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NEUTRON MEASUREMENTS OF A REFLEX DIODE PULSED ION SOURCE EXPERIMENT*

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NEUTRON MEASUREMENTS OF A REFLEX DIODE PULSED ION SOURCE EXPERIMENT*

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ABSTRACT

This report consists of a description of the $D(Dn)He^3$ neutron diagnostics calibration and measurement techniques and their application to a recent pulsed ion experiment.

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I. INTRODUCTION

Considerable attention has recently been given to devices for producing multi-kiloampere 100-500 keV ion currents in pulses of one microsecond or less. Pinched diode^{(1),(2)} and reflex triodes⁽³⁾ have been investigated elsewhere; possible applications include solid pellet implosions,^{(4),(5)} production of ion rings,⁽⁶⁾ and mirror machine startup⁽⁷⁾.

This report concerns a pulsed diode experiment that is an extension of recent reflex diode studies at Physics International^{(8),(9)}. A preliminary report of the experiment was first presented in November;⁽⁷⁾ ~ 100 keV ions were produced at current densities of ≈ 1 K amp/cm².

A sketch of the geometry is presented in figure 1. The negative polarity of the OWL-II generator⁽¹⁰⁾ at Physics International was a serious constraint on the ion diagnostics. Small holes were drilled in the cathode to permit Faraday collector diagnostics inside the cathode stalk; the signals were delayed in a transit time isolater before being brought out to the oscilloscopes⁽⁷⁾.

The $D(Dn)He^3$ nuclear reaction was selected as an independent method of measuring ion production. It used calibrated silver-activation counter neutron detectors to evaluate the total neutron production from shots which used deuterium-loaded anode foils and cathode plates. The total pulsed deuterium ion charge can then be calculated from the neutron pulses, the diode voltage, and the deuterium content of the cathode. The method is not affected by the polarity constraint, nor is it sensitive to electrical noise because the radioactive decay of the activated foil is measured on a 1-minute time scale, long after the OWL-II generator noise pulse is over.

Figure 1

Sketch of the reflex diode experiment and its radiation diagnostics. [current loops and Faraday cup placement are shown in ref. 7]. 1) OWL-II generator with transit time isolator. 2) Reflex diode-negative cathode, thin grounded anode foil. 3) Coils for 16 kG longitudinal magnetic field. 4) Scintillation counter. 5) Geiger tube 6) X-ray pinhole camera

This report is a detailed account of the application of this neutron diagnostic

II. Description and Calibration of Neutron Detectors

Two silver activation detectors were used. The smaller detector consisted of a thin window geiger tube whose end face was covered with a silver foil; a few millimeters of plastic moderator surrounded the tube. The larger detector was buried in over a centimeter of plastic moderator; it was a scintillation counter whose photomultiplier tube viewed a multilayer sandwich of silver foils and plastic scintillator disks. No attempt was made to ascertain the detailed geometry of these existing detectors.

The detectors were calibrated by means of a known Cf-252 source which was borrowed from the Health Physics Dept. This isotope undergoes spontaneous fission, emitting neutrons whose mean energy (2.2 MeV) is close to the 2.45 MeV energy of DD neutrons⁽¹¹⁾. The source-detector distance was 10 inches, which was approximately the same as for the diode experiments.

The source was exposed to the counters for 10 minutes; it was then withdrawn, and the counting rates were measured. Let $\dot{S}_C$ be the neutron emission rate of the calibration source, and let $\dot{N}_C$ be the counting rate of the counter at the instant the source is removed. Then we have:

$$\dot{N}_C \equiv \frac{A_C}{R_C^2} \dot{S}_C (1 - e^{-\lambda \Delta T}) \quad (1)$$

where R_C is the source-detector distance, A_C is a function of the absorbing

materials in the vicinity, ΔT is the 10 minute irradiation time, and λ is the decay constant of the silver isotope Ag-110 which is made by the reaction:

Thus we have:

$$\lambda = \frac{\ln 2}{24.7} = .028 \text{ sec}^{-1}$$

The buildup factor $1 - e^{-\lambda \Delta T}$ is essentially unity for $\Delta T = 10$ minutes. In practice one cannot measure the instantaneous counting rate; in our apparatus we accumulated counts every 0.2 minutes (12 sec) and printed them on a paper tape. After correction for background, the first of these accumulated counts $N_c(0.2)$ would be:

$$N_c(0.2) = \int_0^{0.2} \dot{N}_0 e^{-\lambda t} dt = \dot{S}_c \frac{A_c (1 - e^{-12\lambda})}{R_c^2 \lambda} \quad (3)$$

The diode experiment is a very short pulse neutron source for which we have $\lambda \Delta T \ll 1$; in that case the instantaneous counting rate $\dot{N}_e$ at zero time is:

$$\dot{N}_e = \frac{A_e}{R_e^2} S_e \lambda \quad (4)$$

where A_e and R_e are similar to A_c and R_c , and where the source strength $S_e = \dot{S}_e \Delta T$. The corresponding practical measurement is:

$$N_e(0.2) = S_e \frac{A_e}{R_e^2} (1 - e^{-12\lambda}) \quad (5)$$

Finally, we solve Eq. (3) and (5) simultaneously for S_e :

$$S_e = \left(\frac{A_c}{A_e} \right) \left(\frac{R_e}{R_c} \right)^2 \left(\frac{\dot{S}_c}{\lambda N_c} \right) N_e \quad (6)$$

where N_c and N_e are now understood to mean the accumulated counts in the first 0.2 minutes.

The calibration measurements were made with different combinations of absorbers, moderators, and reflectors. 1 inch of lead decreased the response (absorption), but adding 4 inches of wood increased the response again (moderation). Lifting the source and the counters above the floor increased the response. All of these changes in response varied over a total range of $\pm 25\%$ from the average. The lead-wood absorber combination was chosen for calibration as the closest mockup of the copper-epoxy magnetic field coil used in the experiment. It was also assumed that $A_c = A_e$ to an accuracy of $\pm 10\%$.

The inverse square law was found to be obeyed over a range of distances from 10 to 46 inches, to the $\pm 5\%$ accuracy of the calibration measurements. Corrections for the 2.41 minute Ag-108 activity were made for all the calibration measurements, but were negligible for the diode experiment. Since the parameter $\dot{S}_c$ is known for the calibration source, λ is known (Eq. 3), and N_c is measured in the calibrations, we can then use Eq. (6) to calculate the pulsed neutron source strength S_e from the experimental measurement N_e . The principal source of error is believed to be setting $A_c = A_e$.

TABLE I

Measurements and Calibrations of the Silver Activation Detectors^(a)

<u>Parameter</u>	<u>Geiger Counter</u>	<u>Scintillation Counter</u>
Cf-252 Source $\dot{S}_C$	$1.46 \times 10^7 \text{ n}^*/\text{s}$	Same
Calibration Count $N_C(0.2)$	$1.32 \times 10^3 \text{ cts.}$	$2.2 \times 10^4 \text{ cts.}$
Ag-110 Decay Constant	$.028 \text{ sec}^{-1}$	Same
Calibration Distance R_C	10 in.	Same
Experiment Distance R_E	8.6 in.	7.8 in.
$\frac{1}{4\pi} \frac{\dot{S}_C}{\lambda} \equiv K$	$4.14 \times 10^7 \frac{\text{n}^*}{\text{ster.}}$	Same
$\frac{1}{4\pi} \frac{S_e}{N_e} = K \frac{R_E^2}{R_C} \frac{1}{N_C}$	$2.33 \times 10^4 \frac{\text{n}^*}{\text{ster}/\text{ct}}$	$1.14 \times 10^3 \frac{\text{n}^*}{\text{ster}/\text{ct}}$

(a) n^* denotes number of neutrons.

Finally, for purposes of comparison with the diode $D(Dn)$ reaction measurements at 90° , we divide Eq. (6) by the solid angle 4π :

$$F_e \left(\frac{\text{neutron}}{\text{sterradian}} \right) \equiv \frac{S_e}{4\pi} = \frac{1}{4\pi} \left(\frac{R_E}{R_C} \right)^2 \left(\frac{\dot{S}_C}{\lambda N_C} \right) N_e \quad (7)$$

Table I shows the results of the calibration measurements which were used in the application of Eq. (7) to each counter.

III. Preparation of Anodes and Cathodes

The cathodes were machined from titanium metal and loaded with deuterium in the "2X2B" titanium washer vacuum apparatus.⁽¹²⁾ Special RF heating coils and holding jigs were made to adapt the system to our geometry. Even so, the heating and cooling cycle was not uniform over the whole sample; lack of time prevented us from rectifying this problem. The overall D/Ti ratio $\bar{C}_D$ was monitored by weighing each cathode before and after loading. The results for all samples are:

$$\bar{C}_D \equiv (D/Ti)_{\text{overall}} = 0.50 \pm .01 \quad (8)$$

This ratio choice was less than the usual 0.9 loading for the 2X2B washers; this ameliorated the problems of swelling and fragility of the cathode.

Several unsuccessful attempts were made to construct deuterium-loaded titanium anode foils by this same technique, but the fragility of the thin loaded foils was too great. The titanium and mylar anode foils that were actually used for neutron diagnostics were coated with a thin layer

of deuterated polyethylene (approximate chemical formula CD_2) by the Chemistry Dept. The anodes were immersed in a hot solution of CD_2 in xylene, and were then pulled out and dried.⁽¹³⁾ The thickness of the coating was about $0.2 \pm 0.1 \text{ mg/cm}^2$; this was an appreciable fraction of the weight of the thinnest foil used in the experiments.

Only a few of the shots on the OWL-2 machine used deuterium-loaded electrodes. The other experiments were done with aluminum cathodes and with anodes which had been coated with a thin layer of pump oil to provide protons (instead of deuterons.).

A few "null tests" were done on shots where only one electrode (either the anode or the cathode) was loaded with deuterium. Neutrons were detected only when both electrodes contained deuterium.

IV. Experimental Measurements of Neutrons

The procedure for taking neutron data began about 15 minutes before each shot. First a counter sensitivity check was taken with a Co-60 source to make sure both counters were operative. Then the counters were allowed to run, accumulating background counting data for sufficient time to assure good statistical accuracy. At "shot time", (when the OWL-2 generator was discharged) the counters were restarted. For neutron-producing shots, a decay curve was seen. The raw data (stored on paper tape) were then corrected for background and plotted on a graph similar to figure 2.

Figure 2 shows decay curves for two of the experiments; the background corrections were approx. 2400 counts for the scintillation counter and 4 counts for the geiger counter. The fluctuations are consistent with

Figure 2

Two typical counting rate records from the silver activation counters. The abscissae are counts per 0.2 minute, corrected for background. X's represent scintillation counter points; o's are the geiger counter data.

the counting statistics. In the high counting rate case, the scintillation counter curve for shot 2392 shows evidence of the longer lived isotope 2.41 min Ag-108. Within the accuracy of the measurements, this agrees with the Ag-108 level that was expected.

The 24.7 sec Ag-110 decay curve was aligned with the data to derive a "best value" for $N(0.2)$ (the accumulated count in the first 0.2 minutes). Equation (7) was then used to calculate the neutrons emitted per sterradian in the direction of the counters. From Fig. 1, one sees that the counters are mounted approximately 90° from the direction of motion of the accelerated deuterons.

Table II presents the results for all shots with deuterium-loaded cathodes and anodes. The observed counting rates correspond to a total neutron output in the $10^7 - 10^8$ neutrons per shot range, neglecting the known axial emission enhancement of the $D(Dn)$ reaction.⁽¹⁴⁾ The two low neutron level shots (2384 and 2387) were non-standard (see footnotes to Table II) and will not be included in later calculations in this report.

Table II also presents calculations of emitted neutron output at 90° , based on the calibrations indicated in Table I. Inspection of the data shows that the two counters are in agreement with each other within about 20%. This is consistent with observed fluctuations in counter sensitivity as seen from the Co-60 test. Improvements could have been made in this system, but there are larger errors elsewhere in the measurements, as discussed below.

TABLE II

Silver Activation Detector Measurements at 90° from Diode Axis

OWL-2 Shot No.	Foil Material	Foil Thickness ^(b) (mg/cm ²)	N _e (Ag-110 Counts in first 0.2 min)		10 ⁻⁶ Fe in units of 10 ⁶ n*/ster ^(a)		
			Geiger Ctr.	Scin. Ctr.	Geiger Ctr.	Scin. Ctr.	Average
2380	Ti	6.00	185.	4,170.	4.30	4.75	4.52
82	"	"	116.	2,740.	2.70	3.13	2.91
84 (c)	"	"	(<4)	(<50)	(<.1)	(<.06)	(<.08)
86	"	"	270.	5,000.	6.28	5.70	5.99
87 (d)	"	"	57.	830.	1.33	0.95	1.14
92	"	"	520	9,500.	12.10	10.83	11.46
2410	Mylar	1.09	80.	1,400.	1.86	1.60	1.73
13	"	"	67.	1,450.	1.56	1.65	1.60
14	"	"	80.	1,800.	1.86	2.05	1.95
23	"	0.56	45.	1,200.	1.05	1.37	1.21
24	"	"	55.	950.	1.28	1.08	1.18
25	"	3.76	210.	4,125.	4.88	4.70	4.79

(a) n* denotes number of neutrons

(b) Including 0.20 mg/cm² CD₂ coating thickness

(c) Electrical and Damage diagnostics indicated an anode-cathode short circuit arc occurred on this shot.

(d) This shot had a 7.2 mm anode-cathode gap rather than the standard 9.5 mm spacing.

V. Interpretation of Neutron Measurements — Thick Target Yield

In order to convert the neutron measurements into electrical parameters of the diode, one must make use of the physical properties of the D(Dn) reaction when a 50-250 keV deuteron ion beam penetrates a deuterium-loaded target. The deuteron ions are believed to be extracted from the surface of the anode plasma, and are accelerated into the cathode (and its surface plasma), as discussed in the references. (8),(9)

Let Y be the neutron yield per steradian per incident deuteron at 90° from the beam direction. Y is called the "thick target yield", and is expressed as an integral over the path of the deuteron as it slows down in the target cathode:

$$Y = \int_0^R \sigma_\Omega(E(x)) n_D(x) dx \quad (9)$$

where R is the range of the deuteron, where $\sigma_\Omega(E(x))$ is the differential cross-section at 90° in units of $\text{cm}^2/\text{steradian}$, where $E(x)$ is the local energy of the deuteron at position x , and where $n_D(x)$ is the density of target deuterium atoms (in cm^{-3}). In order to obtain a more practical expression for Y , it is useful to define the slowing down parameter $\epsilon_d(E(x))$ (units of keV-cm^2)

$$\epsilon_d(E(x)) = - \frac{1}{n_{Ti}(x)} \frac{dE(x)}{dx} \quad (10)$$

where n_{Ti} is the density of titanium atoms (in cm^{-3}). We neglect the effect of the deuterium atom concentration n_D on this parameter; it is a small effect, especially at low values of n_D/n_{Ti} . Now substitute Eq. (10) into Eq. (9):

$$Y = \int_0^V C_D(E(x)) \frac{\sigma_\Omega(E(x))}{\epsilon_d E(x)} dE(x)$$

where $E(x) = 0, V$ when $x = R, 0$ respectively, and where $C_D(E(x)) = n_D(x)/n_{Ti}(x)$. We will show later Fig. (4) that over the depths R associated with the deuterium energies of our experiment, this ratio of deuterium to titanium density is a slowly varying function. Furthermore, it is reasonable that the target surface blow-off due to intense energy deposition occurs in a manner that maintains C_D at the value it has near the solid surface, $\bar{C}_D$; i.e., the Lagrangian surfaces describing the blow off material do not interpenetrate. Thus we finally have

$$Y \approx \bar{C}_D \int_0^V \frac{\sigma_\Omega(E)}{\epsilon_d(E)} dE \quad (12)$$

The ratio $y \equiv (\sigma_\Omega(E)/\epsilon_d(E))$ is called the thin target yield, and it has been calculated in ref. 14 for the case $C_D = 1$. We fitted a linear function to those calculations over the relevant deuteron energy range for this experiment:

$$y(E) \approx 3.6 \times 10^{-13} E \quad (13)$$

where $30 \leq E \leq 300$ keV

The fit is better than 10% accurate over this range. This linearity is an accidental consequence of the shape of the functions σ_Ω and dE/dx , which are actually more complicated, as shown in fig. 3.

Substitution of Eq. (13) into Eq. (12) yields a simple expression for the thick target yield $Y = \bar{Y}$:

$$\bar{Y} \approx 1.8 \times 10^{-13} \bar{C}_D V^2 \quad (14)$$

$30 < V \leq 300$ keV

In these experiments the deuteron energy V is the same parameter as the diode voltage ($Z = 1$ for deuterons). This voltage V is carefully measured in the experiment by means of a capacitance voltage monitor

Figure 3

Differential cross-sections at 0° and 90° for the $D(Dn)He-3$ reaction, and the slowing down parameter dE/dx in titanium. See Eq. (9).

which has been corrected for the inductive voltage component.⁽⁹⁾ The voltage V is combined with the neutron measurement F_e in the following way. The total charge Q_D of deuterons which have crossed the gap is given by

$$Q_D = e \frac{F_E}{Y} \quad (15)$$

where e is the unit of charge: Substituting $e = 1.6 \times 10^{-19}$ coulombs, and utilizing Eq. (14) for the case of constant $\bar{C}_D$, we obtain

$$Q_D = 8.89 \times 10^{-7} \frac{F_E}{\bar{C}_D V^2} \quad (16)$$

where $\bar{Q}_D$ is in coulombs and V is in KV

In order to decide on the deuterium current I_D and current density J_D , one must make assumptions about the pulse duration τ and the effective deuteron beam area. These questions will be considered later, after the values of $\bar{Q}_D$ have been obtained.

VI. Depth Variations of D/Ti Ratio:

Consider now the possibility (which has been hinted at above) that the parameter $C_d = D/Ti$ is not equal to its average value near the surface of the cathode. The depth of concern involves the range x_D of the ion in titanium.

$$x_D = \int_0^{x_D} dx = \int_0^V \frac{1}{dE/dx} dE \quad (17)$$

Using the known values⁽¹⁴⁾ of dE/dx (Fig. 3) this range was calculated; for ions of 100-200 KV, one finds a range of only $1 - 1\frac{1}{2}$ microns in metallic titanium. This is such a small distance that it raises considerable doubt that the average value of $\bar{C}_D = 0.5$ is representative of the condition of the surface, particularly during the diode pulse.

As a consequence of these doubts two different attempts to measure the D/Ti versus depth were done with two unused cathode plates. The first method employs neutron time-of-flight measurements during the irradiation of the sample with well-defined deuteron pulses from a Van de Graaf accelerator, using the same $D(Dn)He^3$ nuclear reaction as in the diode diagnostics.^{(15),(16)} The energy spectrum of the forward-emitted neutrons is unfolded to recover the number of reactions versus bombarding energy, and the range distribution of the target atoms is inferred. In principle the method is capable of space resolution as narrow as 0.3 microns, but within the limitations of time and effort available to this project, only 3.0 micron resolution was achieved and no absolute calibration of C_D was possible. The observations did not show any detectable variation in C_D near the surface.

The second method involves an ion probe analyser,⁽¹⁷⁾ which was a mass spectrometer to measure the atoms sputtered from a surface under ion bombardment. This experiment was also seriously curtailed by limitations of time and resources, so that absolute calibrations of depth and atom ratio were not available and only estimates (plus or minus at least a factor of two) could be made. However, the results from two samples indicated a drastic depletion of deuterium near the surface of the sample; the analyses (shown in fig. 4) indicate that C_D is down by more than a factor of 10.

In principle the observed variations in depth (See fig. 4) require that Eq. (11) and (15) be used to calculate the charge Q_D . This was done, but the results turned out to be insensitive to the variation of C_D with depth because most of the nuclear reactions take place in a layer less than 1 micron thick, due to the decrease of the parameter y (Eq. 12) with energy (and depth).

Figure 4

Analyses of two samples of a deuterium-loaded titanium cathode. The solid line was taken by focusing on a visible intersection of 5 crystals, the dotted line by focusing on what appeared to be a single crystal. Estimated calibration errors are a factor of two up or down for both atom ratio and depth.

It was sufficient to replace the integral with the average value $(D/Ti) = \bar{C}_D = 0.036$; this value is used in the subsequent calculations with the understanding that it has at least a factor of two uncertainty.

VII. Calculations of Total Ion Charge Q_D and Total Ion Current I_i

Knowing F_E from Table II, and setting $\bar{C}_D = .036$ as described above, one can use Eq. (16) to find the ion charge $\bar{Q}_D$ from experimental values of V .

A single value of voltage V was assumed in the previous derivations; the actual measurements show variations of this voltage of the order of $\pm 25\%$ over the duration of the ion pulse.⁽⁷⁾ In principle one should take these variations into account, because they introduce even larger errors into Eq. (16) through the parameter V^2 - errors much larger than the uncertainties in F_E . However, this was not done because even these errors are smaller than the uncertainties in our knowledge of C_D in the target.

Table III includes the results of the measurements of average voltage V and the subsequent computations of charge $\bar{Q}_D$. The voltage was averaged by eye over the last ~ 50 nanoseconds of the diode voltage, before diode closure, when the total current was at its highest value (approx. 700 kilamperes).

Estimation of the ion current from the total ion charge depends on the duration τ of the ion pulse. The Faraday collector signals and the total current curve both suggest a value of about 50 nsec from the start of the current plateau until diode closure. This value was used to calculate the ion currents shown in Table III:

$$I_i = \bar{Q}_D / \tau \quad (18)$$

In addition, the average total current I_{TOT} during this time, as measured with a Rogowski loop, is shown for each shot. Also the bipolar flow parameter α is tabulated:

$$\alpha = \frac{I_i}{I_{tot} - I_i} \sqrt{\frac{M}{m}} \quad (19)$$

where M is the ion mass. This experimentally determined value of α represents a sort of average over space and time of the theoretical value of α , which is defined in terms of current density. α is calculated for deuterium for which $\sqrt{M/m} = 60.0$.

TABLE III

Current Calculations Based on Neutron and Voltage Data^(a)

Foil Material	Foil Thickness (mg/cm ²)	OWL-2 Shot No	Average Voltage V(Kv)	$\bar{Q}_D C_D$ Product (micro coulombs)	Ions I _i (Kamp)	Total I _{TOT} (Kamp)	Alpha (Eq. 19) α	Average J _i (Kamp/cm ²)
Ti	6.00	2380	160	157.	87.	766.	7.8	1.9
"	"	82	160	101.	56.	766.	4.8	1.2
"	"	86	20E	123.	68.	733.	6.2	1.5
"	"	92	224	203.	113.	633.	13.2	2.5
Mylar	3.72	2425	144	205.	114.	666.	12.7	2.5
"	1.09	2410	96	167	93.	733.	8.8	2.1
"	"	13	80	222	124.	666.	13.8	2.8
"	"	14	96	188	105.	700.	10.7	2.3
"	0.56	2423	64	263	146.	800.	13.5	3.2
"	"	24	80	164.	91.	766.	8.2	2.0

(a) Assuming that $\bar{C}_D = .036$ and that pulse length $\tau = 50$ nsec.

VIII. Calculations of $\bar{J}_i$ (Average Ion Current Density)

Estimation of the ion current density introduces another question - namely, the choice of the effective area of the diode. The Faraday collector data show large current signals only at the 1.5 cm radius position, not at zero radius or 3.0 cm radius.⁽⁷⁾ The pinhole x-ray data show a pronounced concentration of intensity near the axis, as if the diode were (at least partially) pinched. The calorimeter data show only weak variations of intensity with radius, with the maximum intensity occurring either at the axis or at 1.5 cm radius.

Under these circumstances it was decided to use the total diode area $A = 45 \text{ cm}^2$ (for the 3 inch diameter cathode). This yields a well-defined quantity, the average ion current density $\bar{J}_i$, independent of the radial distribution. Values of $\bar{J}_i$ are tabulated in the last column of Table III.

Summary and Other Possible Applications

The total deuteron current measurement yield 50-150 kA, corresponding to average current densities of 1-3 kA/cm². The principal errors were the factor of at least 2 uncertainty in the D/Ti ratio in the cathode and the 25% uncertainty in the average value of diode voltage V . Since the thick target yield varies as $C_D V^2$, a total uncertainty of a factor of three in the final result would seem to be a moderately conservative estimate.

The method could be improve by less hasty preparation of anode and cathodes - particularly cathodes of better-known D/Ti ratios. It is especially important to be able to control the D/Ti ratio within the depth of the ion range. Considerably stronger neutron outputs are possible with higher D/Ti ratio cathode surfaces. For $C_D = .5$, approximately 10^9 DD neutrons or 10^{11} DT neutrons could have been generated in this experiment. At these neutron output levels fast proton recoil scintillation counters could be used to monitor the time dependance of the neutron output, thus obtaining the instantaneous ion current. Time-of-flight measurements of the neutrons might be used to obtain their energy spectrum, but even 10^9 DD neutrons is a marginal source for this application.

For mirror startup experiments, such high neutron outputs are incompatible with the necessity of extracting the ion beam. In this case, however, small probe targets could still be used to monitor the ions. For example, at $J = 1 \text{ kA/cm}^2$, a probe area $A = 1 \text{ cm}^2$, voltage $V = 100 \text{ kV}$, and standard 2X2B titanium washer fragment ratio ($C_D = 0.9$) would give a neutron yield N_n

$$\dot{N}_n \cong 4\pi Y \frac{JA}{e} \cong 1.3 \times 10^5 \frac{\text{neutrons}}{\text{nsec}} \quad (21)$$

where Y is given by Eq. (14). For a 50 ns pulse this is almost $\approx 5 \times 10^6$ neutrons, which is a number that is detectable by the same equipment that was used in this work. These neutron output estimates may be high, since they depend on the assumption that the D/Ti ratio is as high as 0.9 in the target surface.

Another possible application is to monitor neutral beam production and injection into mirror plasmas. The D/Ti target response does not depend on the charge state of the bombarding deuteron. For an 0.1 amp/cm^2 100 KeV neutral source lasting 10 millisec, a 1 cm^2 probe similar to the above example would produce 13 neutrons/nsec for a total output of 1.3×10^8 neutrons. Again this is easily detectable by the silver activation equipment, and is even enough neutrons to be monitored by a close-in proton recoil scintillation counter for obtaining the time dependence of the neutral source provided $C_D \approx 0.9$. Such a probe could be made of a transparent wire grid to sample the whole beam; it could be placed ahead or behind the mirror plasma to monitor the beam absorption.

Altogether the method was a vital part of the pulsed ion source experiment, and it is potentially promising for other ion beam applications, provided the surface physics of deuterium-titanium is controllable and well-understood in each case.

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