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A.E. Costley
and JET Team

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A.E. Costley and JET Team*

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

** See Annex*

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MILLIMETRIC MEASUREMENT SYSTEMS AT THE JET PROJECT

A E Costley*

ABSTRACT

The millimetre wave measurement systems installed at the Joint European Torus (JET) project are briefly described. The systems are used to measure the parameters of the high temperature plasma produced in the tokamak device. Results demonstrating their performance are presented. In the development of the systems novel solutions to several difficult practical problems have been found and these are described. Areas where further developments would be beneficial are identified.

INTRODUCTION

Extensive use is made of millimetre wave systems for measuring the parameters of the plasmas produced in modern day controlled thermonuclear fusion devices. At the Joint European Torus (JET) project [1], there are two major systems in operation and two others in preparation. A multichannel microwave reflectometer system is used to measure the spatial dependence of the electron density, while a microwave and quasi-optical system is used to measure the electron cyclotron emission (ECE) from which the plasma electron temperature is obtained. A scattering system utilizing a high power (400 kW), long pulse (>5s), gyrotron for measuring the fast-ion and alpha particle populations is being constructed. In the new phase of JET planned for 1992 - 1996, a divertor will be used for impurity control in high performance plasmas. It is necessary to measure the parameters of the plasma in the divertor region and an integrated measurement system based on millimetre wave hardware and measurement techniques is in preparation. Frequently the measurement requirements are very demanding and novel solutions to difficult practical problems have to be found.

In this paper, a brief overview of the systems is presented along with some results demonstrating their performance. Attention is concentrated on the microwave hardware and techniques, rather than on the underlying plasma physics, and areas where further developments are required are identified.

MICROWAVE REFLECTOMETRY

In reflectometry, microwave radiation is launched at the plasma along the gradient of the electron density and reflected at the layer where the electron density equals a critical value ($n_e = n_c$ (f)) such that the plasma refractive index has fallen to zero. Phase changes in the reflected radiation are measured by mixing it with a reference beam in a detector. The probing frequency (f) is swept and the corresponding change of phase (ϕ) is measured. Different frequencies are reflected at different density layers with higher frequencies being reflected at higher densities. $d\phi/df$ is determined at each frequency in the range of interest and the spatial profile of the electron density ($n_e(R)$) is determined by an inversion technique [2]. The electron densities of current interest are typically in the range $10^{18} < n_e < 10^{20} m^{-3}$ with corresponding probing frequencies in the range $9 < f < 90$ GHz.

*** JET Joint Undertaking, Abingdon, Oxon OX14 3EA, UK**

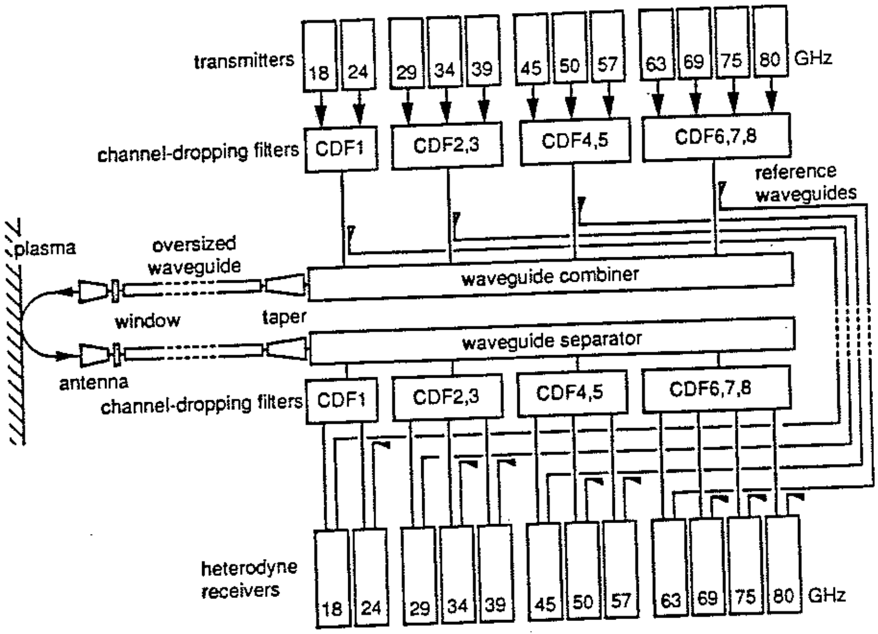

Fig. 1: Schematic of the multichannel JET reflectometer system.

There are two approaches to implementing the technique. In one case the frequency is swept over a *broad* range and $d\phi/df$ is measured as a function of frequency. In the other case, the output from an array of independent sources with different probing frequencies is multiplexed into the same waveguide, and the frequency of each source is swept over a *narrow* range to give $d\phi/df$ at each frequency. $d\phi/df$ is constructed by interpolation at all frequencies in the range in interest.

At JET, the reflectometer is based on the multiple frequency, narrow band sweep, approach. The outputs from 12 Gunn oscillators operating in the range $18 < f < 80$ GHz are multiplexed into an oversized (WG12A) waveguide run (figure 1). A combiner employing band branching/channel filtering systems was developed specifically for this purpose [3]. The waveguide run has a length of 25m and employs reduced height E-plane bends to minimize mode conversion. The radiation is launched and received using separate antennas mounted in the JET vacuum vessel. The separation of the reflected signals is effected with a second band branching/channel filtering system, and the signals are detected using sensitive heterodyne receivers. The data acquisition system includes automatic fringe counting electronics to give ϕ.

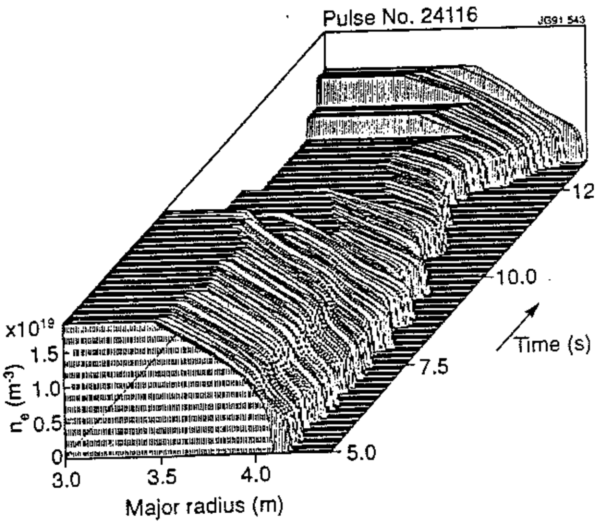

Fig. 2: Typical measurement of the electron density profile.

The system is used routinely at JET to measure $n_e(R)$. A typical result is shown in figure 2. At present the performance of the system is limited by the attenuation in the transmission system and especially in the combiners and separators. This could be tolerated if stable sources at a frequency ~ 70-90 GHz with a power output ~500 mW were available. For future applications, broader bandwidths are likely to be required and combiners/separators operating over the range 12 - 110 GHz would be beneficial.

In addition to the development and use of the multichannel reflectometer, novel reflectometer systems are being developed especially for the study of density fluctuations [4].

ELECTRON CYCLOTRON EMISSION

The electrons in the plasma gyrate around the magnetic field lines and as a result emit electromagnetic radiation at the electron cyclotron frequency and its low harmonics. The intensity of the emission is directly related to the temperature of the electrons (T_e). The frequency of the emission depends on the strength of the magnetic field where the radiation is emitted. In a tokamak like JET, the magnetic field strength varies in a known way across the plasma cross-section. It is therefore possible to determine the spatial profile of the electron temperature ($T_e(R)$) by measuring the spectrum of the emission. Because of the value of the magnetic field strengths employed, the emission occurs in the frequency range 50 - 500 GHz.

An extensive system has been installed at JET for measuring the electron cyclotron emission [5]. Antennas inside the JET vacuum vessel collect the radiation which is then transmitted in a long (~40m), oversized (WG10) waveguide run to the measurement instruments and detectors. Three different instruments are employed. A Michelson interferometer measures the whole spectrum of the emission while a grating polychromator measures the emission at twelve discrete frequencies. Both these devices are fitted with liquid helium cooled indium antimonide detectors. A 44 channel heterodyne radiometer measures the emission at discrete frequencies in the ranges 73 - 103 GHz and 115 - 127 GHz at ~1 GHz intervals (figure 3). The instruments are absolutely calibrated using a large-area, high-temperature (800 K) black-body source which is mounted inside the JET vacuum vessel during maintenance and shutdown periods. The ECE measurements are used in the determination and optimisation of the overall plasma performance and in specific physics studies. A typical measurement is shown in figure 4.

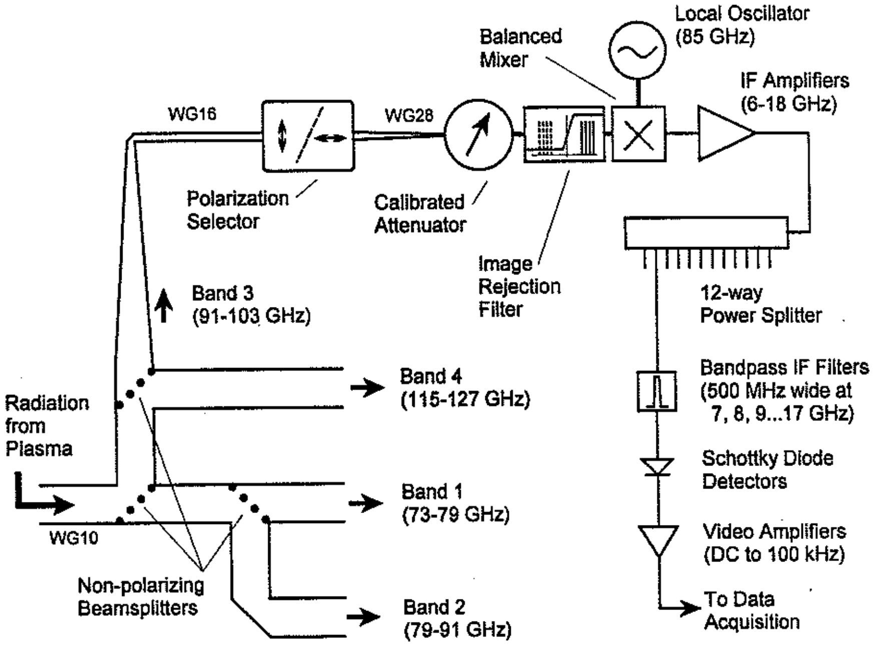

Fig. 3: Schematic of the heterodyne radiometer for the measurement of ECE showing the details of one band.

While the performance of the measurement system is adequate for many applications, some improvements would be beneficial. Heterodyne radiometers operating at frequencies >150 GHz and up to 250 GHz would enable these receivers to be used on high field tokamaks. An improvement in the intermediate frequency bandwidth to frequencies >150 GHz and up to 250 GHz would enable these receivers to be used on high field tokamaks. An improvement in the intermediate frequency bandwidth to >10 GHz, and preferably 20 GHz, would permit a greater spatial coverage with a single mixer. In the measurement of ECE, receiver sensititivity is not the most important parameter, because the signal levels are relatively high, and aconversion loss ~10 - 12 db can usually be tolerated. For next step tokamaks such as the International Thermonuclear Experimental Reactor (ITER), antennas and waveguides that can withstand the harsh radiation environment will be required. Long (~100m), low loss, oversized, waveguide runs which generate minimum mode conversion will also be needed.

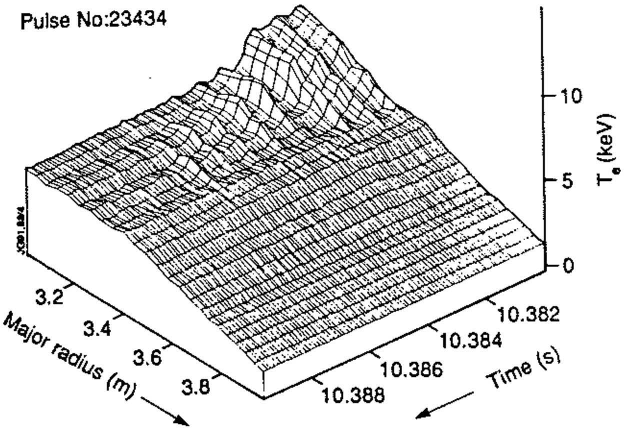

Fig. 4: Typical measurement of the electron temperature profile.

COLLECTIVE SCATTERING

Ions with energies that considerably exceed the thermal energies can be an important component in the plasmas produced in present-day tokamaks. In future devices fast alpha-particles, born with an energy of 3.5 MeV by the fusion process, will play an important role in the plasma heating and possibly affect the plasma stability. The development of techniques for diagnosing these "fast-ions" and alpha-particles is therefore important in current fusion research.

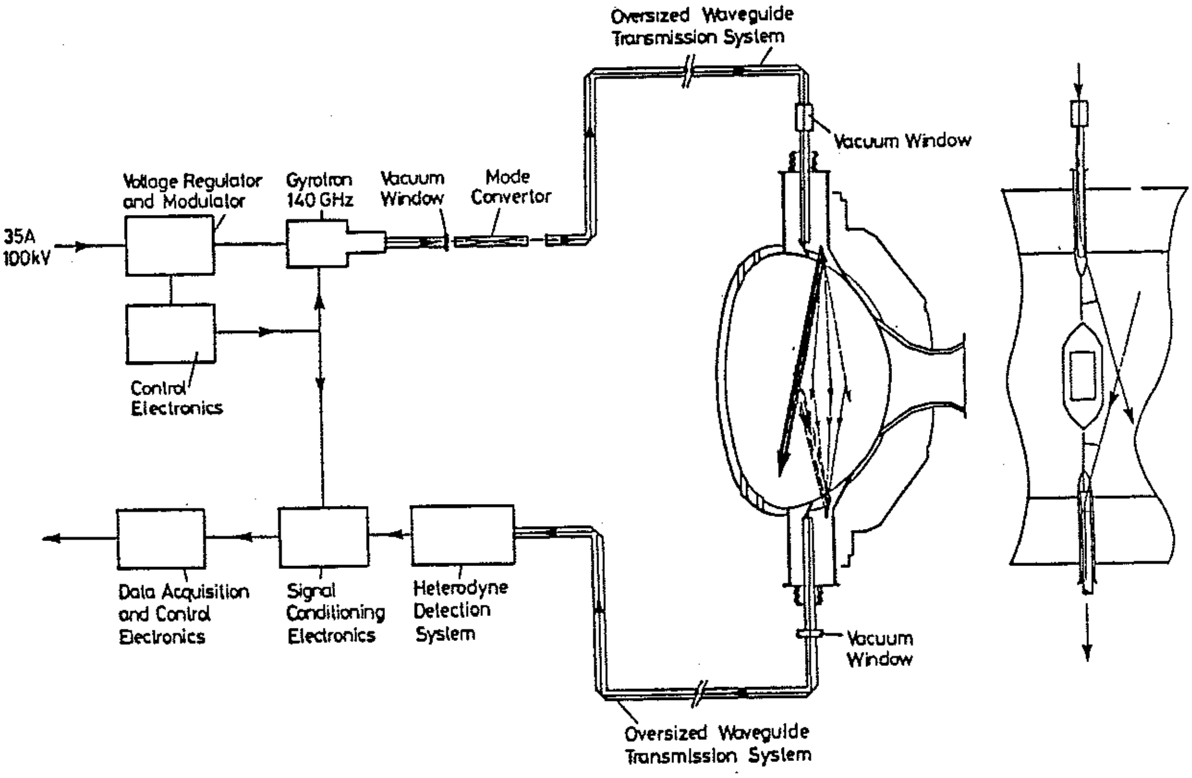

Fig. 5: Schematic of the collective scattering system.

At JET, a system for diagnosing the fast-ions and alpha-particles based on collective scattering is in preparation. Radiation from a high frequency (140 GHz) gyrotron is trasmitted to the plasma and the radiation scattered in a forward direction is spectrally resolved and detected (figure 5) [6]. The cross-section for scattering is extremely small so a high power (>400 kW), long pulse (>5s) gyrotron is employed and sensitive heterodyne detectors are used. It is necessary to site the gyrotron and detection system outside the JET torus hall and so a long, oversized waveguide (diameter 88.9mm), transmission system is used. The system contains several novel components: for example, a mode convertor (Vlasov type) for converting the gyrotron mode ($TE_{15,2}$) to a Gaussian beam for coupling into the HE_{11} mode in the oversized guide, a universal polarizer for changing the polarisation of the gyrotron beam into the optimum for scattering, and resistive waveguide sections to absorb power in unwanted modes. The detectors will be similar to those used for ECE measurements and will have 40 channels between 123 and 156 GHz. Calculations show that the system should provide measurements of the velocity and spatial distributions of the fast-ions and alpha-particles for a wide range of plasma conditions. It is expected that the first measurements will be made with the system at the beginning of the next experimental campaign at JET scheduled for autumn 1993.

PUMPED DIVERTOR DIAGNOSTICS

A substantial upgrade of the JET tokamak is currently in progress. A pumped divertor is being installed in order to obtain improved control over the influx of impurities from the walls. In the pumped divertor, the outer magnetic flux contours of the plasma are brought into contact with special target plates in close proximity to a high speed cryopump. In order to understand and optimise the performance of the divertor, it is necessary to measure the plasma parameters in the divertor region. In general, the values of the plasma parameters in this region will be substantially different to those in the bulk plasma: for example, the electron density and temperature will be an order of magnitude or more higher and lower respectively. The pumped divertor will be located at the bottom of the vacuum vessel. Access to the plasma is very limited and has a major influence on the choice and design of the diagnostic systems.

An integrated microwave system is being prepared. The system will contain a transmission interferometer for measuring the line integral of the electron density; a novel 'comb' reflectometer for measuring the maximum electron density in the line-of-sight, and a system to measure the electron cyclotron absorption (ECA) from which the electron density - temperature product will be determined. The interferometer will operate at two frequencies, typically 130 GHz and 170 GHz. The phase delay due to the plasma will be measured at each frequency and thereby the delay due to the plasma will be separated from that due to small movements in the waveguide structure. The transmission waveguide will be oversized, long and have a considerable number of bends and so it will not be feasible to use conventional swept frequency reflectometry which requires a reflection-free propagation path. Instead it is planned to use a multichannel, fixed frequency, 'comb' type reflectometer. In this device the plasma is irradiated with the output from several sources at different fixed frequencies. The maximum frequency in reflection is determined, and therefore the peak density in the line-of-sight, from the level of fluctuations on the reflected beams - the fluctuation level is high for those beams in reflection. For the pumped divertor, it is planned to use a number of fixed frequencies in the range 60 to 90 GHz.

It will not be possible to measure the electron cyclotron emission from the divertor plasma, since it will be swamped by the much more intense emission, at the same frequencies, from the plasma core. Instead it is planned to measure the absorption of a transmitted beam. For the n_e and T_e values expected in the divertor region the absorption will be in the range 10% to 90%. Only coherent sources have sufficient power for this measurement and it is therefore necessary to overcome the problem of standing waves in the transmission waveguide which would corrupt the required measurements. The solution currently under investigation is to use a rapidly frequency swept source and heterodyne detection using the same source as local oscillator. By adjusting the length of the reference arm through which the local oscillator radiation passes to be about the same as the plasma arm (~100 m), the beat frequency in the heterodyne detector can be adjusted to a suitable value. Standing waves due to multiple reflections within the transmission waveguide will have a longer propagation path, hence a different beat frequency, and will be eliminated by filtering the beat signal. A large-scale mock-up to demonstrate this principle is currently under construction.

All three systems will share the waveguides used to transmit radiation to and from the plasma, as well as the antennas located in the divertor assembly itself. The different measurements will therefore be made along the same sightline. It is planned to install three sets of waveguides to give three different sightlines through the divertor plasma.

SUMMARY

At JET there are four major diagnostic systems - microwave reflectometry, electron cyclotron emmission, collective scattering and pumped divertor diagnostics - which make extensive use of millimetre wave hardware and techniques. The systems are used to measure the values of important plasma parameters, for example the electron density and temperature. In some cases, improvements in the performance of the millimetre wave components would lead to an improvement in the accuracy of the measurements or the range of plasma conditions which can be investigated, or to additional applications. For next step tokamaks, e.g. ITER, substantial millimetre wave systems involving the development of improved and new components are likely to be required.

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Appendix I

THE JET TEAM

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

J.M. Adams[1], B. Alper, H. Altmann, A. Andersen[14], P. Andrew, S.Ali-Arshad, W. Bailey, B. Balet, P. Barabaschi, Y. Baranov, P. Barker, R. Barnsley[2], M. Baronian, D.V. Bartlett, A.C. Bell, G. Benali, P. Bertoldi, E. Bertolini, V. Bhatnagar, A.J. Bickley, D. Bond, T. Bonicelli, S.J. Booth, G. Bosia, M. Botman, D. Boucher, P. Boucquey, M. Brandon, P. Breger, H. Brelen, W.J. Brewerton, H. Brinkschulte, T. Brown, M. Brusati, T. Budd, M. Bures, P. Burton, T. Businaro, P. Butcher, H. Buttgereit, C. Caldwell-Nichols, D.J. Campbell, D. Campling, P. Card, G. Celentano, C.D. Challis, A.V.Chankin[23], A. Cherubini, D. Chiron, J. Christiansen, P. Chuilon, R. Claesen, S. Clement, E. Clipsham, J.P. Coad, I.H. Coffey[24], A. Colton, M. Comiskey[4], S. Conroy, M. Cooke, S. Cooper, J.G. Cordey, W. Core, G. Corrigan, S. Corti, A.E. Costley, G. Cottrell, M. Cox[7], P. Crawley, O. Da Costa, N. Davies, S.J. Davies[7], H. de Blank, H. de Esch, L. de Kock, E. Deksnis, N. Deliyanakus, G.B. Denne-Hinnov, G. Deschamps, W.J. Dickson[19], K.J. Dietz, A. Dines, S.L. Dmitrenko, M. Dmitrieva[25], J. Dobbing, N. Dolgetta, S.E. Dorling, P.G. Doyle, D.F. Düchs, H. Duquenoy, A. Edwards, J. Ehrenberg, A. Ekedahl, T. Elevant[11], S.K. Erents[7], L.G. Eriksson, H. Fajemirokun[12], H. Falter, J. Freiling[15], C. Froger, P. Froissard, K. Fullard, M. Gadeberg, A. Galetsas, L. Galbiati, D. Gambier, M. Garribba, P. Gaze, R. Giannella, A. Gibson, R.D. Gill, A. Girard, A. Gondhalekar, D. Goodall[7], C. Gormezano, N.A. Gottardi, C. Gowers, B.J. Green, R. Haange, A. Haigh, C.J. Hancock, P.J. Harbour, N.C. Hawkes[7], N.P. Hawkes[1], P. Haynes[7], J.L. Hemmerich, T. Hender[7], J. Hoekzema, L. Horton, J. How, P.J. Howarth[5], M. Huart, T.P. Hughes[4], M. Huguet, F. Hurd, K. Ida[18], B. Ingram, M. Irving, J. Jacquinot, H. Jaeckel, J.F. Jaeger, G. Janeschitz, Z. Jankowicz[22], O.N. Jarvis, F. Jensen, E.M. Jones, L.P.D.F. Jones, T.T.C. Jones, J-F. Junger, F. Junique, A. Kaye, B.E. Keen, M. Keilhacker, W. Kerner, N.J. Kidd, R. Konig, A. Konstantellos, P. Kupschus, R. Lässer, J.R. Last, B. Laundy, L. Lauro-Taroni, K. Lawson[7], M. Lennholm, J. Lingertat[13], R.N. Litunovski, A. Loarte, R. Lobel, P. Lomas, M. Loughlin, C. Lowry, A.C. Maas[15], B. Macklin, C.F. Maggi[16], G. Magyar, V. Marchese, F. Marcus, J. Mart, D. Martin, E. Martin, R. Martin-Solis[8], P. Massmann, G. Matthews, H. McBryan, G. McCracken[7], P. Meriguet, P. Miele, S.F. Mills, P. Millward, E. Minardi[16], R. Mohanti[17], P.L. Mondino, A. Montvai[3], P. Morgan, H. Morsi, G. Murphy, F. Nave[27], S. Neudatchin[23], G. Newbert, M. Newman, P. Nielsen, P. Noll, W. Obert, D. O'Brien, J. O'Rourke, R. Ostrom, M. Ottaviani, S. Papastergiou, D. Pasini, B. Patel, A. Peacock, N. Peacock[7], R.J.M. Pearce, D. Pearson[12], J.F. Peng[26], R. Pepe de Silva, G. Perinic, C. Perry, M.A. Pick, J. Plancoulaine, J-P. Poffé, R. Pohlchen, F. Porcelli, L. Porte[19], R. Prentice, S. Puppin, S. Putvinskii[23], G. Radford[9], T. Raimondi, M.C. Ramos de Andrade, M. Rapisarda[29], P-H. Rebut, R. Reichle, S. Richards, E. Righi, F. Rimini, A. Rolfe, R.T. Ross, L. Rossi, R. Russ, H.C. Sack, G. Sadler, G. Saibene, J.L. Salanave, G. Sanazzaro, A. Santagiustina, R. Sartori, C. Sborchia, P. Schild, M. Schmid, G. Schmidt[6], H. Schroepf, B. Schunke, S.M. Scott, A. Sibley, R. Simonini, A.C.C. Sips, P. Smeulders, R. Smith, M. Stamp, P. Stangeby[20], D.F. Start, C.A. Steed, D. Stork, P.E. Stott, P. Stubberfield, D. Summers, H. Summers[19], L. Svensson, J.A. Tagle[21], A. Tanga, A. Taroni, C. Terella, A. Tesini, P.R. Thomas, E. Thompson, K. Thomsen, P. Trevalion, B. Tubbing, F. Tibone, H. van der Beken, G. Vlases, M. von Hellermann, T. Wade, C. Walker, D. Ward, M.L. Watkins, M.J. Watson, S. Weber[10], J. Wesson, T.J. Wijnands, J. Wilks, D. Wilson, T. Winkel, R. Wolf, D. Wong, C. Woodward, M. Wykes, I.D. Young, L. Zannelli, A. Zolfaghari[28], G. Zullo, W. Zwingmann.

PERMANENT ADDRESSES

1. UKAEA, Harwell, Didcot, Oxon, UK.
2. University of Leicester, Leicester, UK.
3. Central Research Institute for Physics, Budapest, Hungary.
4. University of Essex, Colchester, UK.
5. University of Birmingham, Birmingham, UK.
6. Princeton Plasma Physics Laboratory, New Jersey, USA.
7. UKAEA Culham Laboratory, Abingdon, Oxon, UK.
8. Universidad Complutense de Madrid, Spain.
9. Institute of Mathematics, University of Oxford, UK.
10. Freien Universität, Berlin, F.R.G.
11. Royal Institute of Technology, Stockholm, Sweden.
12. Imperial College, University of London, UK.
13. Max Planck Institut für Plasmaphysik, Garching, FRG.
14. Risø National Laboratory, Denmark.
15. FOM Instituut voor Plasmafysica, Nieuwegein, The Netherlands.
16. Dipartimento di Fisica, University of Milan, Milano, Italy.
17. North Carolina State University, Raleigh, NC, USA
18. National Institute for Fusion Science, Nagoya, Japan.
19. University of Strathclyde, 107 Rottenrow, Glasgow, UK.
20. Institute for Aerospace Studies, University of Toronto, Ontario, Canada.
21. CIEMAT, Madrid, Spain.
22. Institute for Nuclear Studies, Otwock-Swierk, Poland.
23. Kurchatov Institute of Atomic Energy, Moscow, USSR
24. Queens University, Belfast, UK.
25. Keldysh Institute of Applied Mathematics, Moscow, USSR.
26. Institute of Plasma Physics, Academica Sinica, Hefei, P. R. China.
27. LNETI, Savacem, Portugal.
28. Plasma Fusion Center, M.I.T., Boston, USA.
29. ENEA, Frascati, Italy.

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