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PELLET ABLATION AND TRANSPORT STUDIES

MASTER

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CIT-ITER Plasma Fueling Workshop

Oak Ridge, TN

January 27-28, 1988

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FUELING GOALS

Fueling efficiency:

- Get fuel past the scrape-off and poor confinement plasma edge region
- Can be satisfied by pellet injection of nominal 1.5 km/s in CIT and ITER
- Pellet fueling efficiency with present technology should be a factor of 2-3 better than gas fueling in CIT and ITER

Density profile control:

- Penetration of fuel as deep as possible to maximize profile control
- Requires very high velocity pellets or alternate fueling techniques
- Improvements in confinement and control capabilities are difficult to quantify but potentially large

FUELING ISSUES

Minimize tritium injected into torus:

- Delay T injection until just prior to auxiliary heating
- Utilize T pellet injection to maximize T particle confinement

Sustain centrally peaked density profiles:

- Enhanced fusion rate and ignition margin
- Possibly enhanced energy confinement
- Pellet penetration as deep as possible
- Competition between diffusive and pinch terms
- Possible deleterious role of locked modes

Pellet injector technology:

- Minimize T consumption and inventory in gun(s)
- Maximize reliability
- Baseline injector: current technology for pellet size, velocity, and repetition rate (TFTR and JET)
- Exploratory injector: few pellets at high velocity for burn phase

PELLET ABLATION AND CONFINEMENT ISSUES

Pellet ablation:

- Electron ablation in Ohmic plasmas
- Fast ion ablation in NBI plasmas
- Fast ion ablation in ICRH plasmas

Confinement:

- $\bar{n}$ and Δn limits in Ohmic, NBI, and ICRH plasmas
- Density profile response after pellet injection
- Temperature profile response after pellet injection
- Particle accountibility
- Influence of pellet injection on τ_E
- Influence of pellet injection on τ_p
- Outer limiter vs inside wall vs X-point operation
- Influence of penetration depth on plasma response
- Influence of pellet size on plasma response

PELLET ABLATION AND PENETRATION

Neutral gas and plasma shielding model:

- Dense, spherical neutral gas layer surrounding pellet provides primary shielding
- Dense plasma extending along the magnetic field provides additional shielding
- Maxwellian distribution of electrons and slowing-down distribution of alphas and beam ions incident from the plasma

Fast ion and alpha effects:

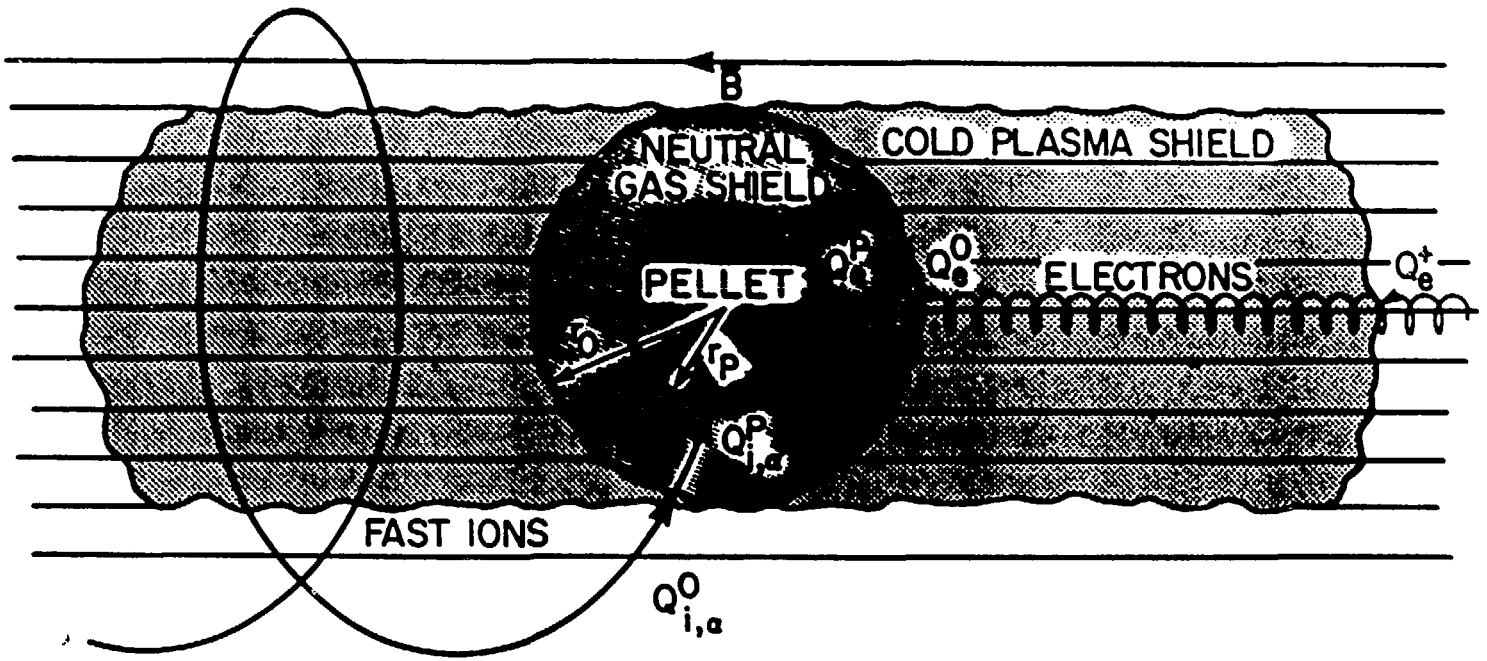
- Fast ions from ICRH heating probably not important when resonance zone is near the plasma center
- Fast alphas should be unimportant since ehield established by the electrons should stop 3.5 MeV alphas

References:

- W. A. Houlberg, S. L. Milora, and S. E. Attenberger "Neutral and Plasma Shielding Model for Pellet Ablation," ORNL/TM-10556, to be published in *Nuclear Fusion*
- M. L. Watkins, W. A. Houlberg, A. D. Cheetham, et al., "A Model for Pellet Ablation in JET," 14th EPS, Madrid, p. 201.

NEUTRAL GAS AND COLD PLASMA SHIELDING

ORNL-DWG 87-2260 FED



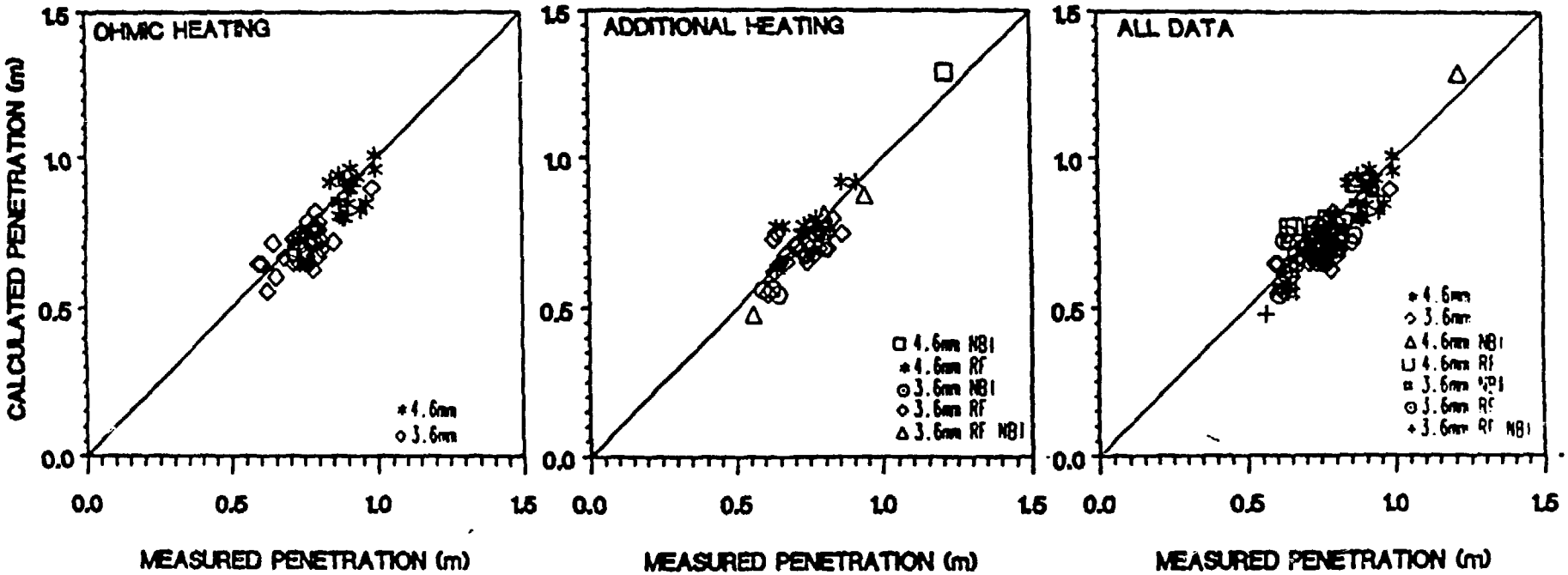
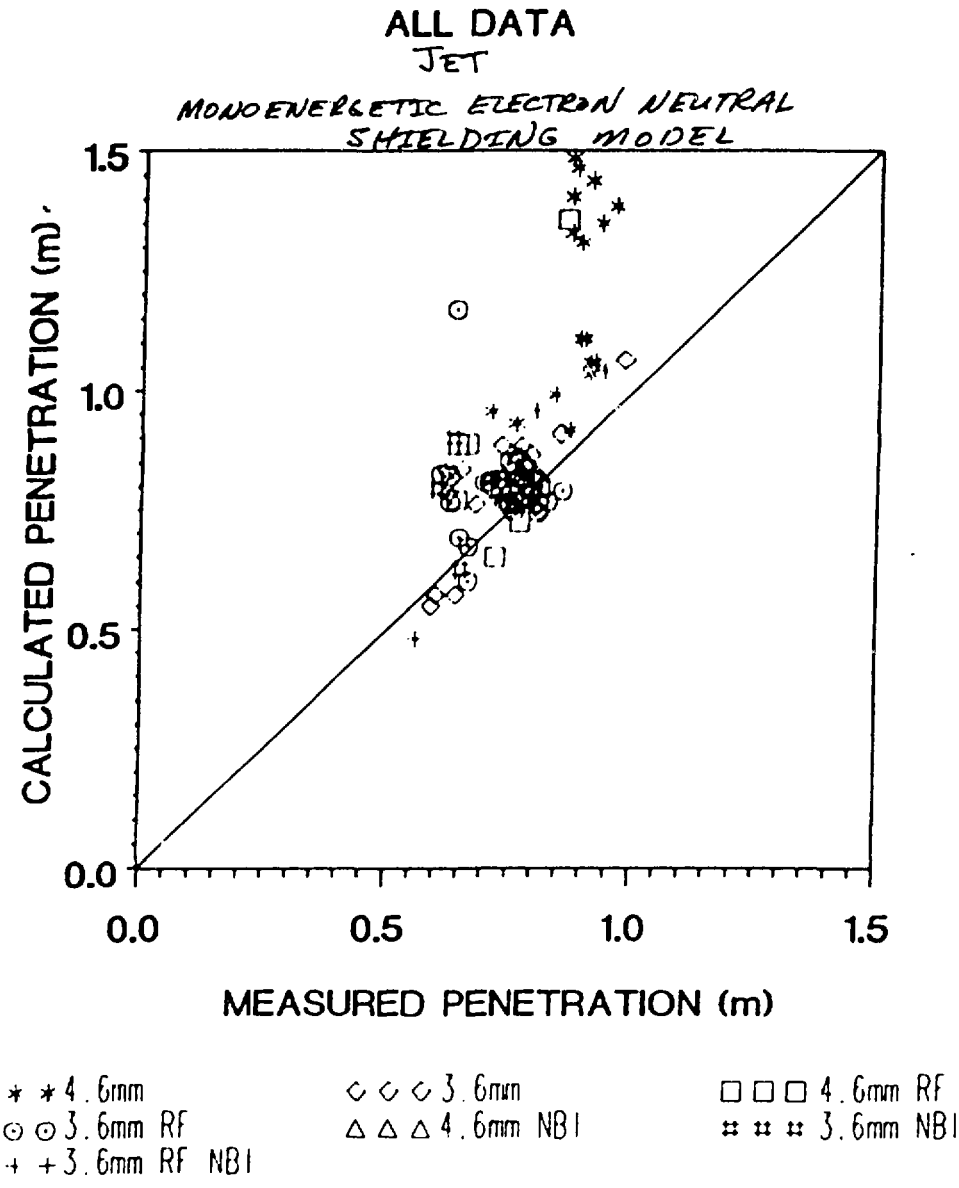

OHMIC HEATING
ADDITIONAL HEATING
ALL DATA
CALCULATED PENETRATION (m)
MEASURED PENETRATION (m)
MEASURED PENETRATION (m)
MEASURED PENETRATION (m)
0.0
0.5
1.0
1.5
4.6mm
3.6mm
4.6mm NBI
4.6mm RF
3.6mm NBI
3.6mm RF
3.6mm RF NBI

Figure 7


ALL DATA
JET
MONOENERGETIC ELECTRON NEUTRAL SHIELDING MODEL
CALCULATED PENETRATION (m)
MEASURED PENETRATION (m)
0.0
0.5
1.0
1.5
S
4.6mm
3.6mm RF
3.6mm RF NBI
3.6mm
4.6mm NBI
4.6mm RF
3.6mm NBI

FAST ION ANALYSIS PROCEDURE

Fast ions impact pellet ablation if two conditions are met:

- Critical Energy: the shield established by the electrons is insufficient to stop the fast ions
- Critical Power: the fast ion energy flux at the pellet surface is larger than the electron energy flux

Evaluate the Critical Energy:

- Assume the neutral shield is dominant
- Compare the line-integrated density required to stop electrons in the tail of the Maxwellian plasma distribution with that required to stop fast ions at their birth energy

Evaluate the Critical Power:

- Assume a typical shielding factor for electrons and assume that the fast ions are unshielded
- Compare the unshielded fast ion energy flux with the shielded electron energy flux at the pellet surface

CRITICAL CONDITIONS FOR ALPHAS

From the condition that neutral shield established by the electrons is not large enough to stop alphas at their birth energy, we find a condition on the local T_e for alpha ablation

$$\int n^o dl\Big|_{ec} \leq \int n^o dl\Big|_{\alpha c}$$

$$\Rightarrow T_e(r) \leq 4.7\,\mathrm{keV}$$

A second temperature constraint comes from comparing the unshielded fast alpha energy flux at the pellet surface to the shielded electron energy flux:

$$Q_\alpha^p \approx Q_\alpha^+ \geq Q_e^p = f_e Q_e^+$$

$$\Rightarrow \langle \sigma v \rangle_{DT} \geq 9.5 \times 10^{-21} f_e\,\mathrm{m}^3/\mathrm{s}$$

which cannot be satisfied for $T_e \approx T_i \leq 4.7\,\mathrm{keV}$ unless $f_e \leq 1.0 \times 10^{-3}$. This is not usually the case at these temperatures

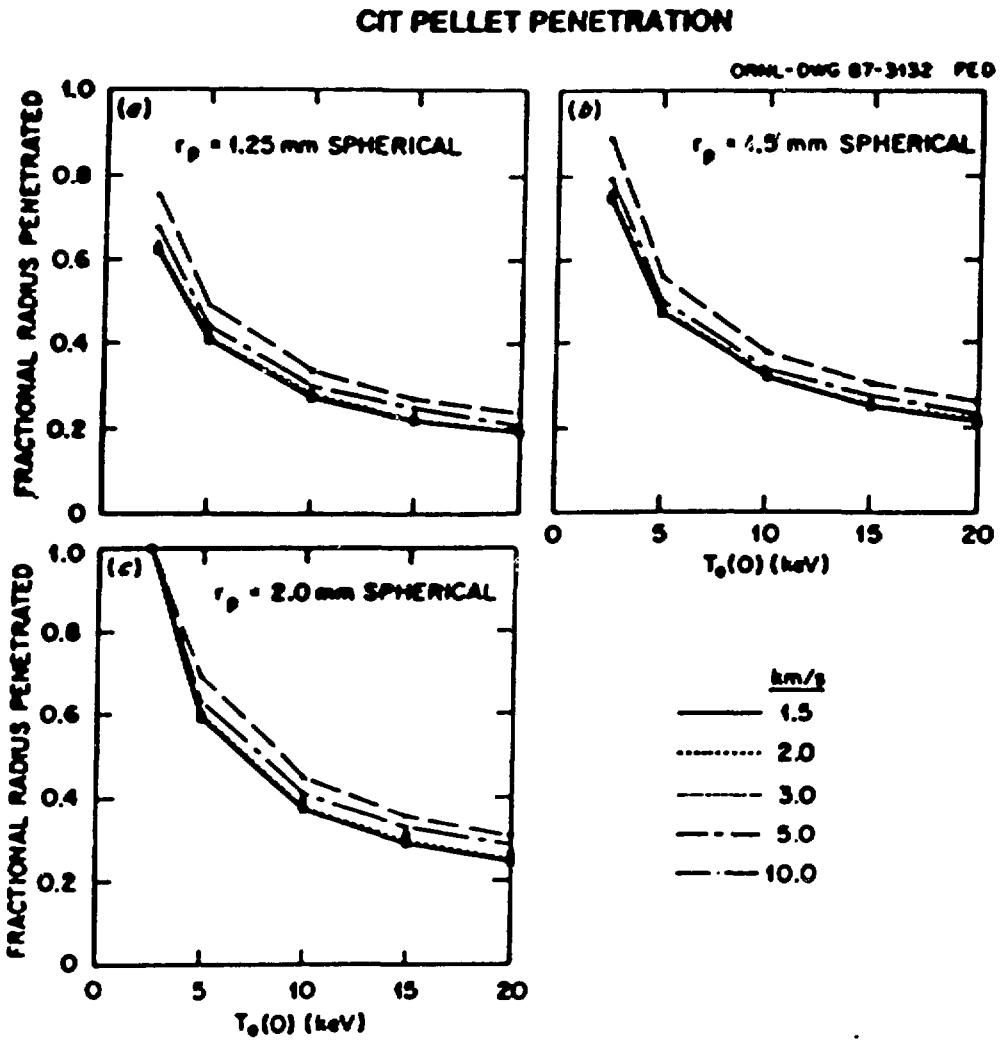
JET, CIT, AND ITER

Machine Parameters

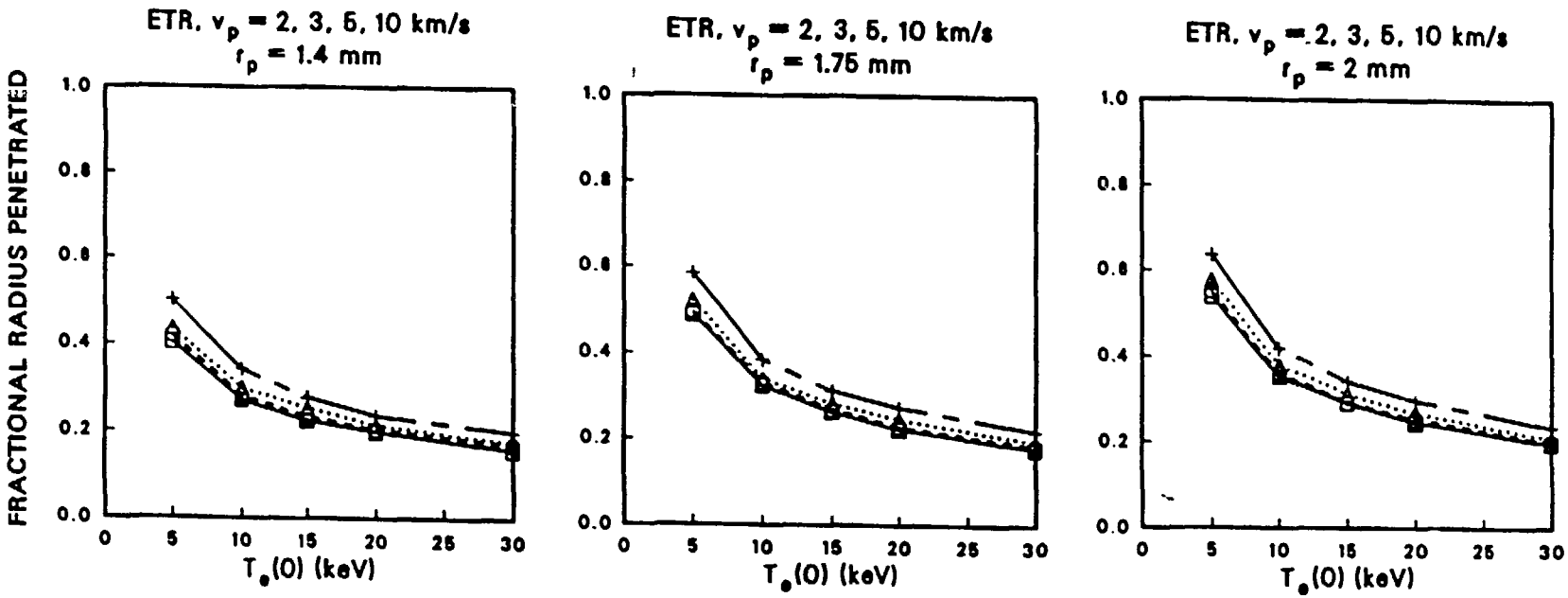
Parameters	JET	CIT	ITER
R_o (m)	2.96	1.75	3.0
a_o (m)	1.20	0.55	0.834
κ	1.8	1.8	2.2
B_{To} (T)	3.4	9.0	6.0
I_o (MA)	7.0	9.0	10.0
Calculated Parameters			
$< n_{\mathrm{Mu}} > (10^{20}\,\mathrm{m}^{-3})$	0.6	3.1	1.2
V_p (m^3)	151.4	21.6	90.6
N_{Mu} (10^{20})	90.8	67.0	108.7

Pellet Sizes and
Fraction of Murakami Density Limit

Spherical Radius	N_p		%	
r_p (mm)	10^{20}	JET	CIT	ITER
1.2	4.6	5.1		
1.25	5.2		7.8	
1.4	7.2			6.6
1.5	8.9		13.3	
1.75	14.2			13.1
2.0	21.0	23.1	34.5	19.3
3.0	70.9	78.1		



- Good penetration for all pellets in Ohmic plasmas
- Weak velocity dependence for $v_p > 1.5\,\mathrm{km/s}$


ETR, v_p = 2, 3, 5, 10 km/s
r_p = 1.4 mm
ETR, v_p = 2, 3, 5, 10 km/s
r_p = 1.75 mm
ETR, v_p = 2, 3, 5, 10 km/s
r_p = 2 mm
FRACTIONAL RADIUS PENETRATED
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
$T_e(0)$ (keV)

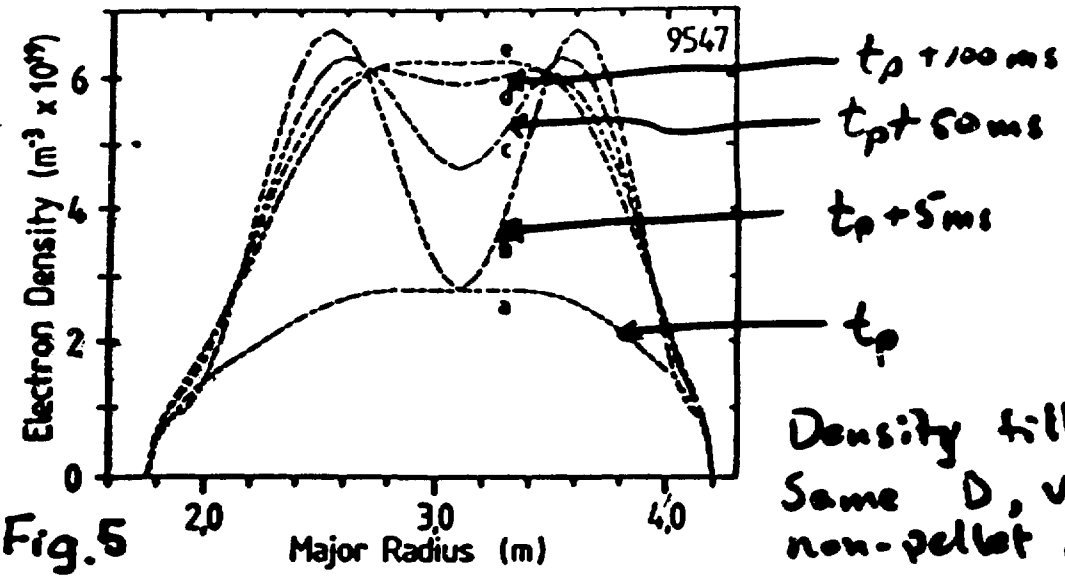
PARTICLE CONFINEMENT

Present models:

- Include Ware pinch and modest anomalous pinch that leads to $n(r) \approx n_o[1 - (r/a)^2]^{1/2}$ under conditions of gas fueling
- Scale anomalous particle losses the same as anomalous energy losses

Further study:

- Improve particle transport models (diffusive and pinch terms): scaling under H- and L-Mode conditions
- Understand the role of locked modes in particle confinement and means of avoidance



Density filling
Same D, v_p as
non-pellet data

Fig.5

Evolution of the electron density profile immediatly after pellet injection (a) at t=0, (b) at 8 ms, (c) at 50 ms, (d) at 100 ms, (e) at 200 ms.

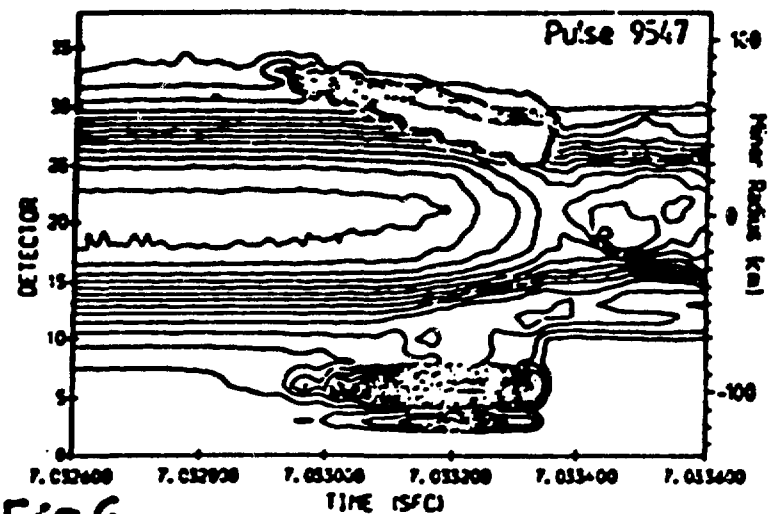


Fig 6

Contour plot of soft xray flux looking vertically down through the plasma from immediately above the pellet path.

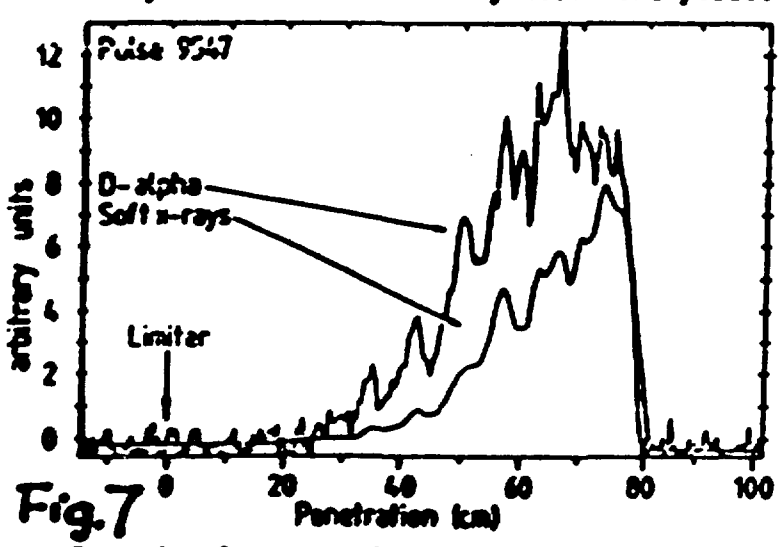
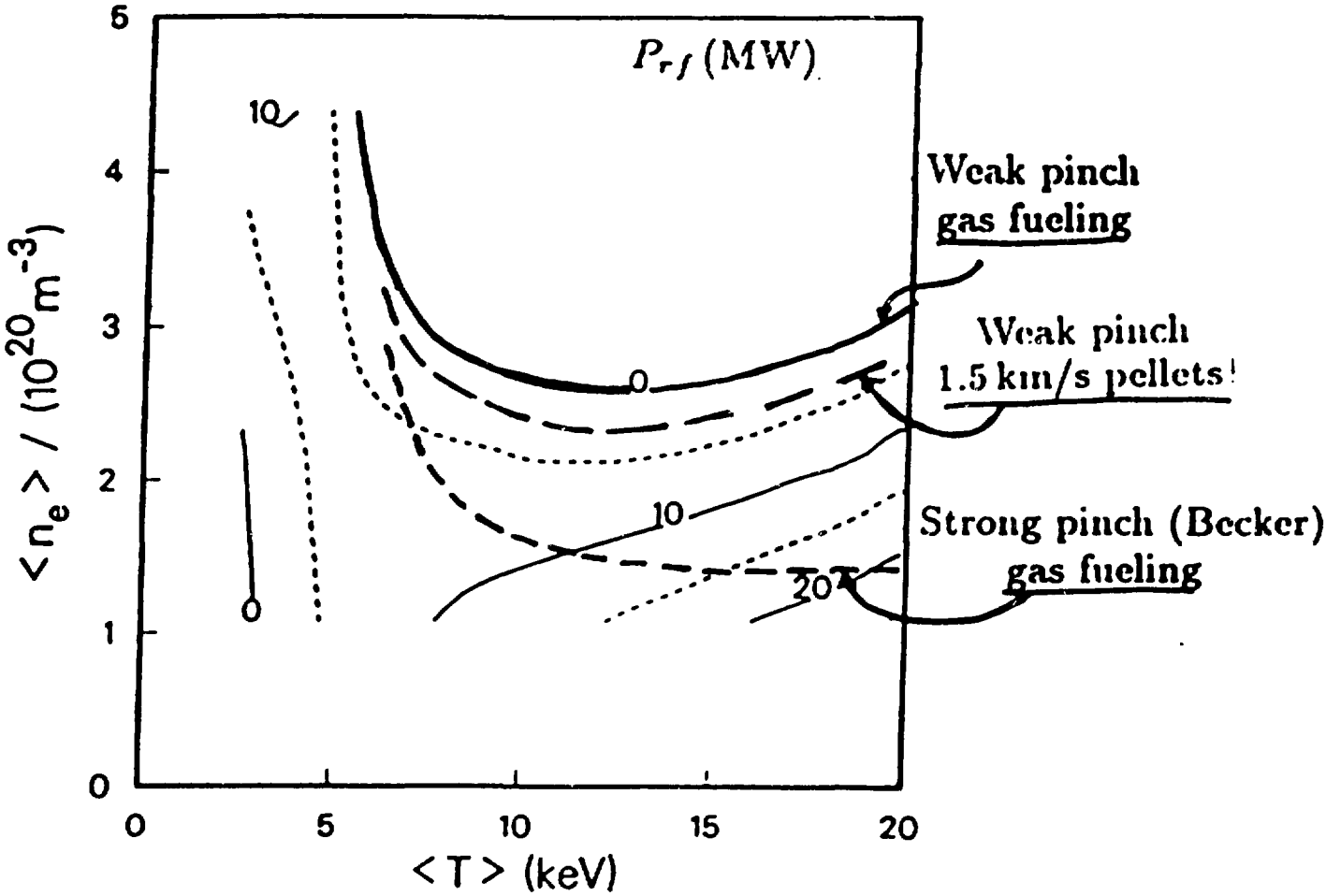


Fig.7

D_α and soft xray emission from the pellet as it penetrates

DENSITY PROFILE EFFECTS IN CIT



FUELING SCENARIOS

Pellet injection:

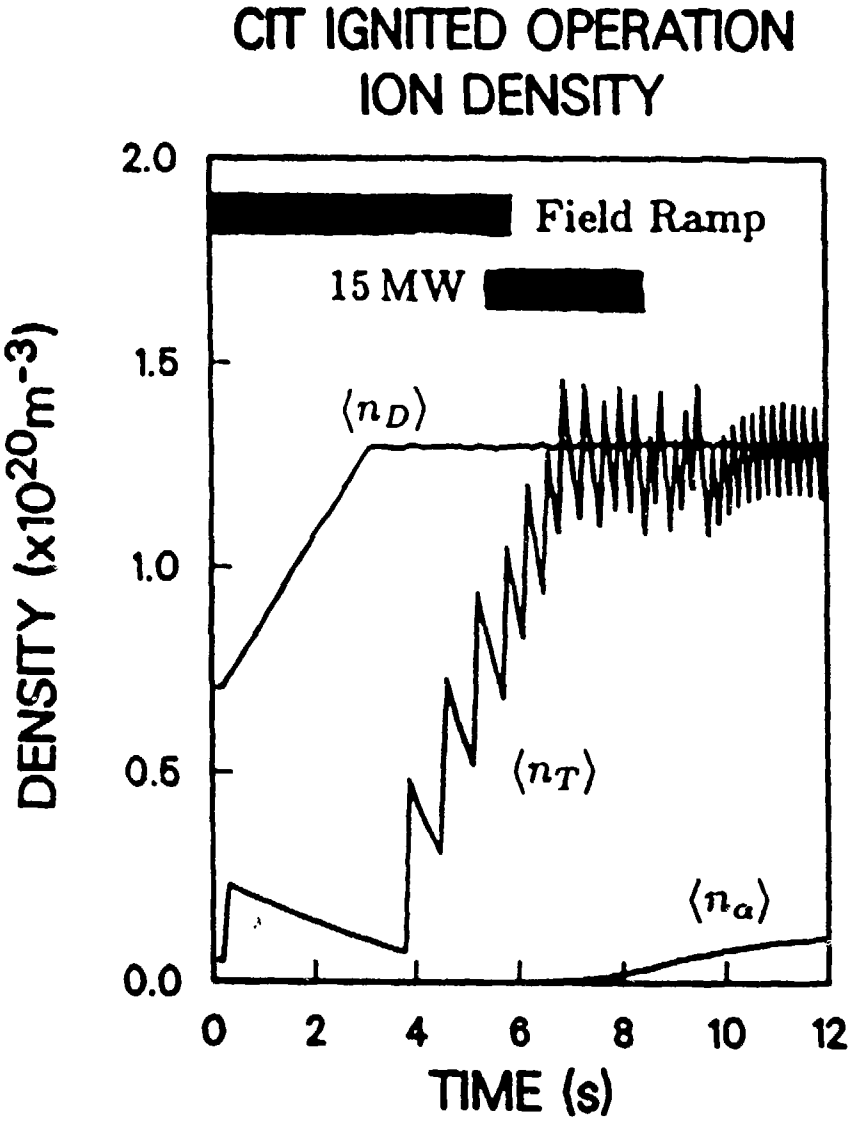
- Injection prior to auxiliary heating can produce strongly peaked density profiles
- Defer tritium injection until late in the density ramp

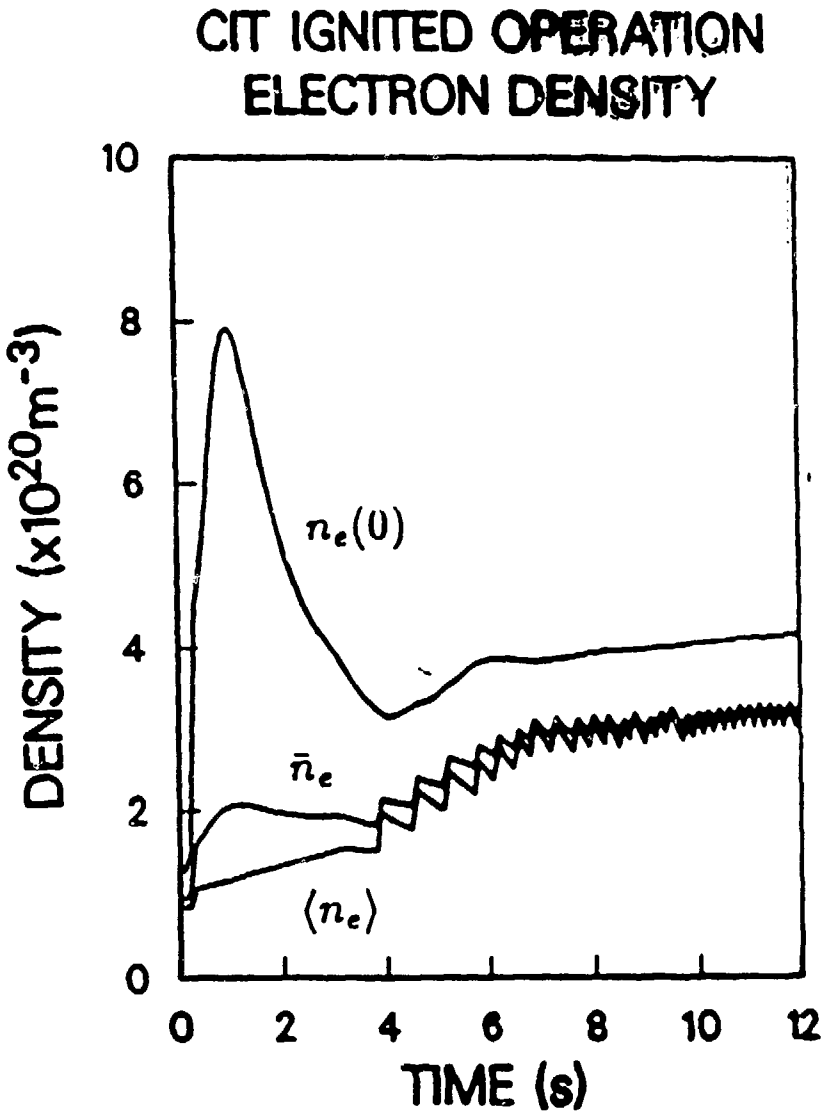
Gas injection:

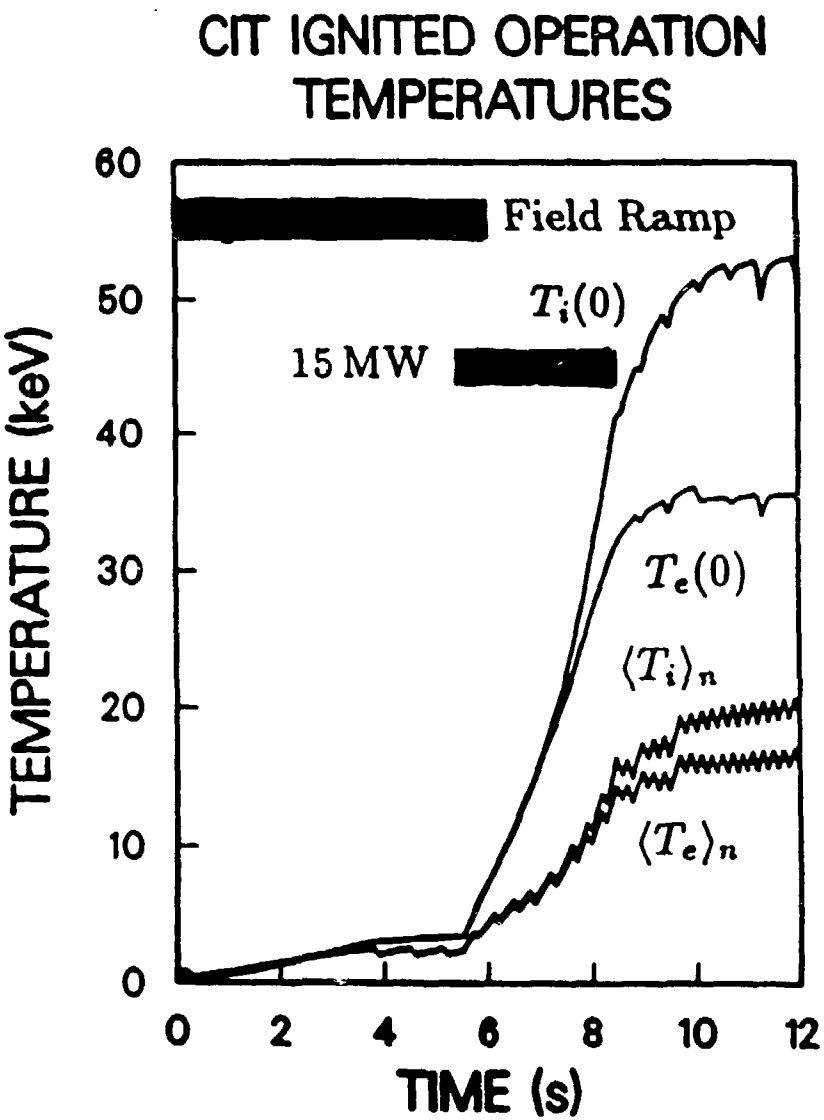
- Provides some control over plasma edge conditions, but masked by recycle
- Primarily reserved for deuterium injection because of tritium inventory issues

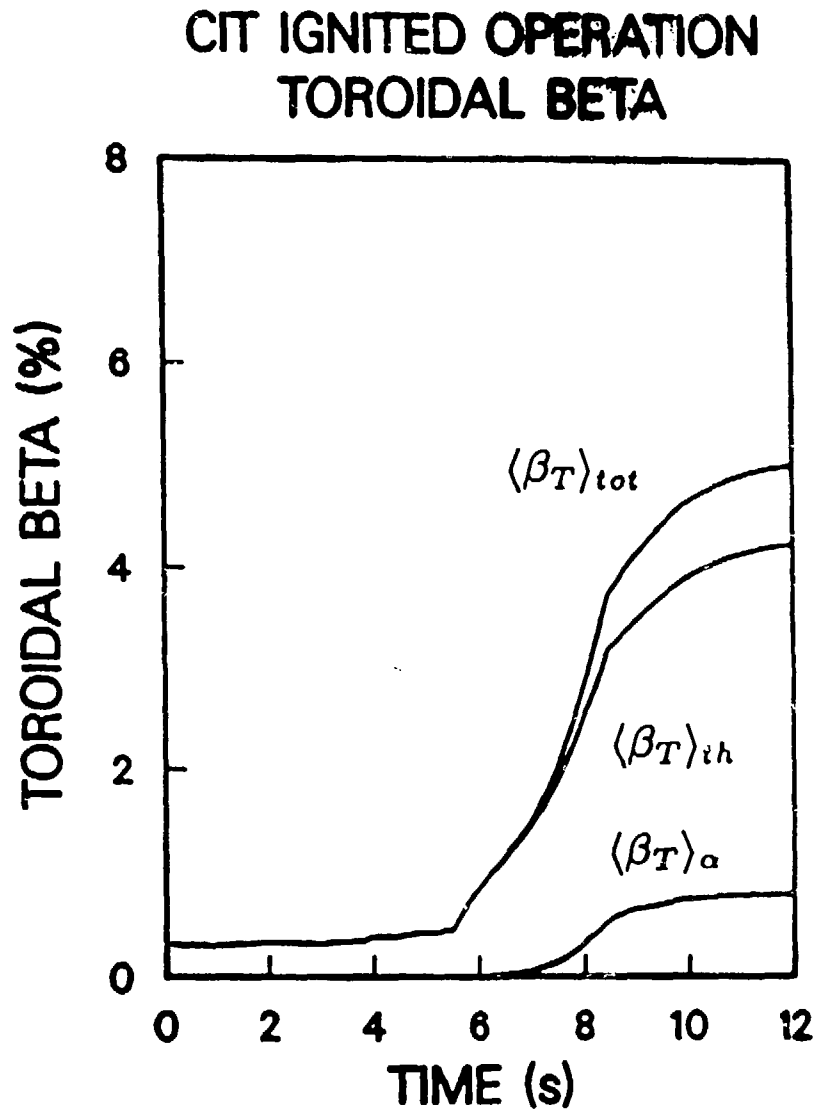
Example cases:

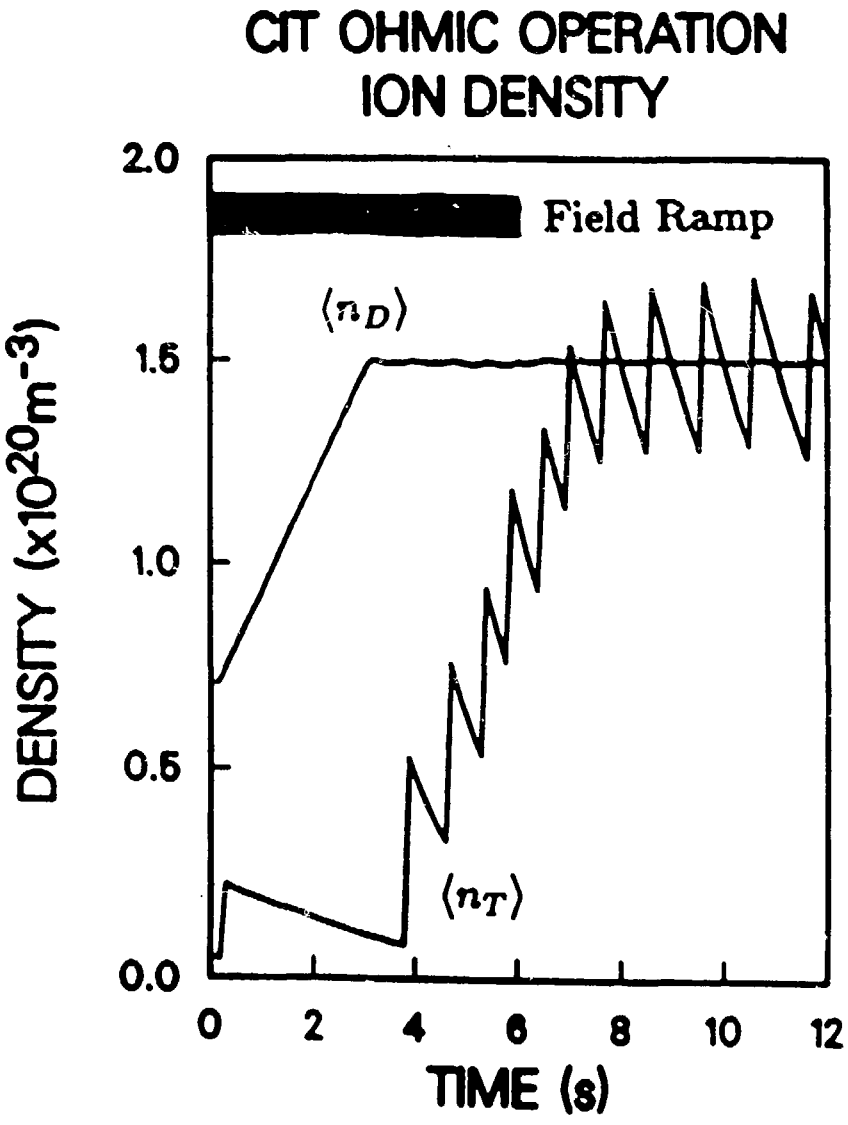
- H-Mode confinement
- D gas and 1.5 mm radius T pellets
- 90% recycle from walls
- Ohmic case: $\Phi_D = 3.2 \times 10^{22}$, $\Phi_T = 1.1 \times 10^{22}$ (12 pellets)
- Ignited case: $\Phi_D = 4.6 \times 10^{22}$, $\Phi_T = 2.6 \times 10^{22}$ (29 pellets)

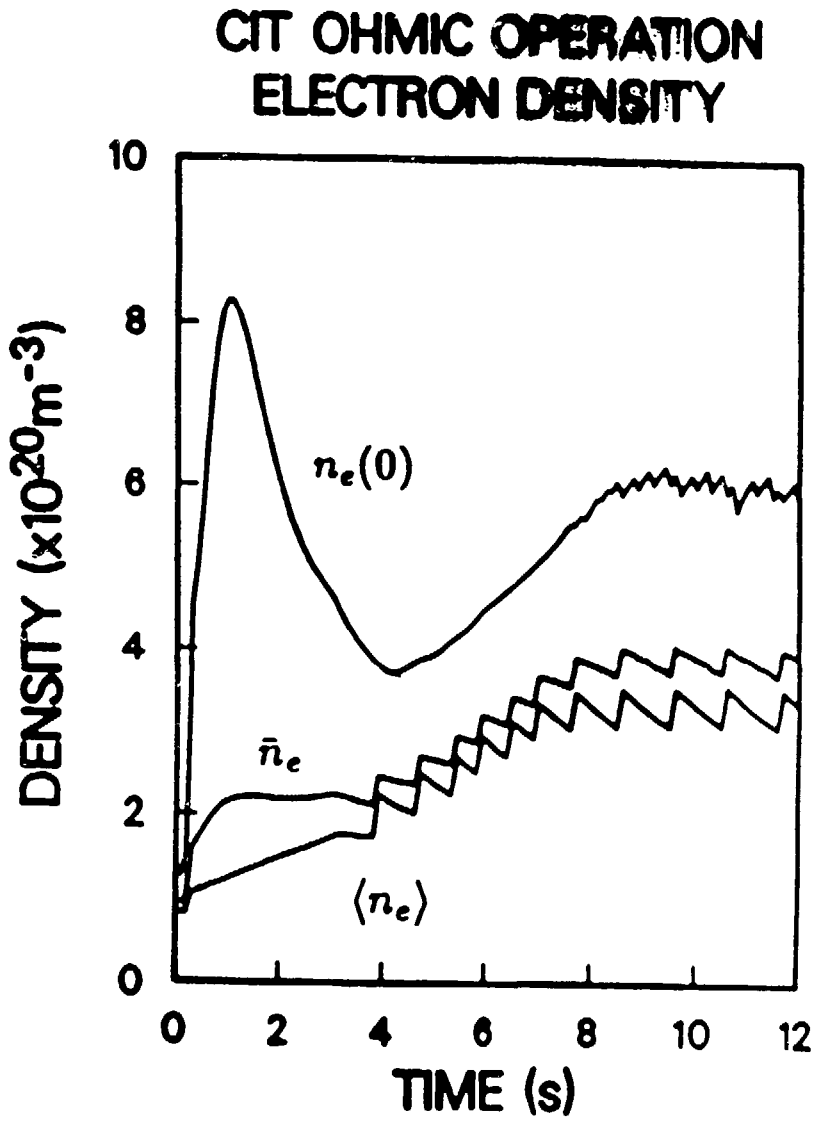

CIT IGNITED OPERATION
ION DENSITY
Field Ramp
15 MW
$\langle n_D \rangle$
$\langle n_T \rangle$
$\langle n_\alpha \rangle$
DENSITY ($\times 10^{20} m^{-3}$)
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
TIME (s)

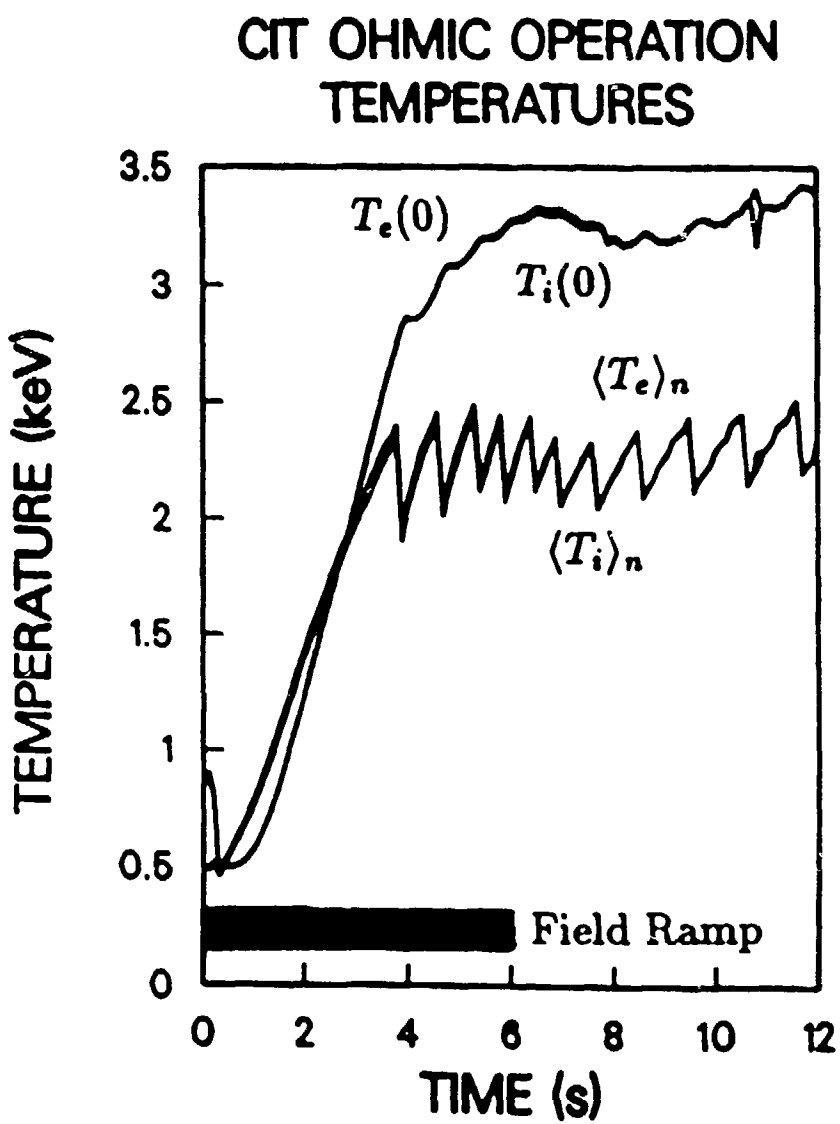

CIT IGNITED OPERATION
ELECTRON DENSITY
$n_e(0)$
$\bar{n}_e$
$\langle n_e \rangle$
DENSITY ($\times 10^{20} m^{-3}$)
10
8
6
4
2
0
0
2
4
6
8
10
12
TIME (s)

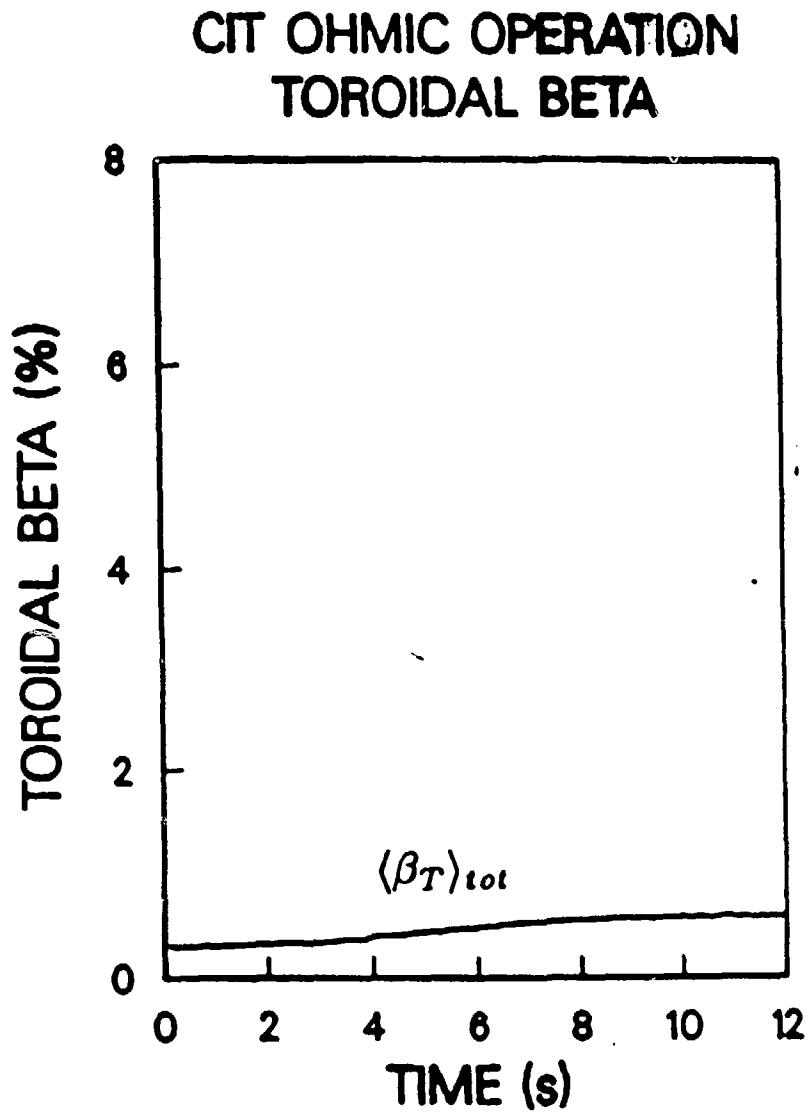

CIT IGNITED OPERATION
TEMPERATURES
Field Ramp
15 MW
$T_i(0)$
$T_e(0)$
$\langle T_i \rangle_n$
$\langle T_e \rangle_n$
TEMPERATURE (keV)
TIME (s)
0
10
20
30
40
50
60
0
2
4
6
8
10
12


CIT IGNITED OPERATION
TOROIDAL BETA
$\langle \beta_T \rangle_{tot}$
$\langle \beta_T \rangle_{th}$
$\langle \beta_T \rangle_{\alpha}$
TOROIDAL BETA (%)
TIME (s)
0
2
4
6
8
0
2
4
6
8
10
12


CIT OHMIC OPERATION
ION DENSITY
Field Ramp
$\langle n_D \rangle$
$\langle n_T \rangle$
DENSITY ($\times 10^{20} m^{-3}$)
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
TIME (s)


CIT OHMIC OPERATION
ELECTRON DENSITY
$n_e(0)$
$\bar{n}_e$
$\langle n_e \rangle$
DENSITY ($\times 10^{20} m^{-3}$)
10
8
6
4
2
0
0
2
4
6
8
10
12
TIME (s)


CIT OHMIC OPERATION
TEMPERATURES
TEMPERATURE (keV)
3.5
3
2.5
2
1.5
1
0.5
0
$T_e(0)$
$T_i(0)$
$\langle T_e \rangle_n$
$\langle T_i \rangle_n$
Field Ramp
0
2
4
6
8
10
12
TIME (s)


CIT OHMIC OPERATION
TOROIDAL BETA
TOROIDAL BETA (%)
8
6
4
2
0
$\langle \beta_T \rangle_{tot}$
0
2
4
6
8
10
12
TIME (s)

SUMMARY

Pellet injector technology:

- Utilize existing technology for basic injector to reach fuel efficiency goals and provide some control over density profiles
- Several options for enhanced velocity injectors are under development to improve density profile control

Adequate models exist for pellet ablation in present plasmas with current velocities but are still untested at higher velocities and plasma temperatures

Improvements in confinement models with pellet inejection can come from the TFTR, JET, and TORE SUPRA programs:

- Scaling of diffusive and pinch terms in particle flux under H- and L-Mode conditions
- Means of sustaining centrally peaked density profiles
- The role of the density profile in energy confinement