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A comparison between a two-material and three-material magnetic current limiter

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This paper investigates the inductance versus current characteristics of a two-material and a three-material magnetic current limiter. The two-material device consists of a NdFeB permanent magnet, a high saturation flux density magnetic material, and a high saturation flux density magnetic pole piece placed on both sides of the magnet. The three-material device consists of a NdFeB permanent magnet, a high saturation flux density magnetic material, and a low saturation flux density material. Finite-element results for the three-material device agree with the results obtained using design equations. In contrast, the results obtained for the two-material device show that the transition current is overestimated and that the ratio of the maximum safe current and transition current, as well as the unsaturated inductance is underestimated. Extending the magnet beyond the adjoining surfaces improves the sharpness of the transition characteristics when the ratio of the core length to the core width is large. © *1998 American Institute of Physics.* [S0021-8979(98)16211-4]

I. INTRODUCTION

Power systems especially in city centers are becoming increasingly interconnected in an effort to increase the reliability of the electric supply. This increasing interconnectivity results in raised short circuit levels, which traditional circuit breakers are straining to limit. A number of current limiting approaches such as tuned impedances, switched impedances, superconductors, series arc devices, and thermistorlike devices have been proposed in the past to address this problem.[1,2] Unfortunately, these approaches all have reliability problems. Recently, a passive current limiting device consisting of three magnetic materials was proposed.[3] The device should be reliable but would be expensive to produce. Two of these devices connected in series and in magnetic opposition to each other would provide bipolar current limiting.

This paper proposes two simplified structures, which address the concern over cost. The inductance versus current characteristic of each device is investigated. Finally, the optimal two-material and three-material device designs are compared.

II. SIMPLIFIED CURRENT LIMITER CONFIGURATIONS

The structure shown in Fig. 1(a) consists of a NdFeB permanent magnet sandwiched between the central pole faces of two high permeability, high saturation, flux density grain oriented E cores. The enlarged core section on either side of the magnet is designed to confine the magnet's flux to the central core area. Most of this core section can be designed to operate out of saturation by choosing its height to be greater than a specified minimum value. The core sections with the reduced area have a coil wrapped around them. Core saturation exists when no coil current is applied. An unsaturated condition occurs if the coil current exceeds a critical value.

The second structure shown in Fig. 1(b) consists of two high permeability, high saturation, flux density C cores placed pole to pole. An additional structure consisting of an extended NdFeB permanent magnet sandwiched between two equally sized blocks of low saturation, flux density moderate permeability materials is centrally placed between the two C cores and has a coil wrapped around it.

III. DESIGN CRITERIA AND ASSUMPTIONS

The major design criteria for a current limiter are shown in Fig. 2. The objective is to maximize the ratio between the unsaturated (L_{unsat}) and saturated (L_{sat}) inductance subject to cost constraints, to extend the current range over which the unsaturated inductance value is maintained, and to maintain a uniform flux distribution in the saturated region. A uniform distribution provides a sharper transition region, at I_{knee}, between the saturated and unsaturated state.

The magnetic devices are assumed to be infinitely long in the z direction so as to allow a comparison between the two $2d$ devices and to minimize the effects of leakage flux in the z direction. The inductance versus current characteristics

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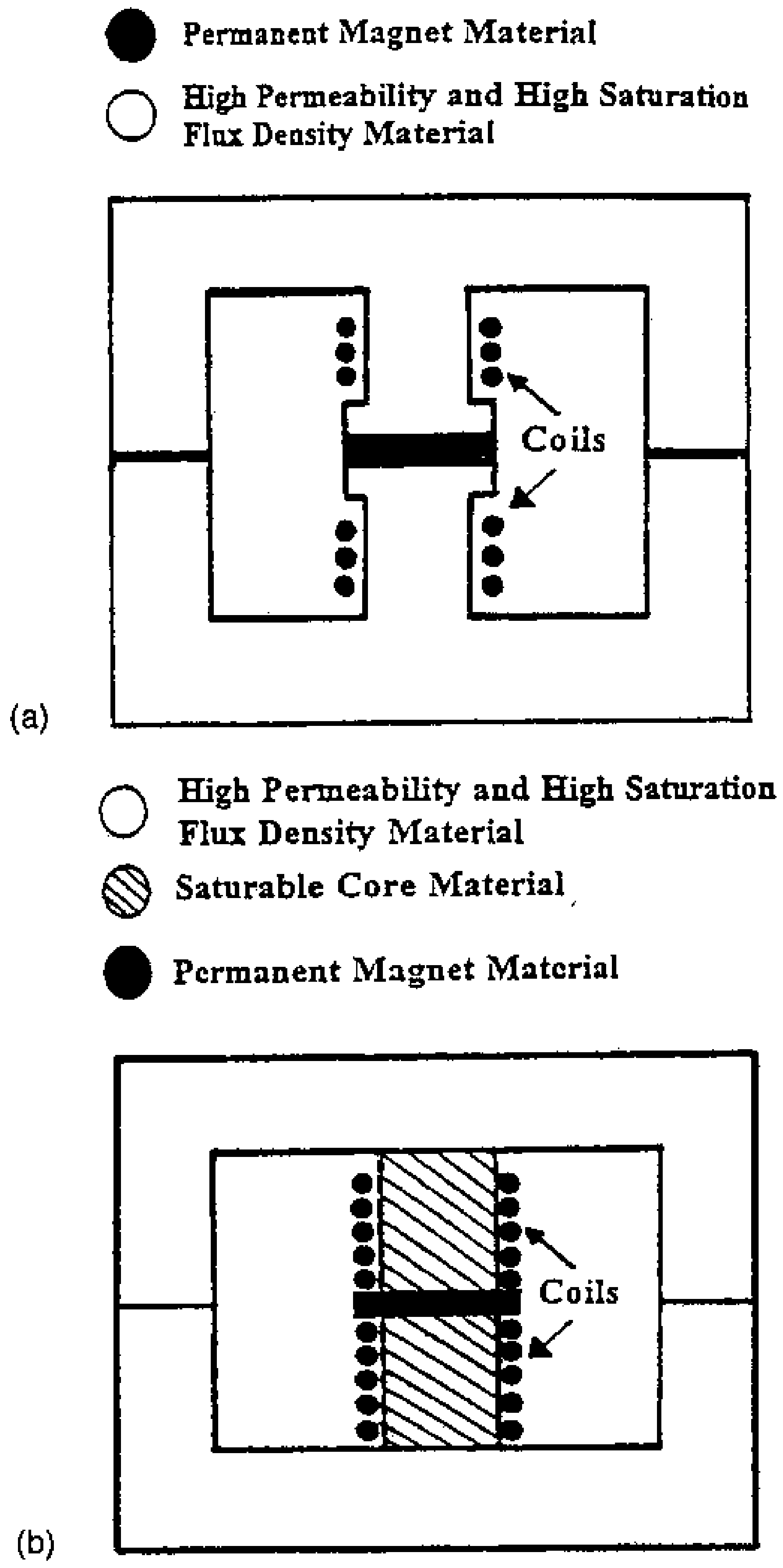

FIG. 1. Unipolar current limiters: (a) two material and (b) three material.

are obtained using Infolytica's MAGNET 5.2 finite-element analysis software package.

The two-material and three-material designs are based on the following specifications and the design equations.[4] Functional: knee current $I_{\mathrm{knee}}=50$ A, $I_{\max}/I_{\mathrm{knee}}=2.1$, $L_{\mathrm{unsat}}=14$ mH, and number of turns $N=100$. Magnet parameters: remnant flux density $B_m=1.144$ T, recoil line slope $u_m=1.1$, and magnet length $l_{\mathrm{mag}}=1$ cm. Central core parameters: $B_c^* A_{\mathrm{core}}/A_{\mathrm{mag}}=0.4$ T where B_c represents the saturation flux density of the saturable core material and A_{core} is the saturable core area. A_{mag} represents the magnet area for the two-material device and is equal to A_{core} for the three-material device. (Note: selecting a value higher/lower than 0.4 T results in a higher/lower $I_{\max}/I_{\mathrm{knee}}$ ratio but a larger/smaller magnet volume.) The choice of 0.4 T, approximately half of B_m, is a compromise. B_c for the two-material design is 1.77 T (i.e., TR66 core material). B_c for the three-material design is 0.4 T.

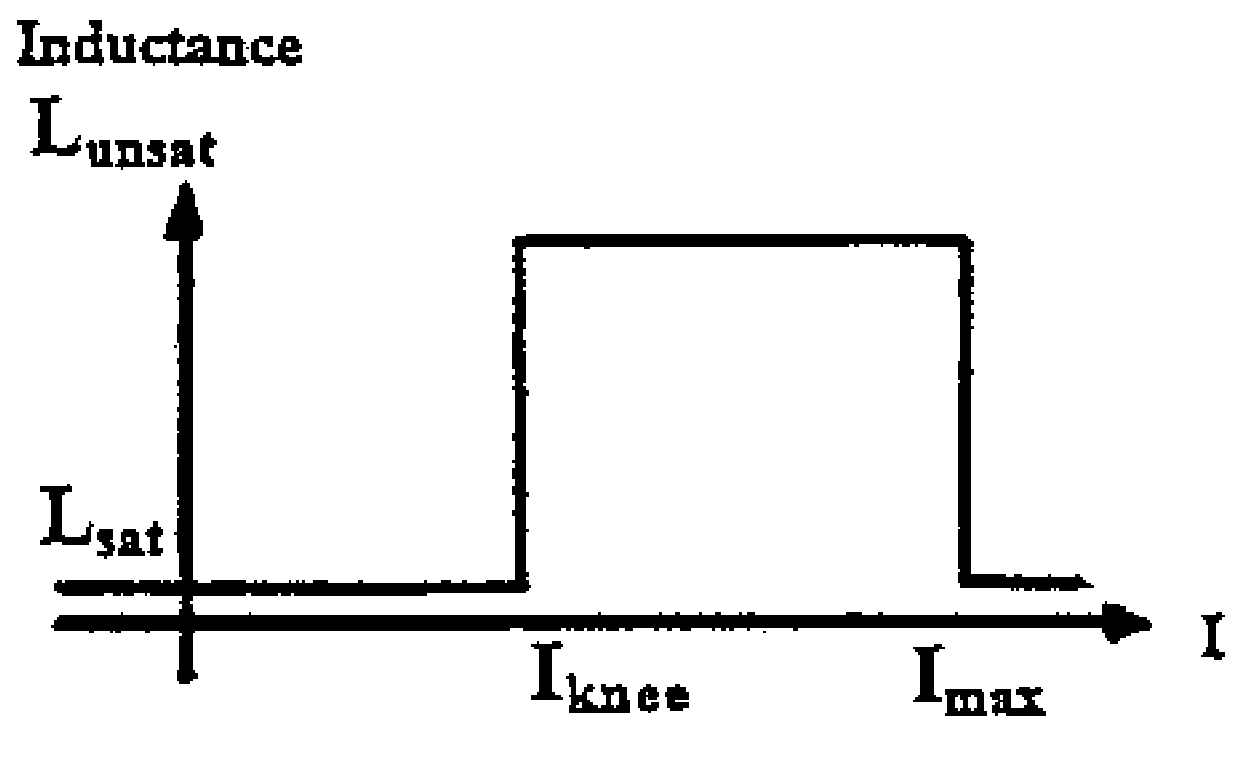

FIG. 2. Design criteria for a magnetic current limiter.

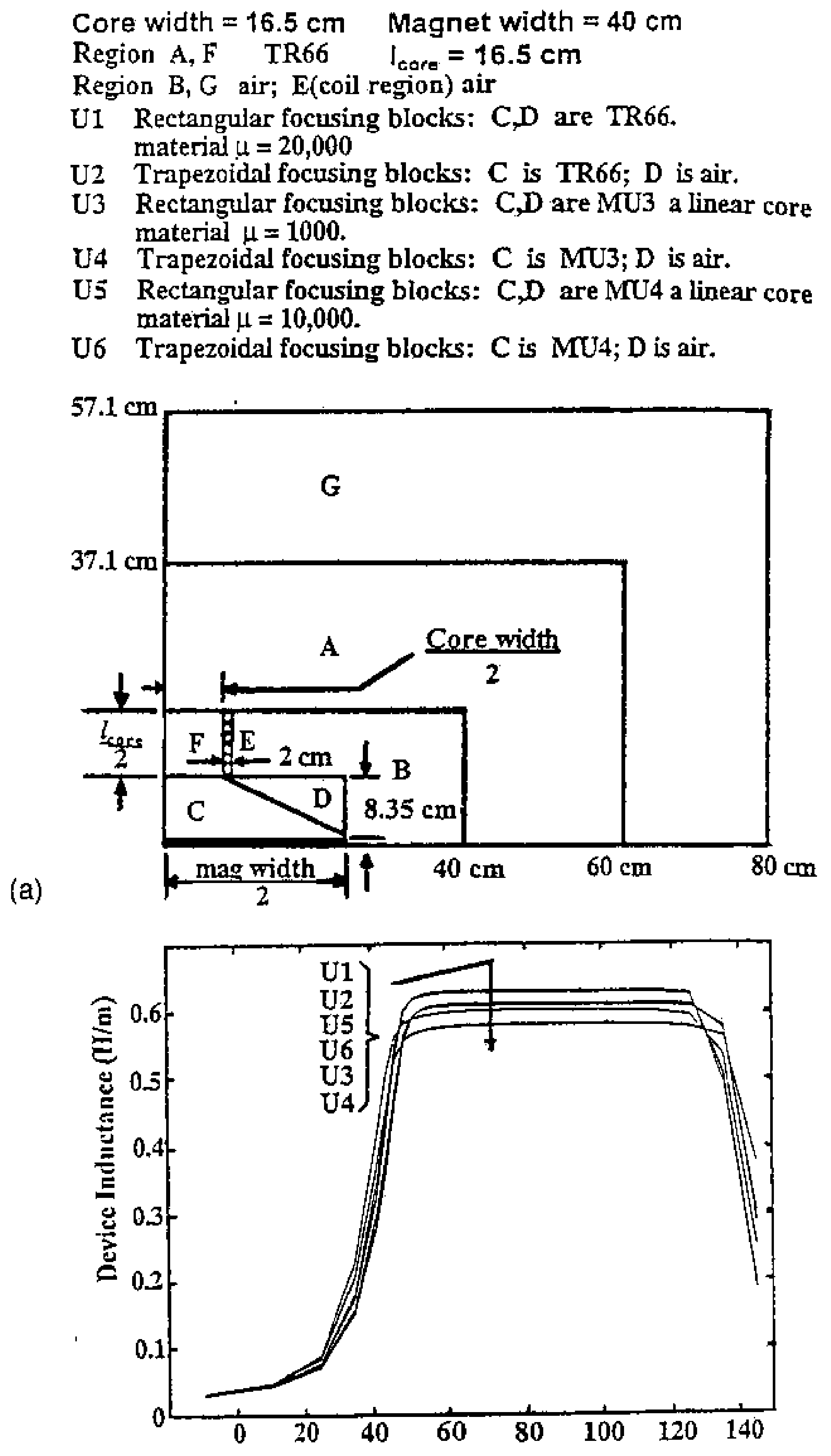
Core width = 16.5 cm Magnet width = 40 cm
Region A, F TR66 l_{core} = 16.5 cm
Region B, G air; E(coil region) air
U1 Rectangular focusing blocks: C,D are TR66. material μ = 20,000
U2 Trapezoidal focusing blocks: C is TR66; D is air.
U3 Rectangular focusing blocks: C,D are MU3 a linear core material μ = 1000.
U4 Trapezoidal focusing blocks: C is MU3; D is air.
U5 Rectangular focusing blocks: C,D are MU4 a linear core material μ = 10,000.
U6 Trapezoidal focusing blocks: C is MU4; D is air.

FIG. 3. Two-material current limiter; (a) geometry of one quarter of the device, and (b) inductance vs current characteristics.

IV. SIMULATED INDUCTANCE VERSUS CURRENT CHARACTERISTICS

A. Two-material device

Figure 3(a) shows one quarter of the device and the tests which were performed. The purpose of these tests was to investigate the effect of the core pole face material and shape on the inductance versus current profile. Figure 3(b) shows the finite-element results for the inductance versus current characteristics. A larger leakage flux is observed with the higher permeability material, therefore, L_{unsat} is high. Tapering of the extended area section reduces the leakage flux, thus lowering the unsaturated inductance. Low permeability material does not contain the magnet flux very well. There-

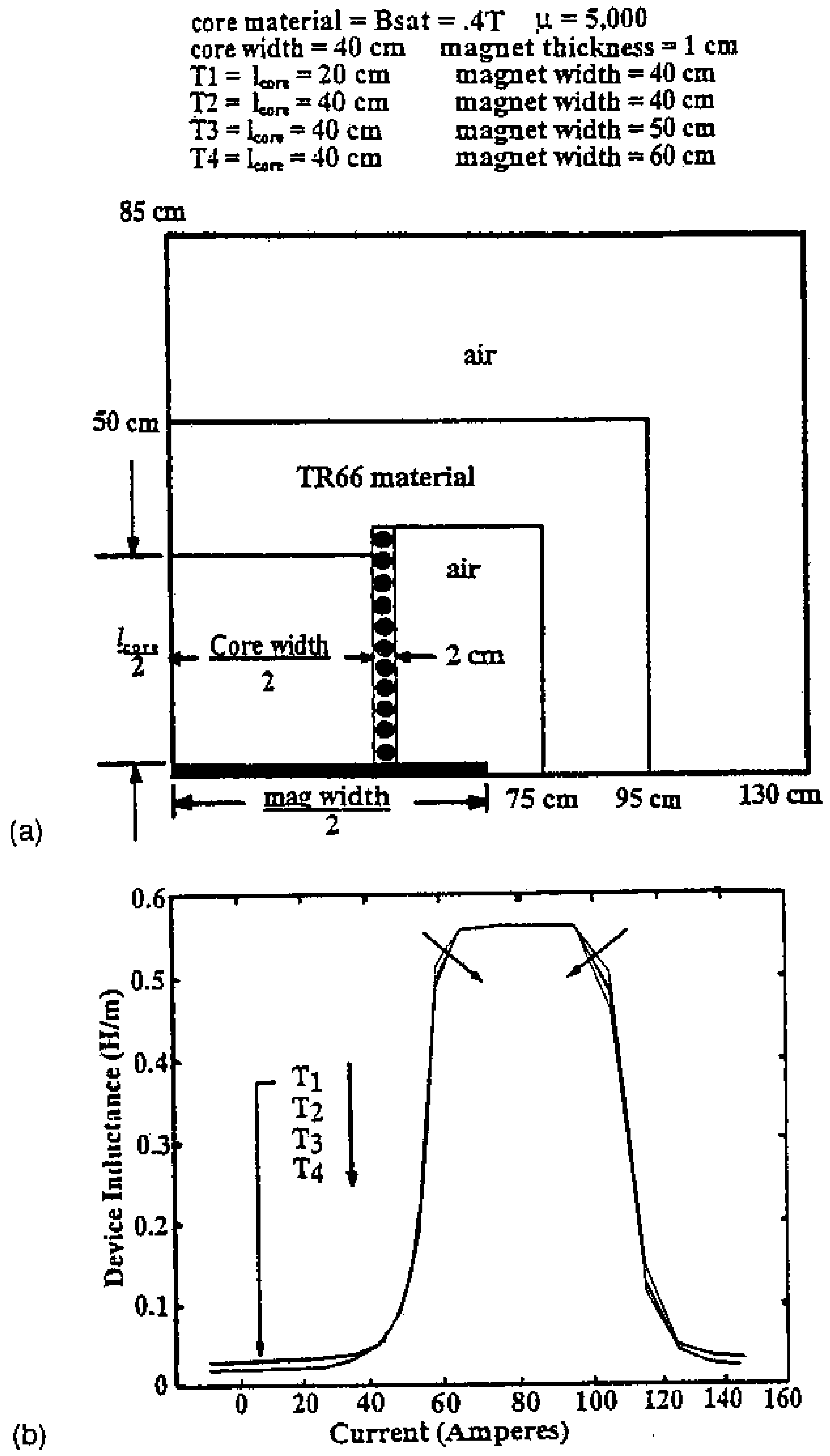

FIG. 4. Three-material current limiter: (a) geometry of one quarter of the device, and (b) inductance vs current characteristics.

fore, the saturated-to-unsaturated transition occurs at a lower knee current and is less well defined. The ratio $I_{\max}/I_{\mathrm{knee}}$ increases due to the reduced flux confinement.

B. Three-material device

Figure 4(a) shows one quarter of the device and the tests which were performed. The purpose of these tests was to determine the effect of the core length and magnet extension on the inductance versus current profile. Figure 4(b) shows the finite-element results for the inductance versus current characteristics. The core length influences only the saturated inductance value. The magnet extension improves the sharpness of the transition from the saturated to the unsaturated state, especially if the core length to core width ratio is large.

C. Comparison of the two-material and three-material current limiter

Both devices were designed according to the specifications in Sec. III and the stipulation that $L_{\mathrm{unsat}}/L_{\mathrm{sat}} = 40$. TR66 material is used for the *E* core on the two-material device. The extended area section is trapezoidal in shape so as to reduce the leakage inductance. This improves the sharpness of the transition at I_{knee} and increases the $L_{\mathrm{unsat}}/L_{\mathrm{sat}}$ ratio.

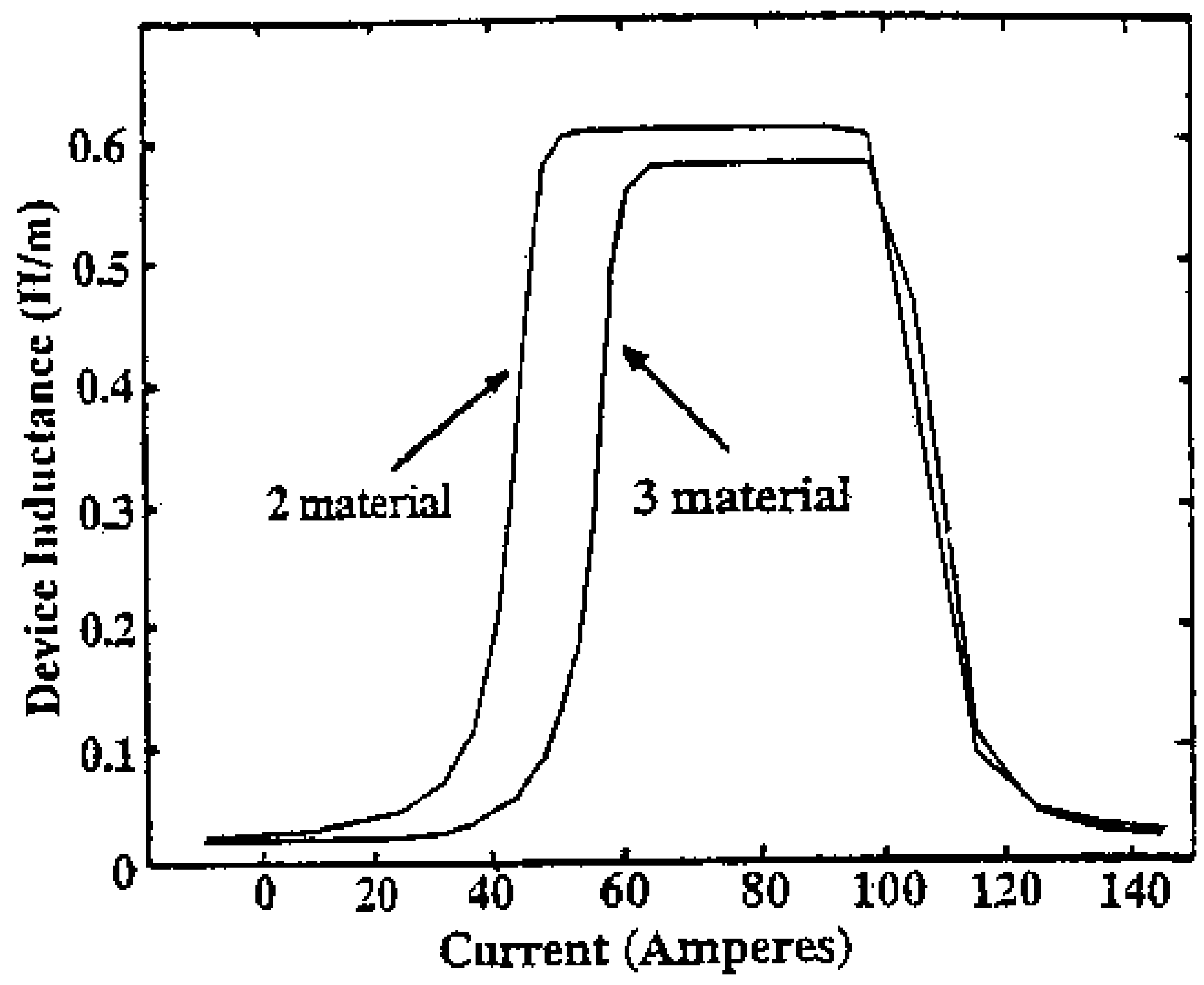

FIG. 5. Comparison of a two-material and three-material inductance vs current characteristics.

The width and thickness of the magnet in contact with the core material for both designs is 40 and 1 cm, respectively. In the three-material case, the magnet extends an additional 5 cm away from the outside surface of the core material. The core length and core width are 40 cm for the three-material device and 10 cm for the two-material device. The height of the extended area sections for the two-material device is 29 cm.

Figure 5 shows the inductance versus current characteristics for the two-material and three-material device. The results of the design equations for the three-material device are in agreement with finite-element results shown in Fig. 5. In contrast, the results of the design equations for the two-material device show that I_{knee} is overestimated, the ratio $I_{\max}/I_{\mathrm{knee}}$ is underestimated, and L_{unsat} is underestimated. Also, the transition characteristic for the two-material device is poorly defined. Thus, under normal ac operating conditions, the flux density in the core of the two-material device cycles between an unsaturated value and a saturated value. This results in a large minor hysterisis loop area, and consequently, high operating losses.

V. CONCLUSIONS

Finite-element results for the three-material current limiting device agree with the results obtained using design equations. In contrast, the results obtained for the two-material current limiting device show that the transition current is overestimated, and that the ratio of the maximum safe current, and the transition current, as well as the unsaturated inductance are underestimated. Extending the magnet beyond the adjoining surfaces improves the sharpness of the transition characteristics when the ratio of the core length to the core width is large.

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