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PHYSICS DESIGN OPTIONS FOR COMPACT IGNITION EXPERIMENTS*

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PHYSICS ASSESSMENTS - DESIGN IMPACT

Physics Area	Design/Engr Impact	Evaluation
Confinement	a, R, B_t, I_p... Ignition Margin Auxiliary Power	0-D, 1-D & 1-1/2-D Analyses
Magnetics	Divertor/Limiter Assessments	MHD Equilibria
	PF Control System	Positional Stability
Startup & Operating Scenarios	Pulse Lengths PF & TF Power Supplies	1-D & 1-1/2-D Analyses
β-limit	a, R, B_t, I_p... Wall/Limiter/ Divertor Loadings	Troyon Limit MHD Stability (Near Walls)
ICRF Heating	Power Port Size	Ant. Coupling Minority Species 2nd Harmonic
α Physics	Flat-top Time Diagnostics	1-D & 1-1/2-D Analyses

0-D Confinement Analysis

Features included in the model:

- Plasma profiles and geometry.
- Neoclassical resistivity enhancement.
- Various forms of χ_e and χ_i.
- Physics constraints

  q_ψ

  $\beta_{crit} \sim I/aB_o$,

  $n_{murakami} \sim B_o/R_o$
- Equilibrium plasma current profile.
- Fuel, alphas and impurities (Z_{eff}).

Steady-state global analysis is a useful complement to full 1-1/2-D transport code calculations.

- A simple analytic global model is developed to establish ignition conditions and plasma parameters operating regimes over large regions of parameter space (R_0/a, b/a, aB_0^2/q_*, etc.) under various physics assumptions (χ_e, χ_i, q_ψ, β_{crit}, n_{crit}, etc.)
- This simple model includes detailed enough physics information to be useful in exploring the options and reproduces many global features and trends of the 1-1/2-D WHIST transport code calculations (especially those of POPCON's).
- For many of the confinement scalings considered, it was possible to generate nearly universal contour plots of ignition, auxiliary power requirements, optimal path to ignition, plasma heating and operating windows, etc. in terms of a small number of parameters (such as aB_0^2/q_*, $\langle n\rangle/n_{mu}$, $\langle T\rangle$, etc.)
  - this is found to be useful for rapid assessment of a particular device and/or classes of devices with equivalent performance
- These contour plots are used to analyze potential physics design space, operating regimes, and plasma performance characteristics of small ($R_0 \sim$ 1-2 m), high field ($B_0 \sim$ 8-13 T) tokamak ignition experiments

Calculations are based on global analysis

► Local enegy balance equation

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial t}\left[\frac{3}{2} n_e k T_e + \frac{3}{2} n_i k T_i\right] = P_{aux} + P_{OH} + P_{\alpha} - P_{con} - P_{rad}$$

averaged over a flux surface for a given plasma profiles.

► Geometry:

Concentric flux surfaces with elongation $\kappa = b/a$ and triangularity δ.

► Profiles: Typical profiles assumed are as shown

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• $\underline{r \leq r_s}$:

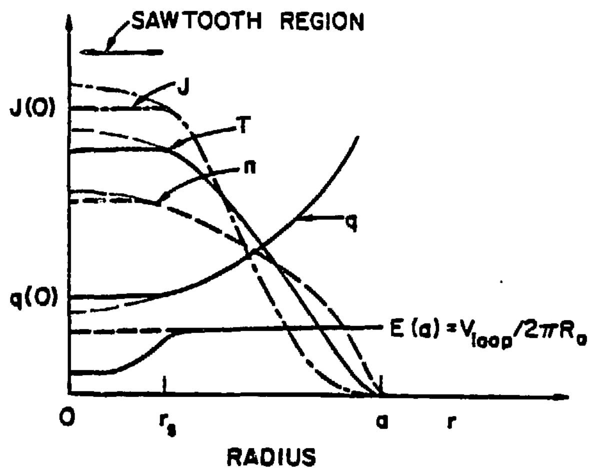
$T = T_0$; $J = J(0)$; $q = q(0)$

• $\underline{r > r_s}$:

$n, T \sim (1 - r^2/a^2)^{\alpha_{n,T}}$

$\alpha_n \sim 0.5$; $\alpha_T \sim 1.0$

$J \sim T_e^{3/2}$



Definitions:

Ignition Margin	$M = \dfrac{P_\alpha + P_{OH}}{P(\text{all losses})}$
MHD safety factor	$q_\psi = q_* \, f(\epsilon, \beta_p, \ldots)$
Equivalent cylindrical safety factor	$q_* = \dfrac{5aB_0}{I}\left(\dfrac{a}{R_0}\right)\left[\dfrac{1+\kappa^2(1+2\delta^2)}{2}\right]$
"Figure of merit"	aB_0^2/q_*

Constraints/Limits:

Density limit	$\bar{n}_{20} \leq n_{murakami} = \nu_{mu} B_0/(q_* R_0)$ $\nu_{mu} \sim 1.5$ (OH) > 1.5 (aux)
Beta limit	$\beta_{total} < \beta_{crit} = 3I/(aB_0)$ (%)

Units:

mks units with T in keV,
n_{20} in $10^{20}\,m^{-3}$, I in MA
P in MW.

The flux-surface-averaged energy balance equation (ions plus electrons) is

$$\frac{\partial}{\partial t}\left[\frac{3}{2}n_e kT_e + \frac{3}{2}n_i kT_i\right] = -P_{con} - P_{rad} + P_\alpha + P_{OH} + P_{aux}$$

where

$$P_{con} = -\frac{1}{V'(\rho)}\frac{\partial}{\partial \rho}\left[A(\rho)\left(n_e\chi_e\frac{\partial kT_e}{\partial \rho} + n_i\chi_i\frac{\partial kT_i}{\partial \rho}\right)\right]$$

$$P_{rad}(MW/m^3) = 5.3\times10^{-43}\, n_e^2 Z_{eff} T_e^{1/2} \simeq 1.68\times10^{-2}\, n_{e20}^2 Z_{eff} T_{e10}^{1/2}$$

$$P_\alpha(MW/m^3) \simeq 0.155\left[4f_D(1-f_D)f_{DT}^2\right] n_{e20}^2 T_{i10}^s$$

$$P_{OH}(MW/m^3) \simeq 10^6\,\eta_\parallel(\text{ohm}\cdot\text{m})\, J^2(MA/m^2)$$

$$\simeq 5.22\times10^{-5}\,\gamma_{NC} Z_{eff}\ln\Lambda\, J^2/T_{e10}^{3/2}$$

$$V(\rho) = 2\pi^2 R_0\rho^2\kappa \quad , \quad V' = \partial V/\partial\rho$$

$$A(\rho) = V'(\rho)\langle(\nabla\rho)^2\rangle \quad , \quad \langle(\nabla\rho)^2\rangle = (1+\kappa^2)/2\kappa^2$$

$$Z_{eff} = \Sigma\, n_i Z_i^2/n_e \quad , \quad n_e = \Sigma\, n_i Z_i$$

$$f_{DT} = n_{DT}/n_e = (n_D+n_T)/n_e \quad , \quad f_D = n_D/n_{DT}$$

$$\eta_\parallel = \gamma_{NC}\,\eta_{spitzer} \quad , \quad \gamma_{NC} \simeq \left[1-1.95(r/R_0)^{1/2}+0.95(r/R_0)\right]^{-1}$$

$$\langle\sigma v\rangle_{DT} \simeq 1.1\times10^{-22}\, T_{i10}^s\ (m^3/s) \begin{cases} s\sim 3 & 4<T_i<10\text{ keV} \\ s\sim 2 & 10<T_i<20\text{ keV}\end{cases}$$

Global power balance

- multiply energy balance eq. with $V'(\rho)\,d\rho$ integrate over ρ with assumed profiles

$$n = n_0 (1-\rho^2/a^2)^{\alpha_n}, \quad T = T_0 (1-\rho^2/a^2)^{\alpha_T}, \quad J = J_0 (1-\rho^2/a^2)^{\alpha_j}$$

$$\frac{\partial W}{\partial t} = -P_{con} - P_{rad} + P_\alpha + P_{OH} + P_{aux} \qquad (\mathrm{MW})$$

Here:

$$W = W_e + W_i = 0.24\, n_{e20} T_{e10} \left(1 + \frac{n_i}{n_e}\frac{T_i}{T_e}\right) V \qquad (\mathrm{MJ})$$

$$P_{con}\,(\mathrm{MW}) = 0.16\, n_{e20} T_{e10} \left(\chi_e + \frac{n_i}{n_e}\frac{T_i}{T_e}\chi_i\right)\left[\frac{4}{a^2}\left(\frac{1+\kappa^2}{2\kappa^2}\right) g_c\left(\frac{\rho_*}{a}, \alpha_n, \alpha_T\right)\right]$$

$$\text{--}\quad g_c = \alpha_T (1+\alpha_n+\alpha_T)\left(\frac{\rho_*^2}{a^2}\right)\left(1 - \frac{\rho_*^2}{a^2}\right)^{\alpha_n+\alpha_T-1}$$

[Temperature gradients are evaluated at $\rho_*/a < 1$
-- typically $\rho_*/a \sim 0.6 - 0.8 \Rightarrow g_c \sim O(1)$]

$$P_{rad}\,(\mathrm{MW}) = C_B\, n_{e20}^2\, T_{e10}^{1/2}\, Z_{eff} V \,; \qquad C_B(\alpha_n, \alpha_T) \sim (1.6-1.9)\times 10^{-2}$$

$$P_\alpha\,(\mathrm{MW}) = C_\alpha\, n_{e20}^2\, T_{e10}^{s}\, V \,; \qquad C_\alpha(\alpha_n,\alpha_T) \sim 0.22 \quad (s\sim 3)$$

for $Z_{eff} \sim 1.5$,
$\alpha_n \sim 0.5, \alpha_T \sim 1.0$

$$P_{OH}\,(\mathrm{MW}) = C_{OH}\, Z_{eff}\, \bar{\gamma}_{NC}\, T_{e10}^{-3/2}\left(\frac{B_0^2}{q_0^2 R_0^2}\right)\left(\frac{1+\kappa^2}{2\kappa}\right)^2 V$$

-- $C_{OH} \sim 5.4\times 10^{-4}$ $(\ln\Lambda \sim 16, \alpha_n \sim 0.5, \alpha_T \sim 1.0)$

-- $\bar{\gamma}_{NC} \sim 2.8 - 2.2$ for $A = R_0/a \sim 2.5 - 3.5$

Also $P_{con} \sim \int \frac{nT}{\tau}\,dV \Rightarrow \chi_j = \frac{3}{8}\frac{a^2}{\tau_{Ej}}\left(\frac{2\kappa^2}{1+\kappa^2}\right) g_{\chi_i}(\rho_*/a) \quad j = e, i$

typically: $g_\chi \sim 0.8 - 1.1$

Confinement Models
(Representative thermal diffusivities)

• <u>Ions</u>: Neoclassical – Chang-Hinton

$$\chi_{iCH}\,(m^2/s) \simeq 2\times10^{-2}\, K_2^* \,\frac{n_{e20}\, Z_{eff}\, q_*^2}{\epsilon^{3/2}\, T_{i0}^{1/2}\, B_0^2}\left(\frac{2}{1+\kappa^2}\right)$$

$$K_2^* = (0.66 + 1.88\,\epsilon^{1/2} - 1.54\,\epsilon)(1+1.5\epsilon^2) \qquad \epsilon = r/R_0$$

• <u>Electrons</u>: Empirical

- Ohmic -- NeoAlcator

$$\tau_{NA} \simeq 0.07\, n_{e20}\, a\, R_0^2\, q_*$$

$$\chi_{NA}\,(m^2/s) \simeq \frac{4.3\, a}{n_{e20}\, R_0^2\, q_*}\left(\frac{2\kappa^2}{1+\kappa^2}\right)$$

- Auxiliary -- various L- and H-mode scalings

Typically $\tau_E \sim I^{(1-1.5)}\,[\,P^{-(1/3-2/3)}$ or $b + a/P\,]$

χ_e (L-mode) $\sim (2-4)\,\chi_e$ (OH)

χ_e (H-mode) $\sim 0.5\,\chi_e$ (L-mode)

-- For example: GMS / Mirnov scaling

$$\tau^L_{E(mir)} \sim 0.12\, a\, I\, \kappa^{1/2} \;\Rightarrow\; \chi^L_{E(mir)} \simeq \frac{2.5\,a}{I\,\kappa^{1/2}}\left(\frac{2\kappa^2}{1+\kappa^2}\right)$$

$$\tau^H_{E(mir)} \simeq (2-3)\,\tau^L_{E(mir)}$$

-- For example: Kaye-Goldston scaling

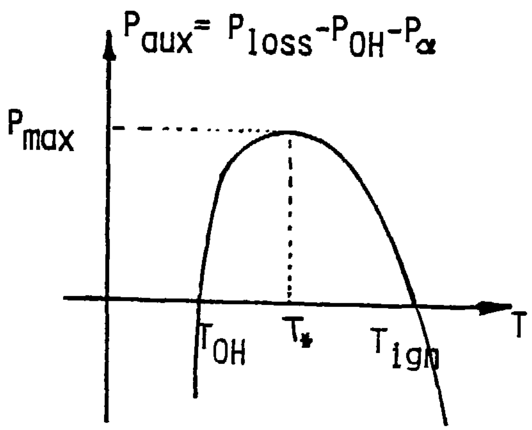
$$\tau^L_{EKG} \simeq 0.056\, I^{1.24}\, P^{-0.58}\, R_0^{1.65}\, a^{-0.49}\, \kappa^{0.28}\, n_{e20}^{0.26}\, B_0^{-0.09}\, A_i^{0.5}$$

$$\tau^H_{EKG} \sim 2\,\tau^L_{EKG}$$

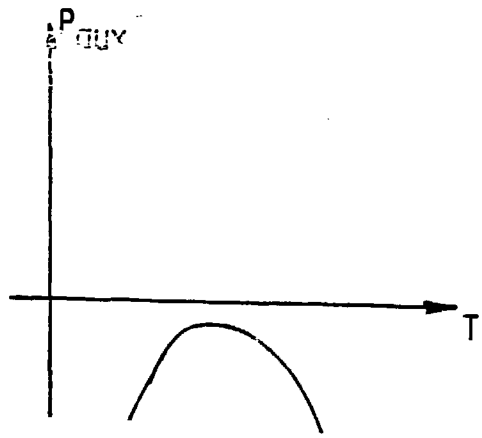
Steady-state (equilibrium) : $\partial W / \partial t = 0$

$$P_\alpha + P_{OH} + P_{aux} = P_{con} + P_{rad} = P_{losses}$$

There are two possibilities



$P_{aux} \geq P_{max}$ is required for ignition



Ohmic ignition

$$P_{max} = P_{aux}(T_*) \longrightarrow \partial P_{aux} / \partial T = 0 \quad \text{at} \quad T = T_*$$

Plasma parameter operating space is constrained by:

- Confinement (ion & electron transport, impurities).
- MHD effects (β limit, q_ψ, etc).
- Density limit (Murakami limit).

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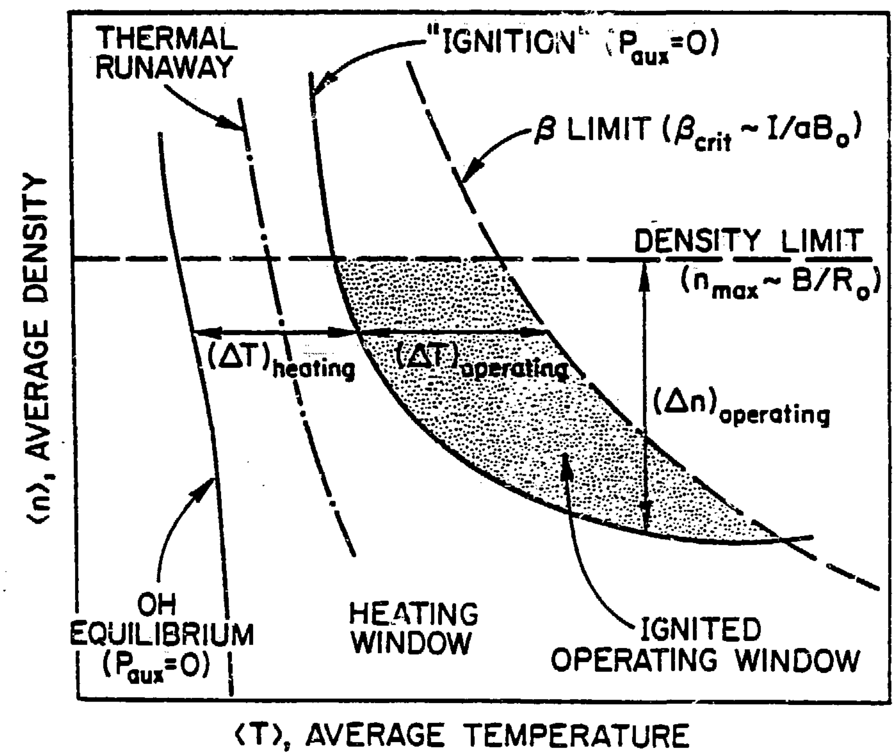


Special Cases:

$(\Delta T)_{heating} \to 0$		Ohmic Ignition
$(\Delta T)_{operating} \to 0$		No Ignition
$(\Delta n)_{operating} \to 0$		No Ignition

Desirable Characteristics:

$(\Delta T)_{heating} \to$ 0-few keV	Low P_{aux}
$(\Delta T)_{operating} \to$ several keV	Ignition margin
$(\Delta n)_{operating} \to (0.2\text{-}0.5)\,n_{max}$	Ignition margin

To cover the range of possibilities for the confinement scalings and to bracket the options for ignition experiments, we choose

- "Optimistic", ohmic-like scaling
  - Neo Alcator ($\tau \sim n$)
- "Pessimistic," L-mode-like scaling
  - Kaye-Goldston ($\tau \sim P^{-\alpha}$)
    with $P = P_\alpha + P_{OH} + P_{aux}$

A generalized ohmic / auxiliary scaling

$$\frac{1}{\tau_E^2} = \frac{1}{\tau_{EOH}^2} + \frac{1}{\tau_{Eaux}^2}$$

$\tau_{EOH} \Rightarrow$ neo-alcator

$\tau_{Eaux} \Rightarrow f\, \tau_{EKG}^{L}$; $f = 1$ L-mode

$= 2$ H-mode

Steady-state power balance equation

$$F = -P_{con} - P_{rad} + P_{\alpha} + P_{OH} + P_{aux} = 0$$

can be reformulated in terms of a small number of parameters, thus identifying classes of devices with equivalent performance.

One such formulation

$$F = F(m, T, X)$$

$$m = \frac{\langle n \rangle}{n_{murakami}} = \text{normalized density}$$
("Murakami parameter")

$$T = \langle T \rangle = \langle nT \rangle / \langle n \rangle$$
= density-averaged temperature

X = "Figure of merit" parameter $\sim (n\tau)$

For neo-Alcator, Kaye-Goldston, Mirnov, etc.-like scalings

$$X = aB_0^2 / q_*$$

Similar parameterization (in terms of these or any other similar quantities) is also possible for other confinement scalings

Examples for ohmic-like scaling

a) $\tau_E = \tau_{neoalcator}$

b) $\chi_e = f_{ex}\, \chi_{neoalcator}$

$\chi_i = f_{ix}\, \chi_{chang\text{-}Hinton}$

- Functional form:

  $(\tau \sim n a R_0^2 q_*)$

- Typical parameter range ("standard" tokamak)

  $A \sim 3 \pm 0.5$

  $\kappa \sim 1.6 - 1.7$

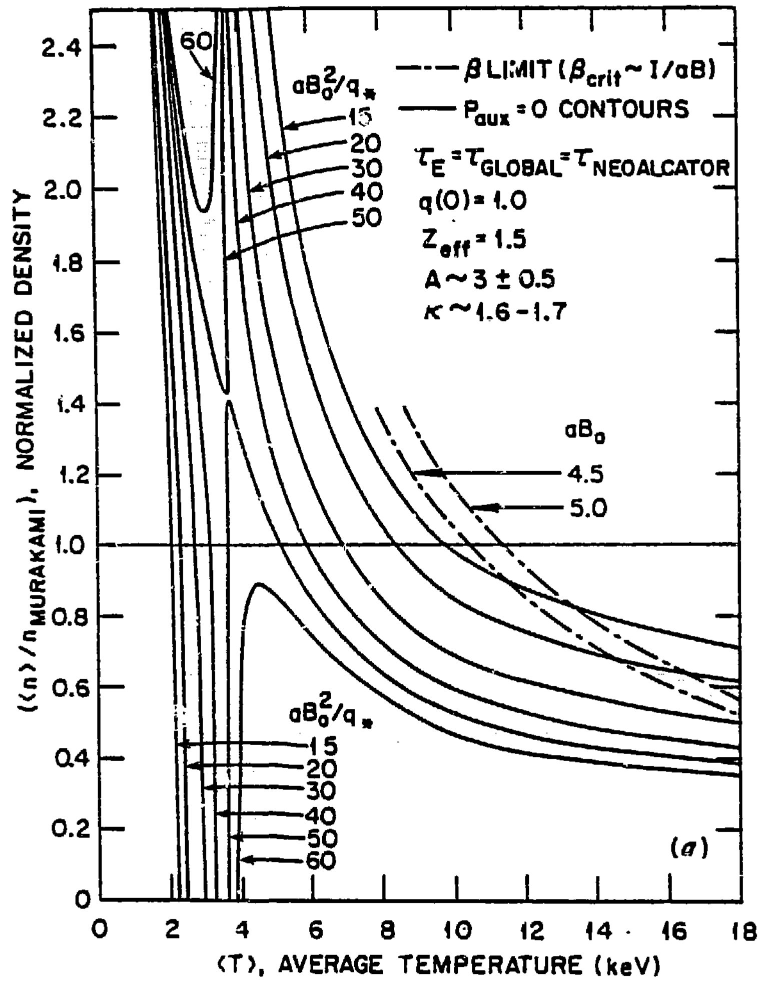
  $q_\psi \sim 2.6$

  $Z_{eff} \sim 1.5$

  $(a B_0 \sim 4.5 - 5.0)$

Steady-state P_{aux} = 0 contours for various values of aB_0^2/q_* showing:

- Requirements for ohmic ignition.
- Relative size of heating and operating windows.
- Optimal route (min P_{aux}) to ignition.



OH ignition if $aB_0^2/q_* > 57$

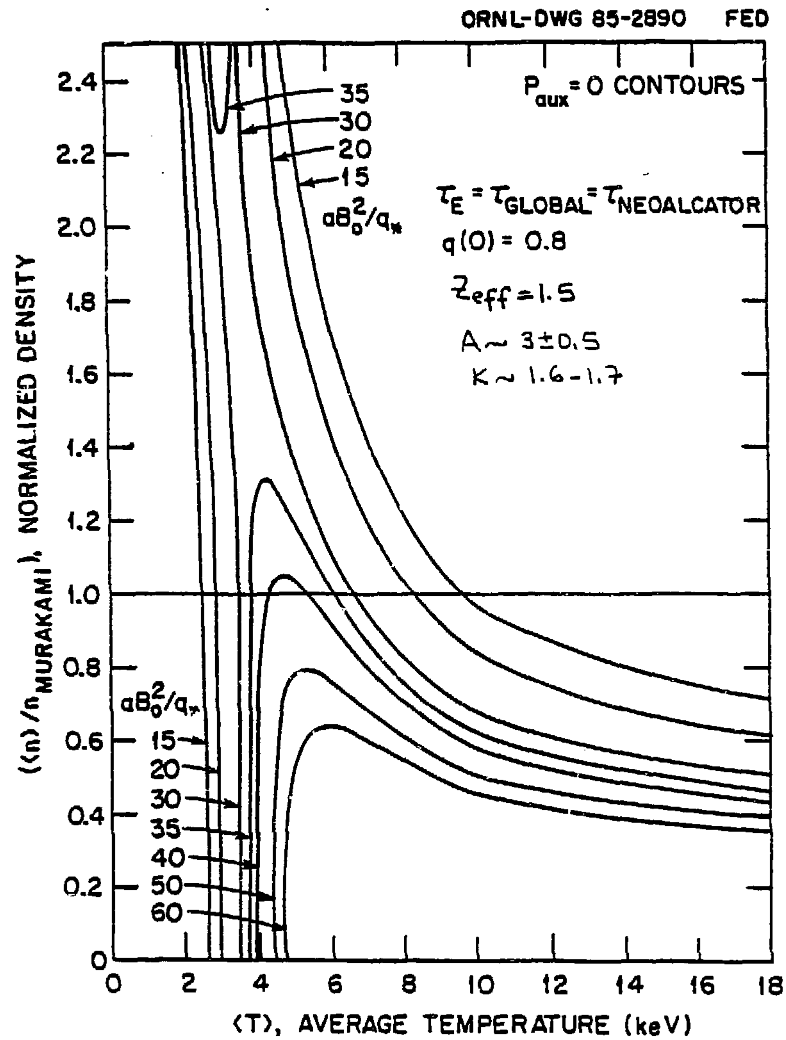
Confinement model: $\tau_E = \tau_{Global}$

$= \tau_{Neoalcator}$

(ohmic-like scaling) $q(0) = 1.0$

Steady-state P_{aux} = 0 contours for various values of aB_0^2/q_* showing:

- Requirements for ohmic ignition.
- Relative size of heating and operating windows.
- Optimal route (min P_{aux}) to ignition.



OH ignition if $\frac{aB_0^2}{q_*} > 41$

Confinement model: $\tau_E = \tau_{Global}$

(ohmic-like scaling) $= \tau_{Neoalcator}$

$q(0) = 0.8$

Summary -- Steady-state $P_{aux} = 0$ Contours

Conf. model : $\tau_E = \tau_{global} = \tau_{neoalcator}$

(a) $q(0) = 1.0$ (b) $q(0) = 0.8$

Superimposed are $\beta = \beta_{crit} = 3\, I/aB_o$ (%) contours

(Geometry: $A \sim 3 \pm 0.5$, $\kappa \sim 1.6$–1.7)

(ohmic-like scaling)

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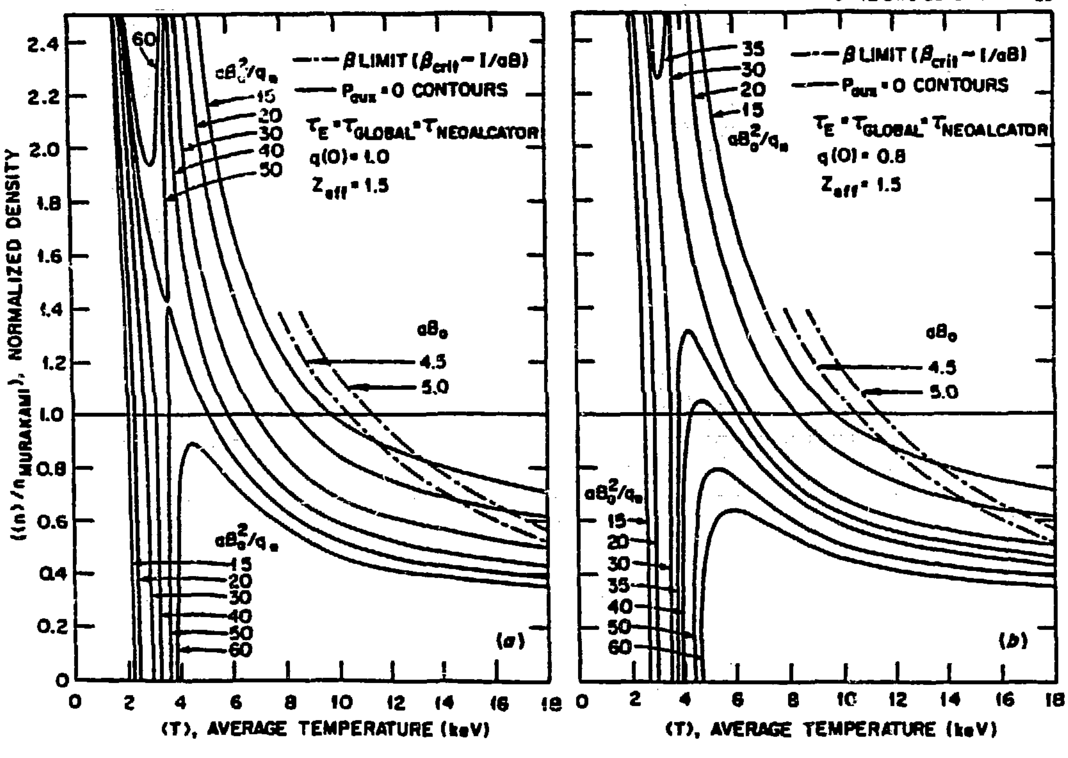

$\tau_{global} = \tau_E = \dfrac{W}{P_{con}}$ (global energy conf. time -- due to conduction)

Steady-state $P_{aux} = 0$ contours for various values of aB_0^2/q_* showing:

- Requirements for ohmic ignition.
- Relative size of heating and operating windows.
- Optimal route (min P_{aux}) to ignition.

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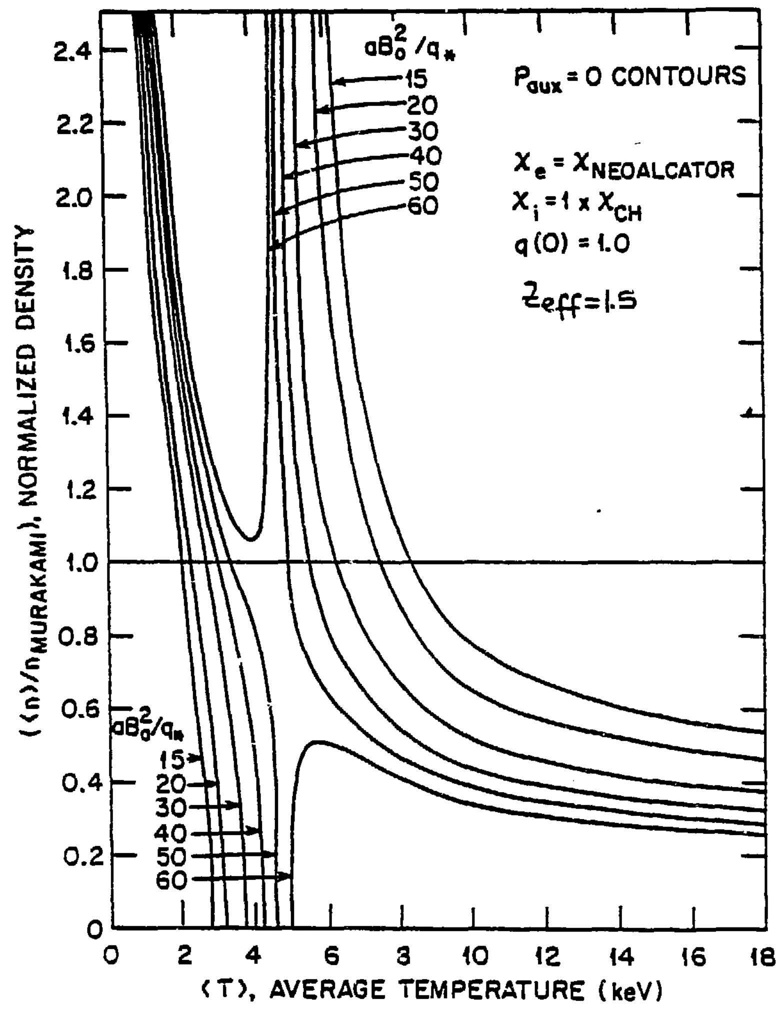

• OH ignition if $\frac{aB_0^2}{q_*} > 52$

Confinement model: $\chi_e = \chi_{Neoalcator}$
(ohmic-like) $\chi_i = 1 \times \chi_{Chang\text{-}Hinton}$
$q(0) = 1.0$

Steady-state P_{aux} = 0 contours for various values of aB_0^2/q_* showing:

- Requirements for ohmic ignition.
- Relative size of heating and operating windows.
- Optimal route (min P_{aux}) to ignition.

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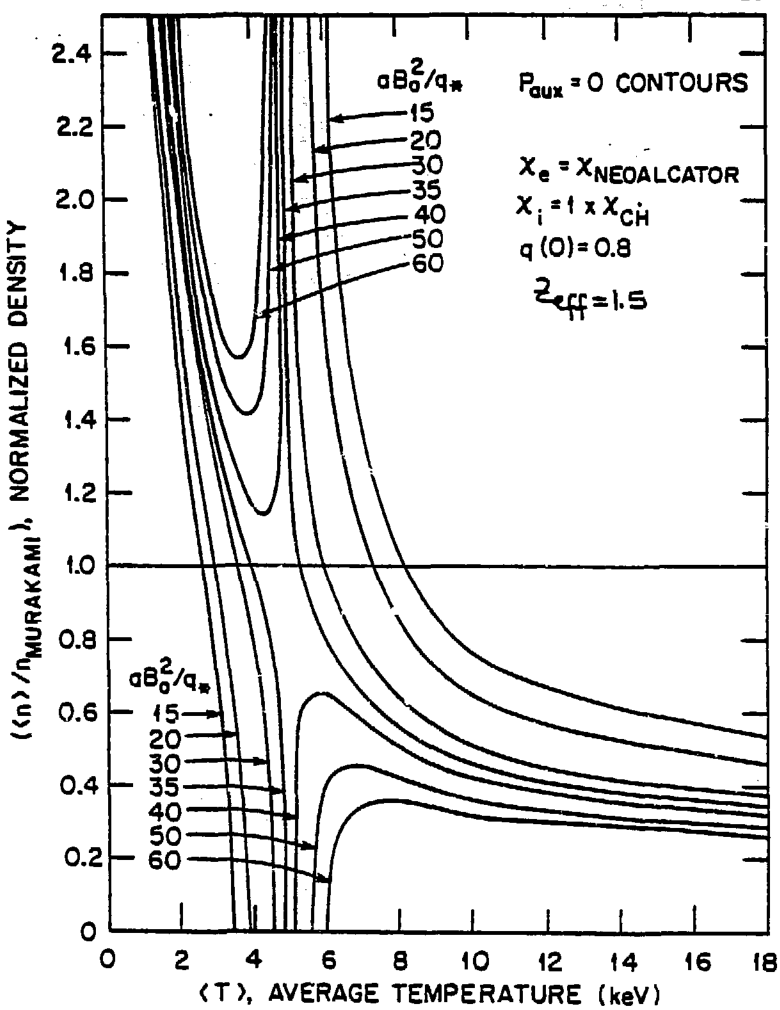


• OH ignition if $\frac{aB_0^2}{q_*} > 37$

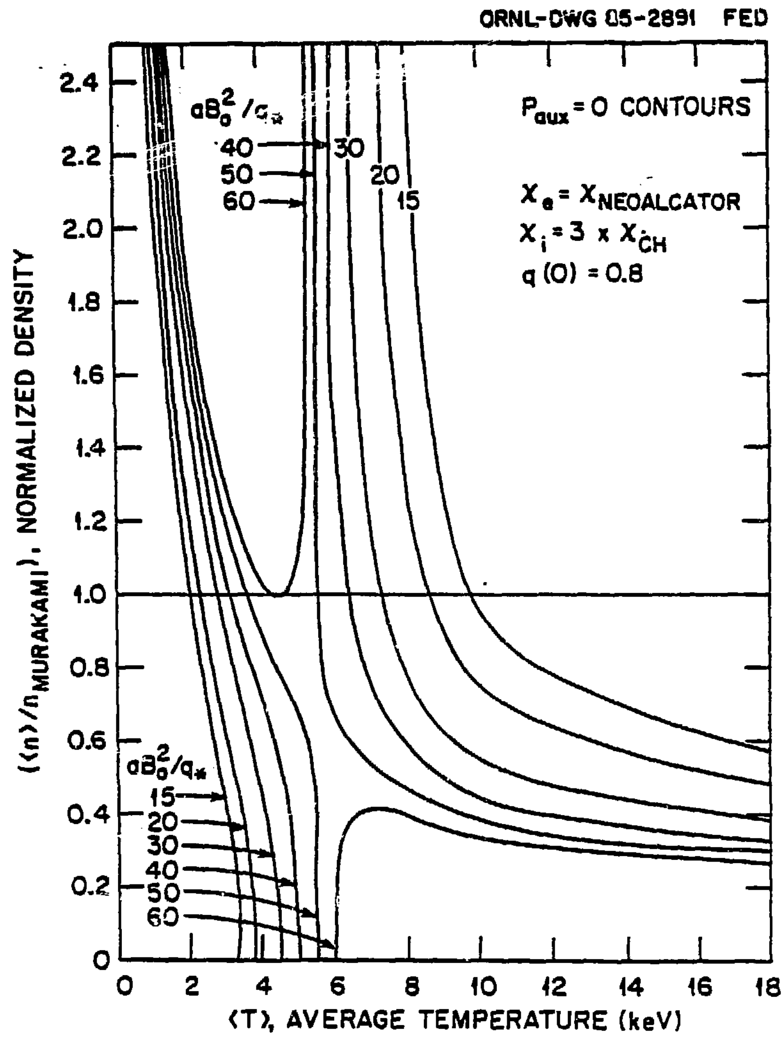
Confinement model: $\chi_e = \chi_{Neoalcator}$

(ohmic-like) $\chi_i = 1 \times \chi_{Chang-Hinton}$

$q(0) = 0.8$

Steady-state $P_{aux} = 0$ contours for various values of aB_0^2/q_* showing:

- Requirements for ohmic ignition.
- Relative size of heating and operating windows.
- Optimal route (min P_{aux}) to ignition.



OH ignition if $\frac{aB_0^2}{q_*} > 55$

Confinement model: $\chi_e = \chi_{Neoalcator}$

(ohmic-like) $\chi_i = 3 \times \chi_{Chang\text{-}Hinton}$

$q(0) = 0.8$

SUMMARY -- Steady-state $P_{aux} = 0$ contours

Conf. models (a) $\chi_e = \chi_{neo\text{-}alcator}$ $\chi_i = 1 \times \chi_{chang\text{-}Hinton}$

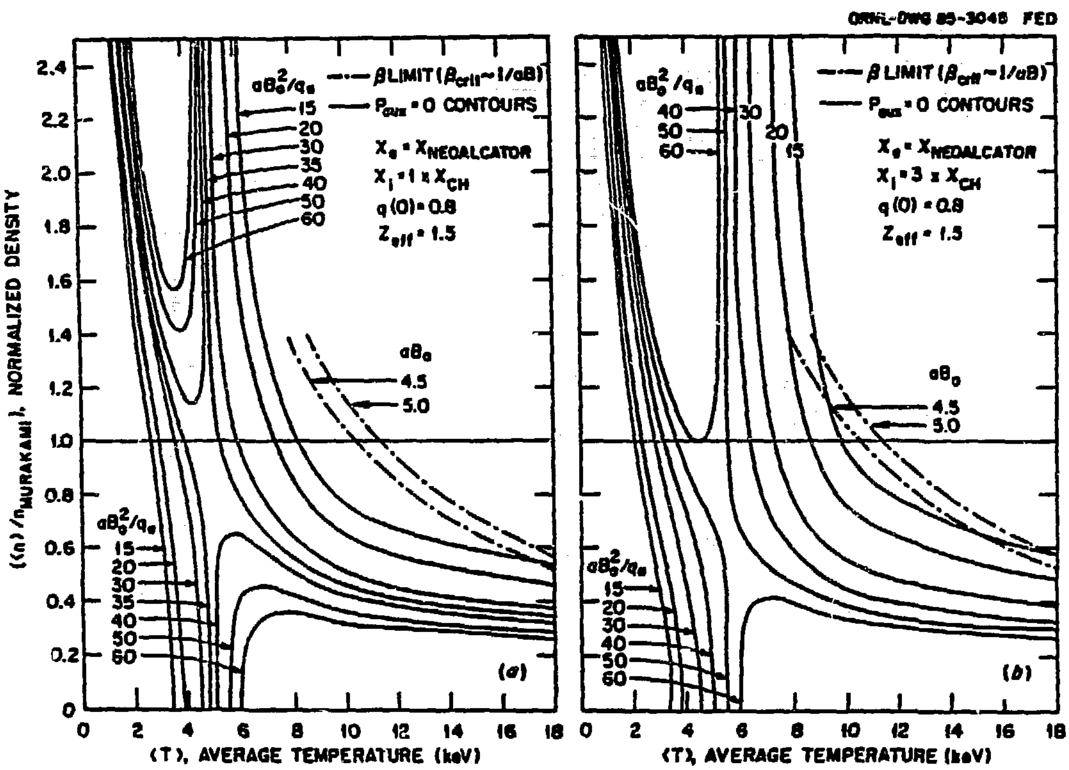
(b) $\chi_e = \chi_{neo\text{-}alcator}$ $\chi_i = 3 \times \chi_{chang\text{-}Hinton}$

Superimposed are $\beta = \beta_{crit} = 3I/aB_o$ (%) contours.

Optimal density path to ignition (narrowest ΔT heating window) is clearly evident and it occurs at

(a) $\langle n \rangle \simeq 0.85\ n_{murakami}$

(b) $\langle n \rangle \simeq 0.65\ n_{murakami}$

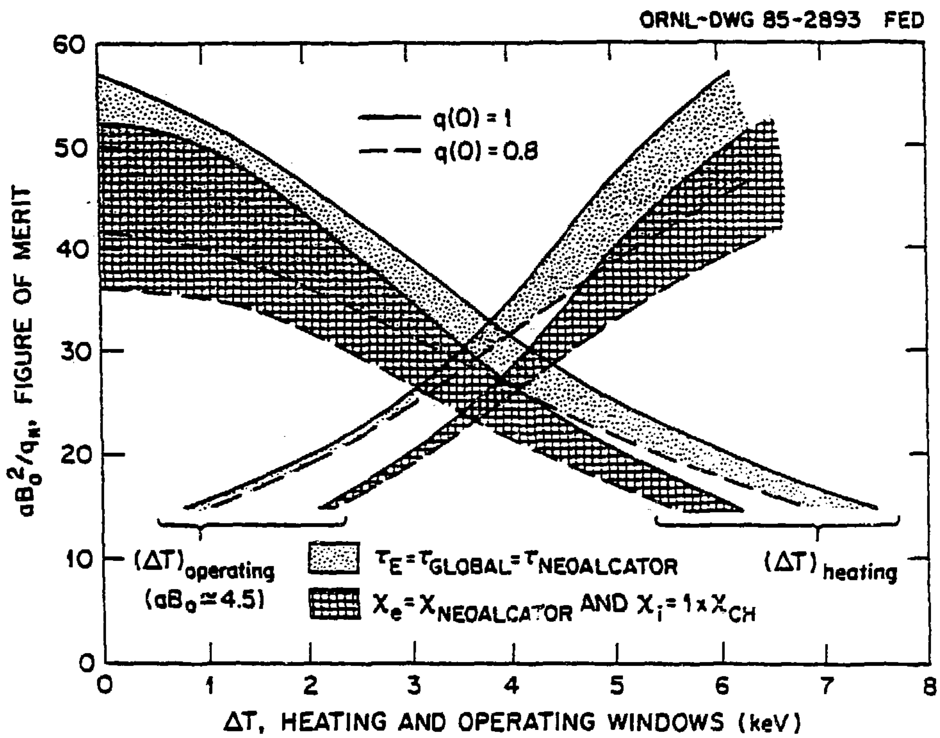


(ohmic-like-scaling)

Devices with large aB_o^2/q_* have favorable heating and operating windows.

As aB_o^2/q_* increases

- (ΔT) heating window decreases
  - ► small P_{aux} requirements
  - ► margin against uncertainties
- (ΔT) operating window increases
  - ► margin against uncertainties
  - ► separation of ignition physics from β and density limits



(ohmic-like scaling)

$(\Delta T)_{op}$ in the figure is measured at the Murakami limit.

$(\Delta T)_{op}$ is larger along the optimal density path.

Note: Assumption of q(0)=1.0 or q(0)=0.8 has very little or no impact on $(\Delta T)_{op}$ for $aB_o^2/q_* < 25$.

Maximum attainable margin for ignition within the plasma operating window increases with increasing aB_o^2/q_*.

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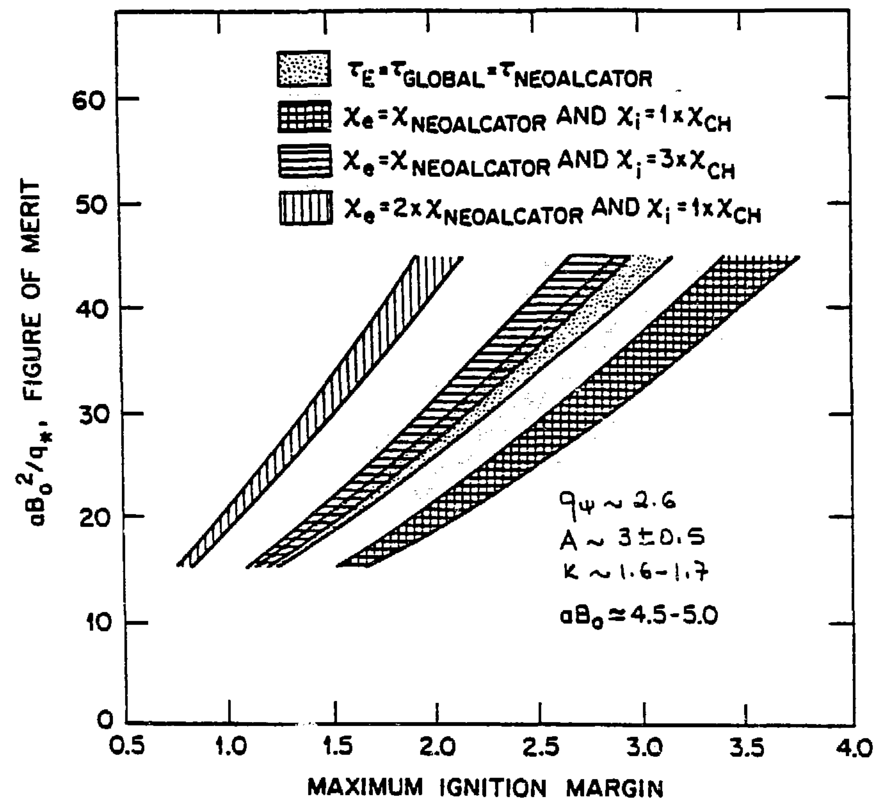

Based on the ohmic-like confinement scaling devices with

$$aB_o^2/q_* \sim 20 \pm 5$$

appear ignitable with a margin $M \sim 1.5 \pm 0.5$. Required auxiliary power P_{aux}(equilibrium) $\sim 10 \mp 5$ MW.

Auxiliary power required for ignition decreases as aB_o^2/q_* increases.

- Figure shows the minimum auxiliary power required for ignition as determined by the maximum equilibrium power along the optimal density path for several confinement models.

- To raise the temperature to ignition in a finite time more auxiliary power is required

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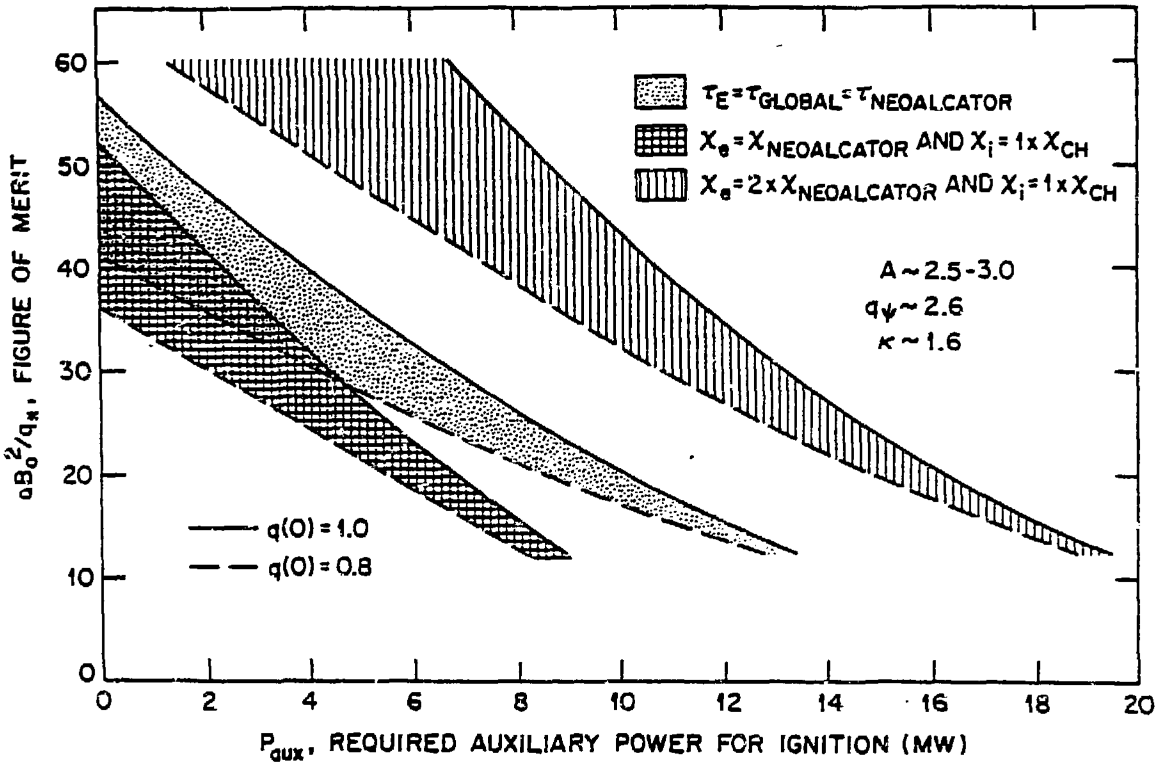

Based on the ohmic-like confinement scalings considered, possibility of ohmic ignition exists for devices with

$$aB_o^2/q_* \sim 40 \pm 10$$

(much of the uncertainty can be removed by some amount of added auxiliary power)

Ohmic + Auxiliary Scaling*

$$\frac{1}{\tau_E^2} = \frac{1}{\tau_{EOH}^2} + \frac{1}{\tau_{EAUX}^2}$$

$$\tau_{OH} = \tau_{neoalcator} \sim n a R_0^2 q_*$$

$$\tau_{aux} = f\,\tau_{Kaye-Goldston} \sim I^{1.24} P^{-0.58} R^{1.65} a^{-0.49}$$

$$\Rightarrow \tau_{KG} \sim I^{2.95}$$

- Strong dependence on plasma shape (κ, δ)

Consider 3 Geometries with Increasing κ

I. "Standard" tokamak : $\kappa \sim 1.6-1.7$; $\delta \sim 0.3-0.1$

II. "Elongated" " : $\kappa \sim 1.9-2.1$; $\delta \sim 0.2-0.0$

III. "More-elongated" " : $\kappa \sim 2.3-2.5$; $\delta \sim 0.2-0.0$

Typical Paramaters

$A \sim 2.8 \pm 0.2$

$q_\psi \sim 2.6$

$Z_{eff} \sim 1.5$

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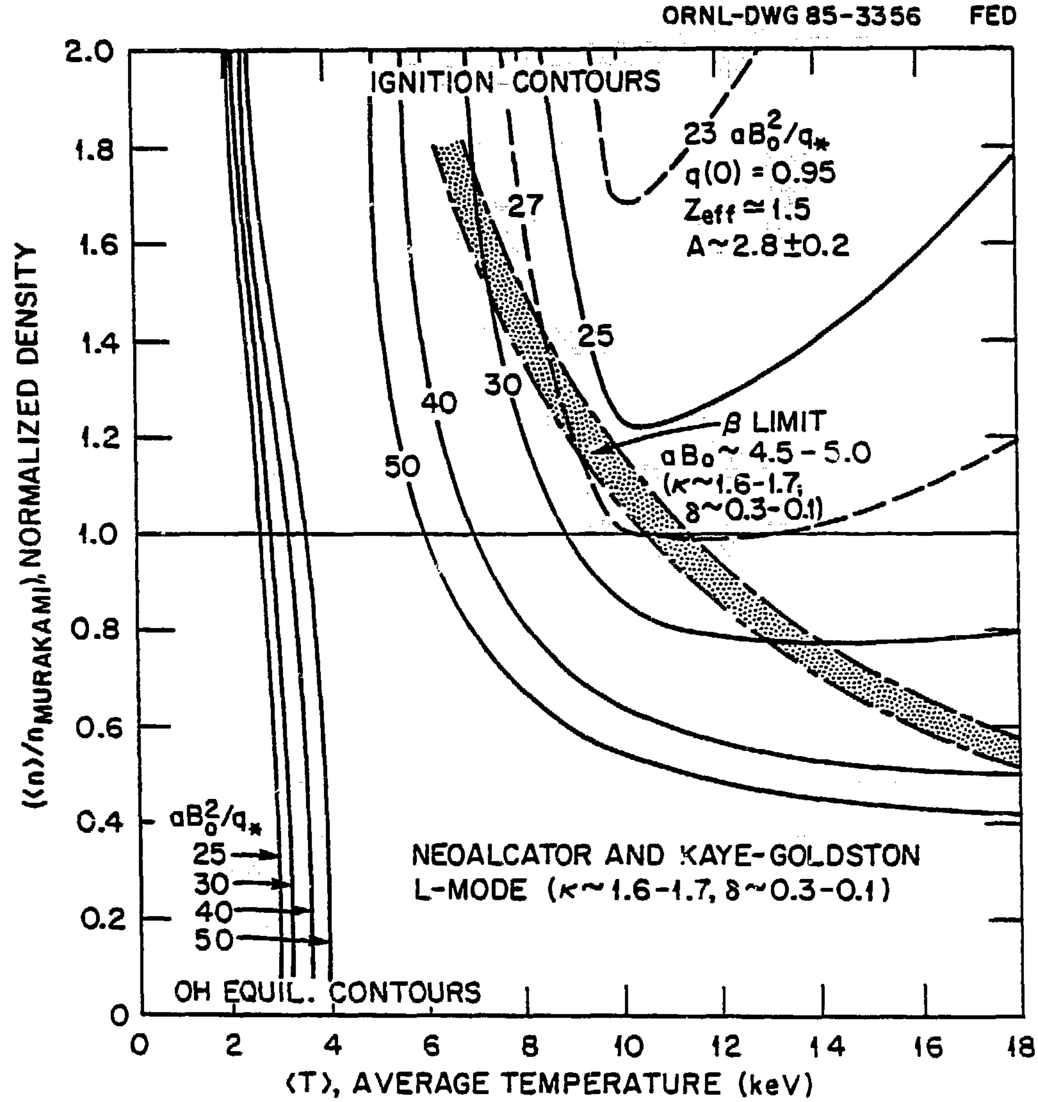
*Note : P_α and P_{OH} is included in P, in addition to Paux, thus the model can be considered as pessimistic.

Steady-state ignition / OH equilibrium contours for various values of aB_0^2/q_*.



Confinement model: NeoAlcator + Kaye-Goldston L-MODE

Geometry: "Standard" tokamak

Steady-state $P_{aux}=0$ (ignition / OH equilibrium) contours for various values of aB_0^2/q_* in two different geometries. Corresponding $\beta=\beta_{crit}$ contours are shown.

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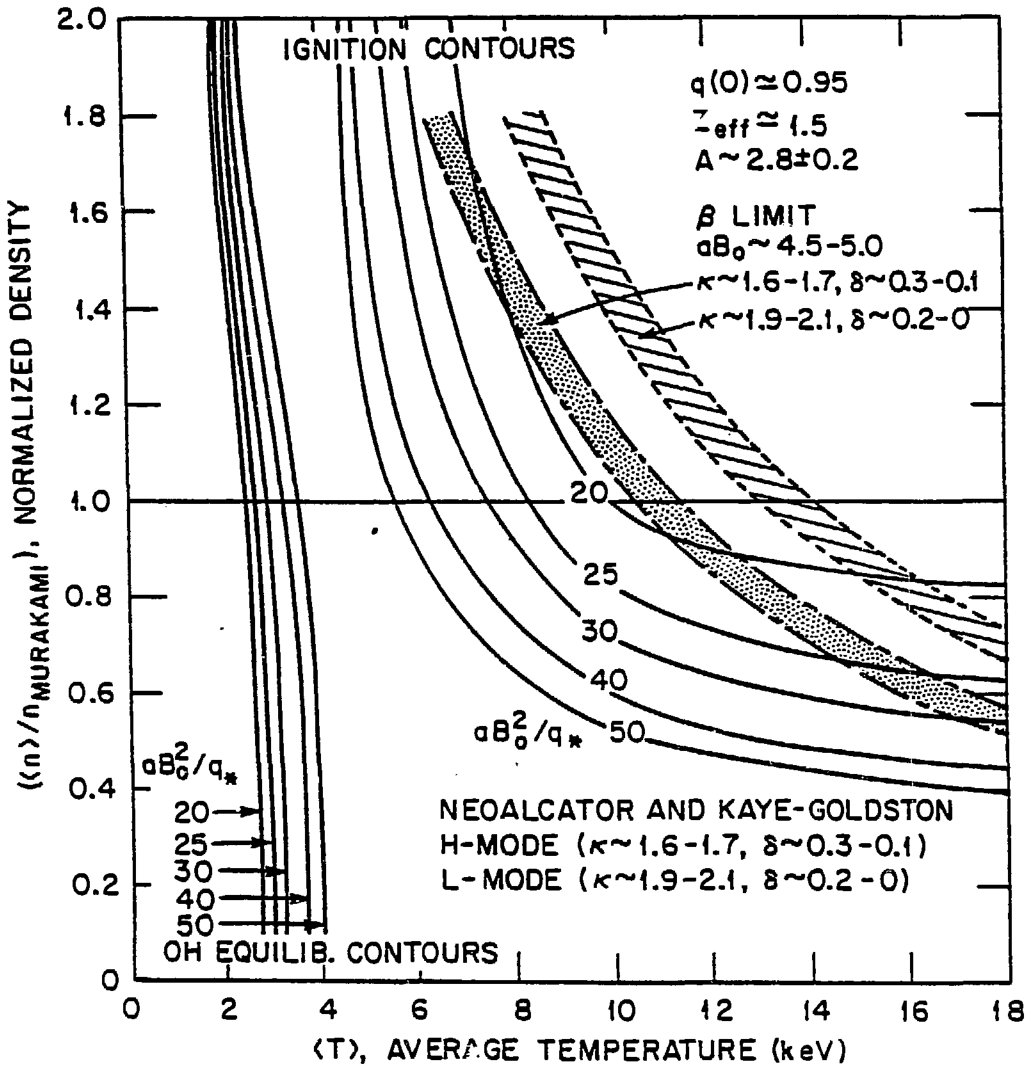


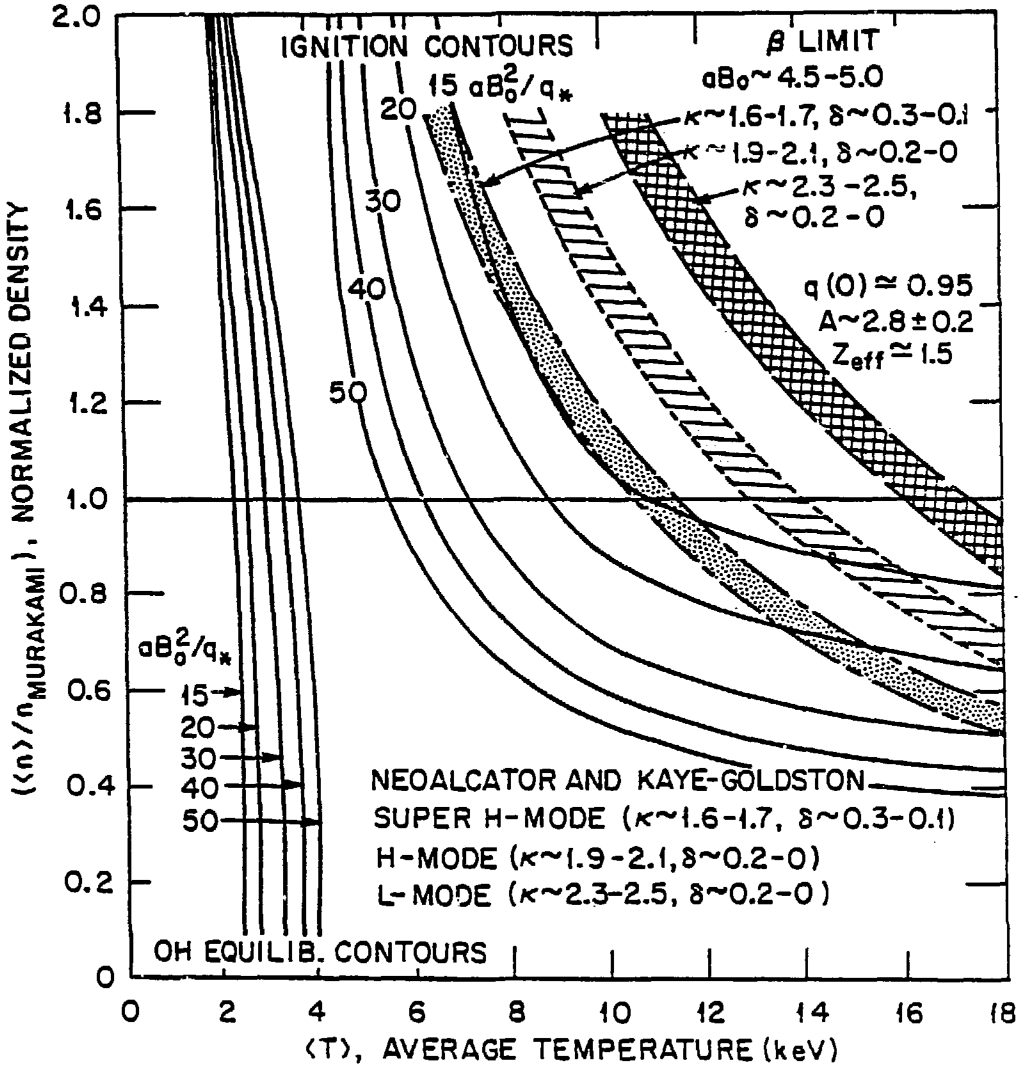
Confinement model: Neo-Alcator + Kaye-Goldston

Geometry : "Standard" tokamak — H-mode

"Elongated" tokamak — L-mode

Steady-state $P_{aux}=0$ (ignition / OH equilib.) contours for various values of aB_0^2/q_* in 3 different geometries. Corresponding $\beta=\beta_{crit}$ contours are shown.

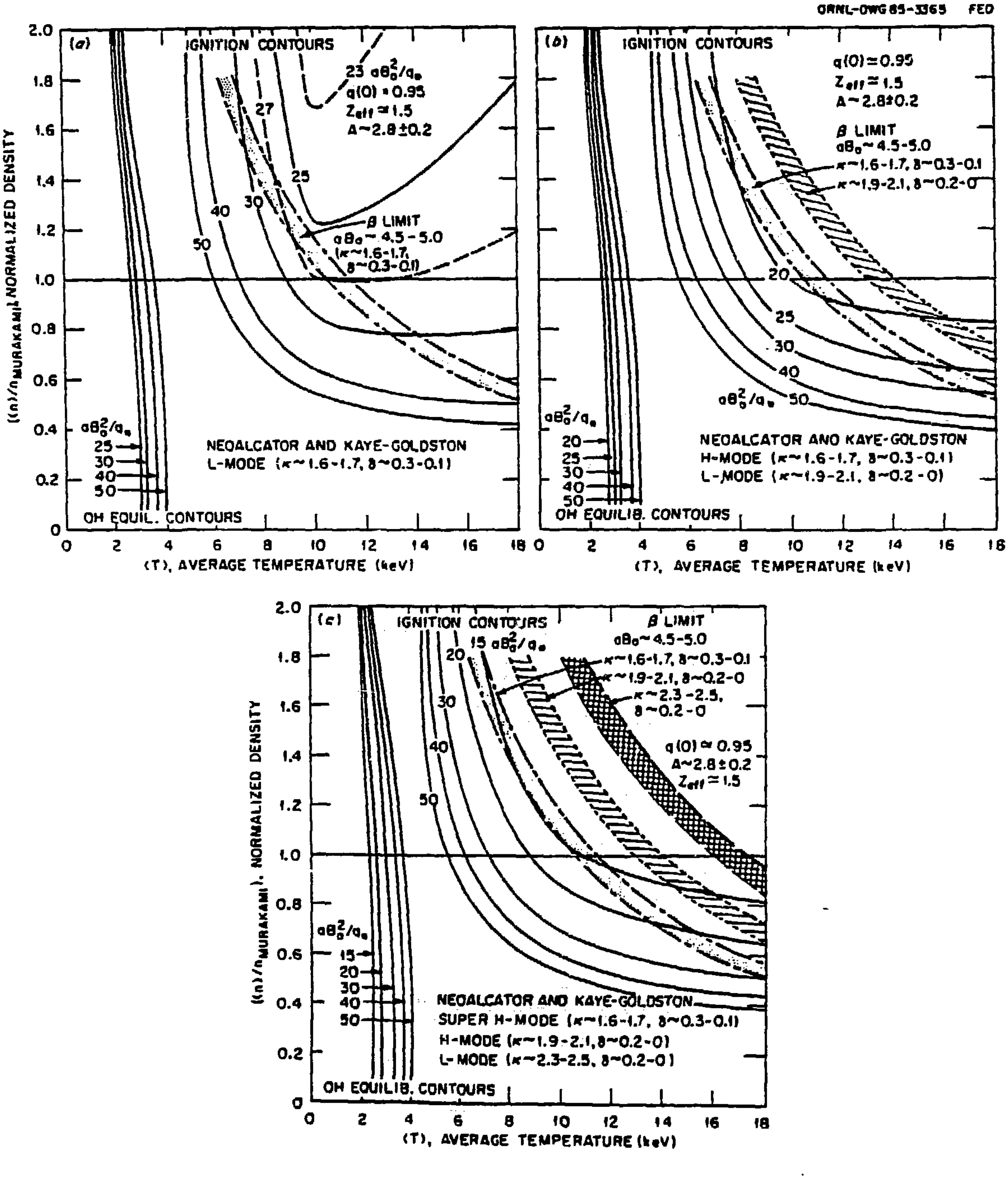
ORNL-DWG 85-3358 FED



Confinement model: Neo-Alcator + Kaye-Goldston

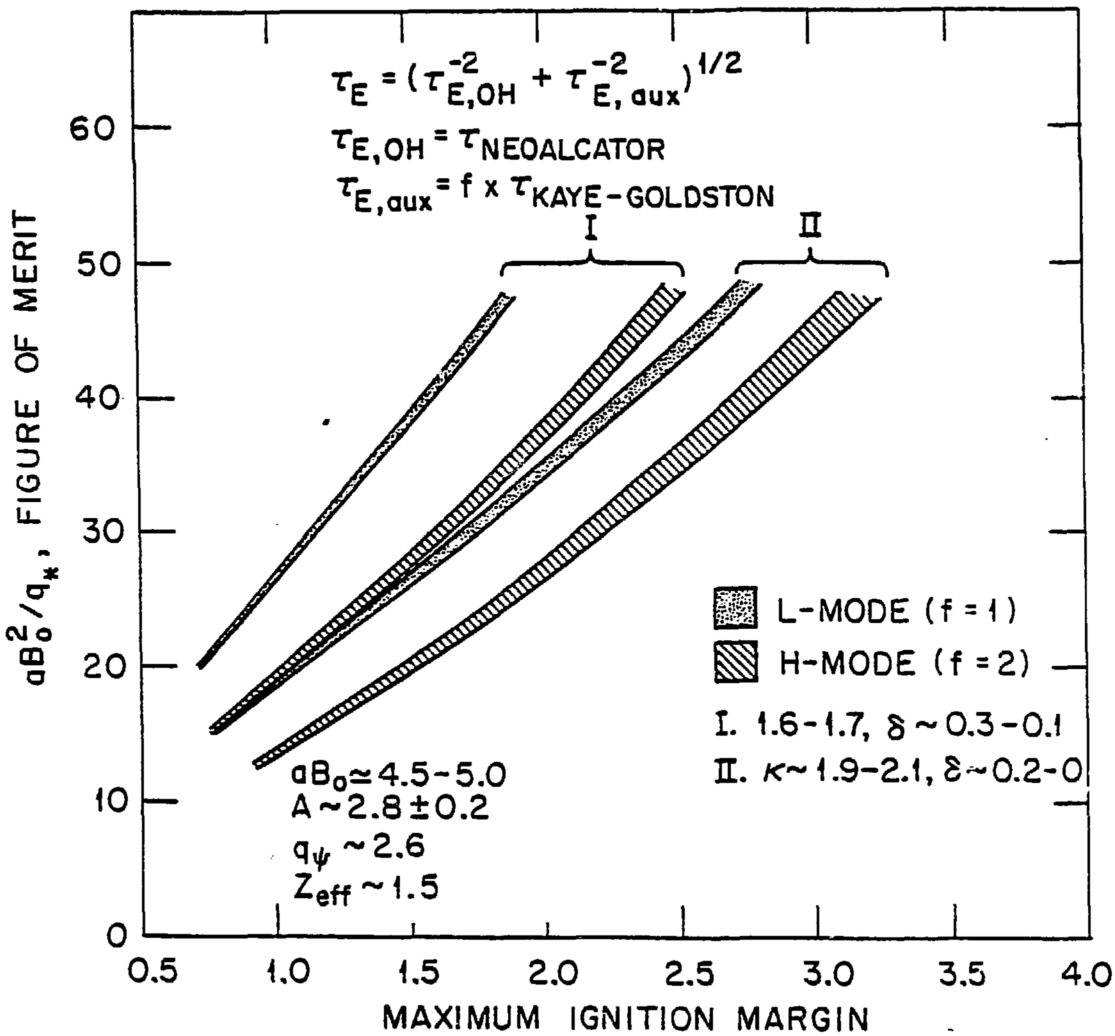
Geometry		
	Standard :	Super-H-mode
	Elongated :	H-mode
	More-Elongated :	L-mode

Summary: Ohmic + Auxiliary scaling $P_{aux}=0$ contours and $\beta=\beta_{crit}$ contours for various values of aB_o^2/q_* (classes of devices with equivalent performance) in three different tokamak geometry with increasing κ.



Maximum attainable margin for ignition within the plasma operating window increases with increasing aB_o^2/q_*.

ORNL-DWG 85-3352 FED



Based on ohmic + auxiliary scalings considered devices with $aB_o^2/q_* \sim 25 \mp 5$, $\kappa \sim 1.8 \pm 0.2$ appear ignitable.

Summary

Comparison of ignition margins for "ohmic-like" and "ohmic + auxiliary" scalings.

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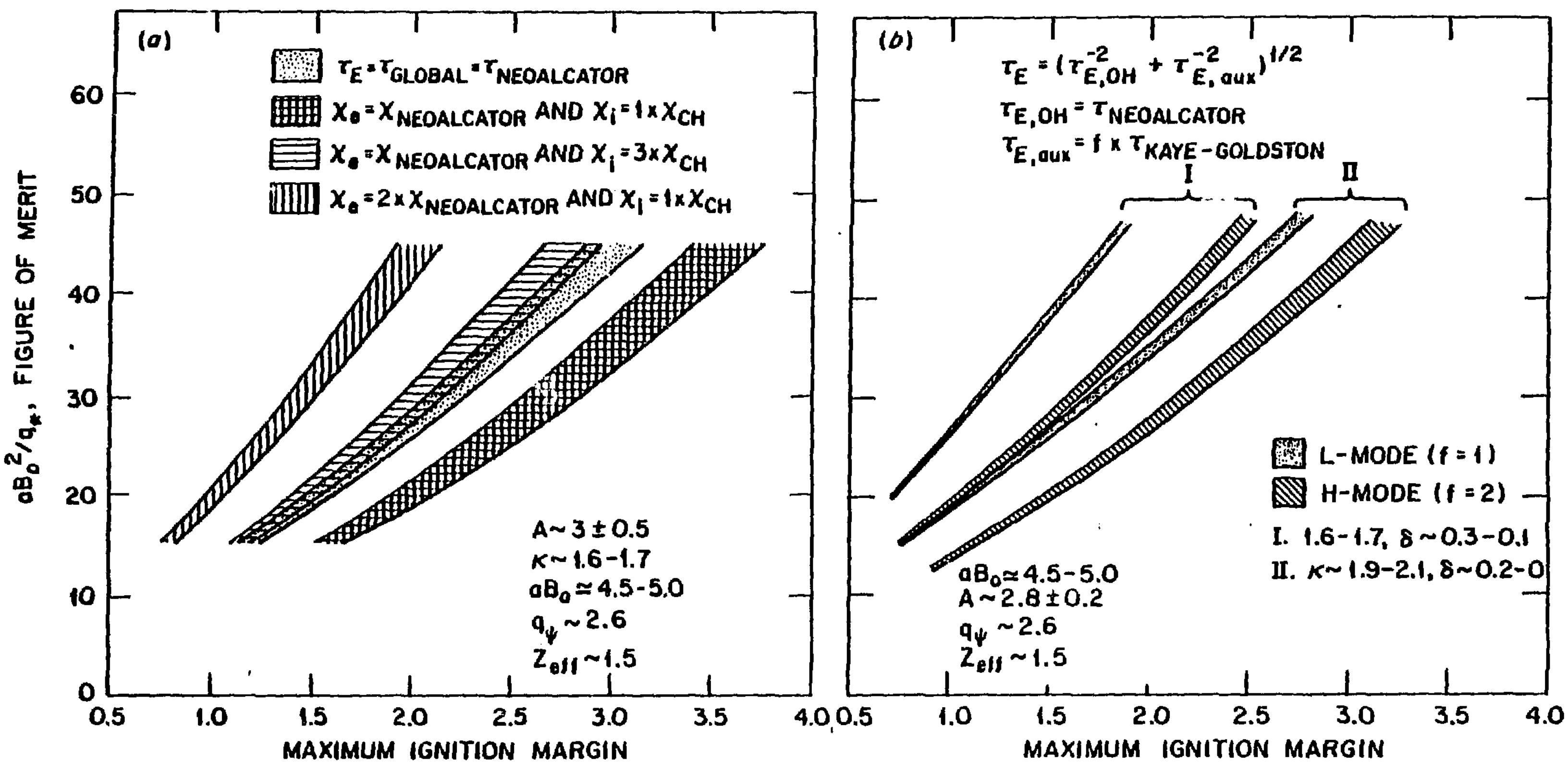

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Applications to Compact Tokamak Ignition Experiments

At present several candidate design options for a compact, high-field ignition experiment are being considered by the U.S. Tokamak Ignition Studies Design Teams. These options include

- Ignitor-A $\rightarrow$ $a \sim 0.39\,m$, $R_0 \sim 1\,m$, $B_0 \sim 12.6\,T$
  $I \sim 10\,MA$, $q_\psi \sim 2.6$, $\kappa \sim 1.67$, $\delta \sim 0.25$
  $\Rightarrow aB_0^2/q_* \sim 32$
- PPPL-ISP (0424) $\rightarrow$ $a \sim 0.53\,m$, $R_0 \sim 1.6\,m$, $B_0 \sim 9\,T$
  $I \sim 8\,MA$, $q_\psi \sim 2.6$, $\kappa \sim 1.6$, $\delta \sim 0.4$
  $\Rightarrow aB_0^2/q_* \sim 20$
- MIT-LITE $\rightarrow$ $a \sim 0.55\,m$, $R_0 \sim 1.75\,m$, $B_0 \sim 8.5\,T$
  $I \sim 7\,MA$, $q_\psi \sim 2.6$, $\kappa \sim 1.6$, $\delta \sim 0.3$
  $\Rightarrow aB_0^2/q_* \sim 19$

Can be categorized in two classes

I. Devices with $aB_0^2/q_* \sim 20$

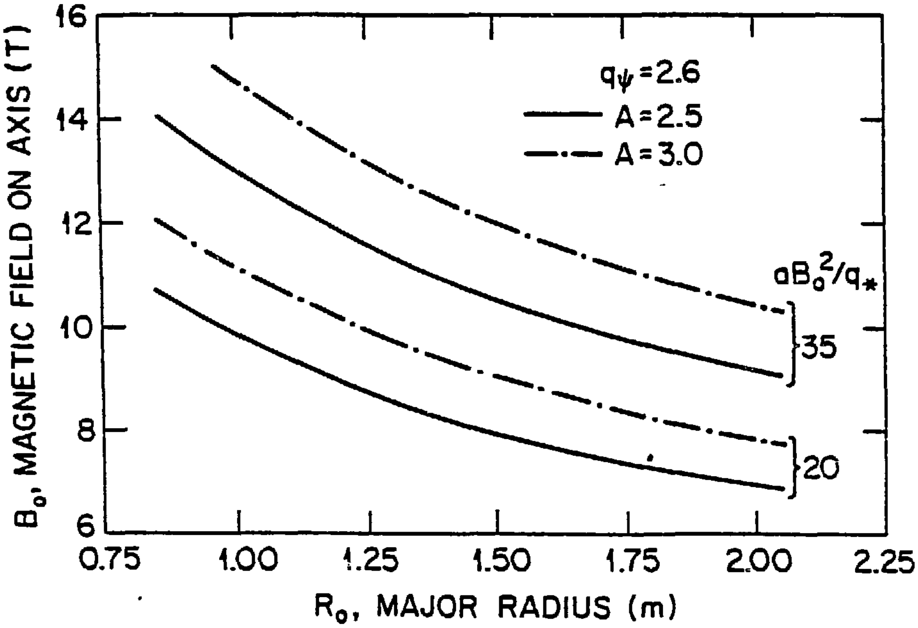
II. Devices with $aB_0^2/q_* \sim 32$

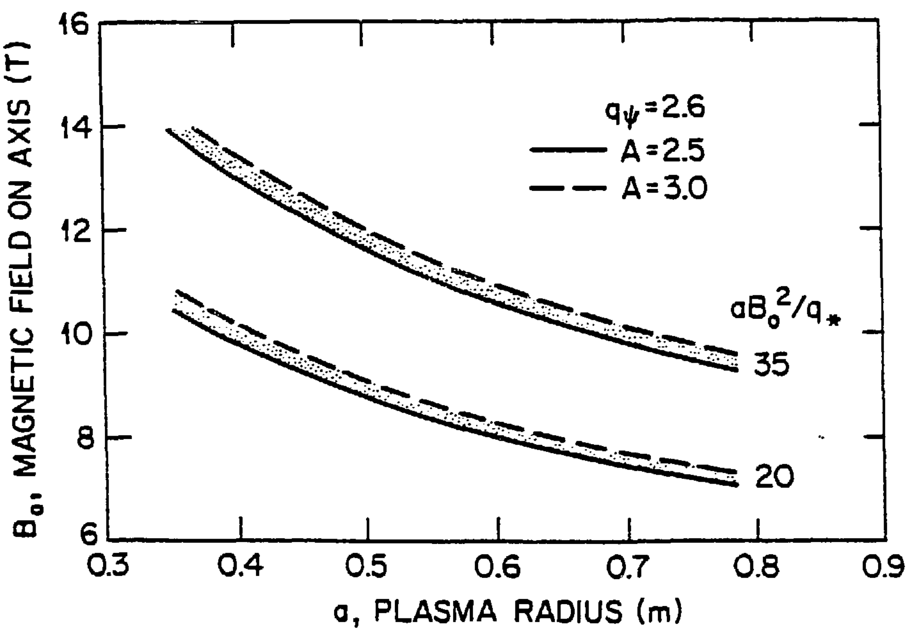
For typical range of aspect ratios ($A \sim 2.5 - 3$) and MHD safety factor ($q_\psi \sim 2.6$), the range of device parameters and plasma current corresponding to $aB_o^2/q_* \sim 20 - 35$ are: $R_o \sim 1 - 2$ m ($a \sim 0.35 - 0.65$ m)

$B_o \sim 8 - 14$ T

$I \sim 7-10$ MA ($\kappa \sim 1.6-1.7$); $\sim 9-13$ MA ($\kappa \sim 1.9-2.1$); $\sim 12-17$ MA ($\kappa \sim 2.3-2.5$)

ORNL-DWG 85-2899 FED





For most parameter range of interest $aB_o \sim 4.5 - 5$ (mT)

Variations of parameters with ignition margin and aspect ratio

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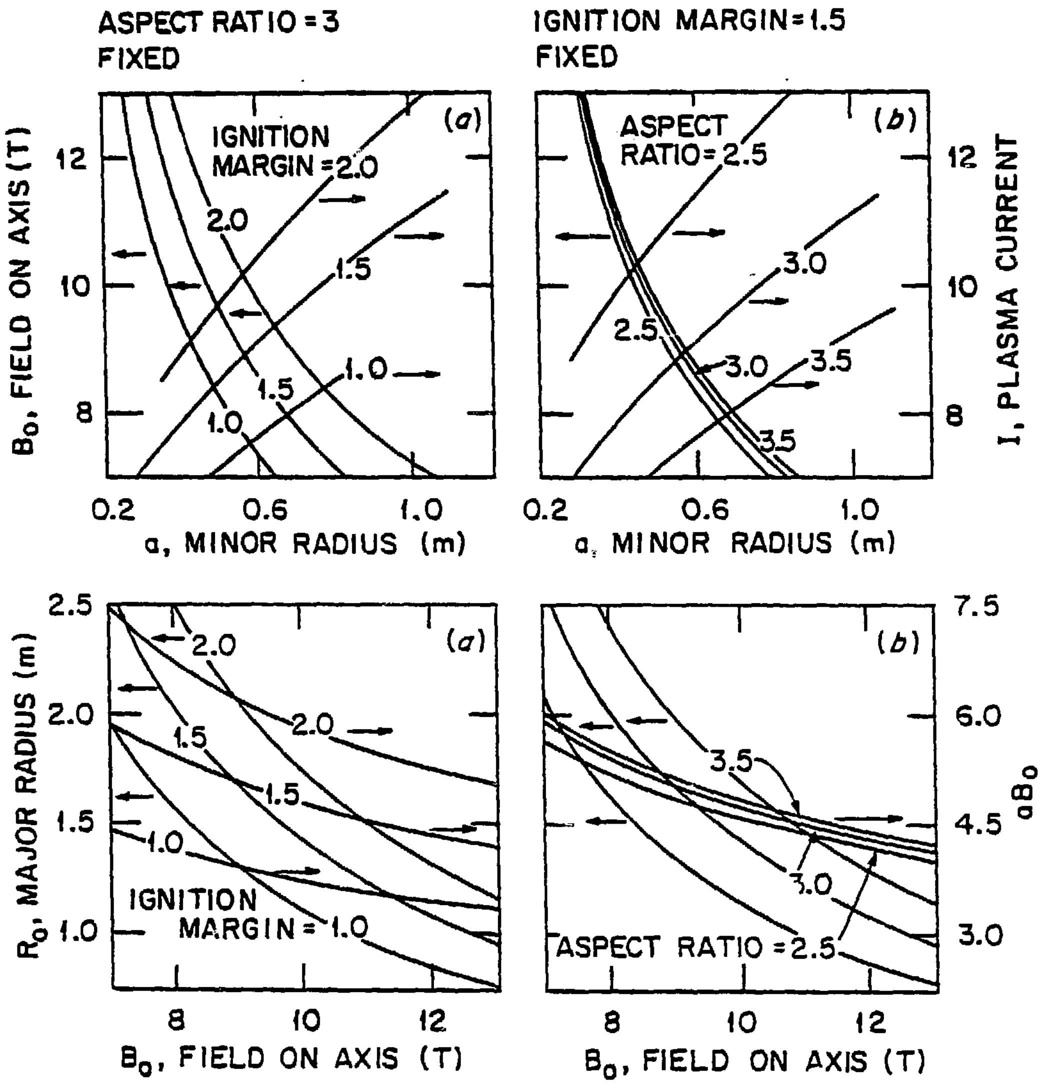

a) A = fixed: increasing ignition margin increases a, B, I

$\Rightarrow$ require larger aB_0^2/q_*

b) M_I = fixed: increasing A increases R, decreases I

but little effect on a, B

$\Rightarrow$ $aB_0 \sim$ const. $aB_0^2/q_* \sim$ const.

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'STEADY-STATE' AND TIME-DEPENDENT ANALYSES

'Steady-state' contours generated by slow time evolution of 1-1/2-D WHIST transport code and 0-D global model.

- IGNITOR-A, PPPL 0424, LITE, and "MX".
- Sensitivity to χ_e (ohmic & auxiliary).

Time-dependent simulation of 'flat-top':

- Time-to-ignition.
- Auxiliary power requirements.

Full startup analysis:

- TF compression with current and density ramps.
- Volt-second consumption.

GENERAL PARAMETERS

R_o	1 - 1.75 m
a	0.4 - 0.6 m
B_o	8 - 13 T
I	8 - 13 MA
κ	1.6 - 2.0

SPECIFIC PARAMETERS

	IGNITOR-A	PPPL-ISP (0424)	MIT-LITE	"MX" (*)
R_o (m)	1.01	1.62	1.76	1.4
a (m)	0.39	0.53	0.55	0.5
$A = R_o/a$	2.6	3.0	3.2	2.8
κ	1.67	1.6	1.6	1.8
δ	0.25	0.4	0.3	0.2
B_o (T)	12.6	9.0	8.6	10.0
I	10.0	8.0	7.0	10.0
q_ψ	2.6	2.6	2.6	2.6
Z_{eff}	1.5	1.5	1.5	1.5

* Not an engineering design. A reference physics device (Middle of the Box) for calculational purpose.

Example 1 (0-D & 1-1/2-D)

Plasma performance contours for devices with

$$aB_0^2/q_* = 20$$

under different scaling assumptions.

Optimal path, P_{aux}, and Max. ignition margins are given.

Summary -- Steady-State auxiliary power contours and critical beta contours for devices with $aB_0^2/q_* = 20$ and $q(0) = 0.8$

Conf. models: (a) $\tau_E = \tau_{neoalcator}$; (b) $\chi_e = \chi_{neoalcator}$, $\chi_i = 1 \times \chi_{CH}$
(c) $\chi_e = \chi_{neoalcator}$ plus $\chi_i = 3 \times \chi_{CH}$

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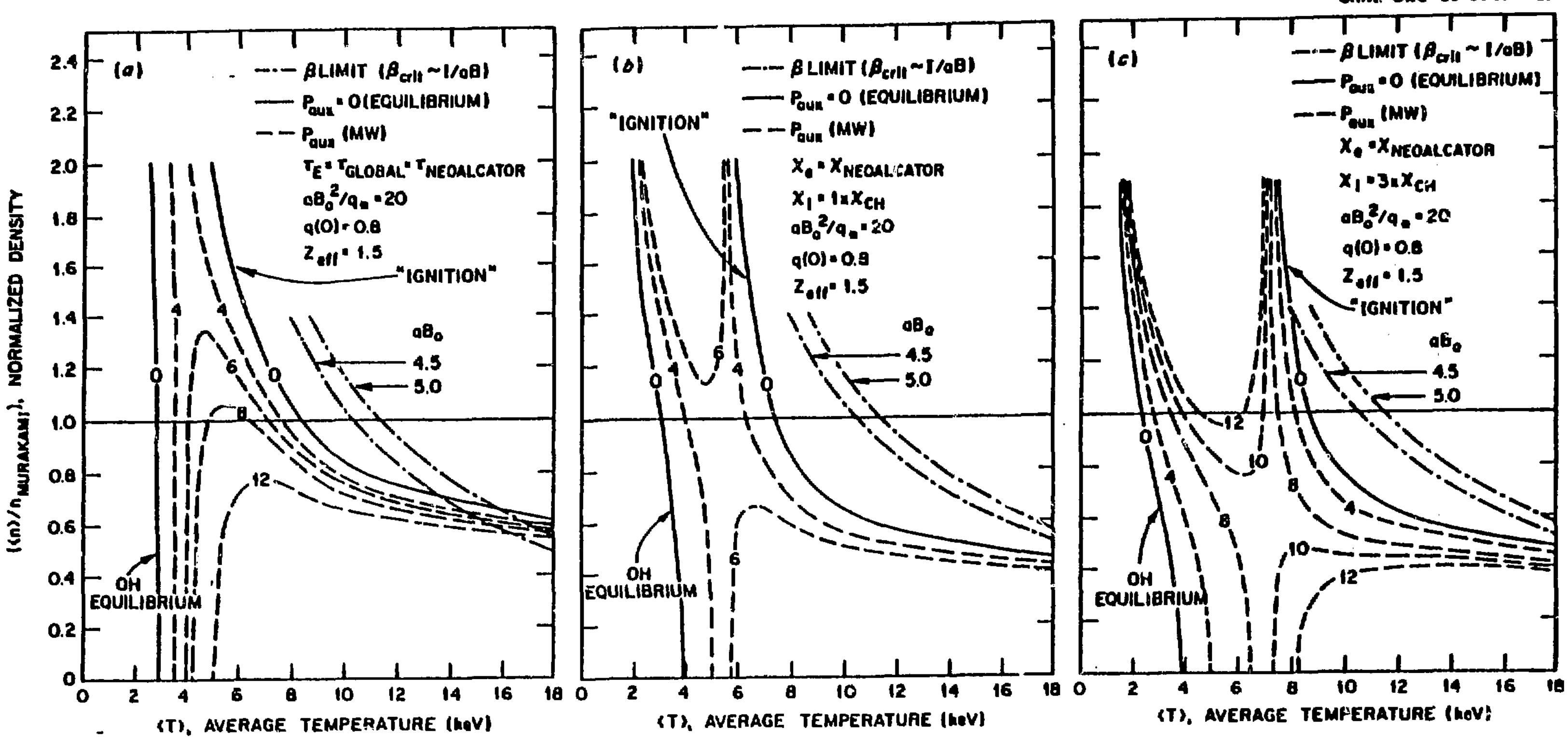

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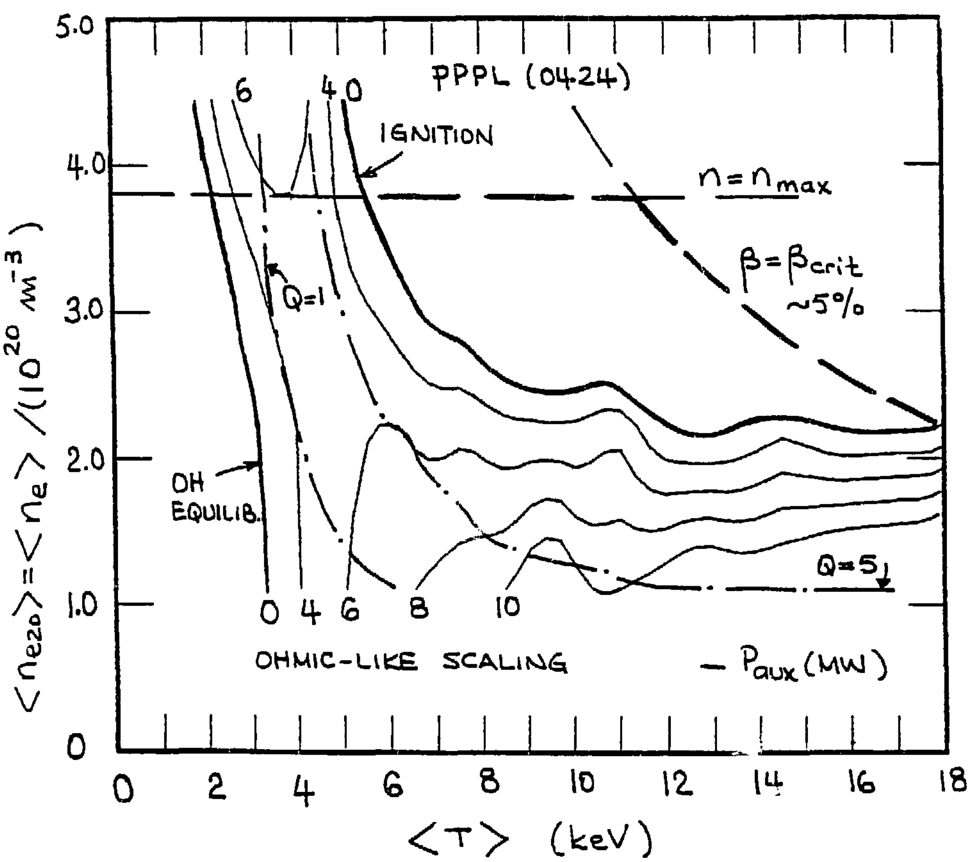
Steady-state POPCON plots (1-½-D code) showing P_{aux} and Q contours for a typical $aB_0^2/q_* \approx 20$ (PPPL – 0424) device.

$n = n_{max}$ (murakami limit)
$\beta = \beta_{crit}$ (~5%)
} are shown

Confinement model: "ohmic-like" scaling

$\chi_e = 0.8\,\chi_{neo\text{-}Alcator}\; g(r)$

$\chi_i = 0.2\,\chi_e + 1 \times \chi_{CH}$



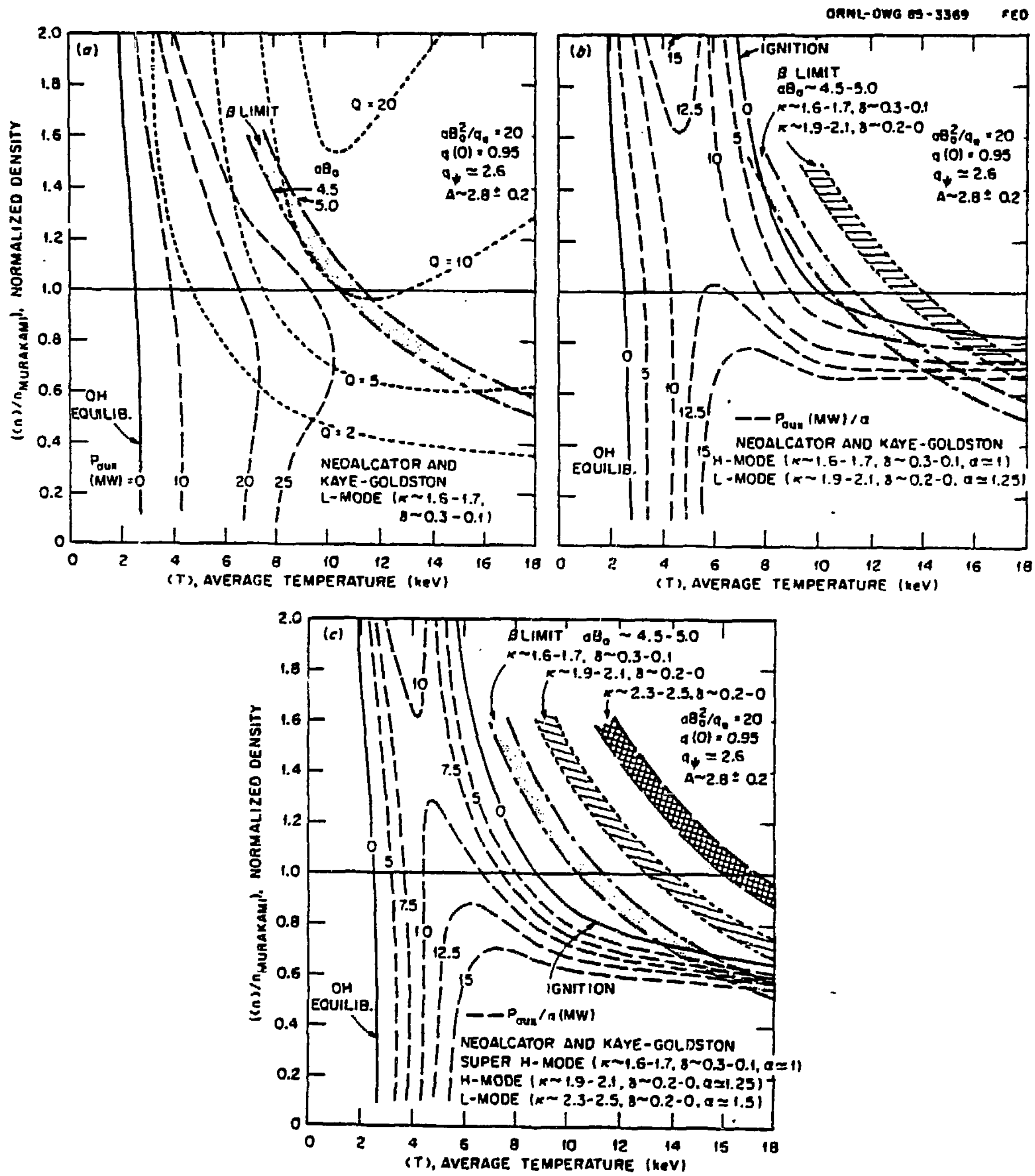
optimal path ~ 0.8 n_{max}

P_{aux} ~ 5 MW

(fluctuations in P_{aux} contours reflect sawtooth activity)

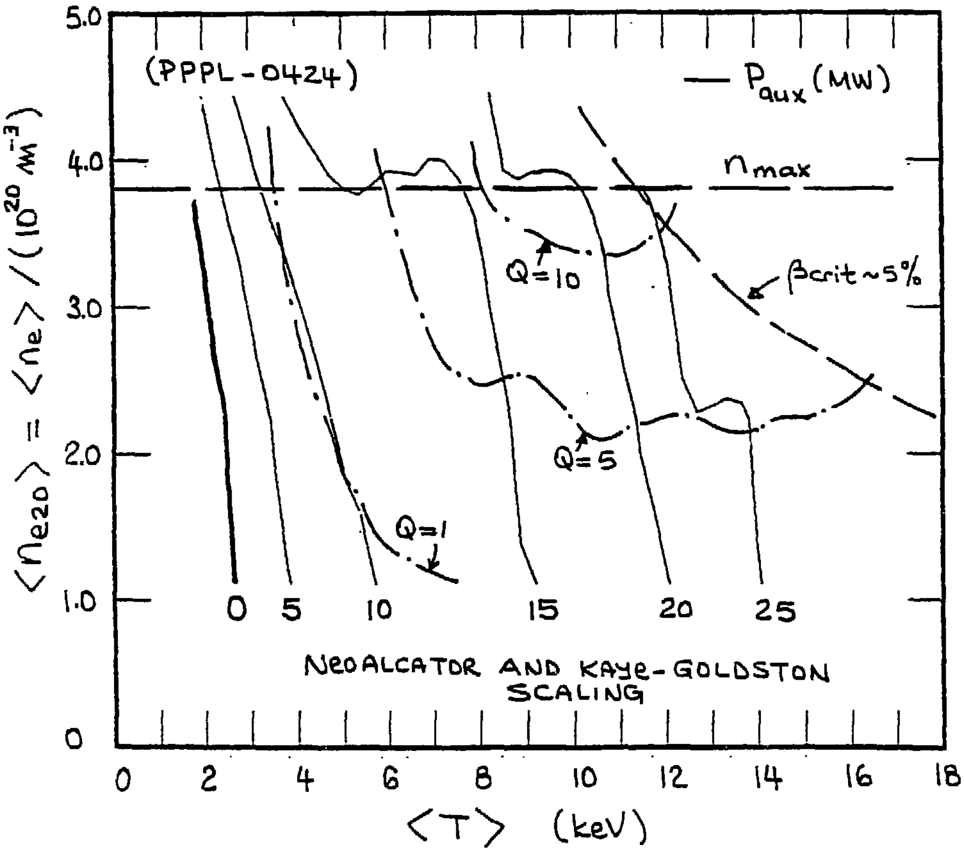
SUMMARY (D-D , analytic model)

Neo-Alcator & Kaye - Goldston Scaling in 3 different geometry with increasing elongation for a class of devices with $aB_o^2/q_* \simeq 20$



Steady-state POPCON (1-1/2-D) plots showing P_{aux} and Q contours for a typical $aB_0^2/q_* \simeq 20$ (PPPL-0424) device.

Confinement model: "ohmic + auxiliary scaling"
OH — neoAlcator
aux — Kaye-Goldston (L-mode)



Ignition is not accessible in this device with L-mode KG scaling. There is a reasonable Q > 5 window ($P_{aux}^{eq} \sim 20 \mp 5$ MW required to access this window).

Example 2 (0-D & 1-1/2-D)

Plasma performance contours for devices with

$$aB_0^2/q_* = 32$$

under different scaling assumptions.

Optimal path, P_{aux}, and max. ignition margin are given.

Summary -- Steady-state auxiliary power contours and critical beta contours for devices with $aB_0^2/q_* = 32$ and $q(0) = 0.8$

Conf. models: (a) $\tau_E = \tau_{neoalcator}$; (b) $\chi_e = \chi_{neoalcator}$ plus $\chi_i = 1 \times \chi_{CH}$; (c) $\chi_e = \chi_{neoalcator}$ plus $\chi_i = 3 \times \chi_{CH}$.

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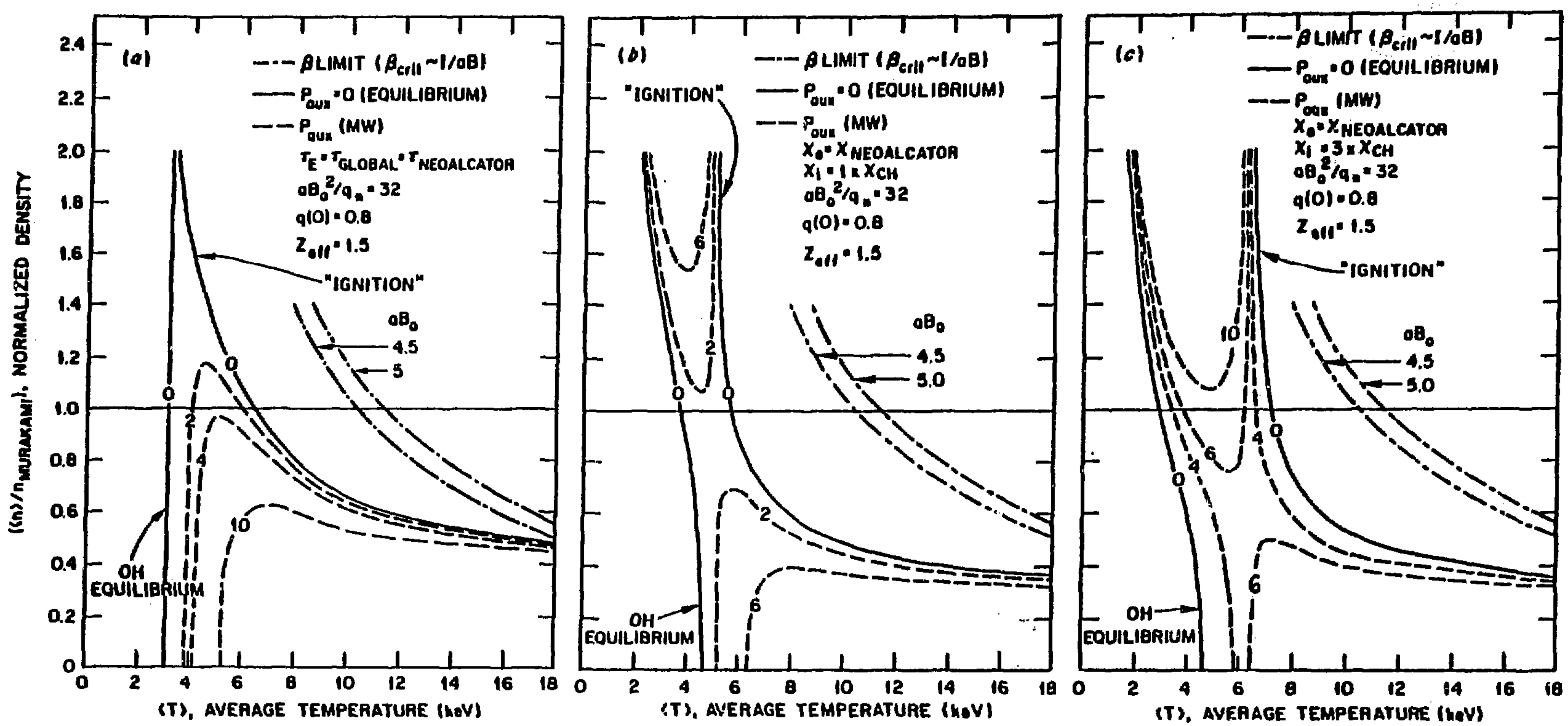

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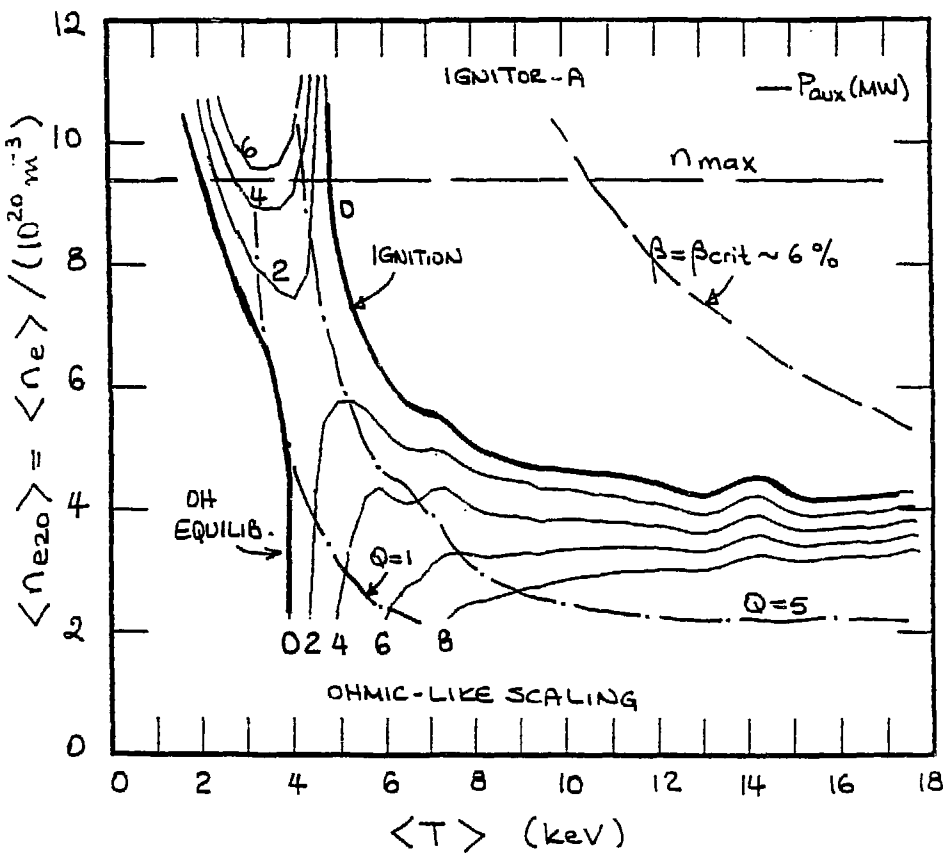
Steady-State POPCON (1-1/2-D) plots

-- P_{aux} and Q contours for Ignitor-A ($aB_0^2/q_* \sim 32$)

Confinement model: Ohmic-scaling

$\chi_e \propto \chi_N$

$\chi_i = 0.2\,\chi_e + 1 \times \chi_{CH}$



Optimal path $\sim 0.7\, n_{max}$

$P_{aux} \sim 1.5$ MW

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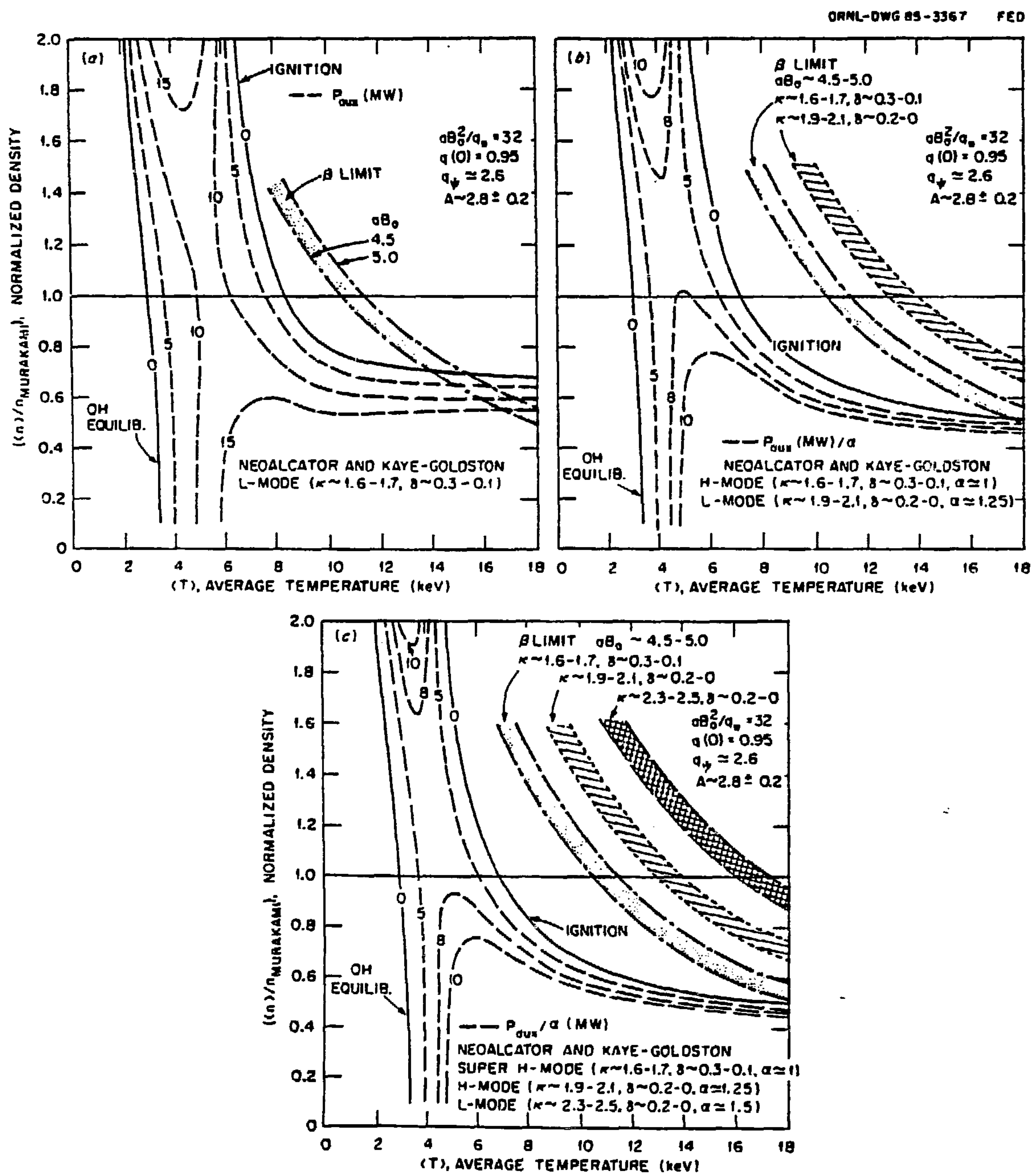
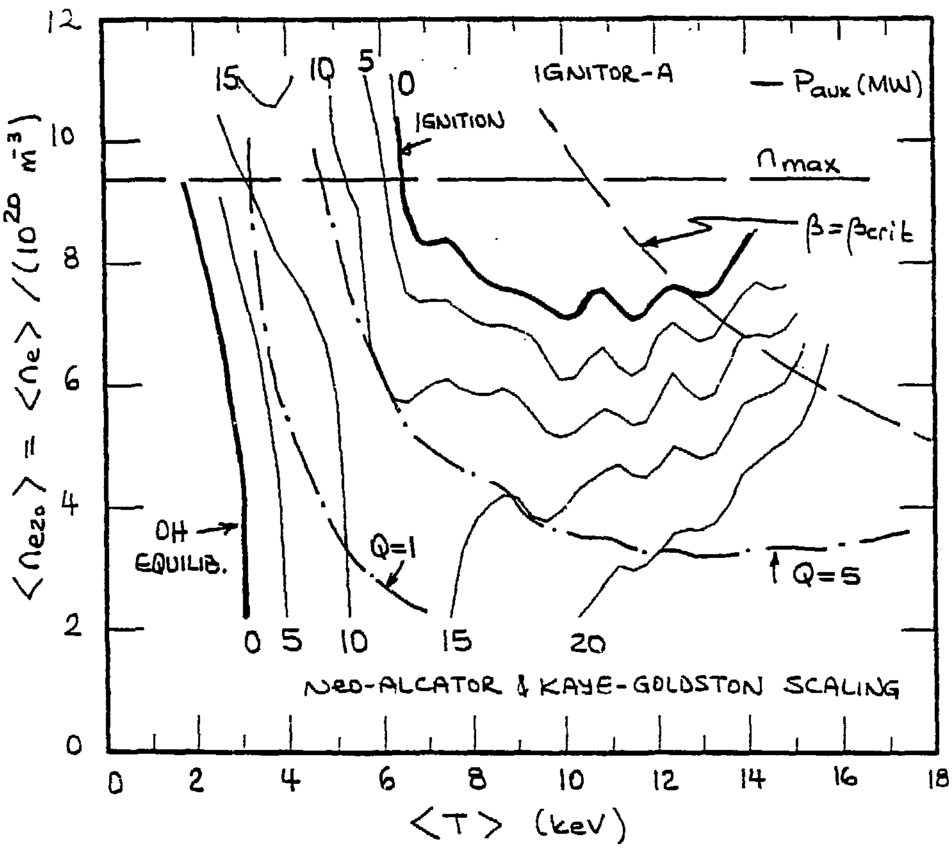
Summary : Neo-Alcator & Kaye - Goldston scaling in 3 different geometry with increasing κ for a class of devices with $aB_0^2/q_* \sim 32$



Steady-state POPCON (1-1/2-D) plots
– P_{aux} and Q contours for IGNITOR-A ($aB_0^2/q_* \sim 32$)

Confinement model: ohmic + auxiliary
OH — neo-Alcator
aux — Kaye-Goldston
<u>L-mode</u>

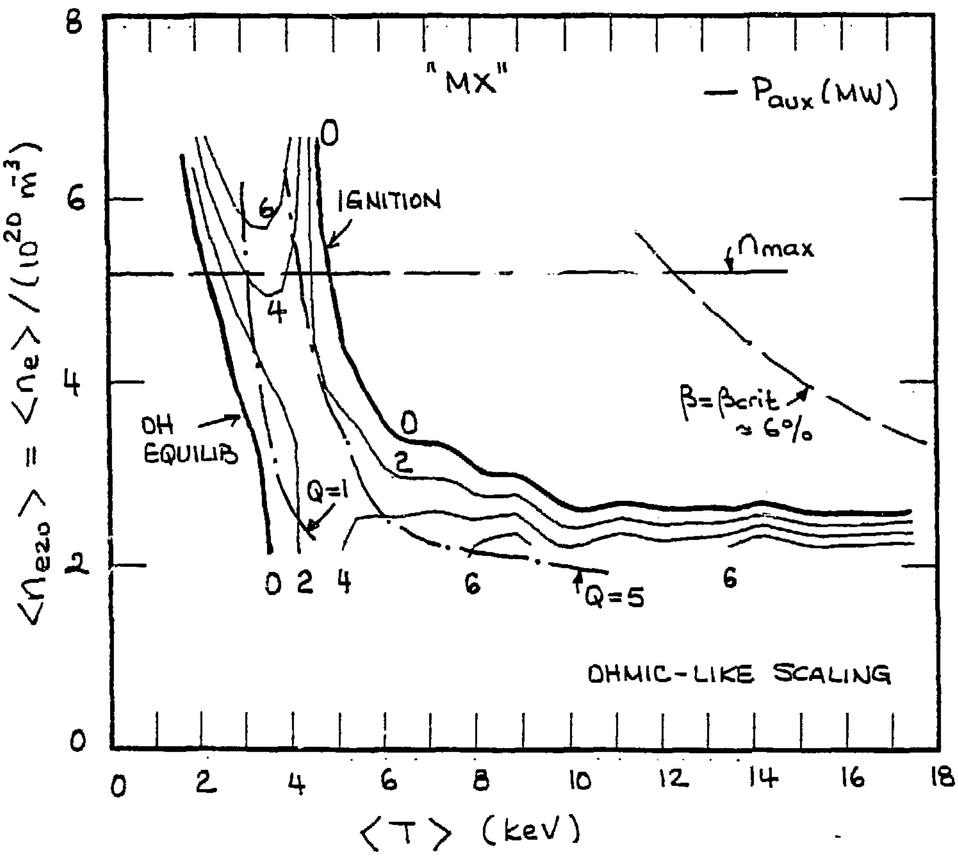


(Fluctuations in P_{aux} contours reflect the effects of descrete sawtooth activity.)

Steady-state POPCON (1-1/2-D) plots
-- P_{aux} and Q contours for "MX"

"MX" -- $aB_0^2/q_* \simeq 25$, $\kappa \sim 1.8$, $A = 2.8$

Confinement model: ohmic scaling
$\chi_e \sim \chi_{NA}$ $\chi_i \sim 0.2\chi_e + 1 \times \chi_{CH}$



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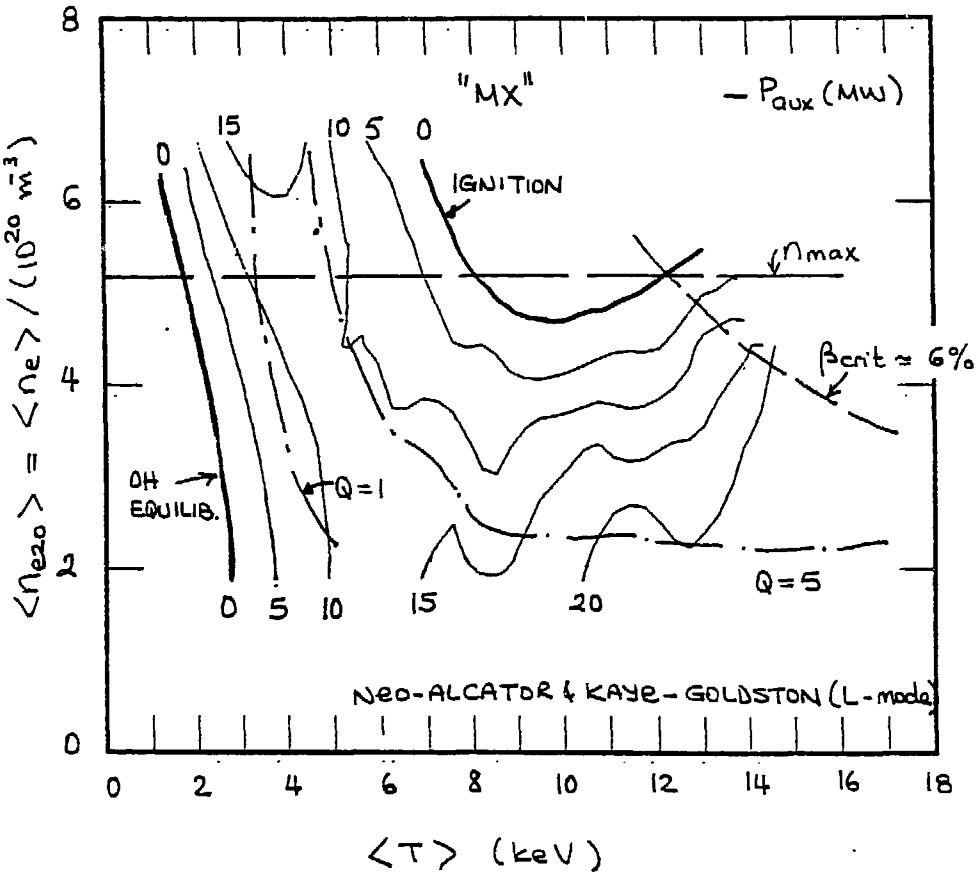
Steady-state POPCON plots (1-1/2-D)
-- P_{aux} and Q contours for "MX"

Confinement model: ohmic + auxiliary
OH – Neo Alcator
aux – Kaye-Goldston
L-Mode



OUTLINE

- Physics assessments - design and engineering impact
- 0-D confinement studies
    - physics requirements and options for ignited plasmas
    - classes of devices with equivalent performance
    - sensivity to variations in confinement models
- 1-1/2-D confinement studies
    - dynamic simulations
    - critical physics issues (sawteeth, α- slowing down, local transport, etc.)
    - startup analysis
    - volt-second consumption