TARGET PLASMA CONDITIONS IN TCA

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ABSTRACT

We discuss the conditions of the target plasma in the TCA tokamak prior to the rf heating pulse. The toroidal field and plasma current are held fixed and the density is varied from \( n_e \sim 0.5 \times 10^{13} \) to \( 5 \times 10^{13} \) \( \text{cm}^{-3} \). Both hydrogen and deuterium discharges are considered. The density and gas dependence of the macroscopic plasma parameters is analysed, as well as the impurity and energy content. We observe an increasing peaking of the electron density profile as the density is increased. This observation is compatible with other small tokamaks and we present a density profile scaling law that depends on the Murakami parameter \( n_e(0)R_0/B_\phi \). We find that for this range of density, the global energy confinement time is proportional to the line density as is typically the case before the saturation of "Alcator Scaling" which provides an adequate representation of the data. We perform a radial electron power balance in order to estimate the electron thermal conductivity \( n_e \chi_e \). Its value at half radius is around \( 4 \times 10^{17} \) \( \text{cm}^{-1}s^{-1} \) for the lowest density discharges and decreasing to \( 2 \times 10^{17} \) \( \text{cm}^{-1}s^{-1} \) at the highest density. The diagnostics used for this study are also briefly described, together with their analysis techniques.
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I. INTRODUCTION

The TCA tokamak has been described in detail [1] and has the following characteristics:

\[
\begin{align*}
R_0 &< 15.2 \text{ kG} \\
I_p &< 170 \text{ kA} \\
P_0, a & = 61.5, 18.0 \text{ cm} \\
n_e(0) &< 10^{14} \text{ cm}^{-3} \\
t_{pl} &\sim 100 \text{ msec flat-top.}
\end{align*}
\]

The experiment is mainly dedicated to the study of Alfvén Wave Heating. The first experiments carried out showed heating but also an increased impurity content [2]. Changes in limiters and antenna design have led to considerable improvement [3]. Standard discharges, made with bare carbon limiters and TiN coated bar antennae without screens, have \( P_{rad}(0)/P_{oh}(0) \sim 5\% \) and TCA can now be considered to produce a clean target plasma. We therefore have systematically studied the ohmically heated target plasmas used for the rf experiments. Typically in these rf experiments we vary the target plasma density over a wide range, as well as the working gas, mainly due to the fact that both change the Alfvén Wave resonance structure.

In this report we discuss the conditions in which the measurements were carried out (section II), the diagnostics used and their analysis (section III) and the results from the density scans in both hydrogen and deuterium as the working gas (section IV).

II. EXPERIMENTAL CONDITIONS

a) Torus

The torus is stainless steel (316 LN), of rectangular cross-section, with a minimum limiter radius to wall separation of 35 mm at the inside wall (Fig. 1). The pumping speed at the torus is \( \sim 300 \) l/sec. The vessel is prepared for tokamak operation as follows. After opening to air, and after pumping to \( \sim 2\times10^{-7} \text{ Torr(G)} \), the Viton O-rings are heated to \( \sim 90 \) °C, using the cooling circuit, for several hours. A
continuous a.f. discharge (5 kHz) is then run in Argon at \( \sim 2 \times 10^{-4} \) Torr(G) for one hour, during which the torus heats up to 80 °C. This is then normally repeated the following day. The mass spectrum of the background gas is then as shown in Fig. 2a). Regular Taylor Cleaning (2x30 ms a.f. pulses/sec) is then carried out each night for \( \sim 10 \) hours in the working gas to be used during the following day. Typical mass-spectra of the prepared torus are shown in Fig. 2b) for H\(_2\) and 2c) for \( D_2 \) operation. The base pressure is typically \( 2.0 \times 10^{-7} \) Torr(G) after the cleaning due to outgassing of the loaded walls, and it drops to typically \( 8 \times 10^{-8} \) Torr(G) after prolonged pumping over a weekend. The mass-spectrum of the residual gas after a normal tokamak shot is shown in Fig. 2d) for H\(_2\) operation and Fig. 2e) for \( D_2 \) operation, in which we see a large production of hydrocarbons from the uncoated carbon limiters. The pump-down curves for some residual gas masses after a tokamak shot are shown in Fig. 3.

b) **Plasma Operation**

The target plasma for this work was run at 133 kA under active current-feedback control for a pulse-length of \( \sim 120 \) msec at which time the loop voltage is cut. The toroidal field was set to 15.2 kG, giving \( q(a) \sim 3 \). A typical discharge is shown in Fig. 4, of which only the period before the rf pulse is used for this study. A total of 0.49 Volt-seconds is consumed before the primary current reaches zero. The plasma current is ramped up at \( \sim 4-7 \) kA/msec to its preset value. The working gas is injected 15-20 msec before the breakdown and the piezoelectric valve is operated under feedback control to maintain a predetermined density waveform. During regular operation a 5-minute shot cycle is operated, limited by the toroidal field coil cooling.

III. **DIAGNOSTICS AND THEIR ANALYSIS**

The following diagnostics were used regularly on TCA during these scans:
- EM diagnostics
- Visible spectroscopy
- Interferometers: 2 mm, 0.5 mm
- X-rays: T_e by filters, Pinhole camera, Hard-X
- Bolometer: single chord scannable
- Thomson Scattering: one-pulse, one-point
- E.C.E.: scanning Michelson interferometer
- Neutral Particle Analyser: 5 channels, one-chord
- Langmuir probes.

The layout of these diagnostics is shown in Fig. 5 and they will now be discussed in turn.

a) EM diagnostics

The loop-voltage is measured by a single-turn shielded loop at R \approx 40.5 \text{ cm}, Z \sim 26 \text{ cm} in a region where there is little stray field from the OH-coil. We have also compared its signals with the total gap-voltages. The \( L_p I_p \) correction is made using a value of \( I_p \) chosen to remove the discontinuity in \( V_R = V_L - L_p I_p \) when a voltage step is applied to the OH-coil.

The plasma current is measured using a single-turn Rogowski coil wound outside the torus.

The horizontal position of the centre-of-gravity of the current distribution is measured using a modified "cos-coil" wound on a square cradle outside the torus. Its winding density was numerically calculated not only to take into account the square frame but also a) to remove the offset due to toroidicity and b) to linearize the response as a function of displacement of the current centre-of-gravity (c.g.). The response was tested using a toroidal loop of variable radius. The vertical position of the current c.g. is similarly measured using a numerically calculated "sine-coil". Both coils are sensitive to net poloidal fields and these effects are subtracted electronically in the screened room. In the horizontal position feedback loop, allowance is made for the distance between the current c.g. and the outer surface centre. For typical profiles, the current c.g. is roughly at 1/3 of the distance from the magnetic axis to the outer surface centre.

The paramagnetic increase in toroidal flux is measured using a
multi-turn "diamagnetic" loop. Absolute calibration of this loop has not yet proved possible and an improved loop has been constructed. We calculate simply

$$\beta_z = 1 - \frac{8 \pi B_z A \phi}{\mu_0 I_z^2}$$

noting that this value is almost independent of both plasma position and shape.

The high frequency modulation of the plasma poloidal field at ~5-20 kHz is measured by pick-up loops in a ceramic tube placed in the shadow of the limiters. This measurement is used for plasma set-up to avoid spending too much time in regions close to integral values of the safety factor q during the current build-up.

In addition the various poloidal control winding currents are measured using standard Rogowskis.

b) Spectroscopic Measurements

We observe the H$_\alpha$+D$_\alpha$ emission (λ=6563 Å) through a narrow band interference filter (λ=6563±5 Å) using a standard photomultiplier tube (EMI 9658 B). The light is collimated to ±3.6 mrad, much narrower than the equivalent filter-bandwidth. One diameter is viewed, well away from the limiters, as a fixed measurement. A second H$_\alpha$+D$_\alpha$ monitor is used to observe toroidal asymmetries in the emission, viewing through all available ports.

In addition we observe the emission of OII (4415 Å) and FeII (2599 Å), again using EMI-interference-filter combinations, with filter transmissions given by 4415±10 Å and 2600±120 Å respectively.

Specially designed dynode chains are used for all tubes, giving a linear response for pulses up to 5 mA x 1 kΩ x 5 msec. This avoids saturation during the initial ionization pulse.

c) Interferometry

A 140 GHz interferometer is used with a 5 mW Gunn diode source as
a regular monitor of line-averaged plasma density, and has already
been described [4]. The published technique using a circulator for
switching in a \(\pi/2\) phase-shift was replaced in 1982 by modulation of
the diode source voltage with a simple square-wave. Since the source
output frequency is slightly voltage dependent, we arrange that the
product path-length \(x \Delta f/c\) is equal to \(1/4\). In this way we have been
able to dispense with the lossy circulator element. The new system
also requires much less setting up effort. Its total phase analogue
output is also used for feedback control of the plasma density.

Electron density profile measurements are performed with an 8
channel FIR interferometer \((y=R-R_0=-15.5, -10.5, -6.5, -2.5, 1.5, 5.5,
10.5, 15.5 \text{ cm})\). It uses a 10 mW CH\(_3\)I laser \((\lambda=447 \mu\text{m})\) optically pumped
by a CO\(_2\) laser. The optical set-up is similar to that used on TFR [5]:
the reference beam and the 8 plasma beams are mixed with a frequency
shifted beam (5-20 kHz, depending on the time resolution required),
producing low frequency beating. The phase shift is then measured with
an electronic clock timing the interval between zero-crossings of the
reference and the plasma signals. Fringe jumps are interpreted by the
time derivative of the phase. Fig. 6 shows the typical behaviour of
the line-integrated densities.

Some studies are made without inverting the profiles, but when
necessary, an asymmetric Abel inversion is used [6]. First a polyno-
mial or a cubic spline is fitted to the discrete data to give a contin-
uous phase shift \(\Phi(y)\) \((y=R-R_0)\); the density is then calculated as
\(n(r,y)=n_0(r)(1+u(y))\), where \(n_0\) is found by applying Barr's inversion
[7] to the even part of \(\Phi\) and \(u\) is the odd part of \(\Phi\) (Fig. 7). The
central density is not sensitive to the fitting used, although a poly-
nomial of too high an order produces artificial oscillations. The
profiles are also stable to imposing a zero phase shift at a position
further out than the limiter radius. Imposing a smaller plasma radius
causes problems for the inversion (Fig. 8).

d) X-rays

The electron temperature of the plasma is determined by using
soft X-ray diagnostics. The so-called "two-foil absorber" method [8],
relies on the a priori assumption that the X-ray power spectrum of a Maxwellian plasma varies as $\exp(-E/T_e)$ [9] and the fact that the transmission coefficient of X-rays through thin foils is strongly energy dependent. Thus $T_e$ can be calculated to a good approximation using a formula of the type:

$$T_e [eV] = \frac{a [eV]}{(\ln (\phi_1/\phi_2))^\alpha}$$

where $\phi_1$ = X-ray flux measured through thinner foil
$\phi_2$ = X-ray flux measured through thicker foil

$a$ and $\alpha$ are plasma and apparatus dependent coefficients, determined by theoretical X-ray emission calculations [10,11].

On TCA, these temperature measurements are performed by using 5 pairs of surface barrier diodes (ORTEC CA-15-100-300), with the following characteristics: surface = 100 mm$^2$ (circular)
- Au contact layer = 0.02 µm
- Si dead layer = 0.2 µm
- Si active layer = 300 µm

The diodes view the plasma in a poloidal plane through a slit (pin–hole technique), and are covered with 25 or 75 µm Be foils to measure $T_e$ at five radii in the plasma, 0, ±5.3 and ±10.6 cm. At present, the values of the coefficients used are: $a=821$ [eV] and $\alpha=1.481$, applicable to a pure hydrogen plasma. More accurate values are under calculation, to take into account the impurity content of the plasma.

The X-ray temperatures at the different radii have been calibrated with respect to a Thomson scattering $T_e$ profile for a typical set of shots. This is performed by means of a correction factor $c$ that multiplies the ratio $\phi_1/\phi_2$.

In addition we use a single pair of diodes with 150 and 375 µm respectively beryllium filters. These diodes observe $\sim 20\%$ of the plasma diameter, viewing at 30° from the vertical. The AC component of these signals is selected in two frequency ranges and used for a) sawtooth amplitude at $f \sim 1$ kHz and b) $f > 5$ kHz for mhd mode activity.
The Hard X-ray flux from the limiters is measured using an NE102A plastic scintillator plus photomultiplier combination.

e) Bolometer

The bolometer on TCA [12] consists of a thin Ge layer (1 μm) which has been evaporated onto a thin foil of stainless steel with 1.5 μm of MgO₂ as electrical insulation. The plasma radiation absorbed by this foil results in a change in electrical resistance of the semiconducting material which is measured through a fine gold structure evaporated onto the semiconductor.

The resistance, being of semiconducting material, follows an exponential law with respect to its temperature.

\[ R(T) = R_0 \, e^{-\alpha T} \]

where \( R_0 \) : calibrated resistance value
\( \alpha \) : temperature coefficient

The absorbed power is obtained by performing the following calculation:

\[ P = c \, \frac{dT}{dt} + G \, T(t) \]

or

\[ P = c \left( \frac{dT}{dt} + \frac{1}{\tau} \, T(t) \right) \]

where \( c \) : heat capacity of the detector
\( G \) : thermal conductance accounting for losses through heat diffusion and reradiation
\( \tau \) : thermal relaxation time

The solution of the second equation is performed numerically.

The bolometer is a single-channel instrument and can therefore view only one chord of the plasma at a time. For spatial radiation profiles a series of 10-15 reproducible shots is needed. To unfold the experimental data, the line intensity profile is fitted by a spline-polynomial of third order. Abel's integral is then solved numerically for the derivative of this polynomial. Care has to be taken when
positive slopes occur, especially near the plasma centre. Typical profiles, both projected and inverted, are shown in Fig. 9.

f) Thomson Scattering

The electron temperature is measured by conventional Thomson scattering of ruby-laser light. The laser system (Apollo, model 35) provides, in principle, two separate pulses of ~10 J during 25 ns. The design, similar to a previously proven system [13], is shown in Fig. 10. The laser, the optical apparatus and the detection system are mounted on a trolley which can be moved between discharges to measure a temperature profile (~12 cm<y<15 cm). The beam dump is constructed with two 17 cm long blue glass plates set at the Brewster angle. The relay optics consist of three lenses and 2 notch filters. The collection lens with a diameter of 110 mm forms an image of the scattering volume on a field lens. Two notch filters positioned symmetrically with respect to the field lens are used to reduce the laser stray light. A third lens focuses the image on the entrance slit (15 mm height, 2 mm width) of a 0.5 m Spex spectrometer. The light refracted by the grating (600 or 1200 l/mm) falls on ten fibre optic channels. The photon flux from each channel is monitored by a photomultiplier, type EM1 9658 RA. The quantum efficiency of these tubes is about 9% at 7000 Å, rising to ~15% at 6300 Å and a gain of 5x10^6 can be easily achieved. The signals are then transferred to a Camac ADC.

The gains of the photomultipliers are chosen to give a signal proportional to the power input in each channel. This is performed with a calibrated tungsten ribbon lamp. Results from a typical pulse are shown in Fig. 11.

The temperature calculation [14] takes into account the relativistic effects which become important for T_e>1 keV.

g) Electron Cyclotron Emission

A scanning Michelson interferometer is employed on TCA to measure the plasma emission spectrum up to 1000 GHz. The system is based on a conventional vibrating mirror polarizing interferometer [15]. Radia-
tion from the equatorial plane of the plasma is transmitted by a
wedged crystal quartz window and a 50 mm diameter light pipe of 1.2 m
length to the spectrometer. The antenna gain has been measured to be
12, corresponding to an image of 10 cm diameter at the centre of the
plasma. The detector is an InSb bolometer operating at 4.2 K. A scan
can be made in 12 ms with a maximum path difference of 30 mm, corre-
sponding to a frequency resolution of 10 GHz. Mirror displacement is
either measured optically with a HeNe laser interferometer or electro-
nically by use of the motional emf in the vibrator coil. This latter
method is more reliable although it requires calibration with a fixed
frequency microwave source. A typical scan and the resulting spectrum
of emission in the extra-ordinary polarisation are shown in Fig. 12.
Both the time and frequency resolution given above can be improved
since the fringes of the interferogram are localized in the central
part of the scan when the mirror is moving most rapidly.

Although the parameters of TCA are such that the plasma should be
optically thick to the extraordinary mode of the second harmonic ece,
the low toroidal field severely restricts its use as an electron tempe-
trature diagnostic. The upper (or right-hand) cyclotron cut-off [16]
appears in the plasma when $n_e > 2.7 \times 10^{13} \text{ cm}^{-3}$, interfering with obser-
vation of the second harmonic. The positions where observation is
blocked can be determined from the density profiles measured by the
FIR interferometer. These are plotted as a function of the line
averaged density in Fig. 13 b). If $n_e < 1.4 \times 10^{13} \text{ cm}^{-3}$ the spectrum is
completely dominated by supra-thermal emission, particularly near the
plasma frequency. Thus there is only a narrow density range in which
complete temperature profiles can be obtained. A further problem of
the low field, and hence low emission frequencies, is the large varia-
tion in the instrumental response spectrum which particularly affects
the profile on the low field side.

Fig. 14 shows the temperature profile deduced from the spectrum
in Fig. 12 and another at slightly higher density, clearly showing the
effects of the cut-off. It appears that the second profile in Fig. 14
is affected even at frequencies higher than cut-off, an observation
that is confirmed in Fig. 13 a). Here the central ece temperature is
shown to drop below that given by Thomson scattering already at densi-
ties below cut-off. This is in contrast with recent work on ASDEX [17] where refractive effects due to cut-off (calculated from assumed density profiles) were not seen to be important. An explanation may lie in the longer wavelengths of emission at low fields, and the relatively larger proportion of the plasma viewed by the TCA ece system.

h) **Neutral Particle Analyser**

The central ion temperature is measured by spectral analysis of the charge exchanged neutral atoms originating in the core of the plasma. The emitted flux

\[ S = n_i n_0 \langle \sigma \nu \rangle \frac{dn_i}{dE} \frac{d\Omega}{4\pi} \]

combined with a detector efficiency given by \( \eta(E,n) \) for channel \( n \) leads to the expression, for a Maxwellian plasma,

\[ T_i \sim \left( \frac{d\eta(E)}{dE} \right)^{-1} \] \( n \) \[ g(E) = \frac{S_n(E) \Delta E}{\sigma_{ex} E \Delta E \eta(E,n)} \]

The NPA used on TCA was constructed by the Ioffe Institute [18] and is shown in Fig. 15. The instrument has 5 channels with relative energies 3.7 : 2.7 : 1.9 : 1.3 : 1.0. There is a constant ratio between the energies of the different channels and the voltage applied on the electric divider \( U_{div} \) \( E_1 : U_{div} = 1 \text{keV}:0.6 \text{keV} \). It is capable of both mass-dependent (E-B) and mass-independent (E-E) analysis, of which the latter is mostly used on TCA. Relative calibrations of the 5 channels was carried out using a source installed in the analyser, and then checked by sweeping the spectral range of the instrument to superimpose the 5 spectra. Only slight modifications to the channel efficiencies were needed to align the separate spectra.

The signal treatment consists of a low-level hybrid discriminator (Lecroy PC100) close to the open multiplier tube which delivers pulses into 50 \( \Omega \). The ECL output signal is then counted in the screened room following further re-shaping. The data analysis consists of a least-squares fit through selected channels as a function of time. Typical data are shown in Fig. 16. The spectrum observed is not a perfect
gaussian, being slightly concave, and the measured value of \( T_i \) depends on the spectral range chosen for analysis. In Fig. 17 we show the ion-temperature as a function of the typical range of energies used. We see that using high energy channels over-estimates \( T_i \) because the noise on these channels is a significant part of the signal. Low energy neutrals emitted by the outer plasma produce a particle excess in the low energy range, giving a too low estimation of \( T_i \). We avoid most of these problems by restricting the analysis between 1 and 4 keV.

i) **Langmuir Probe**

The scrape-off layer has been investigated by means of electrical probes. A movable Langmuir probe is installed in the equatorial plane of the TCA vacuum vessel. The probe is opposite the limiters and is a 5 mm long Molybdenum wire of 0.6 mm in diameter. The probe voltage can be swept between -100 V and 100 V within about 1 ms. The probe current was measured with a current probe. The ion density is obtained from measurements of the ion saturation current (probe bias -120 V). The electron temperatures were obtained through analysis of the Langmuir probe characteristics. The analysis showed that during the ohmic heating phase the boundary plasma is maxwellian.

j) **Database Treatment**

Database analysis software was written for use on TCA, with records representing time-slice information during the tokamak shot. Most data are interactively verified and adjusted if necessary using cursor control. Display software allows windowing, power law combination of parameters, regression analysis and histogramming. Considerable effort was made to guarantee both flexibility and simplicity of operation.
IV. EXPERIMENTAL RESULTS

a) Raw Data

In Figure 18, we show the simplest raw data as a function of line-averaged density for both hydrogen and deuterium as working gases, namely:

a) plasma column resistance $R_{pl}$,
b) peak electron temperature $T_e(0)$ using Thomson scattering,
c) central ion temperature $T_i(0)$,
d) line-integrated radiated power $\int P_r \, dl$,
e) line-integrated line emission of $H_\alpha + D_\alpha$, OII, FeII,
h) $\beta+lj/2$,
j) $\beta_\perp$ as measured by the diamagnetic loop,
k) edge temperature and ionisation current from Langmuir probe measurements.

b) Density Profiles

The symmetric Abel inversions of the FIR 8 channel interferometer measurement for both low and high density discharges are shown in Fig. 19 a). One can notice on the normalised profiles $n_e(r)/n_e(0)$ that increasing the density tends to peak its profile (Fig. 19 b)). This fact is confirmed over the full density range by the plot of the half width at half maximum (Fig. 20) without any difference between hydrogen and deuterium discharges.

Such a density profile behaviour is different from that normally seen on larger tokamaks, but has been observed in Alcator A [19]. In particular, the following scaling has been proposed by them:

$$n_e(r) = n_e(0)(1-r^2/a^2)^{\kappa_n}$$ where $\kappa_n = 0.5 + 0.025 \bar{n}_{e13}$ for $10 < \bar{n}_{e13} < 60$, $I_p = 150$ kA and $B_0 = 60$ kG. Small circular Doublet III discharges ($a = 23$ cm, $I_p = 120$ kA, $B_0 = 24$ kG) [20] also show that the shape parameter $\kappa_n$ of the density profile $n_e(r) = n_e(0)[0.95(1-r^2/a_p^2)^{\kappa_n} + 0.05]$,.
where $a_p = 44$ cm, increases from 5 to 8 when $n_{el13}$ varies from 3 to 9. FT density profiles are also available [21] and, if restricted to values of the safety factor from 3 to 4, they tend to peak at higher densities.

We find that all the results can be matched together if they are plotted versus the Murakami parameter $n_e(0)R_0/B_\Phi$. Fig. 20 shows both the half width at half maximum normalized to minor radius and the peaking factor $\kappa_n$ versus this parameter, and one can see that the Alcator A scaling can be extended to include all these small radius tokamaks with $3 < q < 4$ as

$$\kappa_n = 0.75 + 1.3 \times 10^{-15} n_e(0)R_0/B_\Phi \quad [cm, kG]$$

The correlation coefficient is 0.77 if data from FT is excluded.

Although the Murakami parameter does provide an efficient linking of the data from these tokamaks it does suggest a dependence on $B_\Phi$ not seen in other machines [19]. Since we have used constant $q$ perhaps a scaling with $n_e(0)a^2/I_p$ would be more appropriate because a peaking of the profile as the plasma current is decreased has been observed elsewhere [19].

c) Impurities

We note that the electron temperature (Thomson) tends to decrease only marginally with increasing density, and that the column resistance increases slightly. In Fig. 21 a) we show the value of $Z_{eff}(0)$, assuming $q(0)=0.9$ for all densities, calculated as

$$Z_{eff}(0) = 1.84 \times 10^{-4} T_e(0) \frac{V_r}{B_\Phi} - 0.755 \quad [eV, V, kG]$$

and we notice, particularly in hydrogen, a continuous reduction as the density is increased.

In the core the radiation losses come mainly from heavy impurities and follow $P_{rad} \sim n_e n_I f(T_e)$, where $n_I$ is the impurity
where \( a_T = 44 \) cm, increases from 5 to 8 when \( \bar{n}_{e13} \) varies from 3 to 9. FT density profiles are also available [21] and, if restricted to values of the safety factor from 3 to 4, they tend to peak at higher densities.

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In the core the radiation losses come mainly from heavy impurities and follow \( P_{rad} \sim n_e n_I f(T_e) \), where \( n_I \) is the impurity
density. Taking the heavy impurities to be iron, f is then a weak function in the \( T_e \) range observed on TCA and we numerically estimate their concentration as

\[
\zeta_{\text{metal}} (0) = \frac{n_{\text{metal}} (0)}{n_e (0)} = 6.41 \times 10^{-2} \frac{P_{\text{rad}} [W]}{n_{e13} (0)}
\]

To obtain \( P_{\text{rad}} (0) \) we have assumed that \( P_{\text{rad}} \) has a flat profile. Since this is fairly true (Fig. 9), the error in not having measured \( P_{\text{rad}} (r) \) for all densities is probably only small. We see in Fig. 21 b) that \( n_{\text{metal}} (0) \) drops rapidly with density to less than 0.2%. From this we can go further and estimate the concentration of light impurities, assumed to be oxygen, as

\[
\zeta_{\text{light}} (0) = \frac{n_{\text{light}} (0)}{n_e (0)} = \frac{Z_{\text{eff}} (0) - 1.380 \zeta_{\text{metal}} (0)}{56}
\]

in which the core ionisation states are chosen as \( Z_{\text{metal}} \sim 20 \) and \( Z_{\text{light}} \sim 8 \). The result is plotted in Fig. 21 c), where the rather large scattering comes essentially from the uncertainty on \( Z_{\text{eff}} (0) \), itself due to the statistical error on \( T_e (0) \).

The working gas ion density is then calculated as

\[
\frac{n_i}{n_e} = 1 - 8 \zeta_{\text{light}} - 20 \zeta_{\text{metal}}.
\]

For densities \( n_{e13} > 2.5 \) we find that \( n_i/n_e > 80\% \).

d) Plasma Energy and Confinement Time

In order to calculate the plasma energy content we must know the temperature profiles, which are assumed to be \( T_i (r) = T_{i0} (1-r^2/a^2) \kappa_{T_i} \) and \( T_e (r) = T_{e0} (1-r^2/a^2) \kappa_{T_e} \). \( \kappa_{T_i} \) is set equal to 1.0, the value found with an ion power balance simulation with neo-classical thermal diffusivity enhanced by an anomalous factor of 2, and \( \kappa_{T_e} \) to 2.5 which is in agreement with ece measurements around \( n_{e13} = 2.5 \) and consistent with the calculated current density profile (see section IV e)). \( T_{e0}, T_{i0} \) and \( n_e (r) \) are measured quantities.
density. Taking the heavy impurities to be iron, f is then a weak function in the $T_e$ range observed on TCA and we numerically estimate their concentration as

$$\zeta_{\text{metal}}(0) = \frac{n_{\text{metal}}(0)}{n_e(0)} = 6.41 \times 10^{-7} \frac{P_{\text{Rad}}[W]}{n_e(0)^2}$$

To obtain $P_{\text{Rad}}(0)$ we have assumed that $P_{\text{Rad}}$ has a flat profile. Since this is fairly true (Fig. 9), the error in not having measured $P_{\text{Rad}}(r)$ for all densities is probably only small. We see in Fig. 21 b) that $n_{\text{metal}}(0)$ drops rapidly with density to less than 0.2%. From this we can go further and estimate the concentration of light impurities, assumed to be oxygen, as

$$\zeta_{\text{light}}(0) = \frac{n_{\text{light}}(0)}{n_e(0)} = \frac{Z_{\text{eff}}(0) - 1 - 380 \zeta_{\text{metal}}(0)}{56}$$

in which the core ionisation states are chosen as $z_{\text{metal}} \sim 20$ and $z_{\text{light}} \sim 8$. The result is plotted in Fig. 21 c), where the rather large scattering comes essentially from the uncertainty on $Z_{\text{eff}}(0)$, itself due to the statistical error on $T_e(0)$.

The working gas ion density is then calculated as

$$\frac{n_i}{n_e} = 1 - 8 \zeta_{\text{light}} - 20 \zeta_{\text{metal}}.$$

For densities $\bar{n}_{e13} > 2.5$ we find that $n_i/n_e > 80\%$.

d) Plasma Energy and Confinement Time

In order to calculate the plasma energy content we must know the temperature profiles, which are assumed to be $T_i(r) = T_{i0}(1-r^2/a^2)^{KT_i}$ and $T_e(r) = T_{e0}(1-r^2/a^2)^{KT_e}$. $\kappa_{T_i}$ is set equal to 1.0, the value found with an ion power balance simulation with neo-classical thermal diffusivity enhanced by an anomalous factor of 2, and $\kappa_{T_e}$ to 2.5, which is in agreement with ece measurements around $\bar{n}_{e13} = 2.5$ and consistent with the calculated current density profile (see section IV). $T_{e0}$, $T_{i0}$ and $n_e(r)$ are measured quantities.
We calculate

\[ W_e = \frac{3}{2} e \int n_e T_e \, dV \]
\[ W_i = \frac{3}{2} e (1-8n_{\text{light}}-20n_{\text{metal}}) \int n_e T_i \, dV \]
\[ W_{\text{light}} = \frac{3}{2} e n_{\text{light}} \int n_e T_i \, dV \]
\[ W_{\text{metal}} = \frac{3}{2} e n_{\text{metal}} \int n_e T_i \, dV \]
\[ W_{\text{tot}} = W_e + W_i + W_{\text{light}} + W_{\text{metal}} \]

in which we assume that the impurity ion temperature is equal to the hydrogenic ion temperature everywhere, due to the small energy transfer time between these species, and that the impurity concentrations have flat profiles. This latter assumption is also consistent with the current density profile calculated in section IV e).

\[ W_e, W_i \text{ and } W_{\text{tot}} \text{ are plotted in Figure 22. The fact that } W_e \text{ is greater in deuterium and that } W_i \text{ is greater in hydrogen may partially be explained by the proportionality between the electron-ion equilibration power } P_{ei} \text{ and } 1/A_i \text{, where } A_i \text{ is the ionic mass.} \]

We then calculate the global energy confinement times \( \tau_{Be} = W_e/P_{Oh} \) and \( \tau_E = W_{\text{tot}}/P_{Oh} \), shown in Figures 23 a) and b) respectively. The usual linear dependence on the line averaged density is immediately apparent, although \( \tau_{Be} \) for hydrogen appears to saturate at higher densities when anomalous ion transport becomes an important energy loss mechanism. It is of interest to compare the TCA results with some of the popular scaling laws for ohmically heated plasmas. In Figure 23 b) we show the prediction of the original Alcator A-INTOR scaling as modified by TFR [22]

\[ \tau_E = 5.0 \times 10^{-21} \bar{n}_e a^2 R_0 q^{0.5} \text{ [s,cm]} \]

and the neo-Alcator scaling presented by Goldston [23]

\[ \tau_E = 7.1 \times 10^{-22} \bar{n}_e a^{1.04} R_0^{2.04} q^{0.5} \]

The former law seems to describe the TCA data better, the latter
actually predicting a lower confinement time by a factor of 0.2 \((a/R_0)\) if it is rewritten (valid for PLT) as
\[
\tau_E = 1.0 \times 10^{-21} \, \bar{n}_e \, a^2 \, R_0 \, q^{0.5}.
\]

Equivalently for \(\tau_{Be}\) the TCA data is best approximated by an Alcator A type scaling. In Figure 23 a) we show the scaling law produced by minor radius scaling experiments on Doublet III [20], (corrected for major radius dependance)
\[
\tau_{Be} = 2.5 \times 10^{-21} \, \bar{n}_e \, a^2 \, R_0 \, q^{0.75}
\]
and the Pfeiffer Waltz scaling [24] constrained to geometrical parameters
\[
\tau_{Be} = 5.6 \times 10^{-22} \, \bar{n}_e \, a^{1.25} \, R_0^2.
\]

Clearly TCA falls into the data set best represented by an \(a^2R_0\) scaling, with confinement times higher than those given by an \(aR_0^2\) scaling due to its relatively small aspect ratio. An aspect ratio of 5 would make the two scalings equivalent both for \(\tau_E\) and \(\tau_{Be}\). By varying the profiles used in the calculation of \(W_e\) and \(W_i\) we have found that it is only by replacing the measured relatively flat density profiles with an analytic profile with \(\kappa_n \sim 1.5\) that the confinement times can be reduced significantly. This is not compatible with the profiles obtained by the multi-channel interferometer, as described in Section IV b). Adding a pedestal of 30 eV to the temperature profiles or imposing \(T_i(r) < T_e(r)\) does not change the estimate of \(\tau_E\) by more than 10%.

e) Electron Power Balance

To perform a radial electron power balance, one has to know the current density profile. Therefore we assume that the \(Z_{eff}\) profile has the form:
\[
Z_{eff}(r) = 1 + (Z_{eff}(0) - 1)(1 - r^2/a^2)^{\kappa Z_{eff}}.
\]
The current density is then calculated with classical Spitzer resistivity (no trapping correction) and constant parallel electric field. \(\kappa_{Te}\) and \(\kappa_{Z_{eff}}\) are chosen to match the following conditions:
a) the safety factor at the centre should be 0.9.

b) the assumed $Z_{\text{eff}}$ profile should correspond to the profile determined by a simulation assuming coronal equilibrium [25]. This is achieved with impurity concentrations $\eta_{\text{light}}$ and $\eta_{\text{metal}}$ that are constant throughout the plasma (Fig. 24).

Under these conditions, $\kappa_{T_e}$ and $\kappa_{Z_{\text{eff}}}$ are tied variables and the only reasonable solution is around $\kappa_{T_e}=2-2.5$ and $\kappa_{Z_{\text{eff}}}=1-2$. Within this range, the following analysis is rather insensitive to the choice made.

Then the power balance equation

$$P_{oh} = P_{ei} + P_{rad} - \frac{1}{r} \frac{d}{dr} \left( r \left( n_e \chi_e \right) e \frac{dT_e}{dr} \right)$$

is solved, neglecting convection losses, in order to get the value of the thermal diffusivity $\chi_e$. The result for a deuterium discharge with $n_{e13}=2.6$ is shown in Figure 25. The value at half radius of $n_e \chi_e$ is plotted in Figure 26 versus the central density for both working gases (hydrogen points suffer a large error because of the difficulty in estimating $P_{ei}$ when $T_i$ is close to $T_e$). We can note in deuterium that $n_e \chi_e$ tends to decrease with increasing density. Also shown on this figure is the standard INTOR scaling

$$\chi_e = 5 \times 10^{17}/n_e \ [\text{cm/s}].$$

Here again the scaling used for INTOR produces a better representation of the data. The $\chi_e$ scaling proposed by Goldston [23] gives a value 3 times that seen in the TCA data.

V. CONCLUSION

The characteristics of the ohmic TCA target plasma used for Alfven Wave Heating experiments have been studied. The toroidal field and plasma current were held fixed at the standard conditions ($B_\phi=15.2 \ \text{kG}$, $I_p=133 \ \text{kA}$, $q(a)=3$) and both the working gas and the density varied.
a) the safety factor at the centre should be 0.9.
b) the assumed $Z_{\text{eff}}$ profile should correspond to the profile
determined by a simulation assuming coronal equilibrium [25].
This is achieved with impurity concentrations $\eta_{\text{light}}$ and
$\eta_{\text{metal}}$ that are constant throughout the plasma (Fig. 24).

Under these conditions, $\kappa T_e$ and $Z_{\text{eff}}$ are tied variables
and the only reasonable solution is around $\kappa T_e=2-2.5$ and
$Z_{\text{eff}}=1-2$. Within this range, the following analysis is rather
insensitive to the choice made.

Then the power balance equation

$$P_{oh} = P_{ei} + P_{rad} - \frac{4}{r} \frac{d}{dr} \left( r \left( n_e \chi_e \right) \frac{d T_e}{dr} \right)$$

is solved, neglecting convection losses, in order to get the value of
the thermal diffusivity $\chi_e$. The result for a deuterium discharge
with $n_{e13}=2.6$ is shown in Figure 25. The value at half radius of
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$$\chi_e = 5 \times 10^{17} / n_e [\text{cm}^2\text{s}].$$

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V. CONCLUSION

The characteristics of the ohmic TCA target plasma used for
Alfvén Wave Heating experiments have been studied. The toroidal field
and plasma current were held fixed at the standard conditions
($B_0=15.2$ kG, $I_p=133$ kA, $q(a)=3$) and both the working gas and the
density varied.
The available set of diagnostics allows us to determine the
density dependance of the macroscopic plasma parameters and to per-
form more detailed analysis.

We observe that increasing the density gives more peaked density
profiles. Although the opposite behaviour is displayed on large
tokamaks, this is compatible with small tokamak observations (a<23 cm,
3<q(a)<4) and summarized by the following law:

\[ \kappa_n = 0.75+0.013 \, n_{el}^{3}(0) \, R_0/B_0. \]

We estimate the plasma impurity content and find that the central
metal concentration drops rapidly with density to less than 0.2\% at
\( \bar{n}_{el}^{3} = 2.5 \). Typical light impurities concentration is 3\% over the
whole density range.

TCA global energy confinement time follows the typical propor-
tionality with the line density. Comparison with published scaling
laws shows that the predictions of an original Alcator type \( a^2R_0 \)
scaling provide the best representation of the data; more modern \( aR_0^2 \)
laws underestimating the observed confinement times due to the rela-
tively small aspect ratio of TCA.

The continuous effort made to improve the plasma purity has
reduced the radiated power to very small values (\( P_{rad}(0)/P_{oh}(0) \sim
5\%)\). This small contribution of \( P_{rad} \) to the electron power balance
allows us to safely estimate the electron thermal conduction \( n_eX_e \).
We notice that \( n_eX_e \) drops from \( 4 \times 10^{17} \, \text{cm}^{-1}\text{s}^{-1} \) to \( 2 \times 10^{17} \, \text{cm}^{-1}\text{s}^{-1} \)
when \( \bar{n}_e \) is increased from \( 0.5 \times 10^{13} \, \text{cm}^{-3} \) to \( 5 \times 10^{13} \, \text{cm}^{-3} \).

The results presented here will serve as a basis for comparison
with future plasma conditions and for the study of the plasma during
Alfvén Wave Heating.
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REFERENCES


FIGURE CAPTIONS

1. Cross-section of the TCA vacuum vessel.
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h) β+1i/2

j) βDIAM

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21. a) \(Z_{\text{eff}}(0)\) as a function of density.

b) An estimate of the metal concentration.

c) An estimate of the light impurity concentration.

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b) Global confinement time as a function of density.

24. Simulated \(Z_{\text{eff}}\) profile assuming coronal equilibrium.

25. Radial electron power balance:

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26. \(n_eX_e\) at \(r=a/2\) versus central density.
\[ \bar{i} \approx 2 \times 10^{15} \text{cm}^{-2} \]

**FIGURE 6**
\[ \Phi(b(cm)) = 0 \]

- \( b = 16 \)
- \( b = 17 \)
- \( b = 18-20 \) & free

Figure 8
\[ \int P_{\text{rad}} \, dl \left[ \text{Wcm}^{-2} \right] \]

\[ P_{\text{rad}} \left[ \text{Wcm}^{-3} \right] \]

FIGURE 9
\[ \chi^2 = 2.739 \]

\[ T(EV) = 776 \pm 45 \]

\[ T(MS) = 120 \]

\[ A(CM) = 1.7 \]

\[ ZEFF = 2.26 \]
FIGURE 12
- $T_{e0} (eV)$
- $1000$
- $500$
- $1$
- $r/a$
- $-1$
- $0$
- $1$
- $2$
- $3$
- $4$
- $\bar{n}_{e13}$
- $\text{central ece}$
- $\text{Thomson scattering}$
- $2 \omega_{ce} < \omega_{R}$
- spectrum dominated by suprathermal effects

**FIGURE 13**
\[ T_e (\text{keV}) \]

\[ \bar{n}_{e13} = 2.7 \]

\[ \bar{n}_{e13} = 3.3 \]

\[ 2 \omega_{ce} < \omega_R \]

\[ R_0 - a \]

\[ R_0 \]

\[ R (\text{cm}) \]

**FIGURE 14**
FIGURE 17
Figure 19
$Z_{\text{eff}}$

Approximation: $\kappa Z_{\text{eff}} = 2$

Simulation:
- $\bar{n}_{e13} = 2$
- $T_{e0} = 800$
- $\eta_{Fe} = 3\%$
- $\eta_{O} = 2\%$

FIGURE 24
$n_e X_e (a/2) \times 10^{17} \text{cm}^{-1} \text{s}^{-1}$

**FIGURE 26**