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THE EFFECT OF NON-ADIABATICITY OF ALPHA PARTICLES IN THE AXISYMMETRIC CUSP TMR

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July 20, 1981

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Abstract

One of the end plug configurations we have investigated for use in a tandem mirror reactor is the axisymmetric cusp. We show that because of non-adiabaticity, the containment of 3.5 MeV alpha particles in this configuration is insufficient for the attainment of acceptable plasma performance.

1. Introduction

The axisymmetric cusp TMR study has progressed through the following steps: EFFI magnet design and MHD stability analysis, structural design of the end plug region including the inner coil cantilever[1], addition of plasma currents to the EFFI magnet design, and reassessment of MHD stability, alpha adiabaticity analysis, and performance analysis as a function of alpha adiabaticity. In this report we show that alpha adiabaticity is insufficient for this cusp configuration. (A modified cusp configuration which eliminates the central cell field null is being considered for an axisymmetric version of the TMX experiment and might extrapolate to a reactor.[2] We do not look at that possibility in this report.)

2. The Magnet Design

Figure 1 shows the EFFI magnet design for the axisymmetric cusp TMR. The field strengths produced were 1.6 T in the central cell, 9 T at the plug mirrors, and 2.5 T at the plug midplane. The trim coils centered around the plug midplane were used to maximize MHD stability and to make it the same on field lines 1 and 2. The locations of some of the trim coils (especially the end ones) are incompatible with the requirements for beam injection and neutron shielding. We have assumed that this incompatibility can be eliminated through iterative coil design and MHD stability assessment.

The MHD stability results are shown on Fig. 2. Note the maximum β values of $\beta_c \simeq 0.8$ and $\beta_p \simeq 0.2$. We added imaginary coils as shown in Fig. 3 with appropriate currents to simulate a $\beta_c = 0.8$ plasma. Another stability calculation including the plasma currents gave almost the same β limits.

We originally assumed that the maximum conductor field strength would not exceed 11 or 12 T for this design, i.e., a magnet efficiency of 9/12 to 9/11, or 75-82%. Such a maximum is consistent with the use of niobium-tin superconductor. The assumption proved to be valid for all except the small radius coil nearest the central cell--that coil has a 14.5 T maximum conductor field. We have assumed that we can lower this field to 11 or 12 T by modifying this coil (longer and thinner cross section, smaller radius).

3. Plasma Performance with 100% Alpha Containment

A version of the Boghosian/Campbell "second-generation" code[1] was used to predict the plasma performance of the axisymmetric cusp TMR with the assumption of 100% alpha particle containment. A short table of results is shown in Fig. 4. Note that the assumed magnet parameters are not exactly consistent with the magnet design--plug β and B are 0.4 and 1.6 T instead of 0.25 and 2.5 T. The Q is an attractive 15.4, but the first wall loading is only 0.7 MW/m^2 (the central cell is large-diameter and low-pressure). A parameter set like this might be acceptable if we really had 100% alpha particle confinement. Unfortunately, we don't.

4. Adiabaticity of Alphas

We have analyzed the adiabaticity of 3.5 MeV alpha particles in the axisymmetric cusp TMR. The magnetic field geometry used for the adiabaticity analysis was that described in the Magnet Design section, including the finite β plasma currents. Near the axis of the central cell the alphas are non-adiabatic because of low magnetic field strength and sharp curvature of the field lines.

The details of the adiabaticity analysis are given in the Appendix. For the magnetic field strengths discussed in the Magnet Design section and β_c = 0.8, the overall fraction of alphas contained is only 6 to 9%. We also investigated a higher field case where we increased all of the vacuum magnetic field strengths by the factor of 15/11 and reduced β_c to 0.43 to maintain the same plasma pressure and radius. This scaling of field strength and β_c should preserve MHD stability. The reason for choosing the factor of 15/11 was that if we redesigned the original system so that its maximum conductor field was 11 T, then increasing all of the coil currents by the factor of 15/11 will raise all the fields by that factor and will result in a 15 T maximum conductor field. We take 15 T as a (rather arbitrary) goal for advanced superconductor. For this high field case we found that the overall fraction of alphas contained is 30-37%.

5. Plasma Performance with Reduced Alpha Containment

We have used the Boghosian/Campbell second-generation code to predict the TMR plasma performance as a function of f_α, the overall fraction of alphas contained. We did the performance calculation in two different ways: (1) we forced central cell ignition at the reduced levels of alpha heating by requiring a higher central cell ion-confining potential, ϕ_c; and (2) we held ϕ_c constant and specified that the "missing" alpha heating be replaced by some auxiliary external means. In both cases we calculated Q, the fusion power divided by the total externally-supplied plasma input power. The results are shown in Figs. 5 (low field case) and 6 (high field case). The Method 1 (ϕ_c increase) results are quite attractive: central cell ignition can be maintained with little or no penalty in Q. However, we doubt that these calculated results can be achieved in reality. (The code is zero-dimensional and does not distinguish between radial regions with alpha particle heating and those without.) The adiabaticity analysis (see Appendix) has shown that out to some plasma radius, essentially all of the alphas are non-adiabatic while beyond that radius they are all adiabatic. Thus, with an increased ϕ_c, we will have too much heating in the outer shell of plasma and none at all in the center.

Radial diffusion of the plasma is much too small to heat the center. Synchrotron radiation from the hotter outer electrons transfers some heat to the central electrons, but at a low rate because of the reabsorption in the hot plasma. The intensity of synchrotron radiation at the boundary between hot and cold plasma is less than 1 kW/m^2, much less than the missing $\sim$ 1 MW/m of alpha power per unit of length. Approximately 2 kW/m^2 flows into the center by thermal conduction, but this is also insignificant. It appears, therefore, that the classical methods of heat transfer are inadequate here, and unless some other method (such as local turbulent mixing) is found, the center will remain unheated. Thus, we do not believe that the Method 1 results can be obtained.

The Method 2 (external auxiliary heating) results are quite discouraging. Even for the high field case, with a predicted f_α range of 30-37%, the resulting Q value ($\simeq$4.5) is uninteresting for a TMR. Furthermore, it is not clear how we could selectively heat the central core of the plasma.

6. Conclusion

We conclude that alpha adiabaticity is insufficient for this axisymmetric cusp configuration. In order to achieve an acceptable Q value, it appears that we need a higher fraction of contained alphas than our analysis predicts. The contained alpha fraction with high magnetic fields ($\simeq$35% with 15 T) might be adequate if we increased the central cell ion-confining potential (so that less total alpha heating is required) except that we cannot identify a mechanism for radial redistribution of the contained alpha power. If we do not increase the central cell ion-confining potential, but rather provide the "missing" alpha power by external means, the resulting Q value is unacceptable.

We believe that a more profitable approach for a viable TMR is to pursue the modified cusp configuration which eliminates the central cell field null.

References

1. G. A. Carlson and W. S. Neef, Jr., "Tandem Mirror Reactor Studies at Lawrence Livermore National Laboratory," UCID-18989, March 1981.

2. B. G. Logan, "Improved Axisymmetric Cusp Plugs for Tandem Mirror Reactors," submitted to Comments on Plasma Physics and Controlled Fusion, also UCRL-86085, May 1981.

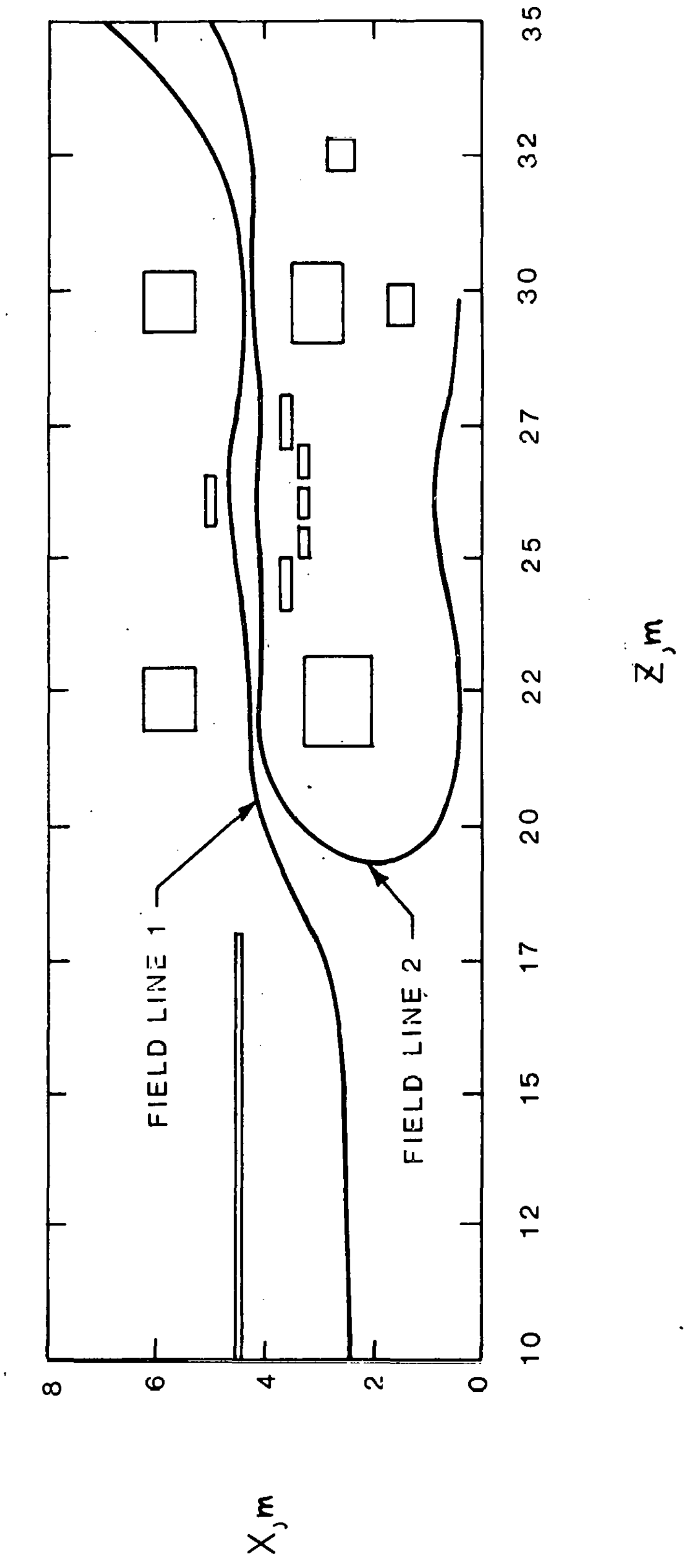

Figure 1. EFFI magnet design for axisymmetric cusp TMR.

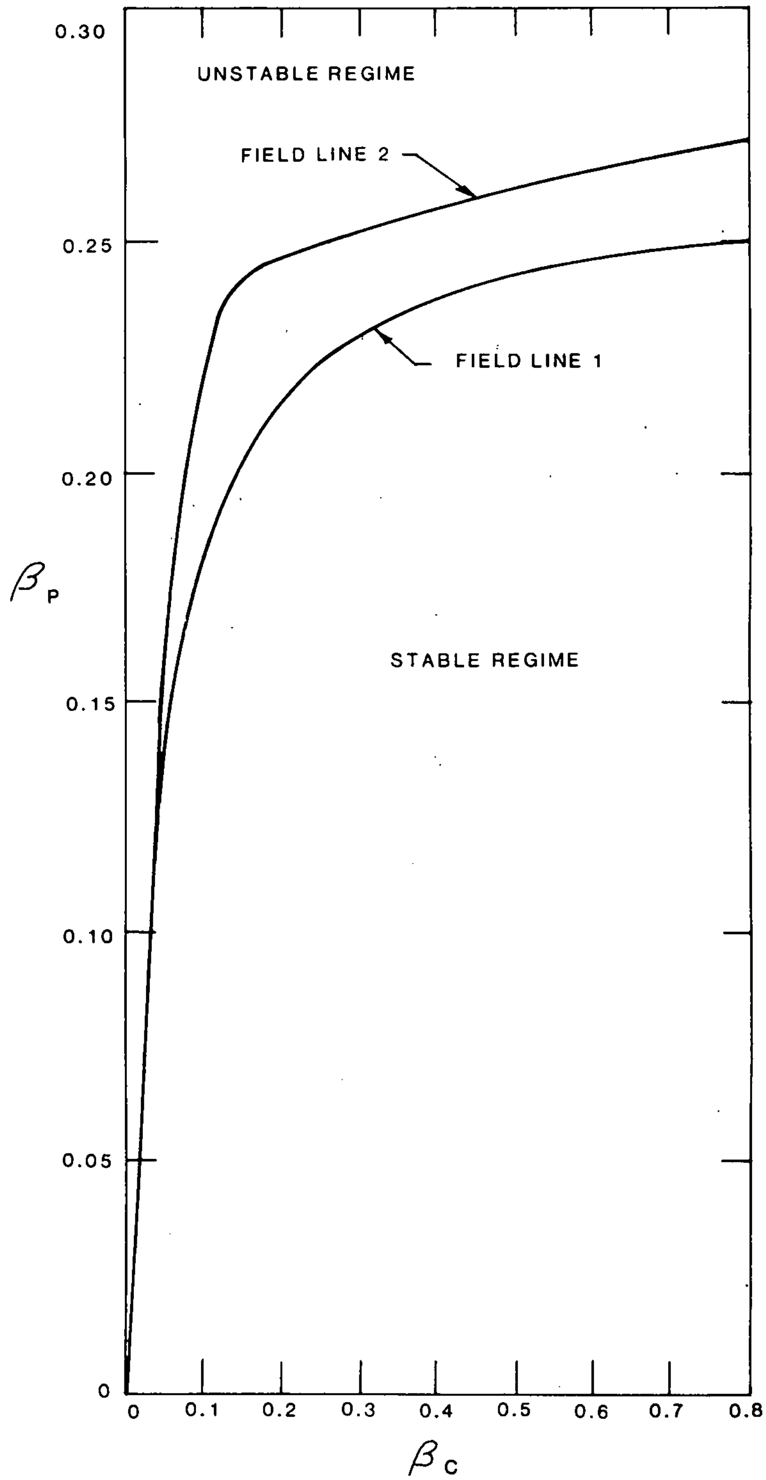

Figure 2. Ballooning stability for the axisymmetric cusp TMR.

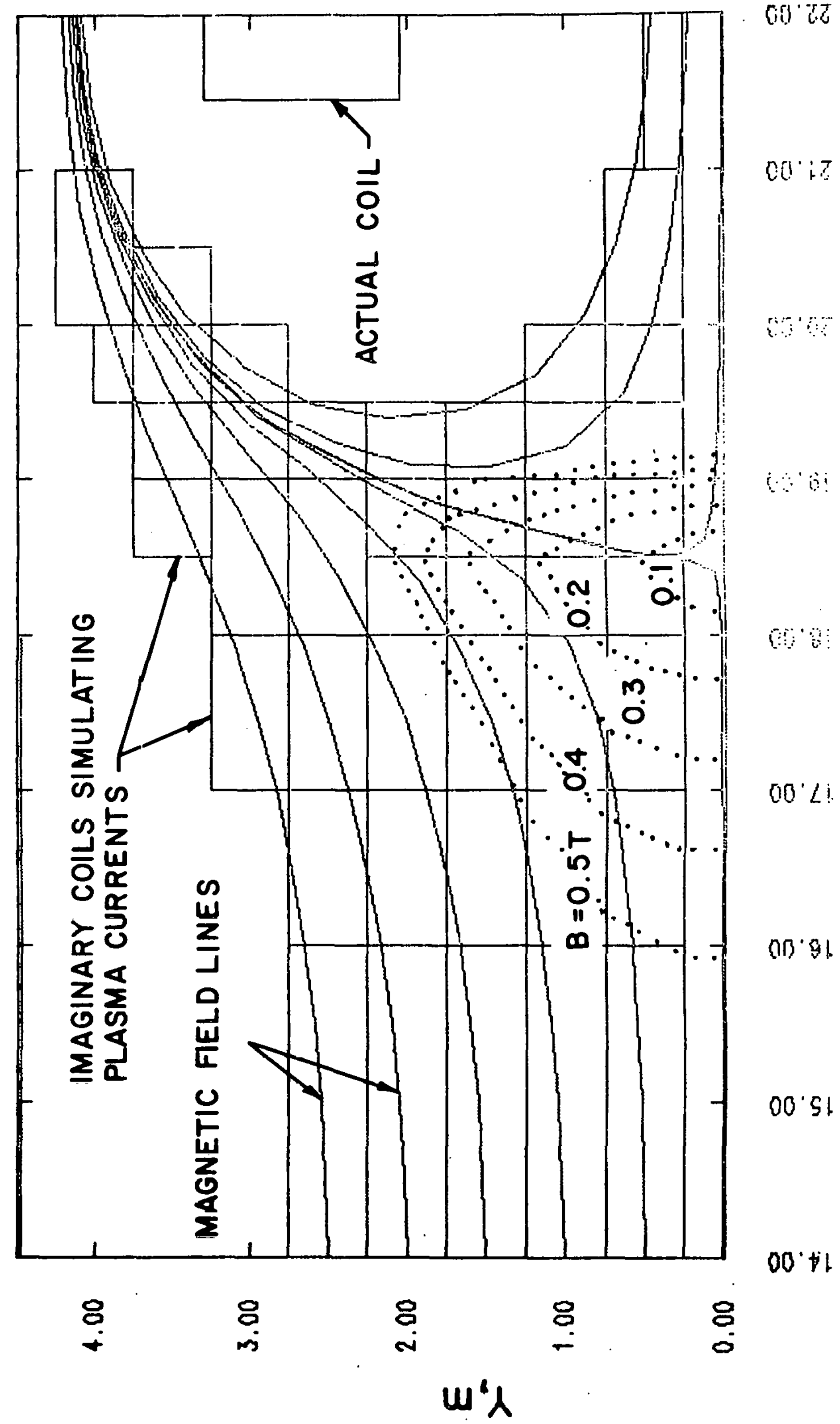

Figure 3. Axisymmetric cusp TMR-magnetic field structure at end of central cell with $\beta_c = 0.8$.

- DIMENSIONS

  $L_C = 150$ M

  $R_C = 3.7$ M

  $R_{FW} = 4.2$ M

  $R_{ANNULUS} = 4$ M

- MAGNETIC FIELDS

  $B_C = 1.5$ T $\beta_C = 0.8$

  $B_M = 9$T $B_B = 1.5$ T $B_A = 3.8$ T $\beta_B = 0.4$

- POWERS

  FUSION = 3500 MW

INPUT:	SLOSHING NEUTRAL BEAMS =	13 MW @ 400 KEV
	CHARGE EXCHANGE PUMP BEAMS =	140 MW
	ECRH AT POINT A =	39 MW
	ECRH AT POINT B =	36 MW
	TOTAL INPUT =	228 MW

- FIGURES OF MERIT

  Q = 15.4 (40 WITH NO PUMP BEAM POWER)

  $\Gamma_{FW} = 0.7$ MW/M^2

Figure 4. Preliminary parameters for axisymmetric cusp TMR (alpha particles assumed adiabatic)

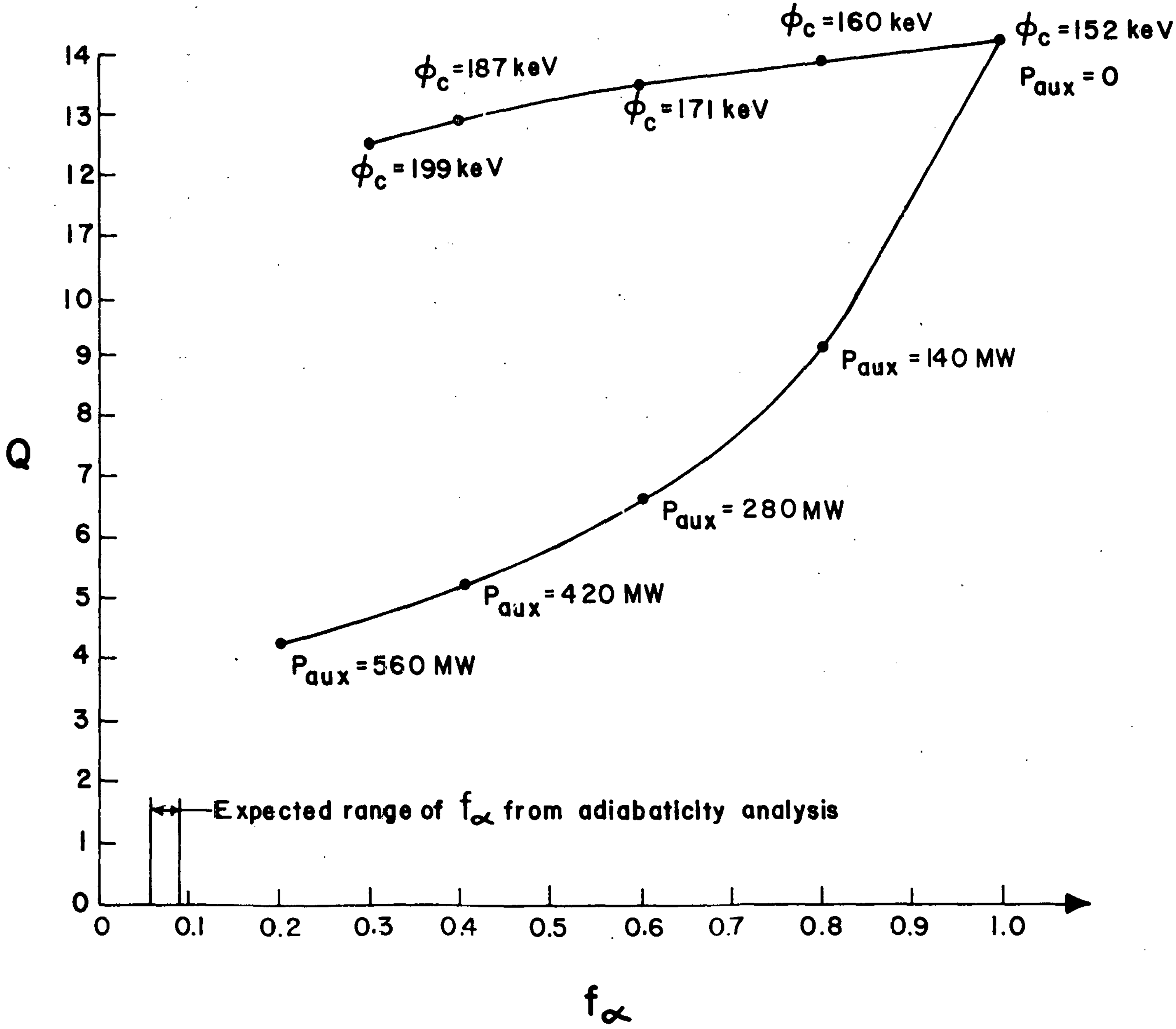

Figure 5. Q as a function of alpha containment fraction--low-field case.

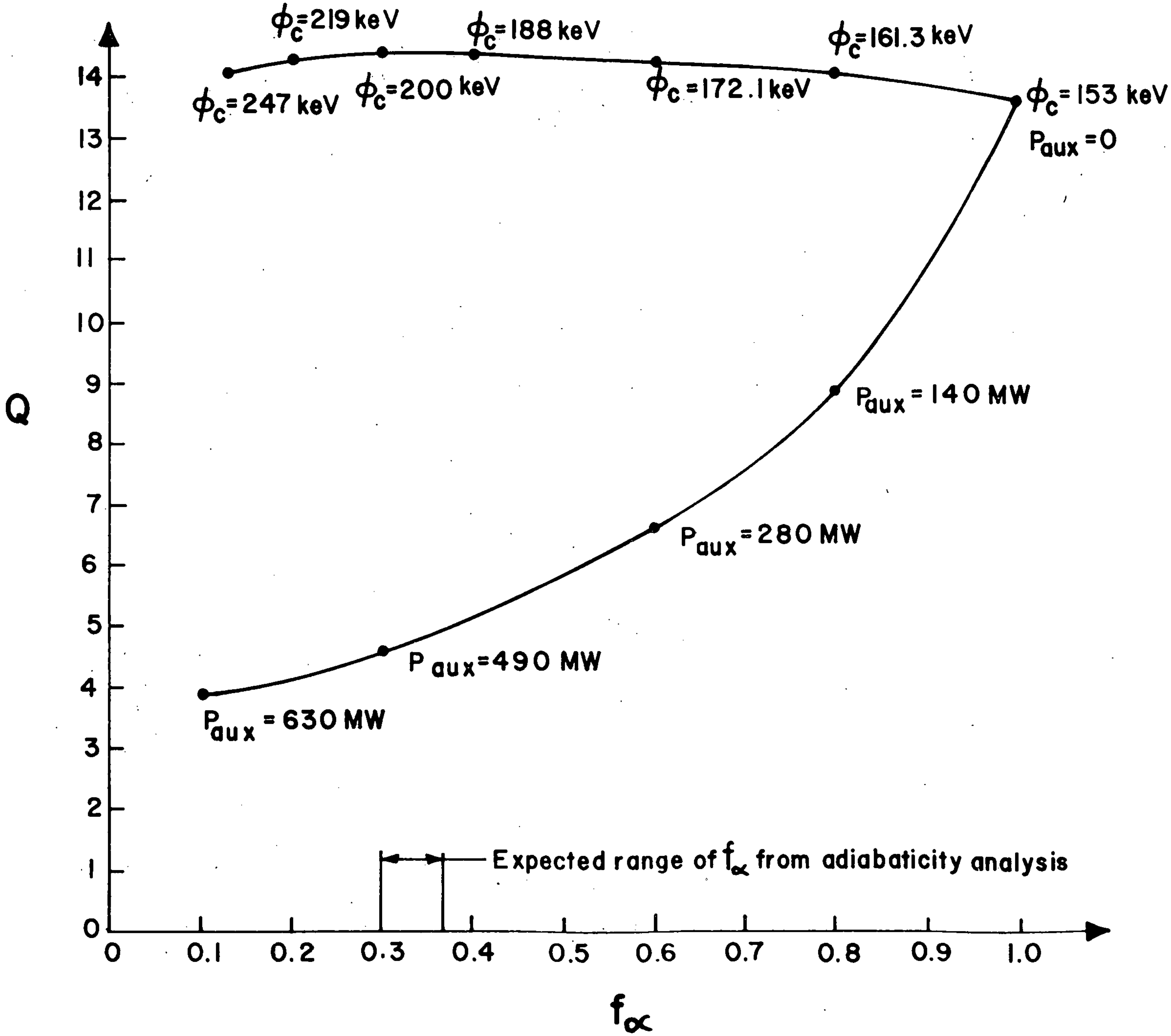

Figure 6. Q as a function of alpha containment fraction--high-field case.

Appendix

The Adiabaticity Analysis

Non-adiabatic jumps in the magnetic moment, μ, of an α particle are given by[1,2]

$$\frac{\Delta\mu}{\mu} = A \frac{v}{v_\perp} e^{-K/\epsilon} \cos \Psi .$$

where $A \approx 4$ if $r > v/\Omega$, $\Omega = ZeB/M$, $\epsilon = v/\Omega_0 L_\parallel$, Ψ is the phase angle of the trajectory, and a subscript o refers to B_0, the minimum B on the guiding center. The scale length $L_\parallel$ is defined by a quadratic fit: $B = B_0 (1 + s^2/L_\parallel{}^2)$ near the minimum. K is given by

$$K = \frac{1}{2\lambda^2} \left(\frac{1+\lambda^2}{2\lambda} \ln \frac{1+\lambda}{1-\lambda} - 1 \right)$$

where

$$\lambda = v_{\perp 0}/v.$$

We assume that the particle has explored enough of phase space to have found the loss cone when $(\Sigma \Delta\mu)^2 = \mu^2$ by successive jumps. If the jumps are uncorrelated, a number $N = (\mu/\Delta\mu)^2$ of jumps is required, and the time between successive jumps is just the transit time $L_m/v_\parallel$, where L_m is the distance between turning points.

The lifetime for loss by non-adiabatic scattering is therefore

$$\tau_a = (\mu/\Delta\mu)^2 (L_m/v \cos \theta_c)$$

where θ_c is the pitch angle in the central cell. An α particle is adiabatically confined if $\tau_a > \tau_d$, where τ_d is the drag time for cooling on electrons. Adiabaticity therefore requires

$$\left(\frac{\Delta\mu}{\mu}\right)^2 < \frac{L_m}{\tau_d v \cos\theta_c}$$

or equivalently (assuming $\cos^2 \Psi_0 = 1/2$)

$$B_0 L_{\parallel} K(\lambda) > \left(\frac{Mv}{2Ze}\right) \ln\left(\frac{8\tau_d v \cos\theta_c}{L_m \lambda^2}\right)$$

Since λ is evaluated at B_0, it is related to θ_c by

$$\lambda^2 = \sin^2\theta_0 = (B_0/B_c)\sin^2\theta_c .$$

For particles of given energy, the adiabatic condition is of the form

$$B_0 L_{\parallel} > f(\tau_d, B_0/B_c, \theta_c, L_m)$$

and for a given field geometry and drag time this determines a critical value of $\theta_c = \theta_{crit}$. The fraction lost from that field line is

$$f_1 = 1 - \cos\theta_{crit}$$

and λ for that case is

$$\lambda^2_{crit} = (B_0/B_c)\left[1 - (1-f_1)^2\right]$$

Figure A-1 shows the dependence of the product $B_0 L_{\parallel}$ on τ_d, B_0/B_c, and f_1 for 3.5 MeV α particles in a TMR with L_m = 150 m. Typically, $\tau_d \approx$ 1 sec and $B_0/B_c \approx 0.5$ requiring $B_0 L_{\parallel} \approx 2.4$ T-m when $f_1 = 1/2$.

We have analyzed three cases for the axisymmetric cusp TMR: (1) vacuum field with B_c = 1.53 T, B_m = 9 T, r_p = 2.5 m in the central cell; (2) the same vacuum field but with β_c = .8 calculated with the EFFI code using plasma currents $j = \nabla p/B$; (3) the vacuum field increased everywhere by a factor of 15/11, and with β_c reduced to .43 for the same plasma pressure and radius. Parameters for this case were obtained by interpolation between the first two cases. The parameters $L_{\parallel}$, B_0, B_c, and B_0/B_c are plotted in Fig. A-2 as functions of the radial position of the field line in the central cell.

Figure A-3 shows the crossover points where B_0 becomes greater than that required for adiabatic α's. The crossover point is rather insensitive to τ. The n^2-weighted volume outside the crossover is indicated in Fig. A-3d. After integrating over $n^2 rdr$, the fractions of the α's that are adiabatically contained for time τ are:

Adiabatic fraction:

τ(sec)	Low B $\beta_c = 0$	Low B $\beta_c = .8$	High B $\beta_c = .43$
2	.43	.07	.33
.5	.50	.10	.40

About 8% of the α's that would have been adiabatic are born inside the loss cone and lost immediately. Accounting for this loss gives us the overall fraction of alpha particles contained:

Fraction contained:

τ(sec)	Low B $\beta_c = 0$	Low B $\beta_c = .8$	High B $\beta_c = .43$
2	0.40	0.06	0.30
0.5	0.46	0.09	0.37

References to Appendix

1. R. H. Cohen, G. Rowlands, and J. H. Foote, "Nonadiabaticity in Mirror Machines," Phys. Fluids 21, 627 (1978).

2. J. H. Foote, "Comparing Adiabatic Lifetimes Estimated from Ion-Trajectory Numerical Calculations and from Analytic Equations (for TMX-Upgrade Axisymmetric End Cell), Memorandum, May 19, 1981.

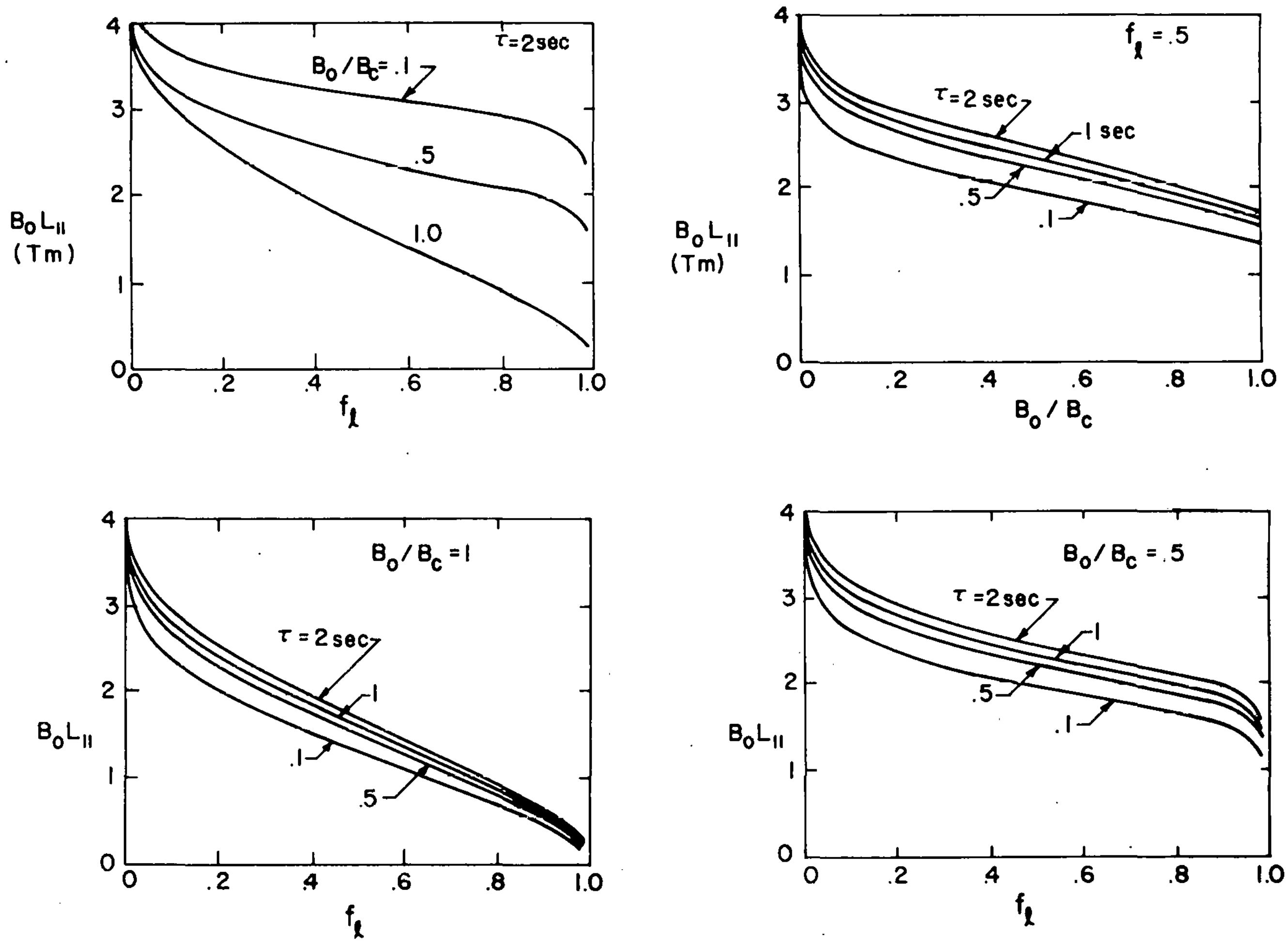

Figure A-1. The dependence of $B_o/L_{\|}$ on τ_d, B_o/B_c, and f_1.

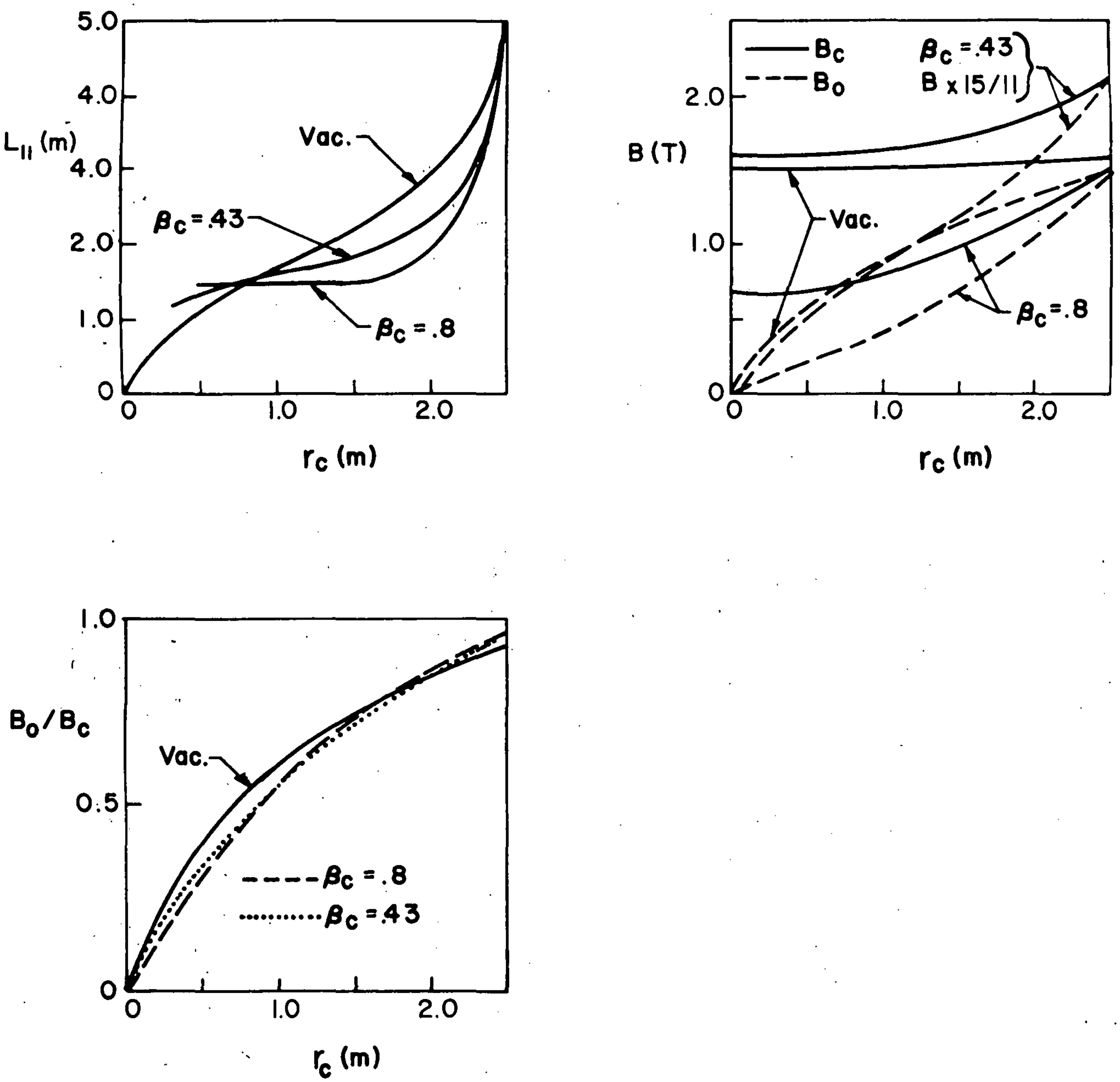

Figure A-2. The parameters $L_{\parallel}$, B_o, and B_c plotted vs r_c, the field line radius in the central cell.

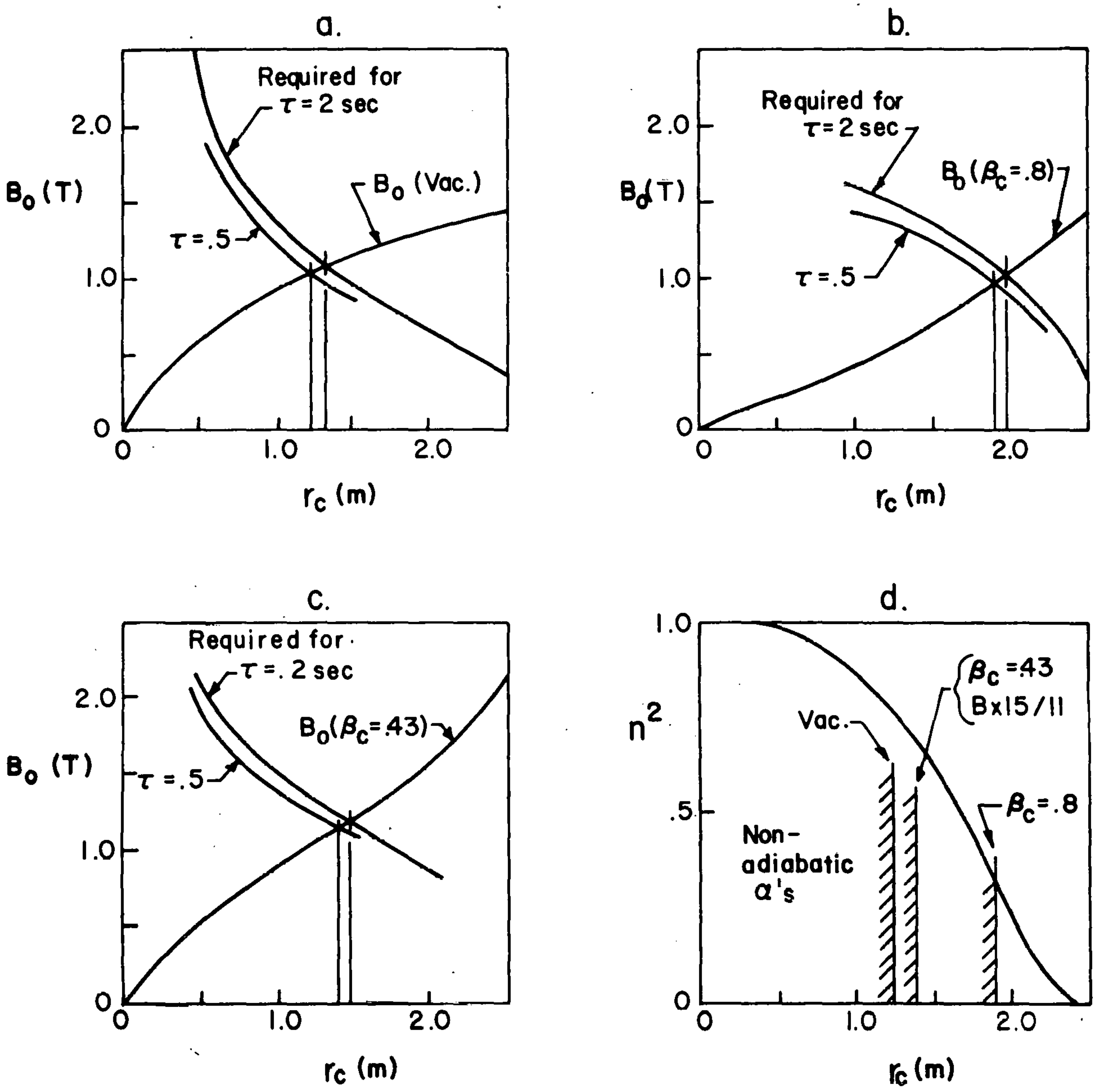

Figure A-3. The crossover points beyond which the α's are adiabatically confined for time τ. In 3d, the n^2 weighting is sketched.

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