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ORNL-TNS/PEPR OVERALL HEATING REQUIREMENTS

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INTRODUCTION (Slides 2-6)

The ORNL TNS/PEPR studies have the objectives[1,2] of 1) leading to a system that demonstrates the fusion reactor core in the mid-to-late 1980's and extrapolates to an economic tokamak power reactor, and 2) providing a near-term focus for the scientific and technological programs toward the power reactor. This discussion of the overall heating requirements for the ORNL TNS/PEPR is concerned with the neutral beams as the primary heating method, the electron-cyclotron resonance (ECR) heating at a lower power level for profile control, and the upper hybrid resonance (UHR) initiation and preheating of currentless plasmas to reduce current start-up loop voltage (V_ℓ) requirements.

NEUTRAL BEAM HEATING SCENARIO WITH CONTROLLED DENSITY BUILD-UP (Slides 7-14)

Neutral beams giving an estimated net power of 50-75 MW into the plasma provide the main plasma heating. To avoid relying on deuterium beam energies around 300 keV for full penetration at averaged densities of $\sim \bar{n} = 2 \times 10^{14}$ cm^{-3}, a neutral beam heating scenario[3] with controlled density buildup is proposed to permit the use of beams of 150-200 keV.

In this scenario, the initial density of the ohmically heated plasma is assumed to be near 0.5×10^{14} cm^{-3}, consistent with the Murakami scaling[4] and permitting full penetration with 150 keV, nearly perpendicular D° beams ($Z_{eff} \simeq 1.5$). Since the increased plasma heating power can support higher plasma density, the plasma density and temperature can be allowed to increase in a controlled fashion. When the volume averaged beta ($\bar{\beta}$) reaches 2% at $B_T = 5.3$ T, the maximum beta (β_{max}) at the plasma magnetic axis reaches 7%. With a peak density of $n_o = 2 \times 10^{14}$ cm^{-3}, the peak temperature becomes 12 keV. The local α-particle heating power density is above 0.8 MW/cm^3, with the particle drift orbit effects included.

Assuming empirical energy confinement, this centralized α-particle heating can be shown to compensate[5] for the lack of beam penetration expected for the 150-keV beam at $n_o = 2 \times 10^{14}$ cm^{-3} and $Z_{eff} \approx 1.5$. When $\overline{\beta}$ increases beyond 2.5%, the plasma is ignited at the center and can reach D-T burning steady states with the magnitude of fusion power output determined by the plasma density. The plasma heating scenario with controlled density buildup may be tested in JET if $\overline{\beta}$ above 5% can be achieved with $B_T = 3.5$ T.

This heating scenario and other scenarios such as ripple injection,[6] expanding plasma,[7] and compression boosting[8] tend to increase the probability of successful heating with D° beam energies of 100-200 keV. This suggests the use of positive ion beams based on present-day beam technologies.[9] However, because of the relatively low overall efficiency (≲20%) of positive ion D° beams when E_b = 150-200 keV, efficient technology of direct recovery[10] of the ion energy should be developed to substantially reduce the neutral beam power supply requirements.

Neutral beam injection heating has one important limitation that calls for some attention, regardless of positive or negative ion beams. Recent 1½-dimensional beam deposition calculations[11] reveal that, for fixed beam energy, the operating window in plasma density is only a factor of two to three. More than 10% of the neutral beam particles pass through the plasma at lower densities, and hollow beam deposition results at higher densities. To increase the operating window in density, independent control of the beam deposition profile during the approach to ignition is required as $n_o a$ increases. This might be achieved by using a variable beam energy or a variable beam species mix. The technologies for achieving this should be studied.

<u>MICROWAVE HEATING NEAR THE ELECTRON CYCLOTRON RESONANCE (ERC)</u> (Slides 15-20)

Recent MHD stability calculations[12] of ballooning kink modes in D-shaped flux conserving tokamak (FCT) equilibria[13] have revealed significant dependence of critical beta ($\overline{\beta}_c$) for stability (and hence the fusion power density) on the plasma pressure profile. This suggests the need for external modification of the pressure profile in a fashion more flexible and localized than the neutral beam deposition profile.

On the other hand, it has been shown that the toroidal current profile in a high β FCT equilibrium[13] is significantly different from the current profile of an ohmically heated equilibrium. The FCT high β equilibrium, left alone, is expected to evolve toward a low β, ohmic equilibrium in a plasma skin time, which is typically a few tens of seconds in a reactor. One conceivable way of maintaining the high β equilibrium beyond the plasma skin time is to reduce the plasma resistivity in regions where high current density is required for high β. Localized heating is one way to make this possible.

The ECR heating, because of its narrow resonance zone, provides for such a mechanism. Recent calculations of ECR heating in ISX shows that the heating profile width can be typically one-fifth of the plasma minor radius. Assuming that the local plasma density and heat conductivity are not altered substantially by the local ECR heating, a 20% increase in local temperature then seems desirable. This would then require a total microwave power of roughly 20 MW, one-twenty-fifth of the total α-particle power in a D-T tokamak reactor. For the ORNL TNS/PEPR with B_T = 5.3 T at the major radius and an aspect ratio of 4, a microwave frequency range between 120-150 GHz is required.

MICROWAVE PLASMA PREHEATING NEAR THE UPPER HYBRID RESONANCE (UHR) (Slides 21-26)

The ohmic heating power supply required to start up the plasma current over the full bore in a tokamak reactor has been estimated[15] to be above 1 GW for a duration of around one-tenth of a second. This pulsed power supply requirement implies substantial technology development and cost. The fundamental reason for this high requirement is the estimated loop voltage (V_ℓ between ~300-500 V) needed to bring the initial plasma current and temperature through the relatively large barrier of energy and volt-second losses due to minute amounts of low Z impurities, when $T_e < 50$ eV.[17] There are strong technology and cost inc-ntives to reduce this start-up loop voltage requirement in a tokamak reactor.

Based on recent experimental observations by Anisimov et al.,[18] plasma initiation and preheating near the UHR are proposed[19] to obtain $T_e \approx 250$ eV at least in a small volume in the toroidal chamber before the toroidal current is initiated by applying V_ℓ. In this new start-up scenario, anomalous absorption of the extraordinary microwaves introduced from the high field side heats the electrons. Energy and particle losses are assumed to be due to magnetic curvature and parallel drifts, ionization of the neutrals, cooling by ions, and radiation by low Z impurities. To estimate the V_ℓ required for current start-up from the microwave plasma, T_e is assumed to remain constant at 250 eV when the plasma current increases to full value after the application of constant V . The plasma safety factor, q, plasma resistive voltage, and Z_{eff} are also assumed to be constant during this process.

Our rough estimates are encouraging in that, using a microwave power of 0.6 MW at 120 GHz, V_ℓ can be reduced to about 30 V without increasing the start-up loss of volt=seconds. Given sufficient support, this start-up scheme can be tested in ISX using the 28-GHz, 200-kW power sources developed for the EBT-S experiment.[20] If verified, the impact of this method on the start-up cost of tokamak reactors is expected to be dramatic.

DISCUSSION (Slide 27)

The ORNL TNS/PEPR studies on the plasma heating requirements form good examples of efforts that contribute strongly toward an economic tokamak reactor. Our considerations have naturally led to the following foci for the technological and scientific programs on plasma heating:

1. Direct recovery of positive ion energy in deuterium beams at E_b = 150-200 keV.

2. Schemes to alter neutral beam energy deposition independently of plasma density during heating, e.g., by varying E_b or energy species mix.

3. CW microwave power around 20 MW at a range of frequencies between 120 and 150 GHz for plasma profile control.

4. CW microwave power around 1 MW at a frequency between 120 and 150 GHz to reduce current start-up loop voltage by an order of magnitude.

Whether these results could benefit the tokamak fusion program depends strongly on whether the necessary developments and experimentations are carried out in a timely fashion.

ACKNOWLEDGEMENT

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Y–K. M. Peng and J. A. Rome

TNS Plasma Engineering

ORNL TNS PROGRAM

THE ORNL TNS PROGRAM AIMS TO REDUCE COST AND RELIANCE ON ADVANCED HEATING TECHNOLOGIES

WORKSHOP ON

PLASMA HEATING DEVELOPMENT REQUIREMENTS

DIVISION OF MAGNETIC FUSION ENERGY

December 5 – 7, 1977

THE ORNL TNS OBJECTIVES ARE TWO-FOLD

- Lead to a system that
  - Demonstrates reactor core in next decade
  - Is extrapolatable to an economic tokamak power reactor

- Provide near-term focus for the scientific and technology engineering programs towards the above objectives

PRE-CONCEPTUAL   CONCEPTUAL   SELECTION

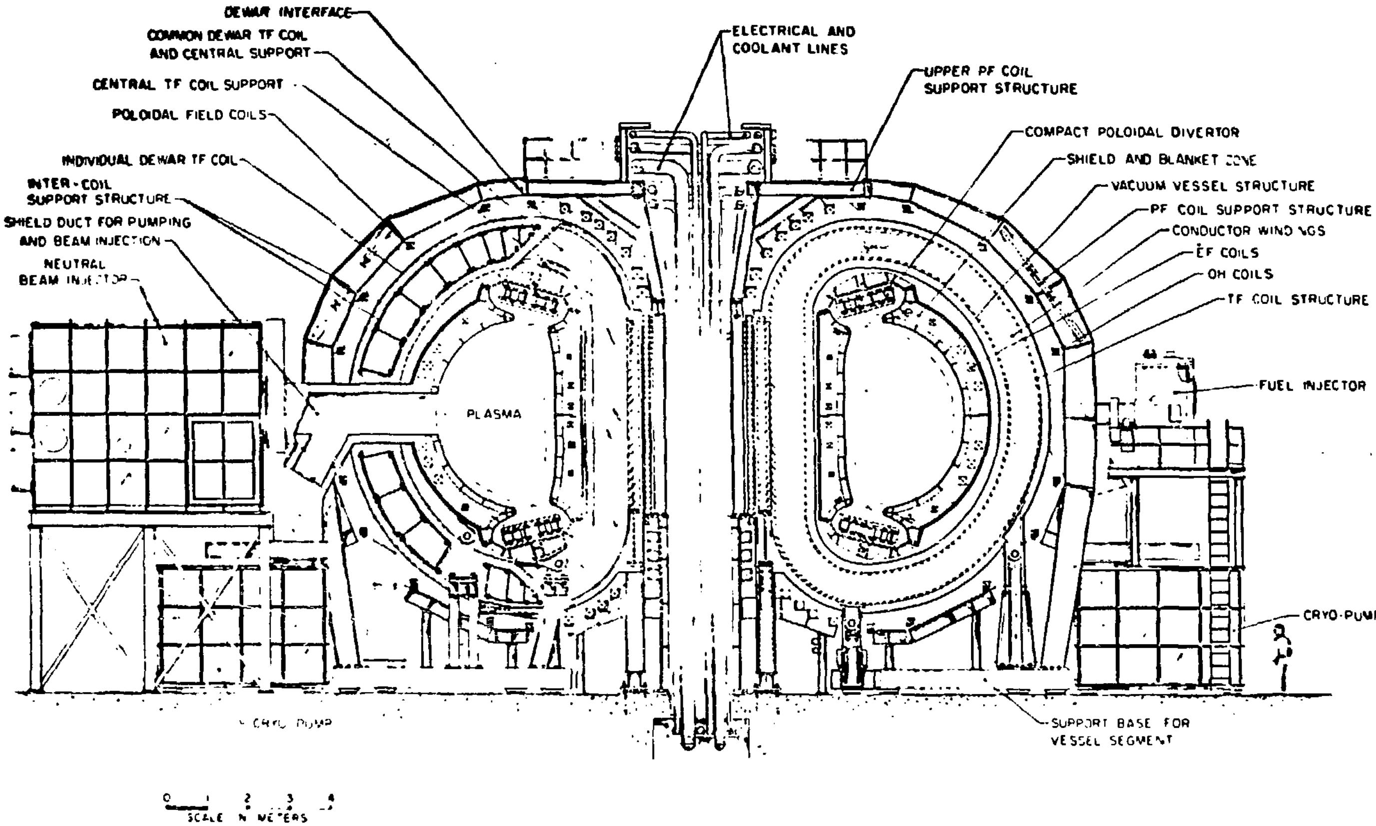
↑

NOW

BASED ON THE FY77 TNS STUDIES WE CHOOSE THE FOLLOWING BASELINE PARAMETERS

- 20 Nb_3Sn COILS, $B_{MAX} = 10.9$ T, $B_T = 5.3$ T
- $R_0 = 5$ m, $a = 1.2$ m, $\sigma = 1.6$, D–SHAPE
- COMPACT POLOIDAL DIVERTOR,
  INTERIOR COPPER EQUILIBRIUM FIELD COILS
- 5 NEUTRAL–BEAM INJECTION LINES (50-75 MW)
  9 CRYO–PUMPS
  1 ORNL PELLET INJECTOR
- COMMON DUCTS FOR INJECTORS AND PUMPS

ORNL/DWG/FED-771073



ELEVATION (CUTAWAY)

Slide 4

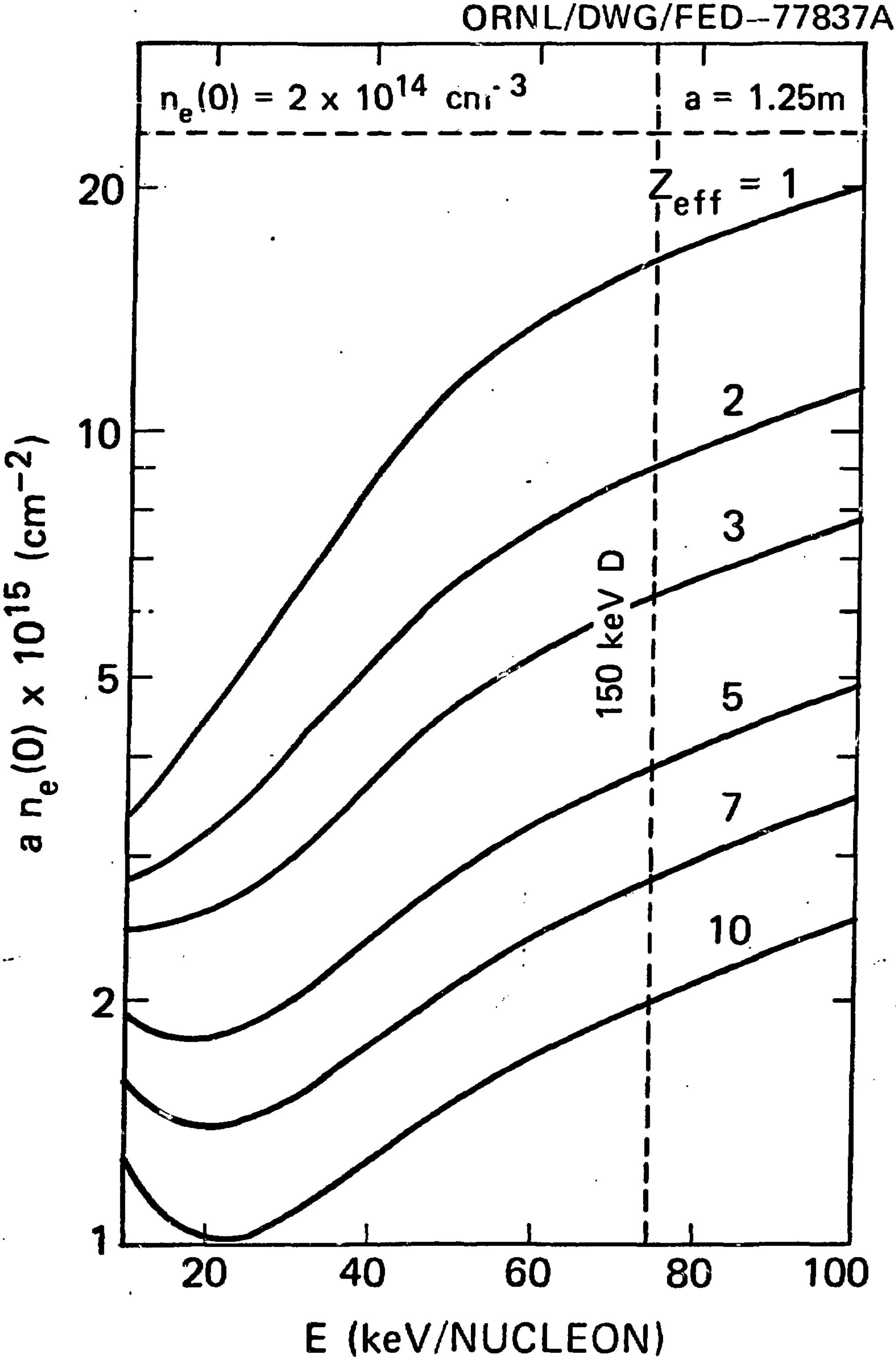
A CONSISTENT SET OF PHYSICS ASSUMPTIONS ARE USED FOR THE OAK RIDGE MEDIUM FIELD IGNITION REACTOR

PARAMETERS REFINED WITH 1-D TRANSPORT, MHD EQUILIBRIUM AND STABILITY CALCULATIONS

	LOW β	IGNITION	BURN
$\bar{\beta}$ (%)	1.0	3.0-5.0	3.5-10.0
I_P (MA)	4.0	4.5-5.5	
$\bar{N}$ (CM^{-3})	0.3-0.5 x 10^{14}	0.6-2.5 x 10^{14}	
$\bar{T}$ (keV)	1-2	4-7	5-10
COLLISIONALITY	0.14-0.98	0.01-0.15	
$\overline{n\tau}$ (CM^{-3} SEC)			0.6-3 x 10^{14}
$P_{D\text{-}T}$ (MW)			100-2000
$P_{D\text{-}T}/V$ (MW/M^3)			0.4-8.0
W_L (MW/M^2)			0.3-5.0

TNS STUDIES IDENTIFY PHYSICS ASSUMPTIONS AND OPERATING SCENARIOS TO REDUCE IMPLIED TECHNOLOGY REQUIREMENTS

- → Neutral beam heating scenarios
  - —— Reduced beam energy
- 1–D transport evaluations of pellet requirements
  - —— Reduced pellet velocity
- Reassessment of toroidal field ripple requirements
  - —— Improved machine access
- Hybrid equilibrium field coils
  - —— Reduced engineering difficulty and power supply
- → Microwave startup near upper hybrid resonance
  - —— Reduced startup costs
- Iron core option
  - —— Improved overall engineering feasibility and reduced power supply
- Compact poloidal divertors

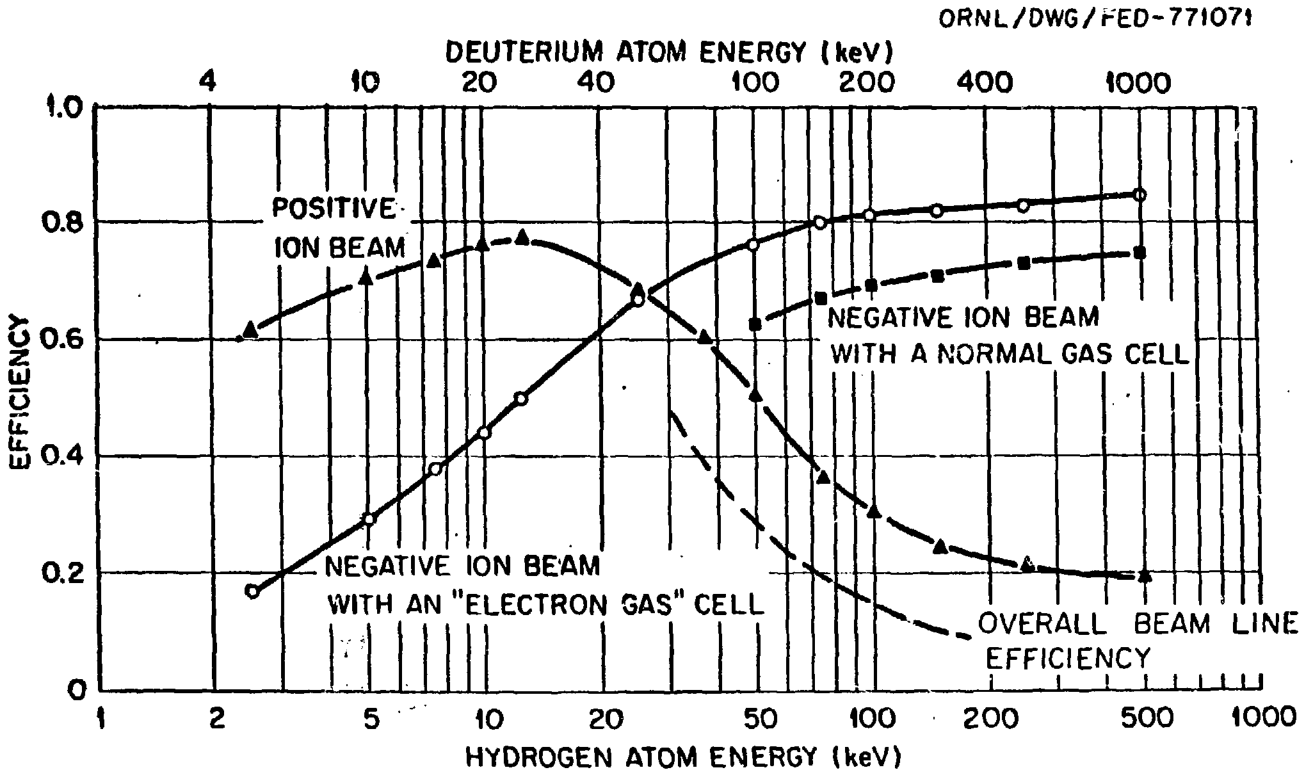


ORNL/DWG/FED--77837A
n_e(0) = 2 x 10^14 cm^-3
a = 1.25m
Z_eff = 1
2
3
5
7
10
150 keV D
a n_e(0) x 10^15 (cm^-2)
1
2
5
10
20
20
40
60
80
100
E (keV/NUCLEON)

Slide 7

POSITIVE ION NEUTRAL BEAM PRODUCTION

EFFICIENCY IS LESS THAN .3 WHEN E_b (D^+) > 200 keV



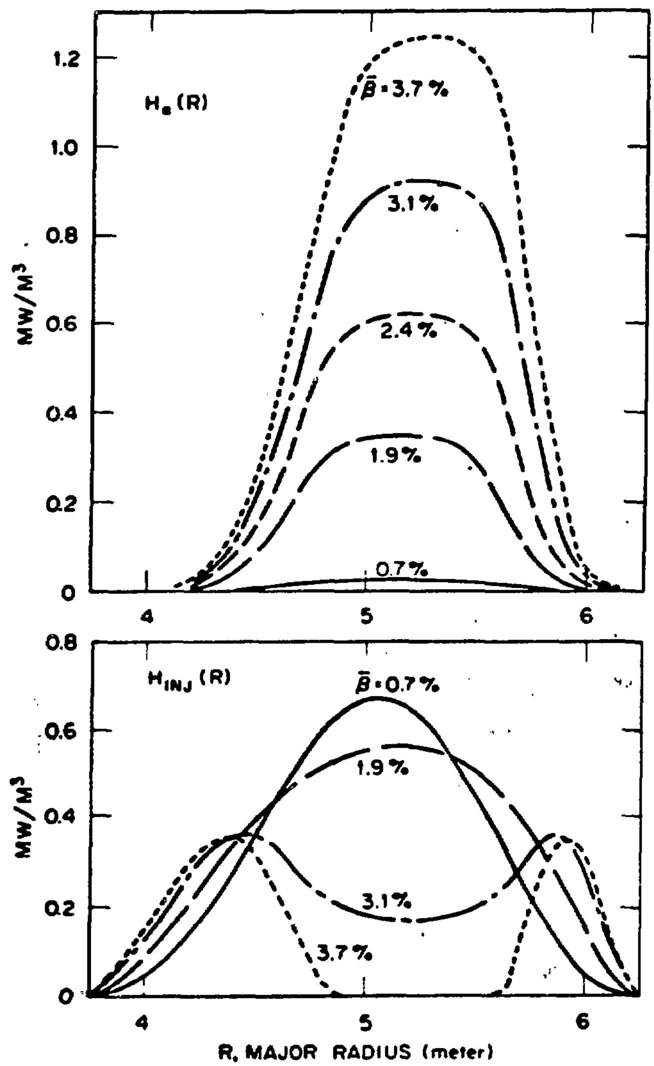
Neutral Beam Production Power Efficiency

REQUIRED H_{INJ} (R) RECEDES FROM CENTER

WHERE H_α (R) peaks when $\beta > .025$

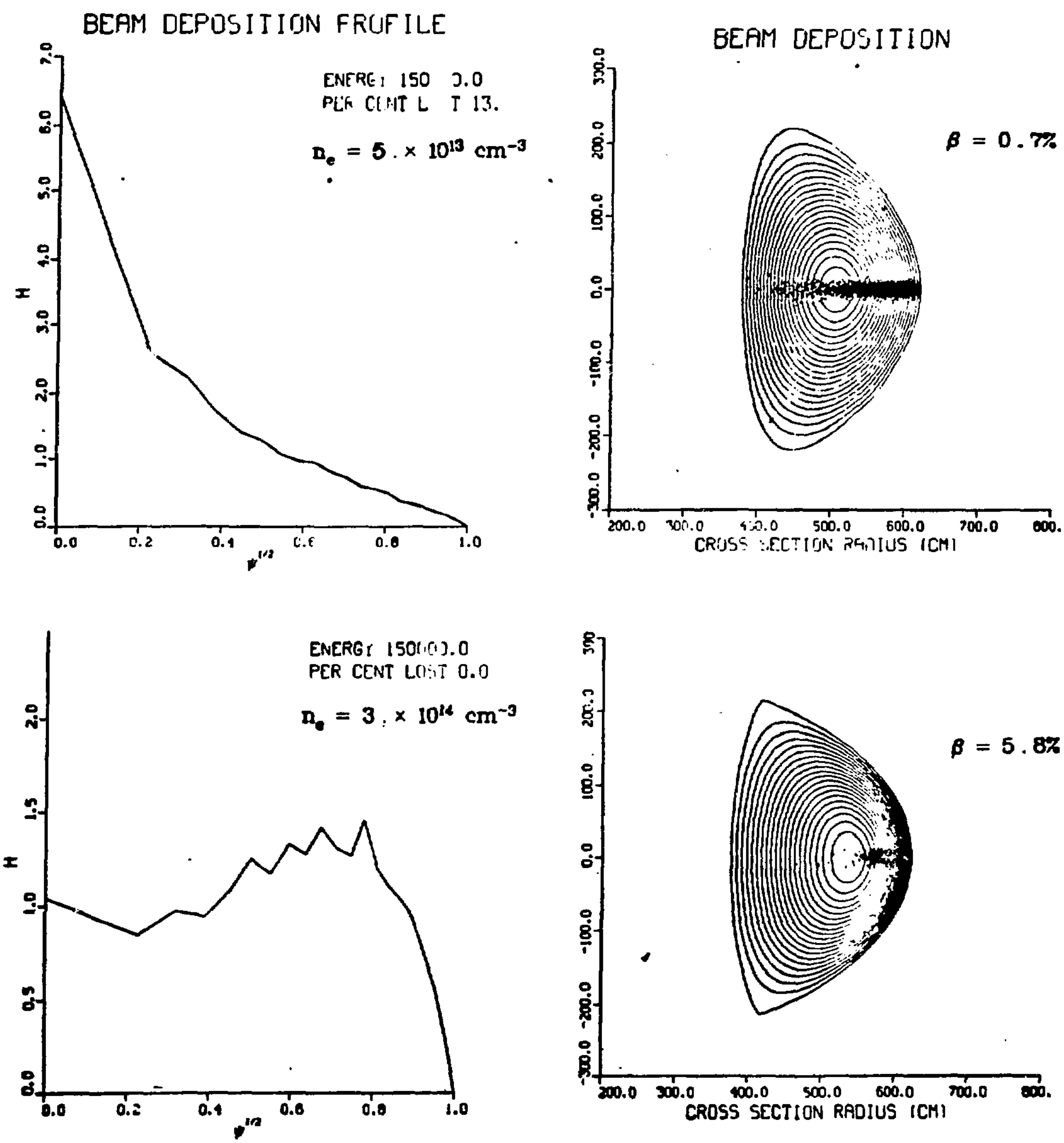
$(\bar{n} \simeq 0.7 \times 10^{14}\ cm^{-3})$

ORNL/DWG/FED-77267



ORNL/DWG/FED-771074

2-DIMENSIONAL BEAM DEPOSITION CALCULATIONS ARE USED

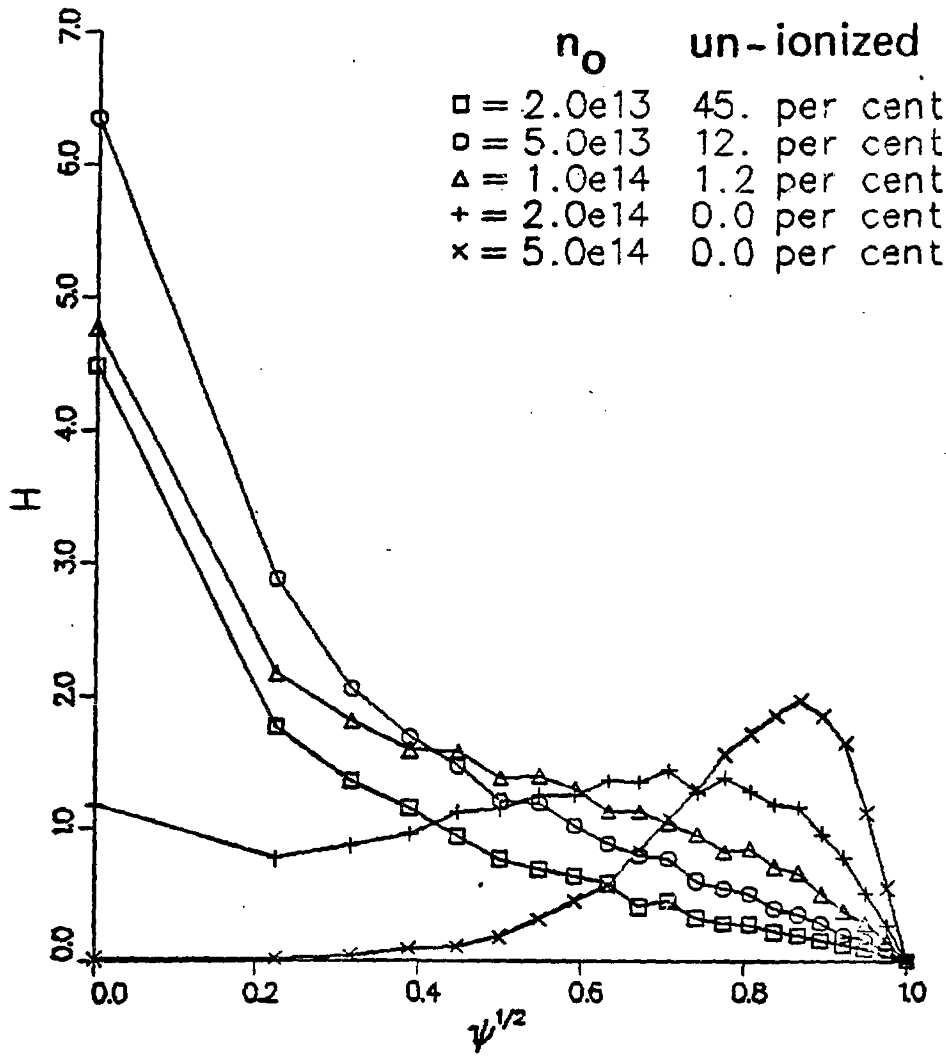


OTHER INJECTION SCENARIOS MAY ALSO SUCCESSFULLY REDUCE REQUIRED E_b

- Ripple injection ⟶ $E_b < 150$ keV
  ripple coils
- Expanding radius ⟶ low E_b
  $\tau_R \sim \tau_E$

ORNL/DWG/FED-771072

FOR A GIVEN BEAM ENERGY, THE ALLOWED DENSITY WINDOW IS ONLY A FACTOR OF 2 – 3



IMPROVEMENTS IN POSITIVE ION BEAM TECHNOLOGY ARE POSSIBLE

- Control H_{INJ} (R) at fixed density to enlarge density window
  - ? Variable E_b
  - ? Varaible species mix
  - ? Switch from D to H
- Increase injector efficiency near 200 keV
  - ? Direct recovery
  - ? Higher D^+ species yield

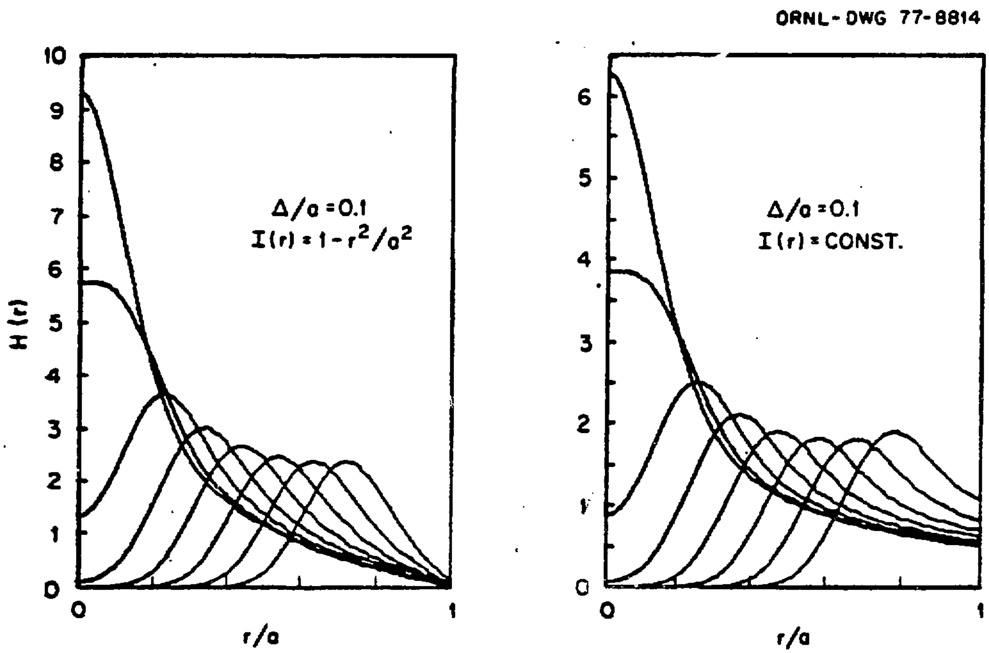
THE ORNL TNS NEUTRAL INJECTION SCENARIO CAN REDUCE COST AND RELIANCE ON ADVANCED BEAM TECHNOLOGY

- Injection heating scenarios suggest $E_b < 200$ keV acceptable
  - ---► Injector reliability, flexibility, and remote maintainability
- Small density window for efficient heating
  - ---► Variable E_b or species mix
- Improvements in efficiency of + ion injectors should be considered

MICROWAVE HEATING OFFERS FLEXIBILITY

- Proven heating scheme
- Good accessibility
- Localized energy deposition profile, H_μ (R)
- Potential need of plasma profile control

$H_\mu(r)$ CAN BE WIDELY VARIED BY VARYING THE LOCATION OF THE ECR ZONE



- Location of $H_\mu(r)$ can be altered by varying B_T or F_μ.

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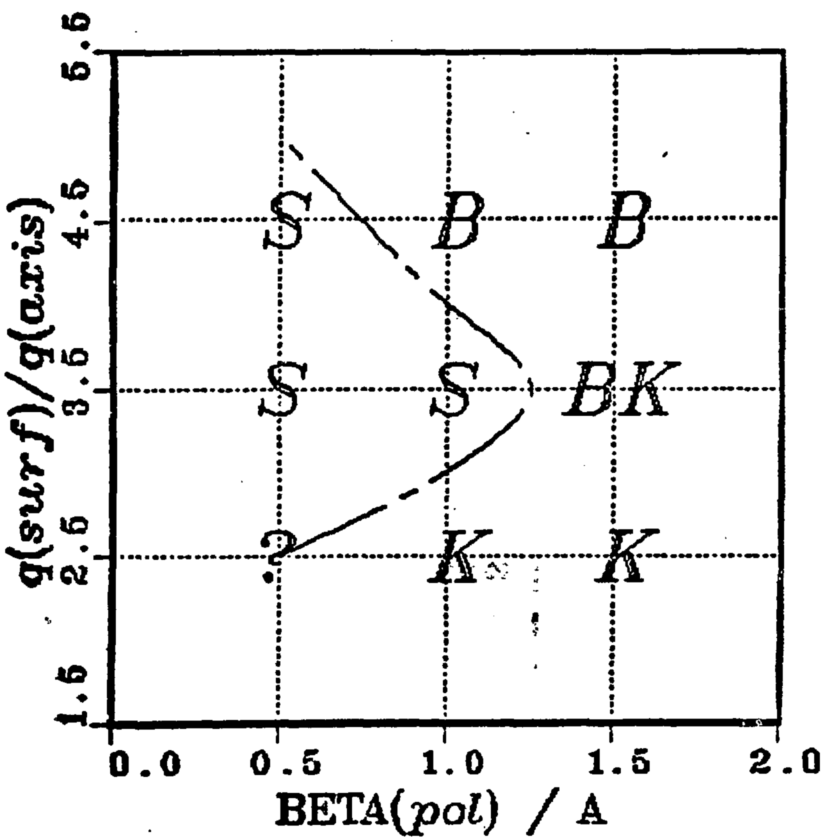
PROPER PLASMA PROFILE CONTROL CAN SUBSTANTIALLY INCREASE MHD STABLE $\bar{\beta}_c$, LEADING TO HIGH FUSION POWER DENSITY



(R. A. Dory et al, DPP APS 5F4)

THE REQUIRED P_μ FOR PROFILE CONTROL CAN BE ESTIMATED TO BE ~ 20 MW AT 120 – 150 GHz

- $p_\alpha \sim \partial(\chi n\ \partial T/\partial r)/\partial r$

  $p_\mu \sim \partial(\chi n\ \partial \Delta T/\partial r)/\partial r$, local T change
- Assume

  n, χ unchanged, $\Delta T \sim T/5$

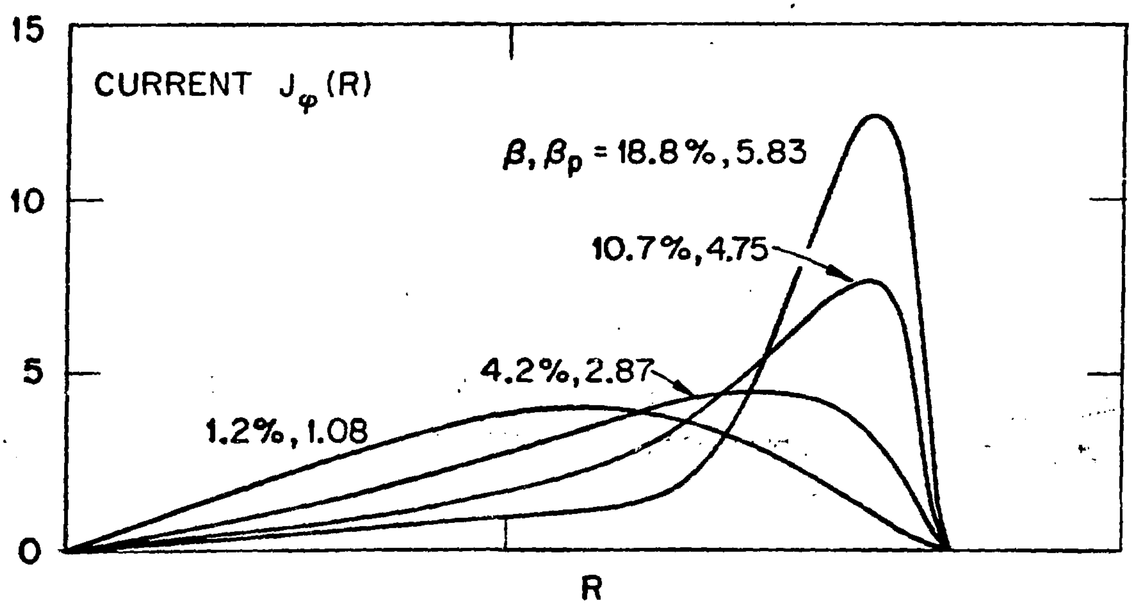
  over $\Delta r \sim a/5$ at $r \sim a/2$
- Then $P_\mu \sim P_\alpha /25 \sim 20$ MW, $\tau \sim \tau_E$
- $B_T = 4.3 - 7.0$ T Within plasma

  $\longrightarrow F_\mu = 120 - 150$ GHz
- Technology yet to be developed

LOCALIZED HEATING IS ONE POSSIBLE WAY TO MAINTAIN HIGH β FCT EQUILIBRIUM PROFILES BEYOND THE PLASMA SKIN TIME

- Assume that proper plasma shape maintained
- High β J_φ (R) profile not compatible with

$$E_\varphi = \eta J_\varphi \text{ for steady state}$$



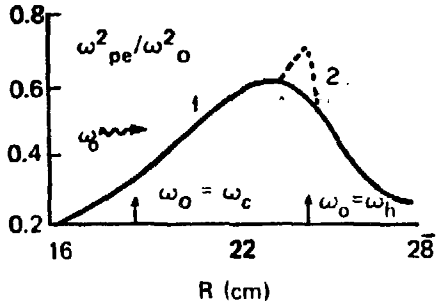
OTHER WAVE HEATING METHODS MAY ALSO BE EFFECTIVE

- Lower hybrid (~ 1.5 GHz)
- Ion cyclotron resonance (25 – 100 MHz)
- Low frequency magnetosonic wave (1 – 10 MHz)
- Low frequency shear Alfven wave (1 – 2 MHz)

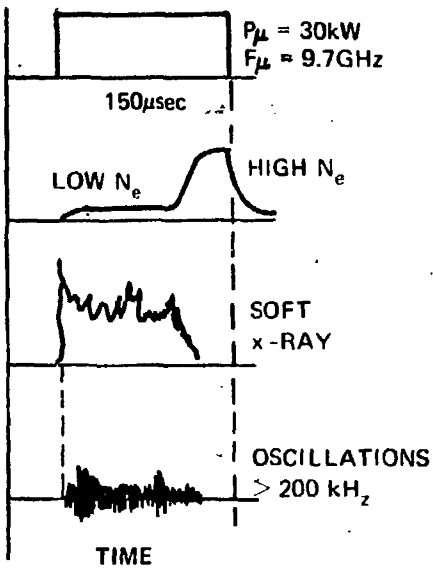
ANOTHER APPLICATION OF MICROWAVES MAY BE TO PREHEAT TOROIDAL PLASMAS TO $T_e \sim 200$ eV BEFORE CREATING LARGE I_p

- Startup V_L = 300 – 500 volts for ~ 50 msec
- OH power supply cost up to 150 M dollars
- Large energy and volt–second barriers by low Z impurities when $T_e < 50$ eV
- Desirable to preheat electrons to above 100 eV in a small volume

EXPERIMENTS BY ANISIMOV, ET AL. HAS PROVIDED SOME INTERESTING POSSIBILITIES USING EXTRAORDINARY MICROWAVES



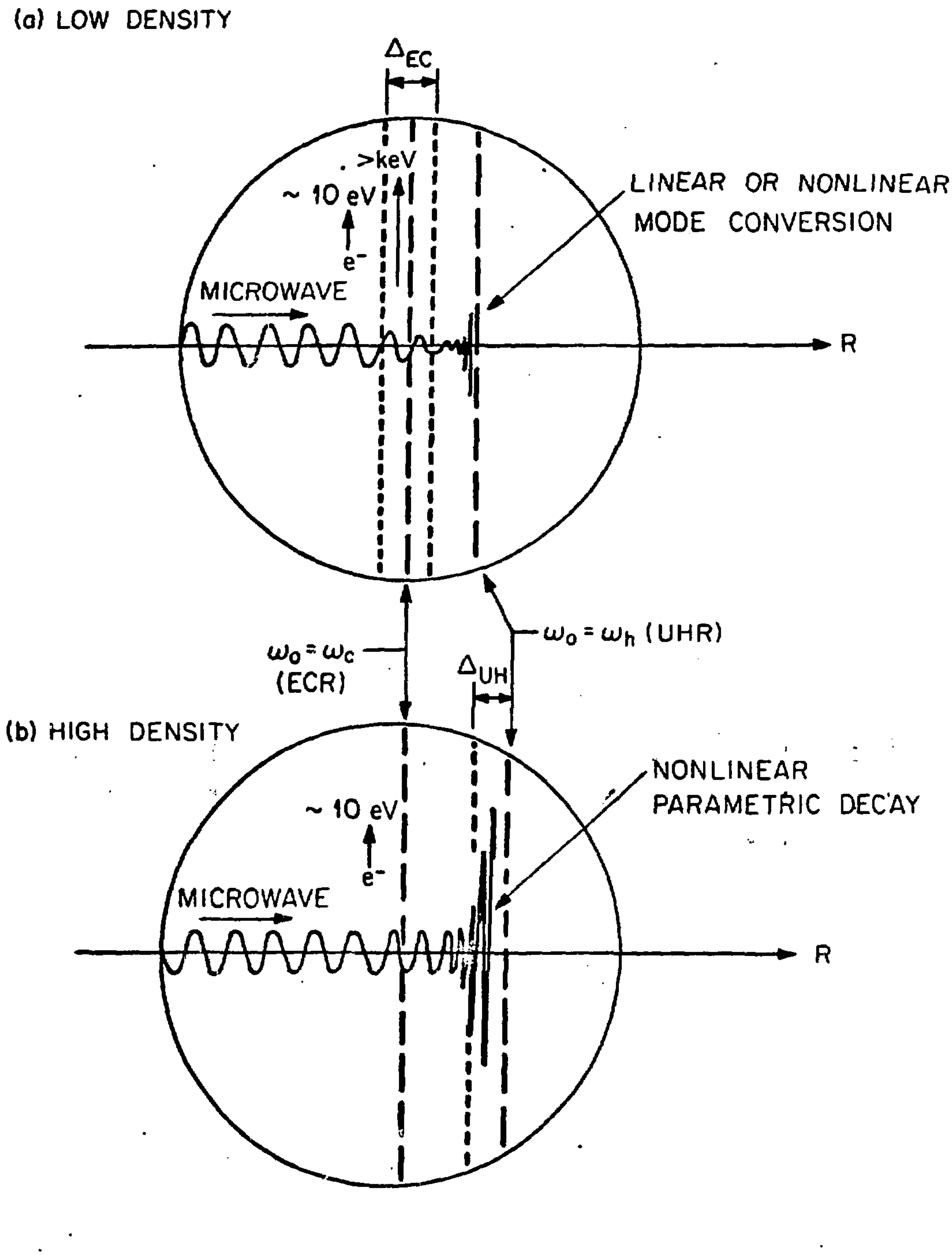
- H_2 AT 2×10^{-4} Torr
- $B_T \sim$ 3kG. $F_\mu \sim$ 9.7GHz
  1) Cw, $P_\mu \cong$ 200W
  2) + PULSED, P_μ = 300W
- EXTRAORDINARY MODE



- AT LOW DENSITY, W_e > 20 keV RUN AWAY ELECTRONS AND LOW FREQUENCY OSCILLATIONS ARE INDICATED.
- AT HIGH DENSITY, Te ESTIMATED TO BE A FEW 100 eV, WITH NO INDICATIONS OF >> keV ELECTRONS AND LOW FREQUENCY OSCILLATIONS FOR ABOUT 30 μsec

ORNL/DWG/FED- 77588R

THE ASSUMED WAVE – PLASMA INTERACTIONS HAVE TWO DENSITY REGIMES



THE FOLLOWING ASSUMPTIONS ARE USED IN OUR ESTIMATES

(ORNL/TM – 6112)

- Anomalous absorption near UHR, heating electrons
- Energy and particle balance:
  - o Curvature and parallel drifts
  - o Ionization of neutrals
  - o Cooling by ions
  - o Radiation by low Z impurities
- For startup V_L requirements
  - o Fixed $T_e \sim 250$ eV, V_L, q, V_{RES}, Z_{EFF}
  - o $a \sim I^{1/2}$

UPPER HYBRID RESONANCE PREHEATING SIGNIFICANTLY REDUCES START-UP REQUIREMENTS

- V_L CAN BE REDUCED BY A FACTOR OF 5-10
- STARTUP PULSE (ΔT) SMOOTHED BY A FACTOR OF 2-5
- MUCH REDUCED LOSS OF VOLT SECONDS DURING STARTUP
- $P_\mu \lesssim$ MW AT 120 GHz

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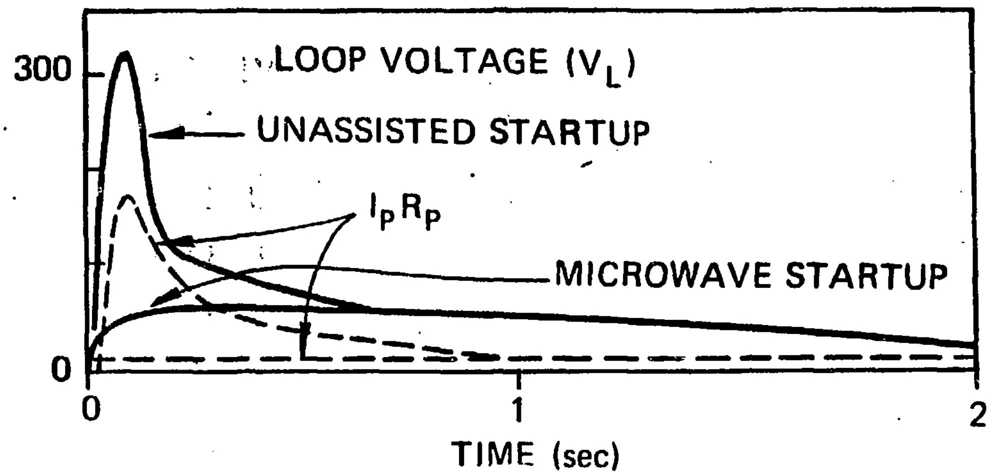

MICROWAVE HEATING SCENARIOS CAN ENHANCE $\overline{\beta}_C$ AND REDUCE STARTUP V_L

- Proper plasma profile control may
  - Increase stable $\overline{\beta}_C$ substantially
  - Maintain high β equilibrium over long times
- Microwave startup near UHR may reduce startup V_L by factor of 10
- Points to the development of

  CW power = 1 MW – startup

  ~ 20 MW – profile control

  ? Tunable frequency, multiple frequencies
- Requirements similar to those of EBT-II

THE ORNL TNS PROGRAM AIMS TO REDUCE COST AND RELIANCE ON ADVANCED HEATING TECHNOLOGY

ORNL TNS STUDIES

- Lead to economic tokamak power reactor
- Identify physics assumptions and operating scenarios to reduce implied technology requirements

NEUTRAL INJECTION

- Neutral beam heating scenario suggests

  $E_b = 150 - 200$ keV

  ⟶ Development of variable beam deposition and improved + ion injector efficiency

MICROWAVE HEATING

- ECR profile heating and UHR pre–heating scenarios may result in large benefits

  ⟶ development of sources

  $F_\mu = 120 - 150$ GHz, CW

  $P_\mu = 1$ MW – startup

  20 MW – profile control