SUMMARY OF THE FOURTH WEEK — AC LOSSES, INSTABILITY AND FLUX PUMPS

S.L. Wipf
Atomics International
A Division of North American Rockwell Corporation
Canoga Park, California

I. INTRODUCTION

The fourth week, reduced to three working days by the Fourth of July weekend, was the shortest of the six week-long sessions. (It is nice to have started with a definitely true statement; the remainder of this summary I dare not present with the same amount of conviction — at best it will be scientific truth, as I understood and remember it from the presentation of my colleagues, at worst it will be my own opinion.)

The shortness of our week was probably justified by it being the least hardware-oriented among the whole set of weekly studies, and we all know the economic difference between brain efforts and big plumbing projects — it is the difference between kilo- and mega-bucks. This, incidentally, may also explain why we never particularly discussed any economics during the three days, to the regret of but few participants.

The titled daily topics were: Ac Losses, Magnetic Instabilities, and Flux Pumps. These three topics all have to do with some aspect of the same phenomenon, namely, "dynamics of flux motion," and are therefore not as disconnected as one might think at first. In this summary I want to talk about each of the three topics in turn, giving you a quick survey of the individual contributions, followed by a somewhat longer resume of the present state of the art as it emerged and came into focus during the meeting. After this there should be some time left to discuss the fourth topic which was also included in the formal sessions and which concerned the present assessment and the outlook for the whole field. This fourth part is easily of most general interest and may serve as dessert after the first three courses of a more bread-and-butter-like character.

II. AC LOSSES

Table I lists the presentations dealing with ac losses, each characterized by a few key words.

The coil studies (Voelker, Morgan) were similar in nature. Losses of a complete coil (designed to be useful for accelerator applications) were measured. The losses per cycle are proportional to H^n, with H the peak-to-peak amplitude in field and $2 < n < 3$. The frequencies are typically of the order of 1 Hz or less for the highest fields ($\sim$ 30 kG).

The resistance of a superconductor in a changing field has been measured in detail for various alloys and wire diameters by Rayroux (see Figs. 8 and 9). It is inversely proportional to the wire diameter which suggests the use of the smallest possible wire for ac applications. If many such filaments are paralleled in a pure copper matrix one has to twist the assembly to avoid breakdown of the outer filaments due to shielding of transverse flux. These ideas were put forward independently both by R. Hancox, reporting on behalf of P.F. Smith,* and by M. Foss. The importance of this will no doubt soon be substantiated by experiments.

*P.F. Smith presented his views in detail in the fifth and sixth week which he attended (these Proceedings, p. 913 and p. 967).

TABLE I* – AC LOSSES

REVIEW: S.L. Wipf, AI.

EXPERIMENTS – Reports on coil studies:

F. Voelker (W.S. Gilbert, R.E. Hintz), LRL: Coils wound with round wire, NbTi.

G.H. Morgan (W.B. Sampson, R.B. Britton, P.F. Dahl), BNL: Coils wound with ribbon, Nb_3Sn.

J.M. Rayroux (D. Itschner, P. Müller), BBC: Dynamic resistivity, NbZr, NbTi.

SHORT COMMENTS:

W.T. Beall (R.W. Meyerhoff), UCC: Short samples of ultra-pure Nb and Nb alloys.

R. Hancox (P.F. Smith), RHEL: Very thin multifilaments, twisted.

M. Foss, Carnegie-Mellon U.: Twisted filaments.

*The names of the authors making the presentation are given with the other authors in parentheses. The affiliation is abbreviated; see list of participants for details.

State of the Art (Resume):

For practical applications one is concerned with ac losses in type II superconductors exhibiting flux pinning, i.e., superconductors with high critical currents in high fields. Energy is lost when magnetic flux has to move inside such a superconductor; pinning is very similar to friction, but we can also look at it in terms of resistivity, as we shall see.

Figure 1 shows the three regions we have to distinguish, demonstrated with the help of a magnetization curve (vs H) of a cylinder in a parallel field H. We remember that a changing field will induce currents at and below the surface of the superconductor which try to shield the field change from the interior. The current density in this shielding layer is always critical (j_c), either positive or negative, and it corresponds to a gradient in magnetic induction B which is given by one of the Maxwell equations (in this case $dB/dx = 4\pi j$). The lower portion of Fig. 1 illustrates the gradient of B in the shielding layer of the cylinder for which the magnetization is shown. In this case the shielding currents are solenoidal but the same illustration is also good for a transport current along the cylinder which then would flow in the shielding layer and produce a circular external field.† The losses are always determined by the ac field

†A discussion of the "critical state" is found in Hart's review of instabilities (these Proceedings, p. 571).

at the surface no matter whether this field is externally applied or due to an applied current. According to the peak of the ac field, H_a, one distinguishes:

$$\text{Region I} : H_a < H_{c1} .$$

Below H_{c1} all the shielding is done by a surface current (in the London penetration depth). There is no flux movement inside and there should be no loss.

$$\text{Region II} : H_{c1} < H_a < H_p .$$

The crosshatched area represents the flux being pushed in and out during a cycle. There is still a step at the surface, ΔH. The loss is represented by the shaded hysteresis loops. The magnetization has a different value for increasing and decreasing fields because the shielding layer during each half cycle consists of two parts, one close to the surface with the direction of j_c given by the present field change, and the remainder with the opposite direction of j_c established by the preceding half cycle. The bulk of the available experiments (50 to 10 000 Hz) belong to region II.

$$\text{Region III} : H_p < H_a < H_{c2} .$$

H_p is the value of the external field for complete penetration of the superconductor. While in region II there is always a core which does not see the ac field, in region III the thickness of the penetration layer $[(H_a - \Delta H)/4\pi\ j_c \geq r]$ would become greater than the radius of the specimen and then ac losses will occur throughout the volume of the superconductor. For the losses in coils this region is of most interest.

$$\text{Region IV} : H_{c2} < H_a < H_{c3}$$

is of more theoretical than practical interest and is only mentioned for the sake of completeness.

Let us discuss the results for region I, II, and III in turn.

Figure 2 shows experimental loss results for Nb where H_{c1} has a value of roughly 1000-1500 Oe (according to purity). It is clear that in region I and II the losses have to be given per unit surface exposed to the ac field and vs H_a. Most of these results represent losses in region I and we notice that they are all over the place. The surface polish and the amount of frozen-in flux seem to be crucial for the differences. We have said that there should be no losses, because there is no flux moving in and out of the superconductor. However, each fluxoid frozen into the specimen has to pierce the surface in two points, one of entry and one of exit. Under the influence of the external ac the position of these points will oscillate with a corresponding loss due to the fluxoid movement at and immediately below the surface. Such a qualitative explanation is substantiated by measurement of losses vs the background field during cooldown (which is a measure of the amount of frozen-in flux) given in Fig. 3.

The transition from region I to region II, which in Fig. 2 does not appear very clearly, is very well demonstrated in Fig. 4 which was presented by Beall (see Table I) who made measurements on Nb of very high purities (up to a resistance ratio of 20 000!).

In Fig. 5 we see the results of most published loss measurements on Nb alloys. With the exception of curves v and w, which belong to region I ($H_{c1} \approx 100$-400 Oe), and the upper parts of curves a, b, c, which belong to region III (and fall much closer together if plotted as loss per unit volume), all others are in region II and show a trend which is close to H^3 at the upper end. The calculation (with the simplifying assumption of j_c = const) gives:

$$\text{Loss/cycle/cm}^2 = 4.22 \times 10^{-9} (H - \Delta H)^3/j_c \qquad (1)$$

with the dimensions for the constant $[J \cdot A \cdot Oe^{-3} \cdot cm^{-4}]$. There are only two material properties, j_c and ΔH, which determine the losses. Of these ΔH, which depends largely on surface qualities, is not very well investigated. Figure 6 shows measurements* of ΔH vs H for NbZr; it is equal to H_{c1} ($\approx$ 500 Oe) at H_{c1} and reduces to less than 100 Oe in higher fields. These data are used in Fig. 7 together with a value of $j_c = 4 \times 10^5$ A/cm^2 to obtain curves 2 and 3 (corresponding to samples 2 and 3 in Fig. 6); the shading indicates the majority of curves in Fig. 5, and curve 1 corresponds to $\Delta H = 0$. Also indicated in this figure are the losses one would have in copper at 4.2°K ($\rho = 10^{-8}$ $\Omega \cdot cm$) provided the conductor is thick in comparison to the skin depth. The loss per cycle depends on frequency as does the skin depth. The superconductor is better only by one or two orders of magnitude for $H_a > 1$ kOe.

In region III the losses become so high that a normal transition due to thermal runaway may already occur at a peak field which is very small compared to H_{c2}, unless, of course, the frequency is drastically reduced. This is the reason why one expects to run coils with high peak fields only at very low repetition rates. In this region, where the whole volume of the superconductor is lossy, it is useful and convenient to talk about the dynamic resistance of the superconductor. A simple case is treated in Fig. 8. A cylinder of diameter 2b is in an external parallel field H ($> H_p$) which increases at a steady rate dH/dt, and the field profile through the cylinder is given at two different times (j_c independent of H is assumed). Faraday's induction law gives the electric field E at a radius r. E is parallel to j_c (which is constant everywhere) and the ratio E/j_c gives the local resistivity which is proportional to r. Should we now send a transport current (small compared to $\pi b^2 j_c$) through the cylinder it would encounter an average resistivity:

$$\rho_{dyn} = A \cdot \frac{b}{j_c} \frac{dH}{dt} \quad . \qquad (2)$$

The distribution of the transport current is a nontrivial problem, but if a uniform distribution is assumed the proportionality constant A becomes ¼.†

Because this is a magnetic diffusion problem, a comparison with the more familiar thermal diffusion problem with its many existing mathematical solutions is helpful. H is equivalent to temperature T and $\rho/4\pi$ to the diffusion constant α. The diffusion equation for a steadily increasing temperature gives the stated solution for the temperature difference between the surface and the center. This also corresponds to an A of ¼. The heuristically valuable comparison, however, has its limitation in the fact that ρ is by no means a constant.

We see a measurement of this resistivity in Fig. 9 which shows the voltage due to a transport current across a bifilar coil in a steadily increasing or decreasing field whose value is given in the abscissa. H_p is about 4.5 kG and below this value the voltage is zero because the transport current flows through the completely superconducting core. The same is true on reversing the field sweep at 15 kG where a shrinking

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*ΔH in Eq. (1) has at least four distinct components, corresponding in origin to: the reversible magnetization, the surface pinning, the surface barrier, and the surface sheath (the last three are not necessarily different mechanisms); thus $\Delta H = \Delta H_{rev} + \Delta H_{s.p.} + \Delta H_{s.b.} + \Delta H_{s.s.}$ The results presented in Fig. 6 do seemingly not include the reversible part except very near H_{c1}, but the irreversible components are included twice. Strictly speaking, ΔH of Fig. 6 and ΔH of Eq. (1) are two different quantities, though very similar in magnitude.

†In practical units: $A = 2.5 \times 10^{-9}\ \Omega \cdot A \cdot sec \cdot cm^{-2}\ Oe^{-1}$.

dc field core remains until 13 kG is reached. Rayroux presented results showing the agreement with the given formula for ρ_{dyn} with regard to b and dH/dt.

Although in a complete coil there are always the losses of region I and region II sections, they disappear in comparison to region III losses. Calculation of these losses — even only approximate — is quite complicated; possibly the concept of the dynamic resistivity will prove useful.

III. MAGNETIC INSTABILITIES

Magnetic instabilities manifest themselves as sudden redistributions of the field profile inside a superconductor, commonly called flux jumps (this term is often avoided when less than the whole cross section of the superconductor is affected). The importance, or the nuisance value, of instabilities is the possibility of a quench or normal transition due to the accompanying large heat dissipation.

Table II lists the presentations related to this topic.

TABLE II — INSTABILITIES

REVIEW: H. Hart, GE.

EXPERIMENTS — Flux jumping in commercial tape conductor (Nb_3Sn):

L.O. Oswald (G. del Castillo), ANL.

A.D. McInturff, BNL.

SHORT COMMENTS:

Y. Iwasa, MIT: Upper field limit of instability (experiments).

R. Hancox, CLA: Survey of instability regions in coils.

S.L. Wipf, AI: Flux annihilation and instabilities.

State of the Art (Resume):

The instability problem is very complex and one is still at the stage of trying to find all the important variables to be fed into the theory. The superconductor under consideration is in general in a stable state of thermodynamic nonequilibrium (e.g., the critical state). Under certain conditions this state becomes unstable, i.e., an excursion caused by a small disturbance will grow and result in a transition to a new (nonequilibrium) state. We restrict ourselves to illustrating why instabilities occur (we follow Hart's review). Consider the field profile inside a superconductor which is always defined by the critical current (j_c) and previous magnetic history. We keep the external field constant, and consider a uniform rise in temperature, ΔT, which will reduce the critical current and require a new field profile. This establishes itself by diffusion of flux coming from the outside. The heat released in this process, ΔQ_m, can be calculated; locally it is of the same order as the change in potential magnetic energy, $(\Delta B)^2/8\pi$; over-all it is a function of temperature and external field. A qualitative picture is given in Fig. 10a. Assuming adiabatic conditions, the heat absorbed by the temperature rise, ΔQ_T, can also be given (Fig. 10b). If ΔQ_m is always less than ΔQ_T, the initial state is stable (Fig. 10c), but if the tangent of

ΔQ_m is above the tangent of ΔQ_T at the origin then it is unstable (Fig. 10d). We observe that in the unstable case the two curves cross again, thus determining another stable field profile. If the temperature of this crossover point is not too high (compared to the critical temperature) one has a limited instability that does not result in a temporary normal transition. Otherwise a runaway instability, a catastrophic flux jump, is the result. One can easily calculate the limit of full stability, but not the experimentally important event, the onset of runaway instability. There are two main complications. At the beginning, the magnetic excursion may be very slow allowing heat conduction out of the superconductor. This reduces the temperature rise and helps to limit the instability, as is seen in Fig. 10e where ΔQ_T is modified to include thermal diffusion. On the other hand, if a superconducting coil is considered, the transport current produces an additional dissipation, raising the effective ΔQ_m and thus the danger of instabilities. Hart presented a few calculations for suitably restricted situations, but he includes some very real coil cases (wound with GE tape, of course).

Although the agreement between experiment and calculations is so far rather poor, our qualitative understanding progresses. Hancox presented a way of looking at instabilities which I think has great appeal and will help to reduce some of the existing confusion. This is illustrated in Fig. 11 where in an I vs H diagram the various stability regions (for a coil) are entered. Both fully stable regions correspond to situations given in Fig. 10c; in the high field region ΔQ_m becomes small because the superconducting wire is fully penetrated and j_c is small. Little flux is required to change the field profile and the dissipation is small. Iwasa presented experimental data for the upper field limit of instability, H_{st}, in 0.010 in. Nb25%Zr wire; it is between 25 and 30 kG. H_{fi} which terminates the lower stability region is around 3 kG. Hancox also gives calculations for I_* and the boundary between limited and catastrophic instabilities (which lead to breakdown in coil performance). He further pointed out that coils have to be designed so that no region of the coil falls into the catastrophic instability area.

One can extend the diagram to include temperature as a third dimension and one may indicate how a low dH/dt (or a high thermal diffusivity) may reduce the catastrophic instability region.

Through coil degradation experiments[1] one has been aware for some time of the shape and position of the catastrophic instability region. The constructors of coils, knowing that instabilities do occur, have always tried to keep them limited to prevent catastrophic jumps. These "stabilization" efforts can be seen as either affecting (a) ΔQ_T, or (b) ΔQ_m by:

(a) avoiding a large temperature rise by increasing the effective specific heat (liquid helium in porous conductor, proximity of other metals such as Pb or Cd); improving the cooling (spaced windings for circulating helium); slowing down flux motion (by providing shorts and copper sheets between layers);

(b) providing a low resistivity bypass to avoid heating by transport current (paralleling the superconductor by copper, silver, etc.), using very thin wire to reduce H_{st}.

Most commercial conductors as well as large coils use a combination of these stabilization techniques. The conservative character of some of these approaches indicates how little one trusts our present understanding of the instability problem.

Having talked about the occurrence and the effect on coils of instabilities, we might ask what is the experimental appearance of an instability? Oswald presented results which show a variety of limited instabilities distinctly different in character.

Plotted against the increasing field in Fig. 12, some look like noise while others represent larger flux movements, seen as temperature spikes; these spikes may form repeating groups with the spikes increasing in size in each group, etc. Such a variety of manifestations shows the complexity of the problem most directly.

The mathematical difficulty seems to me to lie in the fact that two diffusion equations have to be solved simultaneously, one for the temperature and one for the magnetic field, whereby the magnetic diffusion coefficient is not constant but a non-linear function of both T and curl H. From the notorious scattering of experimental results (under equal conditions the catastrophic flux jump field scatter is 5-20%), one might say that nature itself seems to have trouble with this problem.

IV. FLUX PUMPS

The idea of using superconducting coils is not much older than the idea of using superconducting power supplies to feed them. The possibility of very large currents in combination with coils of few turns is a major advantage. What has hampered progress?

Achievements and problems were highlighted in presentations by most flux pump builders in this country, as summarized in Table III.

TABLE III — FLUX PUMPS

PROGRESS REPORTS:

S.L. Wipf, AI:	Moving magnetic field pumps.
R. Rhodenizer, GE:	Rectifier type flux pump (Buchhold).
M.S. Lubell, ORNL:	Comparison between flux pumps and vapor-cooled leads.
H.L. Laquer, LASL:	Automatic switching flux pump (rectifier for asymmetric ac); flux pump equivalent in superfluid helium.
R.B. Britton, BNL:	Flux pump program at Brookhaven.

SHORT COMMENTS:

W.H. Bergmann, ANL:	Possibility of flux pumping by using Nernst-Ettinghausen effect equivalent.

<u>State of the Art (Resume)</u>:

The flux pump principle is illustrated in Fig. 13. (a) A closed loop is shown which because of its zero resistance conserves any flux linked with it. (b) Only if its zero resistance is interrupted can flux from a small magnet be admitted. (c) Removal of the magnet induces a current increment to keep the flux constant. (d) On repeating the process, previously accumulated current is preserved by providing a zero resistance bypass. "Switching" is preferably done by creating a resistive region by exceeding the critical field; this allows the same magnet to be used for both switching and pumping if its field strength close to the pole exceeds the critical field. (e) In a popular arrangement the bypass loop is replaced by a sheet, allowing the creation of a normal, flux containing zone opposite the magnet pole, which it will follow, being swept across the sheet into the closed circuit. The same process can be realized without moving parts as in Fig. 14, which shows a "loop" and a "plate" arrangement. It has become convenient to distinguish between "rectifier type" flux pumps of which the upper is an example, and "moving magnetic field" flux pumps of which the lower is an (albeit impractical) example. In its useful versions the second type employs rotating shafts as a typical example demonstrates in Fig. 15.

To dwell on the achievements we discuss the rectifier type pump (Rhodenizer) which, in the very thoroughly developed version (by Buchhold) of GE, is to date the only commercially available flux pump. Its salient features are best explained by means of the diagram in Fig. 16 where we see an ordinary full wave rectifier arrangement with a primary, a transformer core, a secondary, and a load L. Both primary and secondary are superconducting; we see the parts of the flux pump which are in liquid helium. Instead of the usual one-way-valve rectifying elements, we have switches X and Y (see Fig. 13d and Fig. 14-top) consisting of superconducting tape which can be made resistive by magnets ("power cryotrons"). These elements do not rectify automatically, they have to be driven by programmed current from outside the cryostat. In order to keep the losses to a minimum it is imperative to operate a cryotron only when the current flowing through it is exactly zero. Otherwise there is a resistive loss until the initial current is driven into the other branch by the ohmic voltage. Next to each cryotron, in the GE device there are sensors of the form of saturable reactances, which not only indicate when the current through the cryotrons is zero but also lengthen the time interval of this zero flow, giving the cryotrons time to switch. Sophisticated electronic gear (at room temperature) allows the regulation of the output at a fixed primary frequency ($\sim$ 10 Hz). The losses are quite small and come from the back current through the resistive cryotrons, the ac losses in the superconductive windings (including the s-n transition in the cryotron), and the hysteresis losses in the ferromagnetic cores.

The moving magnetic field type pump is well suited to illustrate a few problems. Figure 17 shows a normal zone in a superconducting sheet and the type of current distribution which is set up during its movement. We see the eddy current distribution induced in the normal spot, which corresponds to the back current through the cryotrons of the rectifier type; the ensuing loss is in principle unavoidable. A more serious loss comes from the current distribution which is encountered by the leading edge as it becomes normal. The resulting ohmic voltage drives this current out of this region, partly in front of, partly behind, and partly into the normal zone, accompanied by considerable dissipation. The difficulty of treating this process analytically makes an (ill-patronized) art out of improving this type of pump. In principle, it is possible to arrange inductively for zero current at the leading edge and to avoid this type of loss which is avoided in the GE pump by the use of Buchhold's saturable reactors.

The moving magnet field pump is attractive in its simplicity and its suitability for producing large currents. Currents in excess of 10 000 A have been reached and maintained, although not in coils of any size. The upper current limit is generally reduced by the occurrence of catastrophic instabilities in the sheet. These seem to be caused by the imbalance of the current distribution when the leading edge (see Fig. 17) switches too much current, either ahead of or behind the spot, to maintain equilibrium during one full rotation (see Fig. 15). Simple remedies for increasing efficiency or increasing the limiting current seem to be divergent, at least in my own limited experience.

Figure 18 shows the reported efficiencies of various pumps. E is the energy stored in the coil and ΔE the energy lost in the pump while the coil is pumped up. The solid curve gives the possible efficiency of a given pump vs the inverse ratio of power output to volume of the periodically switched superconducting material in the flux pump. The shape of this curve is determined by the unavoidable loss (back current, eddy current);

its position with regard to the abscissa is less strictly fixed and reflects considerations of instabilities (degradation) and protection against burnouts of the pump.[2] The superior efficiency of the GE pump (newest results 4-6% higher) which is the only rectifier pump in this graph is evident.

Table IV summarizes a comparison of the two types of pump. We imply that the moving magnet type has not been in the fortunate position — notwithstanding a considerable amount of publicity[3] — of receiving the determined and successful development effort which GE gave to the rectifier pump.

TABLE IV — COMPARISON BETWEEN THE TWO FLUX PUMP TYPES

Moving Magnetic Field	Rectifier
Simple to build (~ 10^3 $)	Complicated (~ 10^4 $)
Not well understood	Well understood
Difficult to develop	Well developed
Good for high current	High efficiency

Two problems:

Shielding (< 100 Oe)

Protection

Shielding and protection are the two problems which need consideration when pumps are to be used in conjunction with large coils. Proper operation is only achieved in low background fields because of ferromagnetic components and, to a lesser degree, because of low field superconductors (such as Nb) in the switches. Pumps without these components, employing thermal switching, tend to be very ineffective (Laquer). The protection problem seems to be solved by a diode, developed by GE, which operates in liquid helium and has a symmetric V-I characteristic. If the voltage exceeds $\pm V_c$, its resistance drops to practically zero.

There is a general consensus that power leads from room temperature will be used for charging or discharging large coils. Any permanent operation will give preference to flux pumps, even at their presently available low efficiency, over the best vapor-cooled leads (Lubell). Flux pumps will function in lieu of persistent switches, able to compensate for small resistive losses in the system.

Other ways of producing currents[4] in superconducting circuits, e.g., by means of the Nernst-Ettinghausen effect as suggested by Bergmann, even if they are shown to be feasible, are unlikely to be of great practical interest for some time to come.

V. ASSESSMENT AND OUTLOOK

The spreading and gathering of opinions and prophecies are parts of the business which are relegated to corridor discussions of bigger and shorter conferences and which many people feel are among the most useful functions which any meeting fulfills. We decided to bring these activities into the lecture hall as much as possible, the audience being comfortably small.

Table V summarizes the contributions under this heading.

TABLE V — ASSESSMENT OF PRESENT AND OUTLOOK

J.P. Blewett, BNL:	Actual and potential uses of superconductors in experimental nuclear physics.
N.S. Nahman, NBSB:	Superconducting transmission lines for power and communications.

REPORTS FROM ABROAD:

JAPAN:	N. Takano, Toshiba.
EUROPE:	J.M. Rayroux (Switzerland, France, Holland). G. Bogner, Siemens (Germany). R. Hancox (England).

OPINION: Questionnaire.

Of the two major talks, Blewett's was for the benefit of the majority of the participants whose main field is solid state physics and who were largely ignorant about the requirements in high energy physics. If I gave details in this gathering I would be carrying coals to Newcastle.

Undoubtedly one of the highlights of the week was Nahman's talk about transmission lines. He interprets this term in its widest sense and points out the possible uses which a trench filled with a Dewar pipeline may have. Not only could the obvious power be transmitted but also — and this in a superior way to most alternatives — information. One might as well use the same hardware to pipe liquid cryogenics around the country and, as a fourth possibility, join small but powerful cryogenic computers and memories into the system with the transmission line facilitating the access. As an expert for many years in superconducting delay lines, he detailed the communication transmission line aspect, extolling the advantages in bandwidth over existing alternatives. If this sounds Utopian to some of you, you should remember that political boundary conditions will most likely prevent the full use of these possibilities long after the technological problems are solved.

The reports from abroad did not sustain any excess optimism generated by Nahman's talk.

Japan has been very successful in producing practical superconducting wires using Nb-based alloys or V_3Ga; it is also engaged in a number of larger magnet projects for MHD and for high energy physics. Maybe progress does not seem to be so rapid as one might have hoped.

The European scenery has similarities to the scenery here, yet bubble chamber projects at CERN and at the Rutherford Laboratory as well as the British homopolar motor, existing in a 50 hp and projected in a 3000 hp version, show great promise.

This brings us to the last item on the agenda, namely an opinion poll. You understand that the results from this poll should be considered as being a good deal less formal than Mr. Harris' and Mr. Gallup's reports in the dailies. There remains the entertainment value.

The questionnaire (see Table VI) had three sections. The first section should reflect the present status of the topics dealt with by comparing their importance with regard to present and future problems, and by indicating the necessity for research. The second section considered the importance of various superconductivity applications in the future and also distributed the responsibility for their research. Of course everybody is aware that the funding source for this research is largely the same in all three cases (namely, 100% for Federal Government, 80-90% for universities, and perhaps 70% for private industries). The third part asked for the background of the respondent, who otherwise remained anonymous. Fifteen returned questionnaires could be evaluated and the results are presented in Table VI. For better visual impact it is the diameter of the black dots which corresponds to the percentage. For "comparative importance," only partial agreement was found and given in words.

Since an equal number of government and industrial representatives answered the "responsibility for research" question, it is interesting to compare the two groups and the percentages are given in each box, top right for industry and bottom left for government. We notice that such a comparison reflects the popularity of a subject. When we find that each group feels that the other ought to carry the ball we are not surprised that the field in question already has a somewhat tarnished history such as MHD and Computers, or has not an immediately strong appeal, like transmission or transportation. Such fields have been marked by a B for beggars.

It is fitting for this Summer Study that the only field showing an enthusiastic reception is the one of accelerators. It has been marked with a P for prima donna.

REFERENCES

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TABLE VI

QUESTIONNAIRE

BROOKHAVEN SUMMER STUDY, WEEK OF JULY 1-3, 1968

Please reflect your opinions as to the present and future status of topics related to this week's discussions:

1. Present Status

	Present Problems or Emphasis of Necessary Research (make up to 100% ←→)				Comparative Importance (rank as: 1,2... ↕)		Remarks
	Basic	Applied	Development	Engineering	Present	Future	
Ac losses	●	●	●	●	fairly	most	
Ac critical currents and fields	●	●	●	●			
Instabilities	●	●	●	●	most		
Flux pumps	●	●	●	●	least	least	
Other							(fatigue properties)

2. Future, with respect to applications:

		When will it become important? (make up to 100% ←→)			Who should sponsor research? (make up to 100% ←→)			Remarks
		1-3 yrs	3-10	> 10 yrs	Fed. Govt.	University	Private Ind.	
Accelerators	P	●	●	●	73 ● 55	19 ● 33	8 ● 12	← Industry ← Government
Transmission	B	●	●	●	31 ● 46	2 ● 4	67 ● 50	
Transportation (levitation)	B			●	40 ● 50	5 ● 10	55 ● 40	
Small devices (weak link, etc.)		●	●	●	15 ● 17.5	52.5 ● 37.5	32.5 ● 45	
Computers	B		●	●	8 ● 26.5	20 ● 26.5	71.5 ● 47	
MHD	B			●	28 ● 55	5 ● 7	67 ● 33	
Other								Machinery (Ind.) Fusion (Govt.) Room temp. s.c. (Govt.)

3. I describe myself as: (answer each column) (make up to 100% ↕)

Experimentalist	●	Basic	●	Government	●
Theoretician	●	Applied	●	University	●
Commercial	●	Development	●	Industry	●
		Engineering	●		

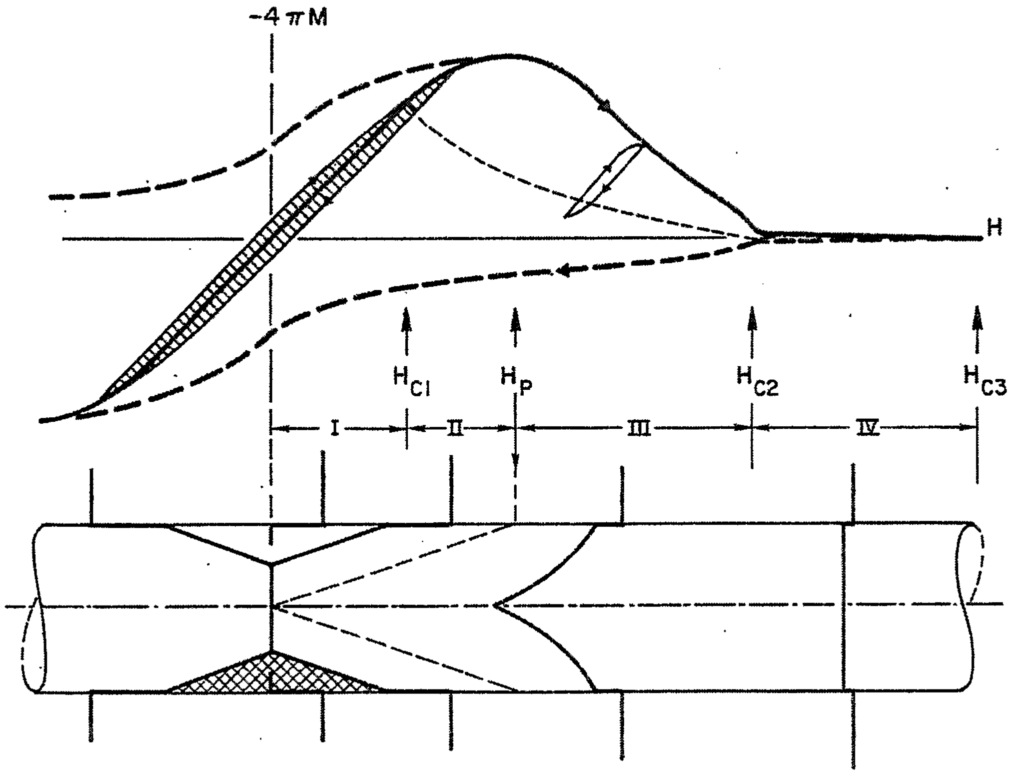

Fig. 1. Ac loss regions.

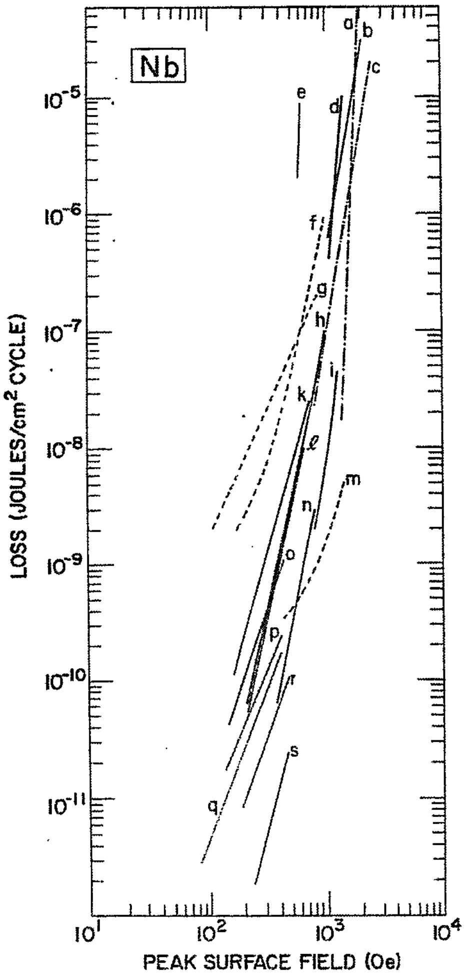

Fig. 2. Reported ac losses of pure Nb (Ref. 5).

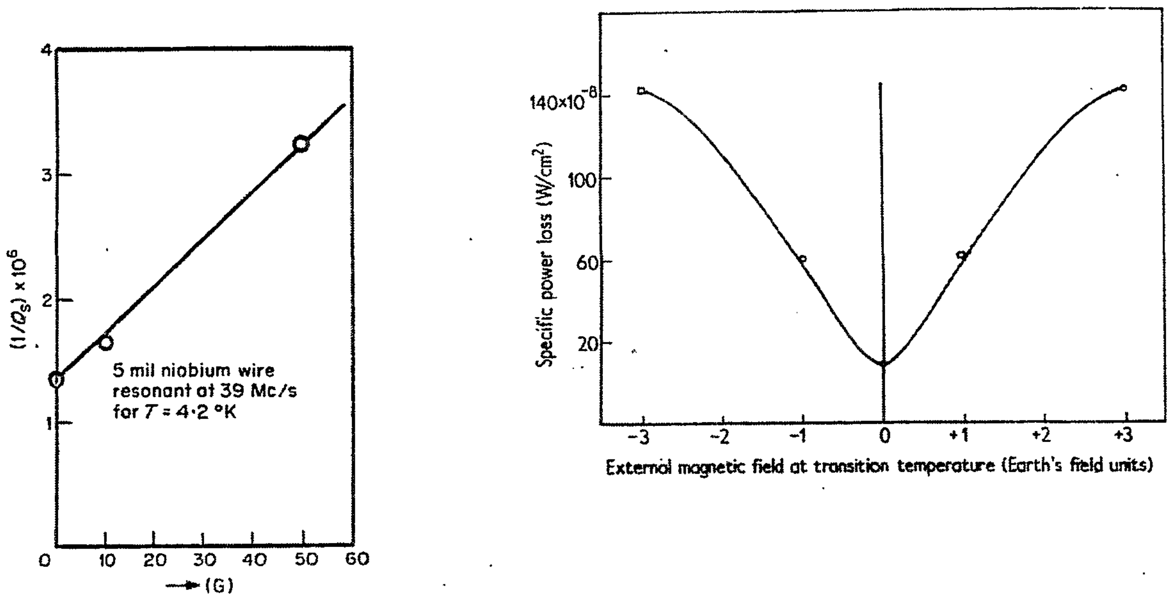

Fig. 3. Illustrating the dependence of ac losses in region I on frozen-in flux (Refs. 6 and 7).

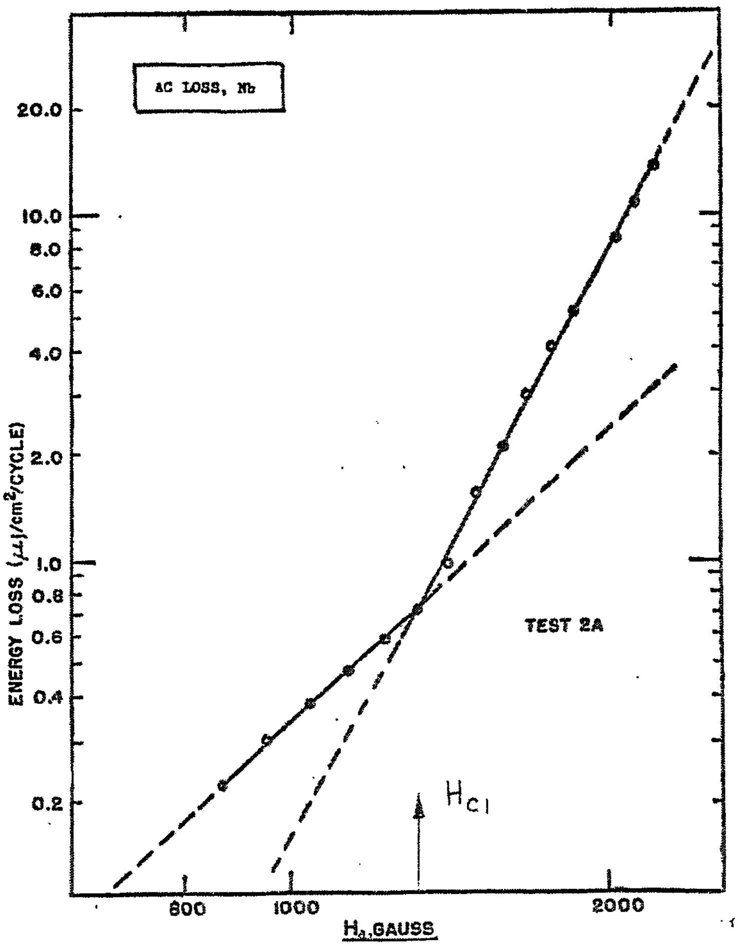

Fig. 4. Ac loss in Nb; transition from region I to region II (Beall and Meyerhoff).

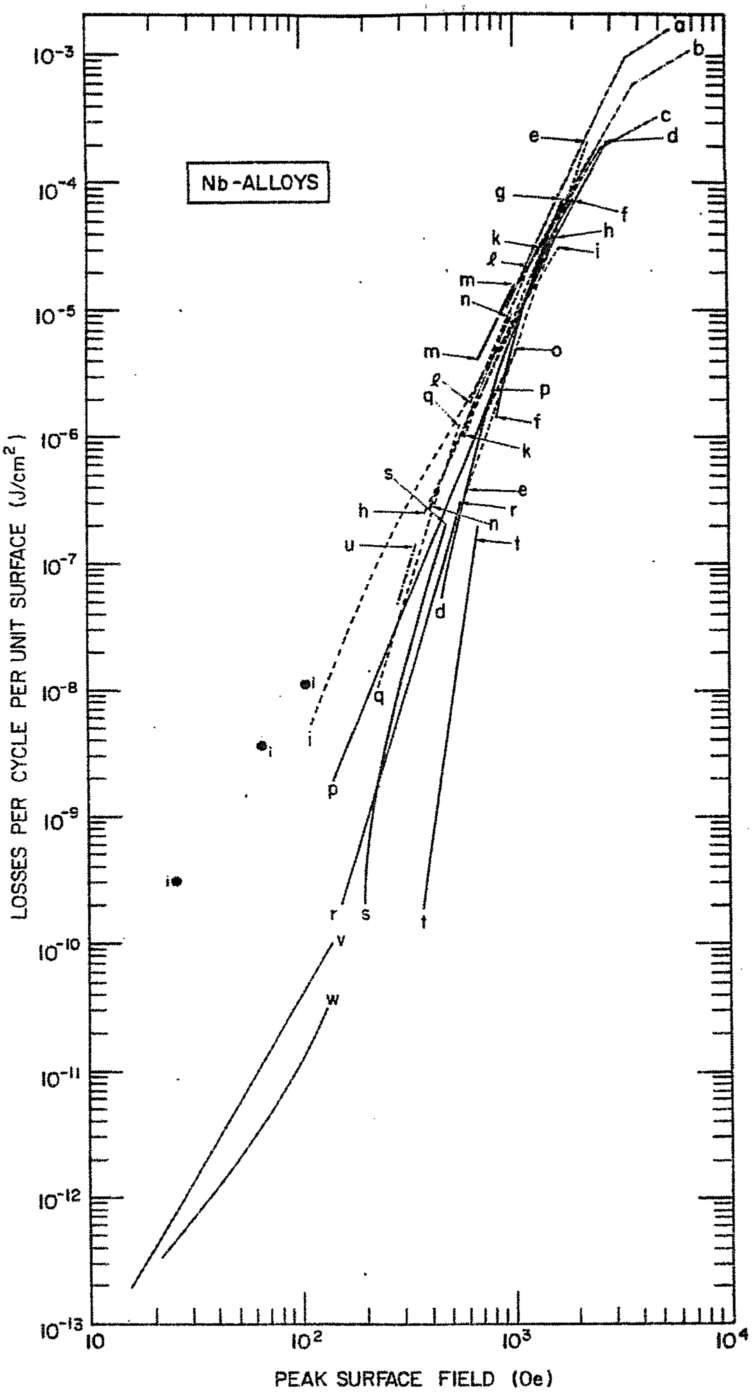

Fig. 5. Reported ac losses of Nb alloys (includes Nb20%-40%Zr, and Nb50%-80%Ti) (Ref. 5).

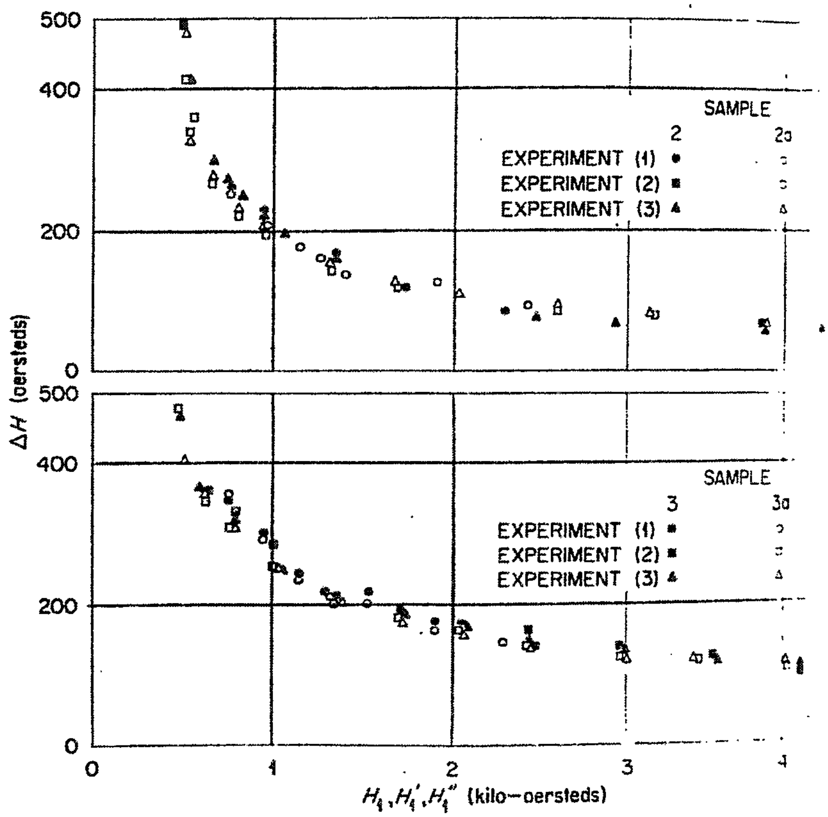

Fig. 6. Measurements of ΔH in Nb25%Zr (Ref. 8).

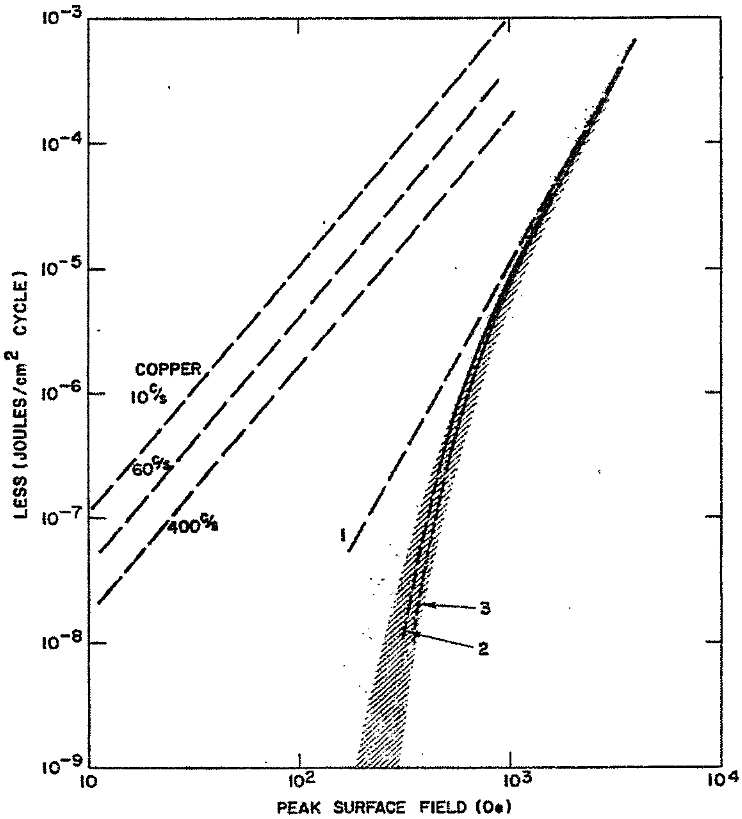

Fig. 7. Comparison of calculations of ac losses in Nb alloys and copper.

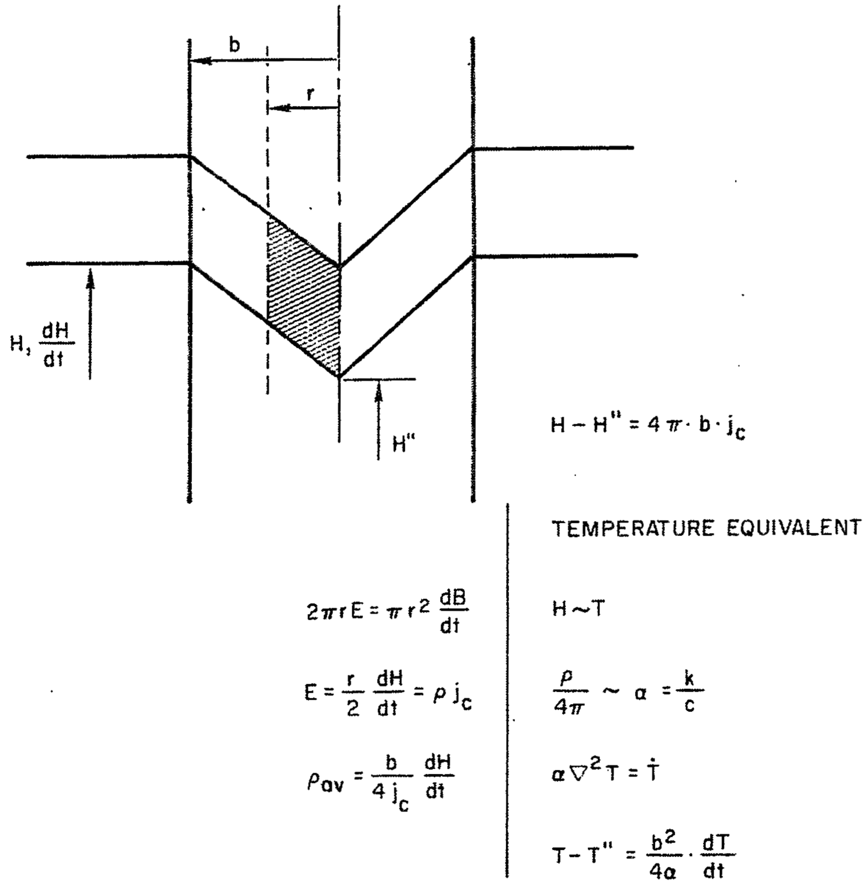

Fig. 8. To illustrate the dynamic resistivity of a cylinder in a parallel, changing field.

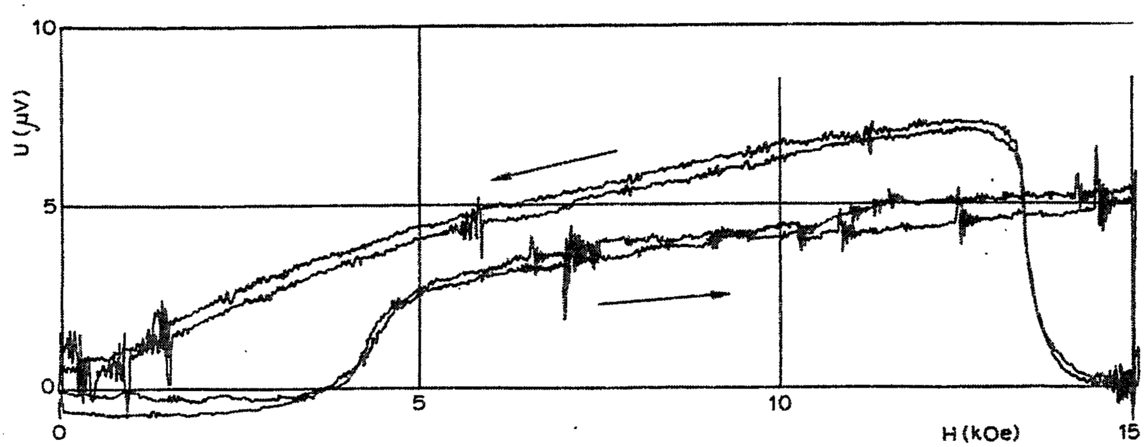

Fig. 9. Measurement of dynamic resistance of bifilar coil in coaxial changing field (Ref. 9).

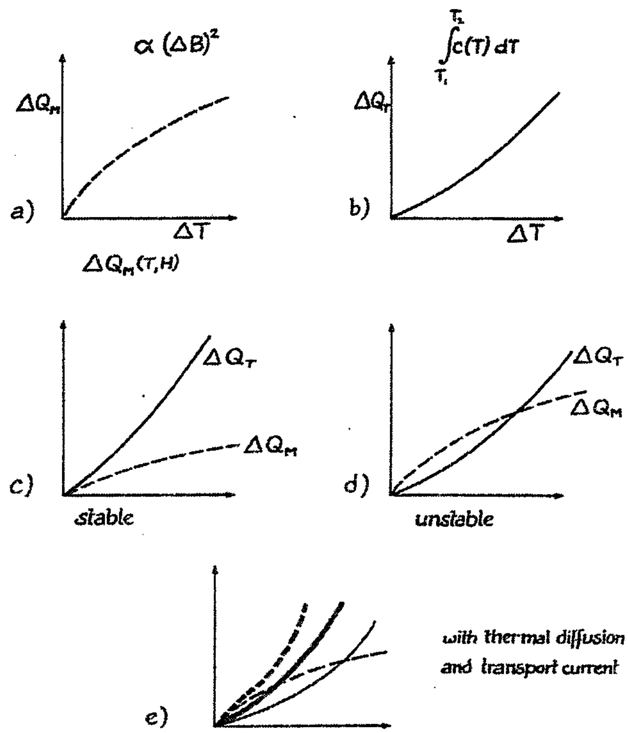

Fig. 10. Illustration explaining the occurrence of magnetic instabilities (after Hart).

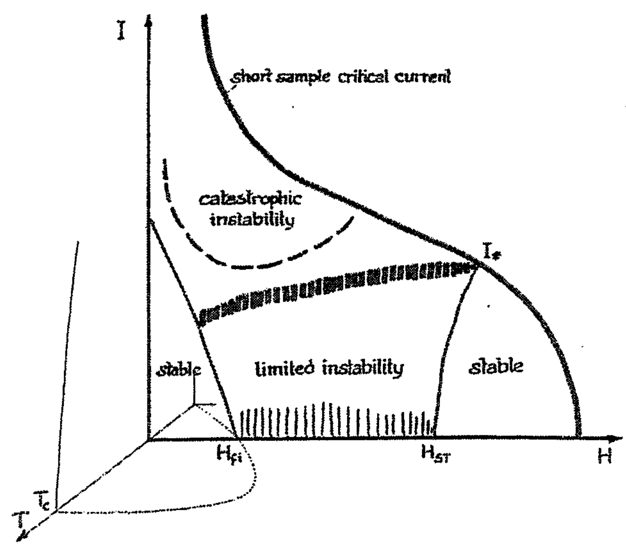

Fig. 11. Sketch of stability regions (for wire wound into a coil) in a I-H (-T) diagram (after Hancox). Heavy black lines indicate boundary between regions of catastrophic and limited instability. Dashed line indicates the effect of very slow dH/dt on this boundary.

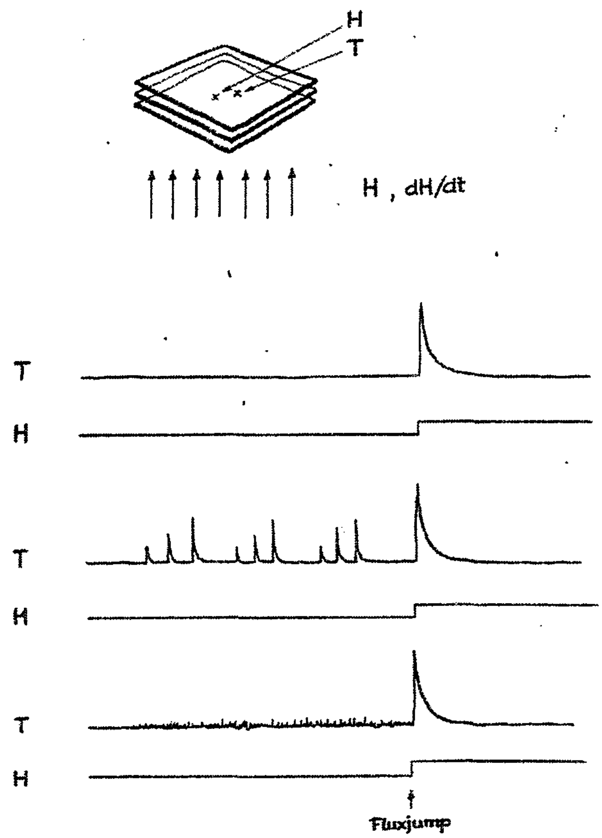

Fig. 12. Measurement of instabilities on specimens of Nb_3Sn tape in perpendicular, changing field. Records of H and T (measured near center of specimen) vs time indicate limited and complete flux jumps (after Oswald).

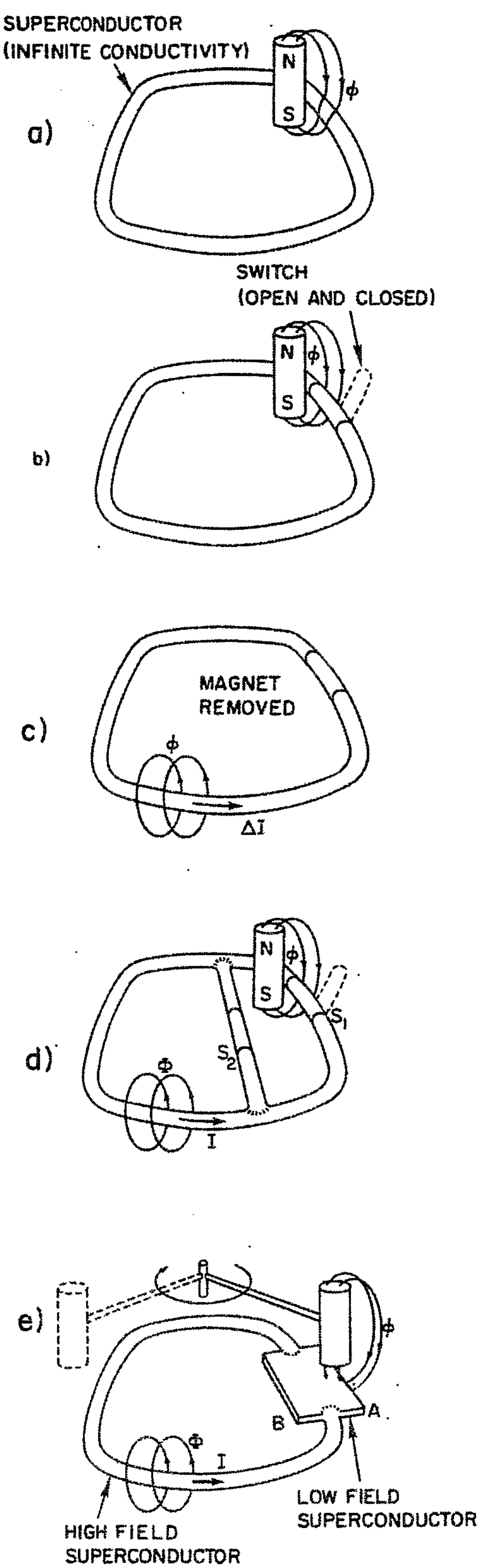

Fig. 13. Illustrating the principle of flux pumping.

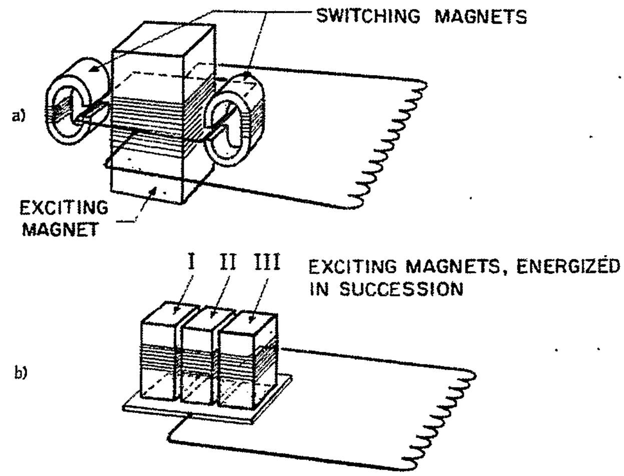

Fig. 14. Two arrangements of flux pumps without moving parts (Ref. 10).

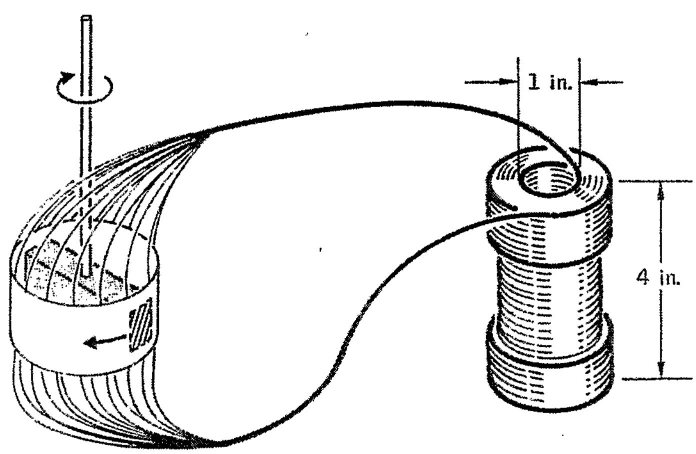

Fig. 15. Typical example of moving magnetic field pump. (Not shown are coils to magnetize the rotor so that the poles all have the same magnetic polarity.) (Ref. 11)

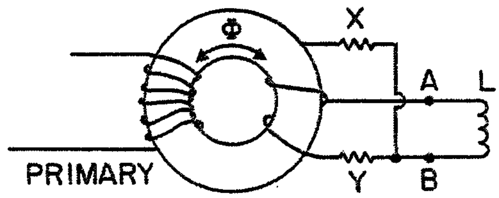

Fig. 16. Diagram of rectifier pump.

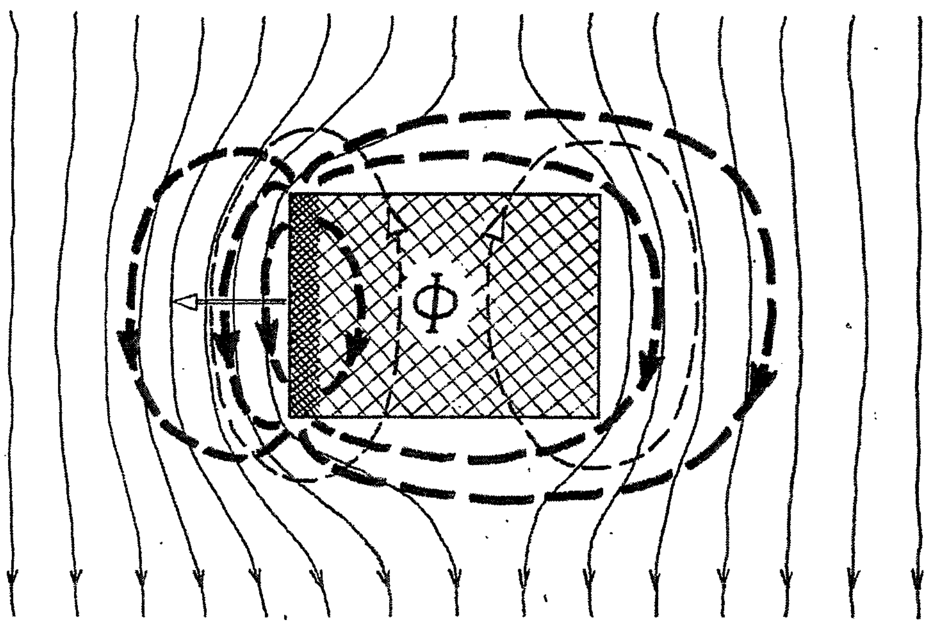

Fig. 17. Schematic current distribution around moving normal spot containing flux Φ.

Horizontal arrow:	Direction of movement
Crosshatch:	Resistive region
Thin solid lines:	Load current distribution
Thin broken lines:	Eddy current distribution
Thick broken lines:	Alternative current distribution for current which is driven resistively out of the leading edge (narrow crosshatch).

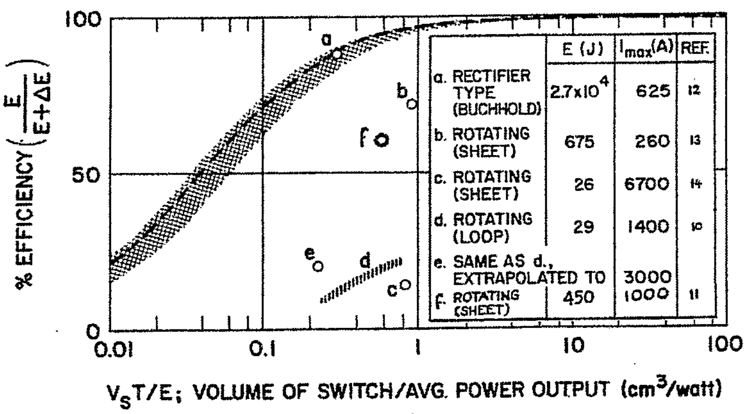

Fig. 18. Energy efficiency as reported for various pumps (Ref. 2).