have a strong moderating effect. While this may be of benefit in a heated discussion, it's not so good with neutrons. The slowing of the neutrons will cause damage and will induce other nuclear reactions. For example, if a thermal or near thermal neutron is captured by hydrogen, a gamma ray will be released. The neutrons will have essentially created an x-ray machine inside your body. Some substances will become radioactive as a result of exposure, causing the release of radiation even after the source of neutrons has been removed. Aluminum under neutron exposure will transmute to two different radioisotopes. One, Mg^{27} , releases 0.84 and 1.02 MeV gamma rays and has a half life of 9.5 minutes. The other, Na^{24} , releases 1.37 and 2.75 MeV gamma rays and has a half life of 14.9 hours. Other materials will have their own unique characteristics.

So, when considering how to shield a neutron source once the neutrons have been moderated, the tactic is to select a material that doesn't become radioactive (or has a very short half life) and emits radiation that is not too penetrating and is therefore easy to absorb. Boron is an effective material. It transmutes to lithium with the release of a 2.3 MeV alpha particle, a particle that is easy to stop.

So, a typical laboratory neutron generator might be surrounded by a couple feet of water or polyethylene, a quarter-inch of boric acid and then some concrete.

The propensity for neutrons to induce radioactivity in other materials have helped them to achieve a rather nasty reputation. On the other hand, this property makes neutrons very valuable as an analytical tool.

IV. NEUTRON ACTIVATION ANALYSIS

As has been discussed in the previous section, when a neutron interacts with matter, it will usually produce a nuclear reaction that will result in the release of other

forms of radiation. The neutron induced radiation can be in the form of an instantaneous or prompt effect, or it can be delayed.

Neutron activation analysis, or NAA, is a highly sensitive analytical technique that is used to determine the elemental content of materials, from the major constituents down to the trace components (often at the part-per-billion level). While other analytical methods exist, NAA is recognized as the "referee method" of choice when new procedures are being developed or when other methods yield results that do not agree. Folks who keep track of such things state that about 100,000 samples undergo NAA analysis every year.

NAA is sort of like sonar: you emit some radiation with known characteristics and observe what comes back. With NAA, you produce a pulse of neutrons which irradiates a sample. The sample becomes activated and then emits secondary gamma radiations as the excited nuclei in the sample decay. The reaction that is induced and monitored is referred to as neutron capture and takes the form (n, γ) . There are two types of response: 1) prompt radiations which result when the excited nuclei quickly de-excite (decay) into more stable configurations through the emission of one or more characteristic gamma-rays and 2) delayed radiations when the reaction(s) yield radioactive nuclei which decay at a slower rate according to the nuclei's half-lives. Half-lives of radioactive elements can range from milliseconds to years. Usually it is the delayed "signature" that is analyzed in the NAA technique. The full name for this is delayed gamma-ray neutron activation analysis or DGNAA. A complete NAA system includes the neutron source, a gamma radiation detector, and a catalog of all possible reactions that happen when neutrons interact with various nuclei.

Fields where NAA is used include archeological specimen analysis, biochemistry, epidemiology, forensics and semiconductor manufacturing technology. In these fields, the samples are usually brought to the analysis facility. Another significant area for NAA is mineral (e.g. oil and gold) exploration. Here the NAA facility usually has to be brought to the sample, usually deep down in a bore hole. This precludes the use of bulky lab-scale neutron generators and has led to the development of a variety of compact sealed accelerators.

V. WELL LOGGING AND COMPACT NEUTRON SOURCES

NAA is routinely used in a technique called radioactive assay well logging. It is a convenient way to determine what materials exist at what depths in a borehole. To perform this sort of *in situ* NAA, the neutron generator and detectors must be small enough to be lowered into

the well. Figure 2 schematically illustrates this type of apparatus [1].

A variety of compact accelerators have been developed for neutron production. Common features include sealed tubes which contain low pressure deuterium or a deuterium/tritium mixture. At opposing ends of the tube are the ion source and target. The target may contain deuterium or tritium gas depending upon the type of tube.

Figure 3 is a cross-section of a sealed tube of this type [2]. The ion source is of the cold-cathode Penning variety and the fill gas is a 50/50 mixture of deuterium and tritium.

The ion source occupies the left side of the device and its major components include a permanent magnet (36), pole piece (38), chamber (52), ring anode (50) and grid structure (54). The target (66) is of the occluded type and is made of titanium. The titanium reacts with the fill gas to form hydrides making the target rich in the atoms of deuterium and tritium. Between the ion source and the target is an electrode structure (68 and 70) that is biased slightly negative with respect to the target. This serves to suppress secondary electrons which are emitted by the target.

The annular region (44) around the ion source contains a titanium sleeve and a heater. Since the gas content of titanium can be modified by changing its temperature, the adjacent heater is used to regulate the internal pressure of the tube. This is not unlike the pressure regulators used in early cold-cathode x-ray tubes.

EMR/Schlumberger manufactures a neutron generator similar to this, the main difference being that the ion source is of the hot-cathode type. The tube itself is about 20 inches long, 3.5 inches in diameter, produces up to 2×10^8 neutrons per second (D-T) or 2×10^6 n/s (D-D) and costs about \$40k, power supply and NRC licensing extra.

VI. A SIMPLE DEVICE BY GOW AND RUBY

In the late 1960s while I was building my ill-fated van de Graaff neutron generator I discovered an article in *Review of Scientific Instruments* [3] about a simple apparatus that did the same thing. The article, *Simple, Pulsed Neutron Source Based on Crossed-Field Trapping*, was authored by James D. Gow and Lawrence Ruby of the Lawrence Radiation Laboratory. It was this article and the discovery of plasma accelerators that stopped my pursuit of traditional potential drop accelerators.

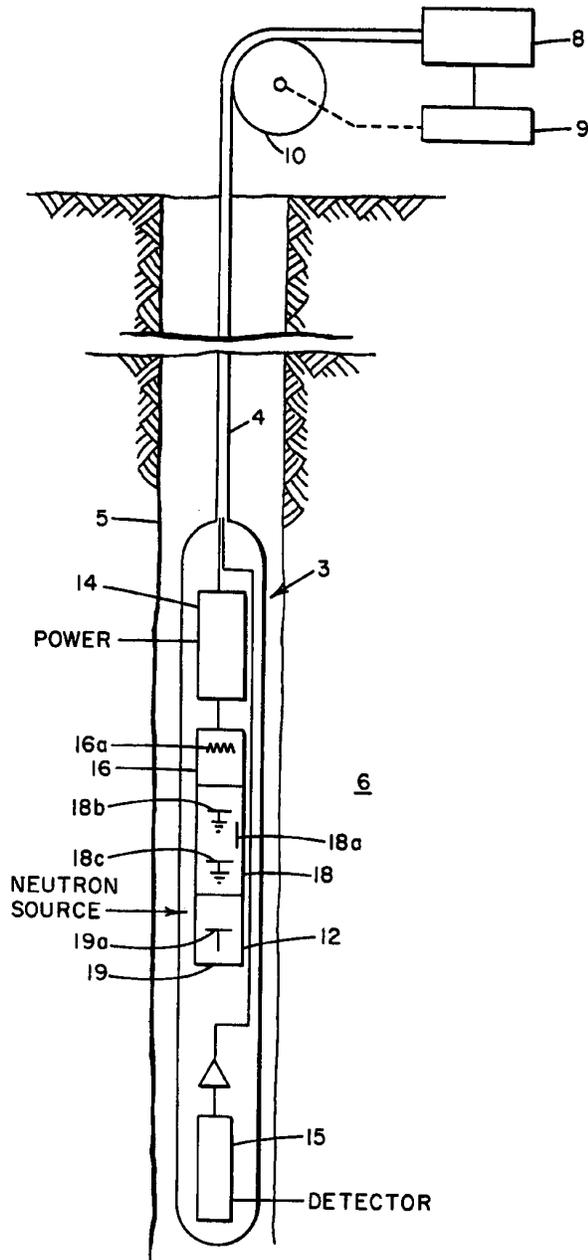


Figure 2 - Well Logging System. Illustration from U.S. Patent 4,310,765, W.W. Givens,

My version of the device is shown in Figure 4. It is essentially a simple discharge tube except that the anode structure consists of a stack of face magnetized ceramic magnets. As stated by Gow and Ruby:

“The theory of operation of this neutron source evolved from the study of several other crossed-field ion-trapping devices. Consider the region adjacent to the side of the anode corresponding, for example, to the north magnetic pole. An electron

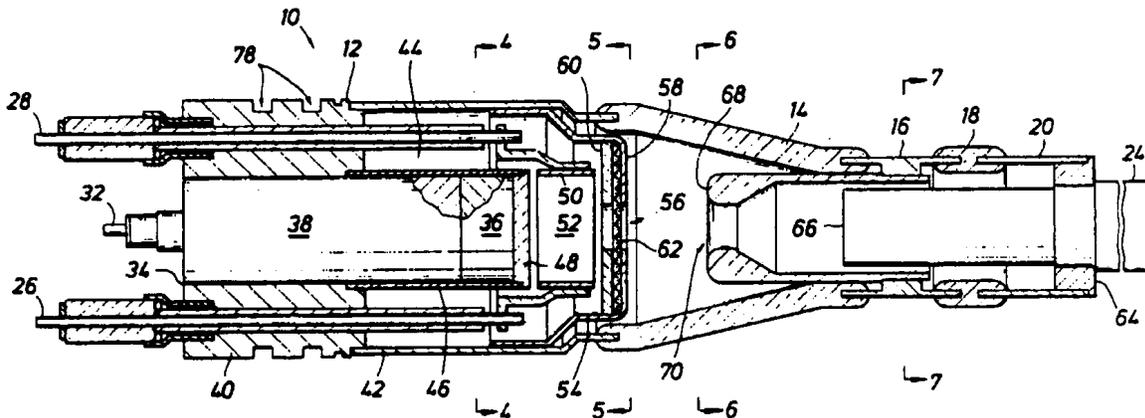


Figure 3 - Neutron Generator Tube. Illustration from U.S. Patent 4,996,017, D.R. Ethridge, Halliburton

born in this region is accelerated toward the anode by the electric field. The radial component of the magnetic field, acting on the axial velocity thus acquired, deflects the motion towards the positive azimuthal direction, finally returning the particle to the axial plane from which it originally came. The force due to the axial component of the magnetic field on the azimuthal component of velocity is directed toward the axis, and results in a composite motion in the form of cycloids which encircle the axis. During these excursions an ionizing collision can occur which releases another low-energy electron and moves the average axial position of the first electron slightly toward the anode. Thus electrons can be trapped and multiplied in such a configuration of fields.”

The electrons that are on-axis are not trapped by this mechanism but are accelerated into the throat of the magnet assembly. The throat forms another region of intense ionization. The illustration attempts to show the general appearance of the plasma in the anode region.

What it all boils down to is that the magnets increase the amount of ionization and also modify the electric potential distribution through the tube.

Gow and Ruby made two devices. One was like the apparatus in the figure. It could be operated as a steady state device (typically 100 kV and 2-3 mA) as long as the electrodes were water cooled. Otherwise it would be operated in a pulse mode using an impulse transformer.

Impulse currents could be as high as 15 amperes at an indicated (ion gauge) pressure of 12 milliTorr.

The other configuration was double-ended with a cathode on each side of the anode. Only one cathode served as a neutron emitting target. This configuration minimized heavy electron bombardment at the end of the anode.

Gow and Ruby noted that the device would not pass appreciable currents until a pressure of about 9 milliTorr was reached, whereupon the current would rise steeply. Best operating conditions occurred from about 10 to 18 milliTorr. With a deuterium fill and a deuterated target, the source would produce about 10^8 to 10^9 neutrons/sec at peak voltages from 70 to 140 kV.

My device is currently operating with air and a mechanical pump. The magnets are surplus and were obtained from American Science and Surplus (847-982-0870) as part number 3383 and are 2-3/8 inch in diameter, 1/2-inch thick and with a 7/8 hole. The chamber is an Ace Glass (800-223-4524) cylindrical addition funnel, catalog number 5822-15. I haven't yet unleashed my 350 kV impulse transformer on it but instead am using a 50 kV current-limited induction coil. At a pressure of around 30 milliTorr it does produce noticeable quantities of x-rays.

In looking at the various nuclear reactions that are within reach of this device, it might be interesting to try some of the ones that are induced by protons. One good reason for this is that protons come from hydrogen, a

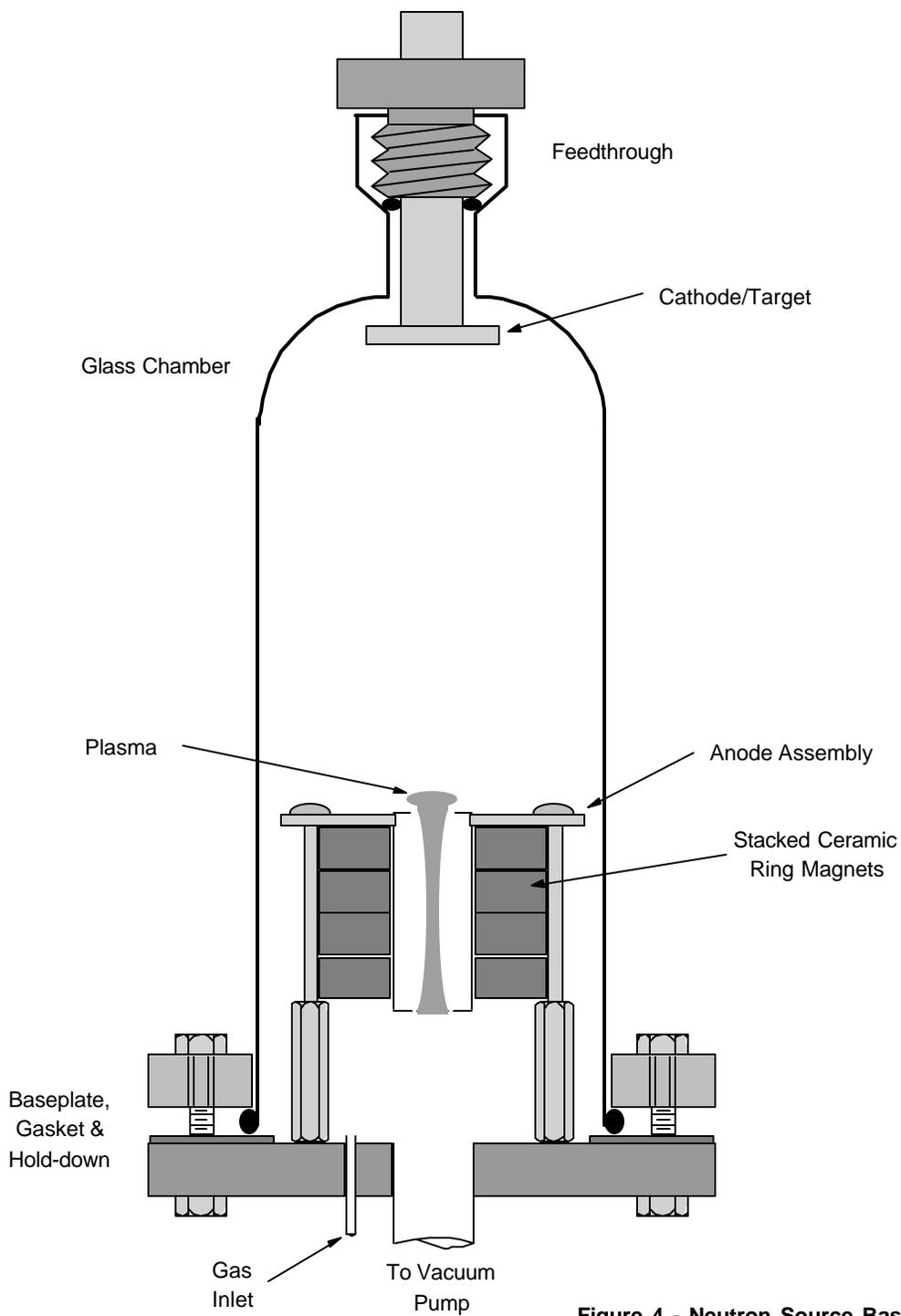


Figure 4 - Neutron Source Based on Crossed-Field Trapping (after Gow and Ruby)

much cheaper gas than deuterium. Lithium, as used by Cockcroft and Walton, is one target material that produces gamma-rays when bombarded by protons. This requires an incident energy of about 440 keV, perhaps a bit on the high side for my apparatus. A proton induced reaction that goes at energies as low as 227 keV is the $F^{19}(p, \alpha\gamma)O^{16}$ reaction. The gamma-rays that are produced have energies of 6.7 to 7.1 MeV. A typical fluorine-containing target material is a thin coating of DuPont Teflon[®]. There will be more on this device in an upcoming issue.

Up to this point, all of the devices have involved a beam of charged particles impinging on a solid target. There is another class of neutron generator which produces the fusion reaction by means of confinement of the plasma. These range from relatively small devices to large-scale fusion reactors. The next section will talk about a type of device that I have a certain fondness for. This one doesn't even require high voltages to make the nuclear reactions go. Instead, the apparatus makes use of intense currents and magnetic fields created by those currents to produce very hot plasmas. The following article by Richard Hull will discuss another type of apparatus that uses electrostatic confinement to produce the conditions for fusion. Both of these devices are well within the capabilities of amateurs.

VII. THE DENSE PLASMA FOCUS

Plasma accelerators have been discussed in these pages in the past (see Vol. 1, No. 2 for some basics and Vol. 2, No. 1 and Vol. 3 No. 3 for designs of simple coaxial plasma guns). The creation and acceleration of dense plasmas became a "hot" topic in the 1950s for such diverse applications as rocket propulsion, aerodynamics, chemical synthesis, and power generation.

The controlled fusion program, in the effort to develop techniques to create and confine dense plasmas, did a fair amount of work on plasma acceleration by the $\mathbf{J} \times \mathbf{B}$ force. The simple plasma guns discussed in the issues cited above work on this principle. In 1964 J.W. Mather discovered a mode of operation of the coaxial plasma gun called the *Dense Plasma Focus*. The focus is achieved at the muzzle end of a fast coaxial accelerator (sometimes called a Mather device in honor of the discoverer) where plasma densities can exceed $10^{19}/\text{cm}^3$ and temperatures may be in excess of a few thousand keV. The process is fast, on the order of 100 nsec. The focus is actually a pinch effect (in this case a *z-pinch* as the pinch lies along the *z* (length) axis of the device).

The basic elements of a plasma focus device are a capacitor bank, a fast spark gap switch, a pair of coaxial electrodes, and a vacuum tank. The design has to ensure a fast current rise (low inductance).

The first order description of any specific device is the energy, in Joules (watt-seconds), that is stored in the capacitor bank. Plasma focus devices have been built in a wide range of sizes from 2 kJ to many tens of kJ. The latter usually require a good dose of government-scale funding. The former are the right size for teaching, industrial R&D programs, and hobbyists.

Figure 5 is a simplified illustration of my plasma focus device. (These devices tend to be named, like pets. Examples include unpronounceable acronyms like UNU/ICTP-PFF to friendlier names like NESSI or POSEIDON. Following custom, mine is tentatively named Mini-F.) Energy storage is a single 10 kV, 60 μF (3 kJ) low inductance, single terminal capacitor. The accelerator is located directly above the capacitor with the terminal connected to the center electrode through a triggered spark gap.

In its first incarnation, the center conductor is 7/8" od copper tubing. The outer conductor is 3" id copper tubing. A critical part of the device is the glass insulating sleeve that surrounds the first inch or so of the inner conductor. It is over this sleeve that the discharge is initiated. The electrodes are 6" in length.

The operation of the plasma focus device is divided into three phases. Each of these is shown in Figure 6:

- 1) The *breakdown phase* in which the voltage pulse that is applied across the electrodes when the spark gap is triggered breaks down over the insulating sleeve. Upon breakdown, a current front is formed and the plasma lifts off from the sleeve.
- 2) The *axial rundown phase* where the current sheath moves down the length of the electrode. The motion is caused by the aforementioned $\mathbf{J} \times \mathbf{B}$ force where \mathbf{J} is the current vector that goes up the inner electrode, across the gap, and down the outer electrode (assuming a positive center electrode). Invoking the right-hand rule, the resulting magnetic field, \mathbf{B} , encircles the inner electrode (counter clockwise looking down the gun from the muzzle end) and the force applied to the plasma, \mathbf{F} , is directed to the muzzle. If you are proficient with your right hand, you will note that if the electrode polarities are reversed, the force vector remains pointed in the same direction. Therefore, it really doesn't matter, at least from the standpoint of rundown, how the electrodes are biased or even if the discharge rings. During the rundown phase, the plasma front will accelerate to a velocity on the order of 10^8 cm/sec and the discharge current will reach levels in excess of 100 kA.
- 3) The *pinch phase*. When the current sheath reaches the muzzle of the accelerator it collapses

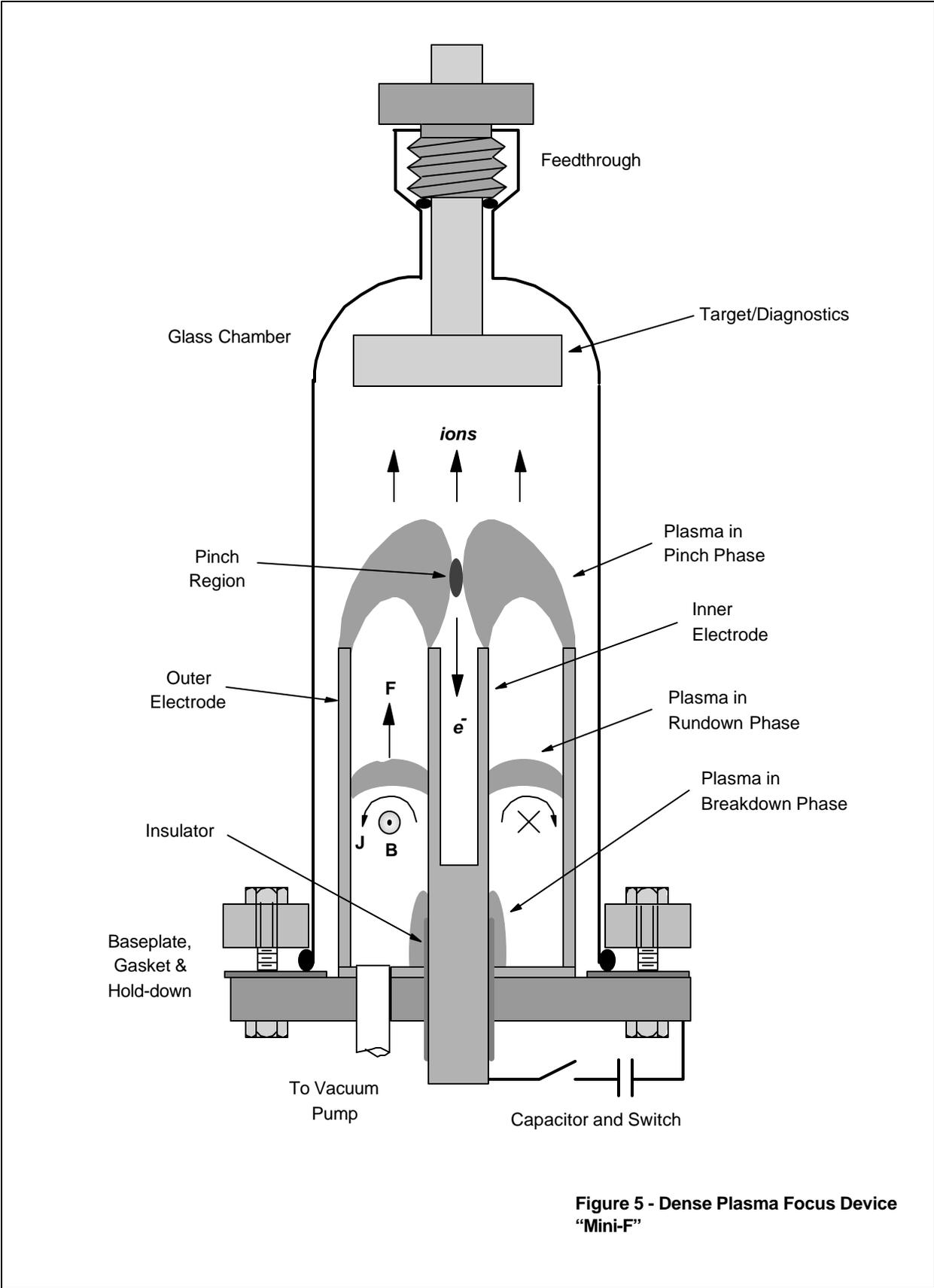


Figure 5 - Dense Plasma Focus Device "Mini-F"

toward the axis due to the geometry of the magnetic field. This collapse creates a small region of high density plasma just beyond the end of the center electrode. This phase is sometimes more dramatically described as the *radical pinch phase*.

A number of factors have to come together to make the device work properly. Significant ones include the geometry of electrodes, the geometry of insulator sleeve, type of fill gas, pressure of the fill gas, rate of rise of the discharge current (the steeper the better) and electrode polarity (a positive inner electrode usually improves the focus action).

If the fill gas is deuterium, the conditions in the pinch are suitable for fusion. A modest plasma focus device will produce about 10^6 neutrons per pulse at a pressure of 1-5 Torr. The focus is also a strong source of soft x-rays. X-ray production does not require any specific fill gas, however it tends to be enhanced with heavier ions such as argon or neon. This has led to the plasma focus being investigated as a point x-ray source for fine-feature semiconductor lithography.

The plasma beam does not stop at the muzzle. It continues along becoming fairly homogeneous a short distance away from the exit of the electrode structure. The composition of the plasma is dependent upon the electrode material and the fill gas. This has promise in terms of processes for materials modification. For example, with a nitrogen fill, titanium inner electrode and graphite outer electrode, a wear-resistant film of titanium carbonitride [Ti(CN)] can be deposited on a substrate [4]. A number of other interesting applications are discussed in a patent assigned to 3M Corporation [5].

Finally, the pinch produces a beam of high energy electrons. These are directed back toward the center conductor. If the conductor is hollow, the beam will propagate through the tube.

My Mini-F is being built mostly to study x-ray emission and for materials modification studies. There will be more about this device as I continue to characterize it.

For those who are interested in learning more about small plasma focus devices, references 6 and 7 provide a good grounding.

CITED REFERENCES

- [1] Wyatt W. Givens, U.S. Patent 4,310,765, issued 12 Jan. 1982.
- [2] D. Ray Ethridge, U.S. Patent 4,996,017, issued 26 Feb., 1991.
- [3] James D. Gow and Lawrence Ruby, *Simple, Pulsed Neutron Source Based on Crossed-Field Trapping*, Review of Scientific Instruments, **30** (5), pg. 315, May 1959.
- [4] P.X. Yan, S.Z. Yang, B. Li and X.S. Chen, *High Power Density Pulsed Power Plasma Deposition of Titanium Carbonitride*, J. Vac. Sci. Technol. A, **14** (1), pg. 115, Jan/Feb 1996.
- [5] Andrew Ouder Kirk, Douglas Dunn, Edward Yu and Susan Bohlke, *Surface Modification by Accelerated Plasma or Ions*, U.S. Patent 5,389,195, issued 14 Feb., 1995.
- [6] S. Lee *et al.*, *A Simple Facility for the Teaching of Plasma Dynamics and Plasma Nuclear Fusion*, Am. J. Phys. **56** (1), pg. 62, Jan. 1988.
- [7] S. Lee and P.H. Sakanaka, Eds., *Small Plasma Physics Experiments*, World Scientific, Singapore, 1988.

FURTHER READING

- Steven Weinberg, *The Discovery of Subatomic Particles*, W.H. Freeman and Co., New York, 1990.
- Irving Kaplan, *Nuclear Physics*, Addison-Wesley Publishing Co., Cambridge, MA, 1955.