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STARTUP AND HEATING TO IGNITION: Steady-State and Time-Dependent Analyses*

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MASTER

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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

'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

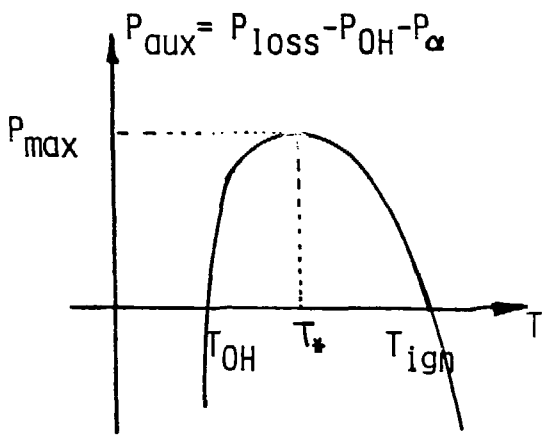
---

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

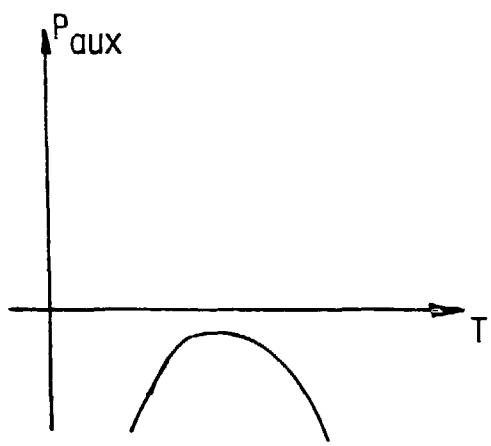
Steady-state (equilibrium) : $\partial W/\partial t = 0$

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

There are two possibilities



$P_{aux} \geqslant P_{max}$ 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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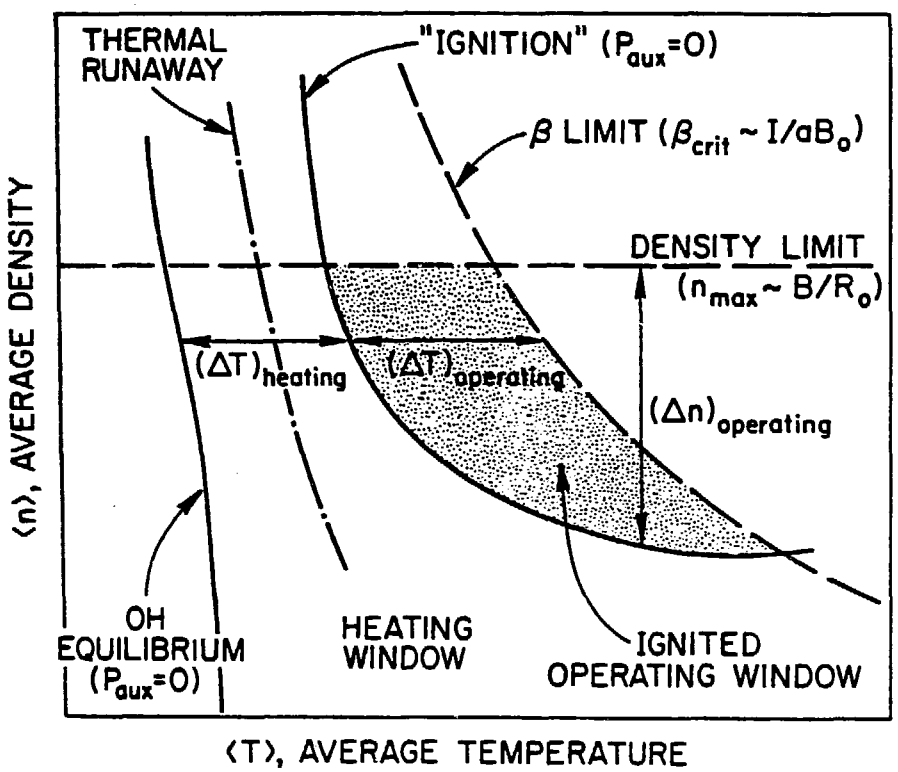

Special Cases:

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

Desirable Characteristics:

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

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.

Steady-state auxiliary power contours for devices with

$aB_o^2/q_* = 20$

(a representative case for PPPL-ISP/MIT-LITE)

Confinement model: $\tau_E = \tau_{Global}$
$= \tau_{Neoalcator}$
$q(0) = 0.8$

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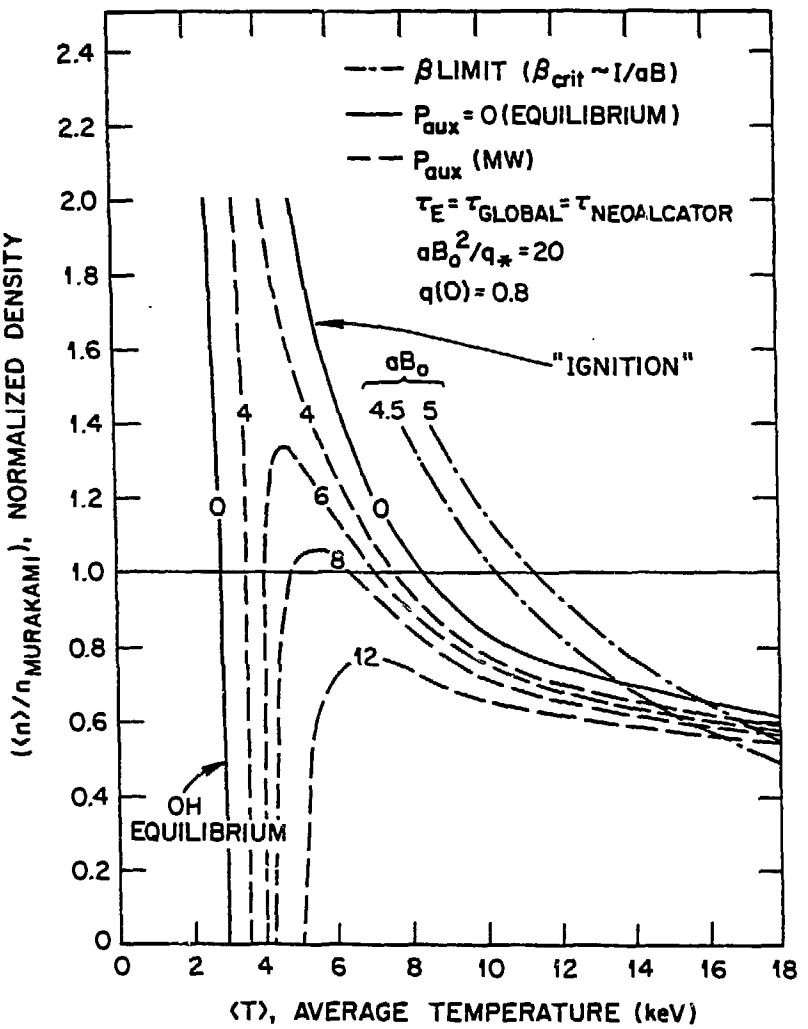


Optimal path : $n = n_{murakami}$

P_{aux}(equilibrium) : ~8.5 MW

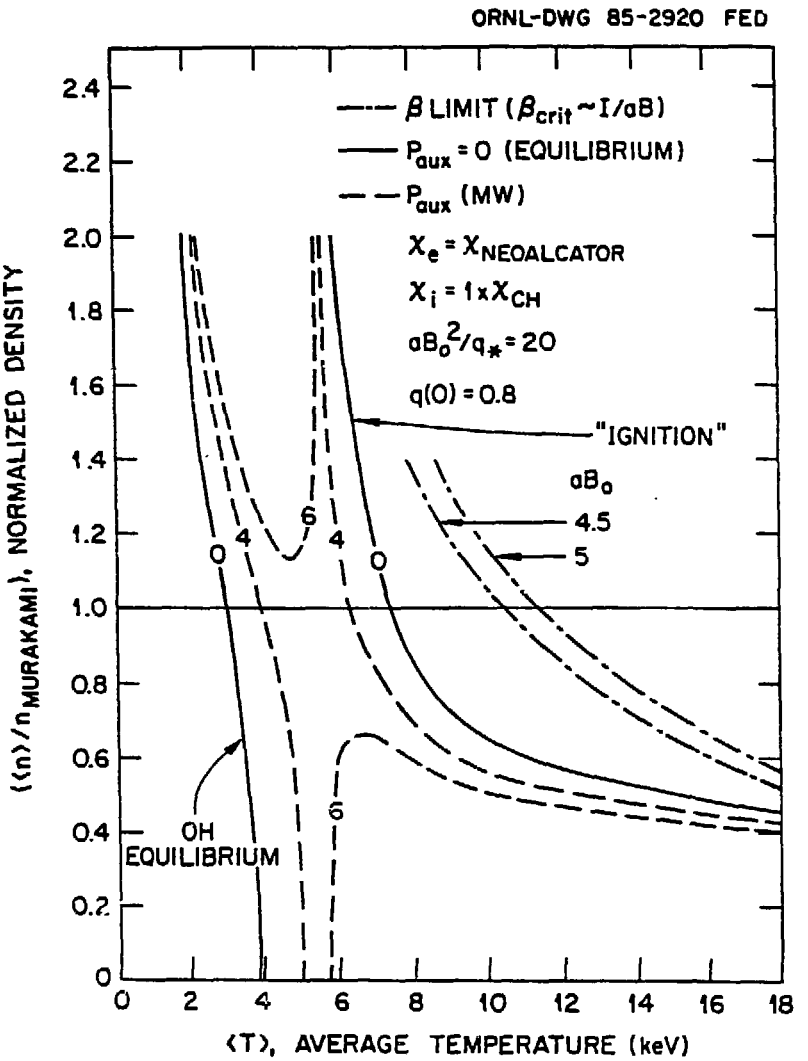
Max. Ign. Margin : ~1.5

Steady-state auxiliary power contours for devices with

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

(a representative case for PPPL-ISP/MIT-LITE)

Confinement model: $\chi_e = \chi_{Neoalcator}$
$\chi_i = 1 \times \chi_{Chang-Hinton}$
$q(0) = 0.8$



Optimal path : $n \sim 0.85\ n_{murakami}$

P_{aux}(equilibrium) : ~ 5.5 MW

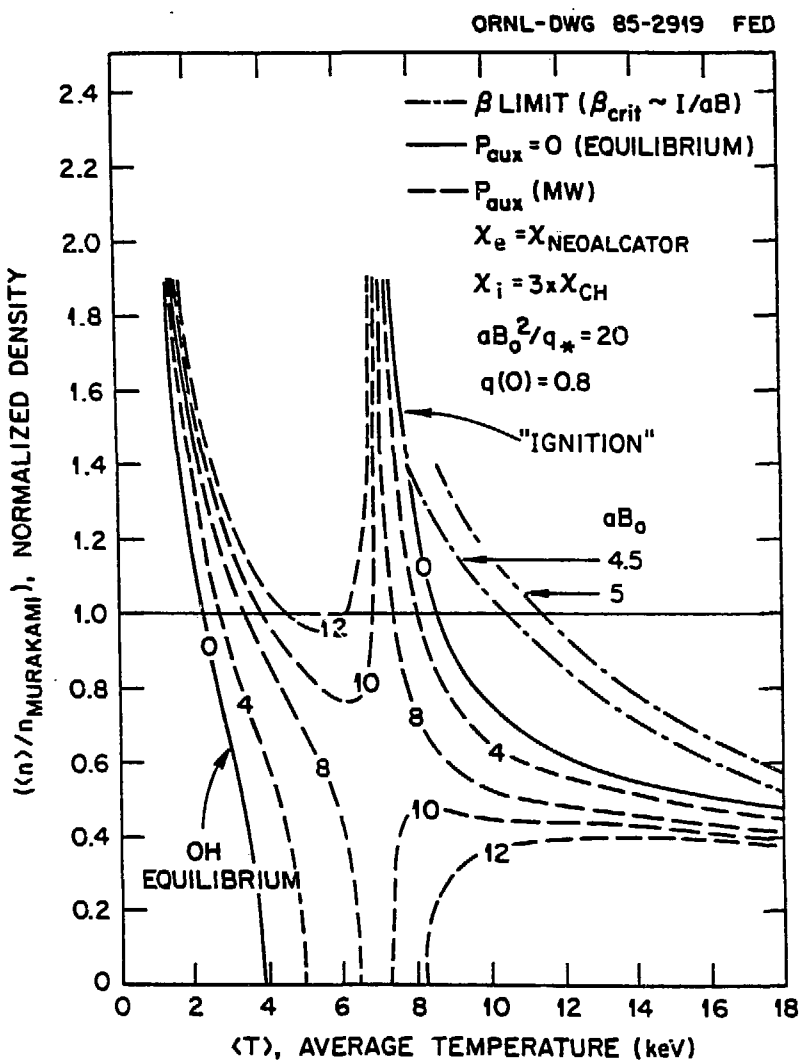
Max. Ign. Margin : ~ 2

Steady-state auxiliary power contours for devices with

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

(a representative case for PPPL-ISP/MIT-LITE)

Confinement model: $\chi_e = \chi_{Neoalcator}$, $\chi_i = 3 \times \chi_{Chang-Hinton}$, $q(0) = 0.8$



Optimal path : $n \sim 0.65\ n_{murakami}$

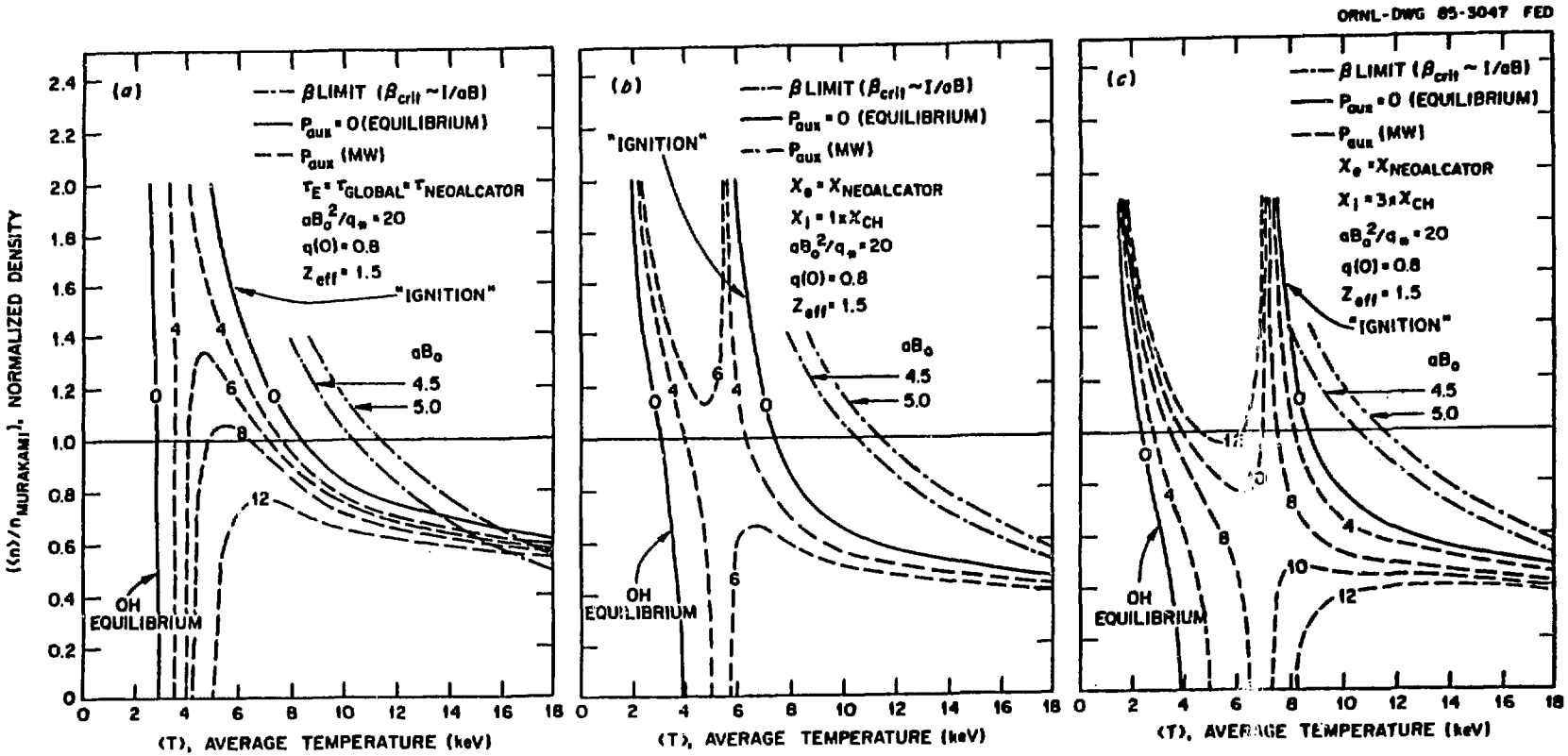
P_{aux}(equilibrium) : ~ 9.5 MW

Max. Ign. Margin : ~ 1.4

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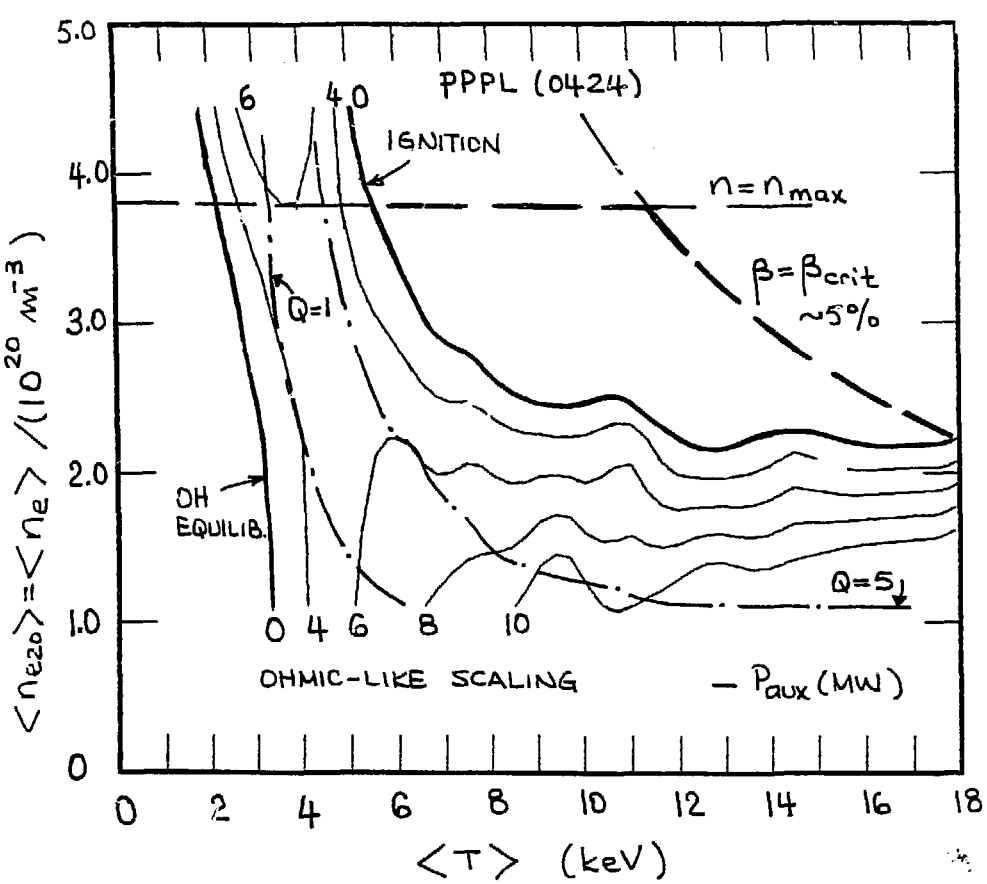
Steady-state POPCON plots (1-1/2-D code) showing P_{aux} and Q contours for a typical $aB_0^2/q_* \approx 20$ (PPPL-0424) device.

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

Confinement model: "ohmic-like" scaling

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

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

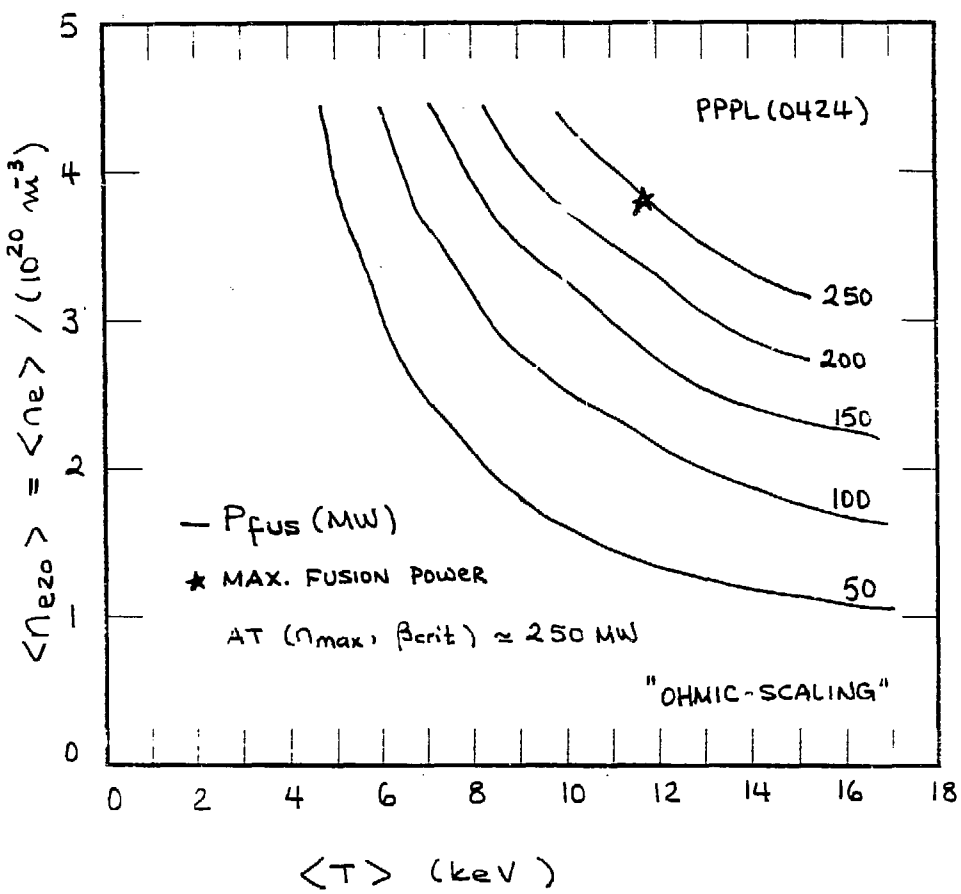


optimal path ~ 0.8 n_{max}

P_{aux} ~ 5 MW

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

Steady-state thermal fusion power contours for PPPL (0424)



[ohmic + auxiliary (L-mode) scaling
P_{fus} contours are similar ~ 10% less power]

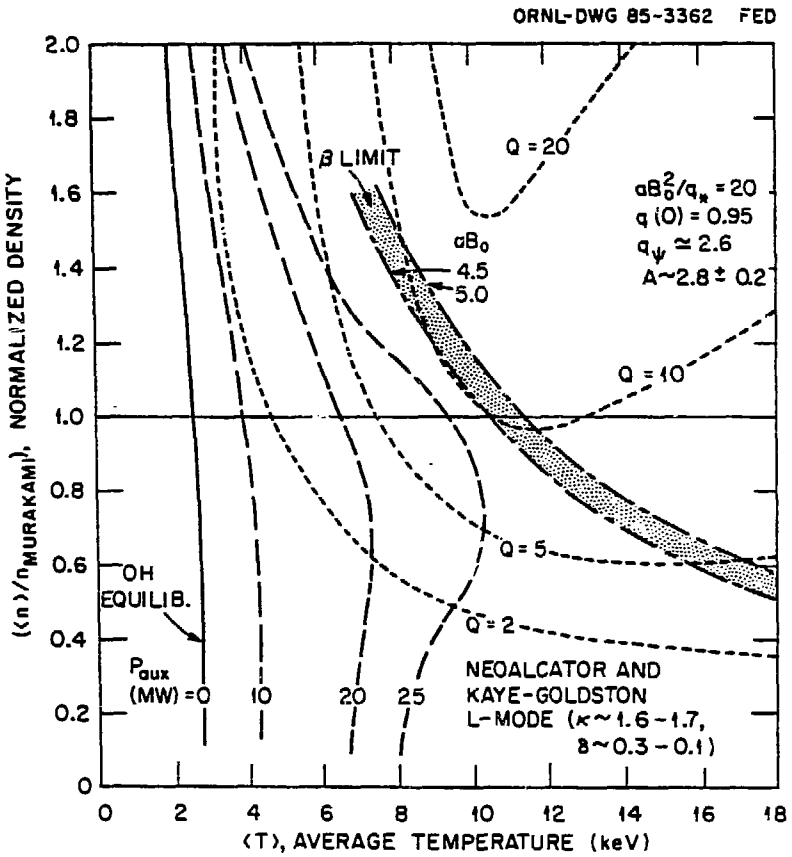
Steady-state auxiliary power contours for devices with

$aB_o^2/q_* = 20$

(a representative case for PPPL-ISP/MIT-LITE)

Confinement model: Neo-Alcator & Kaye-Goldston

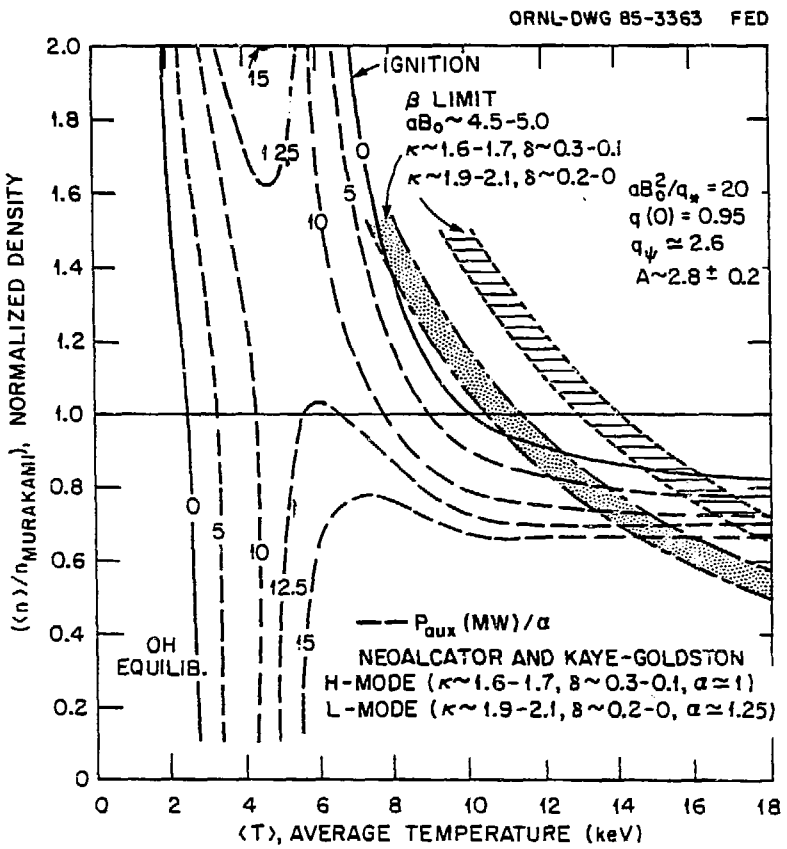
Geometry : "Standard" ($\kappa \sim 1.6$-1.7) — (L-mode)



$Q = P_{fusion} / (P_{aux} + P_{OH})$ are superimposed.

Note: Ignition is not accessible in this class of devices ($aB^2/q_* \sim 20$, $\kappa \sim 1.6$-1.7) for an L-mode Kaye-Goldston scaling. There is a finite $Q > 5$ operating window.

H-mode operation or some plasma shaping (increased elongation) improves the ignition conditions and auxiliary power requirements



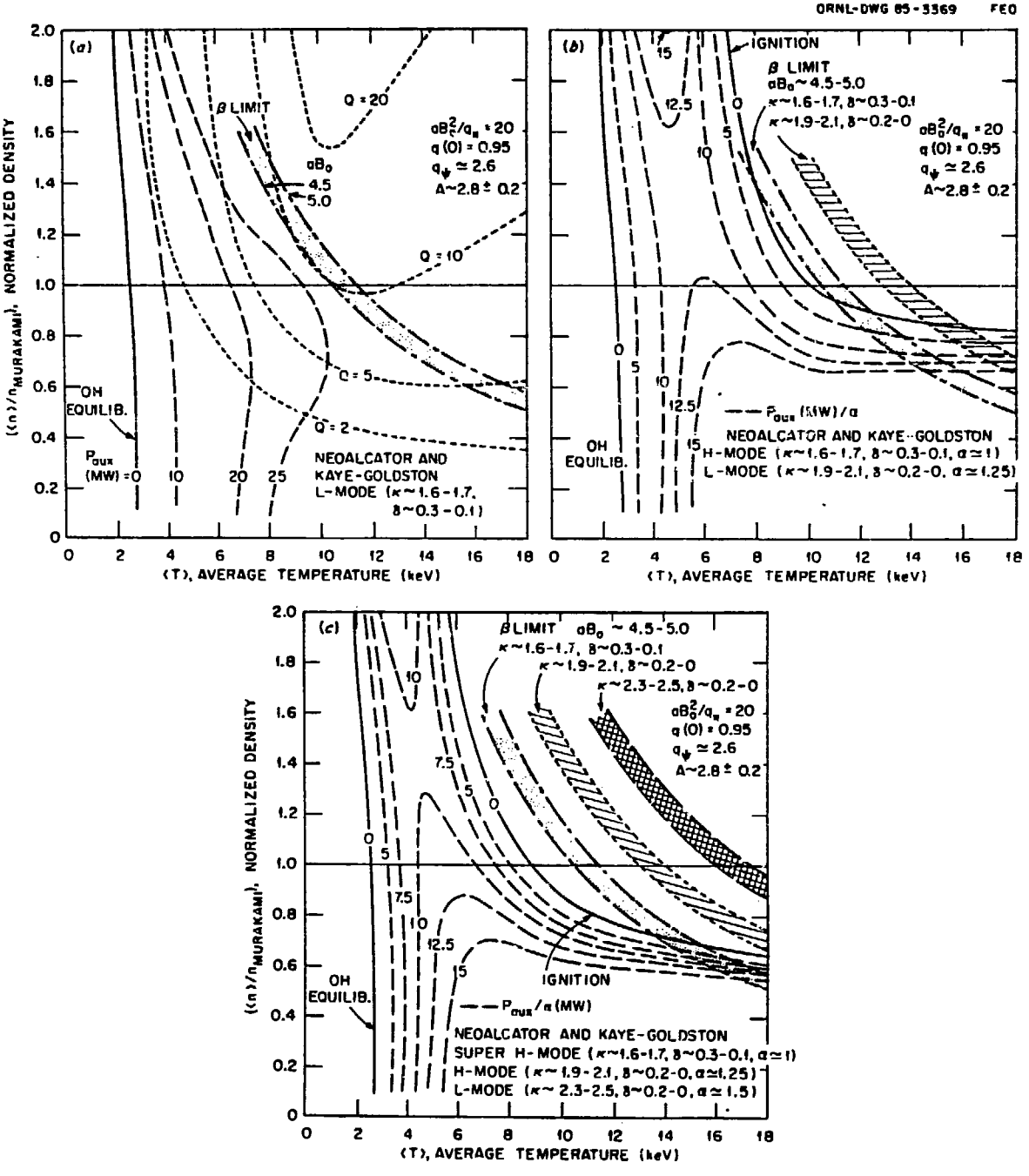
Confinement model: Neo-Alcator & Kaye-Goldston

Geometry : "Standard" ($\kappa \sim 1.6-1.7$) — H-mode

"Elongated" ($\kappa \sim 1.9-2.1$) — L-mode

SUMMARY (D-D , analytic model)

Neo-Alcator & Kaye - Goldston Scaling in 3 different geometry with increasing elongation for a class of devices with $aB_0^2/q_* \simeq 20$

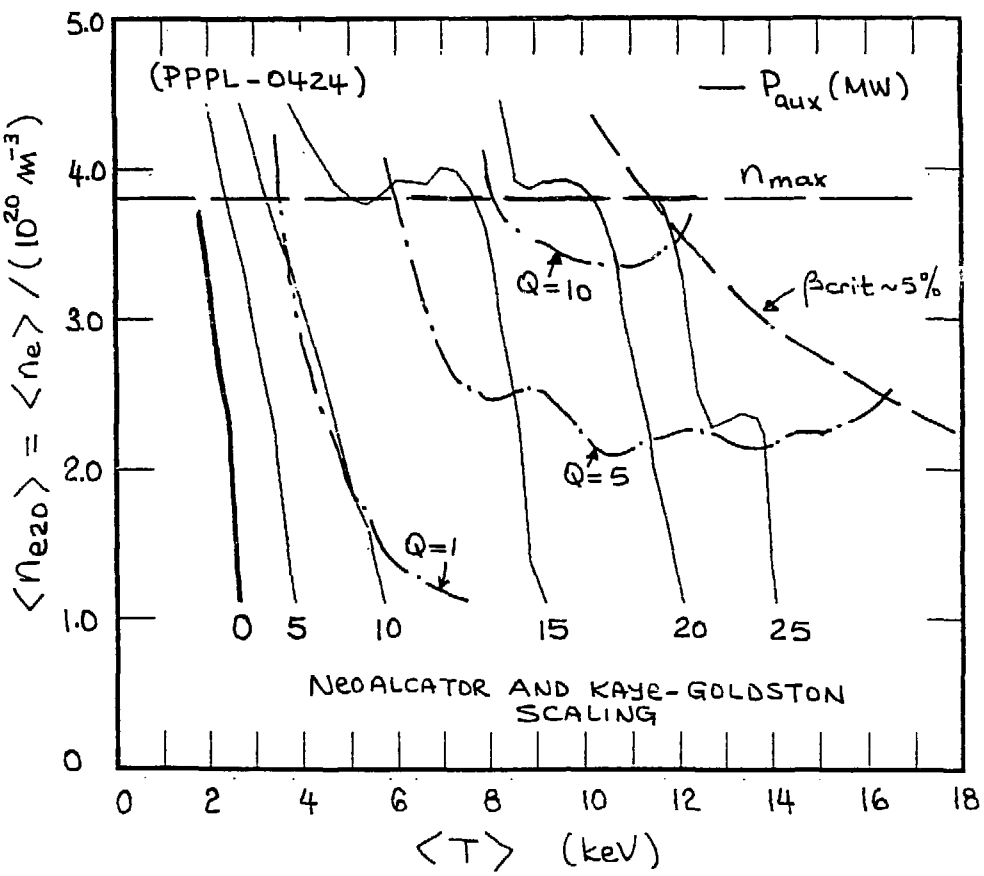


Steady-state POPCON (1-1/2-D) plots showing P_{aux} and Q contours for a typical $aB_0^2/q_* \simeq 20$ (PPPL-0424) device.

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.

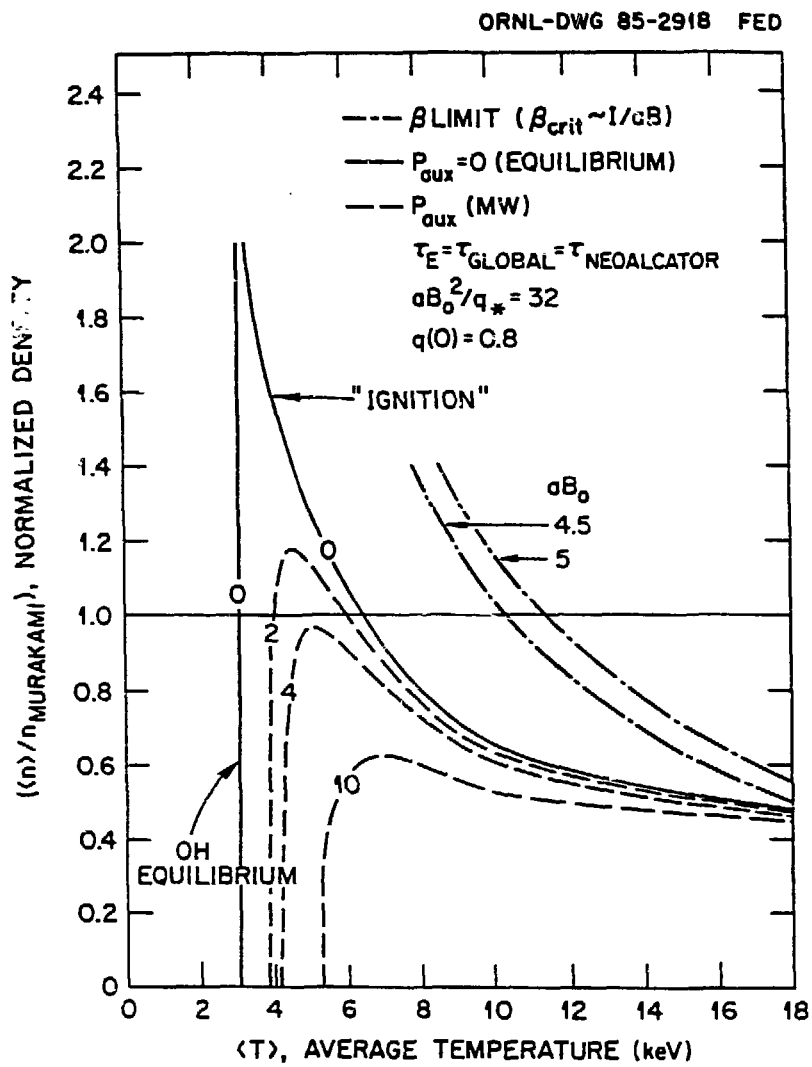
Optimal path, P_{aux}, and max. ignition margin are given.

Steady-state auxiliary power contours for devices with

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

(a representative case for IGNITOR-A/BCX[2])

Confinement model: $\tau_E = \tau_{Global}$
$= \tau_{Neoalcator}$
$q(0) = 0.8$



Optimal path : $n = n_{murakami}$

P_{aux}(equilibrium) : ~ 3.5 MW

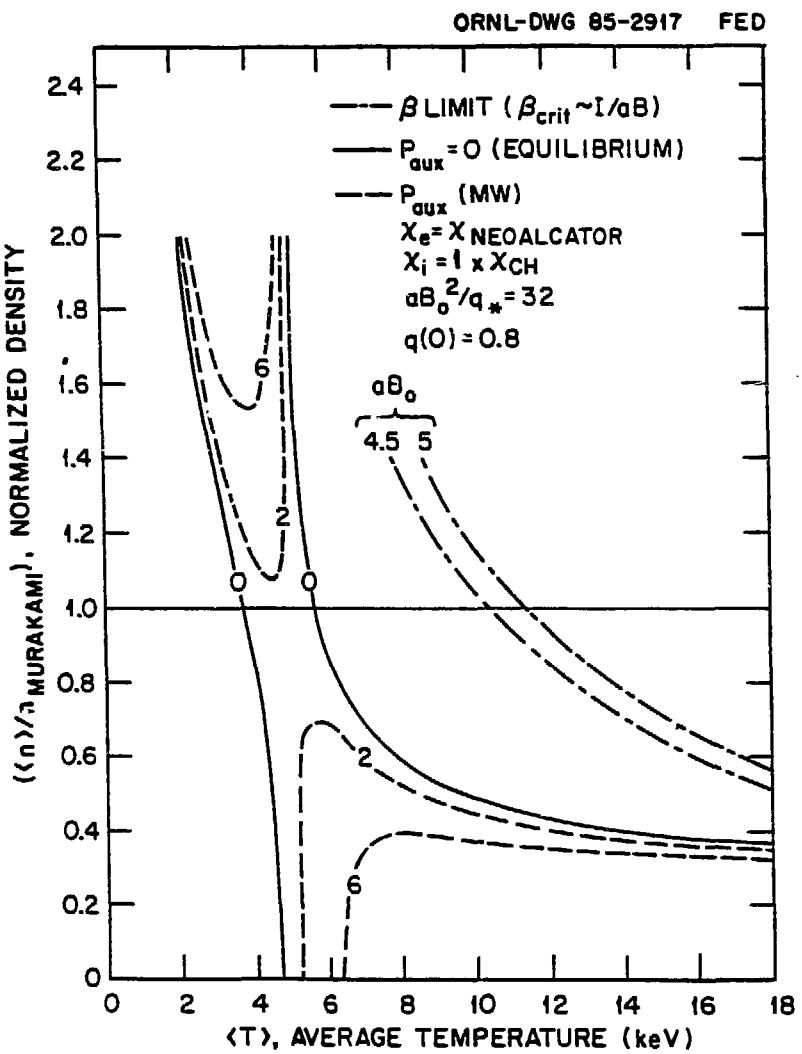
Max. Ign. Margin : ~ 2.3

Steady-state auxiliary power contours for devices with

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

(a representative case for IGNITOR-A/BCX[2])

Confinement model: $\chi_e = \chi_{Neoalcator}$
$\chi_i = 1 \times \chi_{Chang-Hinton}$
$q(0) = 0.8$



Optimal path : $n = 0.8\ n_{murakami}$

P_{aux}(equilibrium) : ~1.5 MW

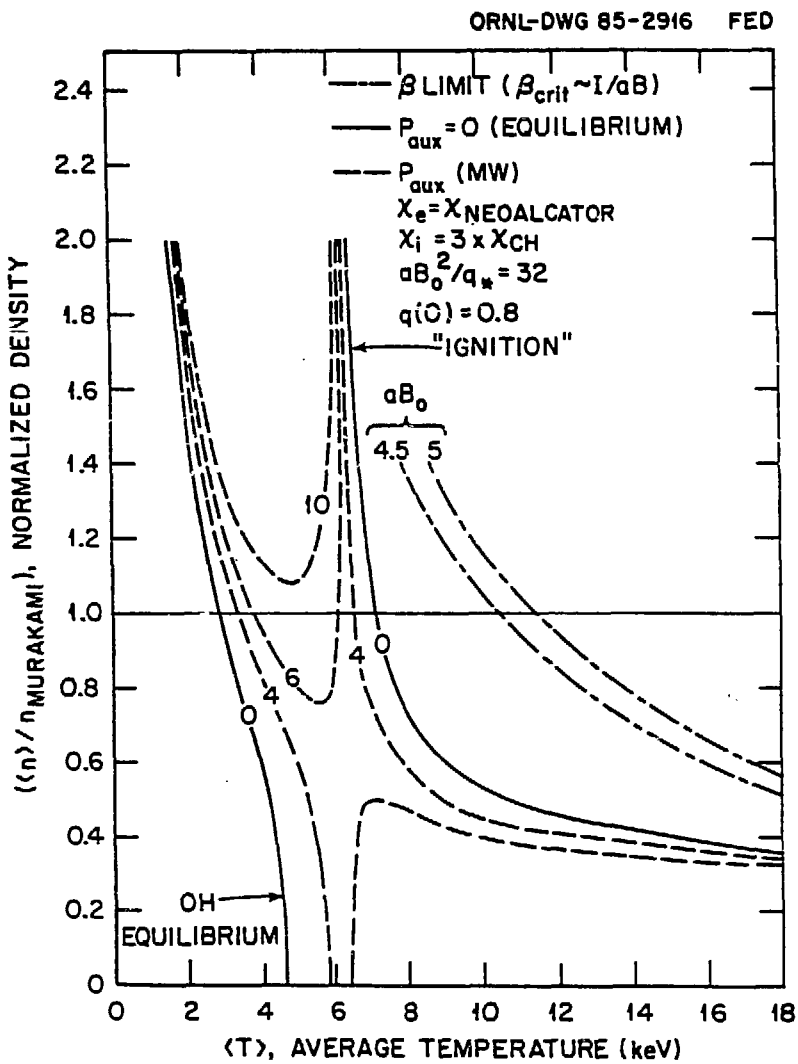
Max. Ign. Margin : ~2.8

Steady-state auxiliary power contours for devices with

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

(a representative case for IGNITOR-A/BCX^2)

Confinement model: $\chi_e = \chi_{Neoalcator}$
$\chi_i = 3 \times \chi_{Chang\text{-}Hinton}$
$q(0) = 0.8$



Optimal path : $n \sim 0.65\ n_{murakami}$

P_{aux}(equilibrium) : ~ 5 MW

Max. Ign. Margin : ~ 2.2

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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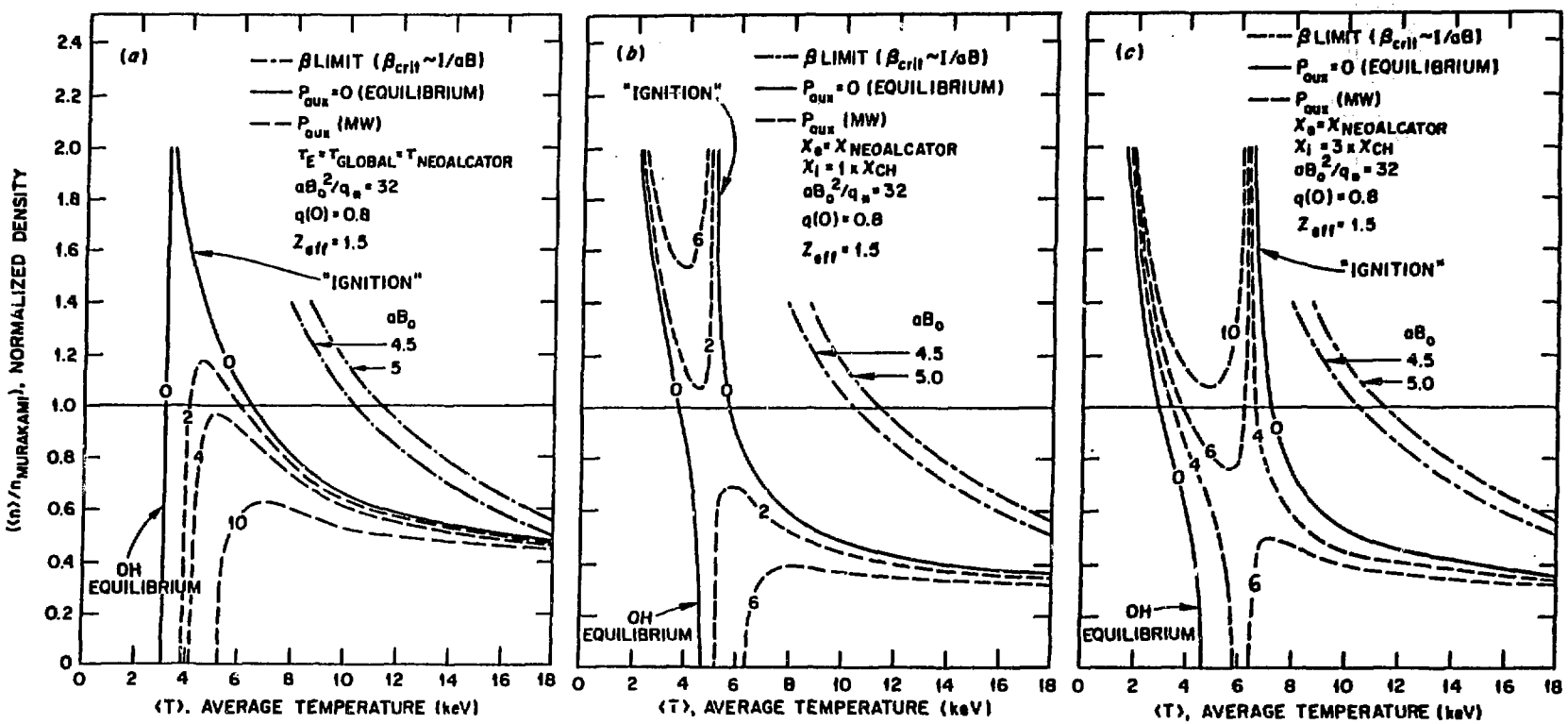

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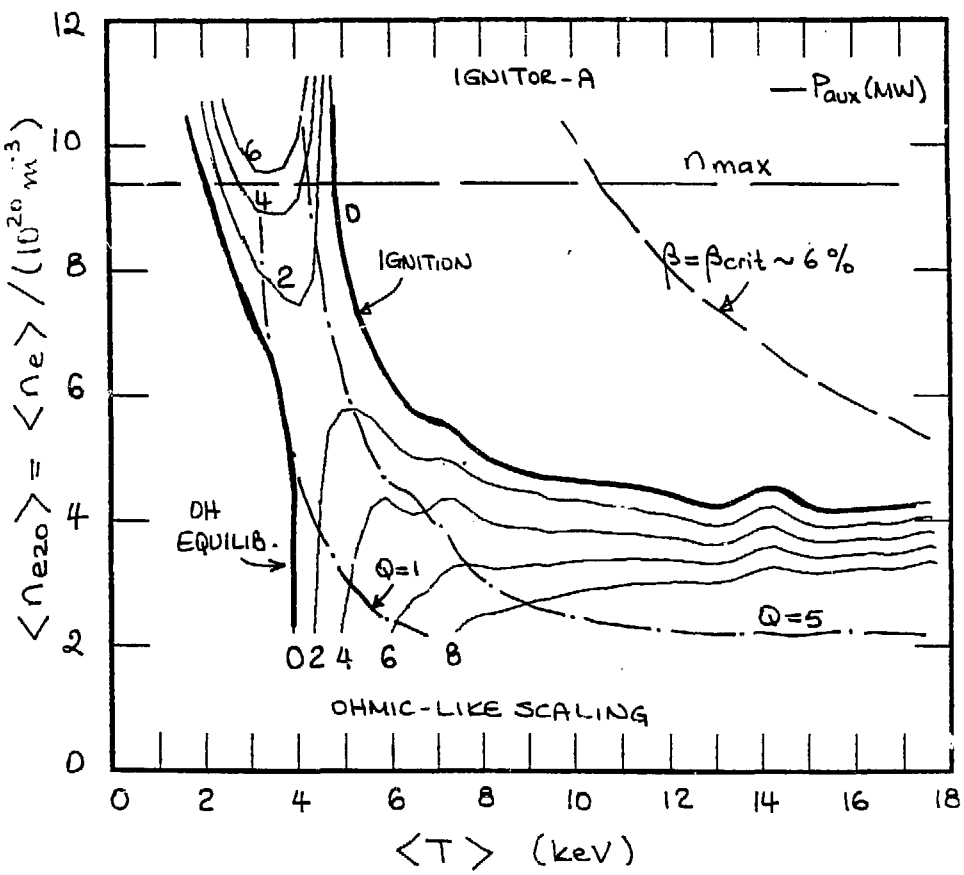
Steady-State POPCON (1-1/2-D) plots
-- P_{aux} and Q contours for Ignitor-A ($aB_0^2/q_* \sim 32$)

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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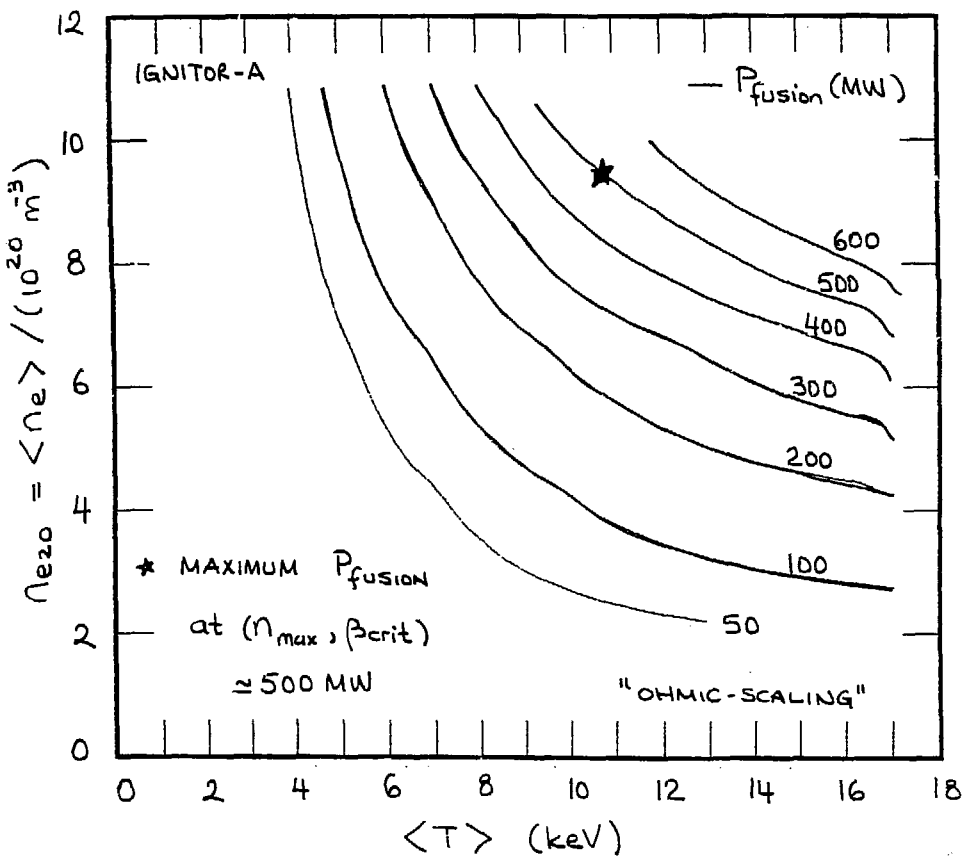
9/85

Steady-state thermal fusion power contours for IGNITOR-A.



[Ohmic + auxiliary (L-mode) scaling power contours are similar ~ 10% less power]

Steady-state auxiliary power contours for devices with

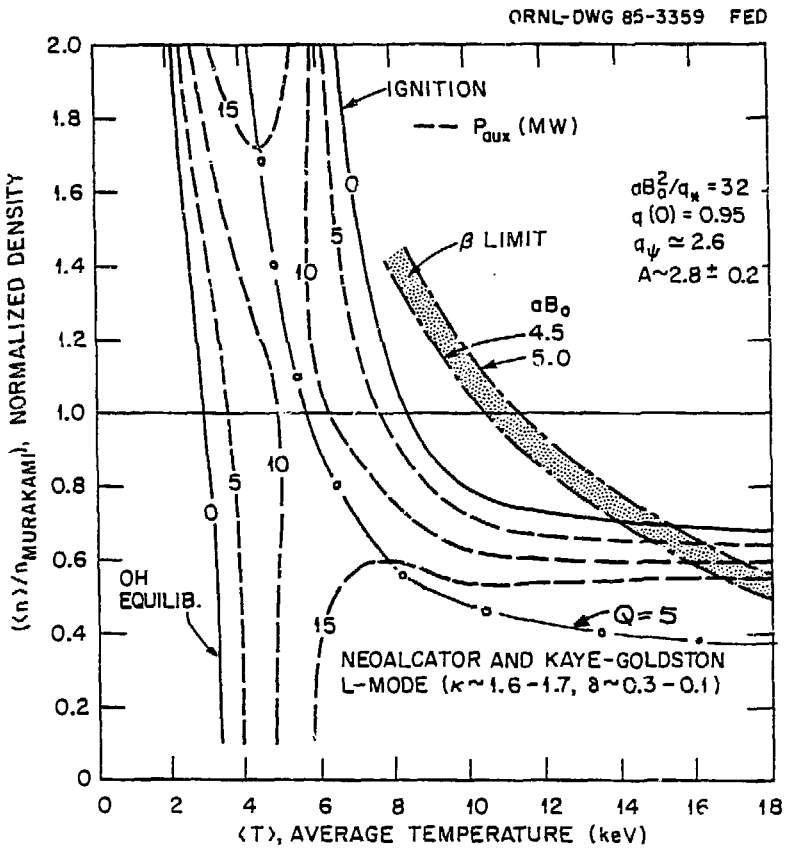
$aB_o^2/q_* = 32$

(a representative case for IGNITOR-A/BCX^2)

Confinement model: Neoalcator & Kaye-Goldston

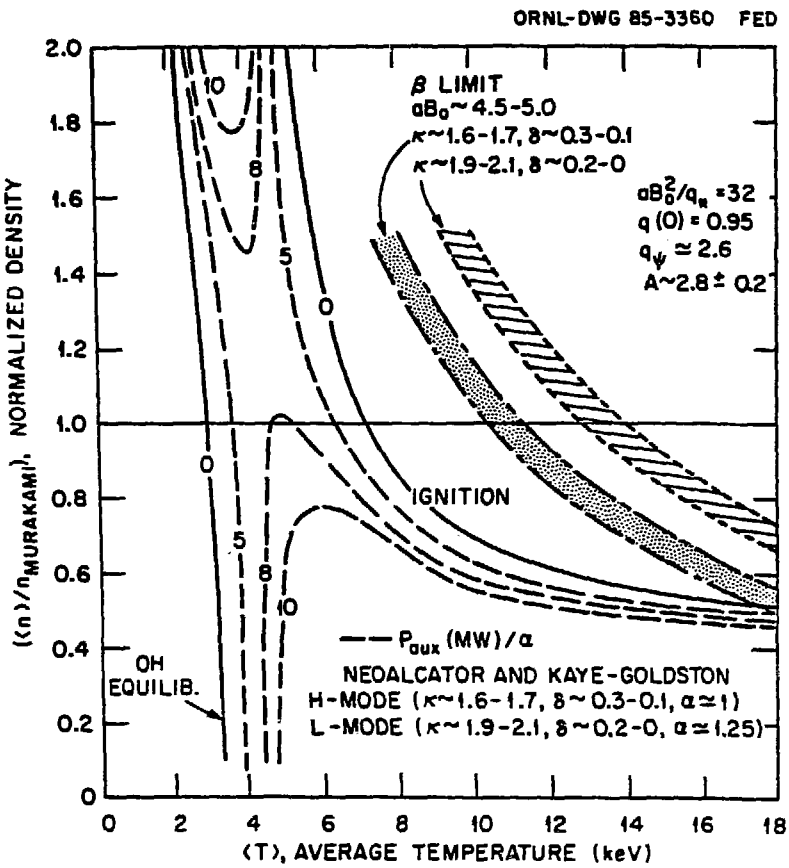
Geometry: "Standard" ($\kappa \sim 1.6$-1.7)

(L-mode)

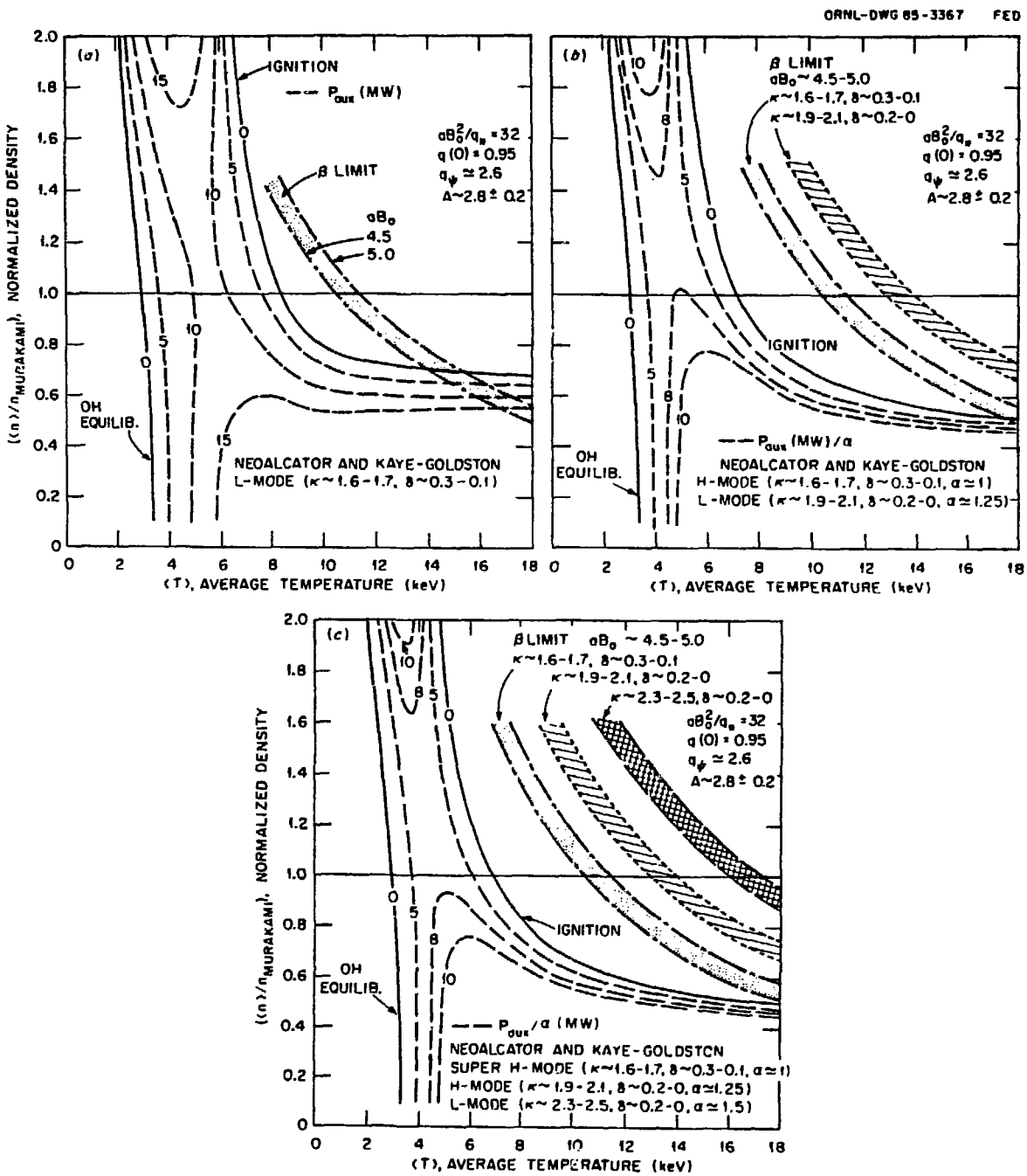


Ignition is possible (with some margin) for an L-mode Kaye-Goldston scaling in this class of devices ($aB_o^2/q_* \sim 32$, $\kappa \sim 1.6$-1.7).

H-mode operation or some plasma shaping (increased k) further improves the ignition margin.

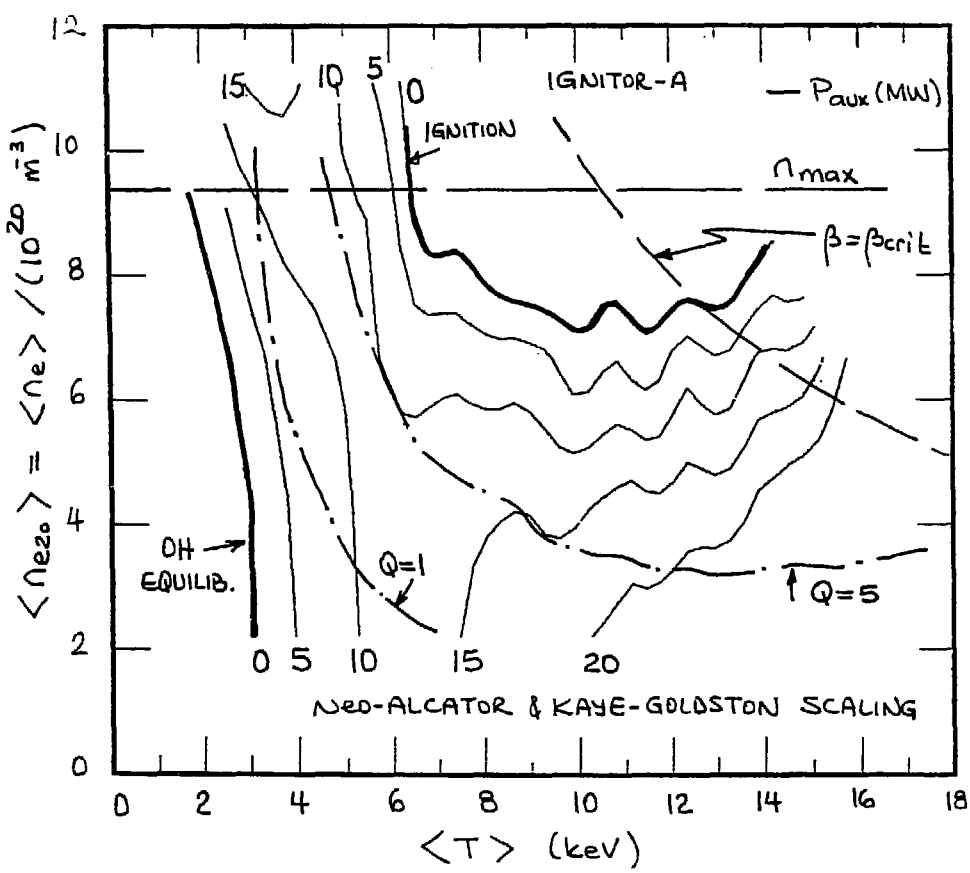


Summary : Neo-Alcator & Kaye - Goldston scaling in 3 different geometry with increasing κ for a class of devices with $aB_0^2/q_* \sim 32$



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
L-mode



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

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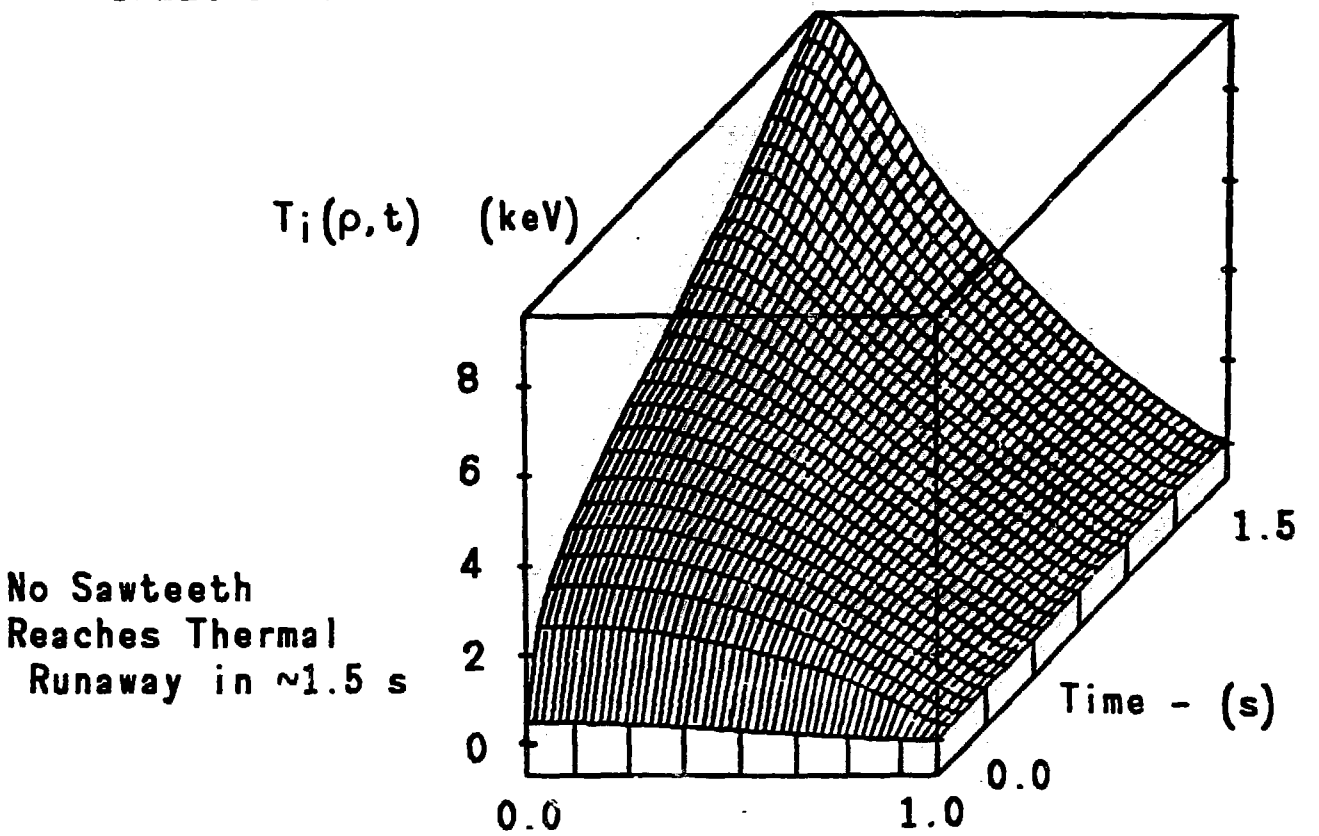
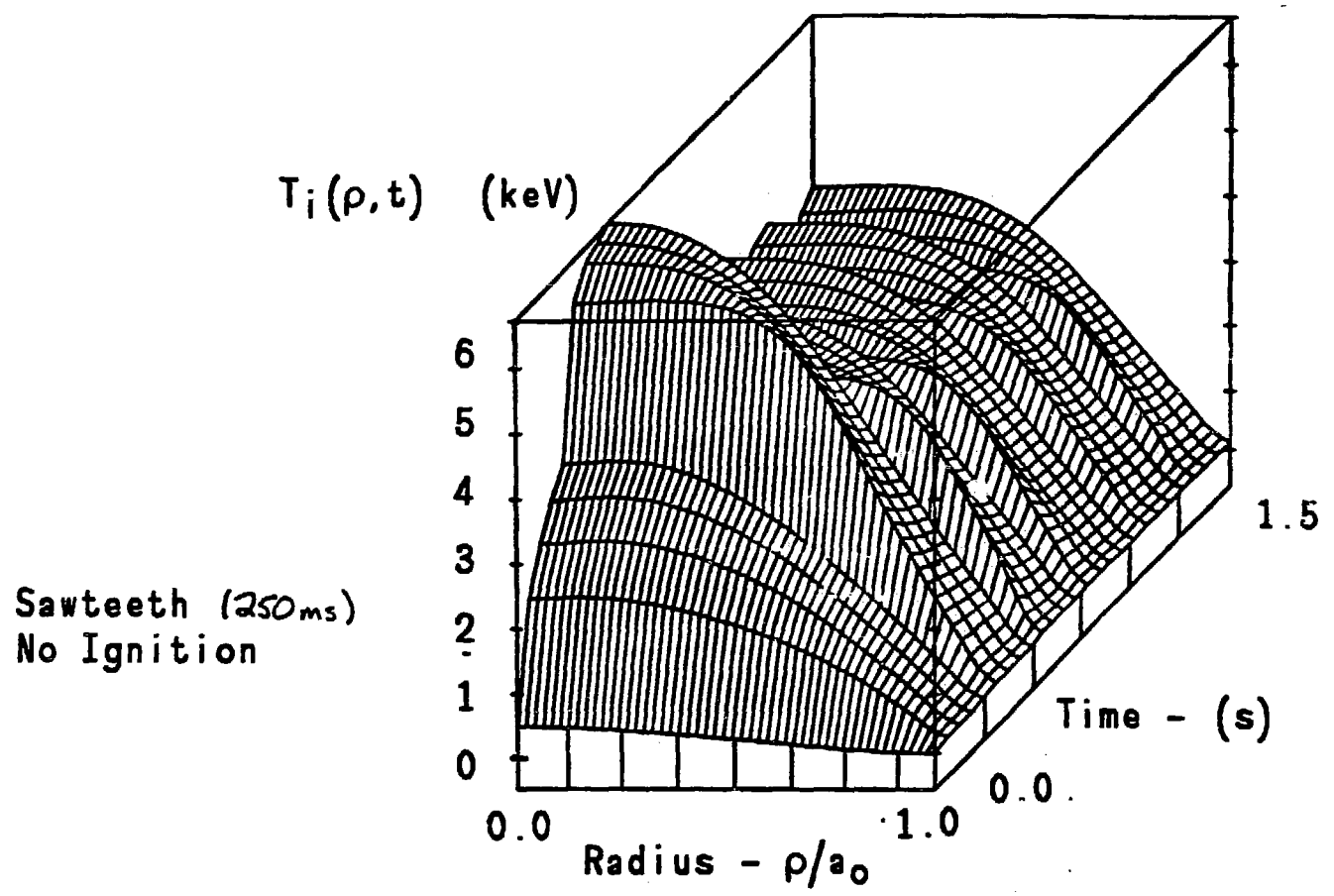
(PPPP et al)

OHMIC IGNITOR-A SIMULATIONS WITH BALDUR

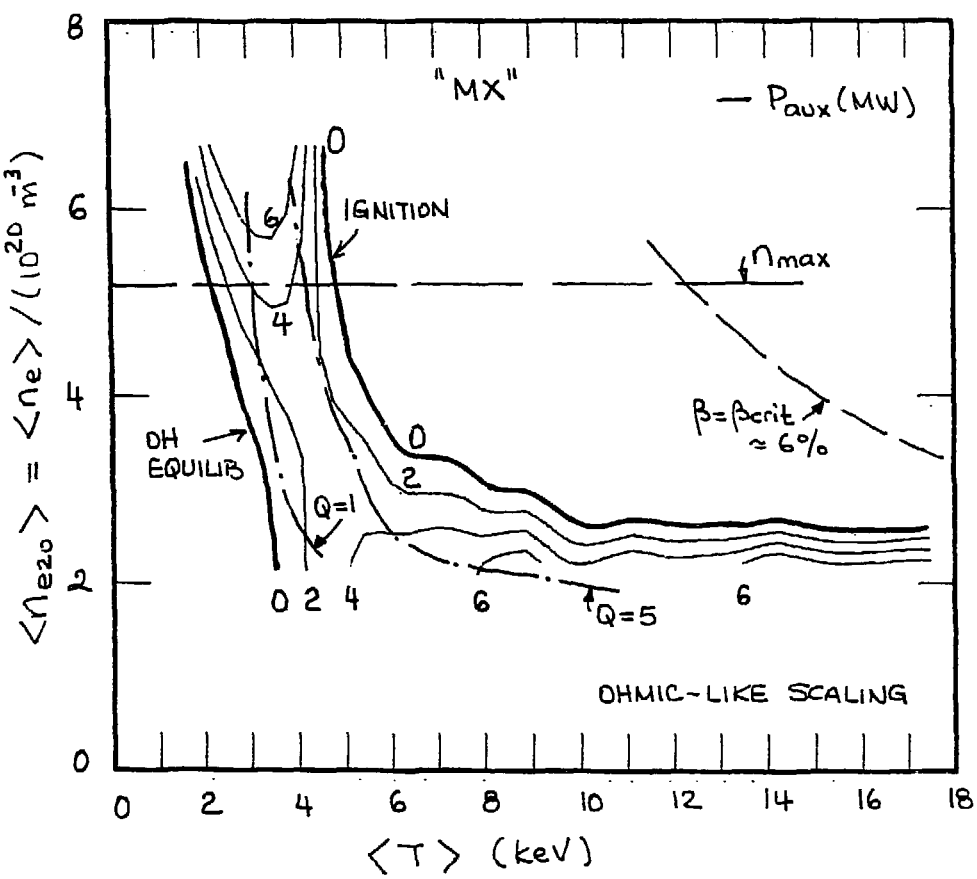




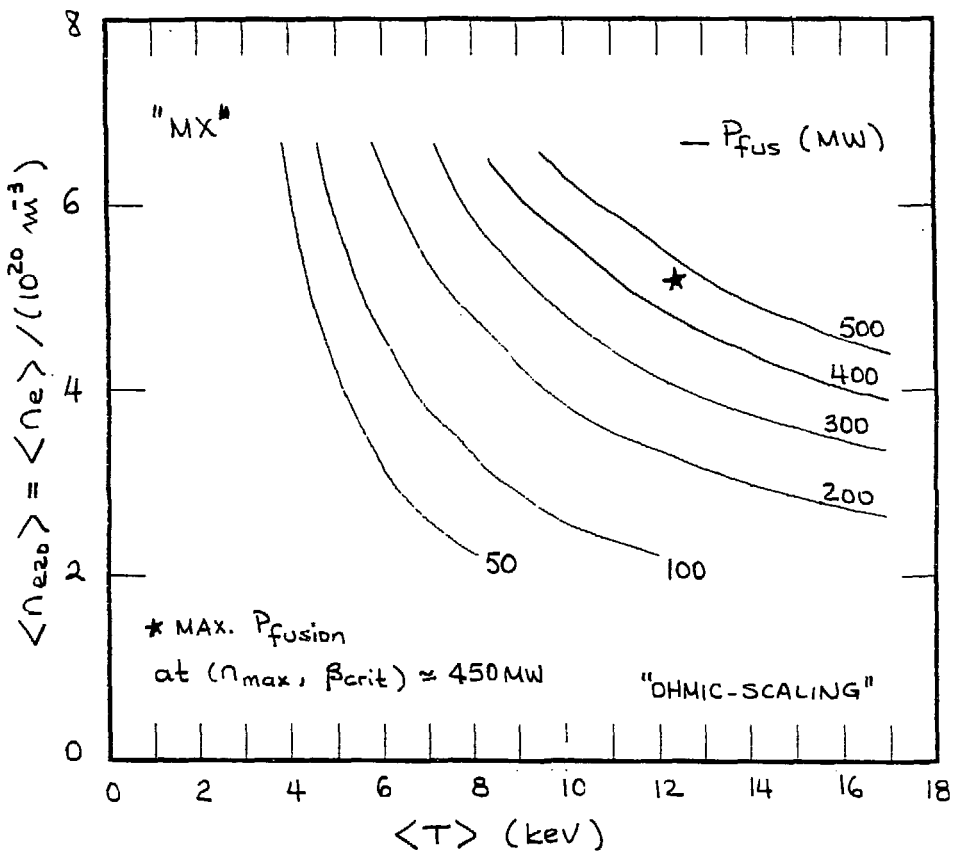
Steady-state POPCON (1-1/2-D) plots
-- P_{aux} and Q contours for "MX"

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

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



Steady-state thermal fusion power contours
"MX"



"MX": $aB_0^2/q_* = 25$, $\kappa \sim 1.8$, $\delta \sim 0.2$, $A = 2.8$

— — ($a \approx 0.5$ m, $R \approx 1.4$ m, $B_0 \approx 10$ T, $I \approx 10$ MA)

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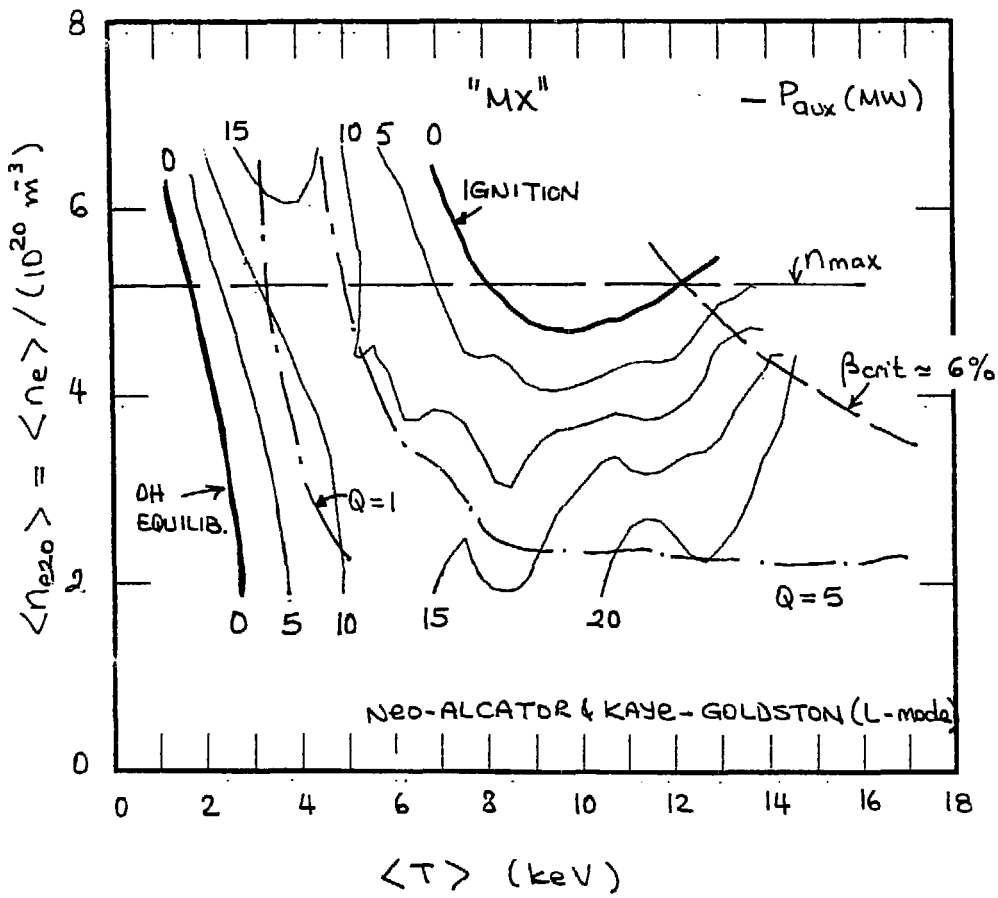
Steady-state POPCON plots (1-1/2-D)
-- P_{aux} and Q contours for "MX"

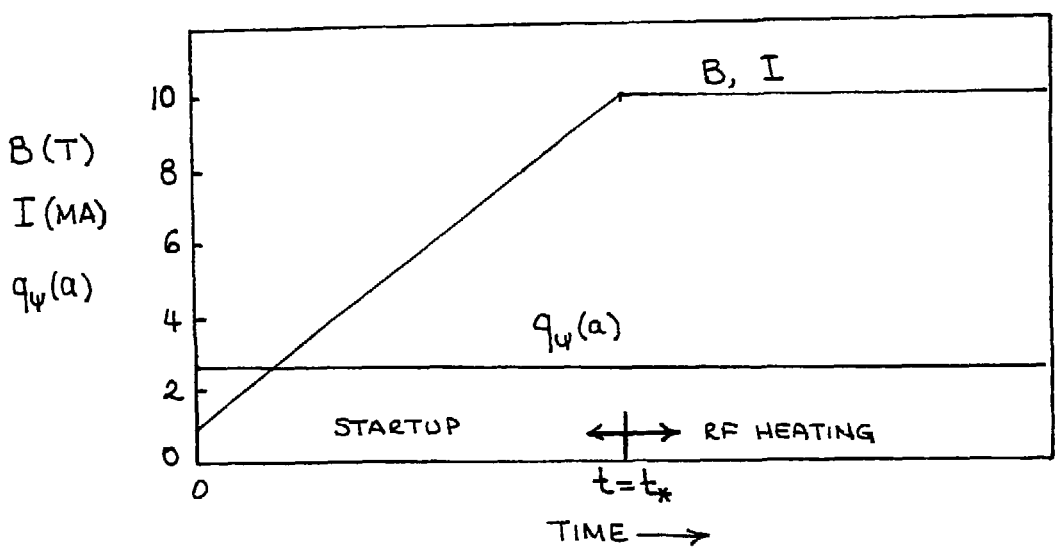
Confinement model: ohmic + auxiliary
OH – Neo Alcator
aux – Kaye-Goldston
L-Mode



STARTUP ANALYSIS

Advantages of simultaneous B_ϕ, I_ϕ, and density ramps:

- Avoid skin current problems with fast ramp.
- Maintain constant $q_\psi(a\ ,t)$.
- Overcome sawtooth activity.
- Maintain $n < n_M$.
- Modest compressional heating and fueling (not included in simulations.
- Increase 'flat-top' time relative to startup time (at the expense of TF and PF power supplies) when temperature rise in coils is limiting factor in pulse.



(t_* = 3 seconds)

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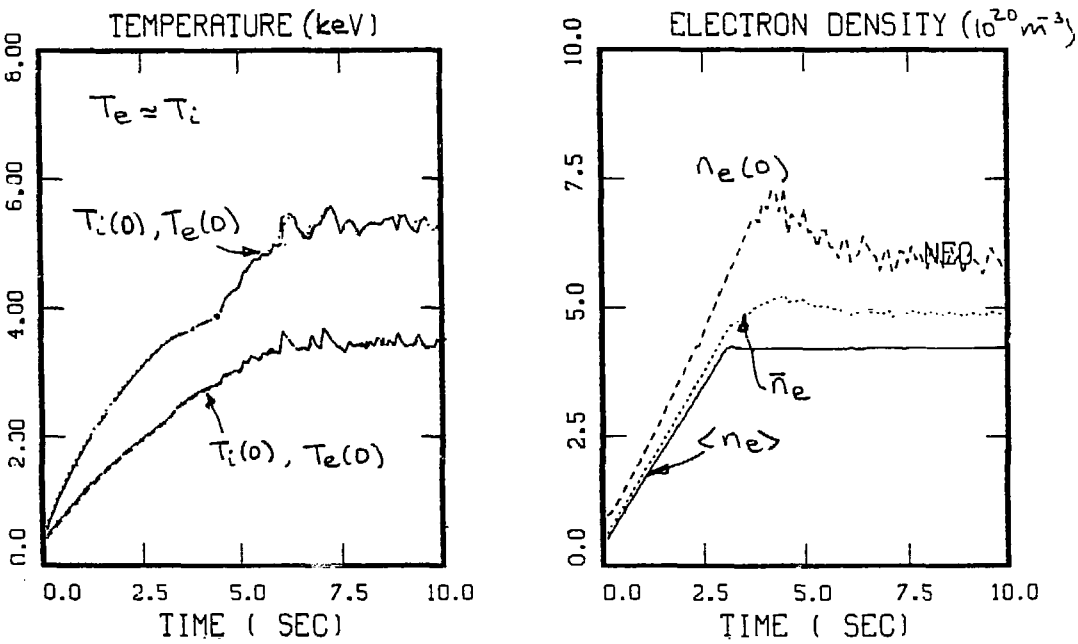
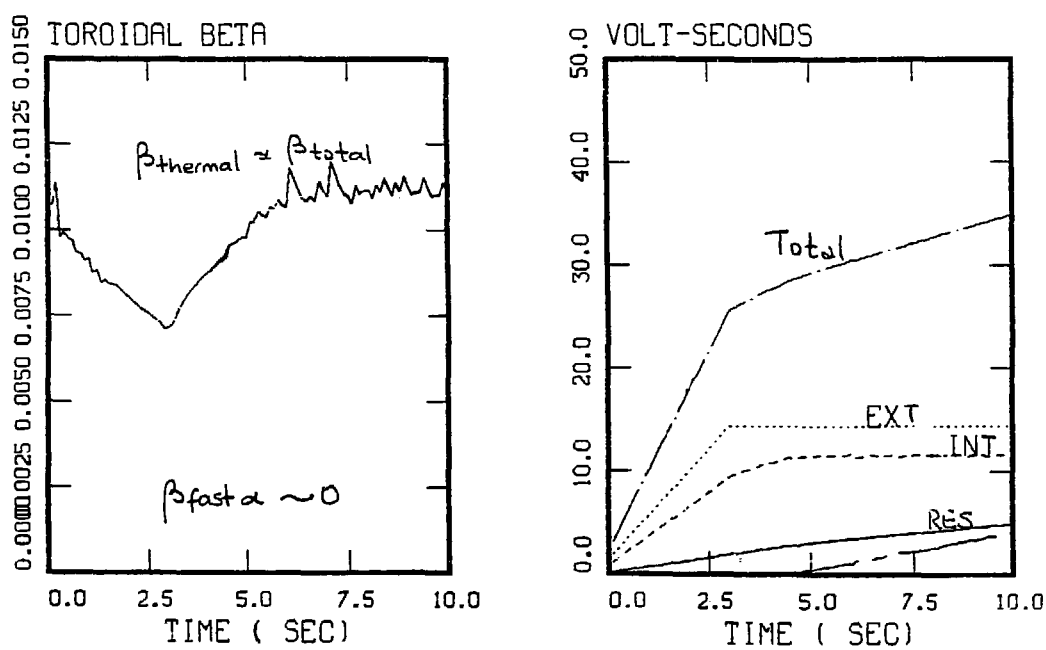
"MX" 3-SECONDS 10-MA STARTUP

OHMIC STARTUP (HEATING)

OHMIC-SCALING -- Neo-Alcator ($\chi_e \sim \chi_{NA}$ $\chi_i \sim \chi_{CH}$)





WAH 10/85
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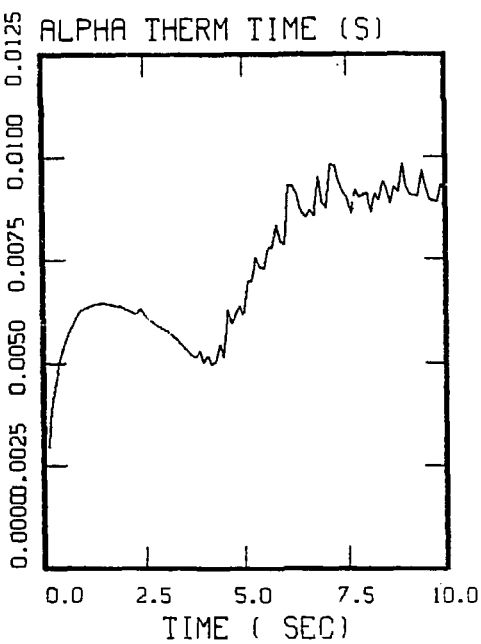
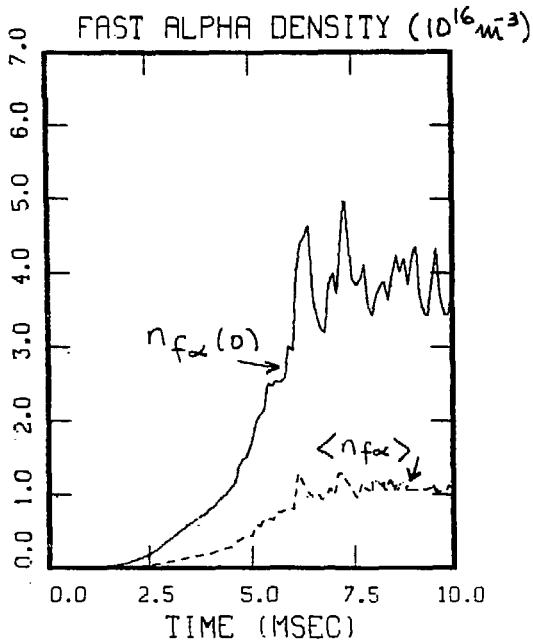
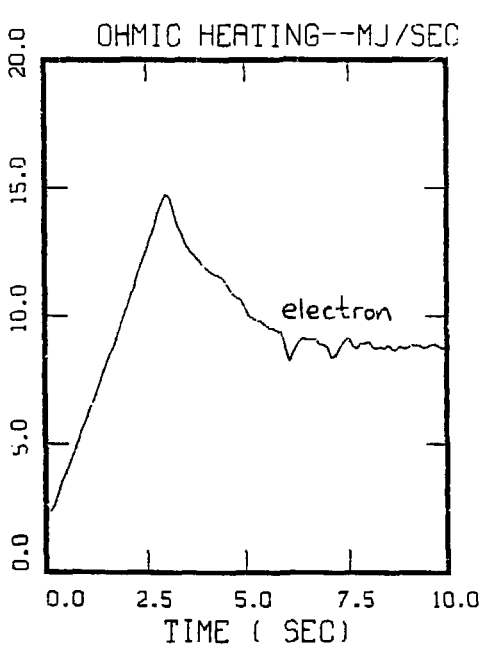
"MX" 3-SEC 10-MA STARTUP

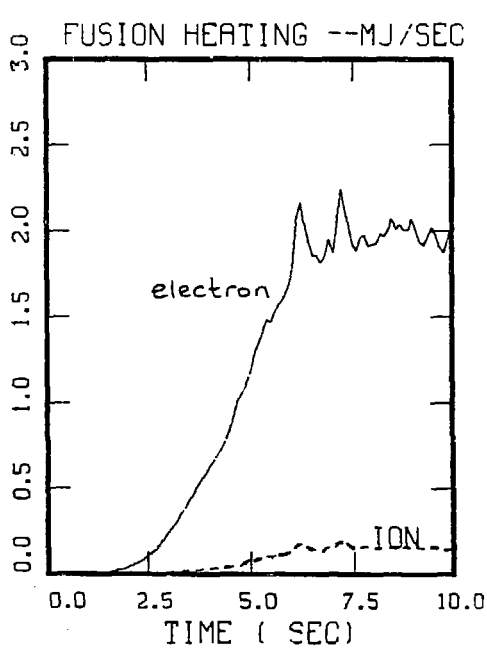
OHMIC STARTUP (HEATING)

"OHMIC" SCALING -- Neo-Alcator $\chi_e \sim \chi_{NA}$, $\chi_i \sim \chi_{CH}$



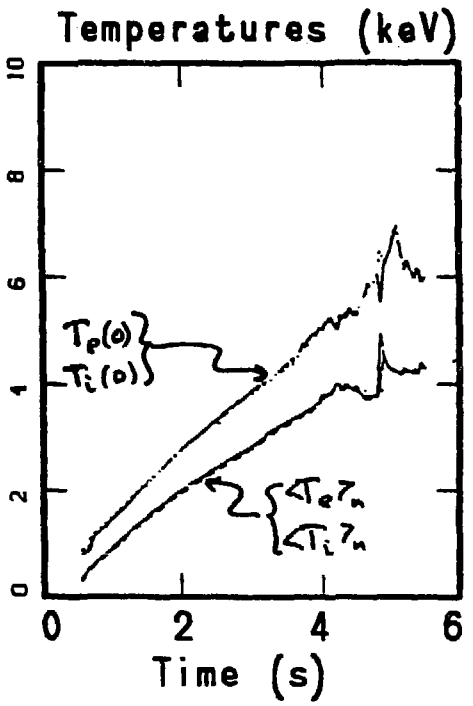


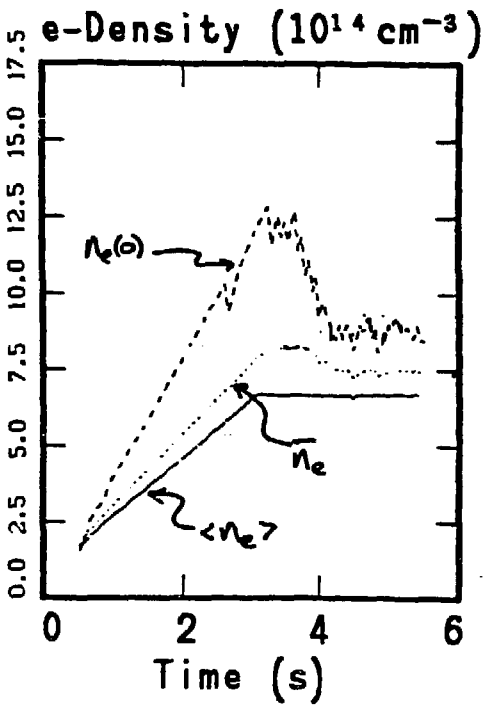


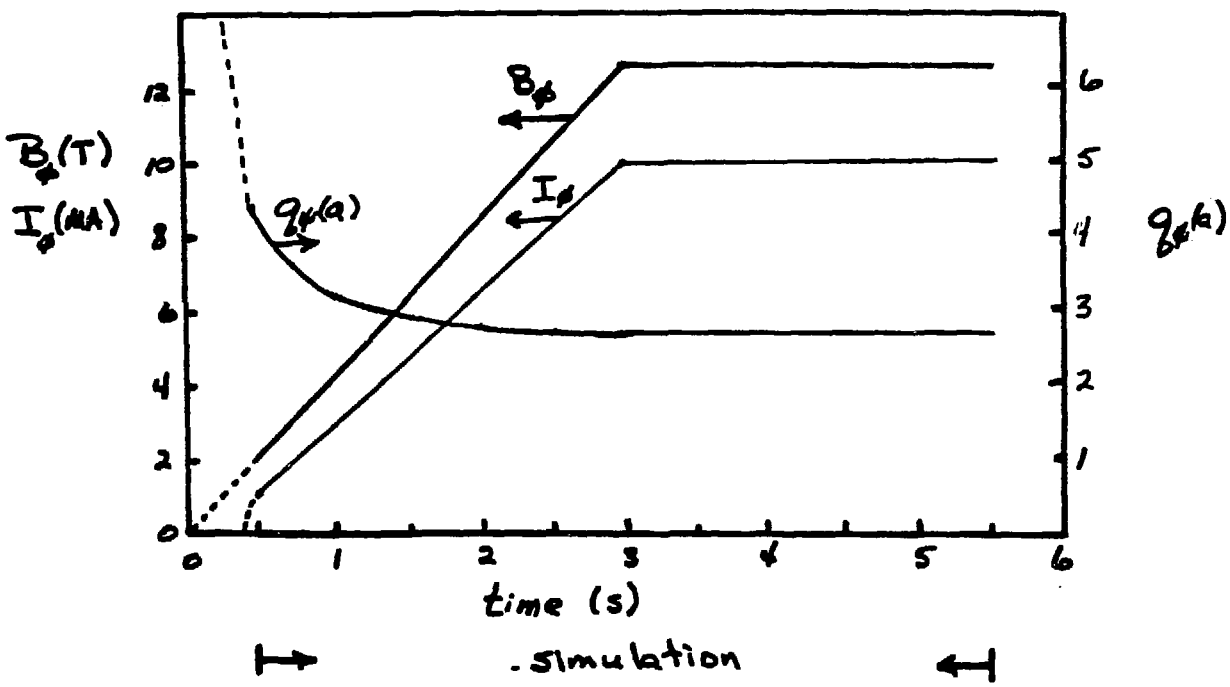


IGNITOR-A, 3-SEC 10-MA STARTUP

χ_e^{JET*}, χ_i^{CH}, OHMIC Heating



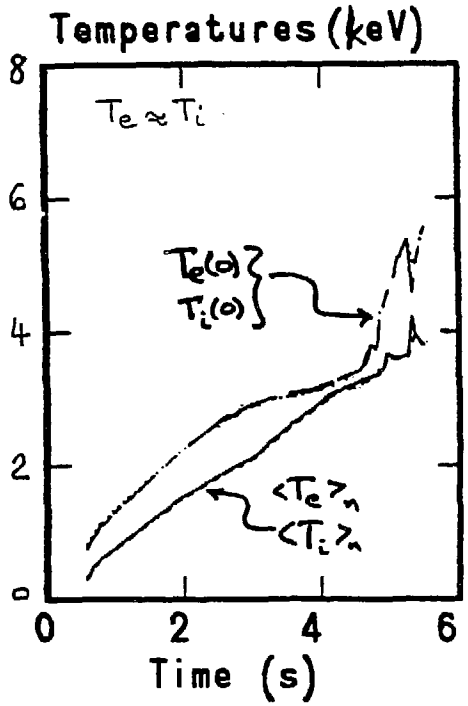


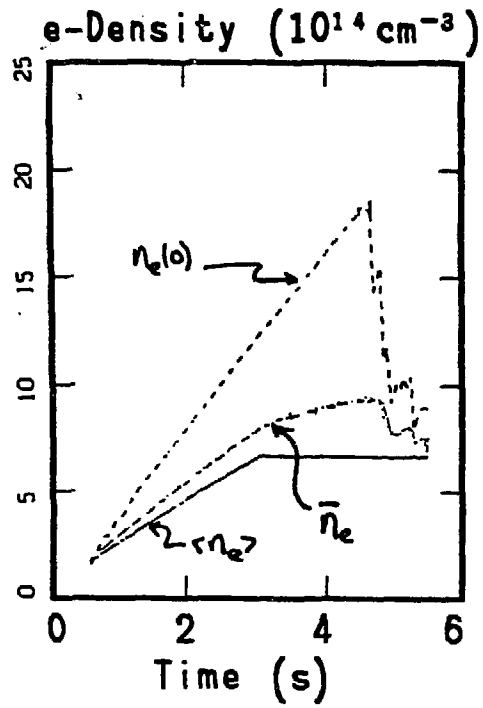


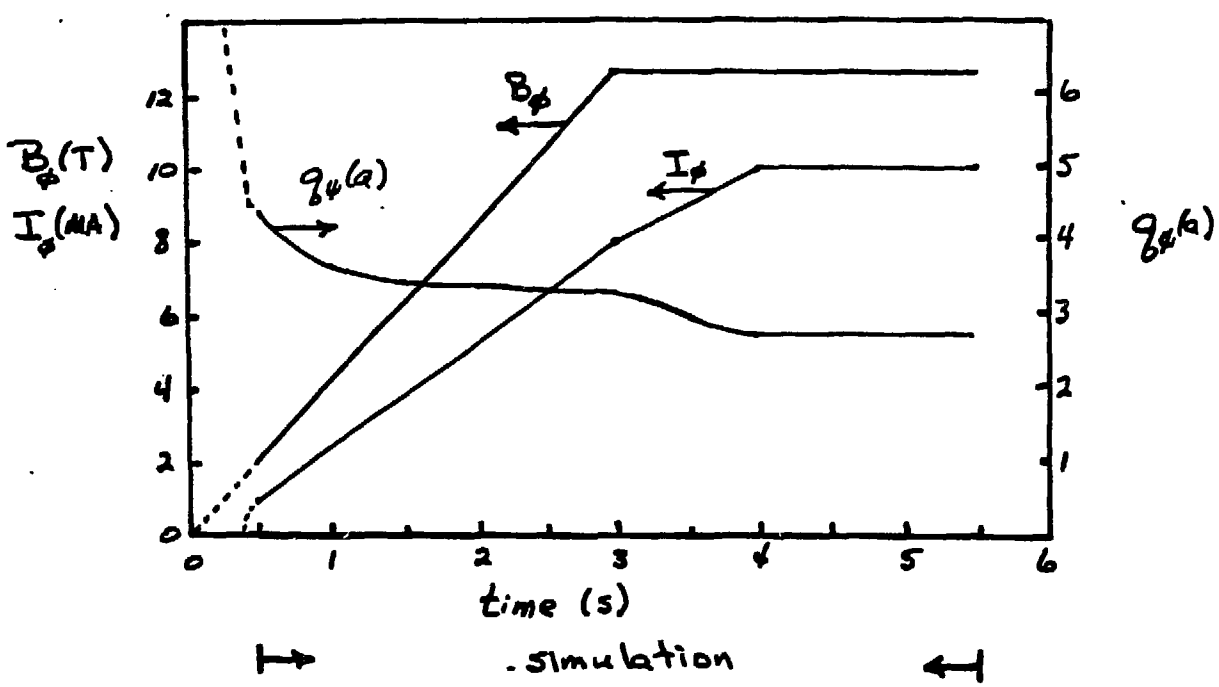
* χ_e^{JET} is very similar to $\chi_{neoalcator}$. ("ohmic-like" scaling)

IGNITOR-A, DELAYED 10-MA STARTUP

χ_e^{JET}, χ_i^{CH}, OHMIC Heating



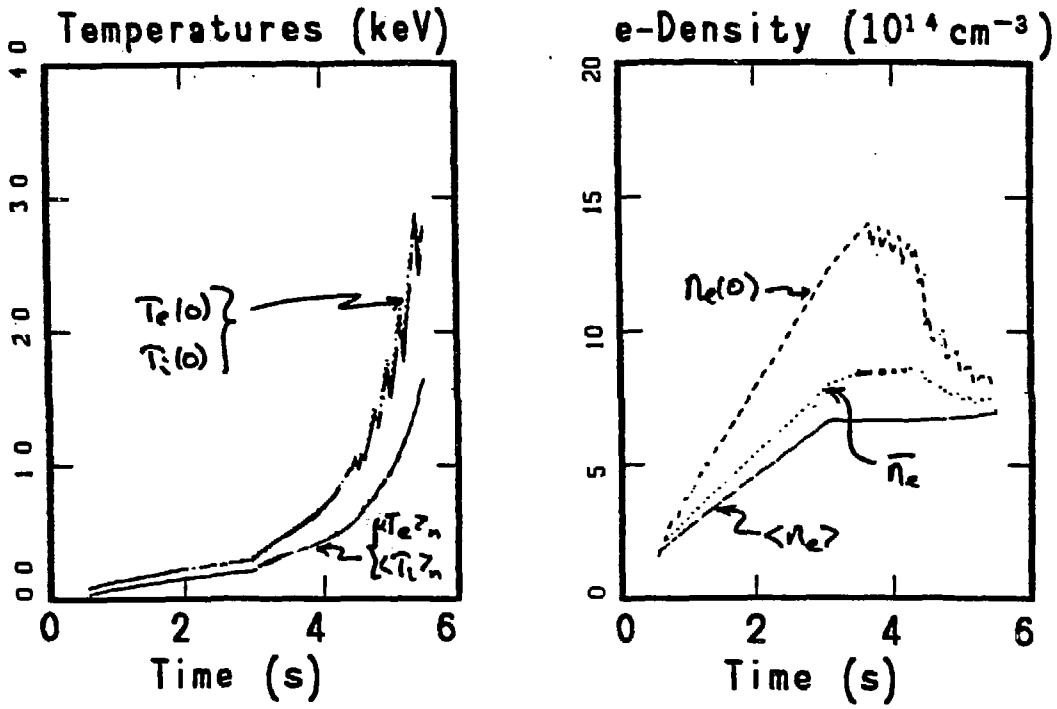


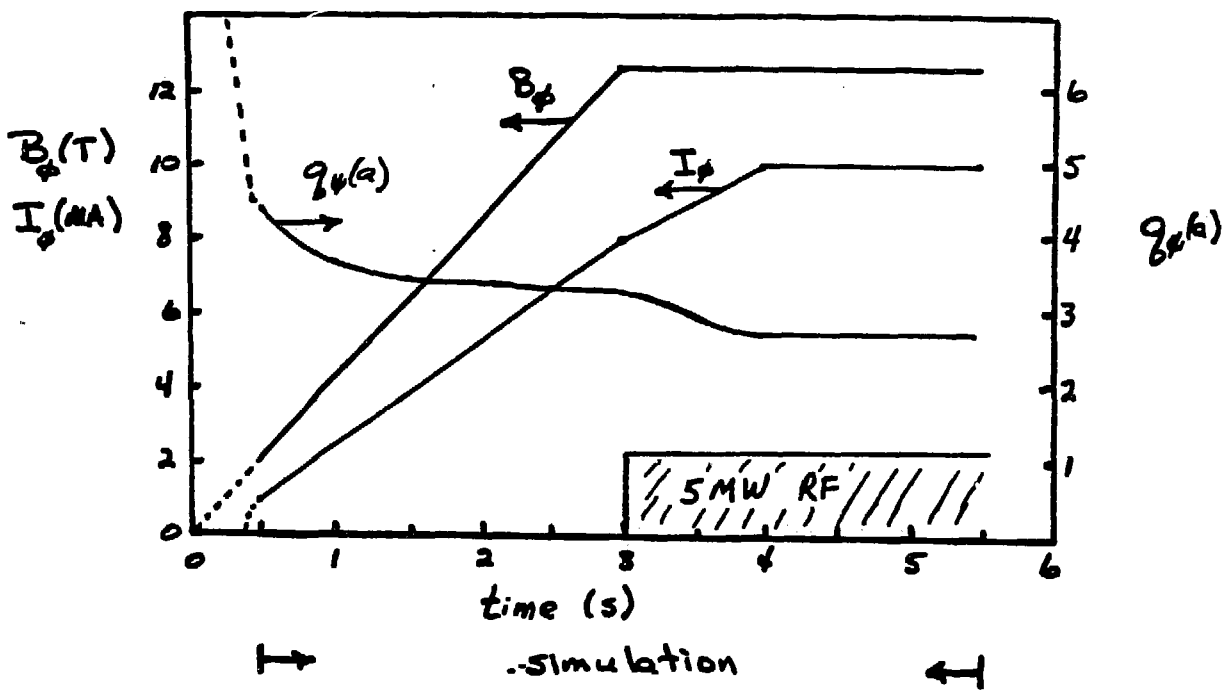


WAH 6/85

IGNITOR-A, DELAYED 10-MA STARTUP

χ_e^{JET}, χ_i^{CH}, 5 MW RF

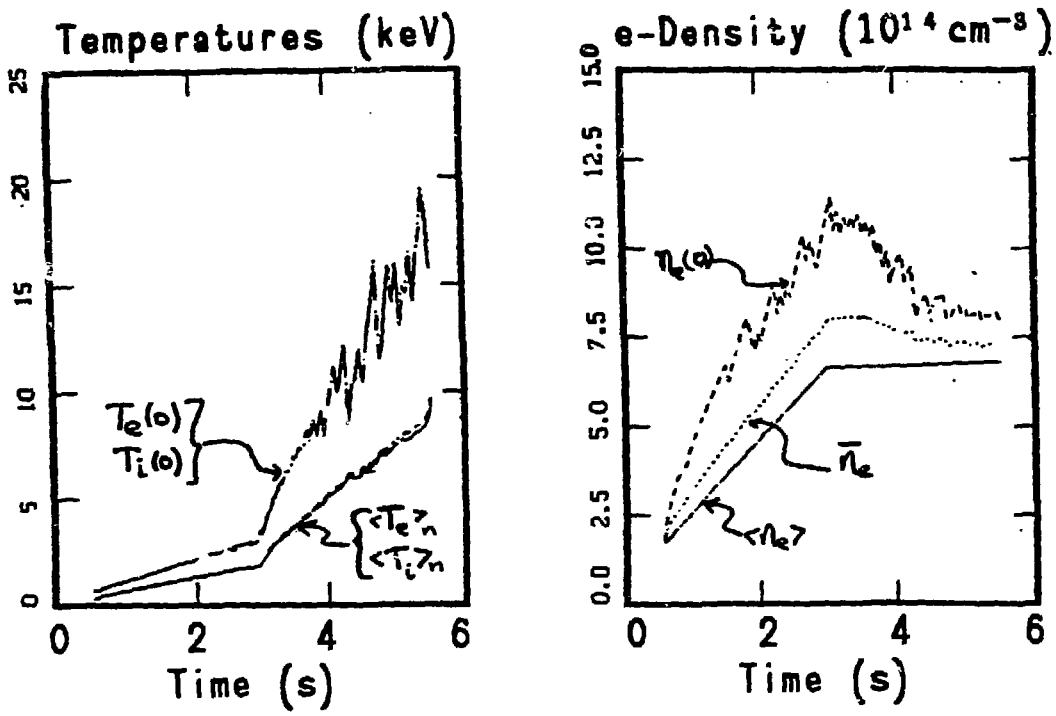


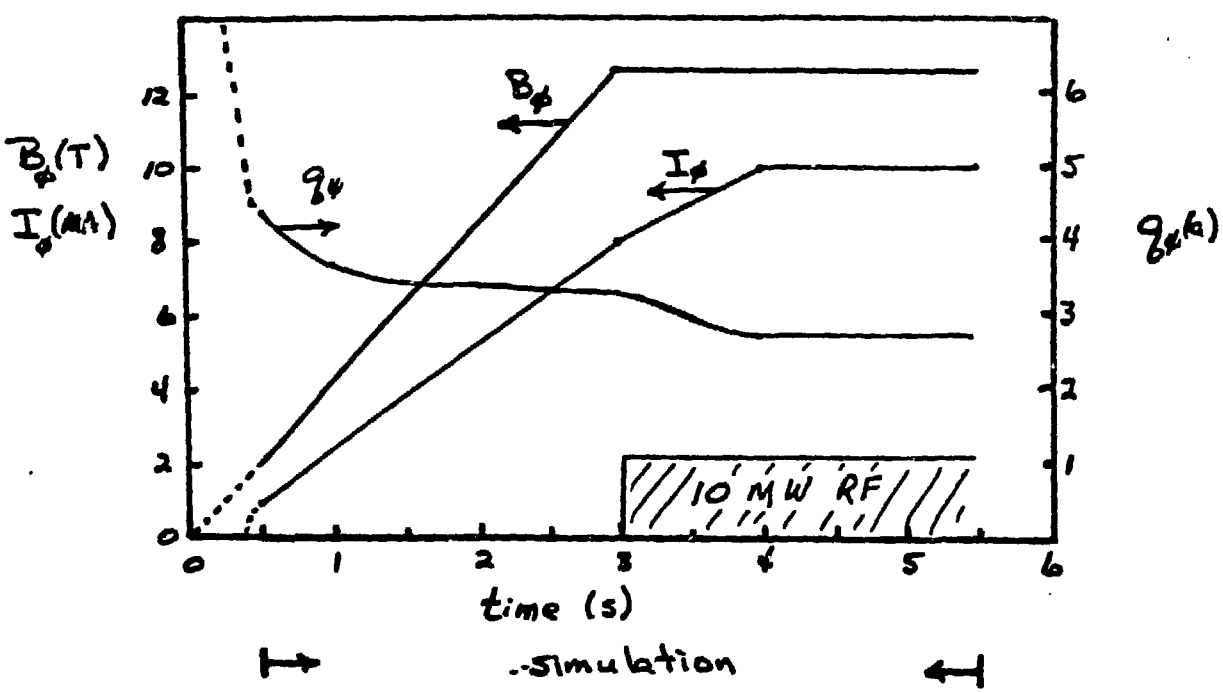


WAH 6/85

IGNITOR-A, DELAYED 10-MA STARTUP

$2\chi_e^{JET}$, χ_i^{CH}, 10 MW RF





WAH 6/85

VOLT-SECOND CONSUMPTION

For a 3 s rise and 2.5 s 'flat-top':

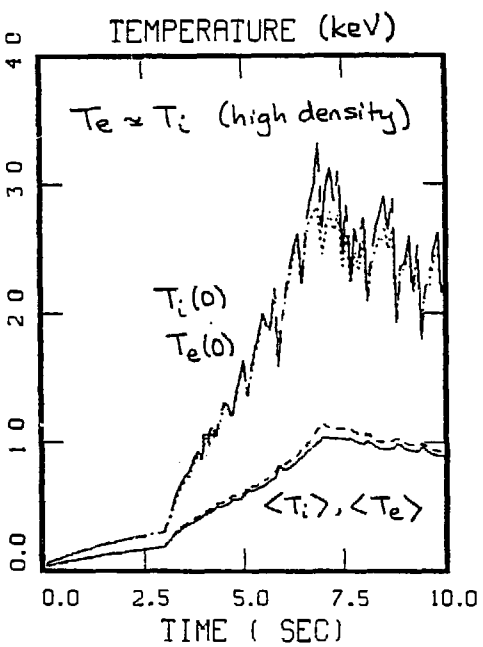
	IGNITOR-A	PPPL-0424/LITE
Internal	8.5	10.0
External	10.0	15.5
Breakdown	0.5-?	0.5-?
Resistive	3.3-4.9	2.0-3.4
B_v in core	?	?
Totals	23.3-24.6+	28.0-29.4+

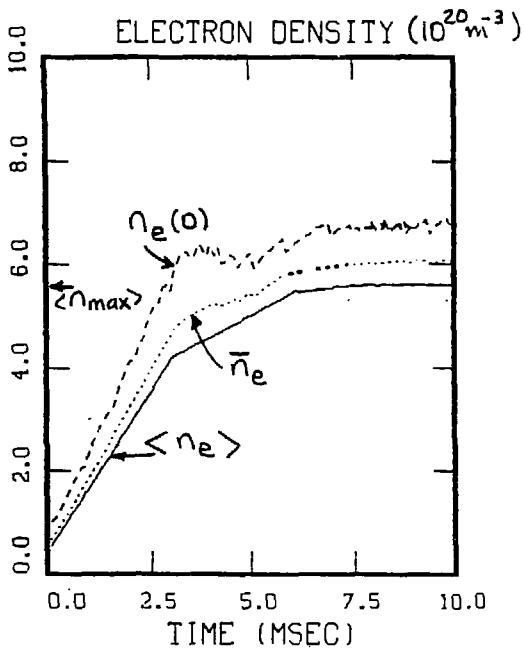
WAH 10/85
NAU

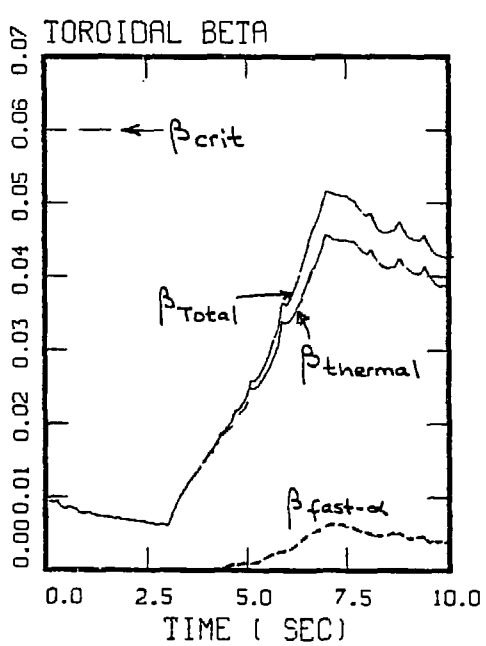
"MX", 3-SECONDS 10-MA STARTUP

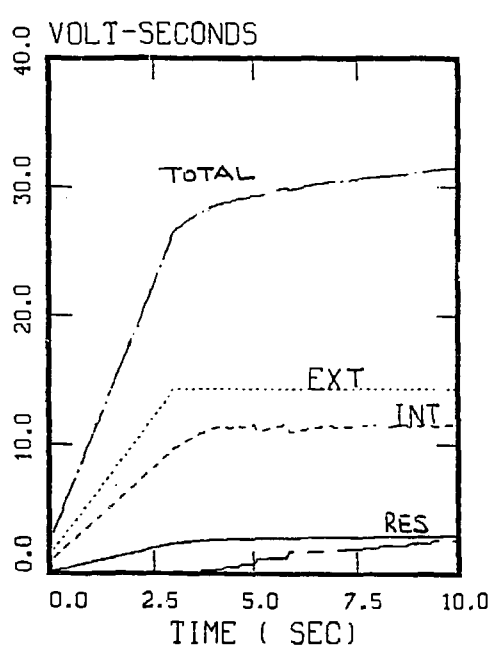
NED-ALCATOR / KAYE-GOLDSTON (L-MODE)

15 MW RF, $(\Delta t)_{heating} = 4$ sec (3 sec. → 7 sec.)







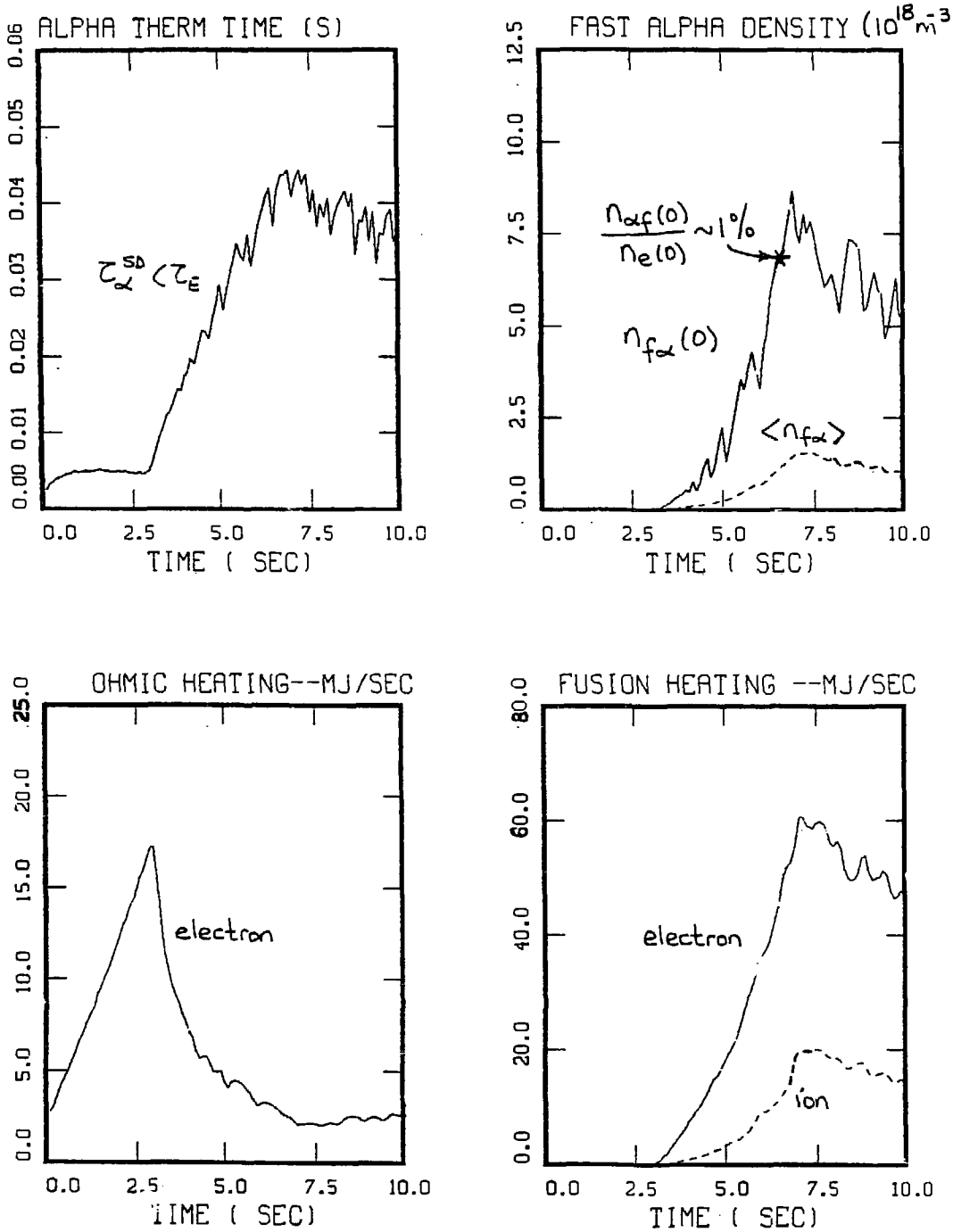


WAH 10/85
NAU

"MX", 3-SECONDS 10-MA STARTUP

15 MW RF, $(\Delta t)_{heating}$ = 4 sec. (3 → 7 sec.)

Neo-Alcator / Kaye-Goldston (L-mode)

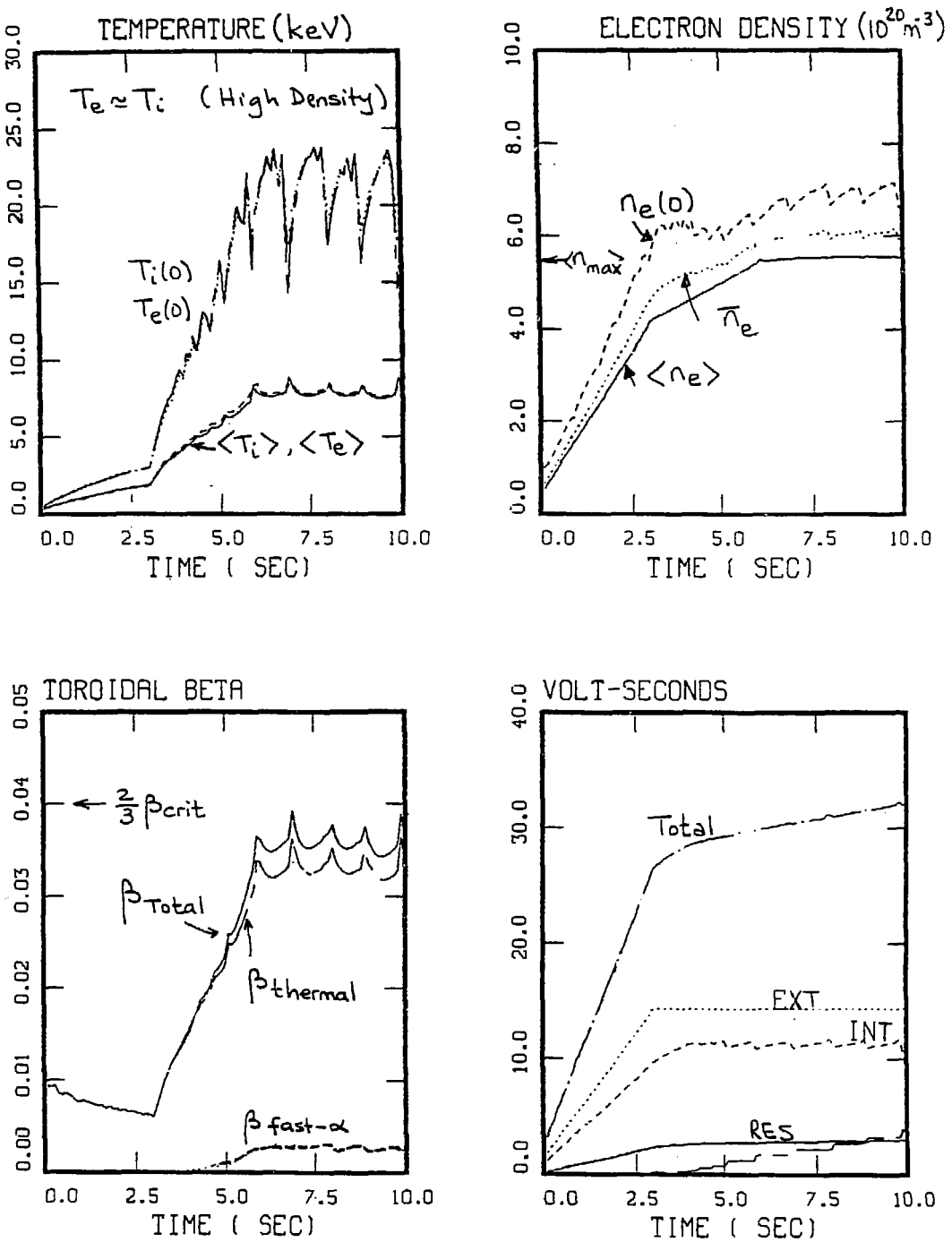


WAH 10/85
NAU

"MX" 3-SECONDS 10-MA STARTUP

15 MW RF, $(\Delta t)_{heating}$ = 3 sec. (3 → 6 sec.)

Neo-Alcator / Kaye-Goldston (L-mode)

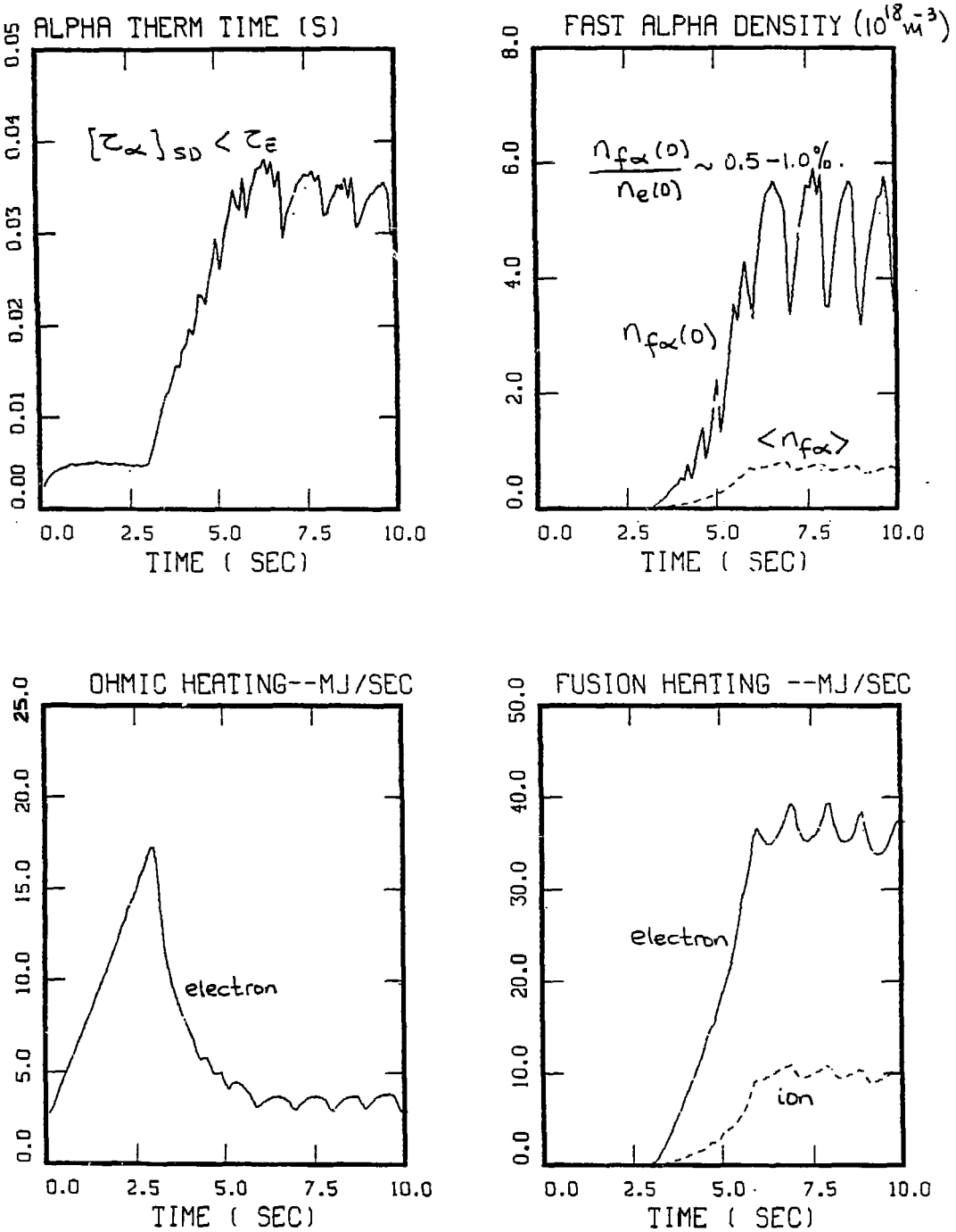


WAH 10/85
NAU

"MX" 3-seconds 10-MA STARTUP

15 MW RF, $(\Delta t)_{heating} = 3$ sec (3 → 6 sec.)

Neo-Alcator / Kaye-Goldston (L-mode)



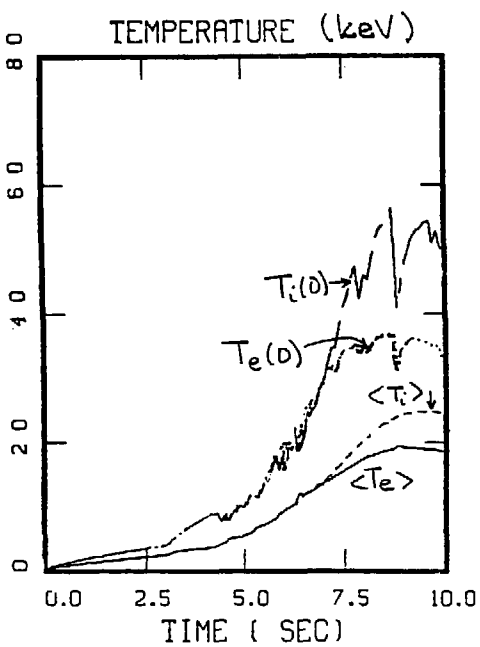
WAH 10/85
NAU

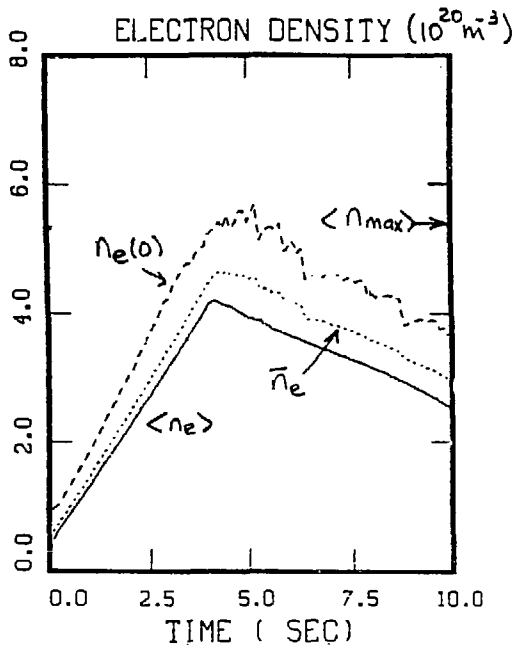
"MX" 3-SECONDS 10-MA STARTUP

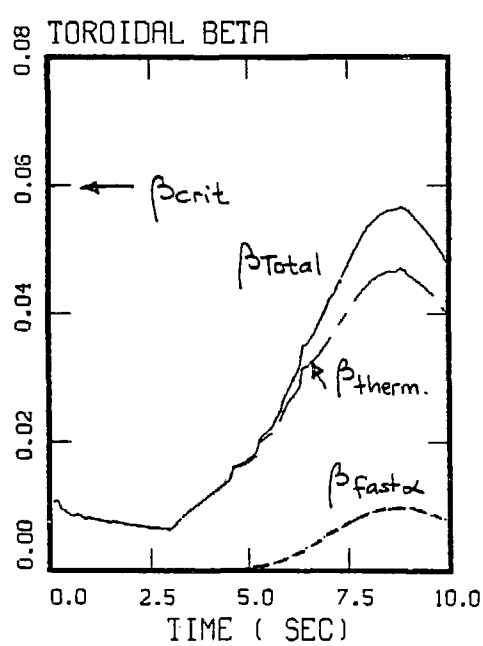
5MW RF $(\Delta t)_{heating} = 3$ sec (3 → 6 sec)

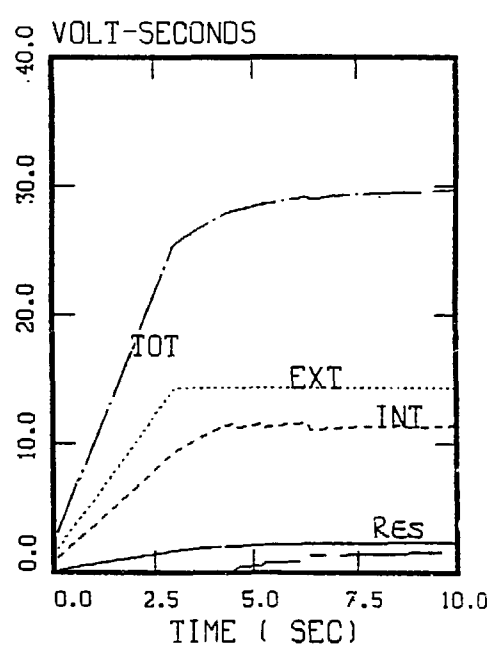
Ohmic scaling → large operating window

Heat along optimal path to ignition followed by pre-programmed density rampdown -- great for α-physics



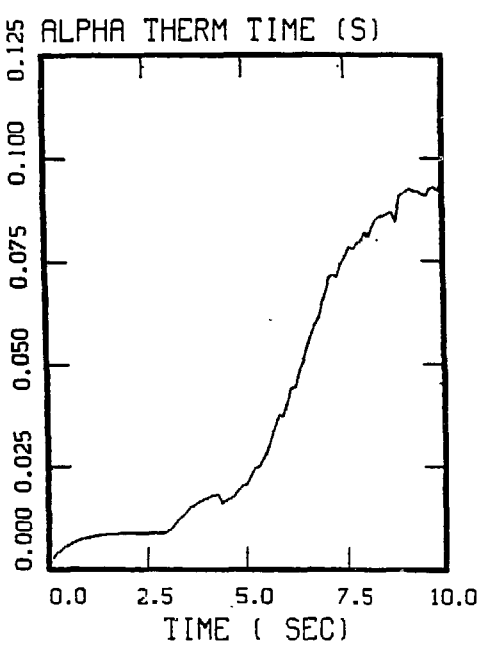
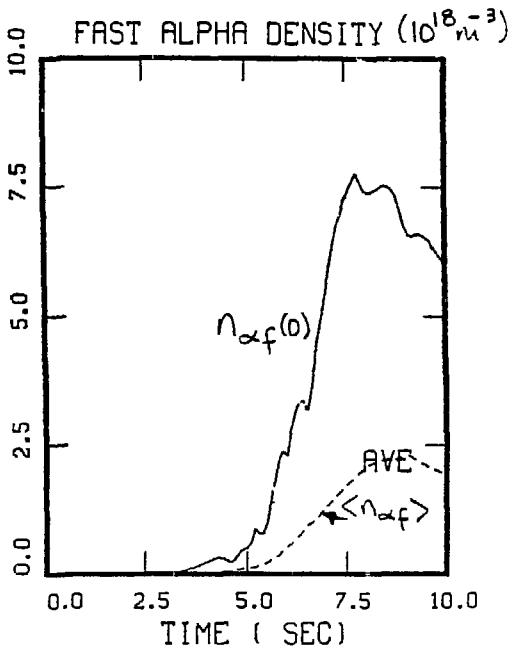
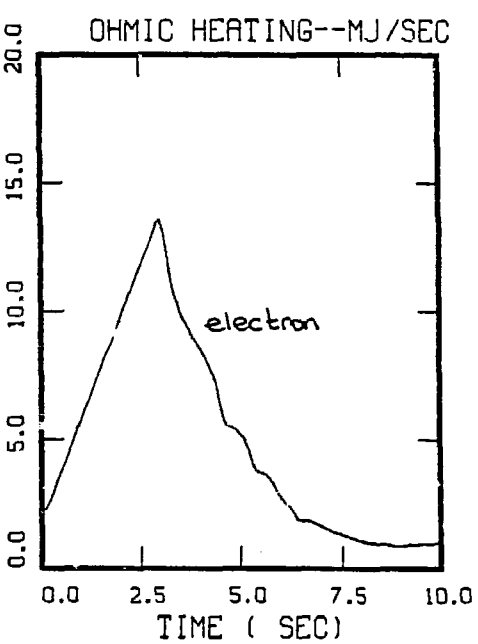
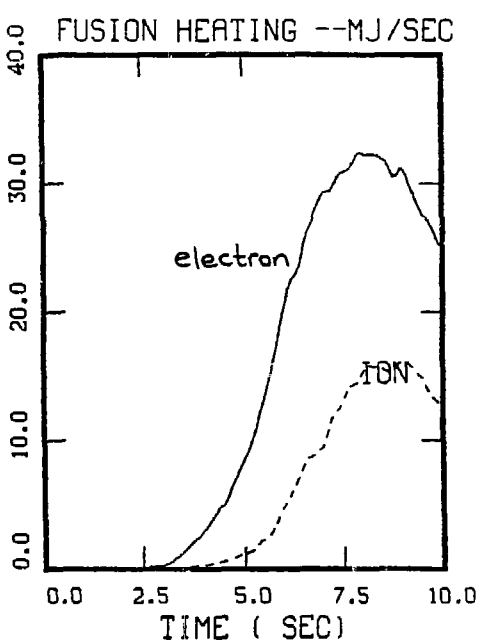






WAH
NAU 10/85

"MX" 3-SEC. 10-MA STARTUP

5MW RF $(\Delta t)_{heating} = 3$ sec. $(3 \rightarrow 6$ sec$)$

Ohmic scaling & density ramp down after ignition.