JOINT EUROPEAN TORUS

JET–P(91)27

C.W. Gowers
and JET Team

LIDAR Thompson Scattering - Report on IAEA Technical Committee Meeting JET 8-l0th April 1991

LIDAR Thompson Scattering - Report on IAEA Technical Committee Meeting JET 8-10th April 1991

C.W. Gowers
and JET Team*

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

* *See Appendix 1*

Preprint of Paper to be submitted for publication in
Nuclear Fusion

CONFERENCES AND SYMPOSIA

LIDAR THOMSON SCATTERING

Report on the
IAEA Technical Committee Meeting
held at
JET Joint Undertaking,
Abingdon, Oxon, OX14 3EA, UK
8-10 April 1991

C.W. GOWERS
JET Joint Undertaking,
Abingdon, Oxon, OX14 3EA, UK

1. INTRODUCTION

This Technical Committee Meeting report is intended as a review for those readers who are not necessarily specialists in this particular plasma diagnostic technique.

Thomson scattering was first used to measure electron temperatures and densities in magnetically confined plasma during the mid 1960's. Since that time with the improvements in laser and detector technologies the technique has become one of the essential standard diagnostic techniques for making spatially resolved temperature and density profile measurements in fusion research. The increase in dimensions of confinement experiments combined with technological developments in a number of key areas, namely high energy short pulse (sub-nanosecond) lasers; fast, high gain detectors; high bandwidth recording techniques; made it possible in the early 1980's to consider a departure from the standard 90^0 scattering geometry for the spatial profile systems and to use instead, a time of flight backscattering or LIDAR (LIght Detection And Ranging) technique. A short laser pulse is launched through the plasma and its progress is monitored by observing the light backscattered from the plasma electrons. The spectrum and total scattered intensity give the electron temperature (T_e) and density (n_e) in the normal way for Thomson scattering but their profiles are also determined since the position of the laser pulse is known by the time of flight principle. In addition LIDAR-

Thomson scattering offers a considerable simplification of the alignment and access requirements, increasingly important factors when diagnostics for the next step fusion machines are being considered.

The meeting was divided broadly into four sections; the first was a short session in which the existing JET LIDAR system was reviewed and advanced plans for a higher resolution extension were presented; the second was devoted to lasers and laser developments; the third dealt mostly with fast detectors and analysis techniques; in the final section the outline designs of LIDAR scattering systems for new fusion machines were discussed.

2. REVIEW OF EXISTING JET LIDAR SYSTEM

C Gowers (JET, Abingdon) reviewed the main features of the existing JET LIDAR Thomson scattering system and described recent enhancements to its original performance. The expected spatial resolution, δx, is related to the laser pulse duration, τ_{las}, and the response times of the major components of the detection system, the detector and digitizer, τ_{det} and τ_{dig}, by the expression $\delta x = (\tau_{las}^2 + \tau_{det}^2 + \tau_{dig}^2)^{1/2} * c/2$ which for the original components gave $\delta x \sim 12$cm. After outlining the optical components of the ruby laser and its overall performance, he described the input and collection optics set up. He pointed out that the potential difficulties associated with out of focus and moving images of the scattering volume are avoided by forming an image of the collection mirror array on both the dispersion elements and the detector photocathode, instead of the scattering volume itself. Also, by using edge filters as the dispersion element a high throughput (1cm^2.sterad) polychromator has been developed. Two tricks are used to deal with stray light, i) by using a quartz 1/2 lambda plate just before the input window to the vacuum vessel and ii) by using a highly doped ruby crystal in front of the laser wavelength channel.

After presenting some recent results he described how the spatial resolution has been enhanced by hardware and software improvements. The bandwidth of the digitizers has been improved and a software deconvolution technique has been applied to the raw signals, obtaining an overall improvement of 25-30% in δx. A system for monitoring any variation in the spectral transmission of the collection windows due to deposits from the plasma has also been recently commissioned and results were presented. An improvement in the repetition rate of the measurements is planned and a second ruby laser with a higher repetition rate has recently been ordered. The results presented showed high signal to noise ratio and good long term reliability and stability indicating the strength of the LIDAR technique.

During the discussion of the paper, in response to a question about the perturbing effect of such high power laser pulses on the plasma, Mr Gowers pointed out that the fluence at which such effects were thought to become important was around 10^{17} Watts/cm^2 and the LIDAR laser was currently producing only ~10^9 W/cm^2 in the plasma. Care would be needed if a LIDAR system were constructed with significantly shorter pulses and a tightly focused beam.

H. Fajemirokun (Imperial College, London) then described a modification of one of the six parallel collection optics paths of the JET LIDAR system which allows the installation of a streak camera based detection system. With this system it is planned to obtain considerably higher spatial resolution since the response time of the detector is reduced substantially, and the response time of the digitizers is eliminated. He anticipated that with 100ps resolution with the streak camera and a laser pulse duration of ~200ps, the system will have a resolution of better than 5cm. However, at this level of resolution the radial extent of the plasma diagnosed is limited to about 50cm by the available length of the streak image. Ideally, high quantum efficiency and single photoelectron recording capability are required because the number of scattered photons expected in each temporal resolution element will be small (~170 for 2J laser energy and 1.10^{19}m^{-3} density). In addition the camera will need to be gated with a high contrast ratio to avoid the effects of pre- and post-pulses of stray light from the input window and the back wall of the torus. Experiments with a new Thomson-CSF camera will commence later this year but stray light characterisation test results have been obtained with a low gain camera on loan from Imperial College (London). These were presented and even showed a small feature which was consistent with being due to scattered light.

3. LASERS AND LASER DEVELOPMENTS

Prof. Weber (Festkörper-Laser-Institut, Berlin) reviewed developments in solid state, visible and near IR lasers pointing out that in recent years, although no dramatic breaks-through had been forthcoming, steady engineering improvements in crystals, cavity design and pumping techniques has resulted in reliable lasers with kW average output powers. Such lasers could be interesting for LIDAR applications. In addition several alternative material geometries eg. slab, moving slab, annular rod and rotating cylinder are being tested in laboratory lasers. Broad band materials like alexandrite and the recently announced Ti:sapphire look attractive although flash lamp pumping looks to be a problem with the latter because of the short energy storage time. Alexandrite has demonstrated impressive average power capabilities, 150W or 10J/pulse free running, but small scale self-focusing of short pulses is difficult to overcome in the low gain material. YSGG:Cr at 780nm output wavelength has reported performance of 0.6J in Q-switched operation at 25Hz. This appears to be another future LIDAR laser possibility.

Improved beam quality is part of the Eureka program where the aim is to obtain CO_2 beam quality with solid state lasers. Programs using parallel or serial amplification and phase conjugating mirrors were outlined. Increased pumping efficiency is also being sought by using co-doping of materials. Doping with additional ions to enhance pumping efficiency is undergoing tests at laboratory level although Prof Weber stressed that the process of developing materials into full production, high performance lasers is very expensive and companies are extremely reluctant to embark on such a course without a clear and marketable application. He concluded that in the short term the lasers available for LIDAR applications will be the familiar materials that are already well developed, namely ruby and Nd:YAG with the latter still being the best from the high repetition rate viewpoint. The tunable materials alexandrite and recently Ti:sapphire are also beginning to produce performance both at the laboratory and commercial level which could be useful for LIDAR work.

When asked if he thought there was any possibility of increasing the repetition rate of ruby lasers by cooling to liquid nitrogen temperatures, Prof Weber replied that such schemes have been tried, but there are serious problems with bubbles induced in the coolant by flash lamp light and heat. These interfere very significantly with efficient pumping on subsequent pulses. He thought that this would be a difficult problem to resolve.

Dr Selden (Culham Laboratory, Abingdon) discussed possible laser sources and he included Excimer lasers at the short wavelength end of the spectrum and CO_2 at the other extreme. Both offer interesting pulse duration and repetition rate performance if suitable detectors can be found. He also brought to the meeting's attention the development of chirping and pulse compression techniques now available as commercial laser packages which offer the possibility of producing high power laser pulses with reduced risk of laser damage. The scheme works by dispersing the short oscillator pulse with gratings, prisms or a long fibre, producing a longer but varying frequency pulse which can then be more safely amplified. After amplification the pulse is compressed using a pair of gratings.

Dr Gol'tsov (Kurchatov Inst. Troitsk, USSR) pointed out that the required beam parameters of lasers for LIDAR are fairly ordinary when viewed from the inertial confinement viewpoint, the repetition rate being the real challenge. He presented a compact design for a Nd phosphate glass system which consists of an oscillator and 6 rod amplifiers. The final amplifier is 75mm diameter and frequency doubling gives 15J in 300ps at 527nm. The whole optical system fits on a 3mx2m table top. Vacuum spatial filters are included in the later amplification stages both to prevent the development of damaging, high order transverse modes and to also magnify the beam diameter for the larger rods. The repetition rate of the laser is limited to 1Hz and at this frequency the energy per pulse will fall from 15J down to 7J during a 10s pulse burst. The recovery time will be about 1/2 an hour.

To obtain better spatial resolution, for example in the divertor region plasma, he suggested a shorter pulse length laser, 30-50ps. To keep within acceptable damage threshold levels ie.1-3GW/cm^2, requires an output aperture of 1-2X10^2 cm^2 and has rather poor extraction efficiency. An alternative technique might be to use a multi-pulse approach either by generating several pulses with the laser by passing the pulse several times through the final amplifier or by passing the same pulse several times through the plasma. By using box car detection techniques the laser energy per pulse could be reduced by about one order.

Dr Nizienko (Kurchatov Inst, Troitsk, USSR) outlined a more advanced laser design built around the use of two additional concepts. Firstly, the bulk of the beam amplification is carried out in what he termed a light boiler. This is a parallel amplification scheme similar to that outlined by Prof. Weber, which consisted of a pumping chamber with a matrix of alternately flash lamps or laser rods. This design gives close, efficient coupling of flash lamps and rods. Secondly, Dr Nizienko incorporated WFR (Wave Front Reversal) cells as the final stage of the amplifier. These are Stimulated Brillouin Scattering mirrors which perform 3 functions; they act as pulse compressors, reducing the pulse length by about one order of magnitude, they also act as spatial filters cleaning up the beam profile by controlling the high order transverse modes and lastly as phase conjugation mirrors enabling effective double passing of the amplifier stages. The overall loss introduced by each WFR is about 50%.

In the latest design the final stage of the system consists of a Raman oscillator/amplifier system to shift the wavelength from 530nm to 630nm and to further compress the pulse duration to give 2J in 50ps. This has the advantage of shifting the wavelength towards the red end of the spectrum, giving the overall system the capability of diagnosing a greater temperature range.

Dr Schunke (JET, Abingdon) discussed the possibilities of using Nd:YAG laser wavelengths in a LIDAR system since this is a well developed laser material and has the added advantage, when compared with Ruby, of a much higher repetition rate. As a reference point she compared JET LIDAR experimental results with the predicted performance from a simulation code for the same conditions, concluding that the experimental profiles and error bars are accurately predicted. She had then used the code to investigate the expected performance for different Nd:YAG laser scenarios. She examined the possibilities for a Nd:YAG laser based system on JET. She proposed exploiting both harmonics of a frequency doubled laser by using the fact that their polarizations are different. The green light spectrum can then be separated from the infra-red by a (broad band) polarizer and directed to a new 5 channel spectrometer with channels optimised for a 530nm laser wavelength. The existing JET spectrometer, given an extra two channels with long wavelength sensitivity, can then be used for the scattered spectrum from the fundamental line. The simulation of this set-up showed that the fundamental wavelength can then be used for temperatures greater than about 3keV and the 2nd harmonic for temperatures from about 200eV up to 4keV. However, this scheme implies a large and very expensive modification to the existing JET LIDAR system and also relies on obtaining acceptable performance from an as yet untested infra-red sensitive GaAs photo-cathode MCP photomultiplier.

Dr Schunke had therefore turned her attention to a LIDAR simulation for

ITER. She concluded that, using the tangential access proposed by Salzmann et al at a recent ITER Diagnostics Workshop, the two wavelengths of Nd:YAG can be used to great advantage. Firstly, the fundamental is better matched to the higher temperatures expected in the bulk of the ITER plasma and secondly the cooler region near the inner wall SOL could be well diagnosed by the 2nd harmonic. She pointed out that 3-5J of laser energy is assumed to be available in each harmonic implying some laser development.

4.DETECTORS AND ANALYSIS METHODS

This session was begun by Dr Surovegin (RADIAN R & D Centre. Moscow) who described the main features of the new SCANCROSS streaking intensifier. The key feature of the device is that unlike a normal streak tube it does not re-image a slit or spot from the photocathode and sweep it across the phosphor but instead transforms the image of the whole of the photocathode area (diam. up to 40mm) into a slit shape 0.08x7mm and sweeps this across the phosphor in the direction orthogonal to its 7mm length. To do this the device uses spherically shaped photocathode and grid anode surfaces giving quasispherical electrostatic focusing. This is followed by a short MCP stage both to convert the energy of the initial photo-electrons and to collimate them. Two quadrupole magnetic lenses then transform the image from round to rectangular. In principle several hundred resolved pixels are possible with down to 2ps duration for each. So far a tube has been made and operated in static mode, sweeping the image only slowly across the phosphor.

In the discussion Drs Hirsch and Gusev pointed out that the low gain of the MCP stage (about 1) will lead to extremely noisy gain for the device. There was also concern expressed about the current density in the cross over region and whether this will induce saturation effects in the MCP. Dr Surovegin commented that he had described the manufacture of this first device and that there were other manufacturing options available which would be tried in the future.

Dr Dymoke-Bradshaw (Imperial College, London, & Kentech Instruments) reviewed detectors for LIDAR Thomson scattering giving the advantages and disadvantages of streak cameras, photo-multipliers and gated intensifiers. He described the advantage of an indirect or capacitive method for gating wafer intensifiers showing an example of a 100ps gate-on period with very little gate induced pick-up noise. He also pointed out that by gating at high speed in conventional 90° Thomson scattering geometry but with a short laser pulse, stray light can be gated out with a gated intensifier tube. Such a system can be used in near backscattering geometry, but sufficient movement of the image will be required to obtain spatial resolution. He also described non plasma LIDAR applications where range gating is used eg in fog, smoke or under water. He went on to review the current technology for pulse generators for gating. concluding that avalanche diodes are now able to generate rise times of <50ps. Finally he suggested that fast Pockels cells are now able to chop Q-switched laser pulses down to <100ps offering a cheap alternative to the conventional mode locking technique.

Dr Gusev (Ioffe Institute, Leningrad) described results of investigations into the use of an AGAT streak camera as a possible LIDAR detector. He first demonstrated with a simple analysis why the excess noise, F, for a device will be large, if the first stage gain, K_1, is low. He then described the results of excess noise measurements showing that F was ~ 1.5 for the camera . Also when the streak camera is compared with a photomultiplier with the same photocathode material, the ratio of quantum efficiency to excess noise is a factor 2.5 less for the streak tube, mostly due to the presence of a mesh electrode in the tube and low gain on the MCP stage.

He also presented some experimental results in which the stray light characteristics of a LIDAR experiment are simulated and the capability of the camera to cope with these spurious signals is tested. He showed very encouraging results which demonstrated that the camera responds linearly to a small "scattering" signal ($\sim 10^4$ photons) despite being struck by a stray light pulse of 10^{12} photons a nsec before. As a result of the tests, a new AGAT streak camera system has been specified and work on its development is starting.

The LIDAR related activities at Kyushu University were outlined by Dr Kajiwara (Interdisciplinary Grad. School of Eng. Sci., Kyushu University). Kyushu University is interested in assessing the possible application of the LIDAR Thomson scattering technique to the Large Helical Device being designed in Nagoya. He described assessment experiments that have been carried out on a Hamamatsu streak camera. His analysis of the signal to noise ratio at the different stages of the detection system closely paralleled the work reported by Dr Gusev. He also concluded that low gain at the streak tube stage could significantly enhance the noise of the system. The camera was tested experimentally using Rayleigh scattering from a 300ps frequency doubled Nd:YAG laser pulse in 90° scattering geometry. From the results Dr Kajiwara concluded that in these experiments the detection limit is determined by the read out noise and dark current of the CCD camera. He also found that an order of magnitude more scattered photons are needed to obtain the same signal to noise ratio as are required when the experiment is repeated using a photomultiplier as the detector. In assessing the performance of a LIDAR system design for a large experiment he concluded that, with realistic assumptions for laser energy, detection solid angle and optical transmission, a streak camera system could be realized but the effective range of plasma covered by the measurement would be limited by vignetting effects to about 1m. He also concluded that an uncooled CCD camera will be required if greater than 1Hz repetition rate is to be used for the measurement system. This will increase the read out noise and dark current noise but could be compensated if higher gain is available at the streak stage.

Dr Hirsch (IPF Stuttgart) presented the details of studies carried out on microchannel plate photomultipliers when determining their suitability for use as the detectors in the JET LIDAR system. He outlined the construction of the ITT F4128 tubes and the factors that contribute to its response time. He then described the rise time tests and the dependence of the measured performance on the voltages applied to the different stages. He also described the gating contrast ratio tests and the remarkably high ratio (10^{13}) measured at the red end of the spectrum. He pointed out that the tubes have a limited life governed by the MCP. The output will start to drop once the accumulated delivered charge begins to approach $20mC/cm^2$. This is not a severe constraint since even at 10Hz repetition rate and 20s JET pulses, each laser pulse producing heavily saturated output, this corresponds in the gated mode of operation to $3x10^4$ JET pulses.

It has been important to look at the recovery time after saturation because each laser pulse produced such heavily saturated output from the detector when it struck the inner wall of the vacuum vessel. His measurements show that the detector is fully recovered after about 30ms. However the following amplifier can easily be damaged by the several hundred volt output pulse unless protective measures are taken.

Dr Hirsch has tabulated for comparison purposes the known performances of ITT, Hamamatsu and ITL MCP photomultipliers and has compared in a similar way the expected performance of a streak camera with the ITT tube's characteristics. He concluded that more experimental data is required on streak cameras generally before their suitability for use as LIDAR-Thomson scattering detectors can be confidently predicted.

Microchannel plate photomultipliers were also the subject of Dr Bassan's (RFX, Istituto di Gas Ionizzati del CNR, Padova) presentation although in his particular application, which was conventional Thomson scattering on the reversed field pinch, RFX, he is studying the multi-anode MCP photomultiplier. High repetition rate is his main concern because of the need to make plasma light measurements very close to the main laser pulse. He has studied the thermal and electrical behaviour for high MCP strip current tubes and in particular has looked at the recovery time for double pulse operation for different levels of charge in the first pulse and different pulse separations. He showed that for 14pC charge in the first pulse, the tube shows no saturation even down to pulse separations of 100ns. However for first pulses of 3X and ~10x this charge, the recovery time is about 1ms. He concluded that high repetition rates are possible with double MCP tubes and the thermal problems associated with high strip currents are manageable. Rise time tests are still to be carried out.

Dr Orsitto (ENEA, Frascati) gave a post deadline talk on the Thomson scattering system for FTU. He briefly reviewed the parameters of the machine and then described the main features of the Nd:YLF 10Hz laser based scattering system. This uses conventional geometry and pulse durations but the laser repetition rate is impressive with 5J/pulse, 10 pulses per laser burst with interpulse spacing from 10-100ms. The laser which uses a slab in double pass geometry for the final amplification stage, maintained good divergence and pointing stability throughout the burst. The recovery time between bursts is 15min. The dispersion and detection systems use 19 separate 5 channel filter monochromators for dispersing the scattered spectrum and avalanche photodiode as detectors. The expected accuracies for central and edge temperature measurements are 4% and 15% respectively.

Dr Nielsen (JET) discussed the need for real time temperature and density measurements on large tokamaks and concluded that for density and current profile control, a real time LIDAR-Thomson scattering system could be a very useful complimentary diagnostic to ECE and Interferometric diagnostics. Unlike ECE measurements, Thomson scattering did not suffer from serious perturbing effects produced by runaway electrons nor from fringe jumping induced by rapid or local density perturbations like interferometry. However, the repetition rate for Thomson scattering measurements was limited (mostly) by the repetition rate of suitable lasers and this was much less than either of the other two diagnostics. Reviewing available or nearly available hardware he concluded that a 10Hz laser suitable for a LIDAR system could be built and detection systems could be made to run at 20-25Hz depending on the type of technology used ie MCP photomultipliers with fast transient recorders or a streak camera with a CCD readout system. He outlined a transputer based scheme for a photomultiplier detection system which is currently undergoing feasibility trials at JET. He described the chi^2 analysis procedure used to fit the T_e and n_e values and demonstrated the fitting procedure running on a PC at close to the required speed (actually 170ms per fit at the current state of development). He concluded that a real time system for an 8-10Hz LIDAR system is feasible using a transputer based control and analysis system.

Dr Giudicotti (Univ. di Padova) moved the discussion to a somewhat different topic when he described some aspects of Raman calibration of scattering systems. He outlined the calibrations he has carried out on the Eta Beta II (conventional) scattering system, concluding that Raman scattering from a few tens of millibars of hydrogen produces a very convenient signal for relative and absolute calibration of the system. It is possible to carry out the relative sensitivity calibration by rotating the grating in the spectrometers and thereby scanning the Raman line across each channel. This method agrees well with the usual tungsten lamp calibration.

Experiments were also conducted to see the pressure at which stimulated Raman scattering occurs so that an upper pressure limit for linear response, given the intensity distribution of the Eta Beta II laser, can be defined. For the laser energy of 8J the J=1->3 line (723.8nm) shows exponential behaviour above ~230mbar. Other lines investigated also show non-linear behaviour above about 300mbar. Deuterium was also used as the scattering gas but only the J=0->2 line was found to be non-linear. Dr Giudicotti calculated the expected

Raman gain for his experiments and with reasonable assumptions the simplified model gave qualitatively similar results to those observed. He has extended the calculations to the cases for Raman scattering from nitrogen in both RFX and JET. In the RFX case where the pressure and temperature will be 100mbar and 350°C respectively, self focusing will not be a problem even at energies up to 15J. For JET, transient stimulated Raman theory should be used but as a first approximation he used steady state theory and applied a correction factor. He concluded that the Raman calibrations will still be in the linear regime but only just.

In the discussion it was pointed out that if the calculation were correct one would expect problems in the beam path between the roof laboratory and the machine since this path was in excess of 25m. To date no beam break-up problems have been observed.

The final paper in this session was given by Dr Salzmann (IPP, Garching) who discussed ideas on recovering calibrations of a data set when things had gone wrong, by simply carrying out a statistical analysis of the data itself. He argued that in a scattering system with more than 2 spectral channels ie. with a level of redundancy in the measurements of n_e and T_e, it should be possible from a statistical analysis of the data to determine:

i) the development of a systematic error in the measurements due to a fault developing in the hardware

ii) which piece of hardware (or software) is causing the problem and

iii) a modified set of calibration constants and T_e and n_e measurements that are consistent with the noise levels on the signals.

He first showed the results of a simulation in which he used the ratio of the channel sensitivities in the chi^2 fitting procedure (using a SAS program). He compared perfect data with the result of perturbing one of the channel ratios by 10% for a data set of 1000 measurements. The value of temperature fitted in the perturbed case changed by only 2% but the frequency distribution of chi^2 values changed dramatically. The distribution of the residuals for the perturbed signal ratio showed a shift of nearly 3 standard deviations, clearly highlighting where the error lay. He also gave an example of JET data where such an event had occurred and had been detected and corrected by this method of analysis.

He then discussed the possibility of taking the method further and trying to determine all the relative calibrations of the scattering system purely from the statistical analysis of a reasonably sized data set. After describing the details of the analysis he showed the results of simulations of the JET 6 channel set-up. To date, when the analysis is started with the relative sensitivity channel ratios both too high and too low, similar phenomena are observed. In both cases the 3 channels closest to the laser line reach final values which were very close to the real values after 5 iterations but the two channels at the blue end of the spectrum do not converge so accurately onto the true values but remain high or low depending on whether the starting value is high or low. The reason for this is not yet clear. Nevertheless, Dr Salzmann has tried to apply the technique to investigate some JET data in which an optical error had induced a relative sensitivity variation with position across the profile. He found that his technique changes the profile, raising the temperature at virtually every point but only to the upper error bar (ie. a few %). The resultant distribution of chi^2 values across the profile shows good values everywhere with no discernable variation with radius.

Dr Salzmann concluded that statistical methods are valuable tools for detecting and correcting problems in Thomson scattering apparatus. The more ambitious idea of calibrating the system using the method has shown some promising results but requires further development.

5.LIDAR SYSTEMS FOR FUTURE DEVICES

The first presentation in the final session was also given by Dr Salzmann (IPP, Garching) who outlined the parameter ranges expected in the three main regions of the ITER plasma. In the core, T_e will range from 0.5 to 40keV and n_e from 1.10^{18} to 2.10^{20} m^{-3} whereas in the plasma edge the ranges are 5 - 500eV and 1.10^{17} - 5.10^{19} m^{-3} respectively. In the X-point region the ranges are expected to be 5 - 200eV and 1.10^{18} - 1.10^{21} m^{-3}. He went on to outline a proposed scattering diagnostic which, with a single LIDAR based system, could measure both the core plasma and the edge region with good spatial resolution if both harmonics of a Nd:YAG laser are used. This scheme requires a tangential line of sight with the beam line passing very close to the inner wall. The effective radial resolution is then enhanced because the line of sight is at an angle to the flux surfaces. He claimed that for a LIDAR resolution of 10cm along the line of sight, the effective radial resolution could be as low as 1-2cm at the inner-most point. He also suggested that the second pass of the laser pulse through the plasma can be used for a second profile measurement and extended this idea to include chords which are out of the mid-plane. In this way he suggested that five different chords can be measured with a set of three double pass LIDAR systems. Each of the proposed systems requires a pair of large, coupled telescopes, one inside the vacuum boundary of ITER and one outside. With such a scheme it would be possible to have a small vacuum window positioned outside the direct line of sight of the plasma and within the shadow of the radiation shield. The only components in the direct radiation path would be a laser input mirror and a large plane mirror in the collection path. About 6J of laser energy are required (in each harmonic) to obtain the same level of accuracy as the present JET LIDAR system.

By far the most important R and D topic for the proposed diagnostic is the development of radiation hard optics capable of also withstanding the thermal loads and the laser power density simultaneously. Other development areas are higher energy lasers with high repetition rates and suitable large area fast detectors.

Dr Johnson (PPPL, Princeton) outlined the main parameters of the proposed burning plasma experiment, BPX, where T_e and n_e are expected to be about 10keV and $1.5\text{-}3.10^{20}$ m^{-3} respectively. The minimum repetition rate required for measurements will be 1-2Hz, but 10-20Hz would be a very useful in studies of MHD phenomena. The spatial resolution, ideally, should be 3cm in the mid-plane. In the divertor region, where T_e and n_e are expected to be 10-100eV and $1\text{-}20.10^{20}$ m^{-3}, 1cm spatial resolution will be required. After listing the rather harsh environmental considerations for BPX diagnostics, Dr Johnson concluded that LIDAR is the only Thomson scattering technique to consider. However, formidable problems remain to be solved. Carbon coating of optics in the direct sight line has been a serious problem on TFTR reducing optical transmission to 20% for one component. Radiation effects are known to cause dimensional changes to optics, and he presented data on the fractional change in dimension for various neutron fluences for fused and crystal quartz showing that parallel cut crystal quartz had the lowest dimensional change. In addition he presented the expected neutron fluences at different diagnostic locations on the machine.

Using a simple code to predict the accuracy of scattering measurements, Dr Johnson showed that, given current detector response characteristics, a laser wavelength in the 700-800nm range is preferable, 5J being sufficient energy to give better than 5% error bars over the 1-30keV temperature range.

For the outline layout of the optics for the mid-plane system, BPX has adopted the ITER design but since no tangential access is possible, the line of sight is along a major radius. In the reference design, a 100ps pulse duration ruby laser is assumed with a streak camera detection system based around an RCA streak tube and ICCD camera read out system. A read out time of 6-8ms using a "frame transfer" technique is thought to be possible.

There are more difficulties with access for the divertor region in the BPX reference design but modification of one of the vertical access ports could provide a suitable view of the lower X-point region. Since it is proposed to minimise the local load on the divertor dump plates by sweeping the separatrix, a single fixed LIDAR system could give a 2-D mapping of the parameters. The reference scattering design is centred around a 100ps Nd laser and streak tube detection system.

Reviewing R & D requirements, Dr Johnson concluded that characterisation of effect of radiological exposure on laser damage thresholds in windows and mirrors is an important issue. Suitable remote cleaning methods for the optics will also require development. Some laser and detection system developments, eg 5J energy in 100-150ps pulses at 1-10Hz will also be necessary within the time frame of the BPX programme ie. currently about 9 years to first plasma.

Dr Nielsen (JET, Abingdon) outlined the difficulties of designing a Thomson scattering system for the divertor region on JET. He concluded that only a LIDAR system could overcome the awkward access problems but this still requires mirrors inside the vacuum system which could be a problem since this is such a hostile environment (adjustment problems, impurity deposition, high temperature 300° C baking). The original LIDAR design for the divertor plasma had called for a 100-200ps, 1J frequency doubled, Nd:YAG laser operating at 10Hz. The collection optics used an F/25 collection cone and delivered the scattered light to a 3 channel spectrometer. The detection system was not yet fully defined but could be built around either the "RADIAN" streak photodiodes or a conventional streak camera. With a streak camera he showed that only about a 1.2m length of the scattering chord could be diagnosed because of vignetting effects. However, the Scancross tube, if its performance promise was realised, offered a much longer scattering chord length being limited only by vignetting at the torus hall ceiling penetration. Dr Nielsen concluded that plasma light, even in the divertor region, should not be a problem because of the short integration time and with a 1J laser and high transmission optics, enough photons can be collected to give 10% accuracy over a 1m scattering length with about 4cm spatial resolution. He added that it had recently been decided that initially the system will use one of the ruby lasers of the existing LIDAR system to demonstrate its viability, with the option of converting later to a Nd:YAG laser source. He also pointed out that it may be possible to consider such a scheme for the ITER divertor region as a mirror system could be sited inside the vacuum system also in the shadow of the radiation shield.

The final talk of the meeting was given by Dr Shcheglov (Kurchatov Inst. Moscow) who outlined the possibilities of using Near-resonant Rayleigh Scattering in a Hybrid LIDAR system for ITER. He argued that NRS had significant advantages over fluorescence scattering since:- a) it is independent of collisions, b) it has no problems of optical depth, c) it can be detuned from the line avoiding background radiation and d) relatively large values for the cross section can be obtained eg 10^3-10^6 times the Thomson scattering cross section. Having looked at possible impurities he suggested that the CI and HeI lines are suitable but he pointed out that there is a significant advantage in moving to shorter wavelengths since there is a very strong inverse wavelength dependence.

He then sketched possible laser schemes based around a picosecond solid state driven dye laser or possibly an excimer driven dye laser where with final amplifier cross sections of $30cm^2$, 350mJ in 20ps is achievable.

In a brief closing address Dr Stott (JET, Abingdon) thanked the participants and their colleagues for all the hard work in preparing for the meeting and commented that he was encouraged to see several groups performing serious experimental investigations and simulations of LIDAR diagnostic set-ups. He looked forward to seeing more results from LIDAR-Thomson scattering from other parts of the world in the near future.

APPENDIX 1.

THE JET TEAM

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, U.K.

J.M.Adams[1], F.Alladio[4], H.Altmann, R.J.Anderson, G.Appruzzese, W.Bailey, B.Balet, D.V.Bartlett, L.R.Baylor[24], K.Behringer, A.C.Bell, P.Bertoldi, E.Bertolini, V.Bhatnagar, R.J.Bickerton, A.Boileau[3], T.Bonicelli, S.J.Booth, G.Bosia, M.Botman, D.Boyd[31], H.Brelen, H.Brinkschulte, M.Brusati, T.Budd, M.Bures, T.Businaro[4], H.Buttgereit, D.Cacaut, C.Caldwell-Nichols, D.J.Campbell, P.Card, J.Carwardine, G.Celentano, P.Chabert[27], C.D.Challis, A.Cheetham, J.Christiansen, C.Christodoulopoulos, P.Chuilon, R.Claesen, S.Clement[30], J.P.Coad, P.Colestock[6], S.Conroy[13], M.Cooke, S.Cooper, J.G.Cordey, W.Core, S.Corti, A.E.Costley, G.Cottrell, M.Cox[7], P.Cripwell[13], F.Crisanti[4], D.Cross, H.de Blank[16], J.de Haas[16], L.de Kock, E.Deksnis, G.B.Denne, G.Deschamps, G.Devillars, K.J.Dietz, J.Dobbing, S.E.Dorling, P.G.Doyle, D.F.Düchs, H.Duquenoy, A.Edwards, J.Ehrenberg[14], T.Elevant[12], W.Engelhardt, S.K.Erents[7], L.G.Eriksonn[5], M.Evrard[2], H.Falter, D.Flory, M.Forrest[7], C.Froger, K.Fullard, M.Gadeberg[11], A.Galetsas, R.Galvao[8], A.Gibson, R.D.Gill, A.Gondhalekar, C.Gordon, G.Gorini, C.Gormezano, N.A.Gottardi, C.Gowers, B.J.Green, F.S.Griph, M.Gryzinski[26], R.Haange, G.Hammett[6], W.Han[9], C.J.Hancock, P.J.Harbour, N.C.Hawkes[7], P.Haynes[7], T.Hellsten, J.L.Hemmerich, R.Hemsworth, R.F.Herzog, K.Hirsch[14], J.Hoekzema, W.A.Houlberg[24], J.How, M.Huart, A.Hubbard, T.P.Hughes[32], M.Hugon, M.Huguet, J.Jacquinot, O.N.Jarvis, T.C.Jernigan[24], E.Joffrin, E.M.Jones, L.P.D.F.Jones, T.T.C.Jones, J.Källne, A.Kaye, B.E.Keen, M.Keilhacker, G.J.Kelly, A.Khare[15], S.Knowlton, A.Konstantellos, M.Kovanen[21], P.Kupschus, P.Lallia, J.R.Last, L.Lauro-Taroni, M.Laux[33], K.Lawson[7], E.Lazzaro, M.Lennholm, X.Litaudon, P.Lomas, M.Lorentz-Gottardi[2], C.Lowry, G.Magyar, D.Maisonnier, M.Malacarne, V.Marchese, P.Massmann, L.McCarthy[28], G.McCracken[7], P.Mendonca, P.Meriguet, P.Micozzi[4], S.F.Mills, P.Millward, S.L.Milora[24], A.Moissonnier, P.L.Mondino, D.Moreau[17], P.Morgan, H.Morsi[14], G.Murphy, M.F.Nave, M.Newman, L.Nickesson, P.Nielsen, P.Noll, W.Obert, D.O'Brien, J.O'Rourke, M.G.Pacco-Düchs, M.Pain, S.Papastergiou, D.Pasini[20], M.Paume[27], N.Peacock[7], D.Pearson[13], F.Pegoraro, M.Pick, S.Pitcher[7], J.Plancoulaine, J-P.Poffé, F.Porcelli, R.Prentice, T.Raimondi, J.Ramette[17], J.M.Rax[27], C.Raymond, P-H.Rebut, J.Removille, F.Rimini, D.Robinson[7], A.Rolfe, R.T.Ross, L.Rossi, G.Rupprecht[14], R.Rushton, P.Rutter, H.C.Sack, G.Sadler, N.Salmon[13], H.Salzmann[14], A.Santagiustina, D.Schissel[25], P.H.Schild, M.Schmid, G.Schmidt[6], R.L.Shaw, A.Sibley, R.Simonini, J.Sips[16], P.Smeulders, J.Snipes, S.Sommers, L.Sonnerup, K.Sonnenberg, M.Stamp, P.Stangeby[19], D.Start, C.A.Steed, D.Stork, P.E.Stott, T.E.Stringer, D.Stubberfield, T.Sugie[18], D.Summers, H.Summers[20], J.Taboda-Duarte[22], J.Tagle[30], H.Tamnen, A.Tanga, A.Taroni, C.Tebaldi[23], A.Tesini, P.R.Thomas, E.Thompson, K.Thomsen[11], P.Trevalion, M.Tschudin, B.Tubbing, K.Uchino[29], E.Usselmann, H.van der Beken, M.von Hellermann, T.Wade, C.Walker, B.A.Wallander, M.Walravens, K.Walter, D.Ward, M.L.Watkins, J.Wesson, D.H.Wheeler, J.Wilks, U.Willen[12], D.Wilson, T.Winkel, C.Woodward, M.Wykes, I.D.Young, L.Zannelli, M.Zarnstorff[6], D.Zasche[14], J.W.Zwart.

PERMANENT ADDRESS

1. UKAEA, Harwell, Oxon. UK.
2. EUR-EB Association, LPP-ERM/KMS, B-1040 Brussels, Belgium.
3. Institute National des Récherches Scientifique, Quebec, Canada.
4. ENEA-CENTRO Di Frascati, I-00044 Frascati, Roma, Italy.
5. Chalmers University of Technology, Göteborg, Sweden.
6. Princeton Plasma Physics Laboratory, New Jersey, USA.
7. UKAEA Culham Laboratory, Abingdon, Oxon. UK.
8. Plasma Physics Laboratory, Space Research Institute, Sao José dos Campos, Brazil.
9. Institute of Mathematics, University of Oxford, UK.
10. CRPP/EPFL, 21 Avenue des Bains, CH-1007 Lausanne, Switzerland.
11. Risø National Laboratory, DK-4000 Roskilde, Denmark.
12. Swedish Energy Research Commission, S-10072 Stockholm, Sweden.
13. Imperial College of Science and Technology, University of London, UK.
14. Max Planck Institut für Plasmaphysik, D-8046 Garching bei München, FRG.
15. Institute for Plasma Research, Gandhinagar Bhat Gujat, India.
16. FOM Instituut voor Plasmafysica, 3430 Be Nieuwegein, The Netherlands.
17. Commissiariat à L'Energie Atomique, F-92260 Fontenay-aux-Roses, France.
18. JAERI, Tokai Research Establishment, Tokai-Mura, Naka-Gun, Japan.
19. Institute for Aerospace Studies, University of Toronto, Downsview, Ontario, Canada.
20. University of Strathclyde, Glasgow, G4 ONG, U.K.
21. Nuclear Engineering Laboratory, Lapeenranta University, Finland.
22. JNICT, Lisboa, Portugal.
23. Department of Mathematics, Univeristy of Bologna, Italy.
24. Oak Ridge National Laboratory, Oak Ridge, Tenn., USA.
25. G.A. Technologies, San Diego, California, USA.
26. Institute for Nuclear Studies, Swierk, Poland.
27. Commissiariat à l'Energie Atomique, Cadarache, France.
28. School of Physical Sciences, Flinders University of South Australia, South Australia SO42.
29. Kyushi University, Kasagu Fukuoka, Japan.
30. Centro de Investigaciones Energeticas Medioambientales y Techalogicas, Spain.
31. University of Maryland, College Park, Maryland, USA.
32. University of Essex, Colchester, UK.
33. Akademie de Wissenschaften, Berlin, DDR.

CR 88.49.1A