RECEIVED BY TIC AUG 14 1974

UCRL-51608

ELECTRON BEAM — DEUTERATED TARGET EXPERIMENT

Bruce L. Freeman, Jr.
(Ph. D. Thesis)

June 14, 1974

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

**LAWRENCE
LIVERMORE
LABORATORY**

University of California/Livermore

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LAWRENCE LIVERMORE LABORATORY
University of California, Livermore, California, 94550

UCRL-51608

ELECTRON BEAM - DEUTERATED TARGET EXPERIMENT

Bruce L. Freeman, Jr.
(Ph.D. Thesis)

MS. date: June 14, 1974

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

Contents

Abstract	1
Quotation by Hannes Alfvén	1
Introduction	2
Motivation	4
Experiment	11
Apparatus	11
Measurements	14
Neutron Yield	14
Optical Diagnostics	19
Electrical Diagnostics	21
Diagnostic Summary	33
Discussion	34
Recommendations for Future Research	44
Summary	46
Addendum	48
Acknowledgments	48
Appendices	
A. Compression Considerations	50
B. A Break-Even Fusion Criterion	53
C. Silver Activation Detector Analysis	55
D. Fission Foil Analysis	62
E. Sulfur Tablet Analysis	65
F. Neutron Time-of-Flight Analysis	72
G. Voltage Measurement Analysis	91
H. Current Measurement Analysis	99
I. Anomalous Plasma Resistance	105
J. Measured Frequency Wavelength and Dimensional Comparison	107
K. Thick Target Yield Calculation	108
L. Beam - Hot Target Considerations	109
M. The Ratio of ($N_{14}/N_{2.5}$) for Thermonuclear Reactions	112
N. Non-Maxwellian Considerations	113
References	114

ELECTRON BEAM - DEUTERATED TARGET EXPERIMENTS

Abstract

The Pulserad 422 electron beam facility at the Lawrence Livermore Laboratory has been used to investigate the interaction of an intense electron beam with a deuterated target assembly. The performance of the apparatus, consisting of a deuterated polyethylene (CD_2) cathode tip, an insulated CD_2 disk with a tapered hole through its axis in the anode plane, and an insulated rear target of CD_2 , was monitored with neutronic, optical, and electrical measurements. Open-shutter and image-converter photographs comprise the main optical measurements. The electrical characteristics observed were the voltage and current at various locations in the geometry along with

microwave observations in the area between the front and rear targets. Neutronic information was obtained in the form of total yield from silver activation, fission foil track and sulfur activation methods, and time-resolved yield with time-of-flight oscillographs from scintillator-photomultiplier detectors. Average neutron total yields of $\sim 10^{10}$ n/pulse were obtained with the standard CD_2 target geometry, and a high-energy neutron group was reproducibly observed by time-of-flight when CD_2 had been used in the cathode tip, anode, and rear target. An energy assignment of 14 MeV for this peak would not be inconsistent with other data obtained.

Quotation

Hannes Alfvén¹:

"The study of plasma physics developed along two parallel lines. The first one, originating about a century ago, comprised investigations into electrical discharges in gases. This approach was, to a great extent, experimental and phenomenological; only very slowly did it reach some degree of theoretical sophistication. Most theoretical physicists looked down on this field, which was complicated and awkward. The plasma exhibited striations and double layers; the electron distribution was non-

Maxwellian; there were all sorts of oscillations and instabilities. In short, it was a field not at all suited for mathematically elegant theories.

The other approach to plasma physics came from the highly developed kinetic theory of ordinary gases. It was thought that with a limited amount of work this field could be extended to include ionized gases as well. The theories were mathematically elegant, and the consequences of them showed that it should be possible to produce a very hot plasma and confine it

magnetically. This was the starting point of thermonuclear research.

However, the theories had initially very little contact with experimental plasma physics, and all the awkward and complicated phenomena that had been treated in the study of discharges in

gases were simply neglected. The result of this was what has been called the "thermonuclear crisis," some ten years ago. It taught us that plasma physics is a very difficult field, which can only be developed by a close cooperation between theory and experiments."

Introduction

One could ask, and I have, in fact, been asked why I chose to be involved with controlled fusion, particularly at the graduate level in an experimental capacity. The primary reason for this question of course is the historical fact that the search for a solution to the problem of laboratory-controlled fusion has been a very long one already, and still does not appear near a practical solution in a time scale short compared with previous efforts. As with other people in this field, I must admit that my main reason is an almost religious conviction that fusion holds one of the few promises for an almost unlimited supply of cheap, relatively clean energy for mankind. In the face of the host of problems which have haunted plasma physicists, this philosophy could well be the one which has kept serious fusion efforts, and hopes, alive for over 20 more or less disappointing years of research. However, my personal sympathies are more with the so-called unconventional approach to this problem simply because the pulsed fusion approach does not seem to be impractical. In fact, with the possible exception of fire, man has never, to my knowledge, developed a continuous-mode power source without first studying and developing the pulsed version.

If we can now pass from the more esoteric philosophy, there were two primary considerations which lead me to be particularly interested in attempts at controlled, pulsed fusion with electron beams. One could argue that a form of pulsed fusion has been studied and developed, and indeed it has. In fact, in nuclear weapons we currently have available controlled fusion which will give up more energy, by several times, than the initial input energy to drive it. However, this form of fusion technology hardly qualifies as laboratory-controlled fusion. Nevertheless, the basic physics involved with our large pulsed fusion devices should be at least partially applicable to a smaller scale of events. Hence, in order to do meaningful experiments, one must have a high-energy-density source other than a conventional atomic bomb. Two outstanding candidates in this respect are lasers and relativistic electron beam machines. One day, lasers may well offer one of the better solutions to this source problem, but currently, this use of the laser is still a largely undeveloped technology. On the other hand, electron beam generators already have been developed to the point of being useful in fusion experiments.²⁻⁷ In fact, relatively modest machines will

deliver energy at powers of 2 to 8 gigawatts (10^9 watts), and some of the largest machines are currently capable of delivering power levels into the several terawatts (10^{12} watts).⁸ We do not currently have any of the very large machines at this Laboratory, but the Pulserad 422, used in the experiments reported here, was capable of routinely delivering energy at rates of 90 to 100 gigawatts during a pulse. Of course, the rate of energy delivery is one aspect of the problem, while the volume of energy deposition is quite another. Since I was using only developed technologies as my tools, this latter subject is the primary basis of this work.

Historically, the events leading to and through the study presented here first began in the Winter of 1972 with a series of discussions between Dr. John Luce, Dr. Harry Sahlin, Oved Zucher, Dan Shumaker, and myself. During this time various lines of reasoning were pursued to try to determine whether or not electron beam technology could be harnessed so that meaningful fusion experiments could be performed. Some of this reasoning will be presented later. Continuing through the Spring, the so-called "Pulsed Fusion Group" congealed, with the members being those above except Dan Shumaker. As summer approached we were able to obtain permission from Dr. Leroy Erickson to use a Field Emission Febatron.

The Febatron is a Marx capacitor bank generator which stores 600 J and delivers about 400 J at 2 MV and 5 kA in 60 ns to a matched load of 400 Ω . During June, 1972 a rather jerry-rigged vacuum system was assembled so that

we could proceed with the experiments with deuterated polyethylene (CD_2) targets. During the months of July and August, a target assembly emerged which is completely non-standard for the electron beam experiments of the past and was to be used essentially intact for all other experiments, with various modifications for various tests. The stages of development with their associated neutron yields on this machine were a solid CD_2 disk in a grounded brass holder with 3.2×10^7 n/pulse, a CD_2 disk with a hole (which later became tapered) in a grounded brass holder with 5.3×10^7 n/pulse, a CD_2 disk with a hole held in an insulated anode plane with 7.1×10^7 n/pulse, and this previous arrangement with a rear target of various configurations but usually with a CD_2 disk held in some fashion (and also a CD_2 cathode tip) giving a maximum yield of 2.1×10^8 n/pulse. The last configuration yielded the highest neutron yield we measured on the Febatron^{9,10} and compared very favorably with the work of other experimenters doing similar work at other laboratories.¹¹⁻¹⁴

By September, our yields and target configuration on the Febatron had pretty much stabilized, and plans were made to use the Boeing Radiation Facility which has an Ion Physics FX-75 electron beam generator. This is a Van-de-Graaf machine which stores 11 kJ when charged to 6 MeV and delivers about 5 kJ in 30 ns. The output voltage and current may be altered relatively easily by changing the diode configuration. With an 80 Ω diode these parameters were of the order of 80% of the charging voltage and 50 to 60 kA with a 6 MV charge. Early yields

from work on this machine with a geometry similar to the one used with the Febatron were about 10^{10} n/pulse. By the second trip to Seattle these yields stabilized at about 2×10^{10} n/pulse^{9, 10} until at a later date the diode configuration was modified for a lower output impedance. At that point yields of 10^{11} n/pulse were recorded, using CD_2 at the cathode tip, anode, and rear target.¹⁵

At the time of the second trip to the FX-75, three factors intervened to provide a split in emphasis within our group. These were difficulty in obtaining travel for me, availability of the Physics International Pulserad 422 on site, and a difference in interest. Dr. John Luce, group leader, hypothesized the existence of collective acceleration during the operation of the machine,^{16,17} while several of us professed an interest only in fusion work. Thus, a rather natural and, by hindsight, convenient division of labor within the Pulsed Fusion Group occurred. Hence, while a division of interest did occur, the group was not divided in the usual sense. Drs. John Luce and Harry Sahlin continued the FX-75 experiments with a primary interest in studying collectively accelerated, highly stripped ions,^{15,18} and Richard Gullickson, a new member to

our group, Oved Zucker and I proceeded to prepare and conduct experiments on the Pulserad 422 in order to optimize neutron yields and attempt time-resolved measurements of important properties of the discharge with the support and guidance of Drs. John Luce and Harry Sahlin. It is this experimental effort which forms the basis for my thesis work.

The experiments on the Pulserad 422, which will be described in detail later, began in late October, 1972, with a once-more jerry-rigged target configuration. However, changes came fairly quickly and by March, 1973, we were in a position to perform nanosecond time-scale current measurements in various parts of the target structure, along with other measurements. Our neutron yields peaked at $\sim 5 \times 10^{10}$ n/pulse with the machine in the high impedance mode, and most of the time-resolved data hoped for were obtained by September, 1973.¹⁹ During the summer months, we were very fortunate to have the help, advice, and strong back of Dr. Winston Bostick with us on the Pulserad effort, and a new member to the group, Harris Klapper, joined us to assist with microwave measurements. At the end of the September run, I withdrew from the mainline of the group's activities in order to write this thesis.

Motivation

Until very recently, there seemed to be only one accepted approach to the problem of controlled fusion outside of weapons research, which, with few exceptions, was essentially dc magnetic

confinement of a relatively hot, ≈ 8 to 10 keV, low density, $\approx 10^{13}$ to 10^{14} cm^{-3} , plasma for time scales of the order of 1 sec. One reason for this was the difficult-to-achieve, huge energy densities

which are necessarily associated with the high-density fusion regime. Then, several years ago several investigators began to realize that if one could reach solid or super-solid densities at temperatures of 3 to 10 keV, then net thermonuclear burn could occur in time scales proportional to ρ^{-1} , the reciprocal fuel density.²⁰⁻²⁵ Since the time of onset for major MHD instabilities is of the order of the characteristic inertial disassembly time,

$$t_D = r/v_s \quad (1)$$

where

r = the radius of a cylindrical or spherical system,

v_s = the sound speed in the fuel,

one would need to only arrange for the assembly and burn time to be shorter than t_D to avoid all questions concerning MHD stability.²⁶ Thus, a comparatively simple inertial or near-inertial confinement could be used to advantage. It is exactly this advantage that makes a pulsed system attractive over a DC system at the present time. The real problem arises in considering a power source to drive such a device. One almost classical candidate in this area is the plasma focus, which was evolved in 1957 by N. V. Filippov and co-workers.²⁷⁻²⁹ In more recent years, electron beams and lasers have been added to this small but elite list of high-power density energy sources.

The most obvious considerations to be immediately raised are those of the relevant plasma conditions required for break-even fusion and some general reactor characteristics. The most

widely used criterion for a net power break-even thermonuclear reactor is the famous Lawson criterion,³⁰

$$n\tau \geq 10^{14} \text{ sec cm}^{-3} \text{ for D-T, } (2)$$

where

n = the particle density (cm^{-3}),

τ = the confinement time.

This condition applies for a plasma temperature of 10 to 20 keV. An alternative expression of the Lawson condition in the inertially confined regime is the density-radius product, ρr .³¹ For D-T in a 50% ratio, the requirement for break-even with a 3-keV plasma temperature is $\rho r \geq 1 \text{ (g cm}^{-2}\text{)}$. The next general consideration is the size of explosion which might be contained economically, i. e., a damage rate giving rise to a lifetime of at least 10^{10} pulses before major maintenance.³² Current estimates place this figure in the vicinity of 1 to 10 MJ.²² This amount of energy corresponds to burning 2.5×10^{-5} grams of a 50% D-T mixture. In other terms, this represents a fluence of 3×10^{18} n/pulse. Obviously, once one accepts a high fraction of the fusion energy as high-energy neutrons, the reactor vessel becomes subject to deterioration by neutron knock-on collisions in addition to low-energy photon absorption and subsequent wall ablation.³³ Also, energy recovery and conversion techniques are then primarily limited to a thermal cycle of some variety. However, starting with Dr. John Luce who suggested the $^3\text{He (D, p)} ^4\text{He}$ reaction,³⁴ various candidates for use in a fusion reactor other than the traditional $\text{T (D, n)} ^4\text{He}$, $\text{D (D, p)} \text{T}$, and $\text{D (D, n)} ^3\text{He}$ reactions have been presented. Another

clean reaction, which has recently been suggested by Weaver *et al.*³⁵ is the ^{11}B (p, $3\ ^4\text{He}$) reaction with only 0.1% or less of the produced energy appearing in neutrons. However, both the ^3He (D, p) ^4He and the ^{11}B (p, $3\ ^4\text{He}$) reactions require temperatures >100 keV and quite high densities. Nevertheless, with more sophisticated fuels, direct conversion of the charged-particle energy to electricity by various techniques becomes possible. Also, as the energy fraction in neutrons is decreased, the problems of reactor vessel endurance become less severe with the major problem now presented by only the low-energy photon radiation, with the assumption that most if not all of the energy is extracted from the charged-particle microexplosion debris. Thus, the principal considerations here are the fuel, the $n\tau$ or the ρr product, the plasma temperature, the thermonuclear burn time, and the disassembly time.

The product, $n\tau$, is proportional to the energy density associated with the plasma at any time. In order to achieve any given value for this product in the plasma, the energy source must be able to deliver energy at a high enough rate into a small enough volume to produce an energy density at least incrementally larger than that of the plasma. The energy delivery problem may be considered in two parts. First, the energy source must have an exceedingly high power level for the plasma conditions of interest here, and second, this energy must be deposited into a small volume. This process involves the way that the energy is coupled into the plasma and may be in the form of a pinch, ablative rocket

compression, etc. Nevertheless, one must generally regard the power source as an energy compression device in which the target, plasma, pellet, or whatever is, itself, the last compression stage. In other words, the target must be considered as part of the machine. Hence, the energy source with its associated rate of energy delivery is crucially important since this will determine both the ultimate plasma temperature and density.

Of the two equivalent conditions for break-even fusion, one can use the ρr product to gain some quite fundamental understanding of inertially or near-inertially confined thermonuclear systems.³¹ In Appendix A, it is shown that

$$\rho r \propto Ef_{\text{th}} \quad (3)$$

where

Ef_{th} = thermonuclear efficiency, since one may define this efficiency for an inertial system as

$$Ef_{\text{th}} = Y/Y_{\text{max}} \quad (4)$$

where

Y = the thermonuclear yield,

Y_{max} = the total thermonuclear yield possible (100% burn-up). This follows since Y is proportional to the disassembly time,

$$\tau_D = r/v_s \quad (5)$$

$$\approx r/\sqrt{\frac{2NA}{A}(kT)}, \quad (6)$$

if one assumes the thermonuclear burn time to be equal to τ_D . Also, by a simple proof, the ρr of a system may be increased only via convergent compression. Therefore, since the thermonuclear

burn efficiency is proportional to ρr , and this product may only be increased by convergent compression, either cylindrical or spherical compression must be used in any pulsed system to get a net energy multiplication.

Historically, the plasma focus has been one of the highest power experimental tools for fusion research. The devices typically may deliver 1 to 3 MA at 40 to 60 kV to a coaxial gun or Filippov geometry with an associated power level of $>10^{11}$ W.^{29,36-40} The time of energy delivery for these systems is of the order of 1 μ sec. As noted previously, electron beam generators have been built which deliver energy at terawatt levels, but this energy is delivered to a comparatively large volume, of the order of a meter or more in diameter.⁸ However, with smaller machines which still may deliver 10 to 20 kJ, this spatial distribution is not too hard to minimize. The advantage of the electron beam is evident from its time scale of delivery, of the order of 100 nsec. Thus, high powers are available with relatively small energy storage. Lasers have been built which reach gigawatt power levels, but they are still not available in the form of >10 kJ - multigigawatt fusion research tools. Nevertheless, lasers do hold out the promise of extremely short pulses with very high power levels.⁴¹ It has been argued that a laser system is capable of very high energy density storage since the electronic levels of molecules are the energy storage medium which has a potential for exceeding the dielectric energy storage density by a factor of 10. However, the lasers that have been

built to date are either a solid that has been doped to a ratio of 10^{-3} or a gas that is used at reduced pressure giving rise to a density ratio to that of a solid of about 10^{-2} , so currently the energy density of storage in a dielectric is favored by a factor of the order of 10 to 100 over laser media. Of course, future developments may eventually change this situation.

The deposition of the energy into a plasma after it has arrived from the source device is quite another matter. There have been a number of arguments as to whether photons or electrons are the better coupling medium. For example, photons are charge-free and can, in principle, be focussed to finer dimensions than charged particles, but on the negative side, they are also massless and carry less energy per quanta than charged particles. Also, the ability to provide a finer focus has not shown itself to be a necessarily superior characteristic,⁴² while one must tolerate reflection from the plasma body as the plasma density increases to the point at which the electron plasma frequency,

$$\omega_{pe} = \sqrt{4\pi n e^2 / m_e} \quad (7)$$

where

e = the charge per electron

n = the number density

m_e = the mass of the electron

is equal or greater than the incident laser radiation. On the other hand, electrons may couple with a plasma via electric and magnetic fields since they are charged, and intense beams may be generated relatively efficiently. However, since they are charged and carry

an associated field, they are susceptible to MHD instabilities, and as the accelerating potential is increased, the energy deposition per unit length is decreased, classically. Hence, arguments may be made for and against either type of energy coupling medium and ultimately the power source which delivers it, and thus the important question in the current case is what tools are available today for experimental, high-density, pulsed fusion research. The answers today are the plasma focus and the electron beam machine. The lasers necessary to do fusion studies are still a technology of the future.

To gain some insight into what the actual requirements might be on a pulsed fusion energy source, an example problem for an electron beam machine will be worked out using the following assumptions:

- n_i = initial ion density = 10^{19} cm^{-3}
- n_f = final ion density = 10^{24} cm^{-3}
- N = total number of ions = 10^{19}
- $n_f \tau_B$ = particle density - burn time product = $10^{15} \text{ sec/cm}^{-3}$
- τ_B = thermonuclear burning time = 10^{-9} sec
- τ_D = the compression time = 10^{-8} sec
- τ_P = machine pulse duration = $4/3 \tau_D$
- T_f = final plasma temperature = 10 keV
- $T(\tau)$ = temperature as a function of time = $K\tau \text{ keV}$
- $n(\tau)$ = particle density as a function of time = $(n_i + K\tau) \text{ cm}^{-3}$
- V = electron beam machine delivery voltage = 10 MV .

For the moment, only the general break-even conditions will be addressed, while the coupling efficiency of machine energy

to plasma energy will be assumed to be unity. One should, however, note that the assumed dependences in time of the plasma temperature and particle density will lead to a very conservative calculation. Also, a "square" electron beam generator pulse will be assumed which is another conservative postulate. As shown in Appendix B, a break-even condition may be derived with an energy balance between the energy produced by fusion, E_F , and the sum of the total bremsstrahlung energy radiated, E_B^T , and the energy necessary to heat the plasma to T_f , E_H . Clearly, during the compression and burning phases of the pulse, the electron beam generator must deliver an energy,

$$E_D = E_B^T + E_H \quad (8)$$

where

E_D = delivered energy = deposited energy (by assumption).

The E_H is simply the thermal energy in the plasma and, for this specific problem, is

$$E_H = \frac{3}{2} N k T \quad (9)$$

$$= 4.8 \times 10^4 \text{ J}$$

where

$$k = \text{Boltzmann constant} = 1.38 \times 10^{-23} \text{ J/}^\circ\text{K}.$$

The bremsstrahlung radiation energy, E_B^T , may be divided into two parts, energy radiated during the compression phase, E_B^C , and energy radiated during the burning phase, E_B^B . Before determining E_B^C , the constants of proportionality for the time-dependent behavior of the temperature and particle density are

$$K = T_f / \tau_0 \quad (10)$$

$$= 10^9 \text{ keV/sec}$$

and

$$\bar{K} = (n_f - n_i) / \tau_D \quad (11)$$

$$\approx 10^{32} \text{ cm}^{-3} \text{ sec}^{-1}.$$

Now, E_B^C is⁴³

$$E_B^C = \int_0^{\tau_D} 5.35 \times 10^{-31} N n(\tau) \sqrt{T(\tau)} d\tau \quad (12)$$

$$= 5.35 \times 10^{-31} N \sqrt{\bar{K}}$$

$$\times \int_0^{\tau_D} [n_i \tau^{1/2} + \bar{K} \tau^{3/2}] d\tau$$

$$= 6.78 \times 10^4 \text{ J}.$$

Since the temperature and density will be assumed to be static during the thermonuclear burn time, E_B^B is simply⁴³

$$E_B^B = 5.35 \times 10^{-31} N n_f \tau_B \sqrt{T_f} \quad (13)$$

$$= 1.69 \times 10^4 \text{ J},$$

so the total radial bremsstrahlung energy is

$$E_B^T = E_B^C + E_B^B \quad (14)$$

$$= 8.47 \times 10^4 \text{ J}.$$

Thus, the total energy to be delivered during $(\tau_D + \tau_B)$ is

$$E_D = E_B^T + E_B$$

$$= 4.80 \times 10^4 \text{ J}.$$

Recalling the assumptions specifically relating to the electron beam generator,

the remaining machine characteristics are

$$P = E_D / (\tau_D + \tau_B) \quad (15)$$

$$= 4.36 \times 10^{12} \text{ W},$$

$$E_T = P (4/3 \tau_D) = P \tau_p \quad (16)$$

$$= 5.82 \times 10^4 \text{ J},$$

$$I = P/V \quad (17)$$

$$= 4.36 \times 10^5 \text{ A},$$

and

$$Z = V/I \quad (18)$$

$$= 22.9 \Omega$$

where P , E_T , I , and Z are the power, total energy delivered, current, and impedance. In return for this investment of energy, the energy produced by fusion reactions⁴³ with D-T fuel will be at least

$$E_F = 5.6 \times 10^{-13} N n_f \tau_B \langle \sigma v \rangle \quad (19)$$

$$= 5.6 \times 10^5 \text{ J},$$

where

$\langle \sigma v \rangle$ at $T_f = 10 \text{ keV} = 1 \times 10^{-16} \text{ cm}^3 \text{ sec}^{-1}$, since the onset of an appreciable reaction rate will occur at about 4 keV. One should note that the energy which would be available if 100% of the fuel were burned, E_F^C is

$$E_F^C = \frac{N}{2} Q \quad (20)$$

$$= 1.41 \times 10^7 \text{ J},$$

where

Q = the energy released per reaction
 $= 17.6 \text{ MeV},$

so we have only retrieved 4% of the total energy which was available. Finally, we note that the various equilibration

times⁴⁴ are sufficiently short during τ_B that a thermal plasma is assured, i. e.,

$$t_{ee} = 6.2 \times 10^8 T_e^{3/2}/n_e \\ = 1.96 \times 10^{-14} \text{ sec} \quad (21)$$

$$t_{ei} = 2.33 \times 10^{12} T_e^{3/2}/n_e \\ = 7.37 \times 10^{-11} \text{ sec} \quad (22)$$

$$t_{ie} = 4.65 \times 10^{12} T_i^{3/2}/n_e \\ = 1.47 \times 10^{-10} \text{ sec} \quad (23)$$

$$t_{ii} = 3.72 \times 10^{10} T_i^{3/2}/n_i \\ = 1.18 \times 10^{-12} \text{ sec} \quad (24)$$

where the Coulomb logarithm is

$$\ln \Omega \approx \ln \left[4.9 \times 10^{14} T_e^{3/2}/\sqrt{n_e} \right] \\ = 9.65 \quad (25)$$

and t_{ee} , t_{ei} , t_{ie} , and t_{ii} refer to the electron-electron, electron-ion, ion-electron, and ion-ion times.

To visualize a possible target geometry which might be used with the preceding example, consider the radial implosion of an annulus into a dense cylinder. Possible dimensions for the pre-shot geometry annulus may be a length, l , of 3 cm, a minor radius of 2 mm, and a major radius of 3.82 mm. In order to achieve the particle density used, the final volume and radius of the cylinder would be

$$\text{Vol} = N/n_f = 10^{-5} \text{ cm}^3 \quad (26)$$

and

$$r = \sqrt{\text{Vol}/\pi l} = 1.03 \times 10^{-3} \text{ cm} \quad (27)$$

The net compression factor, η , during the implosion is

$$\eta = n_f/n_i = 10^5. \quad (28)$$

Since the density, ρ , associated with the final particle density is 8.31 g cm^{-3} , the ρr product of the system is

$$\rho r = 8.56 \times 10^{-3} \text{ g cm}^{-2}, \quad (29)$$

but the fact that $\rho r \ll 1$ is not surprising since the example in question is not an inertial system since

$$t_D = r/v_s \text{ (at burn time)} \\ = 1.05 \times 10^{-11} \text{ sec} \ll t_B \quad (30)$$

where

v_s = the sound speed in the medium

$$\approx \sqrt{RT_f} = 9.82 \times 10^7 \text{ cm/sec}$$

for

R = gas constant

$$= 8.32 \times 10^7 \text{ ergs K}^{-1} \text{ mole}^{-1}.$$

In summary, this has been a rather crude calculation which was only intended to give one the flavor of the problems to be faced in the larger fusion problem.

Finally, I am forced to face the reality of not being in a position to give any of these considerations the acid test of experimental conditions since the various considerations lead us consistently to machines capable of delivering $\geq 100 \text{ kJ}$ at 1 to 10 MV and 1 to 10 MA over ~ 10 to 30 nsec. A machine with these characteristics, however, is clearly within technological achievement. With the facilities available, we have been able to produce neutron yields, which are probably non-thermonuclear, with greater efficiency than a plasma focus with the

same energy storage capability by a factor of 10 to 20. In essence, while a direct test of the gross theory has not been possible, I am also not discouraged by the results of the experiments which have been within our means since this work is only a first step in the research program of our group. Thus, advanced laboratory work employing larger electron beam facilities or the

electron burst in a plasma focus must be pursued, in my opinion, in order to answer the question raised at length here. Can a large electron beam machine be coupled to a suitably designed target structure in order to achieve sufficient fusion burn to allow attainment of the goal of powerline break-even? This is the ultimate objective of the Pulsed Fusion Group.

Experiment

APPARATUS

The experimental system will be rather artificially broken down into four major components which will each be further differentiated for ease of description. The major parts are the target structures, the associated supports, the experimental chamber along with its external support functions, and the electron beam machine itself. The purpose behind differentiating between the target structures and their supports is twofold. First, the target itself is relatively complex, and second, with only one or two exceptions, no diagnostic capability could be mounted directly on the target structures without completely altering the experiment being performed. On the other hand, the supports provided a convenient location for monitoring the current returning to ground from various parts of the target structure without noticeably interfering with the phenomenon being measured.

A three-part structure was used for all experiments (Fig. 1). These are referred to as the cathode, the anode

plane, and the rear target. The cathode consisted of the machine cathode, a tapered adapter section, and a CD_2 tip. The anode plane consisted of a CD_2 disk with a tapered hole drilled through on axis, a teflon holder, and the anode centering support. The rear target had several configurations, but the one most typically used was a CD_2 disk held in a teflon cup on a polyethylene-teflon insulator. This insulator, in turn, was attached to a stainless steel shaft which passed out of the vacuum chamber through a plexiglass port. The most common spacings of interest are a gap between the cathode tip and the front face of the anode CD_2 disk of 6 mm and a distance between the rear face of the anode CD_2 disk and the front face of the rear target CD_2 disk of 6.35 cm.

In the earlier phases of the experiment, simple disk-shaped metal supports were used to hold the anode plane and rear target structures and to provide a radial current return path. However, these radial supports were replaced with low L/R resistive current shunts as quickly as it was possible to get them

Fig. 1. Basic target geometry.

built (Fig. 2). In this way, the fundamental electrical configuration was not altered by the addition of current diagnostics. The shunts were constructed in such a way as to provide an anchorage ring at a 33-cm diameter while being able to be positioned arbitrarily along the entire axis of the experimental chamber. These shunts were anchored, physically and electrically, by unscrewing five brass bolt heads, located symmetrically around the shunt ring, against the inner wall of the vacuum chamber.

The experimental chamber was actually in two parts, the diode section and the "drift" chamber. The diode section consisted of the plexiglass-aluminum insulator rings which formed the main cathode insulator for the machine, and a pumping collar. The vacuum was provided by a Kinney KDH-46 roughing

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Fig. 2. Relative positions of the current shunt (single-shunt geometry) and capacitance pads.

pump and a NRC 6-in. diffusion pump, using Dow-Corning DC704 as the working fluid. The base pressure of this system was usually about 1.5×10^{-4} Torr, with a volume of approximately 0.535 m^3 . This rather high base pressure was imposed by a slow leak of transformer oil through the main machine insulator. Ideally, a vacuum of 10^{-5} torr or slightly lower would have been used, as experience on other machines indicated an improved performance of the target structures at these lower pressures. Also, it would have been possible to bleed D_2 gas into the chamber in order to control the residual gas contamination to some extent. The "drift" chamber was simply

a 60-cm-i. d. by 92.4-cm-long cylinder with various access ports.

The actual electron beam machine used was a Physics International Pulserad 422. This device is basically a Marx generator, storing 27 kJ at a 100-kV charge voltage, coupled to a transmission line. This line could either be a simple coaxial line or a Blumlein configuration. The first option has an output impedance of 10Ω and is referred to as the low-impedance mode, while the Blumlein has an impedance of 40Ω and is, thus, the high-impedance mode. Results of the experiments indicated that the high-impedance mode was the more optimal configuration of the two for this

application. Since the anode initially would appear as an open circuit, the higher impedance preference would seem reasonable. Also, since the Pulserad works on the theory of resonant energy transfer, the high-impedance mode would be expected to deliver a greater fraction of the stored Marx energy because the Blumlein capacitance is more nearly matched to that of the Marx generator. In the high-impedance mode the Pulserad will characteristically deliver a 2.5 MeV, 30 kA, and 60 nsec pulse. Thus, only about 2 kJ are actually delivered to the load with the maximum Marx charging voltage. A larger fraction of the stored energy could be transferred by matching the Blumlein capacitance to that in the Marx bank exactly and by adjusting the Blumlein inductor and switch characteristics for optimal firing.

MEASUREMENTS

Neutron Yield

Total Neutron Yield

The integrated fraction of the total neutron yield with energies in the vicinity of 2.5 MeV was monitored by three methods. The first and primary method used for all experiments was the silver activation detector (see Appendix C).⁴⁵⁻⁴⁷ The yield in all cases was determined by direct calibration using a Pu-Be source of known flux in the experimental geometry and counting the β decay curve of the two activated silver isotopes, ^{108}Ag and ^{110}Ag . With this information, linear least-squares methods were used to separate the ^{110}Ag part of the decay spectrum from that of the ^{108}Ag . Thus,

the actual yield determination was made with only the thermal neutron transmutation of ^{109}Ag to ^{110}Ag with its associated half-life of 24.2 sec.⁴⁸ In addition to measuring the total neutron yield, these detectors were also used to measure simultaneously the neutron yield at 0° and 90° to the target axis to determine the isotropy of the neutron burst. The ratio of these angles was found to be

$$0^\circ/90^\circ = 1.1 \pm 0.1$$

The activation detectors recorded average experimental neutron yields of about 10^{10} n/pulse during the work on the Pulserad, with a maximum burst fluence of 5×10^{10} neutrons.

The second method used for these total yield measurements was uranium fission foil analysis (see Appendix D). The purpose of this measurement was to check to see if the yields measured by the silver detector were actually due to high-energy neutrons or rather to copious quantities of relatively low-energy neutrons. This determination is possible since the ^{238}U threshold for (n, fission) is 1.2 MeV.⁴⁹ The measurement consists of exposure of ^{238}U and ^{235}U foils to a neutron fluence, etching them in NaOH, and correlating the number of tracks per unit area with statistics obtained with a known source calibration in the experimental geometry. Physically, one strip each of a ^{238}U and a ^{235}U foil was positioned parallel to the target axis at a radius of 12.75 cm. They extended from about 8 cm toward the electron beam machine from the cathode tip to about 13 cm behind the rear target. The silver detector measured an average neutron fluence for two series of shots

of 2.64×10^{10} n/pulse. The fission foils showed yields of 1.55×10^{10} n/pulse on ^{238}U for a 41% deviation, 2.94×10^{10} n/pulse on ^{235}U for a 11% deviation, and 2.25×10^{10} n/pulse for a two-foil average for a 15% deviation. All of these variances are well within experimental tolerances.

The third method of total yield detection used was sulfur activation (see Appendix E). The $^{32}\text{S}(\text{n}, \text{p})\ ^{32}\text{P}$ reaction was used which has a threshold of 1.58 MeV with subsequent β emission from the ^{32}P decay.⁴⁹ A calibration with the Lawrence Livermore Laboratory Insulated Core Transformer facility to irradiate tablets with a fluence of 10^{10} n cm^{-2} with 14-MeV neutrons yielded a calibration factor of 1.16×10^{-7} (dis/min) cm^2/n . This procedure eliminated many uncertainties involving such difficulties as β self-absorption and counting geometry differences. Two tablets of reagent-grade sulfur were used with dimensions of 2.54-cm diameter and 0.64-cm thickness. These tablets were located (1) at a radial distance of 6.10 cm from the target axis on the anode positioning support, and (2) on axis behind the rear target CD_2 disk. Interestingly enough, this was the only diagnostic which could be placed directly on the target structures without altering the experiment noticeably. Even so, during the 12 shots used for activation, the tablet behind the rear CD_2 disk was partially pulverized. Fortunately, this pellet was recovered with approximately 50% of its mass in large pieces, 40% in powder, and 10% lost, so the difficulties arising from crushing were partially or wholly offset

by material loss. This experiment yielded two quite important confirmations of other diagnostics used. The high threshold energy assured measurement of only relatively high energy neutrons. In fact, a crude calculation with a time-of-flight trace as the energy spectrum for correlating relative energy contributions with the appropriate cross sections resulted in a yield figure of 3.74×10^{10} neutrons from the sulfur activation as compared with a summed-shot, yield figure of 7.21×10^{10} neutrons from the silver activation detector. Also, the use of two tablets and the assumption of an isotropic point neutron source permitted a calculation of the source location. This procedure indicated the source was approximately 1 mm $\pm$ 2 mm in front of the front face of the rear CD_2 disk which provided a good confirmation of earlier time-of-flight data that indicated the source location to be near the front of the rear target.

Time-of-Flight Measurements

Relatively noise-free, reproducible time-of-flight spectra have been obtained with a RCA 6342 photomultiplier optically coupled to a 17.7-cm-diam by 20.3-cm-long cylinder of MEL-150C plastic scintillator (see Appendix F). Two important spectrally independent results are the agreement with the quantitative yield of the silver activation detector, total neutron measurement and with the qualitative observation of the neutron source location with sulfur activation analysis. On Shot #5, 8-31-73, the low-energy neutron yield, measured with the time-of-flight detector, was integrated and computed with a calibration factor obtained from

a known, pulsed-neutron source. The estimated yield by this method was 7.8×10^9 n/pulse with an accuracy of about a factor of 2. The silver detector registered 1.7×10^{10} n/pulse which is a factor of 2.18 in variance. Since no attempt was made to correct for spectral energy dependence, the entire measurement must be considered as only a "ballpark" verification of the quoted neutron yields. In this spirit, the measurement can be considered to be in good experimental agreement. The approximate location of the neutron source was obtained by moving the target geometry along the axis of the experimental chamber through the time-of-flight observation space. The neutron source was concluded to be in the vicinity of the front face of the rear target. Later, sulfur activation measurements confirmed this observation with a more precise source location identification.

A typical time-of-flight trace can be separated into three distinct spectral regions, the γ peak, the high-energy neutron group, and the group of lower energy neutron peaks (Fig. 3). The γ peak is the Bremsstrahlung radiation associated with the machine voltage pulse. This conclusion is consistent with observations of the coincidence between the start of the radiation peak and the machine voltage to within about 2.5 nsec and of a radiation peak full width of 75-90 nsec which is comparable with the electron generator's pulse time with our target geometry as a load. This radiation was intense enough to necessitate placement of the detector inside a 5-cm-thick lead radiation shield to prevent non-linear and saturative,

long-time effects. The high-energy neutron group is the result of either $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ or $\text{T}(\text{D}, \text{n})^4\text{He}$ reactions, and the only way to definitely resolve this ambiguity is to perform another series of experiments.* The energy represented by this peak is quite probably between 13.4 and > 14 MeV. This is the result of a three-part analysis involving a " $\Delta t - \Delta d$ " measurement, an assumed time of production, energy calculation and consideration of the reaction kinematics for the two reactions of interest. The time of neutron production appears to be ~ 70 nsec into the machine pulse, which coincides with the establishment of the large, rotating current in

*See Addendum for recent results.

Fig. 3. Yield contributions in a typical time-of-flight spectrum.

the anode plane. This observation would support an energy compression model for the electrical behavior of the target structures during a shot. For ease in analysis, an energy of 14 MeV has been somewhat arbitrarily assigned to the high-energy neutron peak with an estimated error of $\leq 10\%$. Three reactions seem to be responsible for the lower energy group of peaks, $D(D, n)^3He$, $^{12}C(D, n)^{13}N$, and $^{19}F(D, n)^{20}Ne$. The $D(D, n)^3He$ and $^{12}C(D, n)^{13}N$ reactions are obvious candidates based on their respective cross sections and abundances. In fact, the characteristic β decay radiation of ^{13}N has been measured in post-shot analysis. The $^{19}F(D, n)^{20}Ne$ reaction is possible since the rear target holder is teflon, CF_2 . By comparison of several shots and a sum-average spectrum, composed from Shots 17, 18, and 20 of 2-14-74 (Fig. 4),

a consistent set of peaks, occurring reproducibly, have been identified.

In addition to the local spectral considerations, more general correlations and observations have been possible. Elimination, to as great an extent as practical, of detector spectral dependence is possible by considering three energy-dependent neutron interactions with the detector. These effects are scintillator light production per neutron interaction, scintillator neutron absorption, and radiation shield neutron transmission as a function of energy. This correction is performed by a computer code on digitized information in a discrete, semi-continuous manner across the spectrum between the energies of 0.1 and 20 MeV, with all correction factors normalized at 14.1 MeV. A rough, monoenergetic calculation at 2.45 MeV gives a total correction factor of 5.2, where the factor

Fig. 4. Sum-average, time-of-flight spectrum of Shots 17, 18, and 20, 2-14-74.

due to light production is 0.21, ^{50}Ne neutron absorption is 1.14, and neutron transmission is 0.80. The reduction of the ratio of the high-energy yield to the total low-energy yield from $\sim 1/20$ to $\sim 1/104$ demonstrates the relatively large effects that this correction may have (Fig. 5). Due to the ambiguous origin of the high-energy peak, the two possible analyses must be pursued. For the

Fig. 5. Energy representation of a response-corrected time-of-flight spectrum. (a) Uncorrected spectrum; (b) corrected spectrum.

model of a strictly beam-target neutron yield, analysis of the reactions responsible for the lower energy neutrons has given a set of theoretical neutron peaks. There is a fairly good correlation between the observed and predicted neutron groups (Table 1). Generally, $^{12}\text{C}(\text{D}, \text{n})^{13}\text{N}$ peaks account for the lower energy portion of this group, while $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ peaks coincide with the higher energy portion. However, there are four problems with this analysis. Three of the observed peaks either do not have theoretical matches, or have ambiguous or multiple matches. This is the case for the 8.1-, 6.8-, and 3.5-MeV peaks. In addition, there seem to be some quite strong theoretical peaks which are not represented in the observed spectrum. On the other hand, if the high-energy peak is due to $\text{T}(\text{D}, \text{n})^4\text{He}$ reactions, the implied plasma temperatures and yield ratios must be considered. The fwhm of the 14.1-MeV peak is

Fig. 5(c). Detector response correction factor.

Table 1. Neutron peak correlation with known reaction peaks.

Observed peaks (MeV) ±0.1 MeV	Predicted peaks with 4.25 MeV deuterons on:		
	^{19}F	^{12}C	D
1.7		1.65	
2.9		2.8	
3.5		3.6	3.5
4.5	4.5		
5.5	5.4		
6.8	7.0 or 6.6		
8.1			
9.8	10.0		
14.1	14.1		

Note: Thick target interactions tend to give ledge contributions to a spectrum rather than distinct peaks.¹²²

~3.1 MeV which would imply a plasma "temperature" of 308 keV by Muir's relation.⁵¹ This is rather high, but not impossible in light of further results. Also with a plasma temperature of ~6 keV, obtained with thermoluminescent crystals and matched Ross x-ray filter foils, the implied fwhm for the D (D, n) ^3He would be ~116 keV. This peak width would imply a ratio of d (D, n) ^3He yield to the total low-energy yield of ~3%; however, this would mean a ratio of D (D, n) ^3He yield to T (D, n) ^4He yield of ~1/3.25. Therefore, while this constitutes only a small fraction of the total neutron yield, the ramifications concerning plasma temperature and confinement time are rather startling. Of course, the presence or absence of the T (D, n) ^4He yield does not disqualify the low-energy peak correlation since collective acceleration work within our group¹⁸ and else-

where⁵²⁻⁵⁴ would indicate the presence of beam-target reaction neutrons in any event. However, the presence of a confirmed T (D, n) ^4He neutron group would be of paramount importance in the controlled fusion community.

Optical Diagnostics

Open-Shutter Photographs

Time-integrated, open-shutter observations were made with the use of 4- X 5-in. Polaroid-type 58 color film and a Graflex camera. This technique was employed to try to get a visual understanding of the electron beam discharge before time-resolved optical instrumentation was available and to have another very nearly fail-proof diagnostic in addition to the silver activation neutron detectors. It was realized, both theoretically in the beginning and very practically in short order, that this method of observation had the very serious drawback of recording everything during and after the discharge, including the late-time plasma afterglow and expansion. However, in spite of this rather severe handicap, these observations did prove quite useful. One of the more important benefits of this technique was the realization that under various circumstances the phenomenon of shank fire, spurious cathodic discharges, could be enhanced or suppressed (Fig. 6). The early time presence of shank fire was hypothesized when an inverse correlation between the size of the neutron yield and the intensity of the spurious discharge was noted. Also, evidences of plasma streaming and bright spots helped to indicate

Fig. 6. Open-shutter photograph of the target during a shot.

regions of high-energy density throughout the target geometry (Fig. 7). These indications proved quite valuable when more specific instrumentation came into use. Finally, an empirical understanding of the process of rear target insulator breakdown was gained which eventually led to the fabrication of relatively long-lived structures for this application.

Image Converter Photographs

Time-resolved optical information was obtained with the use of an Abtronics single-frame-per-trigger image converter. The exposure time was 10 nsec and the electronic trigger was taken from the Pulserad installation's B signal cable. Unfortunately, various problems, both electrical and mechanical, prevented acquisition of a photograph during the early part of the machine pulse, so all of this data occurs 30 nsec or later into the electron burst. The camera was oriented at an angle of 45°

to the target axis to permit observation of the rear target side of the anode CD_2 disk. Also, during the time that this instrument was operational, the anode CD_2 disk and its associated insulator-holder were supported in a 2.54-cm-thick polyethylene disk to a radius of 15 cm where the radial current shunts were located (see Fig. 8). The single most important piece of information learned from this diagnostic was that the return current in the vicinity of the anode hole had a definite filamentary structure. Close inspection of these photographs reveals both single long filaments as well as those which seem to be splitting in two. This result is somewhat similar to the work of Bostick *et al.*⁵⁵⁻⁵⁹ who observe filaments in a plasma focus. In addition to this, several of the current-carrying filaments terminated on the second front current shunt ring in a bright spot. This would lend evidence to an earlier assumption

Fig. 7. Open-shutter photograph of the rear target assembly during a shot.

Fig. 8. 10-nsec exposure, image converter photograph of the rear of the anode plane.

that any currents circulating in the near vicinity of the anode to ground would be preferentially conducted through the current shunts due to their relatively closer ground potential than the experimental chamber wall. Also, the observation from studies of open shutter

pictures and post-shot examinations that the rear insulator material breakdown occurs with the current running predominately on the surface of polyethylene and tending to puncture through the bulk teflon was reaffirmed by this tool.

Electrical Diagnostics

Voltage Measurement

The voltage diagnostic system employed small, fast response capacitance pads mounted on a 22,225-cm radius from the target axis on divider rings (see Appendix G). There were two locations at which these divider rings supplied good information (Fig. 2). One ring was located 45 to 46 cm from the anode plane inside the machine's diode section, while the other was concentric with the rear target. Early-time asymmetries in the discharge made a third location immediately on the cathode

side of the anode plane unsuitable for any decipherable observations at all.

The diode location yielded very consistent, clean, symmetric voltage traces for which time correlation with the anode current measurements was possible (Fig. 9). Typically, a ~ -175 to -350 kV plateau, depending on machine output, is present for the first 12 to 15 nsec of one of these voltage traces. After this time, the voltage rises at a rate of ~ -280 kV/nsec until an inflection point with an amplitude of ~ -1.05 to -1.75 MV at ~ 20 nsec is reached. For maximum generator outputs, the rise in voltage then continues to an average peak of ~ -2.5 MV at ~ 28 nsec into the pulse. A comparison of the Marx bank charging voltage with the average peak diode voltage, time of peak diode voltage, and width of voltage pulse (half-cycle) demonstrates that along with lower peak diode voltages with lower Marx voltages, both the time of peak diode voltage and

the duration of the pulse are Marx charge-dependent. For example, the average time of peak voltage is 26.2 nsec for all shots diagnosed, as compared with the 28 nsec quoted earlier. By 70 nsec into the shot, the diode voltage is $\sim +88$ kV and is fairly independent of machine output. Occasionally, some small oscillations, with a frequency of ~ 200 MHz, were present in this measurement, but this was never more than an effect of $\sim 3.5\%$.

In contrast to the relatively easy measurements taken in the diode region, the rear target observation proved to be considerably less reliable and more complex. This was quickly evident when we were forced to conclude that only the first 15 nsec or less of this trace contained useable information (Fig. 10). After this time, very large asymmetries were seen in the cylindrical geometry. The most significant feature in this trace is a ~ 76.5 V (on the oscilloscope),

Fig. 9. Time history of the machines diode voltage as measured with a capacitance pad.

Fig. 10. Time history of the voltage measured in the vicinity of the rear target with a capacitance pad.

~3.3 nsec wide voltage spike at about 3.1 nsec from the start of the signal. With the derived voltage division ratio from the quasistatic spherical approximation, the implied peak voltage on the rear target is ~30.4 MV. If this voltage were believed, then the rate of change of the signal would be ~9.2 MV/nsec. In addition to this peak, there is also a relatively persistent positive spike at ~13 nsec, with an implied voltage of ~24.8 MV. As indicated, these amplitudes are not correct since they would imply charge accumulations on the rear target of more than a coulomb (enough to literally explode it), while the electron beam machine will deliver less than an optimistic 3×10^{-3} coulombs. The

obvious reason for this problem is the violation of the assumptions upon which the voltage division derivation is based. The "correct" approach to interpreting these traces would be to pursue a relativistic, time-dependent calculation; however, there is currently insufficient experimental data to justify such an effort. The other question which arises is whether or not these two voltage spikes are real. Data, obtained by placing a high-Z loaded polyethylene disk over one of the capacitance pads, would indicate that the signal is not spurious, but this is, admittedly, a preliminary conclusion at this time. However, for the moment we will assume that these signals are real and leave their interpretation as

Fig. 11. Relative positions of the various target components for the double-shunt measurement.

a matter to be resolved with future experiments. Finally, direct time correlation between this signal and either the anode current or the diode voltage is not available.

Current Measurements

Current observations were possible with the use of very low inductance, high-current capacity shunts (see Appendix H). We used two different geometries to monitor the currents in the anode plane. The simpler one consisted of merely using a single shunt to hold the anode structure in place (Fig. 2). Although currents in our geometry are not constrained, most, if not all, of the current returning to ground in this region would pass through the shunt because of its relatively smaller radius than the chamber wall. The more sophisticated anode measurements employed two shunts, one on either side of a disk of polyethylene (Fig. 11). This disk provided a dielectric support for the front target holder and front target. Thus, all metal "grounds" were moved to a 30.5-cm diameter from the standard 10.4-cm diameter of the teflon front target holder. For convenience, we will refer to the high-current shunt on the cathode side of this anode plane as I_1 and the lower current shunt on the rear target side as I_2 . In addition to the anode observations, another shunt monitored any current returning to ground through the rear insulator support rod.

The rates of current rise in the two anode geometries compare very closely in the first 5 nsec. This rate of change for the single shunt was ~ -3.5 to

4.0 kA/nsec (Fig. 12), while the sum, $\dot{I}_1 + \dot{I}_2$, was ~ -3.2 kA/nsec (Figs. 13, 14). After this time the changes in I_1 and I_2 tend to be in opposite directions until about 70 nsec into the pulse. The single shunt measurements displayed a maximum current of ~ -50 kA at ~ 30 nsec. On the other hand, I_2 has its first major current peak at 13 to 15 nsec with an amplitude of ~ -4.5 kA. This current then goes positive in the interval between 24 and 35 nsec with a peak amplitude of $\sim +740$ A occurring at ~ 29 nsec. Meanwhile, I_1 reaches a peak current of ~ 45 to 50 kA at ~ 25 nsec. Thus, when I_1 is peaking, I_2 is either zero or positive which implies a rotating current from the rear of the anode plane to the cathode side. After this positive interval I_2 is generally becoming more negative, but there is usually an inflection, if not a peak, at the time when I_1 becomes positive at ~ 55 to 60 nsec. By 70 nsec,

Fig. 12. Time history of the anode current as measured with the single-shunt geometry.

Fig. 13. Time history of the cathode-side shunt current for the double-shunt configuration.

Fig. 14. Time history of the rear-target-side shunt current for the double-shunt configuration.

both I_1 and I_2 have stabilized with currents of $\sim +6.8$ and ~ -6.3 kA, respectively. Hence, late in the pulse a rather large, stable, rotating current exists from the cathode side to the rear target side of

the anode plane with an amplitude of ~ 6.3 kA. The oscillatory behavior exhibited by the single shunt traces is readily understood with the double shunt measurements. The single shunt observations display oscillations between ~ 5 and 70 nsec, while the directions of change in I_1 and I_2 tend to be opposite during this time. In addition, neither I_1 nor I_2 shows oscillatory behavior. Due to the decided differences in the two geometries, a comparison between the amplitude of the single shunt oscillations and the instantaneous differences between I_1 and I_2 is not warranted. In addition to geometry differences, there is some evidence which indicates that there may be currents circulating in the vicinity of the front insulators which do not necessarily short to ground. These currents may or may not be observed in the double shunt case, but they almost certainly are not seen in the single shunt geometry. If these currents can exist, then one must recognize the distinct possibility that the current structures which give rise to neutron production may be decoupled from the anode current diagnostics in spite of their close electrical proximity. This would imply phenomena occurring on even faster time scales than those observed due to dimensional scaling.

The rear target current measurements showed two results. First, we saw a consistent oscillation at a frequency of ~ 780 MHz with relatively large amplitudes (Fig. 15). No attempt is made to explain the size of this behavior since this shunt is further removed from the proximity of the front and rear targets (>30 cm) than the anode shunts, but the frequency may be evidence for the fast phenomena

Fig. 15. Time history of the rear-target-shunt current.

implied from the anode measurements. The most significant finding was a correlation between rear insulator breakdown and the neutron yield. The total neutron yield would decrease a factor of two or more when significant net current was observed in the rear shunt. Therefore,

in this target geometry optimal neutron yields require a good rear target insulator.

Voltage and Current Correlation

The comparison between the voltage and current diagnostics utilizes only data from high-output shots. Specifically, the voltage and current traces from Shot No. 4 on 8-29-73 and the cathode-side current, I_1 , from Shot No. 13 on 9-7-73 are the sources for the specific figures quoted (see Tables 2 and 3). The neutron yields on these shots were 9.89×10^9 n/pulse and 2.14×10^{10} n/pulse, respectively. There are two reasons for the use of the voltage from one shot with the current from another. The first consideration is the absence of a diode voltage measurement during the double shunt observations of the anode. Secondly, the diode voltage, as compared over many shots, was very consistent with a variance of <10%.

Table 2. Instantaneous voltage, current, power, and target impedance for Shot 4, 8/29/73.

Voltage - Current Correlation				
Time (nsec)	Voltage (MV)	Current (kA)	Power (GW)	Impedance (Ω)
0.0	-0.0	- 1.30	0.0	—
5.0	-0.219	- 2.28	0.498	96.3
10.0	-0.307	-13.0	3.99	23.6
15.0	-0.298	-37.7	11.2	7.90
20.0	-1.62	-32.5	52.7	49.9
25.0	-2.24	-40.3	90.4	55.7
30.0	-2.47	-29.6	73.1	83.5
35.0	-2.45	-20.8	51.0	118.0
40.0	-2.32	-14.6	34.0	159.0
45.0	-1.75	- 6.50	11.4	270.0
50.0	-0.920	- 6.18	5.68	149.0
55.0	-0.613	-10.4	6.38	58.9
60.0	-0.350	-15.6	5.46	22.4

Table 3. Instantaneous voltage (Shot 4) current (Shot 13) power, and target impedance.

Voltage — Current Correlation				
Time (nsec)	Voltage (MV) (Shot 4, 8/29/73)	Current, I_1 (kA) (Shot 13, 9/7/73)	Power (GW)	Impedance (Ω)
0.0	0.0	0.0	0.0	—
2.5	-0.131	- 3.25	0.426	40.3
5.0	-0.219	- 5.20	1.14	42.1
7.5	-0.219	-15.6	3.42	14.0
10.0	-0.307	-22.1	6.79	13.9
12.5	-0.307	-23.4	7.18	13.1
15.0	-0.298	-29.9	8.91	9.97
17.5	-1.23	-33.8	41.5	36.3
20.0	-1.62	-34.5	55.8	47.1
22.5	-1.88	-44.9	84.5	42.0
25.0	-2.42	-49.4	111.0	45.4
27.5	-2.41	-44.2	107.0	54.5
30.0	-2.47	-41.6	103.0	59.4
32.5	-2.28	-36.4	82.9	62.6
35.0	-2.45	-32.5	79.7	75.5
37.5	-2.41	-26.0	62.7	92.7
40.0	-2.32	-22.1	51.3	105.0
42.5	-2.19	-19.5	42.7	112.0
45.0	-1.75	-13.0	22.8	135.0
47.5	-1.40	- 9.75	13.7	144.0
50.0	-0.920	- 7.80	7.18	118.0
52.5	-0.745	- 6.50	4.84	115.0
55.0	-0.613	- 5.20	3.19	118.0
57.5	-0.526	- 2.60	1.37	202.0
60.0	-0.350	- 1.30	0.455	269.0

Hence, while there is some risk in combining measurements from different shots, this particular combination should give the general characteristics that would be expected on any given shot. The instantaneous power during the pulse is simply the product of the instantaneous voltage and current. We have made no attempt to allow for the reduction in voltage at the end of the cathode due to

an LI term in the impedance since this correction would be misleading in this case. Our inability to use a voltage divider very near the anode plane on the cathode side strongly suggests that a constant inductance calculation in that region is clearly not justified because rather wild behavior is seen. Also, for the single shunt geometry, the anode shunt probably does not intercept all of

the machine current, so its measurement provides a lower bound on the total machine output. Since charge is conserved, a power calculation will be conservative; however, all of the indicated power should not be assumed to necessarily interact directly with the target structures. The double shunt results are more confusing due to the presence of rotating currents in the anode geometry. The instantaneous impedance was obtained in a similar fashion to the power ($Z = V/I$), but this quantity is less well defined. Probably the least ambiguous interpretation would be to regard this impedance as if it were a variable resistor connecting the machine cathode to the chamber wall at the position of the voltage monitor. Thus, we are observing all of the impedance represented by the target configuration, but only with the use of the anode current.

Before examining the power and impedance results, let us compare the various characteristics of the voltage and currents used in this analysis. The comparison between the single shunt current, I , which was obtained simultaneously with the voltage, and the double-shunt cathode-side current, I_1 , is particularly significant (Fig. 16). The behavior of both of these currents is generally the same, with three notable exceptions. The single-shunt current, I , displays a definite peak at 15 nsec, while the cathode-side current, I_1 , shows only an inflection. Next, I is about 20% less than I_1 at peak current, but this peak in both currents occurs at ~25 nsec in this particular set of traces. Then, very late in time, I becomes larger than I_1 and remains negative while I_1 becomes

Fig. 16. Time history of the anode currents for Skt 4, 8-29-73 and Shot 13, 9-7-73.

positive at ~60 nsec. Due to the similarity between I and I_1 , the voltage comparison will use I_1 since it is the cleaner trace. Early in the pulse, the rate of current change in I_1 is ~4 kA/nsec during the voltage plateau, which has an amplitude of ~200 to 300 kV (Fig. 17). By 15 nsec into the machine pulse, I_1 has already risen to ~60% of its peak value, while the voltage only has an amplitude of about 12% of its peak. The final distinctive point between the voltage and current is the difference in time between their peak values. The current peaks at ~25 nsec, while the voltage is about 5 nsec later with its peak value.

The instantaneous power for both cases, I and I_1 , is essentially the same except for the amplitude differences noted in the current comparison (Fig. 18). Initially, the rate of energy delivery builds up quite slowly to ~10 GW at the end of the first 15 nsec. This represents a rate of change of ~530 MW/nsec. However, the

Fig. 17. Time history of the machine diode voltage for Shot 4, 8-29-73.

Fig. 19. Time history of the instantaneous target impedance for these two examples.

Fig. 18. Time history of the instantaneous power for these two examples.

rate of power change increases to a respectable ~ 12 GW/nsec immediately after this first interval. By 25 nsec, the powers peak at 90 GW and 110 GW for I and I_1 , respectively. After this time the power level decreases in a manner similar to the current,

As in the power evaluation the instantaneous impedances are fairly similar in both cases, but with some decided differences (Fig. 19). During the first 15-nsec interval, the I impedance, Z , decreases from $\sim 70 \Omega$ to $< 10 \Omega$, while the I_1 impedance, Z_1 , starts at an essentially matched condition to the machine ($\sim 40 \Omega$) and also falls to $< 10 \Omega$. Between 15 and 25 nsec, both Z and Z_1 increase to values close to 40Ω , with Z being the larger of the two. During the next 13 nsec, these impedances increase rather rapidly to substantially higher values than the output impedance of the electron beam machine. For example, Z_1 has risen from $\sim 42 \Omega$ at 25 nsec to 80Ω by 36 nsec. These values peak at the end of this period with Z at $\sim 270 \Omega$ and Z_1 at $\sim 145 \Omega$. After this time, the behavior of the two cases is quite different. In the single shunt case, Z monotonically decreases during the rest of the pulse to $\sim 20 \Omega$ by 60 nsec. On the other hand, Z_1 dips to $\sim 120 \Omega$

from 50 to 55 nsec and then increases to $\sim 270 \Omega$ by 60 nsec. The effect of this behavior in Z_1 is not clear, but this impedance dip may be responsible for the inflection in the rear anode current, I_2 . However, the coupling between the front and the rear of the anode plane is highly uncertain and complex, particularly since this local minimum in the impedance is still roughly three times the machine's output impedance.

With this information, we may now compare the voltage, current, power level, and impedance during a typical pulse. In the first 15 nsec of the shot, both the voltage and power increase quite slowly, while the current rapidly increases to a significant fraction of its peak value. Meanwhile, the effective impedance is decreasing. Thus, one must conclude that the voltage plateau time of the pulse, or prepulse, is a time of shorting in the target geometry. After 15 nsec, the voltage, power, and impedance increase significantly, and by 25 nsec both the current and the power are peaking, with an impedance of $\geq 40 \Omega$. Subsequently, the voltage peaks at a time (~ 30 nsec) when the current and power are decreasing and the impedance is rapidly increasing. In fact, Z_1 has risen to a value of $\sim 80 \Omega$ by 36 nsec which implies that the machine is essentially cut off from the target assembly at this time. This open circuit condition becomes more dramatic by ~ 48 nsec when both impedances show peaks at several times the machine's matched condition. From this time to the end of the pulse, the conclusions reached in the two current cases are distinctly different. Since Z has fallen to about half of the machine impedance

by 60 nsec with a slightly increased current, one observes a second period of shorting behavior. However, the I_1 result would lead us to expect that this shorting is not directly involved with the target interaction. This must be the case since Z_1 increases to $\sim 270 \Omega$ by 60 nsec. Recall that this is the interval in time when the large rotating current in the anode starts to be established. Thus, it appears that although the machine may have a decided tendency to short to the front face of the single-shunt anode, the rotating currents observed in the double-shunt case are essentially independent of the machine. Another indication that this may be the correct interpretation, even much earlier in the pulse to some extent, is illustrated by integrating the instantaneous powers to obtain approximations of the energies actually delivered by the machine. For several single-shunt geometry shots the average energy delivered is ~ 1.6 kJ, while the double-shunt case would imply that ~ 4.5 kJ are dumped. Actually, the figure of 4.5 kJ is in error since the rotating currents in the anode would probably not be driven with the same voltage as that of the machine. Therefore, a net energy of ~ 1.6 kJ is delivered by the electron beam machine to our target geometry.

Microwave Observations

The possible presence of quite fast phenomena, indicated by the shunt measurements and the work of Friedman^{60,61} and others,^{59,62} prompted us to attempt wide-band, passive microwave observations. The basic principle used in the spectrometer construction was that a

waveguide will sustain all frequencies down to a threshold or cut-off. Thus, if for example one wishes to detect 10 and 20 GHz separately, then a 10-GHz waveguide is branched with one leg to a 10-GHz detector and the other passing through a reduction section to a length of 20-GHz waveguide and a 20-GHz detector. The result is one signal for 10 GHz and higher and one for 20 GHz and higher. The true amplitudes are obtained by multiplication by a factor of about 4, assuming random phase and allowing for diode termination. After the 20-GHz signal is subtracted from the combined signal, one is then left with a signal for frequencies between 10 and 20 GHz and a signal for 20 GHz and higher. We detected at 10, 20, 35, and 70 GHz in our spectrometer (Fig. 20), which was attached to a section of 10-GHz, rectangular waveguide extending into the

experimental vacuum chamber. The antenna consisted of a 10-GHz, wide-band horn with a nylon dielectric probe insert for both detection and vacuum sealing. This entire assembly "looked" at the rear of the anode target at an angle of $\sim 45^\circ$ from the machine axis. The distance from the microwave horn to the front-rear target vicinity was about 45 cm.

The results of this measurement are summarized in Table 4, and, indeed, our suspicions of very fast phenomena occurring were correct. Unfortunately, these measurements were very preliminary in nature, so some obvious problems are present in the data. For example, the peak area for the 10-GHz signal should be larger than that of the 20-GHz signal (Figs. 21, 22). Currently, it is not clear what the problem is in this regard, but this is only a quantitative detail and does not affect the experimental,

Microwave Spectrometer Schematic

Fig. 20. Schematic of the microwave spectrometer.

Table 4. Summary of results of microwave measurements.

Microwave Analysis				
Frequency (GHz)	Average peak voltage (V)	Average time of peak (nsec)	Average peak area (V-nsec)	Detector correction factor
10	1.33	28	16	8
20	2.00	20	91	16
35	0.3	40	13	32
70	0.6	—	6	32
	Corrected peak voltage (V)	Corrected peak area (V-nsec)	Pure frequency peak areas (V-nsec)	Approximate energy (J)
10	10.4	128	?128?	
20	32.0	1450	836	2.4×10^{-4}
35	9.6	422	230	1.8×10^{-5}
70	19.2	192	192	1.3×10^{-6}

qualitative result. Since the contributions from 20, 35, and 70 GHz were both on a separate leg of the spectrometer and reasonably consistent in their peak area fractions, one can with some caution quantitatively utilize their results. The effect of the correction, noted in the table, is to adjust the raw detector reading to the value it would assume if it were the only detector behind the micro-

Fig. 21. Time history of the 10-GHz signal from the spectrometer.

Fig. 22. Time history of the 20-GHz signal from the spectrometer.

wave horn and a detector which was capable of measuring the TE and TM modes simultaneously with perfect termination, with the assumption of a random phase signal. With the corrected peak voltage, V , from the 20-GHz signal, the peak instantaneous power in this frequency and higher, P_{20} , is

$$P_{20} = V^2/R$$

where R is the transmission line termination impedance, $50\ \Omega$ in this case. This figure may be corrected to an instantaneous, peak source power, P_S , by

$$P_S = P_{20} 4\pi r^2 / A$$

where r is the distance from the microwave horn to the source and A is the area subtended by the horn itself. The result of this calculation with a 15 cm^2 horn area implies a peak microwave source power of $\sim 35\text{ kW}$ in frequencies of 20 GHz and higher, with the two assumptions of random phase and spherically symmetric radiation. In addition to this, the 10-GHz signal displays a distinct second contribution to its pulse at about 70 nsec into the trace; however, it is difficult to determine whether or not this corresponds in time with our other results since relative timing information is unavailable for this diagnostic at the present time.

Diagnostic Summary

After the preceding diagnostic analysis, there have been basically neutronic, optical, and electrical observations performed during these experiments. The total neutron yield was the optimization parameter during the entire course of these studies, so while the silver activation detector was used to give this information on each shot, we employed three different approaches to total yield measurement in order to insure the accuracy of this yield number. Sulfur activation confirmed this yield by giving a 58% overestimate with a monoenergetic neutron assumption and a 48% underestimate with a crude spectral correction. Then uranium fission foils of ^{238}U and ^{235}U

gave an average result over seven shots of $\sim 15\%$ less than the averaged silver detector yield. Finally, time-of-flight techniques, on a single-shot basis, gave a yield figure of $7.8 \times 10^9\text{ n/pulse}$ as compared with a silver detector yield of $1.7 \times 10^{10}\text{ n/pulse}$. The accuracy of this measurement was no better than a factor of 2. Hence, one may conclude that in addition to being very reliable and simple to use, the silver activation detector gave yield numbers which are as accurate as may be expected under these experimental conditions. Also, the sulfur activation experiment gave a neutron source location of $\sim 0.8\text{ mm} \pm 2\text{ mm}$ from the front face of the rear target with the assumption of a point, isotropic source. This correlates with the time-of-flight study which also gave fairly accurate neutron spectra.

The optical studies, consisting of open-shutter and image converter photographs, yielded four results. The shank-fire from the machine cathode was inversely correlated with the total neutron yield. In addition, the predominant presence of this phenomenon near the end of the cathode explains the inability to take reasonable voltage measurements in this area. The attempts at this, in turn, confirm that this is an early-time event. Then, bright streaming from the rear target indicated something interesting occurring in this region. Indeed, time-of-flight and sulfur activation techniques verified that this was the source of the observed neutrons. The other notable contribution from the open shutter work was an indication that the rear insulator electrical breakdown might adversely affect the total neutron yield. This was

later verified with current shunt measurements of the current returning to ground from the insulator support rod. Finally, the image converter study revealed the filamentary nature of the currents running over the dielectric surfaces of the anode and gave an indication that rotating currents in this region might be present. These rotating currents were explicitly observed with the double-shunt anode current measurements in the same series of shots.

The electrical diagnostics include voltage, current, and microwave measurements. The cumulative results of most of these observations are summarized in Table 5 along with a notation on the time of neutron production from the time-of-flight study. There are several specific instances which should be mentioned. The rather large spike in the rear target voltage most likely coincides with the first minor peak in I_1 and I_2 along with the onset of oscillation in the single-shunt anode measurement.

Then at 15 nsec, the first major peak in I_2 occurs along with the minimum in the impedance and the "take-off" of the diode voltage and machine power. Along with these phenomena, at this time positive spikes are seen in the single-shunt trace, and the rear target positive voltage spike most likely occurs too. Next, with the impedance about matched to the machine again the peaks in power and the I_1 current occur at ~ 25 nsec, at a time when I_2 is going positive and giving the first good evidence of a rotating current in the anode structure. The peak voltage occurs ~ 5 nsec later. Quite late into the pulse (~ 70 nsec) the single shunt current stops oscillating, I_1 and I_2 display the establishment of a ~ 6.3 -kA rotating anode current, and the 14-MeV neutron burst would be produced. Finally, the implied peak microwave power of < 35 kW at frequencies of 20 GHz and higher confirm indications of very fast phenomena occurring in the target geometry from the anode current and rear target voltage measurements.

Discussion

To give one the flavor of the difficulties involved with discharge work, a slightly more detailed historical development of this field than outlined earlier will be given. I have the explicit personal opinion that the same phenomena occur in nearly all pinch devices, regardless of their superficial differences, so a rather informal mixing of these developments should be expected. Since the early work in this country is fairly common knowledge, at least in the fusion community, the Russian work will be the source for

the initial work covered by this historical sketch.

The long-standing debate in all discharge research is centered on the mechanism for producing the neutrons that are inevitably observed in pinch discharges. In 1956, Kurchatov⁶³ was quite optimistic about eventual success at making a Z-pinch into a working thermonuclear reactor. However, along with his optimism, he also noted that the correlation between higher voltages in the pinch capacitor banks and higher neutron yields suggested

Table 5. Electrical diagnostic summary

	Diagnostic timing														
	Pulse time (nsec)														
	0	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	
Diode Voltage	~300 kV Plateau					$V = 280 \text{ kV/nsec}$			Inflection point ~1.75 MV		Peak $V \sim 2.5 \text{ MV}$				
Rear Target Voltage	-75.5 V					+			Signal not usable						
Target Voltage	Spike ~3.1 nsec wide					Voltage spike									
Anode Current Single Shunt	Oscillations start (~1 nsec wide)					Some + spikes			Maximum current ~50 kA						
Anode Current Double Shunt: Front Shunt	$i_1 \geq -4 \text{ kA/nsec}$		Minor peak		Inflection or minor Peak			Peak Current ~45-50 kA							
Anode Current Double Shunt: Rear Shunt	Minor peak		+i		1st Major Peak			+Current +i		$\pm 740 \text{ A Peak}$		-i current			
Machine Power	$p \sim 530 \text{ MW/nsec}$				to ~10 GW			$p \sim 12 \text{ GW/nsec}$		Peak power ~100 GW		Generally monotonic			
Target Impedance	Starts High $\geq 40 \Omega$		~Z			<10 Ω		+Z		~40 Ω		+Z			
Time-of-Flight	Start of radiation pulse														

¹ There are sometimes present oscillations ~200 MHz. Effect is $\leq 3.4\%$.

² Trace is substantially free of very fast oscillations.

³ Note the distinction between single and double shunt impedances after ~50 nsec.

y for various events during a shot.

2

that neutron production may be due to deuteron acceleration in electric fields produced by anomalous processes which were not yet understood. At about the same time, Artsimovich *et al.*⁶⁴ pointed out that the plasma phenomena which occur after the first pinch in a linear discharge are not clear. Then, Artsimovich *et al.*⁶⁵ experimentally observed a correlation between hard x-ray production and the time of neutron emission. Since this hard radiation would directly imply high-energy electrons and associated large electric fields, Kurchatov's earlier suspicions were well founded. The total neutron yields in Z-pinches were about 10^8 n/pulse with capacitor banks storing ≤ 50 kJ at this time.⁶⁵ Petrov *et al.*²⁹ reported the first experimental results of a "metal walled Z-pinch," better known today as the plasma focus. This work, which was performed between 1954 and 1957, noted neutron yields of 5×10^9 n/pulse with a 270-kJ, 45-kV capacitor bank. They commented that a basic fraction of the total neutron yield "is associated with some sort of accelerating mechanism." Interestingly enough, one of their diagnostic tools was a 30-m flight path, time-of-flight instrument which consisted of a scintillator-photomultiplier combination with a response time of ~ 100 nsec (not too different from detectors used today).

By 1965, Händel and Berg⁶⁶ reported further experimental correlation between hard radiation and neutron production in a linear vacuum discharge. The observation of the so-called sausage instability was related to the presence of high induced electric fields. Thus, it would

seem that nearly the entire neutron yield was due to accelerated deuterons in these "necks" of the discharge. Meanwhile in 1966, Mather⁴⁰ reported that most of the neutron yield in a plasma focus was due to thermonuclear processes. This conclusion was based on the comparative neutron yields observed with D (D, n) ^3He and T (D, n) ^4He reactions. This comparison was made by using a deuterium-tritium gas mixture as a fill gas instead of the usual pure deuterium. Hence, there seemed to be a clear difference between the neutron production mechanisms in the Z-pinch and the plasma focus, but Bostick⁵⁶ disagreed and proposed a filamentation model for plasma focus neutron production.

In more recent work, Baker and Phillips⁶⁷ point out that magnetic field diffusion in a linear pinch may well be a destabilizing influence. Also, Kvartskhava *et al.*⁶⁸ reported enhancement of electron energies which could be obtained by a low-pressure operation in a Z-pinch. The induced emf theory is used here, but Karchevskii *et al.*⁶⁹ in 1969 and Karchevskii and Strakhov⁷⁰ in 1971 suggest that the actual cause of the electric fields in the linear pinch is the two-stream instability which subsequently produces an anomalous plasma resistivity. They also see an enhancement in electron energies at lower gas fill pressures and note that between 20 and 80% of the capacitor bank energy may appear in an intense electron beam within the discharge. Presiantsev *et al.*⁷¹ confide, in 1972, that there is still no convincing mechanism for charged particle acceleration in the Z-pinch in their opinion. They present experimental data which indicate that the

x-ray sources are off-center and have a varied and different distribution on a shot-to-shot basis. The model suggested is one proposing the formation of current filaments at the onset of a two-stream instability. This formation process is used to predict electric fields of 10^4 to 10^5 V/cm. Also, Imshennik *et al.*⁷² note that the neutron production mechanism in the plasma focus is "complex and cannot be explained in thermonuclear terms," but they imply that this does not prevent net fusion energy output since they present a scaling prediction that a neutron yield of $\sim 4 \times 10^{18}$ n/pulse (~ 10 -MJ equivalent energy) may be obtained using deuterium-tritium gas with a 200-kV, 10-MJ plasma focus capacitor bank. Experimental data presented by Bernstein and Hai⁷³ and Bernstein *et al.*⁷⁴ support this view of non-thermonuclear processes in a plasma focus. Collisionless plasma conditions, resulting from magnetic diffusion through the current column at pinch time, are believed to cause high voltages and subsequent ion acceleration. Bernard *et al.*⁷⁵ and Bernard *et al.*⁷⁶ support a non-thermal neutron production mechanism, but present evidence that filamentation may in fact be the ultimate explanation. They also report an enhancement of accelerated ion energies when the device is operated at lower pressures. This data lends further support to views and experimental evidence presented by Bostick *et al.*⁵⁷ in 1971 and earlier. However, in recent work Nardi⁷⁷ and Bostick *et al.*⁵⁸ suggest that neutron production is due to the formation of "toroidal vortices" in the plasma focus instead of the usually supposed cylindrical ones. Therefore, apparently the mechanisms

for neutron production in the Z-pinch and the plasma focus may not be as different in nature as once supposed.

With these comments concerning earlier discharge work in mind, we come to the advent of the relatively recent relativistic electron beam research. Before presenting a heuristic discussion of the experiments reported here, a brief review of our group's earlier results is in order. Before we did any experimental work a rather simplistic computer simulation for a plasma focus was performed which indicated two very interesting possibilities, the diameter of a cylindrical, solid target in a pinch should be inversely related to the neutron yield, and very high densities may be achieved via refrigerative compression.⁷⁸ Subsequent work by Stephanakis *et al.*¹³ with exploding deuterated wires in Gamble II confirmed this yield dependence on the wire diameter. More recently, Dr. Sahlin⁷⁹ has noted that an intense ion burst incident on a super-compressed filament, obtained in an analogous manner to that suggested by the calculation but invoking stimulated radiation for a faster collapse, could trigger a net fusion yield.

With the start of experimental research we reported, in addition to the results discussed earlier, that lower initial pressures tended to favor higher neutron yields. A good rear target insulator also favored higher neutron yields, along with little if any rear target damage on the Febatron. Striations were noted as evidence for the presence of filaments in the discharge, and a change in the character of the time-of-flight neutron spectrum was seen when the electron beam was permitted to drill its own hole

through the anode target (shift in central neutron energy from ~ 2.5 to ~ 3.3 MeV at $\sim 20^\circ$ from the machine axis).^{9,10} Along with these results on the Febatron and FX-75, we suggested that the reported yields might be scaled up to as much as an equivalent energy release equal to $\sim 0.8\%$ of the electron beam energy by the use of solid DT in the target rather than CD_2 .¹⁷ In more recent work, four preliminary reported results for the Pulserad work are a maximum neutron yield of 5×10^{10} n/pulse in the high impedance mode (40 Ω), 350 MHz oscillations in the anode current with amplitudes as large as 20 kA (single-shunt), microwave radiation at 10 GHz and higher with an implied peak power of >100 W, and the presence of a large, sharp, 2-nsec-wide voltage spike in the rear target vicinity.¹⁹ One should note that the neutron source location was not in the anode plane, as reported, but rather near the rear target. Also, the so-called electrostatic ram effect^{80,81} was mentioned in conjunction with apparent energy compression at the anode plane. In quite recent results, Dr. Luce⁸² has reported neutron yields on the FX-75 of $>10^{11}$ n/pulse with CD_2 targets and $\sim 4.5 \times 10^{11}$ n/pulse with a ^9Be rear target. Also, with the use of a very accurately positioned carbon cathode with a CD_2 anode and rear target, a neutron yield of $\sim 10^{11}$ n/pulse was obtained on the Pulserad.

Collectively accelerated ion bursts of $>10^{13}$ ions/pulse have been consistently reported by our group.^{9,16-18,82,83} Ion energies >15 MeV were reported in May 1973,⁸³ and energies ~ 30 MeV were noted by Dr. Luce in March 1974.³² The source for accelerated ions in beam-

target interactions and the deuterons for neutron production is the anode target. This conclusion is based on a neutron yield reduction by as much as a factor of $\sim 10^2$, reported earlier,^{9,83} and an observed reduction by a factor of $\sim 10^3$ in the Pulserad work when the CD_2 anode target was replaced with one of CH_2 . Luce and Sahlin¹⁵ pointed out that the accelerated ion beam energy represented $\sim 5\%$ of the total beam energy on the FX-75. They noted that if this ion beam were incident on a ^9Be target with a ^{238}U slab in back of it, one should observe an energy release equivalent to the energy in the ion burst. This yield would be within a factor of ~ 20 of "scientific break-even" via an electro-nuclear process. In addition to these results, the occurrence of the "Linhart effect"²⁴ during the machine pulse has been reported.^{18,83} Quite probably this effect is basically the same phenomenon as the electrostatic ram effect and the effects observed by Grishaev and Shenderovich,⁸⁴ Wachtel and Safran,⁸⁵ and Friedman⁶¹ and discussed by Askar'yan.⁸⁶ Finally, we have emphasized the importance of being able to make many shots with a single target configuration^{9,16,19,82} and have noted that anomalously poor results are characteristic of the first shot or two.⁸³ Other research teams such as Presiantsev *et al.*,⁷¹ among many others, confirm this type of behavior in discharge work.

Our diagnostics in general have provided us with outstanding performance and results, but there is one, almost fatal, omission in these measurements: good, consistent radiation diagnostics. The use of radiation can provide such information as the electron temperature

and density along with estimates of hot pinch sizes. A rough estimate of an electron temperature of 2 to 5 keV has been obtained via the use of thermoluminescent crystals and matched x-ray filter foils in the cathode-anode region.⁸³ However, this is an uncollimated, time-integrated result, so this figure must be used with caution. A particle density inferred from radiation is not available, but consideration of the pressure rise in the vacuum chamber to 0.1 Torr immediately after a shot would indicate a number density of $\sim 10^{18} \text{ cm}^{-3}$ in a small volume around the target structures. Since this would represent a total gas evolution, a density of $\sim 10^{16} \text{ cm}^{-3}$ will be used for the remainder of this discussion. This density compares favorably with those reported by other efforts.⁸⁷ The pre-shot number density is $\sim 3 \times 10^{11}$ molecules cm^{-3} at a pressure of 10^{-5} Torr of air at room temperature. Open-shutter photographs indicate visible light pinches with diameters of ~ 0.1 cm at the cathode, but one must use this result with quite a bit of caution indeed. There is also evidence for a pinch in the rear target area, but no fine details are decipherable. The real problems involved with radiation measurements on electron beam machines are intensity and duration or speed. The hard bremsstrahlung radiation from the machine's voltage tends to obscure any low-energy emission (several keV) which may be present. Since the duration of any emission zones may be ≤ 1 nsec, time-resolved measurements on this time scale will prove to be a formidable task.

With this additional information, a discussion of the results from the experi-

mental work will be presented. One will quickly realize that no effort is made to provide a unified model for the processes occurring during the discharge. The reason for this is my personal belief that there is currently insufficient data to warrant such an attempt. In the past, premature efforts to explain poorly understood phenomena have resulted in quite large delays in their final understanding in other phases of discharge work. Thus, I will attempt only to point out various possibilities for these explanations and relate these points back to other results originating from discharge work where possible. Therefore, a rather heuristic, intuitive exposition will follow.

The beginning of the pulse starts with an essentially shorted mode of operation in which the effective target impedance falls from a relatively high value to $< 10 \Omega$ by 15 nsec. Then, within the next 5 nsec, this impedance again rises to a value of the order of 40Ω . Plasma physical consideration reveals that, of course, an instability probably results in an anomalous resistance. Since a 30-kA current driven by a ~ 300 -kV voltage has an Alfvén current limit ($17,000 \beta\gamma$) of ~ 13 kA, any analysis will be tricky due to the probable presence of a hollow, mildly relativistic electron beam. A rough analysis is presented, but the presence of a hollow beam is ignored. Bernstein *et al.*⁷³ have suggested that if the current in a plasma focus diffuses to the center of the pinch, it is possible for the electron cyclotron frequency to exceed the electron-ion collision frequency. This would result in a collisionless plasma with an anomalous resistance.

A pinch radius of 0.05 cm and an electron number density of 10^{16} cm^{-3} will be used. A temperature will be discussed, but one should not be misled into thinking of this as a well defined quantity in the presence of electrons with velocities of the order of $1.8 \times 10^{10} \text{ cm/sec}$. From Appendix I, a diffusion time of 15 nsec would imply an electron "temperature" of $\sim 46 \text{ eV}$ which is not inconsistent with the result one gets from the Bennett relation. Consistency, here, means that the temperature is such that the diffusion time is no longer than 15 nsec. The implied electron cyclotron frequency is $\sim 2.1 \text{ THz}$, and the electron-ion collision frequency is $\sim 930 \text{ kHz}$. Hence, to this approximation the conditions for a collisionless plasma, and thus an anomalous resistance, are met. From vacuum spark work, Epstein *et al.*⁸⁸ suggest that the onset of longitudinal Langmuir waves, the two-stream instability, may cause turbulence and an associated high plasma impedance. Similarly, Karchevskii and Strakhov⁷⁰ and Presiantsev *et al.*⁷¹ adopt this explanation for the Z-pinch. Kuswa *et al.*⁵² mention this instability in connection with their relativistic, collective acceleration work, and a subsequent report by Mix *et al.*⁸⁷ presents holographic evidence for turbulence which implies the presence of an anomalous impedance. If an electron density of 10^{16} cm^{-3} is used for both the electron beam and background plasma, the e-folding time of this instability is $\sim 0.25 \text{ psec}$. From the threshold condition for this phenomenon, the wavelength of the unstable mode must be $\geq 7.1 \times 10^{-3} \text{ cm}$ which is about half of the assumed radius for the current column. If one

considers the ion and electron components of a two-stream calculation over their thermal distributions, the conditions for the ion acoustic instability, $T_e \gg T_i$, are obtained which is suggested by Lee⁸⁹ as the instability in his vacuum spark experiment. The application of this theory in our case is not consistent with experimental conditions when even an electron temperature is not well defined. Some type of anomalous impedance is also reported by Plyutto *et al.*^{53,54} in their collective acceleration work (non-relativistic and relativistic), but they are somewhat vague about its exact nature. In contrast, Kapetanakis *et al.*⁹⁰ report that in their experiments the diocotron instability is the most probable one for the hollow electron beam. In any event, there seems to be ample evidence for an instability of some description to occur with a growth time sufficiently fast to significantly affect the pulse within 15 nsec. It is interesting to note that it is exactly this anomalous resistance which is necessary to "turn on" the machine's power to the target assembly, so this is at least one instance in which an instability is beneficial, as also noted by Mix *et al.*⁸⁷ In addition to these considerations about how the machine voltage is allowed to rise, one should note that the Pulserad and Febatron (both with a prepulse) operate with only minimal damage per shot to the target structures. On the other hand, FX-75 operation (no prepulse) results in massive target damage on nearly every shot. It would seem likely that the low power or prepulse phase of the machine pulse allows plasma creation and current flow to be established before the bulk of the machine

power is applied. This viewpoint is also accepted by Gordeev et al.⁹¹ in their "Triton" experiments.

The currents circulating in the anode structure present something of a paradox. On the one hand, a relativistic stream of electrons is fairly stiff to turning corners, and on the other, there is good evidence for rotating currents in the anode from current measurements and image converter observations. Quite probably the measured currents in the anode are ancillary in nature. This view is supported by the relative estimates of the energy delivered by the machine in the double-shunt case (4.5 kJ) as opposed to the single-shunt case (1.6 kJ). Thus, the effective voltage driving these rotating currents is probably small in comparison with the machine's diode voltage. However, the fact that the observed current-carrying filaments near the anode are non-relativistic in nature does not rule out the possible presence of fast electrons occurring within them.⁵⁷ In addition to this phenomenon, there are three clues to the presence of energy compression at the anode plane. These are large, rapid oscillations in the single-current shunt measurement, large rotating currents which change direction in the double shunt measurement, and the "shorting-open" circuit behavior exhibited by the impedance which is indicative of open circuiting an inductor into a transmission line. The explanation for this behavior may be some form of the so-called "Linhart effect"²⁴ which addresses the problem of the transient field behavior when a relativistic electron beam enters a good conductor. Hence, while there is good evidence for energy

compression at the anode structure, the nature of relativistic electrons leads to the conclusion once more that there is in fact fast phenomena occurring in the anode region which are decoupled from the measuring circuit. For this very reason, the true magnitude of this behavior cannot be estimated with the data available so far. Both Lee⁸⁹ and Bernard et al.⁷⁶ also find themselves in a similar situation.

The microwave signals measured so far, ~35 kW at 20 GHz and higher, would indeed tend to confirm the presence of some sort of rapid behavior in the front-rear target volume. There are essentially two distinct mechanisms for generating this radiation. One is the excitation of various fundamental frequencies inherent in the chamber and target dimensions, such as noted in Friedman's work,^{60,61,92} and the other would be due to relatively low frequency plasma phenomena, such as a long wavelength instability. Some of the frequencies which we have observed do indeed have wavelengths comparable to physical dimensions (see Appendix J); e.g., 400 MHz implies the spacing between the anode and rear target support shunts. However, there are some of these frequencies for which no very obvious dimension seems appropriate. Epstein et al.,⁸⁸ Lee and Elton,⁶² and Bostick et al.⁵⁸ have reported observations of 10-GHz radiation in the vacuum spark and plasma focus. The drift mode instabilities are the most commonly recognized plasma-induced source for this emission. This phenomenon may quite possibly be present in our system, but the scarcity of information makes a

detailed pursuit of these frequency sources not worthwhile at this time.

The mechanism for the neutron production is ambiguous, even though this yield was the optimization parameter. Perhaps the most disappointing puzzle is the origin of the high-energy neutron peak. This neutron group is the result of either $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ or $\text{T}(\text{D}, \text{n})^4\text{He}$ reactions. In contrast to the results of Plyutto *et al.*,⁵⁴ the time of neutron production does not coincide with the peak and subsequent collapse of the machine voltage. Rather, the time of neutron production in our experiments is ~ 70 nsec into the machine pulse, which is quite late and a time when the rotating current in the anode plane is established (~ 6.3 kA). An energy of 14 MeV is assigned to this peak, which is not inconsistent with other data available. Just prior to this time, the target impedance has become quite large indeed ($\sim 270 \Omega$). Thus, this could be a time of maximum energy compression in the target structures. If energy compression is a crucial process to the neutron production mechanism, one would expect a variation in the machine impedance to have some effect on the efficiency of producing neutrons. In fact, we have observed neutron yields of only $\leq 10^{10}$ n/pulse when the Pulserad was used in its low-impedance mode ($\sim 10 \Omega$) rather than in the high-impedance mode ($\sim 40 \Omega$). Mosher⁹³ has noted that a target geometry may be able to adjust the effective machine impedance to some extent for optimum operation. Nevertheless, whatever the source of the high-energy neutron group, the production mechanism must provide an essentially

monoenergetic burst with a time of production which is probably much less than 8 nsec to be consistent with recent Febatron work.⁹⁴ In addition to the reaction ambiguity, there is also another puzzle. From the neutron activation study, the neutron source is located near the rear target, but we have already concluded that energy compression is quite probably occurring in the anode plane. Therefore, one must eventually account for energy compression at the anode and its subsequent transmission and deposition near the rear target. Three relatively obvious candidate mechanisms for this high power density transport are a nearly monoenergetic, collectively accelerated ion burst, some form of a Z-like pinch (perhaps even a moving one), or a filamentary energy transport. There is certainly some good evidence for the collective model, particularly when the rear target is well grounded,¹⁸ so there is probably a contribution from this mechanism regardless of others which may be operative. Of course, it is not absolutely clear how a collective burst is launched, as also noted by Bradley and Kuswa¹¹ and Kuswa *et al.*⁵² Thus, things are not as simple as they might seem. Then, there is some open-shutter evidence to support the pinch concept, but this diagnostic has particularly unfortunate shortcomings for detailed, time-resolved discrimination. Finally, while there are image converter photographs of the filamentary nature of the currents in the anode plane similar in appearance to those observed by Bostick *et al.*,^{55,57} Bernard *et al.*,⁷⁶ and Presiantsev *et al.*,⁷¹ and suggested for relativistic beams by Stallings

et al.,⁹⁵ there is no firm evidence for the existence of these structures in the vicinity of the rear target. However, these structures may well have the capability to stably transport the power densities required and display the high-frequency behavior inferred from the shunt and microwave measurements.

Once the power density is available at the rear target, in whatever form, there are several possible mechanisms for producing neutrons. The most obvious of these is the so-called beam - cold target interaction or the thick target yield. The neutrons would be produced by simply having a beam of energetic deuterons collide with the CD_2 rear target. One should note that the ^{12}C (D, n) ^{13}N reaction has a larger total cross section at higher energies than D (D, n) 3He , so the target need only contain ^{12}C to produce quite copious quantities of neutrons. In all "beam" considerations, a 4.5-MeV deuteron energy will be assumed. From Appendix K, the implied numbers of incident deuterons on a CD_2 target to explain a total neutron yield of 10^{10} n/pulse are 5.6×10^{13} and 2.9×10^{13} d/pulse for the D (D, n) 3He and ^{12}C (D, n) ^{13}N reactions, respectively. This quantity of high-energy deuterons represents a total energy of ~ 40 J or about 2.5% of the estimated, delivered energy from the Pulserad. This result is consistent with the FX-75 work. Recall that the ratio of the high-energy peak to the total low-energy yield is 9.5×10^{-3} or $\sim 10^{-2}$. If one asks whether the production and subsequent reaction of tritium could produce this ratio in a thick target situation, the answer is no since the cold target reaction efficiency for T (D, n) 4He is ~ 3.5

$\times 10^{-5}$. Physically, the tritium ion is created with about 1 MeV, but it loses most of this energy in Coulomb scatters on electrons before there is a reasonable chance to react with a deuteron. An extension of this form of interaction would be the beam - hot target mechanism. Since the range of a fast ion in a plasma, R , is approximated by

$$R = v_i \tau_{ie}$$

where v_i is the ion velocity and τ_{ie} is the e-folding time for the ion to give up its energy to the plasma's electron population, the number of fast ions may again be estimated from the ratio of the number of reactions to the number of incident particles, the reaction efficiency (Appendix L). The salient point here is the dependence of the ion range, and therefore the yield ratio, on the three-halves power of the electron temperature. Hence, the yield ratio of 14-MeV neutrons to 2.5-MeV neutrons, $(n_{14}/n_{2.5})$, is

$$(n_{14}/n_{2.5}) = 1.04 \times 10^{-5} T_e^{3/2}$$

An electron temperature of 1 keV would give a ratio of $\sim 1.04 \times 10^{-5}$, but a temperature of 100 keV gives $\sim 1.04 \times 10^{-2}$. Notice that this electron temperature would lead to a beam number of only $\sim 10^{11}$ d for a neutron yield of 10^{10} n/pulse for the ^{12}C (D, n) ^{13}N reaction. Another distinct neutron production mechanism is thermonuclear burning. Previously, we have estimated that only about 3% of the total low-energy yield could be due to D (D, n) 3He thermonuclear reactions at a plasma temperature of ~ 6 keV. This is, of course, the assumption used to obtain the experimental ratio of

$(n_{14}/n_{2.5})$ of ~ 0.31 . In Appendix M a theoretical ratio is derived with the result that

$$(n_{14}/n_{2.5}) = 10^{-7} n_D \tau \langle \sigma v \rangle_{DT}$$

where

n_D = the total number of deuterons confined

τ = the confinement time

$\langle \sigma v \rangle_{DT}$ = the Maxwell averaged cross section for the T (D, n) ^4He reaction.

To obtain this fractional burn-up ratio, assuming a plasma temperature of 10 keV and a time of 1 nsec, the total number of deuterons confined must be $\sim 3 \times 10^{24} \text{ cm}^{-3}$ which is large. The final mechanism which will be considered is the possibility of non-Maxwellian burn and fusion chain reactions. The key to this process is the depletion of the low-energy electron population. The existence of this mechanism is hinted to in Appendix L where one realizes that the effective range of an ion in an electron cloud may become quite large at elevated electron tempera-

tures. This is physically equivalent to "turning off" the electron slowing-down process and necessitating the slowdown of the fast ion on the cold background ion population. In fact, the important point is that the strongest ion-electron coupling occurs between ions and electrons which have comparable velocities. In Appendix N, we show explicitly that the equivalent electron energies which would effectively slow down a $\sim 1\text{-MeV}$ triton born in the D (D, p) T reaction are $\lesssim 200 \text{ eV}$. The actual computation of the ratio $(n_{14}/n_{2.5})$, is quite complex and beyond the scope of this work, but John Wyatt⁹⁶ has pointed out that in the high magnetic fields and with the fast electron population present during a typical pulse, the rather large implied $(n_{14}/n_{2.5})$ ratio is quite possible. Other researchers have noted the possible importance of this mechanism in relation to fusion studies.^{21,97-99} Nevertheless, none of these various neutron production mechanisms may be clearly singled out until one has more detailed experimental knowledge on this discharge.

Recommendations for Future Research

In the previous discussion, we have attempted to point out flaws and omissions in the work presented here. Thus, in addition to the work already performed, I have some rather decided opinions of what future work should be done to clarify the important questions which must remain unanswered at this time. This suggested research may be divided into those measurements which can be performed in a relatively short time and

those which will require rather extensive investments in time and effort. The immediate qualification, which I must mention, is that this grouping of relative difficulty is based on our particular group's resources and personnel.

Naturally, the relatively easy work includes efforts which have already been actively discussed or tried at various stages by various members of my research group, so this list is more

extensive than the more difficult research. In my mind, the most important single item which must be pursued is the experiment in which all teflon, and therefore all ^{19}F , has been removed from the target geometry. This series of shots will resolve the ambiguity or the origin of the high-energy neutron group and tell us whether we have been performing low-energy nuclear physics experiments (without an accelerator) or fusion experiments. Then, the radiation diagnostics deserve a high priority since these measurements are crucial in determining the electron temperatures and densities along with probable dimensions of any hot pinches which may be present. The easiest methods involve time-integrated, x-ray pinhole photographs and collimated thermoluminescent crystal work with matched, x-ray band-pass foils. The use of silicon PIN detectors with these same foils should not, in principle, be too difficult, but this approach has a minimum time resolution of 15 to 20 nsec which will limit its ultimate usefulness when nanosecond response is needed. More image converter work is also clearly desirable, especially in the region near the rear target. Ideally, future work should include a method for correlating the exposure time with the relative time in the electron beam machine pulse. Here again, a faster system than the 10-nsec exposure unit that we have available is clearly desirable, and, in fact, such systems are existent at the Livermore Laboratory. So far, the current measurements have monitored only the current returning to ground through various target components. This diagnostic needs to be extended to

measure the currents which may be terminating on the experimental chamber walls in order to obtain a more precise picture of the total current flowing through and around the target structures during the pulse. In addition, an accurate measurement of the total current returning to the electron beam machine must be made. One method of doing this would utilize a cylindrical current shunt inserted between the experimental vacuum chamber and the diode section of the machine. This would be relatively difficult for our group to manage with its resources, but this would not be an unreasonable piece of equipment for the Pulserad facility to obtain for its experimenters' use. Finally, the double shunt measurement should be redone with a small B-loop probe embedded inside the thick polyethylene disk. The detection of a magnetic field inside the plastic in conjunction with the rotating current indications from the current shunts would provide final proof of the existence of this phenomenon in the anode plane. Also, this method could give some insight to the lower frequency microwave phenomena if the response of the probe is fast enough.

On the other hand, the list of the more difficult diagnostics is relatively short and probably reflects my lack of knowledge in some of these areas. In the same spirit as Bernard *et al.*,⁷⁶ various laser measurements, such as fringe shift, scatter, and holography, seem to be in order. These observations could provide such information as electron and ion temperatures and densities along with mass motion characteristics of the plasma. However, care will be necessary since this will be a density-dependent measurement.

Charged particle identification and energies are badly needed. This includes work on not only the primary accelerated ion burst but also on any reaction product particles. Two possible approaches to this are an extension of the reaction threshold work that Dr. Luce and Dr. Sahlin have already started and the use of an electrostatic particle guide¹⁰⁰ in conjunction with time-of-flight and nuclear particle identification methods. Finally, very fast time resolution radiation measurements will ultimately be necessary. One possible candidate for this type of detector is the x-ray diode, XRD, which is believed to have nanosecond response times.

Regardless of the exact measurements and their associated methods which are eventually employed, I feel that there are four important points which should be remembered. Probe measurements in the vacuum will always be a highly speculative procedure due to the high voltages and associated large currents

which are present with electron beam research. The general emphasis should be on faster and faster diagnostic capability in preparation for the day when the 10-nsec electron beam must be studied, e.g., response times of ~ 100 psec. However, the two most important points here are that one should always beware of changing the experiment being performed with the diagnostic tools used to measure its performance and that the diagnostic effort should be implemented only as empirical results justify it. This last point is probably best expressed by Schumacker's¹⁰¹ comment, "It is never wrong to look at a subject with one's eyes and get as much information as possible from visual inspection." These twin problems of the method of introduction and the practical speed of implementation of diagnostics into an experiment are perhaps the most difficult ones that an experimenter must face on a day-to-day basis.

Summary

As indicated several times earlier, I can make no claims that the phenomena studied in this experiment are understood and the work complete. This effort was originally started with this understanding in mind, and is intended to be only the first step in preparation for studies using electron beams with currents of several megamperes and lasting only about ten nanoseconds. The confession of incompleteness in this thesis is not apologetic by any means since many discharge phenomena, which have been studied since the early years of fusion research,

are still only poorly understood in many cases. Therefore, one could hardly hope to reasonably enter a faster time regime (by a factor ~ 100) in discharge work and hope to solve all of the problems within two years.

Within this time period, we have developed an entirely non-standard geometry, from those in use by most electron beam researchers which enables us to make many shots between target changes. The total neutron yield has consistently been the optimization parameter for these experiments. These yields have

averaged $\sim 10^{10}$ n/pulse with a peak yield reported here of 5×10^{10} n/pulse, as measured with silver activation techniques and verified by various other approaches. Relatively noise-free, reproducible time-of-flight spectra have been obtained that display a monoenergetic, high-energy neutron group which could be the result of $T(D, n)^4\text{He}$ reactions, along with a fairly complex low-energy yield. Various arguments have been employed to pin down the energy of this spectrum to within an estimated error of $\pm 10\%$ at the higher energies. In addition to measuring these neutron yields, electrical diagnostics have been developed and successfully used which have frequency responses of not less than 1 GHz; therefore, all of these measurements have been limited only by cable and oscilloscope response times. This is a capability which is unmatched at the Lawrence Livermore Laboratory and probably elsewhere as well. Of particular significance, the current measurements have clearly indicated rotating or circulating currents in the anode plane which are as large as 6.3 kA. In spite of the close electrical proximity of these shunts to the target structures, there is evidence to indicate the occurrence of very fast phenomena which are, at least to some extent, decoupled from our measuring circuits.

Unfortunately, the conclusions which one can draw from this data so far are few, and only relatively vague inferences are justified at this time. Chiefly, there seems to be three areas about which something can be said. The initial shorting of the electron beam seems to play an important role in establishing the

current flow in the target geometry before the bulk of the machine power is turned on. The "turn-on" process is quite probably brought about by either an instability, such as the two-stream phenomenon, or magnetic field diffusion into the beam, causing a transition from a collisional to a collisionless plasma. Either of these processes would lead to an anomalous plasma resistance. This would be one illustration supporting Dr. Sahlin's philosophy that plasma physics should be able to make plasma instabilities work for us instead of against us. Then, energy compression in the vicinity of the anode is definitely implied by the presence of rotating currents and the behavior of the target impedance. This process is classically typified as the open circuiting of an inductor into a capacitor. Hence, part of our target may indeed be the last energy compression stage of the electron beam machine. In other words, the target may be part of the machine. Finally, the mechanisms for neutron production are the vaguest point in this study due, in large measure, to an unfortunate ambiguity in the origin of the high-energy neutron group. If, however, this group is the result of $T(D, n)^4\text{He}$ reactions, a non-thermonuclear, hot electron model will probably be necessary to explain the relatively large contribution of these neutrons to the total yield. One should note that such a process could be used for net fusion power output or to ignite a subsequent thermonuclear burn.

In conclusion, the phenomena studied in these experiments are extremely complex and difficult, at best, to diagnose.

Depending on the outcome of future measurements, the first laboratory observation of non-thermal fusion chain reactions in a controlled fusion effort may have been made. The importance of this observation cannot be overstated since this mechanism would promise to considerably relax the conventional Lawson conditions for a break-even

fusion reactor. Therefore, while this experiment was certainly not intended to be a feasibility study, a less well understood phenomenon may have been observed and, hopefully, point the way for eventual power production via fusion reactions with less stringent conditions than are generally believed to be necessary.

Addendum

In a series of experiments performed on June 3, 1974, the teflon components of the target structures were replaced by polyethylene parts. Time-of-flight data clearly indicates the lack of a high energy neutron peak under these conditions. Therefore, one must conclude that the high energy neutron group is due to $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ reactions and that substantially all of the neutron yield

observed is due to deuteron beam-thick target interactions. In addition to this conclusion, there is also strong evidence indicating that the $\text{D}(\text{D}, \text{n})^3\text{He}$ contribution to the neutron yield is quite small. Since a parallel analysis for the $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ and $\text{T}(\text{D}, \text{n})^4\text{He}$ reactions was presented in the thesis, one should use only the $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ results in future discussion.

Acknowledgements

During the performance of the research reported in this thesis, many people throughout the Lawrence Livermore Laboratory have contributed in some manner or other toward the completion of this work. The most outstanding of these are the members of the Pulsed Fusion Group, Dr. John Luce, Dr. Harry Sahlin, Oved Zucker, Richard Gullickson, Dale Dalgas, and Harris Klapper. I consider it a real privilege to have been able to work with each of these men. In particular, Dr. Harry Sahlin has provided invaluable guidance and help, as my thesis advisor, when it was needed most. Then, Dr. John Luce gave me the opportunity to do

this work in the first place and acted as an invaluable example of an experimental physicist. Oved Zucker helped extensively to make the electrical diagnostics possible and provided me with most of my knowledge of electrical engineering. Richard Gullickson has provided us with the radiation measurements that we have thus far, and Harris Klapper helped extensively with the microwave measurement effort. Dale Dalgas, as the mechanical technician of the group, was invaluable in getting the experimental arrangement built and providing sound advice for various design problems. In addition to this rather small group,

Prof. Edward Teller has my most sincere thanks and appreciation for his continual help and guidance throughout my graduate career. I am also indebted to Dr. Montgomery Johnson and Dr. Winston Bostick for the many hours of help that each of these men have given me. Finally, the Fannie and John Hertz Foundation has made my graduate work possible in the first place, for which I am deeply grateful.

In addition to this rather immediate group of individuals to whom I am indebted for aid in the completion of this research, various other people have had an almost equal impact. In particular, I wish to thank the staff of the Pulserad facility, John Claar, Norman Carlin, Herbert Robson, and Raymond Netherton,

for their patience and cooperation in the actual performance of the experimental work. Then, Kenneth Culp, Donald Aguiar, and Thomas McLaurin made this whole show possible in a very fundamental way indeed. Acting as the Instrument Loan department, these men provided us with the diagnostic tools to run our experiments and represent one of the truly "right" aspects of the Lawrence Livermore Laboratory, circulation of unused equipment for maximal benefit to all. There are many other people who have helped both directly and indirectly, but it is really not possible to list everybody here. Therefore, I will attempt to get a copy of this thesis to these people in the hope that they will accept it as my thanks for their help.

Appendix A

Compression Considerations

In any inertially confined thermonuclear system, the two fundamental quantities of interest are the disassembly time, τ_D , and the thermonuclear burn efficiency, f .³¹ The disassembly time is characterized by the sound crossing time of the system or

$$\tau_D = r/v_s \quad (A-1)$$

where

r = a characteristic scale length
 v_s = sound speed in the medium

$$= \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_0}$$

where P is the pressure and ρ is the material density, evaluated around an equilibrium condition. For isothermal flow in a fully ionized homogeneous plasma (ideal gas), the sound speed is

$$v_s = \sqrt{\frac{2N_A}{A}} (kT), \quad (A-2)$$

where

A = atomic mass
 T = medium temperature
 N_A = Avogadro's number = 6.025×10^{23} mole⁻¹
 k = Boltzmann constant = 1.38×10^{-16} erg /°K,

since

$$P = 2n kT = 2\rho \frac{N_A}{A} kT.$$

With this result, τ_D is obtained from substitution of (A-2) into (A-1) giving

$$\tau_D = r / \sqrt{\frac{2N_A}{A}} (kT). \quad (A-3)$$

Thus, τ_D is directly proportional to the characteristic scale length of the system and inversely proportional to the square root of the temperature. It can be shown that this time, τ_D , is also the characteristic time scale for the onset of magneto-hydrodynamic, MHD, instabilities.²⁶ Then, the thermonuclear burn efficiency, f , may be defined as

$$f = Y / Y_{MAX} \quad (A-4)$$

where

Y = the thermonuclear yield
 Y_{MAX} = the total thermonuclear yield possible (100% burn).

The thermonuclear yield is⁴³

$$Y = \frac{1}{2} NQ n \langle \sigma v \rangle \tau_B, \quad (A-5)$$

where

n = ion number density
 N = total number of ions in the system
 Q = energy released per reaction
 $\langle \sigma v \rangle$ = Maxwell averaged cross section
 τ_B = burn time or confinement time of the system,

and the total possible yield is

$$Y_{MAX} = \frac{1}{2} NQ. \quad (A-6)$$

Hence, by substitution of (A-5) and (A-6) into (A-4), the thermonuclear burn efficiency becomes

$$f = n \langle \sigma v \rangle \tau_B \quad (A-7)$$

However, in an inertial system $\tau_B = \tau_D$, so consideration of (A-3) and (A-7) gives

$$f = nr \langle \sigma v \rangle / \sqrt{\frac{2N_A}{A} (kT)} \quad (A-8)$$

Now, we notice that

$$n = \rho \frac{N_A}{A} \quad (A-9)$$

and define $\langle \sigma v \rangle$ (for a DT plasma) to be

$$\langle \sigma v \rangle \equiv 10^{-16} F(T) \text{ cm}^3/\text{sec} \quad (A-10)$$

where $F(T)$ denotes the functional dependence of the cross section on the temperature. If (A-9) and (A-10) are incorporated into (A-8), then the thermonuclear efficiency becomes

$$f \approx 0.614 \left[\frac{F(T)}{\sqrt{T}} \right] (\rho r)$$

where the temperature is now expressed in keV for a 50% DT plasma. Therefore, the efficiency of an inertially confined thermonuclear burn is directly proportional to the product of the characteristic scale length with the material density.

With a result, the natural problem becomes the circumstances under which the ρr product may be increased, or charged at any rate. For simplicity, the ideal gas approximation of a density inversely proportional to the volume it occupies will be used. Three simple geometries will be considered: the slab, the cylinder, and the sphere. For all examples, a change in the scale length of a factor of two will be considered.

A. Slab:

If $r = 2r'$, then $\rho = \rho'/2$, so $\rho r = 2r'\rho'/2 = \rho'r'$. Thus, $\rho r \propto F(\eta)$ where η , $\equiv (\rho_f / \rho_i)$, is the compression factor.

B. Cylinder:

If $r = 2r'$, then $\rho = \rho'/4$, so $\rho r = 2r'\rho'/4 = (\rho'r')/2$. Thus since $r \propto \eta^{-1/2}$, then $\rho r \propto \eta^{1/2}$.

C. Sphere:

If $r = 2r'$, then $\rho = \rho'/8$, so $\rho r = 2r'\rho'/8 = (\rho'r')/4$. Thus, since $r \propto \eta^{-1/3}$, then $\rho r \propto \eta^{2/3}$. From this exercise in simple geometry, ρr can be increased, or decreased, only by convergent compression, or divergent expansion.

In summary, we have two rather important results for inertially confined systems. First, the importance of ρr as related to the thermonuclear burn efficiency has been established. Second, the ρr of a system may be increased only via convergent compression. Thus, for

any inertially confined thermonuclear system, high burn efficiencies require convergent compression to take place.^{31,32}

This then becomes a ruling factor for all pulsed, laboratory-controlled thermonuclear fusion efforts.

Appendix B

A Break-Even Fusion Criterion

Break-even fusion will be defined here to mean a fusion energy output equal to the energy radiated plus the energy necessary to heat the plasma to ignition conditions. Formally, this may be written as

$$E_F = \epsilon [E_B + E_H] \quad (B-1)$$

where

E_F = fusion energy yield
 E_B = radiated bremsstrahlung energy
 E_H = plasma thermal energy
 ϵ = the fractional efficiency of the fusion burn.

Thus, if $\epsilon < 1$, the system is endothermic, and if $\epsilon > 1$, the system is exothermic. The break-even condition is the circumstance in which $\epsilon = 1$, and this value will be assumed. It is advantageous to eliminate E_F from (1) by defining the ratios,

$$B = E_B/E_F \quad (B-2)$$

and

$$H = E_H/E_F \quad (B-3)$$

Substituting (B-2) and (B-3) into (B-1) and eliminating E_F ,

$$1 = [B + H]. \quad (B-4)$$

The fusion energy remaining in the system, Bremsstrahlung energy radiated, and the thermal plasma energy may be written as⁴³

$$E_F = \kappa_F nN \langle \sigma v \rangle \tau \xi, \quad (B-5)$$

$$E_B = \kappa_B nN \sqrt{T} \tau, \quad (B-6)$$

and

$$E_H = \frac{3}{2} 2N(kT) = 4.8 \times 10^{-16} NT \quad (B-7)$$

where

n = the ion particle density (cm^{-3})
 $\left\{ \begin{matrix} n_i \\ n_e \end{matrix} \right\}$
 N = the total number of ions in the system

$\langle \sigma v \rangle$ = the Maxwell averaged cross section ($\text{cm}^3 \text{sec}^{-1}$)

τ = the length of confinement time (sec)

T = plasma temperature (keV)

ξ = efficiency with which energy is retained in the reacting system

κ_F = proportionality constant for the fusion yield

κ_B = proportionality constant for the Bremsstrahlung radiation. If (B-5), (B-6), and (B-7) are substituted into (B-2) and (B-3), then

$$B = \kappa_B \sqrt{T} / (\kappa_F \langle \sigma v \rangle \xi) \quad (B-8)$$

and

$$H = 4.8 \times 10^{-16} T / (\kappa_F n \tau \langle \sigma v \rangle \xi). \quad (B-9)$$

Finally, we obtain our result by combining (B-8) and (B-9) into (B-4) such that

$$n\tau = \left[4.8 \times 10^{-16} T / (\kappa_F \langle \sigma v \rangle - \kappa_B \sqrt{T}) \right].$$

(B-10)

To get a numerical estimate of $n\tau$, a 50% D-T mixture plasma with a temperature of 10 keV will be assumed. The D-T plasma means that κ_F is 2.82×10^{-12} and κ_B is 5.35×10^{-31} , and the 10-keV temperature determines $\langle \sigma v \rangle$ to be $\sim 10^{-16} \text{ cm}^3/\text{sec}$. Hence, by this calculation $n\tau$ is numerically

$$n\tau \approx 5.0 \times 10^{15} \text{ sec cm}^{-3}$$

where ξ has been assumed to be 19.9% which is appropriate for a high-density system. This is in good agreement with Lawson's criterion of

$$n\tau = 10^{14} \text{ sec cm}^{-3} \text{ @ } T = 10 \text{ keV}$$

for a D-T plasma.³⁰

Appendix C

Silver Activation Detector Analysis

DETECTOR CONSTRUCTION

λ_m = Mean free path for neutrons
(5 cm for 2.45-MeV neutrons)

different overall lengths scaled
according to the mean free path
consideration.

Note: Dimensions are not given since
different geiger tubes would require

ELECTRICAL SCHEMATIC

OPERATIONAL PHYSICS

Consider the activation of a single isotope. The activity due to irradiation as a function of exposure time is¹⁰²

$$A(t_e) = \phi \sigma N_T (1 - e^{-\lambda t_e}) \quad (C-1)$$

where

$A(t_e)$ = activity of sample as a function of irradiation time

ϕ = incident radiation flux

σ = reaction cross section

N_T = number of target atoms/unit area

t_e = irradiation time or exposure time

λ = decay constant = $0.693/t_{1/2}$

$t_{1/2}$ = half-life of activity.

After irradiation has stopped, the activity as a function of time, t , is

$$A(t) = \phi \sigma N_T (1 - e^{-\lambda t_e}) e^{-\lambda t}. \quad (C-2)$$

Thus, the activation-decay process has the general graphical representation

The number of counts that a detector will register between times t_1 to t_2 during the decay period is

$$C = Ef [A(t_1) - A(t_2)] \quad (C-3)$$

where

Ef = total counting efficiency

$$\equiv Ef_d * Ef_g$$

Ef_d = detector efficiency

Ef_g = geometrical efficiency or factor.

Substituting (C-2) into (C-3), the count registered is

$$\begin{aligned} C &= \phi \sigma N_T Ef (1 - e^{-\lambda t_e}) (e^{-\lambda t_1} - e^{-\lambda t_2}) \\ &= \phi \left[N_T \sigma Ef_d (1 - e^{-\lambda t_e}) \right] \\ &\quad \times Ef_g (e^{-\lambda t_1} - e^{-\lambda t_2}). \end{aligned} \quad (C-4)$$

Calibration of a detector may be accomplished in two steps. In both steps, an accurately known source is used over an irradiation time long enough to insure an equilibrium state of activation. In the first phase, an accurately known geometry is used such that Ef_g is determined, and an "overall detector efficiency," κ_1 , is obtained by

$$\kappa_1 \equiv N_T \sigma Ef_d (1 - e^{-\lambda t_1}) \quad (C-5)$$

$$= C / \left[\phi (e^{-\lambda t_1} - e^{-\lambda t_2}) Ef_g \right]. \quad (C-6)$$

Calibration is completed by fixing the detector relative to the unknown source position and using a known source in this geometry to determine the particular geometrical factor for this experiment, or

$$Ef_g = C / \left[\kappa_1 (e^{-\lambda t_1} - e^{-\lambda t_2}) \phi \right]. \quad (C-7)$$

To solve for the unknown fluence, the approximation that $\lambda t_e \ll 1$ is applied to the factor $(1 - e^{-\lambda t_e})$,

$$\begin{aligned} (1 - e^{-\lambda t_e}) &= 1 - (1 - \lambda t_e + \dots) \\ &\approx \lambda t_e \text{ for } \lambda t_e \ll 1. \end{aligned} \quad (\text{C-8})$$

With the use of (C-8), the fluence, Φ , in (C-4) becomes

$$\Phi \equiv \phi t_e \quad (\text{C-9})$$

$$= C / \left[\kappa_2 \left(e^{-\lambda t_1} - e^{-\lambda t_2} \right) \right] \quad (\text{C-10})$$

where

$$\kappa_2 \equiv \kappa_1 \lambda.$$

However, this result applies if and only if there is only one isotope activated.

Natural silver occurs in two isotopes, ^{107}Ag and ^{109}Ag . The ^{107}Ag constitutes 51.3% of natural silver and has a thermal neutron cross section of 30 b.¹⁰³ The daughter, ^{108}Ag , has a half-life of 2.3 min and emits a 1.49 MeV β in decaying to stable cadmium, ^{108}Cd .¹⁰⁴ The ^{109}Ag has an abundance of 48.65% and a thermal neutron cross section of 110 b. The ^{110}Ag produced has a half-life of 24.2 sec and emits a 2.82-MeV (40%) or a 2.24-MeV (60%) β in decaying to stable cadmium, ^{110}Cd . Also, ^{110}Ag may be produced in a metastable state, but since the cross section is 2.8 b and the half-life is 250 days, this may be ignored. Thus, the observed decay from an activated natural silver foil will be

$$A(t) = N_{01} e^{-\lambda_1 t} + N_{02} e^{-\lambda_2 t} \quad (\text{C-11})$$

where

N_{01} = species 1 zero time activity

N_{02} = species 2 zero time activity

λ_1 = species 1 decay constant

λ_2 = species 2 decay constant.

The rationale behind calibrating with a known source long enough to establish an equilibrium activation is to eliminate the associated complexity introduced by a two-isotope system. In practice, a decay curve is measured, and the two zero time activities are obtained by applying a linear least-squares fit to the counting data. For the work reported here, only the ^{110}Ag activity is used in getting neutron yield information.

Since the silver cross sections are thermal neutron capture,¹⁰⁵ the fast neutrons to be measured must be moderated suitably in order to obtain a reasonable detection efficiency (Fig. C-1). Generally, polyethylene, which has about 8×10^{22} protons/cm³, is used in preference to paraffin because of its superior mechanical properties.⁴⁶ The moderator thickness, the neutron mean free path, and the neutron energy determine the fraction of the incident neutrons which are moderated and thus the detector efficiency through σ . The D(D, n) ^3He -produced neutrons have an energy of 2.45 MeV and a mean free path in polyethylene of about 5 cm.¹⁰⁶ If the moderator is made to be one mean free path thick, then the detector response versus energy curve is given by Fig. C-2. While the mean free path for the T(D, n) ^4He -produced 14.1-MeV neutrons is 20 cm¹⁰⁶ and appreciably different from that of the 2.45-MeV neutrons, one is not

Fig. C-1. Total neutron cross section for silver.¹⁰⁵

Fig. C-2. Silver activation detector efficiency versus incident neutron energy.

able to build a detector with sufficient selectivity with gieger tubes to differentiate between these two energies, to our knowledge, so this moderation thickness was generally not used very much in these experiments.

Finally, the small size of the laboratory-style silver detectors and the relatively large radial distance between the neutron source and the detectors allowed a determination of neutron isotropy. However, a complete angular map was not made due to an insufficient number of detectors for simultaneous measurement. At a radius of 157 cm from the source location, the detector subtended about 6° of arc, and the measured isotropy was

$$0^\circ/90^\circ = 1.1 \pm 0.1, \quad (\text{C-12})$$

LABORATORY PROCEDURE

If it is assumed that the first phase of calibration has been performed, the detector is oriented with its long axis perpendicular to the radius vector from the neutron source location to the detector. Electrical set-up is diagrammed in the

schematic. Then a PuBe source of known flux is situated at the source location to complete the second phase of calibration. Once the detector has reached an equilibrium activation level, the source has been removed, a calibration decay curve has been measured and a zero-time activation for the ^{110}Ag has been obtained, the detector may be used to measure the unknown neutron fluence by counting the activation decay resulting from the neutron pulse. In these experiments, the most commonly used counting cycle was four counts for 0.2 min each, four counts for 0.3 min each, five counts for 0.5 min, and six counts for 1 min each. Using these statistics, a linear least-squares computer program is used to extract the zero time count rate for the ^{110}Ag activation which is free from the effects of the longer lived ^{108}Ag activity. A hand calculation is included here as an illustration (see Fig. C-3) of the method used along with an example of a computer calculation (see Fig. C-4), since computer reduction is highly recommended for a long-term basis.

Fig. C-3. Illustration of a "hard" data reduction for a silver activation detector measurement.

SHOT 05 04-02-73 PORTABLE DET.					
INITIAL	FINAL	AV. TIME	INPUT DATA	CORRECTED DATA	FITTED DATA
1.00	13.00	7.00	4874	2.434500E+04	2.2359169E+04
13.00	25.00	19.00	3412	1.763500E+04	1.6192169E+04
25.00	37.00	31.00	2243	1.119000E+04	1.178038E+04
37.00	49.00	43.00	1597	7.969000E+03	8.621123E+03
49.00	61.00	55.00	1169	5.655000E+03	6.359825E+03
61.00	73.00	70.00	1184	3.621555E+03	4.359822E+03
73.00	85.00	88.00	761	2.511555E+03	2.859331E+03
85.00	115.00	116.00	650	1.618533E+03	1.971123E+03
115.00	133.00	124.00	419	1.371555E+03	1.359441E+03
133.00	163.00	148.00	467	9.781000E+02	9.439123E+02
163.00	193.00	178.00	346	6.661000E+02	6.439123E+02
193.00	223.00	208.00	254	4.631000E+02	4.631000E+02
223.00	253.00	238.00	209	3.170000E+02	3.170000E+02
253.00	283.00	268.00	171	2.171000E+02	2.171000E+02
283.00	313.00	298.00	148	1.530000E+02	1.530000E+02
313.00	343.00	328.00	123	1.090000E+02	1.090000E+02
343.00	373.00	358.00	100	7.500000E+01	7.500000E+01
373.00	403.00	388.00	89	5.100000E+01	5.100000E+01
403.00	433.00	418.00	85	3.500000E+01	3.500000E+01
433.00	463.00	448.00	93	2.400000E+01	2.400000E+01
463.00	493.00	478.00	80	1.600000E+01	1.600000E+01
493.00	523.00	508.00			
523.00	553.00	538.00			
553.00	583.00	568.00			
583.00	613.00	598.00			
613.00	643.00	628.00			
643.00	673.00	658.00			
673.00	703.00	688.00			
703.00	733.00	718.00			
733.00	763.00	748.00			
763.00	793.00	778.00			
793.00	823.00	808.00			

CALCULATED PARAMETERS
 2.595439E+04 1.102485E+03
 YIELD = 4.802654E+10
 NUMBER DATA POINTS 24
 CHI SQUARED 2.679559E+01

Fig. C-4. Illustration of a computer data reduction for a silver activation detector measurement.

Appendix D

Fission Foil Analysis

GEOMETRY

EXPERIMENTAL APPLICATION

A ^{238}U and a ^{235}U foil were placed side-by-side at a radius of 12.75 cm from the target axis. Exposure was for three and four shots, and the foils were then removed from the experimental chamber. Processing of all foils involved etching for 1.5 hr at 60°C in NaOH, rinsing for 0.5 hr, and drying for 1 hr at 80°C. Then the etched tracks were counted and the resulting statistics normalized against a set of foils which were exposed to a known PuBe source, 1.3×10^8 n/sec, for 5 min for a total dose of 3.9×10^{10} neutron at 12.75 cm or 1.91×10^7 neutrons/cm².

RESULTS

The purpose for using uranium foils was to check the silver activation detector to be sure that a large fraction of the observed yield was not due to low-energy

neutrons. Since the threshold for (n, fission) in ^{238}U is 1.2 MeV (Fig. D-1), this procedure would insure neutron energies of at least this magnitude.¹⁰⁵ The ^{235}U foil does not have a threshold and was used as a check (Fig. D-2). The yields recorded using the fission foils is within reasonable agreement with the silver activation detector results. The silver detector yielded an average neutron fluence for the two series of shots of 2.64×10^{10} n/pulse. The fission foils had yields of 1.55×10^{10} n/pulse for ^{238}U for a 41% deviation, 2.94×10^{10} n/pulse for ^{235}U for a 11% deviation, and 2.25×10^{10} n/pulse for the two-foil average for a 15% deviation (Fig. D-3). There was previous evidence that there were some very energetic particles in the vicinity of the machine cathode during the shot, based on damage observations. Both of the foils were exposed to these particles toward the cathode from the anode plane which may

Fig. D-3. Fission foil experiment results. (a) Source calibration of fission foils; (b) Pulsed Series 2, Shots 4, 5, 6, 7; (c) Pulsed Series 1, Shots 1, 2, 3; (d) Pulsed average fission foil result.

partially account for the higher overall indicated yield in this vicinity, but there seems to be no reasonable way to estimate the possible error involved in this effect. Over the rear target, the foils were shielded by 0.318 cm of aluminum, so

tracking in this area would be due only to neutron radiation. In summary, the fission foil experiment indicated fast neutron yields in good agreement with the silver activation detector measurements.

Appendix E

Sulfur Tablet Analysis

GEOMETRY

$S_{\#2}: N_2 = 89 \text{ dis/min}$
 from $^{32}\text{S}(n, p) ^{32}\text{P}$ reaction.
 The zero-time activity may be calculated
 by recalling

$$N = N_0 e^{-t_c/t_v}$$

where

N = current activity

N_0 = zero-time activity

t_c = time elapsed between irradiation
 and counting

t_v = mean life of isotope

$= (t_{1/2}/\ln(2))$ where $t_{1/2}$ = half-
 life of isotope.

The activity of interest is

$$N_0 = N / e^{-t_c/t_v},$$

so since $t_c = 14 \text{ days}$ and $t_{1/2} = 14.31 \text{ days}$,¹⁰⁸ the activities are

$$S_{\#1}: N_{01} = 4.53 \text{ dis/min}$$

$$S_{\#2}: N_{02} = 175.3 \text{ dis/min.}$$

The calibration was obtained by exposing
 a tablet to a 14-MeV fluence of 10^{10} n/cm^2
 and is equal to $1.16 \times 10^{-7} \text{ (dis/min) cm}^2/\text{n}$,
 κ_{DT} .

Dimensions:

Tablet:

2.54 cm diam

0.635 cm thick

$A = 6.096 \text{ cm}$

$B = 5.40 \text{ cm}$

$Z = \sqrt{A^2 + B^2} = 8.14 \text{ cm}$

$\theta = \tan^{-1}(A/B) = 48.5^\circ$

ACTIVATION DATA

Sulfur pellet activities (counted 9-12-73)

$$S_{\#1}: N_1 = 2.3 \text{ dis/min}$$

CALCULATION

If one assumes

(a) isotropic, point neutron source

(b) monenergetic neutron pulse, then the relative distances to the source from each of the tablets and the source strength may be derived from the three coupled equations,

$$N_{01} = \frac{1}{4\pi} \kappa_E \frac{I_0}{R_1^2} \quad (a)$$

$$N_{02} = \frac{1}{4\pi} \kappa_E \frac{I_0}{R_2^2} \quad (b)$$

$$R_1^2 = R_2^2 + Z^2 - 2R_2 Z \cos \theta \quad (c)$$

where κ_E = the calibration coefficient at a given energy. This coefficient is related to κ_{DT} by

$$\kappa_E = \kappa_{DT} * \frac{\tau_E}{\sigma_{DT}}$$

where σ_{DT} = cross section for $^{32}\text{S}(h, \rho)^{32}\text{P}$ at 14 MeV and σ_E = cross section for this reaction at energy E.

If (a) is divided by (b), then

$$N_{01}/N_{02} = R_2^2/R_1^2$$

or

$$R_2 = R_1 \sqrt{\frac{N_{01}}{N_{02}}}.$$

Now this result may be substituted into (c), the law of cosines. For R_1 this results in

$$R_1 = Z \left[\pm \sqrt{1 - \left(\frac{N_{01}}{N_{02}}\right) \sin^2 \theta} - \sqrt{\frac{N_{01}}{N_{02}}} \cos \theta \right] / \left[1 - \left(\frac{N_{01}}{N_{02}}\right) \right]$$

and for R_2 , we have

$$R_2 = Z \left[\pm \sqrt{\left(\frac{N_{01}}{N_{02}}\right)^{-1} - \sin^2 \theta} - \cos \theta \right] / \left[\left(\frac{N_{01}}{N_{02}}\right)^{-1} - 1 \right].$$

These values of the radial source distances may be substituted into (a) and (b) giving

$$I_{01} = 4\pi \frac{N_{01}}{\kappa_E} \left\{ Z \left[\pm \sqrt{1 - \left(\frac{N_{01}}{N_{02}}\right) \sin^2 \theta} - \sqrt{\frac{N_{01}}{N_{02}}} \cos \theta \right] / \left[1 - \left(\frac{N_{01}}{N_{02}}\right) \right] \right\}^2$$

and

$$I_{02} = 4\pi \frac{N_{01}}{\kappa_E} \left\{ Z \left[\pm \sqrt{\left(\frac{N_{01}}{N_{02}}\right)^{-1} - \sin^2 \theta} - \cos \theta \right] / \left[\left(\frac{N_{01}}{N_{02}}\right)^{-1} - 1 \right] \right\}^2.$$

NUMERICAL CALCULATION

Let us assume a nonenergetic 2.5-MeV neutron source so

$$\begin{aligned} \kappa_E &= \kappa_{DD} = \kappa_{DT} \frac{\sigma_{DD}}{\sigma_{DT}} = 1.16 \times 10^{-7} \frac{60 \text{ mb}}{254 \text{ mb}} \\ &= 2.74 \times 10^{-8} \text{ (dis/min) cm}^2/\text{n}. \end{aligned}$$

The radius from $S_{\#1}$ to the source is

$$R_1 = Z \left[\pm \sqrt{1 - \left(\frac{N_{01}}{N_{02}} \right) \sin^2 \theta} \right.$$

$$\left. - \sqrt{\frac{N_{01}}{N_{02}}} \cos \theta \right] / \left[1 - \left(\frac{N_{01}}{N_{02}} \right) \right]$$

$$= 8.14 \left[\pm \sqrt{1 - \left(\frac{4.53}{175.3} \right) \sin^2 (48.5^\circ)} \right.$$

$$\left. - \sqrt{\frac{4.53}{175.3}} \cos (48.5^\circ) \right] / \left[1 - \left(\frac{4.53}{175.3} \right) \right]$$

$$R_1^+ = 7.41 \text{ cm} \quad R_1^- = -9.19 \text{ cm.}$$

Similarly, the radius from $S_{\#2}$ to the source is

$$R_2 = Z \left[\pm \sqrt{\left(\frac{N_{01}}{N_{02}} \right)^{-1} - \sin^2 \theta} \right.$$

$$\left. - \cos \theta \right] / \left[\left(\frac{N_{01}}{N_{02}} \right)^{-1} - 1 \right]$$

$$= 8.14 \left[\pm \sqrt{\left(\frac{4.53}{175.3} \right)^{-1} - \sin^2 (48.5^\circ)} \right.$$

$$\left. - \cos (48.5^\circ) \right] / \left[\left(\frac{4.53}{175.3} \right)^{-1} - 1 \right]$$

$$R_2^+ = 1.19 \text{ cm} \quad R_2^- = -1.48 \text{ cm.}$$

Now the source strength may be calculated using both (a) and (b). The results are

$$I_{01} = 4\pi \frac{N_{01}}{\kappa_{DD}} R_1^2 = 4\pi \frac{4.53}{2.74 \times 10^{-8}} (7.41)^2$$

$$= 1.14 \times 10^{11} \text{ neutrons using } R_1^+ = 7.41 \text{ cm,}$$

and

$$I_{02} = 4\pi \frac{N_{02}}{\kappa_{DD}} R_2^2 = 4\pi \frac{175.3}{2.74 \times 10^{-8}} (1.19)^2$$

$$= 1.14 \times 10^{11} \text{ neutrons using } R_2^+ = 1.19 \text{ cm.}$$

The yield variance is 0.2% and the source is 0.8 mm forward of the rear target face.

ERROR ANALYSIS

There are five possible sources of error in this measurement:

1. Counting statistics
2. Mass loss
3. Pulverization
4. Competing reactions
5. Neutron contribution at different energies

other than the error involved with geometrical distance measurements which tend to be 1% or less. These error sources will be discussed, in order, and an attempt will be made to assess the contribution to the total error from each source.

1. Counting Statistics

Each of the two tablets were counted 100 min with a detector efficiency of 0.24. The counting results are

$$S_{\#1} R_{N_1} = 55 (\pm 7.4 = \pm 13.5\%)$$

$$S_{\#2} R_{N_2} = 2136 (\pm 46.2 = \pm 2.2\%),$$

so

$$N_1 = \frac{R_{N_1}}{E t} = \frac{55}{0.24 \times 100} = 2.3 \text{ dis/min} \pm 13.5\%$$

$$N_2 = \frac{R N_2}{E t} = \frac{2136}{0.24100} = 89 \text{ dis/min} \pm 2.2\%$$

Since these statistics enter the calculation as multiplication factors, their associated errors are contributed in the summation; thus, all results from this measurement have an error of $\pm 15.7\%$ from the counting statistics.

2. Mass Loss

The initial calibration and subsequent experiment were performed on a "per tablet" basis rather than on a "per unit mass" basis. Thus, the variance in tablet mass must be added onto any error considerations. This variance has been estimated to be an average of $\pm 2\%$. Also, if a tablet is broken and a piece is lost, this enters the error just as if it were a variance in average tablet mass. This did occur on our experiment, but due to complications it will be discussed in the next section.

3. Pulverization

When the experimental chamber was opened after the series of 12 shots, it was found that the rear target sulfur pellet was broken and partially pulverized. We estimate that 50% of the mass was in large chunks, 40% in powder, and 10% lost. Normally, self-absorption effects are automatically taken care of by the method of calibration, but one must note that for counting one side of a 0.635-cm-thick tablet only 32% of the emitted β 's normal to the surface will escape. Thus, a pulverized and spread-out tablet should have a count 3.1 times the uncrushed case. To show this point, from the "Handbook of Radiological Health," the range of a β particle with an energy of 1.71 MeV,

the β from ^{32}P , may be functionally approximated by

$$R = 412 E^{(1.265 - 0.0954 \ln E)}$$

$$(0.01 \leq E \leq 2.5 \text{ MeV})$$

where R is in mg/cm^2 , and E is in MeV.¹⁰⁹ For the ^{32}P β , this is

$$R = 790 \text{ mg/cm}^2.$$

Since the density of sulfur is about 2 g/cm^3 , ρ_s , then the e-folding distance for a β particle of 1.71 MeV in sulfur would be

$$d = R/\rho_s = 0.395 \text{ cm.}$$

From this, the fraction of the total number of β 's emitted normal to the counted face of the pellet and emerging, for a thickness, t , is

$$F = \int_0^t e^{-x/de} dx = t (1 - e^{-t/de}) \bigg|_0^{0.635} = 31.6\%.$$

In this particular case, each tablet is normally placed in a carrier for counting. If our crushed tablet were placed in such a holder one would expect a stacking effect, so this geometry should not yield anywhere near the worst possible error. Also, the 10% mass loss will result in a decreased count rate, so for purposes of this particular measurement I am going to assume that the errors associated with mass loss would be compensated by the reduced self-absorption. Thus, by assumption the contribution to the experimental error from this source is negligible.

4. Competing Reactions

There are three reactions, giving rise to β emission which could conceivably compete with the primary reaction, $^{32}\text{S}(n, p)^{32}\text{P}$, and confuse the results. These are¹⁰⁵

The first and third of these are thermal neutron reactions, so if a case may be made to discount these neutrons, given fast neutrons to start with, then one needs only to argue that an initially thermal neutron source could not account for the activation measured.

First, if one assumed a fast neutron source, would there be significant thermalization to provide a source for these reactions? The best neutron moderator is located at the back target in the form of the CD_2 disk. For the target thickness of 0.794 cm and a scattering cross section of 2.6 b at 2.5 MeV,¹⁰⁵ there is a 76% probability that any given neutron will not even scatter once, much less thermalize. Thus, I think thermalized neutrons may be ruled out as a source of problems.

Next, if one assumes a thermal neutron source, is it possible to account for the activation seen with these competing reactions? For $^{34}\text{S}(n, \gamma)^{35}\text{S}$, one must depend on activating the ^{34}S , which makes up 4.2% of natural sulfur, and has a half-life six times longer than the reaction of interest.⁴⁸ Considering the associated cross section, I estimate that one would need in excess of 30 times the neutron

fluence to produce the same activation as that recorded. This is a neutron yield greater than 2.16×10^{12} neutrons which would be noteworthy in itself but highly unlikely since the silver activation detector would not have measured more than background in a thermal flux. The reaction $^{34}\text{S}(n, \alpha)^{31}\text{Si}$ has a product with a half-life of 2.62 hr, a threshold of 4.8 MeV, and a cross section of 70 mb at MeV.¹⁰⁵ Since the counting of the tablets occurred at the end of the ^{32}P half-life, our competing reaction could hardly be expected to contribute noticeably to the count after 128 half-lives have passed. The reaction $^{31}\text{P}(n, \gamma)^{32}\text{P}$ produces the same product as the reaction of interest with a thermal cross section of 200 mb.¹⁰⁵ However, the sulfur tablets are reagent-grade natural sulfur, so this would be activation of a 0.01% of less impurity with a low cross section. Hence, none of the possible competing reactions could be expected to make any noticeable contribution in this experiment.

5. Neutron Contributions at Different Energies

The neutron yield calculated using sulfur activation was 1.14×10^{11} neutrons compared to 7.21×10^{10} neutrons on the silver activation detector which is a difference of 58%. The calibration was carried out with an essentially monoenergetic 14-MeV neutron source and then corrected for the difference in the cross section at 2.5 MeV. From cross section plots (Fig. E-1), one can see that the slope in the vicinity of 2.5 MeV is quite large.¹¹⁰ Thus, if a more accurate representation of the neutron energy spectrum were used with the appropriate corrections applied

Fig. E-1. Neutron cross section for $^{32}\text{S}^{110}$

in the cross sections, one would expect closer agreement than a factor of 1.58. In order to attempt this correction, I

have applied the neutron spectrum from shot 3 on 8-28-73 with the results given in Table E-1.

This yield is now below the Ag-detector yield by 48%. The procedure used is susceptible to two sources of error. The first is concerned with the accuracy of the energy spectrum used. This could be in error either by a misplacement of the abscissa or by use of a non-representative shot without averaging over all 12 shots. The other source is the numerical error inherent in the crudeness of the approximation. Fortunately, the error in the absolute yield does not affect the reliability of the calculated radii to the source location.

CONCLUSIONS

Sulfur tablets have been used to try to confirm data from silver activation detectors concerning total neutron yield and from the time-of-flight detector concerning the source location. The total yield measured was

Table E-1.

Av energy	% contribution	Sulfur incremental yield
2.25 MeV	3.79	9.77×10^9 neutrons
2.75	5.54	4.03×10^9
3.25	11.48	4.69×10^9
4.00	31.11	7.07×10^9
5.00	26.28	7.32×10^9
6.00	11.38	2.35×10^9
7.00	4.43	9.34×10^8
8.00	3.05	6.43×10^8
9.00	2.94	5.74×10^8
		Total 3.74×10^{10} neutrons

1.14×10^{11} neutrons (for mono-energetic 2.5-MeV source)
 3.74×10^{10} neutrons (for crude app. using TOF).

These yields differ from the silver detector's yield of 7.21×10^{10} neutrons by 58% above and 48% below. The major problem with calculating a total neutron yield for neutrons in the vicinity of 2.5 MeV arises from the very steep nature of the $^{32}\text{S}(n, p)^{32}\text{P}$ cross section in that energy range. The most interesting distance calculated, with an isotropic, point source

approximation, was a distance from the $\text{S}_{\#2}$ tablet of $1.14 \text{ cm} \pm 18\%$. This would place the neutron source at

$0.8 \text{ mm} \pm 2 \text{ mm}$

from the front face of the rear target CD_2 disk which agrees well with the time-of-flight data. The other distance calculated, source to $\text{S}_{\#1}$, is

$7.41 \text{ cm} \pm 18\%$

which is consistent with the previous distance stated.

Appendix F

Neutron Time-of-Flight Analysis

GEOMETRY

There were two 7.6-cm-diameter holes through the 90-cm-thick concrete wall of the Pulserad radiation shield at 0° and 90° to the machine cathode axis (see Fig. F-1). Of the two, the 90° observation port proved to be the most valuable, since most, if not all, of the useful measurements were made through it. Only radially accelerated ions would noticeably affect the neutron spectrum, and the least amount of undesirable mass (neutron moderator materials) was present in this

direction. Also, the 90° hole, together with the ability to move the target geometry along the axis, proved invaluable in showing that the bulk of the total neutron yield originates from the vicinity of the front of the rear CD_2 target.

The distance-of-flight used was usually about 10 to 13 m. For a series of shots in which detectors were operating at both 0° and 90° to the target axis, the distances from the front face of the rear CD_2 target disk to the detector scintillators were the same, 10.8 m. The 90° observations again proved their versatility

Neutron Time of Flight Geometry

Fig. F-1. Schematic of the time-of-flight geometry.

by allowing movement of this detector from 2.4 m to 17 m. The smaller distance is determined by the proximity of the outside wall of the radiation shield to the target, while the maximum separation is the distance at which the asphalt surface the detector assembly can roll on terminates.

Each detector was housed in a 5-cm-thick lead radiation shield and a grounded copper electrical shield. The immediate motivation for placing a high-Z material only in the line-of-flight would be to decrease the effects of the relatively large amount of Bremsstrahlung radiation produced by the machine pulse. However, experimentally, this amount of radiation shielding was not sufficient to prevent photomultiplier saturation and nonlinearity for less than μsec time scales. The need for a six-sided radiation shield was concluded empirically (and painfully). Once adequate results were being obtained, only the rear wall of this shield, opposite to the machine, was removed to determine the magnitude of the spurious radiation problem. This single alteration resulted in more than doubling the width of the photon-induced peak to more than 180 nsec. With the shield intact, the full-width-at-half-maximum, fwhm, was usually comparable to the electron beam pulse duration, about 75-90 nsec. The source of the spurious radiation must be reflected "sky shine" and small-angle deflection from asphalt and concrete structures in the vicinity, but the theoretical amplitude for this phenomenon would be quite difficult to obtain in practice. The purpose of the copper electrical shield was to eliminate the usual problems associated with the electrical noise and time-scale characteristics of electron beam machine opera-

tion. When this shield was absent, the comparison was not readily possible since this copper case constituted an integral component in the detector grounding system. Obviously, when this ground had been violated, no decipherable information was obtained other than the fact that there was a definite problem.

DETECTOR CONFIGURATION

The detector itself consists of a cylinder of MEL-150C scintillator which is optically coupled to two RCA 6342 photomultiplier tubes. This combination is packaged in a mu-metal container to provide light-tightness and electromagnetic shielding. The scintillator cylinder is 8.83 cm in radius by 20.3 cm long and has an energy response illustrated by the graph (Fig. F-2). Both of the photomultipliers use the tube base given by the schematic (Fig. F-3). Each pair of RCA 6342's is selected such that when negative supply voltages of 2500 V and 1500 V are applied to the respective dynode circuits, the 2500 V tube will have a sensitivity of about 10 greater than the lower voltage tube. The most sensitive photomultiplier-scintillator combination has a calibration constant of about $10^{-12} \text{ A sec cm}^2/\gamma \text{ MeV}$. Originally, the dynode circuit used an output impedance of 100 Ω , but to eliminate problems with signal reflection and non-standard cables, this impedance was changed to 50 Ω . Even though the output voltage was reduced by a factor of 2, the improvement in laboratory operation made the trade-off well worthwhile. To further reduce reflection problems due possibly to crimped cables or faulty connections, the incoming signal was

Fig. F-2. Scintillator light response to neutron and photon radiation as a function of energy.⁵⁰

passed through an EG&G foam-flex, 200/100-nsec delay line before sending it into an oscilloscope. Thus, if cable problems were encountered in the diagnostic trailer, the reflected pulse would arrive later in time than the data of interest, or about 1 μ sec after the prompt radiation pulse. The electrical setup for this detector for these experiments is shown below. The major problem with

this prompt diagnostic, as with all others performed during these experiments, was an inability to insert time marks simultaneously on all oscilloscope traces. However, this difficulty was partially remedied by running the time-of-flight signal in tandem with the machine voltage and current traces on 555 Tektronix oscilloscopes. In addition to this, the bremsstrahlung radiation associated with the

Fig. F-3. Electrical schematic for the voltage division circuit used with the RCA 6342 photomultiplier (from LLL drawing LE-13922-1 by I. Martin, LLL).

electron beam machine pulse completely masked any radiation peak which may have been produced either by bremsstrahlung in an extremely hot plasma or by (n, γ) interactions at the time of neutron production. This made absolute quantitative energy analysis of the neutron spectra impossible, but a probable assignment of these energies was possible with the use of a technique which will be discussed.

USEFUL PHYSICS

Various Time and Energy Relationships

Quite often in experimental physics, one finds that the most useful formulas are those which are classed as the "back-of-the-envelope" variety. Three very good examples of this relatively simple but extremely useful form of physics are the relations for energy, time, and energy spread when applied to time-of-flight data in the form of commonly used laboratory units. If the flight distance and the time-of-flight are known, the nonrelativistic neutron energy is simply

$$E \approx \frac{1}{2} m (d/t)^2$$

where

E = the neutron energy

m = neutron mass

d = flight distance

t = time-of-flight.

This formula is only correct as long as a consistent set of units is used, but quite often in the experimental laboratory one will find it most convenient to work with a "mixed" set of units. For present purposes, we will want to use a length in centimeters, an energy in MeV, and a

time in nanoseconds. In the cgs system of units, the mass of the neutron is about 1.6×10^{-24} g, so with the application of the appropriate conversion factors, the energy relation is

$$E(\text{MeV}) = 1.6 \times 10^{-6} (\text{erg/MeV}) \approx \frac{1}{2} 1.6$$

$$\times 10^{-24} \text{ g } (d(\text{cm})/t(\text{nsec}) 10^{-9} \text{ sec/nsec})^2$$

or

$$E(\text{MeV}) = 0.5 (d(\text{cm})/t(\text{nsec}))^2$$

which is a very simple and easy-to-remember relation indeed. In the same spirit, the complementary relation for the time-of-flight when the distance and energy are known is

$$t = d \sqrt{m/(2E)}.$$

The converted formula is also quite simple,

$$t = 0.707 d/\sqrt{E}.$$

Only slightly more complexity is introduced when the energy spread is desired, given the time-of-flight of a neutron peak and the times associated with the fwhm points. Because of the nature of neutron production a symmetric peak is not necessarily expected, so different upper and lower energy spreads should be allowed for in any given neutron peak. With complete generality, an energy spread is

$$\Delta E = E_{>} - E_{<}$$

where

ΔE = the energy spread

$E_{>}$ = the larger energy associated
with the earlier time, $t_{<}$

$E_{<}$ = the smaller energy associated
with the later time, $t_{>}$.

In terms of the times and distances, this relation is

$$\Delta E = \left[(t_{>}^2 - t_{<}^2) / (t_{>}^2 t_{<}^2) \right] 0.5 \text{ m d}^2,$$

and in the units used above, it becomes

$$\Delta E(\text{MeV}) = \left[(t_{>}^2 - t_{<}^2) / (t_{>}^2 t_{<}^2) \right] 0.5 \text{ d}^2 \text{ (cm)}$$

where the times are in nsec. These three formulas are the basis for practically all neutron time-of-flight spectrum analyses.

Theoretical Calibration

There are generally two methods by which a time-of-flight detector may be calibrated, either with the use of a known strength γ , DC source, such as ^{60}Co with its 1.33 and 1.17 MeV photons,¹⁰⁸ or with a pulsed neutron source. Obtaining an expected detector response on the basis of a pulsed neutron source calibration is relatively straightforward, particularly if the pulsed source emits neutrons at more or less the same energy as that of the burst to be measured. However, to gain some insight to the actual working of a detector, the expected response to a neutron burst by an instrument will be derived with the use of its γ -calibration factor. A total scintillator area, A , flight distance, d , total neutron yield, Y , detector termination impedance, Z , and detector sensitivity to γ radiation, S_{γ} , will be assumed. The detector sensitivity to neutron radiation is obtained by

$$S_n = F_{\gamma-n} S_{\gamma}$$

where

$F_{\gamma-n}$ = overall difference in the
detector

response to γ rays and neutrons which may be in the form of geometry differences, light production efficiency in the scintillator, and pulse height distribution. The response, in ampere-seconds/neutron, $R(\text{A-sec})$, is

$$R(\text{A-sec}) = S_n E_n / A,$$

where

E_n = incident neutron energy
(assumed monoenergetic).

The $R(\text{A-sec})$ may be transformed into the volt-second response per neutron, $R(\text{V-sec})$, with the application of Ohm's Law, so

$$R(\text{V-sec}) = R(\text{A-sec}) Z.$$

The total detector response, R_T , with units of volt-seconds, is then

$$R_T = R(\text{V-sec}) N_D,$$

where

N_D = the number of neutrons
incident on the detector.

This number of neutrons, N_D , is related to the total neutron yield, Y , by

$$N_D = A Y / (4\pi d^2).$$

Now, since "square waves" are not usually observed with time-of-flight

methods, a crude "triangular" response will be used to estimate the pulse height, e.g.,

Thus, the maximum voltage, $V_{\max}$, expected from this assumption is

$$V_{\max} = 2R_T/t_{\max}$$

where

$t_{\max}$ = the duration of the total pulse.

Finally, $V_{\max}$ in terms of all pertinent parameters is

$$V_{\max} = (2S_{\gamma} F_{\gamma-n} E_n Z Y) / (t_{\max} 4\pi d^2).$$

A numerical example is obtained by letting

$$S_{\gamma} = 10^{-12} \text{ cm}^2 \text{ A-sec}/(\gamma \text{ MeV})$$

$$Y = 10^{10} \text{ neutrons/pulse}$$

$$Z = 50 \Omega$$

$$d = 10^3 \text{ cm}$$

$$A = 245 \text{ cm}^2$$

$$F_{\gamma-n} \approx 1/8 \text{ (factor 2 in geometry, light production, and pulse-height distribution)}$$

$$t_{\max} = 100 \text{ nsec}$$

$$E_n = 2.45 \text{ MeV.}$$

Then $V_{\max}$ is

$$\begin{aligned} V_{\max} &= [2 \cdot 10^{-12} (1/8) 2.45 \cdot 50 \cdot 10^{10}] / \\ &\quad [10^{-7} 4\pi (10^3)^2] \text{ volts} \\ &= 244 \text{ mV,} \end{aligned}$$

which is well within reason of detection. From the viewpoint of statistics, another figure of interest is the number of neutrons incident on the detector scintillator, N_D . This number is

$$\begin{aligned} N_D &= AY/(4\pi d^2) \\ &= 245 \cdot 10^{10} / 4\pi (10^3)^2 \text{ neutrons} \\ &= 1.95 \times 10^5 \text{ neutrons.} \end{aligned}$$

Therefore, we can conclude that for the parameters assumed, very similar to those of the actual experiment, both a measurable signal would be obtained, and this signal would be the result of reasonable neutron statistics at the detector.

Experimental Detector Calibration

Although a method for theoretically finding the response of the time-of-flight detector to a given neutron burst has been demonstrated, the importance of calibrating the detector unit at the time of the experiment and in its experimental configuration cannot be over emphasized. If the test, pulsed-neutron source has an accurately known fluence per shot, S , then this procedure automatically accounts for all geometrical and physical effects on the

neutron flux which will necessarily affect the pulse. Quite generally, the neutron source will be nearly monoenergetic, so the use of this calibration for different neutron energies, other than the test energy, must depend on an accurately known relative detector response as a function of energy.

To perform the calibration, two quantities must be accurately known, the integrated area of the time-of-flight trace due to the pulsed neutron source, A_T , and the number of neutrons actually arriving at the detector. The trace area is fairly easy to determine, once of course one has the trace itself. The number of neutrons arriving at the detector, N_D , is

$$N_D = S r r^2 / 4 \pi d^2 = S r^2 / 4 d^2$$

where

r = the scintillator radius (assuming cylindrical geometry)

d = the distance from the source to the detector.

The weakest number in this determination is S , which is due to the dependability of the pulsed-neutron sources available today. The calibration constant, C , for the neutron energy emitted by the source is

$$C = A_T / N_D$$

or in terms of directly obtained quantities,

$$C = 4 A_T d^2 / S r^2.$$

For a numerical example, consider the case of a 5-cm-thick by 5.72-cm-radius

scintillator with a pulsed source of $\sim 3 \times 10^5$ n/pulse from the $D(D, n)^3\text{He}$ reaction and a trace area of 10 V-nsec at a distance of 355 cm from the detector. Then the specific calibration constant, C_E , for these circumstances is

$$C_E = 4 \times 10 \text{ V-nsec} \times (355 \text{ cm})^2 / [3 \times 10^5 \text{ n/pulse} \times (5.72 \text{ cm})^2] \\ = 5.14 \text{ mV} \cdot \text{nsec/n}.$$

The yield for a given experimental shot at this energy, Y_E , would then be

$$Y_E = A_M G / C_E$$

where

A_M = the measured trace area
(mV · nsec)

G = the geometrical factor $4 d_E^2 / r^2$
(d_E = the experimental flight distance).
Therefore, a relatively straightforward calibration of the time-of-flight detector may be made in situ, but this method has the inherent problems of fairly unreliable pulsed-neutron sources and of being a monoenergetic determination or a local calibration within any given spectrum.

Theoretical Detector Response to ^{56}Fe (n, γ) Radiation

One very informative calculation which one can do easily involves the response of the time-of-flight detector to the radiation resulting from the associated ^{56}Fe (n, γ) interactions accompanying the passage of the neutron burst through the experimental chamber walls. If, for example, this radiation were intense enough, the time of neutron production could be fairly unambiguously assigned. Thus, in its own right, this estimation could be fairly significant when related to the actual

experimental data, as well as possibly being informative when compared with other possible signal sources.

The first problem that must be solved is the diameter that a finite-size detector will "see" through the time-of-flight hole. This is relevant since the neutrons will pass through two pieces of "visible" chamber wall; the section subtended away from the detector and that which is toward the detector. Using the following geometry,

the image diameter, α , must be determined with l_1 , l_2 , l_3 , a , and d known. Since ψ and θ are opposite angles of intersecting straight lines,

$$\psi = \theta,$$

and

$$\tan \psi = \tan \theta.$$

If $L = l_1 + l_2$, then by construction

$$\tan \psi = \frac{1}{2} (a + d) / L.$$

Similarly, the results,

$$\tan \theta = \gamma / l_3$$

and

$$\alpha = a + 2\gamma,$$

apply via simple geometry. If α is determined between these two relations, the equality is

$$\alpha = a + 2l_3 \tan \theta,$$

but the $\tan \theta$ is identical to $\tan \psi$. Thus, the solution for the image diameter, α , is

$$\alpha = a \left(1 + \frac{l_3}{l_1 + l_2} \right) + d \left(\frac{l_3}{l_1 + l_2} \right) \quad (F-1)$$

and we may now calculate the diameter subtended by the detector through the time-of-flight hole for any set of distances, l_1 , l_2 , and l_3 .

The number of photons produced due to the passage of neutrons through the visible sections of the chamber wall,

N_γ is

$$N_\gamma = N \chi \eta \sigma_{n,\gamma} \quad (F-2)$$

where

N = the total number of neutrons passing through the section

χ = the wall thickness

η = the number density of the wall material

$\sigma_{n,\gamma}$ = the average differential cross section for neutron interaction = $\sigma_T / 4\pi$, where σ_T is the total neutron cross section for the (n, γ) interaction. The neutron number, N , is

$$N = A F_n \quad (F-3)$$

where

$$A = \text{area of wall section} = \left(\frac{\alpha}{2}\right)^2 \pi$$

F_n = neutron fluence,

which is

$$F_n = Y/(4\pi r^2) \quad (F-4)$$

where

Y = the total neutron yield

r = the radial distance to the wall from the source. From these results, the number of quanta reaching the detector, N_D , is

$$N_D = N_\gamma A_D/(4\pi D^2) \quad (F-5)$$

where

A_D = the area of the scintillator perpendicular to the line-of-flight

D = the distance between the detector and the source.

So far, two assumptions have been made which would tend to make N_D slightly larger than reality. First, from the point of view of photon production, the model of a spherical chamber has been used instead of a cylindrical one. Then, these emitting regions have been treated as point radiators instead of area

radiators through a finite-size orifice.

This second assumption is the one most seriously in error of the two since collimator effects are ignored.

The detector response to this number of γ quanta may be estimated. If the detector has an overall response, S , to γ radiation in the energy range of that emitted from the (n, γ) interaction, then the integrated detector response, R , in volt-seconds, is

$$R = S N_D E_\gamma Z/A_D \quad (F-6)$$

where

E_γ = the energy of the γ quanta

Z = the termination impedance of the detector. Since we are observing photons, there will be no time spread in the pulse once it is created. From experience with a small machine with a fast energy compression stage with an associated 8-nsec pulse time, the duration of neutron production must be less than this interval. With this pulse time as an estimate and a 60-cm-diameter chamber, a γ pulse width, τ , of 10 nsec is a quite reasonable approximation. A "triangular pulse" approximation gives the maximum voltage response, $V_{\max}$, as

$$V_{\max} = 2R/\tau. \quad (F-7)$$

Thus, this number should provide a suitable, though optimistic, estimate for the time-of-flight detector response to the radiation associated with (n, γ) reactions at the time of neutron production.

To get a numerical estimate, consider the following quantities as given:

$$l_1 = 1068 \text{ cm}$$

$$l_2 = 91.5 \text{ cm}$$

$$l_3 (\text{near}) = 139.8 \text{ cm}$$

$$l_3 (\text{center}) = 170.3 \text{ cm}$$

$$l_3 (\text{far}) = 200.8 \text{ cm}$$

$$d = 15.2 \text{ cm}$$

$$a = 7.62 \text{ cm}$$

$$D = 1.2993 \times 10^3 \text{ cm}$$

$$r = 30 \text{ cm}$$

$$y = 10^{10} \text{ n/pulse}$$

$$\sigma_T (^{56}\text{Fe}) = 1.3 \text{ b (Ref. 105)}$$

$$\eta = 8.38 \times 10^{22} \text{ cm}^{-3}$$

$$\chi = 0.635 \text{ cm}$$

$$A_D = 245 \text{ cm}^2$$

$$S = 10^{-12} \text{ A-sec-cm}^2/\gamma\text{-MeV}$$

$$Z = 50 \Omega$$

$$E_\gamma = 2.45 \text{ MeV}$$

$$\tau = 10 \text{ nsec.}$$

Quantities referring to the two γ -producing sites will be subscripted "1" for the near section of chamber wall and "2" for the far section. The two diameters subtended from (F-1) are $\alpha_1 = 10.37$ cm and $\alpha_2 = 11.57$ cm.

Since these are opposite sides of the same chamber, the neutron fluence through these areas, from (F-4), is

$$F_n = 8.85 \times 10^5 \text{ n/cm}^2,$$

and the total numbers of neutrons through each area is

$$N_1 = 7.43 \times 10^7 \text{ n and } N_2 = 1.25 \times 10^8 \text{ n.}$$

From (F-2), the numbers of quanta produced are

$$N_{\gamma 1} = 4.08 \times 10^5 \gamma \text{ and } N_{\gamma 2} = 6.88 \times 10^5 \gamma,$$

which gives the numbers of γ quanta incident on the detector as

$$N_{D1} = 4.73 \text{ quanta and } N_{D2} = 7.25 \text{ quanta.}$$

Hence, the total number of radiation photons incident on the detector from the two sources, N_T , is

$$N_T = N_{D1} + N_{D2} = 11.98 \text{ quanta.}$$

The associated detector response, as given in (F-6), is

$$R = 2.08 \times 10^{-12} \text{ V-sec.}$$

With the pulse width of 10 nsec, the figure of merit we seek is

$$V_{\max} = 4.16 \times 10^{-4} \text{ V.}$$

This predicted response is about a factor of 10 below the detection limit of the instrument, even under fairly quiet electrical conditions. Thus, one must

conclude that the radiation associated with the prompt $^{56}\text{Fe}(n, \gamma)$ interactions would not be observable under the somewhat optimistic conditions assumed for this calculation. Without proof here, it is interesting to note that one would get about the same number of neutrons incident on the detector from triton slowing-down reactions in a field of deuterons for an equivalent total $D(D, n)^3\text{He}$ neutron yield as that used with Co electrons in the target. This is partially explained by noting that only about one in 10,000 tritons will interact in this manner. Since the detection efficiency for neutrons is lower than that for γ radiation and the pulse width would be significantly wider, one can also conclude that simple slowing-down triton reactions could not explain any observable signal either.

Results

The experimentally obtained time-of-flight spectrum consists of three distinct and reproducible contributions. These are a large, prompt radiation pulse, a high-energy neutron peak, and a group of relatively lower energy neutron peaks. Each one of these parts of the spectrum has its own special problems associated with detection and interpretation. This basic composition is illustrated by Fig. 3 in the main body of this thesis.

The major problem associated with the prompt radiation peak was detector saturation. If the detector assembly is set up with no radiation shield at all, the result is a signal which rises very quickly to a maximum (within ~ 10 nsec), and then decays over 1 to 2 μsec back to the baseline. Insertion of 5 cm of lead

shielding between the detector and the target chamber at the location of the detector results in a similar signal, but the decay time is reduced to 0.8 to 1 μsec . In its final form, the time-of-flight radiation shield is a 5-cm-thick, six-sided box around the detector. The radiation pulse then appears to be a Gaussian with an exponential, late-time tail. The approximate full width of this peak is 75 to 90 nsec, and one should note that the full-width-at-half-maximum, fwhm, is not referred to here. The electron beam burst is nominally 60 nsec in duration, but quite frequently there are large voltages present for about the duration of the radiation pulse with the particular target geometry studied here. Also, the start of this peak has been time-correlated with the rise of the machine voltage to within ± 2.5 nsec. With this information and the result of the theoretical contribution that the $^{56}\text{Fe}(n, \gamma)$ radiation might make, this pulse must be due to the Bremsstrahlung radiation associated directly with the voltage pulse from the electron beam generator.

The high-energy neutron peak provides both the key to assigning a definite time of neutron production and a puzzle for its own origin. However, the character of this contribution must first be insured. There are six major considerations which indicate quite conclusively that this peak is, in fact, neutron-produced. The most obvious possible source of spurious signal would be a cable reflection, but this problem may be ruled out since the pulse is of the proper polarity, the delay line would move most reflections outside of the time window of interest, and essentially identical spectra have been obtained

with quite different cable arrangements. Since 50-mV signals have been resolved in a highly reproducible fashion with a single-point grounding system, stray pick-up either directly from the machine pulse noise or indirectly from ground-loops is not an observable problem with this measurement. The detection of a late γ pulse from the machine due to main switch restrike, as a third possibility, was checked by observing shots in which a detectable number of neutrons were not produced. This test confirmed the absence of any late-time γ peaks in the time-of-flight spectrum. In the theoretical calculation concerning the detector response to $^{56}\text{Fe}(n, \gamma)$ produced radiation quanta, any signal due to this mechanism was shown to be quite small if not completely unobservable, particularly at shot time. The inverse problem of (γ, n) interactions at the detector itself may be discounted because of the null result obtained while observing nonneutron producing shots which had quite high radiation yields. Finally, the causative factor which produces this peak behaves as a particle with mass not as a photon. Therefore, this must be a neutron-produced signal of relatively high energy.

The puzzle of this peak's origin stems from the two reactions which may give rise to a fast neutron in this geometry, $^{19}\text{F}(\text{D}, n)^{20}\text{Ne}$ and $\text{T}(\text{D}, n)^4\text{He}$. Of these two, the $^{19}\text{F}(\text{D}, n)^{20}\text{Ne}$ is a primary interaction with the teflon rear target holder as the source of fluorine and has a Q-value of 10.65 MeV. The Coulomb barrier for this reaction, as estimated from the nuclear square well model, is 3.24 MeV. Unfortunately, experimental nuclear data are scarce for this interaction, so Wolke's

differential cross-section data at high energies¹¹¹ and the calculated Coulomb barrier have been used to estimate what the total cross section as a function of energy might be for $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$, ground state (Fig. F-4). In addition to these characteristics, the daughter product, ^{20}Ne , is badly deformed and preferentially formed in the 9.3-MeV excited state. Thus, only a small fraction of the total reactions go to the ground state of ^{20}Ne to give its associated fast neutron. On the other hand, $\text{T}(\text{D}, \text{n})^4\text{He}$ is a secondary reaction with a Q-value of 17.6 MeV. If the total low-energy neutron yield is attributed to $\text{D}(\text{D}, \text{n})^3\text{He}$, which is very optimistic, then an upper bound for the total number of tritons produced may be estimated to be about 10^{10} t per shot since both branches of the D-D reaction are about equally probable. The beam target and thermal cross sections for $\text{T}(\text{D}, \text{n})^4\text{He}$ are illus-

trated by Figs. F-5 and F-6. The extremely large cross section, ~ 4 barn at 120 keV, is the factor which demands that the $\text{T}(\text{D}, \text{n})^4\text{He}$ be considered as a candidate for producing the fast neutron group, even though it is secondary in nature. Finally, $\text{T}(\text{D}, \text{n})^4\text{He}$ goes exclusively to the ^4He ground state, so the neutron spectrum would be of a "Gaussian monoenergetic" nature.

To proceed, it is desirable to obtain an energy assignment for the spectrum. From our previous analysis, the (n, γ) radiation produced at the time of neutron production is obscured by the machine-produced bremsstrahlung radiation and noise. Classical time-of-flight techniques would dictate the use of the centroid of the bremsstrahlung peak as time zero with the width of this peak representing the uncertainty in the measurement. In fact, the result of this is a neutron energy of $10.4 \text{ MeV} \pm \sim 20\%$ for the high-energy neutron group. However, this result is essentially useless, and a more accurate determination is possible. Three different arguments will be made to substantiate a more accurate energy assignment. First, a relatively crude " $\Delta t - \Delta d$ " measurement has been made. Since the energy, E, associated with a difference in flight time, Δt , due to a flight distance difference, Δd , is

$$E = \frac{1}{2} m (\Delta d / \Delta t)^2,$$

a Δt of $30 \pm 2.5 \text{ nsec}$ due to a Δd of 157 cm indicates a neutron energy of $14.2 \text{ MeV} \pm \sim 20\%$. The possible error here is still fairly large, but this does give us a better idea of when in the machine pulse the neutrons are produced.

Fig. F-4. Theoretical cross section for the $^{19}\text{F}(\text{D}, \text{n})^{20}\text{Ne}$ (g. s.) reaction.

Fig. F-5. Charged-particle cross section for the $T(D, n)^4\text{He}$ reaction.¹²³

This estimate would indicate the time of production to be ~ 70 nsec into the electron beam machine pulse. Our electrical measurements indicate that during this period of time, a large rotating current is established in the anode plane. If we assume the time of neutron production to be 70 ± 5 nsec, then the neutron energy is $\sim 13.4 \text{ MeV} \pm 4\%$. Actually, this error may be slightly larger due to machine pulse duration differences at different charging voltages. This time of production would be consistent with an energy compression model for the electrical

Fig. F-6. Maxwell-averaged cross sections for the $T(D, n)^4\text{He}$, $D(D, n)^3\text{He}$, and $D(D, p)^3\text{He}$ reactions.⁴³

behavior of the target structures during a shot. Then, we have narrowed the possible reactions which may give high-energy neutrons to $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$ and $\text{T}(\text{D},\text{n})^4\text{He}$. Since the $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$ reaction has a Coulomb barrier of 3.25 MeV, let us assume that we have a 4.5-MeV incoming deuteron beam in order to be higher in this reaction cross section. This would give a ground-state neutron with an energy of 13.8 MeV. The neutron energy associated with the $\text{T}(\text{D},\text{n})^4\text{He}$ reaction is 14.1 MeV, in the center-of-mass frame. Hence, a band of possible energies between ~ 13.4 MeV and >14 MeV seems possible. Therefore, I will somewhat arbitrarily assign an energy of 14 MeV to the high-energy neutron group with a possible error of $\pm 10\%$ to expedite further analysis.

The group of low-energy neutron peaks is quite complex and not easily interpreted. From the materials present in the target geometry, there seem to be only three contributing reactions, $\text{D}(\text{D},\text{n})^3\text{He}$, $^{12}\text{C}(\text{D},\text{n})^{13}\text{N}$, and $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$. A contribution from $\text{D}(\text{D},\text{n})^3\text{He}$ is assured due to its abundance and cross sections (Figs. F-7 and F-8), and only its center energy and peak width are open to debate. $^{12}\text{C}(\text{D},\text{n})^{13}\text{N}$ is also certainly a strong contributor to the yield due to the ^{12}C abundance and the presence of the characteristic β activity of ^{13}N in postshot analysis. The neutron spectrum from this reaction is complex and can range up to 4 MeV in energy, depending on the incident deuteron energy. Since $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$ is considered as a possible source of high-energy neutrons, this reaction must be considered as a likely contributor to the low-energy spectrum

where most of these neutrons would be emitted. As previously noted, however, resource data are scarce here, and an experimental time-of-flight spectrum is not available for this reaction.

With the use of an experimental calibration technique, detailed previously, a time-of-flight detector with a 5-cm-thick NE-213 scintillator was calibrated with a pulsed neutron source, $\sim 3 \times 10^5$ n/pulse from $\text{D}(\text{D},\text{n})^3\text{He}$, in the experimental geometry. The area of the low-energy neutron spectrum was integrated, and a yield was estimated for Shot No. 5, 8-31-73. This yield was 7.8×10^9 n/pulse and compared favorably with the silver activation detector yield of 1.7×10^{10} n/pulse, which is within about a factor of 2. Since this is the accuracy of the calibration and measurement of the particular time-of-flight experiment, the comparison is taken as good agreement between the two methods of neutron detection.

After comparison of several spectra, along with a sum-average spectrum for Shots 17, 18, and 20 on 2-14-74, eight distinct and reproducible peaks appear to make up the bulk of the low-energy contribution to any given time-of-flight measurement (see Fig. 4). All of these energies are accurate to about ± 0.1 MeV and are assigned with the assumption of the 14-MeV high-energy peak. Two important points to be noted are the absence of the 2.45-MeV, $\text{D}(\text{D},\text{n})^3\text{He}$ neutron peak and the complexity of the experimental data. Since the presence of the $\text{D}(\text{D},\text{n})^3\text{He}$ neutron is virtually assured, the absence of the appropriate peak energy means that this contribution has probably been up-shifted in energy by some mechanism. Finally, the spectral complexity, earlier

Fig. F-7. Charged-particle cross section for the $D(d,n)^3He$ reaction.¹²³

supposed, is indeed observed experimentally. This is to be contrasted with the possibility of a single very broad peak accounting for the low-energy yield, which is definitely not the case.

In addition to these relatively local considerations of various portions of the time-of-flight spectrum, some more general observations may be made. One observation which is completely independent of any spectral considerations is the source of the neutron yield. Since the entire experimental arrangement was axially symmetric, it was possible to move various parts of the target geometry through the observation space of the time-of-flight detector. By this method, the neutron source was determined to be in the region just in front of the rear

target. This finding was later confirmed, and the location was more precisely located using sulfur tablet activation. Another rather general point, which is spectrally dependent, is the comparison between a teflon rear target and CD_2 rear target (Fig. F-9). The teflon shots were made by simply using the teflon rear target holder as the rear target. The most apparent difference is the relative strength of the high-energy neutron peak and the change in its character from a simple Gaussian to a rather complex structure. Also, the lower energy neutrons take on a different appearance from the deuterated target case to a spectrum in which there are several very strong and broad contributions to the yield at lower energies.

Fig. F-8. Charged-particle cross section for the D(D,p)T reaction.¹²³

Fig. F-9. Time-of-flight spectrum for a teflon (CF_2) rear target.

In an attempt to obtain the "true" neutron spectrum, the spectral response as a function of energy for our detectors has

been calculated and used to unfold the measured spectrum. This procedure follows the philosophy of trying to minimize instrument-imposed perturbations on the quantity being measured to as great an extent as possible. The three basic processes which tend to modify the neutron spectrum are light production per neutron interaction, scintillator absorption fraction, and radiation shield transmission fraction as a function of neutron energy. As an example, consider the monoenergetic case of 2.45-MeV neutrons (normalized for 14.1-MeV neutron results) passing through 5.08 cm of lead and being absorbed in 20.32 cm of MEL-150C scintillator. The total correction factor at 14 MeV would be 5.2 where the contribution by light production is 0.21, by absorption is 1.14, and by transmission

is 0.80. The correction is executed by digitizing the oscilloscope trace, converting this time domain data into the energy domain, and performing the correction in a semicontinuous manner over the entire spectrum. Once this is done, then the corrected data are available in either the time or energy domain representation (Fig. 5). The large effect that this spectral correction may have is illustrated by the reduction of the ratio of high-energy neutrons to lower energy neutrons from $\sim 1/20$ to $\sim 1/104$.

If the high-energy neutron group is produced from the $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$ reaction, it should be possible to correlate at least some of the lower energy neutron peaks with the lower energy ones expected from this source of neutrons, as well as $^{12}\text{C}(\text{D},\text{n})^{13}\text{N}$ neutron groups. In Table 1 the observed spectral peaks from the time-of-flight data have been listed with those expected neutron groups from $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$, $^{12}\text{C}(\text{D},\text{n})^{13}\text{N}$, and $\text{D}(\text{D},\text{n})^3\text{He}$, with 4.25-MeV deuterons, which seem to be correlated. The peaks for the ^{19}F reaction were predicted with the γ de-excitation systematics for the ^{20}Ne daughter, and the ^{12}C data were extracted from the work of Lefevre et al.¹¹² Quantitative analysis of various peak heights is not readily possible since there is no experimental data on ^{19}F . There are three problems with this tabular listing which cast doubt on its accuracy. The 8.1-MeV observed peak is quite consistent in the experimental data, but there seems to be no obvious companion neutron group from the reference reactions. Then, the 6.8-MeV group has two possible matches from the ^{19}F reaction, 7.0 MeV and 6.6 MeV. The radiative

systematics would indicate that the 7.0-MeV ^{19}F peak should be the second most prominent group in its spectrum by $\sim 2/3$ the 5.4-MeV group, the theoretically most significant peak in the $^{19}\text{F}(\text{D},\text{n})^{20}\text{Ne}$ spectrum. Hence, the 6.8-MeV group should probably be paired with the 7.0-MeV ^{19}F group since the 6.6-MeV ^{19}F peak should be much less pronounced. Finally, the 3.5-MeV group has two possible companions, the 3.6-MeV peak from $^{12}\text{C}(\text{D},\text{n})^{13}\text{N}$ and the 3.5-MeV peak from $\text{D}(\text{D},\text{n})^3\text{He}$. Since this peak is strong in the ^{12}C spectrum and assured for a 4.25-MeV DD target reaction, either there is a definite ambiguity at this point or the two peaks are actually superimposed on one another. In fact, there is some very marginal evidence that this superposition may be taking place. Therefore, if a strictly beam-target model is assumed, a fairly, but not completely, consistent set of reaction peaks may be found to correspond with the consistently observed neutron groups. One must note, however, that the other reaction peaks, some of which are also fairly strong, have not been listed here since they did not seem to match the experimental data. This, of course, is yet another problem with this analysis.

On the other hand, if the $\text{T}(\text{D},\text{n})^4\text{He}$ reaction is responsible for the energetic neutron group, the various implied thermal distributions must be considered along with the various ratios of yield contributions. As Muir has shown,⁵¹ the fwhm for a thermally produced neutron group may be related to the kinetic plasma temperature using two Maxwellian distributions. For a DT and DD plasma, respectively, these fwhm's are

$$\text{fwhm}_{DT} = 5.59 \sqrt{kT} \quad (\text{MeV})$$

and

$$\text{fwhm}_{DD} = 2.6 \sqrt{kT} \quad (\text{MeV})$$

where

kT = the plasma temperature
in MeV.

The 14.1-MeV peak has a fwhm of about 3.1 MeV which would imply a plasma "temperature" of 308 keV, with Muir's relation. Also with the use of an implied plasma temperature of 6 keV, a result obtained with thermoluminescent crystals and matched Ross x-ray filter foils and considered marginal at this time, the predicted $D(D,n)^3\text{He}$ peak width should be about 116 keV wide. This contribution would probably be upshifted in its central energy, by analogy with plasma focus results, and would roughly represent about 3% of the total low-energy neutron contribution. Recall from the response correction calculation that the ratio of the high-energy group to the total low-energy yield was about 1/104. If the relative fraction of the $D(D,n)^3\text{He}$ ther-

mal group to the low-energy result is taken into account, an approximate ratio of $T(D,n)^4\text{He}$ to $D(D,n)^3\text{He}$ is about 1/3.25. This could be a quite important result because of its ramifications concerning fuel temperature and confinement time, even though this contribution to the total yield would seem to be relatively small.

In summary, low-noise, reproducible time-of-flight spectra have been obtained which are in essential quantitative agreement with the total neutron yields recorded with the silver activation detectors. Analysis of the fast neutron group has yielded a spectral energy assignment to within an estimated error of $\pm 10\%$ and an ambiguity of its origin which can only be resolved with additional experimental work. The low-energy contribution to the spectrum is composed of several consistently appearing peaks. Most of these peaks are almost certainly of a deuterated beam-target nature which is consistent with collective acceleration results, also studied by our group. However, the possibility of the presence of a thermal $D(D,n)^3\text{He}$ peak among this group cannot be ruled out and also will require further experimental work for clarification.

Appendix G

Voltage Measurement Analysis

GEOMETRY

Note: Sketch is not intended to be to scale.

Radius of capacitance pad upper surface from centerline = 22,225 cm.

Radius of capacitance pad mounting ring = 22.8 cm.

CAPACITANCE PAD CONSTRUCTION AND USE

The two primary design considerations for a capacitive voltage measuring

system in our experiments are versatility and fast response. The result of these requirements is a relatively small circuit capacitor that mounts on an aluminum ring inside the experimental vacuum chamber. One should note that the necessity for versatility in vacuum immediately eliminated the use of a resistive measuring network, e.g., surface arcing problems. The major problem with the construction of these

capacitance pads was insuring a precisely known dielectric gap with a thin dielectric material. The solution was a silver conductive epoxy material. Each pad was made by first bending a 2.54-cm-wide by 0.635-cm-thick brass rectangular strap to a 22.8 cm radius and cutting it into 5-cm lengths for the pad holder. After all of the corners were rounded off, a 0.4-cm hole was drilled through the center of the holder, and a signal pin was set in it with a high-strength epoxy to provide the pad's signal connection to its mounting ring. Next, the upper surface of the brass pad holder received a coating of silver epoxy and the 1.27×10^{-3} -cm-thick Kapton dielectric. By this procedure, we assured a void-free contact between the Kapton and the pad holder. A wire from the signal pin extends through the Kapton and forms a flat spiral against this dielectric layer. The upper plate of the capacitor is simply another layer of silver epoxy on top of the Kapton with the signal wire bonded in place over a relatively large area. Finally, a fairly thick layer of Dow Corning RTV 891 is applied over the entire capacitor to prevent free plasma charges from getting into the measuring circuit.

The holders for these capacitance pads are 45.7-cm i. d., 60.9-cm o. d., and 2.45-cm thick aluminum rings.

These rings each contain four pad mounting locations which are spaced equally around the internal circumference. A mounting location consists of two anchorage, drilled and tapped holes and the mating receptacle for the capacitive pad's signal pin. The signal receptacle is connected to a coaxial cable connector, mounted on the side of the aluminum ring, through an internal hole in the ring with the signal wire insulated with teflon and the hole filled with RTV 891 for added insulation.

The experimental configuration for the voltage diagnostic consists of the capacitance pads mounted on the aluminum holder rings which are anchored at various locations in the vacuum chamber with jack screws. Contoured, solid-outer-conductor coaxial cables, which are covered with conducting tape to prevent flux linking, form the signal connection between the cable connectors on the voltage divider rings and the vacuum feed-through connectors on the chamber wall. From the experimental chamber to the oscilloscopes, the single-point ground and cabling system is used.

ELECTRICAL CONSIDERATIONS

The electrical diagram for the voltage divider circuit is

where C_1 is the capacitance between the center conductor on the chamber axis and the upper plate of the capacitive divider pad, C_2 is the capacitance of the capacitive pad, R is a series resistor for lengthening the "RC" time constant, and R_T is the termination resistor. We desire two quantities from the circuit analysis, the division ratio of the voltage across R_T , V_T , to the impressed voltage, V . Laplace analysis with a step function for the impressed voltage at time, $t = 0$, is perhaps the most convenient method to use.¹¹³ By Thevenin's theorem, we know that an arbitrary source circuit may be reduced to an equivalent one consisting of only a voltage source and a series impedance.¹¹⁴ Since the Laplace transformed impedance for a capacitor is $1/(sC)$, where s is the transform variable,¹¹⁵ the Thevenin equivalent impedance, Z_{TH} , is

$$Z_{TH} = 1/[s(C_1 + C_2)] ,$$

and the equivalent voltage source, V_{TH} , is

$$V_{TH} = (V/s)[C_1/(C_1 + C_2)] .$$

We have transformed the circuit to the left of points A and B in the schematic, so our equivalent circuit is now

Thus, the Laplace representation for the voltage ratio, V_T/V , is

$$(V_T/V) = \frac{C_1}{C_1 + C_2} \frac{R_T}{R + R_T} \times 1/[s + \{1/(R + R_T)(C_1 + C_2)\}] ,$$

which has the time-domain representation of

$$(V_T/V) = \frac{C_1}{C_1 + C_2} \frac{R_T}{R + R_T} \text{EXP}\{-t/[(C_1 + C_2)(R + R_T)]\} ,$$

where t is time.

For a time which is small compared to the product, $[(C_1 + C_2)(R + R_T)]$, the exponential is approximately unity, and the division ratio is

$$(V_T/V) = \frac{C_1}{C_1 + C_2} \frac{R_T}{R + R_T} , \quad (G-1)$$

where we have imposed a lower bound on the circuit response frequency, f_L , of

$$f_L > 1/[(C_1 + C_2)(R + R_T)] . \quad (G-2)$$

The round-trip time for an electromagnetic pulse to travel from the farthest point on the capacitor to the signal tap gives an estimate for the upper bound on the circuit frequency response, f_u . This frequency is

$$f_u < c/l , \quad (G-3)$$

where c is light speed and l is the largest dimension of the capacitor plate.

In order to obtain the factor, $\frac{C_1}{C_1 + C_2}$, which is the ratio, V_T/V , for the case of $R = 0$, we will show that only radial geometric factors enter the calculation in both the spherical and cylindrical cases. Of course, some approximation to the vacuum capacitance will be necessary to evaluate the lower bound on the frequency response, f_L , however this part of the calculation does not need to be very accurate and probably will not be. For the case of spherical, concentric capacitors, the geometry is

where C_1 and C_2 will be assumed spherical for the present. Gauss's law states

$$\int \vec{E} \cdot d\vec{a} = Q/\epsilon,$$

where Q is the net charge enclosed by the integration, and ϵ is the permittivity of the interelectrode medium (rationalized MKS units).¹¹⁶ Integration over the spherical area between any two electrodes will give

$$E = Q/(4\pi r^2 \epsilon).$$

Hence, between the radii a and b , the vacuum electric field, E_V , is

$$E_V = Q/(4\pi r^2 \epsilon_0),$$

and the field between b and c in the dielectric field, E_D , is

$$E_D = Q/(4\pi r^2 \kappa \epsilon_0),$$

where ϵ_0 is the permittivity of free space and κ is the dielectric constant. Since the potential difference, V , between any two radii, R_1 and R_2 , is

$$V = -\int_{R_1}^{R_2} \vec{E} \cdot d\vec{r},$$

then the vacuum voltage, V_V^S , and dielectric voltage, V_D^S , for the spherical case are

$$V_V^S = -\frac{Q}{4\pi\epsilon_0} \left(\frac{b-c}{ab} \right)$$

and

$$V_D^S = -\frac{Q}{4\pi\epsilon_0} \left(\frac{c-b}{\kappa bc} \right).$$

Capacitance is the ratio of charge to voltage, so the vacuum and dielectric capacitances, C_1^S and C_2^S , respectively, are

$$C_1^S = 4\pi\epsilon_0 \left(\frac{ab}{b-a} \right) \quad (G-4)$$

and

$$C_2^S = 4\pi\epsilon_0 \left(\frac{\kappa bc}{c-b} \right).$$

Therefore, the spherical case calculation for $(V_T/V)_{sp}$ ($R = 0$) gives

$$(V_T/V)_{sp} = ab(c-b)/[ab(c-b) + \kappa bc(b-a)],$$

which is entirely devoid of any area consideration for the capacitive pad. However, for our geometry

$$(b - a) \gg (c - b)$$

and

$$\{ab(c - b)/[\kappa bc(b - a)]\} \ll 1,$$

so to a very good approximation, the voltage ratio is

$$(V_T/V)_{sp} = ab(c - b)/[\kappa bc(b - a)], \quad (G-5)$$

to the first order. For a cylindrical geometry,

by a similar analysis the vacuum, V_V^C , and dielectric, V_D^C , voltages are

$$V_V^C = \lambda \ln(b/a)/(2\pi\epsilon_0)$$

and

$$V_D^C = \lambda \ln(b/a)/(2\pi\epsilon_0\kappa),$$

where λ is the charge per unit length of the cylinder. Notice that, at least in the quasistatic approximation for a conductor, the electric fields will be strictly radial due to vector cancellation of non-radial contributions; however, this is not necessarily the case for an insulator surface, particularly with the rather extreme experimental conditions encountered. With this understanding, the respective capacitances are

$$C_1^C = 2\pi\epsilon_0 L/\ln(b/a) \quad (G-6)$$

and

$$C_2^C = 2\pi\epsilon_0 L/\ln(c/b),$$

where L is the length of the capacitor pad along the cylinder axis. Hence, the cylindrical voltage ratio, $(V_T/V)_C$ ($R = 0$) is

$$(V_T/V)_C = \ln(c/b)/[\ln(c/b) + \kappa \ln(b/a)].$$

Again, we approximate the ratio. It is

$$(V_T/V)_C = \ln(c/b)/[\kappa \ln(b/a)], \quad (G-7)$$

to first order since

$$\ln(c/b)/[\kappa \ln(b/a)] \ll 1.$$

Hence, the ratio,

$$(V_T/V)_{R=0} = C_1/(C_1 + C_2), \quad (G-8)$$

is only dependent on radial geometric factors in the quasistatic approximation in spherical and cylindrical geometries.

In the experimental geometry, the pertinent parameters are

$$a_1 = 3.49 \text{ cm}$$

$$a_2 = 2.54 \text{ cm}$$

$$b = 22.2237 \text{ cm}$$

$$c = 22.225 \text{ cm}$$

$$C_2 \approx 1.24 \text{ nf (by direct measurement)}$$

$$R = 330 \Omega \text{ or } 0 \Omega$$

$$R_T = 50 \Omega$$

$$\kappa = 3 \text{ (for Kapton dielectric),}$$

where the radii for both the machine cathode, a_1 the rear target holder, a_2 , and the two circuit resistance values of R have been included for convenience. Since the cylindrical, quasistatic analysis is marginal for insulators in a plasma environment and gets more so for very short time scales, we will give only the spherical calculation for the rear target

voltage ratio. Actually, only a full relativistic, time-dependent analysis is appropriate for the experimental conditions, but there is currently insufficient experimental data to justify an analysis as extensive as this. The resistance, R , for this measurement was always zero since late-time observations at this location would be meaningless due to plasma movement. Hence, the ratio, (V_T/V) , is just

$$(V_T/V) = (V_T/V)_{sp},$$

which from (G-5) is 2.52×10^{-6} . With the use of (G-2) and (G-4), the lower frequency response for this arrangement is >16 MHz. On the other hand, the geometry and materials in the diode region of the electron beam machine are such that cylindrical, quasistatic analysis is quite useable. The cylindrical voltage ratio, $(V_T/V)_c$, from (G-7) is 1.05×10^{-5} , and the division ratios, (V_T/V) , for the values of R of 330Ω and 0Ω , respectively, are 1.39×10^{-6} and 1.05×10^{-5} with the use of (G-1) and (G-8). With (G-2) and (G-6), the lower frequency bounds are >2.1 MHz and >16 MHz. From (G-3), the upper frequency limit for all cases is <15 GHz, which means that the circuit will be limited by oscilloscope and cable frequency responses (~ 1 GHz) rather than the diagnostic probe response.

OBSERVATIONS

As shown in Fig. 2, there were two useful locations for the voltage measurements. One voltage divider ring was placed about 45-46 cm from the anode plane in the machine's diode section to

gain an accurate check on the Pulserad facility's voltage monitoring system and a voltage measurement closer to our target geometry. The other ring was concentric with the rear target to try to detect any very fast, high-voltage phenomena which we thought should be present with the insulated rear target. Initially, we attempted to use a third divider ring placed immediately on the cathode side of the anode plane. However, the single field emission point used as the cathode in the target geometry emits quite energetic electrons in the radial direction at very early times in the pulse. As a result of this, the useful period of this location before anisotropies and plasma emission made any decipherable observations impossible was generally less than 5 nsec.

We obtained very satisfactory diagnostic information from the voltage probes on the ring in the machine's diode section. These measurements were very consistent on a shot-to-shot basis, and simultaneous observations of several of the capacitance pads revealed that the results were cylindrically symmetric. This indicates that large plasma movements in this region are not likely until possibly quite late in time. Each trace (Fig. 9), consistently displayed a relatively low voltage plateau, 175-350 kV depending on machine output, for the first 12 to 15 nsec of the pulse. After this prelude, the rate of voltage rise is ~ 280 kV/nsec until a persistent inflection point is reached at ~ 20 nsec. The voltage amplitude of this inflection point on the leading edge of the voltage pulse is ~ 1.05 - 1.75 MV, again reflecting low- and high-energy deliveries. From this point in time, the

voltage rises to its maximum value and begins a relatively slow decay. In Table G-1, the charging voltage on the Marx bank capacitors is correlated with the peak diode voltage, the time of peak voltage, and the pulse duration. Lower charging voltages consistently resulted in earlier peak voltages and shorter pulse durations. The average time of peak diode voltage, over all diagnosed shots, is ~ 26.2 nsec. By ~ 70 nsec, the diode voltage is positive with an average value of ~ 885 kV, which is independent of the Marx charging voltage. Occasionally, small oscillations (~ 89 kV compared to a peak of 2.6 MV) appear on the voltage signal which have a characteristic frequency of ~ 200 MHz. In summary, we observe a relatively small almost prepulse voltage leading the main pulse that, in turn, has a peak time and duration which are non-trivially dependent on the Marx bank charging voltage, or equivalently on the machine output.

On the other hand, the interpretation of the rear-target voltage measurement was quite a bit less straightforward. With the use of the isotropy test, applied to the diode voltage, it is clear that only about 15 nsec of this voltage trace is useable (Fig. 10). After this time, strong asymmetries are present between

voltage pads around the divider ring's circumference. The probable cause for this anisotropy in nonuniform, radial plasma expansion which would definitely preclude accurately "seeing" the rear target voltage. However, our reasoning for trying this measurement is justified. We consistently observed an averaged, ~ 76.5 V, 3.1-nsec-wide voltage spike at about 3.3 nsec into the voltage trace which was fairly independent of the machine output. With the voltage division ratio derived earlier, this oscilloscope voltage implies ~ 30.4 MV on the rear target in the spherical approximation. The rate of rise of this peak would then be ~ 9.2 MV/nsec. In addition to this initial peak, there is also a fairly persistent positive voltage spike at ~ 13 nsec with an amplitude of ~ 24.8 MV. There are two very serious problems with this measurement and these implied voltages. First, it was not possible to obtain time correlation data with other traces, unlike the anode current, diode voltage, and time-of-flight measurements. Then, the most serious problem is that the obtained voltages imply a charge on the rear target of ~ 1.47 coulombs! This is clearly ridiculous when only 3×10^{-3} coulomb is available from the electron beam machine with the optimistic

Table G-1.

Marx charge voltage (kV)	Averaged diode voltage (MV)	Averaged time of peak voltage (nsec)	Averaged pulse duration (nsec)
100	2.54	30	61
95	2.41	27	57
90	2.31	26	54
85	1.84	26	52
80	1.75	25	50

assumption of a 60-nsec square current pulse with a 50-kA amplitude. There are at least three possible spurious signal sources. Two of these are a fast group of electrons actually colliding with the voltage pad and a radiation-induced Compton current within the pad's dielectric. We attempted an experimental check on these two mechanisms by placing a 0.318-cm-thick disk of ^{238}U -loaded polyethylene over one of the capacitance pads. This resulted in a slight modification of the voltage trace, but the essential characteristics were the same. Hence, we have at least marginal proof that this voltage spike is not due to either of these mechanisms. The third

possibility is an extremely rapidly expanding plasma which must also be symmetric in 2π . There was no way to check this possibility with the instrumentation available, but an expansion of only 1 cm in radius in this time would require a plasma velocity, in the radial direction, of $\sim 3 \times 10^8$ cm/sec. Finally, the explanation which we accept is that the quasi-static approximation used in the derivation of the voltage division ratio is simply not valid under these circumstances. Therefore, we can only conclude that a very rapid phenomenon is occurring in the rear target region which produces relatively large, narrow voltage spikes in our diagnostic system in a very reproducible fashion.

Appendix H

Current Measurement Analysis

GEOMETRY

CURRENT SHUNT CONSTRUCTION AND USE

The radial current shunts consist of three basic sections — the outer ring, the

shunt resistor, and the inner support ring. The inner and outer rings are 1.27-cm-thick copper. Approximately 1400, 8.2 Ω , 0.5 W, carbon composition

resistors constitute the shunt resistor for our highest current shunts. These resistors are stacked between the copper rings (four deep), soft-soldered in place with 50-50, resin core solder, and potted with Dow Corning RTV 3110. A 50 Ω termination resistor with its ground-side lead insulated and conducted through the outer copper ring to a coaxial cable connector replaces one of the interior resistors to provide the external signal connection. As nearly as possible, a 50 Ω impedance was maintained through the copper ring portion of the signal lead, but since this section is only about 3 cm long, spurious cable reflections would be of very high frequency, ~ 60 GHz, and unobservable.

For an experimental series of shots, we position the shunts in the vacuum chamber and fix them in place by jack screws. The inner support rings of the various shunts provide anchorage points for various parts of the target structure. Solid outer conductor, coaxial cables connect the signal output connectors on the several shunts to vacuum feed-through, coaxial connectors at the chamber wall. To prevent a ground loop between the shunts and these chamber-exit connectors, the signal cables are contoured to the chamber wall and covered with conducting tape. From the chamber to the monitoring oscilloscopes, the current signal uses the common, single-point grounding system and cable bundle.

ELECTRICAL CONSIDERATIONS

The electrical schematic for the current shunt circuit is

where R_s is the shunt resistance and the R_T 's are termination resistors. The shunt inductance has not been included since it is negligible in this case. The total circuit resistance, R , is

$$R = 2 R_s R_T / (R_s + 2 R_T).$$

Since $R_T \gg R_s$, expansion of the denominator gives the approximation,

$$R \approx R_s (1 - R_s / 2 R_T + \dots),$$

or to first order, the total resistance is

$$R \approx R_s.$$

The voltage which will appear across the parallel network, $V_{||}$, for a delivered current from the electron beam machine, I , is

$$V_{||} = I R_s \quad (H-1)$$

and is the voltage which the shunt must be insulated against to prevent shorting. The observed oscilloscope voltage, V_o , is simply

$$V_o = V_{||} / 2. \quad (H-2)$$

To a very good approximation the shunt resistor will carry all of the machine current, while the termination resistors will carry a current equal to $V_{||} / 2 R_T$. The associated instantaneous powers, P , and deposited energies, E^D , in the shunt

resistor and the termination resistors are

$$P_S \approx I V_{||}, \quad E_S^D = P_S \tau \quad (H-3)$$

$$P_T = V_{||}^2 / 2 RT, \quad \text{and } E_T^D = P_T \tau, \quad (H-4)$$

respectively, where τ is the pulse duration. In the experiment, the pertinent numerical quantities are

$$\begin{aligned} I &= 10^5 \text{ A} \\ R_S &= 6 \text{ m}\Omega \\ R_T &= 50 \Omega \\ \tau &= 100 \text{ nsec.} \end{aligned}$$

From (H-1), the voltage across the parallel network is 600 V and the current through the termination resistors is 6 A. During the pulse, a power level of ~60 MW and a deposited energy of ~1 J must be endured by the shunt resistor, from (H-3), while these quantities for the termination resistors are 3.6 kW and 0.36 mJ, by (H-4). Hence, although the pulse power level is quite high, the net energy which must be dissipated will not even raise the temperature of the various components by 1°C. The observed voltage at the oscilloscope for a current, I , from (H-2), will be ~300 V, where an ideal cable is assumed.

The condition for a fast-response shunt is that $R_S \gg L\omega^{117}$ which is equivalent to

$$L/R_S \ll 1/\omega,$$

where L is the shunt inductance and ω is the circular frequency of the fastest signal to be seen. In fact, if the inductance and resistance are known, the upper

bound for the shunt response time, τ_R , is

$$\tau_R = 2\pi L/R. \quad (H-5)$$

The experiments yielded clean signals down to a time scale of less than 1 nsec, so with the use of (H-5), the implied shunt inductance is <36 pH, which justifies the earlier assumption of a negligible inductance. Therefore, we have constructed radial current shunts capable of measuring currents in excess of 10^5 A with a response in the gigahertz regime.

OBSERVATIONS

Current measurements on the anode plane employ two different shunt configurations. In the simpler of the two, a single, high-current shunt supports the anode plane of the target structure (Fig. 2). In this manner, all current returning to ground from either the front or rear of the anode plane is passed through this shunt; however, there are qualifications on the nature of these currents. First, currents in this geometry are not restrained to necessarily pass through the shunt. For example, a plasma discharge could conceivably terminate directly on the chamber wall rather than on the inner shunt ring. Also, there are currents circulating in the vicinity of the teflon front target holders which do not necessarily "short" to ground through this shunt.

The results of this particular measurement geometry are illustrated by Fig. 12. We will present only times and amplitudes on a several shot averaged basis, so all of the quoted characteristics

will not necessarily be represented in any particular current trace. Typical maximum current rise rates are -2.3 to -3 kA/nsec. Maximum currents of ~50 kA for full machine output occur at 30 to 35 nsec into the firing pulse. One consistent characteristic of the single-shunt measurements is the presence of oscillatory behavior. Relatively large amplitude oscillations, ~10 kA, about 1 nsec wide are frequently present. These usually start about 5 nsec into the pulse and die out around 70 nsec. Normally, this type of behavior is a clear indication of signal problems and is not real data. Concern on this matter was particularly enhanced with the observation of positive current spikes (~+10 kA) at 10 to 15 nsec. However, these oscillations are, in fact, not spurious signals. The current at 70 nsec is about -11 kA, and after this time the current trace settles down into a relatively quiet decay toward zero.

The second geometry for current measurement at the anode plane employs a high-current shunt on the cathode side and a low-current shunt on the rear target side of the anode (Fig. 11). In this case, a 2.45-cm-thick by 35-cm-diameter polyethylene disk supports the teflon target holder and front target. Therefore, only dielectric surfaces are present out to a diameter of 30 cm, the shunt location. Each shunt is attached directly to its respective side of this disk with nylon screws. Finally, Dow Corning RTV 732 forms a good dielectric interface between the polyethylene disk and each shunt.

The high-current shunt in this configuration, I_1 (Fig. 13) consistently indicated a maximum rate of current rise of

~-2.57 kA/nsec. There tended to be a relatively small, but persistent, peak at about 5 nsec into the pulse. The primary peak of I_1 had an amplitude of about -45 to 50 kA at 22-25 nsec with maximum machine output. Between 55 and 60 nsec the current crossed zero, at the end of the first half-cycle of the machine. By 70 nsec, the current in the cathode-side shunt, I_1 , had risen to a value of about +6.8 kA, which then decayed very slowly over almost 160 nsec.

The low-current or rear target side shunt, I_2 (Fig. 14) registered a maximum rate of current rise of ~650 A/nsec on the leading edge of its first major current peak. As in I_1 , a minor peak was consistently observed at about 5 nsec. The first major current peak had an amplitude of ~-4.5 kA at 13 to 15 nsec into the shot. After this, the trace went positive between the times of 24 and 35 nsec. The maximum positive amplitude reached during this excursion was ~+740 A at about 29 nsec. Then, the trace proceeds negative, usually with a minor inflection at ~55 to 60 nsec (if not a minor negative peak), to reach an amplitude of ~-6.28 kA by 70 nsec. The late-time behavior persists in I_2 in much the same manner as in I_1 .

The correlation between the cathode-side measurement, I_1 , and the rear target side measurement, I_2 , reveals some quite interesting phenomena. Compare Figs. 13 and 14. First, both I_1 and I_2 registered negative peaks, of different amplitudes, at ~5 nsec. Up until this time both currents were generally changing in the same direction; however, after this time the instantaneous slope of each current tended to be opposite in direction,

Next, I_2 was consistently either zero or positive at the time of the major current peak in I_1 at ~ 25 nsec, so one may consider the currents to be rotating at this time from the rear to the front of the anode plane, probably through the front target's hole. The first half-cycle of the electron beam machine ends at 55 to 60 nsec. At this time, I_1 crosses zero and becomes positive, while I_2 shows either an inflection in its negative slope or a distinct negative peak. Finally, by 70 nsec both currents have tended to stabilize in opposite directions with a net difference in amplitude of only ~ 500 A. Thus, a rotating current from the front to the rear of the anode plane is established at ~ 70 nsec with an amplitude of ~ 6.3 kA which persists for some time, $\sim 100 +$ nsec.

Now, a comparison of the single-shunt anode current measurements with those observations made with two shunts reveals the overall, large-scale effects. The rate of current rise in I_1 is quite comparable with that of the single shunt. The difference between the two may easily be accounted for by considering the contribution of I_2 . Numerically, the sum of the I_1 and I_2 rise rates is ~ 3.2 kA/nsec, while the single shunt indicates this value to be ~ 2.9 kA, for full machine energy. Then, the peak current for the single shunt occurs at ~ 30 - 35 nsec, as compared to a maximum in I_1 at ~ 22 - 25 nsec. The difference in peak timing is the result of I_2 swinging positive at the time of the peak current in I_1 . The total current can only show a maximum when the gross machine current can provide for the difference current in I_2 . From another viewpoint, the single-shunt maximum

current is the sum of the "leakage" from the rotating current in the anode target and the increasing generator current. The two shunt correlation easily provides both the mechanism and timing for the oscillations observed with the single shunt. Basically, both I_1 and I_2 are negatively increasing in the first 5 nsec and stabilizing to the large rotating current configuration at around 70 nsec. In the interim, each current is generally changing in a direction opposite to the other. Hence, one would indeed expect to see oscillatory behavior in a single-shunt measurement; however, a direct comparison of the oscillation amplitude with the instantaneous differences in I_1 and I_2 is not possible. The large insulator used in the two shunt observations will necessarily change the current structure during the machine pulse to an undetermined extent from that of the 10.1-cm-diameter insulator situation. Also, we cannot claim a complete knowledge of all the circulating current in the vicinity of the anode plane since, as noted earlier, the current flow is not constrained in space.

In addition to diagnosing the currents in the anode plane, a third shunt was used to monitor any current returning to ground through the rear insulator's steel support rod (not shown in illustrations). This shunt was placed immediately behind the coupling between the rear target insulator and its stainless steel support shaft, which passed out of the chamber through a double O-ring seal in a plexiglass plate. We observed oscillations at a frequency of ~ 780 MHz on a Tektronix 7904 oscilloscope in its direct access mode (frequency response ≈ 1 GHz) (Fig. 16). No attempt will be made to interpret the

amplitude of this oscillation since this shunt was even further removed from the "action" than the anode shunts. The really significant observation made with this measurement is a correlation between the total neutron yield and the amplitude of net current flowing through this rear shunt. The neutron yield consistently decreased at least a factor of 2 whenever the rear insulator would short out to its support rod. Thus, the presence of net current in the rear shunt was accompanied by a decrease in the total neutron yield.

In summary, the current diagnostics revealed two very important phenomena in our experiment. First, relatively large circulating currents (~6 kA late in

time) are present in the anode structure during any given shot. This current changes direction at least once during the pulse. The presence of these currents may indicate even faster phenomena occurring within the plasma and, at least, partially decoupled from the shunt measurements. In other words, even with the close electrical proximity to the target structures, the entire current diagnostic system may still be isolated from the events which give rise to neutron production. Finally, the current measurements, with the total neutron yield diagnostics, have demonstrated beyond doubt that a good rear insulator is necessary for optimal neutron yields in this target configuration.

Appendix I

Anomalous Plasma Resistance

PART A: MAGNETIC DIFFUSION LEADING TO A COLLISIONLESS PLASMA

Bernstein et al.,¹¹⁸ suggests that a possible cause for the anomalous resistance phenomenon in the plasma focus may be due to diffusion of the magnetic field through the current-carrying column. This could lead to the electron-cyclotron frequency in the current column becoming greater than the electron-ion collision frequency. Thus, the plasma would become collisionless and have an anomalously high resistance.

The diffusion time, τ , for the magnetic field to permeate a current column is

$$\tau \sim 2 \times 10^{-9} r^2 / \eta$$

where r is the radius of the current column and η is the plasma resistivity which is $\sim 3.3 \times 10^{-6} T_e^{3/2}$, where T_e is the electron temperature.¹¹⁸ Since the diffusion time is proportional to the three-halves power of the electron temperature, an upper bound may be estimated for this temperature by requiring a diffusion time equal to the total time of interest. In this case the time of interest is 15 nsec, so the implied temperature is 46 eV for a radius of 0.05 cm.

To be consistent, any temperature predicted from the Bennett pinch relation,

$$I = 200 \pi r^2 n_e (kT_e),$$

where I is the current, n_e is the electron number density, and k is the Boltzmann

constant,⁸⁹ must be less than the 46 eV upper bound. For (kT_e) in keV, the Bennett relation is

$$n_e T_e = 9.95 \times 10^5 I / r^2.$$

For a current of 30 kA, the radius already used, and a number density of 10^{16} cm^{-3} , the implied electron temperature is ~ 0.6 eV. Hence, the plasma temperature is consistently cool enough to permit diffusion of the magnetic field to the axis of a 0.05-cm-radius current column with an electron density of 10^{16} cm^{-3} .

The electron cyclotron frequency, ω_c , is

$$\omega_c = eB / m_e = 1.76 \times 10^7 B(\text{gauss}) \text{ Hz},$$

but the magnetic field, B , is

$$B = I / 5r \quad \text{gauss}$$

for a cylindrical current column. Therefore, the cyclotron frequency is

$$\omega_c = 1.76 \times 10^7 I / 5r \quad \text{Hz},$$

and is ~ 2.1 THz for the assumed parameters. Then, the electron-ion collision frequency, ω_{ei} , is

$$\omega_{ei} \sim 1 / \tau_{ei}$$

where the electron-ion collision time is

$$\tau_{ei} \sim 10^{12} T_e^{3/2} / n_e. \quad 43$$

Thus, this frequency is ~ 10 MHz for the conditions stated. Therefore, $\omega_c \gg \omega_{ei}$, and the plasma is collisionless. However, a word of caution is in order. Since the cathode voltage is ~ 300 kV and the implied Alfvén current limit ($17,000 \beta\gamma$) is ~ 13 kA, this analysis is only a rough approximation at best.

PART B: TWO-STREAM INSTABILITY CONSIDERATION

The longitudinal Langmuir wave or two-stream instability may occur for counter-streaming electrons of relative velocity, v_e , if

$$\kappa v_e < 2^{3/2} \omega_{pe}$$

where κ is the wave number and ω_{pe} is the electron plasma frequency.⁴⁴ For a stream of electrons of density, n_2 , flowing through a plasma with an electron density n_1 , the approximate instability growth rate, γ , is

$$\gamma \sim 0.7 (n_2/n_1)^{1/3} \omega_{pe}$$

so the e-folding time, τ_γ , is

$$\tau_\gamma \sim 1/\gamma \sim (0.7 \omega_{pe})^{-1} (n_1/n_2)^{1/3}.$$

For a density of 10^{16} cm^{-3} in both the plasma and the beam, this time is ~ 0.25 psec. With the use of the relativistic velocity for an electron in a 300 kV field, the electron velocity may be as high as

$$v_e = c \left[1 - \left(\frac{m_0 C^2}{T - m_0 C^2} \right)^2 \right]^{1/2}$$

$$\approx 1.8 \times 10^{10} \text{ cm/sec}$$

where C is light speed, T is the kinetic energy of the electron, and m_0 is its rest mass.¹¹⁹ Hence, the wave number must be $\lesssim 887 \text{ cm}^{-1}$ which implies a wavelength of $\gtrsim 7.1 \times 10^{-3} \text{ cm}$, approximately half of the current column radius. Therefore, the conditions for the two-stream instability may also be easily met, and the growth time is easily fast enough to occur within time scales of interest.

Appendix J

Measured Frequency Wavelength and Dimensional Comparison

To compare the various frequencies detected in the course of the experimental work with the geometrical dimensions of the system, consider the wavelength associated with a given frequency in a vacuum. Since the frequency, f , is related to the circular frequency, ω , by

$$f = \omega / 2\pi,$$

and the wavelength, λ , is related to the circular frequency in vacuum by

$$\lambda = 2\pi c / \omega,$$

(c is light speed), then the frequency is very simply related to the wavelength by

$$\lambda = c / f.$$

With the understanding that the presence of a dielectric or plasma will tend to shorten the wavelength for a given frequency, the following table relates the measured frequencies and their wavelengths to some of the physical dimensions in the experimental geometry (see Table J-1).

Table J-1.

Frequency	λ (cm)	Comparable dimensions
200 MHz	150	Overall length of experimental chamber and machine diode section.
400 MHz	75	Distance between the anode and rear target support shunts. Diameter of experimental chamber.
800 MHz	37.5	Diameter of CH ₂ disk used in the double shunt measurements. Diameter of the rear target insulator.
10 GHz	3	—
20 GHz	1.5	Depth of the rear target CD ₂ disk in its holder. Thickness of the anode target holder.
35 GHz	0.86	—
70 GHz	0.43	—

Appendix K

Thick Target Yield Calculation

We wish to calculate the ratio of the number of reactions to the number of particles in an incoming beam for the reactions, $D(D,n)^3\text{He}$, $^{12}\text{C}(D,n)^{13}\text{N}$, and $T(D,n)^4\text{He}$, and estimate the number of ions in an incident beam which would be necessary to result in a yield of 10^{10} n/pulse for the $D(D,n)^3\text{He}$ and $^{12}\text{C}(D,n)^{13}\text{N}$ reactions. The parameters,

Energy of incident deuterons

$$\approx 4.5 \text{ MeV}$$

Range of deuteron in CD_2 , R ,

$$\approx 21.14 \text{ mg/cm}^2^{120}$$

$D(D,n)^3\text{He}$ cross section, σ_{DD} ,

$$(4.5 \text{ MeV}) \approx 98.6 \text{ mb}^{121}$$

$^{12}\text{C}(D,n)^{13}\text{N}$ cross section, σ_{CD} ,

$$(4.5 \text{ MeV}) \approx 440 \text{ mb}^{112}$$

$T(D,n)^4\text{He}$ cross section, σ_{DT} ,

$$(1 \text{ MeV}) \approx 245 \text{ mb}^{121}$$

Atomic weight of CD_2 , A , $\approx 16 \text{ g/mole}$, will be used. In general, the number of reactions, N_R , for a given reaction¹⁰² is

$$N_R = N_B \sigma R \left(\frac{N_A}{A} F \rho \right)_T$$

where

N_B = number of incident ions in the beam

σ = cross section for the reactions as a function of energy

ρ = density of target material

$$\approx 1.03 \text{ g/cm}^3 (\text{CD}_2)$$

R = range of incident ions in the target

F = relative number of particles per molecule

N_A = Avogadro's number $\approx 6.025 \times 10^{23} \text{ mole}^{-1}$

A = the atomic weight of the target material,

Thus, the desired fraction is

$$(N_R/N_B) = \sigma R \left(\rho F \frac{N_A}{A} \right)_T$$

and the number of ions in the incoming beam would be

$$N_B = N_R / (N_R/N_B).$$

The results for the three reactions of interest are given in Table K-1.

Table K-1.

Reaction	(N_R/N_B)	N_B
$D(D,n)^3\text{He}$	1.79×10^{-4}	$5.59 \times 10^{13} \text{ d}$
$^{12}\text{C}(D,n)^{13}\text{N}$	3.50×10^{-4}	$2.86 \times 10^{13} \text{ d}$
$T(D,n)^4\text{He}$	3.46×10^{-5}	

Appendix L

Beam - Hot Target Considerations

We wish to derive the neutron production ratio, $(n_{14}/n_{2,5})$, for the mechanism of a 4.5-MeV deuteron beam entering a hot plasma target (CD_2). The relevant cross sections are $\sigma_{DD}(4.5 \text{ MeV d}) = 98.6 \text{ mb}$ and $\sigma_{DT}(1 \text{ MeV t}) = 245 \text{ mb}$.¹²¹ From Appendix K, we know that the reaction efficiency may be expressed as

$$(N_R/N_B) = R\sigma n$$

where in this case R is in units of cm, so n is the number density for the target. For CD_2 there are generally two density forms, high density (1.08 g/cm^3) and low density (1.03 g/cm^3). The resulting particle densities for the solid are given in Table L-1.

The range, R, of a fast ion in a plasma is typically characterized by the product of the ion velocity, v_i , with the ion-electron energy transfer time, τ_{ie} ,

$$R \approx v_i \tau_{ie}$$

To get τ_{ie} , consider the expression for the energy loss rate of an ion, from Glasstone and Lovberg,⁴³

$$\frac{dW_i}{dt} = \frac{-4 n_e e^4 m_e}{m_i} \sqrt{\frac{2\pi}{m_e k T_e}} \times \left(1 - \frac{W_i}{\frac{3}{2} k T_e}\right) \ln \Lambda$$

in a hydrogenic plasma where

W_i = ion energy

T_e = electron plasma temperature

n_e = electron number density

e = electronic charge

m_e = electron mass

m_i = ion mass

k = Boltzmann constant

$\ln \Lambda$ = Coulomb logarithm (assume ≈ 20).

If $W_i \gg kT_e$, then

$$\frac{1}{W_i} \frac{dW_i}{dt} \approx \frac{8}{3} \frac{\sqrt{2\pi} m_e}{m_i}$$

$$\times n_e \ln \Lambda e^4 \frac{1}{(kT_e)^{3/2}} \equiv \bar{\kappa}$$

which for deuterium is

$$\bar{\kappa}_D = -9 \times 10^{-13} \frac{n_e}{T_e^{3/2}}$$

Table L-1.

Density type	$N_{\text{total}}(\text{cm}^{-3})$	$N_D(\text{cm}^{-3})$	$N_C(\text{cm}^{-3})$	$N_E(\text{cm}^{-3})$
Low	3.88×10^{22}	7.76×10^{22}	3.88×10^{22}	3.10×10^{23}
High	4.06×10^{22}	8.13×10^{22}	4.07×10^{22}	3.25×10^{23}

and for tritium is

$$\bar{k}_T = -6 \times 10^{-13} \frac{n_e}{T_e^{3/2}}$$

where T_e is in keV. Therefore, the e-folding times for the energy loss rate of deuterons and tritons are

$$\tau_{ie}^D \approx 1.1 \times 10^{12} \frac{T_e^{3/2}}{n_e}$$

and

$$\tau_{ie}^T \approx 1.7 \times 10^{12} \frac{T_e^{3/2}}{n_e}.$$

Since the ion velocity for a given ion energy, E_i , is

$$v_i = \sqrt{2 E_i / m_i},$$

the respective velocities (cm/sec) for given deuteron, E_D , and triton, E_T , energies (keV) are

$$v_D = 3.11 \times 10^7 \sqrt{E_D}$$

and

$$v_T = 2.54 \times 10^7 \sqrt{E_T}.$$

Hence, the ranges for deuterons and tritons in a plasma with an electron density, n_e , and an electron temperature, T_e , are

$$R_D = v_D \tau_{ie}^D \approx 3.42 \times 10^{19} \frac{T_e^{3/2}}{n_e} \sqrt{E_D}$$

and

$$R_T = v_T \tau_{ie}^T \approx 4.31 \times 10^{19} \frac{T_e^{3/2}}{n_e} \sqrt{E_T}.$$

Notice that the number density may always be written as the product of the

compression factor, η , and the solid density number, n° .

Now, the ratio, (N_R/N_B) , for deuterons is

$$(N_R/N_B)_{DD} \approx \sigma_{DD} \eta n_D^\circ R_D.$$

Substitution of the appropriate values gives

$$(N_R/N_B)_{DD} \approx \sigma_{DD} \eta n_D^\circ 3.42 \times 10^{19} \times \frac{T_e^{3/2}}{\eta n_e^\circ} \sqrt{E_D} = 7.06 \times 10^{-6} T_e^{3/2},$$

and, by a similar process, the triton ratio is

$$(N_R/N_B)_{DT} = 1.04 \times 10^{-5} T_e^{3/2}.$$

The number of 14-MeV neutrons produced, n_{14} , is

$$n_{14} = N_T (N_R/N_B)_{DT}$$

where N_T is the number of tritons formed from the $D(D,p)T$ reactions. Since σ_{DD} is essentially equal for both reaction channels, the number of 2.5-MeV neutrons produced, $n_{2.5}$, and N_T are

$$n_{2.5} = N_T = N_D (N_R/N_B)_{DD}$$

where N_D is the number of incident deuterons. Therefore, the neutron ratio, $(n_{14}/n_{2.5})$, is

$$(n_{14}/n_{2.5}) = (N_R/N_B)_{DT} \approx 1.04 \times 10^{-5} T_e^{3/2}.$$

This result is not too surprising since this ratio would ultimately have to be the tritium reaction efficiency. For several electron temperatures, this ratio is

$$\begin{aligned} T_e = 1 \text{ keV} : n_{14}/n_{2,5} &\cong 1.04 \times 10^{-5} \\ T_e = 10 \text{ keV} : n_{14}/n_{2,5} &\cong 3.30 \times 10^{-4} \\ T_e = 100 \text{ keV} : n_{14}/n_{2,5} &\cong 1.04 \times 10^{-2} \end{aligned}$$

One should note that this result bears some relation to the nonthermal fusion chain problem, but the apparent simplicity is deceptive.

In addition to these results, it is instructive to note the number of deuterons required in a beam to give 10^{10} neutrons by the $^{12}\text{C}(\text{D},\text{n})^{13}\text{N}$ reaction. For an electron temperature of 100 keV and a

reaction efficiency, $(N_R/N_B)_{\text{CD}}$, of $\sim 9.48 \times 10^{-5} T_e^{3/2}$, the number of deuterons in the beam must be

$$\begin{aligned} N_B &= N_R / (N_R/N_B)_{\text{CD}} \\ &\cong 10^{11} \end{aligned}$$

Hence, conceivably the number of ions in the incident ion burst may be considerably reduced with high enough electron temperatures, but again this analysis is deceiving since for electron temperatures above 50 keV, the ion-ion slowing down mechanism starts to dominate the process. Thus, while the fluence of the incident burst may be reduced, one should note that there are definite limits to this reduction.

Appendix M

The Ratio of ($N_{14}/N_{2.5}$) for Thermonuclear Reactions

To calculate an analytic expression for the neutron production ratio ($n_{14}/n_{2.5}$) in the thermonuclear case, we consider the expressions for the numbers of reactions which are

$$N_{DD} = \frac{1}{2} n_D^2 \langle \sigma v \rangle_{DD} V \tau$$

and

$$N_{DT} = n_D n_T \langle \sigma v \rangle_{DT} V \tau$$

for the D(D,n) and T(D,n) reactions, respectively.⁴³ In these expressions, n_D is the deuteron number density, n_T is the triton number density, $\langle \sigma v \rangle_{DD}$ is the D(D,n) Maxwell-averaged cross section, $\langle \sigma v \rangle_{DT}$ is the T(D,n)⁴He Maxwell-averaged cross section, V is the volume of interest, and τ is the confinement time. Since both branches of the D(D,n) reaction are essentially equally probable,

$$N_T = n_T V = N_{DD},$$

and the numbers of neutrons produced, n_{14} and $n_{2.5}$, are just the numbers of each of these reactions. Therefore, the ratio ($n_{14}/n_{2.5}$), is

$$(n_{14}/n_{2.5}) = n_D \langle \sigma v \rangle_{DT} \tau.$$

With this expression, let us see if some of the results from our experiment make any sense in this context. From Appendix F, we have estimated a ratio ($n_{14}/n_{2.5}$) to be ~ 0.31 with the use of the implied peak widths for a thermal reaction. With a confinement time, τ , of 1 nsec (consistent with recent Febatron results)⁹⁴ and an assumed temperature of 10 keV for a $\langle \sigma v \rangle_{DT}$ of $\sim 10^{-16}$ cm³/sec, the implied deuteron number density is 3.1×10^{24} cm⁻³. This is to be compared with the deuteron number density for solid CD₂ of 7.76×10^{22} cm⁻³. Thus, these figures would imply a ~ 40 -fold compression over the solid deuteron density of CD₂ to obtain the burnup fraction implied from the time-of-flight study.

Appendix N

Non-Maxwellian Considerations

Since the primary coupling between fast ions and an electron plasma occurs for about matched ion and electron velocities, we wish to examine explicitly the electron energies primarily responsible for the slowing down of a 1-MeV triton ion. For nonrelativistic particles, the ion and electron energies are simply

$$E = \frac{1}{2} m v^2,$$

so the electron energy (eV), E_e , in terms of the ion energy (keV), E_i , is

$$E_e = 0.183 E_i,$$

for the special case of tritium ions.

Therefore, a 1-MeV triton will primarily interact with electrons whose energies are $\lesssim 183$ eV.

Along these lines, John Wyatt has made a very interesting point.⁹⁶ If one could selectively depopulate an energy interval in the electron distribution, then the mode of ion slowdown could, in principle, be fairly closely controlled. An excellent example of this idea utilizes the

$T(D,n)^4\text{He}$ reaction. The full-width-half maximum points in the DT cross section are at ~ 60 keV and ~ 300 keV. Thus, if the electron distribution were depopulated between the energies of ~ 55 eV and ~ 11 eV, fast tritons would slow down rapidly to ~ 300 keV, linger, in the energy sense, in the peak of the cross section, and then continue to be rapidly thermalized. The range, R , of an ion in this electron-depopulated regime would then be approximated by

$$R \approx v_i \tau_{ii}$$

where v_i is the ion velocity and τ_{ii} is the ion-ion collision time. Therefore, since

$$\tau_{ii} \propto E_i^{3/2} / n_D$$

(n_D is the deuteron number density of the plasma) and

$$v_i \propto \sqrt{E_i},$$

the range of the fast ion would be proportional to E_i^2 / n_D .

Reference

1. H. Alfvén, "Plasma Physics Applied to Cosmology," Physics Today, p. 28 (February 1971).
2. M. V. Babykin, E. K. Zavisly, A. A. Ivanov, and L. I. Rudakov, "Evaluation of the Possibilities of Using a Powerful Beam of Relativistic Electrons for Thermonuclear Fusion," in Fourth International Conference on Plasma Physics and Controlled Fusion (Madison, Wisconsin, 1971), pp. 635-643.
3. L. S. Levine, "Pulsed Power: A New Technology for Controlled Thermonuclear Fusion," in The 10th Annual IEEE Region 3 Convention (Miami, Florida, 1972), pp. Q1-1 to Q1-7.
4. L. S. Levine and M. G. Ury, "Pulsed Power Generators," IEEE Trans. on Nucl. Sci. NS-20, 1 (February 1973).
5. S. D. Putnam and C. H. Stallings, "Formation of High β Fusion Plasmas with Intense Relativistic Electron Beams," in Proceedings of the Second Topical Conference on Pulsed High Beta Plasmas (Garching, Germany, 1972), pp. 245-248.
6. V. N. Tsytovich, On the Possible Application of High Current Relativistic Beams in Plasma Physics, Lebedev Institute, Rept. CTC/618 (February 1969).
7. F. Winterberg, "Initiation of Thermonuclear Reactions by High-Current Electron Beams," Nucl. Fusion 12, 353 (1972).
8. T. H. Martin, K. R. Prestwich, and D. L. Johnson, Summary of the Hermes Flash X-Ray Program, Sandia Corp., Rept. SC-RR-69-421 (October 1969).
9. B. Freeman, J. Luce, H. Sahlin, E. Chambers, T. Crites, C. Nelson, and O. Zucker, Enhanced Neutron Yields from Electron Beam Deuterated Polyethylene Target Interactions, Lawrence Livermore Laboratory, Rept. UCRL-74158 (October 1972).
10. B. Freeman, H. Sahlin, J. Luce, T. Crites, C. Nelson, and O. Zucker, "Enhanced Neutron Yield from a Relativistic Electron Beam-Deuterated Polyethylene Target Interaction," Bull. Am. Phys. Soc., Series II, 17 (11), 1030 (1972).
11. L. P. Bradley and G. W. Kuswa, "Neutron Production and Collective Ion Acceleration in a High Current Diode," Phys. Rev. Lett. 29 (21) 1441 (November 1972).
12. J. R. Kerns, C. W. Rogers, and J. G. Clark, "Production of Neutrons in a Deuterated Polyethylene Target by an Intense Relativistic Electron Beam," Bull. Am. Phys. Soc., Series II, 17 (5), 690 (1972).
13. S. J. Stephanakis, L. S. Levine, D. Mosher, I. M. Vitkovitsky, and F. Young, "Neutron Production in Exploding Wire Discharges," Phys. Rev. Lett. 29 (9), 568 (August 1972).

14. F. C. Young, S. J. Stephanakis, I. M. Vitkovitsky, and D. Mosher, "Neutron Production by Hot Dense Plasmas Generated with Power Pulsers," IEEE Trans. on Nucl. Sci. **20** (1), 439 (February 1973).
15. J. Luce and H. Sahlin, High Efficiency Relativistic Electron Beam Driven Electro-Nuclear Reactions, Lawrence Livermore Laboratory, Rept. UCRL-75178 (October 1973).
16. J. Luce, H. Sahlin, T. Crites, E. Chambers, C. Nelson, B. Freeman, and O. Zucker, Enhanced Collective Ion Acceleration, Lawrence Livermore Laboratory, Rept. UCRL-74276-Ab (1972).
17. H. Sahlin, B. Freeman, J. Luce, and O. Zucker, "Theoretical Discussion of the Neutron Yield Produced by Electron Beam-Deuterated Target Interactions," Bull. Am. Phys. Soc., Series II, **17** (11), 1030 (1972).
18. J. Luce, H. Sahlin, and T. Crites, Collective Acceleration of Intense Ion Beams in Vacuum, Lawrence Livermore Laboratory, Rept. UCRL-74681 (April 1973).
19. B. Freeman, R. Gullickson, O. Zucker, W. Bostick, and H. Klapper, "Phenomena Relating to Relativistic Electron Beam-Deuterated Target Interactions," Bull. Am. Phys. Soc., Series II, **18** (10), 1351 (1973).
20. M. V. Babykin and V. V. Starykh, "Optimum Temperatures and Critical Parameters of a Self-Sustained Reaction in a Solid Thermonuclear Fuel," Soviet Phys.-Tech. Phys. **16** (8), 1273 (February 1972).
21. M. Gryzinski, "Fusion Chain Reaction," in Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958) **13**, pp. 270-274.
22. J. G. Linhart, "A Note on Power Production by Pulsed Fusion Reactions," Nucl. Fusion **8** (3), 273 (October 1968).
23. J. G. Linhart, Ch. Maisonnier, and J. P. Somon, "Theory of Inertial Confinement of Dense Plasmas," in Proceedings of the Topical Conference on Pulsed High-Density Plasmas (Los Alamos Scientific Laboratories, 1967) pp. H4-1 to H4-9.
24. J. G. Linhart, "Very-High-Density Plasmas for Thermonuclear Fusion," Nucl. Fusion **10**, 211 (1970).
25. J. G. Linhart, "Rocket-Driven Liners for Fusion Triggers and for Very-High-Density Reactors," Nucl. Fusion **13**, 321 (1973).
26. J. G. Linhart, "Theory of Fusion Reactions in an Unconfined Plasma," Nuova Cimento **17** (6), 850 (September 1960).
27. V. I. Agafonov, G. V. Golub, L. G. Golubchikov, V. F. Dyachenko, V. D. Ivanov, V. S. Imshennik, Yu. A. Kolesnikov, E. B. Svirsky, N. V. Filippov, and T. I. Filippova, "Study of a Non-Cylindrical Z-Pinch With Currents Exceeding 1 MA," Nucl. Fusion, Special Suppl., 121 (1969).
28. N. V. Filippov, T. I. Filippova, and V. P. Vinogradov, "Dense, High-Temperature Plasma in a Non-Cylindrical Z-Pinch Compression," Nucl. Fusion, Suppl. Part 2, 577 (1962).

29. D. P. Petrov, N. V. Filippov, T. I. Filippova, and V. A. Khrabrov, "Powerful Pulsed Gas Discharges in Chambers with Conducting Walls," in Plasma Physics and the Problems of Controlled Thermonuclear Reactors, M. A. Leontovich Ed., (Pergamon Press, New York, 1959), pp. 198-212, Vol. IV.
30. J. D. Lawson, "Some Criteria for a Power Producing Thermonuclear Reactor," Proc. Phys. Soc. 70, Pt. 1, 2 (January 1957).
31. L. Wood and J. Nuckolls, "Prospects for Unconventional Approaches to Controlled Fusion," in AAAS Symposium: The Energy Crises, (Philadelphia, Pennsylvania, 1971).
32. J. Nuckolls, Laser Induced Implosion and Thermonuclear Burn, Lawrence Livermore Laboratory, Rept. UCRL-74345 (1973).
33. B. Freeman, L. Wood, and J. Nuckolls, Some General Design Considerations Regarding Laser-Fusion CTR Power Plants, Lawrence Livermore Laboratory, Rept. UCRL-74486 (1971).
34. Program Summary, Research in High Temperature Plasmas, Aerojet-General Corp., Rept. AFAPL-TR-67-95 (August 1967).
35. T. Weaver, G. Zimmerman, and L. Wood, "Exotic CTR Fuels: Non-Thermal Effects and Laser Fusion Application," Bull. Am. Phys. Soc., Series II, 18 (10), 1300 (1973).
36. Proposal, A Feasibility Study of Neutron Generation Techniques, Aerojet-General Corp., Rept. ANU65-24 (March 1965).
37. Proposal, Research on High Energy Pinches, Berkeley Analytical Sciences Services, Inc., Rept. BASS-71-4 (April 1971).
38. Ch. Maisonnier, M. Haegi, and J. G. Linhart, "Hollow Dynamic Pinch," in Conference on Plasma Physics and Controlled Nuclear Fusion Research (Culham, U.K., 1965), pp. 345-365.
39. J. W. Mather, "High Density Deuterium Plasma," in Conference on Plasma Physics and Controlled Nuclear Fusion Research (Culham, U.K., 1965), pp. 389-404.
40. J. Mather, An Intense Source of Neutrons from the Dense Plasma Focus, U.S.A.E.C., Rept. CONF-660925 (1966), pp. 623-634.
41. B. Freeman, H. Sahlin, J. Luce, T. Crites, C. Nelson, and O. Zucker, "Enhanced Neutron Yield from a Relativistic Electron Beam-Deuterated Polyethylene Target Interaction," Bull. Am. Phys. Soc., Series II, 17 (11), 1030 (1972).
42. N. G. Basov, Yu. S. Ivanov, O. N. Krokhin, Yu. A. Mikhailov, G. V. Sklizkov, S. I. Fedotov, "Neutron Generation in Spherical Irradiation of a Target by High-Power Laser Radiation," JETP Lett. 15 (10), 417 (May 1972).
43. S. Glasstone and R. Lovberg, Controlled Thermonuclear Reactions (Van Nostrand Reinhold Company, New York, 1960).
44. L. Spitzer, Physics of Fully Ionized Gases (Interscience Publishers, New York, 1962) Chapt. 3.

45. D. J. Coleman, "A Detector for Health Physics Monitoring of Pulsed Neutron Sources," in 1970 Annual Meeting of the Health Physics Society (Chicago, Illinois, 1970).
46. R. J. Lanter and D. E. Bannerman, The Silver Counter, A Detector for Bursts of Neutrons, Los Alamos Scientific Laboratories, Rept. LA-3498-MC (July 1966).
47. J. R. Severyn and T. L. Ellis, Silver Counter for Neutron Detection, Lawrence Livermore Laboratory, Rept. LER-T3-101201 (March 1973).
48. Chart, Chart of the Nuclides, Knolls Atomic Power Laboratory, 10th ed. (December 1968).
49. J. R. Stehn, M. D. Goldberg, B. A. Magurno, and R. Wiener-Chasman, Neutron Cross Sections, Brookhaven National Laboratory, Rept. BNL-325, Supp. 2 (May 1964).
50. C. M. Ankenbrandt and W. C. Dickinson, "Energy Response of L-24 Fluor Detector to Photons and Neutrons by Monte Carlo," in Detector Handbook, Lawrence Livermore Laboratory, Rept. UCRL-50176 (August 1967).
51. D. W. Muir, Sensitivity of Fusion Reactor Average Cross Sections to Thermal Broadening of the 14 MeV Neutron Peak, Los Alamos Scientific Laboratories, Rept. LA-5411-MS (October 1973).
52. G. W. Kuswa, L. P. Bradley, and G. Yonas, "Ion Acceleration in Electron Beams," IEEE Trans. on Nucl. Sci. **NS-20** (3), 305 (1973).
53. A. A. Plyutto, K. V. Suladze, S. M. Temchin, and E. D. Karop, "Acceleration of Ions in an Electron Beam," Atomnaya Energiya **27**, 418 (November 1969).
54. A. A. Plyutto, K. V. Suladze, S. M. Temchin, G. P. Mkheidze, E. D. Karop, B. A. Tskhadaya, and I. V. Golovin, "Acceleration of Ions by a Relativistic Electron Beam," Soviet Phys.-Tech. Phys. **18**, (8), 1026, (February 1974).
55. W. H. Bostick, L. Grunberger, V. Nardi, and W. Prior, "Vorticity and Neutrons in the Plasma Focus," in Proceedings of the Fifth Symposium on Thermophysical Properties, (Newton, Massachusetts, 1970), pp. 495-502.
56. W. H. Bostick, "Summary and Evaluation of the Plasma Focus," in Third IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research (Novosibirsk, USSR, 1968).
57. W. H. Bostick, V. Nardi, and W. Prior, "Formation and Decay of Vortex Filaments in a Plasma Current Sheath," in Proceedings of the International Symposium on Dynamics of Ionized Gases (Tokyo, Japan, 1971), p. 375-377.
58. W. H. Bostick, V. Nardi, and W. Prior, "X-Ray Fine Structure of Dense Plasma in a Co-axial Accelerator," J. Plasma Phys. (G.E.) **8**, Pt. 1, 7 (1972).
59. W. H. Bostick, V. Nardi, and W. Prior, "Decay of the Magnetic Structure of Dense Plasma and X-Ray and Microwave Emission," in Second Topical Conference on Pulsed High Beta Plasmas (Garching, Germany, 1972).

60. M. Friedman, "A Possible New Mechanism for Generating Coherent Emission of Radio Waves in Astrophysical Phenomena," Astrophysical Lett. **12**, 129 (1972).
61. M. Friedman, "Automodulation of an Intense Relativistic Electron Beam," Phys. Rev. Lett. **32** (3), 92 (January 1974).
62. T. N. Lee and R. C. Elton, "X-Radiation from Optical and Inner-Shell Transitions in a Highly Ionized Dense Plasma," Phys. Rev. **A3** (3), 865 (March 1971).
63. I. V. Kurchatov, "The Possibility of Producing Thermonuclear Reactions in a Gaseous Discharge," in Plasma Physics and the Problems of Controlled Thermonuclear Reactions, M. A. Leontovich Ed. (Pergamon Press, New York, 1959), pp. 359-366.
64. L. A. Artsimovich, A. M. Andrianov, O. A. Bazilevskaya, Yu. G. Pikhov, and N. V. Filippov, "Investigations of Pulsed Discharges at High Currents," in Plasma Physics and the Problems of Controlled Thermonuclear Reactions, M. A. Leontovich Ed. (Pergamon Press, New York, 1959), pp. 367-370.
65. L. A. Artsimovich, A. M. Andrianov, E. I. Dobrokhotov, S. Yu. Lukyanov, I. M. Podgorny, V. I. Sinitsyn, and N. V. Filippov, "Penetrating Radiation from Pulsed Discharges," in Plasma Physics and the Problems of Controlled Thermonuclear Reactions, M. A. Leontovich Ed. (Pergamon Press, New York, 1959).
66. S. K. Händel and J. M. Berg, "Correlated Electrical and X-Ray Measurements in Flash X-Ray Discharges," Arkiv för Fysik **31**, 1 (1966).
67. D. A. Baker and J. A. Phillips, "Pressure-Balance Limitations in Z-Pinches with Diffusion Heating," Phys. Rev. Lett. **32** (5), 202 (February 1974).
68. I. F. Kvartskhava, Yu. V. Matveev, and N. G. Reshetnyak, "Concerning the Mechanism of Charged-Particle Acceleration in a Dynamic Z-Pinch," JETP Lett. **15** (10), 437 (May 1972).
69. A. I. Karchevskii, V. G. Averin, and V. N. Bezmel' nitsyn, "Plasma Heating by an Electron Beam Produced in a Turbulent Linear Discharge," JETP Lett. **10** (1), 17 (July 1969).
70. A. I. Karchevskii and Yu. I. Strakhov, "Thresholds of Two-Stream Instability of Current in a Straight Discharge," JETP Lett. **13** (11) 424 (June 1971).
71. I. G. Presiantsev, V. D. Pis'mennyi, A. T. Rakhimov, and A. N. Starostin, "Radial Distribution of Fast Electrons in a Z-Pinch," JETP Lett. **16** (2), 45 (July 1972).
72. V. S. Imshennik, N. V. Filippov, and T. I. Filippova, "Similarity Theory and Increased Neutron Yield in a Plasma Focus," Nucl. Fusion **13**, 929 (1974).
73. M. J. Bernstein and F. Hai, "Evidence for Neutron Production Via Enhanced Resistivity in a Plasma Focus," Phys. Rev. Lett. **25** (10), 641 (September 1970).
74. M. J. Bernstein, C. M. Lee, and F. Hai, "Time Correlations of X-Ray Spectra with Neutron Emission from a Plasma-Focus Discharge," Phys. Rev. Lett. **27** (13), 844 (September 1971).

75. A. Bernard, A. Coudeville, J. Durantet, A. Jolas, J. Launspach, J. de Mascureau, and J. Watteau, "Neutron Measurements, Thomson Scattering, and Holographic Interferometry on Focus Experiment," in Proceedings of the Second Topical Conference on Pulsed High-Beta Plasmas (Garching, Germany, 1972), pp. 147-150.
76. A. Bernard, A. Coudeville, A. Jolas, J. Launspach, and J. de Mascureau, "Detailed Experimental Study in Various Phases of the Plasma Focus and Evidence for Non-Thermal Processes," Phys. of Fluids (to be published).
77. V. Nardi, "Toroidal Vortices in Pulsed Plasma," in Second Topical Conference on Pulsed High-Beta Plasmas (Garching, Germany, 1972), pp. 163-166.
78. B. Freeman, J. Luce, and H. Sahlin, "Plasma Focus-Solid Target Interactions," in Fifth European Conference on Controlled Fusion and Plasma Physics (Grenoble, France, 1972) p. 68.
79. H. Sahlin, "Theoretical Aspects of Collective Ion Acceleration in Relativistic Electron Beam Deuterated Polyethylene Target Interaction," in Conference on Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams (New York, 1974) (to be published).
80. N. Heese and W. R. Raudorf, "A Compact Low Cost Collective Effect Linac," Rev. of Sci. Instr. **43** (11), 1594 (November 1972).
81. W. Raudorf, "An Electronic Ram," Wireless Engineer **215** (July 1951).
82. J. Luce, "Experiments with Collective Ion Acceleration Using Relativistic Electron Beams," in Conference on Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams (New York, 1974) (to be published).
83. Proposal, Relativistic Collective Acceleration of Intense Linear Ion Beams, Lawrence Livermore Laboratory, Rept. LLL Prop.-101 (May 1973).
84. I. A. Grishaev and A. M. Shenderovich, "Acceleration by Interruption of an Intense Electron Beam," Soviet Phys.-Tech. Phys. **17** (11), 1871 (May 1973).
85. J. M. Wachtel and S. Safran, "Current Amplification in a Relativistic Electron Beam," Phys. Rev. Lett. **32** (3), 95 (January 1974).
86. G. A. Askar'yan, "Induction Acceleration of a Beam of Charged Particles," Atomnaya Energiya **6** (6), 487 (December 1960).
87. L. P. Mix, J. G. Kelly, G. W. Kuswa, D. W. Swain, and J. N. Olsen, "Holographic Measurements of the Plasmas in a High-Current Field Emission Diode," J. Vac. Sci. Technology **10** (6), 951 (1973).
88. H. Epstein, W. Gallagher, P. Mallozzi, and T. Stratton, "Plasma Processes in a Low-Pressure Spark Discharge," Phys. Rev. **A2** (1), 146 (July 1970).
89. T. N. Lee, "High Density Ionization with an Intense Linear Focus Discharge," in Conference on Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams (New York, 1974) (to be published).

90. C. A. Kapetanakis, D. A. Hammer, C. D. Striffler, and R. C. Davidson, "Destructive Instabilities in Hollow Intense Relativistic Electron Beam," Phys. Rev. Lett. **30** (26), 1303 (June 1973).
91. A. V. Gordeev, V. D. Korolev, Yu. L. Sidorev, and V. P. Smirnov, "Production and Focusing of High Current Beams of Relativistic Electrons Up to High Densities," in Conference on Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams (New York, 1974) (to be published).
92. M. Friedman and M. Herndon, "Generation of Intense Infrared Radiation from an Electron Beam Propagating Through a Rippled Magnetic Field," App. Phys. Lett. **32** (12), 658 (June 1973).
93. D. Mosher, "High Energy Density Exploded Wire Discharges," in Conference on Electrostatic and Electromagnetic Confinement of Plasmas and the Phenomenology of Relativistic Electron Beams (New York, 1974) (to be published).
94. B. Freeman and O. Zucker, "Energy Compression Experiment" (to be published).
95. C. Stallings, R. Schneider, and J. Benford, "Compression and Stability Studies of High ν/γ Beams," J. Vac. Sci. Technology **10** (6), 959 (1973).
96. J. Wyatt, Lawrence Livermore Laboratory, private communication (May 14, 1974).
97. J. M. Dawson, H. P. Furth, and F. H. Tenney, "Production of Thermonuclear Power by Non-Maxwellian Ions in a Closed Magnetic Field Configuration," Phys. Rev. Lett. **26** (19), 1156 (May 1971).
98. M. Gryzinski, "Role of Fusion Chain Reactions in the Nonstationary Evolution of Stars - Supernova Stars," Phys. Rev., 2nd Series, **115** (5), 1087 (September 1959).
99. J. L. Wyatt, W. Day, C. K. Hinrichs, and M. M. Reynolds, Properties of Slowing Reactions, Berkeley Analytical Sciences Services, Inc., Rept. AFOSR-70-2101-TR (1970).
100. N. S. Oakey, Fine Structure in Thermal Reaction (n, γ) Reactions, Ph. D. Thesis McMaster University, Hamilton, Ontario, Canada (September 1967).
101. B. W. Schumacker, "A Review of the (Macroscopic) Laws for Electron Penetration Through Matter," in International Conference on Electron and Ion Beam Technology (Toronto, Canada, 1964).
102. M. Barbier, Induced Radioactivity (John Wiley and Sons, Inc., New York, 1969) Ch. 1.
103. W. H. Sullivan, Trilinear Chart of Nuclides, Oak Ridge National Laboratory, 2nd ed. (1957).
104. D. Strominger, J. M. Hollander, and G. T. Seaborg, "Table of Isotopes," Rev. Mod. Phys. **30** (2), Pt. 2, 683 (April 1958).
105. D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, Brookhaven National Laboratory, Rept. BNL-325 (July 1958).

106. F. Reines, C. L. Cowan, F. B. Harrison, and D. S. Carter, "Detection of Neutrons with a Large Liquid Scintillation Counter," Rev. Sci. Instr. 25 (11), 1061 (November 1954).
107. T. Crites, Lawrence Livermore Laboratory, private communication (December 1972).
108. C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes (John Wiley and Sons, Inc., New York, 1937).
109. Radiological Health Handbook (U.S. Dept. of Health, Education, and Welfare, 1960), Rept. PB-12178R.
110. R. Howerton, Tabulated Neutron Cross Sections, Lawrence Livermore Laboratory, Rept. UCRL-5226 (October 1959).
111. S. Gangadharan and R. L. Wolke, "Recoil Angular Distributions of the ${}^6\text{Li}(d,n){}^7\text{Be}$ and ${}^{12}\text{C}(d,n){}^{13}\text{N}$ Reactions," Phys. Rev. C 1 (4), 1333 (April 1970).
112. H. W. Lefevre, Lawrence Livermore Laboratory, private communication (August 1973).
113. O. Zucker, Lawrence Livermore Laboratory, private communication (May 1974).
114. J. J. Brophy, Basic Electronics for Scientists (McGraw-Hill Book Company, New York, 1966), pp. 29-34.
115. R. V. Churchill, Operational Mathematics (McGraw-Hill Book Company, New York, 1958) Ch. 2 and 3.
116. D. R. Corson and P. Lorrain, Introduction to Electromagnetic Fields and Waves (W. H. Freeman and Company, San Francisco, 1962) Ch. 2 and 3.
117. R. H. Huddleston and S. L. Leonard, Plasma Diagnostic Techniques (Academic Press, New York, 1965) pp. 8-27.
118. M. J. Bernstein, D. A. Meskan, and H. L. L. van Paassen, "Space, Time, and Energy Distributions of Neutrons and X-Rays from a Focused Plasma Discharge," Phys. of Fluids 12 (10), 2193 (October 1969).
119. J. B. Marion, Classical Dynamics of Particles and Systems (Academic Press, New York, 1965) Ch. 4.
120. L. C. Northcliffe and R. F. Schilling, "Range and Stopping-Power Tables for Heavy Ions," Nuclear Data Tables 7 (3 and 4), 233 (January 1970).
121. H. Liskien and A. Paulsen, "Neutron Production Cross Sections and Energies for the Reactions $\text{T}(p,n){}^3\text{He}$, $\text{D}(d,n){}^3\text{He}$, and $\text{T}(d,n){}^4\text{He}$," Nuclear Data Tables 11 (7), 569 (June 1973).
122. Anderson, Lawrence Livermore Laboratory, private communication (June 5, 1974).
123. N. Jarmie and J. D. Seagrave, Charged Particle Cross Sections, Los Alamos Scientific Laboratories, Rept. LA-2014 (March 1956).