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JOULE LOSSES IN LINEAR θ PINCHES :
LASER VS MAGNETIC HEATING

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Summary

The dc joule losses per unit length in a θ-pinch compression coil are calculated and compared to the thermonuclear energy production for two different methods of plasma heating. In the first method, conventional staged θ-pinch heating is assumed. In the second method laser heating by long wavelength irradiation from the ends is assumed. Reactor parameters are calculated, and it is shown that for circulating power fractions to be 20% or less, the plasma radius must be at least a few cm in size.

I. Introduction.

The basic motivation for studying straight θ-pinch reactor designs is to have a viable back-up concept for toroidal Scyllac reactor studies.

It is widely accepted that the main virtues of the straight θ-pinch over other configurations such as toroidal Scyllac and Tokamak are its ease of plasma heating and its desirable plasma stability properties. The problem with linear θ-pinches, of course, is end loss, whereby, without mirrors, particles stream out the ends at essentially the ion thermal velocity. It can be shown, however, that the use of mirrors is not the best way in which to use the maximum field, B_{max}, obtainable in a θ-pinch. The maximum nτ product results, other things being equal, when $B = B_{max}$ along the entire pinch column, and consequently the mirror ratio is unity.

In a recent LAMS report,[1] Ellis and Sawyer considered the problem of laser heating vs conventional magnetic heating (shock heating followed by adiabatic compression) in an unmirrored linear θ-pinch geometry. Scaling laws were derived for reactor length, confinement time, ion density, cycle time, etc, as functions of the magnetic field strength, B_o , based upon the assumption that particle end loss is the dominant mechanism limiting plasma confinement. With the further assumption that the plasma was highly compressed (i.e., plasma radius equal to a few ion gyroradii), the thermonuclear energy produced per unit length and the laser energy required for heating were derived. These assumptions lead to values of the plasma radius of 1-2 mm, laser energies of 5-10 MJ, and power plants in the few hundred MWe range.

In this paper we extend the previous analysis of Ellis and Sawyer to include the important energy loss mechanism of joule losses in the compression coil. These losses can be substantial, and theoretically it is predicted that the thermonuclear power can be made to dominate, resulting in an acceptably low circulating power fraction, only if the plasma radius is increased from its minimum value. Our calculations show that the minimum plasma radius must be of the order of a few cm, instead of a few mm, with concomitant increases in the size of the plant, magnetic and laser energy storage requirements, etc.

II. Review of θ-Pinch Scaling Laws.

Scaling laws have been derived[1] for the linear θ-pinch, assuming that plasma loss out of the ends at essentially the ion thermal velocity is the dominant loss mechanism limiting plasma confinement. Radial diffusion and axial thermal conduction are assumed to be small compared to particle end losses. We further assume no applied mirrors, equal electron and ion temperatures, $\beta = 1$, $n\tau = 10^{15}$ cm^{-3} sec for the reactor, and kT = 10 keV during the burn.

The required scaling laws are reproduced below with the magnetic field B_o as the independent variable:

Ion Density

$$n = 1.24 \times 10^{12}\, B_o^2 \tag{1}$$

Confinement Time

$$\tau = 806/B_o^2 \tag{2}$$

Reactor Length

$$L = 1.97 \times 10^5/B_o^2 \tag{3}$$

Plasma Thermal Energy Content

$$E_p = 246\, a^2 \quad \text{MJ} \tag{4}$$

Plant Thermal Power Output

$$P_{th} = 1.67 \times 10^7\, \frac{b}{B_o^2}\left(\frac{\overline{P}_w}{A}\right) \quad \text{MW}_{th} \tag{5}$$

The units are magnetic field B_o in kG, ion density n in cm^{-3}, confinement time τ in sec, reactor length L in km, plasma radius a in cm, first wall radius b in cm, and average wall loading (from primary neutron flux), $(\overline{P}_w/A)$ in MW/m^2.

It can be seen from these equations that unless B_o is large, the reactor size becomes unwieldy. For example if B = 100 kG, b = 10 cm and $\overline{P}_w/A$ = 3.5 MW/m^2 (a commonly quoted value)[2] then the reactor length is 19.7 km (12.2 miles) and the thermal power is 58.5 GW_{Th}. It follows that the way to reduce the plant size, and hence cost, is to make B_o as large as possible.

III. Maximum Practical Magnetic Field.

The maximum magnetic field that can be used will be governed by strength of materials since the coil winding must be capable of supporting the magnetic pressure produced by the confinement field, whether dc or pulsed.

A survey[1] of the literature on high magnetic field technology indicates that the largest magnetic fields have been obtained in single turn solenoids.[3] The limits for coils that last many shots are about 600 kG for coils of 1 cm bore and 300 kG for coils of 10 cm bore. One MG is definitely out of reach with present technology.

IV. Compression Coil Design.

In this paper we will be considering magnetic fields in the range 100-400 kG, corresponding to magnetic pressures in the range 6000-96,000 psi. The yield points of some possible coil materials are plotted against magnetic pressure in Fig. 1. Since the coil material should also be a good electrical conductor to minimize joule losses, the best choice appears to be Be-Cu, with a yield strength of 1.5×10^5 psi. We will assume that the Θ-pinch coil is located inside the breeding blanket (probably necessary with the high fields assumed here), in which case it will operate hot. The resistivity of Be-Cu at 500°C is $\eta = 5 \times 10^{6}$ Ω-cm. The coil thickness Δb (see Fig. 2) will be taken as 10 cm, a compromise between neutron damage effects and strength requirements. The coil radius b depends in a complicated way on the choice of B_o, plasma heating mechanisms, etc. This dependence will be discussed in detail below.

V. Joule Losses in the Compression Coil.

Joule losses in the compression coil of a pulsed reactor are of two types. The eddy current losses arise from time variations of the magnetic field, and can be minimized by laminar construction. The dc, or transport current, losses are associated with the solenoidal field B_o, and are subject only to minor control. In the calculations which follow we will assume that eddy current losses are negligibly small compared to the transport current losses, which may be optimistic.

During one burning pulse the transport current losses per unit length of the reactor are

$$\frac{E_j}{L} = \tau \int_b^{b + \Delta b} \eta\, j^2(r)\ 2\pi r\ dr \qquad (6)$$

where $j(r)$ is the current density distribution in the coil. Equation (6) is minimized when B(r) reaches its steady state solution, i.e., satisfies the time independent diffusion equation. This solution is

$$B(r) = \begin{cases} B_o & r \leq b \\ B_o \dfrac{\ln (c/r)}{\ln (c/b)} & b \leq r \leq c \end{cases} \qquad (7)$$

where $c = b + \Delta b$ is the outer coil radius as shown in Fig. 2. Although the compression coil is shown in Fig. 2 as a one turn solenoid for simplicity, in practice laminations will definitely be required if B(r) attains the steady state distribution given by Eq. (7) on the millisecond time scales of interest. The skin depth associated with a risetime of 1 msec and a coil resistivity of 5×10^{-6} Ω-cm is 0.7 cm.

The required distribution j(r) is calculated from $\nabla \times B = \mu_o j$. In MKS units,

$$j(r) = \frac{1}{r} \frac{B_o}{\mu_o \ln (c/b)} \ . \qquad (8)$$

By direct integration we then find

$$\frac{E_j}{L} = \frac{2\pi\ \eta B_o^2 \tau}{\mu_o^2 \ln (c/b)} \ . \qquad (9)$$

Substituting from Eq. (2) for τ eliminates B_o^2:

$$\frac{E_j}{L} = \frac{3.2 \times 10^5\ \eta}{\ln\ (1 + \frac{\Delta b}{b})} \qquad (10)$$

where E_j/L is in MJ/m for η in Ω-cm.

Thus joule losses are only weakly geometry dependent, and in particular are independent of the number of turns. Once η is fixed, the joule losses are essentially fixed also.

VI. Magnetic Energy Stored in the Coil.

The magnetic energy stored in the coil includes a contribution from the coil thickness Δb:

$$E_M = L \int_0^{b + \Delta b = c} \frac{B^2(r)}{2\mu_o} 2\pi r\ \ dr \ . \qquad (11)$$

Substituting Eq. (7) for B(r) and integrating yields

$$E_M = \frac{\pi b^2 L\ B_o^2}{2\mu_o} \ (1 + f) \qquad (12)$$

where f represents magnetic energy stored in the coil wall:

$$f(c/b) = \frac{(c/b)^2}{(\ln\ c/b)^2} \left| \frac{1}{2} \left(1 - \frac{b^2}{c^2}\right) - \frac{b^2}{c^2} (\ln \frac{c}{b})(1 + \ln \frac{c}{b}\right| \qquad (13)$$

Finally, substituting from Eq. (3) for L yields

$$E_M = 246\ b^2\ (1 + f) \qquad (14)$$

where E_M is in MJ for b in cm.

VII. Thermonuclear Energy Production in the Plasma.

In one pulse the thermonuclear energy produced per unit length is given by

$$\frac{E_n}{L} = \frac{1}{4}\ \pi\ a^2\ n^2\ Q\ \overline{\sigma v}\ \tau \qquad (15)$$

where Q is the energy released per reaction, $\overline{\sigma v}$ is the Maxwell-averaged D-T cross-section (equal to 1.1×10^{16} cm^3 sec^{-1} at 10 keV), and τ is the burn time. If we take Q = 18.9 MeV/reaction* (which is somewhat pessimistic, since it ignores the 3.52 MeV energy of the trapped alpha particle), $n\tau = 10^{15}$ cm^{-3} sec, and n from Eq. (1) (the pressure balance condition), we obtain

$$\frac{E_n}{L} = 3.22 \times 10^{-5}\ a^2\ B_o^2 \qquad (16)$$

where E_n/L is in MJ/m for a in cm and B in kG. For a given magnetic field, E_n/L is thus directly proportional to the plasma cross-sectional area.

*From 14.1 MeV birth energy per neutron plus 4.8 MeV from the $Li^6(n,\alpha)$ T breeding reaction in the blanket.

VIII. Plant Circulating Power Fraction.

We form the dimensionless ratio of joule losses to thermonuclear energy production from Eqs. (10) and (14):

$$\frac{E_j}{E_n} = \frac{9.94 \times 10^9\ \eta(\Omega\text{-cm})}{a^2(\text{cm})\ B_o^2(\text{kG})\ \ln\left(1 + \frac{\Delta b}{b}\right)} \quad (17)$$

The ratio E_j/E_n must be less than unity for any viable reactor. For example, in the RTPR toroidal reactor design,[2] E_j/E_n as defined here is 6.2%, compared to the total circulating power fraction of 12.8%. Circulating power fractions greater than about 20% are usually considered unacceptable in a reactor. Therefore we will assume $E_j/E_n = 1/2(0.20) = 0.10$ in the following calculations, which is probably at the upper limit of acceptable values.

In order to obtain closed-form analytic solutions for a and b, we replace the logarithm term in Eq. (17) by its expansion

$$\ln(1 + \frac{\Delta b}{b}) \approx 2\left[\frac{2b}{\Delta b} + 1\right]^{-1} \quad (18)$$

For $2b/\Delta b \geq 1$, Eq. (18) is accurate to better than 10%. For the smallest value of b discussed in this paper, b = 2.17 cm, Eq. (18) is still accurate to better than 20%. With this substitution, Eq. (17) becomes

$$\frac{E_j}{E_n} = 4.97 \times 10^9\ \frac{\eta\left(1 + \frac{2b}{\Delta b}\right)}{a^2\ B_o^2} \quad (19)$$

(cm, Ω-cm, kG). Note that E_j/E_n is minimized by operating at the largest possible value of B_o.

IX. Conventional θ-Pinch Reactor Parameters.

In conventional θ-pinches, plasma heating is accomplished in stages[4] by a combination of shock (or implosion) heating followed by adiabatic compression to the ignition temperature in a rising magnetic field. Using the so called "free-expansion" implosion model (which predicts a first stage equilibrium position at a/b = 0.76) Ribe has calculated the final temperature after compression, kT_o, as a function of B_o, E_θ, and compression ratio:

$$E_\theta\left(\frac{\text{kV}}{\text{cm}}\right) = 0.244\left(\frac{a_o}{b}\right)^{7/3}[kT_o(\text{keV})]^{1/2}\ B_o(\text{kG}). \quad (20)$$

We denote the ignition-state quantities (a_o, n_o, kT_o, B_o) by a subscript "o" to distinguish them from the average quantities during the burn (a, n, kT, B). If we assume kT_o = 5 keV and kT = 10 keV, as predicted by computer burn codes[5] ($kT > kT_o$ because of alpha particle heating), then the average and ignition values are related approximately by $a = \sqrt{2}\, a_o$, $n = 1/2\, n_o$, $B = B_o$, and $kT = 2kT_o$. Thus Eq. (20) becomes

$$b = 0.55\ a\left[\frac{B_o(\text{kG})}{E_\theta\left(\frac{\text{kV}}{\text{cm}}\right)}\right]^{3/7} \quad (21)$$

(b in cm for a in cm). Substituting b from Eq. (21) into Eq. (19) yields

$$\frac{E_j}{E_n} = \frac{4.97 \times 10^9\ \eta}{a^2\ B_o^2}\left[1 + \frac{1.10a}{\Delta b}\left(\frac{B_o}{E_\theta}\right)^{3/7}\right]. \quad (22)$$

Equation (22) is quadratic in a^2, with solution

$$a = \frac{-\beta' + \sqrt{\beta'^2 - 4\alpha'\gamma'}}{2\alpha'}\ \text{cm} \quad (23)$$

where $\alpha' = B_o^2(\text{kG})\left[\frac{E_j}{E_n}\right]$

$$\beta' = -5.47 \times 10^9\ \frac{\eta(\Omega\text{-cm})}{\Delta b(\text{cm})}\left[\frac{B_o(\text{kG})}{E_\theta(\text{kV/cm})}\right]^{3/7}$$

$$\gamma' = -4.97 \times 10^9\ \eta(\Omega\text{-cm}) \quad .$$

By inspection, a will be minimized by choosing both E_θ and B_o as large as possible. In the following examples we will fix $E_j/E_n = 0.1$, $\eta = 5 \times 10^{-6}$ Ω-cm, Δb = 10 cm, and P_w/A = 3.5 MW/m^2, as discussed previously.

__Example 1:__ B_o = 200 kG, E_θ = 2 kV/cm.

These might be reasonable choices for a linear reactor. We calculate a = 5.97 cm and b = 23.6 cm. From Eqs. (1) to (5) and (14) it follows that n = 5 x 10^{16} cm^{-3}, τ = 20 msec, L = 4.9 km, E_n = 178 GJ, and P_{Th} = 34.5 GW.

__Example 2:__ B_o = 400 kG, E_θ = 4 kV/cm.

This is a more extreme case. We calculate: a = 2.00 cm, b = 7.92 cm, n = 2 x 10^{17} cm^{-3}, τ = 5 msec, L = 1.2 km, E_M = 29 GJ, and P_{Th} = 2.9 GW.

In Example 1 the requirements on B_o and E_θ are relatively modest, and yield a large, but conceivable, power plant. In Example 2, the values of B_o and E_θ are more difficult to achieve, but the plant size is much smaller. Somewhere in between there will exist an optimum compromise set of parameters.

X. Laser-Heated θ-Pinch Reactor Parameters.

One proposal for a fusion reactor is based upon a magnetically confined plasma column which is heated to ignition via long wavelength (e.g., 10.6 μ) laser irradiation from the ends.[6-9] Some potential problem areas in this scheme which require further investigation are the beam channeling problem, anomalous backscatter, size of laser, etc. For the purposes of this paper we will assume that laser heating is possible. Based on simple energy arguments, similar to those employed for the conventional θ-pinch reactor above, we next proceed to calculate the reactor parameters and the required laser energy, as was done above for the case of the conventional magnetically heated θ-pinch.

From Eq. (4), the plasma thermal energy content at 10 keV is E_p = 246 a^2 MJ, for a given in cm. The laser energy required to ignite the plasma at 5 keV is therefore 1/2 E_p, assuming no loss of laser light or overheating at the ends. The overheating effect has previously been estimated by Ellis and Sawyer[1] at roughly a factor of 2 energy penalty for laser-heated systems of 5 keV temperature and km lengths. Therefore the laser energy required will be approximately

$$E_L = 246\, a^2(\text{cm})\ \text{MJ}. \tag{24}$$

The coil radius b in a laser heated reactor can be much smaller than in a conventional θ-pinch reactor because no compressional heating is involved. To avoid alpha particle collisions with the wall we require that b satisfy

$$b = a + r_g(\alpha) \tag{25}$$

where $r_g(\alpha) = 272/B(\text{kG})$ is the alpha gyroradius in cm at 3.52 MeV. Substituting b from Eq. (25) into Eq. (19) again yields a quadratic equation in a, with solution

$$a = \frac{-\beta'' + \sqrt{\beta''^2 - 4\alpha''\gamma''}}{2\alpha''}\ \text{cm} \tag{26}$$

where $\alpha'' = B_o^2(\text{kG}) \left[\frac{E_J}{E_n}\right]$

$$\beta'' = -\,9.94 \times 10^9\, \eta(\Omega\text{-cm})/\Delta b(\text{cm})$$

$$\gamma'' = -\left[4.97 \times 10^9 + \frac{2.7 \times 10^{12}}{B(\text{kG})\ \Delta b(\text{cm})}\right] \eta(\Omega\text{-cm}) .$$

In this problem, since E_B is not involved, B_o is the only free parameter.

As in the θ-pinch case, Sec. IX, we will assume $E_J/E_n = 0.1$, $\eta = 5 \times 10^{-6}$ Ω-cm, $\Delta b = 10$ cm, and $\bar{P}_w/A = 3.5$ MW/m^2 as reasonable choices for a high-field reactor. We then consider operation at two values of the magnetic field, $B_o = 200$ and $B_o = 400$ kG.

<u>Example 1:</u> B = 200 kG.

In this case we calculate a = 3.50 cm, b = 4.86 cm, $n = 5 \times 10^{16}$ cm^{-3}, τ = 20 msec, L = 4.9 km, E_M = 14.2 GJ, P_{Th} = 7.1 GW, and E_L = 3.0 GJ.

For comparison with the reactor length of 4.9 km the laser absorption length for 10.6 μ radiation is given by

$$\ell_{ab} = \frac{2.12 \times 10^8 (kT)^{7/2}}{\ell n[1.54 \times 10^5 (kT)^{3/2}]}\ \frac{1}{B^4} \tag{27}$$

where ℓ_{ab} is in km for kT in keV and B in kG. For 5 keV and 200 kG we calculate ℓ_{ab} = 2.6 km, and hence L/ℓ_{ab} = 1.9. In this case, where the reactor length is less than two absorption lengths at ignition, some laser energy may be lost from the open ends of the pinch. This could have the effect of increasing E_L from 3 GJ to, say, 5 GJ.

<u>Example 2:</u> B = 400 kG.

As in the case of the conventional θ-pinch 400 kG represents a rather extreme value of magnetic field. This case probably yields the minimum practical plasma radius, and hence the minimum laser energy requirements. We calculate a = 1.49 cm, b = 2.17 cm, $n = 2 \times 10^{17}$ cm^{-3}, τ = 5 msec, L = 1.2 km, E_M = 5.3 GJ, P_{Th} = 0.79 GW and E_L = 0.546 GJ.

For B = 400 kG, we calculate ℓ_{ab} = 162 meters and hence L/ℓ_{ab} = 7.4. This value is large enough to imply essentially total absorption of the laser energy by the plasma.

XI. Discussion and Conclusions.

In this paper we have estimated the joule losses in a θ-pinch coil by assuming that certain of the coil parameters – namely the resistivity and wall thickness – are essentially fixed parameters. Certainly the values used here ($\eta = 5 \times 10^{-6}$ Ω-cm and Δb = 10 cm) cannot be lowered appreciably without affecting credibility of the reactor. The resistivity of pure copper, for example, is ~ 1.7×10^{-6} Ω-cm at room temperature, a very unlikely operating point for an inside coil.

Many of the energy losses associated with a fusion reactor have been neglected in the above, such as eddy current losses, pumping losses, etc. On the other hand some sources of recoverable energy have also been neglected: direct conversion from the alpha particle heating and expansion, the recoverable fraction of joule losses in the hot coil, etc. These items have all been lumped together in our basic assumption of a 20% circulating power fraction, based upon energy flow calculations for the RTPR.[2]

In order to keep the length and power output of a straight reactor to reasonable proportions, it appears that operation at high magnetic fields, in the range of 200 to 400 kG, is desirable. At such high field strengths, it is probable that the compression coil should be located inside the lithium blanket, as assumed in the present paper. If an outside coil were assumed instead, the minimum value of the coil radius b would increase by perhaps half a meter from the values calculated in this paper. This would be a difficult proposition from the standpoint of both strength of materials and magnetic energy storage requirements. An inside coil, on the other hand, is subject to heating and structural damage from the intense bremsstrahlung, neutron and gamma-ray fluxes it encounters, and a careful study will be required to see if it can survive in such an environment.

Looking beyond the coil problem, a linear high-field reactor is not without attractions. It is basically a simple design, lends itself to modular construction, and provides ready access from the ends. The reactor thermal output power and magnetic energy storage requirements are modest when compared to some other fusion reactor designs, at least in the 400 kG case.

Of the two plasma heating methods considered here, the magnetic heating scheme would seem preferable. It is true that the laser heating method provides a somewhat smaller power plant, but against this possible advantage must be set the difficulty of reliably procuring at least 500 MJ of laser energy per pulse (approximately once per second), and the largely unknown physics problems involved in heating a plasma filament over 1000 meters long by means of photon absorption from the ends.

The conventional θ-pinch, on the other hand, involves more familiar technology and a proven method for producing thermonuclear plasmas.

We conclude that plasma radii in the several cm range, which are required to keep the circulating power fraction below 20%, are acceptable in a linear θ-pinch reactor which uses conventional magnetic heating techniques. In the case of laser heating without magnetic compression, however, the required laser energy is uncomfortably large by present standards.

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References

1. W. R. Ellis and G. A. Sawyer, "Scaling Laws for the Linear Theta Pinch: A Comparison of Magnetic and Laser Heating," Los Alamos Scientific Laboratory report LA-5434-MS (November 1973).

2. S. C. Burnett, W. R. Ellis, T. A. Oliphant, and F. L. Ribe, "A Reference Theta Pinch Reactor (RTPR): A Study of a Pulsed High-Beta Fusion Reactor Based on the Theta Pinch," Los Alamos Scientific Laboratory Report LA-5121-MS (December 1972).

3. H. Knoepfel and R. Lupi, Journal of Physics E: Scientific Instruments 5, 1133 (1972).

4. F. L. Ribe, ed., "Proposed Experiments on Heating, Staging, and Stabilization of Theta Pinches," Los Alamos Scientific Laboratory Report LA-5026-P (Rev.) (February 1973).

5. T. A. Oliphant, private communication.

6. J. M. Dawson, A. Hertzberg, R. E. Kidder, G. C. Vlases, H. G. Ahlstrom, and L. C. Steinhauer, Plasma Physics and Controlled Nuclear Fusion Research, Vol. 1, p. 673 (IAEA Vienna, 1971).

7. N. A. Amherd and G. C. Vlases, Proc. 2nd Topical Conf. on Pulsed High-β Plasmas, Garching Laboratory report IPP 1/127, p. 241 (1972), Garching, Germany.

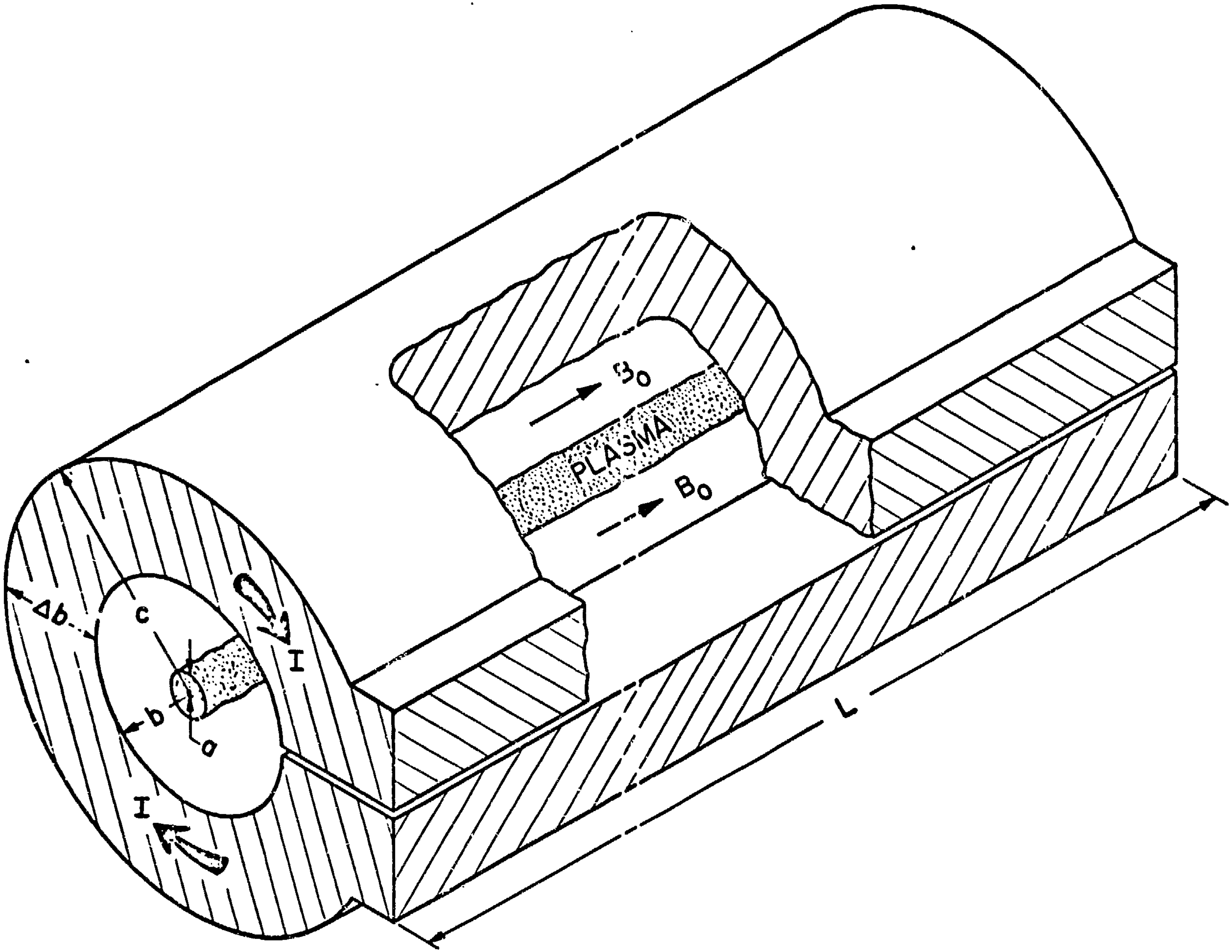
8. G. C. Vlases, Proc. Japan-U.S. Seminar on Laser Interactions with Matter (September 1972).

9. A. Hertzberg, AIAA paper 73-258, presented at AIAA 11th Aerospace Sciences meeting, Washington, D. C. (January 1973).

Figure Captions

Fig. 1. Magnetic Pressure vs Magnetic Field Strength.

Fig. 2. Linear θ-Pinch Geometry.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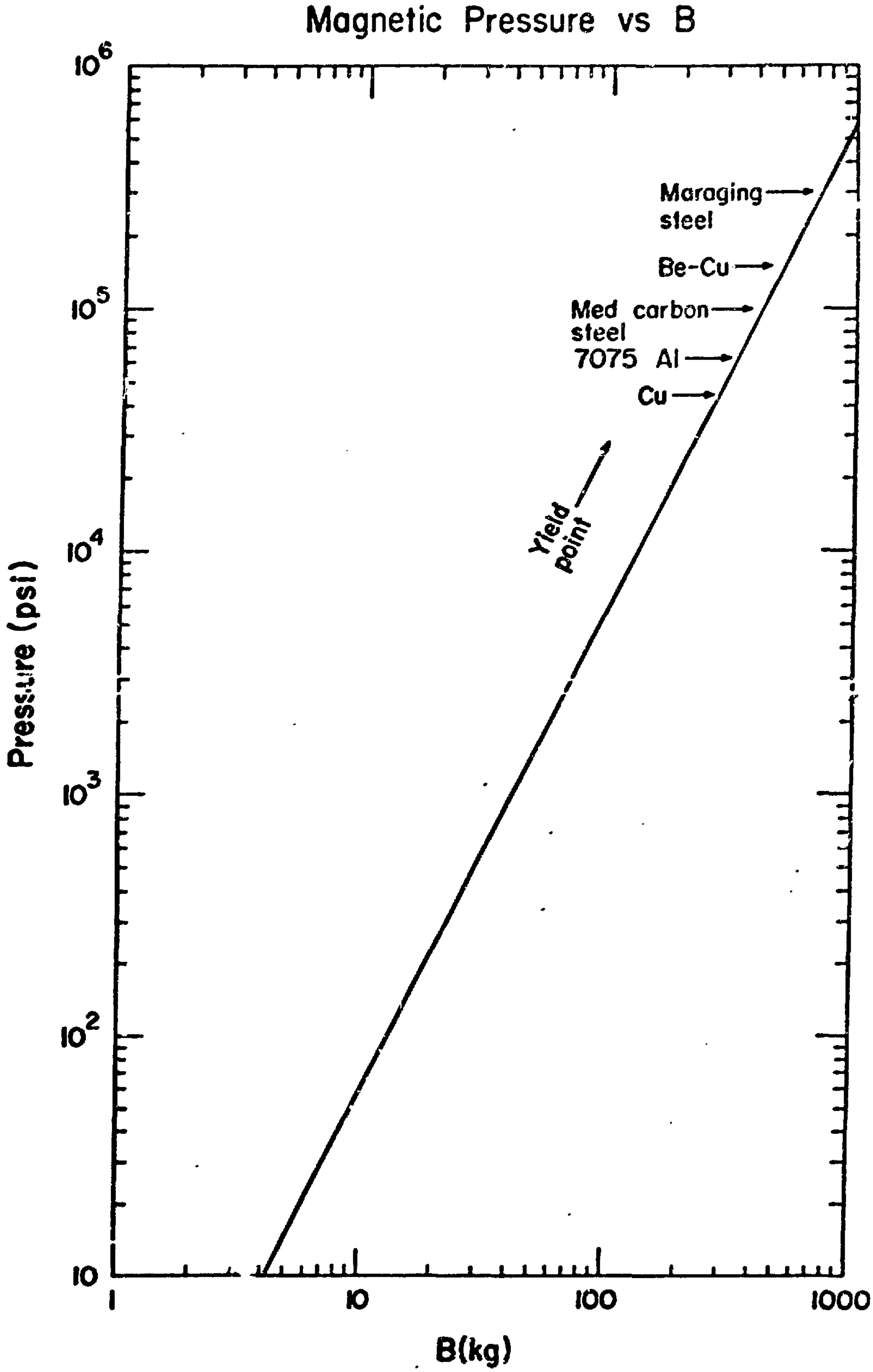

Magnetic Pressure vs B
Pressure (psi)
B(kg)
10
10^2
10^3
10^4
10^5
10^6
1
10
100
1000
Maraging steel
Be-Cu
Med carbon steel
7075 Al
Cu
Yield point