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CONFINEMENT OF HIGH-DENSITY PELLET-FUELED DISCHARGES IN TFTR *

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INTRODUCTION: TFTR pellet injection results reported by Schmidt [1] have been extended to higher density and $n\tau$ in plasmas limited by a graphite inner-wall belt limiter. Increased pellet penetration and larger density increases were achieved by operation at reduced plasma current (1.6 MA), minor radius (70 cm), and major radius (235 cm). Under these conditions, beam heating results have been extended to 7 MW.

OHMIC RESULTS: The evolution of a typical discharge for a three-pellet ohmic sequence is shown in Fig. 1. Injection of each pellet (2.7 mm in diameter, 7×10^{20} D^0) is accompanied by a reduction in the central electron temperature and an increase in the surface voltage associated with the addition of cold fuel. The largest perturbation of the central plasma density is created by the third pellet, which penetrates beyond the magnetic axis and increases the line-averaged density to 1.4×10^{14} cm^{-3}. This corresponds to a Murakami parameter of 6.5×10^{15} cm$^{-2} \cdot$ T^{-1}, which represents the highest value attained on TFTR. This is more than a factor of two greater than the disruption limit for deuterium gas fueling, which was established during operation with the outer blade limiter. The high-density disruptions reported by Schmidt [1] are not observed in these experiments.

The plasma density profile immmediately following the third pellet is strongly peaked on axis, with the highest central value achieved approaching 4×10^{14} cm^{-3}. This profile shape is maintained in time as the density decays and the central electron temperature recovers. Sawtooth activity can be suppressed for ~1 s after the third pellet, suggesting a broadening of the current density profile. As shown in Fig. 2a, the plasma stored energy from the diamagnetic measurement increases after each pellet and appears to reach a plateau of ≈750 kJ, implying a gross energy confinement time of 0.4 s. This is in agreement with Goldston's empirical H-mode model [2] and lies within the saturated region. As shown in Fig. 2b, the plasma density profile is still highly peaked 0.35 s after the third pellet, with a central value of 2.7×10^{14} cm^{-3}, five times the central density of the gas-fueled case shown for comparison. When taken with the increased confinement time, this large central density yields a value of 1×10^{14} cm$^{-3} \cdot$s for the parameter $n_e(0)\tau_E(a)$.

Although the electron temperature for the pellet-fueled case is lower, the plasma pressure inside the half-radius is substantially larger than in the no-pellet case because

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of the high density. The electron temperature profiles exhibit similar shapes, but the flat region inside $r = 25$ cm in the pellet-fueled example is a consequence of higher radiation and not sawtooth activity. The power radiated from this region is comparable ($\gtrsim$50%) to estimates of the ohmic input power (≈ 0.25 W/cm^3 on axis) as determined from an equilibrium calculation that assumes a neoclassical resistivity model to match the resistive surface voltage. About 20–40% of the radiated power from this region can be accounted for as hydrogenic bremsstrahlung. We estimate a central $Z_{eff} \approx 1.5$. The principal impurities are chlorine (Z_{eff} contribution ≈ 0.04) and carbon and oxygen (Z_{eff} contribution ≈ 0.5).

NEUTRAL BEAM HEATING RESULTS: A comparison of ohmically heated and 7-MW neutral beam (80-kV $D^0 \rightarrow D^+$) injection results is shown in Fig. 3. A stored energy increase of ~300 kJ is achieved by the addition of auxiliary heating. This corresponds to a global energy confinement time of 0.13 s which is ≈30% higher than Goldston L-mode scaling [2]. Because beam penetration at this high density is poor, the central input power remains low (~ 2× ohmic). Under these conditions, although the fraction of total input power radiated is ≈35%, strong central radiation from carbon and oxygen (≥100% of local input power) produces a hollow temperature profile during neutral injection, and the confinement properties of the plasma core cannot be evaluated.

The confinement properties of 80-cm, 2.2-MA, beam-heated plasmas limited by the outer blade limiter [1] have been studied in detail using a one-dimensional time-dependent transport code, TRANSP. These discharges have beam power deposition profiles similar to those of the discharge in Fig. 3, but they are at lower density and do not exhibit such strong central radiation. Figure 4 compares the calculated power deposition profiles for gas-fueled and pellet-fueled discharges at 5.7 MW. In the pellet case, the beam power deposition is peaked off axis, with roughly 50% of the total power absorbed outside the $q = 2$ surface. The global confinement times and the temporal evolution of the plasma pressure profiles are comparable, suggesting a different radial dependence in the local energy confinement times. This is illustrated in Fig. 5a, where we compare values of $\tau_E(r)$ at 2.6 and 2.8 s (0.2 and 0.4 s after the last pellet and the start of beam heating). These findings are consistent with the results of off-axis heating experiments reported by Speth [3] and Goldston et al. at this conference. Accompanying the improvement in central confinement with pellet injection is a decrease in the electron thermal diffusivity, as shown in Fig. 5. At small radii ($r \approx 30$ cm), values of χ_e that are comparable to the neoclassical ion heat diffusivity are inferred.

SUMMARY: High-density plasmas with peak-to-average values greater than 2 have been produced by pellet injection in TFTR. In ohmically heated plasmas at [illegible].6 MA, $n\tau$ values of 1×10^{14} cm$^{-3}\cdot$s have been achieved. Neutral beam injection in these plasmas is characterized by strong edge heating, but global confinement does not deteriorate relative to central heating conditions.

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[3] E. Speth et al., p. 284 in *Proceedings of the 12th European Conference on Controlled Fusion and Plasma Physics, Budapest, Hungary, September 2-6, 1985: Contributed Papers*, Vol. II, European Physical Society, 1986.

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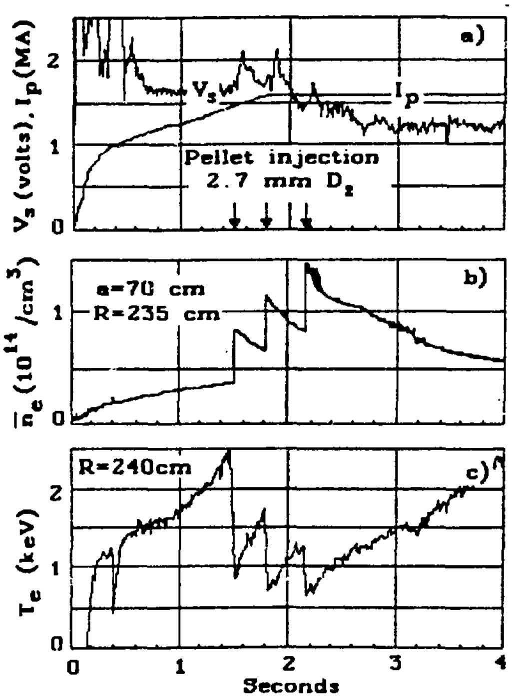

Fig. 1

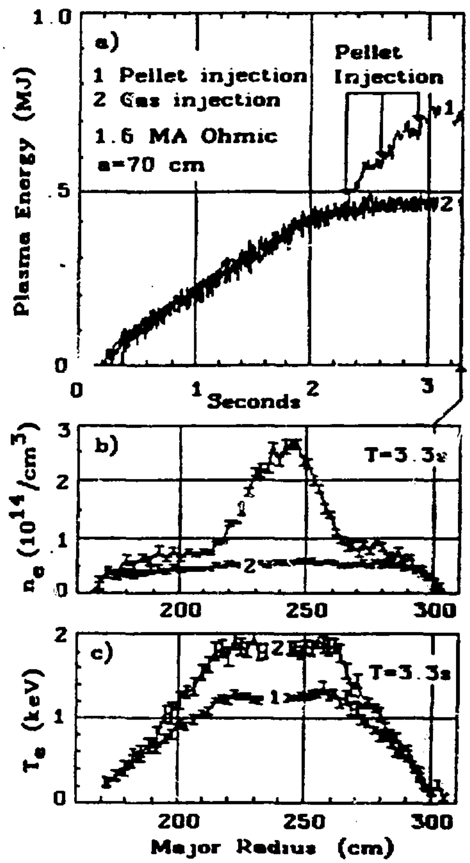

Fig. 2

Fig. 1. Injection of three pellets into an ohmic discharge, showing surface voltage V_s, plasma current I_p, line-averaged density $\bar{n}_e$, and central electron temperature T_e.

Fig. 2. Comparison of plasma stored energy and electron density and temperature profiles for pellet injection and gas fueling cases.

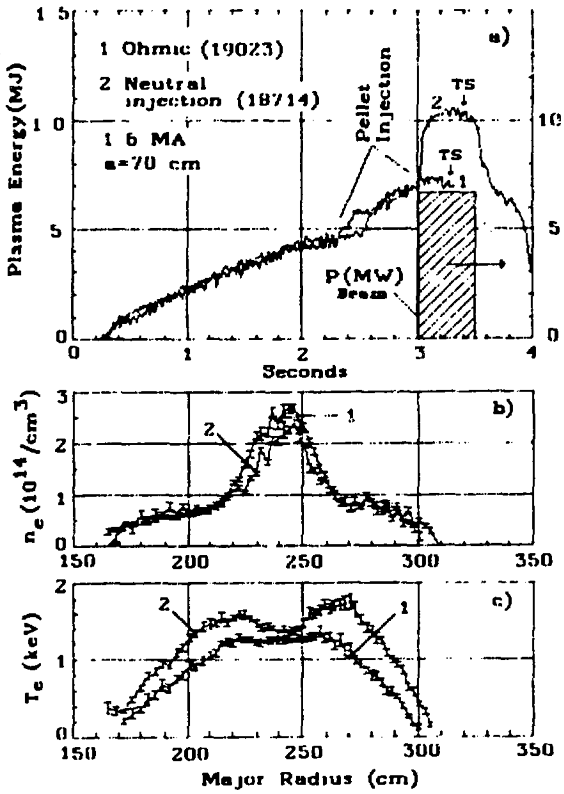

Fig. 3

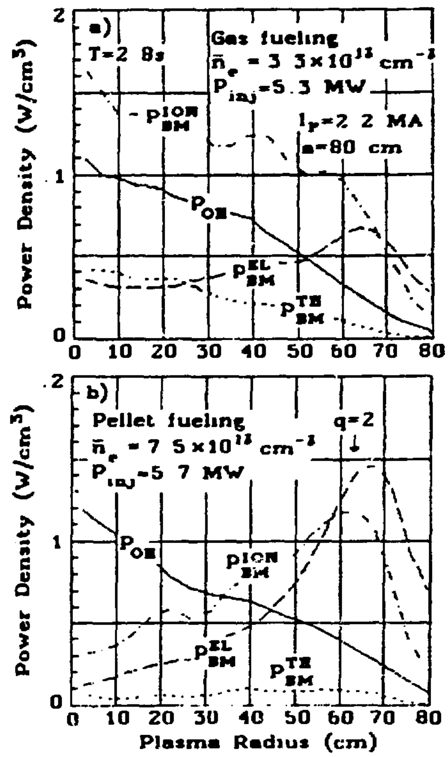

Fig. 4

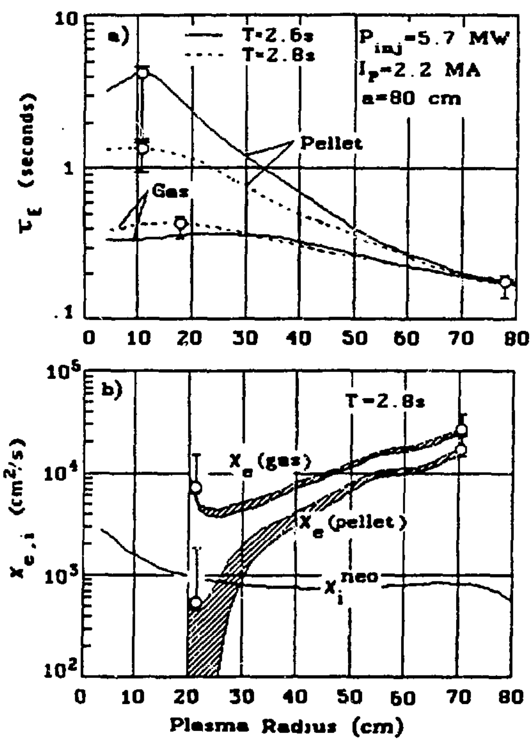

Fig. 5

Fig. 3. Comparison of plasma stored energy and Thomson scattering profiles for three pellet-fueled ohmic and neutral beam discharges. I_p = 1.6 MA, a = 70 cm.

Fig. 4. Power deposition profiles calculated by TRANSP for gas-fueled and pellet-fueled beam-heated discharges. P_{OH} = ohmic power, P^{ion}_{BM} = ion heating, P^{el}_{BM} = electron heating, P^{th}_{BM} = beam ion thermalization power.

Fig. 5. Comparison of radial profiles of energy confinement time and electron thermal diffusivity calculated from TRANSP for the cases shown in Fig. 4. Error bars represent uncertainties in the electron temperature measurement. The upper and lower limits of χ_e correspond to calculations based on ion heat conductivity values of 1 and 3 $\times$ neoclassical, respectively.

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Schliersee, Federal Republic of Germany

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- The present experiments are a continuation of the 1985 program as reported by Schmidt (EPS 1985)

- Objective: Extend TFTR physics data base to high density in ohmic and high power neutral beam heated plasmas (up to 27 MW)

- Present experiments use the ORNL Repeating Pneumatic Injector (RPI)
  - 2.7 mm D_2 pellets (7×10^{20} D°)
  - 4/s at 1300 m/s

- Future experiments (May 1986) will feature ORNL 8-shot injector
  - 4 mm, 3.5 mm, 3 mm
  - 1500 m/s

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PRESENT EXPERIMENTAL CONFIGURATION

- The present experiments differ from those reported by Schmidt (1985) in that:
  - Only 2.7 mm pellets are used as compared with 2.7 mm and 4 mm
  - The plasma is defined by full toroidal inner wall bumper limiter (graphite) as compared with outer blade limiter
  - I_p, a, R reduced to 1.6 MA, 70 cm, 235 cm from 2.2 MA, 80 cm, 258 cm to achieve larger density perturbations and deeper pellet penetration for 2.7 mm pellets
  - Beam power extended to 7 MW

- Results of modifications:
  - Pellets reach magnetic axis in OH discharges
  - $\bar{n}_e$ increased from 7×10^{13} to 1.4×10^{14} cm^{-3}
  - $n\tau$ increases from 6×10^{13} to 1×10^{14} s cm^{-3} in OH plasmas

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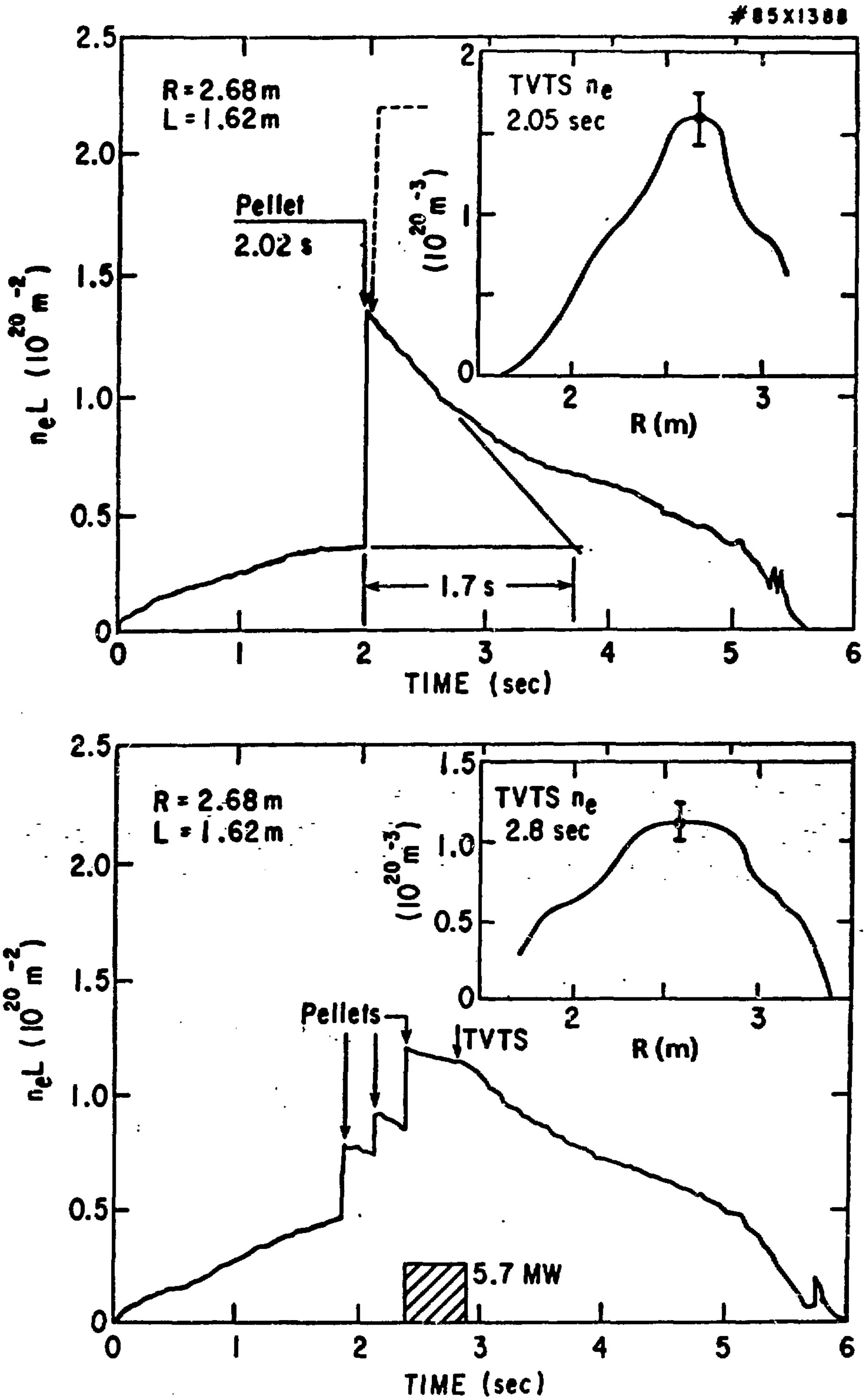
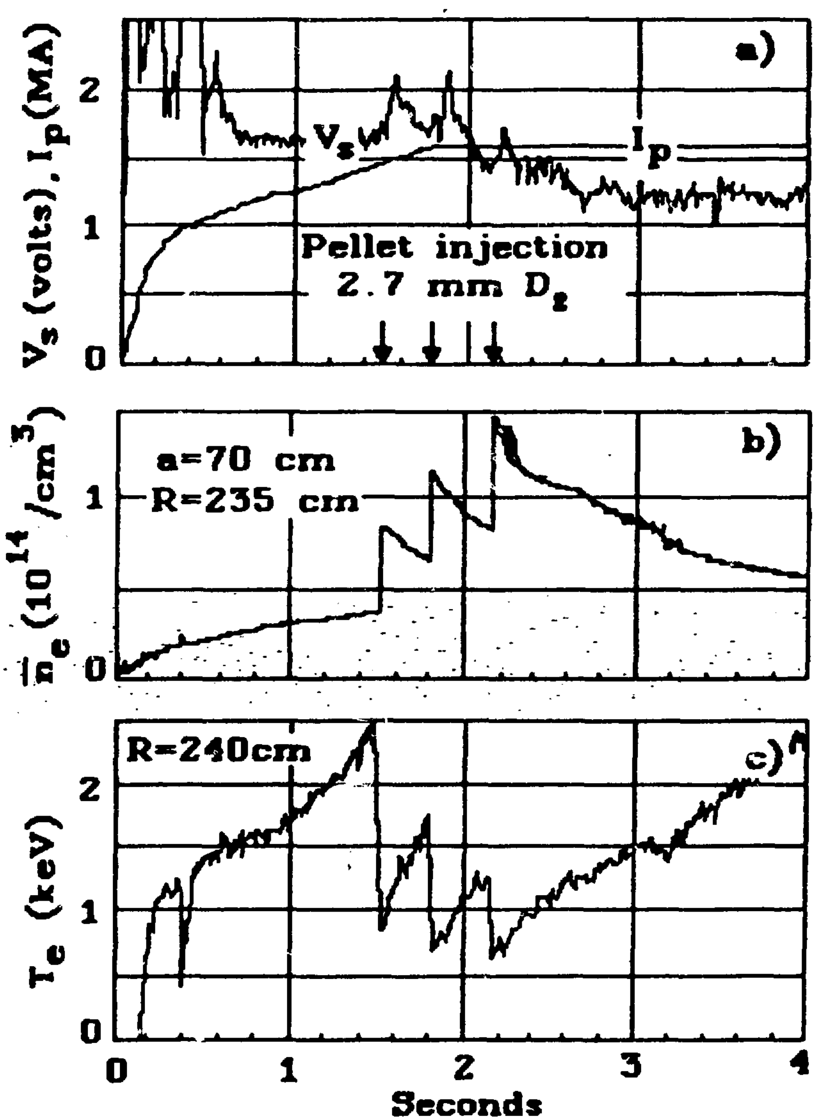
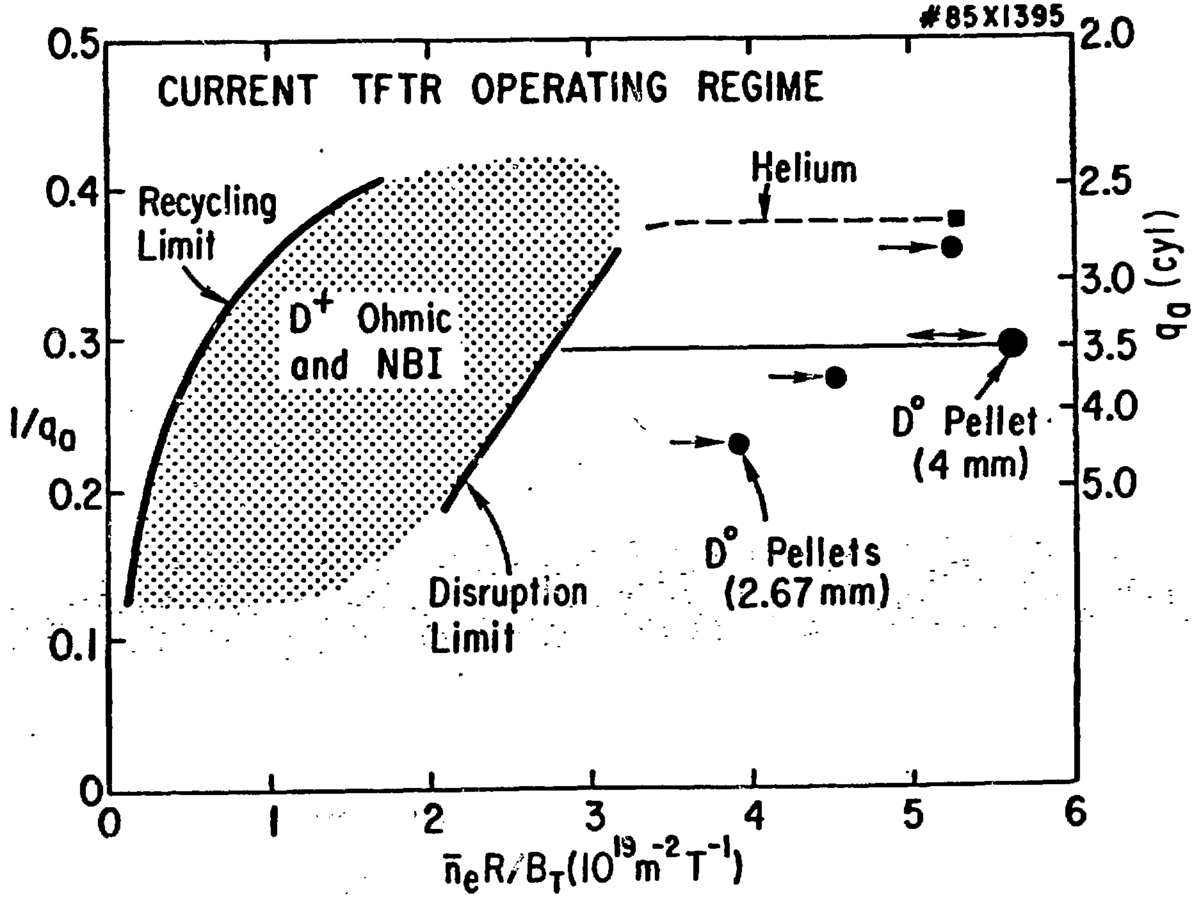


April 1985 Results



a)
V_s
I_p
Pellet injection
2.7 mm D_2
V_s (volts), I_p (MA)
b)
a=70 cm
R=235 cm
$\bar{n}_e$ (10^{14}/cm^3)
c)
R=240cm
T_e (keV)
Seconds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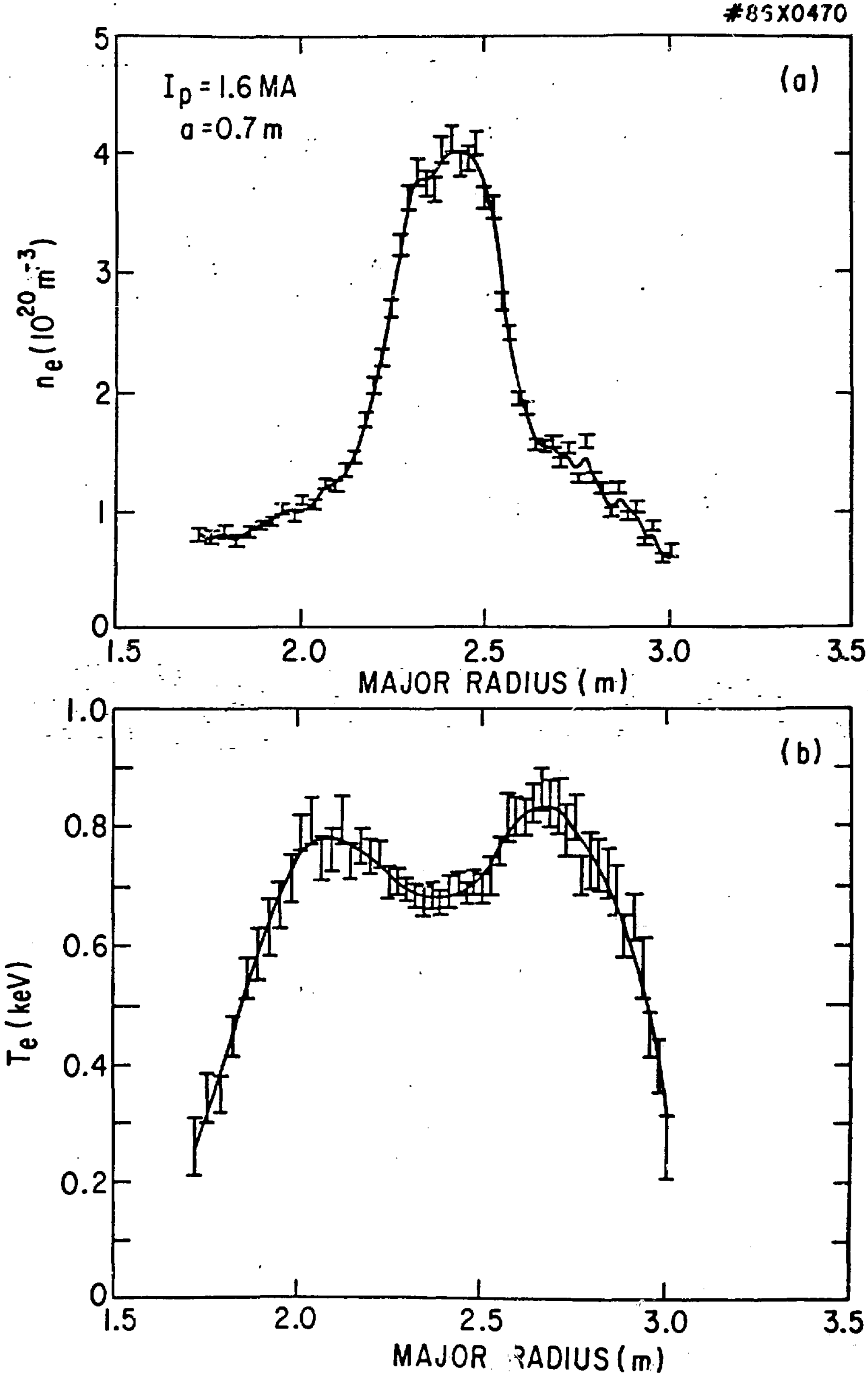
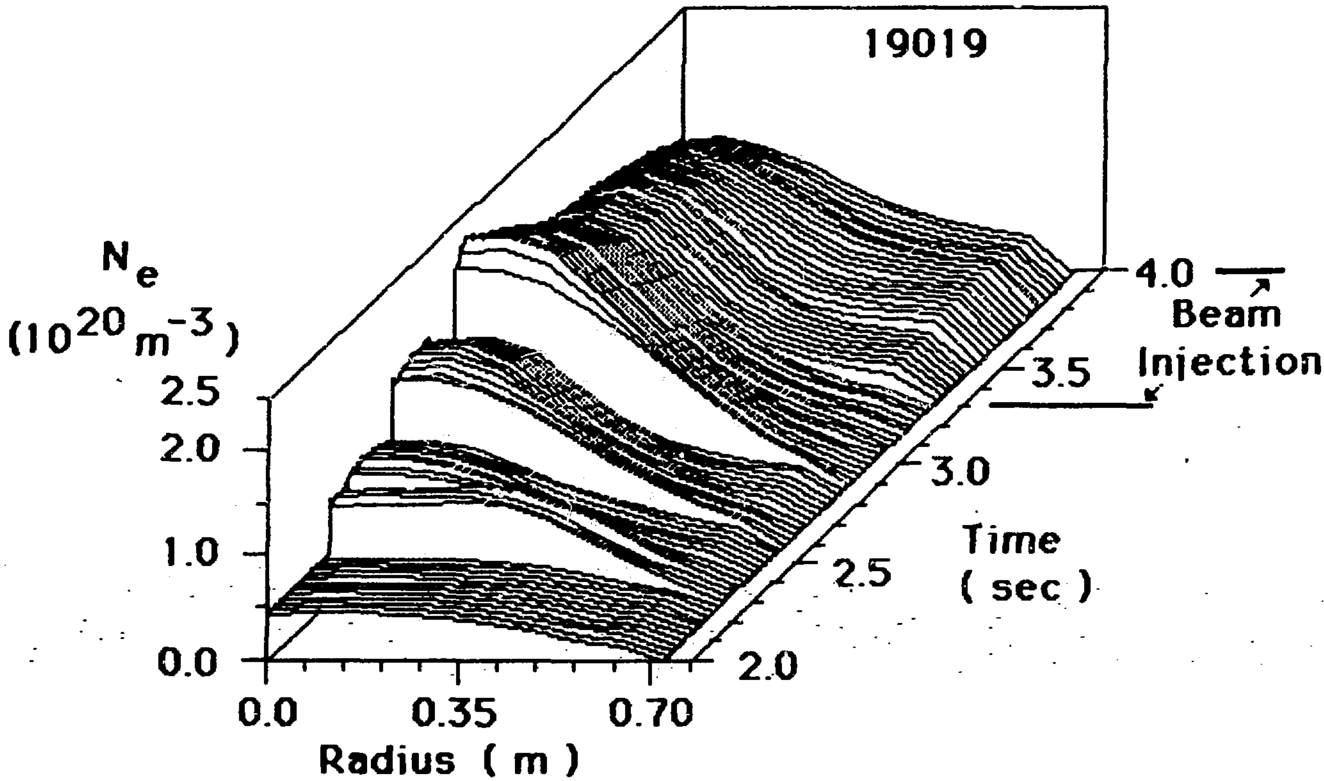
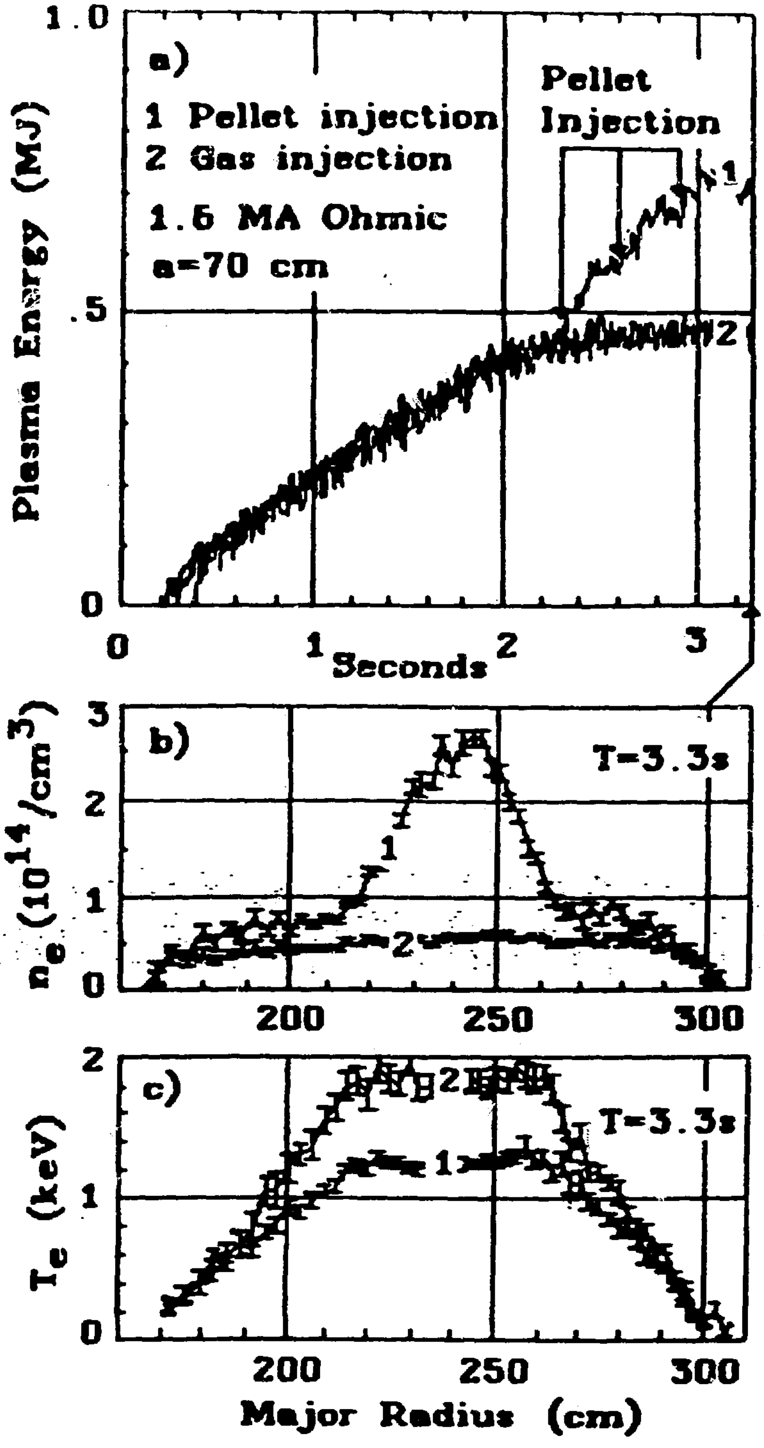
CURRENT TFTR OPERATING REGIME
Recycling Limit
D+ Ohmic and NBI
Helium
Disruption Limit
D° Pellets (2.67 mm)
D° Pellet (4 mm)
1/qa
qa (cyl)
0.5
0.4
0.3
0.2
0.1
0
2.0
2.5
3.0
3.5
4.0
5.0
0
1
2
3
4
5
6
n̄eR/BT(10^19 m^-2 T^-1)

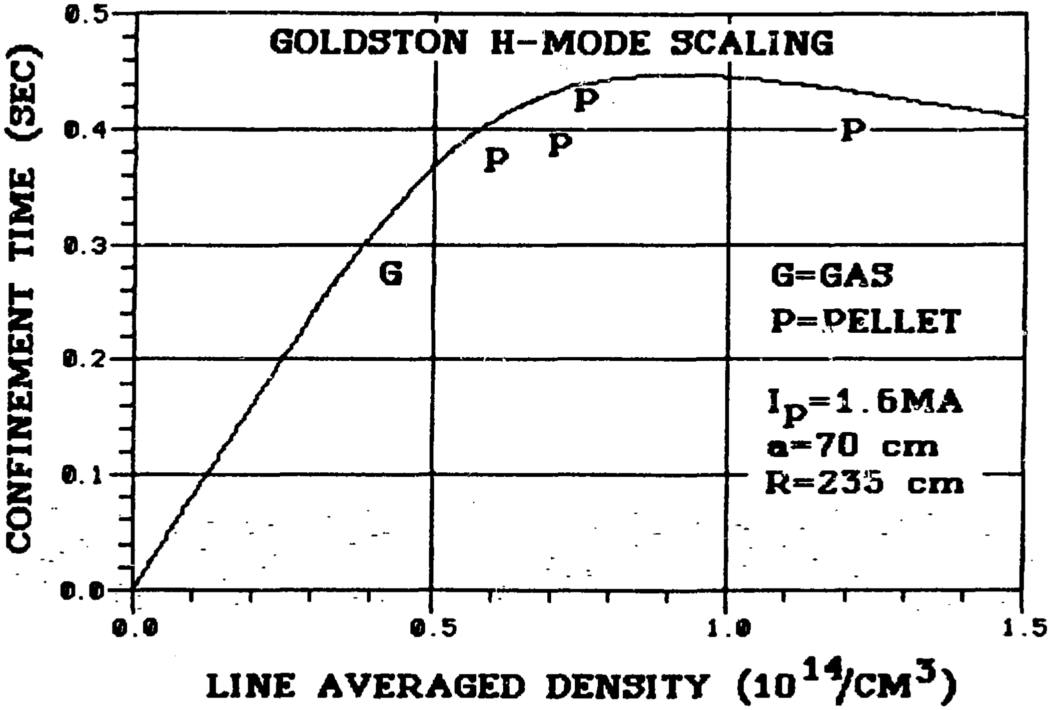


- Immediately after the third pellet
  -- calibration uncertainties ≈ 10% in $n_e(r)$


19019
N_e
$(10^{20} m^{-3})$
2.5
2.0
1.0
0.0
0.0
0.35
0.70
Radius (m)
2.0
2.5
3.0
3.5
4.0
Time
(sec)
Beam
Injection



At 3.3 s, $n_e(o)\tau_E = 1 \times 10^{14}\ cm^{-3}\ s$


GOLDSTON H-MODE SCALING
CONFINEMENT TIME (SEC)
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
LINE AVERAGED DENSITY (10^{14}/CM^3)
G
P
P
P
P
G=GAS
P=PELLET
I_p=1.6MA
a=70 cm
R=235 cm

HIGH DENSITY OHMIC CONFINEMENT RESULTS

- At 1.6 MA (P_{OH} = 1.6 – 1.8 MW) and $\bar{n}_e = 1.2 \times 10^{14} cm^{-3}$, $\tau_E(a) = 0.4$ seconds in agreement with Goldston H-mode scaling and is consistent with previous TFTR results in the saturated region at highest $\bar{n}_e q R^2 a$.

- Central electron temperature is limited to 1.3 keV at highest densities [$n_e(o) > 2.7 \times 10^{14}/cm^3$] by $P_{rad} \approx P_{oh}$ (on axis) = 0.25 W/cm^3

- P_{rad} from central core:

    - ~ 20 – 40 % from hydrogenic bremsstrahlung

    - Remainder from Cl, C, O giving central $Z_{eff} = 1.5$

- Because of $n_e(o)/\bar{n}_e > 2$, $n\tau = 1 \times 10^{14} cm^{-3} s$ has been achieved

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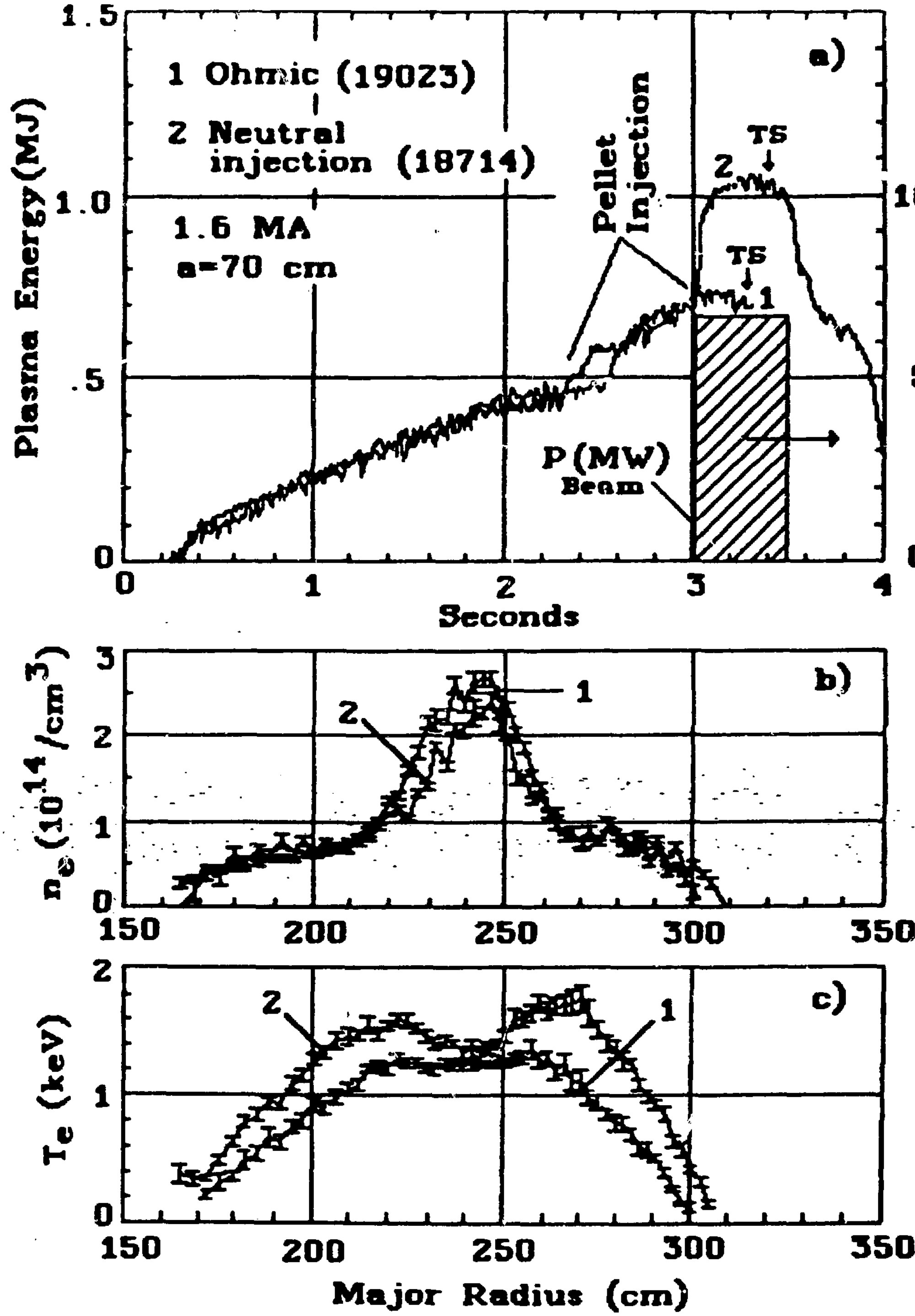

a)
1 Ohmic (19023)
2 Neutral injection (18714)
1.6 MA
a=70 cm
Pellet Injection
TS
P (MW) Beam
Plasma Energy (MJ)
Seconds
b)
n_e (10^{14}/cm^3)
c)
T_e (keV)
Major Radius (cm)

Latest Neutral Beam Heating Results

- At $P_{aux} = 7$ MW and $\bar{n}_e = 1.2 \times 10^{14}$, $\tau_e(a) = 0.13$ s in agreement with Goldston L-mode scaling correctedfor $D^\circ \rightarrow D^+$ (this meeting).

- At these high $\bar{n}_e$ beam penetration is poor, (central plasma core is predominantly ohmically heated) and P_{rad} (central) > P_{input} (central) from low Z impurities.

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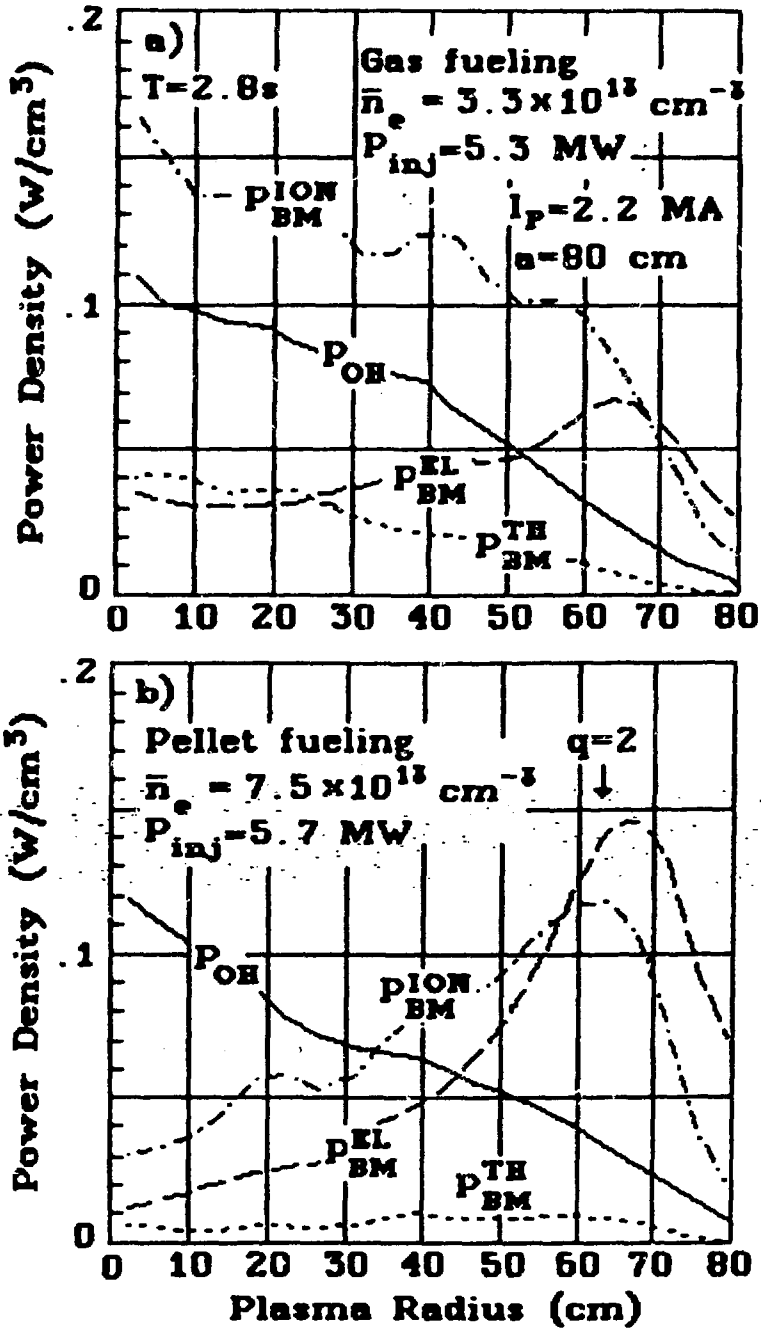
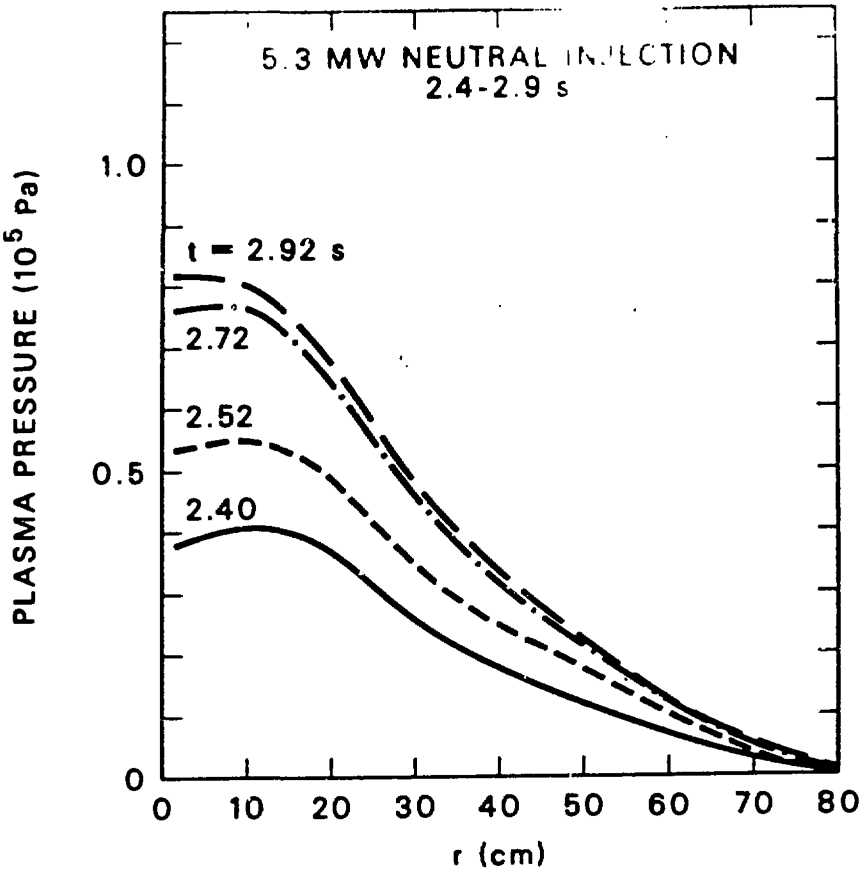
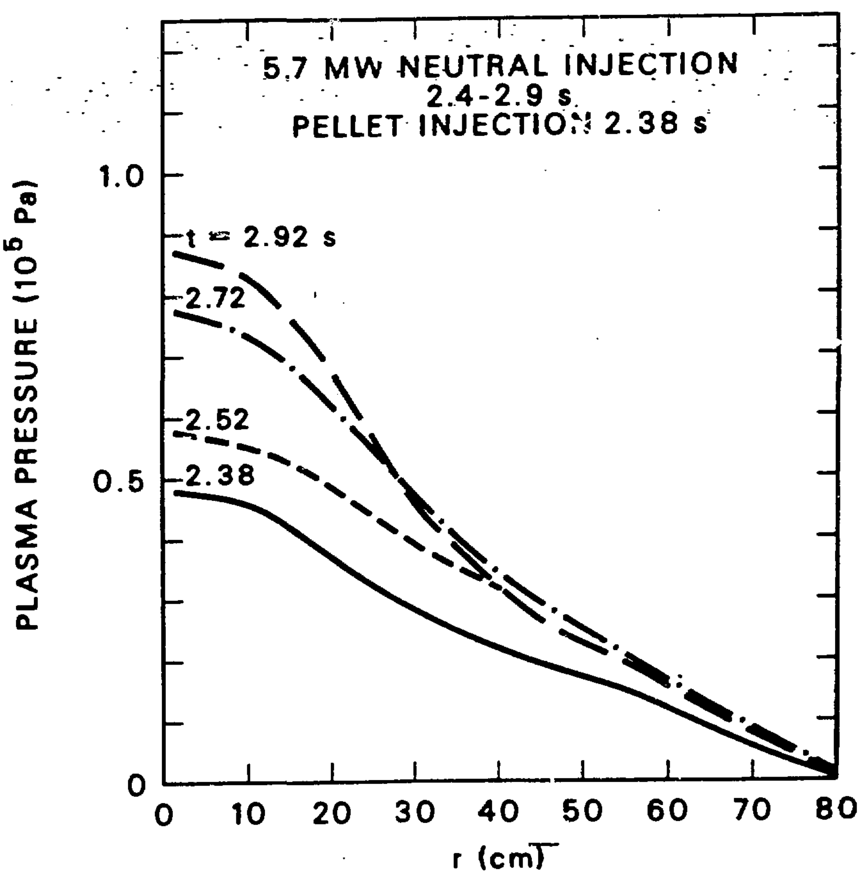
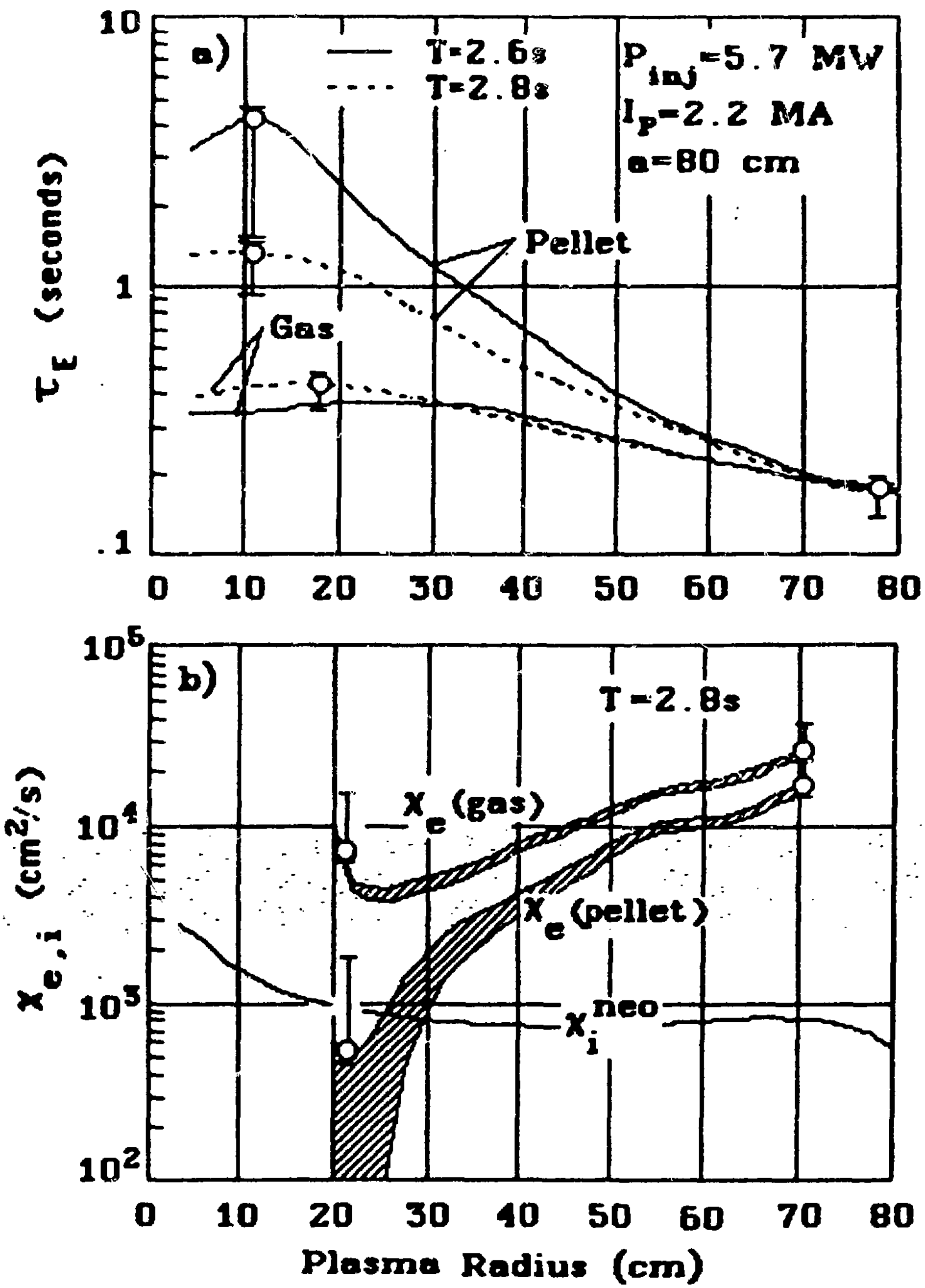


a)
T=2.8s
Gas fueling
$\bar{n}_e$ = 3.3×10^13 cm^-3
P_{inj}=5.3 MW
I_p=2.2 MA
a=80 cm
P_{BM}^{ION}
P_{OH}
P_{BM}^{EL}
P_{BM}^{TH}
b)
Pellet fueling
$\bar{n}_e$ = 7.5×10^13 cm^-3
P_{inj}=5.7 MW
q=2
Power Density (W/cm^3)
Plasma Radius (cm)


5.3 MW NEUTRAL INJECTION
2.4-2.9 s
PLASMA PRESSURE (10^5 Pa)
1.0
0.5
0
t = 2.92 s
2.72
2.52
2.40
0
10
20
30
40
50
60
70
80
r (cm)


5.7 MW NEUTRAL INJECTION
2.4-2.9 s
PELLET INJECTION 2.38 s
PLASMA PRESSURE (10^5 Pa)
1.0
0.5
0
t = 2.92 s
2.72
2.52
2.38
0
10
20
30
40
50
60
70
80
r (cm)



a)
T=2.6s
T=2.8s
P_{inj}=5.7 MW
I_p=2.2 MA
a=80 cm
Pellet
Gas
τ_E (seconds)
10
1
.1
0 10 20 30 40 50 60 70 80
b)
T=2.8s
χ_e(gas)
χ_e(pellet)
χ_i^{neo}
$\chi_{e,i}$ (cm^2/s)
10^5
10^4
10^3
10^2
0 10 20 30 40 50 60 70 80
Plasma Radius (cm)

CONCLUSIONS

- With deep pellet penetration in ohmic plasmas, high density discharges [$\bar{n}_e(o) \sim 4 \times 10^{14} cm^{-3}$] with peak-to-average values >2 have been produced on TFTR

- $n\tau = 1 \times 10^{14} cm^{-3}$ s has been achieved at 1.6 MA in 70 cm plasmas

- Beam heating at high density is characterized by strong edge heating and low power on axis. Even so, global confinement does not degrade relative to central heating results implying improved central confinement

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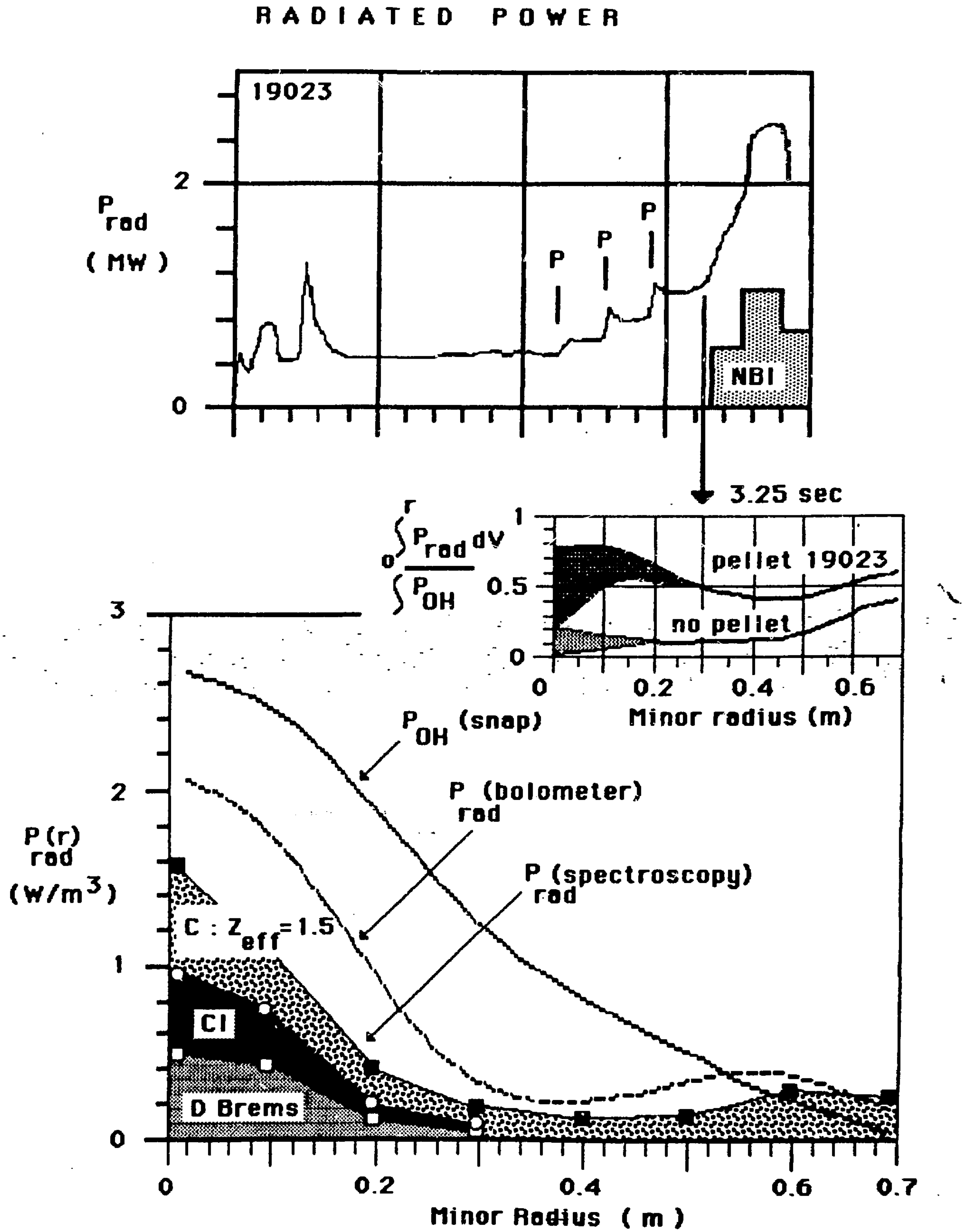
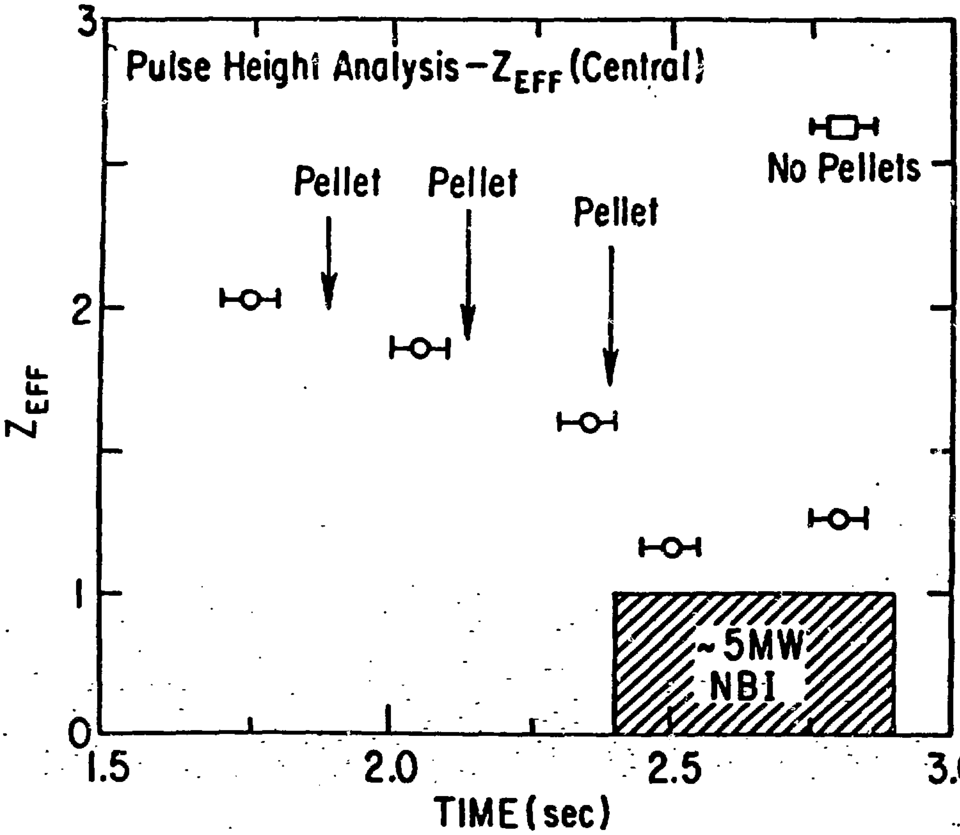
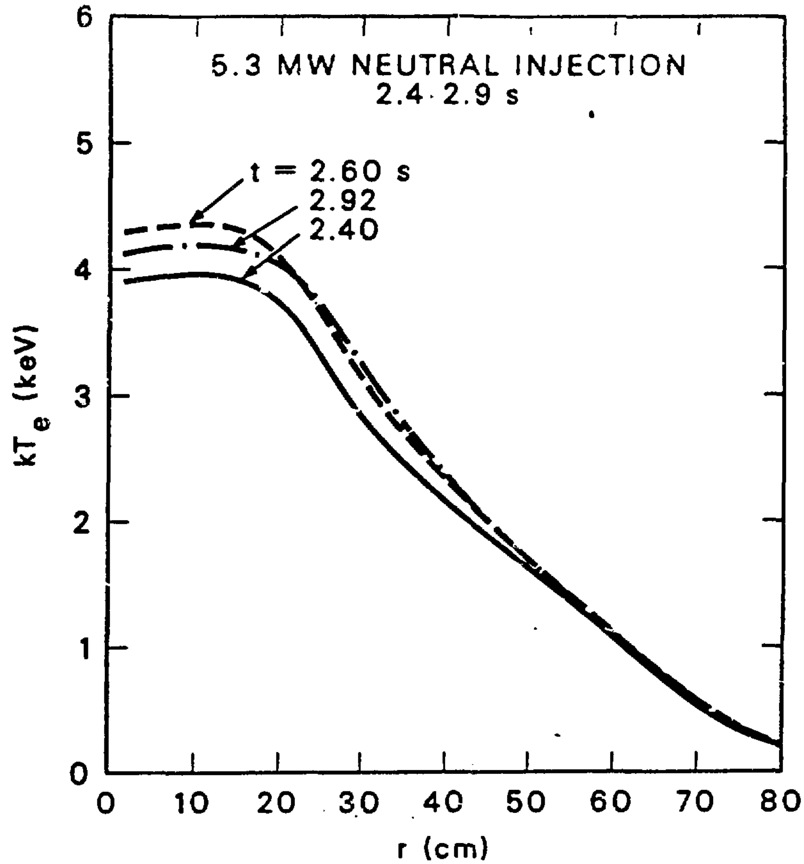


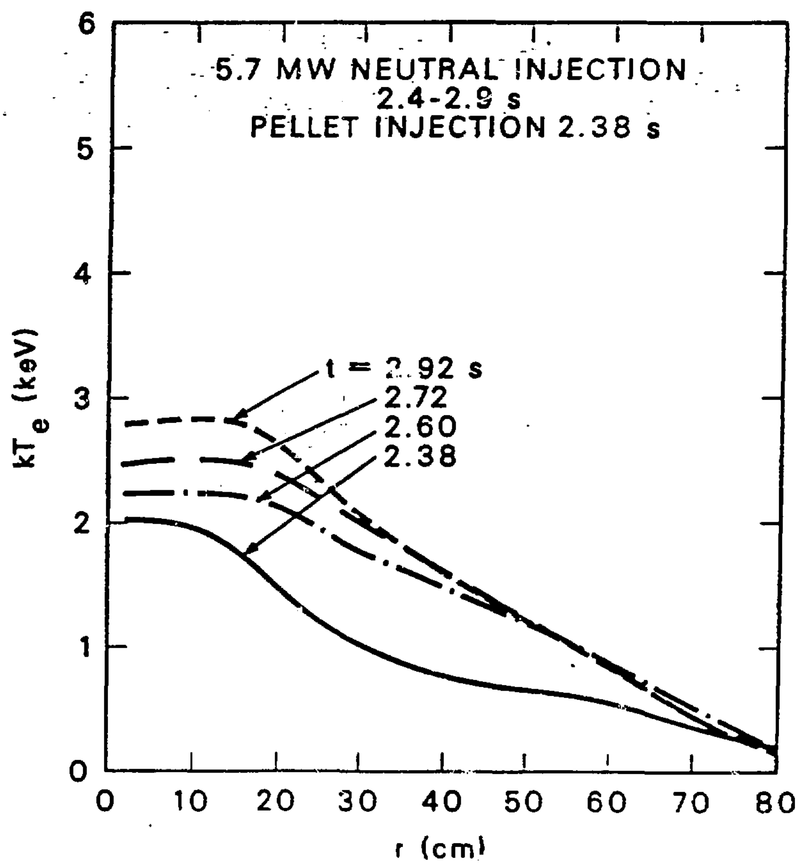
RADIATED POWER
19023
P rad (MW)
2
0
P
P
P
NBI
3.25 sec
pellet 19023
no pellet
1
0.5
0
0.2
0.4
0.6
Minor radius (m)
P OH (snap)
P rad (bolometer)
P rad (spectroscopy)
P(r) rad (W/m3)
C : Zeff=1.5
CI
D Brems
3
2
1
0
0.2
0.4
0.6
0.7
Minor Radius (m)

#85X1401



2.8 sec	Pellets	No Pellets
n_e	10	$5.7 \times 10^{19} m^{-3}$
n_{Ni}	0.3	$2 \times 10^{16} m^{-3}$
n_{C+O}	0.6	$1.9 \times 10^{18} m^{-3}$
Z_{EFF}^{METAL}	0.03	0.37


5.3 MW NEUTRAL INJECTION
2.4-2.9 s
t = 2.60 s
2.92
2.40
kTe (keV)
r (cm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80


5.7 MW NEUTRAL INJECTION
2.4-2.9 s
PELLET INJECTION 2.38 s
t = 2.92 s
2.72
2.60
2.38
kTe (keV)
r (cm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80