Thermal Equilibrium, Stability and Burn Control

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A number of aspects of thermal stability and equilibrium control of ignited tokamak plasmas have been investigated.

1-D calculations have been made of thermal instability eigen modes. It was found that for electron thermal induction loss given by Alcator scaling and for neoclassical ion transport, there is only one growing eigen mode with temperature profiles similar to the equilibrium profiles.

The effects of coupling of temperature fluctuations and fluctuations in major radius were investigated. Temperature driven radial motion combined with a small amount of ripple transport loss was found to be a very effective mechanism for passive thermal stability control.

Thermal stability studies of driven plasmas show that for constant external heating power, plasmas with $\phi_p < 2$ will be thermally stable. Active control by variable external heating has also been investigated.

Thermal equilibrium control will be needed to adjust the power output from fusion reactors. The use of impurities to vary power loss and allow for increase fusion power production at equilibrium has been studied.

THERMAL EQUILIBRIUM AND STABILITY OF IGNITED PLASMAS

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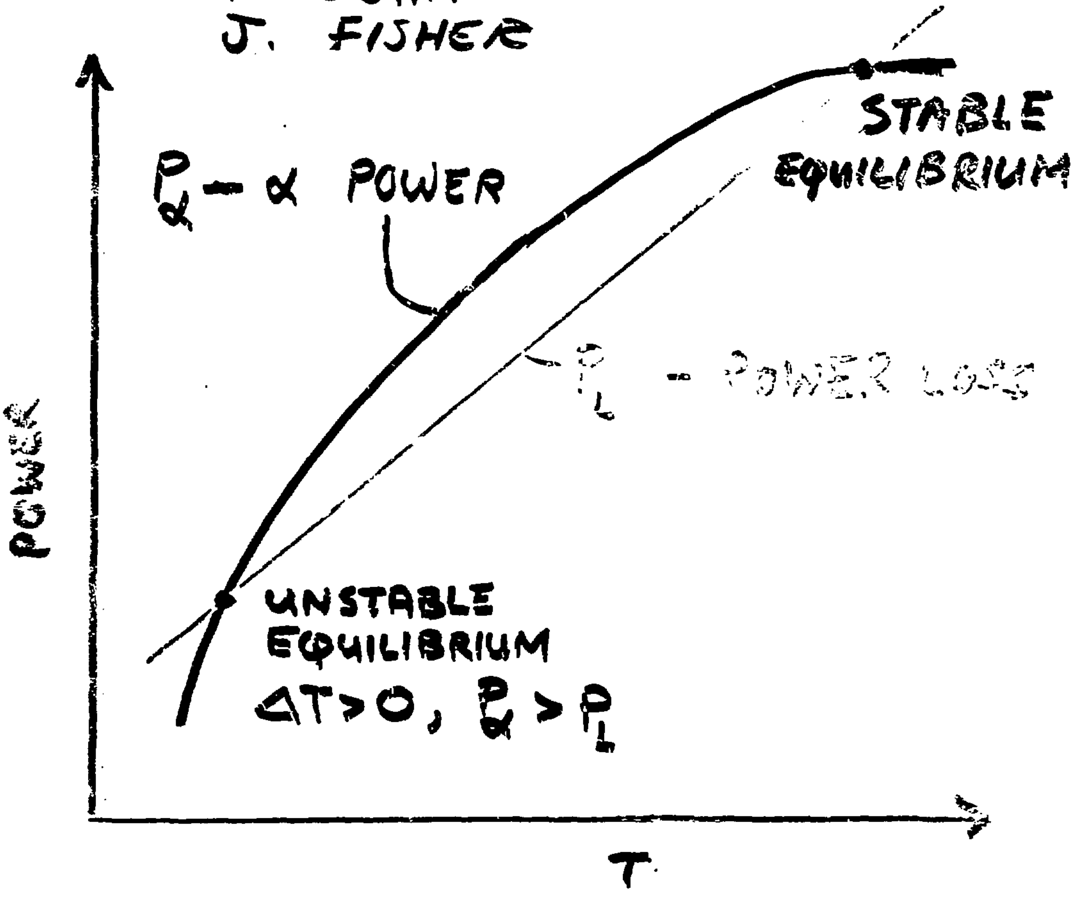


IGNITED THERMAL EQUILIBRIUM

$$P_\alpha = P_L$$

References: Nuc. Fusion 21, 201 (1981)
Nuc. Fusion 20, 203 (1980)
Nuc. Fusion 21, 109 (1981)
MIT Fusion Center Report RR-80-16

FUNCTIONS OF BURN CONTROL

- THERMAL STABILITY CONTROL
  - MAINTAIN REACTOR OPERATION AT TEMPERATURE WHICH MAXIMIZES PERFORMANCE:
    - HIGHEST FUSION POWER DENSITY FOR FIXED MAGNETIC PRESSURE $\langle T \rangle \approx 15$ keV
    - MINIMIZATION OF IMPURITY BUILD UP
    - MINIMUM $n\tau_E$ FOR IGNITION FOR FIXED MAGNETIC PRESSURE
  - PREVENT THERMAL RUNAWAY WHICH COULD LEAD TO PLASMA DISRUPTIONS, RAPID POWER SWINGS
  - MINIMIZE THERMAL FLUCTUATION LEVEL AROUND A STABLE POINT
- THERMAL EQUILIBRIUM CONTROL
  - SET OPERATING POINT TO OPTIMIZE REACTOR PERFORMANCE
  - VARY OUTPUT POWER LEVEL

BURN CONTROL APPROACHES EXAMINED IN ZEPHYR STUDY

- THERMAL STABILITY CONTROL MECHANISMS
  (BOTH 0-D AND 1-D)
  - PASSIVE CONTROL
    - EFFECT OF RADIAL MOTION. CHANGE IN MAJOR RADIUS CAUSED BY CHANGE IN TEMP.
    - EFFECT OF RADIAL MOTION AND SMALL ADDITIONAL TRANSPORT LOSS (BY MAGNETIC FIELD RIPPLE EFFECTS)
      (ANALOGOUS TO NEG. REACTIVITY IN FISSION REACTOR)
  - ACTIVE CONTROL
    - COMPRESSION AND DECOMPRESSION OF PLASMA
    - SUBIGNITED OPERATION WITH SMALL AMOUNT OF VARIABLE EXTERNAL HEATING
    - DENSITY CONTROL
  - THERMAL EQUILIBRIUM CONTROL
    - ADDITIONAL POWER LOSS FROM IMPURITY RADIATION
    - ENHANCED TRANSPORT FROM INCREASED RIPPLE

CALCULATION OF THERMAL STABILITY CHARACTERISTICS

1-D

- PLASMA DIVIDED INTO SEVERAL RADIAL ZONES: ION AND ELECTRON POWER BALANCE DESCRIBED BY SET OF DIFFERENCE EQUATIONS

χ_e - Alcator scaling

χ_i - $\chi_{neoclassical}$

- DIFFERENCE EQUATIONS LINEARIZED ABOUT THE EQUILIBRIUM PARAMETERS IN EACH ZONE

- EIGENMODES OF RESULTING SET OF COUPLED LINEAR EQUATIONS OBTAINED

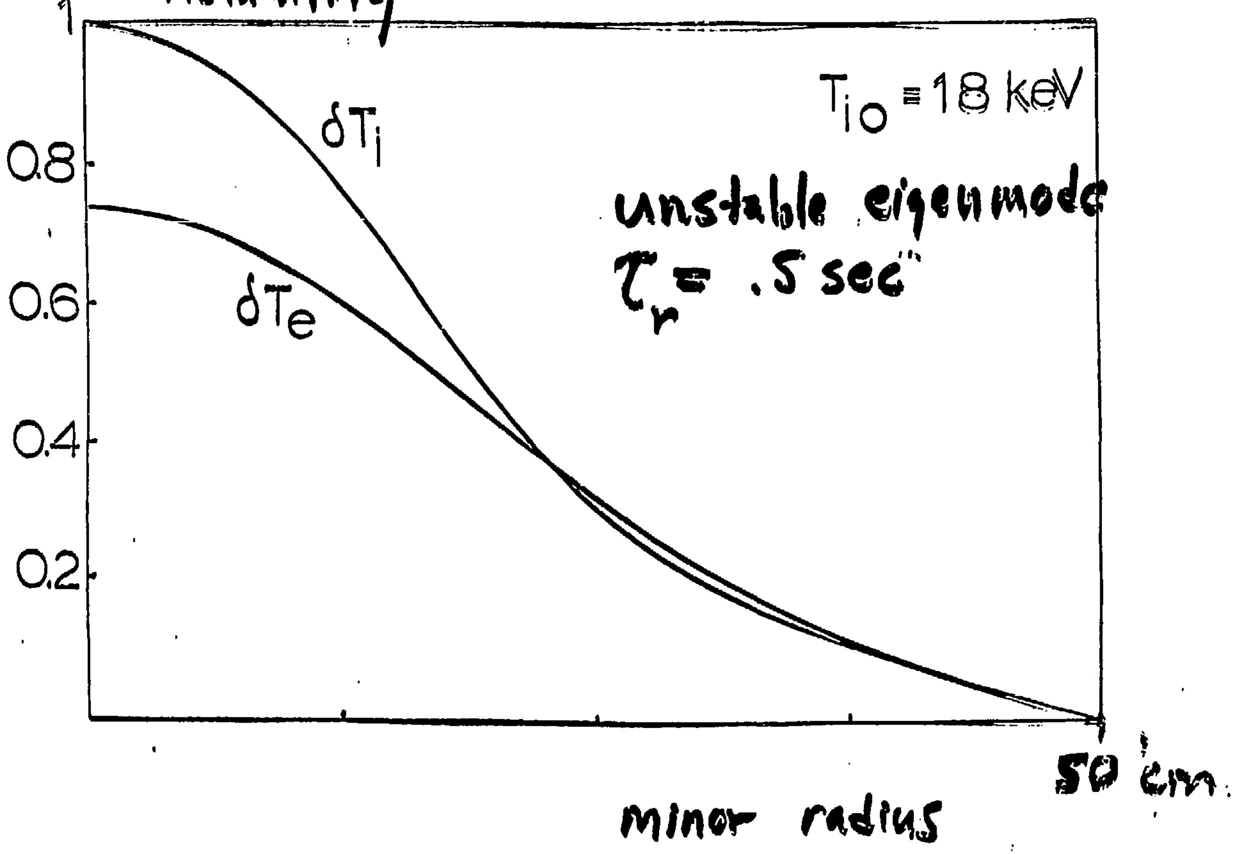
- IF LARGEST EIGENVALUE, γ_{MAX}, IS POSITIVE THE SYSTEM IS UNSTABLE

$$\tau_{RUNAWAY} = \frac{1}{\gamma_{MAX}}$$

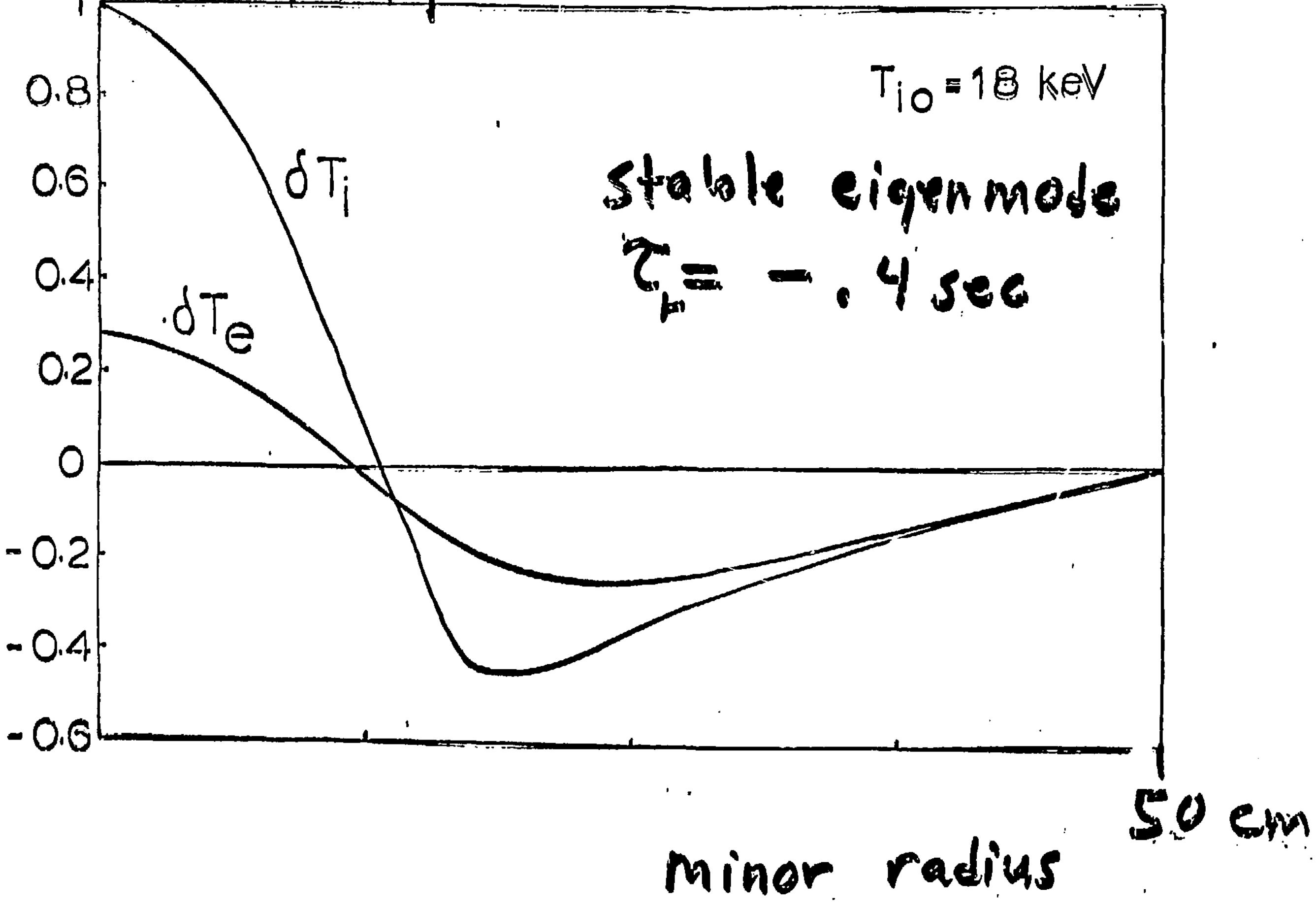
THERE IS ~~ONLY~~ AT MOST ONE UNSTABLE MODE (WITH A TEMPERATURE PROFILE WHICH MAINTAINS THE TEMPERATURE PROFILE AT THERMAL EQUILIBRIUM)

DAMPED EIGENMODES DO NOT MAINTAIN PROFILES

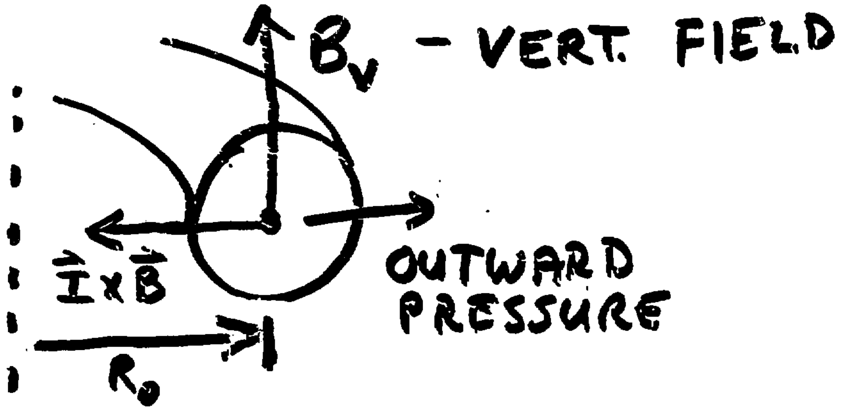
1-D Calculation of Thermal Instability



1-D calculation of thermal instability



EFFECTS OF COUPLING OF POSITION OF MAJOR RADIUS WITH THERMAL PERTURBATIONS



- PLASMA IN POSITIONAL EQUIL. BECAUSE OF BALANCE BETWEEN OUTWARD PRESSURE AND INWARD FORCE FROM VERTICAL FIELD

- FOR FIXED VERTICAL FIELD: TEMP EXCURSION → PRESSURE EXCURSION → CHANGE IN MAJOR RADIUS

- RADIAL MOTION → REDUCED DENSITY → REDUCED ALPHA POWER

$$n = n_0 \left(\frac{R_0}{R}\right)^2$$ by conservation of particles and flux

$$P_\alpha \sim n^2 \sim \left(\frac{R_0}{R}\right)^4$$

ILLUSTRATIVE CALCULATION OF THERMAL INSTABILITY

THERMAL STABILITY DETERMINED BY LINEARIZING POWER BALANCE AROUND IGNITED THERMAL EQUIL. POINT

POWER BALANCE: $(0\text{-D}, T_e = T_i)$

$$n \frac{dT}{dt} = P_\alpha - P_\ell = P_{NET}$$

AT EQUILIBRIUM : $T = T_0$; [redacted]; $R = R_0$; $P_{NET} = 0$

$T = T_0 + T_1$

$$\frac{dT_1}{dt} = \frac{1}{n}\left[\frac{\partial}{\partial T}(P_{NET}) + \frac{\partial}{\partial R}(P_{NET})\frac{dR}{dT}\right] T_1$$

$\frac{dT_1}{dt} = \gamma T_1$; $\gamma < 0$ PLASMA STABLE

τ_r – RUNAWAY TIME ; $\tau_r = \frac{1}{\gamma}$

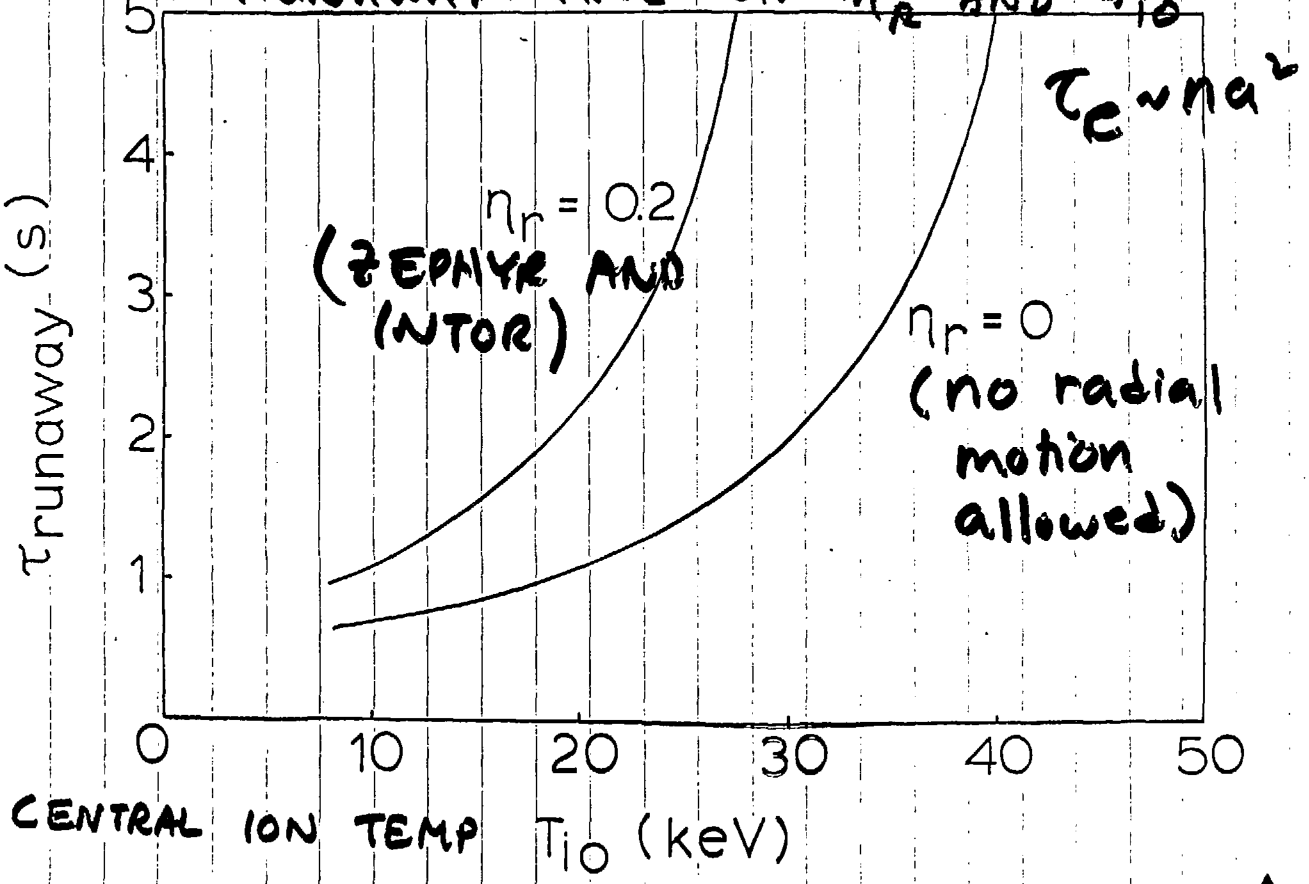
$\gamma = f(\eta_r)$; $\eta_r = \frac{1}{R}\frac{dR}{dT}$

η_r -- ELASTICITY OF RADIAL MOTION

$$\eta_r = f(n, \beta_p)$$

$$n_r = -\frac{R}{B_v}\frac{dB_v}{dR} \; ; \; \beta_p = \frac{nkT}{B_p^2/2\mu_0}$$

1-D CALCULATION OF DEPENDENCE OF RUNAWAY TIME ON η_R AND T_{io}



THERMAL STABILITY — $\tau_{RUNAWAY} \to \infty$

PASSIVE THERMAL STABILITY CONTROL BY RADIAL MOTION AND RIPPLE TRANSPORT

PRESENCE OF MAG FIELD RIPPLE PROVIDES ADDITIONAL LOSS

$$P_{ADD} = \frac{nT}{CT^{-\epsilon} f(R)} \sim \frac{T^{\epsilon+1}}{C} \left(\begin{array}{l} \epsilon = 7/2 \text{ FOR RIPPLE TRAPPING} \\ \epsilon = 3/2 \text{ FOR RIPPLE PLATEAU} \end{array} \right)$$

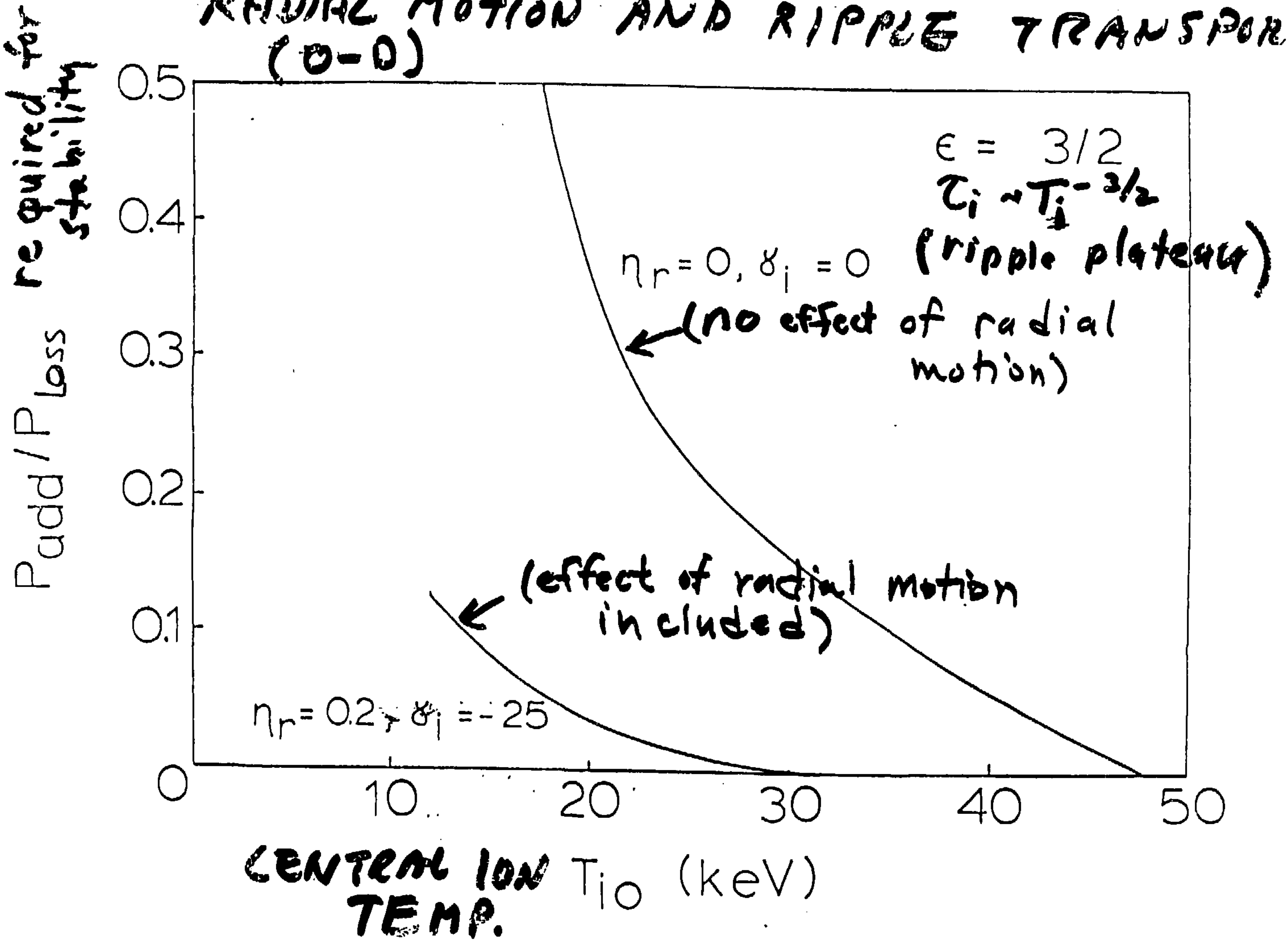
C - ADJUSTABLE PARAMETER WHICH REPRESENTS AMOUNT OF LOSS

- THREE STABILIZING MECHANISMS
  - EFFECT OF RADIAL MOTION
  - P_{ℓ} (= P_{ℓ}, INTRINSIC + P_{ADD}) INCREASES WITH T
  - P_{ℓ} INCREASES WITH R; R INCREASES WITH T

- P_{ADD} for thermal stability found by linearizing power balance equations and finding C necessary for $\gamma = 0$

- Very effective thermal stability control mechanism

THERMAL STABILITY CONTROL BY RADIAL MOTION AND RIPPLE TRANSPORT (D-D)



ACTIVE CONTROL BY COMPRESSION-DECOMPRESSION

- FEEDBACK ON VERT. FIELD TO INCREASE n_r

$$n_r = n_r + \underset{\substack{\uparrow \\ \text{feedback}}}{g}$$

- ADIABATIC COMPRESSION-DECOMPRESSION.

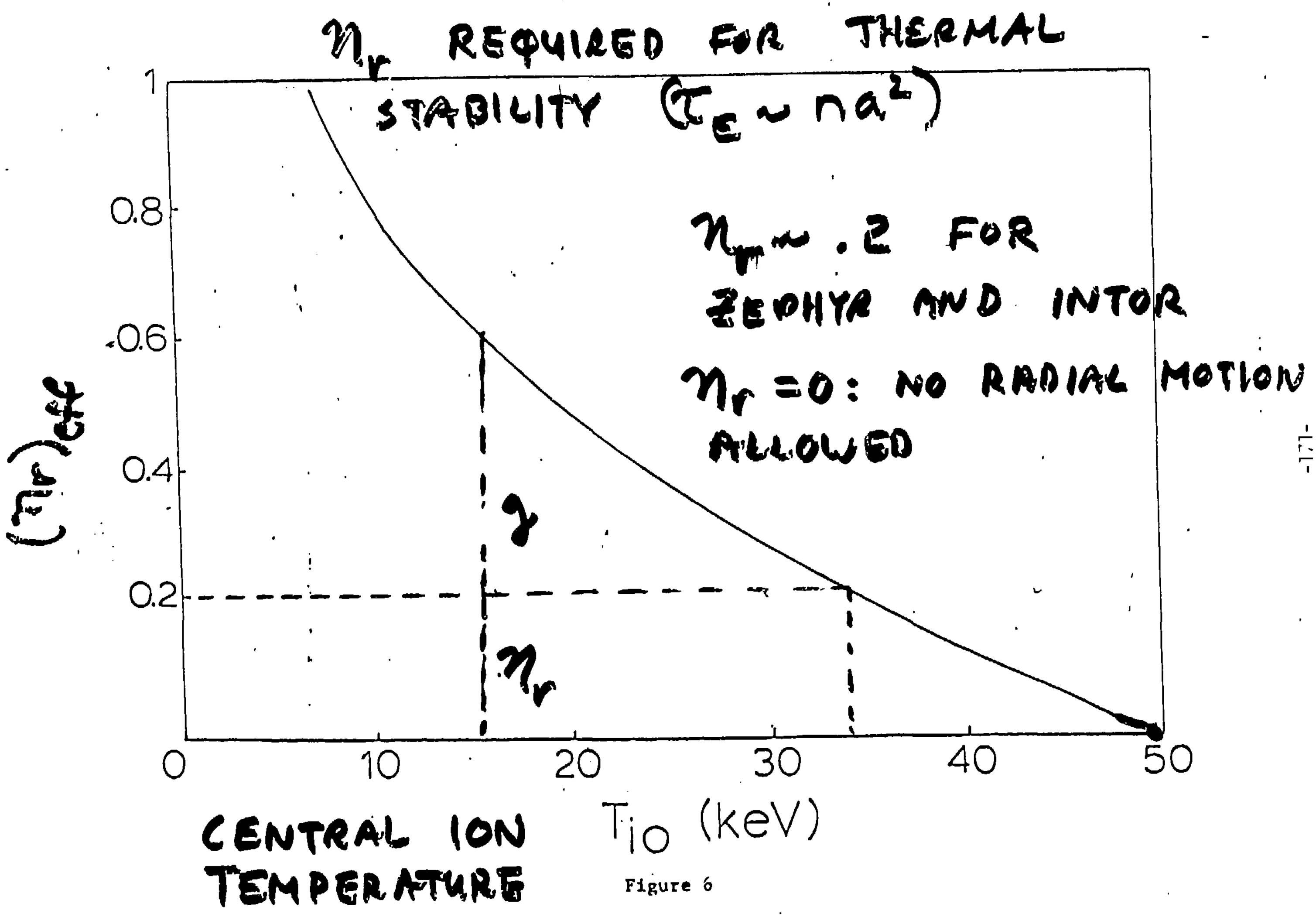

η_r REQUIRED FOR THERMAL STABILITY $(\tau_E \sim na^2)$
$\eta_r \sim .2$ FOR ZEPHYR AND INTOR
$\eta_r = 0$: NO RADIAL MOTION ALLOWED
1
0.8
0.6
0.4
0.2
$(\eta_r)_{eff}$
γ
η_r
0
10
20
30
40
50
T_{io} (keV)
CENTRAL ION TEMPERATURE

Figure 6

ACTIVE CONTROL BY VARIABLE EXTERNAL HEATING OF SUBIGNITED PLASMA

- HIGH Q OPERATION

$$Q = \frac{P_F}{P_H} = \frac{P_F}{P_\alpha - P_L}$$

P_H = EXTERNAL HEATING POWER

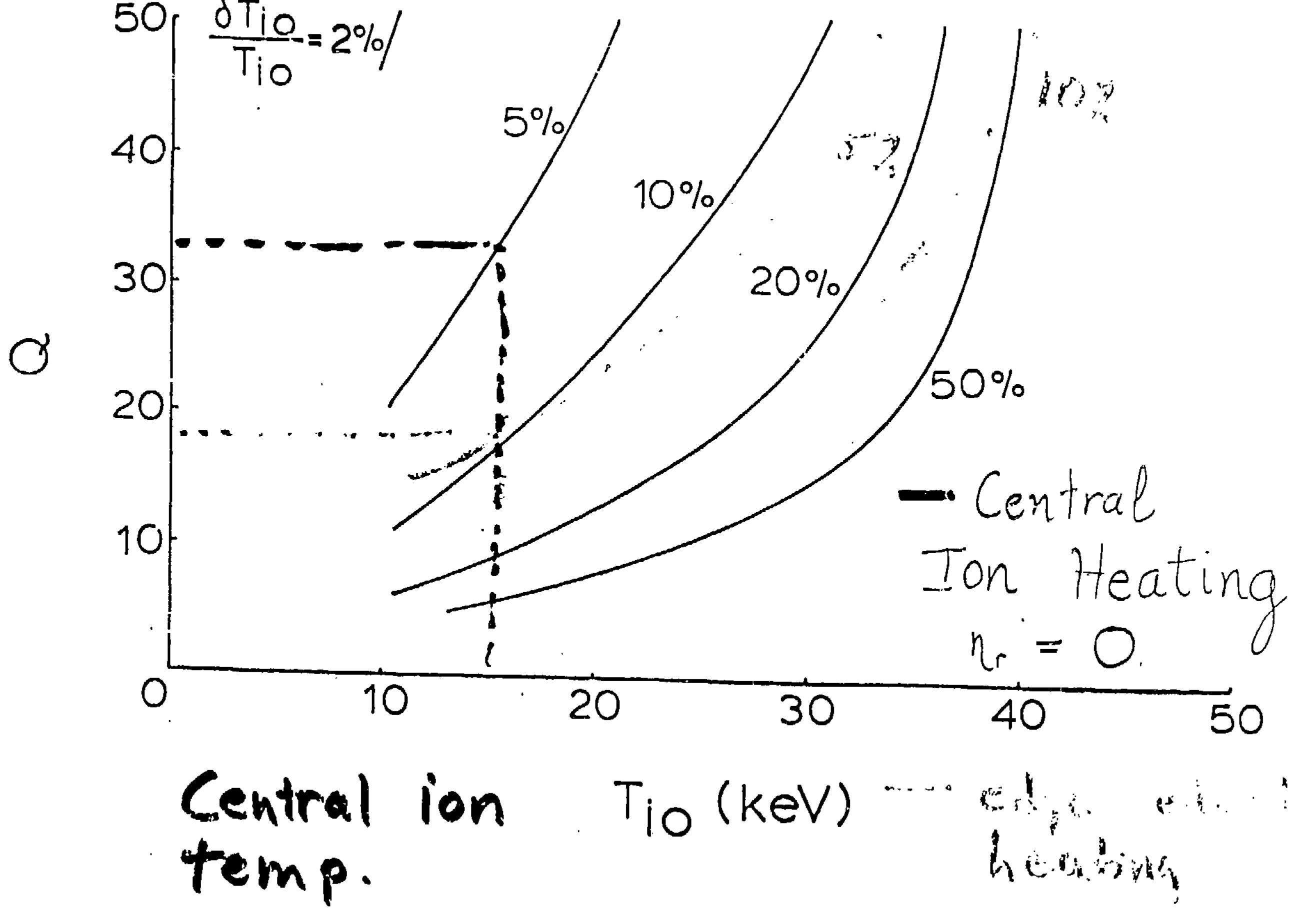
- CONTROL
  - FOR POSITIVE TEMP. EXCURSION: DECREASE P_H
  - FOR NEGATIVE TEMP. EXCURSION: INCREASE P_H
  - LIMIT OF CONTROL: THERE IS A MAXIMUM POSITIVE PERTURBATION THAT CAN BE CONTROLLED BY SETTING $P_H = 0$.

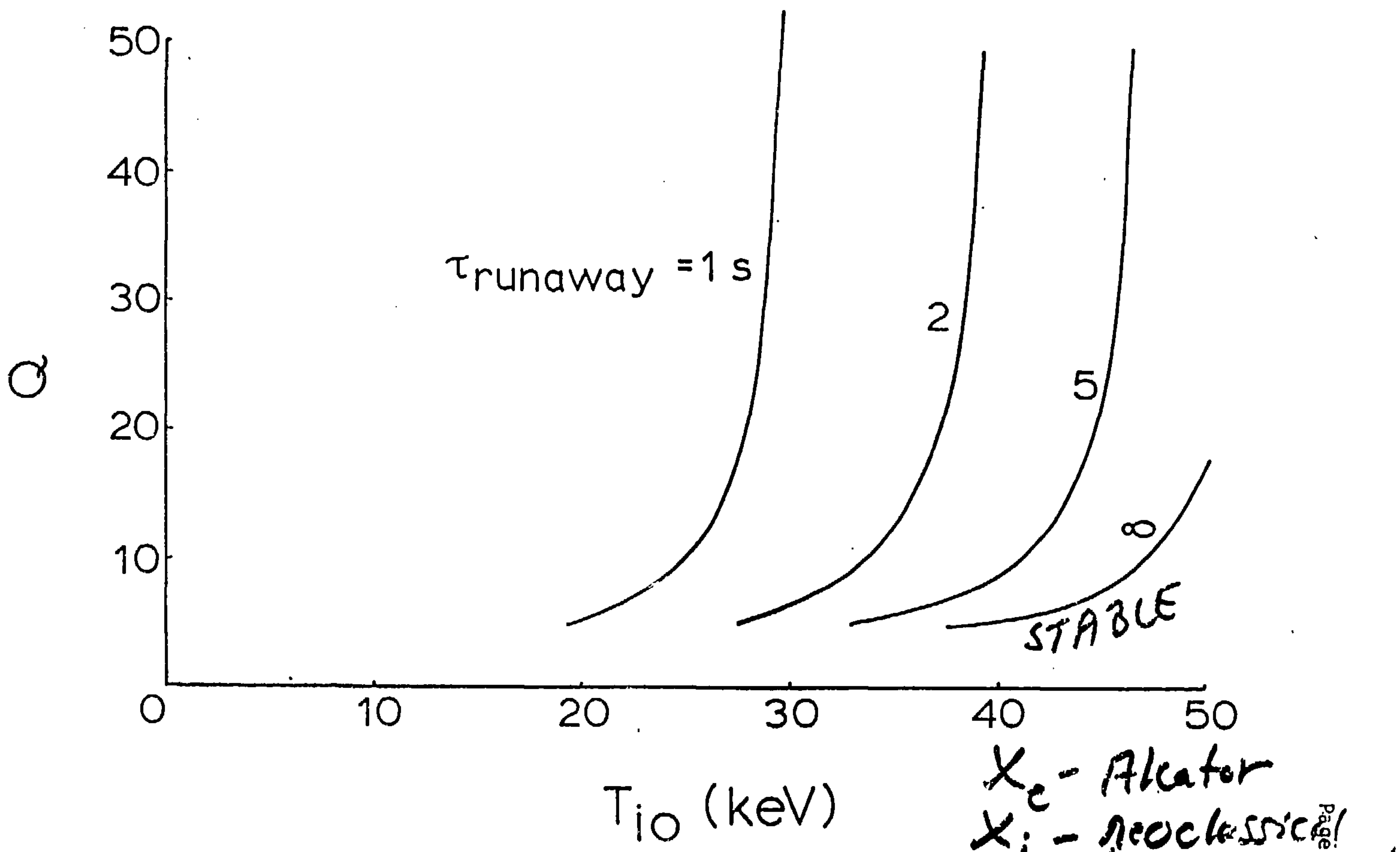
$$\partial(P_\alpha - P_L) \leq P_H$$

$$\frac{\partial}{\partial T}(P_\alpha - P_L)\,\delta T \leq P_H$$

- OR FOR GIVEN δT THERE IS A MINIMUM VALUE OF P_H AND HENCE A MAXIMUM Q

MAXIMUM Q FOR CONTROL BY VARIABLE HEATING





χ_e - Alcator
χ_i - neoclassical ion transport

Figure 1

EFFECT OF DRIVEN OPERATION ON
THERMAL STABILITY

POWER REGULATION OF SELF SUSTAINED TOKAMAKS

- COMPARISON TO FISSION REACTORS

<u>FISSION</u>

$\phi \longrightarrow$ POWER

ϕ - neut. flux

$K = 1 \longrightarrow$ EQUILIBRIUM

$K \neq f(\phi)$

<u>FUSION</u>

$P_F = 5P_\alpha \longrightarrow$ POWER

$P_{NET} = (P_\alpha - P_{LOSS}) = 0 \longrightarrow$

EQUILIBRIUM

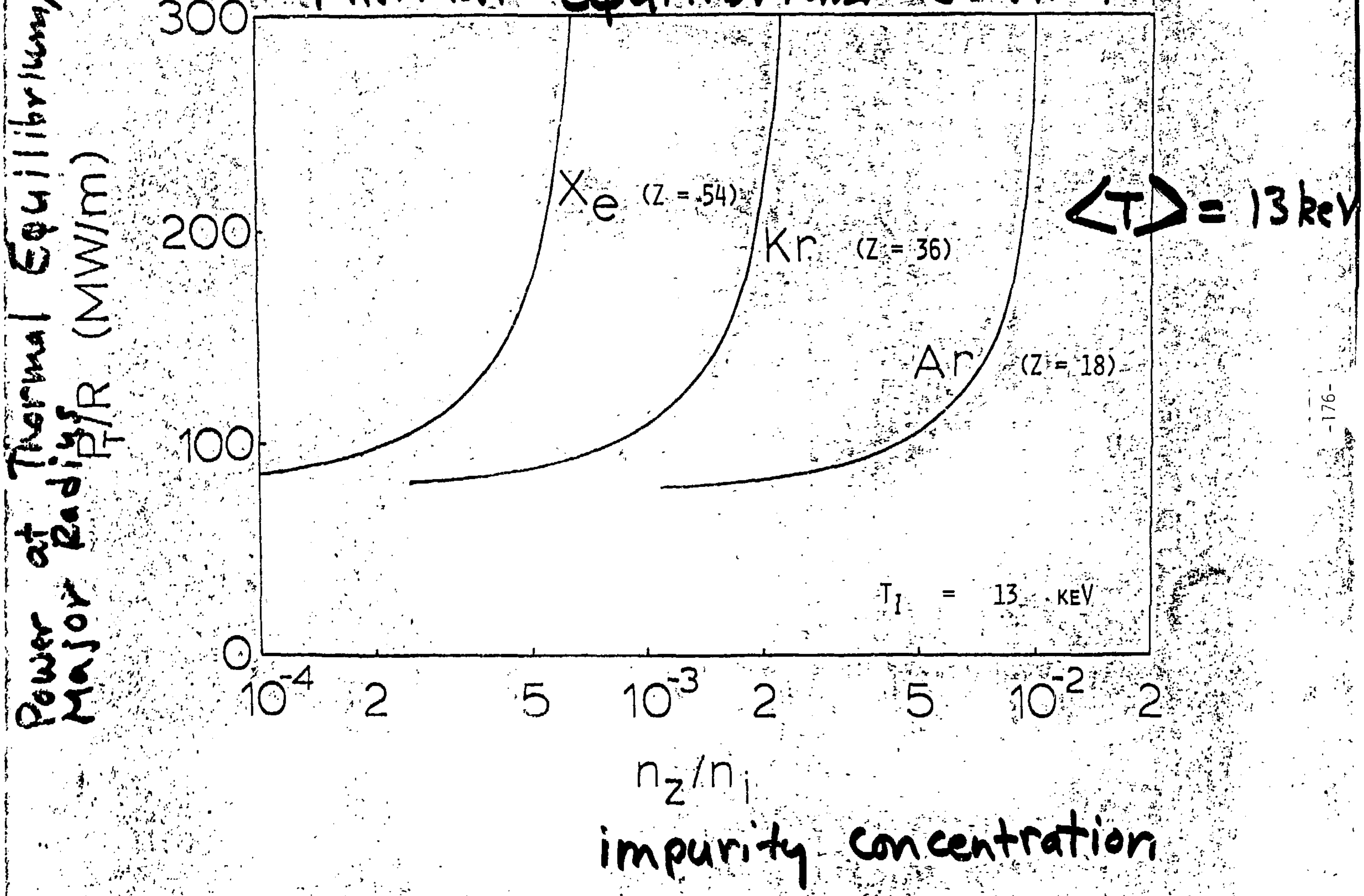
TO CHANGE POWER MUST VARY

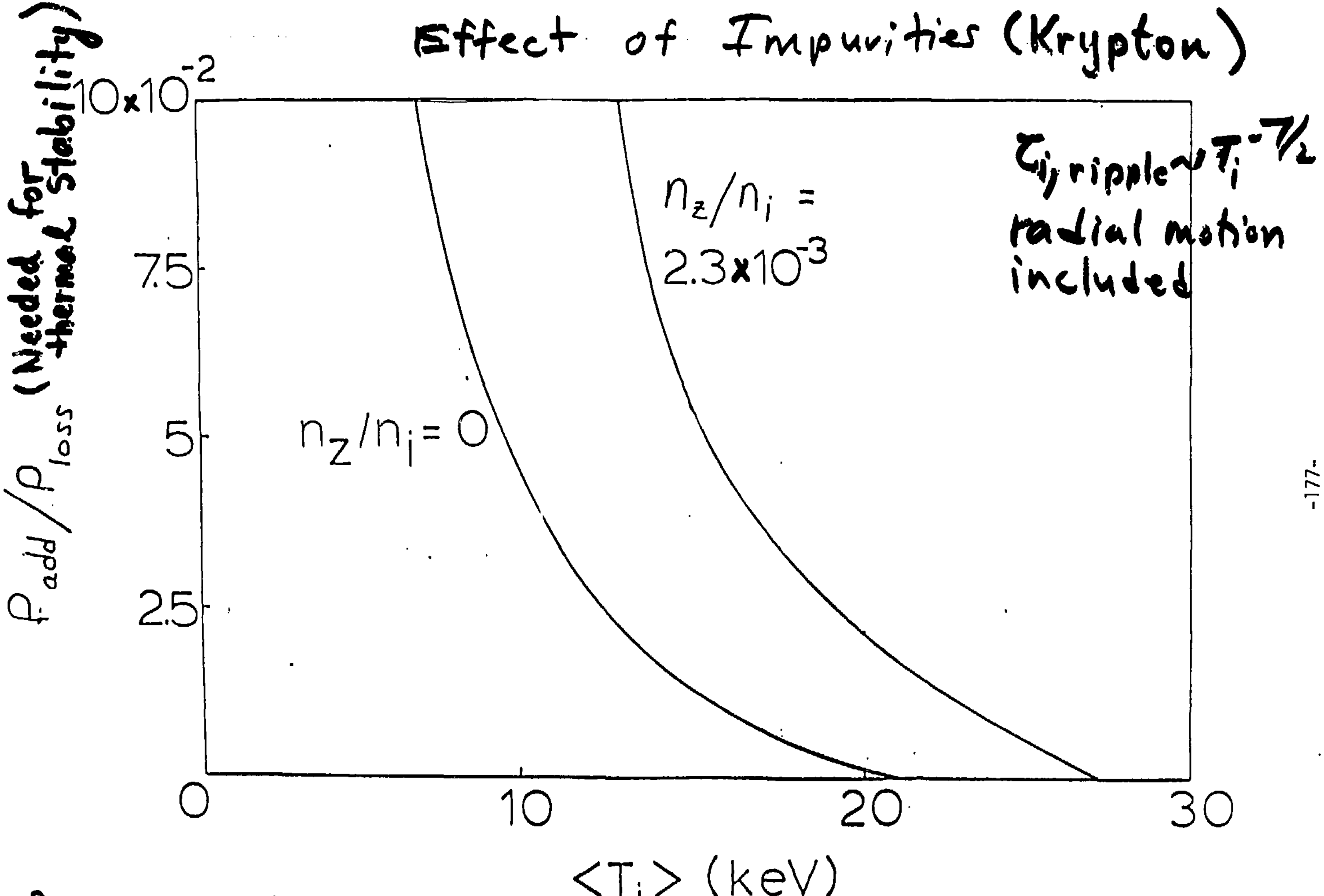
P_α AND P_{LOSS}

$P_{LOSS} = P_{LOSS, INTRIN} + P_{ADD}$

- USE OF IMPURITIES
  - SMALL AMOUNTS OF ARGON (Z = 18), KRYPTON (Z = 36) OR XENON (Z = 54) TO INCREASE POWER LOSS
  - P_α INCREASED TO BALANCE LOSS.
  - INCREASED POWER LOSS UNIFORMLY DISTRIBUTED
  - INDEPENDENT TEMPERATURE AND POWER LEVEL CONTROL
  - INCREASED TENDENCY TOWARD THERMAL INSTABILITY
  - THERMAL STABILITY BY RADIAL MOTION AND SMALL AMOUNT OF RIPPLE

Thermal Equilibrium Control





PASSIVE THERMAL STABILITY WITH RIPPLE
(AND RADIAL MOTION)