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NEUTRON PRODUCTION IN A LINEAR PINCH

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Abstract

The neutron-producing linear pinch devices that were built at Berkeley are described, and the experiments pertaining to a possible thermonuclear process are discussed. It was finally shown that the neutrons were produced by plasma instabilities.

Introduction

The Sherwood Project group at UCRL Berkeley, headed by W. R. Baker, has had a pioneering role in the field of high-temperature plasma production. The first of many systems tried was a "medium-energy" linear pinch, which turned out to be the first machine of any kind in the thermonuclear research field to produce a significant number of neutrons. An important series of measurements was made to determine the origin of these neutrons in space and time, and in general, whether the production was due to a thermonuclear or an acceleration process. As has frequently been pointed out,[1] useful power cannot be obtained from the fusion reactions that occur when beams of accelerated deuterons interact with a plasma.

Fusion Reactions

The fusion reactions most suitable to a controlled thermonuclear device are:

$$(1)\quad D + D \begin{cases} \xrightarrow{50\%} He^3 + n + 3.25\ \text{Mev} \\ \xrightarrow{50\%} T + p + 4\ \text{Mev} \end{cases}$$

and

$$(2)\quad D + T \longrightarrow He^4 + n + 17.6\ \text{Mev.}$$

For several reasons, one of the most important being safety, researchers in this field prefer to use a pure deuterium gas, and it is this reaction that will be discussed. The yield of neutrons per second from a cubic centimeter of plasma is given by the expression $N = \frac{1}{4} n^2 \overline{\sigma v}$, where n is the density of deuterium ions and σ is the cross section for a reaction to occur between ions of relative velocity, v. The product, σv, is averaged over the distribution of velocities existing in the plasma.

The reaction cross section is shown in Fig. 1 as a function of ion velocity and energy for the case where one deuteron is at rest. It is seen that this cross section is changing very rapidly in the low-energy region where research is now being carried on. If the ions are in thermal equilibrium, the velocities are described by a Maxwellian distribution; this is shown in Fig. 2 for the special case where the mean ion energy, $\overline{W}$, is 600 electron-volts. (More frequently, such a plasma is described by the "kinetic temperature", $\theta = 2/3\ \overline{W}$, or by a conventional definition of temperature, T (^{o}K) = $1.16 \times 10^4\ \theta$ (ev). The average of the product, $\overline{\sigma v}_{DD}$, is given in Fig. 3 as a function of kinetic temperature for a Maxwellian distribution.

The value of $\overline{\sigma v}$ is strongly energy-dependent at temperatures lower than a few kilovolts, and consequently the ion temperature of a plasm can be determined by counting the number of neutrons emitted per second (Fig. 1). This is one of the principal means used at present by scientists working on controlled fusion projects However, the distribution of ion energies must be know before the method has validity.

The Linear Pinch

Among the devices considered for thermonuclear experiments, the linear dynamic pinch stands alone in its simplicity. The pinch tube i merely a non conducting cylinder, such as a gla pipe, capped by metal electrodes and surrounde by a coaxial copper return conductor. This apparatus is filled with gas at low pressure, usua ly a few ten-thousandths of an atmosphere. The system is completed by an assembly of condens and a spark gap or similar switch for connectin the tube to the condenser bank.

In operation, after the connection is made, the gas is rapidly ionized to the point where it becomes a good conductor, or "plasma". The ra ly increasing current is then restricted by the effect to a thin layer at the plasma surface. Th current reacts with its own self-generated magnetic field in producing an inward force, as indi ed in Fig. 4; this is commonly known as the "pi effect". (This is a specialized example of the well-known interaction of moving charges, whic is responsible for all the mechanical effects of magnetic fields. More common descriptions ar Lorentz force, motor force, magnetic pressure When the current becomes sufficiently large, th magnetic pressure, $B^2/8\pi$, exceeds the gas pressure, nkT, and the plasma column collapse radially. As the plasma is driven inward, stro shocks are produced; eventually these shocks re the axis and are reflected. Then, moving outwa they meet the incoming current sheath and reve the direction of motion. This reversal is known as a "bounce". The plasma radius at which a bounce occurs depends on the magnitude and wa form of the impressed current. Generally there are subsequent bounces of increasingly smaller radii as the current continues to increase. (If t deuteron energies are sufficient at one or more these bounces, nuclear reactions will occur.) It is an important fact that the magnetic pressure for a given current is proportional to the inverse square of the radius. Thus, while it seems fortuitous that the pressure can reach very high values as the plasma column collapses, there is the unfortunate corollary that any section of the collapsing column that has a head start will run away from the rest. Because this effect eventually leads to a necking-in at one or more places, it is known as the "sausage instability". It is usually assumed to be the most important problem in the dynamic pinch.

The hope in these early experiments was that, starting the pinch as symmetrically as possible, one could produce "thermonuclear" plasma energies by some combination of resistive, shock, and compression heating before instabilities caused any serious difficulty. This hope was unfulfilled, at least in the bulk of the experiments. However, some interesting data were obtained in the process: shock velocities in deuterium corresponding to Mach 60, peak magnetic pressures of several hundred atmospheres, and kinetic "temperatures" of one or two million degrees centigrade. These figures apply to the experiments that are the main subject of this report. Temperatures about twice as high, and some possibly "thermonuclear" neutrons were obtained in an experiment employing a special capacitor constructed at the Berkeley Radiation Laboratory. This operated at 160 kv, and had very low inductance because it employed water as the dielectric medium. (Water has a dielectric constant of about 80, and a maximum dielectric strength of about 400 kv per cm in this voltage region. The working strength was about 140 kv per cm.) In this experiment, neutrons were produced at the first bounce, when the pinch was apparently still uniform; however the operating life of the capacitor was so short that no neutron energy distributions could be made. For this reason, the water-capacitor experiment is mentioned here only in passing and will not be referred to again in this report.

Experimental Equipment

After the Berkeley Sherwood program was organized in 1954, a pinch circuit was designed, which achieved the following objectives: (1) reasonably low inductance, (2) use of readily available condensers, (3) minimum external electrical noise, (4) pinch tubes outside the condenser box to allow juxtaposition of measuring apparatus, (5) convenient mounting arrangements to allow interchange of tubes. This last feature was almost a necessity; in the first year or so of the experiments over 30 pinch tubes of various sizes, shapes, and materials were used.

The condenser bank contained 25 standard Cornell-Dubilier capacitors of 0.5-μf, 50-kv rating. The bank-circuit inductance (including spark gap but not the pinch tube) was 0.2 μh. The arrangement is shown semi-schematically in Fig. 5. The peak discharge current was usually about 200,000 amp.

Pinch tubes ranged in length from 4 in. to 10 ft, and in diameter from 0.5 in. to 12 in. Experiments were made with various insulators surrounding the pinch. These arranged themselves in operating efficiency more or less in the order of their volatility: Epon, Teflon, soft glass, Pyrex, alumina ceramic, and fused quartz. (Note that the ceramic contained binder material of relatively high volatility.) Electrode materials used were: copper, aluminum, and graphite; the choice did not seem to be critical.

Figure 6 shows an early pinch tube in exploded view; note the quartz insulator, aluminum electrodes, and copper return conductor. The tube-voltage signal was monitored with a compensated voltage divider employing salt water, and the current signal was obtained from a noninductive shunt. (Neither method would now be recommended because more convenient means are available.)

Electrical Signals

Even though the neutron flux received the most attention, the current and voltage waveforms were also studied extensively in an attempt to understand the phenomena occurring in the pinch. Typical signals are drawn in Fig. 7. The current is seen to have a more or less sinusoidal shape on the average, as would be expected because most of the inductance is in the external circuit except at times of maximum pinch. Note the current dips that coincide with the plasma bounces; the negative rate-of-change of current just before the bounces occur will be discussed subsequently. The bounces are evident in the "discharge-radius" curve, which was roughly computed graphically from the voltage and current signals. The interesting features of the voltage wave shape are interpreted as follows, referring to the letters marked on the figure:

A. The full condenser voltage is across the pinch tube before appreciable ionization takes place.

B. The gas is ionized, and $V = L_0\, dI/dt + IR$, where L_0 is the "unpinched" inductance. Very shortly, however, IR becomes negligible.

C. The current sheath is moving toward the tube axis and the increase in voltage is caused principally by $I\, dL/dt$.

D. The bounce previously described takes place; the direction of motion reverses and the $I\, dL/dt$ term changes sign very rapidly.

E. $I\, dL/dt$ is still negative, but the outward speed of the sheath is decreasing.

F. The sheath has made its maximum radial excursion and a new pinch is about to start. This pinch is followed, in this case, by a third and fourth pinch. In some cases the peak tube voltages are many times the voltage originally applied.

G. The voltage trace consists of a large, high-frequency signal lasting for approximately 10^{-7} sec, following which all detail disappears. Apparently the insulator surface becomes conducting, and the interior of the pinch tube is isolated from the external circuits.

Theory of the Voltage Signal

These signals can be more fully explained with the help of the equivalent circuits of Fig. 8. These all neglect electrical resistance which is relatively unimportant here (except briefly as the discharge forms).

In Fig. 8a the inductance of the spark gap and connection and the internal inductance of the condensers have been lumped into L_c. The pinch tube is represented by a variable inductance. The tube voltage is broken into two parts in Fig. 8b, namely the L dI/dt and I dL/dt terms used previously in describing the voltage waveform. These terms may be obtained very simply from the expressions

$$V = 10^{-8} \frac{d}{dt}(\phi) = \frac{d}{dt}(LI) = L\frac{dI}{dt} + I\frac{dL}{dt},$$

where L is the instantaneous pinch-tube inductance. A clear identification of the last term with the plasma motion is obtained from the dynamo formula,

$$V = 10^{-8} B \ell v,$$

which gives the voltage measured in a nonmoving frame just outside the instantaneous plasma boundary, along a plasma column of length ℓ, collapsing radially with a velocity v, under the pressure of the self-field B. But because the instantaneous inductance of the pinch of radius r in a tube of radius R is

$$L = 2 \times 10^{-9} \ell \ln \frac{R}{r},$$

we have

$$\frac{dL}{dt} = -2 \times 10^{-9} \frac{\ell}{r} \frac{dr}{dt} = +2 \times 10^{-9} \frac{\ell v}{r}$$

if v is considered positive when directed toward the axis. Substituting this relation for ℓv along with the formula for the self-field, $B = I/5r$, into the dynamo formula,

$$V_p = I\frac{dL}{dt}$$

and the assumption implicit in Fig. 8b is justified.

The voltage transients generated by the plasma motion are often so large compared to the voltage V_c of the condenser bank that this voltage can be neglected for purposes of discussion. In this limiting case Fig. 8c applies, and it is seen that the measured tube voltage V will be less than the plasma voltage in the ratio $L_c/(L + L_c)$. In this approximation one can write for the plasma voltage

$$V_p = V\left(1 + \frac{L}{L_c}\right).$$

A typical pinch tube is 7.5 cm in diameter and 90 cm long. Because at moments of maximum compression, the pinch diameter is quite small, (a few millimeters), the maximum inductance may be several times the bank inductance of 0.2 μh. One finds for the peak plasma voltage a value approximately four times the peak measured tube voltage. In one experiment, the condenser bank was charged to 40 kv and the tube voltage rose to 80 kv just before the second bounce, implying a plasma voltage of over 300 kv. Transients of around 300 kv have been observed near the end of the dynamic action, as at point G in Fig. 7, giving an internal voltage over 1 Mv, if we assume the previous ratio. There is reason to believe that the instability responsible for these spikes causes an abnormally high inductance, and furthermore, that this high inductance is probably concentrated in a number of local regions so that in these places very high voltage gradients indeed are expected near the plasma.

The Neutron Measurements

The total number of neutrons emitted during a discharge was monitored by counting the scintillation pulses produced by thermalized neutrons that were captured in LiI(Tl) crystals; the timing of the neutron emission was obtained from the proton recoil pulses (Fig. 7) produced in plastic scintillation. The neutrons were produced in one or more bursts of about 2 to 3 $\times 10^{-7}$ sec duration. The times of the bursts corresponded to maximum radial compressions, usually at the third and fourth bounce but sometimes at the second bounce as well. By using several detectors and collimators, it was found that the emission occurred simultaneously and uniformly along the axis of the tube within a cylinder of radius no larger than one centimeter. Another experimental result which was suggestive of a thermonuclear origin was the strong quenching of the neutron emission when small percentages of heavy gases (e.g. argon) were added to the deuterium.

There were, however, other experimental results that did not seem consistent with a thermonuclear process. Foremost among these was the large yield, 10^7 to 10^8 neutrons per discharge, that was obtained after the insulating sleeve was changed from pyrex to quartz and the operating parameters were optimized. If the plasma is considered to be at a fairly uniform temperature throughout, such yields imply kinetic temperatures of 600 v or more; temperatures of this size seemed inconsistently large when compared to rather simple theoretical predictions. Moreover, an axial magnetic field of 100 gauss reduced the neutron yield by about a factor of ten, although it was difficult to see how such a small field could have such a large effect if the pinch behaved properly. (During the pinching process the axial field was trapped in the conducting plasma and compressed along with the gas. The calculated pressure of this field was negligible compared to the gas pressure.)

It seemed likely that some nonthermonuclear process was responsible for the neutron production in particular one by which a small percentage of the deuterons in the plasma was accelerated to very high energies so that the increased reaction cross section could account for the observed yield.

If high-energy deuterons react with deuterons that are approximately at rest in the laboratory system, the neutrons that are produced have larger energies when emitted in the same direction as the high-energy deuteron than when emitted in the opposite direction (Fig. 9). A crucial experiment was performed in which the neutron energies were measured by exposing nuclear emulsions at the ends of the pinch tube. An energy shift was found that corresponded to deuterons of approximately 50 kev striking deuterons at rest, with the high-energy deuterons always moving in the direction of the applied electric field. A typical histogram of the observed neutron-energy shift is shown in Fig. 10.

Discussion

The type of instability that is thought to accelerate the deuterons is the "sausage" instability (Fig. 11) in which the magnetic and plasma forces become so unbalanced that the plasma column is severely and rapidly constricted in one or more places. A theory has been developed[2] by means of which it is shown that the rapidly changing magnetic fields at the points of instability give rise to electric fields of sufficient magnitude to accelerate deuterons to 50 or more kilovolts energy, and in sufficient numbers to quantitatively account for the observed yield of neutrons.

More recently, members of the Los Alamos Sherwood group have proposdd theories that also involve the growth of "sausage" instabilities but that differ from the above theory in the details of the mechanism by which the energy shift is produced. It is clear that much fundamental research remains to be done in this field although the simple picture of thermonuclear production has clearly been ruled out. In conjunction with other techniques, the measurement of neutron emission has proved to be a very useful diagnostic aid in our attempt to understand the simple linear pinch and the more sophisticated devices which have followed it.

Acknowledgments

In addition to our co-workers William R. Baker, Sterling Colgate, R. Stephen White, and John Ise, Jr., we wish to express our appresiation to many others, in particular to Jack Riedel for his early work on this project, to Ernest O. Lawrence, Edward Teller, Chester M. Van Atta, and Herbert York for their encouragement and advice, and to the members of the fine technician groups headed by Arthur Hartwig and Louis A. Biagi, who worked so closely with us in the design and construction of the experimental apparatus. Special thanks are due to Edward Creutz for his adtive participation in the program during his visit to UCRL.

References

1. See e.g. Richard F. Post, Reviews of Modern Physics 28, 338 (1956). This is a general article on controlled fusion research. A rather complete list of references applying specifically to the pinch effect is included in a recent article by Burkhardt, Dunaway, Mather, Phillips, Sawyer, Stratton, Stovall, and Tuck, Journal of Applied Physics 28, 519 (1957).

2. Anderson, Baker, Colgate, Furth, Ise, Pyle, and Wright, Phys. Rev. 109, 612 (1958), and in more detail by Anderson, Baker, Colgate, Ise, and Pyle, in UCRL-3725, 2nd Rev. (November 1957) to be published.

Figure Legends

Fig. 1. The D-D reaction cross section as a function of ion velocity and energy for the case of the target deuteron at rest.

Fig. 2. The Maxwellian distribution of ion velocities in a deuterium plasma with a kinetic temperature of 400 v.

Fig. 3. σv_{DD} for a Maxwellian distribution. Also shown are neutron-emission rates for three values of ion density.

Fig. 4. The pinch mechanism.

Fig. 5. A semi-schematic of the pinch-apparatus circuit.

Fig. 6, An exploded view of an early pinch tube.

Fig. 7. Typical signals from a pinch tube.

Fig. 8. Pinch-circuit schematics.

Fig. 9. Neutron energies from D-D reactions as a function of incident-deuteron energy.

Fig. 10. Recoil-proton histograms from neutrons emitted at 0° and 180° to the applied electric field.

Fig. 11. The "sausage" instability.

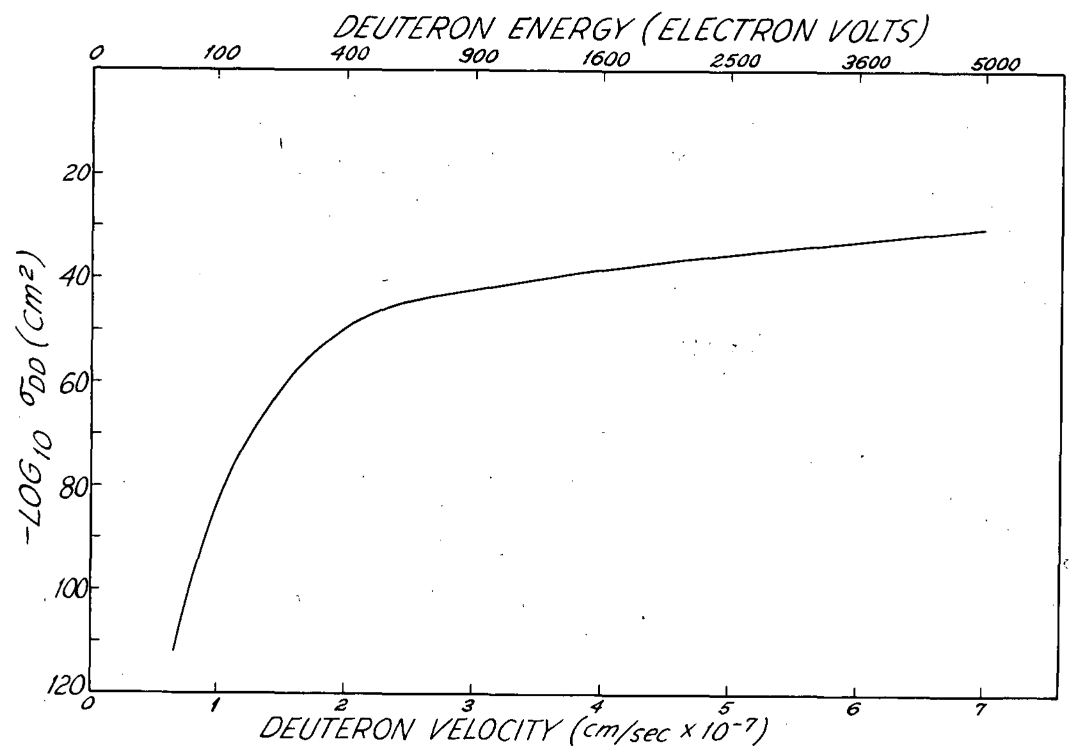

DEUTERON ENERGY (ELECTRON VOLTS)
0
100
400
900
1600
2500
3600
5000
-LOG10 σDD (cm²)
20
40
60
80
100
120
0
1
2
3
4
5
6
7
DEUTERON VELOCITY (cm/sec × 10⁻⁷)

Fig. 1.

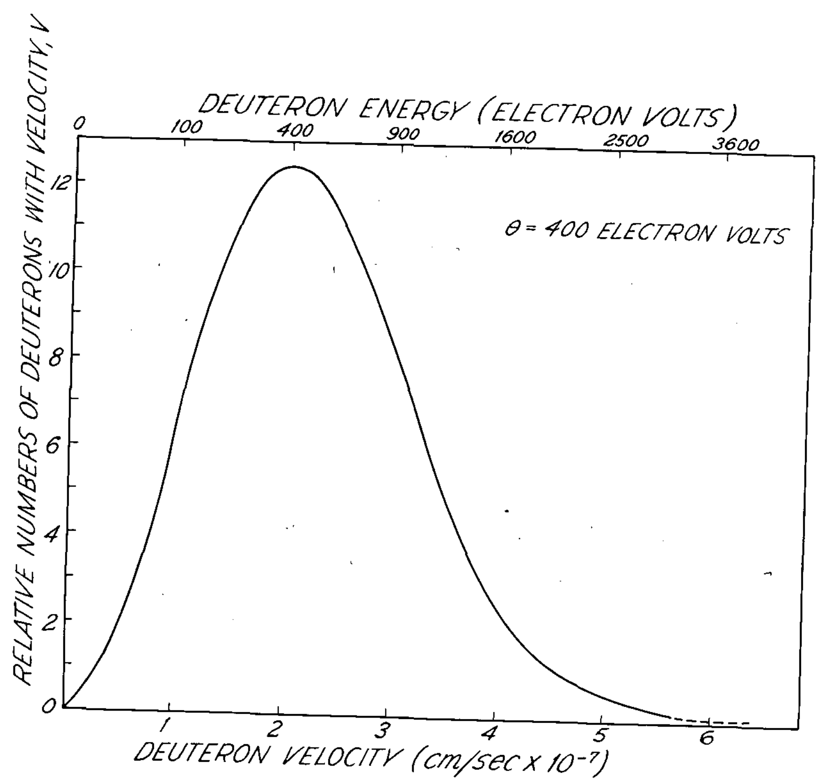

DEUTERON ENERGY (ELECTRON VOLTS)
0
100
400
900
1600
2500
3600
θ = 400 ELECTRON VOLTS
RELATIVE NUMBERS OF DEUTERONS WITH VELOCITY, V
0
2
4
6
8
10
12
1
2
3
4
5
6
DEUTERON VELOCITY (cm/sec x 10⁻⁷)

Fig. 2.

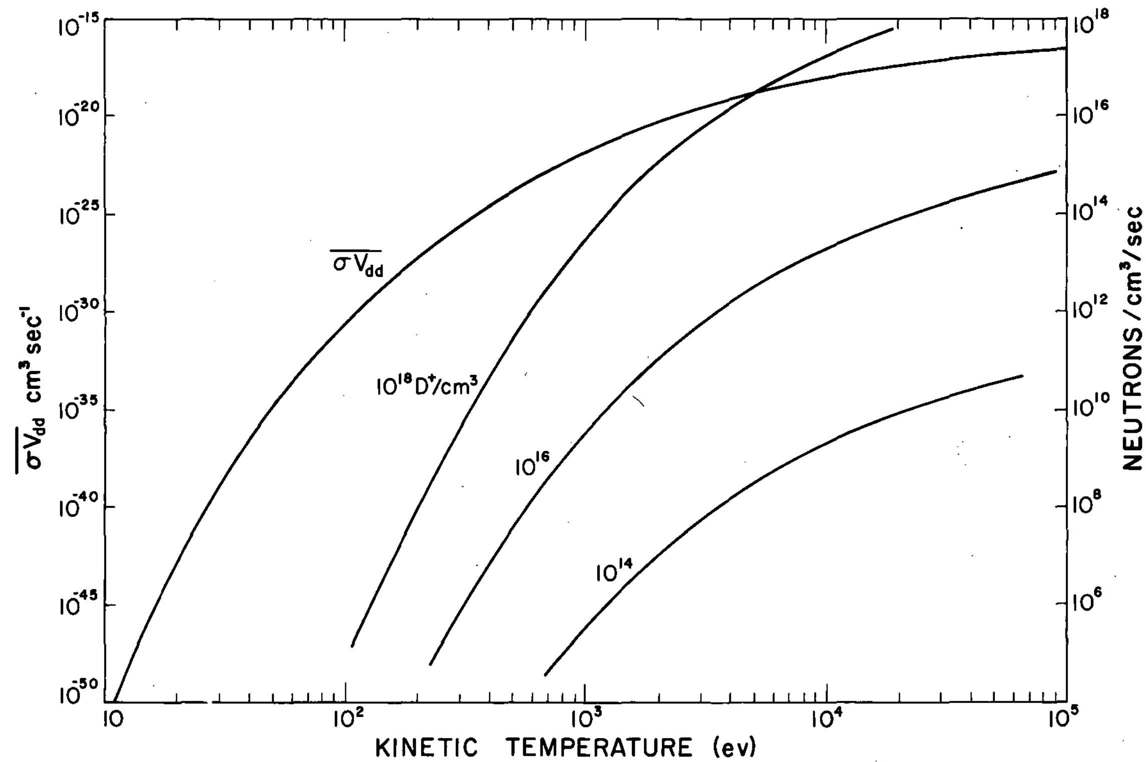

$\overline{\sigma V_{dd}}$
$10^{18} D^+/cm^3$
10^{16}
10^{14}
$\overline{\sigma V_{dd}}$ cm³ sec⁻¹
NEUTRONS/cm³/sec
KINETIC TEMPERATURE (ev)

Fig. 3.

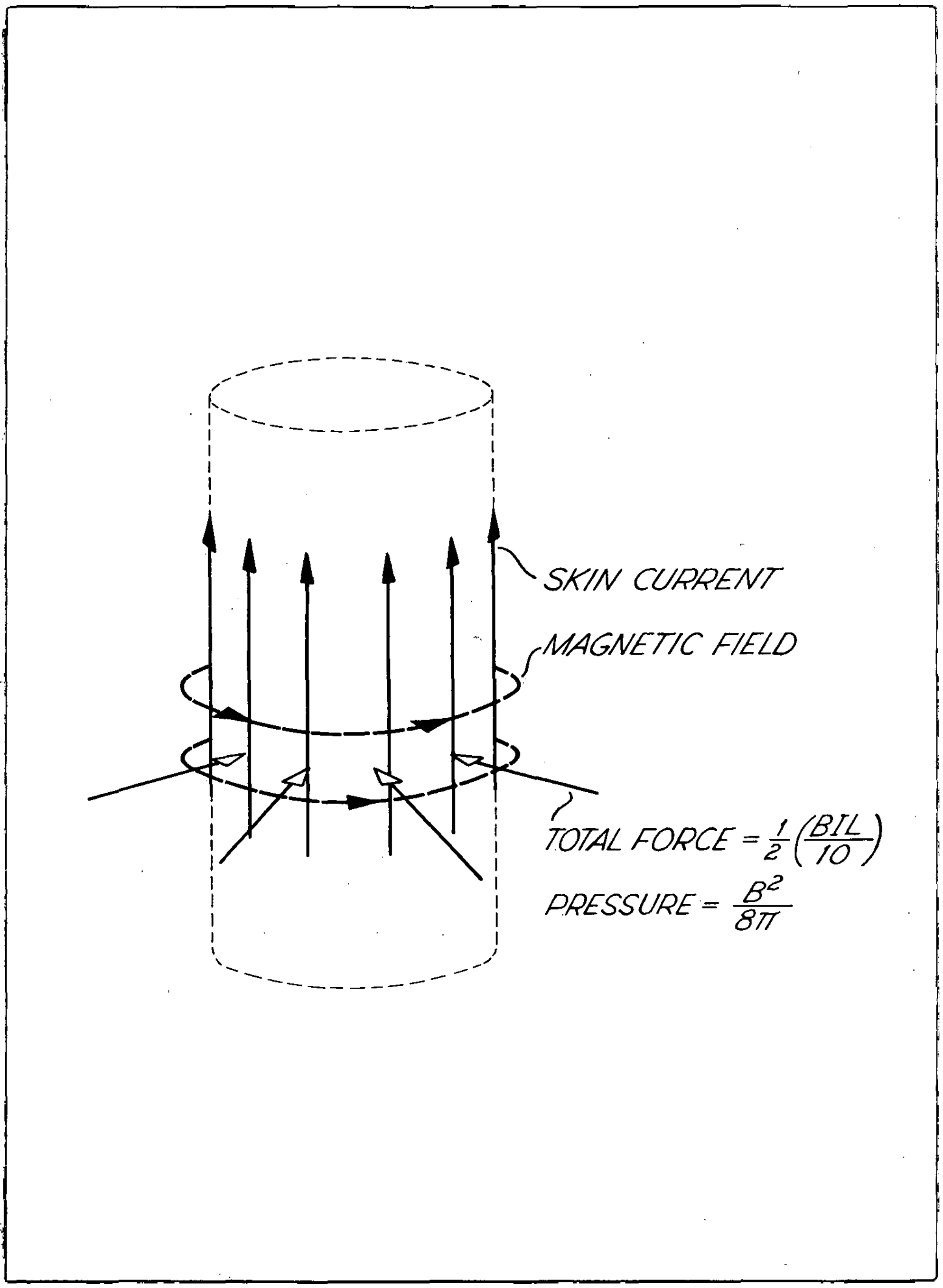

SKIN CURRENT
MAGNETIC FIELD
TOTAL FORCE = $\frac{1}{2}\left(\frac{BIL}{10}\right)$
PRESSURE = $\frac{B^2}{8\pi}$

Fig. 4.

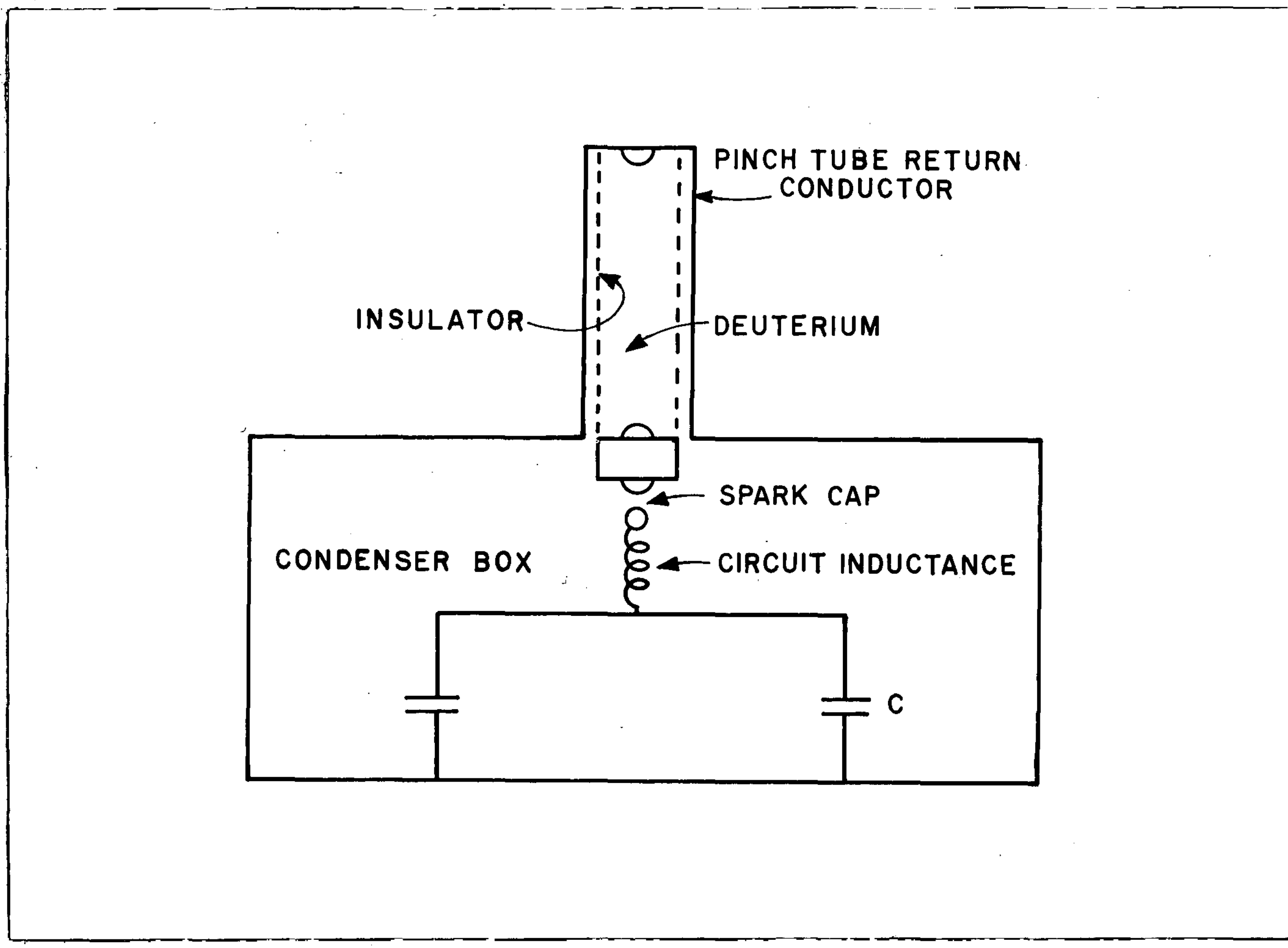

PINCH TUBE RETURN CONDUCTOR
INSULATOR
DEUTERIUM
SPARK CAP
CONDENSER BOX
CIRCUIT INDUCTANCE
C

Fig. 5.

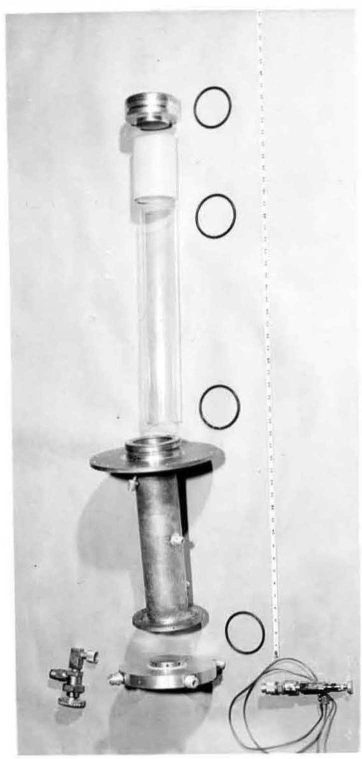


Fig. 6.

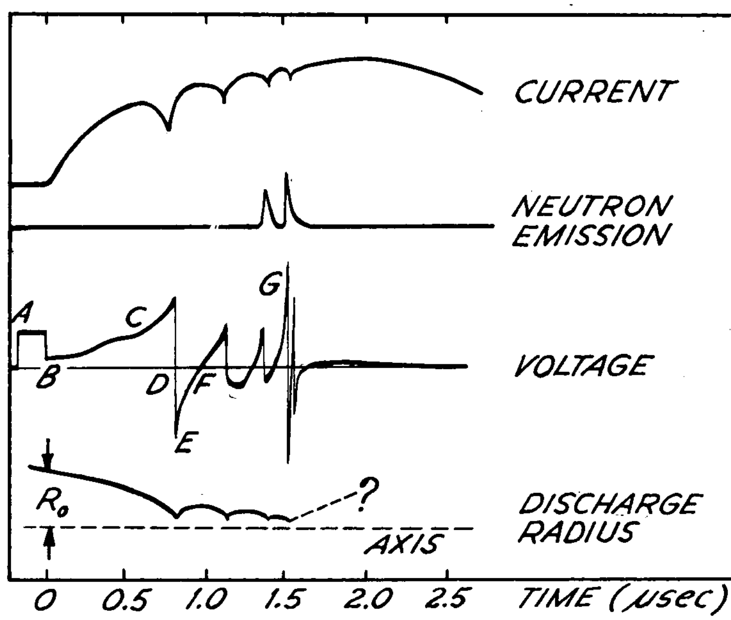
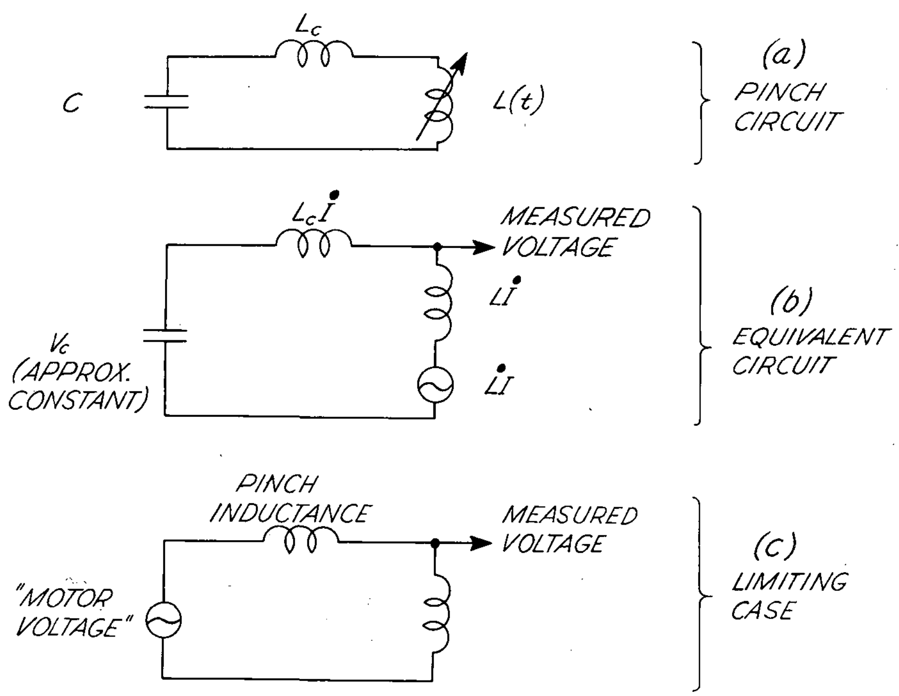

CURRENT
NEUTRON EMISSION
A
C
G
B
D
F
E
VOLTAGE
R_o
?
DISCHARGE RADIUS
AXIS
0
0.5
1.0
1.5
2.0
2.5
TIME (μsec)

Fig. 7.



L_c
C
L(t)
(a)
PINCH
CIRCUIT
$L_c\dot{I}$
MEASURED
VOLTAGE
$L\dot{I}$
V_c
(APPROX.
CONSTANT)
$\dot{L}I$
(b)
EQUIVALENT
CIRCUIT
PINCH
INDUCTANCE
MEASURED
VOLTAGE
"MOTOR
VOLTAGE"
(c)
LIMITING
CASE

Fig. 8.

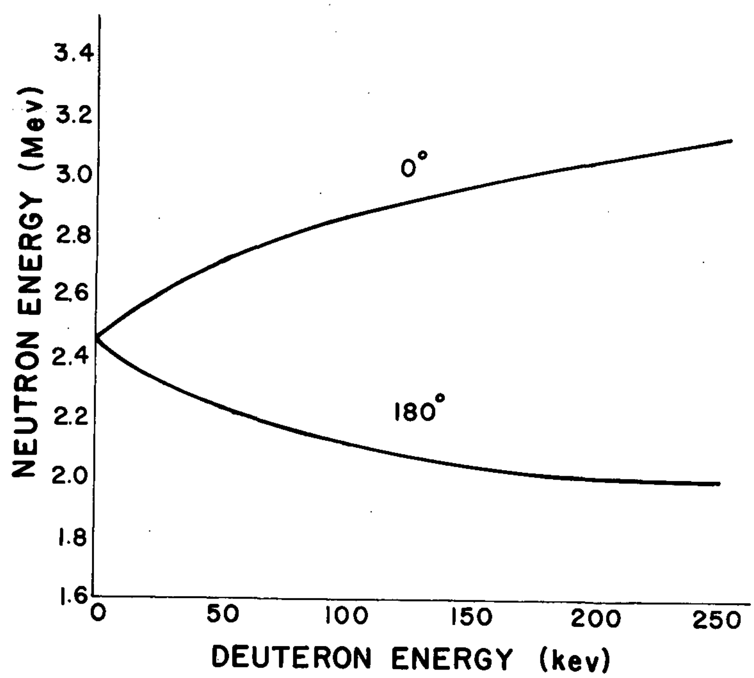

NEUTRON ENERGY (Mev)
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
0°
180°
0
50
100
150
200
250
DEUTERON ENERGY (kev)

Fig. 9.

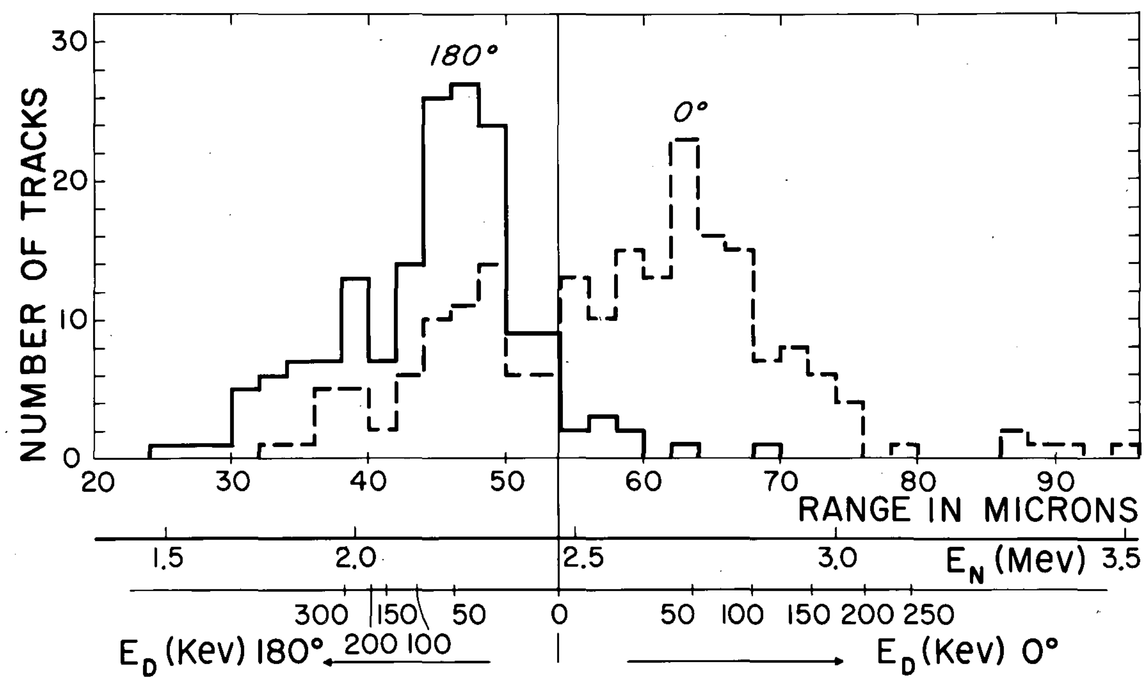
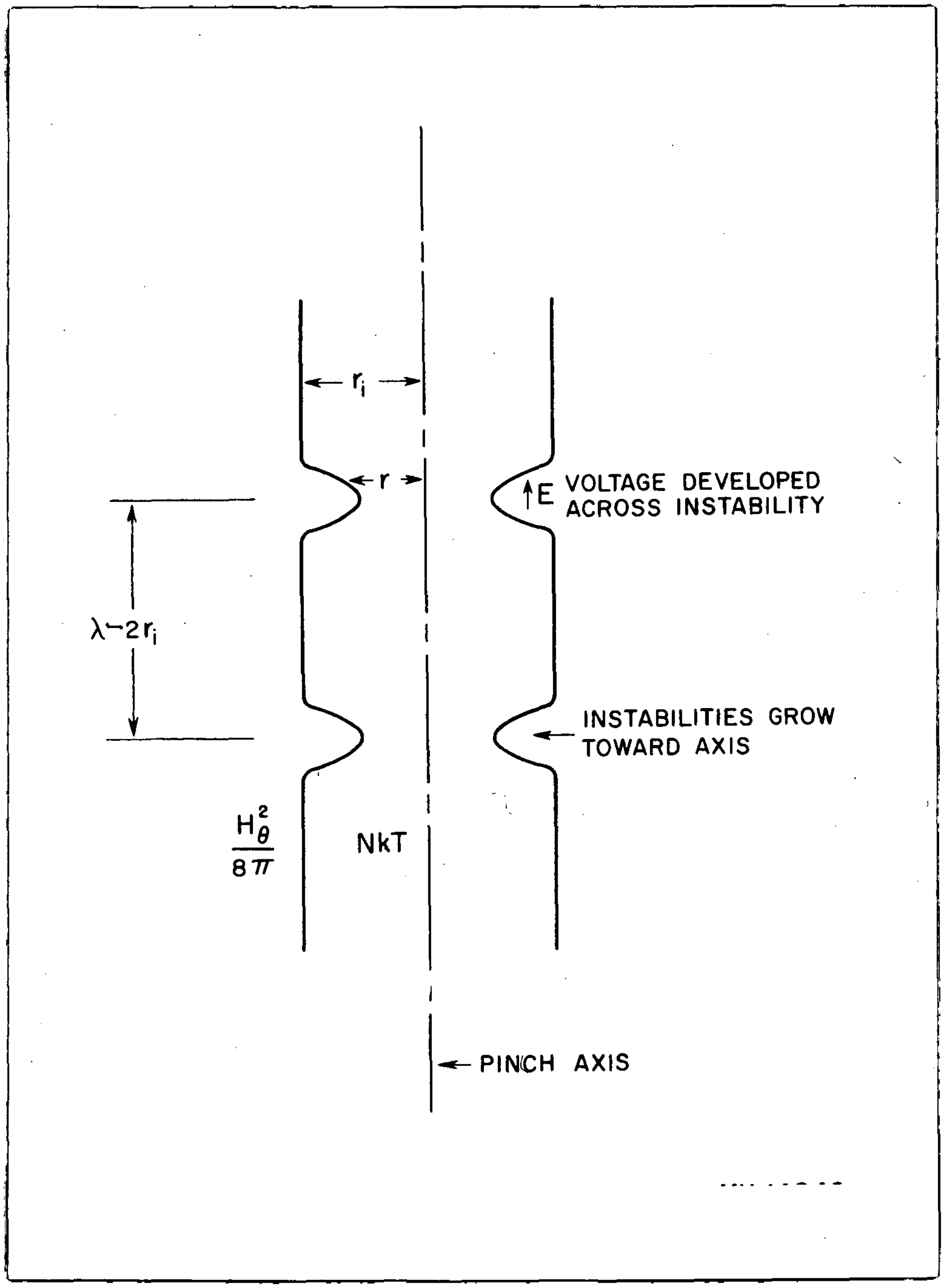

180°
0°
NUMBER OF TRACKS
0
10
20
30
20
30
40
50
60
70
80
90
RANGE IN MICRONS
1.5
2.0
2.5
3.0
E_N (Mev) 3.5
300
150
50
0
50 100 150 200 250
200 100
E_D (Kev) 180°
E_D (Kev) 0°

Fig. 10.



r_i
r
E
VOLTAGE DEVELOPED ACROSS INSTABILITY
$\lambda \sim 2 r_i$
INSTABILITIES GROW TOWARD AXIS
$\frac{H_\theta^2}{8\pi}$
NkT
PINCH AXIS

Fig. 11.