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A Thomson Scattering Scheme for Obtaining T_e and n_e Profiles of the ITER Core Plasma

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ABSTRACT

The hostile environment, the very restricted access geometry, the required spatial resolution and the target accuracy all impose severe constraints on the design of many techniques proposed for spatially resolving ITER plasma parameters. Despite the constraints it appears feasible using LIDAR Thomson scattering to make measurements of the electron temperature and density profiles in the ITER core plasma. A generic scheme using reflective optics for the front end is adopted. The scheme uses a folded mirror system positioned inside a shielded labyrinth located in a standard radial port. The same mirror surfaces and vacuum window are used for both the laser input and the collection path. Radial and tangential sight lines are considered. The sight line uses a single 30 cm diameter blanket penetration and an exit window of <20 cm diameter. The specified spatial resolution of 30 cm can be met using existing laser and detector technology. Calculations of the expected accuracy of the temperature measurement are presented for different laser/detector combinations. The results are based on extrapolations from the existing JET LIDAR system and are therefore bounded by the constraints of a realistic optical system. The background to the design will be reviewed and some details of the front end optical design will be presented. Possible methods of obtaining some of the necessary calibration data will also be discussed. The critical outstanding problem for the design is to identify suitable materials which can simultaneously withstand the heat, gamma, neutron and laser beam fluxes.

INTRODUCTION

In the following the applicability of Thomson scattering to the ITER core plasma is investigated. This is not done to the extent of a complete design study. The main scope of the work presented is to demonstrate the access requirements and to show that the requirements for the measurement of electron temperature and density profiles, i.e. spatial resolution, parameter range and accuracy, can be fulfilled.

GENERAL CONSIDERATIONS

In this section a few general considerations regarding the applicability of different scattering schemes to the ITER geometry and plasma parameters are discussed. From this discussion some guidelines for the design of suitable diagnostics are derived.

LIDAR vs Conventional Scattering

There are two ways to provide spatial resolution for a scattering system. Either the laser beam is crossed with the beam of the collection optics ("conventional" set-up) or the origin in space of the scattered light is determined by a time-of-flight method (LIDAR). In the conventional set-up the spatial resolution can easily be made high, being limited only by the reduced signal-to-noise ratio (SNR) resulting from the fact that the number of scattered photons decreases with the length of the scattering volume. In the LIDAR scheme the time-of-flight differences and thus the spatial resolution are maximised for a backscattering arrangement and go to zero for small scattering angles (forward scattering). For back-scattering, the spatial resolution is given by

$$\Delta x = \frac{c}{2}\sqrt{(\tau_{\text{laser}}^{2} + \tau_{\text{detection}}^{2})}$$

where c is the speed of light, τ_{laser} is the laser pulse duration and $\tau_{\text{detection}}$ is the risetime of the detection system.

In the LIDAR scheme, a good spatial resolution requires a short, high-energy laser pulse and a high-speed detection system. Provided the spatial resolution is sufficient, these drawbacks are however more than compensated for by the following factors

i) the plasma background radiation added to the scattered signal is very small due to the high-speed detection, thus improving the SNR

ii) in the backscattering arrangement the collection and laser optics are coupled mechanically, making alignment both stable and simple

iii) only one access route/window to the plasma is required,

iv) all the spatial channels are transmitted via one line of optics. This means that simpler relay optics (and much less space close to the machine) are required than for the wide field-of-view collection optics needed in a conventional system,

v) all spatial channels are measured with one single detection system. This has the advantage that the absolute (density) calibration of the system need not be performed separately for each spatial channel, comparison to a density line integral is sufficient (see 'Density Calibration' section).

These arguments, especially those pertaining to the access problem, lead to the conclusion that a LIDAR system is to be preferred, as long as the spatial resolution is sufficient.

Choice of Laser Wavelength and Dynamic Range of the Measurements

For the LIDAR backscattering scheme the choice of laser wavelength is based on the following criteria:

i) high-speed detectors with a sufficiently large sensitive area (to cope with the large étendue, dF*dΩ, of the collection optics) are presently available only in the visible spectral range (MCP photomultiplier tubes, streak tubes). The laser should therefore yield scattering spectra which cover this spectral range for the electron temperatures of interest.
ii) the 'blue' wing of the scattered spectrum should be located in the accessible spectral range since this wing varies more strongly with temperature (at high temperatures) than the 'red' one.
iii) there should be a possible laser candidate already with today's laser technology.

Fig. 1a shows Thomson scattered spectra for a laser wavelength of 1.06 µm. It shows that for temperatures above 2 - 3 keV, spectral power measurements in the wavelength range 400 nm - 800 nm could well resolve the temperature.

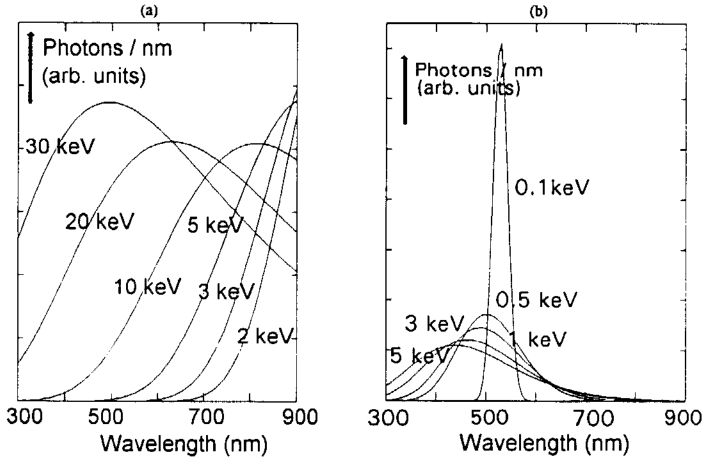

Figure 1a & 1b Scattered spectra for Nd fundamental and 2nd harmonic wavelengths respectively

For temperatures below that value the use of the harmonic laser wavelength seems advantageous, as can be seen from Fig.1b. For this purpose, frequency doubling of the laser is required which can be done with an efficiency well above 50%. So as not to confuse the measurements at both wavelengths, use can be made either of the different polarisation of the fundamental and the harmonic and thus of the related scattered light or of a delay of one of the laser pulses by about 100 ns.

However, account must be taken of the spectral response of commercially available photocathodes. Their quantum efficiency tends to decrease at both the red and blue edge of the measurements. The combinations of different laser wavelengths with different types of photocathodes has been investigated and the results are summarized in Fig.2. The figure shows the dynamic range for electron temperature measurements. The use of GaAs photocathodes extends the long wavelength limit of the accessible spectral region. The error curves are derived by calculating the expected signal in 20 equally sized spectral channels over a fixed wavelength range. The spectra are convoluted with simplified quantum efficiency curves; i.e. a straight line between the wavelength extremes. GaAs is taken to have a constant 10 % quantum efficiency between 600 - 900 nm; MA-1 (extended red tri-alkali) is 10% at 400 nm and 1% at 800 nm.

The numbers for the error bars in Fig.2 are scaled to match the actual performance of the JET LIDAR system. All the curves are then calculated using fixed geometry (F#), fixed laser energy and fixed transmission. As can be seen, measurements with the Nd fundamental wavelength can cover a dynamic range (defined here as <20% statistical error) from 2 keV up to 50 keV when using GaAs detectors. The dynamic range for measurements with the frequency doubled laser radiation can extend up to 6 keV. Thus the simultaneous use of these two wavelengths with some GaAs detectors will indeed cover the interesting temperature range without a gap. Without using GaAs photocathodes the accuracy is inadequate in the 5-10 keV range. It is interesting to note that this analysis shows that a laser at 790 nm (e.g. Alexandrite) can cover the full temperature range using extended red photocathodes.

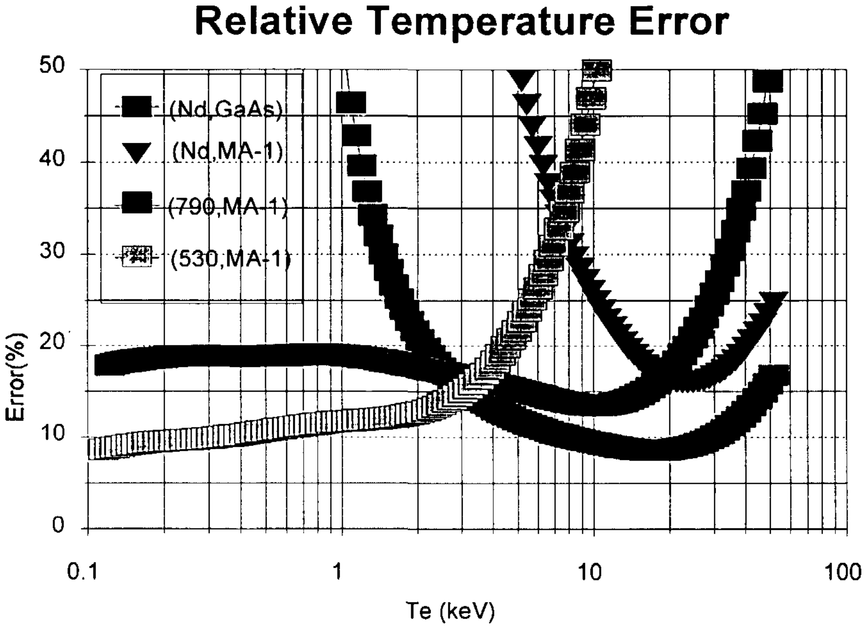

Fig.2 Relative error in temperature from Thomson scattering in five cases:
(Nd,GaAs) - Nd laser, 1064 nm, detector quantum efficiency $\eta = 0.1$ from 400 to 900 nm
(Nd,MA-1) - Nd laser, 1064 nm, detector $\eta = 0.1$ at 400 nm dropping to 0.01 at 800 nm
(790,MA-1) - 790 nm laser, same detector
(530,MA-1) - Nd laser 2ω, 530 nm, detector $\eta = 0.1$ at 400 nm dropping to 0.01 at 800 nm

Access

Access will be provided through a large horizontal port. Since the size of the window(s) on this port should be as small as possible, the front collection optics must be located inside the port and the window(s) should be positioned at a waist of the beam(s) of collected light. In addition, it is advisable to have this/these window(s) shielded from the flux of streaming neutrons. We also believe that the first optical element, which has to face the plasma, should be a mirror, preferably a metallic one.

These considerations lead to a folded optical arrangement within the port. In order to make the output window as small as possible, these optics should image the blanket penetration onto this window, demagnifying the image as much as possible.

In the following, we will consider only optics and lines of sight which can be realised using a standard radial port. It seems advisable that the optics located within the area of the horizontal port and the cryostat, should all be contained within the cross section of the port flange.

The idea of introducing optics into the vessel structure immediately raises the question of alignment between the laser and the collection optics. We intend to solve this problem by transmitting the laser via the same optical components as those being used for the collection optics. Thus the alignment is guaranteed for all time and allows us to use non-adjustable optics.

However, metallic mirrors like those intended for the front optics have a lower laser damage threshold than dielectric ones. This requires that a rather large area of the collection optics must be filled with the laser beam which could then lead to 'Vignetting" (see below) when viewing the laser beam with the collection optics.

"Vignetting"

When collecting scattered light in a backscattering arrangement the solid angle of collection unavoidably decreases with distance from the collection optics. This represents no problem as long as the laser energy is great enough to ensure a sufficient signal-to-noise ratio for the most distant spatial points.

Another effect which has to be considered carefully, is that of vignetting. In optics, the usual meaning of vignetting is the variation of the solid angle of collection across the field of view. This effect occurs when stops exist in the collection optics which are located outside either the plane of the collecting lens or the image plane. In a Thomson scattering set-up vignetting across the laser beam renders density measurements difficult if the laser beam intensity profile changes from shot to shot. A special case exists when this is not a problem. If we assume a perfect relay system then our collection optics may be defined by two apertures. We may select these apertures to correspond to the blanket penetration and the first collection mirror. These two apertures are in turn imaged on the final focusing lens and the detector front surface. The two apertures define a cone with apex at P0 (Fig.3). Scattering that takes place within this double cone shows no variation in solid angle across the cone axis. We obviously still have the 1/R dependence of the F# as we move away from the apertures, but the solid angle of collection for points in the region of P1 is defined solely by the collecting mirror. Conversely the solid angle of collection in the region of P2 is defined solely by the blanket penetration. From this it is clear that the scattered signal does not depend on the location or the distribution of the laser beam, as long as it is confined within this double cone. In the design we take advantage of this and make the laser fill as much of the collecting mirror as required by damage considerations. The laser must of course be focused at the apex point P0.

Lines of Sight

Of course, it is desirable to realise the maximum possible number of optical chords for T_e and n_e profile measurements.

One line of sight is essential, namely a line of sight through the plasma centre. Further chords passing through the plasma inclined with respect to the horizontal will yield information about plasma movement in the vertical direction. Up to two additional chords seem to be feasible.

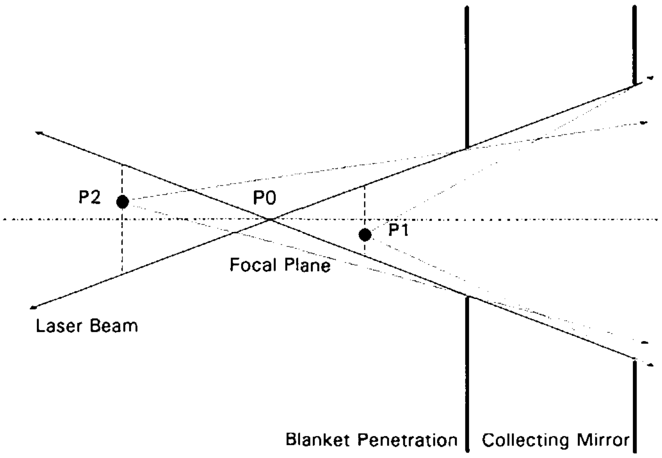

Fig. 3 Vignetting (Schematic)

Sharing with other diagnostics

From the point of view of density calibration of the Thomson scattering diagnostic alone, sharing the optical chord with another diagnostic is advisable. This diagnostic could be

i) a single interferometer chord collinear with the LIDAR line of sight (possible for both radial and tangential LIDAR geometry),
ii) a single polarimeter chord collinear with the LIDAR line of sight (only for a tangential LIDAR geometry)
iii) a reflectometer collinear with the LIDAR line of sight (only for a radial LIDAR chord, normal to the outer flux surfaces). This diagnostic would be compatible with the intended use of metallic mirrors for LIDAR.

In addition, the LIDAR collection optics could also be used for spectroscopic diagnostics in the visible and infra-red and ECE.

Optical Components

The environment faced by the components inside the ITER vacuum vessel is the major challenge to making a Thomson scattering system. This is particularly true for the first component (mirror) facing the plasma. This mirror has to withstand a high 14 MeV neutron flux in addition to a possible high temperature (400 ^{O}C) and possibly plasma erosion.

This environment precludes the use of refractive optics near the front end where bulk damage will be highest. As the albedo for neutrons is high the neutrons in the beginning of any labyrinth tend to slow down, but the neutron flux remains high. We should therefore keep refractive elements as far down the labyrinth as possible. It should be noted that Thomson scattering requires a high light throughput which is incompatible with a tight labyrinth.

We have conducted neutron damage tests of conventional laser mirrors, ie. dielectric coatings on quartz substrates. High Z compounds in a few layers survived best. However, these tests together with earlier tests at high temperatures suggest that we cannot use this type of element.

An alternative is to use all metal mirrors, possibly with some overcoat. Tests conducted with silver mirrors on quartz with an overcoat of sapphire show very high reflectivity over the wavelength of interest and good laser power handling performance. Tests at high temperature showed some promise. We would like to propose silver mirrors on e.g. Be substrates, possibly with sapphire protection. Tests on this and other types of mirrors are outstanding.

"Temporal Resolution" , Repetition Rate of Measurements

The target resolution with respect to temporal resolution could be confusing since no distinction is made between the integration time for a single measurement and the repetition rate of the measurements, e.g.: the target measurement resolutions and accuracies for ITER are given in task agreement S 56 TD 01 94-09-27 FE. The time resolution of the electron temperature and density profile measurements is given as 10 ms. It should be noted that the temporal resolution of the Thomson scattering measurement of these quantities is about 50 ns (nanoseconds). The repetition rate of the measurements, as far as the laser technology of the 2000's can be foreseen, will be of the order of 100 pps. Thus, fast events such as ELMs can be frozen and temporally resolved by sampling several events.

CORE

The target specifications for the core measurements foresee a spatial resolution of 30 cm, which is a factor 3 worse than that already achieved with a LIDAR system on JET using yesterdays technology. Thus, according to the discussion in the section on 'LIDAR vs Conventional Scattering' above, for the core plasma LIDAR is the optimum technique for Thomson scattering.

Multichord System

To achieve the maximum possible number of chords the lay-out of the front optics inside the radial port needs to be optimised. This has not yet been completed but to demonstrate that a multichord system is feasible, Fig. 4 shows as an example a possible set-up with 3 tangential chords. In this set-up the angles between the chords are still small enough (10°) to allow sharing of a single blanket penetration and a single output window and the chords pass close to the inner wall. A fan of rays is shown which originates from the inner plasma boundary (the laser focal plane for this set-up). The folding optics within the port consist of sets of plane and spherical mirror pairs, imaging the centre of the blanket penetration (30 cm dia.) onto a common window (17 cm dia.). All the optics have not yet been optimised with respect to imaging quality. This example of optics is shown just to demonstrate that the port volume is sufficiently large to allow the introduction of a multichord system. Such a system may use tangential or radial lines of sight.

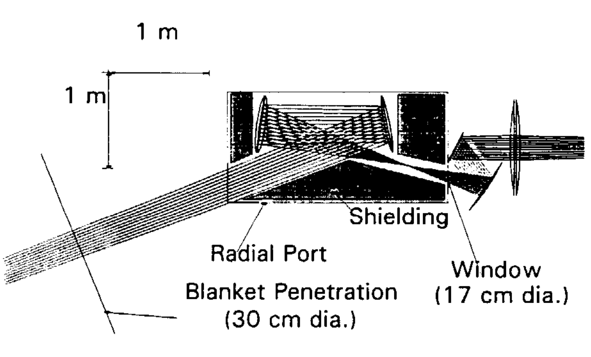

Fig. 4a Tangential multichord system, top view

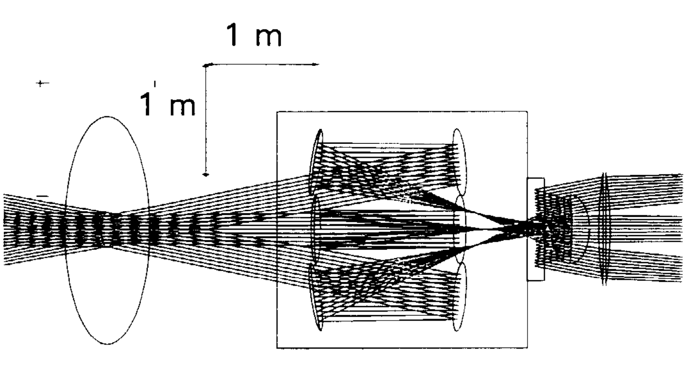

Fig 4b Tangential multichord system, side view

Tangential vs Radial Lines of Sight

Two lines of sight, radial and tangential, are possible giving different advantages and disadvantages. The current LIDAR system at JET is radial. A radial system cannot measure close to the inner wall due to an intense stray light signal resulting from the laser beam hitting the inner wall. A tangential view, tangent to the plasma at the inner wall avoids this problem and additionally offers

a) the possibility of better spatial resolution near the inner plasma edge (limited to the diameter of the laser beam as it passes the inner wall)
b) the possibility in principle of measuring temperature and density on the second pass through the plasma.

In the case of an inclined beam this gives additional flux surface information. The tangential view also allows lines of sight through the plasma for calibration measurements, e.g. interferometry.

However, the ability of the tangential system to provide better spatial resolution is subject to a number of restrictions. The length over which the spatial resolution is actually better than that obtained in the radial set-up is limited to only 3 or 4 spatial points and in any case cannot meet the 5 mm requirement. The location of this restricted high resolution region may not actually coincide with the location of the plasma region of interest. Also improved spatial resolution is not in fact realised if the error bars are too large. As the scattering volume is further removed from the collection mirror we may find that the necessary laser energy to achieve the required accuracy is too high. In addition one loses spatial resolution at the *outer* boundary because we propose to fill the optics with the laser beam and unlike the radial case the beam is not normal to the flux surfaces so different points across the beam diameter will be on different flux surfaces.

SNR, Required Laser Energy

We have adopted a design criterion which avoids "vignetting" problems. The laser beam is allowed to fill the collection optics and the étendue is fixed by the detector. Aiming at a spatial resolution of 10 cm, a maximum sensitive detector area of 20 mm is assumed to ensure the required detector risetime. For the optics that concentrate the collected light onto the detector, the maximum possible F number, F/1, is chosen.

In the tangential design the laser must be focused at the inner edge, whereas we focus the laser at the plasma centre in the radial design. The size of the first collection mirror and the size of the blanket penetration is then given and we can calculate the resulting vignetting curve in the two cases (F# vs. major radius), see fig 5.

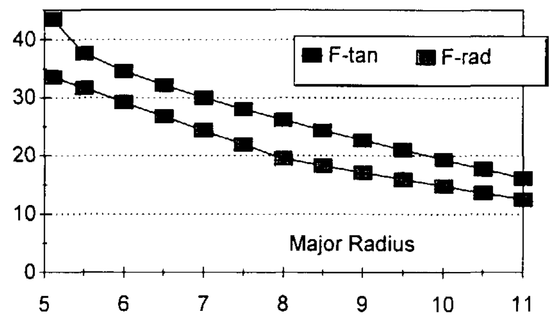

Figure 5 Collection F# versus major radius

Using JET experience we know that we need ~1 Joule at F/12. The required energy in the two ITER designs becomes 2.5 J and 5 J for the radial and tangential designs respectively.
The energy required to make good measurements at the inner edge is ~13 Joules, and the concept of the second pass of the plasma is clearly not realisable. It is worth noting that if we choose a larger, slower detector (~ 40 mm dia.) we can manage with a laser energy of less than 1 Joule and still meet the criterion of 30 cm spatial resolution in the radial design.

Spectral Calibration

The relative spectral sensitivity of the detection system, which must be known to infer the electron temperature from the scattered signals, is measured by illuminating with a calibrated, tuneable, monochromatic light source. This light source is usually placed outside the vessel and thus the transmission of the window and of optical in-vessel components is not measured, (except at the very beginning before the start-up of plasma experiments). However, it has been observed on a number of experiments, during plasma operation absorbing layers build up on in-vessel optics. These can lead to chromatic absorption of the transmitted light. For ITER, effects of neutron and gamma irradiation are expected to add to this problem. There are potentially several solutions:

i) Rayleigh scattering from a gas filling using a tuneable laser or lasers at a number of different emission wavelengths.
ii) Observation of plasma radiation at different wavelengths in the visible with known intensity ratios and bremsstrahlung on standard Ohmic discharges

Investigation of the feasibility of these schemes has to be part of a detailed design study.

Density Calibration

Density calibration of a Thomson scattering arrangement is usually done by performing either Rayleigh or Raman scattering from a rather high pressure (up to 1 bar) gas filling of the discharge vessel. Of course, such a procedure will not be possible on ITER after the initial start-up. However, the absolute (density) calibration could be obtained by taking advantage of the fact that a LIDAR system measures the different spatial points with the same set of detectors, i.e. with constant sensitivity. This is the method currently used at JET. The variation of the solid angle of collection along the line of sight is purely geometrical in nature, it does not vary with time and can either be measured before the start-up of the experiment by Raman scattering or can be calculated sufficiently precisely by optical ray-tracing. Thus the LIDAR system measures directly a relative density profile along the chord. The unknown ratio to the absolute density, which is constant for all spatial points, can be inferred either from comparison to

i) a line integral of the electron density n_e obtained from an interferometer
ii) a line integral of $n_e * B_{||}$ obtained from a polarimeter
iii) a comparison with the density at a single point measured by another diagnostic, such as a single fixed frequency reflectometer channel.

Item i) is a well-established method on JET[1]. In item ii) a polarimeter replaces an interferometer along a tangential line. Since the magnetic field along the tangential path is known, the density can be determined from the measured polarization change. [In fact this could evolve into a density profile measurement diagnostic in its own right.] iii) simply requires a direct comparison of the LIDAR profile with the position of the cut-off density measured by the reflectometer. This sets the LIDAR absolute level for the whole profile.

There is a minor caveat for the applicability of methods i) and ii) to the proposed LIDAR scheme: Since, as we have seen above, it may be difficult to cope with the whole temperature range of an ITER plasma using a single laser wavelength, the relative density profile along the chord may have to be fitted together from two profiles: one for the high temperature core and one for the 'low temperature' (< 3 keV) outer edge.

Spatial Resolution

The LIDAR system at JET has a spatial resolution of 13 cm. Using a 300 ps laser and a 20 mm diameter MCP photomultiplier with a response time of 450 ps and a 1 GHz recorder a spatial resolution of 10 cm is achievable. This is all based on performance figures of commercially available equipment, much of which is already in use in the JET LIDAR system. However, since we are only asked for 30 cm resolution we can relax all these parameters. A large MCP photomultiplier, e.g. 40 mm diameter, would improve the light gathering power and reduce the required laser power. A longer laser pulse improves the damage limit and is obviously easier to make. We could therefore aim for something like a 1.5 ns laser and a 1 GHz recorder (commercial portable oscilloscope), the larger photomultiplier would have a response time of ~1 ns. The resultant resolution of this combination is still within the 30 cm.

SUMMARY AND ACTIONS

The required specifications can be met by a LIDAR system without difficulties once it is established that the front optics can withstand the ITER conditions. It should be possible to provide three lines of sight, one crossing the plasma centre and two inclined ones. This will yield information on the plasma vertical position. At the rather low level of laser energy necessary for a spatial resolution of 30 cm, a repetition rate of the measurements of 100 Hz seems possible. This would enable the possibility of using this diagnostic for control purposes.

The actions required can be listed as follows:

i) Laser damage, thermal and irradiation tests should be conducted for metal mirrors, e.g. Be mirrors both with a high reflectivity silver coating and an aluminium coating (each with and without a dielectric protective coating) in the following sequence:
  a) laser damage threshold tests
  b) reflectivity and laser damage threshold after heating to relevant temperatures
  c) reflectivity and laser damage threshold after irradiation

ii) Conduct a design study for the layout of the front optics inside the port and of the relay optics between port and cryostat, thereby continuously assessing (in discussion with ITER) the required blanket penetrations and their effect on shielding. Determine the levels of heat, gamma and neutron flux at the position of the optical components.

References

1. Salzmann et al, JET Report JET-R(89)07, 1989
2. ITER task agreement S 56 TD 01 94-09-27 FE