Eindhoven University of Technology

Optical Diagnostics

3MP180

Optical Diagnostics Assignment 3

Tim Heiszwolf (XXX)

Proposal for measuring:

1. The density of O radicals.
2. The electron temperature.
3. The electron density.

in a **repetitively pulsed non-LTE** plasma consisting of **Air with H2O** at medium pressure (around **10 mbar**).

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Contents

1 Possible diagnostics

1.1 Requirements

The task in this report is to determine:

- The density of the Oxygen radicals n_O.
- The electron temperature T_e.
- The electron density n_e.

of a repetitively pulsed non-LTE plasma consisting of air with water at a pressure of around 10 millibar.

To quickly get an idea of potential conditions that can occur a few sources are discussed:

- According to the course Plasma Physics and Radiation the electron density of a typical cold Argon plasma is $1 \cdot 10^{16}$ per m^3 and has a temperature of $34 \cdot 10^3$ K [20].
- Next according to E. Carbone and S. Nijdam a 40 mbar gass would have an electron density of $5.15 \cdot 10^{19}$ and a temperature of $12 \cdot 10^3$ K [3].
- Finally according to Oxford Instruments a typical 20 mbar Nitrogen plasma has a electron density around $5 \cdot 10^{19}$ electrons per m^3 and a electron temperature around $13 \cdot 10^3$ Kelvin.[2]

1.2 Options

There are multiple ways to design a diagnostic for these requirements but in this report the following will be considered

- Thomson scattering, which can be used to measure both the electron density n_e and/or temperature T_e [19].
- Reflectometry can be used to measure the electron density n_e [6].
- Optical emission spectroscopy, which can be used to measure the Oxygen radicals n_O and electron temperature T_e [16] and n_e [8].

Other options are that were considered and might have worked are

- Microwave interferometry to measure the (integral of the) electron density [6]
- Raman scattering for electron density [3]
- Electron cyclotron emissions can also measure T_e based on Planck's law for black-body radiation but requires a magnetic field to function [6].

1.3 Thomson scattering

Thomson scattering is a form of scattering photons on a charged particle and can be incoherent or collective. It is determined by the Saltpeter parameter

$$\alpha = \frac{\lambda_0}{4\pi\lambda_D \sin\left(\frac{\theta}{2}\right)} \tag{1}$$

where λ_0 is the wavelength of the input laser, θ is the observation angle and λ_D is the Debye length [19]

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}} \approx 743\sqrt{\frac{T_e[\mathrm{eV}]}{n_e[\mathrm{cm}^{-3}]}} \tag{2}$$

[20]. If $\alpha \ll 1 \rightarrow \lambda_0 \ll \lambda_D \sin\left(\frac{\theta}{2}\right)$ then it is incoherent and interacts with electrons. If $\alpha \geq 1$ the scattering is collective and has (indirect) interaction with the ions [19].

Incoherent scattering allows one to measure T_e

$$\Delta\lambda_e = 2\frac{\lambda_0}{c}\sin\left(\frac{\theta}{2}\right)\sqrt{\frac{k_B T_e}{m_e}} \tag{3}$$

where $\Delta\lambda_e$ is the $\frac{1}{e}$ width of the scatter profile [7].

From the intensity of the signal one can measure the electron density, which is $\propto n_e$ for incoherent scattering and $\propto n_e^2$ for collective scattering. Thus if one wants to measure n_e it often works better if one uses collective scattering, in this mode one can also measure the ion temperature via similar methods as the electron temperature [7]. To measure n_e with Thomson scattering one needs to do calibration first (often using Raman scattering) [4].

Thomson scattering has a big advantage

- It has a high spatial resolution.

However the downsides are

- High laser power needed or very low temporal resolution due to low amount of scattered light.
- Needs two ports to perform measurement.

1.4 Reflectometry

[6].

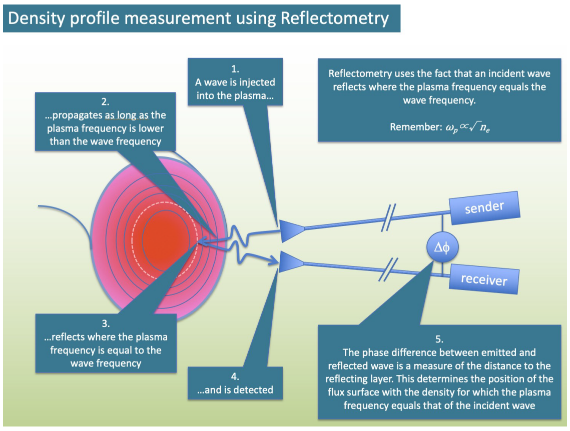


Figure 1: Schematic of the reflectometry. Taken from [6] made by N.J. Lopes Cardozo.

Reflectometry (see figure 1) is a technique based on the fact that the plasma frequency depends on the electron density

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}}, \quad f_{pe}[s^{-1}] \approx 9\sqrt{n_e[m^{-3}]} \tag{4}$$

where ω_{pe} and f_{pe} are the plasma frequency, e is the charge of an electron, n_e is the electron density and m_e is the electron mass [20]. It then uses this in combination with the fact that waves injected into plasma can only propagate if their frequency is higher than the plasma frequency [6]

$$\frac{2\pi c}{\lambda_0} = \omega_0 \geq \omega_{pe} \tag{5}$$

So to do a measurement a frequency sweep from high to low frequency is done. If the waves don't propagate through the plasma (but reflect) one knows what the plasma frequency and thus electron density is. If one also keeps track of the time of flight this also allows the position to be calculated [6].

It has the following advantages [13]

- High temporal resolution/sample rate.
- Perturbations caused by measurements are negligible [1].

and disadvantages

- Low spatial resolution on flat density profiles.
- Spatial resolution only up to the maximum of the profile.
- Relatively complex/expensive system

1.5 Optical emission spectroscopy

Finally optimal emission spectroscopy is, in concept, the most simple but also most versatile of these options. One uses a spectrometer and just measures the spectrum. There the various transitions between different energy levels will be visable which all contain information about various properties of the plasma.

1.5.1 Molar fractions and temperature

To determine the molar fraction and the temperature a software, like Specair, can be used to make a fit of the relevant spectral lines and determine the densities of the components (including the oxygen radicals) and the different temperatures (including the electron temperature) [8].

1.5.2 Electron density

To use optical emission spectroscopy for determining the electron density one needs to find a emission/transition for which the Stark effect is dominant. This depends on electron density and what transition is being measured. Typically the H_β (486 nm) is used for high electron densities or H_α (656 nm) is used for low electron densities [9]. Since this plasma contains hydrogen (from the water) these two commonly used transitions can likely be used. However other transitions such as from Argon can also be used [11]. Each transition has it's own unique dependencies (resulting from quantum mechanics).

1.5.3 Advantages and disadvantages

This method has the following advantages

- It is a very passive method.
- Can be very fast.
- It can give a lot of information.

and also a big disadvantage

- Fitting can be very tedious.

2 Diagnostics set-ups

2.1 Thomson scattering

Thomson scattering works based on the scattering of photons as described in section 1.3. A schematic of such a set-up can be seen in figure 2, a laser emits pulses of light into the plasma vessel where it then scatters. This scattered light is then measured, often at a 90 degree angle, using a spectrometer.

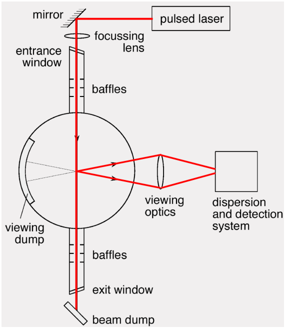


Figure 2: A schematic of a typical Thomson scattering configuration. Taken from [7] by R. Jaspers.

In this report the goal is to use Thomson scattering to measure the electron temperature thus it is best to use incoherent scattering. Thus the inequality of equation 2 needs to be satisfied. Two parameters can be tweaked here the input laser wavelength λ_0 or the measurement angle θ. Deviating form the typical 90 degree angle can only improve the criteria by a factor $\sqrt{2} \approx 1.4$ at most but has the disadvantage of reducing the intensity of the scattered light [19].

Thus the best option is to make sure that the Saltpeter parameter is low enough. In figure 3 what regions the (electron) temperature an density need to be in for the scattering to be incoherent if using a Nd:YAG laser can be seen. The exact region you are willing to accept depends on how high one allows the Saltpeter parameter α to be (and thus how incoherent/collective it is). According to H.J van der Meiden if $\alpha < 0.1$ the collective effects can be neglected [18].

Since the plasma is not in LTE the electron temperature likely is quite high, thus using a frequency doubled Nd:YAG laser will work well up to densities of 10^{20} electrons per m^3 (this value also nicely lines up with literature [11]). Another advantage is that such a laser can have a high repetition rate. If one instead desires significantly more power per pulse (and thus better spatial resolution) one can also use a Ruby laser [7].

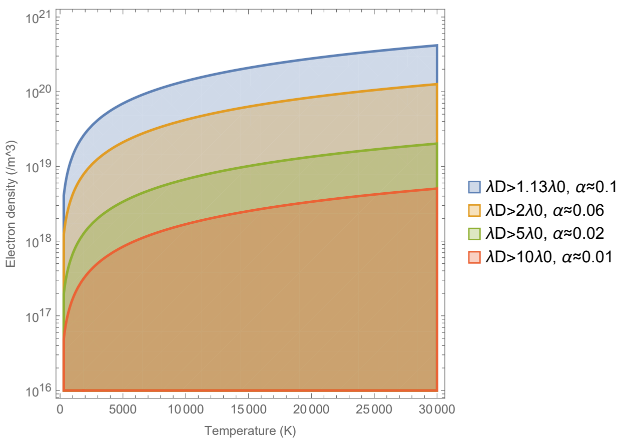


Figure 3: Region of incoherent scattering with a frequency doubled Nd:YAG laser.

More specifically a Quanta-Ray Pro-290 would be a good fit, at a repetition rate of 50hz it can emit 0.5 joule per pulse at 532 nm. If needed, it can function at a lower wavelength of 266 nm albeit at a much lower power/repetition rate (for higher densities) or it can also function at a much higher power while having a wavelength of 1064 nm (for lower densities) [17].

For the spectrometer a Oxford Instruments Andor iStar 320T CCD would be a good option, it can make up to 322 spectra per second which is more than enough. If one wants to have better spatial resolution one can also use the 334T or 340T model [2]. Often a notch-filter at the wavelength of the laser is places in front of the spectrometer to remove any direct remnants of the laser itself [3].

2.2 Reflectometry

In figure 4 a typical reflectometry set-up can be seen. It consists of a generator, transmission lines to the (emitting) antenna, transmission lines coming back from the (receiving) antenna which either go directly to a detector (together with some of the generated signal) or get mixed with the generated signal before it is measured [1]. If one plans to measure only the highest density (meaning that during your frequency sweep a lot of the time your signal will pass through the plasma) a microwave absorbing material can be useful to place on the walls of your vessel.

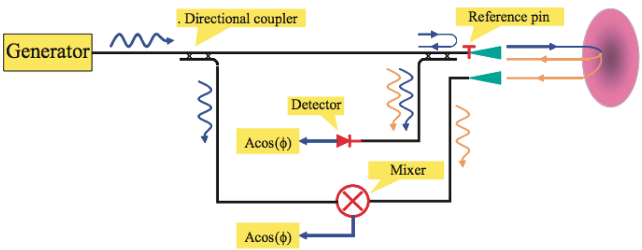


Figure 4: A typical reflectometer configuration. Taken from [1] by D. Aguiam.

In the configuration where the reflection is measured directly there can be ambiguity when measuring distance since the output depends on both the phase and amplitude of the reflected signal while in the configuration with the mixer they are properly mixed resulting in a beat frequency signal which allows one to more directly measure the phase shift (and thus spatial aspects) [1]. More complex techniques which are even better also exists in however this report the exact spatial aspects are not so important so the middle ground is chosen with the mixer configuration.

One very important aspect of reflectometers is that the range electron densities that can be measured is limited by the signal that can be generated. If equations 4 and 5 are combined the density can be calculated from the laser frequency, but the reverse can of course also be done to calculate the density range in which a reflectometer works. Reflectometry typically uses microwaves which range from 1 meter to 1 mm giving a density range between $1.11 \cdot 10^{15}$ and $1.11 \cdot 10^{21}$ electrons per m^3.

In reality most generators don't cover the entire spectrum so a generator which has sufficient range needs to be found. For this report two microwave generators were found

- Rohde and Schwarz RSMAB [14] which depending on the model has a range from 9 kHz to 72 GHz (SMAB-B167) which corresponds to a electron density between $8 \cdot 10^6$ and $6.4 \cdot 10^{19}$ electrons per m^3. But it does have a relatively slow switching time of up to 2.5 ms.

- Berkeley Nucleonic Corp Model 845 [12] which has a range from 100 kHz to 26.5 Ghz which corresponds to a electron density between $1.2 \cdot 10^8$ and $8.7 \cdot 10^{18}$ electrons per m^3. The switching time can be as fasts as 30 μs

As can be seen in figure 7a to better measure the distance of the plasma density a fast sweep time is needed. So between those two microwave generators there is the trade-off between density-range and attainable time/spatial resolution. There is not necessarily much interest in spatial resolution and for high enough electron densities optical emission spectroscopy can be used, so the Berkely Nucleonic Model 845 seems best (which has a high temporal resolution).

2.3 Optical emission spectroscopy

The set-up for a spectrometer can be as complex or simple as desired. A attempt could be made to construct a spectrometer, one could make a spectrometer using basic cameras and filters or a spectrometer could just be bought. The first is very complex, the second one only works for a select few wavelengths and not the whole spectrum. So instead the third option is chosen. The same spectrometer as for the Thomson scattering can also be used here a Oxford Instruments Andor iStar 320T CCD (or the 334T or 340T variant if more spatial resolution is required) [2].

A set-up consists of a port to the plasma vessel. Through that port emission light flows, potentially through a few mirrors/lenses into a spectrometer (almost like figure 2 but without the laser). A very basic look into a spectrometer can be seen in figure 5, the light falls on a diffraction grating which causes differing constructive or destructive interference based on wavelength, thus separating them. It can also be based on a prism which works on the fact that each wavelength has a slightly different refraction index [5].

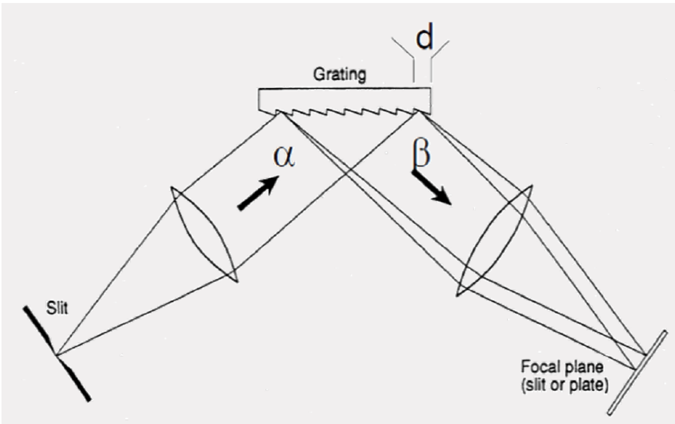


Figure 5: Basic inner workings of a spectrometer. Taken from [5] by R. Jaspers.

3 Measurements to perform

3.1 Thomson scattering

To do a Thomson measurement one first must make sure the laser is properly configured and that the spectrometer is properly configured to measure the (scattered photons of the) pulses of the laser. It can be good to do a measurement without the laser active to check if the of normal emission will not interfere. Then a measurement can be performed, the data extracted from the spectrometer and a fit can be made to calculate the electron temperature. If the results are off it might be good to check if the measured scattering indeed is incoherent scattering (see section 2.1).

To measure electron density calibrations need to be done. The proportionality constant between the intensity measured and the electron density needs to be determined. Since it is needed to measure the electron density (using Raman scattering or other methods) to do this calibration it seems somewhat self-defeating and Thomson scattering won't be used for measuring the electron density.

3.2 Reflectometry

Performing reflectometry measurements is relatively simple, perform a frequency sweep, measure any returning signal. The highest frequency a returned signal corresponds to the highest electron density present (see equations 4 and 5). The phase difference can then be used to calculate the distance.

To improve the measurements it is best to get an idea/estimation of the expected (range of the) electron density (either through theory or measurements already performed) and to then focus the frequency sweep around the corresponding plasma frequency of the expected (range of the) electron density. This can the increase the accuracy of the measurement by either having a shorter sweep or a sweep with more data-points.

3.3 Optical emission spectroscopy

To do a optical emission spectroscopy measurement the plasma is simply turned on and then the (calibrated) spectrometer is used to do the measurement, while also noting down (or measuring afterwards if unknown) the slit function of the spectrometer.

4 Typical measurements

4.1 Thomson scattering

In figure 6 a typical measurement from Thomson scattering as mentioned in section 2.1 can be seen. On this data a Gaussian fit then can be made, the higher the temperature the wider this distribution will be, after which equation 3 can be used to determine the electron temperature. If the instruments has been calibrated the electron density can also be extracted by looking at the total intensity (which is proportional to the electron density) [3].

Depending on the exact set-up this process can be repeated for each pixel which represents a different point to get spatial data.

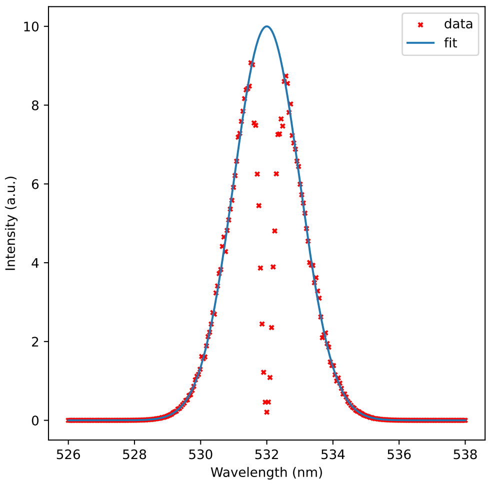
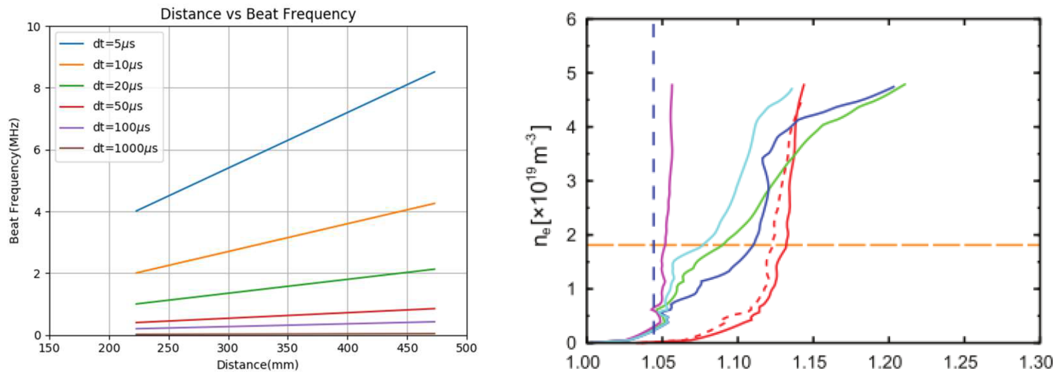


Figure 6: A schematic of a typical Thomson scattering spectrum with notch to filter out the wavelength of the laser itself.

4.2 Reflectometry

In figure 7a the frequency of the beat of the measured signal (which was mixed with the generated signal) behaves as a function of distance can be seen. Keep in mind that this curve can changes based on all kind of things [6]. Based on the measured signal, the curve from figure 7a, the emitted signal and equations 4 and 5 a electron density profile like in figure 7b can then be reconstructed. If no (significant) signal comes back or if the measured distance is around the distance to the wall of the vessel then there likely is no density of the corresponding frequency. The maximum frequency which is reflected represents the maximum density present in the plasma.



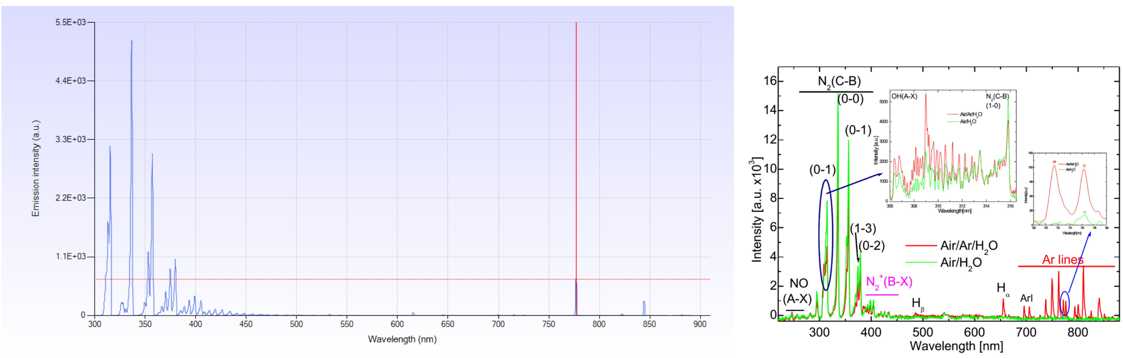
(a) The measured beating frequency versus distance for different sweep times. Taken from [13] by M. Rishabhumar.

(b) Typical density profile using reflectometry in a Tokamak plasma. Taken from [1] by D. Aguiam.

Figure 7: Measurement results of reflectometry.

4.3 Optical emission spectroscopy

Once the measurement has been made a spectrum like figure 8 can be expected. A fit can then be made using software like Specair, it consists of finding interesting transitions, fitting the temperatures by looping through the different kinds of temperatures (the (electron) temperature is already know from other accurate measurements this part can be (partially) skipped and this would improve accuracy) and fitting the relevant mole fractions [16]. If the spectrometer is very improperly calibrated it might be needed to shift the wavelengths based on a known transition. To determine the density of the O radicals the transition at 776.3 nm and 844.6 nm are of particular interest since that is the O I transition [15]. Other transitions around 391 nm and 418 nm also exist and are relatively strong [10]. However since the the N2 transitions are so much stronger these are hard to see while the higher wavelength transitions are visible.



(a) A spectrum generated with Specair, including the N2 transitions and the O radical transitions but not including the transitions like H_β or H_α. The 776 nm transition is marked for clarity, the amount of O radicals in the model has been purposefully made large to enhance the transition.

(b) An experimental spectrum from optical emission spectroscopy (not at medium pressure but atmospheric pressure). Taken from [15] by N.C. Roy.

Figure 8: Examples of spectrum's generated with Specair or from experimental measurements.

Finally the electron density can be determined by finding a emission which has a dominant amount of Stark broadening. This could be transitions like H_β or H_α, which are traditionally used and should be available due [9] or other transitions like Ar I or He I (which can also be seen in figure 8b) can be generated by adding some of those gasses into the mixture or might already be present in the spectrum [11].

The electron density can then be calculated, if the Stark effect is dominant (n_e needs to be above $10^1$5 electron per m^3 [9]), by making a Voight fit (see figure 9) and using known and transition depended equations for the width of the distribution [9].

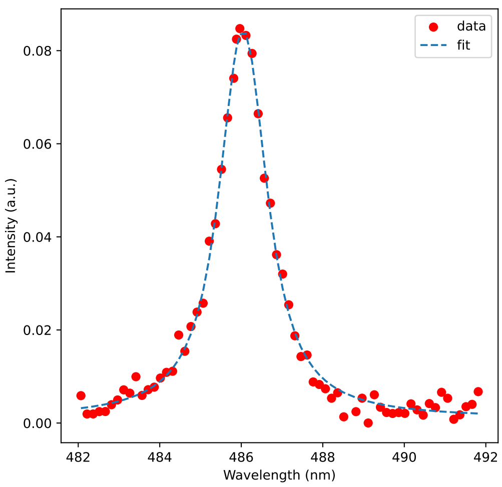


Figure 9: Example of a fit of a Balmer peak, in this case taken from assignment 1 and adjusted to make it look like a H_β transition.

5 Conclusion

So to conclude one can use the following diagnostics:

- Thomson scattering to determine the electron temperature T_e and with calibration the electron density n_e as long as $\sqrt{\frac{T_e}{n_e}}$ stays above a certain threshold for incoherent scattering.
- Reflectometry to determine the electron density n_e as long as the densities stay within a certain electron density range up to approximately $8.7 \cdot 10^1$8 electrons per m^3.
- Optical emission spectroscopy to determine the density of O radicals n_O and to an lower accuracy the electron temperature T_e. The density of electrons n_e can also be determined if there are emission lines for which the Stark effect dominates. These are typically above an electron density of 10^{15} electrons per m^3.

Thus the author recommends the following:

- Use Thomson scattering to determine the electron temperature T_e, if the scattering is not incoherent fall back on optical emission spectroscopy.
- Use optical emission spectroscopy to determine the density of electrons n_e, if there are no suitable emission lines consider using reflectometry.
- Use optical emission spectroscopy to determine the density of O radicals n_O.

These fallback options are not likely needed, for example all the potential properties as listed in section 1.1 should work.

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