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Mechanisms for Fast Flare Reconnection*

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Normal collisional-resistivity mechanisms of magnetic reconnection have the drawback that they are too slow to explain the fast rise of solar flares. We will examine two methods proposed for the speed-up of the magnetic tearing instability: the anomalous enhancement of resistivity by the injection of MHD turbulence[1] and the increase of Coulomb resistivity by radiative cooling.[2] We describe the results of nonlinear numerical simulations of these processes which show that the first does not provide the claimed effects, while the second yields impressive rates of reconnection, but low saturated energy outputs.

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1. D. Biskamp and N. Welter, Phys. Letts 96A, 25 (1983).

2. R. Steinolfson and G. Van Hoven, Astrophys. J. 276, 391 (1984).

TURBULENT RESISTIVITY: MODEL AND DEFINITIONS

Our two-dimensional force-free model has an initial sheared periodic field

$$\underset{\sim}{B}_0 = \hat{x}\, B_0 \sin\pi y/a - \hat{z}\, B_0 \cos\pi y/a.$$

We further assume an incompressible inviscid plasma with constant nominal resistivity η_0.

The MHD and energy equations are Fourier-transformed into the wavenumber domain with $\partial/\partial z = 0$, modeled over a finite spectrum, and evolved in time using a predictor-corrector algorithm.

Biskamp & Welter [Phys. Letts. 96A, 25 (1983)] have analytically examined the case where the turbulent spectrum is well separated from the tearing spectrum. They report that in this case the turbulence has the effect of introducing an additional effective resistivity term

$$\eta_t = 1/2\, \tau_{corr} \left\{ \langle v^2 \rangle_{turb} - \langle B^2 \rangle_{turb} \right\},$$

where τ_{corr} is the correlation or relaxation time of the small-scale spectrum.

Note that η_t is a measure (at least semi-quantitative) of how a given process deviates from being Alfvenic.

TIME-EVOLUTION EQUATIONS

$$\frac{\partial B_x(0,i)}{\partial t} = -\frac{\pi \eta_0^2 c^2}{4a^2} i^2 B_x(0,i) + \frac{\pi \ell i^2}{4a^2} \sum_{\substack{m,n=-\infty \\ m\neq 0}}^{\infty} \frac{1}{m} B_y(m,n)\, v_y(m,i-n)$$

$$\frac{\partial B_y(j,i)}{\partial t} = -\frac{\pi \eta_0^2 c^2}{4\ell^2}\left(j^2 + i^2\frac{\ell^2}{a^2}\right) B_y(j,i) + \frac{\pi j}{4\ell} \sum_{n=-\infty}^{\infty} B_x(0,i-n)\, v_y(j,n)$$

$$+ \frac{\pi j}{4a} \sum_{\substack{m,n=-\infty \\ m\neq 0,j}}^{\infty} \left(\frac{n}{m} - \frac{j-n}{i-m}\right) v_y(m,n)\, B_y(j-m,i-n)$$

$$\frac{\partial v_y(j,i)}{\partial t} = \frac{j}{16\rho\ell(j^2 + i^2\ell^2/a^2)} \left\{ \sum_{n=-\infty}^{\infty} \left(j^2 + \frac{i(2n-i)\ell^2}{a^2}\right) B_y(j,n)\, B_x(0,i-n) \right.$$

$$\left. + \frac{\ell}{a} \sum_{\substack{m,n=-\infty \\ m\neq 0,j}}^{\infty} \left(m^2 + n^2\frac{\ell^2}{a^2}\right) \frac{nj-mi}{m(j-m)} \left[B_y(m,n)\, B_y(j-m,i-n) - 4\pi\rho\, v_y(m,n)\, v_y(j-m,i-n)\right]\right\}$$

where, for example,

$$B_y(x,y,t) = \frac{1}{4} \Sigma_{m,n} B_y(m,n,t) \sin(m\pi x/\ell) \cos(n\pi y/a)$$

is the reconnecting field component, and ρ is the mass density.

Because of the assumed periodicities in both $\underline{x}$ and y (with scale lengths $\underline{\ell}$ and $\underline{a}$ respectively), the wavenumbers in those directions are multiples of $k_{x0} = \pi/\ell$ and $k_{y0} = \pi/a$.

TEST CASES

The test cases whose results are illustrated here are designed to realize η_t artificially by continually injecting turbulence into the model (starting at time $t = 0.4$ sec in each case). The chosen parameters include $S = 1000$; $|k_x/k_{x0}| \leq 30$; $|k_y/k_{y0}| \leq 15$; and $k_{x0}a \cong 0.36\pi$, specifying the dimensionless wavelength in the x direction (along the tearing plane) for the most unstable tearing perturbation. (This last means that the scale length in the x direction is about twice that in the y direction.)

The cases illustrated are as follows:

1) The baseline - the normal tearing mode is allowed to proceed through linear, nonlinear, and saturation phases; no turbulence is added.

2) Turbulence is added to the magnetic induction spectrum at the rate

$$\frac{\text{energy injected/unit time}}{\text{background field energy}/\tau_e} \lesssim 10\%$$

(τ_e being the e-folding time of linear tearing growth).

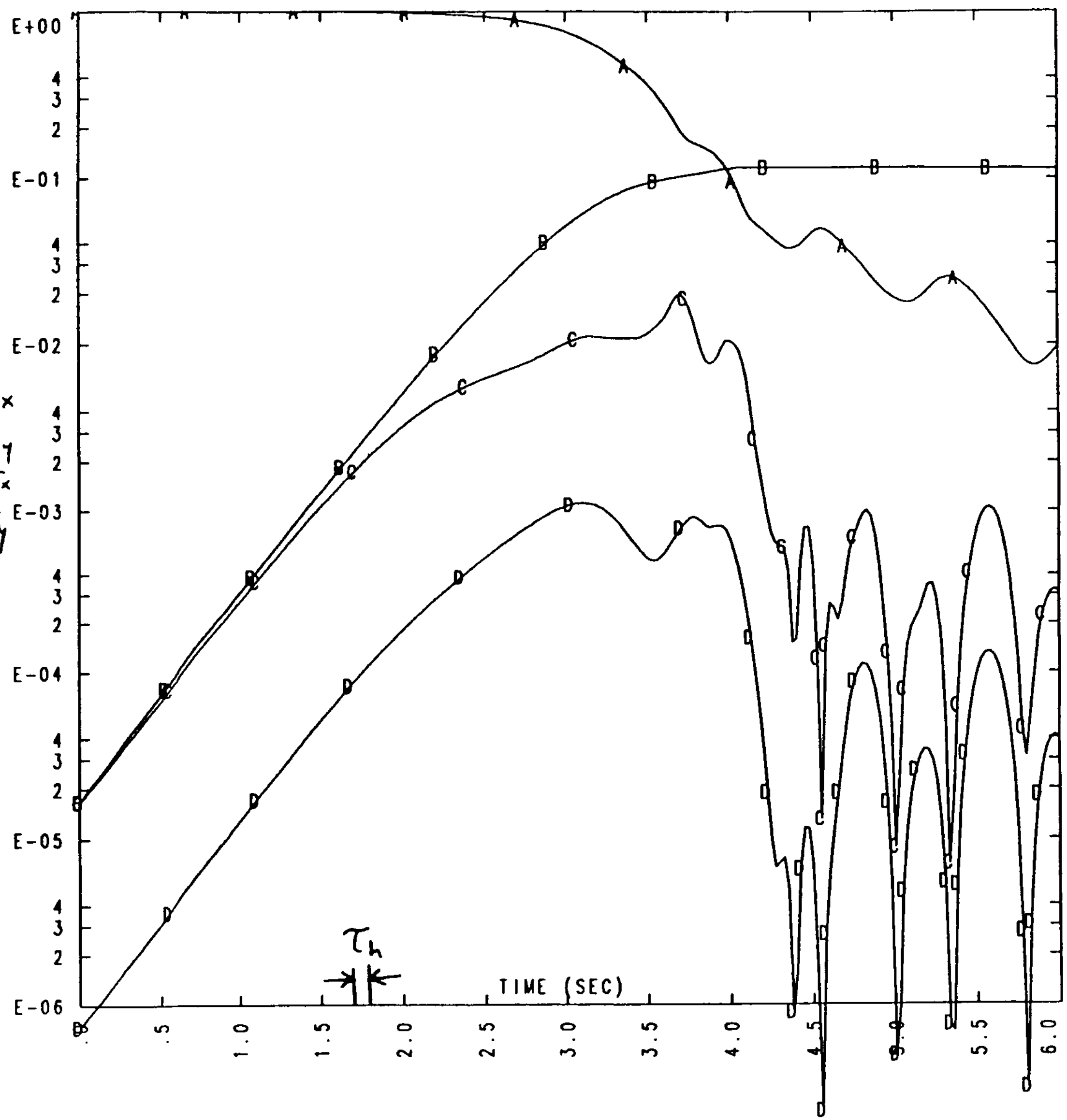
3) As for case 2, but turbulent energy is added to the velocity rather than the induction spectrum.

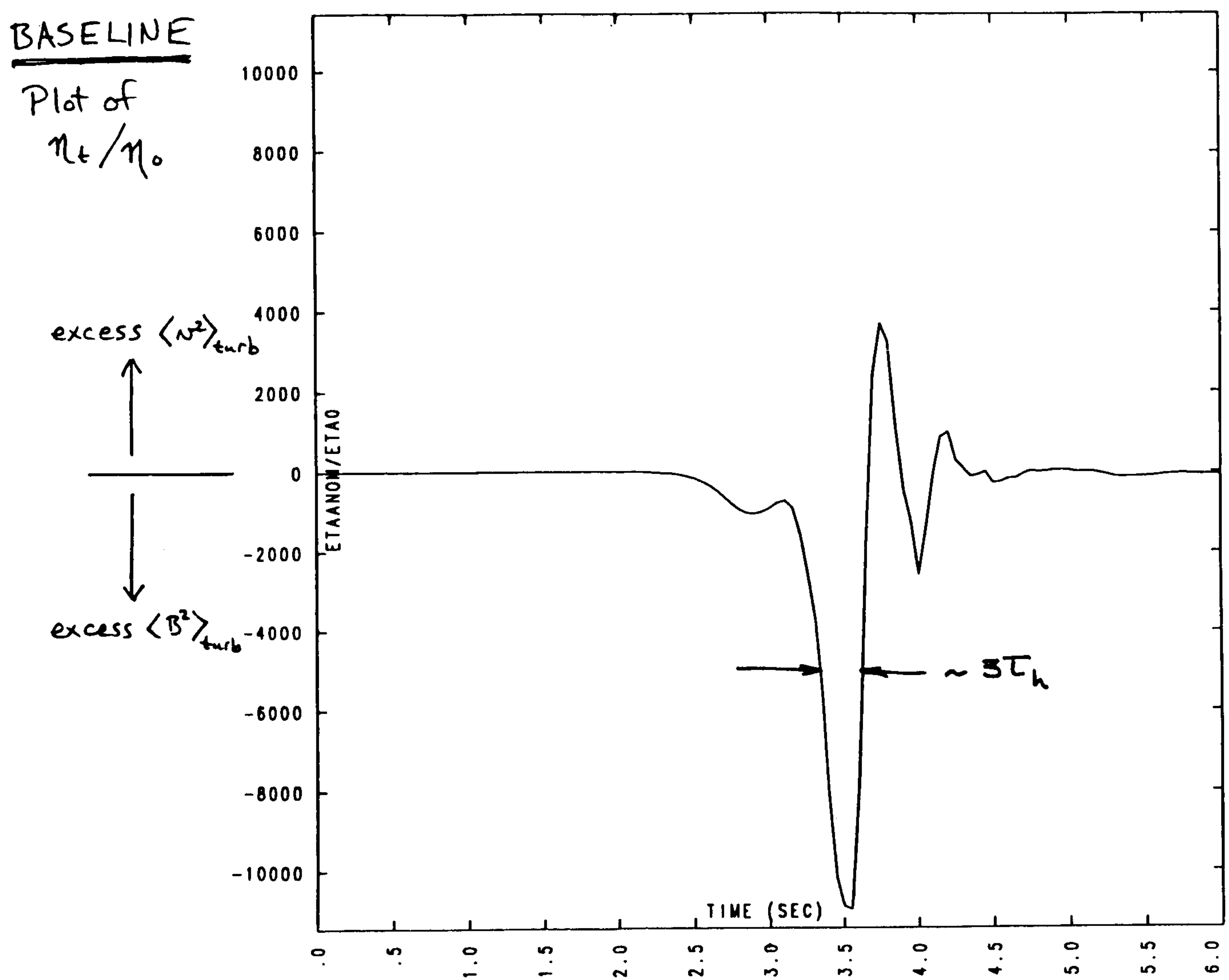
Plotted for each case are the energy in B_x, B_y, v_x, and v_y for the linear tearing portion of the spectrum $\left(|k_x/k_{x0}| \leq 1\text{ , all } k_y\right)$, and the quantity η_t normalized to the nominal resistivity η_0. [n.b.: η_t is calculated according to a prescription given by Montgomery and Hatori, Plasma Phys. and Contr. Fusion 26, 717 (1984)].

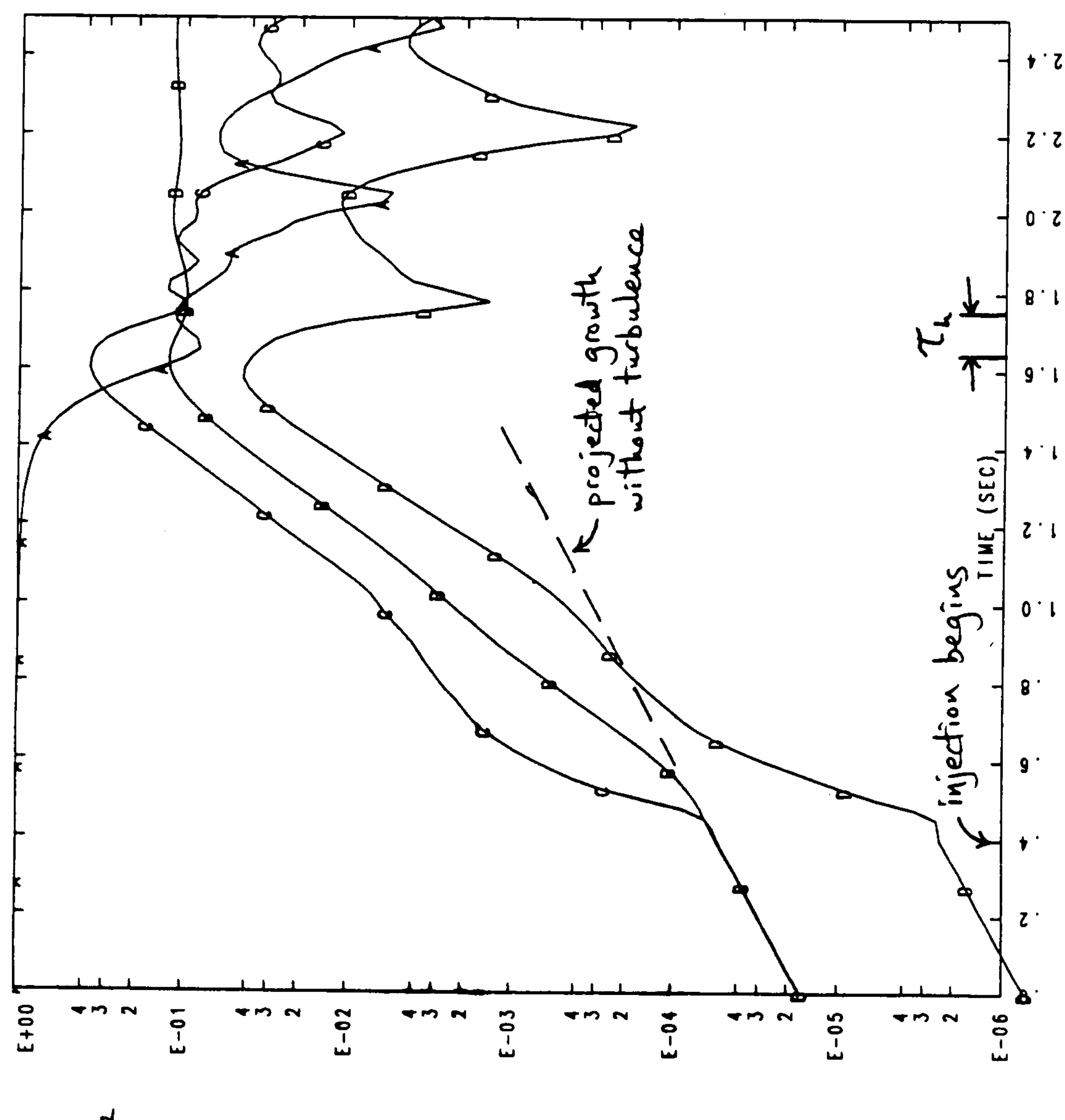
BASELINE

Tearing energies without turbulence injection

A: energy in B_x
B: " " B_y
C: " " v_x
D: " " v_y

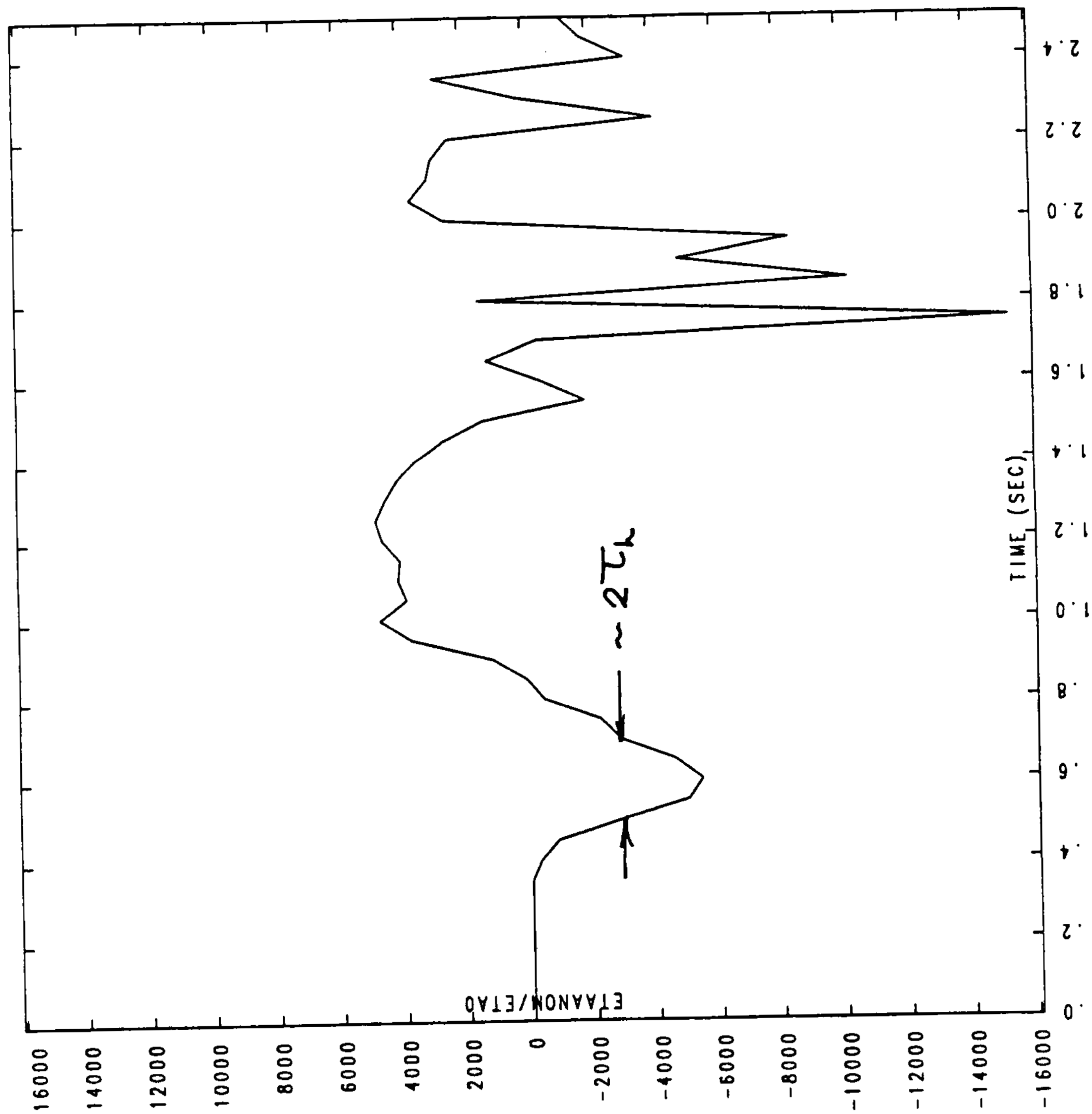



BASELINE
Plot of η_t/η_0
excess $\langle v^2\rangle_{turb}$
excess $\langle B^2\rangle_{turb}$
ETAANOM/ETAO
TIME (SEC)
~ $3\tau_h$
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
.0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0



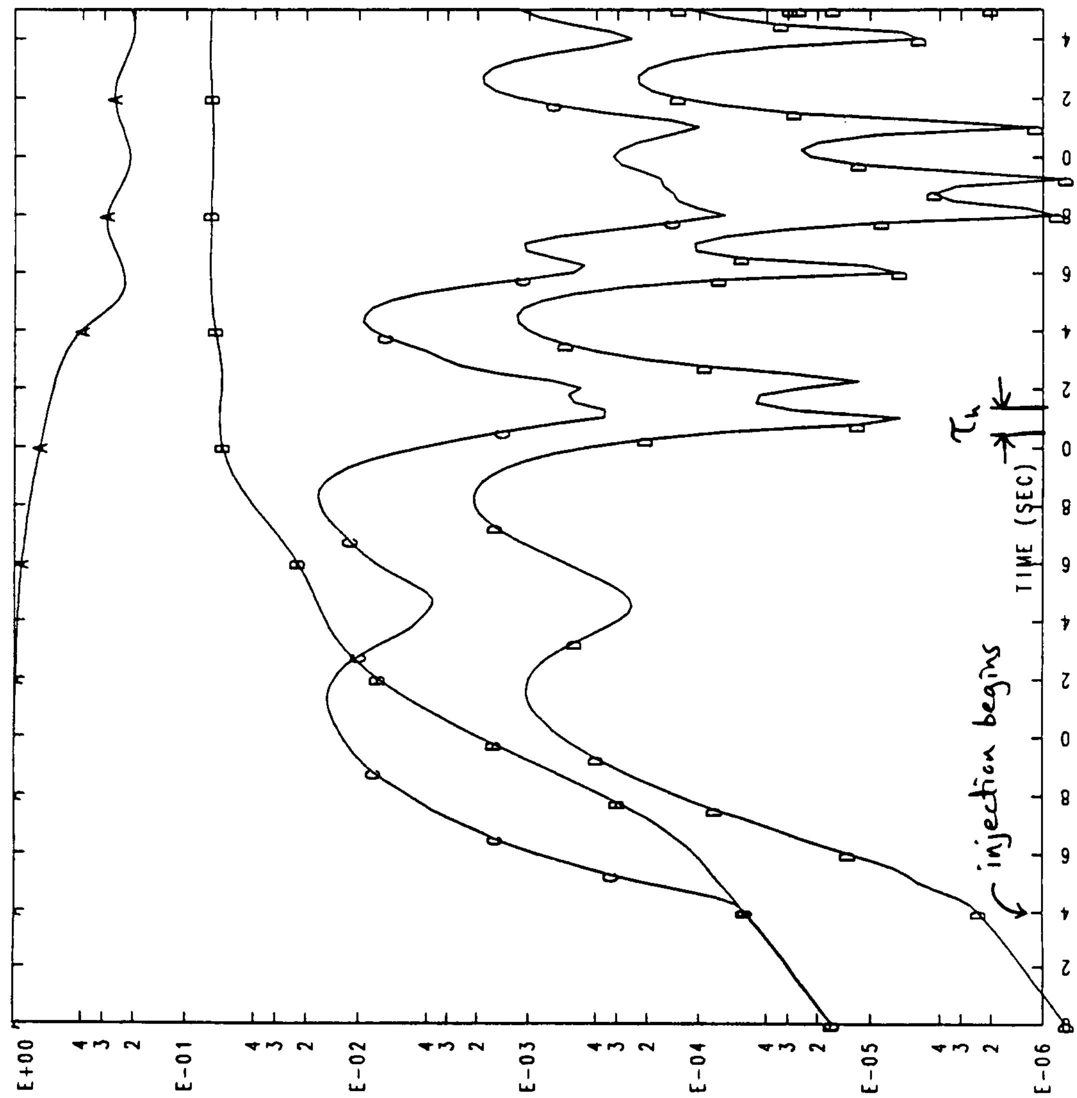
CASE 2

Turbulence injected in $\langle B^2 \rangle$: Energies



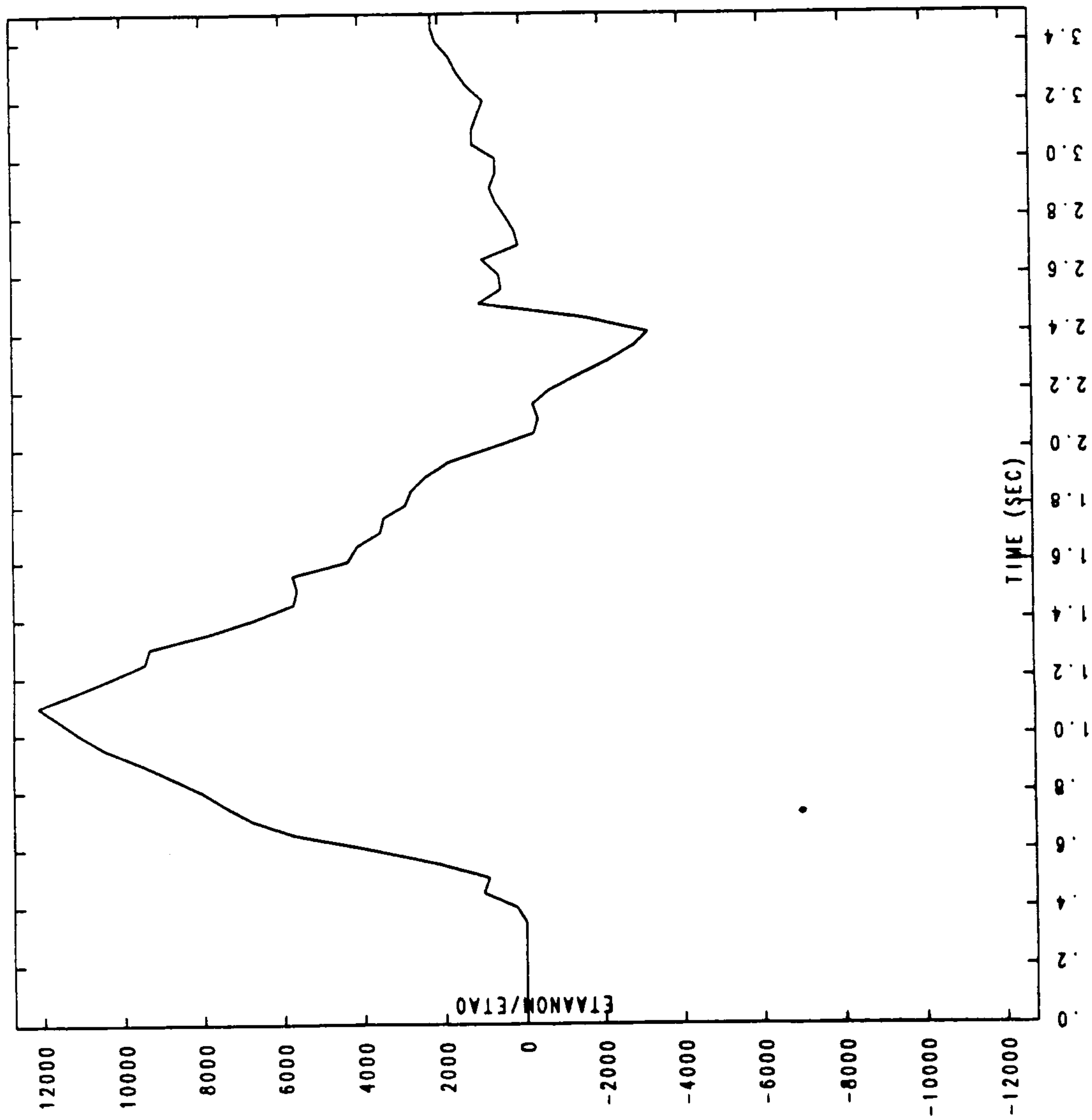
CASE 2

η_t/η_0



CASE 3

Turbulence injected in $\langle v^2 \rangle$: Energies



CASE 3

η_t / η_o

TURBULENT RESISTIVITY: OBSERVATIONS AND CONCLUSIONS

1) The quantity η_t is zero for linear growth and after saturation of the unperturbed tearing process; but it deviates markedly from zero during nonlinear growth. Hence it may serve as a measure of what might be called Alfvenicity (or equipartition).

2) The presence of turbulence, whether in $\underset{\sim}{B}$ or in $\underset{\sim}{v}$, catalyzes a weak increase in the ~~linear tearing~~ growth rate, with consequent earlier saturation. Saturation levels are not much altered. Other cases (not illustrated) show that this effect is only weakly dependent on the level of turbulence.

3) The quantity η_t shows a strong tendency to restore itself to zero (representing equipartition between kinetic and magnetic energies), both in its natural behavior and when it is being artificially driven positive or negative.

4) Because η_t takes on large positive and negative values while the enhanced growth rate changes little, its interpretation as a resistivity is questionable.

RADIATIVE RECONNECTION — SUMMARY

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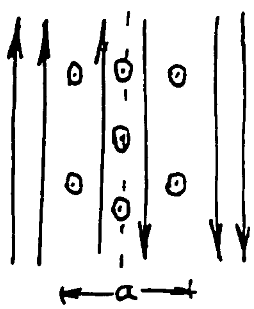
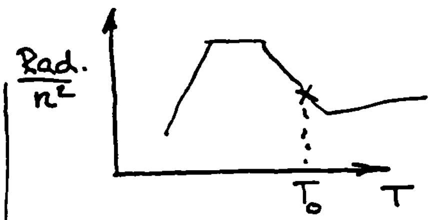
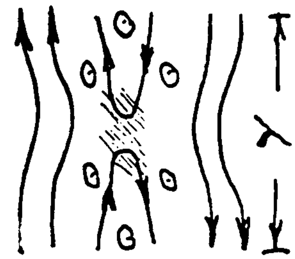


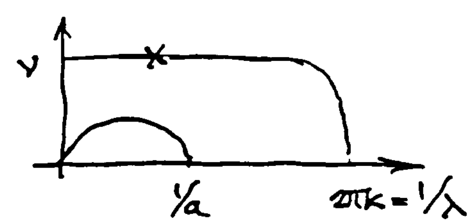




$$\eta(T) = \eta_0 \left[T/T_0\right]^{-3/2}$$

Radiation Resistivity

Two <u>unstable</u> modes:



<u>1.</u> Start with <u>fast</u> ($\sim 10^2 x$) radiative mode

$\Longrightarrow$ fast magnetic reconnection and energy release;

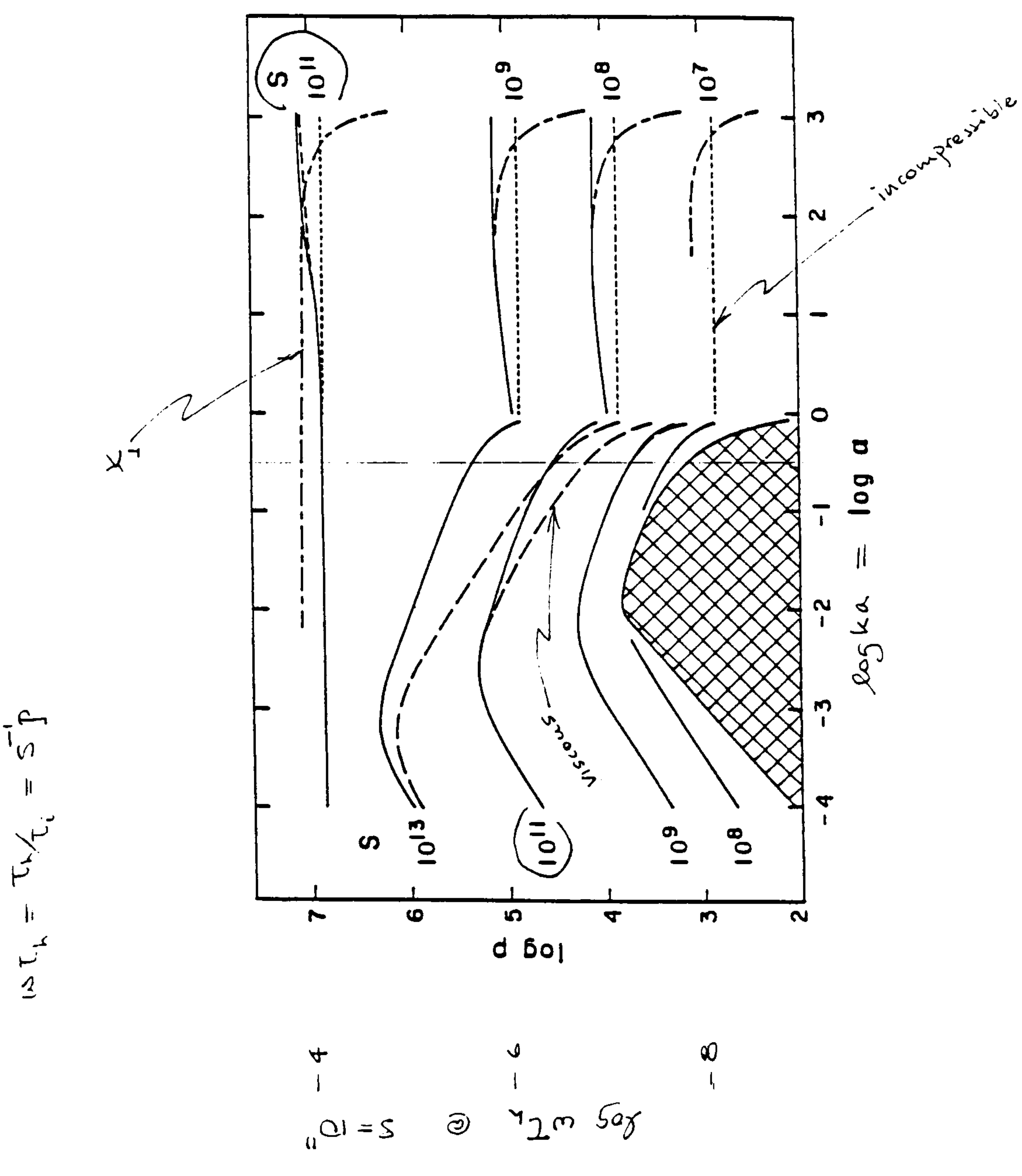
<u>2.</u> Nonlinear limit by computer experiment

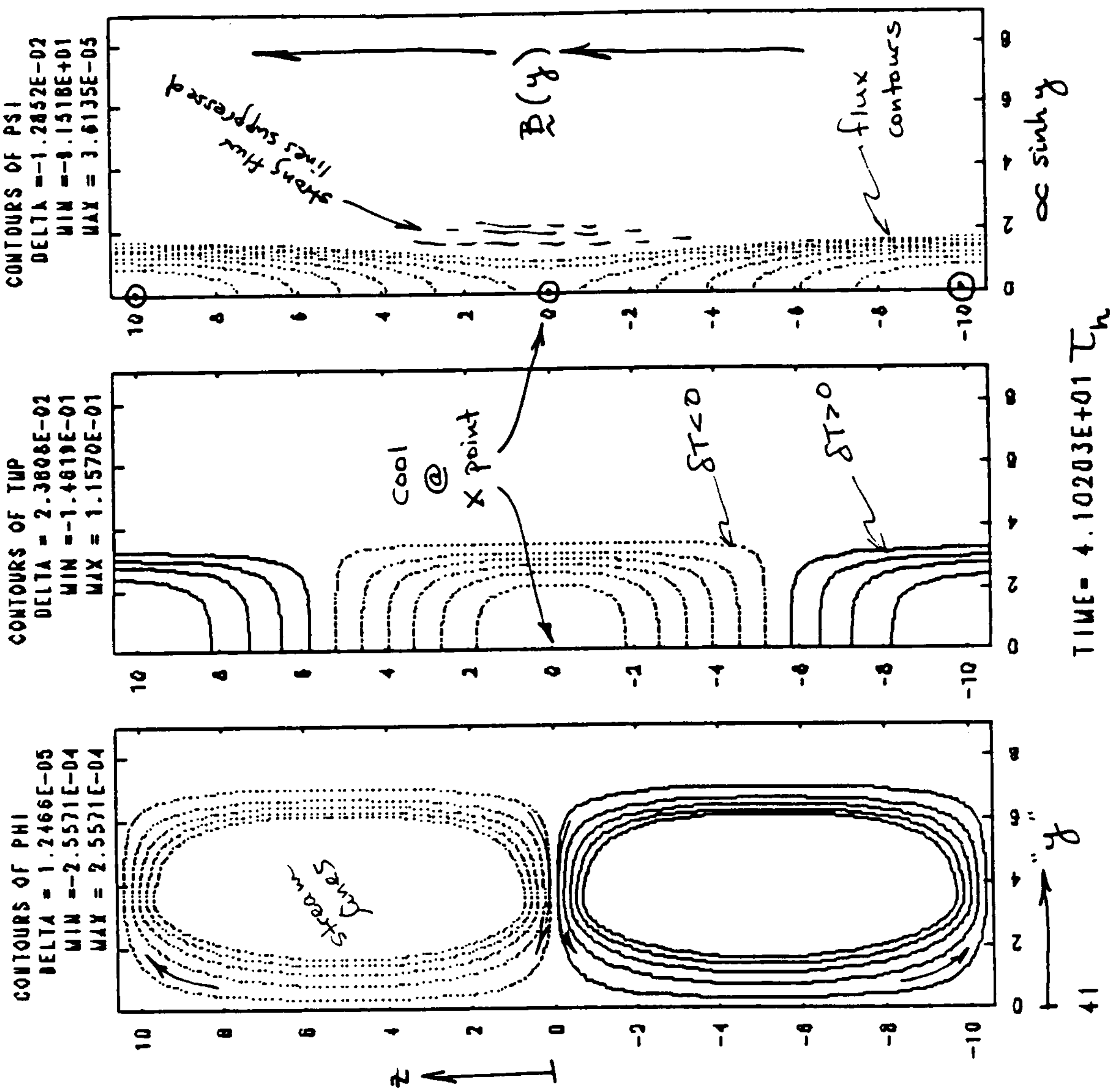
$\Longrightarrow$ a) sharp reconnection gradients

b) $T/T_0 \longrightarrow 10^{-2}$, $\eta/\eta_0 \longrightarrow \underline{\underline{10^3}}$

$\Longrightarrow$ burst of <u>very</u> <u>fast</u> reconnection

$$\frac{\partial B}{\partial t} \sim \frac{\eta(T)}{\mu_0}\nabla^2 B \longrightarrow B/\tau_h$$


log p
log a
log ka = log a
S
10^13
10^11
10^9
10^8
10^7
viscous
incompressible
ωτ_h = τ_h/τ_i = S^-1 P
log ωτ_h @ S = 10^11
-4
-6
-8



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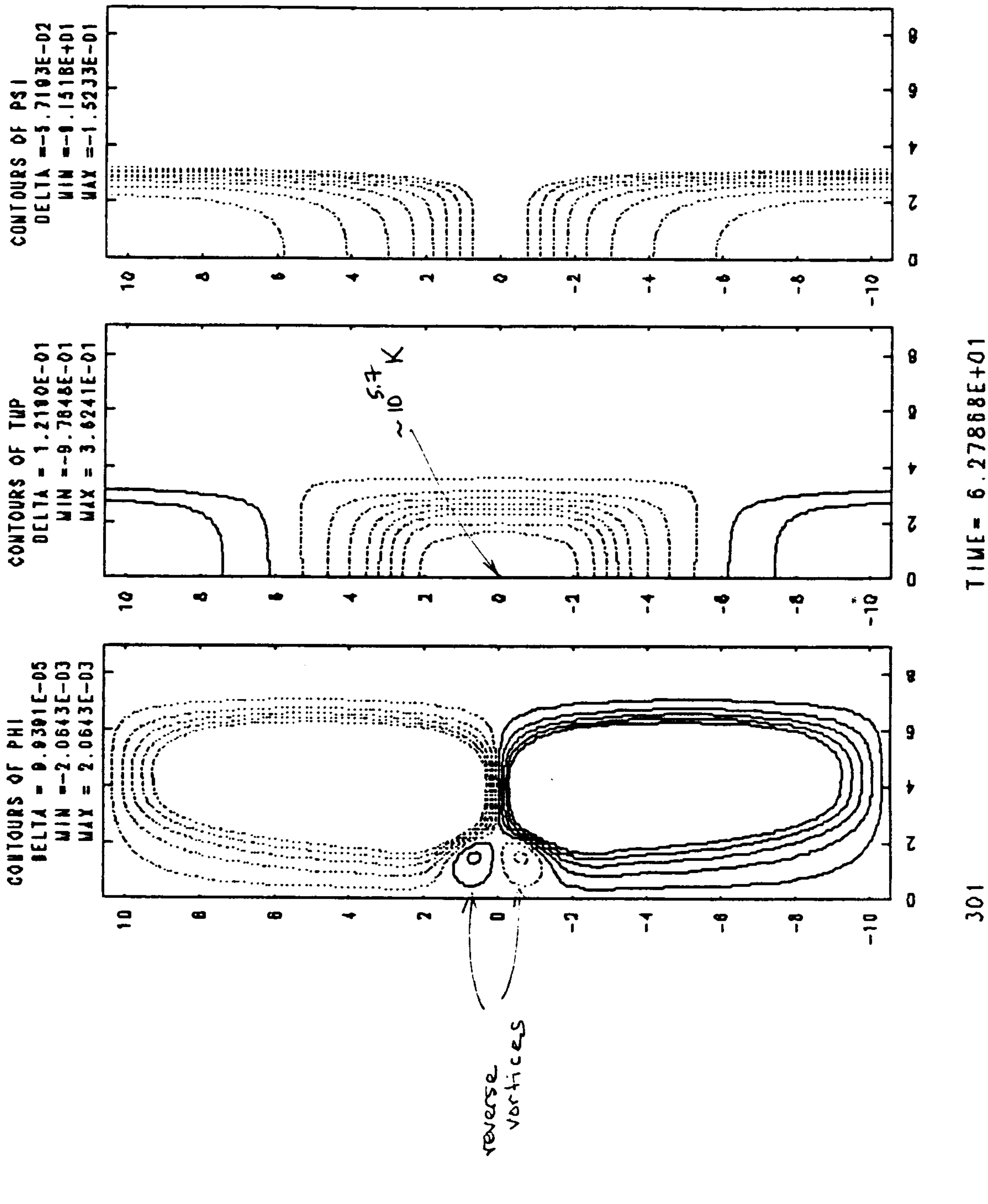
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MAX =-1.5233E-01
CONTOURS OF TMP
DELTA = 1.2190E-01
MIN =-9.7848E-01
MAX = 3.6241E-01
~10^5.7 K
CONTOURS OF PHI
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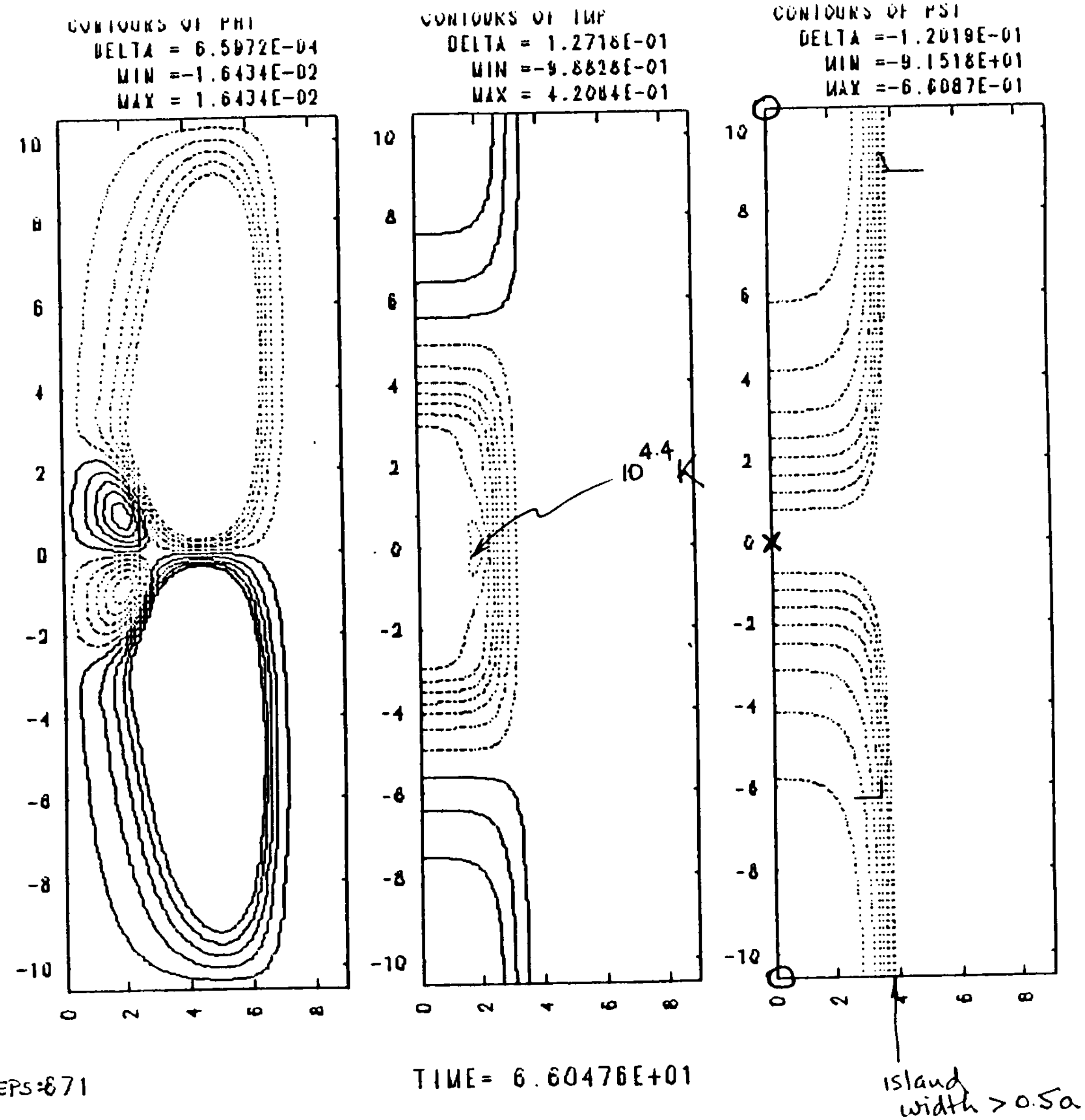
reverse vortices
TIME= 6.27868E+01
301



IMPLICIT TIME STEPS: 671

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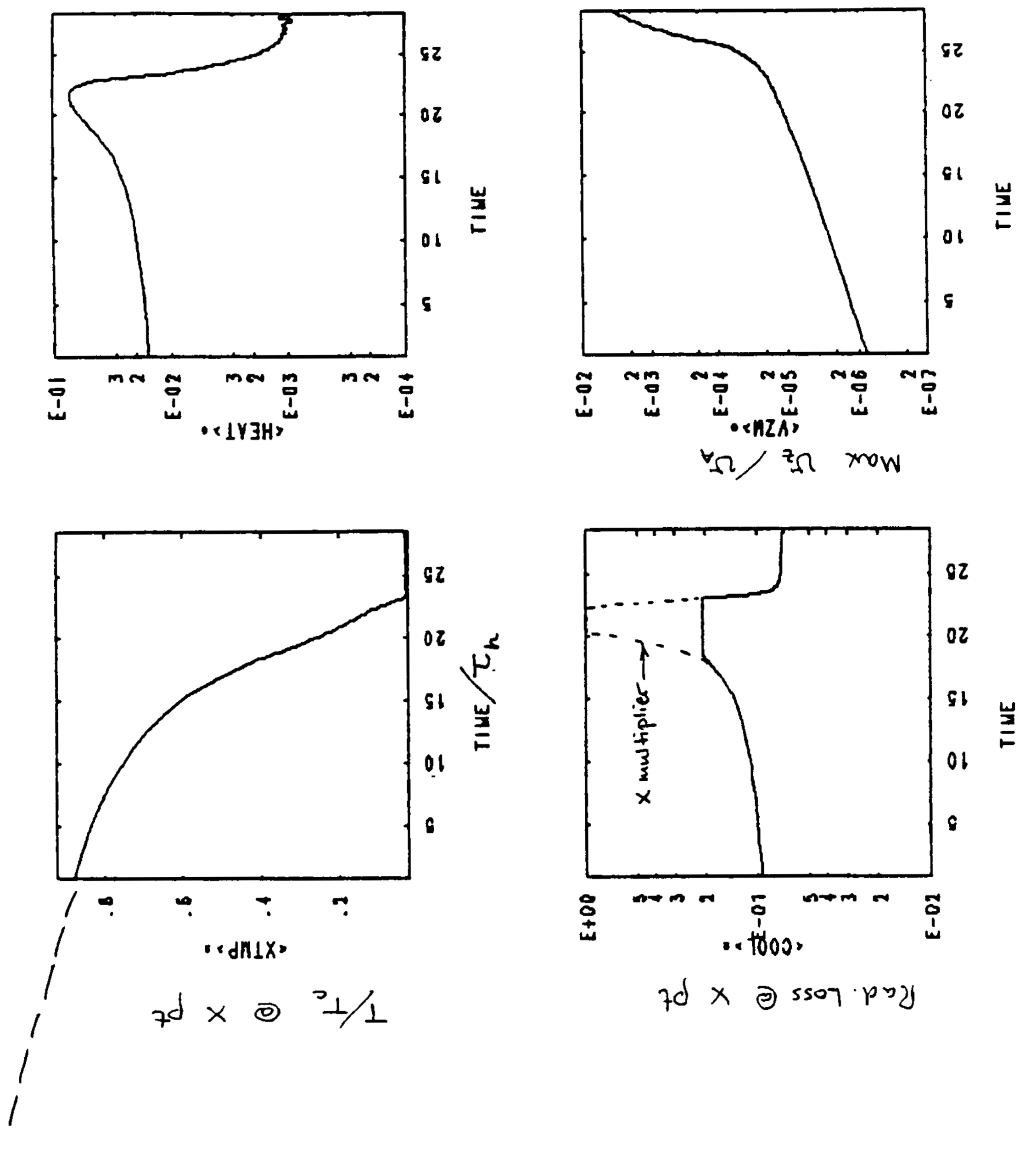

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Max U_z / U_A
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TIME
T/T_o @ x pt
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TIME/τ_h
Rad. Loss @ x pt
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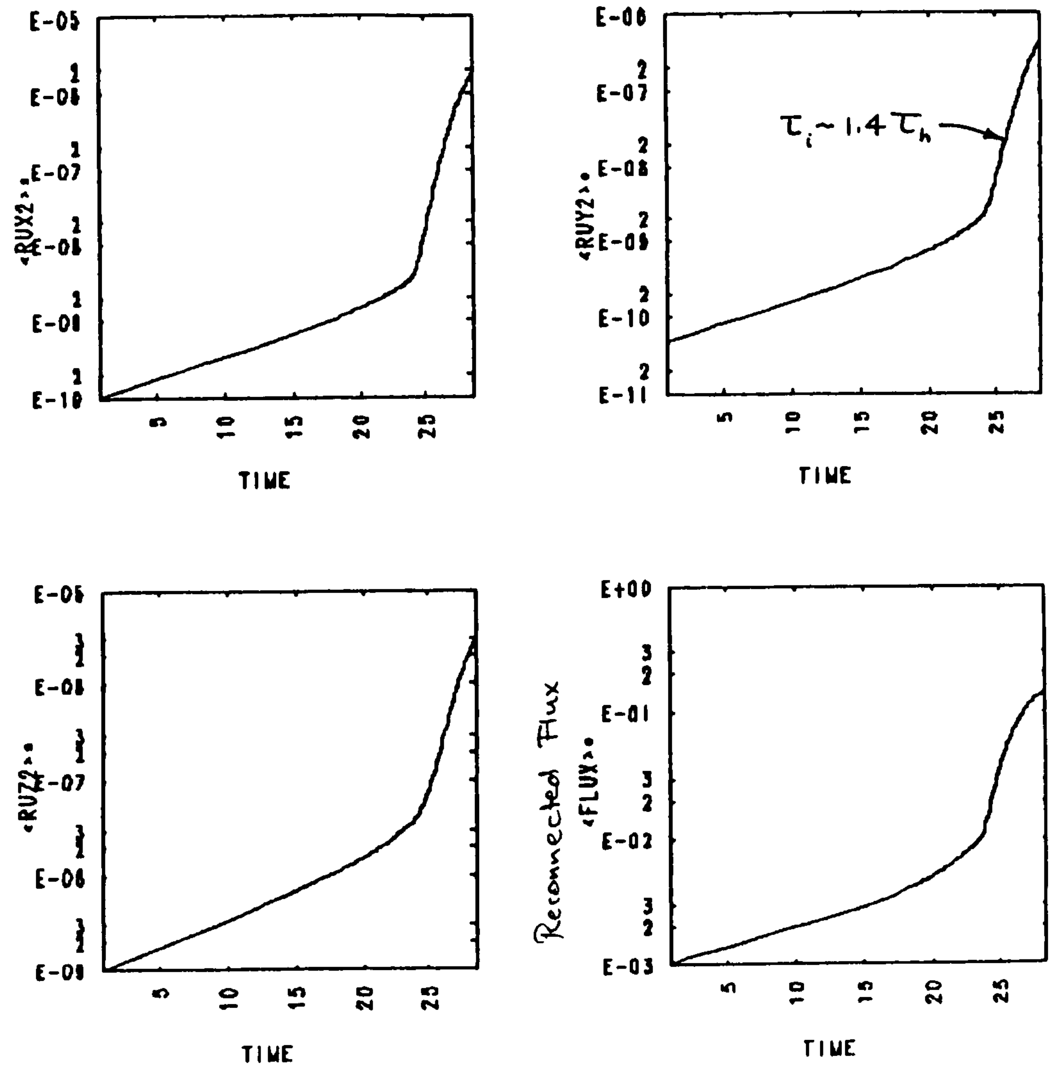
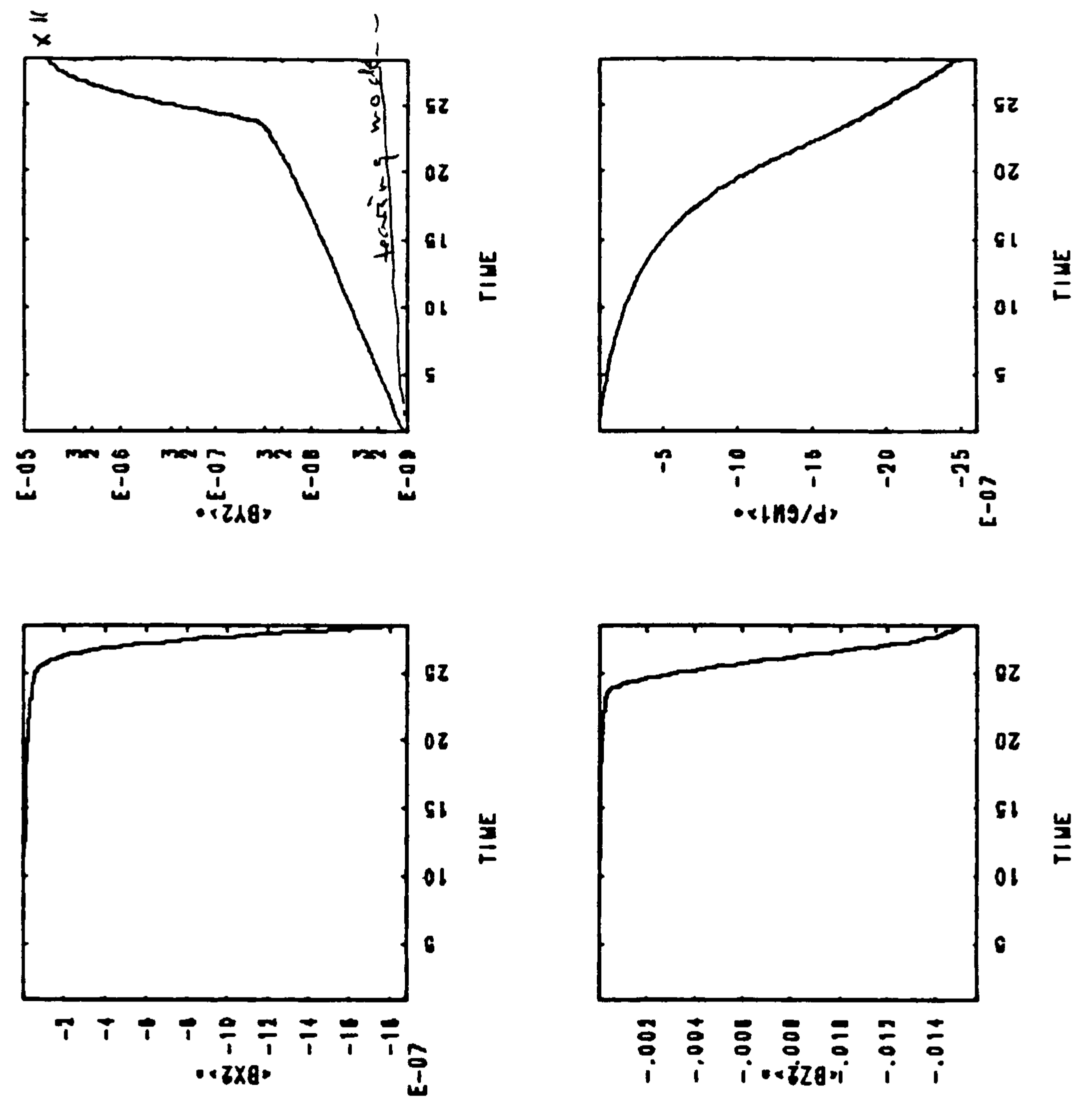
x multiplier
TIME

da870310 (lib[illegible])





<BY2>
<BX2>
<P/GM1>
<BZ2>
TIME
E-07
tearing mode

RESULTS:

1. Magnetic tearing occurs initially at a fast radiative-instability rate, $\Omega_{rad} \sim 10^{-0.9}\, n T^{-2}$

2. Temperature falls from 10^6K to 10^4 K, so that the Coulomb resistivity $\eta \sim T^{-3/2}$ increases by 10^3x

3. The high resistivity and sharp gradients ($\delta/a \sim 10^{-1}$) lead to a burst of <u>very</u> fast* reconnection $\Omega_{rec} \tau_h \sim 1$

4. Saturation appears to occur in the same way as for the normal tearing mode.

$$* \quad \tau_{rl} \sim \left(\frac{T}{T_0}\right)^{3/2} \left(\frac{\delta}{a}\right)^2 S_0\, \tau_{hg}$$