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ITER HELIUM ASH ACCUMULATION

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ABSTRACT

Many studies have shown the importance of the ratio τ_{He}/τ_E in determining the level of He ash accumulation in future reactor systems. Results of the first tokamak He removal experiments have been analysed, and a first estimate of the ratio τ_{He}/τ_E to be expected for future reactor systems has been made. The experiments were carried out for neutral beam heated plasmas in the TEXTOR tokamak, at KFA/Julich. Helium was injected both as a short puff and continuously, and subequently extracted with the Advanced Limiter Test-II pump limiter. The rate at which the He density decays has been determined with absolutely calibrated charge exchange spectroscopy, and compared with theoretical models, using the Multiple Impurity Species Transport (MIST) code. An analysis of energy confinement has been made with the PPPL TRANSP code, to distinguish beam from thermal confinement, especially for low density cases. The ALT-II pump limiter system is found to exhaust the He with a maximum exhaust efficiency (8 pumps) of ~8%. We find $1<\tau_{He}/\tau_E< 3.3$ for the database of cases analysed to date. Analysis with the ITER TETRA systems code shows that these values would be adequate to achieve the required He concentration with the present ITER divertor He extraction system.

INTRODUCTION

The earliest considerations of fusion reactor requirements showed that He ash accumulation would have to be controlled [1]. More detailed analysis showed that the ratio τ_{He}/τ_E determines the ash concentration, where τ_{He} is the intrinsic He confinement time and τ_E is the energy confinement time [2]. Considerations of energy and particle balance have recently been shown to establish the requirement that $\tau^*_{He}/\tau_E< 7\text{-}15$ in reactor systems [3], where $\tau^*_{He}=\tau_{He}/(1-R_{He})$ is the effective He confinement time. Thus, the present ITER

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guidelines allow a 10% concentration of He, relative to n_e. The purpose of this paper is to describe the analysis of recent experiments on the TEXTOR tokamak, with the ALT-II pump limiter system, in which He was injected and removed. Modeling of these experiments has allowed a first estimate of experimentally determined values for the ratio τ_{He}/τ_E. We have also carried out calculations with the TETRA systems code to determine the values τ_{He}/τ_E which are required to attain n_{He}/n_e=10% in the ITER reference design. We compare the experimental results obtained to date with the ITER requirements.

EXPERIMENTS and ANALYSIS

TEXTOR experiments

The TEXTOR He removal experiments have been described in detail in [4,5]. A short He puff is introduced into a discharge with a low background He concentration, and the evolution of the He density is followed in space (at 3 radial locations) and time using Charge Exchange Spectroscopy of the recombination of H neutral beam particles with He^{++} in the plasma core. Measurements of He concentration are also made at the ALT-II limiter and in the pumping duct outside the plasma. These measurements are consistent, and indicate that He is removed with an exhaust efficiency of ~ 8%, when all 8 of the ALT-II pumps are activated. The TEXTOR system is unique, in that its turbomolecular pumps actually remove the He, unlike cryogenic immobilization or getter systems in which the He can recycle. Thus, by examining the He decay, as the number of pumps is increased, the intrinsic He confinement time τ_{He} is discriminated from the effective He confinement time, τ^*_{He}. In order to estimate ITER ash accumulation we must differentiate the intrinsic He confinement time, which is a property of the underlying plasma transport, from τ^*_{He}, whose value depends on details of the removal system.

He diffusion analysis

The TEXTOR He extraction experiments have been modeled with the Multiple Impurity Species Transport (MIST) code [6], to establish values of the diffusivity and pinch coefficient which are required to match the observed spatial profiles and temporal decay rates. The MIST model for He diffusion is

$$\Gamma = D_A(-\partial n_{He}/\partial r + c_v\, n_{He}\, \partial \ln n_e/\partial r)$$

where D_A is the anomalous diffusivity, and the He pinch is characterised by the value of c_v In this parameterisation of the pinch coefficient, the steady state distribution is $n_{He} \sim n_e^{c_v}$, and the simplest neoclassical results would suggest $n_{He} \sim n_e^{Z}$, so that $c_v(=Z) = 2$ for He.

Figure 1 shows the values of c_v required to match a sequence of cases in which ALT-II pumps are enabled, in pairs, starting from the no-pumping case (shot 41066) up to the maximum of 8 (shot 41059). The decay of He at the r=25cm point is fit with a model in which D_A varies from 0.1 m^2/s in the center to 1 m^2/s at the plasma edge. The pinch coefficients shown in Figure 1 are similar for the cases with pumping (c_v~0.65 - 0.85), but must be increased to c_v~1.5 for the case (shot 41066) without pumping. Modeling of the full pumping shot (41059), for which a radial profile is available, indicates that the assumed energy of recycling He, which is taken to be 0.1 eV for the cases shown in Fig. 1, must be increased to ~ 1 eV to match the outermost (35cm) data, keeping D_A and c_v approximately the same. Alternatively, both a higher D_A (~4 m^2/s) and a higher c_v (~ 1.6) also fit the evolution, with E_{He} = 0.1 eV. However, spectroscopc observations showing the presence of energetic recycling He have been made with a special graphite test limiter in TEXTOR [7], and this evidence supports the model with higher edge energy.

Energy confinement analysis

Some of the TEXTOR measurements have been conducted at low density ($n_e \sim 2\ 10^{19}\ m^{-3}$), and thus the energy confinement time of the thermal plasma component must be distinguished from the beam contribution. We have used the PPPL TRANSP analysis code [8] to do this. ECE electron temperature profiles, electron density profiles from HCN laser measurements, bolometer radiation measurements, the recycling hydrogen light and plasma current and voltage measurements have been used in the analysis.

Results

The results of the He particle and confinement and energy analysis are shown in the Table. Results are shown for a pumping sequence 41059-41065 and for other cases which have been analysed. The no-pumping case (41066) is omitted because the effective recycling coefficient is near unity. Shots 40545 and 40549 have similar parameters : shot 40545 is a discharge with co-injection (1.6 MW), while shot 40549 has both this co-injected beam and a counter beam, with P_{ctr}=0.8 MW. The case with both beams present has approximately half the He confinement time. These results give $0.98 < \rho < 1.41$ [where $\rho \equiv \tau_{He}/\tau_E$] for the pumping sequence, and $0.89<\rho< 3.3$ for all the cases analysed to date. The results should be regarded as a first look at the data for He removal experiments. Additional study is planned on TEXTOR using a multi-chord CXE system with enhanced spatial resolution and with a more extensive survey of the operating space.

Table

Shot	τ_{He}^{*} (ms)	τ_{He} (ms)	τ_E (ms)	$\rho \equiv \tau_{He}/\tau_E$	$\rho^{*} \equiv \tau_{He}^{*}/\tau_E$
Pumping sequence					
41059	563	45	32	1.41	12.5
41062	691	41.4	32	1.29	21.6
41063	1040	41.4	34.	1.22	30.6
41065	1760	35.2	36.	0.98	48.9
Co-NBI					
40545	757	60.6	40	1.51	18.9
Both co- and counter- NBI					
40549	390	31.2	35	0.89	11.1
40349	766	61.3	28	2.19	27.4
38110^{+}	505	40.4	12	3.33	42.

$^{+}$Low density case : may not be typical of this regime

ITER He accumulation

Calculations of the value of ρ which is required for ITER have been made using the TETRA systems code [9]. Figures 2 and 3 show the impact of ρ and the He recycling coefficient, R_{He}, on ITER performance. Figure 2 shows the required enhancement of energy confinement for the ITER reference design, with I_p=22 MA and a neutron wall load of 1 MW/m^2. The corresponding He concentration is shown in Fig. 3. Fig. 2 shows, from the indicated range of ρ in the TEXTOR results, that efficient He pumping is required. A He recycle coefficient $R_{He} \leq 0.9$ is needed for the lower ρ values observed, and $R_{He} \leq 0.6$ for the higher values of ρ, to maintain the same confinement margin and a He concentration ~ 10%. These values of R_{He} are approximately equal to the present He removal efficiency found in modeling the ITER divertor. However, the present models rely on the isotopic segregation of the He density on the ITER divertor strike point to push the He density toward the outside (nearer the pump). Present multifluid ITER modeling predicts this effect because of the strong friction of incoming He with D-T ions recycling from the divertor plate.

Conclusions

A first glance at results of He removal experiments with the ALT-II pump limiter on the TEXTOR tokamak suggests that the intrinsic He diffusivity does not prohibit the attainment of the He concentration guidelines in the ITER reference design. The TEXTOR experiments, which employ active He pumping, allow the discrimination of the intrinsic He confinement time from the "effective" confinement time $\tau^*_{He}=\tau_{He}/(1-R_{He})$. A ratio of He particle confinement time to thermal energy confinement time in the range ~1-3 has been observed. Systems analysis results for the ITER reference design suggest that efficient He pumping is required. The required pumping is approximately matched by the present capabilities of the ITER divertor design.

References

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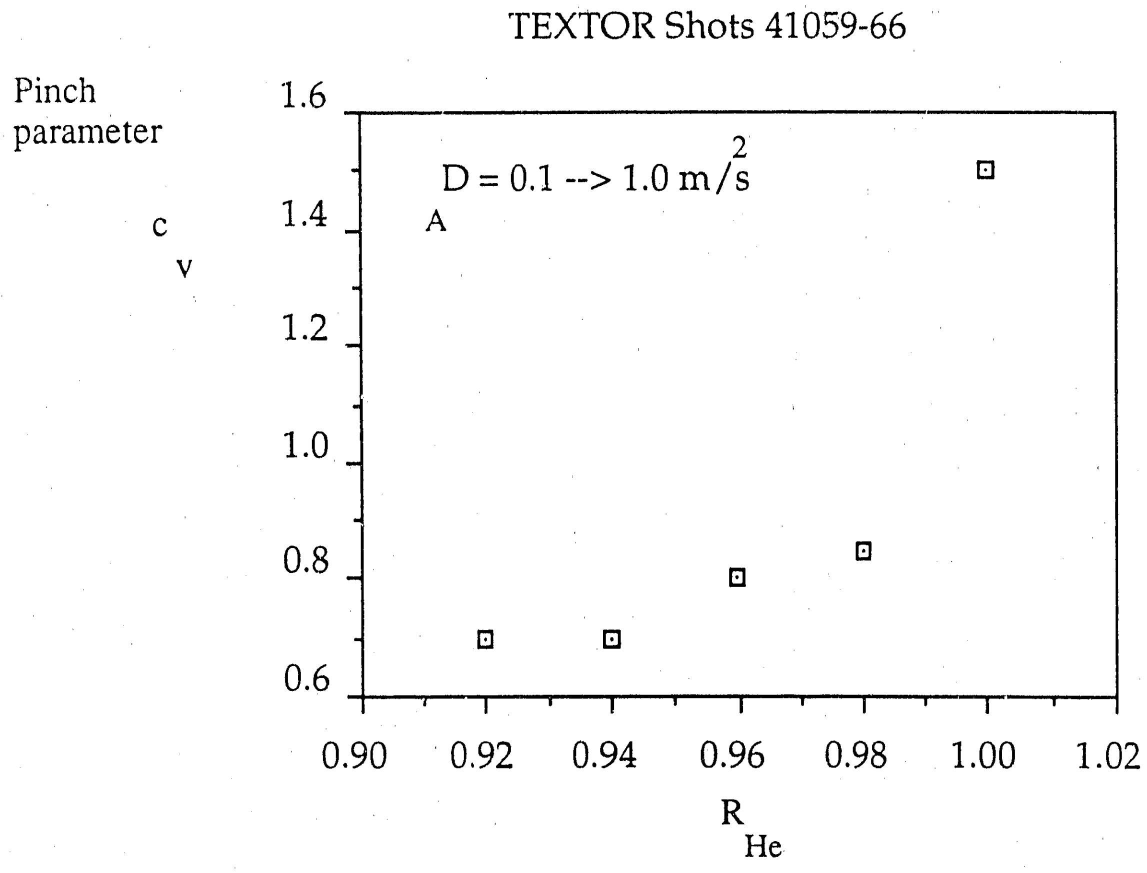
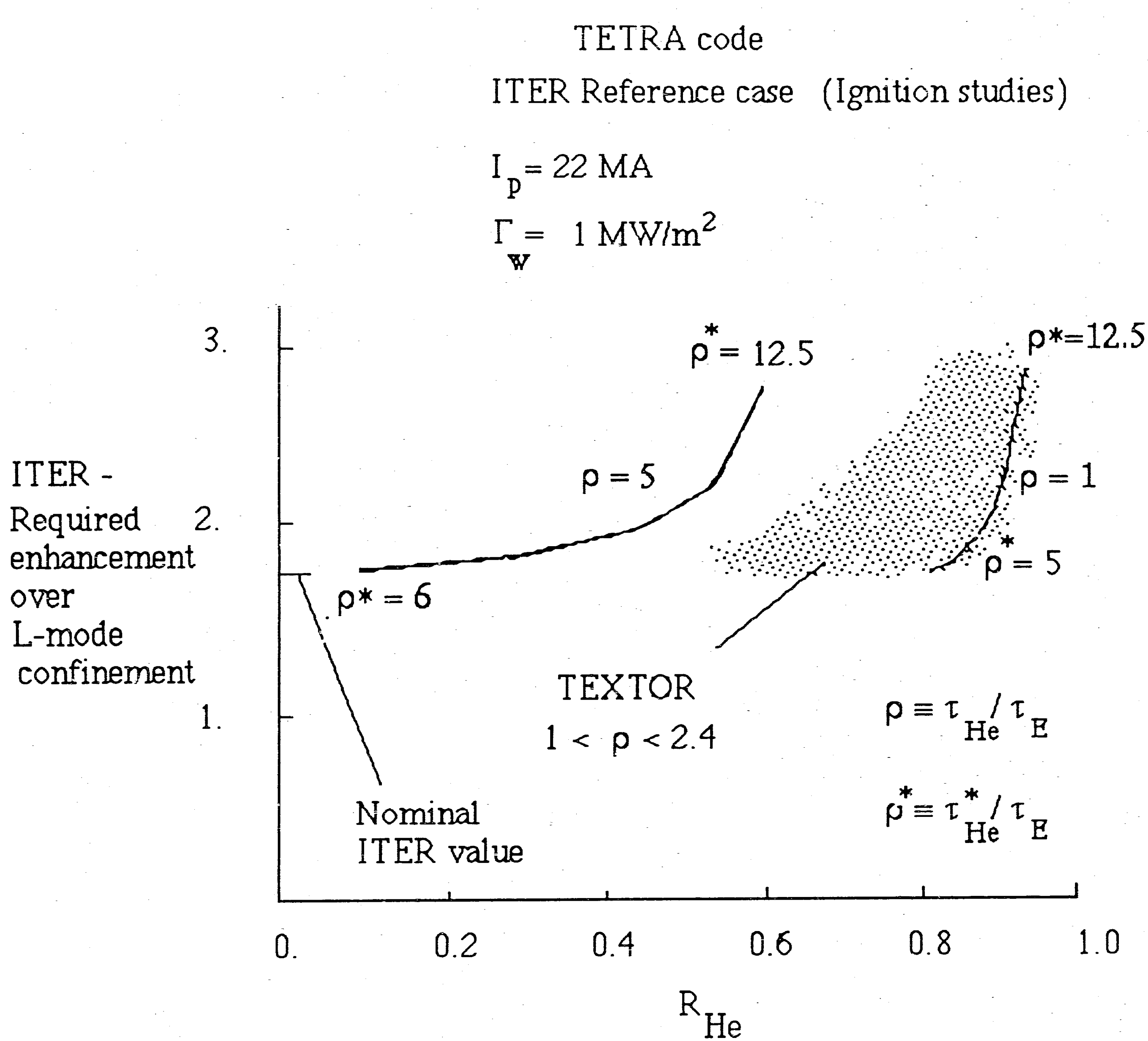
Figure Caption

1. Pinch parameter, c_v, required to match the measured He^{++} density evolution at r=25 cm with diffusivity varying from 0.1 m^2/s in the core to 1m^2/s at the edge, in a sequence of TEXTOR shots varying from full (41059) to no pumping (41066). [MIST code].

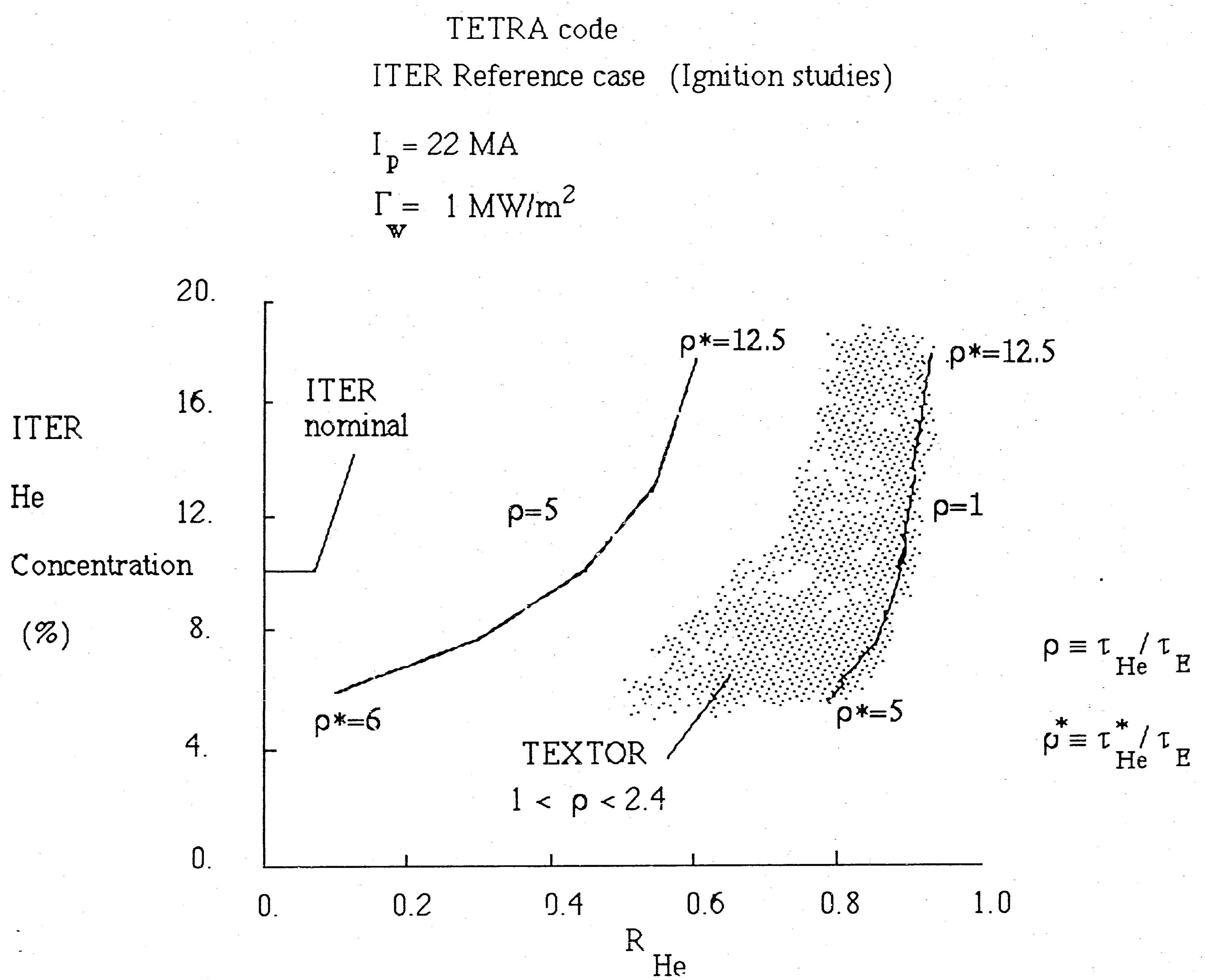
2 Energy enhancement over L-mode scaling required for ignition in the ITER reference design, as a function of the He recycling coefficient. Values for ρ ($\equiv\tau_{He}/\tau_E$) =1 and 5 are shown. Also, the value of ρ^* (which depends on R_{He}) is shown as is the range of values indicated by preliminary analysis of TEXTOR He removal experiments. [TETRA code]

3. Same as Fig. 2, for the He^{++} concentration at ignition.


TEXTOR Shots 41059-66
Pinch parameter
c
v
A
D = 0.1 --> 1.0 m/s
2
1.6
1.4
1.2
1.0
0.8
0.6
0.90
0.92
0.94
0.96
0.98
1.00
1.02
R
He



TETRA code
ITER Reference case (Ignition studies)
$I_p = 22$ MA
$\Gamma_w = 1$ MW/m^2
ITER - Required enhancement over L-mode confinement
3.
2.
1.
$\rho^* = 12.5$
$\rho = 5$
$\rho^* = 6$
$\rho^* = 12.5$
$\rho = 1$
$\rho^* = 5$
Nominal ITER value
TEXTOR
$1 < \rho < 2.4$
$\rho \equiv \tau_{He} / \tau_E$
$\rho^* \equiv \tau^*_{He} / \tau_E$
0.
0.2
0.4
0.6
0.8
1.0
R_{He}


TETRA code
ITER Reference case (Ignition studies)
$I_p = 22$ MA
$\Gamma_w = 1$ MW/m^2
ITER
He
Concentration
(%)
20.
16.
12.
8.
4.
0.
ITER
nominal
ρ*=12.5
ρ=5
ρ*=6
ρ*=12.5
ρ=1
ρ*=5
TEXTOR
1 < ρ < 2.4
$\rho \equiv \tau_{He} / \tau_E$
$\rho^* \equiv \tau^*_{He} / \tau_E$
0.
0.2
0.4
0.6
0.8
1.0
R_{He}

END

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