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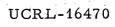
## Title

PROPAGATION OF MIXED STATE PHASE BOUNDARY IN TYPE-II SUPERCONDUCTOR

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# Ernest O. Lawrence Radiation Laboratory

PROPAGATION OF MIXED STATE PHASE BOUNDARY IN TYPE-II SUPERCONDUCTOR

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## PROPAGATION OF MIXED STATE PHASE BOUNDARY IN TYPE-II SUPERCONDUCTOR

R. G. Boyd

October 1965

#### PROPAGATION OF MIXED STATE PHASE BOUNDARY

#### IN TYPE-II SUPERCONDUCTOR

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#### October 1965

Recently R. B. Flippen<sup>1</sup> reported some measurements on the velocity of magnetic field penetration of thick-walled cylindrical type-II superconductors. In this letter we derive an expression for the velocity in thick slabs.

Consider a semi-infinite solid extending in the positive x-direction with its surface at x = 0. We turn on at t = 0 an external magnetic field  $\circ$ H parallel to the surface, with constant sweep rate H. Flux initially penetrates at a field which we shall consider to be negligibly low, and thereafter the mixed state phase boundary propagates to the right with some velocity v. We shall assume that the external field H is less than  $H_{c2}$  during the time region of interest, to avoid the appearance of a normal phase chasing the mixed state phase.

As in the type-I superconductor case,<sup>2</sup> the motion of the phase boundary is controlled by eddy currents in the part of the metal which is penetrated by flux. We shall assume that the relation between current J and electric field E given by Kim et al.<sup>3</sup> is obeyed:

 $J = J_{c} + (H_{c2}E)/(\rho H).$  (1)

This relation fails to hold when J or H are too large, but the limits of applicability must at present be established experimentally for each specimen. In general, it holds over the widest range in H if  $T/T_c \ll 1$ ,

 $H_{cl} \approx 0$ , and the  $H_{c2}$  of the specimen is not paramagnetically limited. The limitation on current is still an unknown quantity.

Introducing the vector potential A, we get from Maxwell's equations in our one-dimensional case

$$\frac{d^2 A}{dx^2} = \frac{4\pi}{c} \left[ -J_c + \frac{H_c 2}{\rho c} \frac{dA/dt}{dA/dx} \right].$$
(2)

To make the problem tractable, we assume that the resistive critical current  $J_c$  is constant, as in the naive form of the Bean model.<sup>4</sup>

The equation is non-linear, but has a simple wave solution. If we assume A = A(x-vt), then we find

$$H = -\frac{4\pi}{c} \left( J_{c} + \frac{H_{c2}v}{\rho c} \right) (x-vt).$$
 (3)

The magnetic field is linear in x and translates to the right with velocity v. The current is uniform throughout the mixed state region. When  $H_{cl}$  is not negligible however (as at the phase boundary itself), then physical intuition suggests the presence at the phase boundary of a "surface current" of order of magnitude  $(cH_{cl})/(4\pi)$ .

If 
$$J_c = 0$$
, ther

$$v^{2} = \frac{\rho c^{2}}{4\pi H_{c2}} \stackrel{\circ}{H}, \qquad (4)$$

whereas if J is large, then

$$\mathbf{v} = \frac{cH}{4\pi J} \cdot (5)$$

Since the resistivity appears only in the ratio  $\rho/H_{c2}$ , the velocity v is independent of resistivity in the dirty limit, in contrast to propagation velocities in normal metal where v  $\propto \rho$ .

No detailed comparison between our results and Flippen's data is possible. We have been unable to solve the equivalent equations for a thick walled cylinder. Furthermore, in his specimen of Nb we cannot

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consider  $H_{cl}$  to be negligible, nor can we assume that only the mixed state phase is present, since it appears that the external field may have exceeded  $H_{c2}$  before the wave front reached the interior of his cylinder. Nevertheless, our expression for v gives the correct order of magnitude for Flippen's results on Nb 25% Zr, and we have accounted for the fact that phase velocities in his experiment on Nb depended only weakly on resistivity.

We suggest that subsequent experiments be performed on thin-walled cylinders of substances with negligible pinning and with  $H_{c2} \gg H_{c1}$ .

This work was supported under the auspices of the United States Atomic Energy Commission.

## FOOTNOTES

- 1. R. B. Flippen, Phys. Letters <u>17</u>, 193 (1965).
- 2. A. B. Pippard, Phil. Mag. <u>41</u>, 243 (1950).
- Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. <u>139</u>, Al163 (1965).

4. C. P. Bean, Rev. Mod. Phys. <u>36</u>, 31 (1964).

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