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FLUX MOTION AND PINNING IN A
TYPE II SUPERCONDUCTOR

by

Antide Georges Putz

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INTRODUCTION

"There was no 'one, two, three and away,' but they began running when they liked and left off when they liked, so that it was not easy to know when the race was over." Lewis Carroll.

Since the publication of the B.C.S. and G.L.A.G. theory, much work has been done on the reversible properties of superconductors which are now well understood. This is not the case for the irreversible properties which are observed in type II superconductors. Those are generally discussed qualitatively in terms of movement and pinning of flux lines, but no satisfactory quantitative treatment has yet emerged. These irreversible effects are important in a number of applications of superconductivity such as the transmission of high currents or fast pulses and the production of high magnetic fields.

While they were studying the relation between the pinning of vortex lines and the magnetic field by increasing the current through a type II superconducting crystal, Good and Kramer found that the critical current for which a voltage appeared, was dependent on the history of the flux line lattice (the critical current was defined by them as the current for which the voltage was 200 nanovolts when the current was ramped up from zero). They first observed that there was a difference between the results of measurements done with a steady field and done with a swept field; the critical current I_c under swept field was systematically 10% less than I_c obtained in a steady field. They also found that when the current was ramped up and then decreased, the V-I characteristic on the way down was higher than the one found when the current was swept up. Figure 1 represents a typical hysteresis curve.

The mechanism which they proposed was that defects were formed in the flux line lattice at high current and swept field conditions. The presence and motion of these FLL defects was thought to give rise to a higher V at a given I. In order to study this effect, a feedback

Figure 1. A typical hysteresis curve after Good.²³ $H = 1.5$ KG.
Sweep rate: 13 a/min.

mechanism was built: a preset voltage was established, and the current ramped up at a constant rate till the preset voltage was reached. Then, the variations of the current with time were observed. It was found after certain treatments ("degradation") that the current at constant V increased with time during the first minutes, and this was called "recovery." Degradation, followed by recovery, was found after:

- 1) application of a transport current to give a large E.M.F. across the sample.
- 2) rotation of the crystal relative to an external field.
- 3) reduction of the external field by a few hundred gauss.

A typical recovery curve is reproduced on Figure 2. It is composed of three parts: a logarithmic portion, a linear one and a horizontal one corresponding to the cessation of the recovery. Very high purity niobium crystals were used. Niobium was chosen because it is a type II superconductor which can be produced in high purity and in which a known crystal dislocation system can be formed. Niobium is also convenient in that liquid helium at atmospheric pressure can be used to provide the low temperature environment.

Good and Kramer interpreted the various phenomena which they found in terms of defect movements, and found good agreement between the theory they proposed and their results. But the basis of their experimental study is rather limited: only two crystals were tested of which the deformation was similar; and a complete study of all the parameters was not done.

It was to extend the experimental results on degradation and recovery of the lattice in deformed niobium crystals and to confirm or modify the theory which Good and Kramer proposed to explain their results, that we undertook this study.

Figure 2. Typical recovery curve after Good.²³ Voltage $.3\mu\text{V}$.

CHAPTER I

TYPE II SUPERCONDUCTIVITY IN A DEFECT FREE METAL

1.1 Magnetic Flux Penetration

Type II superconductors are characterised by a partial penetration of the magnetic flux into the superconducting medium called the mixed state. This partial exclusion occurs for fields between H_{C1} , below which there is a flux exclusion in the bulk and H_{C2} , above which, except for a surface sheath, the superconducting state is completely destroyed.

Figure 3 shows a typical $B(H)$ curve, and Figure 4 the variation of the limiting fields H_{C1} and H_{C2} versus the temperature. At H_{C1} the tangent is vertical, corresponding to an infinite permeability, as we will see later. On the other hand at H_{C2} the curve is continuous and there is only a break in the slope of it corresponding to a second order phase transition.

1.2 Microscopic Structure of the Mixed State

In a type II superconductor, the surface energy of a macroscopic superconducting-normal phase boundary is negative. Hence the configuration that results in a minimum free energy is a thinly divided one where the wall energy contribution is important. Computations based on a principle similar to Sommerfield quantisation show that the lowest energy configuration is the one of parallel circular flux threads or current vortices of a minimum quantized value of flux,

$$\phi_0 = \frac{ch}{2e} = 2 \times 10^{-7} \text{ gauss} \cdot \text{cm}^2$$

1.3 Description of a Single Vortex

Each vortex consists of a normal state core of radius ξ , the coherence length, surrounded by screening currents limiting the penetration

Figure 3. Induction in a type II superconductor as a function of the applied field.

Figure 4. Critical fields. H_{c1} and H_{c2} as functions of the temperature.

of the field only to a region of depth λ , the penetration depth. The structure of a vortex is schematically illustrated in Figure 5. The detailed structure may be derived, following deGennes,¹ by first minimizing the expression of the energy:

$$E = E_0 + \frac{1}{8\pi} \int [h^2 + \lambda^2 \text{curl}(h)^2]$$

which gives the London equation

$$h + \lambda^2 \text{curl curl } h = 0$$

If we consider that the singularity at the hard core can be represented by a δ function, this equation over any point of the whole space can be written:

$$h + \lambda^2 \text{curl curl } h = \phi_0 \delta(r)$$

which results in:

$$h = \frac{\phi_0}{2\pi\lambda} K_0 \left(\frac{r}{\lambda} \right)$$

At large distances from the vortex core, the local magnetic field h decays exponentially as

$$e^{-r/\lambda}$$

The energy per unit length of the vortex line is then, integrating the expression given for E above:

$$J = \left(\frac{\phi_0}{4\pi\lambda} \right)^2 \ln \left(\frac{\lambda}{\xi} \right)$$

This indicates that, as the dependence on ϕ_0 is quadratic, it is indeed of the interest of the vortex to carry the minimum of flux.

Figure 5. Structure of a vortex line.

1.4 Interacting Vortices

The above description is only valid for an isolated vortex. When several vortex lines are present, the same reasoning leads to interaction energy terms.

For two interacting vortex lines, writing

$$h_{12} = \frac{\phi_0}{2\pi\lambda^2} K_0 \left(\frac{r_1 - r_2}{\lambda} \right)$$

the interaction energy is:

$$U_{12} = \phi_0 \frac{h_{12}}{4\pi}$$

This results in a repulsive force:

$$f_2 = -\partial U_{12} = - \frac{\partial U_{12}}{\partial (r_1 - r_2)}$$

By using Maxwell's equations we get

$$f_2 = \frac{\phi_0}{c} j_y$$

where j_y is the superfluid current that would exist in the presence of the first vortex alone at the core of the second. This can be extended to any number of vortex lines.

1.5 Magnetization Curves

By minimizing the free energy, it is possible to compute the number n of vortex lines per unit area, or the magnetic induction, as $B = n\phi_0$. First, by comparing the free energy of a medium threaded by vortices and a completely field free medium it is easy to find the value of the field H_{C1} when flux penetration takes place:

$$H_{C1} = \frac{\phi_0}{4\pi\lambda^2} \log \frac{\lambda}{\xi}$$

then, by minimizing the free energy for every value of H , a theoretical $B(H)$ curve is established. See Figure 3.

The free energy has also to be minimized with respect to the lattice structure. Such a computation based on London model leads to a triangular lattice organization.² When the distance of vortex lines is of the order of ξ , an overlap of the normal cores occurs, and complete penetration results at an upper critical field H_{C2} . The derivation of these results is given by deGennes.¹

1.6 Experimental Confirmation of Flux Line Lattice Structure

Neutron diffraction experiments by Cribier⁵ produced the first confirmation. But the best results have been obtained by Trauble and Essman⁶⁻⁷ who decorated the flux line lattice with ferromagnetic particles.

It is interesting to note that even at low fields, many defects are seen in the lattice. These include edge dislocations, edge dislocation dipoles, stacking faults, interstitials and vacancies and even fluid like structure at very low B. Screw dislocations probably also exist but cannot appear with such a technique. We will discuss later the importance of such defects which we believe are mainly responsible for the hysteresis and recovery phenomena.

Another very important point is that instead of always observing a triangular lattice, Essmann has found that in the case of a [100] niobium disk at 1.2°K, the flux line lattice at low B was organized in square lattice. The stability of this structure is assumed to be due to an attractive interaction still unknown.⁸

1.7 Flux Line Dislocations

Labusch¹¹ has given some elementary laws concerning the existence of flux line dislocations:

1. Lattice lines in the z direction, which is the magnetic field direction, are flux lines and therefore cannot end inside the material.

2. Lattice lines in the z direction cannot be cut and reconnected to other lattice lines. Hence cross slip is forbidden for flux line dislocations.
3. There is no lattice structure in the z direction. Any type of lattice defect therefore is glissile in this direction.

Stacking faults can exist, as seen on the Trauble and Essmann prints, due to splitting of perfect dislocations into partials. On the other hand, two dislocations can add to form a third one. From this consideration it is seen that a flux line dislocation source can operate as if two partial dislocations in different non-parallel planes meet, they add to form a dislocation that can propagate.

1.8 Lorentz Force

We summarise here the reasoning of deGennes.¹

If a gradient of induction is set in a region of constant applied magnetic field H, that is to say if the fluxoid density is not constant, the vortex lines will tend to spread to equalise their density; and at a given time and given place we can speak of a pressure p which acts on the vortex lines. This pressure can be computed by thermodynamic means. Consider a surface S intersected by N vortex lines. If G is the free energy of a single vortex in presence of the others, the total free energy equals SG, and $p = -G - S \frac{\partial G}{\partial S}$. Since at fixed N, $\frac{dS}{S} = - \frac{dB}{B}$;

$$p = -G + B \frac{\partial G}{\partial B}$$

Isolating the electromagnetic energy term, we have:

$$G(B) = F(B) - \frac{BH}{4\pi}$$

The equilibrium condition yields: $\frac{\partial G}{\partial B} = 0$, thus $H(B) = 4\pi \frac{\partial F}{\partial B}$ and,

$$\text{as } \frac{\partial p}{\partial x} = B \frac{\partial^2 G}{\partial B^2} \frac{\partial B}{\partial x} = \frac{B}{4\pi} \frac{\partial H(B)}{\partial B} \frac{\partial B}{\partial x}$$

$$\frac{\partial p}{\partial x} = \frac{B}{4\pi} \frac{\partial H(B)}{\partial x}$$

Following Maxwell's law and reasoning after Evetts et al¹²

$$\mathbf{J} = \frac{c}{4\pi} \text{curl } \mathbf{H}(\mathbf{B}) .$$

In the one dimensional case we have: $\frac{\partial p}{\partial x} = \frac{BJ}{c} y$

So, the action of a macroscopic current perpendicular to the vortex lines is the same as the one that would result from a Lorentz force exerted on a normal medium wire carrying the same current and subjected to the same field. This result is valid only on a macroscopic scale. As we have seen, on a microscopic scale the force on a vortex is given by $f = \frac{\phi_0}{c} j_y$ where j_y is the microscopic current.

What happens to the vortex lines when a macroscopic current is set through a crystal penetrated by flux lines? The vortex rearrange themselves so that the sum of the microscopic currents that surround them equals the macroscopic one. As we shall see, this rearrangement is not instantaneous and, at first, the extra current is carried by the surface sheath of thickness approximately the penetration depth.

1.9 Elastic Constants of the Fluxoid Lattice

As we have seen, the lattice deforms under an applied stress. Hence, elastic moduli can be obtained. These have been calculated by thermodynamic argument and, close to T_c , by using the Landau-Ginzburg equations.⁴

By using thermodynamic arguments similar to those used by deGennes in calculating the Lorentz force Labusch⁴ finds:

- The bulk modulus to be:

$$C_L = C_{11} - c_{66} = \frac{1}{4\pi} B^2 \frac{\partial^2 H(B)}{\partial B^2}$$

- The tilt modulus to be:

$$C_{44} = \frac{B}{4\pi} H_{eq}(B)$$

Those two expressions are valid for H between H_{C1} and H_{C2} .

- The shear modulus to be

$$C_{66} = \frac{1}{2} \int_0^l \xi^2 H''(\xi) d\xi$$

for H far from H_{C2} .

- For H close to H_{C2} , the Ginzburg Landau equation yields

$$C_{66} = A \left(1 - \frac{H}{H_{C2}} \right)^2 = A' \left(1 - \frac{B}{B_{C2}} \right)^2.$$

where A and A' are constants.

The intermediate region where neither of the derivations is valid is not well understood at the present time. These results are shown on Figure 6.

C_{66} is much smaller than C_{11} . Hence, in most of the cases the variations of the structural properties of the lattice are related to the variation of C_{66} .

1.10 Vortex dynamics

If it is not pinned, under the influence of the magnetic pressure gradient as described above, the vortex lattice is forced to move through the crystal. It is well known that the movement of vortex lines results in dissipation.⁹⁻¹⁰ The energy loss is viscous in nature so that the damping force is proportional to the velocity of the vortex lines.

$$f = \eta v$$

If this force results from a current passing through the medium, we have for a unit surface:

$$F = \frac{JB}{c} = \eta v_0 \frac{B}{\phi_0}$$

The energy dissipated results in a voltage drop across the crystal and conservation of energy requires:

Figure 6. Elastic coefficients of the flux line lattice after Labusch.⁴

$$VJ = \frac{\phi_0}{\eta c^2} BJ^2$$

where V is the voltage drop across 1 cm of the sample. This leads to the expression of a flux flow resistivity

$$\frac{\partial V}{\partial J} = \frac{\phi_0}{\eta c^2} B = \rho_f$$

So, if the crystal were perfect, the V-I characteristic would be a straight line passing through the origin, of slope ρ_f .

In the case of a constant driving current, the lattice is moving from one side of the crystal to the other. Vortex lines are nucleated on one edge of it and destroyed when they reach the other side.

CHAPTER II

INFLUENCE OF THE PINNING

Every crystal lattice inhomogeneity tends to either attract or repel the vortices. As the flux line lattice (FLL) moves, we expect to see an influence of the pinning effects of these inhomogeneities on the motion. Either the pinning is sufficient to stop the movement by balancing the pressure completely, or the FLL still moves and experiences a distortion and relaxation and possibly a disordering. We expect that there can be three regimes in the response of the FLL to the Lorentz pressure.

- 1) The whole FLL remains immobile and experiences only elastic strains.
- 2) Part of the FLL moves, the rest remains fixed.
- 3) The whole FLL moves across the crystal.

2.1 Nature of the Pinning

The pinning interaction of an inhomogeneity results either from the fact that it changes the condensation energy of the vortex core or the fact that it modifies the kinetic energy of the surrounding currents. The minimum effective inhomogeneity size is the core radius ξ but increases in inhomogeneity size above several times λ do not increase the pinning.

The pinning can be due to either¹³

- Point pins such as voids, second phase particles, defect clusters.
(e.g., those introduced by radiation damage).
- Line pins, mainly dislocations which of course act more strongly when they are parallel to vortex lines.
- Surface pins: the surface of the specimen, stacking faults and grain boundaries. According to Good and Kramer¹⁴ the influence of the irregularities at the surface of the specimen and of the defects

close to it is much enhanced by the fact that at a depth less than the penetration depth, the elastic shear modulus C_{66} of the flux lattice decrease from its bulk value.

A void results in a pinning force of about 10^{-6} dyne,¹⁵ a non-parallel dislocation results in a force of about 10^{-7} dyne,¹⁶ and if the dislocation is parallel to the vortex line a force of about 10^{-3} dyne/cm results.

But it is not sufficient, even for static pinning, to consider the interaction of a single pin with a single vortex line. The flux line lattice being a rigid entity, all vortices cannot be pinned simultaneously and the pinning is expected to increase only as the square root of the number of pinning defects.¹⁴ If the lattice is soft, vortex lines can have more freedom to accommodate the defect distribution and hence experience a much stronger pinning. This effect may be responsible for the so-called peak effect: close to H_{C2} the pinning force may be enhanced by a decrease of lattice stiffness in shear.

According to Anderson,¹⁷ at non-zero temperatures a movement of the lattice can occur due to thermal creep. Because of thermal activations, flux bundles are permitted to jump over barriers which they would not overcome at zero temperature. The jump rate is given by the Arrhenius law: $R = R_0 \exp(-\epsilon/kT)$; R_0 being the vibration frequency of the bundles and ϵ an effective activation energy of the process.

2.2 Dynamic Pinning

When the whole lattice moves the interaction of a pinning center with a given vortex line can be only instantaneous. The consequences of this interaction have been explained by Yamafuji and Irie.¹⁸ As a vortex line in the FLL moves through the crystal, it is subjected to a pinning force whose direction changes rapidly with time. The energy lost due to this interaction is dissipated by vibrations of the entire vortex lattice. The power dissipated is proportional to the speed: each

interaction results in deformation energy which is independent of the speed, and the rate of interaction is proportional to the speed.

Calling P the dissipated power due to pinning, $P = F_p v$, where F_p is defined as the dynamic pinning force, and writing the balance between the energy supplied and the energy dissipated by the pinning and by the flow we have:

$$VJ = (F_p v + \eta v^2) \frac{B}{\phi_0}$$

If we consider a point on the V - I characteristic for flow without pinning, we must equate the Lorentz force to the viscous drag force.

$$F_L = \eta v = \frac{BJ}{c}$$

or
$$vF_L = \eta v^2 = \frac{BJ}{c} v$$

If now we add the pinning, the extra current J necessary to maintain the same voltage is:

$$V\Delta J = F_p v = B \frac{\Delta J}{c} v$$

or
$$\Delta J = c \frac{F_p}{B}$$

which is a constant, assuming that F_p is a constant. The assumption that F_p is a constant requires the elastic distortion of the FLL by pins to be independent of the average fluxoid lattice speed. Experimental results confirm that the V - I characteristic is a straight line at high currents.

So, the V - I characteristic for a moving lattice with dissipative pinning is parallel to the V - I characteristic without dissipative pinning, but it is shifted by the amount of current necessary to overcome the fictitious pinning force F_p (see Figure 7).

As pointed out by Good and Kramer,¹⁴ if several neighboring pins act at the same time, the stored energy, and F_p will be proportional to the square of the number of cooperating pins instead of the number of

Figure 7. V-I characteristic in the flux flow condition.

pins. This is one explanation why dislocations organised in braids are much more effective pinning centers than regularly scattered ones.

2.3 The Curved Part Region of the V-I Characteristic

For small current levels in type II superconductors in a magnetic field H ($H_{C1} \leq H \leq H_{C2}$), the voltage drop across the sample is zero.

At some critical current (I_0 in Figure 8) the voltage increases, the initial slope being small. At larger current levels, the V-I characteristic is linear, corresponding to the Yamafuji Irie equation, as shown on Figure 8. The non-linear portion of the V-I characteristic, corresponding to currents between I_0 and I_1 in Figure 8 will be referred to as the curved region.

As opposed to the case where the lattice is immobile and to the case where it is in the flux flow condition, where the characteristic is independent of the previous history of the lattice, the observed characteristic in the curved region is very history dependent. We now review the hypotheses that can be made to explain the V-I characteristic in terms of vortex movement.

Another hypothesis is that the lattice is unpinned by parts while it is pinned on other parts: we would have superimposed waves of pinning and unpinning. The lattice would progress through the pinning centers like a worm does in the earth. This may happen only when complete unpinning is close to occur and cannot be the mechanism which acts throughout the curved region. Besides that, it is very difficult to see how the characteristic would be history dependent.

We can think also of a macroscopic shear: a region of the lattice would move past another. In order for this to happen, it is necessary that a large shear stress is created. If we consider the values given by Labusch⁴ for the shear modulus C_{66} we see that the shear modulus is too high under most conditions. For example, we study the simple case of an unpinned portion included between two pinning planes. A constant

Figure 8. A V-I characteristic when the current is ramped up.

gradient of shear stress results if the Lorentz force is parallel to the planes (Fig. 9).

Calling y the distance from the center and y_0 the distance between the planes and taking typical values: $H = 2 \text{ kO}_e$, $J = 100 \text{ A/cm}^2$ we have

$$\sigma_{yz} = 20,000 \times \frac{1}{2} (y - y_0)$$

If we consider that in order that a macroscopic plastic shear occurs the shear stress should be of the order of $\frac{C_{66}}{10}$, then:

$$\sigma_{yz} = \frac{C_{66}}{10} = 4 \times 10^3 = 20,000 \times \frac{1}{2} (y_0 - y) .$$

This leads to a spacing between pins of several millimeters, which is unlikely to be found. This order of magnitude argument shows that a macroscopic shear is not likely to occur.

Another example which shows that a macroscopic shear is unlikely to occur and gives an order of magnitude of the deformation of the lattice is the very simplified picture of a vortex in the center of four immobile vortex lines (Figure 10). We compute the increase in stored energy for the central moving vortex to be displaced by $\lambda/10$ as follows: using the London model and the relation

$$U_{12} = \frac{\phi_0^2}{8\pi^2 \lambda^2} K_0 \left(\frac{r}{\lambda} \right)$$

where r is the distance between two vortex lines and U_{12} the London interaction energy we find:

$$U_{12} = 2.664 \times \frac{\phi_0^2}{8\pi^2 \lambda^2}$$

with U and U' total initial interaction energies before and after movement of the central vortex. For $\lambda = 1000 \text{ Angstroms}$, $U' - U = .172 \times 10^{-4} \text{ ergs}$ corresponding to a displacement of 100 Angstroms or $10^{-6} \text{ centimeters}$. To obtain such a displacement it would be necessary to exert a pinning force of at least $20 \text{ dynes/centimeter}$ on the vortex, which is several

Figure 9. Shear stress on a flux line lattice pinned by two planes parallel to the Lorentz force.

Figure 10. A pinned vortex displaced with respect to four vortices surrounding it.

orders of magnitude more than the force that can be exerted by a crystalline defect.

2.4 Movement of Defects

In view of the pictures by Essmann and Trauble,⁶⁻⁷ and considering that the inhomogeneous character of the pinning is very likely to favor flux line lattice disorder; one might assume that as the Lorentz force is increased the first movement of vortices which would be observed would be movements of less than a lattice spacing. Defects would move through the lattice while individual vortex lines experience only a limited movement in space.

If FLL dislocation sources exist and operate, dislocations move repetitively and a constant voltage results. For these defects to be created and move a rather small shear stress is sufficient--much smaller than the one necessary for a macroscopic shear. The idea originated a number of years ago (Frank, 1964) but a quantitative analysis has been only recently given by Kramer.²¹ He first pointed out that dislocation dipoles are more likely to propagate than single dislocations: across a propagation line the shear stress reverses many times whereas the shear gradient has always the same orientation (except at pinning centers where the shear stress is discontinuous). For the sake of simplicity, a complete mathematical description has been made in the case of a screw dislocation dipole moving between two parallel pinning planes (Fig. 11). This dipole is stable in all physically possible cases.

The power dissipated due to the viscous motion of the vortex lines is obtained by summing the dissipation due to the movement of each single vortex while the dipole moves. A dipole speed v proportional to the driving force is found. Let y_s be the dipole width, and r_0 be the dislocation core radius. If there is no straddling of pinning planes:

$$v = \frac{2\pi\phi_0 y_s J}{\eta b \ln(y_s/2r_0)}$$

Figure 11. A screw dislocation dipole between two pinning planes parallel to the force.

If the dipole straddles a secondary pinning plane:

$$v = \frac{2\pi\phi_0 y_s}{\eta b \ln(y_s/2r_0)} \left(J - \frac{f_p}{By_s} \right)$$

f_p being the pinning force.

The voltage drop across the crystal resulting from the dipole motion is:

$$V = (Bby_s) \Lambda v,$$

Λ being the number of moving dipoles.

Physically it is easy to visualize the quantity (Bby_s) for an edge dislocation dipole as the flux contained in the extra plane or missing plane between the dislocations. This movement is not due to localised forces, since the Lorentz force acts on all the lattice, which as a whole reacts so that the defects are created and move.

In the most general case the $V(J)$ relation for dipoles moving is

$$V = \frac{2\pi\phi_0 y_s^2 \Lambda}{\eta \ln(y_s/2r_0)} B(J - f_p/By_s)$$

where f_p/By_s represents a critical current density below which the dipole cannot move because it cannot surmount the pinning force f_p offered by straddled pinning planes.

This model is very convenient for rationalizing the rounded part of the $V(I)$ characteristic: as I is increased, the speed of the defects increases and more and more sources can create defects. Recovery and yield (a decrease in current at constant v) can be accounted for in terms of defect movements in a rather straightforward manner.

We will discuss the complete theory and the results in Chapters VI and VII.

CHAPTER III

THE RESEARCH TECHNIQUES

3.1 Principles

The main parameters we measured were current and voltage. However a lot of other parameters could be varied in order to interpret the current or voltage results. These include magnetic field, the crystal temperature, the orientation of the crystal, the current direction, and all the history of the variation of these parameters. As we shall see, the results obtained are highly history-dependent. The product voltage-current measures the power dissipated by movement of the vortex lines: $VI = \eta v^2$. The current is directly related to the Lorentz force by the relation: $F = \frac{BJ}{c}$.

Systematic studies have been undertaken by:

- 1) cycling the current up and down, and measuring the voltage
- 2) keeping the current constant and observing the voltage evolution.
- 3) keeping the voltage constant and observing the current evolution.
- 4) sending current pulses in the sample and recording the voltage response.
- 5) changing the field to create non-equilibrium states for which the pressure is too high to be balanced by pinning forces. A vortex movement then results.

Not only can we change the way the lattice evolves, but also, we can vary the conditions of its formation. We have observed large differences in the V-I characteristic at 4.2°K when the lattice was formed by:

- 1) lowering the field from above H_{c2}
- 2) raising it from below H_{c1}
- 3) lowering the temperature from above T_c in a magnetic field $H_{c1} < H < H_{c2}$.

The results have been compared with those of Good and Kramer,²² and the influence of each parameter has been isolated to study the validity of the defect movement model.

3.2 The Crystal

The crystal we used throughout the experiment was processed by A. Das Gupta²⁴ for his surface pinning study, with the number 7001. Material was polycrystalline niobium obtained from Murex Limited in the U.K. A cylindrical single crystal of 1/4" in diameter and 9" in length was then grown by electron beam zone refining technique.

This crystal was then cut into a prism-like shape with an equilateral triangular cross section, each face being 1/8" wide by 2 1/2" long. The faces were then polished, subsequently purified by outgassing in a high frequency induction furnace at 1800°C in high vacuum (10^{-8} torr) for approximately 24 hours. This treatment resulted in a high purity crystal. The resistivity ratio was 470 [the 4.2°K resistivity was measured by extrapolating the curve $R(H^2)$ to the $H = 0$ axis as the crystal was found to be somewhat magnetoresistive].

Then the crystal was deformed 1% in tension at room temperature. The orientation of the faces is indicated in Figure 12: Face A is a [110] plane. The dislocation structure of this crystal is thought to be similar to that of crystals studied by Good and Kramer²²⁻²³ which was deformed in tension and then observed by transmission electron microscopy. In crystals of Good and Kramer, the dislocations were arranged in braids, 1000 angstroms in diameter and about 4 microns apart. As found for compressed high purity niobium crystals, the defects introduced were edge dislocations of which 80% were oriented within 10 degrees of a [110] direction perpendicular to the A face (see Figures 13 and 14).

This was confirmed for our crystal by the surface pinning measurements which showed that the A face was threaded by twice as many defects as face B and face C.

At about half way of the research, the crystal was bent by accident. Curiously enough there was only a quantitative change in the results obtained--at least those for which a comparison was possible.

Figure 12. Orientations of the faces of the specimen.

Figure 13. Electron microscopy photographs of the crystal used
by Good.²³

Figure 14. Schematic specimen configuration.

While presenting the experimental results, we will indicate whether they were obtained before or after the crystal was bent.

CHAPTER IV

THE EXPERIMENTAL APPARATUS

The experimental apparatus which we have used is a slight modification of the one described²⁴ by A. Das Gupta with whom we collaborated in constructing it; only the electronic part was very different. We summarise his descriptions, with modifications due to slight changes in the design to achieve our own experimental goals or improve the reliability. The electronic circuits being different and rather original, we describe them thoroughly.

4.1 Crystal Disposition

The specimen was held vertically in a dewar filled with liquid helium between the poles of the magnet which delivered a homogeneous horizontal field. The magnetic field could be varied and rotated about an axis of the specimen in the horizontal plane. The transport current was fed to the crystal through superconducting leads which were spot-welded on both extremities. The voltage was measured between two spring loaded brass point contacts one centimeter apart on the specimen. The potential difference developed across the point contacts was transmitted to a Keithley 148 nanovoltmeter by high purity thermocouple grade copper wires.

A Lucite holder was used to hold the crystal. Figure 15 gives the details of this holder. The copper leads were directly spotwelded on the brass contacts. A complete description of the crystal holding system is given by Das Gupta²⁴ in sections 3.3, 3.4 and 3.5. In order to conduct electric current to the specimen, a high current transport probe was built with two brass tubes; brass was chosen to reduce the heat dissipated by thermal leak. Superconducting ribbons were soldered on the sides of the tubes to minimise heat generation by allowing a parallel path for the current (Figure 16). With such a system, it is dangerous

Figure 15. Specimen holder.

to close the dewar completely. A resistor shunt is not enough to ensure security and a more sophisticated safety system should be inserted.

4.2 Crystal Heater

In order to form a lattice by cooling the crystal in the field, it was necessary to build a system which permitted us to raise the temperature above the critical value. This was achieved by forming an envelope around the crystal and setting close to the crystal a resistor that can dissipate up to 2 watts. This 2 ohms resistor was made with a few spirals of chromium-nickel cotton coated wire. The envelope was a cylinder closed at the top, formed by a thin wall plastic sheath. In order to avoid escape of helium gas at the top, rubber was polymerized in situ and formed a leakproof top section. Dow-Corning Silastic 589 RTV silicone rubber was chosen. After mixing it with the polymerizer, the rubber is a very viscous liquid that can be poured in the bottom part of the holder tube. No problems due to thermal stresses were observed. When it was necessary to remove the crystal the rubber, as it did not stick on the wires and on the walls of the tube, could be very easily stripped off with tweezers.

The change in state (normal to superconducting) was observed by passing a small current of .1 ampere and observing a voltage across the crystal with the nanovoltmeter. Only one or two seconds heating were necessary to observe the transition to the normal state.

4.3 Field Disturbing Wire

A superconducting wire was attached to a groove along the bottom of V-notch crystal holder (Fig. 15) in order to create a local field disturbance. This wire was connected with a current supply which could generate up to 3.5 amperes, resulting in a perturbing field of about 10 gauss at the nearest edge of the crystal and 1 gauss on the opposite face.

4.4 The Power Supply Regulation

A regulated low voltage high current power supply was necessary to pass high currents (100 amperes max.) through the low resistance specimen. The order of magnitude of the voltage across it is about 1 to 10 microvolts. A feedback regulated system has been built in order to achieve the following functions:

1. sweep the current up and down at a constant rate.
2. keep the current constant.
3. keep the voltage constant.
4. send current pulses of controlled duration and magnitude through the crystal.

In all cases a control voltage representative of either the current or the voltage to be obtained was compared with a reference voltage. The difference or error signal resulted in a correction by a feedback circuit.

4.5 The Sweep Unit

The sweep unit generates a voltage signal which can be increased or decreased with time at preset rates. The initial and final values are preset with potentiometers. Sweeping is achieved by a circuit, which integrates a constant error voltage delivered by an operational amplifier whose output is at +12 or -12 volts, depending on the sign of the difference between the reference voltage and the output voltage.

Figure 17 schematically indicates the structure of the sweep unit.

Figure 18 shows the detailed diagram of the sweep unit: Switch (1) turns on the batteries. Switch (2) chooses the operating battery, either 1.2 volts or 12 volts depending on whether we want to obtain at the output current a voltage of the order of several volts to control the current or a voltage less than one volt to control the voltage (this will be explained later in detail). Switches (3) and (4) are potentiometers, which can be set to select the reference voltage. Switch (5)

Figure 17. Schematic of the sweep unit.

Figure 18. Sweep unit diagram.

selects which pre-selected voltage is used [either (3) or (4)]. Meter (6) is a voltmeter indicating the value of the reference voltage. Switch (7) makes a selection between the preset voltage and the ground; it is used to ramp the current up or to keep it down. Switch (8) changes the divider ratio, thus changing the speed of the integrator. The symbols F and S in Table 1 refer to the fast and slow positions of this switch. Switch (9) holds the voltage at the output of the integrator constant, because when (9) is open, no current flows through the integrator (hold function). Switch (10) is the sweep speed selector, by changing the integrating resistor (from 500 Ω to 20 K Ω). See below a chart of the speeds.

Table 1
Rates of the Current Sweep, in A/min.
[0.1 Ω reference resistor]

Speed	Up	Down
F ₁	96	84
F ₂	37.2	32
F ₃	19.8	16.2
F ₄	9.6	8.4
F ₅	6.8	4.9
F ₆	3.7	3
F ₇	1.6	1.5
S ₁	16.4	4
S ₂	4.0	0.92
S ₃	2.0	0.4
S ₄	1.2	0.24
S ₅	0.6	0.14

4.6 Power Circuit

The power is supplied by two 6 volt car batteries (see Figure 19); the amount of current flowing is controlled by two power transistors MP 504. The control voltage is derived from the current flowing through .1 Ω or .01 Ω calibrated resistor. An inverter (12) has been incorporated to reverse at will the direction of the current through the crystal.

Figure 19. Schematic of the power unit.

4.7 Control of the Current

As seen on Figure 20, the sweep signal, divided by potentiometer (15) is matched against the control signal. The coefficient of proportionality of the signals can be regulated by the variable resistor (14). The resulting error signal is compared to the signal (13), which is zero usually, but which can be a reference pulse. The difference is multiplied and transformed into current by cascaded transistors.

4.8 Control of the Voltage (Figure 21)

The Keithley nanovoltmeter model 148 and the Keithley isolator model 399 have a very low bandpass (.3 Hertz for the isolator on low mode). In order to avoid oscillators and have a stable loop, it was necessary to strongly damp the error signal. This was achieved by Zener diodes which limited the error signal level and an integrator with a very high time constant (1 to 10^4 seconds). The Keithley nanovoltmeter has a high gain output such that the output voltage is 1 volt when the deviation is full scale on the meter. This output voltage is then floated with respect to ground by the isolator [oriented at the proper polarity for negative feedback by the inverter (19)] and matched against the sweep unit voltage. The error signal is then amplified and integrated. The voltage result of the integration acts as did the sweep unit for the current control.

The diode on the multiplier is used to improve the switching performances of the transistor bank.

By inserting a switch (16) before the high time constant integrator and using a very high input impedance operational amplifier and a low leak capacitor (mylar) a steady current control could be achieved. Switch (17) selects the mode of control: either current mode by connecting the potentiometer (15) directly on the sweep or voltage mode by connecting it to the integrator. A zero reset system (18) for the

integrator has been added and a voltmeter (21) indicates the voltage at the level of selector (17).

4.9 Pulsing

Sending current pulses through the sample was obtained by pulsing the reference voltage (13). This method ensures that a very high input impedance is seen by the pulse generator ($\sim 10^8$ ohms). The pulses could be very high (up to 100 amperes), but the raise time and fall time was long, of the order of 100 microseconds. Reference pulses were obtained by a Tektronic 161 pulse generator, which could operate from .1 millisecond to 100 milliseconds without limitation in voltage. A potentiometer was used to limit the voltage across (13).

In order to achieve faster raise time current pulses, a completely different system was built (Figure 22). Pulses were sent directly across the crystal by a pulse generator. As the voltage response of the crystal is very low (less than 10 microvolts), this did not affect the control. We used a General Radio 1397 A pulse amplifier, which could deliver 1.2 amperes with a raise time less than 1 microsecond. A coaxial cable was inserted through the holder and connected to the superconducting leads, close to the crystal.

4.10 Operating the System

Figure 23 describes the position of various components of the system on the rack.

4.11 Very Low Current Control

To control accurately very low currents (less than one ampere), it is possible to bypass the MP 504 transistors. This is represented by dotted lines on Figure 20.

Figure 22. Diagram of the pulse system.

Figure 23. The rack panel.

CHAPTER V

HYSTERESIS IN CURRENT VOLTAGE CURVES

Part I. The Results

Following Good,²²⁻²³ we began the investigation of our crystal by studying the hysteresis in the V-I curve when the current is swept up and down. As was already observed by Good, and as we confirm, the width of the hysteresis is a measure of the possibility of recovery.

5.1 Parameters of the Study

There are many parameters which all have a great influence on the results: these are the magnitude of the magnetic field, the orientation of the crystal relative to the field, the speed of the current cycling and its amplitude (provided that the flux flow condition is not reached) and the history of the flux line lattice before the beginning of the cycling (including the conditions under which it is nucleated). A systematic study has been done of all the effects of these varying parameters on the hysteresis.

5.2 Conditions of the Experiment

The current was measured by recording the voltage across calibrated standard resistor (Figure 19); this voltage was plotted on the X axis of a Hewlett Packard 7004 A XY recorder. The voltage, after amplification by the Keithley 148 nanovoltmeter was plotted on the Y axis.

Some noise was recorded on the voltage signal, part of it due to the nanovoltmeter itself, which was sharply reduced by using the filter of the isolator set on slow mode. In spite of our precautions some drift due to thermal E.M.F.'s remained. In some cases mechanical vibrations were also seen to degrade the signal.

5.3 Influence of the Conditions of Nucleation on Hysteresis

Figure 24 represents the typical shape of a hysteresis curve obtained at 2.2 KG, with $\phi = -30^\circ$ (Fig. 14), raising the field from zero and sweeping the current at 0.44 amperes per minute.

As already noted, we used three different methods to form the flux line lattice: by raising the field from zero, or by lowering it from above H_{c2} (these processes taking a few seconds) or by cooling the crystal in the field from above the critical temperature. The three methods are schematically represented on the H-T phase diagram in Figure 25. We observed that the nature of the first hysteresis cycle was completely different, depending on the nucleation condition. The subsequent cycles were always identical.

For all three nucleation conditions the first cycle was much broader (10 or 20 times) than the following ones; but the extreme point (Ω on Figure 24), corresponding to the highest current where significant hysteresis was observed, was the same for all cycles starting from the same nucleation conditions. This can also be observed in Good's results.

First cycle hysteresis curves have different shapes, some of which are represented on Figure 26. A very important result is that, while the up curves were different, the down curve was the same, for a given field and orientation, regardless of the cycle number or the orientation condition. In our case, for the fields used by Good, the up curve of the first cycle was above the down curve; whereas his first cycle up curve was below the down one. On further cycling, our up curves were always slightly lower than the down curves.

Let us define I_{100} as the current which produces a voltage of 100 nanovolts. A systematic study has been made of the magnetic field dependence of I_{100} on the ascending curves for different nucleation conditions as well as I_{100} on the descending curve. These data are shown in Figure 27, and in detail near H_{c2} in Figure 28. We see that there is a crossover of I_{100} curves at about 2.35 kO_e . Below that field the

Figure 24. Shape of the hysteresis. Major up curve: obtained while ramping the current up to flux-flow region. Major down curve: obtained while ramping the current down from the flux flow region.

Figure 25. H-T phase diagram.

Figure 26. Hysteresis curve for various fields and nucleation conditions. (bent crystal).

Figure 27. I_{100} versus field for lattice formed by cooling in the field and lattice formed by decreasing the field.

Figure 28. I_{100} around the peak effect.

ascending V-I curves lie at higher voltage and lower currents than the descending V-I curves. The cycles about 2.45 kg are very narrow and widen again as the field is increased further. At these high magnetic fields, I_{100} after the flux line lattice is created by cooling in the field is greater than either the I_{100} after the flux line lattice is created by decreasing the field from above H_{c2} or the I_{100} after flux flow (down sweep cycle after renewal of the FLL).

5.4 Influence of the Magnetic Field

We already have seen that for the three conditions of nucleation of the flux line lattice, the field at which the V-I characteristic is determined is very important. Figure 29 shows additional evidence for this importance; the flux line lattice in this case being created by increasing the field from zero to H. At low fields, the pinning is strong and the hysteresis is large. They both decrease as H increases until the value of the field is about 2.50 KG. At higher fields, the hysteresis still narrows but the pinning (as measured by I_F) is enhanced. After that, the hysteresis no longer exists and the pinning falls off. This peak in pinning is called the peak effect; we think that it is due to the fact that the vortex lattice being less rigid can better accommodate to the pinning centers. The relative strength of the cooled in the field lattice at high fields relative to the flux line lattice created by other treatments does not seem to be directly connected to the peak effect, as at 2.65 KG the pinning is maximum but the difference between nucleation conditions has largely disappeared (Fig. 28).

For a given orientation of $\phi = -30^\circ$, we have plotted on Figure 30 the ratio of the hysteresis width, which was measured at 100 nanovolts, to the extrapolated critical current I_F versus the field for a lattice nucleated by raising the field. It is seen that, exactly as found by Good, we find that the ratio is constant for values not close to H_{c2} where it falls to zero. This suggests that the hysteresis is connected

Figure 29. Currents corresponding to a voltage of 100 nV on up and down curves, as well as the extrapolated critical current I_F , versus field.

Figure 30. $\Delta I_{100}/I_F$ versus magnetic field (unbent crystal). $\phi = -30^\circ$.

with the crystalline state of the flux line lattice, since when the field is close to H_{c2} , the shear modulus C_{66} becomes very small and a fluid like structure of flux lines is probable.

5.5 Influence of the Orientation

Das Gupta²⁴ has made a complete study of the dynamic pinning force in our crystal. For a field of 2.2 KG the influence of the surface pinning is especially marked (Figure 31); anisotropic bulk pinning due to the interaction of the FLL with the $[1\bar{1}0]$ oriented crystal dislocation array in the interior is also observed.

We have done a systematic study of the orientation dependence of the hysteresis for a lattice formed by increasing the field to 2.2 KG. We also observe a strong enhancement of the pinning when the field was close to parallel to one of the faces but this enhancement was not accompanied by an enhancement of the hysteresis width. The surface pinning does not seem to participate in the hysteresis phenomenon as can be seen on Figure 32 where the ratio $\Delta I_{100}/I_F$ was plotted versus the orientation: a pronounced minimum occurs when the field is parallel to each face. Also, whereas the surface pinning force is very dependent on the direction of the current through the crystal (rectification effect), the hysteresis is not.

These observations indicate that the hysteresis effect is connected with the pinning in the bulk of the crystal and is independent of the surface pinning. The fact that no hysteresis was found before the crystal was 1% deformed, where the pinning is almost entirely due to the surface supports this conclusion. Good²²⁻²³ found that the surface perfection influenced the hysteresis width: polishing the crystal resulted in an increase in the hysteresis width. Our results show that his observations are probably not due to changes in surface pinning.

Figure 31. Dynamic critical current as a function of the orientation (unbent crystal). $H = 2.2$ Kg.

Figure 32. The hysteresis width normalized by the dynamic critical current as a function of the orientation of the magnetic field. $H = 2.2$, kOe unbent crystal.

5.6 Influence of the Sweep Rate

The hysteresis observed was very dependent on the rate of the sweep. A typical hysteresis curve is shown on Figure 33 which was obtained at a field of 2.2 KOe, the field being first raised from below H_{c1} , with a crystal oriented so that $\phi = 30^\circ$ (Fig. 14). We observe that:

- The ascending curve is not very sweep rate dependent over the range of rates employed.

- The slower the sweep rate, the larger the hysteresis; this is very suggestive of a relaxation process.

- The voltage at which the descending curve separates from the ascending curve is not very speed dependent.

We have observed that at rates below .5 amperes per minute the descending curve was no longer sweep rate dependent, at least in the limit of precision of our apparatus. Also the up curve was measured at rates down to .02 amperes per minute and no dependence on rate was found (within the limits of the apparatus, which was subject to thermal E.M.F.'s resulting in a drift of about .02 microvolts per hour). The up curve starting from $I = 0$ following flux line lattice nucleation will be called the major up curve; the down curve determined at a sweep rate below .5 amperes per minute will be called the major down curve.

5.7 Minor Cycles

When cycling the current, it is possible to raise it and then decrease it before the flux flow part of the characteristic is reached. Under these conditions, then, a minor hysteresis cycle is obtained.

Figure 34 shows a typical family of curves obtained by decreasing the maximum current in each hysteresis loop, the starting condition being the same: the field was decreased every time below H_{c1} and reset to a value of 2.2 KG. The shape of the down curve was almost identical. However these curves were not exactly parallel, but tended to become less steep as they approached the major cycle down curve (or as the

Figure 33. Hysteresis curves for different speeds.

Figure 34. Minor hysteresis cycles for the unbent crystal. H = 2.2 Kg.
Sweep rate = .44 amps/min.

maximum current was increased). It is also worth noting that the slopes of all the minor cycle up and down curves, as well as the major cycle down curve are greater than that of the flux flow line.

No particular feature (point of inflexion, break in the curve) was observed when the minor cycle down curve crossed the extrapolated flux flow line. This suggests that this extrapolation might have no physical significance inside the hysteresis loop. We may conclude that the hysteresis result cannot be explained by adding to, or subtracting from, the flux flow voltage another voltage due to a separate phenomenon.

If after the first minor cycle is completed we start up again, the up curve is slightly below the down curve of the preceding minor cycle, then it reaches the major up curve and is identical with it. If now the current is decreased again, the down curve is identical to a down curve of a simple minor cycle (Fig. 34 solid line).

Part II. The Interpretation of the Results

Firstly, we rule out thermal effects such as a temperature rise in the crystal, because we have several times observed that when the current was interrupted for a long time (of the order of 15 min.) and reset, the subsequent hysteresis curves did not depend on the length of this interruption.

Following Kramer,²² we will attempt to interpret the hysteresis in terms of defect formation and defect movements in the flux line lattice.

5.8 Degradation Effect

We have seen that after the flux flow line has been reached, the behavior of the lattice is independent of its prior history. It is also independent of the history during the flux flow, at least if the time spent in the flux flow condition is more than several seconds.

This is easily interpreted: when flux flow exists, the lattice gets renewed as a whole by a uniform translation. The new defects and defect sources which are inherently of different nature because of the different conditions under which they are formed, are generated by this nucleation and translation while the old lattice is completely swept away.

There is a strong difference between Good's²²⁻²³ results and ours. In our case, for fields Good used, and for fields raised from below H_{c1} , the up curve of the first cycle is above the down curve, whereas his first up curve is below the down curve. We might attempt to explain the discrepancy by noting that the formation of defects by translating the lattice may be very different from the formation of defect sources by changing the field or the temperature. The shape of the specimen, round in Good's case and triangular in ours, is another possible cause for this difference in the results. The flow of the lattice through the crystal, across the pinning points was expected by Kramer²² to degrade it and form a rather dense distribution of flux line lattice defects.

5.9 Defect Theory of a V-I Curve

We now relate the voltage-current-time relation to our hypothesis that the defect movement in the hysteresis region may be the origin of the power dissipation. The voltage measurement is made on a 1 centimetre length, and the crystal dislocations are in braids which are rather irregularly distributed in the crystal on a micron scale. Each region of the crystal has a particular pinning capacity. Some parts have very little pinning and others, by cooperative action of pins, can pin rather strongly. When the current is raised, the regions of low pinning capacity, or low critical current for a given defect, first generate a voltage by defect movements. As the current increases, more and more defects are free to move. But this is not all: the most important factor may be that in order to operate the FLL dislocation sources, necessary for a steady voltage, a driving force must be supplied

by the Lorentz force. Under a certain value of the current, these sources are not able to operate; a critical current is required for a source to work. So, combining the requirements that a minimum current is necessary to activate a given source and another minimum is necessary for a propagation of defects, we arrive at a critical current for defects to flow repetitively through the crystal.

When the current is increased:

- more and more sources are activated and more and more defects can move.
- their speed increases linearly with the current.
- the sources can be expected to produce defects at a faster rate.

The voltage thus should be a monotonically increasing function of the current. This monotonic increase has always been found, both by Good and ourselves.

We now try to give a more quantitative analysis in terms of FLD dipole motion, as suggested by Kramer.²¹ We consider the relation derived in Chapter II:

$$V = \frac{2\pi\phi_0 y_s^2}{\eta \ln(y_s/2r_0)} B(J - J_c) .$$

If we know the number of each type of dipole flowing and if we know the critical current for each dipole, we can extract the voltage corresponding to each current passing through the crystal.

So, the function we need to describe the hysteresis relates the number of dipoles, dN , for which the critical current is reached when the current density changes by a differential amount dJ . Figure 35 is a schematic representation of such a function.

To be more precise, if we assume that the voltage across the specimen is only due to the motion of dipoles, it should be enough to know the quantity

Figure 35. A possible defect activation function.

$$\frac{dN}{dJc} = \sum_{y_s} \frac{dN}{dJc} \frac{2\pi\phi_0 y_s^2 B}{\eta \ln(y_s/2r_0)}$$

which weights the number of dipoles which begin to move when the current changes from Jc to $Jc + dJc$. In this case, we can write:

$$V = \int_0^J \frac{\partial N}{\partial Jc} (J - Jc) dJc$$

The voltage given by this relation can be history dependent through $\partial N/\partial Jc$: As we have seen, the pinning force is rather weak compared to the inter-vortex forces. A FLL defect source is expected to work by a cooperative mechanism, involving a large number of vortex lines. Both the number of sources and the currents at which sources operate should be dependent on the history of the lattice. Furthermore, the FLL is certainly not a single crystal, but it is more likely to be a sort of mosaic of elements separated by less ordered boundaries. From these boundaries may originate the defects which move through an otherwise perfect FLL. When the driving force is increased, we also expect movements in the boundary where the stability of the structure is less. As time goes on, we may expect that there is an evolution in the number of defect sources that are able to operate. Then, there would be an increase or a decrease in the number of defects moving for a given current and a lower or higher voltage. This may explain why for low fields, the slower we sweep the current down, the lower is the voltage. The fact that a current interruption does not influence the V-I characteristic, is readily explained by the fact that the FLL with its imperfections, is frozen in the absence of the Lorentz force.

Unfortunately this analysis remains largely qualitative as it does not seem possible to extract the function $\partial N/\partial Jc$ from the V-I curves. Too many parameters are not accessible to experiment; e.g., the spatial distribution of pinning forces, the width of the dipole defects, the

effect of pile ups of FLD dipoles. Even having this information it should not be easy to relate it to the defect distribution in the crystal because the mechanism of the sources is not exactly known, and because it would be necessary to know the detailed structure of the pinning.

5.10 Minor Cycles

According to the analysis above, when the current is decreased and defect sources are turned off, it should happen that fewer defects are generated, and no new sources are created. If the current is raised again, no additional sources will operate (and it may possibly be that old sources have relaxed and are not able to operate again). So, the V-I up curve after a down curve is expected to be either identical with or slightly below the down curve, independent of the sweep rate. This is observed experimentally.

5.11 Sweep Rate Dependence

At first, we must note a strong difference between our results and Good's at $H = 2.2$ kOe: with our crystal, both before and after bending, the up curve was not very speed dependent, whereas the down curve was. The hysteresis was larger when the sweep speed was smaller. For Good's crystal²² in order to see a marked hysteresis, a fast sweep rate was necessary, and as the sweep rate was lowered, the ascending curve was displaced to lower currents and the descending one to higher currents.

We visualise the sweep rate dependence as due to a purging or multiplication of defects in the FLL. We will reconsider this point in more detail in the next two chapters where recovery at constant current and recovery at constant voltage are investigated.

5.12 Influence of the Nucleation Conditions

We used three different ways to create the FLL: raising the field from below H_{c1} , lowering it from H_{c2} and cooling the crystal in the

field. All these three ways are expected to create flux line lattice disorder, and we will try to relate the extent of disorder to the creation process.

From our previous interpretation, it seems reasonable to attempt to relate the perfection of the flux line lattice to the current for which there is a perceptible voltage across the crystal. So, Figures 27 and 28 might be viewed as a measure of the lattice perfection. For the two first nucleation conditions, when either H_{c1} and H_{c2} are reached, vortex lines are nucleated at the surface (and at H_{c2} in the bulk) of the specimen. Then, to accommodate the increase (or decrease) in B with the further H change, the vortex lattice contracts (or expands) and new vortex lines are formed (or destroyed) at the edges of the specimen. For a flux line lattice formed by cooling in the field, such a movement exists--due to the change of induction with the temperature--but is always less important.

From the GLAG theory, we expect for a perfect crystal that the disorder at the time of nucleation is the same at all positions on the characteristic parabola (mixed state boundary at H_{c2}) (Figure 36). (In the region of interest, $\kappa = \lambda/\xi$ is constant.) We also expect that the disorder created by subsequent flux motion varies inversely with the shear modulus, C_{66} , which varies as a function of H and T (near H_{c2}) as

$$C_{66} = f(\kappa) \left(1 - \frac{H}{H_{c2}} \right)^2$$

where $f(\kappa)$ is roughly independent of T and H . Let us consider Figure 36 on which are shown two paths to point P ; by decreasing H from H_{c2} (path HP) and by decreasing T from above T_c (path TP). To evaluate the amount of motion (expansion) that will occur, we have to evaluate $B(H)$, $B(P)$ and $B(T)$. It is readily seen that $B(P) < B(T) < B(H)$. So in any case, the expansion is larger for decreasing the field than for cooling. The relative difference is more pronounced for representative points

Figure 36. Induction as a function of both temperature and magnetic field.

close to the characteristic parabola since, there, B is close to H . The number of vortex lines in a unit area is $N = \frac{B}{\phi_0}$. Thus, if we call the lattice spacing

$$\ell = \left(\frac{\phi_0}{B} \right)^{1/2},$$

for a change dB of induction

$$\frac{d\ell}{\ell} = - \frac{1}{2} \frac{dB}{B}.$$

We now develop a model in order to attempt to estimate the relative disorder in flux line lattices formed by the paths HP and TP. Our initial assumptions are that:

- The disorders of the FLL's at the time they are created are the same.
- The pinning and shear modulus are temperature dependent only due to the temperature dependence of the ratio $\frac{B}{Bc_2}$.
- The amount of disorder is proportional to the relative expansion of the lattice and to a certain disordering function D which is a function of C_{66} and of the pinning. We believe that the amount of disorder decreases as C_{66} increases and that it increases with pinning.

According to our hypothesis, the final disorder is given by:

$$\Delta = \int_{B_{\text{initial}}}^{B_{\text{final}}} D\left(\frac{b}{b_{c_2}}\right) \frac{db}{b}.$$

For a lattice obtained by decreasing the field, we have a disorder given by

$$\Delta_H = \int_{B_i}^{B_o} D\left(\frac{b}{B_i}\right) \frac{db}{b}$$

or

$$\Delta_H = \int_1^{\frac{B_o}{B_i}} D(u) \frac{du}{u}$$

For a lattice obtained by lowering the temperature:

$$\Delta_T = \int_{H_0}^{B_0} D\left(\frac{b}{b_{c2}}\right) \frac{db}{b}$$

If we change variables such that $\frac{b}{b_{c2}} = u$, the integral is:

$$\Delta_T = \int_1^{\frac{B_0}{H_0}} D(u) \frac{u db_{c2} + b_{c2} du}{b_{c2} u}$$

$$\Delta_T = \int_1^{\frac{B_0}{H_0}} D(u) \frac{du}{u} + \int_1^{\frac{B_0}{H_0}} \frac{db_{c2}}{b_{c2}} D(u)$$

$$= \Delta_H + \int_{\frac{B_0}{B_i}}^{\frac{B_0}{H_0}} D(u) \frac{du}{u} + \int_1^{\frac{B_0}{H_0}} D(u) \frac{db_{c2}}{b_{c2}} = \Delta_H + \Delta' + \Delta''$$

when we move along T_p , b_{c2} increases when b decreases, Δ' and Δ'' are always of the opposite sign of Δ_H . This means that the cooled in the field lattice should be always less disordered.

Thus we cannot explain with the above hypothesis, that the cooled in the field lattice is not as strong at low field. The cooled in the field flux line lattice should have less disorder (if disorder is created in the way considered above) and should generate less voltage at a given current (if the number of defects generated by lattice formation is the only important parameter).

If now we introduce the temperature dependence of the pinning, a higher disorder for cooled in the field lattice at low field is even more difficult to explain as the pinning decreases with an increasing temperature. To explain the crossings on Figure 27 we propose the

hypothesis that the crystal has defects which, acting as preferential sites for the nucleation, certainly modify the order of the nucleated lattice and cannot be accounted for by the GLAG theory. The lattice which results has then an order different of the one which is described by the GLAG theory. As the nucleation temperature increases, the nucleation characteristics may change and the spacing between nucleated vortex lines changes also. Those two factors may contribute in a higher disorder at higher temperature.

CHAPTER VI

VOLTAGE RECOVERY

In order to study the time dependence of our results, only one parameter (voltage or current) is allowed to vary in time and the other is held constant. For observation of voltage recovery, the current is rapidly set to the desired value and maintained constant; the change in voltage with time is then recorded.

Part I. The Results

Experiments have been conducted on both the bent and unbent crystal. The results are represented on Figures 37 to 41. In both cases, recovery exists only after stopping on the major cycle up curve and on fast sweep down curves, but not on the major down curves--so, with respect to voltage recovery, the major down curves have special properties.

The ultimate value reached is always inside the hysteresis loop, and the recovery is always towards the major down curve. It is seen that in no case, is the major down curve crossed. The largest recovery in voltage occurs at a current in the widest part of the hysteresis loop, but there is no constant ratio between voltage change and hysteresis width. The extrapolated flux flow curve was crossed and no sharp change in the recovery rate was observed during and after the crossing.

The curves $V(t)$ were all of the same shape: a rather fast variation at the beginning, getting slower and slower and at the end, after 2 or 3 minutes, no observable change. An attempt to fit the data to curves of the form $V = A \ln t$, or $V = A \exp(-t/\tau) + B$ did not work. It seems that no simple algebraic form can be given to the results.

The shape of the curve is in fact between such an exponential and a straight line. Although it was not possible to define the recovery curves by an algebraic expression, meaningful parameters could be

Figure 37. Voltage recovery.

Figure 38. Voltage recovery.

Figure 39. Voltage recovery.

Figure 40. Voltage recovery.

Figure 41. Voltage recovery.

extracted. For a preset current during the recovery, some obvious ones are the initial voltage during the recovery, the ultimate voltage reached, and the voltage that would have been reached on the major cycle slow speed down curve if the recovery had been complete. During the first seconds, there is a damping due to the low band pass frequency of the Keithley nanometer. So it was not possible to consider the slope of the curve during the first seconds as a reliable parameter. To describe the rate of the recovery, we have found it convenient to measure the time necessary for half the final voltage change to occur. This can be rather easily measured on $V(t)$ curves. The parameters of all measured recoveries are shown in Table 2. The numbers in the first column refer to the numbered curves on Figures 37 to 41.

A magnification of curve 2 of unbent crystal is shown on Figure 42. Before the current was held at the desired values it was raised at a rate of 6.8 amperes per minute. Varying the rates between 1.6 amperes per minute and 9.6 amperes per minute did not affect the recovery. There does not seem to be a straightforward relation between the recovery rate and either the current or the voltage or the power dissipated in the crystal. The recovery rate is not at all proportional to the driving force or to the power dissipated.

Examining the results of Table 2, we see that for cycles in a field less than 2.25 kg, a group of values of the current exists, for which the ratio of characteristic half time over voltage change is a constant. This ratio describes the inverse of an average decay rate. The voltage measured on the down major curve in this region was always zero. It is independent of the voltage and current for currents at which the voltage on the major down curve is zero, but the ratio does depend on the field and on the pinning (for the unbent and bent crystal, the currents in the bent crystal being higher). For higher currents, the decay rate always becomes lower and tends to decrease as the current increases or the hysteresis loop becomes more narrow, as seen on

Table 2

Voltage Recovery Characteristics

Curve Number	I	V (μ v) Initial	V (μ v) Ultimate	V ₀ (μ v) Down Curve	Characteristic Half Time (sec)	Voltage Change	Time Voltage Change
H = 2.20 kOe		Unbent crystal			Field raised from Hc ₁		
1	1.05	0.41	0.24	0	12	.16	75
2	1.25	0.59	0.39	0	14.5	.20	72
3	1.38	0.76	0.53	0	12.5	.23	47
4	1.74	1.01	0.85	.36	16	.16	100
H = 2.00		Bent crystal			Field lowered from above Hc ₁		
1	6.1	.136	0	0	1.85	.14	13.5
2	6.6	.36	.12	0	3.5	.26	14.6
3	7.15	.59	.21	0	5.2	.38	13.5
4	7.55	.89	.39	0	7	.50	14.0
5	8.2	1.24	.58	.38	14.5	.66	22.0
6	8.9	1.92	1.37	1.21	17	.55	31
H = 2.25					Field lowered from above Hc ₂		
7	5.05	.100	0	0	2.2	.10	2.06
8	5.55	.24	0.08	0	3	.16	1.87
9	6.00	.51	.33	.17	4.5	.18	2.5
10	6.55	.95	.82	.76	7	.13	5.3
H = 2.60					Crystal cooled in the field		
11	6.5	0	.075	1.82	.75	.075	1.0
12	7	.88	1.20	2.42	6	.33	1.9
13	7.35	2.20	2.95	3.05	10.5	.60	1.6
H = 2.63					Crystal cooled in the field		
14	8.75	.061	.29	.55	6	.22	29
15	9.1	.38	.59	.89	13.5	.21	64
16	10	7.91	2.17	2.17	12	.26	46

Figure 42. Voltage recovery curve ②.

Figure 37. This law does not apply for a FLL formed by cooling in the field where there is a portion of the up curve that is very close to vertical. The points on this part of the curve have a rather large and fast recovery. It may be that the high slope of the curve corresponds to a zone of pinning instability. An attempt was made to correlate the recovery rate at a given I to the radius of curvature of the major up curve at that I , because both the radius of curvature and recovery rate go to zero as I is raised into the flux flow region, but this correlation fails at lower currents.

In the previous chapter we observed that the up curve is unchanged for current sweep rates down to a very slow value (.02 A/min). The fact that substantial recoveries are observed at constant current (current sweep rate = zero A/min) implies that the up curve does, in fact, become sweep rate dependent at rates somewhere below 0.02 A/min.

6.1 Description of the Flux Line Lattice States

We begin this section with a hypothesis: that any given point on the V-I diagram represents a unique state of the FLL. If this hypothesis is true the subsequent V or I evolution from this point, caused by a given set of imposed conditions, should be independent of the path used to reach this point. Let us note in passing that such a hypothesis is more restrictive than what one would predict from the theory of moving FLD dipoles. There the voltage is of the form

$$V = \sum_{y_s, J_c} AK_y (J - J_c) ,$$

and two different distributions of lattice defects can result in the same voltage across the crystal for the same current.

This hypothesis was tested in two ways:

- 1) After a voltage recovery, the current was swept at a constant rate.

2) During a sweep, the current change was stopped and the recovery was observed.

1) Sweeping after recovery: We have done a systematic study by sweeping down at 1.5 A/min after allowing recovery at constant voltage to a given V-I point on a previously determined minor cycle down curve. We were interested to see if the down curves after recovery were different from the minor cycle down curves. The results are shown on Figure 43. The initial slopes are difficult to compare because of the large response time of the Keithley nanovoltmeter, but after an initial transient no differences between the two curves could be observed. Instead of sweeping down, we also swept up after recovery; the curve which we found was also parallel to minor cycle up curves.

Another experiment was to reach a point inside the hysteresis loop characterised by the same values of voltage and current by two ways: either by recovery from the major cycle up curve or by sweeping down from the flux flow curve at a high rate of speed (4.96 A/min) (Figure 44). In both cases, after the point was reached, the current was swept down at 4.96 A/min. The two sweep curves were exactly the same.

We looked for crossings of two curves obtained by sweeping at the same rate which would have been a proof that two states of the lattice can result in the same point on the V-I plot. No such crossing could be found.

2) Recovery after sweeping: We have compared voltage recoveries from the same point on the major up curve reached by two different ways: raising the current fast (13.2 A/min.) from zero or by lowering it fast (13.2 A/min.) from a value corresponding to flux flow conditions. Again we found that there was no difference between the voltage versus time curves.

All these experiments were carried out at a field of 2.2 kg on the unbent crystal. For these conditions, at least, it seems that once a particular V-I point is reached, the response of the voltage to the

Figure 43. Comparison of down curves after voltage recovery with minor cycle down curves.

Figure 44. Comparison of a V-I curve determined by sweeping the current down rapidly with a V-I curve determined by sweeping down at the same rate after voltage recovery.

subsequent current programs is independent of the path used to reach that point. This generalization is obviously not valid for points on the line $V = 0$, however.

Part II. The Interpretation

6.2 The Mechanism

As already pointed out about recovery of current at constant voltage by Kramer,²² a driving force is absolutely necessary to produce recovery. So, this phenomenon is connected with the unbalance created by the Lorentz force.

It is of interest to remember that there is no recovery from the major cycle down curve, and that all recoveries are towards it, with increasing or decreasing voltage corresponding in terms of defect theory to degradation or purging. This down curve might then be considered as corresponding to the steady state voltage, whereas other stable points, as the ultimate point of the recovery, are probably points at which the kinetics of recovery are unreasonably slow.

We can view the recoveries as due to modification of the number and speed of the defects (in particular FLD dipoles). Only a slight change in the configuration of the sources may be necessary to activate or deactivate them.

6.3 The Rates

We already observed that there exist two regions: the lower current one for which the down curve is along the current axis, which we will call the α region, and the higher current one, the β region, for which the major down curve corresponds to a non-zero voltage. In the α region the major up curve is at non-zero voltage, and the down curve corresponds to a completely immobile lattice. We are led to think that the structure of the FLL represented by the up curve in this region is

relatively unstable and should recover faster than the FLL in the β region.

It is difficult however to explain why the average decay rate is constant at various currents in the α region--at least in the limits of our experiments.

A very simple model can be built as follows: We start from the fundamental relation²² for the voltage due to one species of moving FLD dipole (given y_s and J_c), viz.

$$\begin{cases} V = K_n \Lambda_n (J - J_{cn}) & \text{for } J > J_{cn} \\ V = 0 & \text{for } J < J_{cn} \end{cases}$$

and assume a law of decrease of the number of dipoles of the form:

$$\frac{d(\Lambda(t) - \Lambda(\infty))}{\Lambda(t) - \Lambda(\infty)} = -c dt$$

$$\Lambda_n(t) - \Lambda_n(\infty) = Ae^{-ct},$$

we obtain for the voltage: $V = K_n (\Lambda(\infty) + Ae^{-ct}) (J - J_{cn})$.

For the whole ensemble of dipoles the voltage will be additive:

$$V = \int_0^J K_n (\Lambda_n(\infty) + (\Lambda_n(0) - \Lambda_n(\infty))e^{-ct}) (J - J_{cn}) dJ_{cn}$$

which is of the form $\alpha + \beta e^{-ct}$, which is roughly what is observed. The value of this model is indeed very limited as it does not explain why c is voltage independent. One expects that the rate at which the number of dipoles decay will increase with the rate of overall vortex motion, i.e., the voltage.

CHAPTER VII

CURRENT RECOVERY

Part I. The Results

Here we report the results if the voltage is held constant and the evolution of the current followed as a function of time. The current was driven rather fast until the desired reference voltage was obtained. Then, by the use of the servo control, the voltage was kept constant and the change in current observed. Good made similar experiments and his results are compared with ours. Observations have been made on unbent and bent crystal at several fields.

7.1 The Experimental Procedure

First the flux line lattice was formed, by changing the field or by cooling in the field. The reference voltage was set and the current ramped at a constant speed till the desired voltage was obtained. The variation of the current was observed at constant voltage. A slight oscillation due to the slow response of the Keithley nanovoltmeter was observed just after the right voltage was obtained. But this did not last more than a few seconds whereas the evolution of the current lasted several minutes. This oscillation was larger when the curve $V(I)$ was close to vertical, possibly because of the corresponding increase in gain of the system which creates a favorable situation for instability. The current was usually ramped at a rate of 8.2 A/min., but we observed that the sweep rate did not influence the results as long as no instability in the feedback loop was created.

A typical $I(t)$ curve is shown on Figure 45. In all cases, we observed that the current increase was logarithmic in time. Referring to Good's results,²³ Figure 2, we did not observe that the current increased linearly with time over any substantial portion of the recovery, nor did the current appear to saturate. After half an hour, however,

Figure 45. A typical current recovery curve. $H = 2.2$. Unbent crystal.

the results were difficult to interpret due to the inherent noise in the system. We did not observe a yield effect like the one described by Good and Kramer.²²

7.2 Voltage Dependence of the Current Recovery

A systematic test of voltage dependence has been conducted on the unbent crystal in a 2.2 KG field. Figure 46 indicates the amount of recovery obtained for the different reference voltages. The dotted line indicates the limit of the zone of the points which can be reached in half an hour by current recovery from the major up curve. Afterwards, the evolution of the current cannot be followed, being hidden by the noise and the thermal voltage fluctuations. As was the case for the voltage recovery, we see that the prolongation of the flux flow line cuts through this region--and again we observed that there were no changes in the recovery behavior on crossing of this line.

After the first 20 or 30 seconds, the recovery curve was of the form $I = A \log t$. On Figure 47 we have plotted the current versus $\log$ (time) for different voltages in the hysteretic region. The logarithmic dependence seems to be well established. It is clear that there is an abrupt break in the recovery rate (slope of the curve) at the value 1.39 amps, which corresponds to the foot of the major down curve. This break occurs in the middle of a recovery curve and is very sharp. Again we find a difference in behavior between the α region and the β region. In Table 3, we indicate the values of the slope $\frac{dI}{d \log t}$ with I in amperes and t in seconds at the various voltages.

We find that the α and β regions are characterised by a constant rate within the accuracy of the experimental measurements. It is of interest to compare these rates with the voltage recovery rates reported in Table 2: unfortunately, we did not make enough voltage recovery measurements in the β region to see if there is also a constant voltage recovery rate there. It may be worth noting that the β region corresponds to a part of the major down curve which is approximately linear.

Figure 46. Voltage recovery on the VI diagram.

Figure 47. Current recovery. (See Fig. 46):

Table 3
Current Recovery Rates

V	$\frac{dI}{d(\log t)}$ amps
.15 μ	.115
.30 μ	.105
.60 μ	.105 .040
.90 μ	.040
1.20 μ	.045
1.50 μ	.035

H = 2.2 KG field raised from H_{c1} in the unbent crystal.

Experimentally the points which can be reached by voltage recovery can not always be reached by current recovery: the ultimate curve after half an hour recovery is closer to the major up curve for the current recovery than for the voltage recovery.

7.3 Dependence of Current Recovery on Field and Nucleation Conditions

Using the bent crystal, we have done a systematic study of the dependence of the nucleation conditions and field values on the current recovery direction and rate. As for the voltage dependence, we have found that the recovery always took place in the direction of the major cycle down curve. Also, we have seen that in all cases, after a short period of time of about 10 seconds, the curve $I(t)$ was always of the form: $I(t) = A \log t$.

We have conducted two sets of measurements both with orientations close to $\phi = 30^\circ$. The first was from 1.5 to 2.6 KG and the second from 2.5 to 2.7 KG. The results of these two sets are displayed in Table 4. The corresponding hysteresis cycles are those in Figures 27 and 28 and have already been commented on. We first note an increase of the

recovery rate at voltages corresponding to a widening hysteresis loop at any given field. But this increase seems to be rather slight and reciprocally a large hysteresis loop does not necessarily ensure a fast recovery, as it is obvious in the second set at 2.55 KG.

Table 4

Current Recovery Rates at Different Fields and for Different Lattice Nucleation Conditions for the Bent Crystal

Magnetic Field KOe	$\frac{dI}{d(\log t)}$ (amps) Conditions of Nucleation			
	Down from H_{c2}		Up from H_{c1}	Cooled
Set 1	Voltage = 1 μ V			
1.5	.52			
1.8	.62			
2.00	.45			.48
2.2	.15			
2.3	.10			.11
2.4	.03			
2.5	0			0
2.6	-.08			-.075
2.65	0			0
Set 2				
2.5	150 nV	0	0	0
	1 μ V	0	0	0
2.55	150 nV	0	0	0
	1 μ V	0	0	0
2.6	150 nV		-.08	-1.15
	1 μ V	0	0	0
2.65	150 nV	.12	.14	.08
	1 μ V	0	0	0
2.70	150 nV	.12	.12	.12
	1 μ V	.12	.12	.12

Part II. Interpretation of the Results

It is well known that in the flux flow region, the lattice moves through the crystal, being created on one side and destroyed when it reaches the other side. It is possible to compute the speed of this lattice renewal by considering the work done by the Lorentz force as follows:

We start from the fundamental concept that the only way by which energy is given to the system is the action of the Lorentz force on the vortex lines. Then the power supplied to the crystal VJ is equal to the power dissipated by the movement of the lattice (which is the product of the average force exerted on a vortex line, $\frac{J\phi_0}{c}$, times the number of vortex lines, $\frac{B}{\phi_0}$, times the speed of the lattice).

$$VJ = \frac{J\phi_0}{c} \times \frac{B}{\phi_0} \times v_y$$

$$VJ = v_y \frac{JB}{c}$$

$$v_y = \frac{Vc}{B}$$

Assuming that the movement of the vortex line lattice takes place as a whole (i.e., if no defect moves), then the speed with which the array progresses through the crystal is:

- proportional to the voltage.
- proportional to the inverse of the induction.

From this relation, it is easy to compute the time it takes for the lattice to be completely renewed.

Assuming

- that the crystal is 2 mm wide
- that the induction is 2 KG
- that the voltage across one centimeter of the crystal is one

microvolt, we have, using gaussian units:

$$v_y = \frac{10^{-6}}{300} \frac{3 \times 10^{10}}{2 \times 10^3} = .05 \text{ cm/sec} = .5 \text{ mm/sec}$$

So, with the hypothesis of a homogeneous displacement of the flux line lattice, the time necessary for a complete renewal of the lattice is:

4 seconds for a voltage of $1 \mu\text{V}$.

40 seconds for a voltage of $.1 \mu\text{V}$.

The recovery rates we observed are very much slower than this and, furthermore, the observed rates are not proportional to the voltage. Thus we conclude that it is not the uniform renewal of the lattice which is mainly responsible for the recovery phenomenon.

Following Kramer,²² we examine the possibilities that the mechanism of activation and deactivation of flux line dislocation sources may be the origin of the recovery phenomena: The voltage recovery would simply correspond to a deactivation of defect sources. The current recovery results from a more sophisticated mechanism: when some sources cease to be effective, the voltage tends to drop. In order to avoid this, the feedback mechanism increases the current and this increase results in the activation of new sources for which the critical current was not reached before. As it is expected that the regions of higher pinning correspond to a higher critical current than the low pinning one, we expect a gradual activation of the sources in regions of higher pinning, accompanying deactivation in the regions of lower pinning. Even with this mechanism however it is difficult to understand why the rate of current recovery should be independent of voltage.

CHAPTER VIII

EFFECT OF CURRENT PULSES ACROSS THE CRYSTAL

Another way of investigating the lattice behavior when acted on by a Lorentz force is to send pulses of current of different magnitude and duration through the crystal. As the driving force is momentarily increased to somewhere close to flux flow conditions, a higher disorder presumably results. The degradation can result in a higher voltage through the crystal for the same current passing through it.

8.1 Actions of the Pulses on the Flux Line Lattice

The pulses which we applied to the crystal were of a relatively long duration, more than a microsecond, with a raise time of about 100 nanoseconds. In this case, only low frequency harmonics are present: the upper frequency was less than 10^9 Hertz. When a superconductor is pulsed, it is the loss by the normal electrons which attenuates the high frequency response. It has been computed that for a frequency less than 5×10^9 Hertz this is negligible. The other limitations, such as the necessity that the penetration depth be less than the skin depth impose less severe limitations. In type II superconductors there is a loss due to vortex motion. This we already know to be of the order of a few microvolts for our crystal.

When the pulse starts, the excess pulse current is carried uniformly along the surface. The resulting Lorentz force reorganises the lattice and the vortices rearrange so that the current flows through the bulk.

8.2 Degradation Action of the Pulses

If we consider a long enough pulse so that a new equilibrium is reached during the time of the pulse, we can follow the evolution of the voltage on the V-I diagram.

The action of the pulse is very dependent on the preceding state of the lattice. The nucleation condition and the history of the flux line lattice have to be considered. The voltage after the pulse has been applied (when the current returned to the measuring current) is always equal to or greater than the voltage before pulsing. In order to investigate the history dependence, we introduced current pulses of 100 millisecond duration and of different magnitudes at different points on the V-I characteristic as the current was ramped up and down. The lattice was formed by raising the field from below H_{c1} .

When the pulses were triggered at a point on the major up curve, even high pulses of 10 amperes induced only a small change in voltage (as long as the major curve was above the major down curve). The observation of this voltage change was made difficult by the fact that voltage recovery takes place without pulsing, starting from the major up curve. When the pulse was triggered from a point on the major down curve at low field, the voltage change was more significant and could be easily followed since the degradation due to the pulse is more important, and since no recovery exists. So, the procedure was as follows:

1. The flux line lattice was formed, by raising the field from below H_{c1} .
2. The current was ramped up into the flux flow region and then slowly swept down to a preset value.
3. During a short time, the current was kept at this value, and no voltage change was observed.
4. A single pulse was sent, and the response in voltage versus time after the pulse was observed. The time constant of the Keithley is extremely large compared to the width of the pulse; it was thus impossible to follow the voltage change during the pulse itself.

Figure 48 shows a typical response to a 10 ampere, 100 millisecond pulse, starting from a point on the up curve or on the down curve.

Figure 48. Typical pulse response.

On the down curve for large enough pulses, the maximum voltage reached was the same as the one attained when pulsing on the up curve for the same initial current level.

8.3 Pulse Duration Dependence

We have observed that a minimum pulse duration is necessary to have a persistent (longer than the time constant of the Keithley nanovoltmeter) voltage response to the current pulse. A systematic experiment was performed on the bent crystal, at a field of 2.2 KG, on the major down curve and at a voltage of 150 nanovolts, as shown on Figure 49. Due to the current limitation set by the pulse amplifier and to the width of the bent crystal hysteresis, it was not possible to send pulses with a peak current such that the flux flow curve was reached. We were limited to one ampere pulses.

The pulse duration was increased from 1 microsecond, where no voltage change was observed to one millisecond. The shortest pulse which led to a visible effect was 10 microseconds long. As the pulse duration was increased, the voltage response tended to increase also. This increase took place up to pulse durations of 100 microseconds. For longer pulses, no further change was recorded in the response. Figure 50 displays the voltage change versus pulse duration; it is seen that the most important variation occurred between 10 and 30 microseconds.

Because of the high quantity of helium dissipated for each cycle, it was not possible to make a study of the field dependence of the pulse duration. However, we tried 10 microsecond pulses for the same voltage and the same flux line nucleation conditions at different fields and we saw that a voltage change was always apparent and always less than the change obtained for much longer pulses. From this we conclude that the minimum efficient pulse duration is always of the same order of magnitude. At fields less than 2.3 KG pulses of 100 microseconds or more induce a voltage change after the pulse which is equal to or somewhat

Figure 49. Response to a current pulse of limited duration and amplitude.

Figure 50. Voltage change versus pulse duration for a 1 ampere pulse for conditions of Fig. 49.

greater than the voltage hysteresis at the given current. The voltage hysteresis thus seems to give approximately a saturation limit of the change in voltage that can be induced by a pulse.

It is of interest to compare the minimum pulse duration necessary to observe a persistent voltage change with the transit time necessary to form a new lattice at the voltage level reached on the V-I characteristic during the pulse. In our experiment, the voltage reached instantaneous during the pulse was of the order of a microvolt corresponding to a velocity of $.45 \text{ mm/s} = 4.5 \times 10^6 \text{ \AA/sec}$ (see Chapter VII, Part II). If we consider that the fluxoid lattice spacing is about 900 angstroms at 2.2 KG the time for the lattice to move uniformly a distance equal to the lattice spacing is then of 200 microseconds. This value is an order of magnitude greater than the observed lower threshold for disorder (10 microseconds). That we did not quite reach flux flow during our experiment does not modify our conclusion since when there is no flux flow, we have even less chance to have a lattice renewal at an edge.

Now, we try to relate this time to what happens when defects are nucleated and move through the lattice. We have seen that defects propagate more rapidly in a fixed lattice than would the entire lattice without defects. We have, for a dipole:

$$V = \frac{2\pi\phi_0 y_s}{\eta b \ln(y_s/2r_0)} (J - J_c)$$

and for the lattice

$$V = \frac{\phi_0}{\eta} (J - J_c) .$$

If y_s is large enough--let us say more than $5b$ --the dipole moves more than 10 times faster than the uniform lattice translation. During the duration of the pulse time, they can overcome the barrier they were pinned by, and move further on. But the main effect may be that new defect sources can be activated and remain in a state where they can operate several seconds.

8.4 Pulse Repetition

We have found that the repetition of pulses resulted in greater effect than a single pulse: for example, a voltage response approximately 3 times greater (both transitory and permanent) has been found by pulsing 10 times for five milliseconds with 50 milliseconds interval between pulses than by pulsing one time for 100 milliseconds.

8.5 Pulse Shape

In view of the results obtained for pulse repetition, we expected to find a greater effect for short rise time pulses than for long rise time pulses. We thought that a greater disturbance in the vortex distribution would result from a sharper change of current and therefore have a greater effect on the voltage change--however, in our experiments, we found no such change.

The output of the General Radio pulse amplifier 1397-A is 1 ampere pulses with a rise time variable from 100 nanoseconds to 100 microseconds, and with a linear initial slope. For one millisecond pulses, we did not see a difference with a change of rise time from 100 nanoseconds to 100 microseconds. Only once did we see a difference: we were sending 5 milliseconds pulses, and observed a pronounced effect. When the pulse duration was set to 10 milliseconds, no effect was seen. Observing the signal shape, we saw that the 5 millisecond signal was rectangular, whereas the 10 millisecond pulse had a very slow decrease in a slope due to a saturation of the pulse amplifier (Figure 51a). But this result could not be repeated; we could send similar signals, and never did we again observe a difference.

We did the major part of our experiments by pulsing the reference level of the current feedback control system. As we said, this results in a rise time of about 100 microseconds, with roundings at the beginning and end of the pulse (Figure 51b). The rise time is independent of the pulse height or duration. We compared the results of both ways

Figure 51(a). Pulse shapes at the output of the pulse generator.
1397-A.

Figure 51(b). Pulse shape obtained by pulsing the reference level.

Figure 51(c). Filtered pulse.

of pulsing and found them identical.

By introducing a RC filter between the pulse generator and the feedback operational amplifier [(13) on Figure 20], we could alter the shape of the pulse passing through the crystal, and give to the raise and fall part of the pulse a smooth exponential shape as illustrated in Figure 51c. Here also, we found no effect due to the shape of the pulse. Due to limitations in the experimental system, it was not possible to make longer the raise and fall time for short pulses. We would expect for short pulses an increase in ΔV when a rise and fall time are a significant fraction of the time duration of the pulse maximum.

8.6 Recovery after Pulsing

Now we compare the evolution of the voltage in two cases:

- Case a: the current is raised slowly to a fixed current I_0 . A current pulse is applied to the crystal, raising the current passing through it to I_1 . The evolution of the voltage when the current has returned to I_0 after the pulse we call $V_a(t)$.

- Case b: the current is slowly swept up to I_1 , and then suddenly decreased to I_0 . The evolution of the voltage after this sharp decrease we call $V_b(t)$.

For long enough pulses, it appears that the two curves $V_a(t)$ and $V_b(t)$ are exactly the same.

We have done the experiment on the bent crystal with pulses sent through the current control system, which results in slightly rounded pulse contours. As can be seen on Figure 52, the recovery curves, $V_a(t)$ after 100 msec pulses and $V_b(t)$ after a sharp reduction in current are exactly the same, but it is also seen that the curve corresponding to 10 msec pulses has to be translated 5 seconds on the time axis to superimpose on the 100 msec curve. This leads us to think that the 100 millisecond pulses create a state of higher disorder, and therefore the FLL needs a longer time to recover. The state of the crystal 7 seconds

Figure 52. Effect of pulses and recovery after a sharp current change.

after the 100 millisecond pulses is the same as that 2 seconds after the 10 milliseconds pulse. The subsequent response curves are identical in the two cases. This is another observation that supports the previous assertion that a given V-I point represents a unique state of the FLL. If the conditions imposed after such a point are the same, the V or I evolution is the same even if the previous paths to that V-I point are different.

8.7 Pulsing the Cooled-in-the-Field Lattice

When the cooled-in-the-field FLL formed at high field is pulsed, a permanently higher voltage results presumably because a higher disorder is created. When the pulses are high enough, which means a current during the pulse of approximately 25 amperes, the voltage after the pulse recovery approximately corresponds to the major down curve at the steady current level.

8.8 Field Disturbing Wire

Before describing these experiments, we have to point out some of the important results concerning the theory of the equilibrium of vortex lines. When no transport current flows through the crystal, and a field steady but varying in space is imposed, the vortex configuration will eventually be in equilibrium, even if pinning is absent. Only when the field is changed with time, is there a transient force which can result in vortex motion; if the field is steady again, the vortex distribution tends rapidly to an equilibrium. This behavior is different from the behavior when we set a transport current across the crystal; then, as we already saw in Chapter I, a steady Lorentz force on the vortex array results.

By imposing an additional field, which we could vary with time, we could examine several points of interest which are: the pinning in the new equilibrium resulting from a different field distribution, the

recovery after a change in the field distribution occurs, and the influence of disturbing the lattice at the place where the vortex lines nucleate in the flux flow condition.

A current of 20 amperes through the crystal results in a change of field of about 7 gauss from one edge of the crystal to the other. For a linear wire, the field created, at a distance r from it has the value: $B = \frac{2I}{r}$ with B in gauss, I in amperes and r in centimeters. So a current of 3.5 amperes through the wire, in close proximity to the crystal, is enough to produce a change of field at the edge of the crystal approximately equal to that due to the passage of a current of 10 amperes through the crystal itself. Since the magnetic field of a wire varies as $\frac{1}{r}$, the strongest perturbation of the flux line lattice is close to the wire--so, in our case, the perturbation was mainly localised close to an edge of the crystal. By making this edge the place where vortex lines nucleate or not by changing the direction of the Lorentz force, we could see if introducing a disorder at the nucleation site was a major factor in the voltage evolution. Figure 53 indicates the geometry of the experimental arrangement.

We compared the hysteresis loops with and without a current through the field disturbing wire. We fixed the current in the wire and changed the direction of the current through the crystal, thereby changing the edge at which vortices nucleated. Although no major difference was found, the V-I curves did not exactly superimpose. The up curves were shifted to slightly higher current levels (approximately .1 ampere) when the nucleation region was far from the wire. The fact that no large increase occurs argues against a uniformly translating FLL in the hysteretic part of the current-voltage characteristic as defect sources, created in the nucleation part, should be more active than those created in the destruction, since the latter are rapidly purged from the crystal. However, we did introduce an unbalanced force in the vortex lattice as we modified its configuration by changing the applied field distribution.

Figure 53. Geometrical configuration of the disturbing field.

This extra, transient, force may outweigh any possible effects of changing the nucleation site.

We found a large voltage increase followed by recovery after the current was switched on or off in the perturbing field wire (corresponding now to a temporary additional force on the lattice). The experiment was done under the conditions described in Figure 52. The voltage evolution curves were similar for both directions of transport current. These recovery curves obtained are identical to those obtained by sending a pulse of 10 milliseconds. So, with another way of perturbing, we arrived at the same recovery curves. This again seems to confirm that the subsequent evolution of a state defined by a point on the V-I diagram is independent of its prior history.

We also switched the current in the perturbing wire on and off when the transport current was in the flux flow region. There was no reaction. From this we may conclude that the recovery is due to the overcome of barriers which no longer exist when the entire lattice moves.

CHAPTER IX

A FLUX MOTION MEMORY SWITCH

When the V-I characteristic of a device is multivalued, it is reasonable to assume that a switching mechanism can be found. It should be possible to switch between the two voltage levels corresponding to the same current by a perturbation.

As we have seen, it is possible with a pulse to cause a degradation of the lattice, and thereby permanently raise the voltage from a low value (which can be zero) to some higher value. The switching back to a lower value must be accomplished by producing a more perfect lattice, which can be done in two different ways. We can raise the current up to the flux flow region and then lower it very slowly to the desired level, the voltage level then corresponding to some point on major down curve. Alternately, we can form another flux line lattice, by raising the crystal temperature above T_c and cooling it in the field. The second way is much faster, and for high enough fields close to H_{c2} gives rise to a large difference in voltage level between on and off states. The switching may occur between a zero and a non-zero value, which in terms of technology is a favorable point. Figure 54 indicates this switching schematically.

Once we are in the upper level corresponding to a degraded state of the vortex lattice and attempt to switch to the higher state, the lattice can only degrade more resulting in a higher level. Switching to the lower state can result in a zero voltage output (since an entirely new lattice is formed). There consequently is no problem of degradation of the level difference due to repeated switching, as there is with the amorphous semiconductor memory switches.

9.1 Principles of the Switching

We were interested in having a system with which fast switching could be realised in both directions: disordering by pulsing--which is

Figure 54. Principle of the switching, on the V-I diagram.
H = 2.6, cooled in the field lattice.

fast, and cooling in the field--which, with the technique of using a resistor and a plastic sheath, is relatively slow.

To improve the speed of the heating-cooling process, the best approach is to heat the crystal itself. This we realised by placing a resistor in thermal contact with the crystal and in series with it (we think that actually our resistor was a bad spotweld of the current lead to the crystal). When the current is raised, the crystal temperature is increased. For a certain current passing through the crystal, the critical temperature is reached: the crystal becomes normal. Then, the current is decreased, the temperature lowers, and new, more ordered, lattice is formed and the resulting voltage is zero at the measuring current, if this current has been appropriately chosen. The speed of this switching process is limited only by the time necessary to heat and cool the crystal (the time required for the lattice to nucleate is extremely small). We found that passing a 100 milliseconds, 20 amperes pulse was sufficient to cause switching.

Figure 55 indicates the V-I characteristic of the crystal with a resistor in series. The thermal transition to normal was at about 13 amperes. A curious dip is observed just before the transition. This dip is also found at zero field. We think that it is due to a temperature difference between the contacts in the voltage measurement loop.

So, two different and opposed results are obtained, depending on the magnitude of the pulses: for high and long enough pulses, the critical temperature is overcome and a new, presumably more perfect flux line lattice results, for smaller ones, a disordering of the lattice occurs. For pulses of large enough amplitude, it is sufficient to change the pulse duration to pass from one class to the other, and for pulses of the same duration, it is sufficient to change the pulse height. Figure 56 summarises the results obtained for a field of 2.61 KG.

Figure 55. Characteristic of the crystal in contact with a series resistor.

Figure 56. Example of switching results.

On Figure 57, we give the results of a systematic study of the measured voltage change on switching for different (steady) current levels and magnetic fields, using 7 amperes, 10 and 100 millisecond pulses. As discussed in Chapter VIII, the switching levels are independent of the exact pulse shape (as long as we stay in the same order of magnitude). The highest voltage change, 7 microvolts, is seen to be for 10 amperes and a field of 2.62 KG.

We point out that the shape and pinning properties of the crystal, and the heating resistor were not designed with the goal of achieving a switching device. It should be possible, by using a much smaller superconducting medium and enhancing the pinning, to have both a much faster system and a much larger voltage difference.

9.2 Cooling While Current Is Passing

We compare the processes shown in Figure 58: A) The crystal is cooled in the field, then the current is increased. At I_1 , a non-zero voltage appears and then, the voltage increases rapidly. B) The crystal is cooled in the field and the current is increased. At a current I_1' , above or below I_1 , the crystal is again warmed up and cooled in the field. If the current is increased further the voltage remains zero until much higher current I_2 is reached, which can be of the order of 1.5 times I_1 .

Another way of producing this effect (which can result in a current switching) is to do a constant voltage experiment: the voltage is set to be V_0 , the current in turn must increase to I_1 . If then we form new lattice at I_1 by heating and then cooling in the field, while attempting to maintain the voltage at V_0 , the following sequence of events is seen to occur:

a) During the formation of the new lattice, as this process is fast and the response of the system very slow, the current level does not change (the response time of the Keithley nanovoltmeter is about 3 seconds).

Figure 57. Voltage levels of the switch as a function of current and field (kOe). 10 ms pulses $\rightarrow$ on. 100 ms pulses $\rightarrow$ off.

Figure 58. Effects of cooling while current is passing.

b) The voltage drops to zero.

c) The voltage is restored to V_0 by the feedback mechanism, which increases the current to I_2 .

A small pulse into the flux flow region would decrease the current corresponding to V_0 , presumably by disordering the lattice. This effect is not understood by us at the present time. If we try to explain the curved region behavior in terms of defect creation and motion, we do not see why a lattice formed while current is flowing would have a lower density of defects.

SUMMARY

We investigated the shape of the V-I hysteresis curves when the current was swept up and down. For Good's crystal, at 2.2 KOe he found that the hysteresis narrowed as the sweep rate decreased and the ascending curve was below the descending one. For the same field history we found that the hysteresis widened when the sweep rate was decreased and the ascending curve was above the descending curve. We extended the conditions of the experiment by nucleating the vortex lattice by cooling the crystal with field set. At fields below 2.5 KG the pinning strength of the flux line lattice formed by cooling in the field was lower than that of lattices formed by changing the field as evidenced by the higher ascending curve for cooled-in-the-field flux line lattice, whereas at fields close to H_{c2} the reverse is true. At these high fields all ascending curves are lower than the descending curves.

A given point in the V-I plane appears to represent a unique state of the flux line lattice. Regardless of the path by which that point is reached, the subsequent $V(t)$ in response to a given $I(t)$ is always the same.

Voltage recoveries at constant current and current recoveries at constant voltage are always towards the V-I curve obtained by sweeping the current down at slow rate, regardless of which side of the curve the initial V-I point lies. The major down curve therefore appears to represent the steady state flux line lattice structure, although that steady state cannot be reached from most points in the V-I plane in experimental times. The rates of both voltage and current changes ($\frac{\partial \Delta I}{\partial \log t}$ and $\frac{\Delta V}{\Delta t}$) were approximately constant in the α region of the current where the voltage on the major down curve was zero. These rates decreased sharply for currents above this region.

Current pulses of duration less than 10 microseconds close to or into the flux flow region did not induce persistent changes in voltage

at a constant measuring current, but longer ones always resulted in an increased voltage which then decayed to a voltage either below or above the initial voltage, depending on the current and field history. This result indicates that the pinning and/or the strength of the flux line lattice is always degraded by a current excursion into the flux flow regime. A change in the rise time of the pulses had no influence on the results. Repeating short pulses however was seen to be more effective in increasing the voltage than sending one long one.

Since for a steady current of an appropriate value passing through the crystal, current pulses resulted in an increase of the voltage and cooling the lattice in an appropriate field resulted in zero voltage, we found that it was possible to switch between a zero voltage level and a voltage of about 10 microvolts simply by adjusting the pulse height or width, warming the crystal being accomplished by the pulse current through a series resistor in contact with it. Passing a current when the vortex lattice was formed by cooling the crystal in the field increased the critical current by a factor of about 1.5.

These results have been analysed in terms of the simple model proposed by Good and Kramer where the voltage changes in the hysteresis regions are due solely to increasing or decreasing numbers of moving defects. Trying to explain all our results in terms of the creation and movement of defects leads in many cases to a qualitative agreement with this model. Important points are however in serious disagreement. Chief among these are the field variation of the strength of flux line lattices created under various nucleation conditions, the very short time necessary to degrade the flux line lattice strength in flux flow, and the enhancement of the critical current when the flux line lattice is formed by cooling in the field in the presence of a transport current.

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