CONF-880163--1-Vugraphs—

# LONG-TIME IMPURITY CONFINEMENT AS A PRECURSOR TO DISRUPTIONS IN OHMICALLY HEATED TOKAMAKS

CONF-880163--1-Vugraphs

DE88 006183

Ralph C. Isler
Fusion Energy Division
ORNL

and

William L. Rowan
Fusion Research Center
University of Texas at Austin

*Presented at the IAEA Technical Committee Meeting on Density Limits and Disruptions Abingdon, England - 26 - 28 January, 1988*

Work sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems Inc.

- It has been observed in several tokamaks that the confinement of test impurities increases dramatically when operating near density limits. The characteristics of the working gas transport coefficients also change character under these conditions.

- These changes appear to be caused by a supression of the anomalous transport mechanisms. What role do they play in initiating disruptions?

# TOPICS

- TEST IMPURITY CONFINEMENT NEAR DENSITY LIMITS AND INTRINSIC IMPURITY ACCUMULATION.

- SOFT AND HARD DISRUPTIONS.

- SAWTOOTHING AND LOW MHD MODE BEHAVIOR.

- COMPARISON OF HYDROGEN AND DEUTERIUM DISCHARGES.

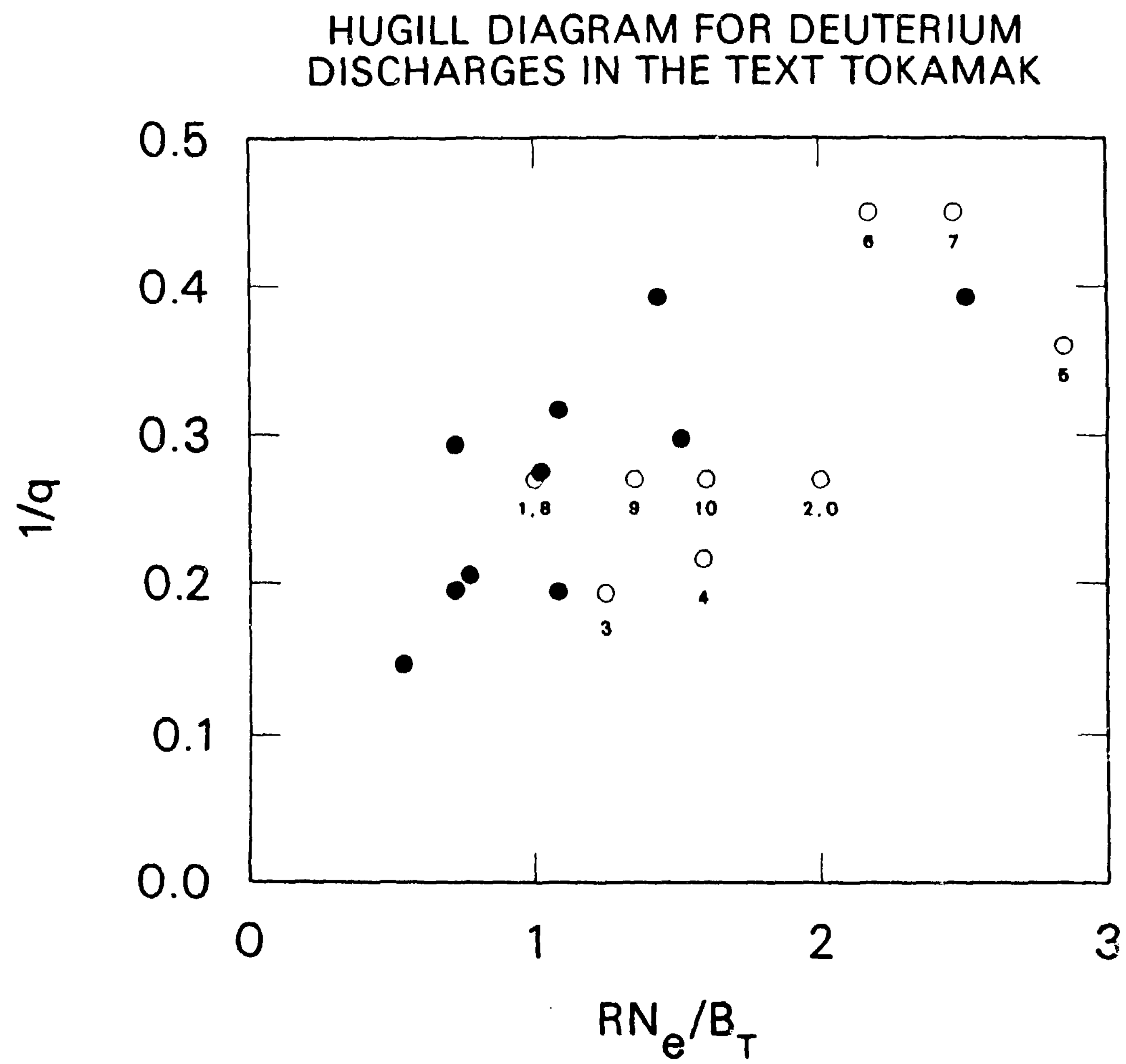
- UNIVERSALITY OF OBSERVATIONS.

## Two Types of Disruptions Are Observed

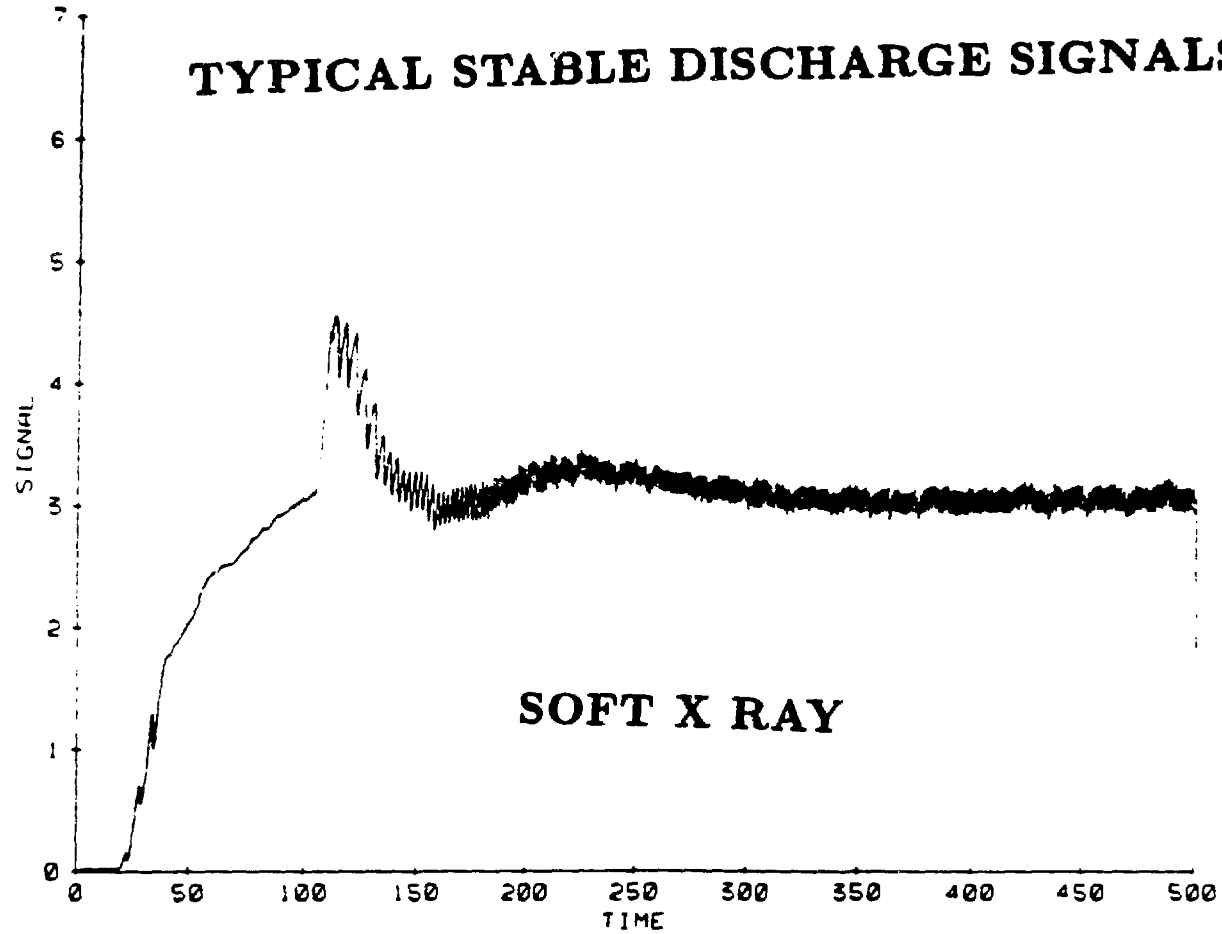
* Soft or partial disruptions. These are preceeded by impurity accumulation, central cooling, and little or no increase in MHD activity. $I_p$ does not go to zero, but confinement is poor after the disruption.

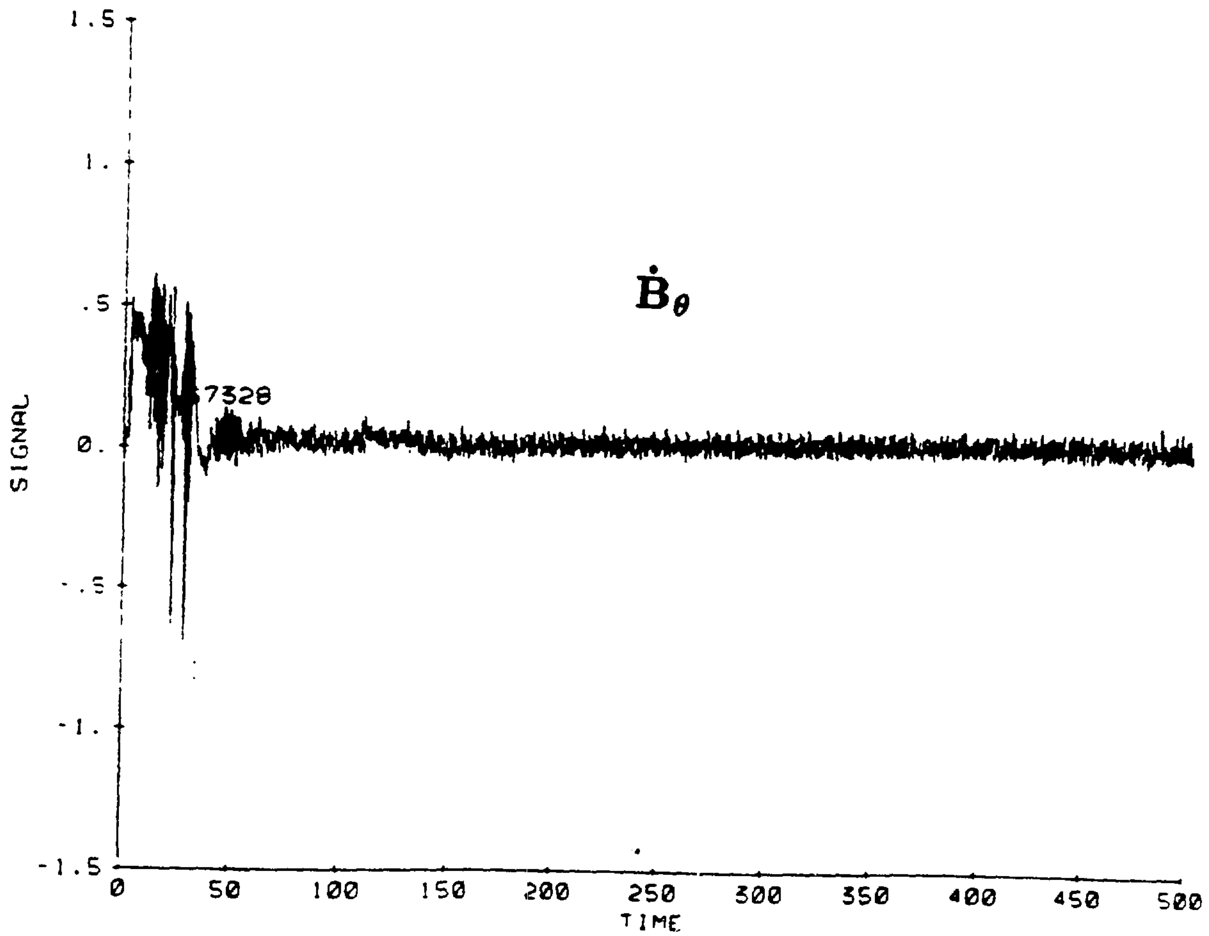
* Hard or complete disruptions. Impurity accumulation may or may not be observed. MHD activity increases before the disruption, then $I_p$ drops rapidly to zero.

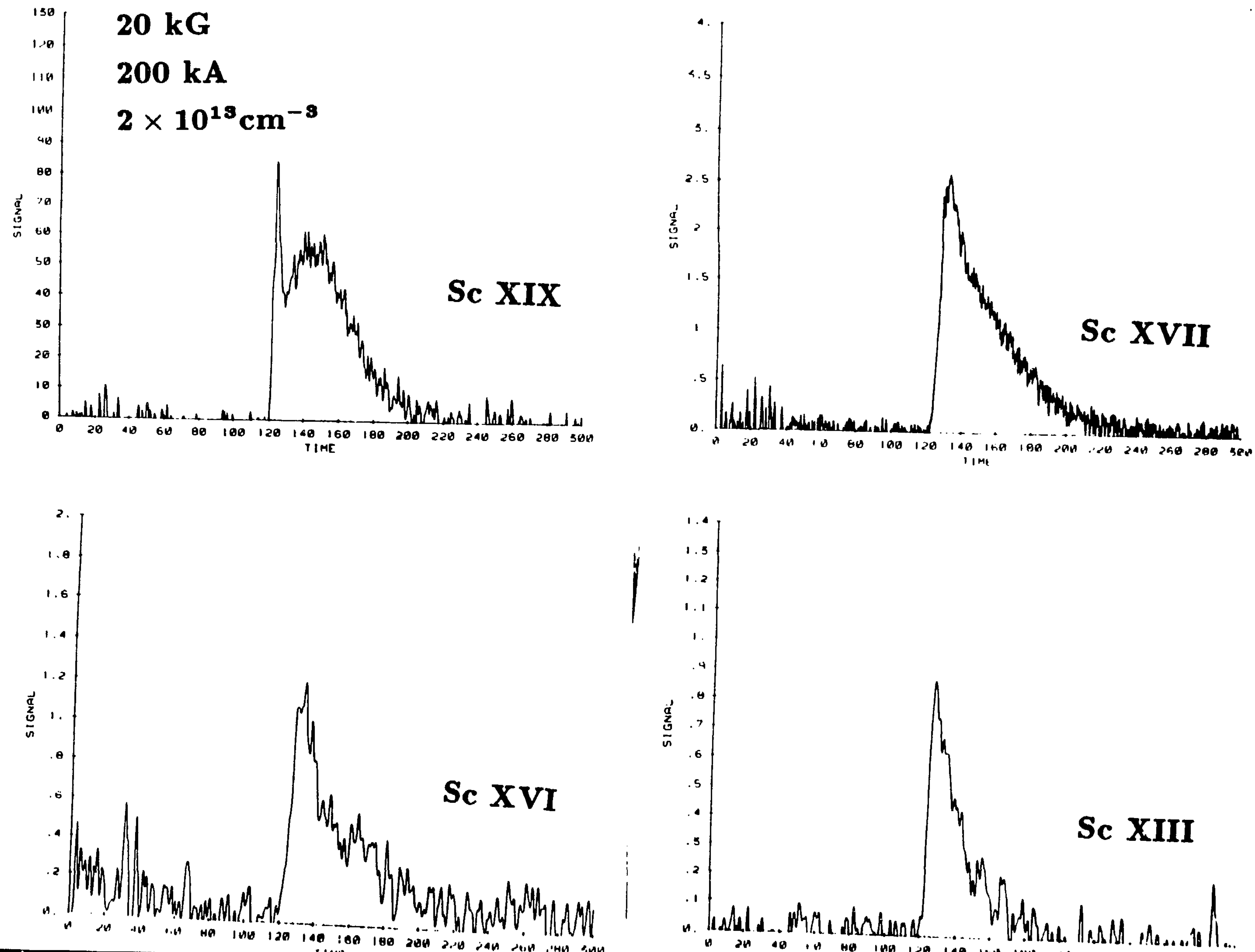
**In both cases observed in the TEXT tokamak, a transition to long-time confinement of test impurities preceeded the disruption**


HUGILL DIAGRAM FOR DEUTERIUM
DISCHARGES IN THE TEXT TOKAMAK
0.5
0.4
0.3
0.2
0.1
0.0
1/q
6
7
5
1,8
9
10
2,0
4
3
0
1
2
3
RNe/BT

# TYPICAL STABLE DISCHARGE SIGNALS




20 kG
200 kA
2 × 10¹³cm⁻³
Sc XIX
Sc XVII
Sc XVI
Sc XIII
SIGNAL
TIME

## Alcator Impurity Scaling

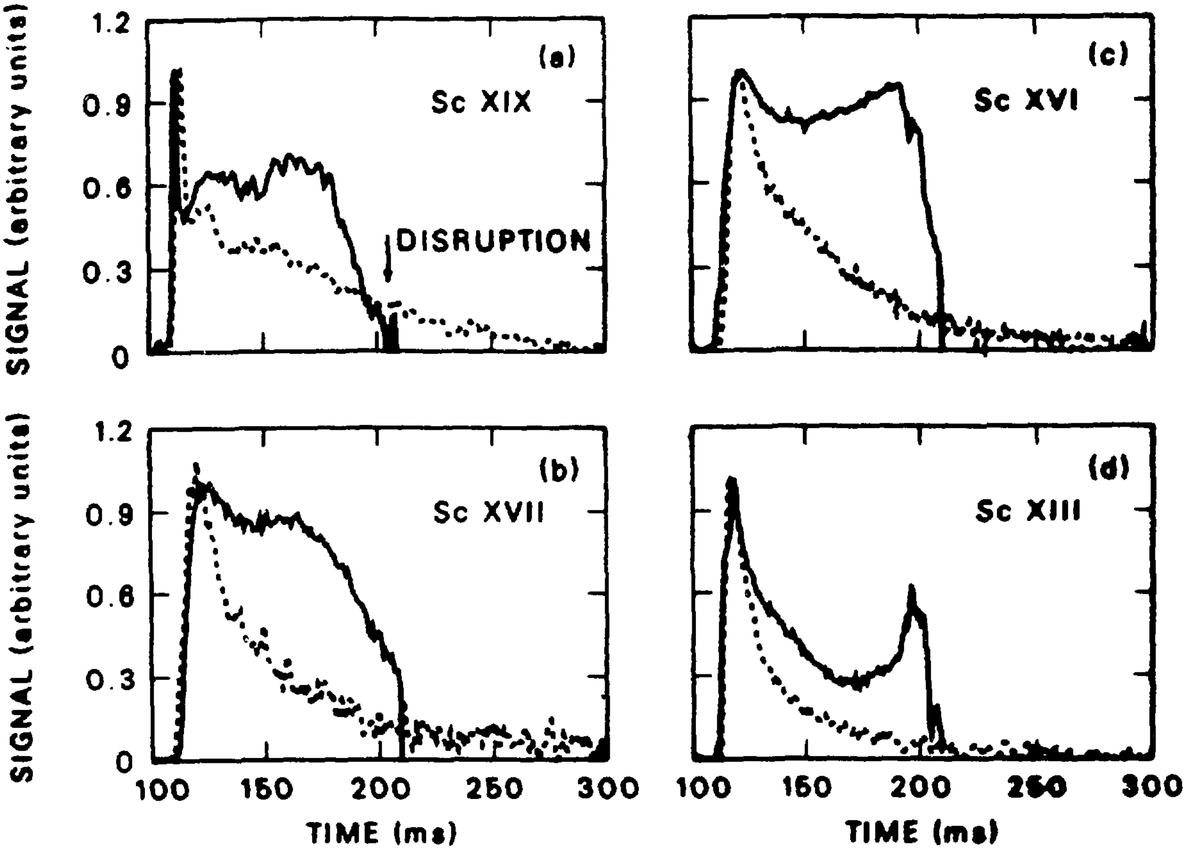
$$\tau_z \propto \frac{m_b I_p}{B_T} \frac{Z_e f f}{Z_b}$$

## TEXT Results for Disruptive Discharges

$$\tau_z \longrightarrow \frac{f_1(n_e)}{f_2(B_T) f_3(I_p)}$$

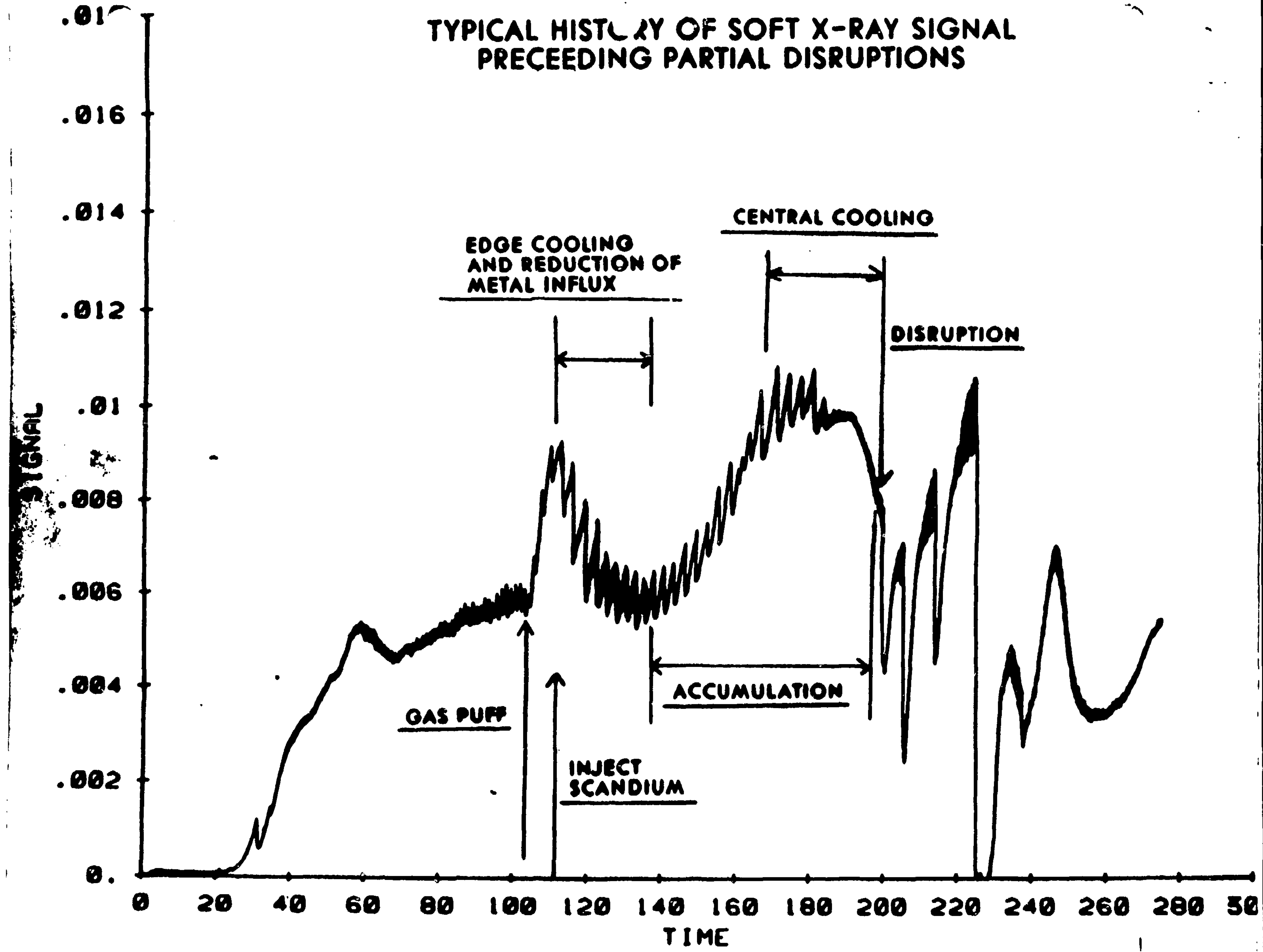
1. $B_T$ DEPENDENCE AGREES
2. $I_p$ DEPENDENCE DOES NOT AGREE
3. $N_e(Z_e f f)$ DEPENDENCE DOES NOT AGREE

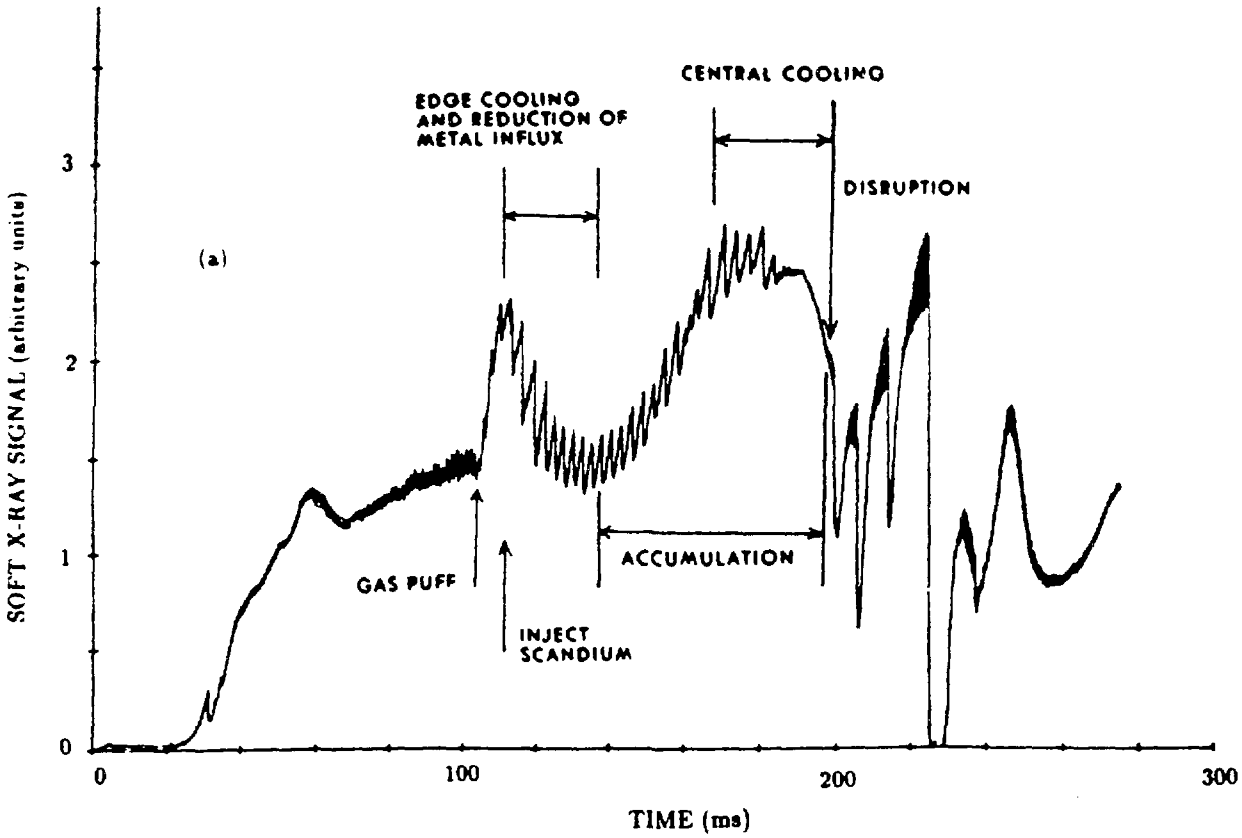
ORNL-DWG 85C-2833 FED

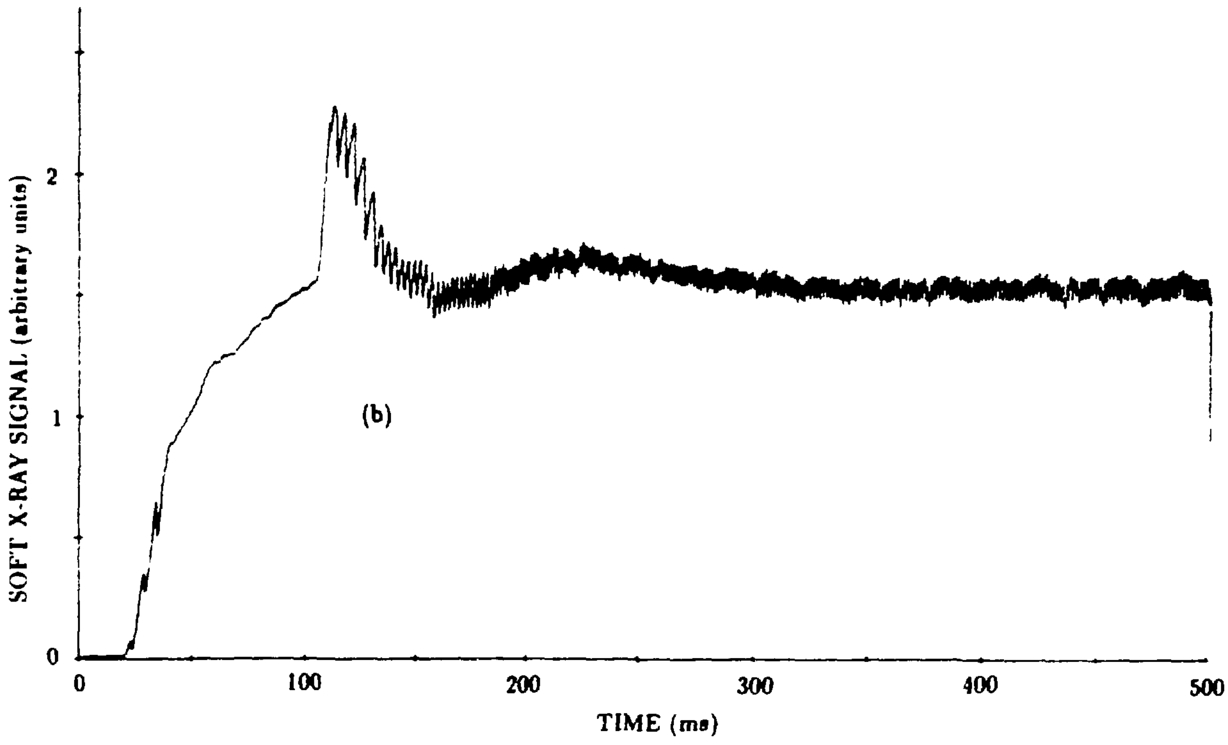



——— $\frac{\bar{n}_e}{B_T I_p} = 1.4 \times 10^4 \ cm^{-3} \ G^{-1} \ A^{-1}$

- - - - - $= 0.62 \times 10^4$


TYPICAL HISTORY OF SOFT X-RAY SIGNAL
PRECEEDING PARTIAL DISRUPTIONS
CENTRAL COOLING
EDGE COOLING
AND REDUCTION OF
METAL INFLUX
DISRUPTION
ACCUMULATION
GAS PUFF
INJECT
SCANDIUM
SIGNAL
TIME
.016
.014
.012
.01
.008
.006
.004
.002
0.
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280


EDGE COOLING
AND REDUCTION OF
METAL INFLUX
CENTRAL COOLING
DISRUPTION
(a)
GAS PUFF
INJECT
SCANDIUM
ACCUMULATION
SOFT X-RAY SIGNAL (arbitrary units)
TIME (ms)
0
1
2
3
100
200
300

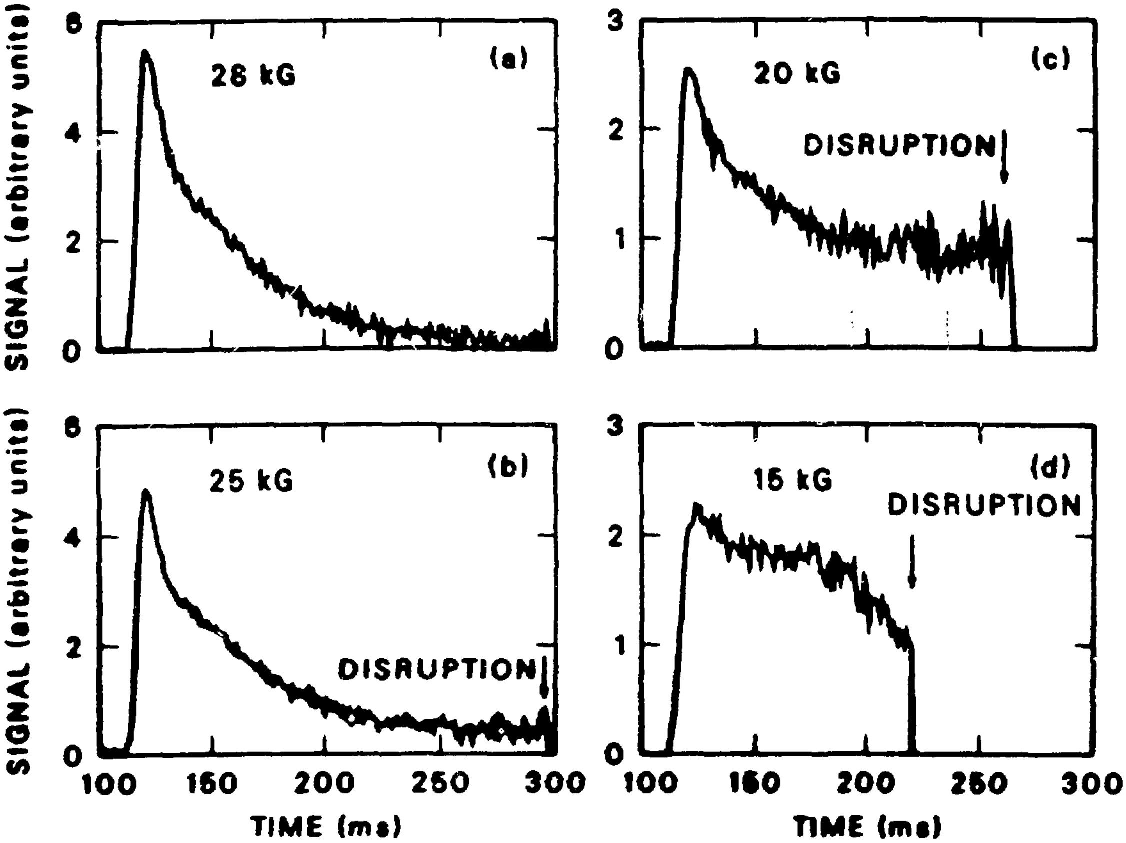

(b)
SOFT X-RAY SIGNAL (arbitrary units)
TIME (ms)
0
1
2
100
200
300
400
500

## [illegible] and Impur[illegible] Accum[illegible] [illegible]ithout Pe[illegible]

[illegible] ccumulation is [illegible] inhib[illegible] [illegible] (1981; TEX[illegible] (1985) [illegible] accumulation preferentially raises $Z_{eff}$ an[illegible] radiative losses in the plasma center. Th[illegible] increased resistance stops the sawtoothing.

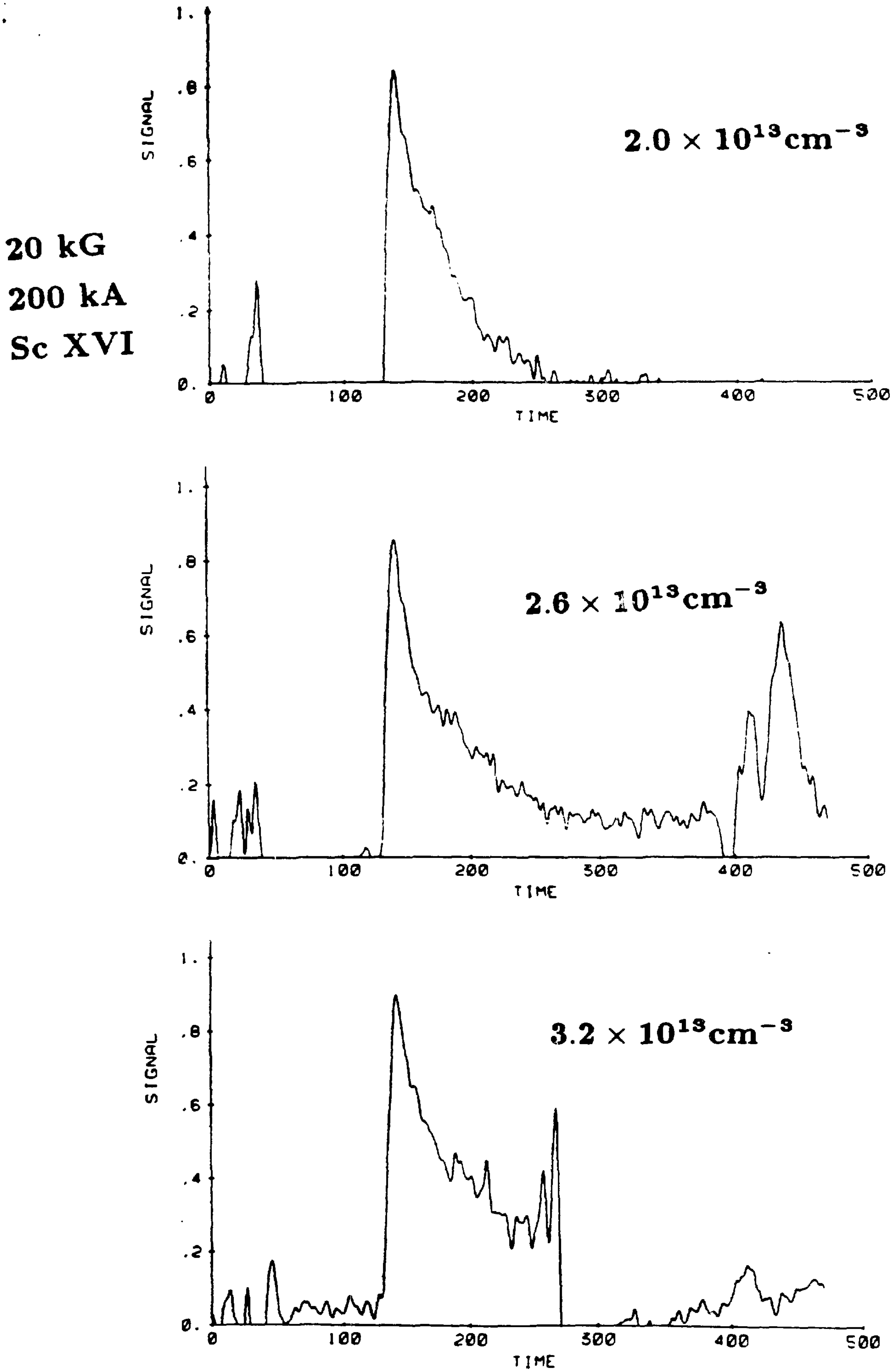
Sc XVII TEXT

ORNL-DWG 85C-2836 FED



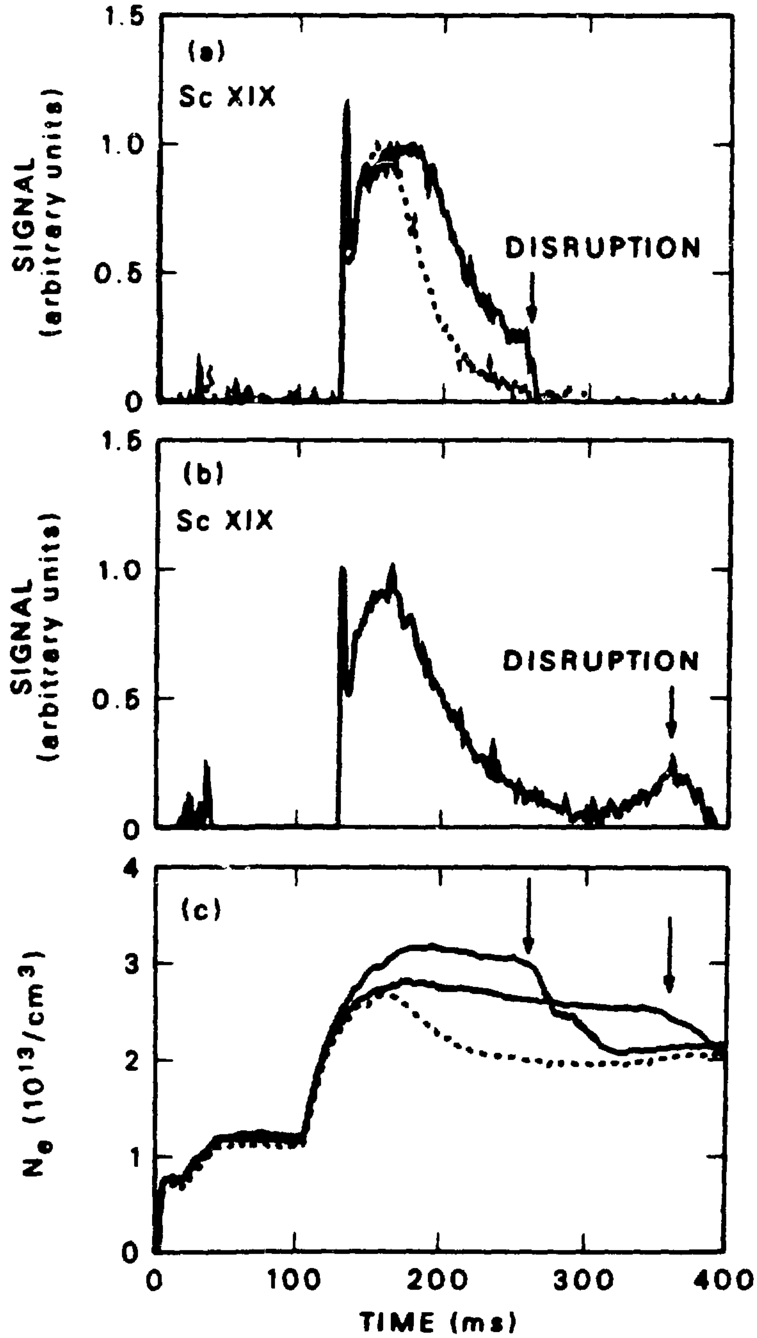

$\bar{n}_e(max) = (3.5-4.3)\times10^{13}/cm^3$

$I_p = 200\ kA$



20 kG
200 kA
Sc XVI
2.0 × 10^13 cm^-3
2.6 × 10^13 cm^-3
3.2 × 10^13 cm^-3
SIGNAL
TIME
0. .2 .4 .6 .8 1.
0 100 200 300 400 500

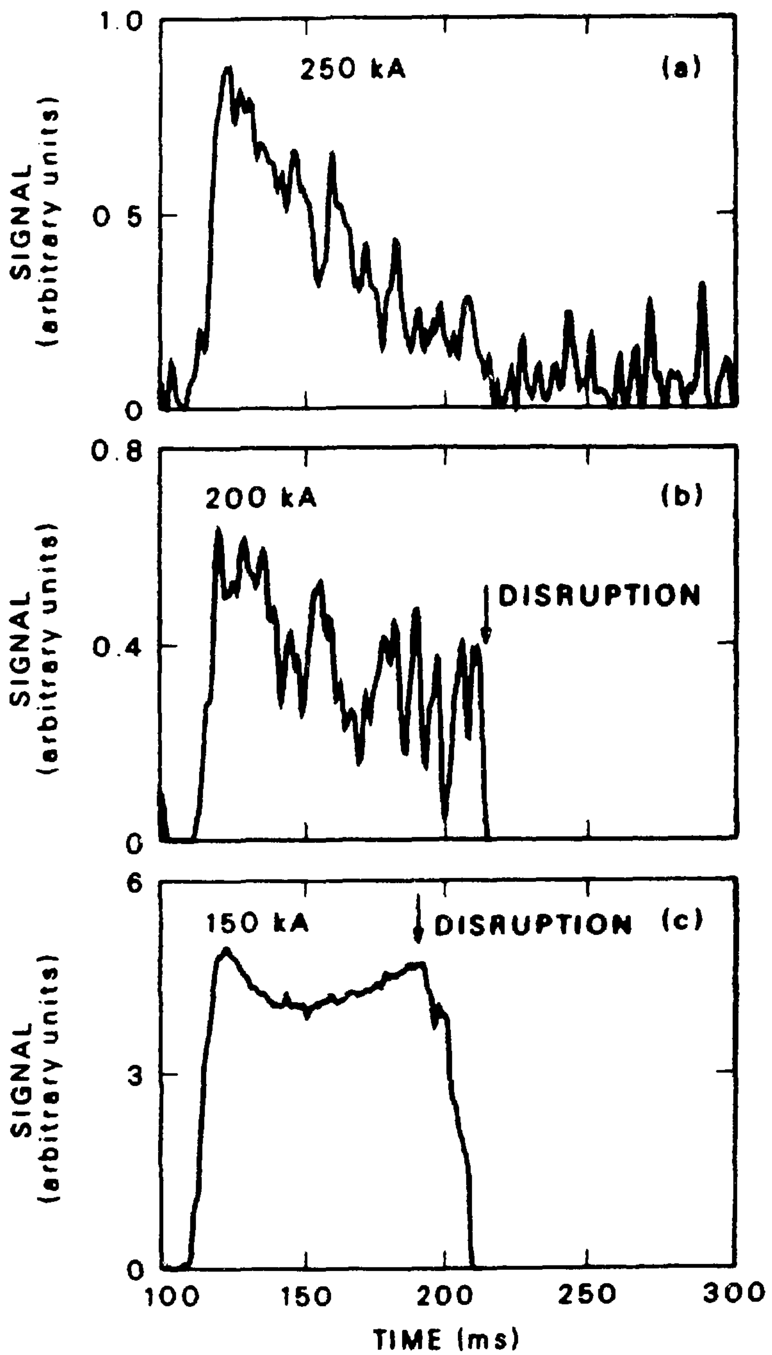
ORNL-DWG 85C-2835 FED




Isler et al., Fig. 5

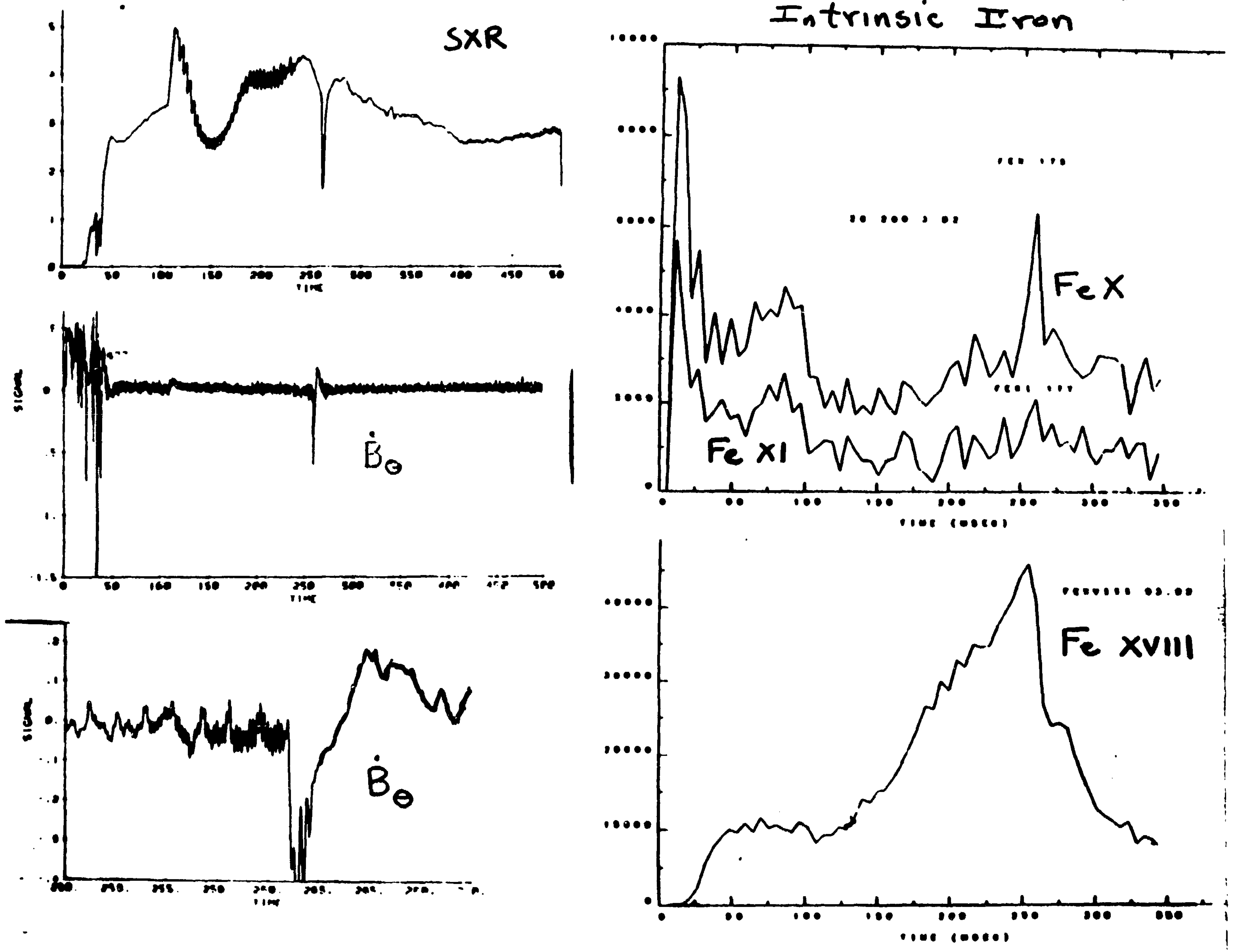
Sc XVI

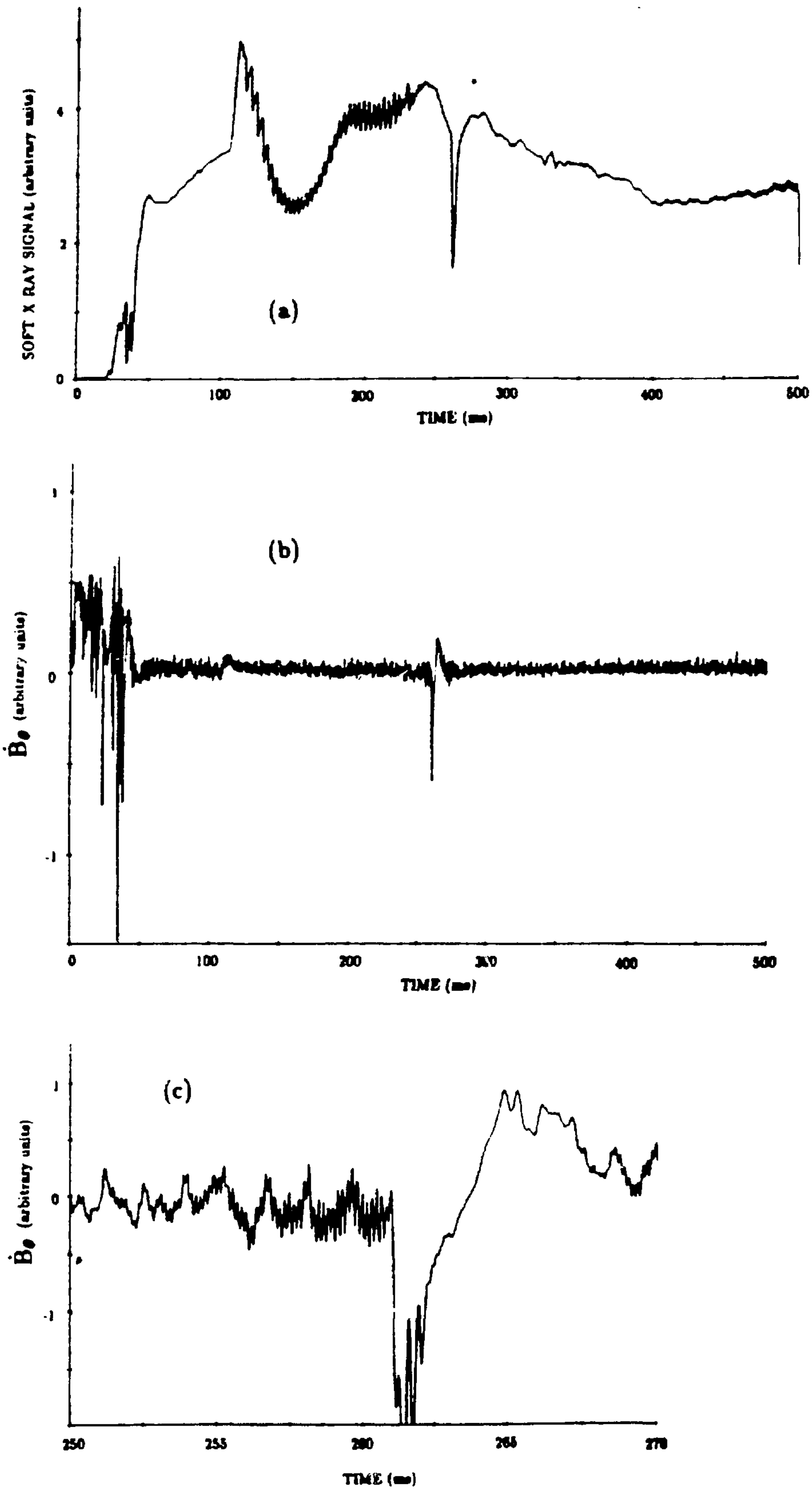
ORNL-DWG 85C-2832 FED



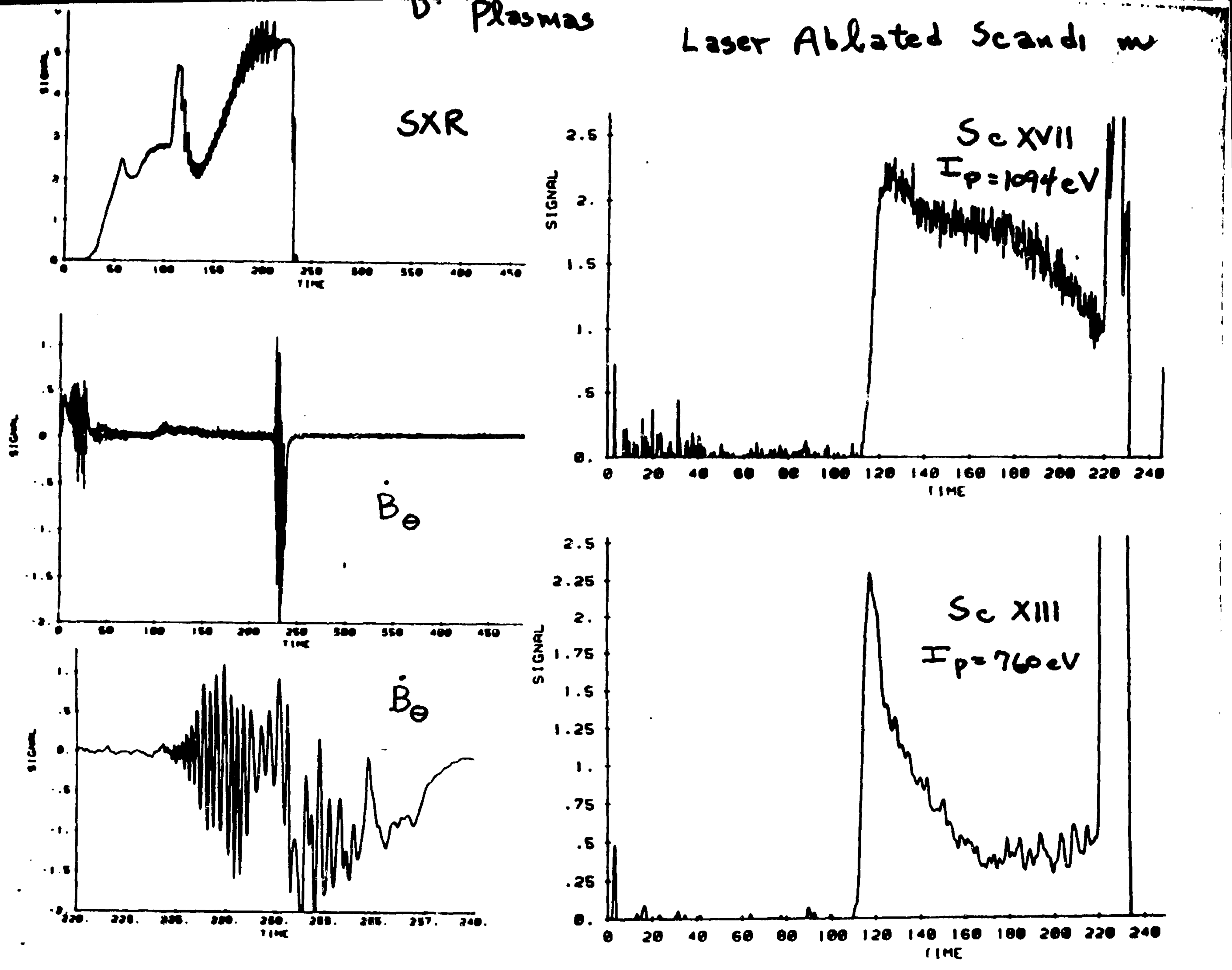

$\bar{n}_e(max) = 3.5\text{-}4.3 \times 10^{13}/cm^3$

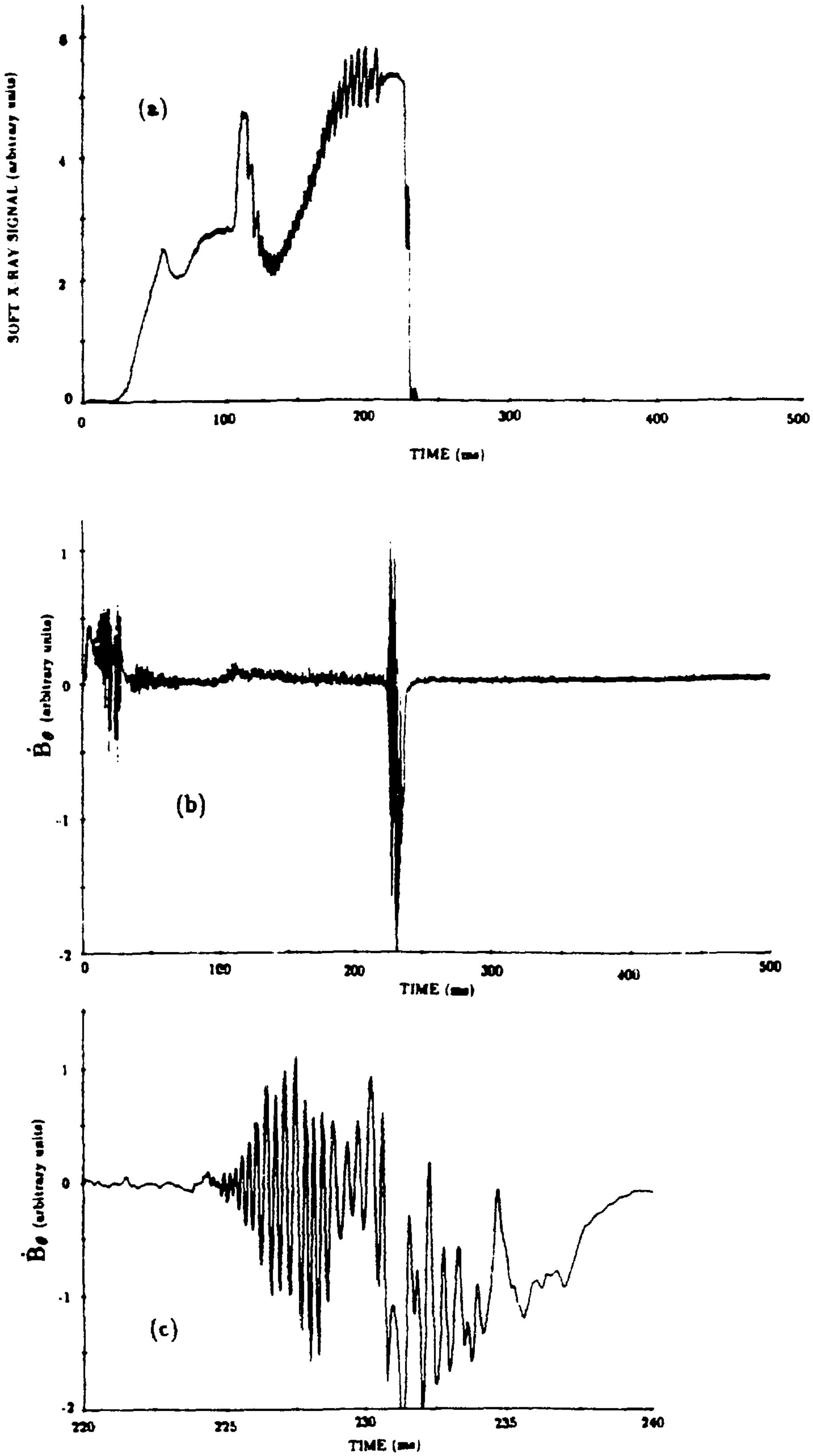
$B_T = 15\ kG$


Intrinsic Iron
SXR
TIME
SIGNAL
$\dot{B}_\theta$
TIME
SIGNAL
$\dot{B}_\theta$
TIME
Fe X
Fe XI
TIME (MSEC)
Fe XVIII
TIME (MSEC)

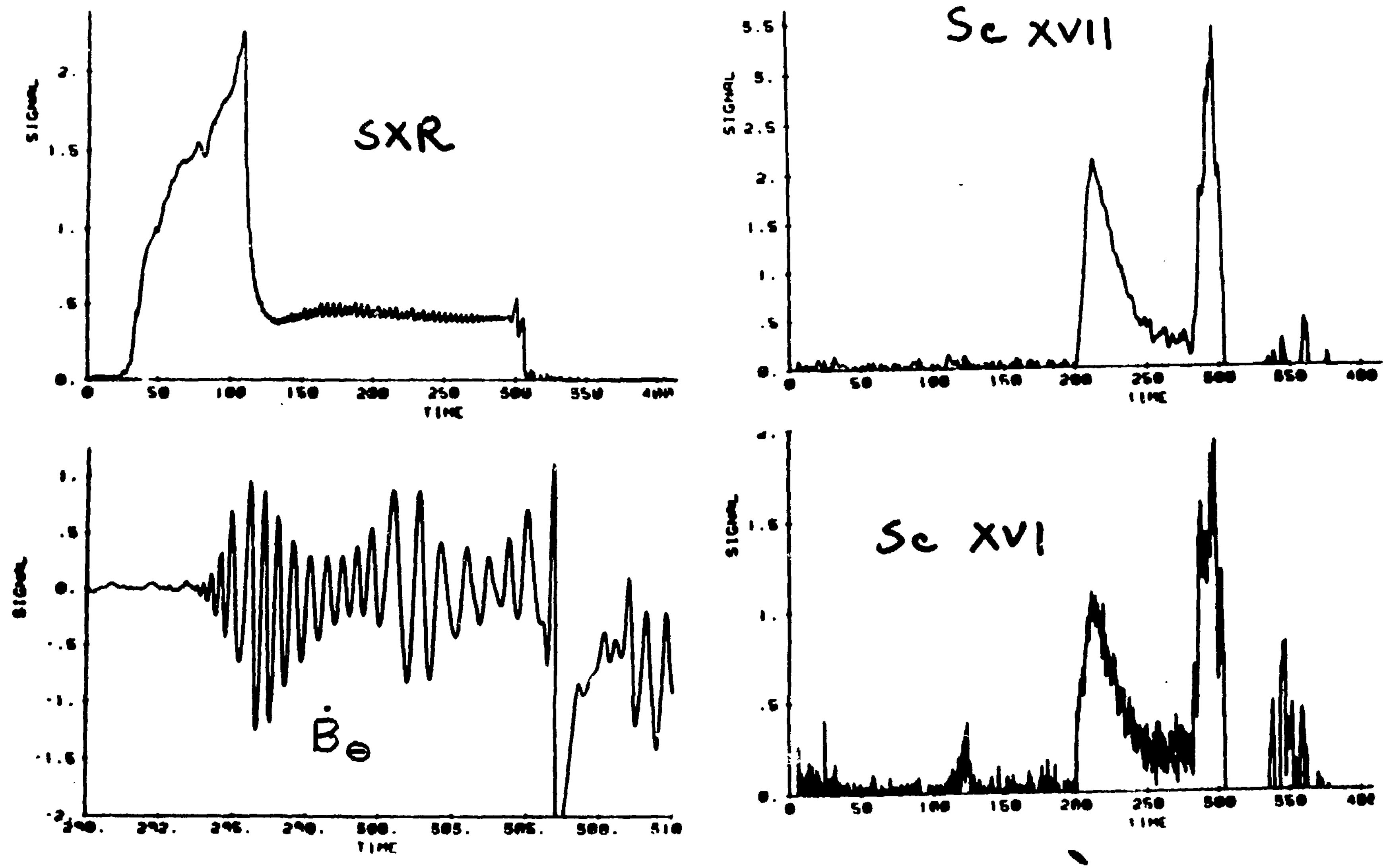

SOFT X RAY SIGNAL (arbitrary units)
0
2
4
(a)
0
100
200
300
400
500
TIME (ms)
(b)
$\dot{B}_\theta$ (arbitrary units)
1
0
-1
0
100
200
300
400
500
TIME (ms)
(c)
$\dot{B}_\theta$ (arbitrary units)
1
0
-1
250
255
260
265
270
TIME (ms)

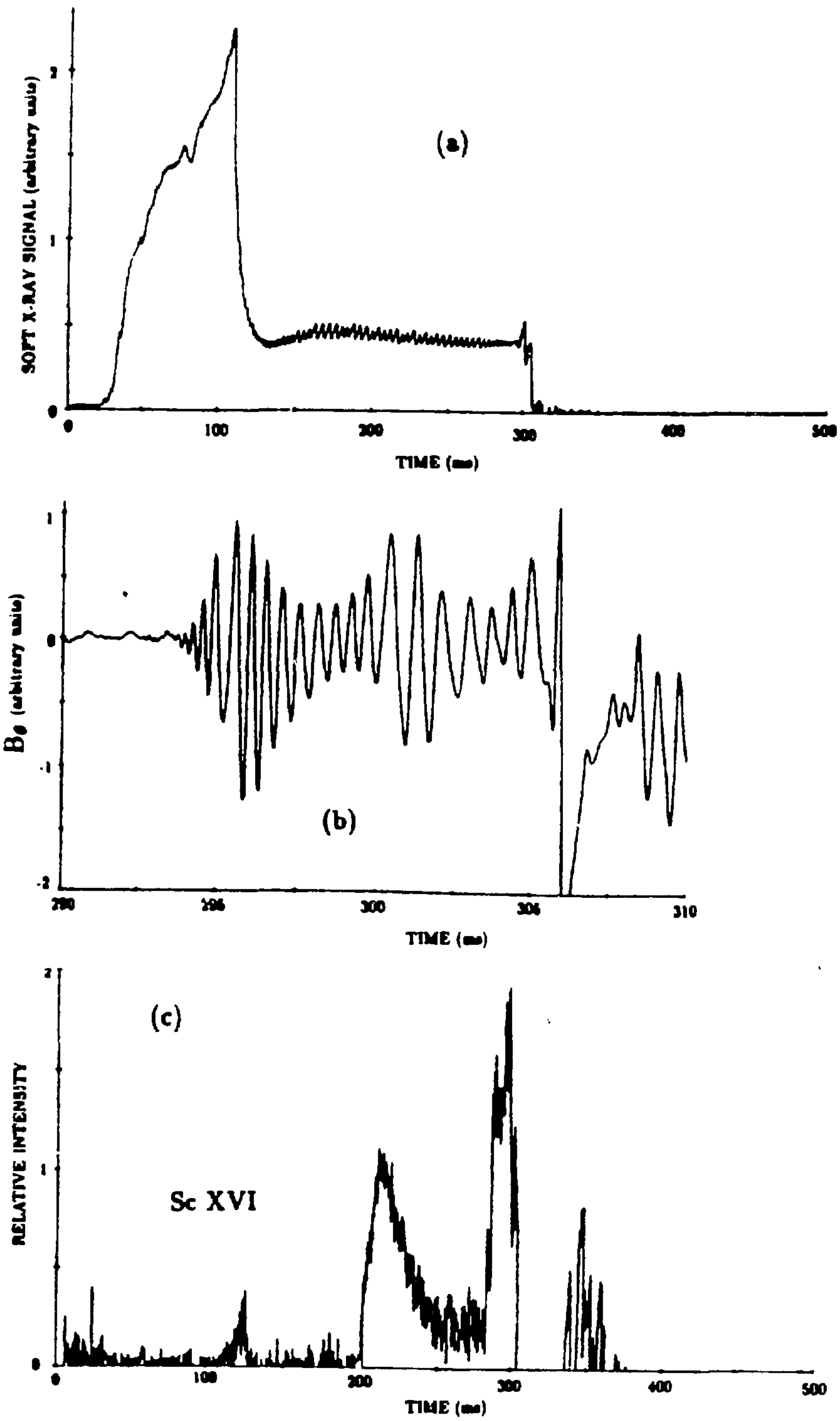
D⁺ Plasmas    Laser Ablated Scandium

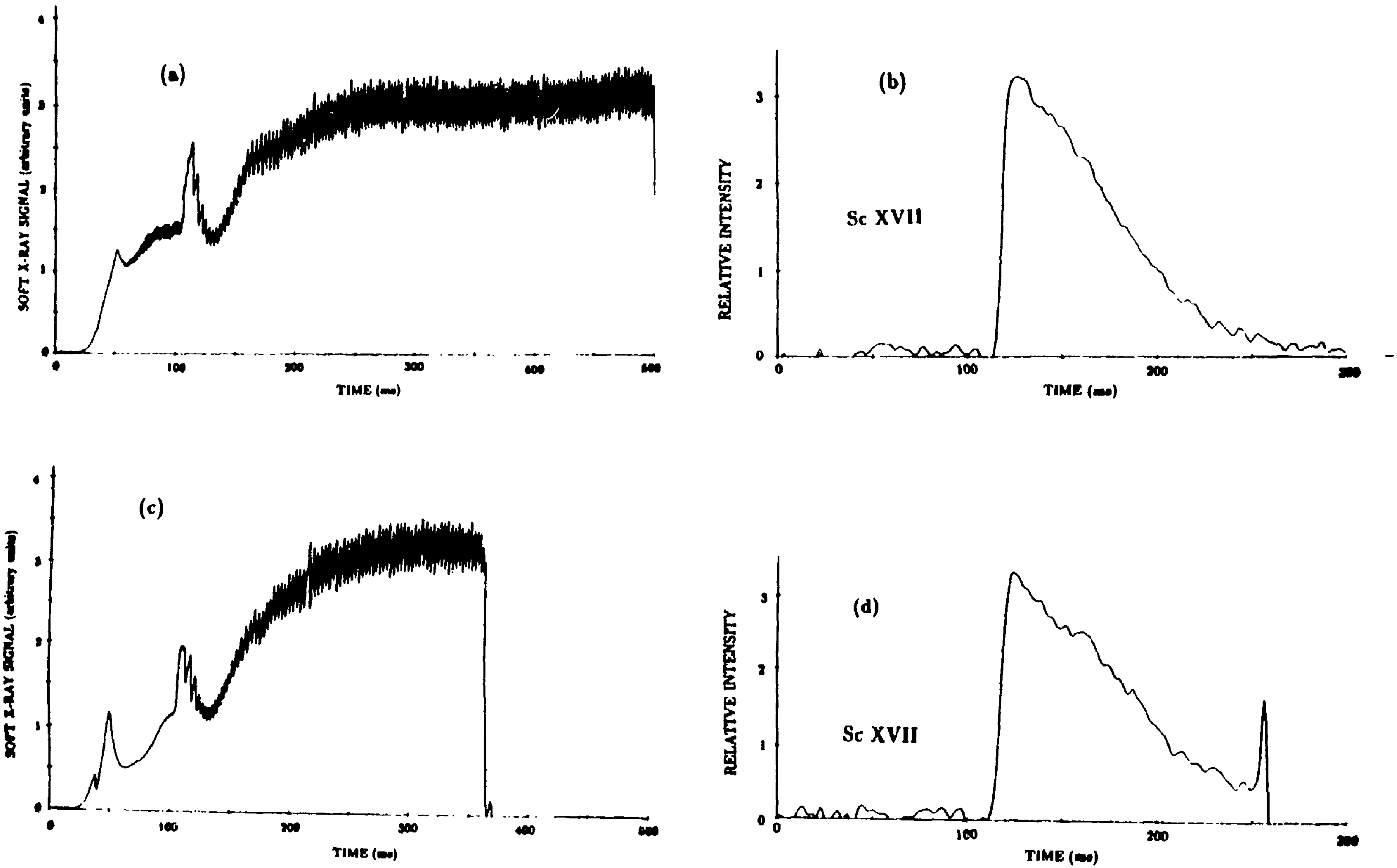



(a)
SOFT X-RAY SIGNAL (arbitrary units)
TIME (ms)
(b)
$\dot{B}_\theta$ (arbitrary units)
TIME (ms)
(c)
$\dot{B}_\theta$ (arbitrary units)
TIME (ms)

$H^+$ plasmas




(a)
SOFT X-RAY SIGNAL (arbitrary units)
TIME (ms)
(b)
$B_\theta$ (arbitrary units)
TIME (ms)
(c)
Sc XVI
RELATIVE INTENSITY
TIME (ms)



(a)
SOFT X-RAY SIGNAL (arbitrary units)
TIME (ms)
(b)
Sc XVII
RELATIVE INTENSITY
TIME (ms)
(c)
SOFT X-RAY SIGNAL (arbitrary units)
TIME (ms)
(d)
Sc XVII
RELATIVE INTENSITY
TIME (ms)

# RESULTS OF TRANSPORT STUDIES OF HYDROGEN AND DEUTERIUM IN THE TEXT TOKAMAK

K. Gentle, B. Richards, F. Waelbroeck

- WORKING GAS TRANSPORT CAN BE MODELED BY CONSTANT D AND V EXCEPT NEAR DENSITY LIMITS. D AND V SCALE AS 1/nq.

- D FOR DEUTERIUM IS SYSTEMATICALLY LOWER THAN FOR HYDROGEN.

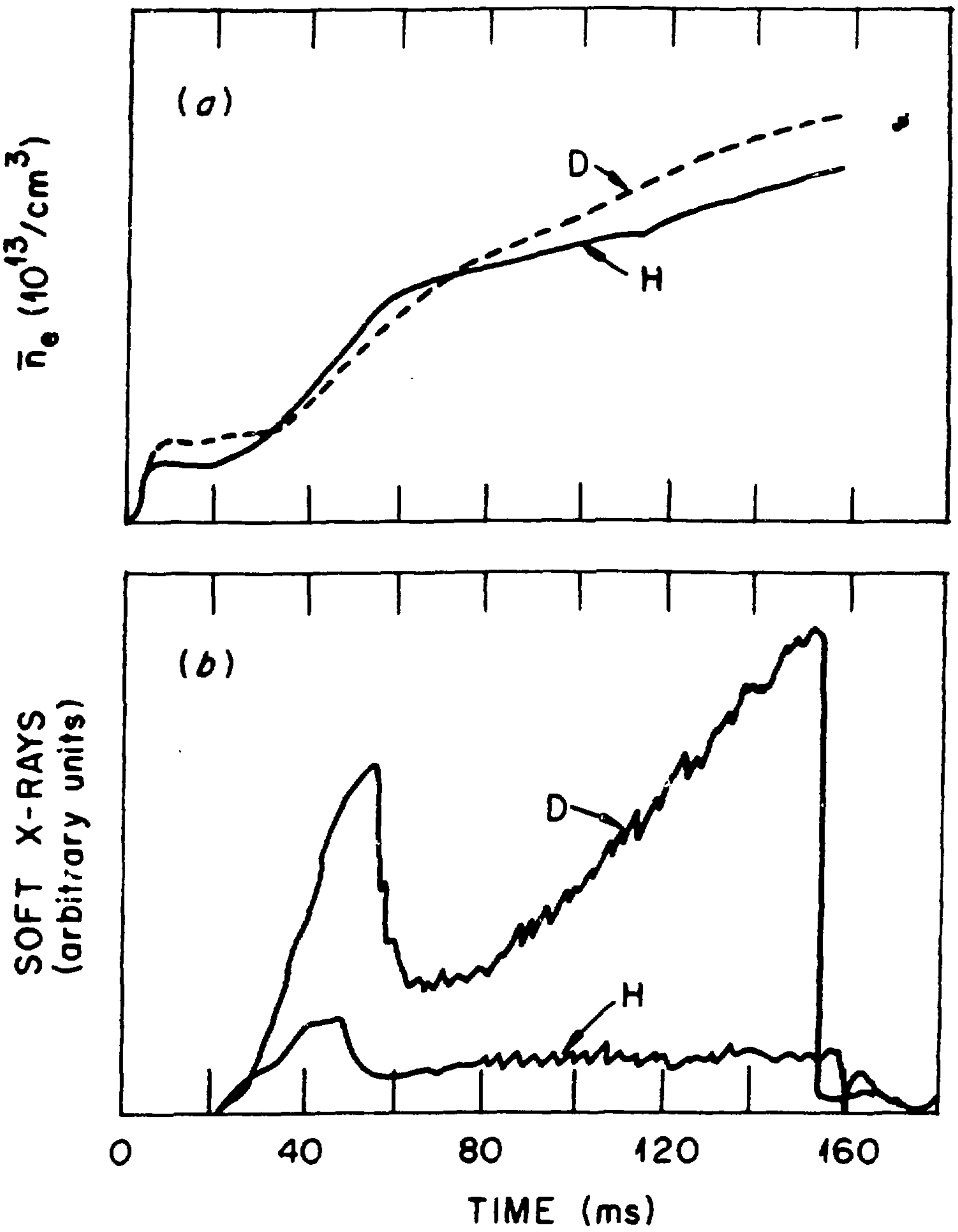
- NEAR THE DENSITY LIMIT D AND V ARE NOT UNIFORM:

  * IN THE CORE, D IS SMALLER THAN EXPECTED FROM THE 1/nq SCALING, $V \approx 0$,

  * IN THE EDGE D AND V ARE BOTH HIGHER THAN EXPECTED FROM THE 1/nq SCALING.

# SOFT X-RAY (PIN) SIGNALS REFLECT THE DIFFERENCES OF IMPURITY ACCUMULATION BETWEEN DEUTERIUM AND HYDROGEN

ORNL-DWG 80-3668A FED



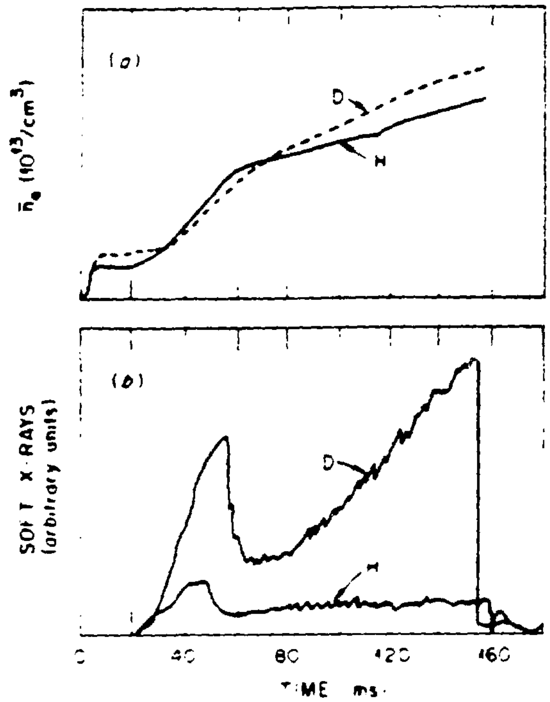



FIG. 1. The line-averaged electron concentrations and the soft-x-ray signals during Ohmically heated deuterium (D) and hydrogen (H) discharges.

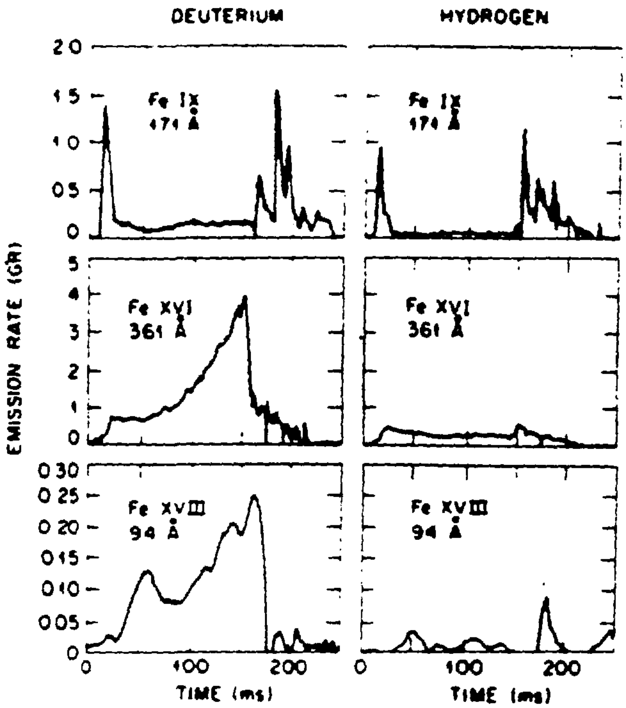
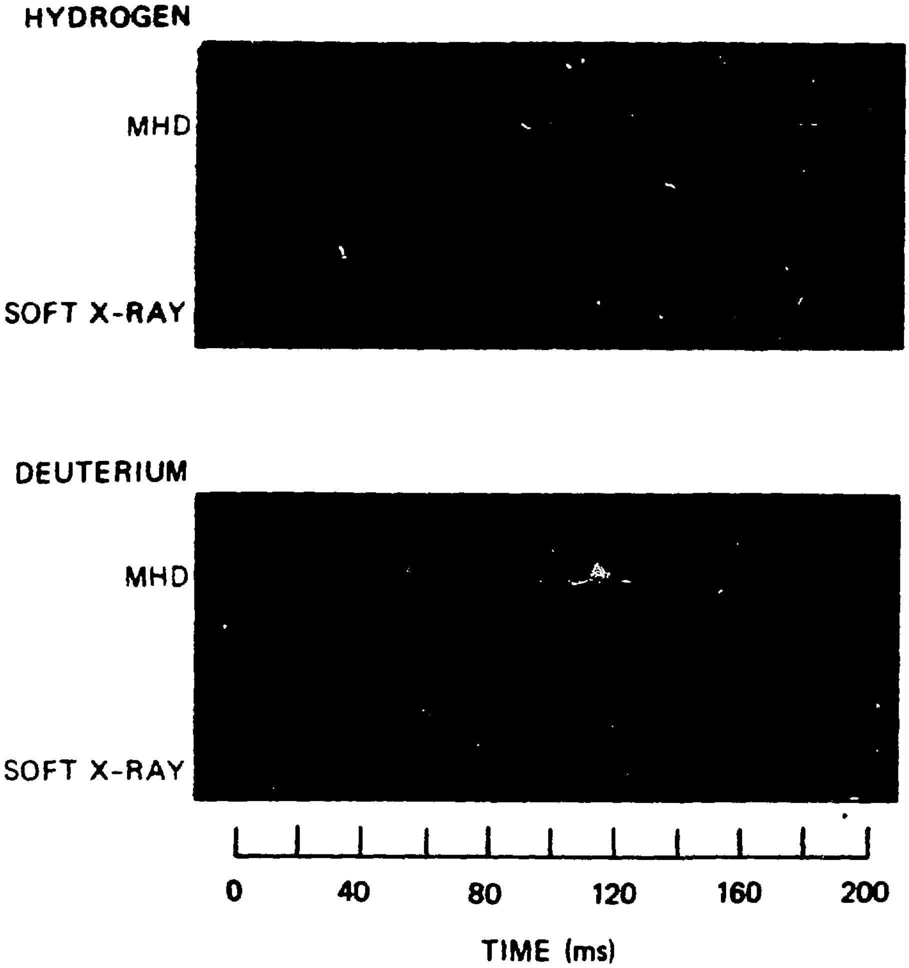
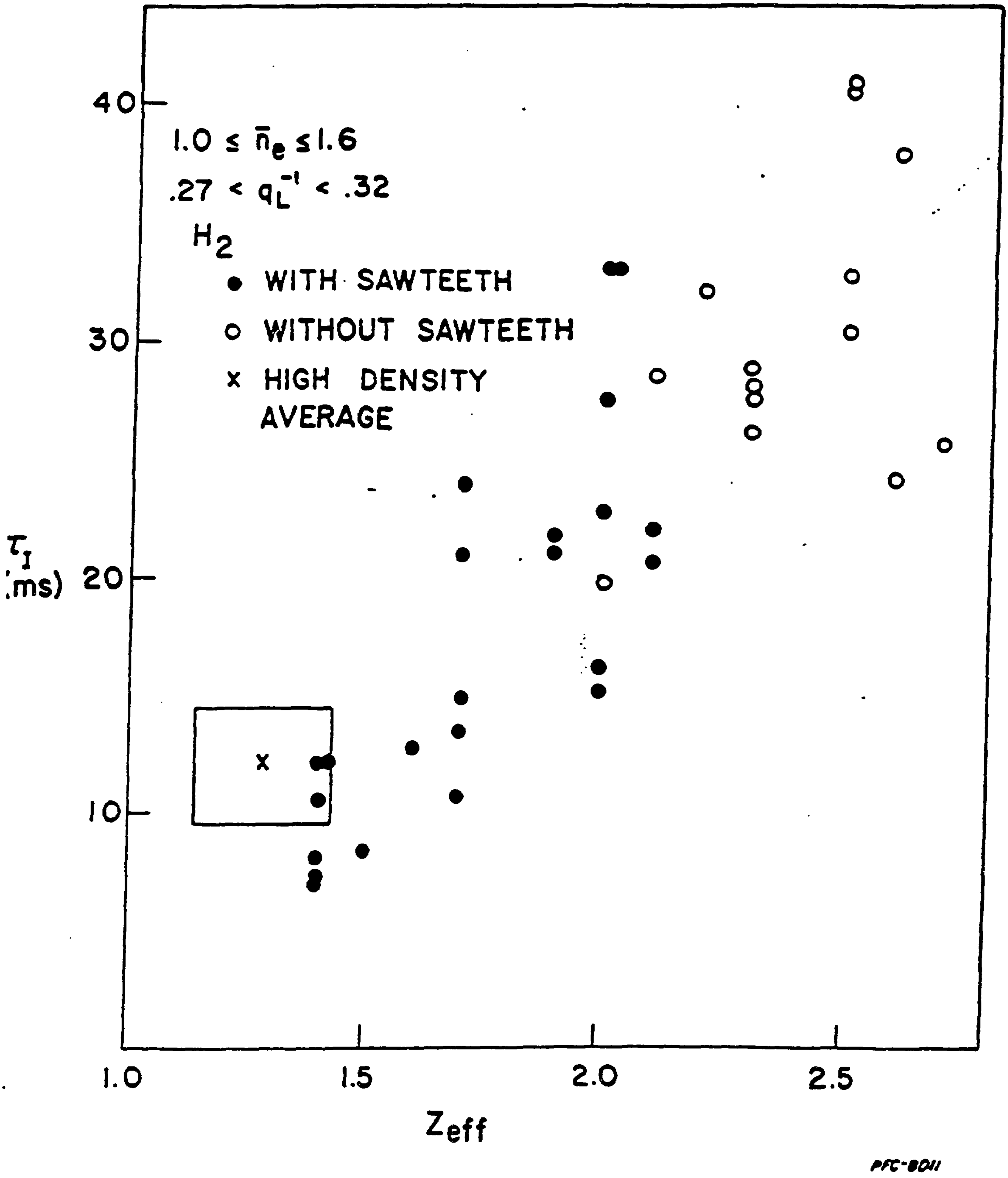



FIG. 2. Comparisons of the emission rates (1 gigarayleigh = $10^{15}$ photons/cm$^2$ s) from several iron lines during Ohmically heated deuterium and hydrogen discharges.

**SOFT X-RAY SIGNALS INDICATE THAT THE IMPURITY CONTENT INCREASES DURING DEUTERIUM DISCHARGES BUT SOON REACHES AN ALMOST STEADY STATE IN HYDROGEN DISCHARGES.**

ORNL–DWG 81-3407 FED





1.0 ≤ n̄e ≤ 1.6
.27 < qL⁻¹ < .32
H2
● WITH SAWTEETH
○ WITHOUT SAWTEETH
x HIGH DENSITY AVERAGE
τI (ms)
40
30
20
10
1.0
1.5
2.0
2.5
Zeff
PFC-8011

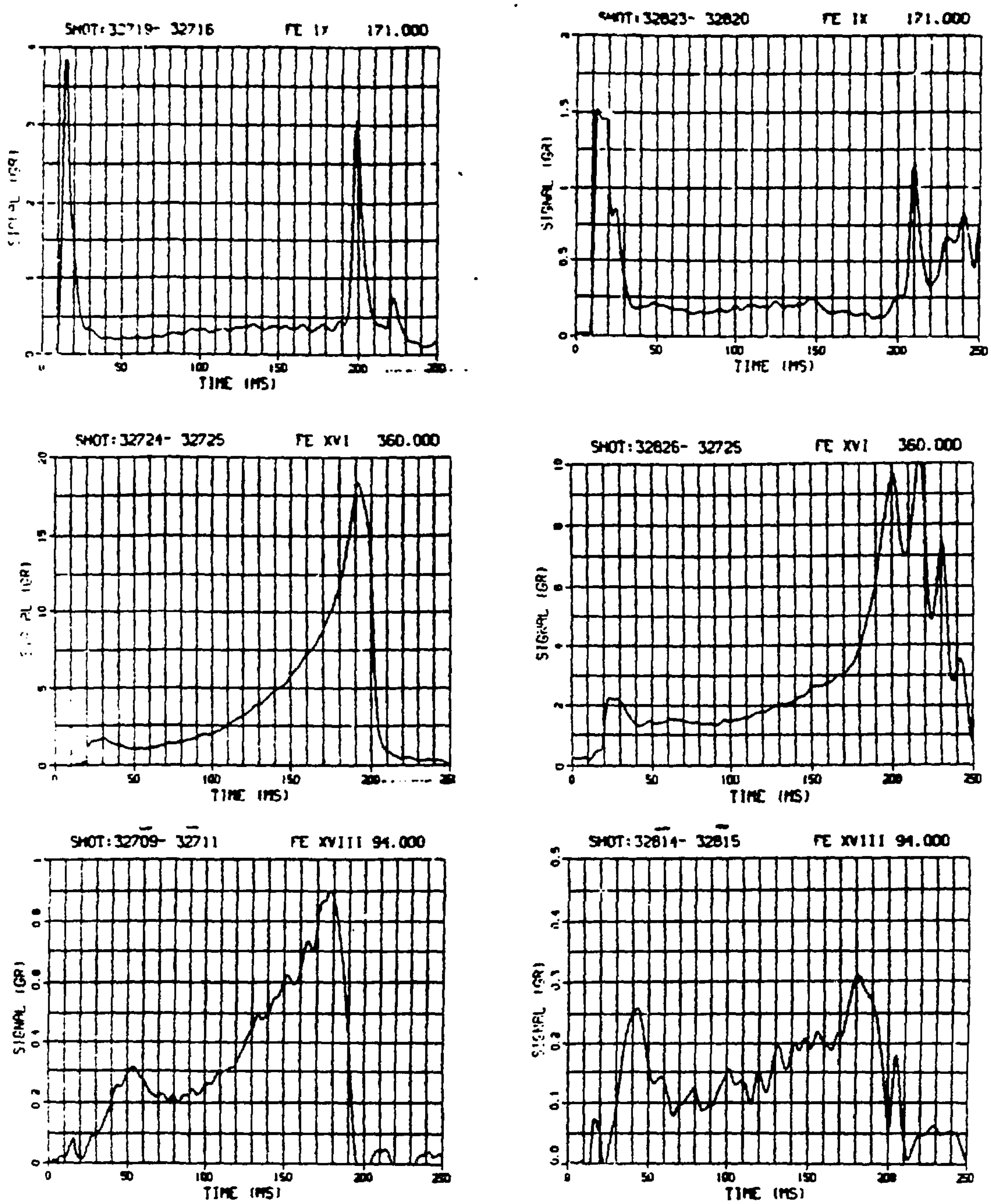

FIGURE 10

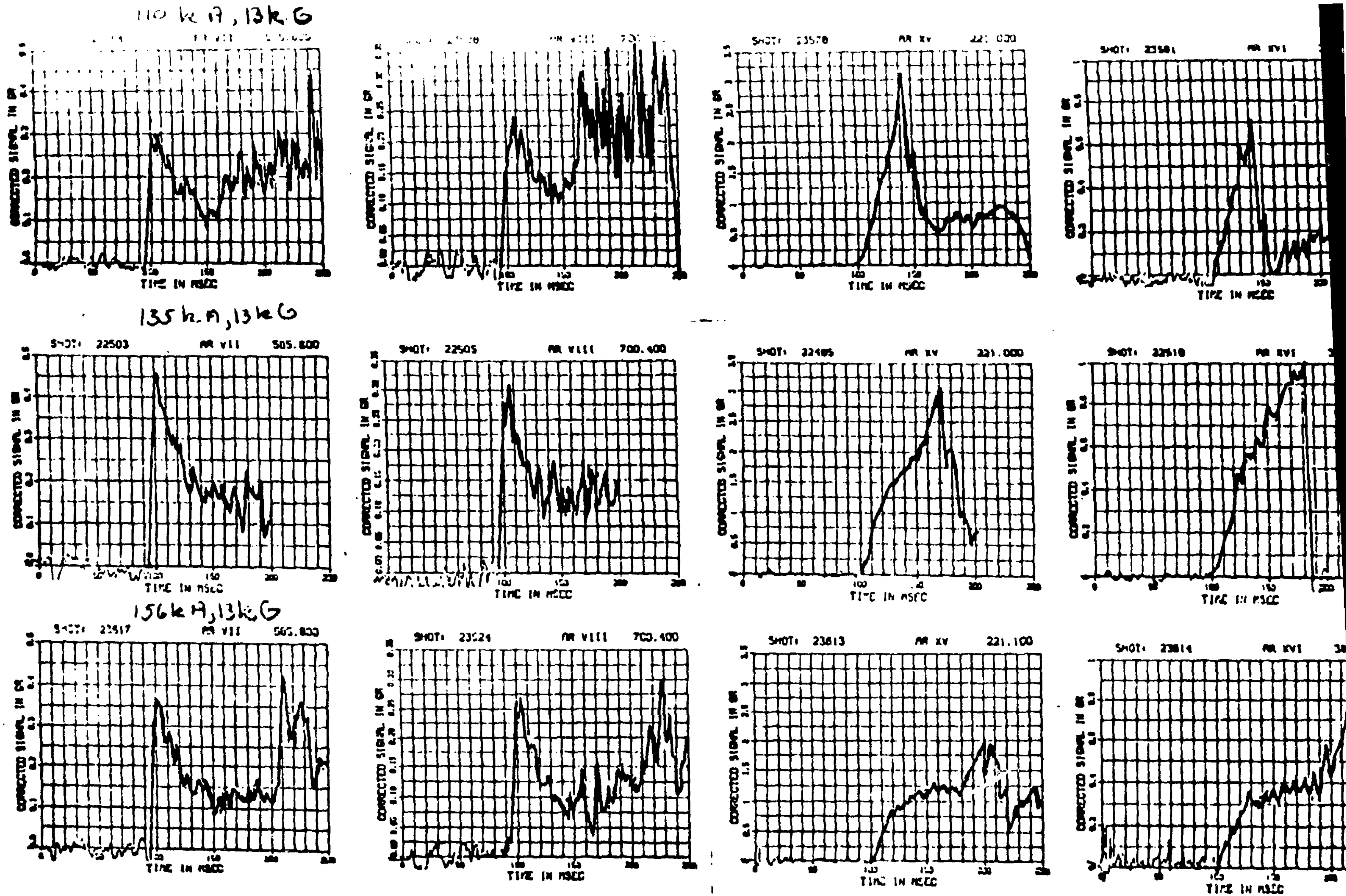
**NON-GETTERED**

$Z_{eff}=2.8$

**GETTERED**

$Z_{eff}=1.5$



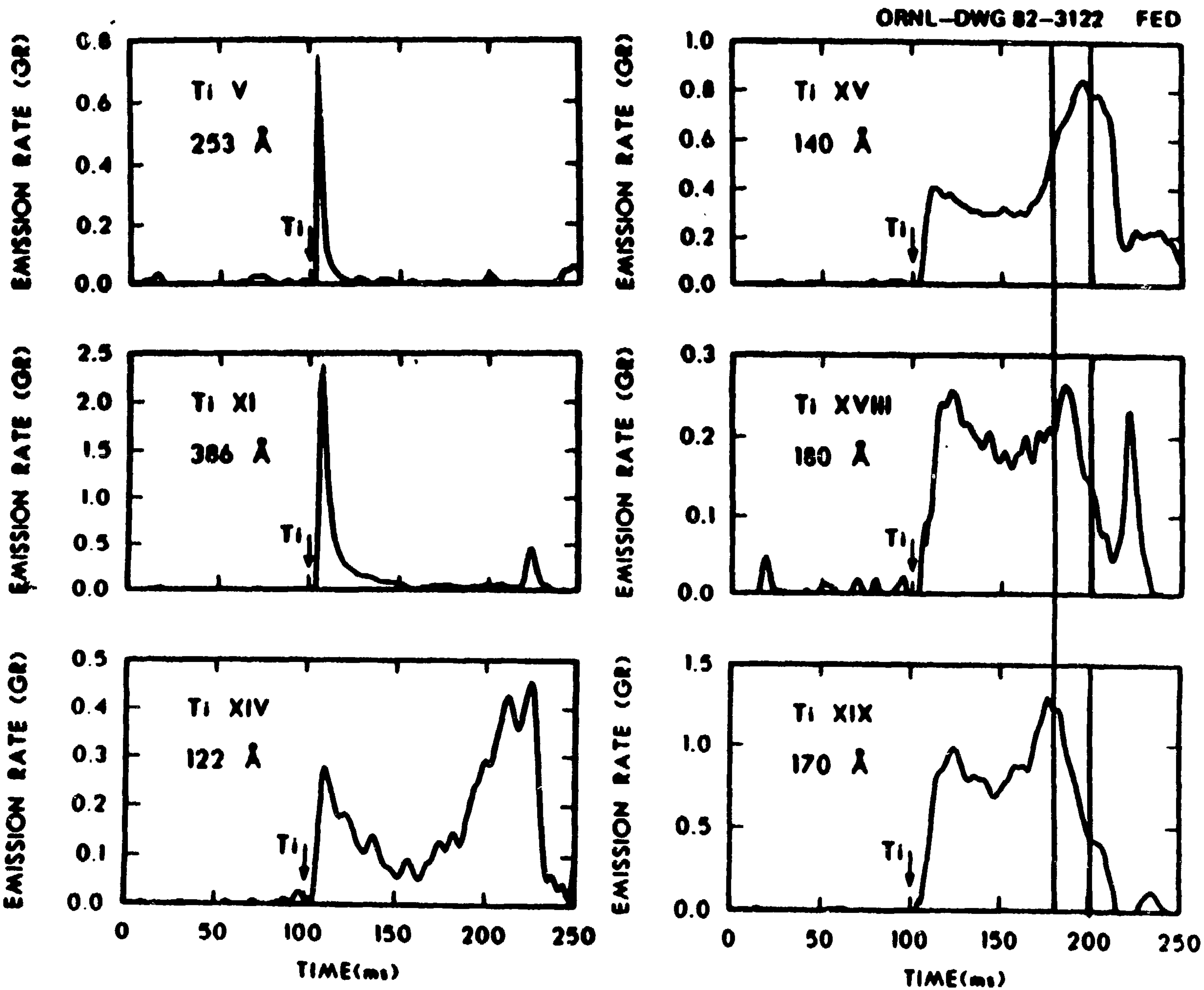

110 kA, 13kG
AR VIII
SHOT: 23578
AR XV
221.000
SHOT: 23581
AR XVI
135 kA, 13kG
SHOT: 22503
AR VII
505.800
SHOT: 22505
AR VIII
700.400
SHOT: 22485
AR XV
221.000
SHOT: 22510
AR XVI
156 kA, 13kG
SHOT: 23517
AR VII
505.800
SHOT: 23524
AR VIII
700.400
SHOT: 23813
AR XV
221.100
SHOT: 23814
AR XVI
CORRECTED SIGNAL IN GR
TIME IN MSEC

# Confinement Times and Transport Coefficients Near Density Limits

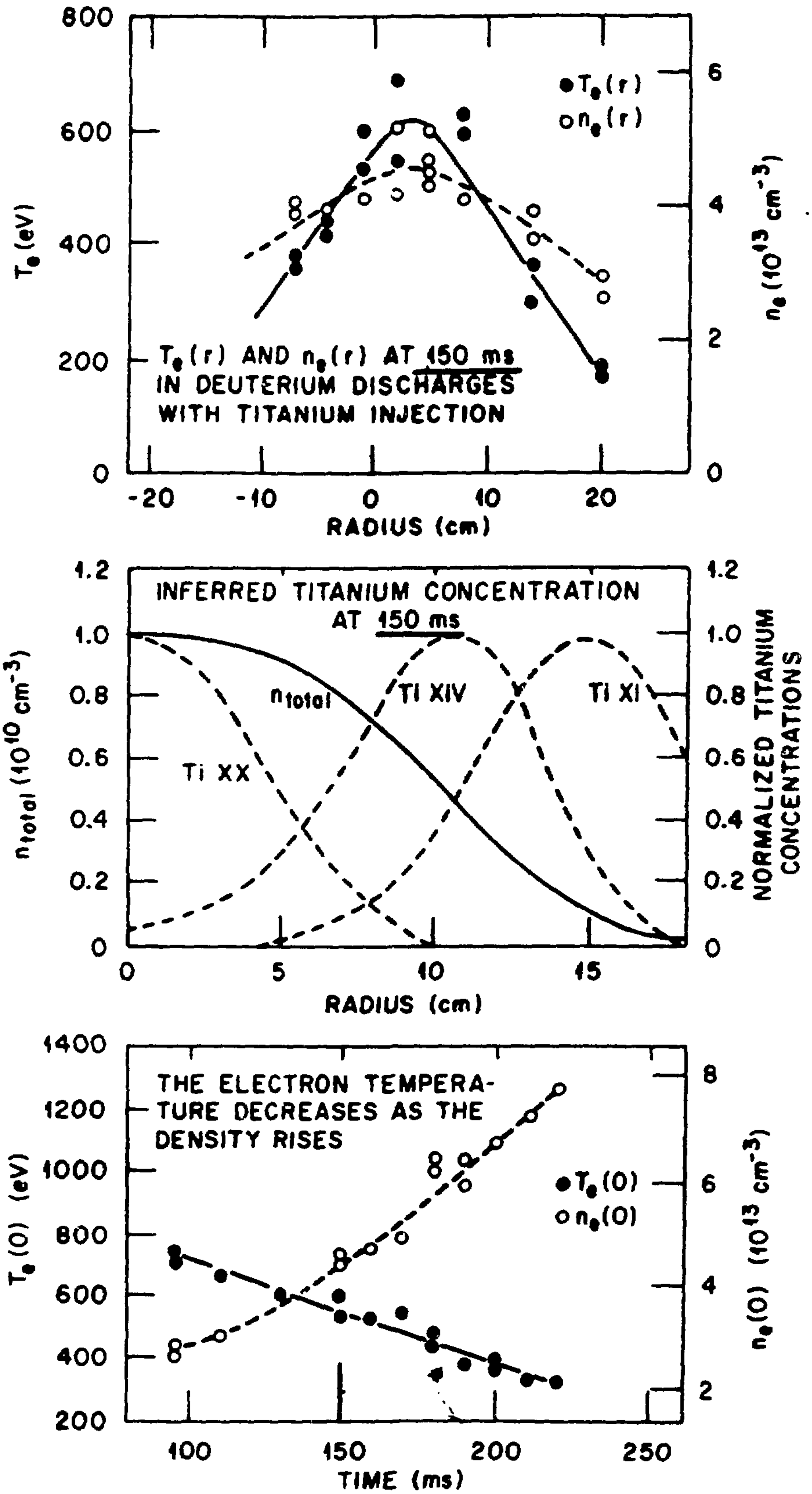
# Neoclassical Impurity Transpo[illegible]

"Observation of Long Impuri[illegible]
finement Times in the ISX To[illegible]
K.H. Burrell et al. - NF 21 (1981) [illegible]

.....it is found that both impurity pe[illegible]
times and impurity containment times are cons[illegible]
with neoclassical predictions.

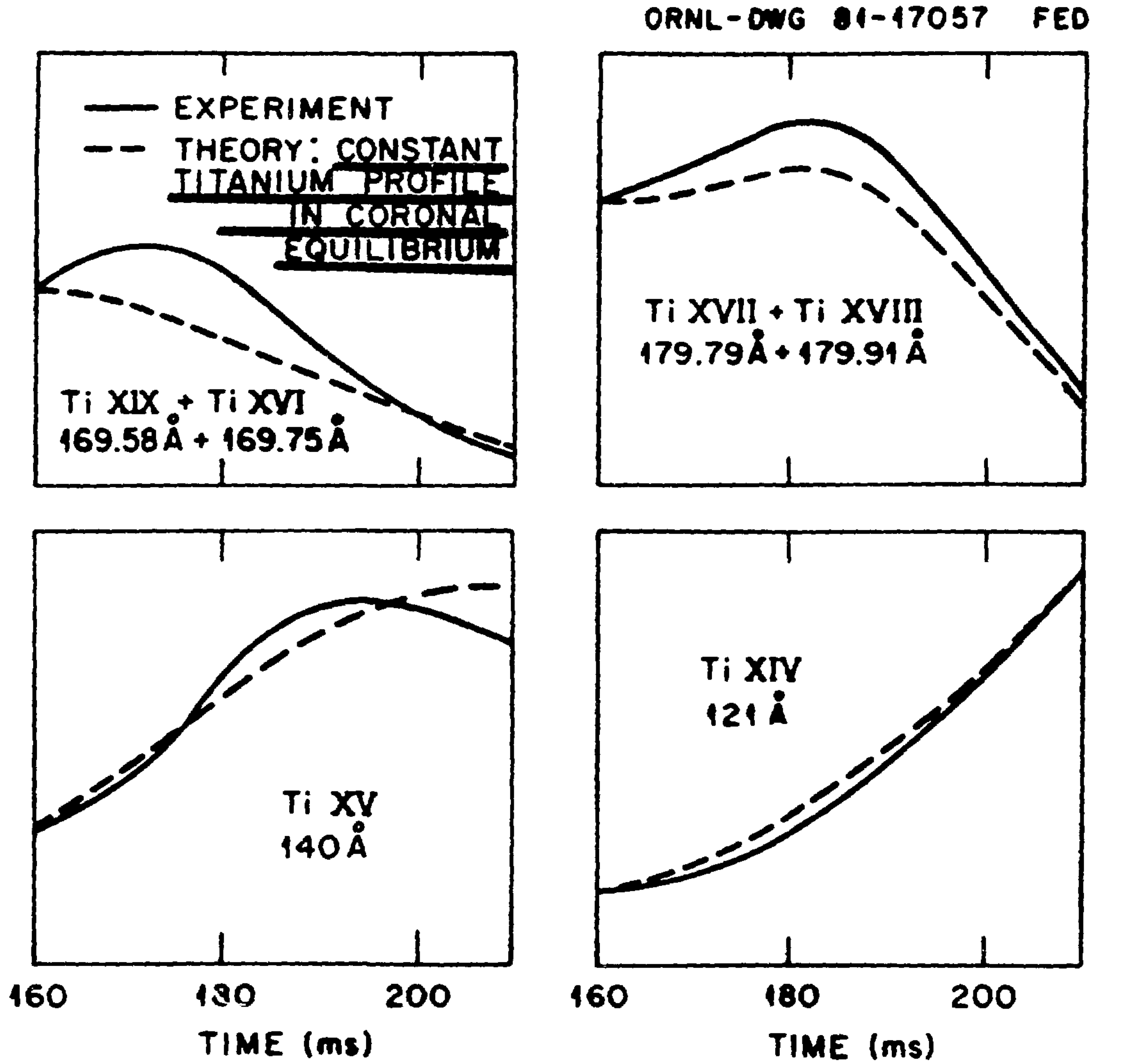



Isler et al., Fig. 11



$T_e(r)$ AND $n_e(r)$ AT 150 ms IN DEUTERIUM DISCHARGES WITH TITANIUM INJECTION
● $T_e(r)$
○ $n_e(r)$
$T_e$ (eV)
$n_e$ ($10^{13}$ cm$^{-3}$)
RADIUS (cm)
INFERRED TITANIUM CONCENTRATION AT 150 ms
$n_{total}$
Ti XX
Ti XIV
Ti XI
$n_{total}$ ($10^{10}$ cm$^{-3}$)
NORMALIZED TITANIUM CONCENTRATIONS
RADIUS (cm)
THE ELECTRON TEMPERATURE DECREASES AS THE DENSITY RISES
● $T_e(0)$
○ $n_e(0)$
$T_e(0)$ (eV)
$n_e(0)$ ($10^{13}$ cm$^{-3}$)
TIME (ms)

# TEMPORAL EVOLUTION OF TITANIUM EMISSION AFTER TRANSPORT EQUILIBRIUM IS ESTABLISHED



# EMPIRICAL DESCRIPTIONS OF IMPURITY TRANSPORT

$$\frac{\partial N^I}{\partial t} + \nabla \cdot \Gamma^I = Q$$

$$\Gamma_r^I = -D(r)\frac{\partial N^I}{\partial r} - V_o f(r) N^I$$

IF D = CONSTANT

AND $f(r) = \frac{r}{a_\ell} = \rho$

THE TIME DEPENDENT SOLUTIONS ARE

$$N^I = \Sigma C_n e^{\frac{-t}{\tau_n}} e^{-S\rho^2} M\left(-\frac{\lambda_n a_\ell^2}{4SD}, 1, S\rho^2\right)$$

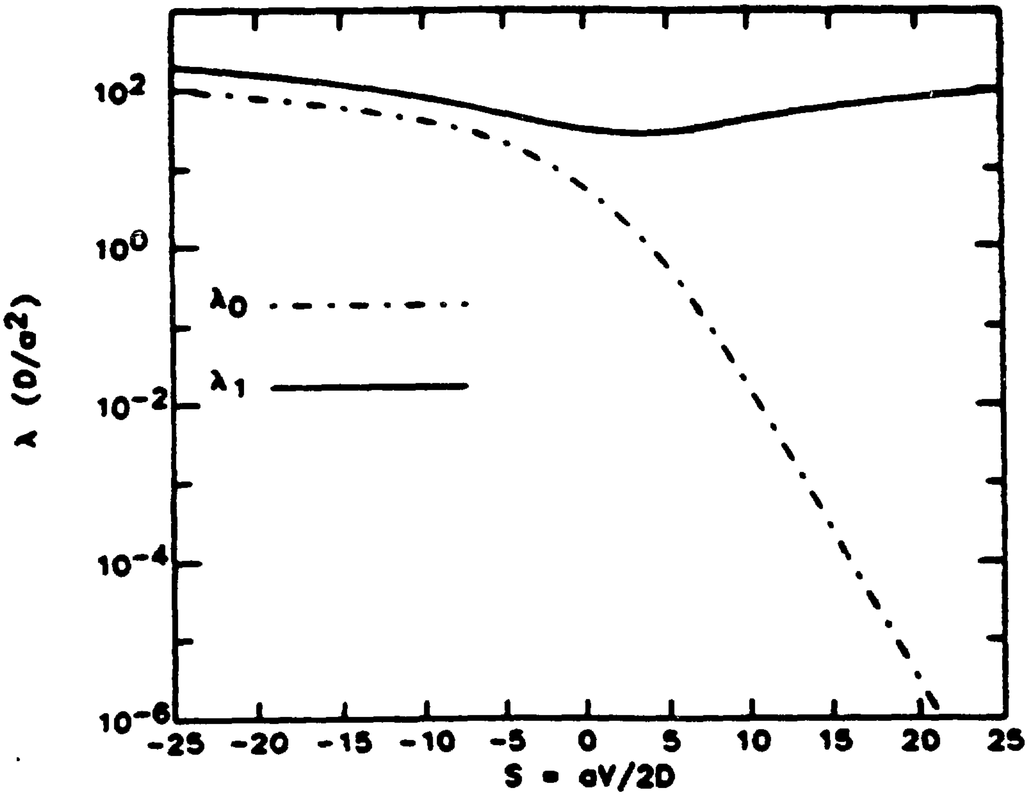
WHERE $S = \frac{a_\ell V_o}{2D}$, $\lambda = \frac{1}{\tau_n}$, AND M = THE CONFLUENT HYPERGEOMETRIC FUNCTION.

THE STEADY STATE SOLUTION ($\Gamma_r^I = 0$) IS

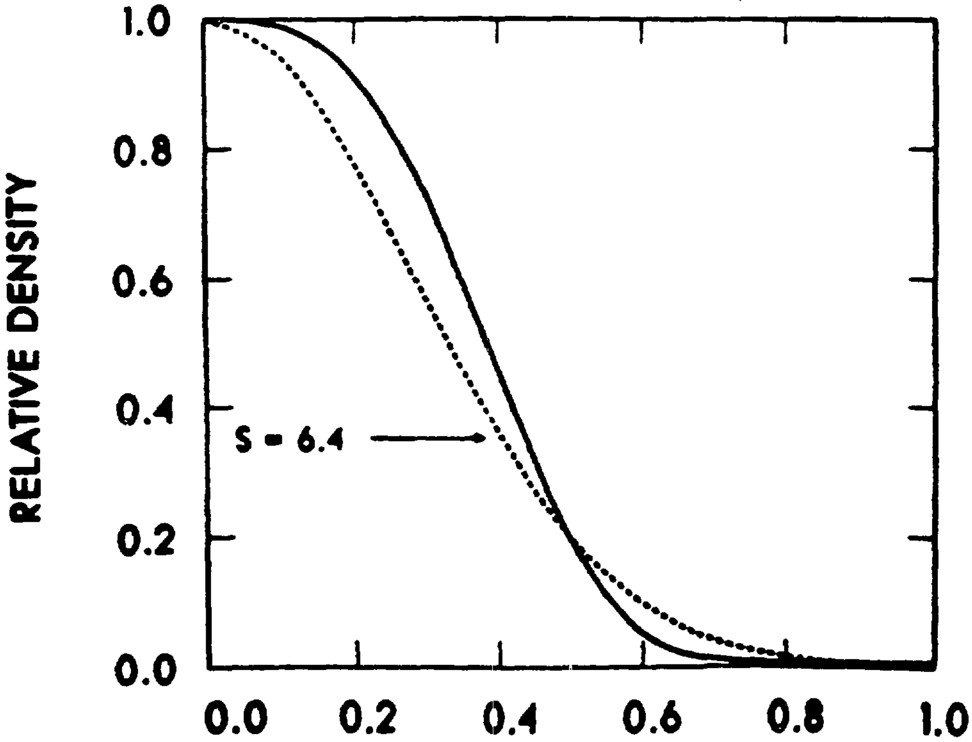
$$N_I = N_I(0)\,exp\left[-\frac{V_o\rho^2}{2Da_\ell}\right] = N^I e^{-S\rho^2}$$

THIS RESULT IMPLIES THAT THE INTRINSIC IMPURITY LEVEL IS STRONGLY PEAKED AT $\rho = 0$ if $\frac{V_o}{D}$ IS LARGE.

$N_I$ IS UNIFORM AS A FUNCTION OF $\rho$ IF CONVECTION IS NEGLIGIBLE COMPARED TO DIFFUSION.




TITANIUM DISTRIBUTION AT 150 MS
SOLID - MODELING OF SPECTRAL INTENSITIES
DASH - GAUSSIAN DISTRIBUTION



# ANALYSIS OF TITANIUM INJECTION EXPERIMENTS ON ISX-B WITH DEUTERIUM AS THE WORKING GAS

TAKE $S = 6.4$ TO GIVE AN ACCEPTABLE MATCH BETWEEN THE PROFILE DETERMINED FROM SPECTROSCOPY AND THE GAUSSIAN $exp[-S\rho^2]$.

$$\frac{V_o a_\ell}{2D} = 6.4$$

$$\underline{V_o = 0.48D}$$

ASSUME THE RISE TIME OF THE Ti XIX SIGNAL (0.020 S) EQUALS $\tau_1$.

$$\tau_1 = \gamma \frac{a_\ell^2}{D}$$

$$\gamma \simeq 0.06 \text{ for } S = 6.4 \text{ (FROM GRAPH OF } \lambda_1)$$

$$\underline{D = 1.8 X 10^3 cm^2/S}$$

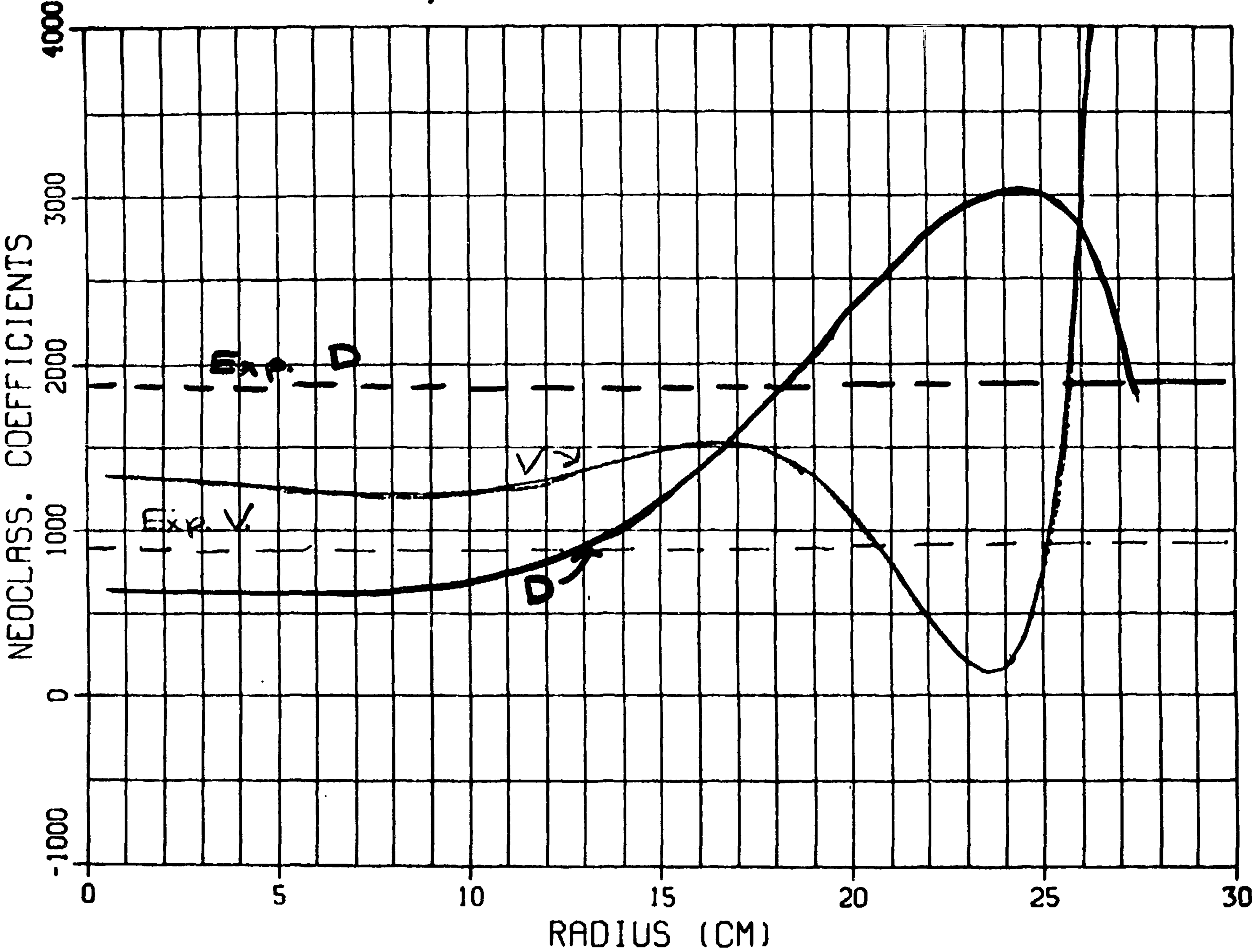
$$\underline{V_o = 870 \text{ cm/S (FROM GRAPH OF } \lambda_0)}$$

$$\underline{\tau_0 = 3.1 \text{ S !}}$$

AS EXPECTED FROM THESE NUMBERS, TYPICAL ISX-B OH DISCHARGES IN DEUTERIUM EVIDENCE ACCUMULATION OF INTRINSIC IMPURITIES.

THE COMBINATION OF TEXT AND ISX-B DATA SHOWS THAT THE IMPURITY CONFINEMENT TIME CAN CHANGE BY A FACTOR OF 100 FOR CHANGES OF LESS THAN A FACTOR OF 2 IN $B_T$, $I_p$, or $N_e$.

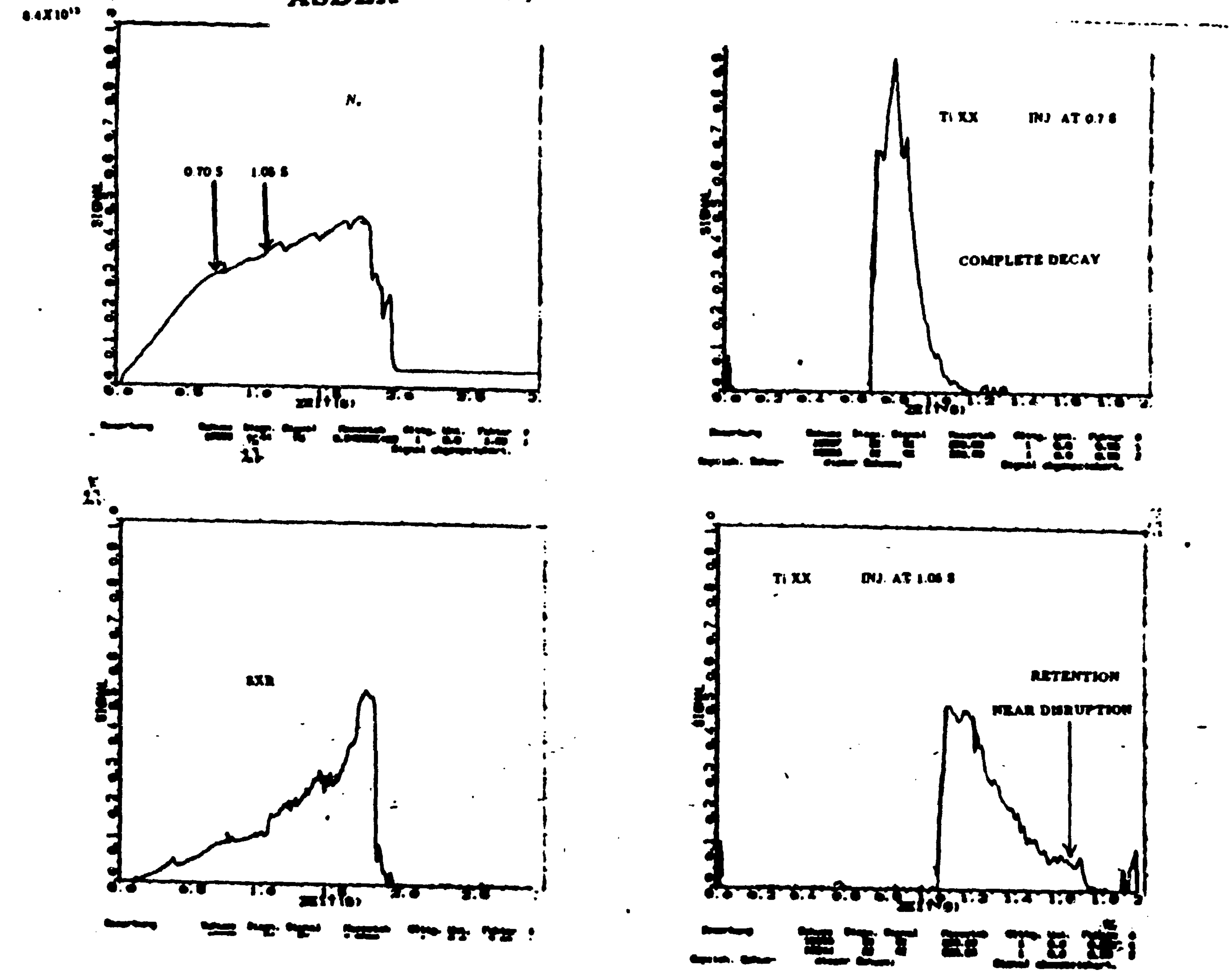
Parabolic Density Profile



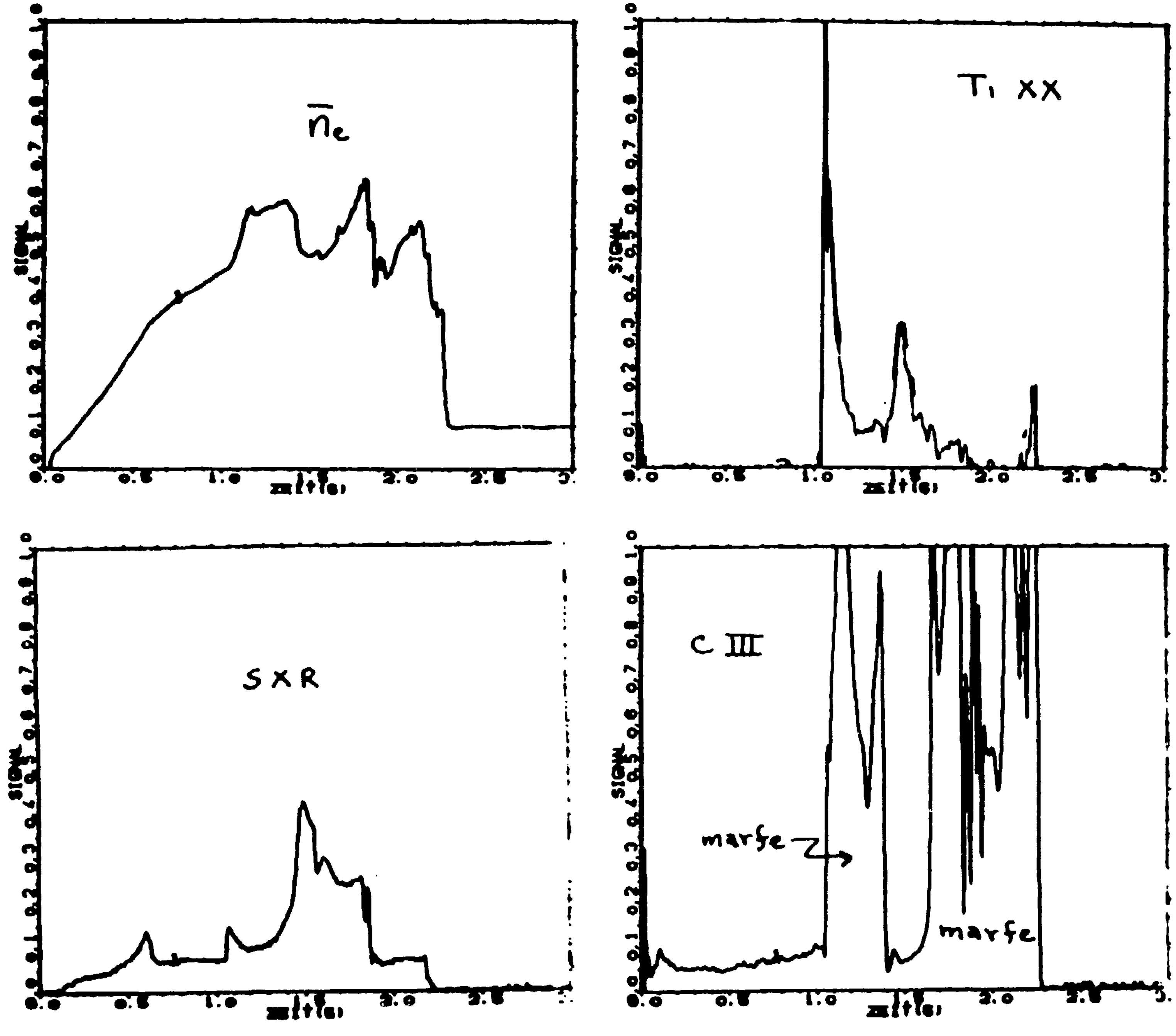

Neoclassical Transport Coefficients

# Evidence of Long Confinement Times Near Density Limits in ASDEX, T-10, and TEXTOR

# ASDEX $B_T = 15kG$ $I_p = 280kA$



ASDEX $B_T = 2.2$ T $I_p = 280$ kA



T-10

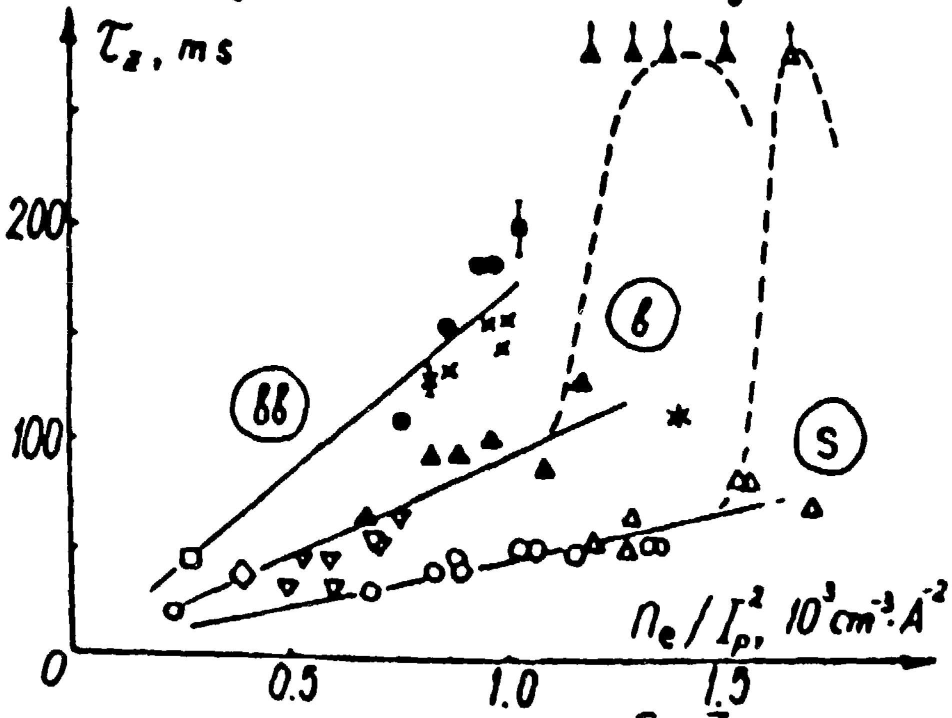



Fig. 7.

Fig. 6.

| | I, kA | B, kG | q(a) | $Z_{eff}(0)$ |
|---|---|---|---|---|
| × | 185 | 14 | 2,7 | 4 ÷ 5 |
| ● | 185 | 20 | 3,8 | |
| ■ | 185 | 31 | 6,0 | |
| □ | 360 | 31 | 3,0 | |
| ◇ | 230 | 16 | 1,9 | 3.5 |
| ✱ | 125 | 20 | 4,5 | 2 ÷ 3 |
| ▲ | 160 | 20 | 3,5 | |
| ▽ | 230 | 20 | 2,4 | |
| △ | 160 | 22 | 4.1 | 1,2 ÷ 1,7 |
| ○ | 180 | 22 | 3,7 | |

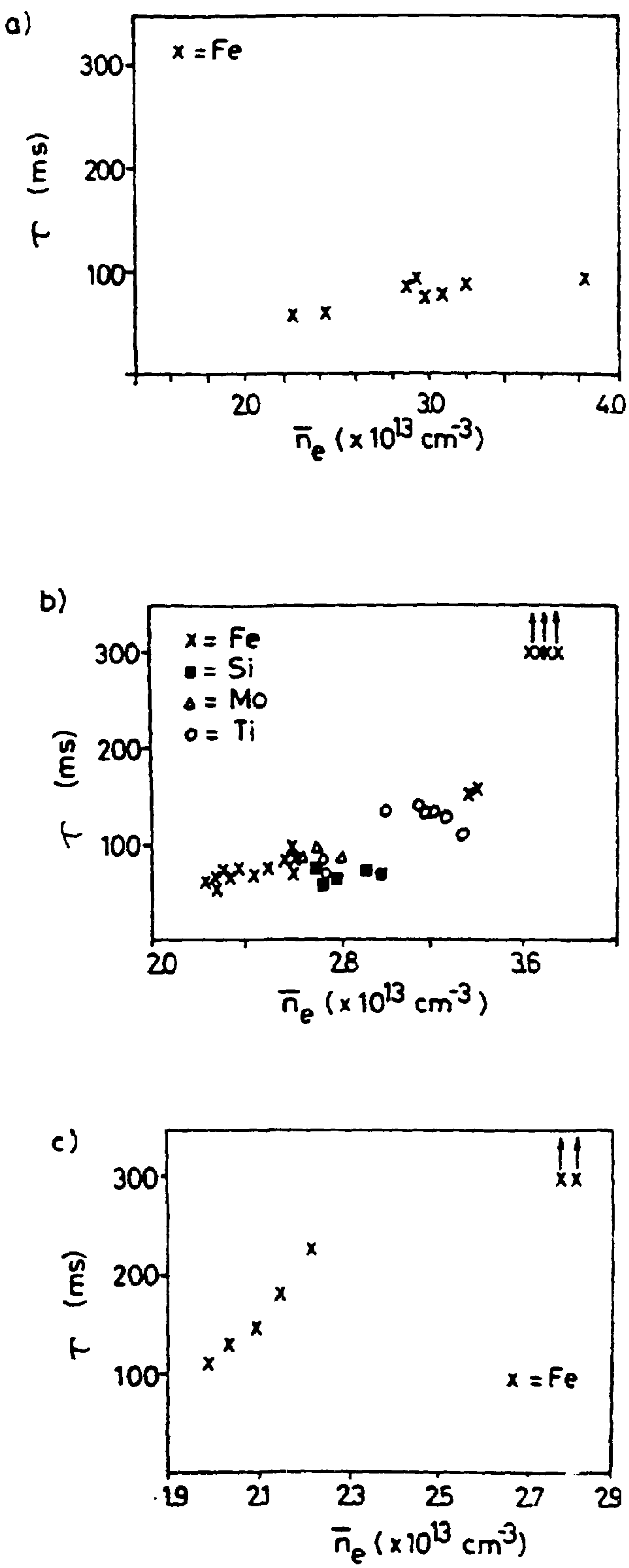
# TEXTOR

Castracane et al.

480 kA

360 kA

220 kA



## SUMMARY

- ANOMALOUS DIFFUSION OF IMPURITIES (AND POSSIBLY THE WORKING GAS) IS SUPRESSED IN THE INTERIOR OF TOKAMK PLASMAS NEAR DENSITY LIMITS. INWARD CONVECTION THEN RESULTS IN RETENTION OF INJECTED TEST IMPURITIES.

- THIS CHANGE TO CONVECTION DOMINATED TRANSPORT OFTEN RESULTS OFTEN RESULTS IN THE ACCUMULATION OF INTRINSIC IMPURITIES, AT LEAST ABOVE $q \approx 3$. IF SO, A THERMAL COLLAPSE AT THE CENTER INITIATES A PARTIAL DISRUPTION.

- SHARP INCREASES IN $\tau_z$ ARE ALSO OBSERVED BEFORE MAJOR DISRUPTIONS. THE ROLE OF ENHANCED IMPURITY CONFINEMENT IN INITIATING SUCH DISRUPTIONS IS UNCERTAIN.

- FURTHER DOCUMENTATION OF $\tau_z$ IN DISRUPTIVE DISCHARGES COULD BE ENLIGHTENING FOR UNDERSTANDING DENSITY LIMITS. ALSO, CHANGES OF IMPURITY TRANSPORT NEAR DENSITY LIMITS IN AUXILLIARY HEATED DISCHARGES HAVE NOT BEEN STUDIED.