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Core Concentrations of Hydrogen Isotopes and Light Elements in Burning Plasmas

Summary Report of an IAEA Consultants' Meeting

IAEA Headquarters, Vienna, Austria

11 – 12 December 2006

Prepared by

R.E.H. Clark

November 2007

IAEA Nuclear Data Section, Wagramer Strasse 5, A-1400 Vienna, Austria

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Abstract

The Atomic and Molecular (A+M) Subcommittee of the International Fusion Research Council has recommended that the Atomic and Molecular Data Unit hold a Consultants' Meeting (CM) to assess and discuss the changing core concentrations of hydrogen isotopes and light elements in burning plasmas. Accordingly, four international experts on burning plasmas attended a CM at IAEA Headquarters, Vienna on 11 and 12 December 2006 to define and debate these issues. After a review of the current understanding, specific recommendations were made to the IAEA. The discussions, conclusions and recommendations of the CM are briefly described in this report.

November 2007

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Introduction

A Consultants' Meeting (CM) on "Core concentrations of hydrogen isotopes and light elements in burning plasmas" was held on 11-12 December, 2006 at IAEA Headquarters, Vienna, Austria. The goals of the CM were to review methods for the determination of core concentrations, such as charge exchange, diagnostic beam injection and ionic e-fluxes, and to evaluate the relative merits of nuclear and atomic diagnostics techniques.

Four international experts on light elements in burning plasmas participated in the resulting CM in order to undertake an in-depth assessment of these issues (see Appendix 1). Each participant gave a summary of their relevant research activities and areas of expertise. Discussion took place among all participants on the relative merits of different techniques, and the atomic and molecular (A+M) data needed for support of those techniques. The participants formulated a set of recommendations for the A+M Unit of the IAEA.

Meeting Proceedings

R. Clark (Scientific Secretary) welcomed the participants to the IAEA. He noted the increased need for a number of diagnostic techniques as catalysed by the recent signing of the agreement to move forward with the multinational ITER project. The proposed agenda was reviewed and accepted without change (see Appendix 2).

Each participant reviewed current research activities and capabilities through their presentations to the group. These technical presentations were collected electronically and distributed on CD. Brief summaries of the presentations are given below.

M. Sasau (Tohoku University, Japan) presented work on atomic and molecular (A+M) processes relevant to beam neutralization alpha-particle diagnostics, and the importance of the helium metastable fraction in these processes. She gave a brief introduction to beam neutralization alpha-particle diagnostics, and described the A+M processes relevant to He^0 and He^- beam production and He^0 attenuation. Methods of measuring the helium metastable fraction were described. A number of data requirements were specified: important data needs exist for the determination of the metastable fractions of light elements, neutralization processes, beam attenuation, impurity ion impact ionization and charge exchange for light elements.

M. Petrov (A.F. Ioffe Physical Technical Institute, St. Petersburg, Russia) reported on neutralization processes of thermal and fast ions in burning plasmas, and the use of the analysis of outgoing atoms for isotope ratio density measurements and the study of confined MeV ions. Important issues identified with neutral particle analysis (NPA) on ITER include the determination of the isotope composition to control the n_D/n_T ratio for optimization of burning, and measurement of the distribution function of high-energy particles in the MeV range that result from fusion reactions and additional heating. Neutral beam (NB) heating in ITER can provide an NPA signal which interferes with the measurements of the n_D/n_T ratio. Measurements of the n_D/n_T ratio are possible for a burning plasma in ITER without having to use NB heating. Numerical modelling shows that NPA can provide sufficient statistics to measure the n_D/n_T ratio in the ITER plasma core with a time resolution of 100 ms and an accuracy of 10%. For supra-thermal neutral particle flux generation in the plasma, numerical modelling shows that NPA can detect the spectrum of neutralized alpha particles if the densities of the He-like ions Be^{2+} and C^{4+} in the ITER plasma are in the range of 10^6 to 10^7 cm^{-3}. Knock-on deuterons can also be detected by high-energy NPA (HENPA) if the densities of the H-like ions Be^{3+} and C^{5+} in the ITER plasma are ~ 10^7 cm^{-3}. Resolution of the distribution functions of alpha particles and other fast ions requires information about the densities of hydrogen- and helium-like ions of C and Be in the plasma core. The main problem in this form of analysis is the ability to monitoring the core densities of Be^{2+}, C^{4+}, Be^{3+} and C^{5+}, perhaps by means of spectroscopy.

S. Tugarinov (ITER CXRS Diagnostic Development, Russia) summarized work on the diagnostic concept of charge exchange recombination spectroscopy (CXRS) for ITER, and specified the data needed to implement the technique satisfactorily. CXRS is an active spectroscopic method of measurement aided by DNB (diagnostic neutral beam). This combination provides a means of determining density profiles of light elemental impurities (including He ash) by quantification of the relevant line intensities, ion temperature profiles through Doppler broadening of intrinsic impurity lines, and plasma toroidal and poloidal rotation velocities using the Doppler shift of the same impurity lines. Precise knowledge is required of "effective" atomic rate coefficients (Q) for charge exchange and beam emission spectroscopy. These data must include the effects of all physical processes affecting the charge exchange recombination reaction inside the beam volume, including "halo" and "gyrotron" rotation effects. Numerical modelling can provide an estimate of the abilities and efficiency of the CXRS diagnostic for application to ITER. There is also the additional need for total cross sections of the DNB attenuation for DNB and plasma parameters, Gaunt factor values for various plasma parameters, and knowledge of the radial distributions of bulk atoms, D and T.

L. Baylor (Oak Ridge National Laboratory, USA) reported on the fueling and isotopic tailoring of burning plasmas. Fueling requirements for a burning plasma are substantial, and gas fueling will not be very effective for a reactor size device. Pellet injection of hydrogen isotopes will be the primary method for fueling the ITER core. Further research into ITER fueling procedures and pellets for edge localized mode (ELM) triggering is on-going within the USA and elsewhere. An inner wall injection port will allow pellet injection with speeds up to 300 m s^{-1}. Modelling of the proposed pellet injection isotopic fueling of ITER looks promising. Further validation and improvement of the ExB polarization drift model is needed with respect to diagnostics and scaling studies. Control of the isotopic mixture in ITER by means of multiple pellet injectors looks feasible, but measurement of isotopic mixtures beyond fusion output is necessary for more accurate control of the mixture.

Recommendations and Conclusions

Comprehensive discussions took place on the methods that exhibit greatest promise for the determination of core concentrations of hydrogen isotopes and light elements in burning plasmas. The major methods along with data needs were agreed and summarized.

Charge exchange recombination spectroscopy (CXRS) in the core region requires precise knowledge of "effective" atomic rate coefficients $<\sigma v>$ at beam energies of 20-100 keV amu^{-1} for CX and BES transitions. Specific requirements include HeII n = 4-3 transitions at a wavelength of 468.6 nm, CVI n = 8-7 transitions at a wavelength of 529.1 nm, BeIV n = 6-5 transitions at a wavelength of 465.8 nm and H, D and T alpha (and beta) transitions. Pure atomic physics data are available for He, C and H, but not for Be.

Data are needed for various DNB and plasma parameters involving all physical processes affecting the CXRS reactions inside the beam volume, including "halo" and "gyrotron" rotation effects

A full set of atomic data in the form of total cross sections for DNB attenuation for various DNB and plasma parameters is required for numerical simulation. Gaunt factors for various plasma parameters and bulk atoms (D and T) radial distributions are also needed.

Beam neutralization alpha-particle diagnostics in the 100-2000 keV range require data on the metastable fraction of neutral atoms from $He^{++} + He^0 \rightarrow He^0 + He^{++}$, impurity ion impact ionization (such as Be^{4+} and C^{6+}) and charge exchange cross sections of He neutrals with D^+ or T^+, Be^{4+} and C^{6+}.

Some calculations exist for neutral particle analysis (NPA), but more such studies are needed. There is a need for data for $H^+ + A^{Z-1} \rightarrow H^0 + A^Z$ for A representing Be^{3+}, Be^{4+}, C^{5+} and C^{6+} in the 0.1 – 3 MeV energy range. Data would also be beneficial for $He^{2+} + A^{Z-2} \rightarrow He^0 + A^Z$ with A representing Be^{2+}, Be^{3+}, C^{4+} and C^{6+} in the 0.1 to 5 MeV energy range. Measurements are required in order to monitor C^{4+}

and Be^{2+}, and $C^{5+}$and Be^{3+} densities in the plasma core, as well as the He^{+} density over the plasma cross-section.

Time-of-flight measurements with collimated neutrons look promising for the determination of the D-T ratio in ITER. Several channels will be needed to determine the DT ratio profile in the plasma, with an anticipated uncertainty in the range of 10-20% at a time resolution of 1 sec.

The use of a Penning gauge in the divertor pumping duct appears to be the most promising technique for studies of the scrape off layer (SOL).

Efficient control of the burning plasma fueling system needs accurate definition of the isotopic mix in the plasma (preferably as a function of radius) in order to control precisely the plasma burn. NPA measurements of the temporal evolution of the T density profile would be valuable in the study of the transport of T following pellet injection and gas puffing.

These same diagnostic methods can be applied to the study of tritium retention by measuring the plasma tritium content in clean-up plasmas. Spectroscopy of the tritium alpha line and low-energy NPA would be especially useful for this task. A residual gas analyzer (RGA) Penning gauge could also be used to study the tritium release from material surfaces.

Some data exist for most of the techniques, but significant quantities of additional data are required. Consideration should be given to holding a Technical Meeting to discuss in much further detail these and other data needs for isotope measurements, with the possibility of the formulation and launch of a well-defined Coordinated Research Project to address the important issues raised with respect to core concentrations of hydrogen isotopes and light elements in burning plasmas.

IAEA Consultants' Meeting on "Core Concentrations of Hydrogen Isotopes and Light Elements in Burning Plasmas"

11–12 December 2006, IAEA Headquarters, Vienna, Austria

Scientific Secretary: R.E.H. Clark

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Appendix 2

IAEA Consultants' Meeting on "Core Concentrations of Hydrogen Isotopes and Light Elements in Burning Plasmas"

11–12 December 2006, IAEA Headquarters, Vienna, Austria

Scientific Secretary: R.E.H. Clark

Meeting Agenda

Monday, 11 December **Meeting Room: C-07-41**

09:30 - 09:45 R.E.H. Clark Welcoming remarks, Adoption of Agenda

Session 1: Review of current research topics

M. Sasao "A & M processes relevant to beam neutralization alpha particle diagnostics, and the importance of helium metastable fraction in these processes"

M. Petrov "Neutralization processes of thermal and fast ions in burning plasmas and the use of the analysis of outcoming atoms for isotope ration density measurements and for the study of MeV confined ions"

Coffee break

S. Tugarinov "CXRS diagnostic concept for ITER and data needed"

L. Baylor "Fueling and Isotopic Tailoring of Burning Plasmas"

Lunch

Session 2: Discussion of techniques

All

Tuesday, December 12

Session 3: Discussion of data needs

All

Lunch

Session 4: Discussion of possible research projects

All

Meeting adjournment

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