Inertial Electrostatic Confinement Fusion: Suitability for Neutron Production

Charles Vorbach

November 5, 2015

Abstract

Inertial Electrostatic Confinement (IEC) is a method of using electric potential wells to contain plasmas at energies suitable for fusion. IEC fusion devices are of potential interest as neutron sources for neutron analysis as well as for use in neutron capture therapies. This paper attempts to inform evaluations of the usefulness of the deuterium-deuterium reaction in IEC devices as a neutron source by measuring the fusion rate and neutron flux produced at several different voltages by one IEC device design.

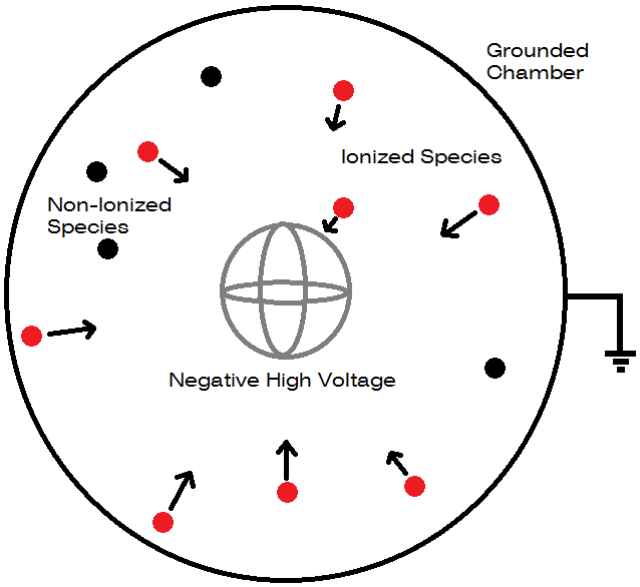
1 Introduction

IEC devices confine non-Maxwellian plasmas using electric fields. As shown in Figure 1, the basic mechanism uses a high voltage difference between a negatively charged wire cage cathode and a grounded metal chamber to ionize a low-pressure deuterium (${}^{2}_{1}\mathrm{D}$) atmosphere. The ionized deuterons are accelerated towards the inner cathode. They collide in a point-like poisor and, if the potential between the chamber and cathode is high enough, some deuterons fuse into tritium (${}^{3}_{1}\mathrm{T}$) or helium (${}^{3}_{2}\mathrm{He}$) through the reactions ${}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$ and ${}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{1}\mathrm{T} + {}^{1}_{1}\mathrm{p}$. Rider [8] as well as Miley and Murali [7] provide a more through examination of IEC fusion schemes and their limits. Of interest to this paper, however, is that the deuterium-deuterium reaction produces a fast neutron with $2.45 \times 10^{6}\,\mathrm{eV}$.

Neutrons play a crucial role in several scientific fields. Neutron activation analysis (NAA) is a highly sensitive and accurate elemental analysis technique which can nondestructively determine the composition of bulk materials. NAA has long been an important tool in fields ranging from the environmental sciences to geochemistry [2]. Neutrons are also used in neutron capture therapies - potential treatments for primary high-grade brain cancers. In these techniques, patients are administered a tumor-seeking compound containing an isotope with a high cross section for thermal neutrons. The patients are then exposed to a low neutron dose which activates the isotope, producing a gamma ray and destroying the cell containing the isotope. Research on this technique is ongoing [10].

The numerous practical applications of neutrons create a need for an inexpensive and easy-to-operate source. Several solutions do currently exist, but all have drawbacks.

Figure 1: Basic IEC Device



Radioisotopes are one type of neutron source. Large $^{252}_{98}$Cf sources can produce 1×10^{11} $n \cdot sec^{-1}$ through spontaneous fission and are available for less than $50,000. These sources, however, must be replaced frequently due to $^{252}_{98}$Cf's relatively short half-life of 2.65 years [6]. Alpha-emitting isotopes embedded in low-Z elemental matrices can also produce neutrons through the alpha-neutron reaction. Americium-beryllium or plutonium-carbon mixtures would be examples of this type of neutron source. These sources produce a somewhat lower neutron rate, usually around 1×10^6 $n \cdot sec^{-1}$, but are longer-lasting and often less costly [11]. All radioisotope sources emit constantly - necessitating rigorous safety precautions, complicating their use, and making transportation difficult.

For higher neutron rates and fluxes, we must turn to more complex devices. Neutrons can be produced from relatively small and moderately expensive neutron generators which produce neutrons by accelerating deuterium or tritium into a metal hydride target also containing one or both of these materials. These sources typically can produce neutron fluxes of up to 1×10^8 $n \cdot sec^{-1} \cdot cm^{-2}$ and can cost approximately $100,000. [5] They have the added advantage that they can be turned off and on - unlike radioisotope sources - and require fewer precautions to safely use. However, their moderate neutron flux and relatively high cost limits these devices' usefulness.

For the highest neutron rates, we must turn to fission reactors and linear accelerators. Reactor sources, such as the High Flux Isotope Reactor at Oak Ridge National Laboratories, can provide a flux of up to 1×10^{15} $n \cdot sec^{-1} \cdot cm^{-2}$ [3]. Accelerator spallation sources, such as the Spallation Neutron Source also at Oak Ridge National Laboratories, can produce the very highest neutron fluxes of up to 1×10^{16} $n \cdot sec^{-1} \cdot cm^{-2}$. These facilities require enormous and continuing investments of hundreds of millions of dollars [4].

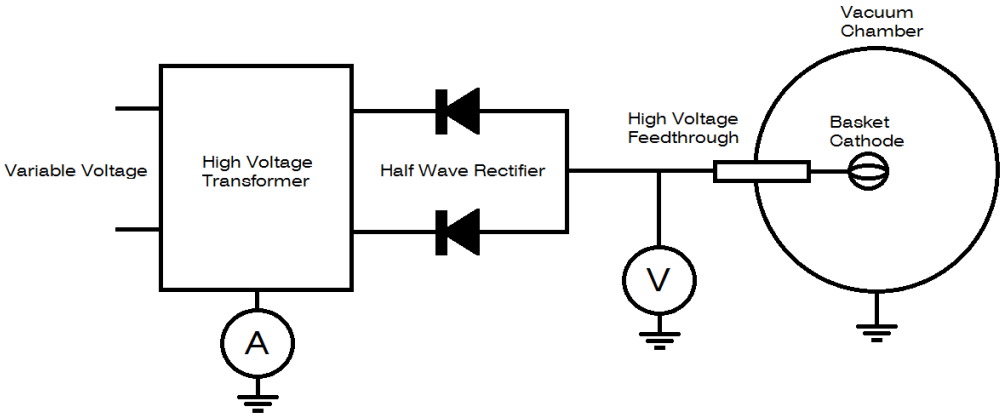
In order to be a viable alternative to traditional neutron sources, IEC devices would have to provide advantages over one of the solutions proposed above. That is to say, they would have to provide similar neutron fluxes at a lower cost or in some way be easier to operate than one of those sources.

2 Methods and Materials

2.1 Experimental Apparatus

The IEC fusion device used to collect data was constructed from several subsystems: a high voltage supply, deuterium supply and leak, vacuum system, and neutron counter. This section will briefly describe the construction of and assembly of each of these.

Figure 2: Diagram of High Voltage Supply

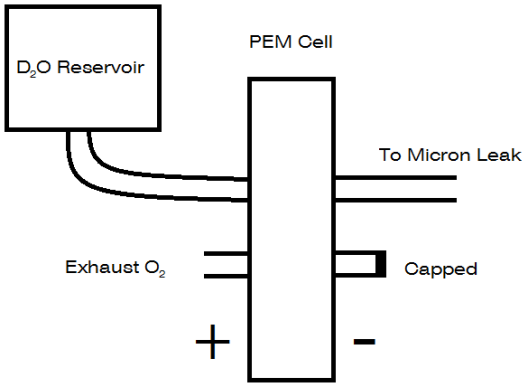


The high voltage supply consisted of a repurposed x-ray transformer, high voltage half-wave rectifier circuit, high voltage vacuum feedthrough, and basket cathode as well as an inductively ballasted variable low-voltage supply and high voltage current and voltage meters. These were assembled as shown in Figure 2.

The vacuum system was built from two 2.00×10^{-3} m thick 1.52×10^{-1} m outer diameter stainless steel hemispheres welded into two 2.03×10^{-1} m outer diameter conflat ring flanges. Each hemisphere had three 3.81×10^{-2} m bores drilled in it. Four KF and two CF flange stubs were welded into these six bores. The resulting chamber was spherical with an inner diameter of 1.52×10^{-1} m. An Edwards EO50/60 diffusion pump was installed onto the chamber and a Welch DuoSeal 1400 mechanical pump was connected to the diffusion pump to complete the system.

The deuterium supply was constructed from a proton exchange membrane (PEM) cell connected to a reservoir of D_2O and exhaust port. The opposite side of the PEM cell was connected to a mineral oil bubbler and to an adjustable micron-gap needle as shown in Figure 3. This needle connected the deuterium supply to the vacuum chamber.

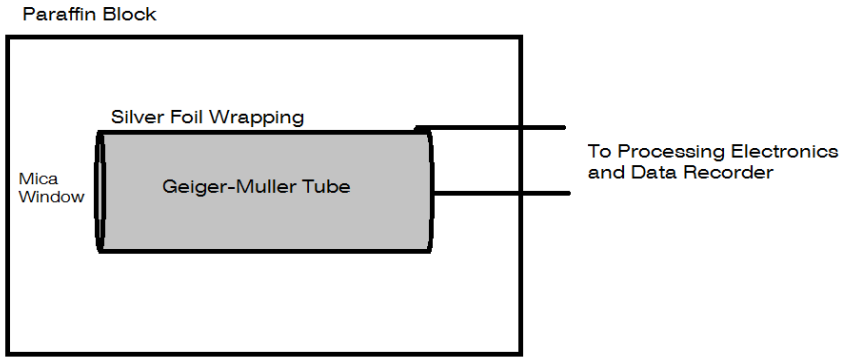
Figure 3: Diagram of Deuterium Supply



The neutron counter was constructed from a Geiger-Muller counter with a $1.26 \times 10^{-2}\,\mathrm{m}^2$ mica window, paraffin moderator, and $8.0 \times 10^{-5}\,\mathrm{m}$ thick silver foil. As shown in Figure 4, the counter tube was wrapped in silver foil and inserted into the moderator. The tube was then connected to the rest of the counter system. This counter system was monitored by a microcontroller which allowed for accurate timing of data recording sessions. The moderator-encased tube was placed over the chamber body with the mica window facing towards the chamber.

The neutron detector counts neutrons by measuring the activation of the silver foil. Naturally occurring silver contains two isotopes, ${}^{107}_{47}\mathrm{Ag}$ and ${}^{109}_{47}\mathrm{Ag}$, both of which can capture a neutron, decay into cadmium, and release a beta particle. The mixture of these isotopes in natural silver has a relatively high cross section for neutron absorption, $6.33 \times 10^{1}\,\mathrm{b}$, at thermal energies [9]. Neutrons are detected by measuring these beta particles.

Figure 4: Diagram of Neutron Detector



2.2 Experimental Procedures

Three experiments of four trials were performed at three different voltages. In each trial, the apparatus was run at the treatment voltage for a 20.00 minute period without introducing deuterium gas while data was recorded. This data set formed the control group for the trial. Then deuterium gas was introduced and the system was run at the same voltage for another 20.00 minute data recording period. This data set formed the experimental group for the trial.

Each treatment was performed over several hours on different days. In preparation, the vacuum system was evacuated using the mechanical pump to approximately 1 Pa over a twenty-four hour period. The high vacuum pump was then activated to further reduce the pressure to around 1×10^{-2} Pa. This process took around four hours.

Having prepared the system, the voltage across the chamber was then slowly raised to the treatment value. After a 'tuning' period, voltage, current, and pressure stabilized. At this point, the data recorder was activated and the 20.00 minute data recording session began.

Having recorded control data, the deuterium supply was activated and deuterium allowed to slowly leak into the system. After waiting for an approximately 20 minute period for the system to purge itself of air, a second data recording session was begun.

This process was repeated four times for each treatment. Between each trial, the system was allowed a 20 minute period to purge itself of deuterium.

2.3 Statistical Methods Used

Four trials measuring the control and experimental runs were made for each treatment. For each run, the number of counts produced by the neutron detector was measured by the data recorder. This sample n_s approximates n, the true mean number of counts. Counts are produced by a random process so it can be shown that σ, the standard deviation of counts, is equal to $\sqrt{n}$ using Poisson statistics. σ can then be approximated by using $\sigma_s = \sqrt{n_s}$. Therefore, the estimate for the counts of each trial is $n_s \pm \sigma_s$.

From this interval for the number of counts, an interval for the counting rate can be constructed. The counting rate interval is equal to $\frac{n_s}{T} \pm \frac{\sigma_s}{T} = R_s \pm \sqrt{\frac{R_s}{T}}$ where T is the length of the recording session.

Using these counting rates for the control and for the experimental runs, the number of counts attributable to neutrons produced as a by-product of deuterium-deuterium fusion can be found. The experimental run included the background count and any neutrons counted while the control run only included the background count. Therefore, $R_n = R_e - R_c \pm \sqrt{(\delta R_e)^2 + (\delta R_c)^2}$ where R_n is the neutron count rate, R_e is the experimental count rate, and R_c is the control count rate.

Using these methods, the differences in number of neutrons counted between treatments can be shown. Predicting the number of neutrons produced by the device, however, is a more involved problem which requires several simplifying assumptions.

For the purposes of these estimations, the counter tube is assumed to have perfect efficiency and the interactions between neutrons and moderator and between beta particles and silver foil are ignored. The first assumption is reasonable because Geiger tubes have a high efficiency for beta particles of the energy produced. Justifying the second, the effects of the moderator and foil are relatively small and ignoring them greatly simplifies calculation.

Since the neutrons are measured indirectly through their interaction with a 8×10^{-5} m Ag foil, the flux can be found from the number of beta decays detected. The induced beta decay activity detected is $A_b = \frac{1}{2} N \sigma_{Ag} x \Phi_i$ where N is the number of target nuclei, σ_{Ag} is the absorption cross section of natural Ag, x is the thickness of the foil, Φ_i is the incident neutron flux, and A_b is the detected beta activity. The coefficient of $\frac{1}{2}$ represents that beta particles emitted away from the tube will not be detected.

Having calculated the incident neutron flux, the total number of neutrons being produced per second can be calculated by finding the area of a sphere with radius 2.28×10^{-1} m, the distance of the detector, centered at the central cathode of the apparatus. Then, knowing that the two deuterium reactions ${}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$ and ${}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{1}\mathrm{T} + {}^{1}_{1}\mathrm{p}$ occur with relative probabilities of 0.51 and 0.49 given a reaction has occurred, we can find the total number of fusions produced per second by multiplying the neutron production rate by $(0.49)^{-1}$ [1].

3 Results

A control count and experimental count were collected for each trial of each treatment. These were used to find the neutron count rate for the three treatment voltages of 3.3×10^4 V, 2.7×10^4 V, and 2.3×10^4 V. These values are listed along with their standard errors in Table 1. A 95% confidence interval for the rate of neutron production for each trial of each treatment voltage was constructed. As can be seen in Figure 5, the rate of neutron production was found to be significantly greater than zero for the treatment voltages of 3.3×10^4 V and 2.7×10^4 V at a 95% confidence level. The null hypothesis that the IEC fusion device does not produce neutrons was disproved for these treatments. For the treatment voltage of 2.3×10^4 V, however, the rate of neutron production was not found to be significantly greater than zero.

The standard deviations of each set of four trials σ were 3.78 and 0.26 respectively for the 3.3×10^4 V and 2.7×10^4 V treatments. The greatest neutron rate detected was $14.35\ n \cdot min^{-1} \pm 1.53\ n \cdot min^{-1}$. The neutron flux Φ_n at 20 cm was then found for the 3.3×10^4 V and 2.7×10^4 V treatments. This value was then used to find total number of fusions produced per second. The results are summarized in Table 2.

The highest neutron flux found was $12.60 \pm 1.36\ n \cdot sec^{-1} \cdot cm^{-2}$ with a fusion rate of $1.29 \times 10^5 \pm 1.40 \times 10^4\ f \cdot sec^{-1}$.

Table 1: Neutron Counter Recordings

Voltage	Control Counts	Experiment Counts	Neutron Rate ($n \cdot min^{-1}$)
33 kV	324 ± 18.00	447 ± 21.14	6.15 ± 1.39
	325 ± 18.02	608 ± 24.66	14.15 ± 1.53
	326 ± 18.06	479 ± 21.89	7.65 ± 1.41
	323 ± 17.98	548 ± 23.41	11.25 ± 1.47
27 kV	322 ± 17.94	391 ± 19.77	3.45 ± 1.34
	322 ± 17.94	404 ± 20.10	4.10 ± 1.35
	323 ± 17.97	402 ± 20.04	3.95 ± 1.35
	322 ± 17.94	394 ± 19.85	3.60 ± 1.34
23 kV	323 ± 17.97	323 ± 17.97	0 ± 1.27
	325 ± 18.03	322 ± 17.94	-0.15 ± 1.27
	323 ± 17.97	321 ± 17.92	-0.01 ± 1.27
	322 ± 17.94	323 ± 17.97	0.05 ± 1.27

Figure 5: Neutron Rates

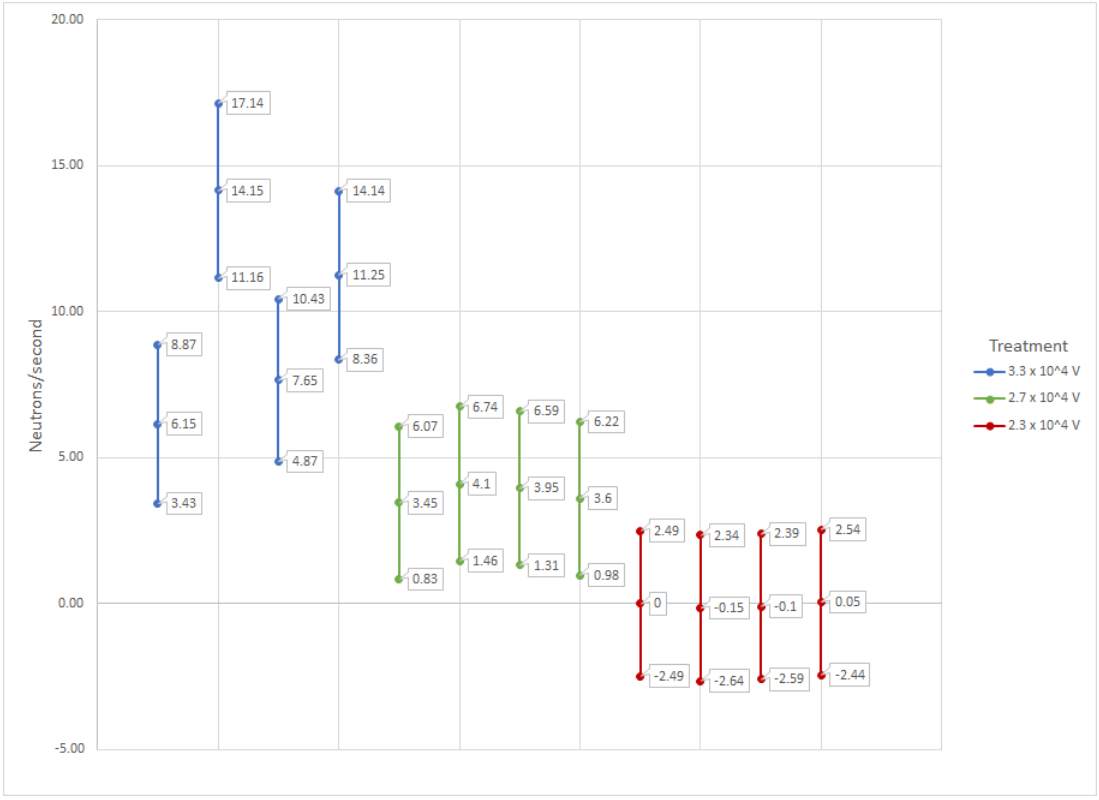


Table 2: Reaction Statistics

Voltage	Neutron Flux at 20 cm ($n \cdot sec^{-1} \cdot cm^{-2}$)	Fusion Rate ($f \cdot sec^{-1}$)
33 kV	5.47 ± 1.24	$5.61 \times 10^4 \pm 1.27 \times 10^4$
	12.60 ± 1.36	$1.29 \times 10^5 \pm 1.40 \times 10^4$
	6.80 ± 1.26	$6.98 \times 10^4 \pm 1.30 \times 10^4$
	10.00 ± 1.31	$1.03 \times 10^5 \pm 1.35 \times 10^4$
27 kV	3.07 ± 1.19	$3.15 \times 10^4 \pm 1.22 \times 10^4$
	3.65 ± 1.20	$3.74 \times 10^4 \pm 1.23 \times 10^4$
	3.51 ± 1.20	$3.60 \times 10^4 \pm 1.23 \times 10^4$
	3.20 ± 1.19	$3.28 \times 10^4 \pm 1.22 \times 10^4$

4 Discussion

The fusion rate and neutron flux found are likely too low to successfully employ IEC fusion devices as neutron sources for most purposes. The highest fusion rate found was $1.29 \times 10^5 \pm 1.40 \times 10^4$ $f \cdot sec^{-1}$ producing a neutron rate of $6.45 \times 10^4 \pm 7.00 \times 10^3$ $n \cdot sec^{-1}$. This neutron rate is similar to that produced by alpha-reaction sources. The neutron flux found was 12.60 ± 1.36 $n \cdot sec^{-1} \cdot cm^{-2}$, necessarily far lower than this rate since the size of the chamber limits how close the detector can be brought to the central cathode.

This low fusion rate and lower neutron flux would appear to disqualify IEC sources from effectively providing the higher fluxes provided by neutron generators, fission reactors, or sputtering sources. It is possible IEC devices might be useful in the range of fluxes typically provided by alpha-reaction isotope sources - in fact, they may have some advantages over them. IEC devices can be switched on and off without leaving residual radiation which could simplify handling and operation. The flux produced can also be controlled by changing the voltage and current provided to the device.

However, IEC devices have their own drawbacks. They are relatively complex devices which require hundreds of watts of power and which break down fairly frequently. IEC devices are difficult to precisely control and take a substantial period of time to 'tune' a stable current, voltage, and pressure. While running, these devices pose a radiation hazard due to the Bremsstrahlung x-rays produced.

While IEC neutron sources may enjoy a few advantages over radioisotope sources, such as the ability to be easily switched on or off, they also have serious drawbacks. They take longer to prepare to use and struggle to maintain a consistent fusion rate. It is unlikely they will become a viable neutron source in the future.

5 Acknowledgments

This work would not have been possible without the help and advice of so many people. I am deeply indebted to them and grateful for their help. Mr. Johnathan Peter, Mrs. Justine McClellan, Ms. Ann Meyer, the amazing Open Source Fusor Research community, Mr. Jim Murry, Mr. Joseph Landy, Dr. Henry Kressel and many others were invaluable to this project. Thank you.

I would be remiss not to thank my parents who have been unbelievably understanding and supportive. Thank you for tolerating a kooky science project monopolizing your garage and waking you up at odd hours. Nothing would have been possible with out you.

References

[1] *Tables of Physical and Chemical Constants (16th edition 1995).* Kaye and Laby Online, 1995, ch. 4.7.4 Nuclear Fusion.

[2] Bode, P., et al. Use of research reactors for neutron activation analysis. Tech. rep., International Atomic Energy Agency, 1998.

[3] Flanagan, G. Description of the high flux isotope reactor and future upgrades. In *Proceedings of the fourth meeting of the International Group On Research Reactors (CONF–9505218)*, International Atomic Energy Agency (IAEA).

[4] Gardner, I., et al. A review of spallation neutron source accelerators. In *Proceedings of the 6th European Particle Accelerator Conference (EPAC 98).*

[5] International Atomic Energy Agency (IAEA). *Manual for troubleshooting and upgrading of neutron generators (IAEA-TECDOC-913)*, November 1996.

[6] Martin, R., and Kos, S. Applications and availability of californium-252 neutron sources for waste characterization. *Oak Ridge National Laboratory* (2000).

[7] Miley, G., and Murali, S. *Inertial Electrostatic Confinement (IEC) Fusion Fundamentals and Applications.* Springer, 2014.

[8] Rider, T. A general critique of inertial-electrostatic confinement fusion systems. Master's thesis, Massachusetts Institute of Technology, 1994.

[9] Sears, V. Neutron scattering lengths and cross sections. *Neutron News* (1992).

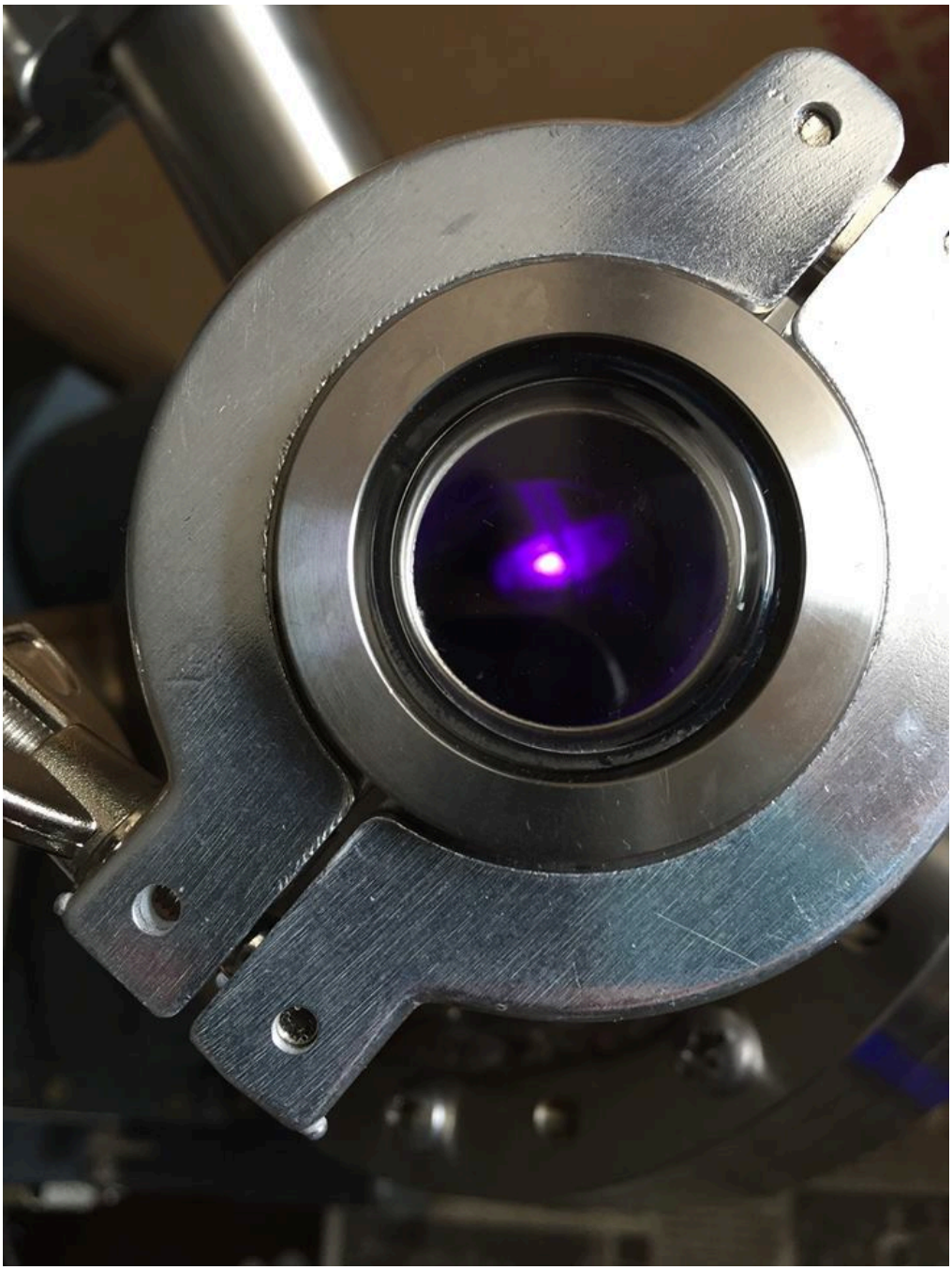
[10] Shokr, A., et al. Current status of neutron capture therapy. Tech. rep., International Atomic Energy Agency (IAEA), 2001.

[11] Uckan, T., et al. *241AmBe Sealed Neutron Source Assessment Studies for the Fissile Mass Flow Monitor.* Oak Ridge National Laboratory.

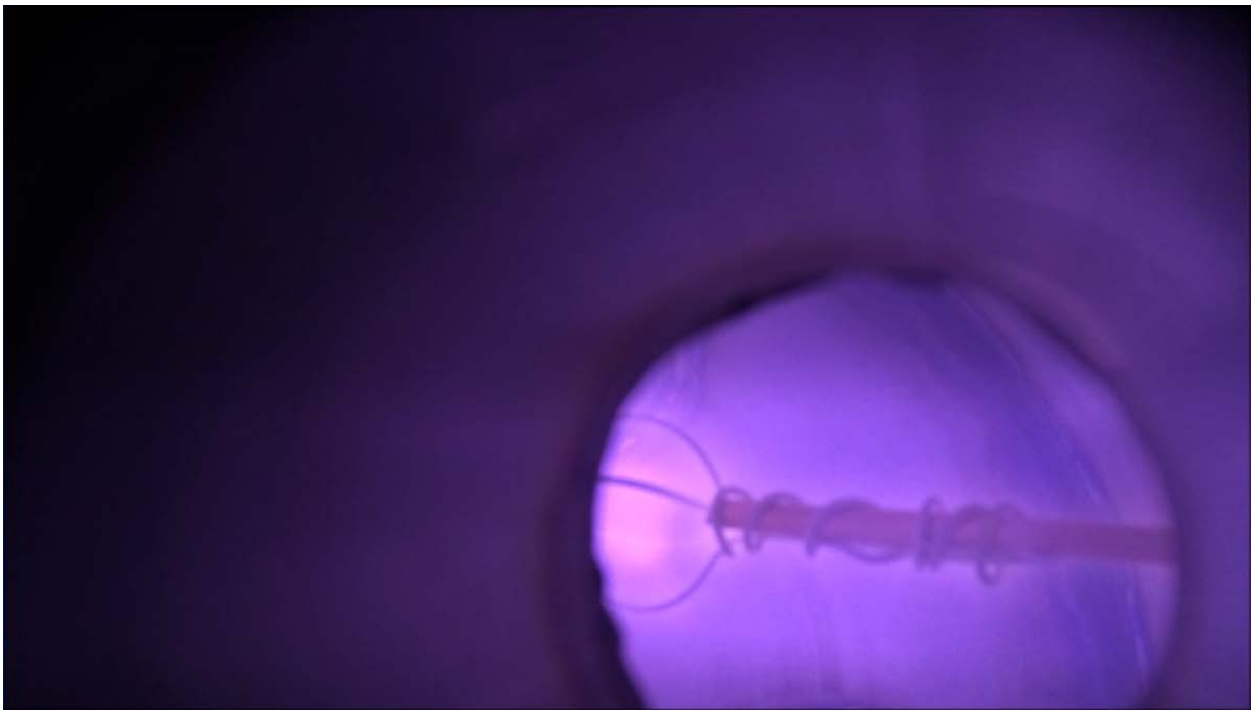
IEC Fusion Photos – Charles Vorbach 2015

Chamber, High Voltage Supply, and Vacuum System

Vacuum Chamber and Diffusion Pump



Low Voltage Plasma



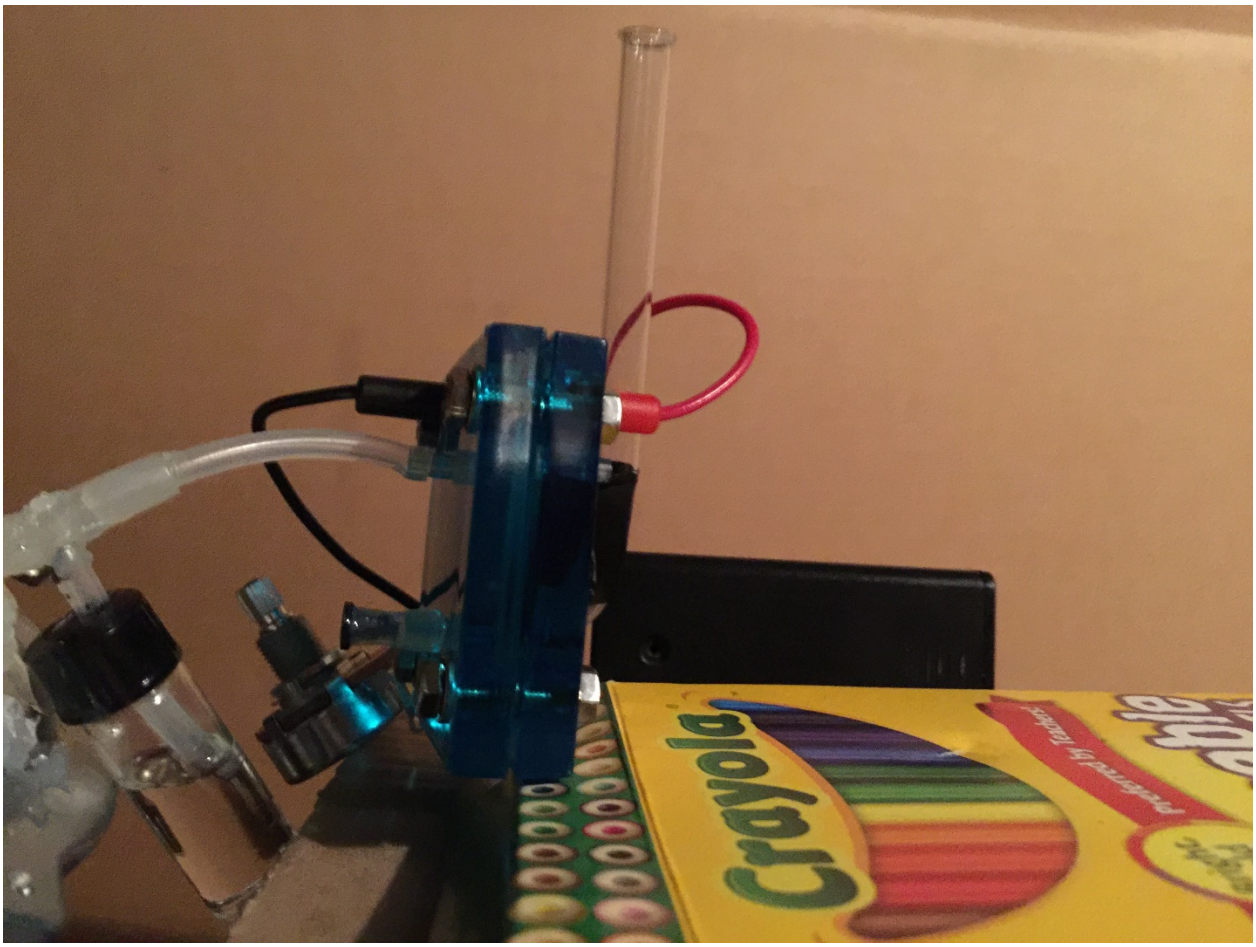
30 kV Plasma

High Voltage Feedthrough

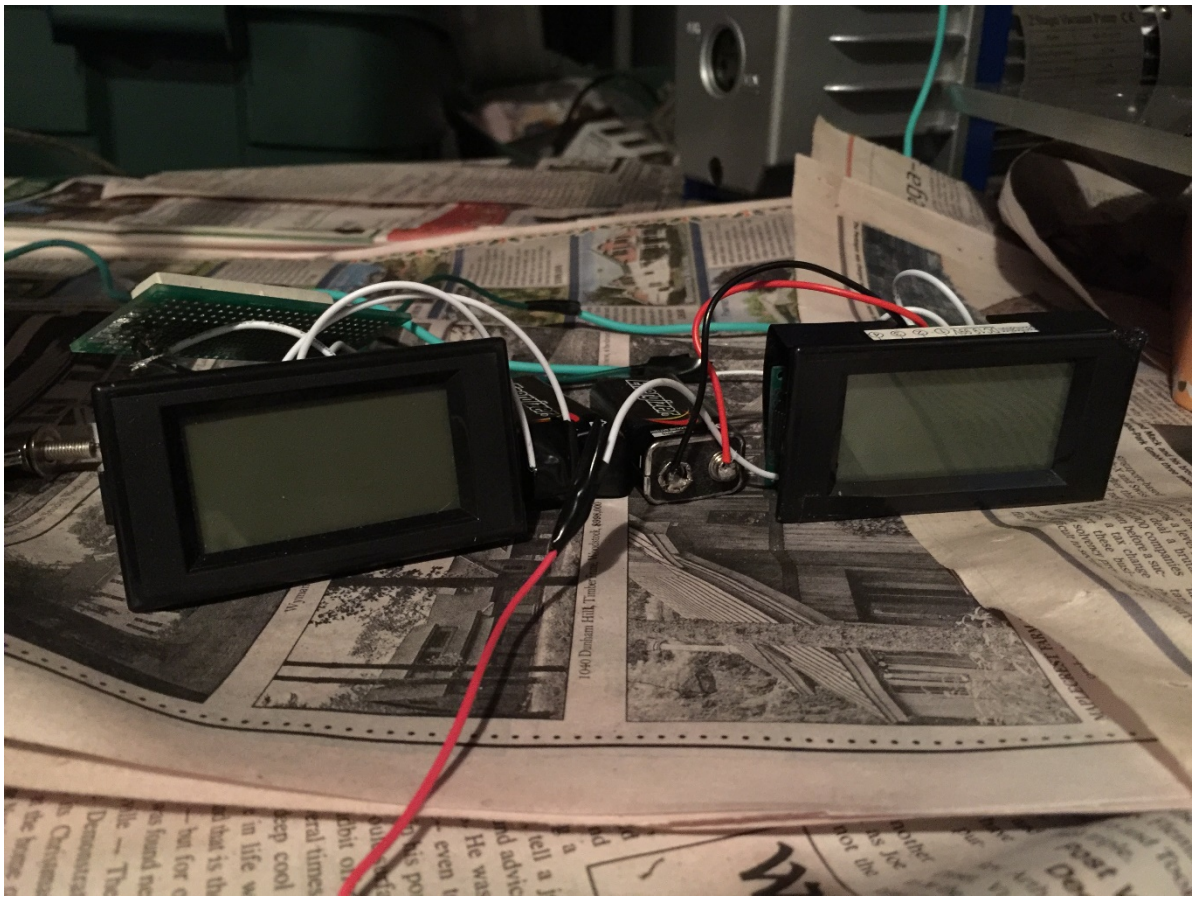
X-Ray Transformer with Rectifier Under Oil

Disassembled X-Ray Head with High Voltage Transformer, Current Transformer, and Tube

Autotransformer and Inductive Ballast



Deuterium Electrolysis System



Voltage and Current Metering