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AN EXPERIMENTAL INVESTIGATION OF THE TRAPPING AND ENERGY LOSS
MECHANISMS OF INTENSE RELATIVISTIC ELECTRON RINGS IN HYDROGEN
GAS AND PLASMA: Volume II

Adrian Charles Smith, Jr.

April 25, 1977

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CHAPTER 5

TRAPPING AND CONFINEMENT OF ELECTRON RINGS IN A PREIONIZED MEDIUM

CHAPTER 5

TRAPPING AND CONFINEMENT OF ELECTRON RINGS IN A PREIONIZED MEDIUM

5.1 Introduction

As discussed in Chapters 1 and 3, it became apparent during the early stages of the field-reversing electron ring research work at Cornell that the main experimental limitation on the overall lifetimes of the rings was the classical, collisional interaction of the ring electrons with the background gas fills present. In light of these developments, three immediate experimental approaches were possible by which the lifetimes of the rings could be extended from the existing 10-20 μsec to the range of 100-1000 μsec :

(1) decrease the collisional scattering of the high-energy electrons by increasing the injected beam energy;

(2) preionize a low-density hydrogen environment into which the beam could be injected, i.e., reduce the collision frequency by reducing the density of background scattering sites, or

(3) a combination of (1) and (2).

The first approach has been the motivation behind the RECE-Christa experiment, in which the beam energy has been increased from the 500 keV typical of the beam energy of the experimental work described in this thesis to 2-4 MeV ($5 \leq \gamma \leq 9$). Humphries¹⁰⁶ has shown that the diffusion of the high energy electrons out of the ring should proceed at a rate proportional to $n_o B_{zo} / \beta^3 \gamma^2$, where n_o is the density of scattering sites, B_{zo} is the ambient magnetic field, and β and γ are the high energy electron relativistic factors. Hence, owing to the γ^{-2} dependence, significantly lower ring diffusion loss rates should be observed at these higher beam energies.

The second approach, ring trapping and confinement in a preionized medium, was applied to the RECE-Berta device; the results of this experimental work are described in this chapter.

If existing ring magnetic field decay rates were to scale directly in Berta (~ 0.1 Gauss/ μ sec-mTorr for hydrogen¹⁰⁷), plasma densities of the order of 5×10^{12} cm⁻³ would ideally permit electron rings with lifetimes of the order of ~ 20 -30 ms. In practice, however, contributions of impurities from the plasma source, as well as neutrals brought into the plasma column from the vessel walls, might be expected to raise the neutral

background (or plasma density) in the discharge, thereby reducing these estimates considerably. In addition, we might expect to see a radically different trapping phenomenology upon injecting the electron beam into the pre-ionized medium. For instance, the ion immobility arguments set forth in the discussion of the gas-trapping process (Section 3.4) would certainly not hold true in background densities of the order of $5 \times 10^{12} \text{ cm}^{-3}$. Hence, beam-plasma interactions not seen in gas-trapping might now occur in plasma-trapping.

In this chapter, the discussion shall proceed from a description of the plasma source--along with associated apparatus--used in the work to a discussion of the plasma properties relevant to the experiment, and then to the two main subjects of investigation:

- (1) the trapping of rings in a background plasma and,
- (2) their subsequent long-term confinement in the preionized mirror trap.

We shall close by considering the phenomenology of the trapping process in light of existing theory dealing with rotating-beam/plasma injection processes.

5.2 Experimental Arrangement

The configuration of the arcjet plasma source relative to RECE-Berta as it was used in this set of experiments is shown in Figure (5-1). As shown in the illustration, the arcjet source and its attendant guide field modules were mounted coaxially with Berta on the downstream end flange of the device. The injected plasma streams into the mirror trap along the magnetic field lines from the gun nozzle.

5.2.1 The Plasma Gun

A number of different mechanisms were considered for preionizing the large (~ 350 liters) mirror trap region in RECE-Berta. Ultimately, only two possibilities were explored: the Z-discharge, and plasma guns. The final decision to use a Magnetoplasma dynamic Arcjet ("MPD Arcjet") was based on two factors:

(1) the magnetic fields in Berta (and also in the cusp-injected device, to which the preionization source was also to be applied) were no higher than 200 G (600 G in the cusp device), whereas Z-discharges typically utilize guide fields of 1 kG or more to enhance the stability of the discharge and prevent it from striking to the walls of the vacuum vessel.¹⁰⁸ Also, some questions

FIGURE 5-1

Schematic diagram of RECE-Berta with arcjet and associated field-grading coils attached.

PLASMA-TRAPPING APPARATUS

FIGURE 5-1

exist as to the spatial uniformity of the afterglow plasma following such high-current, axial discharges--an important issue when one considers the size of the electron rings, their susceptibility to magnetic field perturbations, and the volume of the vacuum vessel to be preionized.

(2) Berta has a serious asymmetry in the form of the injection snout which protrudes into the tank. The possible plasma non-uniformities which this might incur in a discharge struck between the end plates of the vacuum vessel (and possibly to the snout as well) appeared to be more trouble than they might be worth.

The arcjet does not appear to suffer severely from either of the above two limitations. The characteristic plasma from these devices tends to have $T_e \sim T_i \sim 1$ eV, with an ion streaming energy of 20-50 eV.¹⁰⁹ Such a cold plasma can easily be made to stream along magnetic field lines using guide fields as low as 30 Gauss.¹¹⁰ Also, allowing the plasma to stream into the Berta device from the downstream end of the machine precludes injection snout "shadowing" of a region from plasma. As shall be discussed in detail in Section 5.3.2, the plasma was found to be very "quiet" and quite satisfactory for these applications.

The arcjet is a variation of the class of moderate density ($10^{11} \text{ cm}^{-3} < n_p < 10^{15} \text{ cm}^{-3}$) coaxial plasma accelerators known generically as "Magnetoplasdynamic Arc Thrusters."¹¹¹ An excellent description of the historical development of these devices is available elsewhere.¹¹¹ Explored initially as a potential ion-engine rocket thruster, the MPD Arcjet has found application in such diverse areas as studies of the Earth's bow shock in a "Plasma Wind Tunnel" configuration¹¹² and in open-field-line plasma magnetic confinement devices for thermonuclear applications such as 2X-IIB,¹¹³ as well as in the electron ring trapping studies described here.

The actual mechanisms responsible for the axial acceleration of the arc plasma were the subject of lively experimental work in the mid-1960's, when the possible use for devices like the arcjet as rocket thrusters was being actively explored. A detailed description of the experimental findings¹¹⁴ goes beyond the scope of our interest here. An excellent discussion of the first-order plasma dynamics of coaxial plasma accelerators may be found in the text by Jahn.¹¹⁵

A 1/2-scale sketch of the MPD Arcjet used in this work is shown in Figure (5-2a).

Of first consideration in the gun's overall design

FIGURE 5-2a

One-half-scale section view of the MPD-arcjet used
for the preionization studies.

-312-

FIGURE 5-2a

was the size of the plasma column to be produced in Berta's interior. Presuming adiabatic expansion of the plasma column as it streams into the trapping region, and knowing the electron rings to have a mean diameter of approximately 10 cm and radial thicknesses of the order of 10 cm in a field of ~ 200 G, one finds that the arcjet anode-cathode gap must be of the order of 11 mm, with a mean gap radius of 2.25 cm in the cylindrical geometry, assuming arcjet fields of the order of 4 kG. Such an annular design in a field of this strength might be expected to increase the gun's characteristic electrical impedance somewhat, but this proved to be a necessary trade-off.

The gun's anode consists of a stainless steel "horn" connected to a cylindrical channel around which has been wound a coil which provides a (non-uniform) magnetic field of up to 6 kG in the channel region. A bevelled, cylindrical, high-density graphite (Poco, AXF-5Q) cathode is located coaxially inside the stainless anode, with the anode horn flare being co-planar to the stalk cathode bevel. The carbon cathode is cantilevered into position via a quartz-sleeve-insulated 2.5 cm brass rod seated firmly in a nozzle-housing machined from Delrin. Tightening the cathode onto its

threaded brass support also secures the vacuum seals through the rear flange-mounted O-ring (with O-ring seals located to the inside, rear section of the stainless anode channel).

To avoid premature build-up of neutral hydrogen in the gun and vacuum vessel during a plasma injection cycle, the gas puff valve assembly was located inside the gun itself. The plenum housing the injection gas is 4.8 cm^3 in volume and made from Black Delrin (excellent mechanical shock and stress characteristics). The plenum shell seats against an O-ring located inside the brass cathode cantilever section. The pressure exerted by the plenum shell against this O-ring can be adjusted by varying the valve spring compression, which is achieved by turning the threaded and sealed spring base block. Added valve closing pressure also comes from the reservoir gas trapped behind the plenum. Eight 4.7 mm diameter holes are situated around the O-ring seat and directly to an annular channel within the White Delrin nozzle assembly. Eight 2.1 mm diameter flared ports form the nozzles connecting this annular chamber to the "drift region" in the channel between the anode and the cathode. First-order orifice- and tubular-flow calculations with collisional flow of the gas indicated a plenum "emptying time" of $\sim 2 \text{ ms}$ for ports and nozzles of the sizes

indicated here.¹¹⁶

The Black Delrin plenum shell is connected to the valve driver via a 4.7 mm flanged stainless steel driver rod with a small (0.34 mm diam.) gas bleed hole connecting the plenum with the gas reservoir. A small stem spring assures the return of the driver rod flange to its seat at the end of the plenum shell after each firing of the valve mechanism.

The other end of the stainless driver rod connects through sliding O-ring seals to a solenoid plunger via a slotted, slip-sleeve-and-pin assembly made from Blue Nylon (high impact durability) and stainless steel. For shot-to-shot reproducibility, a rather weak driver solenoid spring returns the solenoid plunger to its original position for the next firing of the valve. The driver solenoid assembly is electrically insulated from the gun cathode as shown, using Epoxy-impregnated fiberglass plates.

A photograph of the arcjet is shown in Figure (5-2b).

5.2.2 Pulse-Line Design and Construction

The various ways in which energy may be supplied to the arcjet are as diverse as are the gun's applications.

FIGURE 5-2b

Side and frontal views of the arcjet; the scale is
in inches.

SIDE VIEW

NOZZLE VIEW

FIGURE 5-2b

Dense Plasma Focus experiments¹¹⁷ operate similarly-configured plasma sources (without the applied magnetic field) at currents on the order of 1 MA for time intervals of 100-150 ns. On the other hand, the first "thruster" experiments¹¹⁸ operated the MPD Arcjets continuously at currents of 1000-1500 A. Our particular requirements of the arcjet for this work were that it be possible to achieve a constant plasma density for time intervals of up to 1 ms, and that the plasma density be variable up to a density $\sim 1-5 \times 10^{13} \text{ cm}^{-3}$: the first restriction being to provide a constant plasma density for rings should they be confined for 500-1000 μsec intervals, and the second requirement allowing flexibility in finding optimal plasma density values for best ring trapping/confinement. Ultimately, the most direct way of operating the gun in this mode appeared to be through the use of a discrete-element transmission line, or "pulse-line".

A schematic drawing of an n-stage discrete-element pulse-line is shown in Figure (5-3). An exact, analytic solution of the pulse characteristics of such an array of series inductances and shunt capacitances is quite complicated in general. It suffices for our purposes, however, to consider the first-order

FIGURE 5-3

- (Top) Electrical schematic of sections of an
N-stage, discrete element transmission line;
- (Bottom) Electrical schematic of the pulse-line used
to energize the MPD-arcjet.

FIGURE 5-3

characteristics of such a transmission line, since the second-order details of its operation are not particularly important in the use to which we shall be putting this device. From standard distributed transmission line theory, it may be shown¹¹⁹ that, to first order, the transit time required for a pulse to proceed down the length of the line, l , and return is

$$\tau_{\text{TRANSIT}} \cong 2n\sqrt{LC} \quad (5.1)$$

where n is the number of discrete stages in the line, and L and C are the inductance and capacitance per stage, respectively. The characteristic impedance of the line is

$$Z_0 = \sqrt{\frac{L}{C}} \quad (5.2)$$

Combining Equations (5.2) and (5.3), we have the basic design criteria for an n -stage, discrete-element transmission line:

$$Z_0 \tau_{\text{PULSE}} \cong 2nL \quad (5.3)$$

$$\frac{\tau_{\text{PULSE}}}{Z_0} \cong 2nC \quad (5.4)$$

(The difference between these approximate results and

the solutions of more exact calculations is that the left-hand sides of both Equations (5.3) and (5.4) should be divided by a factor of 1.07.¹²⁰⁾

Historically, MPD Arcjets operated in regimes similar to that of the intended use here¹²¹ have exhibited electrical impedances in the range of 15 m Ω to 40 m Ω . As mentioned above, however, given its annular design and wide anode/cathode gap, it was difficult to predict the gun's characteristic impedance. Hence, to avoid negative pulse reflections in the pulse-line (highly deleterious to electrolytic capacitors) arising from an impedance mismatch to the arcjet load, the pulse-line was designed for a low characteristic impedance of 15 m Ω to 25 m Ω . Also, practical considerations (the availability of electrolytic capacitors) limited the number of stages in the pulse-line to eight. Combining this information with the pulse length requirement of 1 ms and using Equations (5.3) and (5.4), one obtains values of the capacitance and inductance per stage as ~ 4000 μfd and ~ 1.5 μH , respectively.

A diagram of the pulse-line as it was actually configured is shown in Figure (5-3). The bank was made from linked modules of 1000 μfd electrolytic capacitors and could be charged to 1350 V with a stored energy of

31 kJ. The net stage capacitances could easily be changed by linking up one or both "C/2" modules. The inductors consisted of 5 turns of 3/0 welding cable wrapped on 15 cm diameter cardboard forms sandwiched between plywood plates for mechanical shock-support. The diodes located at the "open" terminus of the pulse-line prevent any multiple-reflection modes from driving negative voltages across the electrolytic capacitors. The total pulse length could be varied by linking up the desired number of bank modules.

Ordinarily, the charging potential was about 1 kV. Since the stored charge was about 34 C under normal operating conditions, it was necessary to use a 1 kV, 1 A charging supply (Megavolt Corp., Model 1-1000) in order to energize the bank to full potential in a reasonable amount of time (about one minute was typical).

Tests were made on the pulse-line by firing it into a "matched" resistive load of 20 mΩ consisting of a 3.35 m length of RG-8 coaxial cable. Some results from these tests are shown in the lower part of Figure (5-4). Photo "A" shows the pulse-line voltage as a function of time at the loading point of the bank (point "A" in Figure (5-3)). Note that the voltage quickly falls to almost exactly half (52%) its initial

FIGURE 5-4

- (Top) Photograph of the arcjet pulse-line;
- (Bottom) Upper oscillographs are the net pulse-line current into 20 m Ω load; lower oscillographs show pulse-line voltage characteristics at two points along the line (cf. Figure (5-3)).

ARCJET BANK

POINT (A)

POINT (B)

UPPER TRACE: 500A/div
LOWER TRACE: 20V/div
SWEEP: 500 μ s/div

FIGURE 5-4

value for the first half of the pulse, dropping almost to zero during the second half of the pulse. Thus, the characteristic impedance of the pulse line can effectively be estimated at $20 \text{ m}\Omega \pm 10\%$. As it turned out, the characteristic gun impedance was about $80 \text{ m}\Omega$. Hence, the problems with negative reflected pulses did not occur since $Z_{\text{GUN}} > Z_{\text{LINE}}$. The mismatch to the bank--and the resulting extended pulsewidth--proved useful in fine-tuning the plasma density because of the gradual decay of the arc current.

In practice, the arcjet was normally fired utilizing only half of the lumped element line, and only one of the "C/2" modules was engaged in each stage.

5.2.3 Plasma Source Operation

The operation of the arcjet plasma source proceeds as follows. The gas reservoir is pumped to a fair vacuum ($\sim 500 \text{ mTorr}$) and then filled with the gas to be ionized and accelerated (usually hydrogen). This gas proceeds to fill the plenum via the bleed hole in the driver rod. Normally, gas pressures in the gun reservoir ranged from 1.1 - 2.5 Atm of hydrogen. The pulse-line, which is connected directly to the electrodes of the arcjet is charged to 800-950 VDC, depending on operating requirements (generally, the higher potentials

were used with higher base magnetic guide field values to minimize "jitter" in the firing of the arcjet).

The firing cycle is initiated with the SCR-controlled discharge of a 1000 μ fd, 400 VDC capacitor into the driver solenoid. The plunger is pulled freely into the solenoid field until, near the end of its travel, the pin in the Blue Nylon collar engages the end of the slot in the slip-fitting connected to the plenum driver rod. The Black Delrin plenum shell is then pulled away rapidly from its O-ring seat to allow the plenum gas to escape out through the eight holes into the annular nozzle chamber. The gas streams through the nozzles and distributes itself evenly in the azimuthal direction as it drifts towards the flared section and the anode-cathode gap.

When the gas reaches the anode-cathode gap (particularly around the sharply-bevelled sections of the horn and cathode), the 900 V potential readily breaks the gas down, and the charged pulse-line proceeds to discharge through the plasma arc. Owing to the interaction of the radial current channels which form between the anode and cathode with both the (diverging) axial, applied magnetic field and the current's own self B_0 field, the plasma is then accelerated at high velocity from the anode-cathode gap region. The quartz insulating

sleeve prevents the breakdown arc from proceeding backwards towards the nozzle assembly.

Effective use of this plasma source in these experiments was contingent upon accurate timing of the plasma pulse, as well as on a high degree of shot-to-shot reproducibility in the plasma characteristics. Hence, a number of gun characteristics (firing jitter, valve opening time, net injected particles, etc.), were measured to check on the device's operation. Characteristics such as plasma density as functions of space and time shall be discussed in the ensuing text as operating parameters are varied and the need arises. A further listing of those arcjet vital statistics not particularly relevant to this discourse may be found in Appendix V.

The plasma source diagnostics consisted of a high-impedance anode-cathode resistive voltage monitor (268:1) coupled to an oscilloscope via a 9.1:1.0 isolation transformer, and a Weston Instruments 0.250 m Ω series resistive current monitor isolated via a 9.1:1.0 transformer to the same oscilloscope. Typically, both gun current and voltage were monitored on all shots to check on arcjet performance as well as to assure proper timing of the electron beam firing sequences. Typical gun voltage/current traces are shown in Figure (V-1), in Appendix V.

5.2.4 Graded-Field Structures

The first magnetic field interface between the mirror field of Berta and the arcjet's guide field was provided by a set of tapped windings (#14 A.W.G., 600 VDC PVC insulation) wrapped around a 46 cm OD, 1.3 cm thick plexiglass cylinder with vacuum flanges at both ends. Using the tapped windings of two sets of 141 turns each, plus two sets of 71 turns each, one could obtain fields of up to 1 kG on axis from this coil. Owing to its weight (~ 75#), this coil had to be independently supported by a height-adjustable wood-and-aluminum cradle which rested directly on the 1.9 cm aluminum table on which the rest of the experiment was placed. The second magnetic field interface between this set of windings and the arcjet guide field was provided by a double-coil module constructed coaxially in-line on a 15 cm OD plexiglass tube, as shown in Figure (5-1).

As shown in Figure (5-5), the arcjet source itself was attached to the third graded-field coil via nylon bolts, and supported vertically via a support column cantilevered from the aluminum baseplate.

Measurements of the various axial magnetic field profiles available with the graded-field sections were made on a direct-current basis using a Hall Probe

FIGURE 5-5

Photograph of arcjet and graded-field section
attached to the downstream end of Berta.

FIGURE 5-5

Gaussmeter (Bell Model 640) and a regulated, high-current power supply connected to Berta's windings. The field profiles obtained in this fashion are comparable with those to be expected under pulsed-current conditions since the time delay between the pulsed current initialization and beam injection is 18-22 ms, which far exceeds the magnetic penetration time of any of the structural elements within the magnetic field. The field configurations measured for various combinations of windings are shown in Figure (5-6).

As shown in Figure (5-6), the effect of the graded-field section was to shift the minimum of the magnetic well slightly upstream. This shift was augmented in the case of electron rings trapped in fields without the third ("kicker", cf. Figure (2-2)) mirror coil, in which case the rings usually set up 128 cm from the downstream end of Berta-instead of 100 cm from the downstream end (the usual location of the well minimum for Berta's normal field, as shown in Figure (2-3)).

The base magnetic field was usually augmented by a quadrupole (Ioffe) stabilizing field. Typically, all 35 turns per arm (cf. Section 2.3) of the quadrupole were engaged in series with the main solenoidal and mirror windings. As mentioned in Chapter 2, this gave

FIGURE 5-6

Axial magnetic field in RECE-Berta with
various sets of graded-field coils engaged.

FIGURE 5-6

rise to a quadrupole field of $0.9\% B_{z0}$ at the 10 cm ring radius, where B_{z0} is the base magnetic field on axis at the bottom of the mirror well.

The added inductance and resistance of the grading-field sections, plus the arcjet guide-field coils, to the base solenoidal and mirror windings on Berta was found to decrease the 1/4-cycle risetime of the field-energizing bank current pulse by 10-20%. For a given bank charging voltage, the crowbarred current decreased by about 30%: these changes were easily compensated by slightly higher bank charging voltages.

To counter the onset of the "spoke" instability in the arcjet,¹²² a 6 mm-spacing rectangular mesh of stainless steel wire was tightly secured across the interface between the 1 kG coil and Berta's endplate. In this way, the radial electric fields which, along with the axial magnetic fields, drive the "spoke" may be effectively shorted out. Quite strong mechanical connections constraining the mesh are required owing to the violence of the $\vec{J}_r \times \vec{B}_z$ Lorentz interaction of interaction of radial currents flowing in the mesh with the background magnetic field.

5.2.5 Plasma Diagnostics

Three aspects of the injected plasma were studied:

- (1) plasma density and radial profiles;
- (2) plasma reproducibility and "noisiness";
- (3) internal axial plasma currents and associated self-magnetic fields.

In light of the number of gyro-orbits involved in the predicted ring lifetimes (gyroperiod of the ring electrons $\sim 2\text{ns}$), it was important to probe the plasma for isotropy in density as functions of radius and axial position.

In addition, the complex plasma current structure in such a streaming plasma conceivably could give rise to local field perturbations in excess of those allowable for stable ring confinement.¹²³

5.2.5.1 Plasma Density Measurements

The plasma density and profile measurements were made with Langmuir double probes. A double probe was used so that the reference plasma potential could be measured simultaneously, and at the same location, where the density was to be measured. The theory and interpretation of these probes in various geometries and under different plasma conditions may be found elsewhere.^{124,125} Their use in the plasmas employed in these experiments, however, is straightforward.

Owing to collisional as well as ambipolar diffusion effects,¹²⁶ both ions and electrons stream into the

trapping vessel with velocities commensurate with ion energies of the order of ~ 20 eV ($v_i \sim v_e \sim 6 \times 10^6$ cm/sec), and $T_e \sim T_i \sim 1-2$ eV. Thus, the ion streaming velocity greatly exceeds the ion thermal velocity, while the electron streaming velocity is much less than the electron thermal velocity (the electrons stream with energies of $\sim 20/1836$ eV $\ll 1$ eV). Therefore, if the ion-collecting probe can be biased to repel the 1-2 volt "cloud" of virtually non-streaming, thermal electrons, it can act as an optical "black absorber" to the streaming ions. Operated in this way, the probe resembles a "Faraday Collector." Properly biased against the electrons, if the probe has a cross-sectional area transverse to the plasma streaming direction of A_p , the collected current to be expected from the probe is simply

$$I_p \approx A_p q_i n_i v_i \quad (5.5)$$

where q_i is the ionic charge, n_i is the ion density, and v_i is the ion streaming velocity.

The size and shape of the probe used in the measurements is shown in the upper section of Figure (5-7). Two leads of 0.2 mm diam tungsten wire were seated in metal-to-glass seals and burnished to equal

FIGURE 5-7

- (Top) Illustration of Langmuir probe construction details;
- (Bottom) Electrical schematic of Langmuir probe bias and current monitor circuit.

LANGMUIR DOUBLE PROBE

FIGURE 5-7

lengths of 5 mm. The spacing between the wire centers was 1.6 mm. Thus, from Equation (5.5), with $A_p = 0.01 \text{ cm}^2$, we find that a plasma density of $1 \times 10^{13} \text{ cm}^{-3}$ streaming at 20 eV ion energy would produce a collected current of 1 mA, an easily detectable current.

The probe was mounted at the end of a 19.5 cm long section of 1.6 cm OD Pyrex tubing, which itself was attached, via a hinge, to a longer (181 cm) piece of tubing of the same diameter which was cantilevered through a vacuum fitting in the upstream endplate. This arrangement is sketched in Figure (5-8), and was necessitated by the fact that the probe had to enter the machine through an off-axis port in the upstream endplate (the arcjet assembly occupied the entire downstream faceplate) and yet still be capable of making radial profile scans. The radial profiles were made by rotating the probe (bent at 90° with respect to the cantilever) through angles of $\pm 46^\circ$, $\pm 31^\circ$, $\pm 15^\circ$, and 0° (vertical alignment of the probe) to make measurements at $\pm 15 \text{ cm}$, $\pm 10 \text{ cm}$, $\pm 5 \text{ cm}$, and 0 cm radial displacement from the axis of the machine. Angular positioning of the probe was made possible through alignment of a cursor attached to the cantilever tube with a template divided in angles and attached to the plexiglass upstream endplate. The probe

FIGURE 5-8

Configuration of Langmuir probe inside RECE-Berta
for plasma profile measurements.

FIGURE 5-8

could be translated along the axis of Berta by sliding the cantilever tube through the vacuum fitting.

The electrical bias circuit used with the probe is shown in the lower section of Figure (5-7). The 1000 μ fd electrolytic ballast capacitor insures proper voltage regulation, should large pulsed currents be drawn for extended periods of time. Electrically-isolated (to 500 V) monitoring of the probe current passing through the 50.8 Ω resistor was performed using a Tektronix Type 1A5 differential amplifier. No passive filtering of the probe signals was found necessary, as the plasma proved to be very "quiet" as far as electrical turbulence was concerned.

Before use, each lead of the probe was "discharge cleaned" by backfilling the vacuum vessel to about 500 mTorr nitrogen and running a 1 mA DC glow discharge from the lead to the conducting liners in the vacuum vessel. The duration of the discharge was usually about one minute.

Several scans of the probe voltage-current characteristics were made with bias voltages from -3 to -63 volts to locate the bias necessary for ion-saturation current. The "knee" in the i-v current was found to be about -8 to -10 volts, and the probe was biased

at -17 volts to insure that saturation was achieved.

An overlay of several probe traces used to measure the profiles are shown in Figure (5-9). As seen in the traces, the plasma was found to be both "quiet" and reproducible.

The radial plasma density profile at the bottom of the mirror well (127 cm from the downstream mirror), and parameterized to time intervals following the onset of the discharge, is shown in Figure (5-10). For comparison, a similar profile taken 177 cm from the downstream mirror (6 cm downstream from the injector snout) is shown in Figure (5-11). A plasma streaming energy of 20 eV is presumed in the plasma density calculation, Equation (5.5), for these data. As seen in the figures, the plasma density in the beam injector section at early times is smaller by about 20% than the densities measured at the well minimum. However, as time progresses, the density profile "flattens" radially, and the measured densities become quite similar. A slight asymmetry is also apparent in the profile taken in the injector section: the plasma density seems to be "pulled" slightly to the left in the figure. This is probably due to the local field perturbation brought about by the soft-iron lining in the injector snout. The effect is seen

FIGURE 5-9

Oscillographs showing Langmuir probe currents at various radial positions in the arcjet plasma; top trace is arcjet current profile; probe is located at the axial minimum of the magnetic mirror well (plasma density in cm^{-3}).

FIGURE 5-9

FIGURE 5-10

Arcjet plasma radial density profiles parameterized to time after the initialization of arcjet current; probe axial location is 130 cm from downstream end of Berta.

FIGURE 5-10

FIGURE 5-11

Arcjet plasma radial density profiles parameterized to time after the initialization of arcjet current; probe axial location is 177 cm from downstream end of Berta (about 6 cm away from the axial position of the end of the injector snout).

FIGURE 5-11

to smooth itself out after about 1 ms. The peak axial density is seen to be $\sim 1.6 \times 10^{13} \text{ cm}^{-3}$ at the well minimum. The 10 cm radius of the electron rings places the circulating current very close to the FWHM point of the bell-shaped density profile.

The overall shape of this profile was found to be quite independent of the details of the downstream (with respect to the electron beam) magnetic mirror strength, and agreed quite well (FWHM ~ 20 cm) with the previously mentioned predictions based on adiabatic expansion of the plasma column as the plasma streams into the lower field regions of Berta's magnetic well.

For experimental and analytical purposes, it was desirable to have a plot of plasma density as a function of time into the discharge at the electron ring radius of 10 cm off-axis. For reference, the plot of this data is shown in Figure (5-12). The data used in this plot were obtained by averaging several density profiles from both sides of the vertical symmetry plane of the plasma. The shot-to-shot variations are indicated as error bars in the figure.

5.2.5.2. Plasma Reproducibility and Noise

Although the interior regions of the plasma column were found to be quiet (cf. Figure (5-9)), measurements near the extreme boundaries (± 15 cm) of the column

FIGURE 5-12

Arcjet plasma density at the minimum of the magnetic well as a function of time after the initialization of arcjet current; probe radial position is at ± 10 cm.

FIGURE 5-12

occasionally showed some evidence of the spoke mode. This characteristic appeared only near the column edges, and was therefore ignored as a possible source of density anisotropy.

Sets of radial and axial plasma density profiles taken at the outset, and then at the conclusion, of the experimental work were found to be consistent with one another to within the relative accuracy of the measurement (20%). Thus, the plasma profiles and operating characteristics of the arcjet were found to be unchanged after several thousands of firings. Furthermore, the shot-to-shot reproducibility of the plasma characteristics was always found to be within the 20% margin of error--with the exception of measurements made at the plasma boundary, where, as mentioned, the tenuous measurements were also quite "noisy".

5.2.5.3 Plasma Currents and Self-Magnetic Fields

In experiments such as these where one fills a magnetized volume with a plasma, it is important to check the perturbation wrought upon the base magnetic fields by internal plasma currents as well as the plasma's inherent diamagnetism.

The plasma fields and currents were examined with two sets of magnetic probes. One set of probes was a

matched pair of 200-turn windings wrapped on 6.3 mm diam lucite spindles. Both probes were positioned axially at the center of the mirror well, with one probe located between the layers of copper screening lining the tank and the solenoid windings, and the other located on the axis of Berta at the end of the 5.7 cm diam Lexan cantilever. Both probes were oriented parallel to Berta's axis. The probe outputs were null-balanced against the pulsed background field via operational amplifiers (Tektronix Type "O" Plug-Ins) with variable resistance in series to one of the amplifiers. Hence, with the integration constant for one probe fixed, the relative gain of the other probe signal could be varied via the integrated signal's amplitude dependence on $(RC)^{-1}$ (cf. Section 3.2.2.1).

The other diagnostic probe used was an 800-turn winding wrapped on a 6.3 mm diam lucite spindle. It was placed inside a glass tube (to protect it from plasma-blast damage) hinged at a right angle to a Pyrex cantilever tube which was arranged in an identical fashion to that shown for the Langmuir probe in Figure (5-8). Like the Langmuir probe technique described earlier, this probe could be translated radially by twisting the cantilever tube through various angles.

Both sets of probes were calibrated in the fashion described in Section 3.2.2.2. Using 1.0 ms integrators, the probe calibrations were measured to be 1.24 ± 0.05 G/mV and 0.23 ± 0.01 G/mV for the matched axial probes, and the B_θ probe, respectively.

Using both sets of independent probes, one could monitor the axial magnetic field changes brought about by the plasma simultaneously to a measurement of the axial plasma currents via their B_θ "signatures" as a function of radial displacement.

Since the ballast inductance greatly exceeds the solenoidal winding inductance, the solenoid windings on Berta tend to be magnetic field-conserving (as opposed to flux-conserving) on the time scale of the plasma pulse, and the signal difference obtained between the two axially-oriented probes can be taken to be a fairly accurate measurement of the incremental axial field changes owing to the plasma diamagnetism. This field change was measured to be 2 Gauss maximum, a 1% variation on the base field. Hence, one would not expect to see dramatic gyroradius changes in the electron rings owing to the plasma diamagnetic effect.

The radial scans of B_θ currents in the plasma,

and the resulting J_z axial current densities inferred from them via Ampere's Law, are shown in Figure (5-13). As seen in the figure, the axial current densities are quite low (less than 0.2 A/cm^2), as are the azimuthal magnetic fields (less than 0.8 Gauss). The B_θ fields are seen to be neither asymmetric about the origin nor large enough to have much effect in stabilizing the precessional dump instability (which requires B_θ strengths of about 5% B_{z0} for stabilization of the dump, or at least 10 Gauss in B_{z0} .¹²⁷)

Thus, we see the plasma currents are fairly insignificant, and that the stainless shorting mesh located in front of the arcjet appears to be effective in quenching plasma current-carrying modes.

5.2.6 Experimental Diagnostics

Our interest in this series of beam/plasma injection experiments centers around two questions:

(1) How do the beam primary electrons behave upon injection into the preionized medium?, and

(2) Presuming that the beam, in fact, does circulate into the mirror trap and an electron ring is established in the plasma, is the lifetime of the ring enhanced in a way consistent with the low plasma "background density"?

FIGURE 5-13

(Top) B_{θ} field from the arcjet plasma currents;

(Bottom) Arcjet axial plasma current distribution.

FIGURE 5-13.

From a diagnostics point of view, the most direct way to address these two questions was to use arrays of fast magnetic pickup probes, as well as the fast electron current monitor, as described in Chapter 3, to study beam/ring diamagnetism and circulating high energy electron densities. Hence, to a large part, the study of ring trapping in a plasma proceeded along the same diagnostic lines as the gas trapping studies described in Chapter 3.

5.2.6.1 Magnetic Probes

The probe array used to monitor the axial diamagnetic profile of the circulating electrons was identical to that described in Chapter 3 and is shown in Figure (5-1). In this set of measurements, however, it was necessary to cantilever the probes axially inside the machine with a piece of 5.7 cm diam Lexan tubing closed at the end with a vacuum-sealed plexiglass disc, since the arcjet was located at the other end of the machine. The end of the cantilever was about 25 cm from the spoke-suppressing stainless steel mesh and did not appear to interfere with the transport of the plasma from the arcjet into Berta's mirror well.

5.2.6.2 Fast Electron Current Monitor

The technique and calibration used to monitor the fast electron current densities as a function of axial position and time was identical in all respects to that procedure described in Chapter 3.

5.2.7 Experimental Timing Sequence

As mentioned, the plasma density in the trapping region could be varied on beam injection by adjusting the time at which the beam was injected into the plasma discharge (cf. Figure (5-12)). Given the relatively small jitter in the arcjet firing time (less than 100 μ sec), this method proved to be quite satisfactory. A schematic of the timing sequence used in this experimental work is shown in Figure (5-14).

5.3 Experimental Results

5.3.1 Diamagnetic Field Profiles

Axial scans of the diamagnetic field profiles from the injected beam and trapped ring were made for beam injection into plasmas having densities of 1.3×10^{12} , 1×10^{12} , 8×10^{11} , 5×10^{11} , 1×10^{11} , and 8×10^{10} cm^{-3} . For completeness and systematic checks, the beam was also injected immediately following the termination of the plasma pulse, i.e., into what amounted to a low

FIGURE 5-14

Timing sequence used in the plasma-trapping experiments.

FIGURE 5-14

density (~ 10 mTorr) backfill of neutral hydrogen gas.

Two general arenas of post-injection behaviour became evident almost immediately--and neither resembled the trapping phenomenology described earlier for neutral gas trapping! These two types of behavior may be called the "stalled" and the "trapped" modes of injection, and the only parameter that appeared to determine which type of circulating current behaviour prevailed was the plasma density into which the beam was injected.

Plots showing the salient features of the "stalled" and the "trapped" modes are displayed in Figure (5-15). In these examples, the beam was injected into plasma densities of $1 \times 10^{12} \text{ cm}^{-3}$ and $5 \times 10^{11} \text{ cm}^{-3}$, respectively.

Located at the far left and far right sides of Figure (5-15) are the oscilloscope traces from the axial magnetic probe array for the "stalled" and the "trapped" currents, respectively. In the center of the figure are the two corresponding plots of axial diamagnetic profiles for the two cases, parameterized to time intervals following the onset of diode beam current.

The contrast with Figures (3-11) - (3-15) in Chapter 3 is immediately apparent. In the "trapped" case, as in gas-trapping, one sees initial, fast-rising

FIGURE 5-15

"Stalled" and "Trapped" modes of electron ring
injection into a background plasma.

FIGURE 5-15

(≤ 40 ns) spikes on the signals from those probes located towards the injector end of Berta. However, as one moves away from the injector, these spikes get smaller and smaller until, at 61 cm from the downstream mirror, the spikes have altogether disappeared. After a couple of hundreds of nanoseconds, the overall features of the probe signals are similar to the gas-trapping case insofar as the probe signals at the extreme ends of the mirror trap have dropped to zero, while one finds persisting tails on the probe signals as the center of the mirror well is approached, indicating the presence of a trapped electron ring. In further contrast to the gas-trapping case, however, one now finds that the self-magnetic field strength of the rings was consistently lower, with $\zeta \sim 10$ -25%.

In the case of the "stalled" beam, referring to the right-hand side of Figure (5-15), one finds the same characteristics as the trapped case, but now with no evidence of a trapped electron ring. Rather, the upstream spikes are seen to decay away--again with decreasing evidence of axial circulating current diamagnetism as one moves away from the injector region.

In the long-term picture, as shown in the lower left- and lower right-hand oscilloscope traces of

Figure (5-15), the "stalled" beam probe signals remained quiet after injection, while the "trapped" case revealed the presence of a long-lived electron ring which persisted for about 300 μ sec. (For these data, the full stabilizing quadrupole field was applied, hence the absence of the precessional dump in the "trapped" case.)

In light of this singular trapping behaviour, the beam trapping was studied at five plasma densities which straddled the "stalled" and the "trapped" behaviour regions. Data characteristic of the trends observed as one moved from higher to lower plasma densities on beam injection are shown in Figures (5-16) - (5-20).

Figure (5-16) illustrates the effect of injecting the beam into a plasma of density $1.3 \times 10^{12} \text{ cm}^{-3}$. As shown in the figure, in contrast to gas-trapping, the diamagnetic profile peaks sharply near the injector (located at 180 cm in these drawings) 100 ns after beam injection. The profile then drops rapidly as one moves away from the injector region at this same time period. At subsequent time intervals after beam injection, this spike then evanesces, the overall diamagnetic profile falling uniformly to zero quite rapidly with little evidence of any trapped circulating particles: the beam appears to have been "stalled" near its point

FIGURE 5-16

Axial diamagnetic profiles characteristic of beam
injection into a plasma density $n_p \sim 1.3 \times 10^{12}$
 cm^{-3} .

FIGURE 5-16

FIGURE 5-17

Axial diamagnetic profiles characteristic of beam
injection into a plasma density $n_p \sim 1 \times 10^{12} \text{ cm}^{-3}$.

FIGURE 5-17

FIGURE 5-18

Axial diamagnetic profiles characteristic of beam
injection into a plasma density $n_p \sim 5 \times 10^{11} \text{ cm}^{-3}$.

FIGURE 5-18

FIGURE 5-19

Axial diamagnetic profiles characteristic of beam
injection into a plasma density $n_p \sim 8 \times 10^{10} \text{ cm}^{-3}$.

FIGURE 5-19

FIGURE 5-20

Axial diamagnetic profiles characteristic of beam
injection into a neutral background density

$$n_0 \sim 2 \times 10^{14} \text{ cm}^{-3}.$$

FIGURE 5-20

of injection into the machine.

Figure (5-17) illustrates that this trend continues when the beam is injected into a plasma of density of $1 \times 10^{12} \text{ cm}^{-3}$. Once again, we clearly see that the beam diamagnetism--although now about 50% larger than in Figure (5-16)--still stalls near the injector and then rapidly decays to zero.

Decreasing the plasma density to $5 \times 10^{11} \text{ cm}^{-3}$ brings out quite a different injection behaviour as shown in Figure (5-18). Once again, we see the diamagnetic signal strongly peaked near the injector at 100 ns after injection. However, at subsequent times, the diamagnetism persists, and a ring-like diamagnetic profile is seen to "walk" slowly away from the injector region of the machine down to the minimum of the magnetic well (130 cm from the downstream mirror) where it stops--and where a long-lived (200-300 μsec) electron ring is now established. Note that no appreciable fraction of the circulating current distribution ever passes beyond the axial center of the mirror trap. The field-reversal strength of these rings remained at about 20% of B_{z0} .

Injecting the beam into a further-diminished plasma density of $8 \times 10^{10} \text{ cm}^{-3}$ (Figure (5-19) shows many of the same features as injection into $5 \times 10^{11} \text{ cm}^{-3}$,

with a slight overall increase of the field-reversal strength of the rings to about 25%. Once again, the circulating beam is initially confined to the injector region of the machine, but then is seen to "walk" downstream to the mirror well trough, where it forms a ring which lives for several hundreds of microseconds.

The inducement to trap greater amounts of circulating current led to injection into very low density plasma, i.e., densities below $5 \times 10^{10} \text{ cm}^{-3}$, achieved by injecting the beam quite late (2.0 ms) into the arcjet plasma pulse. However, as Figure (5-20) shows, the optimistic trapping trends do not continue. In fact, as shown in the figure, we now see trapping behaviour strongly reminiscent of gas-trapping. At early times following injection of the beam, the circulating current diamagnetism is seen to be fairly uniformly distributed along the axis of the machine. At subsequent time intervals, this uniform distribution is seen to decay rapidly to reveal the diamagnetic profile of a very weak ring trapped at the magnetic well minimum. As time passes, this profile is observed to fall rapidly (within 1-2 μsec) to zero, with no net circulating current to be found thereafter.

This behaviour can be explained through the arcjet

characteristics: at this low plasma density (and late time delay into the arcjet current pulse, cf. Figure (5-12)), most of the background into which the beam has been injected is neutral gas. Hence, it is consistent to expect the observed trapping to resemble gas-trapping, since that is essentially what it is. However, there is not sufficient gas or plasma to fulfill the charge neutralization requirements of the confined ring (the time required for ionization-charge neutralization is about 0.5 μ sec at these pressures ¹²⁸) so that the otherwise gas-trapped electron ring dies away from electrostatic effects. (The lowest neutral hydrogen gas pressure in which electron rings could be successfully confined was about 100 mTorr.)

5.3.2 High-Energy Electron Current Observations

Because of the possible existence of long-term counter currents induced in the background preionized medium by the electron beam, it became especially important in this set of measurements to cross-check the diamagnetic field profile behaviour to make sure that the observed field behaviour was not the product of such effects as plasma magnetic shielding. To this end, measurements of the circulating high-energy electron current density provided an independent diagnostic

on the beam's behaviour during the trapping and stalling processes.

An illustration of the direct comparison between the diamagnetic probe signals and the detected X-ray signals is presented in Figure (5-21) for the various axial locations studied during the experimental runs. The first spike on the traces is a time-marker fiducial; the X-ray signal begins with the second spike. As inspection of Figure (5-21) shows--with the exception of the initial spike on the X-ray signals--the two sets of signals resemble one another quite strongly at the corresponding axial locations. Both the X-ray signals and the probes indicate the build-up of the circulating current upstream, near the injector, followed by its subsequent movement down to the center of the machine (again indicated by persisting "tails" on both sets of signals). The downstream regions of the machine--in corroboration with the observations made in Section 5.4.1--do not indicate the presence of significant amounts of circulating high energy electron currents.

As noted in Chapter 3 (cf. Section 3.3.3), the initial burst of X-rays apparent on the signals shown in Figure (5-21) results from both intense diode-generated X-rays as well as beam primaries striking the

FIGURE 5-21

Direct comparison of magnetic pickup probe signals
with the X-ray detector responses for injected
currents at various axial positions in Berta.

COMPARISON OF MAGNETIC PROBE AND X-RAY SIGNALS

FIGURE 5-21

vessel walls, etc. Thus, as before, it was necessary to obtain a background radiation profile which was then subtracted from the "target-in" data. All X-ray flux measurements were made at time intervals ≥ 200 ns following beam injection, where the "tail" from the initial X-ray burst was $\leq 20\text{-}40\%$ of the total X-ray signal.

Fast electron current measurements were made at the same five plasma densities discussed in the preceding section. As in the case of gas trapping, since multiple target-and-detector combinations were neither feasible nor available, each circulating current axial profile was actually a composite of several different shots taken under the same plasma/beam conditions.

The results of these profile measurements are shown in Figures (5-22) - (5-26). (The data-trace digitizing and plotting programs written for the PDP-15 [cf. Chapter 3] were modified to process the data from the X-ray detector and display it in the same output format as that of the axial ring diamagnetic profiles.) To give an indication of the shot-to-shot variation in the data, Figures (5-23) and (5-24) represent data averaged over at least 4 shots per target location, with the error bars indicating absolute shot-to-shot

FIGURE 5-22

High-energy circulating electron current axial profiles characteristic of beam injection into a plasma density $n_p \sim 1.3 \times 10^{12} \text{ cm}^{-3}$.

FIGURE 5-22

FIGURE 5-23

High energy circulating electron current axial profiles characteristic of beam injection into a plasma density $n_p \sim 1 \times 10^{12} \text{ cm}^{-3}$. The "error bars" show shot-to-shot variations in the data.

FIGURE 5-23

FIGURE 5-24

High-energy circulating electron current axial profiles characteristic of beam injection into a plasma density $n_p \sim 5 \times 10^{11} \text{ cm}^{-3}$. The "error bars" show shot-to-shot variations in the data.

FIGURE 5-24

FIGURE 5-25

High-energy circulating electron current axial
profiles characteristic of beam injection into a
plasma density $n_p \sim 8 \times 10^{10} \text{ cm}^{-3}$.

FIGURE 5-25

FIGURE 5-26

High-energy circulating electron current axial profiles characteristic of beam injection into a neutral background density $n_0 \sim 2 \times 10^{14} \text{ cm}^{-3}$.

FIGURE 5-26

signal variations from the averaged data points. The statistics of the data show that the trends indicated in the plots reproduce faithfully to 20-30% in most cases.

In general, the fast electron current densities corroborated the data obtained from the diamagnetic probe array. As in the gas-trapped case, there was a strong resemblance between the fast current density axial profiles and the diamagnetic axial profiles as a function of time. As seen in Figures (5-22) and (5-23), beam injection into plasma densities of $1-1.3 \times 10^{12} \text{ cm}^{-3}$ shows that the fast circulating electrons clearly stall near the injector, with the initial build-up in the injector region evanescent rapidly in time and space with no resulting trapped currents. Decreasing the density to $5 \times 10^{11} \text{ cm}^{-3}$, as shown in Figure (5-24), we see--as inferred from Figure (5-18)--evidence that the fast circulating electron current initially builds up near the point of injection, but, in subsequent times, moves downstream to relocate at the bottom of the magnetic mirror well to form an electron ring. Injecting into a plasma density of $8 \times 10^{10} \text{ cm}^{-3}$, we observe (Figure 5-25) a trend like that found in Figure (5-19) from the stronger ring diamagnetism in that we now obtain

2

a build-up of almost twice the initially-circulating current density as for the case of injection into $5 \times 10^{11} \text{ cm}^{-3}$. And, similar in fashion to Figure (5-24), we also note the circulating current to move downstream from the injector region to the trough of the magnetic mirror well. Finally, injecting into the very low density plasma ($n_p < 10^{10} \text{ cm}^{-3}$, i.e., largely a tenuous gas backfill), Figure (5-26) indicates behaviour quite like that of the current profiles noted in gas-trapping: at early times following injection, the circulating current is found to be quite uniform along the axis of the machine. Then, as time proceeds, the current profile relaxes axially to the outline of the confined current distribution which, in this case, continues to collapse--owing, possibly, to the poor charge/current neutralization in such a low background density--on a time scale of about 1 μsec .

Therefore, it appears that the X-ray measurements confirm the results of the diamagnetic probes. That is, one may define three regions of trapping behaviour: the "higher" plasma densities ($n_e/n_p \sim 0.03-0.06\%$) where the circulating current is effectively stalled near the point of injection and proceeds no further downstream; the "intermediate" plasma densities ($n_e/n_p \sim 0.1-1.0\%$)

where the beam "walks" downstream to the magnetic well minimum from the injector region to form rather tenuous ($\zeta \leq 20-25\%$) confined electron rings, and the "low" plasma densities ($n_e/n_p \geq 1\%$), where very small probe/X-ray signals, and no confinement, were observed to occur.

5.3.3 Trapping of Electron Rings sans Quadrupole

Stabilization

All of the data presented thus far represents rings trapped with a background stabilizing quadrupole magnetic field. However, the presence of the quadrupole does not appear to alter either the initial ring field strength or the trapping process dramatically. Figure (5-27) shows some typical data obtained from an electron ring trapped in a plasma with $n_p \sim 5 \times 10^{11} \text{ cm}^{-3}$ and without a quadrupole field (*i.e.*, with only wall stabilization). The trapping behaviour is seen to be quite similar to those rings described above: the injected beam diamagnetism is seen to pause near the injector end of the machine, with subsequent movement down the machine axis until the ring eventually settles down at the minimum of the magnetic mirror trap. The initial field-reversal strength of the ring, about 25%, is

FIGURE 5-27

Electron ring trapping in a preionized medium without
a quadrupole field.

PLASMA-TRAPPING WITHOUT A QUADRUPOLE FIELD

FIGURE 5-27

about the same as for those rings trapped and confined in quadrupole fields. The ring's oscillations about its equilibrium location in the mirror trap prior to "settling down" at the well minimum are quite similar to those oscillations noted in the Livermore data shown in Figure (1-4).

It is worth noting, however, that, experimentally, it turned out to be considerably more difficult to trap electron rings in a background plasma without the stabilizing Ioffe field. That is, while trapping in the Ioffe field resulted in very reproducible ring behaviour and lifetimes over the range in parameter space described by these experiments, the trapping without the quadrupole field was so unproductive as to render few results (one shot in forty is a good percentage for successful trapping without the quadrupole field).

5.3.4 Long-Term Electron Ring Confinement in a Background Plasma

Having passed through the "trapping" phase, those quadrupole-stabilized electron rings which remained confined in the background plasma typically "lived" for periods of time ranging up to 400 μ sec. The features of their decay were quite similar to those rings normally confined in high background gas pressures: the "tails"

of the decay (cf. Figure (5-15)) appeared exponential in shape, with evidence of neither a "dump" nor further axial motion, both characteristics being hallmarks of the quadrupole-stabilized gas-confined rings.¹²⁹

Trapping and confinement of rings without the quadrupole field, however, resulted in quite different long-term confinement behaviour. As shown in Figure (5-28), (as well as in the lower left-hand traces in Figure (5-27)), the ring decay in a plasma without the quadrupole field is quite linear and flat for a period of 55 μ sec. However, the signal then suddenly collapses, indicating the loss of circulating current in a manner like that of the "precessional dump".¹³⁰ This is corroborated by the burst of high-energy X-rays as monitored by a side-on detector, the signal of which is shown in the lower trace of Figure (5-28).

From a measurement of the linear decay rate of rings confined sans quadrupole field, it is possible to determine the scale factor by which plasma trapping enhances the ring lifetimes. For example, from Figure (5-28), one obtains a decay rate of 0.2-0.3 Gauss/ μ sec. From Phelps, et al.,¹³¹ we have, for field reversals of the order of 50%, that rings trapped in ordinary hydrogen gas decay with a rate constant of about 0.014 Gauss/ μ sec-

FIGURE 5-28

Long-term electron ring confinement in a preionized medium without a quadrupole field.

MAGNETIC PROBE (130cm)

40 G
0

10 μ s/div

X-RAY DETECTOR

10 μ s/div

FIGURE 5-28

mTorr. Hence, the plasma-trapped layer of Figure (5-28) decays with a rate consistent with an effective background of 10-20 mTorr of pure hydrogen. This is much higher than the actual plasma density, but neither the actual neutral atom density, nor the effective atomic number distribution of the background neutrals, are known. (Also, higher-Z contaminants in the plasma, such as carbon or stainless steel, could play an important role here.) One must resort to spectroscopic techniques to resolve the plasma's atomic composition accurately.

Finally, under no conditions was an electron ring/plasma "wind" interaction ever observed. That is, physically the diamagnetic rings form a magnetic "obstacle" in the streaming plasma "wind" in which they are confined.¹³² Hence, some concern arose that the streaming plasma might effectively "blow" the rings out the upstream (with respect to the electron beam) mirror. However, the electron rings were consistently observed to remain confined at the same axial position in the magnetic mirror field for both gas and plasma trapping.

5.4 Plasma-Trapping and the Model of Chu and Rostoker

We now turn to a further consideration of the interesting ring trapping behaviour in the background

plasma described phenomenologically in Section 5.4 in light of existing theoretical treatments of rotating beam/plasma interactions.

The problem of the interaction of a rotating, relativistic electron beam with a magnetized plasma has been treated by Chu and Rostoker.¹³³ While the model which they employ in their theoretical treatment represents a significant idealization of the experimental conditions examined in this work, consideration of the predictions of their theory is certainly worthwhile.

5.4.1 Description of the Theoretical Model

No attempt will be made here to reproduce the formalism of the theoretical work. Rather, the direct discussion of their treatment of the problem will be limited to a description of their approach, with the emphasis on results as applied to the experimental findings of this thesis.

The model of Chu and Rostoker consists of the following physical picture: a uniform, semi-infinite, rotating, annular cross-section, rigid electron beam is introduced into a background, magnetized plasma, as shown in Figure (5-29). The system is presumed to be in the steady-state in the reference frame in which the beam has no axial velocity, i.e., the actual physics

FIGURE 5-29

The beam-plasma model of Chu and Rostoker.

FIGURE 5-29

of the beam injection process is not considered per se. Rather, concern centers around non-oscillatory plasma currents resulting directly from the beam/plasma interaction and the effects these currents have back on the rotating beam. The beam is assumed to rotate rigidly about the z-axis with an angular frequency, $\omega = eB_0/\gamma m_e c$, and proceeds down the z-axis with a constant velocity, v_0 .

The theoretical treatment begins from the cold-plasma, two-fluid equations including momentum transfer collision frequencies. The equations are linearized, Fourier-transformed, and transformed to cylindrical coordinates.

Using a Green's Function approach, a solution for the electric field from an infinitesimally-thin charge cylinder in Fourier-space is obtained by combining Ohm's Law (from the two-fluid equations) with Faraday's Law and Ampere's Law. Faraday's Law then gives the magnetic fields, and Ohm's Law the plasma current density, both in Fourier-space. The real-space quantities are then obtained through Fourier-inversions of the Green's Function relationships.

At this point, two assumptions are made regarding the properties of the plasma:

(1) it is assumed that the electrons are magnetized, but that the ions are not; that is,

$$\Omega_e \gg \nu_e \text{ and } \Omega_i \ll \nu_i \quad (5.6)$$

where Ω_e and Ω_i are the electron and ion cyclotron frequencies, and ν_e and ν_i are the electron and ion momentum transfer collision frequencies;

(2) collective plasma behaviour is not damped away by collisional processes, i.e., $\omega_p \gg \nu_e$, where ω_p is the plasma frequency.

With these two assumptions nonoscillatory solutions for $\vec{E}$, $\vec{B}$, and $\vec{J}$ are sought in real space via integration of the Green's Functions over the radial thicknesses of the annular electron beam current channel. Ultimately, the axial Lorentz reaction force back on one beam electron from the beam-induced plasma fields is calculated. It is found to consist of two components:

$$F_z = F_{z||} + F_{z\perp} \quad (5.7)$$

$F_{z||}$ is similar to the retarding fields found in linear, non-rotary beam treatments, and results from the electric fields induced by the decay of axial return currents behind the beam head. $F_{z\perp}$, however, is peculiar to the decay of the angular counter currents induced by

the beam head in the nature of the induced angular counter currents in the plasma under the assumptions of Equation (5.6), an argument similar to that leading to Equations (3.17) and (3.18) of Chapter 3 may be constructed. That is, using the general form for the conductivity tensor, (3.10), the conductivity tensors for the plasma electrons and ions under the restrictions of Equation (5.6) are

$$\sigma_e = \epsilon_o \omega_{pe}^2 \begin{vmatrix} \frac{\nu_e}{\Omega_e^2} & -\frac{1}{\Omega_e} & 0 \\ \frac{1}{\Omega_e} & \frac{\nu_e}{\Omega_e^2} & 0 \\ 0 & 0 & \frac{1}{\nu_e} \end{vmatrix} \quad (\Omega_e \gg \nu_e) \quad (5.8)$$

$$\sigma_i = \frac{\epsilon_o \omega_{pi}^2}{\nu_i} \begin{vmatrix} 1 & \frac{\Omega_i}{\nu_i} & 0 \\ \frac{\Omega_i}{\nu_i} & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \quad (\nu_i \gg \Omega_i) \quad (5.9)$$

Therefore, we may express the azimuthal counter currents induced in the plasma for the α^{th} species as

$$J_{\alpha\theta} = \sigma_{\alpha\theta r} E_r + \sigma_{\alpha\theta\theta} E_\theta \quad (5.10)$$

However, from Equations (5.8) and (5.9),

$$\sigma_{e\theta r} \left\{ \sim \frac{1}{\Omega_e} \right\} \gg \sigma_{e\theta\theta} \left\{ \sim \frac{v_e}{\Omega_e^2} \right\} , \quad (5.11)$$

$$\sigma_{i\theta r} \left\{ \sim \frac{\Omega_i}{v_i^2} \right\} \ll \sigma_{i\theta\theta} \left\{ \sim \frac{1}{v_i} \right\} . \quad (5.12)$$

Thus, for the current-carrying electrons,

$$J_{e\theta} \sim \sigma_{e\theta r} E_r . \quad (5.13)$$

That is, for this situation of "magnetized" electrons, the particle trajectories are almost exclusively in the form of $\vec{E}_r \times \vec{B}_z$ -driven drift currents, instead of a combination of Hall drifts and E_θ -drive "resistive" currents, as was the case over most of the pressure ranges in the experiments described in Chapter 3. (In a sense, the situation under consideration here is analogous to a very low pressure-limit of the work of Chapter 3. However, in this case, v_e is now the electron-ion collision frequency instead of the electron-neutral collision frequency, and, as shall be discussed shortly, $v_e \sim 10^8 \text{ sec}^{-1}$ for our experimental situation, which is less than Ω_e by about a factor of 10--instead of a

factor of ~ 3 , as was the case in gas-trapping.)

The collisional ions, under the influence of the space-charge-induced radial electric field, move out radially, causing the electric field driving the angular electron drift currents to die away, and consequently, the abatement of the electron angular currents. Thus, the circulating beam current, which had previously been current-neutralized, begins to make its diamagnetism "known". This forces the magnetic field lines (up to this time, essentially the base magnetic field) out of the region surrounded by the circulating beam which follows the beam head. In this way, the magnetic field lines acquire a radial component, and the resulting force on the (rigid) beam is therefore a $\vec{J}_\theta \times \vec{B}_r$ retarding force, $F_{z\perp}$. This process is illustrated in Figure (5-30).

As the authors point out, one potentially important aspect of the radial electric field which drives the cross-field electron drift current (Equation (5.13)) is that it could provide a source of electrostatic ion acceleration (since the ions are collisionally unaffected by the magnetic field). That is, the ions would essentially be dragged radially from the beam channel at the Alfvén speed. Thus, harkening back to the

FIGURE 5-30

Illustration of the emergence of the beam diamagnetism
behind the beam head.

FIGURE 5-30

discussion of Chapter 3, the effect of a small $\eta_{\theta\theta}$ (which would have implied the long "L/R" time for the induced plasma currents under the conditions of gas trapping) is offset by the rapid radial ion motion which serves to decrease the electric field driving the Hall currents.

Since the basic model assumed a constant axial velocity for the rigid electron beam, the authors make note that these retarding effects may be assumed to be quantitatively valid until the induced plasma currents decay to about half their initial values. Nevertheless, presuming the axial energy per beam electron to be $(\gamma - \gamma_{\perp})m_e c^2$, where

$$\gamma = \frac{1}{m_e c} (m_e^2 c^2 + P_{B\theta}^2 + P_{Bz}^2)^{1/2} \quad (5.14)$$

and

$$\gamma_{\perp} = \frac{1}{m_e c} (m_e^2 c^2 + P_{B\theta}^2)^{1/2} \quad (5.15)$$

(P_{Bz} and $P_{B\theta}$ refer to the beam's axial and azimuthal momentum, respectively), they define the fractional energy loss per beam electron per unit length as

$$f = F_z / (\gamma - \gamma_{\perp}) m_e c^2 (\text{cm}^{-1}). \quad (5.16)$$

Neglecting skin effects, Chu and Rostoker then use the analytic force expressions in Equation (5.17) with Equation (5.16) to obtain

$$f = \frac{n_e v_o a^2}{(\gamma - \gamma_{\perp}) n_o c^2 (a^2 + \lambda^2)} \left(v_e \exp\left(\frac{z}{\ell_{\parallel}}\right) + \frac{r^2 \omega^2}{v_o^2} v_{\perp} \exp\left(\frac{z}{\ell_{\perp}}\right) \right) \quad (5.17)$$

where n_e is the beam density, $r \approx a$ is its mean radius, n_o is the background plasma density, c is the speed of light, λ is the plasma skin depth, ω is the beam cyclotron frequency, z is an axial reference distance behind the beam head (as shown in Figure (5-29)), v_e , Ω_e , v_i , and Ω_i are the plasma electron and ion collision and cyclotron frequencies, respectively, $v_{\perp} = v_e (1 + \Omega_e \Omega_i / v_e v_i)$ is the effective collision frequency in the perpendicular direction, $\ell_{\parallel} = (a^2 + \lambda^2) v_o / \lambda^2 v_e$ and $\ell_{\perp} = (a^2 + \lambda^2) v_o / \lambda^2 v_{\perp}$ are effective current decay distances in the axial and azimuthal directions, respectively, and v_o is the beam's axial velocity.

5.4.2 Comparison with Experimental Results

As mentioned in the previous section, the theoretical treatment by Chu and Rostoker represents a highly idealized simplification of the experiments at hand: the inherent limitations of the theory are discussed in

greater detail in Section 5.4.3. Consequently, in comparisons with experiment, we may anticipate only order-of-magnitude accuracy in these theoretical predictions.

To compare the experimental results of Section (5.3) with the predictions of Equation (5.17), we make use of the experimental parameters for a clear case of beam "stalling" in the injection region, i.e., injection at 0.5 - 0.75 ms into the arcjet discharge, when $n_p \sim 1 \times 10^{12} \text{ cm}^{-3}$ (cf. Figures (5-17) and (5-23)) and the neutral gas density is $n_0 \sim 3 \times 10^{12} \text{ cm}^{-3}$ (~ 0.1 mTorr base pressure) [see Table 5-1].

These various quantities were obtained in the following way:

(1) Referring to Figure (5-23), we see that the stalled circulating current density is $n_e \sim 4 \times 10^8 \text{ cm}^{-3}$ under the existing experimental conditions;

(2) Typically, in these experiments, the beam energy was measured to be $E_0 = 440 \text{ keV}$, i.e., $\gamma \sim 1.86$;

(3) Our angle of beam injection is about 10° , from which one may infer that $0.1 \leq \beta_z \leq 0.25$, depending on the beam's location in the mirror well;

(4) We consider a thin annulus, where $r \sim a \sim 10 \text{ cm}$;

(5) With a base magnetic field of $\sim 150\text{G}$,

TABLE 5-1

Summary of Arcjet Plasma and Injected Electron Beam
Parameters

Plasma Parameters

$$n_p \cong 1 \times 10^{12} \text{ cm}^{-3}$$

$$\omega_p \cong 5.7 \times 10^{10} \text{ rad-sec}^{-1}$$

$$v_e \cong 1.2 \times 10^8 \text{ sec}^{-1} \quad (T_e = 1 \text{ eV})$$

$$\Omega_e \cong 2.6 \times 10^9 \text{ rad-sec}^{-1} \quad (B_0 = 150 \text{ G})$$

$$v_i \cong 1.3 \times 10^6 \text{ sec}^{-1} \quad (T_i = 1 \text{ eV})$$

$$\Omega_i \cong 1.4 \times 10^6 \text{ rad-sec}^{-1}$$

$$\lambda_{\text{Debye}} \cong 7.5 \times 10^{-4} \text{ cm}$$

$$\lambda_{\text{skin}} \cong 0.53 \text{ cm}$$

$$n_o \cong 3 \times 10^{12} \text{ cm}^{-3}$$

Beam Parameters

$$n_e \cong 4 \times 10^8 \text{ cm}^{-3}$$

$$\gamma \cong 1.86$$

$$I_B \cong 8 \text{ kA}$$

$$.1 \leq \beta_z \leq .25$$

$\Omega_e \sim 2.6 \times 10^9$ rad/sec, $\Omega_i \sim 1.4 \times 10^6$ rad/sec;

(6) The ring gyrofrequency $\omega = \Omega_e/\gamma = 1.4 \times 10^9$ rad/sec;

(7) The plasma skin-depth is $\lambda = c/\omega_p = 0.53$ cm $\ll a$;

(8) With a presumed background neutral density of 0.1 mTorr, ($\sim 3 \times 10^{12}$ cm $^{-3}$), a plasma density of 1×10^{12} cm $^{-3}$, and an electron/ion temperature of ~ 1 eV in the arcjet plasma, $\nu_{en} \sim 4 \times 10^5$ sec $^{-1}$ and $\nu_{ei} \sim 1.2 \times 10^8$ sec $^{-1}$ (cf. Section (3.4)) i.e., as expected the collisions are highly Coulomb-interaction-dominated;

(9) The ion momentum transfer collision frequency may be calculated based on momentum "relaxation times" due to ion-ion collisions.¹³⁴ By this we mean that period of time required for a single ion to undergo a large-angle scattering due to a manifold process of several small-angle scatterings. Presuming the limits of the scattering impact parameter to be

i) that required for a 90° scattering (minimum), and

ii) the plasma Debye length (maximum), we have the ion-ion relaxation time $t_{ii} \approx 7 \times 10^{10} W_i^{3/2}/n_i$, where W_i is the ion energy in keV, and n_i the ion density.

Assuming $W_i \sim 1$ eV and $n_i \sim 1 \times 10^{12} \text{ cm}^{-3}$, we have $\nu_{ii} = t_{ii}^{-1} = 1.3 \times 10^6 \text{ sec}^{-1}$;

(10) Based on the above values for ν_e , ν_i , Ω_e , and Ω_i , we compute $\nu_{\perp} \approx 45 \nu_e$.

First of all, from the data we see that $\Omega_e \sim 20 \nu_e$ and $\Omega_i \sim \nu_i$. Thus, the electrons are truly "magnetized" under these experimental conditions, while the ions are semi-collisional, with their cyclotron frequency being comparable to their collision frequency. A computation of $\ell_{\perp}$ and $\ell_{\parallel}$ shows them both to be of the order of 50-100 m, which far exceeds any scale distances of interest in the experiment. Hence, since $Z \ll \ell_{\parallel}$, $\ell_{\perp}$, both exponential terms in Equation (5.17) are well approximated by unity. Next, although the exact value of v_0 in our (scattered) beam is not known, the rigid, rotating beam approximation implies $a\omega \gg v_0$. Thus, the first term in brackets in Equation (5.17) may be neglected in comparison with the second term; physically, this implies that the "braking force" on the beam arising from the decay of axial plasma currents is considerably less than the $\vec{B}_r \times \vec{J}_0$ force spawned by the decay of the azimuthal beam-induced plasma currents. Thus, for our experimental conditions, expression (5.17) simplifies to

$$f \sim \frac{2.15 \times 10^9}{\gamma(1 - \sqrt{1 - \beta_z^2})v_o} \frac{n_e}{n_p} \text{ (cm}^{-1}\text{)} \quad (5.18)$$

where the parametric dependences upon beam and plasma densities have been left in the expression.

A plot of "f" as a function of $\beta_z = v_o/c$ appears in Figure (5-31) for the experimental conditions leading to Equation (5.18), as well as for the variations of parameters relevant to the experimental regime studied. The curves shown are, predictably, rather sensitive to plasma and beam density excursions of the order of factors of two, but they are useful for first-order beam braking-distance predictions in the context of this model.

Referring to Figure (5-31), we see that for $\beta_z \sim 0.1 - 0.15$, $n_p \sim 1 \times 10^{12} \text{ cm}^{-3}$, and $n_e \sim 4 \times 10^8 \text{ cm}^{-3}$, the theory predicts roughly a 50% axial beam energy loss in a distance of the order of 50 - 100 cm. This distance is comparable to the experimentally-observed axial beam penetration distances of $\sim 40 \text{ cm}$ (cf. Figures (5-16), (5-17), (5-22), and (5-23)). Presumably, given the strong axial retarding force predicted, the circulating beam could be stalled close enough to the injection point in the machine that the beam particle losses are

FIGURE 5-31

Percentage of beam electron energy loss per centimeter ("f") as a function of beam axial velocity,

$$\beta_z = v_z/c.$$

FIGURE 5-31

augmented by the beam's proximity to the injector snout (either through direct collisions with the snout, or through the azimuthal asymmetries brought about by the local magnetic field perturbations near the iron in the snout's interior).

In light of the sensitivity of "f" to variations in beam and plasma parameters, however, considerable caution must be exercised in claiming this agreement to be a vindication of the theory. The main point to be made here is that the predicted stopping distances for the beam are of the same order of magnitude as the axial length of the Berta device (for this choice of β_z). More elaborate deductions than this are not justified in light of the theoretical assumptions involved, as well as the uncertainties in the experimental measurements.

5.4.3 Limitations of the Theory

In the adaptation of the theory to the experimental results, a number of important experimental conditions must be considered. First, the injected beam in this experiment is not a uniform cylinder of rotating charge; rather, it is a spiralling beam with roughly a 10° pitch angle. The axial period of the spiral is therefore of the order of 12-15 cm near the injector, i.e., about

equal to the beam's gyroradius. In addition, as noted parenthetically above (also, see Chapter 2), the titanium scattering foil spreads the beam axially through an RMS angle of about 20° . Hence, the approximation of the beam by a rotating cylinder is probably not too bad. Of greater importance, however, is the (understandable!) absence, in the theory, of the injection process itself. Conceivably, another mechanism which could account for this same beam behaviour is the reflection of the beam by the conducting plasma as it is injected into the machine. That is, as the beam leaves the injector snout, induced plasma image currents could possibly reflect the beam--either back towards the snout, or axially, out through the upstream mirror. However, it is also hard to predict such an effect in this geometry and under the existing plasma conditions since, for example, the ions are now quite mobile (in contrast with the gas-trapping case). This is also difficult to diagnose experimentally, owing to the high flux of diode X-radiation which could swamp target Bremsstrahlung signals in the injector section of Berta.

It is also not clear from the theory exactly what happens when the beam's axial velocity is decreased significantly, i.e., as the ions move radially to abrogate

the driving $\vec{E}_r$ fields. That is, at this stage, could plasma density effects become important? We have seen experimentally that the beam penetration into the mirror well increases as the plasma density decreases, which is quite the opposite of the effect predicted by the first order, linear theory (i.e., in Equation (5.17), "f" decreases as the plasma/beam density ratio gets larger, thereby predicting better beam penetration at higher relative plasma densities). Also, the neutral contribution from the plasma source, even at the low plasma density end of the discharge, should still be negligible in terms of the collision frequency (as compared with the Coulomb collision frequency), so it is doubtful that neutrals might be playing a significant role here. As noted earlier, the signals on the diamagnetic probes were observed to rise very rapidly (cf. Figure (5-15)) in response to the injection of the electron beam--in fact, on a time-scale commensurate with the risetime of the probes themselves (~ 40 ns). Thus, induced angular plasma currents did not appear to play a significant role in "magnetically-shielding" the beams self-fields. As mentioned above, radial ion motion is one conceivable explanation for this rapid risetime: the Alfven speed in a hydrogen plasma is¹³⁵

$$V_A = 2.2 \times 10^{11} \cdot \frac{B(\text{Gauss})}{\sqrt{n_p} (\text{cm}^{-3/2})} \text{ cm/sec} \quad (5.19)$$

Therefore, with $B \sim 150\text{G}$, $n_p \sim 1 \times 10^{12} \text{ cm}^{-3}$, $V_A \sim 3 \times 10^7 \text{ cm/sec}$, giving a maximum ion transit time across the $\sim 5 \text{ cm}$ radial thickness of the beam channel of about 150 ns --which is comparable with the observed diamagnetic probe risetimes near the injector region.

(It might also be noted that consideration of the radial magnetosonic wave thus launched, and its possible applications to plasma heating, have been the subject of recent theoretical work.^{136,137})

However, because the ends of our experimental vessel are conducting walls, magnetic field "line-tying" in the plasma may be an important effect (a point not considered in the Chu-Rostoker Theory). Certainly, line-tying could significantly modify both the energy transfer to the plasma ions and the movement of the magnetic field lines in response to the beam, i.e., the axial force on the fast electrons.

Finally, the theory treats a semi-infinite beam, the effects of interest occurring only near the beam front. The injected beams in the experiment do not have this quality, and it is not clear that rotating

beams of finite axial extent, with the attendant oppositely-induced plasma currents at the trailing edge of the beam, will incur the same strong, net axial retardation forces.

Despite this spate of practical objections, braking mechanisms such as those proposed by Messrs. Chu and Rostoker might certainly be responsible for the experimental results obtained in this work. The current status of both the theoretical treatment and the experimental results, however, permit no concrete corroboration at this time. As to why the trapping efficiency in these experiments was consistently so low, one can, at this stage, only surmise. One possibility, for example, is the inherent asymmetry of the injection process. However, while the arguments for the advantages of such alternate schemes for rotary-beam injection as cusp-injection (see Chapter 6) sound encouraging, it has not been shown experimentally that electron beams injected into a plasma through a magnetic cusp are necessarily azimuthally uniform, either.^{138,139}

5.5. Summary and Discussion of the Results

This chapter has described a set of experiments designed to study the trapping and confinement of electron rings in a background plasma. The primary interest

was in the enhancement of electron ring lifetimes, as well as in the trapping process--and how it compared/contrasted with that observed in gas-trapping.

Electron rings were successfully trapped in a plasma with densities in the range of $5-8 \times 10^{10} \text{ cm}^{-3}$ $< n_p < 5-12 \times 10^{11} \text{ cm}^{-3}$, with $n_e \sim 4-6 \times 10^8 \text{ cm}^{-3}$. The field-reversal strengths of the rings did not exceed 25%, albeit the ring lifetimes were extended from the 20 μsec limitation of gas-trapping to over 350 μsec in the plasma. The decay rates were seen to be linear (without the quadrupole field), and were consistent with predictions based on gas-trapping data with a slightly higher effective backfill of hydrogen neutral density than would have been expected from a pure hydrogen plasma, although the difference could easily be explained by high-Z plasma impurities.

The "surprise" of the experiments was that, under certain plasma density conditions, the beam appeared to "stall" near the point of injection into the machine. Further study showed the rotating beam to penetrate varying distances into the magnetic mirror well, depending upon the background plasma density which was present at the time of injection. The theory of Chu and Rostoker was examined and, despite its variances with

experimental reality, was found to predict beam-stopping distances of the same order as those measured experimentally, granted appropriate choices for β_z . The observed plasma density dependence on f , however, was not predicted in the theory. Conceivably, further development of the theory to include rotating charge cylinders of finite axial extent may shed new light on the observed trapping behavior.

Evidently, the fundamental differences between the physics of gas-trapping, as examined in Chapter 3, and plasma-trapping lie in

- (1) the ion mobility, and
- (2) the nature of the beam-induced plasma behaviour.

In the plasma-trapping case, the ions may move radially out of the beam channel at the Alfvén speed to decrease the electric fields which drive the beam-induced (Hall) plasma return currents. This may happen on a very short (10-100 ns) time scale. If the beam current channel is radially-thin (2-5 cm), for example, such induced azimuthal return currents could be cancelled out in 10-100 ns, which is well within the beam pulsewidth. As discussed in Section 5.5.1, the resulting beam diamagnetism serves to generate self-inflicted

$\vec{J}_\theta \times \vec{B}_r$ retarding forces--which could act on the beam in the short time scale of the return current cancellation. However, in the gas-trapping case, as discussed in Section 3.4, no such ion motion is possible, the ions having been locked effectively into place by collisions. Therefore, beam-induced counter electron plasma currents may persist for significantly longer periods of time, implying that no such retarding force can act on the beam on the time scale of its first axial transit of the magnetic mirror well. (Unfortunately, owing to the plasma-trapping behaviour of the electron beam, it was not possible to make measurements of the decay of the induced plasma electron currents as it was in the case of gas trapping, where their decay at the axial ends of the confinement volume could be clearly discerned.) Rather, the beam is observed to "fill" the mirror trap effectively with circulating charge, and the ring trapping mechanism takes on an entirely different perspective.

The other significant contrast between gas-trapping and plasma-trapping is the difference in overall plasma behaviour. In plasma-trapping, the beam induces return currents in a plasma that had been created prior to beam injection. In gas-trapping, however, the beam must first create its own plasma as an integral part of

its propagation mechanism. The difference between these two situations is that the beam-created plasma serves to "freeze" the initial beam field perturbations (diamagnetism) via induced electron currents, while the pre-ionized plasma induces counter currents in order to prevent those beam-generated field perturbations from taking place at all. Thus, by the time the plasma currents begin to decay in the gas-trapped case, the beam no longer has a definable axial velocity, and these induced currents serve, instead, to counteract an entirely different fast electron dynamic mechanism, i.e., the axial focussing of the electron current layer into an electron ring.

In this regard, the observed electron ring trapping behaviour in a preionized medium is similar to the resistive E-layer trapping investigated in the Livermore experiments mentioned in Chapter 1. Both schemes rely upon dissipative processes: in the Livermore Astron work, the axial ring energy was dissipated resistively in the wall and cantilever resistor arrays via the currents induced around the resistive structures as the E-layers moved through them (the L/R time of the resistors was about 25 ns); in the plasma, on the other hand, the axial "braking" force relies upon the dissipation

of the drift angular counter currents to bring about a $\vec{J}_\theta \times \vec{B}_r$ self-body force onto the beam. (In both experiments, the axial speeds of the circulating beams are about the same, $\sim c/10$.) The fundamental advantage of the plasma trapping, however, is that the beam braking mechanisms couple directly to the "resistive medium" of the plasma which permeates the interior of the circulating beam. This was borne out in the Livermore work by the fact that the E-layers typically required many times their length to come to a halt due to resistor interactions. This is to be contrasted with the situation found in this work, where the rings were usually observed to be stopped completely within a couple of ring diameters of their point of injection.

In light of the above arguments, and in view of the limited diagnostics used in this experimental work to monitor the beam trapping mechanisms in a preionized medium, the experimental results discussed in this chapter can only offer--as yet--an interesting phenomenology. The overriding question--whether we are truly observing beam deceleration via Chu-Rostoker resistive plasma trapping, or just managing to "irritate selectively" one of the "in-house" processes which mysteriously limits the beam trapping efficiency to no more than 1-2%

under the best of circumstances (such as the "hybrid" instability, for example,¹⁴⁰ observed during injection in the Livermore Astron)--remains unanswered.

CHAPTER 6

THE CONFINEMENT OF CUSP-INJECTED, RELATIVISTIC ELECTRON RINGS IN NEUTRAL GAS AND PLASMA

CHAPTER 6

THE CONFINEMENT OF CUSP-INJECTED, RELATIVISTIC ELECTRON RINGS IN NEUTRAL GAS AND PLASMA

6.1 Introduction

Despite a wide variation of experimental parameters including magnetic mirror geometry, beam injection angle, and degree of beam scattering (via the drift tube foil thickness), the trapping efficiency of the beam injection system on RECE-Berta never exceeded 2%. Thus, from an experimental point of view, it was of interest to explore alternate beam injection schemes which might permit greater trapping efficiencies. This chapter describes some preliminary experimental work dealing with one such alternate beam injection technique utilizing cusped magnetic fields.

In this scheme, usually termed "cusp-injection", an annular electron beam is injected through a non-adiabatic cusped magnetic field which, in these experiments, is aligned coaxially to, and at one end of, a magnetic mirror trap. Passage of the electrons through the cusped field converts a portion of their parallel energy into perpendicular energy (cf. Reference 141 and Section 6.2). Presuming azimuthal symmetry of the

hollow, rotating beam, the physical picture of E-ring formation then becomes one of confining a rotating cylinder of charge which enters one end of a magnetic mirror well, axially, through one of the mirrors. The principle advantages of this method of injection are twofold:

- (1) it is azimuthally symmetric, and
- (2) it provides a greater spread in axial beam velocities, which may relax the experimental restrictions on the mirror well geometry necessary for trapping rings of higher net circulating current (and, possibly, of greater axial length).

Historically, the experimental study of cusp-injected electron beams has proceeded under widely-varying beam parameters. Kusse¹⁴² studied the wave interactions resulting from the injection of a low-current, low-energy cusp-injected DC electron beam (1A, 200-600 V) into a background plasma. More recently, with the advent of pulsed-power technology, Friedman,¹⁴³ following the low-energy and current (1-4 keV, unspecified beam current) experimental work of Sinelnikov and Akshanov,¹⁴⁴ first used cusp-injection as an alternative to the traditional Astron-like tangential injection scheme for filling a mirror trap with circulating, high-energy "clouds" of

electrons. The injected beam in Friedman's work was typically 8.5 kA, 500 keV, with a 50 ns pulsewidth, the experiments achieving diamagnetic signals of $\zeta \sim 0.3$ which lasted for about twice the beam pulsewidth.

Following Friedman, Kribel, et al.,¹⁴⁵ reported confinement of field-reversing electron rings in a cusp-injected mirror device for 9.5 μ sec, the short lifetime caused by the high background gas fills (1100 mTorr H₂) used in the experiment for charge-neutralization. In this work, the injected beam was 10-20 kA, 350 keV, with a 60 ns pulsewidth.

Another novel area of ongoing investigation is the collective acceleration of clouds of ions by electron rings--the rings having been formed by passing a high-energy, annular electron beam through a magnetic cusp. Reiser and co-workers¹⁴⁶ are currently using a 35 ns, 1-2 MeV, 2-4 kA beam of electrons in this application to study accelerated electron ring dynamics.

The experimental studies of this chapter extend the work of Kribel, et al., to the confinement of cusp-injected rotating beams in both puffed background gas fills and a preionized hydrogen medium.

6.2 The Basic Principles of Cusp-Injection

The main ideas behind the production of rotating,

hollow beams of electrons via injection of an annular electron beam through non-adiabatic cusped-magnetic fields are sketched in Figure (6-1). Shown in the figure is an idealization of the cusp-shaped magnetic field geometry resulting at the intersection of two uniform, oppositely-directed magnetic fields separated spatially by some material of high magnetic permeability. Physically, such a field configuration may be achieved by two oppositely-wound solenoids separated by an annulus of soft iron or cold-rolled steel.

Detailed calculations of particle trajectories passing through non-ideal cusped magnetic fields have been performed by Rhee and Destler¹⁴⁷ and Friedman and Sprangle.¹⁴⁸ For the purposes of this discussion, we may represent the magnetic field in the cusp region (neglecting fringing fields) as being purely radial and having the magnitude (satisfying flux conservation) of

$$\vec{B}_c = \frac{r_0}{2D} |\vec{B}_1 - \vec{B}_2| \hat{e}_r \quad (6.1)$$

where $\vec{B}_1$ and $\vec{B}_2$ are the (uniform) magnetic fields to either side of the cusped field section, as shown in Figure (6-1), and D is the axial thickness of the permeable annulus. We shall consider the trajectory of a charged particle initially injected along the magnetic

FIGURE 6-1

The principle features of cusp-injection.

FIGURE 6-1

field lines to the left of the cusped field at some radial distance, r_0 , from the central axis of the field. The ensuing discussion closely follows the treatment given by Kusse.¹⁴⁹

As the charged particle streams into the cusp, with the above assumptions, it suddenly enters a region of transverse magnetic field, $\vec{B}_C$. While under the influence of $\vec{B}_C$, the particle will, to first order, execute a $\vec{v}_z \times \vec{B}_C$ force-guided trajectory with a gyroradius $r_L = \gamma m v_0 / e B_C$, where m is the charged particle mass and e is its charge. If $r_L \ll r_0$, the curvature of the problem may be neglected and the trajectory considered in a planar geometry, as shown in Figure (6-2). As the particle exits the region of $\vec{B}_C$ on the other side of the cusped field, it is easy to show that its velocity vector has the components

$$v_{\perp} = \frac{e r_0}{2 m \gamma} |\vec{B}_1 - \vec{B}_2| \quad (6.2)$$

$$v_z = (v_0^2 - \frac{r_0^2 e^2}{4 m^2 \gamma^2} |\vec{B}_1 - \vec{B}_2|^2)^{1/2} \quad (6.3)$$

From Equation (6.3), one sees that the particles having an initial velocity

FIGURE 6-2

Transverse view (looking radially outward at the cusp field-piece) of the charged particle trajectories under the influence of the cusped field.

FIGURE 6-2

$$v' \leq \frac{er_o}{2m\gamma} |\vec{B}_1 - \vec{B}_2| \quad (6.4)$$

will be reflected from the cusp region.

Further details of single-particle trajectories for varying relative values (and directions) of $\vec{B}_1$ and $\vec{B}_2$ have been described by Kusse.

The experimental arrangement used in this work provided oppositely-directed magnetic fields of the same strength, $|\vec{B}_0|$, on either side of the cusped region. In this case, the electron orbits beyond the cusp transition section are symmetric about the central axis. Hence, for $\vec{B}_2 = -\vec{B}_1 = \vec{B}_0$, Equations (6.2) and (6.3) simplify to

$$v_{\perp} = \frac{er_o B_0}{m\gamma} = \frac{v_o r_o}{r_L} \quad (6.5)$$

$$v_z = v_o \left(1 - \left(\frac{r_o}{r_L} \right)^2 \right)^{1/2} . \quad (6.6)$$

Thus, for a given v_o , a particle's azimuthal velocity, $v_{\perp}$, will depend linearly on its initial displacement (radius of injection), r_o , from the field's central axis.

When used in such high beam current applications as is the case with the experiments described here, it is usually the procedure (although not always¹⁵⁰) to fill the cusp region with either neutral gas or plasma to provide adequate space-charge neutralization of the electron beam as it transits the cusped-field region.

Experimental experience showed that the best geometry to use for the steel cusped-field shaping piece might not be a solid annulus of metal. Rather, with our electron beam currents, the self-magnetic fields of the beam can severely distort the cusp-shaped field and degrade its ability to generate a rotating beam.

Sketched in Figure (6-3) is a cutaway view of a hollow beam passing through the cusped-field section. As shown, the beam is presumed to begin its rotary motion as it enters the cusped-field. Also, drawn independently in Figure (6-3) are some representative magnetic field lines from both the cusp base fields and the self-field of the beam as it executes its rotational motion. As shown, since the magnetic penetration time of the cusp ring is much longer than the beam pulse, the diamagnetic field lines from the rotational beam can close back upon themselves at the point where the beam begins its rotary

FIGURE 6-3

Sketch of the magnetic fields present as an intense, hollow electron beam transits a cusped magnetic field.

FIGURE 6-3

motion only by passing between the outside of the beam and the inside of the cusp ring. These returning field lines are directed counter to the base field lines which enter the leading edges of the cusp ring. Thus, if the diamagnetic fields (labelled "B'" in the figure) are of comparable strength to $|\vec{B}_0|$, then the net magnetic field--the sum of these two sets of magnetic field lines--may show a significant distortion of the magnetic field at the leading edge of the cusp field-piece. This could adversely affect rotational transformations to be wrought upon that portion of the hollow electron beam yet to be injected through the cusp.

By flux conservation, if B'_0 is the axial diamagnetic field generated by the rotating beam of average radius r_0 and radial thickness Δr , then

$$B'_{\text{gap}} \cong \frac{\left\{r_0 - \frac{\Delta r}{2}\right\}^2}{r_c^2 - \left\{r_0 + \frac{\Delta r}{2}\right\}^2} B'_0, \quad (6.7)$$

where r_c is the inside radius of the cusp ring. Given the dimensions typical of our experiment ($r_0 \approx 2.8$ cm, $\Delta r \approx 1$ cm, $r_c \approx 5$ cm), then $B'_{\text{gap}} \sim 0.3 B'_0$. For a field-reversing situation, $B'_0 \sim B_0$. Hence, a more desirable arrangement might be to allow the beam self-field lines to close on themselves without seriously deteriorating

the cusped field. One way of doing this is to slot the cusp ring radially with lollipop-shaped cuts, making it similar in appearance to a magnetron field-piece. Such an arrangement is shown in Figure (6-4). In this way, the beam self-fields may return through the circular slotted gaps in the cusp, decreasing their perturbing effects on the cusp field in the region between the beam and the field piece labelled " B'_{gap} " in Figure (6-3). In the field-piece used in these experiments, the addition of the slots and holes increased the area available for closing beam flux lines by about a factor of two over that provided by a solid annulus.

No quantitative measurements were performed on beam transport characteristics of the slotted cusp. However, use of the slotted cusp led to far better electron ring trapping performance than was achieved with a solid, annular field piece, permitting a fairly wide range in B_0 (~ 500G - ~ 630G) over which rings could be trapped successfully.

6.3 Experimental Cusp-Injection Apparatus

The device in which the studies of the confinement of a cusp-injected electron beam were carried out is shown in Figure (6-5), and was constructed by Kribel, et al. For the purpose of the present set of

FIGURE 6-4

Section view of the slotted cusp field-piece.

COLD-ROLLED
STEEL

$r_c = 5.1\text{cm}$
 $D = 1.6\text{cm}$

FIGURE 6-4

FIGURE 6-5

Schematic diagram of the cusp-injection apparatus.

FIGURE 6-5

experiments, a number of modifications were made to the existing apparatus, including adaptation of the arcjet plasma source described in Section 5.2.1 for preionization of the trapping volume.

Basically, the device consists of a 15 cm OD cylindrical Lucite vacuum vessel around which a set of solenoidal windings has been wrapped. Near the injector end of the device, the solenoidal windings are separated from a set of counter-wound windings by the cusp field-piece. The magnetic mirror windings, as well as the field-grading windings, provide a smooth field transition from the downstream mirror to the arcjet field. The plasma source was located at the opposite end of the vacuum vessel. Various diagnostic magnetic pick-up probes were distributed around the interior of the device as shown in Figure (6-5).

For completeness, a detailed description of the apparatus is provided in the following sections.

6.3.1 Confinement Tank and Vacuum Systems

The vacuum vessel consists of a 125 cm long section of 15.2 cm OD x 6.4 mm wall Lucite tubing, interrupted at a point 14 cm from one end by the annular steel magnetic cusp core described earlier. A liner of 3.2 mm x 12.7 cm OD aluminum tubing was inserted down

the full length of the Lucite tube. At the downstream end of the tube were attached the graded-field section (for the arcjet), the pumping station, and, at the extreme end, the arcjet plasma source.

The vessel was evacuated by a mechanical roughing pump and 5 cm diffusion pump combination. With this arrangement, base pressures of the order of 5×10^{-5} Torr could be obtained.

The vacuum vessel rested on top of a wooden trestle which was, in turn, bolted to a steel cart. The cart ran on tracks which were parallel to the axis of QWIBLE's diode, thereby allowing easy removal of the experiment from the diode for diode maintenance, anode foil replacement, etc.

6.3.2 Magnetic Field Structures

Solenoidal field windings were wrapped using #16 A.W.G. stranded copper wire in a double layer along the length of the main confinement section, with a shorter, counter-wound solenoidal section having the same winding density located on the other side of the cusp structure. The turns density in both sections was 5.5/cm, resulting in a measured base solenoidal field of 7.0 G/A. The winding density was increased threefold for a distance of about 1 cm on either side of the cusp field-piece

to sharpen the cusp field.

The mirror windings consisted of annular plexiglas forms onto which were wound 20 turns (for the upstream mirror) and 45 and 80 turns (for the two downstream mirrors). These could be connected in series combinations as desired. The windings were mechanically secured tightly to the solenoidal field windings, and could be translated axially, should that be necessary.

The graded-field section has been described earlier (Section 5.3.1) and, as mentioned, fulfills the same purpose of matching the arcjet magnetic fields smoothly to the downstream mirror fields.

Again, as in RECE-Berta (Section 5.3.1), DC-magnetic field profiles were obtained using a Bell (Model 640) Gaussmeter (absolute accuracy = 0.5%). In this case, the Hall probe was attached to a mechanical drive which translated it axially down the center of the machine while a mechanically-linked potentiometer transmitted the probe's position to the abscissa of an X-Y plotter. The plotter ordinate was driven directly by the Gaussmeter.

A field profile typically used in the experimental trapping work is shown in Figure (6-6). With the exception of a 10% trough in the field between the gun field

FIGURE 6-6

Axial magnetic field profile in the cusp-injection apparatus.

FIGURE 6-6

and the 3 kG windings (leading to, at most, an insignificant "ballooning" of the plasma column diameter by about 5% in that small axial region), the field is seen to decrease smoothly to the minimum of the mirror well. Owing to the small strength of the upstream mirror ($1.1 B_0$), the well is quite shallow; increasing the upstream mirror renders the cusp non-symmetric and was found to decrease the trapped electron current dramatically.

As in the case of RECE-Berta, the coils were energized via the 294 μ fd, 40 kJ capacitor bank in series with the ballast windings described in Chapter 2. The magnetic field could be varied by adjusting either the voltage to which the bank was charged or the point in time after bank current initialization at which the electron beam was fired. The magnetic penetration times of the elements in the field volume were of the order of a few milliseconds. The cusp ring, with a saturation field of 4-7 kG, is penetrated by the magnetic field 5-10 ms into the bank current pulse.

6.3.3 Beam Injection Structure

The hollow, annular electron beam was formed via cold-cathode emission from a shaped cathode attached to the end of a special 3.8 cm brass extension piece

cantilevered from the rear plate of QWIBLE's diode. The annular cathode used in this experiment to generate the hollow electron beam has a significant radial thickness. In particular, the cathode was made from high-density graphite (Poco AXF-5Q) machined into an annulus, with a mean radius of 2.8 cm, a radial thickness of 1.3 cm, and a depth of 1.4 cm. This cathode was attached to an aluminum baseplate which then connected to the cathode stalk extension. The cathode assembly was centered axially to a tolerance of ± 2 mm in the counterwound solenoidal section.

The anode consisted of a 1.27×10^{-3} cm titanium foil stretched across the circular mouth of a brass insert section known as the "top hat". A liberal application of silicone vacuum grease around the opening of the top hat prior to stretching the anode foil across it insured independence of the diode and main tank vacuum systems. Typically, the anode/cathode separation was varied between 0.5 and 1.0 cm.

A number of different cathode materials and designs were tested for optimum hollow beam production. These included: annuli from smooth brass; epoxy-filled, grooved brass, and stainless steel razor-blade-edged annuli. The graphite, slightly roughed-up to enhance

field emission, proved to give the most uniform azimuthal symmetry to the hollow beams, as evidenced by the anode foil damage patterns. The cathode, and one of the damaged foils, are shown in Figure (6-7).

6.3.4 Plasma Source

The preionization source consisted of the arcjet plasma gun described in Section 5.2. As in the case of RECE-Berta, the gun was located beyond the downstream mirror and the plasma injected into the vessel axially. Also, as in Berta, a stainless steel mesh (optical density $\sim 50\%$) was positioned rigidly in the aluminum liner 20 cm in front of the gun to short out spoke-mode plasma currents.

6.3.5 Diagnostics

Owing to the small size of this device, measurement techniques were quite limited: for the purposes of this preliminary set of experiments, magnetic pickup probes and a side-on X-ray monitor were the principle diagnostics.

6.3.5.1 Magnetic Probes

The probes were identical in construction to those described in Chapter 3, except that the number of windings was doubled to 80 for greater signal-to-noise values.

FIGURE 6-7

The annular, carbon cathode used to create the hollow electron beam and one of the titanium anode foils; note the circular damage pattern on the anode foil.

— 1.27×10^{-3} cm Ti
ANODE FOIL

— ANNULAR CARBON
CATHODE

FIGURE 6-7

Using Tektronix "Type O" integration units at $RC = 100 \mu\text{sec}$, the probe calibrations were 1.7 G/mV .

Since both ends of the machine were devoted to either electron beam or plasma injection purposes, an acrobatic arrangement was necessary to insert and locate the axial magnetic probes so that they would interfere with neither the streaming plasma nor the rotating electron beam. To accomplish this, the probes were placed in 6.3 mm OD sections of Pyrex tubing bent at 90° and sealed closed at the ends. In lieu of the brass tubing used for Berta's probes, the double shielding for the coaxial cables carrying the signals away from the probes was provided by flexible copper braid which sheathed the RG-174 transmission cables. The glass tubes were then inserted radially into the machine at various azimuthal positions as shown in Figure (6-5). The probe locations could then be shifted by pushing/pulling the probe cables into/out of their glass tubes, hence moving the attached probes axially.

For most of the experimental work, the probes remained off-axis, the glass tubes being pressed against the inside of the aluminum liner. To obtain an off-axis/on-axis diamagnetic field calibration (in order to translate the off-axis probe signals into on-axis field-

reversal parlance), the top-most probe was lowered down to the machine axis (as shown in Figure (6-5)). The necessary data was then taken with electron rings confined in static backfills of hydrogen. Since the ring diameter will be a function of magnetic field, these measurements were repeated for rings trapped in gas in base magnetic field strengths between 510 and 630G.

For the physical situation at hand, conservation of magnetic flux leads to the first-order relationship

$$\frac{r_o}{r_w} = (1 + K)^{-1/2} \quad (6.8)$$

where K is the ratio of on-axis/off-axis probe signals, r_o is the ring radius, and r_w is the radius of the cylindrical conducting liner. Woodall¹⁵¹ has performed a more exact calculation of r_o/r_w , including the axial length of the rings as well as the effects of image wall currents. In the parameter range of interest, these effects amount to corrections of $\leq 10\%$ to Equation (6.8).

Experimentally, the cantilevered axial probe proved to be too much of a perturbation to the rings: a very slight misalignment easily destroyed the layers. Hence, it was necessary to place this probe off-axis

for all but the off-axis/on-axis magnetic field calibrations.

6.3.5.2 X-ray Monitor

A side-on X-ray detector was located 117 cm away from the axis of the device and was collimated to view a 15 cm axial stretch of the confinement region at the bottom of the well. Its primary function was to corroborate the presence of high-energy electrons in the device. A lamination of tin (1.9 g/cm^2) and lead (2.52 g/cm^2) absorbers placed in front of the collimator effectively discriminated against X-rays below $\sim 200 \text{ keV}$.

6.4 Puffed-Neutral Gas Confinement of Electron Rings

As mentioned above, the lifetimes of the field-reversed electron rings confined in the experiments of Kribel, et al., appeared to be limited to $9.5 \text{ } \mu\text{sec}$ by the rather high background pressures of hydrogen. Also, preliminary experimental work indicated that the trapping of electron rings in the cusp might have been augmented by the presence of an axial gradient in the backfill neutral gas density, i.e., by injecting the rotating electron beam into a cloud of gas which had been "puffed" into the vacuum vessel. It was natural, therefore, to consider experiments in which the

background gas pressure at the bottom of the mirror well was varied from ~ 10 - ~ 1000 mTorr H_2 in order to study the effects of lower gas pressures and density gradients on the strength and longevity of the electron rings. Hence, for this set of experiments, the arcjet valve was used to puff gas into the vacuum vessel, with the electron beam subsequently injected at different points in time into the transient gas backfill. The timing sequence used in this set of experiments is virtually identical to that sketched in Figure (5-14) of Chapter 5.

6.4.1 Transient Gas Density Measurements

Experimental measurements were made of the spatial and temporal behaviour of the transient neutral gas density as the puff of hydrogen is injected into the vessel. At room temperature, the thermal speed of hydrogen is about 1600 m/sec. Thus, since the length of the device is about 1.3 m, a single transit time for an average thermal hydrogen molecule will be around 1 ms. If densities are to be measured at axial intervals of 10 cm down the containment volume, response times of 50 - 100 μ sec would therefore be required of the diagnostic.

The method used to make the axial gas pulse

density profiles was to employ a planar-geometry ionization gauge tube (Westinghouse WL7676) which had been removed from its glass envelope.¹⁵² Because of the tube's thin, planar design, obstruction to the gas flow through the vanes of the tube was minimized, and errors arising from gas stagnation against the tube's structural framework were minimized. The set-up and experimental details of the transient gas-pulse measurement are described in Appendix VI.

The neutral gas densities were measured as a function of both axial position in the vessel and time interval, τ , following the electrical current pulse to the arcjet valve (arcjet plenum pressure = 2#, Gauge). The results are shown in Figure (6-8), each point on the plot representing the average of at least five independent pulsed-gas measurements. The overall RMS fluctuations in the measurement are indicated as error bars in the figure, and were consistently about 12%.

Three milliseconds following the valve current pulse, the gas puff is seen to be en route on its first transit of the machine. At subsequent times, the gas fill is fairly uniform along the axis of the machine. The region of interest for these experiments terminated

FIGURE 6-8

Transient neutral density profiles for hydrogen
puffed into the cusp-injection apparatus.

FIGURE 6-8

6.5 ms after the valve firing, since the vessel pressure was, at that time, about 350-400 mTorr, and the electron ring lifetimes obtained at those pressures were only about a factor of two longer than those achieved in the high-pressure gas work of Kribel, et al.

6.4.2 Experimental Results

Attempts to trap rings in constant, steady-state backfills of low pressure (≤ 100 mTorr) neutral gas were not successful during these experimental runs. However, within the range of gas pressures studied, it was possible to confine electron rings of initial field-reversal strengths of 95% and lifetimes as long as 80 μ sec by injection into transient "puffed" gas backfills at time delays of 3.0 - 6.5 ms after firing the gas pulse-valve. Evidence of such a long-lived ring confined in 80 mTorr H_2 is shown in Figure (6-9). For this data, the electron beam was injected 4.0 ms after the valve firing time and, at this time in the gas puff, a density difference of about 15% (cf. Figure (6-8)) exists over the length of the trapping region. The first two traces in Figure (6-9) are the diode voltage and current, respectively, with 10 shots overlayed on the photographs. The diode shot-to-shot characteristics were, as can be seen, quite reproducible. The third trace is the base magnetic

FIGURE 6-9

Characteristic diode, pulsed-field current, diamagnetic probe, and X-ray monitor signals for an electron ring confined in 80 mTorr hydrogen in the cusp-injection device.

FIGURE 6-9

field, with the timing fiducials shown together in the fourth and fifth traces. The next three oscillographs show the diamagnetic probe signals (the probes were separated 5 cm apart, axially). The bottom trace shows the output from the X-ray detector. As may be seen in the figure, the "dump" of the magnetic probe signals is accompanied by a burst of high-energy X-rays. This sudden loss of signal on the magnetic probes is consistent with the precessional instability which was observed in the Livermore Astron as well as in RECE-Berta.¹⁵³ No experimental work has been done thus far to verify this supposition, however.

Given the limitations of the off-axis probe array installed in the machine, it was, nevertheless, possible to make rough axial profiles of the rings as a function of time, T , after injection of the relativistic electron beam. Such a profile is shown in Figure (6-10) for the data of Figure (6-9), i.e., trapping in 80 mTorr hydrogen. From Figure (6-10), one may infer ring FWHM's of ~ 12 cm, which, when corrected to on-axis FWHM's,¹⁵⁴ gives an axial FWHM ~ 9 cm. Thus, these rings appear to be noticeably longer in axial dimension relative to their diameter (~ 6 cm) than the rings observed in RECE-Berta (by a factor of 1.5 - 2 viz. Berta's rings had FWHM's

FIGURE 6-10

Axial diamagnetic field profile of an electron ring confined in 80 mTorr hydrogen in the cusp-injection device.

FIGURE 6-10

of ~ 20 cm with ring diameters of ~ 18 - 20 cm). As time proceeds, the rings are seen to decay smoothly, constantly maintaining their initial profile.

It was of interest to see how the decay rates of the electron rings confined in this cusp-injected device scaled with varying background neutral gas pressure, and how these decay rates compared with similar measurements made on RECE-Berta. To this end, a number of rings were confined in background gas fills from 80 to 350 mTorr H₂ and their linear decay rates measured. The result of this sequence of data is shown in Figure (6-11). The decay rate of the rings is seen to be a fairly linear function of background pressure, the constant of proportionality being about 0.095 G/μsec-mTorr. The error in each of the data points is about 20% in both ordinate and abscissa.

To scale these results to the experimental conditions of rings confined in RECE-Berta, one may utilize the ring electron diffusion theory of Humphries.¹⁵⁵ Presuming the relative cusp-injected electron ring/liner wall geometries to be similar to those in RECE-Berta, we may make use of the general results of Phelps¹⁵⁶ that

$$\frac{\delta B_z}{\delta t} \propto B_0 \frac{r_0}{\Delta z}, \quad (6.9)$$

FIGURE 6-11

Electron ring axial diamagnetic field decay rate as
a function of backfill pressure (hydrogen).

FIGURE 6-11

where, as before, r_0 is the gyro-radius of single electrons in the magnetic field, and Δz is the axial ring dimension serving as a diffusion boundary. However, in the case of rings confined in this device--as in the case for rings confined in Berta--the primary constraint which is most important as a diffusion boundary is not the axial length of the rings but the radial thickness. That is, for doughnut-shaped rings, radial losses to the walls are probably a more important loss mechanism than end-effects.

Presuming that $r_0/\Delta z \sim r_0/\Delta r \sim \text{constant}$, and is about the same for rings confined in both devices, the fact that the magnetic field in the cusp-injected device ($B_0 \sim 630\text{G}$) is about a factor of 3 higher than the base field in Berta ($B_0 \sim 190\text{G}$) implies--from Equation (6.9)--that the ring decay rates in Berta should be about 3.5 times slower than the decay rates observed in the cusp-injected device for a given neutral gas backfill pressure. Measurements on Berta¹⁵⁷ indicated ring strength decay rate constants of $\sim 0.11 \text{ G}/\mu\text{sec-mTorr}$ in the absence of any magnetic field gradients. This is about a factor of 9 times slower than the cusp-injected ring decay constant of proportionality. Thus, within a factor of 2.5, the decay rates of the cusp-injected

rings are seen to be consistent with the decay rates of rings confined in RECE-Berta, according to the theory of Humphries. The discrepancy can probably be attributed to anomalous ring particle losses in the cusp device--such as scraping of the ring against the liner walls due to a slight radial offset of the ring's equilibrium position, for example.

6.5 Confinement of Cusp-Injected Beams in a Preionized Medium

Given the success of having extended the lifetimes of field-reversing, cusp-injected electron rings by almost a factor of 10 over the previous results using puffed-gas trapping, the motivation followed naturally to find out how cusped-beam injection into a background plasma would work. This section describes both the results of these first measurements as well as some qualifying discussion about hardware constraints which limited the unambiguous interpretation of these results.

6.5.1 Plasma Density Measurements

Plasma density measurements in this experiment were made using a 2 mm microwave interferometer in the Mach-Zehnder mode of operation.¹⁵⁸ The setup was identical to that described in Section 3.2.1.1, with the

transmitting and receiving horns located on opposite sides of the vacuum vessel at the bottom of the mirror well. In this way, it was possible to measure the plasma line density across the diameter of the device at this axial location. Unfortunately, it was not possible to make the plasma density measurements during the actual operation of the experiment: to do so would have required opening two 3.5 cm diameter holes in the aluminum liner to admit the microwaves. Holes of this size would have drastically perturbed the induced liner currents which serve to center the ring radially (these hole diameters being about half the ring diameter), and would probably have prohibited confinement of rings for the periods of time of interest here.

A discussion of the details of the plasma density measurement may be found in Appendix I. Suffice it to say here that the plasma density was typically observed to rise smoothly to densities close to microwave cutoff ($n_p \approx 2.4 \times 10^{14} \text{ cm}^{-3}$) in about 350 μsec , followed by a slower, afterglow decay. These density characteristics were found to be quite insensitive to the details of arcjet operation and magnetic field strengths in the parameter range studied.

6.5.2 Experiments and Results

The experimental technique used in studying ring confinement in a plasma in this set-up was quite similar to that followed in the plasma-trapping studies in RECE-Berta. The electron beam was always injected into the same magnetic field, with the relative firing time of the arcjet plasma being altered to bring about variations in plasma density. Initially, the electron beam was fired "early" (200 μ sec after the onset of arcjet current into the discharge, with subsequent shots fired at successively later times.

The phenomenology of the results was as follows: injection of the electron beam at times less than ~ 300 μ sec into the plasma discharge gave no indication that fast electrons were being injected into the confinement volume of the device. Beam injection at times greater than ~ 300 μ sec into the discharge did lead to long-lived, confined electron rings. As shown in Figure (6-12), electron rings of up to 70% field-reversal and lifetimes of 140 μ sec were obtained by injecting the electron beam 350 μ sec into the plasma discharge. (The slanted baseline on the upper trace resulted from noise pickup on the Type O operational amplifier.) According to the plasma density measurements, this point in

FIGURE 6-12

Axial diamagnetic field signals from plasma-trapped
electron ring confined in the cusp-injection device.

$B_{z0} = 530 \text{ G}$

$\zeta = 0.7$

370
 δB_z
0

FIGURE 6-12

time in the arcjet discharge corresponds to a plasma density of $5-10 \times 10^{13} \text{ cm}^{-3}$.

A characteristic axial diamagnetic profile of a plasma-trapped electron ring parameterized to time, T , following beam injection, is shown in Figure (6-13). The layer is seen to have an off-axis FWHM of about 12 cm, correspondent with its gas-trapped counterpart.

Parenthetically, note is made of the low "dump" level of the rings trapped in the plasma compared to those trapped in gas. This may be an inadvertent "fringe benefit" of using a plasma source such as the arcjet: as described in Chapter 5, small azimuthal magnetic fields from the plasma currents were measured within the plasma injected into Berta. Undoubtedly, similar currents flow in the cusp vessel--possibly of even greater density owing to the constricted size of the aluminum liner. It is therefore possible that these currents generate a toroidal magnetic field of adequate strength to stabilize, in part, the precessional "dump" of the rings. For instance, the gas-trapped rings were observed to dump at $\zeta \sim 20-25\%$, in contrast to the plasma-trapped rings, where the dump levels dropped to $\zeta \sim 2-3\%$. (A toroidal stabilizing field of about 2% of B_0 , 10-15 G, would require an axial current of 150-200 A, which is not unreasonable for axially-flowing currents beyond the stainless mesh in the cusp tank since

FIGURE 6-13

Axial diamagnetic field profile of an electron ring
confined in a plasma density $n_p \sim 10^{14} \text{ cm}^{-3}$ in the
cusp-injection device.

FIGURE 6-13

the arcjet normally deliver currents of the order of 4 kA into the discharge.) Unfortunately, time limitations did not permit measurements on the strength of this field.

A note of caution is in order, however, in interpreting these results. It was also found, experimentally, that the injection of the beam into a puffed-gas backfill at a time which would have corresponded to beam injection 500 μ sec into the arcjet discharge (had it been fired) also leads to confined electron rings (although with lifetimes no longer than 70-80 μ sec). Hence, one of the difficulties of a small device: are the observed effects truly the result of a beam/plasma interaction, or are we just looking at a weakly-ionized backfill of pulsed hydrogen? Also, owing to the confined geometry of the apparatus, neutrals could conceivably be blown off the inside walls of the aluminum liner by the energetic plasma, thereby contributing to anomalously high neutral backgrounds on the axis of the machine. (Due to the much larger tank volume, this ambiguity was never an issue in RECE-Berta.)

6.6. Discussion and Summary

Five rather interesting results emerged from this

brief study of cusp-injecting electron beams into a mirror device:

(1) It was shown that the ring lifetimes could be enhanced over previous results by a factor of 10 by beam injection into neutral hydrogen gas background pressures of ~ 80 mTorr.

(2) A parameter scan of the decay rates of these rings at different steady-state background neutral densities showed that the ring behaviour scaled with the decay rates of rings confined in RECE-Berta. That is, there appeared to be no inherent difference between the decay mechanisms of these 50-80 μ sec gas-trapped layers and those of the 15-20 μ sec gas-trapped layers confined in Berta, despite the differences in geometry (the cusp-injected layers were about 50% longer, axially) and injection techniques.

(3) It was found to be possible to trap and confine electron rings in background plasma densities of the order of 10^{14} cm^{-3} , although the neutral content of that plasma is not known. These rings were observed to "live" for time periods of up to 140 μ sec, with initial field-reversal parameters of up to 70%.

(4) It was found that the trapping efficiency of the cusp-injected beams in the mirror well was not higher than the traditional "tangential injection" technique,

3

such as was used on Berta and the Livermore Astron. For example, considering (to first order) a field-reversing electron layer in the cusp-injected device having a FWHM ≈ 10 cm and $\Delta r \approx 2$ cm, we have, using Equation (3.22), a circulating current of about 5 kA. With a gyroperiod of 0.7 ns, we can therefore estimate the total confined charge at about 4×10^{-6} Coulombs (Berta typically confines about 6×10^{-6} Coulombs, about the same amount of charge). With a peak injected current of 17 kA in a triangular current pulse lasting 120 ns, this represents a trapping efficiency of about 0.3 - 0.5%. Typically, the trapping efficiency in Berta (with a similarly-shaped current pulse, but peak current ~ 8 kA) ranged between 1-2%. Based on these measurements, a symmetric injection scheme does not as yet represent a noticeable improvement in the total quantity of charge trapped and confined as a ring in the mirror well. That is, it appears that some other mechanism--such as large values of $v_{||}/v_{\perp}$ for a significant fraction of the injected electrons, for example--seems to be limiting the field-reversal strength of the confined electron rings.

(5) The entire set of experiments demonstrated the substantial stability of these electron rings. With a gyro-radius of about 3 cm, the gyroperiod of

400 keV electrons in the ring, as mentioned above, is about 0.7 ns. Hence, a ring lifetime of 140 μ sec indicates approximately 2×10^5 single-particle orbits. Thus, the rings show good stability properties, their decay modes being reasonably predicted by purely classical arguments.

Further work on a scaled-up version of this preliminary apparatus should be undertaken. It is imperative that studies of the plasma trapping mechanism, for example, be studied in greater detail than was possible here. A cantilevered axial probe array, for example, could discern whether, as inferred in Chapter 5, a beam/plasma interaction of the Chu-Rostoker genre could be put to beneficial use in effective beam trapping in a background plasma. It has been the limited scope of interest of this first work to demonstrate that such an injection scheme can lead to the confinement of electron rings that are of practical use and interest.

APPENDICES

APPENDIX I

PLASMA DENSITY MEASUREMENTS VIA MICROWAVE INTERFEROMETRY

I.1 Partial Fringe-Shift Data Analysis

As discussed in Chapter 3, the plasma densities produced on beam injection into the background gasfills in Berta were not sufficient to advance the phase shift of the microwave signal passing through the plasma arm of the interferometer through 2π ("one fringe"). It was therefore necessary to infer plasma densities from partial fringe-shift measurements on the oscilloscope traces.

Presume that a square-law detector monitors the superposition of two sinusoidally-varying signals of equal frequency, ω_0 , but shifted in phase by an angle ϕ :

$$S_1 = A_1 e^{i\omega_0 t}$$

$$S_2 = A_2 e^{i(\omega_0 t + \phi)} \quad (\text{I.1.1})$$

The time-averaged signal output from the square-law detector is then

$$A_O^S = \frac{1}{2} (S_1 + S_2) (S_1 + S_2)^* = \frac{1}{2} (A_1^2 + A_2^2 + 2A_1 A_2 \cos \phi) \quad (\text{I.1.2})$$

where the asterisk (*) denotes a complex conjugate. If the signal amplitudes have been initially adjusted to be equal, then, for $A_1 = A_2 = A_O$,

$$A_O^S = A_O (1 + \cos \phi) \quad (\text{I.1.3})$$

Consider a sample partial fringe-shift trace as illustrated in Figure (I-1). If the phase shift has been adjusted initially to some angle $0 < \phi_O < \pi$, as shown in Figure (I-1), then the baseline displacement, y_1 , is, from Equation (I.3),

$$y_1 = \frac{y_f}{2} (1 + \cos \phi_O) . \quad (\text{I.1.4})$$

Subsequent phase shifts in time, $\phi(t)$, lead to time-dependent variations from y_1 given as

$$y_2(t) = \frac{y_f}{2} (1 + \cos[\phi_O + \phi(t)]) \quad (\text{I.1.5})$$

One may solve for $\phi(t)$ by combining Equations (I.4) and (I.5) to obtain

FIGURE I-1

Main features of typical partial-fringe shift data.

FIGURE I-1

$$\phi(t) = \cos^{-1} \left(\frac{2y_2(t)}{y_f} - 1 \right) - \cos^{-1} \left(\frac{2y_1}{y_f} - 1 \right) \quad (\text{I.1.6})$$

Since the fringe shifts to be measured are small (less than 2π), we may use Equation (3.3) for the line-integrated plasma density and Equation (I.8) to give

$$(\omega_0/2\pi = 140 \text{ GHz})$$

$$\bar{n}D = \int_0^D n(x) dx = (1.67 \times 10^{13})$$

$$x \left\{ \cos^{-1} \left(\frac{2y_2(t)}{y_f} - 1 \right) - \cos^{-1} \left(\frac{2y_1}{y_f} - 1 \right) \right\} \quad (\text{I.1.7})$$

where $\bar{n}$ is the average plasma density, D is the width of the plasma slab, and the arguments of the arc-cosines are expressed in radian measure.

I.2 Plasma Density Measurements in the Cusp-Injected Device.

Density measurements of the plasma injected into the cusp device were performed using a 140 GHz microwave

interferometer in the Mach-Zehnder mode of operation. A 5.1 cm wide Lucite annulus, 20 cm OD, 14 cm ID, into which two 2.5 cm opposing lateral ports had been bored, was located directly in the center of the axial magnetic field well. Two 25 db horns were then inserted into the ports, aimed at one another across the inside diameter of the machine. The microwave circuitry was otherwise identical to that sketched in Figure (3-2). A photograph and sketch of the setup is shown in Figure (I-2).

As expected, the arcjet plasma produced within the rather confined device was found to be quite dense. A right-angle Langmuir Probe inserted down the axis of the machine was used in the same fashion as described in Section 5.2.5.1 to make radial profiles of the plasma. Such a profile is shown in Figure (I-3). As may be seen from the figure, the plasma density profile was fairly uniform across the inside the diameter of the machine. Hence, the plasma density, $n(x,t)$, was assumed to be independent of position: $n(x,t) = n_0(t)$ inside the plasma column (about 8 cm in width), and $n(x,t) = 0$ elsewhere.

The plasma density as a function of time as derived from these measurements is plotted in Figure (I-4), along with a set of sample interference traces.

FIGURE I-2

- (Top) Configuration of interferometer in performing density measurements on the cusp-injection device;
- (Bottom) Photograph of the general interferometer layout on the cusp device (the railroad train is shown for scale).

EXPERIMENTAL SETUP

FIGURE I-2

FIGURE I-3

Radial plasma density profile of the plasma column
injected into the cusp tank.

FIGURE I-3

FIGURE I-4

Plasma density in the cusp tank as a function of time
(based on the radial density profile of Figure (I-3)).

FIGURE I-4

As shown in the plot, the density rises rapidly to about $1 \times 10^{14} \text{ cm}^{-3}$ in approximately 325 μsec , holds that density for about 100 μsec , and then decays as the arc-jet current begins to decrease. This behaviour was found to be independent of the magnetic field strength over the range of fields tested, i.e., $435 \text{ G} < B_z < 630 \text{ G}$.

APPENDIX II

PHOTON MASS-ATTENUATION COEFFICIENTS

FOR NaI, Sn, Pb, AND Cu

For reference, the photon mass-attenuation coefficients for NaI, Sn, Pb, and Cu are plotted as functions of photon energy in Figures (II-1) - (II-4).

FIGURE II-1

Photon Mass Attenuation Coefficient for NaI (after
Reference 87).

FIGURE II-1

FIGURE II-2

Photon Mass Attenuation Coefficient for Sn (after
Reference 67).

FIGURE II-2

FIGURE II-3,

Photon Mass Attenuation Coefficient for Pb (after
Reference 159).

FIGURE II-3

- FIGURE II-4

Photon Mass Attenuation Coefficient for Cu (after
Reference 67).

FIGURE II-4

APPENDIX III

MONTE CARLO CODE CALCULATIONS

III.1 Summary of Transport Code Interactions

This section outlines the interactions followed by the photon and electron transport codes and presents the references and energy ranges of validity (where applicable) for the cross-sections used. A complete reference to this information may be found in the work of Thompson.¹⁶⁰

I. Electron Interactions

A. Elastic electron-nuclear scattering:

the screened Coulomb scattering cross-section, taking into account relativistic and spin effects; as obtained by Spencer for all energy ranges and low- and high-Z nuclei. (L. V. Spencer, NBS Monograph 1, National Bureau of Standards (1959)).

B. Inelastic electron-electron scattering:

the inelastic interaction of high energy electrons with atomic electrons is treated for all energy ranges. The general

cross-section used to describe this ionization process is that derived by Møller. (C. Møller, Ann. Physik, 14, 531 (1932)).

1. Density effects: alteration of electron energy loss from ionization owing to the decrease in electric field from the incident particle because of the material's dielectric properties. (R. M. Sternheimer, Phys. Rev. 145, 247 (1966)).
2. Delta rays: enough energy is transferred to an orbital electron to knock it out of its shell. May lead to creation of a new energetic electron. (R. B. Leighton, Principles of Modern Physics, McGraw-Hill Book Company, Inc., 501 (1959)).
3. Characteristic X-rays: Radiation emitted from the rearrangement of orbital electrons following the ejection of a single shell electron because of an inelastic electron-electron collision. (H. Kolbenstvedt, J. App. Phys. 38, 4785 (1967)).

- C. Bremsstrahlung: electromagnetic radiation produced as a charged particle is accelerated. The total radiated intensity is proportional to $z^2 e^6 / m^2$ when the trajectory of the charged particle of mass, m , and charge, e , is deflected by a scattering center of charge Ze . Owing to the z^2 / m^2 dependence, Bremsstrahlung is primarily an electron-nuclear interaction. The validity of the various analytic forms for the Bremsstrahlung cross-sections are dually-dependent upon the energy of the incident electron as well as on the energy of the resultant photon. The analytic forms used in the codes are those listed in the review article of Motz, where the ranges of validity are also tabulated. (H. W. Koch and J. W. Motz, Rev. of Mod. Phys. 31, 920 (1959)).
- D. Annihilation Radiation: radiation emitted following the annihilation of a positron with an electron. The radiation is in the form of two 0.511 MeV X-rays emitted 180°

relative to one another. (P. A. M. Dirac, Proc. Camb. Phil. Soc., 26, 361 (1930)).

- E. Elastic electron-electron scattering: a process of importance at incident electron energies less than 100 eV, and which is therefore neglected from consideration here.

II. Photon Interactions

- A. Compton Scattering: the scattering of photons on atomic electrons (bound or free). (O. Klein, Y. Nishina, Z. Physik, 52, 853 (1929)).
- B. Photoelectric Effect: the absorption of an X-ray photon resulting in the ejection of a shell electron (usually K- or L-shell) possessing the photon's initial energy minus the electron's binding energy. Photon energies have been subdivided into three energy ranges and cross-sections appropriate to each have been used:

- (1) $E_0 < 0.35 \text{ MeV}$ (J. Fischer, Ann. Physik 8, 358 (1936))

(ii) $0.35 < E_0 < 2.0$ (H. R. Hulme, et al., Proc. Roy. Soc. London, A149, 131 (1935))

(iii) $E_0 > 2.0$ (H. Hall, Revs. Mod. Phy., 8, 358 (1936))

C. Pair Production: photons possessing energies greater than $2m_0c^2$ (m_0 = electron rest mass) interact with the Coulomb field of a nucleus and disappear, resulting in the production of an electron-positron pair. That part of the photon's energy in excess of $2m_0c^2$ is imparted to the electron/positron pair as kinetic energy. (H. A. Bethe, W. Heitler, Proc. Roy. Soc. London, A146, 83 (1934)).

D. Fluorescence and Auger Electrons: an X-ray or electron resulting from the rearrangement of shell electrons following the photoelectric ejection of (usually) a K- or L-shell electron. Fluorescence and Auger electrons are competing processes, the probability for which process is most

likely to occur being dependent on the Z of the atom involved. An Auger electron is ejected from an outer shell, absorbing the excitation energy (less the outer shell binding energy) that otherwise would have gone into a fluorescence X-ray.

(L. Bergström, C. Nordling, in "Alpha-, Beta-, and Gamma-Ray Spectroscopy", K. Siegbahn, ed. North-Holland Publishing Co., Amsterdam, 1523ff (1965)).

III.2 Operational Use of Transport Codes

This section describes the manner in which the various radiation absorbers, collimators, and detectors were operationally loaded into the computer code to account for the actual geometry used in the experiment.

An illustration of the overall setup used in the codes appears in Figure (III-1), with a diagram of the details of the cell and surface divisions entered into the code illustrated in Figure (III-2).

The use of a uniform, parallel X-ray illuminating source, instead of an extended line source (as would best approximate the actual wire radiator) is justified in light of the small Compton effect (less than 1%) observed in the absorbers (see Appendix III.6) i.e., source geometry was

FIGURE III-1

Absorber and Collimation geometry used for calculation of NaI(Tl) crystal detector efficiency and absorber transmission coefficients.

GEOMETRY USED FOR CALCULATION OF DETECTOR EFFICIENCY AND ABSORBER TRANSMISSION

[†]APERTURE = $(1.27 \text{ cm})^2$

FIGURE III-1

FIGURE III-2

Schematic illustration of the details of the materials and surface designations used in the absorber transmission coefficient calculations.

6 DENOTES CELL N°
 ⑥ DENOTES SURFACE N°
 CYLINDRICAL SYMMETRY ABOUT Y-AXIS

FIGURE III-2

found to play an insignificant role in the computations.

To compute the absorber transmission coefficients, a cylindrical collimator was used (for simplicity) with an area normalized to the 1.27 cm x 1.27 cm square collimation port used in the experiment. The transmission coefficient was then the ratio of the total energy passing across Surface #9 divided by the energy passing across Surface #1. The influence of Compton scattering could be monitored through an inspection of the energy spectrum passing across Surface #9.

To compute the detector efficiencies, the geometry of Figure (III-3) was used. That is, the front surface of the crystal, Material #1 and Surface #1, is assumed to have been illuminated by the source over a square quadrant centered on the crystal axis and 1.27 cm on a side. For this calculation, the square geometry of the area illuminated by the source was kept i.e., it was not approximated by a circle of equal area.

The crystal detector efficiency was taken as the percentage of the total photon energy passing across Surface #2 which is deposited in Cell #2. In both sets of computations described above, the source was taken as being monoenergetic, with the source energy being varied for each computer run from 0.1 - 1.0 MeV in 50 keV steps.

FIGURE III-3

Schematic illustration of the details of the materials and surface designations used in the detector efficiency calculations.

6 DENOTES CELL N°
⑥ DENOTES SURFACE N°
CYLINDRICAL SYMMETRY ABOUT Y-AXIS

FIGURE III-3

The descriptions of the material composition and configuration used in the transport code calculations of absorber transmission coefficients, Figure (III-2), and detector efficiency, Figure (III-3), are presented in Tables III-1 and III-2, and the accompanying, explanatory notes appended to the tables.

III.3 The Wire Target Geometry

Two independent techniques were utilized to take into account the wire geometry of the tungsten target. The first, most direct, and most expensive approach was to incorporate cylindrical boundary conditions (replicating the wire in cross-section) in the electron and photon transport codes themselves. The second procedure was to take advantage of the simplicity of working with slab targets in the code and to approximate the wire geometry using a combination of "weighted slabs". For two examples (300 and 700 keV), both techniques produced results which were identical to one another within the statistics of the code accuracy. Hence, owing to economic considerations, the second alternative was used exclusively in generating the Bremsstrahlung production spectra.

The "weighted slab" approach is illustrated in Figure (III-4). Basically, the idea is to treat the wire's 0.00254 cm diameter circular cross-section as a

TABLE III-1

ABSORBER+COLLIMATOR TRANSMISSION COEFFICIENTS.

1	1	.0330046	1,11	-2,2	-11,12	
2	1	.0330046	2,1	-3,3	-11,12	
3	1	.0330046	3,2	-4,4	-11,12	
4	2	.0371065	4,3	-5,5	-11,12	<u>CELLS</u>
5	3	.0847690	5,4,12	-6,6	-12,14	
6	0		6,5	-7,7,8	-12,14	
7	0		7,6	-8,9	-14,8	
8	1	.0330046	7,6	-8,9	14,7	-12,14
9	0		8,7,8	-9,10,13		-12,14
10	4	.0294944	9,9	-10,15	-13,13	
11	0		-1,1,12,14			
12	0		1,11	-5,5	-12,14	11,1,2,3,4
13	0		9,9	-10,15	-12,14	13,10
14	0		1,11	-10,15	12,5,6,8,9,12,13	
15	0		10,10,13,14			
1	PY	43.99153				
2	PY	44.21251				
3	PY	44.44111				
4	PY	44.66209				
5	PY	44.92625				
6	PY	45.085				
7	PY	45.72				<u>SURFACES</u>
8	PY	60.96				
9	PY	61.595				
10	PY	66.675				
11	CY	2.2225				
12	CY	5.0				
13	CY	2.2225				
14	CY	0.716520771				

TABLE III-1 (Continued)

[illegible]

TABLE III-2

NaI Crystal Detection Efficiency Arrangement.

1	1	.06026758	1,5	-2,2	-5,4	
2	2	.02949440	2,1	-3,3	-5,4	<u>CELLS</u>
3	3	.07821264	3,2,4,6	-4,8	-7,7	
4	1	.06026758	1,5	-3,3	5,1,2	-6,6
5	0		-1,1,4,6,7			
6	0		1,5	-3,3	6,4	-7,7
7	0		1,5	-4,8	7,3,6	
8	0		4,3,7			

1	PY	0.0
2	PY	0.0381
3	PY	5.1181
4	PY	5.3562
5	CY	2.2225
6	CY	2.2606
7	CY	2.58

SURFACES

M1	13000.	1.						
M2	11000.	.5	53000.	.5				
M3	8000.	2.	14000.	1.				
I0	1	1	1	1	0	1	0	0
Q	2							

MATERIALS

FOOTNOTES TO TABLES III-1 AND III-2[†]

Cell Data

Column 1 = cell number
Column 2 = material type in cell
Column 3 = atom density of material ($\times 10^{-24} \text{ cm}^{-3}$)
Column 4 = Surface enclosing cell, coupled with cell
number on other side of surface. The plus/minus
sign indicates the cell "sense" to the surface
for increasing coordinates.

Surface Data

Column 1 = surface number
Column 2 = surface type: PY = plane perpendicular to Y
CY = cylinder coaxial with
Y-axis
Column 3 = location along Y-axis (or radius of cylinder)
in cm.

Material Data

Column 1 = material number
Column 2 = atomic number of element $\times 10^3$
Column 3 = atom fraction of element in the given material

[†] (Courtesy of Dr. Clarke E. Swannack, LASL).

FIGURE III-4

The "weighted-slab" approximation to the cylindrical geometry of the wire target.

FIGURE III-4

lamination of ten semi-infinite slabs, each 2.54×10^{-4} cm in thickness. The code first computes the Bremsstrahlung spectra from a series of slab targets of thicknesses ranging from 2.54×10^{-4} cm to 2.54×10^{-3} cm, in 2.54×10^{-4} cm increments. If a circle 2.54×10^{-3} cm in diameter is then superposed onto the laminations, one may easily calculate an effective transverse (relative to the direction of the impinging electrons) width of each slab thickness as it is circumscribed by the circle. This is illustrated in Figure (III-4). These widths are denoted " F_1 ", " F_5 ", etc., in the figure, with the subscript equal to the thickness of the particular slab in question, in mils.

Normalized to the wire radius, r , these laminar widths then serve as weighting factors [termed " W_n " in Figure (III-4)] which describe each particular slab's effective contribution to the wire geometry. For example, the semi-infinite slab of thickness 1.27×10^{-3} cm has only a 5.0% contribution to the wire geometry because, with the laminar subdivision of the circular cross-section of the wire as shown in Figure (III-4), this particular slab would only contribute a lateral width of 5.0% of the circular diameter to the wire's circular shape.

Therefore, the total Bremsstrahlung spectrum for the "wire" is then the sum of the incremental Bremsstrahlung

spectra from each slab, times its particular weighting factor.

Figure (III-5a) illustrates a direct comparison between the 2π -integrated Bremsstrahlung spectra for a 2.54×10^{-3} cm tungsten slab and a 2.54×10^{-3} cm diameter tungsten wire (weighted slab technique). Figure (III-5b) illustrates a direct comparison between the 2π -integrated spectra for a 2.54×10^{-3} cm diameter tungsten wire (weighted slab technique) and a wire target of the same diameter using the actual circular wire cross-section in the code.

III.4 Code Output for Absorber Transmission Coefficients, NaI(Tl) and Pilot B Detector Efficiencies, and Detector Signal Ratios as Functions of Electron Energy.

For reference, the digital data obtained from the code calculations for the absorber transmission coefficients, and NaI(Tl) and Pilot B detector efficiencies are shown in Tables III-3, III-4, and III-5, in energy increments of 12.5 keV from 100 keV to 1000 keV. The data lists for the detector signal ratios as functions of electron energy for both types of detectors are shown in Table III-6 and III-7.

FIGURE III-5a

Comparison between the 2π -integrated Bremsstrahlung spectra from a 2.54×10^{-3} cm thick tungsten slab and a 2.54×10^{-3} cm diameter tungsten wire (weighted slab technique).

FIGURE III-5a

FIGURE III-5b

Comparison between the 2π -integrated Bremsstrahlung spectra from a 2.54×10^{-3} cm diameter tungsten wire (weighted slab technique) and a wire target of the same diameter incorporating the true cylindrical wire cross-section into the code computations.

FIGURE III-5b

TABLE III-3

GAMMA TRANSMISSION FROM 100 TO 1000 KEV, 12.5 KEV STEPS
FOR 1,2,3,60 PB ABSORBER COMBINATIONS

0.00000E 00	0.00000E 00	0.00000E 00	0.50000E-03	0.26000E-02	0.64000E-02	0.13600E-01	0.23500E-01	0.43000E-01	
	0.64000E-01	0.87000E-01	0.11300E 00	0.14100E 00	0.16700E 00	0.19600E 00	0.22300E 00	0.25100E 00	
	0.27600E 00	0.30000E 00	0.32200E 00	0.34400E 00	0.36300E 00	0.38300E 00	0.39800E 00	0.41700E 00	
	0.43100E 00	0.44600E 00	0.45900E 00	0.47200E 00	0.48300E 00	0.49500E 00	0.50500E 00	0.51700E 00	
	0.52600E 00	0.53500E 00	0.54200E 00	0.55100E 00	0.55900E 00	0.56600E 00	0.57300E 00	0.58000E 00	
	0.58700E 00	0.59200E 00	0.59700E 00	0.60200E 00	0.60800E 00	0.61200E 00	0.61700E 00	0.62100E 00	
	0.62700E 00	0.63000E 00	0.63300E 00	0.63900E 00	0.64100E 00	0.64600E 00	0.64900E 00	0.65100E 00	
	0.65300E 00	0.65800E 00	0.66000E 00	0.66300E 00	0.66600E 00	0.66900E 00	0.67000E 00	0.67100E 00	
	0.67200E 00	0.67600E 00	0.67800E 00	0.67900E 00	0.68000E 00	0.68200E 00	0.68400E 00	0.68800E 00	
0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.50000E-03	0.14000E-02	0.36000E-02	
	0.88000E-02	0.14700E-01	0.21600E-01	0.32500E-01	0.46000E-01	0.61500E-01	0.78000E-01	0.95000E-01	
	0.11200E 00	0.13000E 00	0.14800E 00	0.16700E 00	0.18600E 00	0.20500E 00	0.22100E 00	0.23900E 00	
	0.25500E 00	0.27000E 00	0.28500E 00	0.30000E 00	0.31300E 00	0.32600E 00	0.33800E 00	0.35100E 00	
	0.36200E 00	0.37500E 00	0.38300E 00	0.39400E 00	0.40200E 00	0.41200E 00	0.42000E 00	0.42900E 00	
	0.43700E 00	0.44300E 00	0.45000E 00	0.45800E 00	0.46400E 00	0.47000E 00	0.47600E 00	0.48200E 00	
	0.48800E 00	0.49300E 00	0.49900E 00	0.50200E 00	0.51000E 00	0.51500E 00	0.52000E 00	0.52300E 00	
	0.53000E 00	0.53400E 00	0.53900E 00	0.54200E 00	0.54800E 00	0.55000E 00	0.55200E 00	0.55500E 00	
	0.55800E 00	0.56000E 00	0.56200E 00	0.56300E 00	0.56800E 00	0.56900E 00	0.57000E 00	0.57300E 00	
0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00	0.10000E-03	
	0.12500E-02	0.24000E-02	0.45000E-02	0.90000E-02	0.15000E-01	0.21000E-01	0.27800E-01	0.36600E-01	
	0.47500E-01	0.59000E-01	0.71000E-01	0.84000E-01	0.97000E-01	0.11100E 00	0.12400E 00	0.13900E 00	
	0.15200E 00	0.16600E 00	0.17800E 00	0.19200E 00	0.20300E 00	0.21600E 00	0.22700E 00	0.24100E 00	
	0.25200E 00	0.26400E 00	0.27400E 00	0.28500E 00	0.29400E 00	0.30400E 00	0.31200E 00	0.32100E 00	
	0.32900E 00	0.33600E 00	0.34300E 00	0.35100E 00	0.35900E 00	0.36600E 00	0.37200E 00	0.37900E 00	
	0.38500E 00	0.39100E 00	0.39900E 00	0.40500E 00	0.41100E 00	0.41800E 00	0.42300E 00	0.43000E 00	
	0.43500E 00	0.44100E 00	0.44800E 00	0.45100E 00	0.45700E 00	0.46000E 00	0.46300E 00	0.46800E 00	
	0.47100E 00	0.47600E 00	0.48000E 00	0.48200E 00	0.48700E 00	0.48900E 00	0.49200E 00	0.49600E 00	
0.26000E-01	0.61000E-01	0.13500E 00	0.20000E 00	0.25200E 00	0.31000E 00	0.36200E 00	0.41300E 00	0.45300E 00	
	0.49600E 00	0.52600E 00	0.55000E 00	0.57000E 00	0.58900E 00	0.60500E 00	0.62100E 00	0.63400E 00	
	0.64900E 00	0.66100E 00	0.67200E 00	0.68200E 00	0.69100E 00	0.69900E 00	0.70700E 00	0.71000E 00	
	0.71900E 00	0.72600E 00	0.73000E 00	0.73500E 00	0.73900E 00	0.74200E 00	0.74800E 00	0.75100E 00	
	0.75500E 00	0.75900E 00	0.76100E 00	0.76400E 00	0.76700E 00	0.76900E 00	0.77000E 00	0.77100E 00	
	0.77200E 00	0.77300E 00	0.77600E 00	0.77900E 00	0.78000E 00	0.78100E 00	0.78300E 00	0.78500E 00	
	0.78800E 00	0.78900E 00	0.79000E 00	0.79100E 00	0.79300E 00	0.79400E 00	0.79700E 00	0.79800E 00	
	0.79900E 00	0.79900E 00	0.80000E 00	0.80100E 00	0.80200E 00	0.80300E 00	0.80600E 00	0.80900E 00	
	0.81000E 00	0.81100E 00	0.81200E 00	0.81300E 00	0.81500E 00	0.81700E 00	0.81900E 00	0.82000E 00	

TABLE III-4

NAI CRYSTAL EFFICIENCY FROM 100 TO 1000 KEV, 12.5 KEV STEPS

0.98754	0.98800	0.98800	0.98750	0.98607	0.98550	0.98350	0.98100	0.97675
	0.97200	0.96450	0.95350	0.93888	0.92600	0.91000	0.89350	0.87473
	0.85800	0.84050	0.82200	0.80629	0.78900	0.77300	0.75550	0.73868
	0.72400	0.70900	0.69450	0.68098	0.66850	0.65650	0.64550	0.63452
	0.62550	0.61600	0.60650	0.59851	0.58900	0.58100	0.57300	0.56653
	0.55830	0.55200	0.54600	0.54048	0.53500	0.53050	0.52600	0.52060
	0.51590	0.51250	0.50830	0.50470	0.50160	0.49760	0.49450	0.49110
	0.48750	0.48440	0.48190	0.47830	0.47560	0.47260	0.47030	0.46690
	0.46480	0.46240	0.45910	0.45670	0.45410	0.45120	0.44860	0.44610

TABLE III-5

PILOT B CRYSTAL EFFICIENCY FROM 100 TO 1000 KEV, 12.5 KEV STEPS

0.21160	0.21860	0.22500	0.23120	0.23680	0.24230	0.24210	0.25200	0.25590
	0.25980	0.26320	0.26650	0.26910	0.27200	0.27410	0.27640	0.27830
	0.28020	0.28150	0.28320	0.28430	0.28570	0.28680	0.28750	0.28810
	0.28870	0.28900	0.28940	0.28980	0.29000	0.29010	0.29020	0.29030
	0.29030	0.29030	0.29030	0.29020	0.29010	0.29000	0.29000	0.28980
	0.28970	0.28950	0.28920	0.28900	0.28890	0.28860	0.28820	0.28800
	0.28780	0.28750	0.28720	0.28690	0.28660	0.28620	0.28590	0.28560
	0.28520	0.28490	0.28450	0.28410	0.28380	0.28330	0.28290	0.28250
	0.28210	0.28170	0.28120	0.28080	0.28030	0.27990	0.27950	0.27900

TABLE III-6

NaI(Tl)

THE INTENSITY RATIOS OF BREMSSTRAHLUNG INTO THE DETECTOR
AS A FUNCTION OF ABSORBER AND INITIAL ELECTRON ENERGY

ELECTRON ENERGY (KEV)	1PB/2PB	1PB/3PB	2PB/3PB	0PB/1PB
100.000	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00
125.000	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00
150.000	0.00000E 00	0.00000E 00	0.00000E 00	0.78915E 03
175.000	0.62913E 03	0.00000E 00	0.00000E 00	0.14061E 03
200.000	0.29237E 02	0.14627E 05	0.50028E 03	0.54754E 02
225.000	0.12801E 02	0.14880E 03	0.11624E 02	0.27194E 02
250.000	0.84148E 01	0.57871E 02	0.68773E 01	0.16946E 02
300.000	0.48905E 01	0.18264E 02	0.37345E 01	0.87583E 01
350.000	0.36235E 01	0.10504E 02	0.28990E 01	0.60301E 01
400.000	0.29555E 01	0.72230E 01	0.24439E 01	0.46590E 01
450.000	0.25664E 01	0.55776E 01	0.21733E 01	0.38644E 01
500.000	0.23201E 01	0.46302E 01	0.19956E 01	0.33866E 01
550.000	0.21483E 01	0.40175E 01	0.18701E 01	0.30540E 01
600.000	0.20204E 01	0.35831E 01	0.17735E 01	0.28151E 01
650.000	0.19306E 01	0.32944E 01	0.17064E 01	0.26419E 01
700.000	0.18573E 01	0.30677E 01	0.16517E 01	0.25068E 01
750.000	0.17965E 01	0.28804E 01	0.16033E 01	0.24030E 01
800.000	0.17348E 01	0.27066E 01	0.15602E 01	0.22718E 01
850.000	0.16988E 01	0.26001E 01	0.15305E 01	0.22123E 01
900.000	0.16639E 01	0.25015E 01	0.15034E 01	0.21474E 01
950.000	0.16296E 01	0.24089E 01	0.14782E 01	0.20762E 01
1000.000	0.16052E 01	0.23403E 01	0.14580E 01	0.20343E 01

TABLE III-7

PILOT B

THE INTENSITY RATIOS OF BREMSSTRAHLUNG INTO THE DETECTOR
AS A FUNCTION OF ABSORBER AND INITIAL ELECTRON ENERGY

ELECTRON ENERGY (KEV)	1PB/2PB	1PB/3PB	2PB/3PB	0EB/1PB
100.000	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00
125.000	0.00000E 00	0.00000E 00	0.00000E 00	0.00000E 00
150.000	0.00000E 00	0.00000E 00	0.00000E 00	0.76680E 03
175.000	0.62180E 03	0.00000E 00	0.00000E 00	0.13556E 03
200.000	0.28686E 02	0.13967E 05	0.48690E 03	0.52530E 02
225.000	0.12552E 02	0.14380E 03	0.11457E 02	0.25860E 02
250.000	0.82495E 01	0.56028E 02	0.67917E 01	0.16001E 02
300.000	0.47603E 01	0.17487E 02	0.36736E 01	0.81472E 01
350.000	0.34996E 01	0.99423E 01	0.28409E 01	0.55285E 01
400.000	0.28364E 01	0.67689E 01	0.23864E 01	0.42163E 01
450.000	0.24502E 01	0.51823E 01	0.21151E 01	0.34645E 01
500.000	0.22042E 01	0.42679E 01	0.19363E 01	0.30116E 01
550.000	0.20343E 01	0.36828E 01	0.18103E 01	0.26997E 01
600.000	0.19082E 01	0.32700E 01	0.17136E 01	0.24754E 01
650.000	0.18208E 01	0.29991E 01	0.16471E 01	0.23159E 01
700.000	0.17502E 01	0.27884E 01	0.15932E 01	0.21910E 01
750.000	0.16899E 01	0.26104E 01	0.15447E 01	0.20917E 01
800.000	0.16344E 01	0.24589E 01	0.15045E 01	0.19811E 01
850.000	0.15989E 01	0.23579E 01	0.14748E 01	0.19249E 01
900.000	0.15660E 01	0.22686E 01	0.14486E 01	0.18681E 01
950.000	0.15353E 01	0.21879E 01	0.14250E 01	0.18099E 01
1000.000	0.15122E 01	0.21252E 01	0.14054E 01	0.17727E 01

III.5 Bremsstrahlung Code Output: Electrons Incident
on Tungsten Slab and Wire Geometry Targets,
 $100 \text{ keV} < E_0 < 1000 \text{ keV}$

Included for reference in this Appendix are the listings from the Monte Carlo Electron and Photon Transport Codes, MCG and MCGE, which were used in generating the Bremsstrahlung spectra discussed in Section 4.4.2. The printouts included here contain the following information:

(1) total differential Bremsstrahlung spectra integrated over the forward 2π hemisphere for tungsten targets of slab geometry of thicknesses of 2.54×10^{-4} cm - 2.54×10^{-3} cm in increments of 2.54×10^{-4} cm;

(2) total differential Bremsstrahlung spectra integrated over the forward 2π hemisphere for a wire target 2.54×10^{-3} cm in diameter ("weighted slab" technique);

(3) Bremsstrahlung spectra differential in both energy and angle, $d^2/d\Omega dk$, for a slab target 2.54×10^{-3} cm in thickness, for $0^\circ - 90^\circ$.

For practical use, one must become acquainted with the notations and normalizations used in the codes. These are discussed briefly below:

(1) RANGE FRACTION: Another manner in which to express target thickness, the Range Fraction--or "Z/R", as it is labelled in the code outputs--represents the target thickness normalized to the energy loss range of electrons of energy E_0 in tungsten. For use of the code data, a table of electron ranges in tungsten in the energy interval 10 keV E_0 100 MeV, taken from Reference 37 is included in Table III-8.

(2) UNITS: The code outputs the spectra as intensities having units of $dn_Y(E'_Y)/dE_Y$ ("Number/MeV") and $dn_Y^2(E'_Y)/dE_Y d\Omega$ ("Number/MeV-Sr"), where $dn_Y(E'_Y)$ is the number of photons within the energy increment dE_Y at the photon energy E'_Y , normalized to one incident electron in the target. Multiplying these figures by the average "bin" energy, E'_Y , in the increment ("bin") dE_Y gives the spectral data in terms of differential energy yields, ("MeV/MeV", or "MeV/MeV-Sr") i.e., total energy produced per electron in the photon increment, dE_Y . For the purposes of statistics, the cutoff energy bin actually extends 1 keV beyond cutoff and is 2 keV wide. However, the code uses only half of this increment. Therefore, the intensities for the cutoff energy bin must be multiplied by two to obtain the true intensities.

The code printouts are shown in Table III-9. The

TUNGSTEN

ENERGY MEV	LOSS OF ENERGY			RANGE G/CM2	BREMSSTRAHLUNG YIELD
	BY IONIZATION	BY RADIATION MEV*CM2/G	TOTAL		
1.0E-02	8.8727E 00	3.9207E-02	8.9119E 00	5.6105E-04	2.1997E-03
1.5E-02	6.8747E 00	4.0548E-02	6.9153E 00	1.2031E-03	3.1770E-03
2.0E-02	5.6983E 00	4.1802E-02	5.7401E 00	2.0002E-03	4.0260E-03
2.5E-02	4.9160E 00	4.3027E-02	4.9590E 00	2.9398E-03	4.8167E-03
3.0E-02	4.3551E 00	4.4282E-02	4.3993E 00	4.0122E-03	5.5757E-03
3.5E-02	3.9315E 00	4.5416E-02	3.9769E 00	5.2091E-03	6.3139E-03
4.0E-02	3.5995E 00	4.6513E-02	3.6460E 00	6.5234E-03	7.0357E-03
4.5E-02	3.3318E 00	4.7414E-02	3.3792E 00	7.9489E-03	7.7422E-03
5.0E-02	3.1110E 00	4.8402E-02	3.1594E 00	9.4800E-03	8.4355E-03
5.5E-02	2.9257E 00	4.9193E-02	2.9749E 00	1.1112E-02	9.1166E-03
6.0E-02	2.7677E 00	4.9910E-02	2.8177E 00	1.2839E-02	9.7840E-03
6.5E-02	2.6315E 00	5.0593E-02	2.6821E 00	1.4659E-02	1.0438E-02
7.0E-02	2.5127E 00	5.1324E-02	2.5640E 00	1.6566E-02	1.1081E-02
7.5E-02	2.4082E 00	5.1980E-02	2.4602E 00	1.8557E-02	1.1714E-02
8.0E-02	2.3155E 00	5.2520E-02	2.3680E 00	2.0629E-02	1.2335E-02
8.5E-02	2.2327E 00	5.3149E-02	2.2859E 00	2.2778E-02	1.2946E-02
9.0E-02	2.1584E 00	5.3787E-02	2.2122E 00	2.5002E-02	1.3548E-02
9.5E-02	2.0912E 00	5.4390E-02	2.1456E 00	2.7297E-02	1.4142E-02
1.0E-01	2.0302E 00	5.5001E-02	2.0852E 00	2.9662E-02	1.4728E-02
1.5E-01	1.6327E 00	6.0361E-02	1.6930E 00	5.6417E-02	2.0157E-02
2.0E-01	1.4281E 00	6.5933E-02	1.4941E 00	8.7916E-02	2.5090E-02
2.5E-01	1.3056E 00	7.1740E-02	1.3773E 00	1.2280E-01	2.9694E-02
3.0E-01	1.2254E 00	7.7804E-02	1.3033E 00	1.6013E-01	3.4060E-02
3.5E-01	1.1700E 00	8.3826E-02	1.2539E 00	1.9925E-01	3.8234E-02
4.0E-01	1.1303E 00	8.9977E-02	1.2202E 00	2.3968E-01	4.2242E-02
4.5E-01	1.1009E 00	9.5743E-02	1.1966E 00	2.8106E-01	4.6990E-02
5.0E-01	1.0788E 00	1.0149E-01	1.1803E 00	3.2313E-01	4.9781E-02
5.5E-01	1.0620E 00	1.0700E-01	1.1690E 00	3.6570E-01	5.3324E-02
6.0E-01	1.0490E 00	1.1240E-01	1.1614E 00	4.0861E-01	5.6727E-02
6.5E-01	1.0390E 00	1.1776E-01	1.1568E 00	4.5175E-01	6.0001E-02
7.0E-01	1.0313E 00	1.2305E-01	1.1543E 00	4.9502E-01	6.3157E-02
7.5E-01	1.0253E 00	1.2858E-01	1.1539E 00	5.3834E-01	6.6215E-02
8.0E-01	1.0208E 00	1.3443E-01	1.1552E 00	5.8165E-01	6.9195E-02
8.5E-01	1.0174E 00	1.3969E-01	1.1571E 00	6.2489E-01	7.2098E-02
9.0E-01	1.0149E 00	1.4465E-01	1.1595E 00	6.6806E-01	7.4911E-02
9.5E-01	1.0131E 00	1.4967E-01	1.1628E 00	7.1112E-01	7.7638E-02
1.0E 00	1.0120E 00	1.5366E-01	1.1656E 00	7.5407E-01	8.0270E-02
2.0E 00	1.0353E 00	2.5199E-01	1.2873E 00	1.5714E 00	1.2203E-01
3.0E 00	1.0709E 00	3.1878E-01	1.3897E 00	2.3196E 00	1.5221E-01
4.0E 00	1.1011E 00	4.2567E-01	1.5268E 00	3.0069E 00	1.7768E-01
5.0E 00	1.1261E 00	5.3918E-01	1.6652E 00	3.6347E 00	2.0240E-01
6.0E 00	1.1469E 00	6.5360E-01	1.8005E 00	4.2126E 00	2.2590E-01
7.0E 00	1.1647E 00	7.6826E-01	1.9329E 00	4.7490E 00	2.4795E-01
8.0E 00	1.1801E 00	8.9312E-01	2.0732E 00	5.2488E 00	2.6872E-01
9.0E 00	1.1935E 00	1.0152E 00	2.2087E 00	5.7164E 00	2.8833E-01
1.0E 01	1.2055E 00	1.1408E 00	2.3463E 00	6.1558E 00	3.0679E-01
2.0E 01	1.2816E 00	2.4321E 00	3.7137E 00	9.6332E 00	4.3867E-01
3.0E 01	1.3231E 00	3.4821E 00	4.8052E 00	1.2020E 01	5.2237E-01
4.0E 01	1.3507E 00	4.7154E 00	6.0661E 00	1.3885E 01	5.7953E-01
5.0E 01	1.3711E 00	5.9881E 00	7.3592E 00	1.5389E 01	6.2272E-01
6.0E 01	1.3871E 00	8.1557E 00	9.5428E 00	1.6592E 01	6.5796E-01
7.0E 01	1.4002E 00	9.5692E 00	1.0969E 01	1.7572E 01	6.8733E-01
8.0E 01	1.4113E 00	1.0989E 01	1.2400E 01	1.8431E 01	7.1132E-01
9.0E 01	1.4209E 00	1.2415E 01	1.3836E 01	1.9195E 01	7.3137E-01
1.0E 02	1.4293E 00	1.3844E 01	1.5273E 01	1.9884E 01	7.4842E-01

TABLE III-9

E₀ = 100keV

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.1639	.3279	.4918	.6557	.8196	.9836	1.1475	1.3114	1.4754	1.6393
.1010 -	.0990	6.801E-04	6.098E-04	6.098E-04	5.863E-04	5.629E-04	5.394E-04	4.925E-04	4.690E-04	4.456E-04	4.456E-04
.0990 -	.0900	5.311E-03	5.081E-03	4.748E-03	4.518E-03	4.247E-03	4.018E-03	3.820E-03	3.601E-03	3.471E-03	3.346E-03
.0900 -	.0750	1.272E-02	1.291E-02	1.186E-02	1.082E-02	9.916E-03	9.256E-03	8.615E-03	7.999E-03	7.483E-03	7.029E-03
.0750 -	.0500	3.035E-02	3.762E-02	3.639E-02	3.480E-02	3.341E-02	3.215E-02	3.095E-02	2.986E-02	2.883E-02	2.780E-02

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = 1.63930 * ELECTRON CSUA RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR)), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.1010 -	.0990	0.	0.	0.	0.	1.494E-04	1.644E-04	9.011E-05	3.095E-05	1.442E-05
.0990 -	.0900	0.	7.785E-04	6.826E-04	9.910E-04	1.038E-03	8.194E-04	6.568E-04	4.265E-04	1.154E-04
.0900 -	.0750	8.170E-04	1.869E-03	2.633E-03	2.218E-03	2.092E-03	1.791E-03	1.391E-03	8.894E-04	2.231E-04
.0750 -	.0500	6.863E-03	7.101E-03	6.249E-03	7.053E-03	6.403E-03	6.060E-03	5.320E-03	4.336E-03	1.701E-03
INTEGRAL (/SR),		1.838E-04	2.126E-04	2.019E-04	2.185E-04	2.011E-04	1.861E-04	1.591E-04	2.345E-04	4.693E-05

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN	INTENSITY
1.010E-01	9.900E-02
9.900E-02	9.000E-02
9.000E-02	7.500E-02
7.500E-02	5.000E-02
	4.84638E-04
	3.71164E-03
	8.25724E-03
	3.00539E-02

E₀ = 200keV

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0553	.1105	.1658	.2211	.2764	.3316	.3869	.4422	.4975	.5527
.2010 -	.1990	2.264E-04	3.018E-04	3.018E-04	3.018E-04	3.018E-04	3.018E-04	3.018E-04	3.018E-04	3.018E-04	3.018E-04
.1990 -	.1900	1.811E-03	2.280E-03	2.297E-03	2.297E-03	2.264E-03	2.264E-03	2.247E-03	2.213E-03	2.196E-03	2.166E-03
.1900 -	.1750	3.461E-03	5.211E-03	5.654E-03	5.644E-03	5.583E-03	5.483E-03	5.432E-03	5.382E-03	5.302E-03	5.211E-03
.1750 -	.1500	4.993E-03	9.308E-03	1.120E-02	1.176E-02	1.172E-02	1.191E-02	1.138E-02	1.116E-02	1.097E-02	1.083E-02
.1500 -	.1250	7.123E-03	1.458E-02	1.884E-02	2.066E-02	2.125E-02	2.096E-02	2.062E-02	2.014E-02	1.965E-02	1.916E-02
.1250 -	.1000	1.005E-02	2.126E-02	2.872E-02	3.244E-02	3.375E-02	3.351E-02	3.257E-02	3.149E-02	3.048E-02	2.943E-02
.1000 -	.0750	1.473E-02	3.133E-02	4.337E-02	4.927E-02	5.121E-02	5.026E-02	4.814E-02	4.557E-02	4.308E-02	4.059E-02

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .55275 * ELECTRON CSDA RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.2010 -	.1990	0.	0.	0.	0.	1.202E-04	1.511E-04	0.	0.	4.640E-05
.1990 -	.1900	0.	1.670E-03	1.255E-03	4.905E-04	5.610E-04	3.862E-04	4.123E-04	3.209E-04	1.650E-04
.1900 -	.1750	0.	2.004E-03	1.694E-03	1.104E-03	1.362E-03	1.078E-03	8.272E-04	7.303E-04	5.011E-04
.1750 -	.1500	4.731E-03	2.705E-03	2.485E-03	2.428E-03	2.606E-03	2.285E-03	1.883E-03	1.585E-03	9.391E-04
.1500 -	.1250	9.462E-03	3.607E-03	4.517E-03	4.635E-03	4.481E-03	3.827E-03	3.456E-03	2.991E-03	1.544E-03
.1250 -	.1000	7.885E-03	6.012E-03	7.792E-03	7.637E-03	7.049E-03	6.087E-03	5.506E-03	4.613E-03	1.941E-03
.1000 -	.0750	1.262E-02	9.919E-03	1.096E-02	1.165E-02	1.064E-02	9.177E-03	7.993E-03	6.055E-03	1.689E-03
INTEGRAL (/SR),		8.674E-04	6.012E-04	6.805E-04	6.758E-04	6.450E-04	5.943E-04	4.871E-04	3.949E-04	2.677E-04

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN	INTENSITY
2.010E-01	1.990E-01
1.990E-01	1.900E-01
1.900E-01	1.750E-01
1.750E-01	1.500E-01
1.500E-01	1.250E-01
1.250E-01	1.000E-01
1.000E-01	7.500E-02
	3.00672E-04
	2.21558E-03
	5.32583E-03
	1.10088E-02
	1.95921E-02
	3.04725E-02
	4.37990E-02

E₀=300keV

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0303	.0607	.0910	.1213	.1517	.1820	.2123	.2427	.2730	.3034
.3010 -	.2990	1.176E-04	1.176E-04	1.176E-04	1.176E-04	1.176E-04	1.176E-04	1.176E-04	1.176E-04	1.176E-04	1.176E-04
.2990 -	.2900	1.045E-03	1.385E-03	1.463E-03	1.463E-03	1.463E-03	1.437E-03	1.437E-03	1.437E-03	1.437E-03	1.437E-03
.2900 -	.2750	1.396E-03	2.775E-03	3.324E-03	3.575E-03	3.622E-03	3.591E-03	3.575E-03	3.591E-03	3.591E-03	3.591E-03
.2750 -	.2500	1.853E-03	3.942E-03	5.297E-03	6.134E-03	6.633E-03	6.840E-03	6.924E-03	6.906E-03	6.877E-03	6.840E-03
.2500 -	.2250	2.256E-03	5.109E-03	7.395E-03	9.051E-03	1.016E-02	1.071E-02	1.102E-02	1.121E-02	1.118E-02	1.111E-02
.2250 -	.2000	2.672E-03	6.435E-03	9.935E-03	1.269E-02	1.441E-02	1.547E-02	1.608E-02	1.637E-02	1.635E-02	1.633E-02
.2000 -	.1750	3.425E-03	8.449E-03	1.293E-02	1.687E-02	1.956E-02	2.152E-02	2.306E-02	2.359E-02	2.377E-02	2.383E-02
.1750 -	.1500	4.864E-03	1.068E-02	1.697E-02	2.234E-02	2.698E-02	3.002E-02	3.200E-02	3.307E-02	3.350E-02	3.361E-02
.1500 -	.1250	6.360E-03	1.455E-02	2.288E-02	3.055E-02	3.649E-02	4.071E-02	4.353E-02	4.508E-02	4.598E-02	4.584E-02
.1250 -	.1000	8.345E-03	1.986E-02	3.066E-02	4.097E-02	4.924E-02	5.531E-02	5.936E-02	6.208E-02	6.273E-02	6.248E-02

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .30335 * ELECTRON CSUA RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.3010 -	.2990	0.	0.	0.	0.	0.	0.	0.	0.	7.761E-05	0.
.2990 -	.2900	0.	0.	0.	0.	3.822E-04	4.163E-04	3.141E-04	3.012E-04	2.242E-04	4.821E-05
.2900 -	.2750	0.	7.808E-04	5.868E-04	1.032E-03	6.745E-04	8.166E-04	7.471E-04	4.863E-04	2.796E-04	
.2750 -	.2500	4.916E-03	1.874E-03	1.493E-03	1.583E-03	1.454E-03	1.376E-03	1.272E-03	9.685E-04	6.653E-04	
.2500 -	.2250	2.458E-03	3.748E-03	1.760E-03	3.096E-03	2.308E-03	2.242E-03	1.909E-03	1.639E-03	1.140E-03	
.2250 -	.2000	2.458E-03	1.874E-03	3.521E-03	2.959E-03	3.357E-03	3.364E-03	2.488E-03	2.639E-03	1.846E-03	
.2000 -	.1750	7.374E-03	5.153E-03	3.873E-03	6.330E-03	5.411E-03	4.447E-03	4.258E-03	3.570E-03	2.360E-03	
.1750 -	.1500	9.832E-03	9.838E-03	6.865E-03	7.637E-03	7.030E-03	6.596E-03	5.972E-03	5.041E-03	3.413E-03	
.1500 -	.1250	1.721E-02	1.171E-02	1.109E-02	9.564E-03	1.013E-02	9.243E-03	8.163E-03	6.910E-03	4.276E-03	
.1250 -	.1000	1.229E-02	1.499E-02	1.285E-02	1.479E-02	1.379E-02	1.261E-02	1.180E-02	9.798E-03	4.906E-03	
INTEGRAL (/SR).		1.413E-03	1.242E-03	1.043E-03	1.168E-03	1.101E-03	1.012E-03	9.103E-04	8.847E-04	5.733E-04	

E₀=300keV

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
3.010E-01	2.990E-01	1.17603E-04
2.990E-01	2.900E-01	1.43410E-03
2.900E-01	2.750E-01	3.53451E-03
2.750E-01	2.500E-01	6.64709E-03
2.500E-01	2.250E-01	1.05978E-02
2.250E-01	2.000E-01	1.53995E-02
2.000E-01	1.750E-01	2.20636E-02
1.750E-01	1.500E-01	3.08519E-02
1.500E-01	1.250E-01	4.20889E-02
1.250E-01	1.000E-01	5.73830E-02

E₀=400keV

ENERGY SPECTRA OF TRANSMITTED PHOTONS (NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0202	.0405	.0607	.0810	.1012	.1215	.1417	.1620	.1822	.2025
.4010 -	.3990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.3990 -	.3900	6.752E-04	9.003E-04	9.378E-04	9.753E-04	9.378E-04	9.753E-04	9.753E-04	9.753E-04	9.753E-04	9.753E-04
.3900 -	.3750	7.653E-04	1.688E-03	2.048E-03	2.296E-03	2.341E-03	2.363E-03	2.341E-03	2.318E-03	2.296E-03	2.296E-03
.3750 -	.3500	9.723E-04	1.999E-03	2.795E-03	3.390E-03	3.876E-03	4.092E-03	4.213E-03	4.254E-03	4.294E-03	4.281E-03
.3500 -	.3250	1.134E-03	2.728E-03	4.092E-03	5.294E-03	6.104E-03	6.590E-03	6.914E-03	7.063E-03	7.144E-03	7.184E-03
.3250 -	.3000	1.161E-03	3.147E-03	4.916E-03	6.524E-03	8.089E-03	9.129E-03	9.777E-03	1.014E-02	1.061E-02	1.088E-02
.3000 -	.2750	1.837E-03	3.930E-03	5.942E-03	7.954E-03	9.588E-03	1.102E-02	1.213E-02	1.286E-02	1.356E-02	1.402E-02
.2750 -	.2500	1.796E-03	4.308E-03	7.117E-03	9.791E-03	1.199E-02	1.426E-02	1.585E-02	1.726E-02	1.810E-02	1.866E-02
.2500 -	.2250	2.620E-03	5.780E-03	9.413E-03	1.255E-02	1.531E-02	1.791E-02	2.015E-02	2.180E-02	2.325E-02	2.454E-02
.2250 -	.2000	3.039E-03	6.499E-03	1.091E-02	1.481E-02	1.835E-02	2.154E-02	2.434E-02	2.682E-02	2.844E-02	2.962E-02
.2000 -	.1750	3.417E-03	8.008E-03	1.302E-02	1.831E-02	2.359E-02	2.795E-02	3.157E-02	3.479E-02	3.760E-02	3.960E-02
.1750 -	.1500	4.578E-03	1.097E-02	1.735E-02	2.344E-02	2.970E-02	3.556E-02	4.142E-02	4.573E-02	4.939E-02	5.191E-02
.1500 -	.1250	5.874E-03	1.371E-02	2.204E-02	3.067E-02	3.892E-02	4.644E-02	5.321E-02	5.900E-02	6.331E-02	6.734E-02
.1250 -	.1000	8.035E-03	1.804E-02	2.952E-02	4.053E-02	5.173E-02	6.130E-02	6.928E-02	7.752E-02	8.336E-02	8.802E-02

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH A SLAB OF THICKNESS = .20248 * ELECTRON CSDA RANGE = 4.902E-02 G/CM2 (NUMBER/(MEV*SK), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.4010 -	.3990	0.	0.	0.	0.	0.	0.	0.	0.	0.
.3990 -	.3900	0.	0.	0.	2.743E-04	4.183E-04	2.630E-04	2.018E-04	4.951E-05	4.613E-05
.3900 -	.3750	0.	0.	1.263E-03	9.876E-04	6.813E-04	5.184E-04	4.324E-04	2.822E-04	9.688E-05
.3750 -	.3500	0.	2.017E-03	7.580E-04	4.938E-04	1.076E-03	8.791E-04	7.783E-04	5.436E-04	4.567E-04
.3500 -	.3250	1.058E-02	2.017E-03	1.769E-03	1.580E-03	1.872E-03	1.609E-03	1.266E-03	9.179E-04	5.979E-04
.3250 -	.3000	3.528E-03	3.362E-03	2.274E-03	2.963E-03	2.108E-03	2.083E-03	1.733E-03	1.649E-03	1.304E-03
.3000 -	.2750	0.	6.725E-04	7.327E-03	3.358E-03	3.227E-03	2.637E-03	2.356E-03	1.836E-03	1.628E-03
.2750 -	.2500	3.528E-03	4.035E-03	3.537E-03	4.247E-03	3.614E-03	3.868E-03	3.207E-03	2.691E-03	2.101E-03
.2500 -	.2250	7.056E-03	2.690E-03	6.004E-03	5.629E-03	5.615E-03	4.598E-03	4.182E-03	3.672E-03	2.608E-03
.2250 -	.2000	7.056E-03	2.017E-03	5.811E-03	6.913E-03	6.519E-03	5.913E-03	5.230E-03	4.447E-03	3.106E-03
.2000 -	.1750	1.411E-02	6.032E-03	1.137E-02	1.086E-02	8.563E-03	7.926E-03	6.206E-03	5.855E-03	4.360E-03
.1750 -	.1500	7.056E-03	1.210E-02	1.162E-02	1.314E-02	1.261E-02	9.495E-03	8.666E-03	7.905E-03	5.273E-03
.1500 -	.1250	1.058E-02	1.614E-02	1.718E-02	1.570E-02	1.422E-02	1.258E-02	1.229E-02	1.054E-02	6.428E-03
.1250 -	.1000	3.175E-02	2.287E-02	1.920E-02	2.133E-02	1.997E-02	1.863E-02	1.632E-02	1.311E-02	6.927E-03
INTEGRAL (/SR),		2.382E-03	1.849E-03	2.192E-03	2.173E-03	1.999E-03	1.758E-03	1.504E-03	1.334E-03	8.716E-04

E₀ = 400keV

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
4.010E-01	3.990E-01	0.
3.990E-01	3.900E-01	9.66322E-04
3.900E-01	3.750E-01	2.26864E-03
3.750E-01	3.500E-01	4.05999E-03
3.500E-01	3.250E-01	6.67487E-03
3.250E-01	3.000E-01	9.66078E-03
3.000E-01	2.750E-01	1.22138E-02
2.750E-01	2.500E-01	1.61069E-02
2.500E-01	2.250E-01	2.07646E-02
2.250E-01	2.000E-01	2.51717E-02
2.000E-01	1.750E-01	3.30587E-02
1.750E-01	1.500E-01	4.32316E-02
1.500E-01	1.250E-01	5.58357E-02
1.250E-01	1.000E-01	7.33031E-02

$$E_0 = 500 \text{ keV}$$

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0150	.0300	.0450	.0600	.0750	.0900	.1050	.1200	.1350	.1500
.5010	.4990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.4990	.4900	3.699E-04	6.473E-04	6.935E-04	8.322E-04	8.322E-04	8.322E-04	8.322E-04	8.322E-04	8.322E-04	7.860E-04
.4900	.4750	4.161E-04	8.877E-04	1.111E-03	1.276E-03	1.332E-03	1.387E-03	1.387E-03	1.387E-03	1.387E-03	1.387E-03
.4750	.4500	5.992E-04	1.165E-03	1.714E-03	2.260E-03	2.730E-03	3.046E-03	3.112E-03	3.229E-03	3.279E-03	3.362E-03
.4500	.4250	6.491E-04	1.381E-03	2.164E-03	2.979E-03	3.495E-03	3.911E-03	4.477E-03	4.843E-03	5.043E-03	5.143E-03
.4250	.4000	8.655E-04	2.047E-03	3.246E-03	4.011E-03	4.927E-03	5.592E-03	6.192E-03	6.574E-03	6.857E-03	7.074E-03
.4000	.3750	1.032E-03	1.897E-03	3.190E-03	4.411E-03	5.542E-03	6.591E-03	7.307E-03	7.972E-03	8.738E-03	9.271E-03
.3750	.3500	1.098E-03	2.347E-03	4.327E-03	5.775E-03	7.157E-03	8.322E-03	9.287E-03	9.953E-03	1.080E-02	1.147E-02
.3500	.3250	1.182E-03	2.530E-03	4.161E-03	6.108E-03	7.773E-03	9.137E-03	1.047E-02	1.168E-02	1.270E-02	1.346E-02
.3250	.3000	1.448E-03	3.512E-03	5.792E-03	7.873E-03	9.653E-03	1.172E-02	1.305E-02	1.436E-02	1.580E-02	1.684E-02
.3000	.2750	1.548E-03	3.612E-03	6.025E-03	8.568E-03	1.085E-02	1.273E-02	1.488E-02	1.671E-02	1.831E-02	1.957E-02
.2750	.2500	2.314E-03	5.093E-03	8.224E-03	1.057E-02	1.370E-02	1.658E-02	1.894E-02	2.147E-02	2.425E-02	2.603E-02
.2500	.2250	2.547E-03	5.309E-03	8.738E-03	1.230E-02	1.599E-02	1.987E-02	2.363E-02	2.660E-02	2.953E-02	3.201E-02
.2250	.2000	2.829E-03	6.724E-03	1.079E-02	1.458E-02	1.871E-02	2.330E-02	2.741E-02	3.134E-02	3.517E-02	3.828E-02
.2000	.1750	4.011E-03	8.821E-03	1.393E-02	1.877E-02	2.422E-02	2.996E-02	3.502E-02	4.011E-02	4.511E-02	4.915E-02
.1750	.1500	4.877E-03	1.062E-02	1.710E-02	2.352E-02	3.001E-02	3.660E-02	4.316E-02	4.908E-02	5.464E-02	5.980E-02
.1500	.1250	6.491E-03	1.410E-02	2.225E-02	3.069E-02	3.845E-02	4.675E-02	5.478E-02	6.240E-02	7.012E-02	7.605E-02
.1250	.1000	7.856E-03	1.739E-02	2.770E-02	3.865E-02	4.970E-02	6.025E-02	6.999E-02	7.940E-02	8.837E-02	9.565E-02

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAR OF THICKNESS = .15002 * ELECTRON (SDA RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	20.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	20.000	30.000	45.000	60.000	75.000	90.000
.5010	.4990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.4990	.4900	1.208E-02	0.	8.650E-04	1.014E-03	2.210E-04	9.260E-05	1.066E-04	3.051E-05	8.529E-05	
.4900	.4750	0.	1.381E-03	5.190E-04	6.086E-04	7.513E-04	2.222E-04	1.066E-04	2.014E-04	6.823E-05	
.4750	.4500	0.	8.288E-04	1.557E-03	8.520E-04	9.015E-04	7.001E-04	4.869E-04	4.064E-04	3.889E-04	
.4500	.4250	8.697E-03	1.658E-03	1.246E-03	8.520E-04	1.193E-03	1.083E-03	9.465E-04	6.810E-04	4.913E-04	
.4250	.4000	0.	8.288E-04	4.048E-03	1.217E-03	1.777E-03	1.317E-03	1.253E-03	8.237E-04	8.393E-04	
.4000	.3750	0.	4.973E-03	4.048E-03	2.313E-03	2.121E-03	1.834E-03	1.433E-03	1.373E-03	9.416E-04	
.3750	.3500	1.305E-02	4.144E-03	3.114E-03	3.652E-03	2.386E-03	2.334E-03	1.944E-03	1.549E-03	1.208E-03	
.3500	.3250	1.305E-02	4.144E-03	4.983E-03	3.286E-03	3.580E-03	2.217E-03	2.302E-03	1.801E-03	1.494E-03	
.3250	.3000	8.697E-03	3.315E-03	4.583E-03	4.625E-03	3.580E-03	3.467E-03	2.699E-03	2.394E-03	1.842E-03	
.3000	.2750	4.368E-03	3.315E-03	4.360E-03	5.964E-03	3.765E-03	3.250E-03	3.568E-03	2.856E-03	2.374E-03	
.2750	.2500	0.	3.315E-03	9.031E-03	5.964E-03	5.701E-03	4.817E-03	4.157E-03	3.965E-03	2.989E-03	
.2500	.2250	8.697E-03	6.630E-03	8.404E-03	7.912E-03	7.133E-03	6.101E-03	5.372E-03	4.767E-03	3.398E-03	
.2250	.2000	1.739E-02	9.117E-03	8.404E-03	1.023E-02	7.584E-03	7.585E-03	6.817E-03	5.711E-03	3.889E-03	
.2000	.1750	1.305E-02	1.160E-02	1.588E-02	1.327E-02	1.026E-02	9.951E-03	7.930E-03	7.623E-03	4.892E-03	
.1750	.1500	8.697E-03	1.243E-02	1.650E-02	1.704E-02	1.342E-02	1.217E-02	1.072E-02	8.172E-03	5.783E-03	
.1500	.1250	4.348E-03	1.243E-02	1.993E-02	2.033E-02	1.816E-02	1.504E-02	1.321E-02	1.126E-02	6.929E-03	
.1250	.1000	4.348E-02	2.653E-02	2.616E-02	2.605E-02	2.193E-02	1.997E-02	1.727E-02	1.396E-02	7.780E-03	
INTEGRAL (/SR):		3.697E-03	2.652E-03	3.332E-03	3.107E-03	2.601E-03	2.300E-03	2.005E-03	1.749E-03	1.191E-03	

E₀=500keV

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
5.010E-01	4.990E-01	0.
4.990E-01	4.900E-01	8.03530E-04
4.900E-01	4.750E-01	1.34663E-03
4.750E-01	4.500E-01	3.06048E-03
4.500E-01	4.250E-01	4.50667E-03
4.250E-01	4.000E-01	6.20243E-03
4.000E-01	3.750E-01	7.71195E-03
3.750E-01	3.500E-01	9.62674E-03
3.500E-01	3.250E-01	1.11167E-02
3.250E-01	3.000E-01	1.39118E-02
3.000E-01	2.750E-01	1.59720E-02
2.750E-01	2.500E-01	2.09694E-02
2.500E-01	2.250E-01	2.55677E-02
2.250E-01	2.000E-01	3.03688E-02
2.000E-01	1.750E-01	3.89550E-02
1.750E-01	1.500E-01	4.75187E-02
1.500E-01	1.250E-01	6.06400E-02
1.250E-01	1.000E-01	7.66986E-02

$E_0 = 600\text{keV}$

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0119	.0237	.0356	.0474	.0593	.0711	.0830	.0948	.1067	.1185
.6010 -	.5990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.5990 -	.5900	4.042E-04	5.557E-04	6.063E-04	6.063E-04	6.063E-04	6.063E-04	6.063E-04	6.063E-04	6.063E-04	6.063E-04
.5900 -	.5750	3.334E-04	6.669E-04	9.094E-04	1.152E-03	1.394E-03	1.425E-03	1.425E-03	1.425E-03	1.425E-03	1.455E-03
.5750 -	.5500	4.911E-04	9.458E-04	1.382E-03	1.873E-03	2.164E-03	2.273E-03	2.419E-03	2.528E-03	2.601E-03	2.655E-03
.5500 -	.5250	3.638E-04	7.457E-04	1.200E-03	1.710E-03	1.964E-03	2.401E-03	2.710E-03	2.910E-03	3.183E-03	3.274E-03
.5250 -	.5000	4.729E-04	1.128E-03	1.837E-03	2.564E-03	3.110E-03	3.565E-03	4.256E-03	7.603E-03	7.839E-03	8.130E-03
.5000 -	.4750	7.093E-04	1.291E-03	1.928E-03	2.546E-03	3.492E-03	4.052E-03	4.492E-03	5.038E-03	5.511E-03	5.857E-03
.4750 -	.4500	6.184E-04	1.400E-03	2.146E-03	3.163E-03	4.147E-03	5.129E-03	5.747E-03	6.620E-03	7.421E-03	7.912E-03
.4500 -	.4250	8.548E-04	1.728E-03	2.710E-03	3.819E-03	4.929E-03	6.038E-03	6.893E-03	7.839E-03	8.530E-03	9.330E-03
.4250 -	.4000	1.000E-03	2.183E-03	3.492E-03	4.638E-03	5.638E-03	6.948E-03	8.185E-03	9.149E-03	9.858E-03	1.064E-02
.4000 -	.3750	1.200E-03	2.237E-03	3.801E-03	4.947E-03	6.202E-03	7.512E-03	8.949E-03	1.022E-02	1.126E-02	1.211E-02
.3750 -	.3500	9.640E-04	2.146E-03	3.692E-03	5.820E-03	7.402E-03	9.054E-03	1.080E-02	1.233E-02	1.371E-02	1.491E-02
.3500 -	.3250	1.328E-03	3.037E-03	5.020E-03	7.053E-03	8.694E-03	1.135E-02	1.326E-02	1.530E-02	1.719E-02	1.868E-02
.3250 -	.3000	1.400E-03	3.528E-03	5.820E-03	7.803E-03	1.000E-02	1.200E-02	1.384E-02	1.608E-02	1.797E-02	1.984E-02
.3000 -	.2750	1.673E-03	4.220E-03	6.566E-03	9.403E-03	1.222E-02	1.510E-02	1.750E-02	2.044E-02	2.263E-02	2.488E-02
.2750 -	.2500	2.273E-03	4.692E-03	7.566E-03	1.089E-02	1.420E-02	1.748E-02	2.079E-02	2.399E-02	2.712E-02	2.979E-02
.2500 -	.2250	2.455E-03	5.275E-03	8.767E-03	1.233E-02	1.584E-02	1.975E-02	2.297E-02	2.668E-02	3.032E-02	3.328E-02
.2250 -	.2000	3.183E-03	6.857E-03	1.129E-02	1.624E-02	2.163E-02	2.626E-02	3.041E-02	3.510E-02	3.969E-02	4.351E-02
.2000 -	.1750	3.874E-03	8.530E-03	1.393E-02	1.972E-02	2.594E-02	3.117E-02	3.647E-02	4.209E-02	4.782E-02	5.209E-02
.1750 -	.1500	4.001E-03	9.840E-03	1.671E-02	2.390E-02	3.025E-02	3.725E-02	4.393E-02	5.044E-02	5.699E-02	6.344E-02
.1500 -	.1250	5.929E-03	1.353E-02	2.204E-02	3.072E-02	3.636E-02	4.769E-02	5.604E-02	6.363E-02	7.154E-02	7.907E-02
.1250 -	.1000	8.421E-03	1.764E-02	2.854E-02	3.971E-02	4.958E-02	6.051E-02	7.121E-02	8.083E-02	8.993E-02	9.839E-02

E₀ = 600keV

ENERGY SPECTRA AND ANGLAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .11851 * ELECTRON CSDA RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.6010 -	.5990	0.	0.	0.	0.	0.	0.	0.	0.	0.
.5990 -	.5900	0.	0.	9.453E-04	0.	5.634E-04	5.060E-05	7.765E-05	0.	3.107E-05
.5900 -	.5750	0.	1.509E-03	1.134E-03	1.108E-03	2.415E-04	2.732E-04	2.329E-04	2.400E-04	7.456E-05
.5750 -	.5500	0.	9.057E-04	1.021E-03	1.157E-03	8.693E-04	6.193E-04	3.774E-04	3.001E-04	1.901E-04
.5500 -	.5250	0.	0.	1.021E-03	1.556E-03	7.823E-04	7.286E-04	5.451E-04	2.881E-04	3.914E-04
.5250 -	.5000	4.752E-03	1.811E-03	1.021E-03	1.157E-03	5.540E-03	9.472E-04	8.805E-04	7.321E-04	5.704E-04
.5000 -	.4750	0.	2.717E-03	1.701E-03	2.354E-03	1.623E-03	1.129E-03	7.967E-04	9.362E-04	4.809E-04
.4750 -	.4500	0.	1.811E-03	1.021E-03	2.261E-03	2.028E-03	1.639E-03	1.230E-03	1.116E-03	8.053E-04
.4500 -	.4250	0.	4.528E-03	3.063E-03	2.354E-03	2.318E-03	1.949E-03	1.551E-03	1.200E-03	9.283E-04
.4250 -	.4000	0.	3.623E-03	3.403E-03	1.955E-03	2.724E-03	2.222E-03	1.617E-03	1.248E-03	1.186E-03
.4000 -	.3750	4.752E-03	3.623E-03	1.701E-03	2.753E-03	2.695E-03	2.477E-03	2.166E-03	1.560E-03	1.353E-03
.3750 -	.3500	4.752E-03	4.528E-03	4.424E-03	3.950E-03	3.535E-03	3.257E-03	2.069E-03	1.824E-03	1.875E-03
.3500 -	.3250	4.752E-03	7.246E-03	7.487E-03	4.123E-03	4.217E-03	3.771E-03	2.865E-03	2.640E-03	2.058E-03
.3250 -	.3000	9.504E-03	3.623E-03	4.084E-03	3.950E-03	4.491E-03	3.771E-03	3.564E-03	2.700E-03	2.248E-03
.3000 -	.2750	4.752E-03	5.434E-03	4.424E-03	6.917E-03	6.462E-03	5.046E-03	3.634E-03	3.589E-03	2.651E-03
.2750 -	.2500	4.752E-03	6.340E-03	9.528E-03	6.918E-03	7.699E-03	5.209E-03	5.018E-03	4.141E-03	3.523E-03
.2500 -	.2250	4.752E-03	5.434E-03	7.827E-03	9.444E-03	7.447E-03	6.594E-03	5.437E-03	4.717E-03	2.669E-03
.2250 -	.2000	1.426E-02	2.355E-02	1.399E-02	1.157E-02	9.504E-03	8.525E-03	7.268E-03	6.265E-03	4.407E-03
.2000 -	.1750	4.752E-03	1.902E-02	1.429E-02	1.224E-02	1.269E-02	1.005E-02	8.931E-03	7.550E-03	5.033E-03
.1750 -	.1500	1.901E-02	1.359E-02	1.599E-02	1.809E-02	1.530E-02	1.251E-02	1.080E-02	9.062E-03	5.827E-03
.1500 -	.1250	9.504E-03	2.264E-02	2.240E-02	2.128E-02	2.026E-02	1.951E-02	1.371E-02	1.091E-02	7.248E-03
.1250 -	.1000	3.326E-02	3.260E-02	2.859E-02	3.113E-02	2.559E-02	2.008E-02	1.754E-02	1.395E-02	7.226E-03
INTEGRAL (1/SR),		3.089E-03	4.098E-03	3.701E-03	3.665E-03	3.400E-03	2.669E-03	2.259E-03	1.872E-03	1.293E-03

$E_0 = 600\text{keV}$

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
6.010E-01	5.990E-01	0.
5.990E-01	5.900E-01	6.02475E-04
5.900E-01	5.750E-01	1.37273E-03
5.750E-01	5.500E-01	2.40781E-03
5.500E-01	5.250E-01	2.78794E-03
5.250E-01	5.000E-01	6.32722E-03
5.000E-01	4.750E-01	4.84163E-03
4.750E-01	4.500E-01	6.38060E-03
4.500E-01	4.250E-01	7.50034E-03
4.250E-01	4.000E-01	8.68956E-03
4.000E-01	3.750E-01	9.76382E-03
3.750E-01	3.500E-01	1.18399E-02
3.500E-01	3.250E-01	1.47793E-02
3.250E-01	3.000E-01	1.56433E-02
3.000E-01	2.750E-01	1.96286E-02
2.750E-01	2.500E-01	2.33292E-02
2.500E-01	2.250E-01	2.60644E-02
2.250E-01	2.000E-01	3.42275E-02
2.000E-01	1.750E-01	4.10599E-02
1.750E-01	1.500E-01	4.94049E-02
1.500E-01	1.250E-01	6.22365E-02
1.250E-01	1.000E-01	7.82836E-02

$E_0 = 700\text{keV}$

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0098	.0195	.0293	.0391	.0489	.0586	.0684	.0782	.0880	.0977
.7010 -	.6990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.6990 -	.6900	1.057E-04	1.097E-04	1.645E-04	1.645E-04	1.645E-04	1.645E-04	1.645E-04	1.645E-04	1.645E-04	1.645E-04
.6900 -	.6750	2.632E-04	5.592E-04	6.579E-04	8.553E-04	9.540E-04	1.053E-03	1.086E-03	1.053E-03	1.053E-03	1.053E-03
.6750 -	.6500	2.566E-04	6.119E-04	9.869E-04	1.342E-03	1.559E-03	1.757E-03	1.934E-03	1.994E-03	2.072E-03	2.092E-03
.6500 -	.6250	3.158E-04	6.908E-04	1.165E-03	1.500E-03	1.717E-03	1.954E-03	2.250E-03	2.428E-03	2.605E-03	2.724E-03
.6250 -	.6000	3.750E-04	7.895E-04	1.105E-03	1.559E-03	1.954E-03	2.309E-03	2.665E-03	2.921E-03	3.217E-03	3.434E-03
.6000 -	.5750	5.724E-04	1.066E-03	1.638E-03	2.171E-03	2.680E-03	3.233E-03	3.928E-03	4.441E-03	4.836E-03	5.053E-03
.5750 -	.5500	3.948E-04	1.007E-03	1.790E-03	2.645E-03	3.198E-03	3.809E-03	4.520E-03	4.895E-03	5.325E-03	5.724E-03
.5500 -	.5250	7.303E-04	1.342E-03	1.875E-03	2.369E-03	3.079E-03	3.652E-03	4.382E-03	4.994E-03	5.625E-03	5.961E-03
.5250 -	.5000	8.093E-04	1.658E-03	2.526E-03	3.158E-03	4.066E-03	4.777E-03	5.875E-03	6.527E-03	7.277E-03	7.849E-03
.5000 -	.4750	7.698E-04	1.480E-03	2.270E-03	3.276E-03	4.184E-03	5.211E-03	6.060E-03	7.007E-03	8.093E-03	8.803E-03
.4750 -	.4500	8.290E-04	1.678E-03	2.645E-03	3.828E-03	5.053E-03	6.000E-03	7.165E-03	8.014E-03	8.981E-03	9.672E-03
.4500 -	.4250	9.869E-04	1.796E-03	3.020E-03	4.283E-03	5.645E-03	6.928E-03	8.270E-03	9.573E-03	1.092E-02	1.208E-02
.4250 -	.4000	1.026E-03	2.112E-03	3.079E-03	4.362E-03	5.682E-03	7.303E-03	8.310E-03	9.494E-03	1.072E-02	1.156E-02
.4000 -	.3750	1.382E-03	2.566E-03	3.790E-03	5.448E-03	7.303E-03	8.941E-03	1.088E-02	1.283E-02	1.421E-02	1.553E-02
.3750 -	.3500	1.362E-03	2.783E-03	4.244E-03	6.079E-03	7.675E-03	9.711E-03	1.163E-02	1.352E-02	1.532E-02	1.668E-02
.3500 -	.3250	1.322E-03	2.546E-03	4.579E-03	6.573E-03	8.724E-03	1.153E-02	1.376E-02	1.615E-02	1.806E-02	2.001E-02
.3250 -	.3000	1.678E-03	3.928E-03	6.138E-03	8.487E-03	1.072E-02	1.320E-02	1.559E-02	1.816E-02	2.088E-02	2.309E-02
.3000 -	.2750	2.171E-03	4.362E-03	6.908E-03	1.011E-02	1.269E-02	1.553E-02	1.883E-02	2.189E-02	2.463E-02	2.730E-02
.2750 -	.2500	2.072E-03	4.441E-03	7.165E-03	1.030E-02	1.330E-02	1.731E-02	2.116E-02	2.428E-02	2.795E-02	3.103E-02
.2500 -	.2250	3.158E-03	6.553E-03	1.069E-02	1.382E-02	1.780E-02	2.181E-02	2.554E-02	2.909E-02	3.281E-02	3.660E-02
.2250 -	.2000	3.691E-03	7.540E-03	1.214E-02	1.626E-02	2.100E-02	2.548E-02	3.109E-02	3.618E-02	4.076E-02	4.514E-02
.2000 -	.1750	4.224E-03	9.376E-03	1.520E-02	2.059E-02	2.682E-02	3.217E-02	3.802E-02	4.327E-02	4.881E-02	5.444E-02
.1750 -	.1500	4.619E-03	1.068E-02	1.705E-02	2.359E-02	3.040E-02	3.752E-02	4.423E-02	5.114E-02	5.827E-02	6.447E-02
.1500 -	.1250	6.612E-03	1.386E-02	2.181E-02	2.954E-02	3.865E-02	4.714E-02	5.604E-02	6.522E-02	7.430E-02	8.249E-02
.1250 -	.1000	7.875E-03	1.676E-02	2.740E-02	3.758E-02	4.844E-02	5.892E-02	6.974E-02	7.933E-02	8.974E-02	9.933E-02

E₀=700keV

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .09773 * ELECTRON CS/CM RANGE = 4.962E-02 G/CM2
(NUMBER/(MEV*SR)), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	5.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.7010 -	.6990	0.	0.	0.	0.	0.	0.	0.	0.	0.
.6990 -	.6900	0.	0.	0.	0.	8.735E-05	1.098E-04	0.	0.	0.
.6900 -	.6750	8.595E-03	0.	0.	1.684E-03	2.096E-04	2.636E-04	1.264E-04	1.085E-04	4.046E-05
.6750 -	.6500	0.	1.966E-03	1.846E-03	1.010E-03	5.031E-04	6.326E-04	3.034E-04	2.084E-04	9.710E-05
.6500 -	.6250	0.	0.	1.108E-03	1.010E-03	1.006E-03	6.326E-04	3.185E-04	2.345E-04	3.034E-04
.6250 -	.6000	0.	1.966E-03	7.386E-04	1.010E-03	8.176E-04	7.116E-04	6.371E-04	4.038E-04	3.398E-04
.6000 -	.5750	0.	6.880E-03	2.216E-03	2.165E-03	1.604E-03	8.895E-04	7.584E-04	5.731E-04	4.612E-04
.5750 -	.5500	5.157E-03	9.829E-04	7.386E-04	1.877E-03	1.725E-03	8.658E-04	9.707E-04	7.424E-04	6.433E-04
.5500 -	.5250	5.157E-03	3.931E-03	1.477E-03	2.558E-03	1.572E-03	1.087E-03	9.556E-04	6.903E-04	6.676E-04
.5250 -	.5000	0.	2.949E-03	3.693E-03	2.743E-03	1.518E-03	3.716E-03	1.359E-03	9.769E-04	6.554E-04
.5000 -	.4750	0.	3.931E-03	2.585E-03	2.310E-03	1.729E-03	1.838E-03	1.517E-03	1.211E-03	9.467E-04
.4750 -	.4500	0.	1.966E-03	2.216E-03	3.753E-03	2.524E-03	1.956E-03	1.168E-03	1.303E-03	1.032E-03
.4500 -	.4250	0.	3.931E-03	4.432E-03	3.609E-03	3.365E-03	2.234E-03	1.881E-03	1.511E-03	1.347E-03
.4250 -	.4000	5.157E-03	3.931E-03	6.278E-03	3.753E-03	3.015E-03	2.352E-03	1.941E-03	1.550E-03	1.165E-03
.4000 -	.3750	1.031E-02	5.897E-03	5.909E-03	5.918E-03	3.805E-03	3.103E-03	2.427E-03	2.006E-03	1.578E-03
.3750 -	.3500	5.157E-03	6.880E-03	5.909E-03	4.166E-03	4.402E-03	2.985E-03	2.867E-03	2.188E-03	1.748E-03
.3500 -	.3250	5.157E-03	1.179E-02	7.755E-03	4.908E-03	5.163E-03	3.914E-03	3.034E-03	2.709E-03	2.173E-03
.3250 -	.3000	2.063E-02	9.829E-03	6.278E-03	5.630E-03	5.629E-03	4.981E-03	3.883E-03	2.879E-03	2.330E-03
.3000 -	.2750	0.	6.880E-03	9.571E-03	8.517E-03	6.667E-03	5.456E-03	4.793E-03	3.426E-03	2.707E-03
.2750 -	.2500	0.	4.914E-03	8.863E-03	1.025E-02	8.364E-03	5.555E-03	5.339E-03	3.960E-03	3.265E-03
.2500 -	.2250	1.031E-02	1.769E-02	1.366E-02	1.039E-02	9.717E-03	7.294E-03	5.673E-03	4.950E-03	3.557E-03
.2250 -	.2000	1.547E-02	1.573E-02	1.594E-02	1.545E-02	1.179E-02	9.825E-03	6.856E-03	5.848E-03	4.054E-03
.2000 -	.1750	2.578E-02	2.359E-02	2.290E-02	1.750E-02	1.409E-02	1.095E-02	8.676E-03	7.203E-03	5.050E-03
.1750 -	.1500	1.547E-02	2.457E-02	2.290E-02	2.223E-02	1.657E-02	1.313E-02	1.042E-02	8.389E-03	6.070E-03
.1500 -	.1250	2.063E-02	3.834E-02	2.844E-02	2.815E-02	2.123E-02	1.722E-02	1.329E-02	1.102E-02	7.235E-03
.1250 -	.1000	4.125E-02	3.243E-02	3.767E-02	3.624E-02	2.642E-02	2.123E-02	1.652E-02	1.335E-02	7.405E-03
INTEGRAL (1/SR):		4.770E-03	5.775E-03	5.438E-03	4.915E-03	3.852E-03	3.070E-03	2.391E-03	1.935E-03	1.371E-03

$$E_0 = 700 \text{ keV}$$

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
7.010E-01	6.990E-01	0.
6.990E-01	6.900E-01	1.62838E-04
6.900E-01	6.750E-01	1.00778E-03
6.750E-01	6.500E-01	1.88201E-03
6.500E-01	6.250E-01	2.32147E-03
6.250E-01	6.000E-01	2.82499E-03
6.000E-01	5.750E-01	4.20980E-03
5.750E-01	5.500E-01	4.69437E-03
5.500E-01	5.250E-01	4.82483E-03
5.250E-01	5.000E-01	7.83664E-03
5.000E-01	4.750E-01	6.90314E-03
4.750E-01	4.500E-01	7.75872E-03
4.500E-01	4.250E-01	9.37758E-03
4.250E-01	4.000E-01	9.34200E-03
4.000E-01	3.750E-01	1.21996E-02
3.750E-01	3.500E-01	1.30977E-02
3.500E-01	3.250E-01	1.54996E-02
3.250E-01	3.000E-01	1.79159E-02
3.000E-01	2.750E-01	2.12749E-02
2.750E-01	2.500E-01	2.38558E-02
2.500E-01	2.250E-01	2.85951E-02
2.250E-01	2.000E-01	3.51694E-02
2.000E-01	1.750E-01	4.25314E-02
1.750E-01	1.500E-01	5.01995E-02
1.500E-01	1.250E-01	6.40101E-02
1.250E-01	1.000E-01	7.78315E-02

E₀ = 800 keV

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0083	.0166	.0249	.0332	.0416	.0499	.0582	.0665	.0748	.0831
.8010 -	.7990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.7990 -	.7900	6.794E-05	2.018E-04	2.038E-04	2.038E-04	2.038E-04	2.038E-04	2.038E-04	2.038E-04	2.038E-04	2.038E-04
.7900 -	.7750	2.038E-04	2.261E-04	4.892E-04	6.930E-04	7.338E-04	8.153E-04	8.561E-04	8.968E-04	8.968E-04	9.376E-04
.7750 -	.7500	1.957E-04	3.424E-04	5.870E-04	7.093E-04	9.050E-04	1.052E-03	1.198E-03	1.272E-03	1.272E-03	1.345E-03
.7500 -	.7250	2.690E-04	5.381E-04	8.316E-04	1.150E-03	1.345E-03	1.541E-03	1.834E-03	2.006E-03	2.201E-03	2.324E-03
.7250 -	.7000	2.690E-04	5.870E-04	8.561E-04	1.174E-03	1.541E-03	1.761E-03	2.055E-03	2.275E-03	2.593E-03	2.764E-03
.7000 -	.6750	2.935E-04	6.359E-04	9.539E-04	1.223E-03	1.492E-03	1.834E-03	2.128E-03	2.421E-03	2.569E-03	2.813E-03
.6750 -	.6500	4.647E-04	9.539E-04	1.370E-03	1.957E-03	2.446E-03	2.886E-03	3.302E-03	4.011E-03	4.354E-03	4.721E-03
.6500 -	.6250	5.381E-04	1.101E-03	1.908E-03	2.324E-03	3.057E-03	3.644E-03	4.036E-03	4.476E-03	4.819E-03	5.136E-03
.6250 -	.6000	5.870E-04	9.539E-04	1.492E-03	2.103E-03	2.495E-03	3.302E-03	3.840E-03	4.378E-03	4.867E-03	5.454E-03
.6000 -	.5750	2.690E-04	8.071E-04	1.468E-03	2.152E-03	2.911E-03	3.644E-03	4.525E-03	5.332E-03	6.164E-03	6.751E-03
.5750 -	.5500	6.849E-04	1.321E-03	2.226E-03	3.057E-03	3.742E-03	4.500E-03	5.357E-03	6.115E-03	6.824E-03	7.387E-03
.5500 -	.5250	4.892E-04	1.247E-03	1.834E-03	2.568E-03	3.229E-03	3.816E-03	4.914E-03	5.895E-03	6.628E-03	7.436E-03
.5250 -	.5000	7.093E-04	1.492E-03	2.421E-03	3.375E-03	4.329E-03	5.454E-03	6.555E-03	7.533E-03	8.732E-03	9.637E-03
.5000 -	.4750	7.582E-04	1.639E-03	2.617E-03	3.473E-03	4.647E-03	6.090E-03	7.166E-03	8.267E-03	9.123E-03	9.979E-03
.4750 -	.4500	9.784E-04	1.859E-03	3.082E-03	4.011E-03	5.479E-03	6.457E-03	7.925E-03	9.123E-03	1.067E-02	1.152E-02
.4500 -	.4250	1.052E-03	2.055E-03	3.155E-03	4.476E-03	5.846E-03	7.558E-03	8.512E-03	1.022E-02	1.167E-02	1.289E-02
.4250 -	.4000	9.784E-04	2.103E-03	3.669E-03	5.357E-03	6.702E-03	8.341E-03	1.010E-02	1.130E-02	1.265E-02	1.397E-02
.4000 -	.3750	1.272E-03	2.617E-03	4.134E-03	5.992E-03	7.802E-03	9.369E-03	1.098E-02	1.238E-02	1.438E-02	1.597E-02
.3750 -	.3500	1.468E-03	3.180E-03	4.696E-03	7.440E-03	9.417E-03	1.150E-02	1.377E-02	1.578E-02	1.751E-02	1.942E-02
.3500 -	.3250	1.272E-03	2.960E-03	4.892E-03	7.215E-03	9.099E-03	1.137E-02	1.321E-02	1.529E-02	1.744E-02	1.949E-02
.3250 -	.3000	1.688E-03	3.302E-03	5.944E-03	8.487E-03	1.086E-02	1.338E-02	1.631E-02	1.891E-02	2.201E-02	2.419E-02
.3000 -	.2750	2.079E-03	4.672E-03	6.873E-03	9.906E-03	1.304E-02	1.575E-02	1.866E-02	2.187E-02	2.514E-02	2.791E-02
.2750 -	.2500	2.519E-03	4.794E-03	7.680E-03	1.137E-02	1.463E-02	1.810E-02	2.182E-02	2.502E-02	2.837E-02	3.172E-02
.2500 -	.2250	2.744E-03	6.433E-03	1.013E-02	1.375E-02	1.795E-02	2.240E-02	2.686E-02	3.146E-02	3.574E-02	3.948E-02
.2250 -	.2000	3.057E-03	6.807E-03	1.128E-02	1.617E-02	2.059E-02	2.588E-02	3.033E-02	3.510E-02	3.992E-02	4.439E-02
.2000 -	.1750	4.549E-03	9.466E-03	1.414E-02	1.900E-02	2.478E-02	3.070E-02	3.627E-02	4.279E-02	4.841E-02	5.494E-02
.1750 -	.1500	5.087E-03	1.106E-02	1.761E-02	2.522E-02	3.246E-02	3.980E-02	4.687E-02	5.442E-02	6.228E-02	6.974E-02
.1500 -	.1250	6.971E-03	1.448E-02	2.209E-02	3.028E-02	3.982E-02	5.014E-02	5.919E-02	6.739E-02	7.561E-02	8.368E-02
.1250 -	.1000	8.463E-03	1.729E-02	2.764E-02	3.909E-02	4.963E-02	6.181E-02	7.277E-02	8.187E-02	9.130E-02	1.016E-01

$E_0 = 800 \text{ keV}$

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .00310 * ELECTRON DENSITY RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR)), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
.0010 -	.7990	0.	0.	0.	0.	0.	0.	0.	0.	0.
.7990 -	.7900	0.	0.	0.	4.969E-04	1.082E-04	6.904E-05	0.	0.	0.
.7900 -	.7750	1.065E-02	0.	0.	2.981E-04	3.897E-04	2.858E-04	1.253E-04	8.070E-05	2.507E-05
.7750 -	.7500	0.	0.	4.576E-04	8.944E-04	7.014E-04	2.450E-04	1.692E-04	1.453E-04	4.512E-05
.7500 -	.7250	0.	0.	9.153E-04	1.073E-03	5.845E-04	4.654E-04	3.750E-04	3.389E-04	1.805E-04
.7250 -	.7000	0.	0.	9.153E-04	7.155E-04	8.573E-04	6.369E-04	3.195E-04	3.712E-04	2.858E-04
.7000 -	.6750	6.390E-03	1.218E-03	4.576E-04	1.789E-03	5.066E-04	6.859E-04	3.947E-04	4.035E-04	2.254E-04
.6750 -	.6500	0.	3.654E-03	2.746E-03	2.504E-03	1.520E-03	1.151E-03	5.263E-04	5.145E-04	3.410E-04
.6500 -	.6250	0.	2.436E-03	3.203E-03	2.504E-03	1.520E-03	1.225E-03	5.827E-04	6.133E-04	4.362E-04
.6250 -	.6000	0.	2.436E-03	3.661E-03	2.504E-03	1.476E-03	1.102E-03	8.270E-04	5.811E-04	4.663E-04
.6000 -	.5750	0.	2.436E-03	3.661E-03	2.325E-03	1.476E-03	1.543E-03	1.071E-03	6.133E-04	7.821E-04
.5750 -	.5500	0.	2.436E-03	1.373E-03	3.220E-03	2.065E-03	1.494E-03	1.071E-03	9.684E-04	7.210E-04
.5500 -	.5250	0.	1.218E-03	1.831E-03	2.862E-03	1.715E-03	1.935E-03	9.774E-04	1.114E-03	5.864E-04
.5250 -	.5000	0.	2.436E-03	4.119E-03	4.651E-03	2.689E-03	1.862E-03	1.654E-03	1.275E-03	6.768E-04
.5000 -	.4750	0.	8.526E-03	6.864E-03	2.147E-03	3.156E-03	2.033E-03	1.560E-03	1.045E-03	9.175E-04
.4750 -	.4500	6.390E-03	3.654E-03	3.203E-03	3.756E-03	2.922E-03	2.450E-03	2.040E-03	1.324E-03	1.098E-03
.4500 -	.4250	1.278E-02	4.872E-03	4.119E-03	4.830E-03	3.624E-03	2.915E-03	2.030E-03	1.517E-03	1.060E-03
.4250 -	.4000	0.	4.872E-03	6.407E-03	5.903E-03	4.247E-03	2.572E-03	2.237E-03	1.808E-03	1.120E-03
.4000 -	.3750	0.	4.872E-03	3.651E-03	6.082E-03	5.572E-03	3.184E-03	2.331E-03	1.953E-03	1.139E-03
.3750 -	.3500	0.	7.308E-03	7.322E-03	6.618E-03	5.962E-03	3.944E-03	2.895E-03	2.534E-03	1.454E-03
.3500 -	.3250	1.917E-02	4.872E-03	6.854E-03	5.903E-03	5.338E-03	3.944E-03	2.951E-03	2.599E-03	1.895E-03
.3250 -	.3000	6.390E-03	6.090E-03	1.007E-02	7.513E-03	7.476E-03	4.973E-03	3.684E-03	3.115E-03	1.955E-03
.3000 -	.2750	1.278E-02	8.526E-03	1.327E-02	8.049E-03	7.476E-03	6.271E-03	4.060E-03	3.470E-03	2.617E-03
.2750 -	.2500	6.390E-03	1.218E-02	1.281E-02	1.002E-02	8.412E-03	6.393E-03	5.075E-03	3.800E-03	3.144E-03
.2500 -	.2250	0.	1.705E-02	1.556E-02	1.324E-02	1.150E-02	8.158E-03	6.428E-03	4.697E-03	3.475E-03
.2250 -	.2000	1.917E-02	1.949E-02	1.831E-02	1.664E-02	1.204E-02	8.917E-03	7.406E-03	5.363E-03	3.984E-03
.2000 -	.1750	2.556E-02	2.071E-02	1.922E-02	2.021E-02	1.613E-02	1.154E-02	8.064E-03	6.608E-03	5.120E-03
.1750 -	.1500	3.195E-02	2.801E-02	2.929E-02	2.504E-02	1.948E-02	1.541E-02	1.075E-02	9.040E-03	5.388E-03
.1500 -	.1250	7.029E-02	3.654E-02	2.792E-02	2.665E-02	2.486E-02	1.788E-02	1.353E-02	1.067E-02	6.333E-03
.1250 -	.1000	5.112E-02	3.532E-02	4.531E-02	3.542E-02	3.012E-02	2.170E-02	1.658E-02	1.338E-02	6.755E-03
INTEGRAL (/SR).		6.870E-03	6.029E-03	6.338E-03	5.586E-03	4.618E-03	3.371E-03	2.492E-03	2.002E-03	1.317E-03

E₀=800keV

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
8.010E-01	7.990E-01	0.
7.990E-01	7.900E-01	2.01787E-04
7.900E-01	7.750E-01	8.46893E-04
7.750E-01	7.500E-01	1.17061E-03
7.500E-01	7.250E-01	1.92994E-03
7.250E-01	7.000E-01	2.23910E-03
7.000E-01	6.750E-01	2.28496E-03
6.750E-01	6.500E-01	3.78014E-03
6.500E-01	6.250E-01	4.27409E-03
6.250E-01	6.000E-01	4.26430E-03
6.000E-01	5.750E-01	5.18873E-03
5.750E-01	5.500E-01	5.90660E-03
5.500E-01	5.250E-01	5.68366E-03
5.250E-01	5.000E-01	7.45266E-03
5.000E-01	4.750E-01	7.88509E-03
4.750E-01	4.500E-01	8.96055E-03
4.500E-01	4.250E-01	9.98429E-03
4.250E-01	4.000E-01	1.09858E-02
4.000E-01	3.750E-01	1.24074E-02
3.750E-01	3.500E-01	1.52294E-02
3.500E-01	3.250E-01	1.50859E-02
3.250E-01	3.000E-01	1.86788E-02
3.000E-01	2.750E-01	2.15530E-02
2.750E-01	2.500E-01	2.45270E-02
2.500E-01	2.250E-01	3.06293E-02
2.250E-01	2.000E-01	3.44397E-02
2.000E-01	1.750E-01	4.19645E-02
1.750E-01	1.500E-01	5.37689E-02
1.500E-01	1.250E-01	6.55966E-02
1.250E-01	1.000E-01	7.98871E-02

E₀=900keV

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0072	.0145	.0217	.0289	.0361	.0434	.0506	.0578	.0651	.0723
.9010 -	.8990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.8990 -	.8900	2.134E-04	1.423E-04	1.423E-04	2.134E-04	2.134E-04	2.134E-04	2.134E-04	2.134E-04	2.134E-04	2.134E-04
.8900 -	.8750	8.535E-05	1.280E-04	2.987E-04	3.414E-04	3.841E-04	4.268E-04	4.268E-04	4.268E-04	4.268E-04	4.268E-04
.8750 -	.8500	2.817E-04	7.170E-04	9.474E-04	1.203E-03	1.434E-03	1.511E-03	1.588E-03	1.690E-03	1.716E-03	1.741E-03
.8500 -	.8250	2.561E-04	5.377E-04	7.938E-04	1.024E-03	1.178E-03	1.357E-03	1.664E-03	1.895E-03	2.023E-03	2.100E-03
.8250 -	.8000	2.817E-04	6.401E-04	8.962E-04	1.075E-03	1.434E-03	1.588E-03	1.664E-03	1.844E-03	2.048E-03	2.151E-03
.8000 -	.7750	2.305E-04	5.377E-04	7.938E-04	1.050E-03	1.511E-03	1.767E-03	1.997E-03	2.253E-03	2.586E-03	2.791E-03
.7750 -	.7500	2.305E-04	5.633E-04	6.194E-04	1.024E-03	1.408E-03	1.997E-03	2.279E-03	2.535E-03	2.863E-03	2.919E-03
.7500 -	.7250	3.329E-04	7.938E-04	1.024E-03	1.485E-03	1.844E-03	2.279E-03	2.458E-03	2.740E-03	2.996E-03	3.252E-03
.7250 -	.7000	3.329E-04	7.426E-04	1.178E-03	1.741E-03	2.176E-03	2.649E-03	3.175E-03	3.662E-03	4.097E-03	4.558E-03
.7000 -	.6750	3.841E-04	8.194E-04	1.101E-03	1.792E-03	2.253E-03	2.714E-03	3.098E-03	3.508E-03	4.122E-03	4.737E-03
.6750 -	.6500	5.889E-04	1.024E-03	1.767E-03	2.279E-03	2.714E-03	3.329E-03	4.174E-03	5.686E-03	5.900E-03	5.966E-03
.6500 -	.6250	3.585E-04	8.450E-04	1.434E-03	2.176E-03	3.021E-03	3.585E-03	4.174E-03	5.788E-03	5.949E-03	5.992E-03
.6250 -	.6000	4.609E-04	9.474E-04	1.562E-03	2.253E-03	2.817E-03	3.380E-03	4.251E-03	5.993E-03	5.992E-03	6.657E-03
.6000 -	.5750	5.633E-04	1.357E-03	2.074E-03	2.791E-03	3.713E-03	4.635E-03	5.352E-03	6.094E-03	6.709E-03	7.605E-03
.5750 -	.5500	7.170E-04	1.511E-03	2.458E-03	3.252E-03	4.122E-03	5.019E-03	5.633E-03	6.478E-03	7.067E-03	7.784E-03
.5500 -	.5250	6.401E-04	1.485E-03	2.125E-03	2.996E-03	3.943E-03	4.891E-03	5.787E-03	6.504E-03	7.451E-03	8.373E-03
.5250 -	.5000	6.145E-04	1.511E-03	2.381E-03	3.559E-03	4.865E-03	5.992E-03	9.295E-03	1.019E-02	1.119E-02	1.219E-02
.5000 -	.4750	7.682E-04	1.972E-03	2.791E-03	3.943E-03	4.993E-03	6.273E-03	7.195E-03	8.296E-03	9.474E-03	1.022E-02
.4750 -	.4500	9.218E-04	1.792E-03	2.663E-03	4.071E-03	5.377E-03	6.760E-03	7.989E-03	9.244E-03	1.058E-02	1.211E-02
.4500 -	.4250	1.203E-03	2.202E-03	3.303E-03	4.660E-03	6.094E-03	7.579E-03	8.988E-03	1.032E-02	1.180E-02	1.285E-02
.4250 -	.4000	8.962E-04	2.381E-03	3.918E-03	5.480E-03	6.991E-03	8.322E-03	1.034E-02	1.196E-02	1.362E-02	1.554E-02
.4000 -	.3750	1.306E-03	2.842E-03	4.455E-03	6.427E-03	8.322E-03	1.009E-02	1.173E-02	1.349E-02	1.580E-02	1.785E-02
.3750 -	.3500	1.536E-03	2.868E-03	4.455E-03	6.453E-03	8.578E-03	1.040E-02	1.262E-02	1.511E-02	1.703E-02	1.936E-02
.3500 -	.3250	1.613E-03	3.303E-03	5.608E-03	7.170E-03	9.474E-03	1.214E-02	1.416E-02	1.626E-02	1.854E-02	2.066E-02
.3250 -	.3000	1.946E-03	4.020E-03	6.504E-03	8.936E-03	1.155E-02	1.444E-02	1.746E-02	2.015E-02	2.317E-02	2.648E-02
.3000 -	.2750	1.895E-03	4.225E-03	6.581E-03	9.295E-03	1.234E-02	1.521E-02	1.851E-02	2.192E-02	2.566E-02	2.863E-02
.2750 -	.2500	2.023E-03	4.942E-03	7.938E-03	1.145E-02	1.541E-02	1.887E-02	2.281E-02	2.701E-02	3.070E-02	3.426E-02
.2500 -	.2250	3.380E-03	6.811E-03	1.029E-02	1.444E-02	1.846E-02	2.289E-02	2.750E-02	3.211E-02	3.646E-02	4.046E-02
.2250 -	.2000	3.713E-03	7.426E-03	1.198E-02	1.659E-02	2.156E-02	2.650E-02	3.142E-02	3.736E-02	4.243E-02	4.709E-02
.2000 -	.1750	4.583E-03	9.141E-03	1.403E-02	2.025E-02	2.596E-02	3.170E-02	3.792E-02	4.394E-02	5.009E-02	5.633E-02
.1750 -	.1500	5.633E-03	1.203E-02	1.841E-02	2.530E-02	3.180E-02	3.920E-02	4.573E-02	5.321E-02	6.135E-02	6.809E-02
.1500 -	.1250	6.069E-03	1.362E-02	2.200E-02	3.039E-02	3.820E-02	4.650E-02	5.608E-02	6.535E-02	7.418E-02	8.207E-02
.1250 -	.1000	8.757E-03	1.828E-02	2.812E-02	3.851E-02	4.998E-02	6.076E-02	7.272E-02	8.453E-02	9.785E-02	1.055E-01

$E_0 = 900 \text{ keV}$

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .07228 * ELECTRON CSDA RANGE = 4.902E-02 G/CM2
(NUMBER/(MEV*SR)), NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA =	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000	
.9010 -	.8990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.8990 -	.8900	0.	0.	0.	0.	2.266E-04	0.	5.466E-05	0.	0.	0.
.8900 -	.8750	0.	0.	7.985E-04	0.	2.720E-04	1.282E-04	6.559E-05	0.	0.	2.624E-05
.8750 -	.8500	0.	1.275E-03	1.916E-03	1.685E-03	6.527E-04	3.590E-04	3.345E-04	3.379E-05	7.873E-05	
.8500 -	.8250	0.	1.275E-03	0.	1.124E-03	8.567E-04	4.616E-04	3.345E-04	1.859E-04	1.260E-04	
.8250 -	.8000	6.690E-03	0.	4.791E-04	1.124E-03	9.790E-04	4.359E-04	2.361E-04	1.859E-04	1.889E-04	
.8000 -	.7750	0.	0.	1.916E-03	5.618E-04	9.382E-04	7.180E-04	3.739E-04	4.704E-04	2.519E-04	
.7750 -	.7500	6.690E-03	1.275E-03	1.437E-03	1.498E-03	8.567E-04	7.180E-04	3.542E-04	4.873E-04	2.677E-04	
.7500 -	.7250	6.690E-03	2.550E-03	2.395E-03	1.124E-03	1.061E-03	5.642E-04	4.526E-04	4.055E-04	2.834E-04	
.7250 -	.7000	0.	5.100E-03	1.437E-03	1.685E-03	1.224E-03	1.154E-03	6.887E-04	4.562E-04	3.936E-04	
.7000 -	.6750	1.338E-02	2.550E-03	3.354E-03	1.685E-03	1.428E-03	9.745E-04	7.477E-04	4.900E-04	3.936E-04	
.6750 -	.6500	6.690E-03	2.550E-03	1.437E-03	2.247E-03	1.754E-03	1.308E-03	9.051E-04	1.435E-04	4.881E-04	
.6500 -	.6250	6.690E-03	0.	2.874E-03	3.558E-03	1.632E-03	1.385E-03	8.264E-04	6.759E-04	5.039E-04	
.6250 -	.6000	0.	1.275E-03	2.395E-03	2.060E-03	1.876E-03	1.692E-03	1.141E-03	9.928E-04	5.039E-04	
.6000 -	.5750	0.	1.275E-03	4.312E-03	3.932E-03	2.284E-03	1.282E-03	1.200E-03	4.462E-04	6.771E-04	
.5750 -	.5500	0.	6.375E-03	3.833E-03	2.622E-03	1.876E-03	1.821E-03	1.122E-03	4.462E-04	7.400E-04	
.5500 -	.5250	0.	6.375E-03	2.874E-03	3.371E-03	2.611E-03	1.667E-03	1.299E-03	1.014E-03	6.771E-04	
.5250 -	.5000	0.	2.550E-03	2.874E-03	5.992E-03	2.733E-03	2.128E-03	3.148E-03	4.166E-03	8.975E-04	
.5000 -	.4750	1.338E-02	6.375E-03	1.437E-03	3.932E-03	3.059E-03	1.949E-03	1.633E-03	4.301E-03	8.975E-04	
.4750 -	.4500	6.690E-03	8.925E-03	4.312E-03	3.745E-03	3.427E-03	2.436E-03	1.909E-03	4.487E-03	1.134E-03	
.4500 -	.4250	1.338E-02	1.020E-02	6.707E-03	4.682E-03	3.998E-03	2.770E-03	1.436E-03	4.605E-03	1.444E-03	
.4250 -	.4000	0.	3.825E-03	4.791E-03	6.180E-03	3.753E-03	3.282E-03	2.479E-03	4.774E-03	1.732E-03	
.4000 -	.3750	6.690E-03	1.148E-02	9.582E-03	7.490E-03	4.444E-03	3.693E-03	2.342E-03	2.281E-03	1.889E-03	
.3750 -	.3500	2.007E-02	3.825E-03	8.623E-03	8.239E-03	4.977E-03	3.949E-03	3.109E-03	4.214E-03	1.937E-03	
.3500 -	.3250	0.	7.650E-03	6.707E-03	7.865E-03	6.364E-03	4.565E-03	3.050E-03	4.197E-03	1.984E-03	
.3250 -	.3000	6.690E-03	1.658E-02	1.389E-02	8.239E-03	7.873E-03	5.744E-03	4.034E-03	4.957E-03	2.362E-03	
.3000 -	.2750	1.338E-02	1.148E-02	1.437E-02	1.067E-02	8.077E-03	6.001E-03	4.250E-03	4.447E-03	2.945E-03	
.2750 -	.2500	1.338E-02	1.913E-02	1.341E-02	1.142E-02	9.913E-03	6.590E-03	5.569E-03	4.785E-03	3.543E-03	
.2500 -	.2250	6.690E-03	1.658E-02	2.156E-02	1.386E-02	1.163E-02	6.180E-03	6.435E-03	4.816E-03	3.638E-03	
.2250 -	.2000	6.690E-03	2.550E-02	1.868E-02	1.742E-02	1.473E-02	9.591E-03	7.163E-03	5.644E-03	3.984E-03	
.2000 -	.1750	4.014E-02	2.473E-02	2.252E-02	2.116E-02	1.685E-02	1.133E-02	8.520E-03	6.827E-03	5.087E-03	
.1750 -	.1500	2.676E-02	2.933E-02	2.635E-02	2.659E-02	2.027E-02	1.467E-02	1.055E-02	8.094E-03	5.527E-03	
.1500 -	.1250	2.007E-02	3.570E-02	3.689E-02	3.221E-02	2.407E-02	1.798E-02	1.311E-02	7.633E-03	6.268E-03	
.1250 -	.1000	2.007E-02	4.464E-02	4.647E-02	4.232E-02	3.227E-02	2.336E-02	1.795E-02	1.247E-02	6.379E-03	
INTEGRAL (/SR)		6.523E-03	7.746E-03	7.258E-03	6.507E-03	4.968E-03	3.571E-03	2.669E-03	4.976E-03	1.418E-03	

$$E_0 = 900 \text{ keV}$$

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
9.010E-01	8.990E-01	0.
8.990E-01	8.900E-01	2.09468E-04
8.900E-01	8.750E-01	4.29107E-04
8.750E-01	8.500E-01	1.58972E-03
8.500E-01	8.250E-01	1.76154E-03
8.250E-01	8.000E-01	1.81467E-03
8.000E-01	7.750E-01	2.22743E-03
7.750E-01	7.500E-01	2.36147E-03
7.500E-01	7.250E-01	2.65863E-03
7.250E-01	7.000E-01	3.56020E-03
7.000E-01	6.750E-01	3.59669E-03
6.750E-01	6.500E-01	4.62193E-03
6.500E-01	6.250E-01	4.64370E-03
6.250E-01	6.000E-01	5.03521E-03
6.000E-01	5.750E-01	5.93012E-03
5.750E-01	5.500E-01	6.23688E-03
5.500E-01	5.250E-01	6.47296E-03
5.250E-01	5.000E-01	9.47547E-03
5.000E-01	4.750E-01	8.10762E-03
4.750E-01	4.500E-01	9.18318E-03
4.500E-01	4.250E-01	1.00949E-02
4.250E-01	4.000E-01	1.18224E-02
4.000E-01	3.750E-01	1.36327E-02
3.750E-01	3.500E-01	1.47149E-02
3.500E-01	3.250E-01	1.60219E-02
3.250E-01	3.000E-01	2.00723E-02
3.000E-01	2.750E-01	2.17552E-02
2.750E-01	2.500E-01	2.62993E-02
2.500E-01	2.250E-01	3.13515E-02
2.250E-01	2.000E-01	3.64054E-02
2.000E-01	1.750E-01	4.33341E-02
1.750E-01	1.500E-01	5.27751E-02
1.500E-01	1.250E-01	6.38228E-02
1.250E-01	1.000E-01	8.21562E-02

$E_0 = 1000 \text{ keV}$

ENERGY SPECTRA OF TRANSMITTED PHOTONS
(NUMBER/MEV, NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	Z/R=	.0064	.0128	.0192	.0256	.0320	.0384	.0448	.0512	.0576	.0640
1.0010	.9990	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
.9990	.9900	1.666E-04	1.666E-04	1.666E-04	1.666E-04	1.666E-04	1.666E-04	1.666E-04	1.666E-04	1.666E-04	1.666E-04
.9900	.9750	4.997E-05	1.499E-04	2.499E-04	3.498E-04	3.998E-04	3.998E-04	3.998E-04	3.998E-04	3.998E-04	3.998E-04
.9750	.9500	1.199E-04	3.498E-04	5.397E-04	6.596E-04	8.495E-04	9.294E-04	1.079E-03	1.199E-03	1.229E-03	1.259E-03
.9500	.9250	2.698E-04	5.097E-04	6.596E-04	8.904E-04	1.289E-03	1.499E-03	1.589E-03	1.679E-03	1.739E-03	1.949E-03
.9250	.9000	1.499E-04	2.399E-04	3.598E-04	5.906E-04	8.495E-04	1.109E-03	1.229E-03	1.319E-03	1.439E-03	1.529E-03
.9000	.8750	2.998E-04	5.096E-04	6.296E-04	8.695E-04	1.139E-03	1.439E-03	1.619E-03	1.799E-03	2.129E-03	2.309E-03
.8750	.8500	4.497E-04	7.196E-04	9.894E-04	1.149E-03	1.469E-03	1.889E-03	2.249E-03	2.458E-03	2.808E-03	2.818E-03
.8500	.8250	2.698E-04	3.498E-04	7.495E-04	1.109E-03	1.529E-03	2.099E-03	2.499E-03	2.788E-03	3.058E-03	3.448E-03
.8250	.8000	2.099E-04	4.797E-04	8.045E-04	1.139E-03	1.589E-03	2.069E-03	2.429E-03	2.938E-03	3.208E-03	3.658E-03
.8000	.7750	3.598E-04	8.395E-04	1.199E-03	1.499E-03	1.919E-03	2.399E-03	2.999E-03	3.208E-03	3.478E-03	3.748E-03
.7750	.7500	4.197E-04	7.495E-04	1.169E-03	1.499E-03	2.159E-03	2.548E-03	3.029E-03	3.538E-03	4.048E-03	4.737E-03
.7500	.7250	2.698E-04	5.697E-04	1.079E-03	1.379E-03	1.679E-03	2.399E-03	2.999E-03	3.448E-03	3.958E-03	4.407E-03
.7250	.7000	5.097E-04	8.695E-04	1.499E-03	2.049E-03	2.438E-03	3.388E-03	3.868E-03	4.407E-03	4.647E-03	5.037E-03
.7000	.6750	6.596E-04	1.049E-03	1.459E-03	2.009E-03	2.728E-03	3.208E-03	3.629E-03	4.467E-03	5.097E-03	5.906E-03
.6750	.6500	5.097E-04	1.019E-03	1.589E-03	2.129E-03	2.728E-03	3.358E-03	4.167E-03	4.797E-03	5.996E-03	5.996E-03
.6500	.6250	3.898E-04	9.894E-04	1.649E-03	2.518E-03	3.268E-03	4.077E-03	4.947E-03	5.577E-03	6.296E-03	7.106E-03
.6250	.6000	6.296E-04	1.079E-03	1.529E-03	2.309E-03	3.268E-03	4.137E-03	5.067E-03	5.996E-03	6.596E-03	7.076E-03
.6000	.5750	9.294E-04	1.559E-03	2.339E-03	3.058E-03	4.018E-03	4.797E-03	5.697E-03	6.446E-03	7.286E-03	8.365E-03
.5750	.5500	8.395E-04	1.769E-03	2.488E-03	3.298E-03	4.407E-03	5.607E-03	6.294E-03	7.166E-03	8.335E-03	9.264E-03
.5500	.5250	4.497E-04	8.695E-04	1.799E-03	2.788E-03	3.428E-03	4.857E-03	5.724E-03	6.536E-03	7.136E-03	8.095E-03
.5250	.5000	8.395E-04	1.679E-03	2.578E-03	3.478E-03	4.857E-03	5.906E-03	7.194E-03	8.245E-03	1.112E-02	1.238E-02
.5000	.4750	6.596E-04	1.649E-03	2.698E-03	3.898E-03	4.707E-03	6.026E-03	7.765E-03	9.144E-03	1.034E-02	1.184E-02
.4750	.4500	9.294E-04	1.979E-03	3.148E-03	4.407E-03	5.667E-03	7.046E-03	8.455E-03	1.010E-02	1.145E-02	1.265E-02
.4500	.4250	1.379E-03	2.429E-03	3.658E-03	4.877E-03	5.996E-03	7.675E-03	9.234E-03	1.082E-02	1.259E-02	1.469E-02
.4250	.4000	1.169E-03	2.728E-03	4.048E-03	5.617E-03	7.046E-03	8.755E-03	1.061E-02	1.277E-02	1.433E-02	1.610E-02
.4000	.3750	1.379E-03	2.648E-03	4.197E-03	5.726E-03	7.345E-03	9.354E-03	1.131E-02	1.352E-02	1.544E-02	1.739E-02
.3750	.3500	1.679E-03	3.328E-03	5.247E-03	7.286E-03	9.594E-03	1.193E-02	1.424E-02	1.667E-02	1.892E-02	2.120E-02
.3500	.3250	1.469E-03	3.748E-03	6.296E-03	8.465E-03	1.085E-02	1.400E-02	1.718E-02	2.006E-02	2.267E-02	2.590E-02
.3250	.3000	2.309E-03	4.317E-03	7.076E-03	9.624E-03	1.244E-02	1.553E-02	1.811E-02	2.075E-02	2.393E-02	2.692E-02
.3000	.2750	2.189E-03	4.737E-03	7.615E-03	1.049E-02	1.358E-02	1.640E-02	1.901E-02	2.267E-02	2.590E-02	2.953E-02
.2750	.2500	3.088E-03	6.296E-03	9.804E-03	1.301E-02	1.679E-02	2.021E-02	2.387E-02	2.764E-02	3.184E-02	3.643E-02
.2500	.2250	3.388E-03	6.836E-03	1.088E-02	1.466E-02	1.835E-02	2.264E-02	2.734E-02	3.292E-02	3.790E-02	4.267E-02
.2250	.2000	2.848E-03	6.836E-03	1.100E-02	1.568E-02	2.159E-02	2.683E-02	3.214E-02	3.712E-02	4.279E-02	4.800E-02
.2000	.1750	4.048E-03	9.144E-03	1.421E-02	1.973E-02	2.507E-02	3.118E-02	3.858E-02	4.506E-02	5.124E-02	5.694E-02
.1750	.1500	5.607E-03	1.097E-02	1.727E-02	2.348E-02	3.034E-02	3.760E-02	4.482E-02	5.211E-02	6.006E-02	6.705E-02
.1500	.1250	6.926E-03	1.466E-02	2.228E-02	3.109E-02	3.955E-02	4.800E-02	5.691E-02	6.542E-02	7.457E-02	8.399E-02
.1250	.1000	8.215E-03	1.697E-02	2.680E-02	3.706E-02	4.791E-02	5.817E-02	6.917E-02	8.123E-02	9.064E-02	1.014E-01

$E_0 = 1000 \text{ keV}$

ENERGY SPECTRA AND ANGULAR DISTRIBUTIONS OF PHOTONS TRANSMITTED THROUGH
A SLAB OF THICKNESS = .0639 * ELECTRON CSDA RANGE = $4.902 \times 10^{-2} \text{ g/cm}^2$
(NUMBER/(MEV*SR)). NORMALIZED TO ONE INCIDENT PARTICLE)

E (MEV)	THETA=	0.000	2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000
		2.000	5.000	9.000	15.000	30.000	45.000	60.000	75.000	90.000
1.0010	.9990	0.	0.	0.	0.	0.	0.	0.	0.	0.
.9990	.9900	0.	4.147E-03	0.	6.091E-04	0.	0.	0.	0.	0.
.9900	.9750	0.	0.	9.349E-04	3.654E-04	7.961E-05	5.004E-05	1.152E-04	0.	3.073E-05
.9750	.9500	0.	2.986E-03	0.	8.771E-04	3.821E-04	3.603E-04	1.844E-04	1.583E-04	0.
.9500	.9250	0.	2.986E-03	3.927E-03	4.385E-04	5.732E-04	4.204E-04	2.765E-04	1.781E-04	1.291E-04
.9250	.9000	0.	0.	5.610E-04	4.385E-04	6.209E-04	2.102E-04	2.765E-04	2.176E-04	9.218E-05
.9000	.8750	0.	4.479E-03	5.610E-04	1.316E-03	6.687E-04	5.104E-04	2.995E-04	2.374E-04	2.028E-04
.8750	.8500	0.	0.	2.244E-03	1.316E-03	1.003E-03	5.705E-04	4.378E-04	2.770E-04	2.028E-04
.8500	.8250	0.	2.986E-03	1.683E-03	1.316E-03	1.146E-03	6.005E-04	6.221E-04	4.353E-04	2.028E-04
.8250	.8000	0.	1.493E-03	2.805E-03	1.545E-03	8.120E-04	7.807E-04	6.451E-04	4.353E-04	2.950E-04
.8000	.7750	0.	2.986E-03	1.683E-03	1.754E-03	1.337E-03	6.906E-04	5.767E-04	4.353E-04	2.581E-04
.7750	.7500	7.833E-03	4.479E-03	2.805E-03	1.316E-03	1.146E-03	1.171E-03	8.064E-04	3.759E-04	4.793E-04
.7500	.7250	0.	1.493E-03	3.366E-03	1.545E-03	1.481E-03	1.111E-03	5.064E-04	4.748E-04	3.503E-04
.7250	.7000	1.567E-02	1.493E-03	3.366E-03	1.754E-03	1.385E-03	1.441E-03	7.603E-04	5.540E-04	2.397E-04
.7000	.6750	0.	4.479E-03	2.805E-03	3.289E-03	2.436E-03	8.107E-04	8.064E-04	6.925E-04	4.793E-04
.6750	.6500	0.	4.479E-03	3.366E-03	1.973E-03	2.245E-03	1.081E-03	9.907E-04	5.935E-04	4.793E-04
.6500	.6250	7.833E-03	2.986E-03	2.805E-03	4.605E-03	2.054E-03	1.441E-03	8.064E-04	9.695E-04	6.084E-04
.6250	.6000	1.567E-02	2.986E-03	2.805E-03	3.070E-03	2.436E-03	1.621E-03	1.081E-03	6.529E-04	5.162E-04
.6000	.5750	0.	1.493E-03	5.049E-03	3.727E-03	3.248E-03	2.042E-03	1.104E-03	7.123E-04	5.900E-04
.5750	.5500	0.	8.958E-03	5.049E-03	4.385E-03	3.152E-03	2.072E-03	1.313E-03	8.903E-04	6.822E-04
.5500	.5250	0.	4.479E-03	3.366E-03	2.611E-03	2.149E-03	2.102E-03	1.424E-03	8.507E-04	5.347E-04
.5250	.5000	7.833E-03	1.493E-03	1.122E-02	3.947E-03	2.770E-03	2.162E-03	1.797E-03	2.236E-03	9.587E-04
.5000	.4750	1.567E-02	4.479E-03	3.366E-03	4.146E-03	3.869E-03	2.222E-03	1.797E-03	1.464E-03	1.069E-03
.4750	.4500	0.	1.493E-03	6.171E-03	7.674E-03	4.251E-03	2.462E-03	1.864E-03	1.365E-03	9.956E-04
.4500	.4250	0.	1.045E-02	8.414E-03	4.824E-03	4.108E-03	3.483E-03	2.189E-03	1.622E-03	1.235E-03
.4250	.4000	2.350E-02	0.	6.171E-03	6.359E-03	6.353E-03	3.453E-03	2.373E-03	1.444E-03	1.291E-03
.4000	.3750	7.833E-03	8.958E-03	1.010E-02	7.016E-03	6.400E-03	4.054E-03	2.354E-03	1.701E-03	1.217E-03
.3750	.3500	7.833E-03	8.958E-03	1.234E-02	9.648E-03	6.735E-03	4.714E-03	3.418E-03	2.077E-03	1.530E-03
.3500	.3250	0.	1.194E-02	8.975E-03	1.074E-02	8.789E-03	6.215E-03	3.617E-03	2.631E-03	2.028E-03
.3250	.3000	1.567E-02	1.441E-02	1.178E-02	1.142E-02	8.407E-03	6.696E-03	3.617E-03	2.849E-03	2.010E-03
.3000	.2750	1.567E-02	1.344E-02	1.739E-02	1.294E-02	1.041E-02	5.345E-03	4.378E-03	3.264E-03	2.452E-03
.2750	.2500	0.	2.389E-02	1.402E-02	1.535E-02	1.342E-02	7.446E-03	5.483E-03	3.225E-03	3.208E-03
.2500	.2250	2.350E-02	2.239E-02	2.580E-02	1.646E-02	1.390E-02	9.369E-03	5.783E-03	4.590E-03	3.632E-03
.2250	.2000	3.133E-02	2.687E-02	1.683E-02	1.886E-02	1.485E-02	9.999E-03	7.358E-03	5.797E-03	3.817E-03
.2000	.1750	7.833E-03	3.285E-02	3.141E-02	2.785E-02	1.791E-02	1.138E-02	8.788E-03	6.293E-03	4.425E-03
.1750	.1500	6.266E-02	2.538E-02	3.927E-02	3.026E-02	2.245E-02	1.468E-02	9.631E-03	7.281E-03	4.757E-03
.1500	.1250	9.412E-02	4.431E-02	3.534E-02	4.149E-02	2.842E-02	1.904E-02	1.219E-02	8.825E-03	5.605E-03
.1250	.1000	5.483E-02	5.823E-02	4.600E-02	5.263E-02	3.396E-02	2.183E-02	1.588E-02	1.154E-02	5.625E-03
INTEGRAL (1/SR):		1.038E-02	9.182E-03	8.835E-03	8.003E-03	5.884E-03	3.841E-03	2.637E-03	1.934E-03	1.305E-03

TRANSMITTED PHOTON SPECTRUM FROM 0.001 INCH DIAMETER TUNGSTEN WIRE

ENERGY BIN		INTENSITY
1.001E+00	9.990E-01	0.
9.990E-01	9.900E-01	1.66565E-04
9.900E-01	9.750E-01	3.82765E-04
9.750E-01	9.500E-01	1.09868E-03
9.500E-01	9.250E-01	1.61901E-03
9.250E-01	9.000E-01	1.26058E-03
9.000E-01	8.750E-01	1.82348E-03
8.750E-01	8.500E-01	2.31833E-03
8.500E-01	8.250E-01	2.67676E-03
8.250E-01	8.000E-01	2.79384E-03
8.000E-01	7.750E-01	3.05423E-03
7.750E-01	7.500E-01	3.54907E-03
7.500E-01	7.250E-01	3.35914E-03
7.250E-01	7.000E-01	4.10748E-03
7.000E-01	6.750E-01	4.44582E-03
6.750E-01	6.500E-01	4.67188E-03
6.500E-01	6.250E-01	5.47464E-03
6.250E-01	6.000E-01	5.60401E-03
6.000E-01	5.750E-01	6.42731E-03
5.750E-01	5.500E-01	7.19634E-03
5.500E-01	5.250E-01	6.26376E-03
5.250E-01	5.000E-01	9.05775E-03
5.000E-01	4.750E-01	8.91188E-03
4.750E-01	4.500E-01	9.78975E-03
4.500E-01	4.250E-01	1.09392E-02
4.250E-01	4.000E-01	1.23503E-02
4.000E-01	3.750E-01	1.32354E-02
3.750E-01	3.500E-01	1.63137E-02
3.500E-01	3.250E-01	1.96374E-02
3.250E-01	3.000E-01	2.07162E-02
3.000E-01	2.750E-01	2.24846E-02
2.750E-01	2.500E-01	2.77334E-02
2.500E-01	2.250E-01	3.24416E-02
2.250E-01	2.000E-01	3.67170E-02
2.000E-01	1.750E-01	4.38877E-02
1.750E-01	1.500E-01	5.15900E-02
1.500E-01	1.250E-01	6.48095E-02
1.250E-01	1.000E-01	7.87516E-02

digitized spectral data obtained from the averaged curve-fits to the code output is listed in Table III-10, in units of (keV/keV) $\times 10^3$, from 100 keV to 1000 keV, in 12.5 keV steps.

For completeness, the actual code output histograms and the fitted curves for the Bremsstrahlung data are included in Figure (III-6) for the energy range $100 \text{ keV} < E_0 < 1000 \text{ keV}$, in 100 keV steps.

III.6 An Estimate of the Compton Effect in the Absorption Foils

A cross-check on the Monte Carlo calculations of the contribution of Compton scattered X-rays to the overall detected X-ray flux may be carried out, given our experimental collimation geometry, using the Klein-Nishina Compton scattering cross-sections. Given an absorbing slab of thickness Δ , the percentage of the total detected radiation intensity which is due to Compton scattering may be estimated as

$$F = \frac{I_C(\Delta)}{I_{TOT}} = \frac{\int_0^{\Delta} \frac{dI(x)}{dx} R_{C/T} T(\Delta-x) dx}{I_0 e^{-\sigma_T \Delta}} \quad (\text{III.6.1})$$

where $I(x)$ is the radiation intensity at a distance x into the absorbing slab, $R_{C/T}$ is the percentage of all

TABLE III-10

THE FOLLOWING IS THE MONTE CARLO COMPUTED BREMSSTRAHLUNG SPECTRA FOR ELECTRONS INCIDENT ON A 1 MIL DIAMETER TUNGSTEN WIRE.

ELECTRON ENERGY= 100.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 1 ENTRIES.									
0.05700									
ELECTRON ENERGY= 125.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 3 ENTRIES.									
1.03000	0.68000	0.14800							
ELECTRON ENERGY= 150.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 5 ENTRIES.									
1.92000	1.65000	1.26000	0.76500	0.11000					
ELECTRON ENERGY= 175.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 7 ENTRIES.									
2.87000	2.60000	2.23000	1.78000	1.29000	0.76000	0.09900			
ELECTRON ENERGY= 200.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 9 ENTRIES.									
3.66000	3.40000	3.10000	2.71000	2.27000	1.79000	1.26000	0.76500	0.12000	
ELECTRON ENERGY= 225.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 11 ENTRIES.									
4.62000	4.24000	3.96000	3.59000	3.20000	2.72000	2.30000	1.82000	1.32000	
	0.78500	0.08300							
ELECTRON ENERGY= 250.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 13 ENTRIES.									
5.57000	5.12000	4.80000	4.42000	4.05000	3.63000	3.21000	2.68000	2.26000	
	1.76000	1.27000	0.75000	0.03500					
ELECTRON ENERGY= 300.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 17 ENTRIES.									
6.97000	6.50000	6.09000	5.70000	5.30000	4.92000	4.52000	4.14000	3.75000	
	3.35000	2.95000	2.54000	2.14000	1.74000	1.29000	0.78000	0.08200	
ELECTRON ENERGY= 350.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 21 ENTRIES.									
7.85000	7.60000	7.30000	6.99000	6.58000	6.20000	5.79000	5.42000	5.02000	
	4.65000	4.30000	3.94000	3.54000	3.17000	2.78000	2.39000	2.00000	
	1.61000	1.20000	0.72000	0.11100					
ELECTRON ENERGY= 400.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 25 ENTRIES.									
8.55000	8.34000	8.08000	7.78000	7.44000	7.05000	6.68000	6.27000	5.90000	
	5.51000	5.13000	4.80000	4.46000	4.13000	3.87000	3.56000	3.24000	
	2.93000	2.59000	2.26000	1.93000	1.55000	1.15000	0.67200	0.00500	
ELECTRON ENERGY= 450.00000KEV.									
BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 29 ENTRIES.									
8.79000	8.59000	8.32000	8.07000	7.76000	7.38000	7.06000	6.71000	6.38000	
	6.02000	5.70000	5.40000	5.10000	4.86000	4.57000	4.30000	4.05000	
	3.79000	3.52000	3.26000	2.97000	2.69000	2.39000	2.07000	1.77000	
	1.44000	1.04000	0.61500	0.00500					

ELECTRON ENERGY= 500.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 33 ENTRIES.

8.96000	8.76000	8.55000	8.31000	8.07000	7.82000	7.53000	7.21000	6.94000
	6.65000	6.33000	6.01000	5.75000	5.49000	5.20000	4.92000	4.68000
	4.42000	4.15000	3.91000	3.67000	3.43000	3.19000	2.99000	2.73000
	2.51000	2.23000	1.97000	1.67000	1.38000	1.00000	0.60900	0.00500

ELECTRON ENERGY= 550.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 37 ENTRIES.

9.07000	8.89000	8.68000	8.46000	8.23000	8.00000	7.75000	7.49000	7.21000
	6.97000	6.69000	6.41000	6.14000	5.90000	5.61000	5.38000	5.12000
	4.91000	4.69000	4.46000	4.23000	4.01000	3.78000	3.58000	3.36000
	3.16000	2.94000	2.73000	2.50000	2.28000	2.04000	1.81000	1.55000
	1.30000	0.99600	0.65000	0.00500				

ELECTRON ENERGY= 600.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 41 ENTRIES.

9.03000	8.87000	8.70000	8.52000	8.29000	8.04000	7.84000	7.62000	7.38000
	7.16000	6.91000	6.65000	6.40000	6.17000	5.91000	5.65000	5.42000
	5.20000	4.95000	4.75000	4.54000	4.35000	4.15000	3.97000	3.77000
	3.60000	3.40000	3.23000	3.04000	2.87000	2.69000	2.51000	2.32000
	2.14000	1.96000	1.75000	1.51000	1.27000	0.98000	0.63500	0.00500

ELECTRON ENERGY= 650.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 45 ENTRIES.

8.95000	8.83000	8.66000	8.51000	8.32000	8.16000	7.94000	7.62000	7.50000
	7.30000	7.04000	6.83000	6.61000	6.39000	6.15000	5.90000	5.67000
	5.48000	5.23000	5.03000	4.83000	4.65000	4.47000	4.29000	4.10000
	3.93000	3.77000	3.61000	3.44000	3.30000	3.13000	2.98000	2.80000
	2.65000	2.49000	2.31000	2.13000	1.97000	1.77000	1.59000	1.37000
	1.12000	0.84000	0.51500	0.00500				

ELECTRON ENERGY= 700.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 49 ENTRIES.

9.05000	8.95000	8.75000	8.60000	8.40000	8.20000	8.00000	7.80000	7.59000
	7.38000	7.17000	6.95000	6.69000	6.47000	6.25000	6.02000	5.83000
	5.62000	5.42000	5.24000	5.07000	4.90000	4.72000	4.54000	4.40000
	4.22000	4.09000	3.91000	3.77000	3.62000	3.48000	3.32000	3.18000
	3.03000	2.89000	2.73000	2.57000	2.43000	2.27000	2.11000	1.95000
	1.78000	1.62000	1.44000	1.24000	1.03000	0.80000	0.48000	0.00500

ELECTRON ENERGY= 750.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 53 ENTRIES.

9.10000	8.98000	8.82000	8.65000	8.43000	8.25000	8.02000	7.82000	7.60000
	7.38000	7.18000	6.96000	6.72000	6.53000	6.30000	6.10000	5.90000
	5.68000	5.50000	5.32000	5.13000	4.95000	4.78000	4.63000	4.45000
	4.31000	4.14000	4.00000	3.84000	3.70000	3.58000	3.42000	3.30000
	3.17000	3.02000	2.90000	2.78000	2.65000	2.52000	2.42000	2.39000
	2.18000	2.07000	1.98000	1.85000	1.74000	1.59000	1.48000	1.28000
	1.10000	0.90000	0.68000	0.00500				

ELECTRON ENERGY= 800.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 57 ENTRIES.

9.05000	8.95000	8.79000	8.59000	8.39000	8.20000	7.98000	7.78000	7.56000
	7.38000	7.18000	6.98000	6.79000	6.60000	6.41000	6.27000	6.05000
	5.92000	5.75000	5.59000	5.42000	5.29000	5.12000	4.98000	4.81000
	4.70000	4.65000	4.42000	4.26000	4.15000	4.02000	3.88000	3.77000
	3.66000	3.52000	3.41000	3.29000	3.18000	3.06000	2.94000	2.83000
	2.72000	2.61000	2.50000	2.38000	2.25000	2.13000	1.98000	1.83000
	1.68000	1.54000	1.39000	1.23000	1.06000	0.84300	0.56000	0.00500

ELECTRON ENERGY= 850.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 61 ENTRIES.

9.40000	9.20000	9.00000	8.82000	8.60000	8.42000	8.20000	8.00000	7.78000
	7.58000	7.38000	7.20000	7.00000	6.79000	6.61000	6.45000	6.25000
	6.10000	5.95000	5.78000	5.60000	5.45000	5.30000	5.15000	5.00000
	4.83000	4.71000	4.57000	4.42000	4.30000	4.18000	4.04000	3.89000
	3.78000	3.66000	3.55000	3.43000	3.32000	3.20000	3.10000	2.99000
	2.89000	2.78000	2.68000	2.57000	2.47000	2.37000	2.27000	2.17000
	2.08000	1.98000	1.89000	1.77000	1.66000	1.54000	1.41000	1.25000
	1.07000	0.86100	0.58000	0.00500				

ELECTRON ENERGY= 900.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 65 ENTRIES.

9.45000	9.28000	9.03000	8.82000	8.60000	8.39000	8.19000	8.00000	7.79000
	7.60000	7.40000	7.24000	7.03000	6.85000	6.68000	6.52000	6.38000
	6.19000	6.00000	5.87000	5.70000	5.58000	5.40000	5.25000	5.09000
	4.98000	4.81000	4.70000	4.58000	4.43000	4.32000	4.21000	4.09000
	3.97000	3.84000	3.74000	3.62000	3.52000	3.41000	3.31000	3.21000
	3.11000	3.00000	2.91000	2.80000	2.69000	2.60000	2.51000	2.41000
	2.31000	2.21000	2.11000	2.02000	1.93000	1.85000	1.75000	1.66000
	1.54000	1.43000	1.32000	1.18000	1.03000	0.86000	0.64000	0.00500

ELECTRON ENERGY= 550.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 69 ENTRIES.

9.30000	9.10000	8.90000	8.68000	8.52000	8.38000	8.18000	8.00000	7.80000
	7.63000	7.46000	7.30000	7.13000	6.98000	6.80000	6.64000	6.50000
	6.37000	6.20000	6.03000	5.92000	5.78000	5.62000	5.50000	5.38000
	5.22000	5.09000	4.98000	4.82000	4.73000	4.59000	4.45000	4.37000
	4.22000	4.12000	4.02000	3.90000	3.80000	3.70000	3.60000	3.50000
	3.40000	3.30000	3.21000	3.11000	3.03000	2.95000	2.85000	2.75000
	2.66000	2.57000	2.47000	2.38000	2.28000	2.18000	2.08000	1.99000
	1.89000	1.78000	1.68000	1.60000	1.48000	1.37000	1.25000	1.11000
	0.97000	0.79000	0.55300	0.00500				

ELECTRON ENERGY=1000.00000KEV.

BREMSSTRAHLUNG SPECTRA FROM 100 KEV IN 12.5 KEV STEPS HAS 73 ENTRIES.

9.40000	9.20000	9.00000	8.80000	8.61000	8.47000	8.31000	8.12000	7.95000
	7.78000	7.60000	7.41000	7.23000	7.12000	6.95000	6.80000	6.62000
	6.47000	6.35000	6.20000	6.02000	5.85000	5.74000	5.60000	5.45000
	5.32000	5.20000	5.05000	4.97000	4.82000	4.71000	4.60000	4.48000
	4.37000	4.27000	4.18000	4.04000	3.95000	3.84000	3.73000	3.64000
	3.55000	3.45000	3.35000	3.26000	3.17000	3.08000	3.00000	2.91000
	2.82000	2.75000	2.68000	2.59000	2.51000	2.43000	2.36000	2.28000
	2.20000	2.12000	2.04000	1.96000	1.88000	1.78000	1.68000	1.57000
	1.46000	1.33000	1.19000	1.04000	0.88000	0.62000	0.31000	0.00500

FIGURE III-6

Bremsstrahlung code histograms for spectra from
 2.54×10^{-3} cm diameter tungsten wire target
(weighted slab technique).

FIGURE III-6

Compton-scattered photons which are scattered into the acceptance angle of the detector, $T(\Delta-x)$ expresses the attenuation of the Compton-scattered radiation as it traverses the remainder of the slab thickness, and σ_T is the total photon mass-attenuation coefficient for the absorbing material.

The ratio of Compton scattered photons which are scattered into the solid angle subtended by the detector to the total number of Compton scattered photons scattered in all directions is

$$R_{C/T} = \frac{\int_0^{2\pi} d\phi \int_0^{\theta} \frac{d\sigma_C}{d\Omega} \sin \theta d\theta}{\sigma_{CT}} \quad (\text{III.6.2})$$

where $d\sigma_C/d\Omega$ is the differential Compton cross-section and σ_{CT} is the total Compton cross-section, integrated over all scattering angles. Plots of $d\sigma_C/d\Omega$ and σ_{CT} as functions of angle and energy, respectively, are shown in Figures (III-7) and (III-8) (from Reference (83)).

Given our collimation dimensions of 15.4 cm length and 1.27 cm cross-sectional breadth, and using values for $d\sigma_C/d\Omega$ and σ_{CT} from Figures (III-7) and (III-8), we have

FIGURE III-7

Differential Compton cross-section as a function of
angle, $10 \text{ keV} < E_{\gamma} < 500 \text{ keV}$.

FIGURE III-7

FIGURE III-8

Total Compton cross-section as a function of photon energy.

FIGURE III-8

$$R_{C/T}(100 \text{ keV}) = \frac{.41 \text{ mb/e}^-}{.5 \text{ b/e}^-} \approx 0.1\%$$

$$R_{C/T}(1000 \text{ keV}) = \frac{.41 \text{ mb/e}^-}{.22 \text{ b/e}^-} \approx 0.2\% \quad (\text{III.6.3})$$

Thus, we see that the percentage of all Compton-scattered X-rays which intercept the detector is quite small.

We next fold in the slab attenuation of the scattered photons. At lower energies, the Photo cross-section predominates, and the transmission function, T , is just the exponential attenuation due to photoelectric absorption. At higher energies (around 1 MeV), however, the photoelectric cross-section is only about 25% of the total attenuation cross-section in lead, so the Compton contributions to the detected signal could be quite high. To make a "worst case" evaluation at this energy, we therefore assume that only photoelectric attenuation of the Compton-scattered radiation takes place over the remainder of the slab thickness.

The results of these calculations is shown on the following page for several photon energies, with a comparison with the code results at 1 MeV.

TABLE III-11

The Quantity "F" vs Slab Thickness.

<u>Slab Thickness</u> <u>(cm of Lead)</u>	<u>100 keV</u>	<u>200 keV</u>	<u>500 keV</u>	<u>1000 keV</u>	<u>1000 keV</u> <u>(Code)</u>
.22	1.1×10^{-2}	2.5×10^{-3}	5.6×10^{-4}	3.7×10^{-4}	9.8×10^{-4}
.44	2.2×10^{-2}	5×10^{-3}	1.1×10^{-3}	8×10^{-4}	1.75×10^{-3}
.66	3.3×10^{-2}	7.6×10^{-3}	1.7×10^{-3}	4×10^{-3}	2.5×10^{-4}

Thus, we see reasonable agreement with the code predictions at 1 MeV, and that, overall, the Compton-scattered radiation contributes, at most, ~ 3% to the overall detected signal--and then only at the lowest X-ray energies.

III.7 A Simple Model for Estimating the Sodium Iodide Detector Efficiency

As a rough cross-check on the detector efficiency predicted by the Monte Carlo code, one may make some approximations and roughly compute the crystal efficiency from first principles. This section briefly describes the nature and results of such a calculation.

The crystal detection efficiency, ϵ , may be expressed as

$$\begin{aligned}\epsilon &= \frac{1}{E_0} \times (\text{Energy Deposited in Photoabsorption} + \\ &\quad \text{Energy Deposited in Compton Interactions}) \\ &= \frac{1}{E_0} (P_0 \cdot P_{P/T} \cdot E_0 + P_0 (1 - P_{P/T}) \cdot \langle E_c \rangle) \quad (\text{III.7.1})\end{aligned}$$

where E_0 is the X-ray energy, P_0 is the percentage of the incident radiation that interacts with the crystal in any fashion whatsoever, $P_{P/T}$ is the fraction of P_0 which is photoabsorbed in the crystal, and $\langle E_c \rangle$ is the average X-ray energy deposited in the crystal via Compton scattering.

P_o may be simply expressed as

$$P_o = 1 - e^{-\sigma_T \Delta z} \quad (\text{III.7.2})$$

where σ_T is the photon mass-attenuation coefficient for NaI(Tl) [cf. Figure (II.1)], and Δz is the length of the crystal.

The quantity $P_{P/T}$ may be computed from a gamma-ray spectrum of NaI(Tl) (such as the spectrum shown in Figure (III-9) which was obtained from one of the detectors used in the experiment) as the ratio of the area under the photopeak to the total area under the spectral distribution. This quantity, usually called the "Peak-to-Total Ratio", has been measured experimentally¹⁶¹ for several sizes of NaI(Tl) crystals, and is plotted in Figure (III-10) for full-body irradiation of a 4.5 x 5.1 cm right-cylindrical NaI(Tl) crystal as a function of X-ray energy. The effect of collimation is to raise the Peak-to-Total ratio somewhat [cf. Figure (III-9)], but we shall use the full-body irradiation values of $P_{P/T}$ as a first approximation.

Finally, we may compute $\langle E_c \rangle$ by taking advantage of the overall shape of the spectrum of Figure (III-9). As seen in the figure, the Compton spectrum is roughly

FIGURE III-9

Gamma ray scintillation spectrometry for one of the NaI(Tl) detectors used in the ring electron energy measurement.

FIGURE III-9

FIGURE III-10

Peak-to-Total Ratio for 4.5 cm x 5.1 cm right-cylindrical NaI(Tl) scintillation crystal.

FIGURE III-10

constant up to the so-called "cut-off" energy, E_c (labelled "Edge" in the plot), after which it drops steeply to a minimum before becoming totally swamped by the photopeak. A first approximation to the average Compton energy deposited in the crystal would therefore be

$$\langle E_c \rangle \sim \frac{1}{2} (E_c + \frac{(E_o + E_c)}{4}) \quad (\text{III.7.3})$$

where

$$E_c = E_o - \frac{E_o}{1 + \frac{2E_o}{m_o c^2}} \quad (\text{III.7.4})$$

Substituting Equation (III.7.3) and Equation (III.7.2) into Equation (III.7.1) and using the data of Figures (II-1) and (III-9), the detection efficiency was computed as a function of E_o ; a plot of the results appears in Figure (III.11) along with the results of the Monte Carlo code calculations.

Inspection of Figure (III-11) shows the agreement between the predictions of the rough estimate and the code output to be always within 10%, which is certainly acceptable in view of the assumptions made in the above calculations.

FIGURE III-11

NaI(Tl) crystal detection efficiency by simple calculation and by Monte Carlo in the X-ray energy range $100 \text{ keV} < E_{\gamma} < 1000 \text{ keV}$.

FIGURE III-11

APPENDIX IV

PREDICTED X-RAY DETECTOR OUTPUT SIGNALS

IV.1 Sodium Iodide Detector

In this section, a "back-of-the-envelope" calculation of absolute X-ray detector signals is presented for the electron ring parameters which existed when the energy measurements were made. The calculation proceeds as a numerical computation of the intensity integral, Equation (4.2), in three parts:

- (1) the flux of electrons striking the wire is determined;
- (2) the Bremsstrahlung flux to the face of the detector is obtained;
- (3) using absolute calibrations of the detector made with a Co^{60} source [cf. Figure (4-20)], the results from (1) and (2) may be combined to give the absolute detector output signal.

A. Presuming a layer of cross-sectional area, A , and an initial field-reversing strength $\zeta \approx 0.5$, we have (approximating the electron ring by an ideal, thin ring of radius r_0)

$$I \sim B_{z0} \times \frac{5r_o(\text{cm})}{\pi} \sim 1400 \text{ A} \quad (\text{IV.1})$$

where a ring radius of 9 cm has been assumed, to give an estimate of the total, circulating current in the ring. If the ring has a radial thickness of ~ 10 cm and an axial length of ~ 20 cm, we have

$$J \sim 7\text{A/cm}^2 = 4.4 \times 10^{13} \text{ electrons}/\mu\text{s-cm}^2. \quad (\text{IV.2})$$

Since the effective cross-section of the wire in the electron steam is $10 \text{ cm} \times 2.5 \times 10^{-3} \text{ cm}$, we have that the number of electrons striking the wire per unit time is

$$\frac{dn_e}{dt} \sim 1.1 \times 10^{12} \text{ electrons}/\mu\text{sec}. \quad (\text{IV.3})$$

(From the data of Table III-8, one may show that this corresponds to an X-ray current of $\sim 2 \times 10^{12} \text{ keV}/\mu\text{sec}.$)

B. A numeric computation of expression

(4.2) $\div \eta_{\text{XTL}} \eta_{\text{PC}} A_{\text{PMT}}$ was carried out for 0, 1, 2, and 3 "thicknesses" of lead absorber plus tin to determine the energy deposited in the detector crystal. The presumption was made that the ring electrons form a "diffuse" electron beam (cf. Section 4.4.7) and that the target

Bremsstrahlung are therefore radiated isotropically into the forward 2π -hemisphere. The results of this calculation are shown in Table IV-1 for all absorbers in the range of 100 - 1000 keV. The units of the output are normalized to the forward 2π -hemisphere and are expressed as keV/ 2π -Sr.

These calculations indicated that, per 500 keV electron striking the 2.5×10^{-3} cm diameter tungsten wire target, $225 K_c \Delta\Omega/2\pi$ eV, $97 K_c \Delta\Omega/2\pi$ eV, and $47 K_c \Delta\Omega/2\pi$ eV of X-ray energy were deposited in the crystal for "1Pb", "2Pb", and "3Pb" absorbers, respectively, where K_c is a geometric collimation factor ($K_c \sim 1/2$ under our collimation conditions), and $\Delta\Omega$ is the solid angle subtended by the detector from the center of the wire ($\Delta\Omega \sim 4.3 \times 10^{-4}$ Sr in the experiment). Thus, we have 1.6×10^{-2} eV, 6.7×10^{-3} eV, and 3.2×10^{-3} eV deposited in the detector crystals per electron striking the wire target for "1Pb", "2Pb", and "3Pb" absorber thicknesses, respectively.

C. The overall detector response, $\eta_{\text{XTL}} \eta_{\text{PC}}^A A_{\text{PMT}}$, was calibrated using the 1.33 MeV "line" of photoabsorbed radiation from Co^{60} , and was found to be $\sim 2.8 \times 10^{-14}$ A-sec per 1.33 MeV deposited in the crystal, given a tube bias of -540 VDC ($A_{\text{PMT}} \sim 600$). Using the value of dn_e/dt

NaI(Tl)

THE FOLLOWING ARE THE BREMSSTRAHLUNG SPECTRA AS SEEN BY THE DETECTOR SYSTEM
FOR EACH OF 3 PB ABSORBER COMBINATIONS AS WELL AS FOR 0 PB.

125.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.00000E 00	200.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.39113E 02
125.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.00000E 00	225.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.26444E 01
125.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.00000E 00	225.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.20658E 00
125.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.87548E 00	225.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.17771E-01
150.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.74704E-02	225.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.71911E 02
150.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.00000E 00	250.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.67620E 01
150.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.00000E 00	250.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.80358E 00
150.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.58953E 01	250.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.11684E 00
175.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.12762E 00	250.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.11459E 03
175.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.20285E-03	300.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.25610E 02
175.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.00000E 00	300.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.52366E 01
175.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.17944E 02	300.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.14022E 01
200.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.71434E 00	300.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.22430E 03
200.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.24432E-01	350.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.60222E 02
200.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.48837E-04	350.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.16620E 02

350.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.57330E 01
 350.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.36314E 03
 400.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.10822E 03
 400.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.36615E 02
 400.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.14982E 02
 400.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.50419E 03
 450.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.16392E 03
 450.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.63873E 02
 450.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.29390E 02
 450.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.63347E 03
 500.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.22779E 03
 500.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.98179E 02
 500.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.49196E 02
 500.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.77143E 03
 550.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.29272E 03
 550.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.13626E 03
 550.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.72860E 02
 550.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.89396E 03

600.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.35473E 03
 600.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.17558E 03
 600.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.99002E 02
 600.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.99861E 03
 650.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.41444E 03
 650.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.21467E 03
 650.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.12580E 03
 650.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.10949E 04
 700.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.47221E 03
 700.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.25424E 03
 700.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.15393E 03
 700.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.11837E 04
 750.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.51987E 03
 750.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.28938E 03
 750.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.18049E 03
 750.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.12493E 04
 800.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.60041E 03
 800.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.34610E 03

800.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.22183E 03
 800.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.13640E 04
 850.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.65612E 03
 850.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.38622E 03
 850.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.25235E 03
 850.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.14515E 04
 900.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.70936E 03
 900.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.42634E 03
 900.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.26357E 03
 900.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.15232E 04
 950.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.78148E 03
 950.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.47954E 03
 950.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.32441E 03
 950.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.16225E 04
 1000.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.83648E 03
 1000.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.52112E 03
 1000.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.35742E 03
 1000.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.17016E 04

obtained in Equation (IV.3), the deposited energies calculated in (B) may be converted directly to currents (i.e., voltages on the monitoring oscilloscopes) to obtain the following results, compared directly with the actual signal levels measured during the experiment:

<u>$E_o = 500 \text{ keV}$</u>		
Detector Signal (V)		
<u>Absorber</u>	<u>Experiment</u>	<u>Calculated</u>
1Pb	0.45	0.65
2Pb	0.16	0.27
3Pb	0.12	0.14

The calculated figures differ from the actual measured values by a factor of 1-2, which is an acceptable margin of error considering the numeric approximations used in estimating the X-ray fluxes, etc.

IV.2 Pilot B Detector

An identical procedure to that described in the previous section was carried out for the Pilot B scintillation detector and the associated 2×10^{-2} cm diameter tungsten target used in the sub-microsecond trapping studies. Using a Cs^{137} source, the detector calibration was measured to be 2.4×10^{-12} A-sec (tube bias =

-1240 VDC; no gain data available for the EMI9856) per Compton edge energy deposited per 661 keV Compton scattered X-ray. The energy-deposition calculations Equation (4.2) were repeated for this detector, target, and absorber (1.9 g/cm² tin plus 2.52 g/cm² lead) combination to give 54 K_CΔΩ/2π eV deposited in the crystal per 450 keV electron striking the target (the beam energy was slightly lower for these experiments). With ΔΩ ~ 3 x 10⁻⁴ Sr and K_C ~ 1/2, this result, combined with (IV.2) and the tube response calibration factor, gives the relationship,

$$n_e \sim 3 \times 10^7 \text{ cm}^{-3} \text{ mA}^{-1} \quad (\text{IV.4})$$

which agrees with the experimentally-measured result [cf. Equation (3.2)] within a factor of two, again certainly an acceptable margin of error.

For reference, a tabulation analogous to Table IV-1 of the forward 2π-radiated energy deposited in the Pilot B crystal (again, normalized to the forward 2π-hemisphere) for electrons striking a 2.5 x 10⁻³ cm diameter tungsten target wire is presented in Table IV-2. As in Table IV-1, the units of the output are in keV/2π-Sr.

TABLE IV-2

THE FOLLOWING ARE THE BREMSSTRAHLUNG SPECTRA AS SEEN BY THE DETECTOR SYSTEM
FOR EACH OF 3 FE ABSORBER COMBINATIONS AS WELL AS FOR 0 PB.

125.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.00000E 00	200.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.93876E 01
125.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.00000E 00	225.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.66287E 00
125.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.00000E 00	225.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.54405E-01
125.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.19347E 00	225.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.47488E-02
150.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.17561E-02	225.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.17659E 02
150.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.00000E 00	250.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.17950E 01
150.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.00000E 00	250.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.21759E 00
150.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.13466E 01	250.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.32037E-01
175.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.31049E-01	250.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.28721E 02
175.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.49933E-04	300.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.72046E 01
175.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.00000E 00	300.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.15135E 01
175.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.42089E 01	300.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.41199E 00
200.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.17871E 00	300.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS. INTEGRAL = 0.58697E 02
200.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.62298E-02	350.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS. INTEGRAL = 0.17892E 02
200.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS. INTEGRAL = 0.12755E-04	350.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS. INTEGRAL = 0.51124E 01

350.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.17995E 01
 350.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.98914E 02
 400.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.33931E 02
 400.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.11963E 02
 400.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.50128E 01
 400.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.14306E 03
 450.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.54031E 02
 450.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.22052E 02
 450.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.10426E 02
 450.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.18719E 03
 500.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.78575E 02
 500.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.35648E 02
 500.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.18411E 02
 500.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.23663E 03
 550.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.10521E 03
 550.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.51715E 02
 550.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.28566E 02
 550.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.28402E 03

600.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.13243E 03
 600.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.69398E 02
 600.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.40498E 02
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 INTEGRAL = 0.32781E 03
 650.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.15964E 03
 650.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.87676E 02
 650.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.53230E 02
 650.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.36972E 03
 700.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.18726E 03
 700.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.10700E 03
 700.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.67157E 02
 700.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.41030E 03
 750.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.21208E 03
 750.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.12550E 03
 750.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.81244E 02
 750.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.44360E 03
 800.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.25189E 03
 800.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.15412E 03

800.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.10244E 03
 800.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.49901E 03
 850.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.28077E 03
 850.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.17560E 03
 850.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.11907E 03
 850.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.54044E 03
 900.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.30941E 03
 900.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.19757E 03
 900.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.13639E 03
 900.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.57800E 03
 950.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.34740E 03
 950.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.22627E 03
 950.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.15879E 03
 950.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.62876E 03
 1000.00 KEV = ELECTRON ENERGY, 1 PB ABSORBERS.
 INTEGRAL = 0.37759E 03
 1000.00 KEV = ELECTRON ENERGY, 2 PB ABSORBERS.
 INTEGRAL = 0.24970E 03
 1000.00 KEV = ELECTRON ENERGY, 3 PB ABSORBERS.
 INTEGRAL = 0.17767E 03
 1000.00 KEV = ELECTRON ENERGY, 0 PB ABSORBERS.
 INTEGRAL = 0.66936E 03

APPENDIX V

DETAILS OF ARCJET OPERATING CHARACTERISTICS

I. Construction

- (A.) Cathode: high-density carbon (Poco, AXF-5Q)
or Mallory 1000
- (B.) Anode: stainless steel
- (C.) Insulators: Delrin, quartz
- (D.) Vacuum seals: neoprene O-rings

II. Valve Characteristics

- (A.) Plenum construction: black Delrin
- (B.) Plenum Volume: 4.8 cc
- (C.) Number of particles injected: 3.5×10^{20} at
plenum pressure of 30# Gauge
- (D.) Valve opening time: (based on valve position
required for flow to be throttled by the
eight gun nozzles) ~ 250 μ sec
- (E.) Valve jitter: <300 μ sec
- (F.) Valve opening speed: 0.85 mm/ms (measured
with laser/photodiode combination)

III. Electrical Characteristics

(A.) Gun impedance: 75 m Ω

(B.) Gun arc voltage: 620 V

(C.) Gun arc current: 8000-8500 A

With 80 m Ω in series with gun:

(D.) Gun arc voltage: 500-550 V

(E.) Gun arc current: 2500-4000 A

(F.) Total energy partition: Bank (at 850 V): 3100 J

Gun Arc: 2300 J

Series resistor: 800 J

(G.) Arcjet discharge jitter: <100 μ sec

(H.) Axial magnetic field: 3400-4000 G

(I.) L/R magnetic field penetration time of stainless steel horn: 1.2 ms

(J.) Gun guide field windings: 400 turns, #20 A.W.G.

L = 80 mH, R = 4.2 Ω

40 G/Amp maximum on axis.

A set of typical arcjet voltage and current waveforms (80 m Ω series resistor in place) are shown in Figure V-1.

FIGURE V-1

Characteristic arcjet current and voltage oscilloscope waveforms.

FIGURE V-1

APPENDIX VI

PULSED-NEUTRAL GAS DENSITY MEASUREMENTS

For measuring the time-dependent pressure distribution in the cusp device, a Westinghouse WL7676 discharge gauge tube--ordinarily used for making steady-state pressure measurements in moderate vacuum--was used. The WL7676 is a planar-geometry gauge tube consisting of a thoriated-tungsten wire filament stretched midway between the electron collector (a thin tungsten ribbon) and the ion collector (a flat, tungsten-coated pedestal). For the purposes of this work, the glass envelope normally surrounding the tube was cut away and the tube mounted on a carriage which conformed to the curvature of the aluminum liner in the cusp tank [see Figure (VI-1)]. The high lateral optical transparency of this configuration (the planes of the collectors being perpendicular to the tube's vertical axis) was chosen to minimize flowing gas stagnation.

The end of a 1.27 cm diameter brass "umbilical" tube was fitted with an eight-pin, Kovar-sealed feed-through with which the electrical connections to the tube were made. To permit axial movement of the assembly,

FIGURE VI-1

- (Top) WL7676 fast ion gauge tube mounted on carriage
and attached to umbilical;
- (Bottom) Gauge tube bias voltage supply and ion/electron
current monitor.

the brass tube passed through a vacuum feed-through in a Lucite end-plate mounted on the injector-end of the cusp tank.

The electrical circuitry used to operate the gauge tube is shown schematically in Figure (VI-2); a photograph of the apparatus is shown in Figure (VI-1). Tube bias voltages of ± 60.0 VDC were applied to the electron and ion collector plates via the resistive divider shown in the Figure. Regulated (0.02%) direct-current power supplies provided the divider current. The tube filament was powered by its own regulated (0.01%) direct-current supply at currents ranging from 2.0-3.5 A. The precautions with proper power supply regulation were necessary to avoid 60 cycle interference: the time scale of the measurements was 5 ms and the currents to be measured were extremely small, usually $\geq 10^{-8}$ A.

To maintain isolation of the bias potentials, the collected ion and electron currents were measured using Tektronix 1A5 differential amplifiers monitoring the voltage drops across precisely-measured carbon resistances. An added bias circuit was also necessary to offset the minute currents (60 μ A) flowing to ground through the 1 M Ω input resistance of the 1A5 units.

The electron current was observed to rise rapidly

FIGURE VI-2

Electrical schematic of circuits used for biasing the gauge tube and monitoring the ion/electron currents flowing in the tube.

FIGURE VI-2

and monotonically in time after the gas puff was admitted into the vacuum vessel. Hence, it was necessary to monitor both electron and ion collected currents in order to normalize the tube readings against the fluctuating electron currents.

The gauge tube was calibrated absolutely against a Stokes Gauge in static gas backfills between 5 mTorr and 500 mTorr hydrogen. Electron and ion currents were monitored directly by two Keithley Model 602 electrometers. The calibration was performed immediately before, and immediately after, the set of pulsed-gas measurements was completed, to check for possible calibration shifts in the device. The calibration plot is shown in Figure (VI-3); the ratio of collected ion/electron currents is seen to be a fairly (within 20%) linear function of pressure. The reproducibility of the calibration points (taken at random pressures) was excellent, usually within 5%.

Neutral densities as a function of time were measured at seven positions spaced 12 cm apart along the axis of the containment vessel. At least five independent measurements were made at each location, with the sequence of measurement positions being staggered to the center from the end positions. The arcjet valve plenum pressure

FIGURE VI-3

Static gasfill calibration of the ion gauge tube
in hydrogen.

FIGURE VI-3

was 2# Gauge hydrogen for all measurements. A typical set of traces is shown in Figure (VI-4).

The data was reduced in the same fashion as described in Chapter 3. That is, Fortran IV programs were written for a PDP-15 computer, and the trace-digitizing peripheral unit used to digitize the large quantity of data from these experimental runs.

The results of the measurement are shown in Figure (6-8) of Chapter 6. For reference, the time-resolved neutral density at the position in the tank corresponding to the minimum of the magnetic mirror well is shown in Figure (VI-4). A typical set of traces showing the ion and electron currents as functions of time at this tube position are shown in the upper left-hand corner of the plot.

The RMS error in the measurement, calculated as part of the Fortran data reduction routine, was obtained as the standard deviation from the average of all of the data collected at each axial tube position. This error was consistently about 12%, rising to around 40% only at the lowest pressures measured (10-30 mTorr).

FIGURE VI-4

Hydrogen neutral pressure as a function of time at the minimum of the magnetic well in the cusp-injection device; inset in the upper left-hand corner of the plot are a pair of typical collected ion- and electron-current oscilloscope traces for data collected at this particular axial location of the gauge tube (the interruption of the trace brightness is a timing fiducial mark via Z-axis modulation).

FIGURE VI-4

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