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NEUTRAL INJECTION EXPERIMENTS ON THE ISX-B TOKAMAK

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AND
THE ISX-B GROUP

CONF-830908--7
DE84 003312

OAK RIDGE NATIONAL LABORATORY

PRESENTED AT
11TH EUROPEAN CONFERENCE ON
CONTROLLED FUSION AND PLASMA PHYSICS
AACHEN, FEDERAL REPUBLIC OF GERMANY
SEPTEMBER 5, 1983

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TOPICS

1. REVIEW OF CONFINEMENT SCALING IN ISX-B WITH STRONG NEUTRAL INJECTION IN CLEAN PLASMAS.

2. DISCUSSION OF OBSERVED ENERGY CONFINEMENT IMPROVEMENT IN SLIGHTLY CONTAMINATED DISCHARGES (FACTOR $\lesssim$ 2).

3. PRELIMINARY EVALUATION OF CONFINEMENT WITH "BALANCED" (CO + COUNTER) NEUTRAL BEAM INJECTION.

4. SUMMARY.

SUMMARY OF PLASMA CONFINEMENT WITH GETTERING IN ISX-B

1. $\tau_E^* = \dfrac{W_E + W_i + W_f}{P_b + P_{OH}} \quad \alpha \quad I_p^{3/2} \, P_b^{-2/3}$

- NO $\bar{n}_e$ or B_T DEPENDENCE
- DEVELOPED FROM SURVEY OF DATA BASE, CONFIRMED BY SINGLE PARAMETER SCANS.

2. τ_{Ee}, τ_{Ei}, τ_P AND τ_φ DETERIORATE WITH INCREASING P_b.

3. TRANSPORT ANALYSIS INDICATES THAT χ_e IS THE DOMINANT LOSS CHANNEL.

CONFINEMENT IMPROVEMENT WITH INTRODUCTION OF LOW-Z IMPURITY

- INCREASED CONFINEMENT IN CONTAMINATED DISCHARGES HAS BEEN SUGGESTED PREVIOUSLY:

  - ISX-B WITH NBI[+]

    - τ_E^* (NON-GETTERED) > τ_E^* (GETTERED)
    - N_2 INJECTION EXPERIMENT

  - TOKAMAK FOLKLORE, PRIMARILY WITH OH ONLY

- RECENT ISX-B EXPERIMENTS WITH NBI HAVE DEMONSTRATED:

  - IMPROVEMENT FACTOR UP TO 2 (PARTICLE AND ENERGY)
  - A LINEAR DEPENDENCE OF τ_E^* ON $\bar{n}_e$.

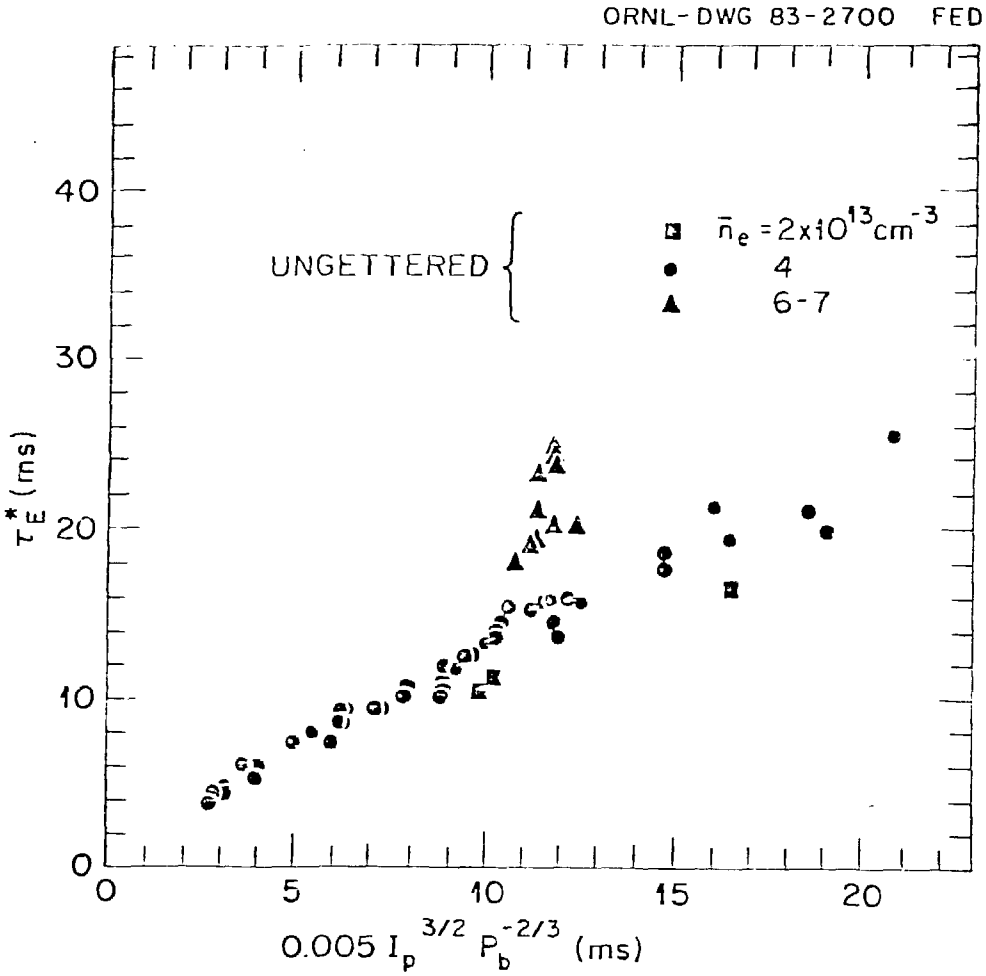
- THESE EXPERIMENTS INVOLVED DOCUMENTED COMPARISON BETWEEN:

  - DISCHARGES WITH AND WITHOUT GETTERING
  - GETTERED DISCHARGES WITH AND WITHOUT NEON INJECTION

- THE IMPURITY CONCENTRATIONS REQUIRED TO ACHIEVE FAVORABLE CONFINEMENT IN THE "Z-MODE" ARE MODEST (e.g. Z_{eff} = 1.5 → 2).

[+] A. J. Wootton, et al., J. Nucl. Mat. 111 112 (1982).

GLOBAL CONFINEMENT TIME IN UNGETTERED DISCHARGES IS UP TO ~ 2 TIMES THAT IN GETTERED DISCHARGES.



$65 < I_p < 220$ kA

$.3 < P_b < 2.4$ MW

$0.75 < B_T < 1.5$ T

$1.1 < \kappa < 1.6$

- FAVORABLE DENSITY DEPENDENCE OF τ_E^* IN UNGETTERED DISCHARGES IS SUGGESTED.

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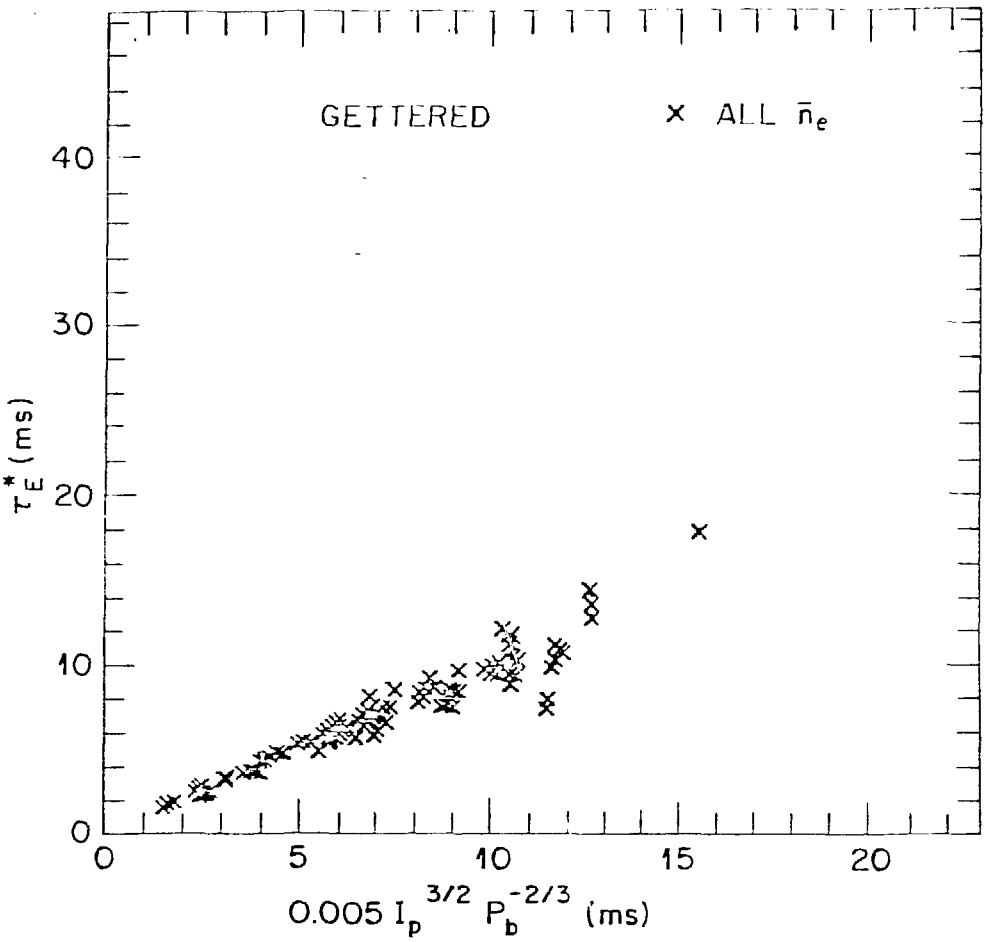
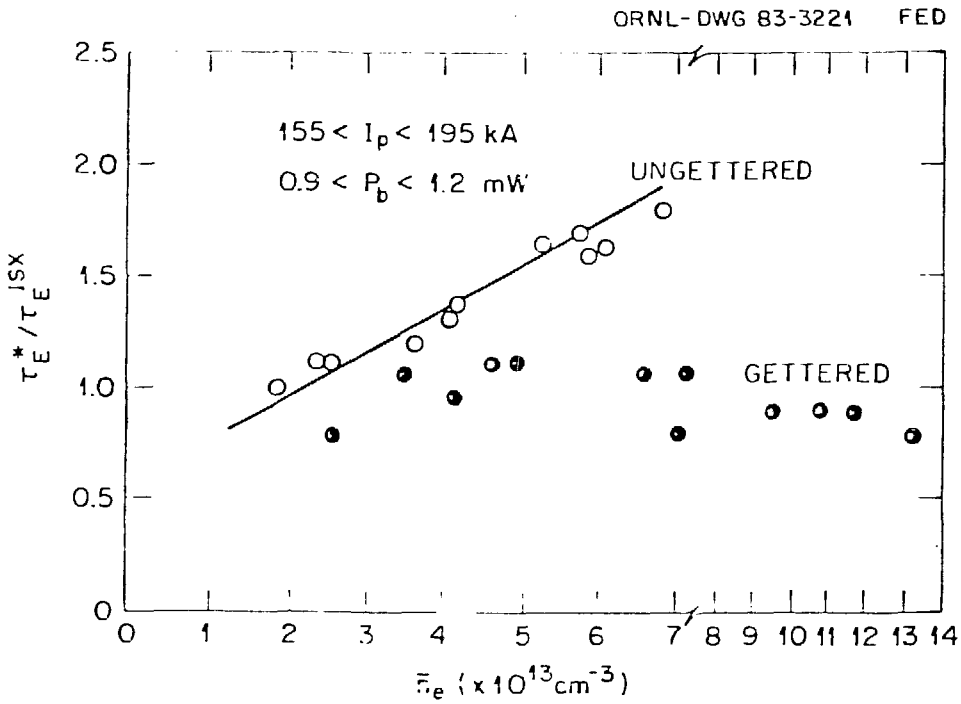
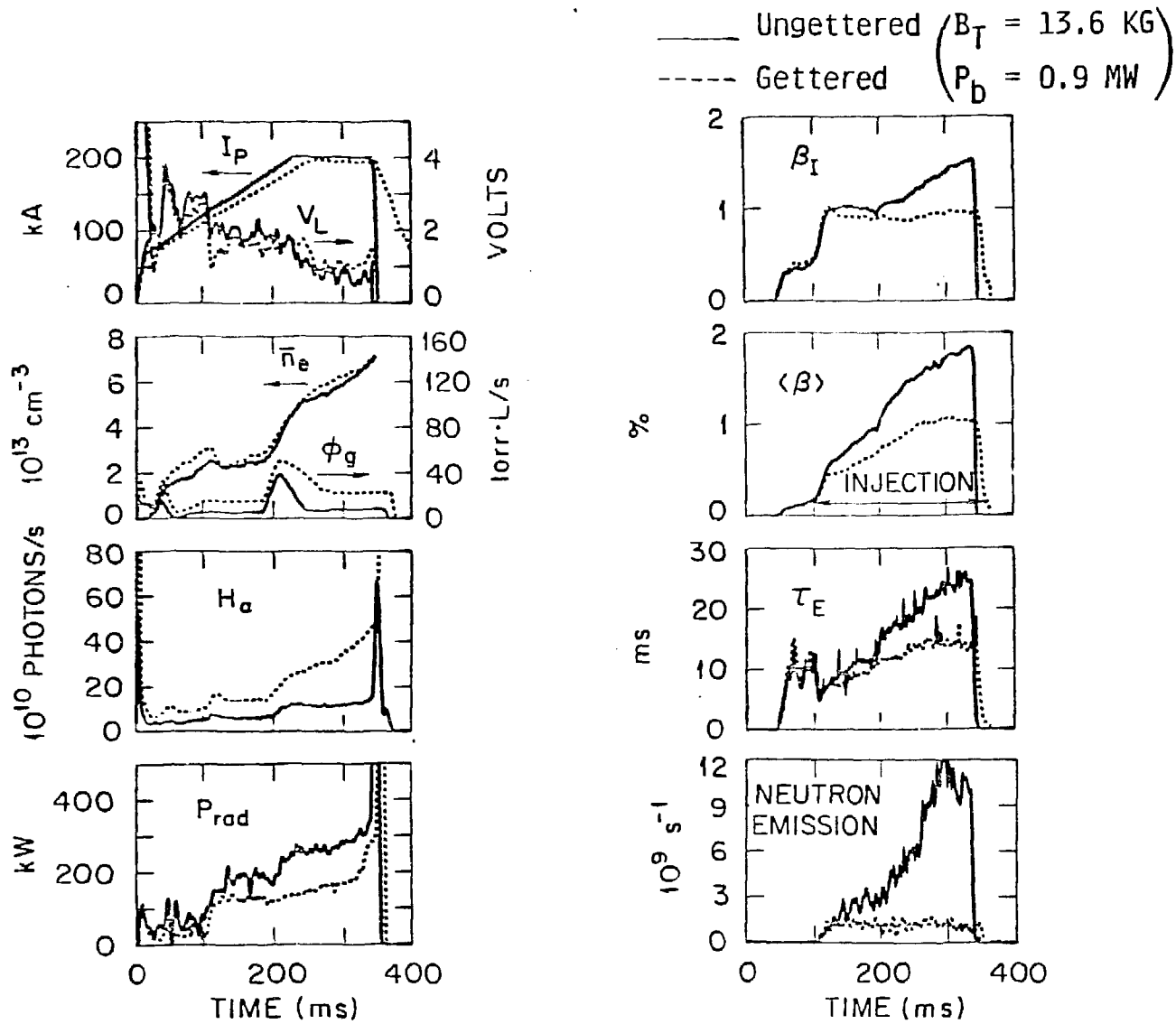


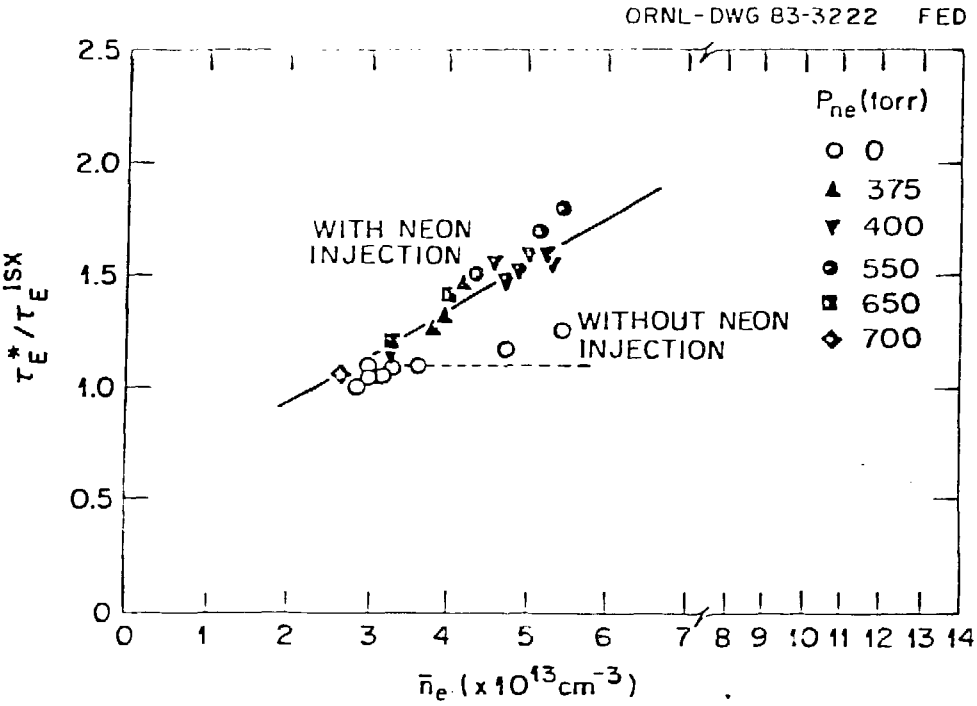
IN CONTRAST TO THE GETTERED DISCHARGES, THE NONGETTERED BEAM-HEATED DISCHARGES SHOW A LINEAR INCREASE IN τ_E^* WITH $\bar{n}_e$.



COMPARISON BETWEEN GETTERED AND UNGETTERED DISCHARGES



NEON INJECTION INTO GETTERED DISCHARGES INTRODUCES A LINEAR DEPENDENCE OF τ_E^* ON $\bar{n}_e$ SIMILAR TO THAT OBSERVED IN UNGETTERED DISCHARGES.



- THE CONFINEMENT IMPROVEMENT DEPENDS <u>DIRECTLY</u> ON $\bar{n}_e$, RATHER THAN ON DETAILS OF IMPURITY INJECTION.

INCREASED CENTRAL DENSITY WITH NEON INJECTION AT SAME D_2 GAS INPUT SUGGESTS IMPROVEMENT OF PARTICLE CONFINEMENT IN THE BULK OF THE PLASMA.

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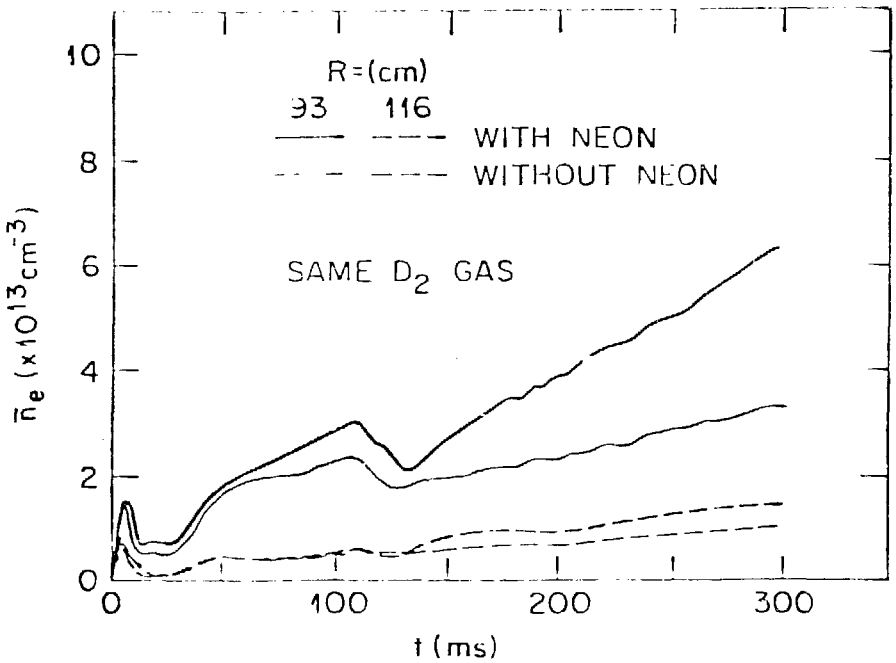


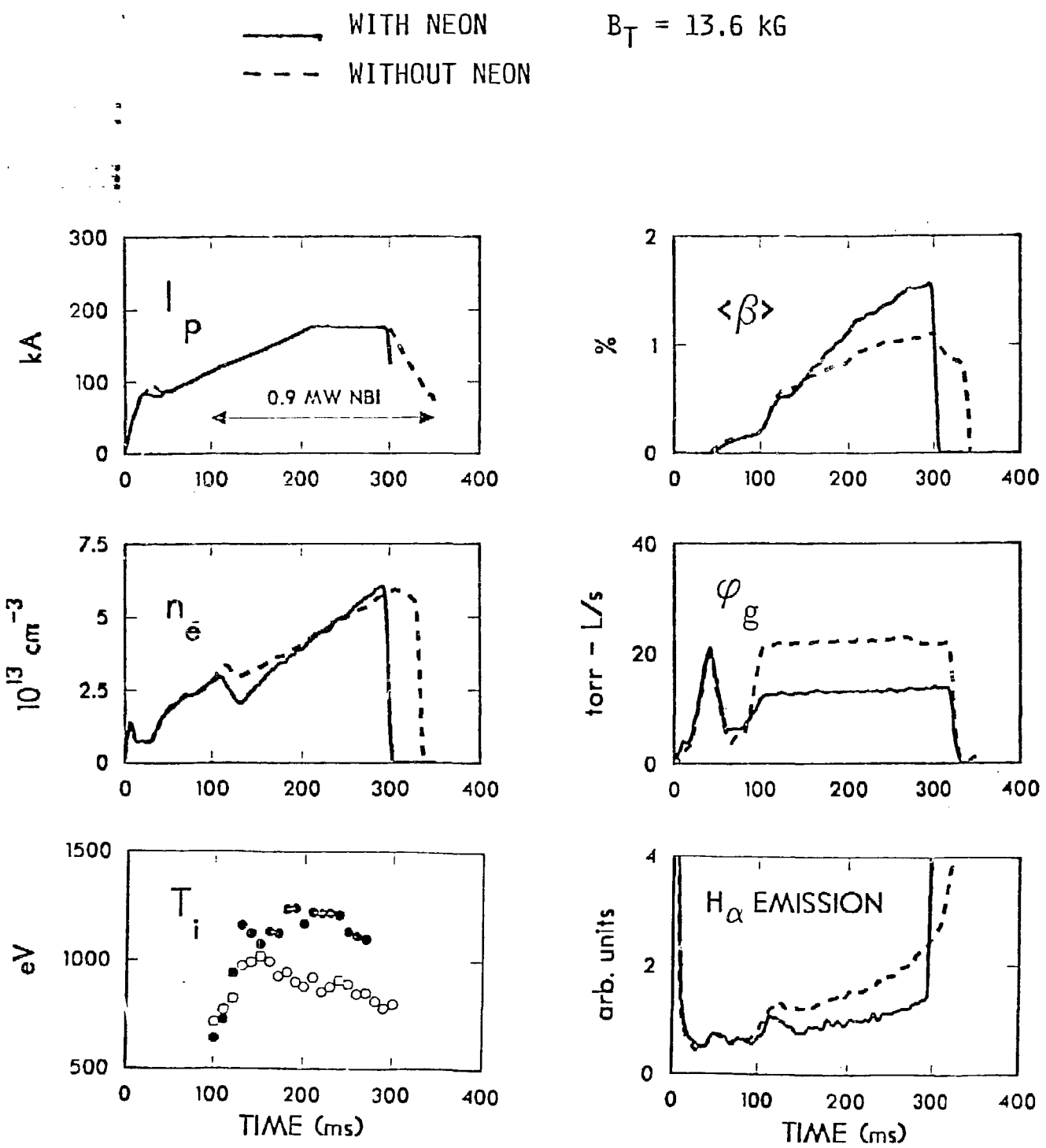
- TOTAL IONIZATION RATE IS SAME FOR BOTH DISCHARGES (H_α/D_α DETECTORS).

- $$\frac{(\Delta n_e)_z}{n_e} = \frac{\Delta Z_{eff}}{Z} \lesssim 10\%$$

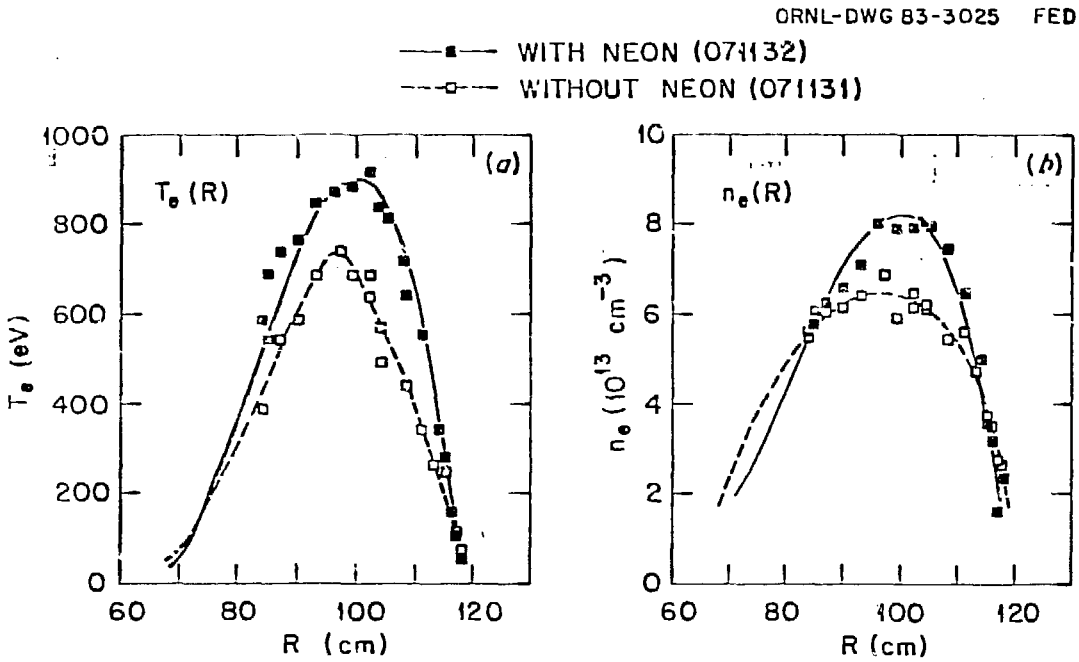
- SPECTROSCOPIC MEASUREMENTS INDICATE <u>SMALLER</u> $(\Delta n_e)_z$.

COMPARISON BETWEEN GETTERED DISCHARGES

WITH AND WITHOUT NEON INJECTION



PROFILES WITH AND WITHOUT NEON INJECTION (AT THE SAME DENSITY)



with neon/without neon

T_e (0)	~1.25
T_e (r)	broader
n_e (r)	more peaked

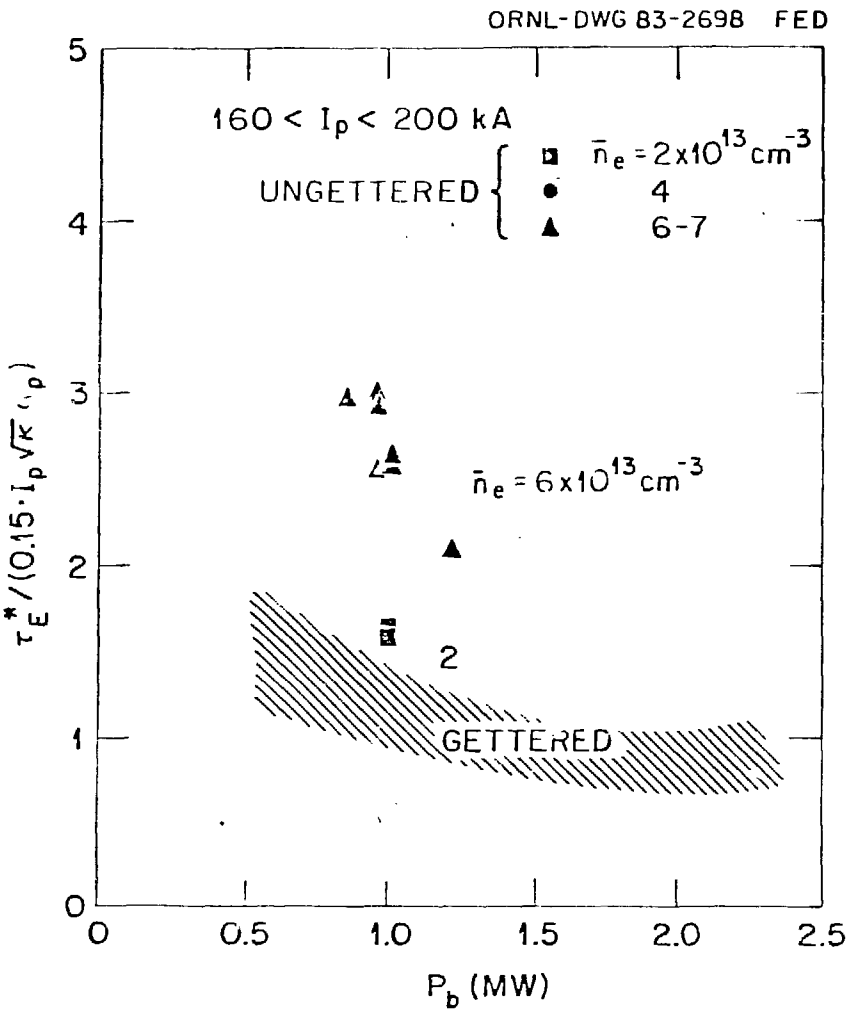
TRANSPORT ANALYSIS OF DISCHARGES WITH AND WITHOUT NEON INJECTION (AT THE SAME DENSITY)

I_p = 174 KA, B_T = 1.33 T, q_ψ = 3.7
R_o = 93 cm, a_p = 25 cm, κ = 1.2
H_0 (0.9 MW) → D^+

	without neon	with neon
n_e (10^{13} cm^{-3})	5.1	5.3
T_e (0) (keV)	0.75	0.90
T_i (0) (keV)	0.82	1.09
Z_{eff}	1.56	1.97
T_i (0) (keV)	0.82	1.09
W_e (a) (kJ)	5.0	7.1
W_i (a) (kJ)	5.3	7.5
P_{be} (a) (kW)	657	604
P_{bi} (a) (kW)	233	317
τ_E (a) (ms)	9.5	13.3

- Improvement of τ_E appears to be linked to reduced χ_e and increased P_{bi} due to higher T_e.
  - χ_e (2a/3) reduced by ~40% or more.

τ_E^* NORMALIZED TO GMS SCALING ($\tau_E^{GMS} = .15\ I_p\ a_p \sqrt{\kappa}$) VERSUS BEAM POWER.



THE DATA FOR $\bar{n}_e = 4 \times 10^{13}\ cm^{-3}$ IN UNGETTERED DISCHARGES SHOW CONFINEMENT DETERIORATION WITH P_b, AS IN GETTERED DISCHARGES.

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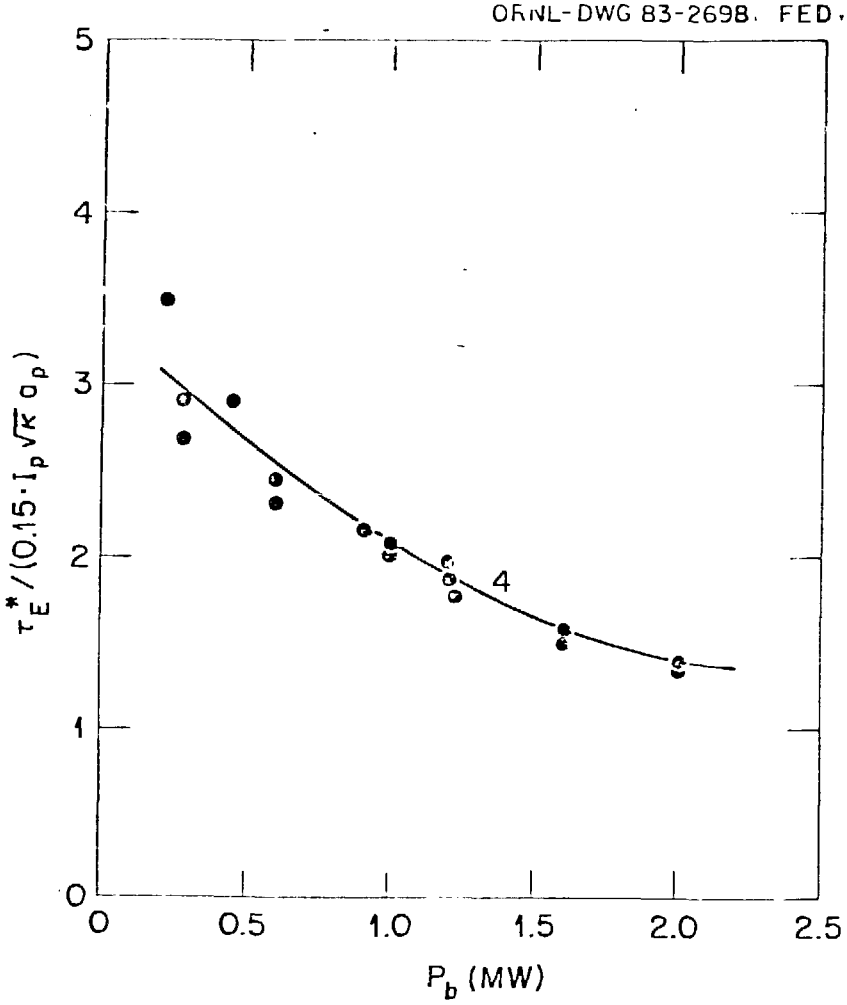


TOROIDAL PLASMA ROTATION AND CONFINEMENT

- Momentum confinement may reflect confinement scaling of energy, particles, etc.

- Toroidal rotation may <u>drive</u> enhanced ion losses.

  - Ion transport can account for as much as 40% of the energy losses in ISX-B during neutral injection.

  - Neoclassical theory predicts χ_i increases by a factor ~2 for $v_\varphi = v_{th}$.

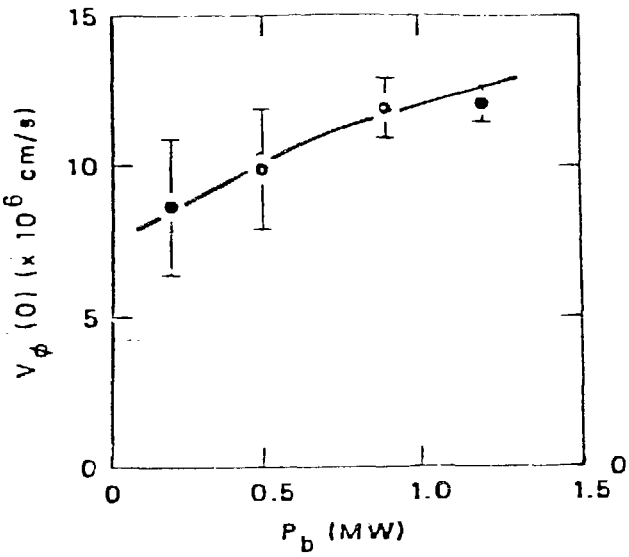
  - $\dfrac{\chi_i}{\chi_i^{nc}}$ appears to increase with P_b during co-injection. A rotation effect?

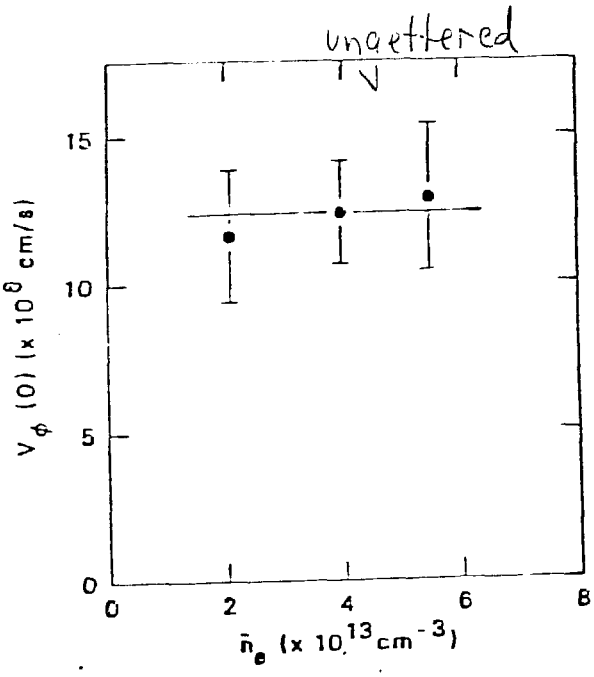
- We can control the net momentum input and V_φ with balanced co- plus counter-injection.

- Studies of rotation and radial electron field effects on confinement will be extended using a HIBP to measure $\varphi(r,t)$. -Hallock (E18)

Parallel momentum confinement appears to reflect some of the properties of global energy confinement.

$$\tau_\phi(0) \sim \frac{m_i n_i(0) V_\phi(0)}{K(0)} \sim \frac{\bar{n}_e V_\phi(0)}{P_b}$$



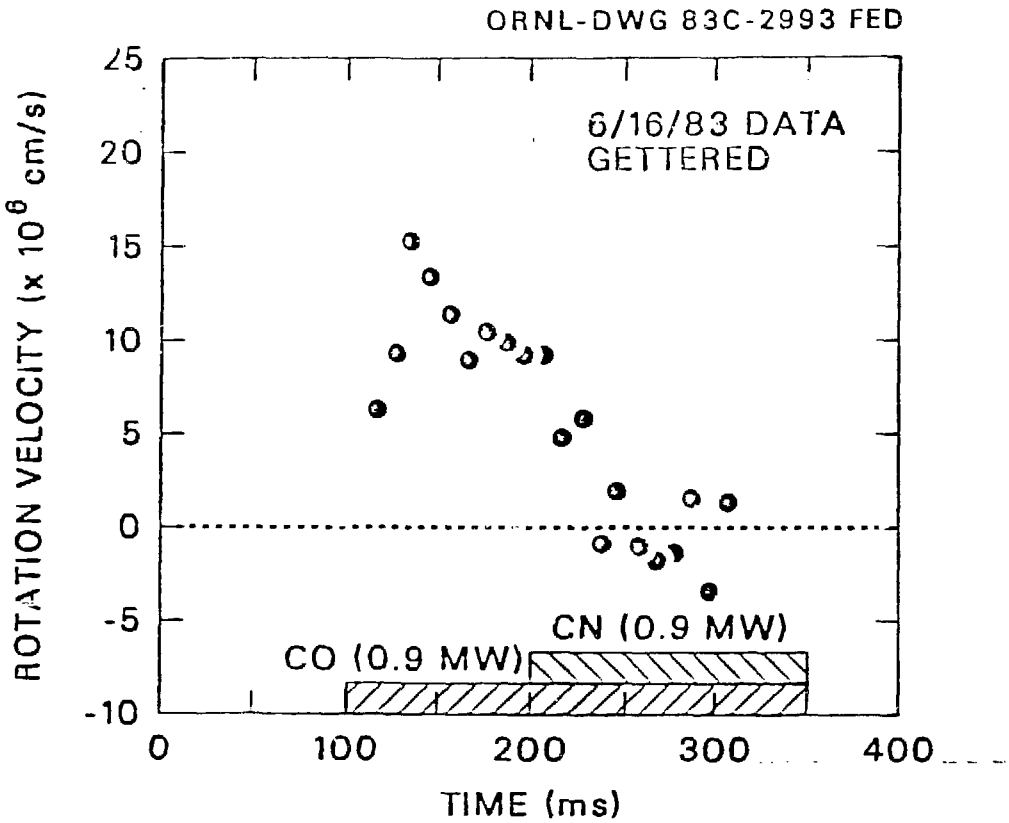


$\tau_\phi(0) \sim P_b^{-\alpha}$

$\alpha \approx 0.5$

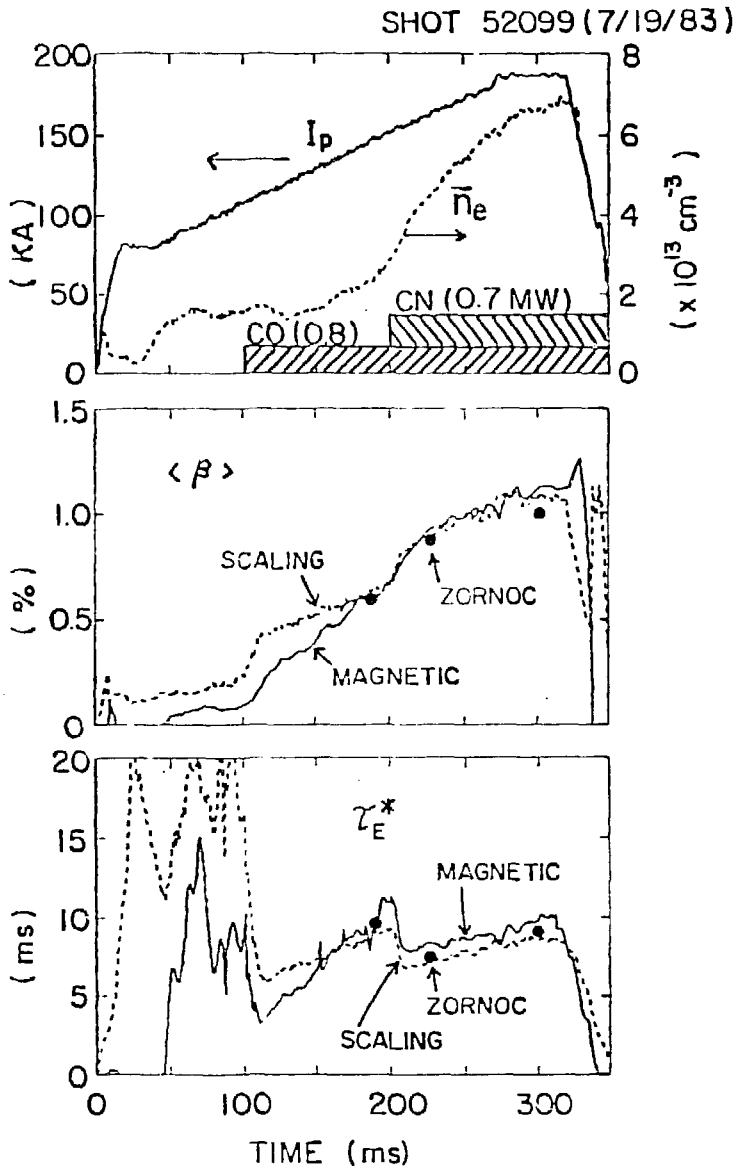
$\tau_\phi(0) \sim \bar{n}_e$

PLASMA ROTATION AND BALANCED BEAM INJECTION



- The central rotation velocity is deduced from the Doppler shift of a charge-exchange O^{7+} line.

THE ELIMINATION OF PLASMA ROTATION WITH BALANCED INJECTION DOES NOT APPRECIABLY IMPROVE GLOBAL ENERGY CONFINEMENT.



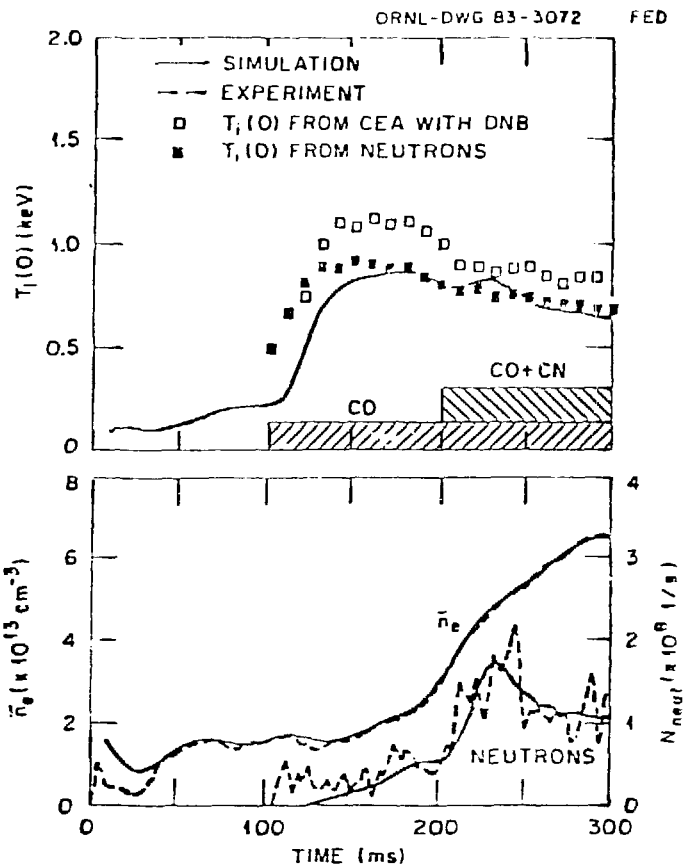
- The agreement of $\langle\beta\rangle$ with the ISX-B scaling implies that τ_E^* with balanced beam injection decreases as $P_{total}^{-2/3}$, as with co-injection.

A TIME-DEPENDENT TRANSPORT CODE (PROCTR) USING

$$\chi_i = \chi_i \qquad \text{(CHANG-HINTON)}$$

$$\chi_e = 4\,\chi_e \qquad \text{(CARRERAS-DIAMOND)}$$

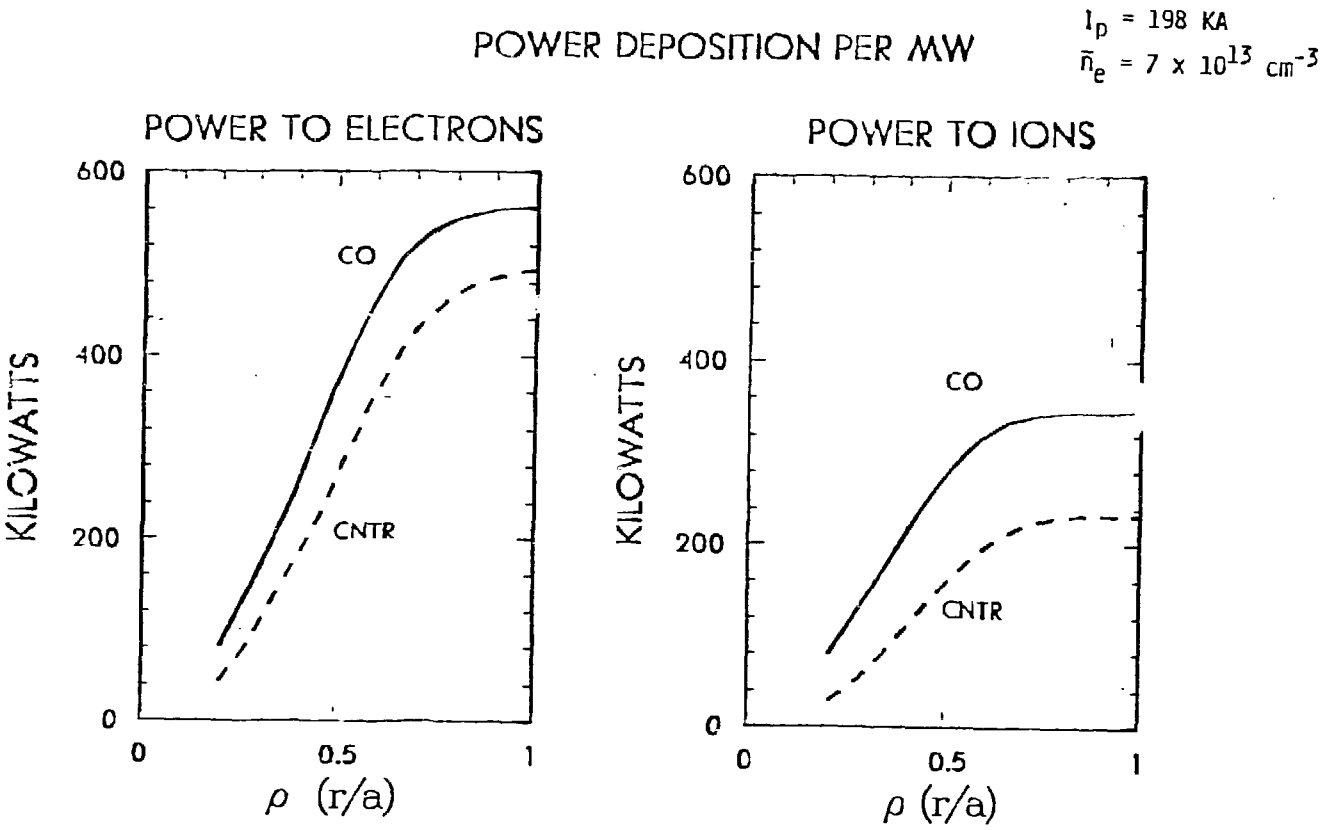
REPRODUCES WELL THE $T_e(r)$ PROFILE AND $T_i(t)$ DURING BOTH CO-INJECTION AND BALANCED BEAM INJECTION.



- PREVIOUSLY WITH STAGGERED TWO CO-BEAM OPERATION, THE CENTRAL ION TEMPERATURE WAS ~ 350 eV LESS THAN PREDICTED BY THE CODE DURING THE TWO CO-INJECTION (BUT NOT DURING THE ONE CO-INJECTION).

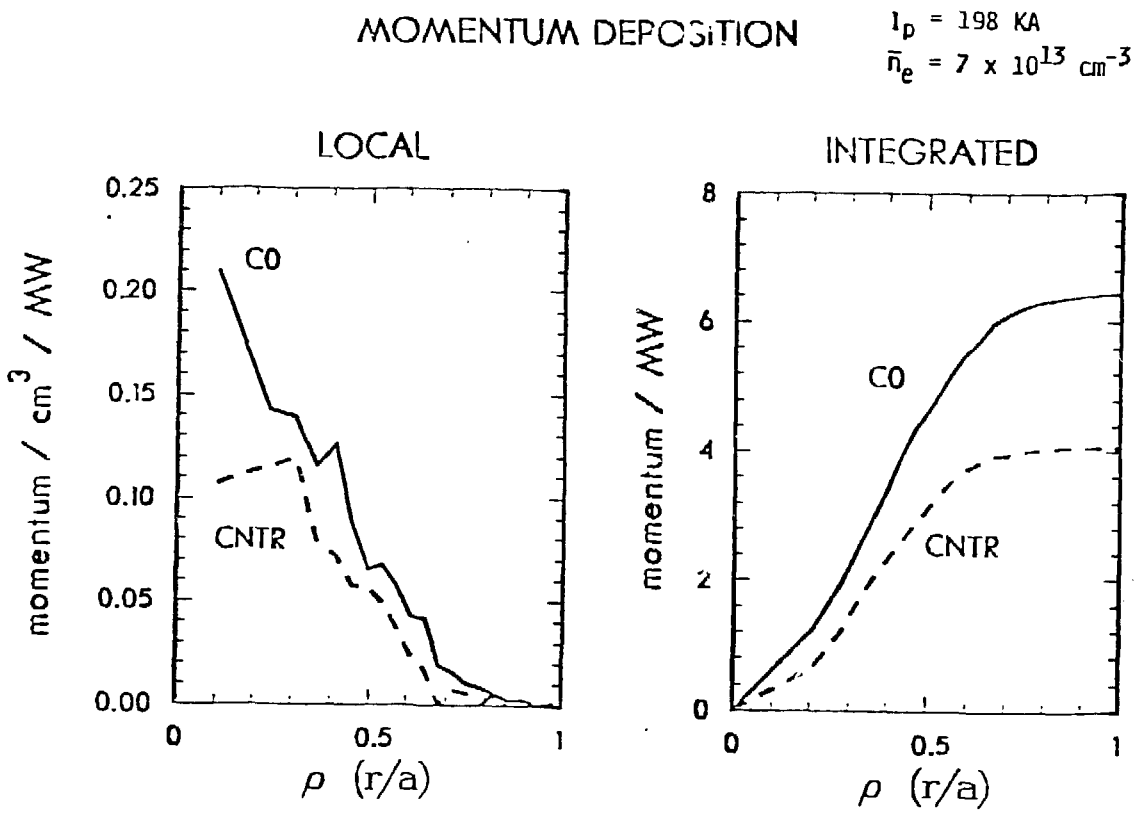
- THIS RESULT IS CONSISTENT WITH THEORETICAL EXPECTATIONS OF IMPROVED ION CONFINEMENT AT $V_\phi = 0$, BUT MORE EXPERIMENTAL STUDIES ARE REQUIRED TO MAKE THIS CONCLUSION DEFINITIVE.

FOKKER-PLANCK CALCULATIONS WITH BOUNCE-AVERAGED DEPOSITION ARE IN REASONABLE AGREEMENT WITH MONTE-CARLO CALCULATIONS WHICH SHOW A ~20% REDUCTION IN HEATING EFFICIENCY WITH A COUNTER BEAM.



	CO		CNTR	
	MC	FP	MC	FP
P_{bi}	0.40	0.32	0.27	0.25
P_{bc}	0.56	0.59	0.50	0.56
P_{fcx}	0.03	0.07	0.05	0.08
P_{lim}	0.02	0.02	0.18	0.11

MONTE-CARLO CALCULATION OF MOMENTUM DEPOSITIONS INDICATES ~40 % REDUCTION OF MOMENTUM INPUT FROM COUNTER BEAM AS COMPARED WITH CO BEAM.



- The elimination of plasma rotation observed with balanced injection indicates either

  - momentum transfer of counter-particles is more efficient than what is calculated in the classical calculation, <u>or</u>
  - overall momentum confinement deteriorates substantially with increasing beam power.

SUMMARY

1. INTRODUCTION OF A SMALL AMOUNT OF LOW-Z IMPURITY (EITHER BY NEON INJECTION OR "NONGETTERING") RESULTS IN:

   - SIGNIFICANT (UP TO A FACTOR OF 2) IMPROVEMENT OF τ_E
   - INTRODUCTION OF A LINEAR DENSITY DEPENDENCE IN ISX-B SCALING
   - REDUCED χ_e AND INCREASED P_{bi} WHICH ARE APPARENTLY LINKED TO CONFINEMENT IMPROVEMENT
   - REDUCTION OF EDGE TEMEPRATURE

2. ELIMINATION OF PLASMA ROTATION BY BALANCED INJECTION DOES NOT LEAD TO APPRECIABLE IMPROVEMENT OF <u>GLOBAL</u> ENERGY CONFINEMENT. HOWEVER, ROLES OF ROTATION IN ION CONFINEMENT ARE YET TO BE STUDIED.

3. THERE APPEAR TO BE LINKS AMONG ENERGY, MOMENTUM, AND PARTICLE CONFINEMENT.

4. TO IDENTIFY THE UNDERLYING MECHANISM DRIVING ENHANCED TRANSPORT, THE FUTURE ISX-B PROGRAM WILL EMPHASIZE STUDY OF CORRELATIONS AMONG CONFINEMENT, V_ϕ AND E_r USING A HIBP TO MEASURE $\phi(r,t)$.