US ITER Forum
Activity Proposal Form

Your name: Donald L Hillis
Your institution: Oak Ridge National Laboratory
Your E-mail address: HillisDL@ornl.gov
Your phone number: 865-576-3739

What is the scope of your proposed activity?
To review the capabilities of the US to provide a diagnostic package for ITER, which would include all of the active spectroscopy diagnostics (Motional Stark Effect, Charge Exchange Recombination Spectroscopy, and Beam Emission Spectroscopy) for ITER.
These are the diagnostics, which utilize a diagnostic neutral beam to perform their measurements. The US could take responsibility for all of the active spectroscopy systems, or some subset of the components.

In which phase(s) would the activity be conducted?
X Pre-construction (2003-5) X Construction (2006-13) X Research (2014-34)

In which phase(s) would the US benefit be realized?
X Pre-construction (2003-5) X Construction (2006-13) X Research (2014-34)

What do you see as the US interest in the programmatic area of your proposed activity?
Taking a leadership role in this ITER diagnostic activity will maintain the present US lead in diagnostic development and capability. It is likely to result in increased international collaboration opportunities (e.g., on JET and DIII-D) for testing of advanced spectrometer and optical detection systems. The results will be available for implementation on present and planned US experiments, thereby providing direct benefits to the US program. Finally, major US participation in physics experiments on ITER will be much more likely if the US is responsible for a major contribution in the ITER diagnostic effort. US national laboratories have seen in the past that hardware and diagnostics delivered to international machines have led to substantial US participation in experimental programs using the equipment. In addition, the US theory support will be needed during the design, construction, and operation of the diagnostic system as the design and operating scenarios are further refined.

For design and fabrication activities, what do you see as the US interest in performing the design and fabrication scope in your proposed activity?
The US lead in this program will maintain the present lead in diagnostic development.

Indicate the nature(s) of the proposed activity:
❏ US preparations for Negotiations
❏ US preparations for the Construction Phase
X US preparations for the Research Phase
X R&D and design work
X Fabrication of US components/systems
X Preparation of tools for the Research Operations Phase
❏ Other: ____

US ITER - Active Spectroscopy Diagnostics

White Paper

May 2, 2003

Oak Ridge National Laboratory, Princeton Plasma Physics Laboratory,
General Atomics, University of Wisconsin

US ITER-Active Spectroscopy Diagnostics
White Paper
prepared by: Donald L. Hillis/ORNL

Oak Ridge National Laboratory, Princeton Plasma Physics Laboratory, General Atomics, University of Wisconsin

1.0 Executive Summary

The purpose of the accompanying White Paper is to review the capabilities of the United States (US) to provide a diagnostic package for ITER, which would include all of the active spectroscopy diagnostics for ITER. These are the diagnostics, which utilize the heating or a diagnostic neutral beam to perform their measurements. This proposal does not include the diagnostic neutral beam for ITER; however, the US certainly has the expertise to take on the beam, as well, if so desired. The US could take responsibility for all of the active spectroscopy systems, or some subset of the components.

The US presently has a leading role worldwide in diagnostic development, detector technology, and the physics for active spectroscopy diagnostics in fusion plasmas. A 20 year US effort in the area of Active Spectroscopy has developed this technology to state-of-the-art detection systems which are currently being employed on US Tokamaks such as DIII-D, Alcator C-Mod, NSTX, and more recently on JET in Europe. The US program has historically been at the forefront of development and implementation of active spectroscopy diagnostics for fusion research. The examples of such active spectroscopy diagnostics include current profile measurements (Motional Stark Effect - MSE), radially resolved measurements of ion temperature, toroidal rotation, Helium ash content, fuel mixture, impurity density measurements, and particle transport coefficients (Charge Exchange Recombination Spectroscopy - CXRS), as well as core plasma density and temperature fluctuations (Beam Emission Spectroscopy - BES). This set of diagnostic measurements would provide a wealth of detailed information to address the many burning plasma physics issues to be addressed by ITER and provide the necessary data to continue the development of our strong US theory and modeling programs in support of future burning plasma devices.

These diagnostics (MSE, CXRS, and BES) all require a diagnostic beam which is used in conjunction with the measurements, but they also require a very detailed knowledge of the details of the beam and its geometry. Each of these diagnostics also utilize the same types of spectrometers, detectors, and similar light collection optics. These common factors for these 3 diagnostics make it an ideal package for US participation. The US currently has a number of unique spectrometer designs with high photon throughput and detectors with quantum efficiencies of > 95%. These spectrometers and detector systems are currently faster and have higher detection efficiencies than are currently available in Europe and Japan. Utilizing traditional spectrometers and optics for these active spectroscopy diagnostics, it is estimated that some 70 spectrometers and detectors would be needed. Utilizing several innovations in US

spectrometer designs with multiple entrance slits, this number could be reduced by about 50%. These spectrometer innovations are already being implemented by ORNL and PPPL, in a Helium Ash measurement on JET which is currently ongoing. Maintaining the absolute calibrations of these diagnostics is a labor intensive effort and reducing the number of active spectrometer systems to be calibrated is a key consideration.

US Participation in this diagnostic package would involve the integration of many institutional contributions. Expertise in developing and operating these active spectroscopy diagnostics is currently being applied on a number of present day tokamak experiments by the University of Wisconsin, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, General Atomics, and Nova Photonics, Inc. All of these research groups also have joint ongoing international research programs with our European and Japanese ITER partners in these diagnostic areas which should further assure the success of this effort. This diagnostic package also provides many opportunities to strengthen the link between university facilities, national laboratories, and industrial partners.

2.0 Active Spectroscopy Diagnostics

The US presently has a leading role worldwide in diagnostic development, detector technology, and the physics for active spectroscopy diagnostics in fusion plasmas. Active Spectroscopy Diagnostics are those diagnostics, which utilize the heating or a diagnostic neutral beam to perform their physics measurements. This proposal does not include the diagnostic neutral beam for ITER; however, the US certainly has the expertise to take on the beam, if so desired. G. Wurden of LANL is presenting at this meeting a proposal for "US participation in ITER with an Intense Diagnostic Neutral Beam".

Active Spectroscopy in the US has developed over the past 2 decades to state-of-the-art detection systems which are currently being employed on US Tokamaks such as DIII-D, Alcator C-Mod, NSTX, and more recently on JET in Europe. The US program has historically been at the forefront of development and implementation of active spectroscopy diagnostics for fusion research and is well suited to providing this diagnostic system to ITER. We propose that US research institutions and industry take a major role in the design, construction, and testing, and operation of the ITER MSE, CXRS, and BES diagnostics. The US could take responsibility for the entire ITER active spectroscopy system including the diagnostic neutral beam, or some subset of the components. The three active spectroscopy diagnostics which are proposed for this diagnostic system are the (1) Motional Stark Effect (MSE), (2) Charge Exchange Recombination Spectroscopy (CXRS), and (3) Beam Emission Spectroscopy (BES). These three diagnostics provide radial profile measurements of the following important physics parameters:

a. **MSE**
   - Measured : Local magnetic field pitch angle and Lorentz field
   - Deduced: q-profile (safety factor) and current profile

b. **CXRS**

- Helium Ash measurement
- Impurity ion densities (He, C, Be, Ne, Ar, Kr, …)
- Fuel mixture and density (H, D, T)
- Plasma rotation (V_{rot})
- Ion Temperature (T_I)
- Particle transport properties (D, □)

c. BES

- Localization of active beam volume
- Local Beam Density
- Density Fluctuations

This set of diagnostic measurements would provide a wealth of detailed information to address the many burning plasma physics issues to be addressed by ITER and provide the necessary data to continue the development of our strong US theory and modeling programs in support of future burning plasma devices.

2.1 Motional Stark Effect (MSE)

Measurements of the profile of the safety factor, q, play an important role in understanding the physics of high-performance tokamak operating regimes, such as Optimized Shear Regimes and plasmas with internal transport barriers (ITBs). The MSE diagnostic provides a way of measuring the magnetic field pitch angle and Lorentz field in the plasma interior, and these measurements are used to constrain a magnetic equilibrium reconstruction of the plasma, which yields the current and q-profile. The current profile measurements are important measurements for determining ohmic, bootstrap, and RF and Electron Cyclotron driven currents.

$D_□$ emission from the neutral heating atoms is split into Stark components by the electric field seen by the atoms due to their motion through the magnetic field of the tokamak. The □ and □ lines of the Stark spectrum are polarized perpendicular and parallel, respectively, to the local electric field, which is perpendicular to the magnetic file. In MSE polarimetry, the magnetic field pitch angle is deduced from measurement of the polarization angle of a spectrally-resolved region of the Stark spectrum which has a high polarization fraction. Light emitted by the neutral beams is collected by optics which transport the plasma image outside the vacuum vessel and through a pair of photoelastic modulators and polarizers. The light is then fiber-optically coupled to high throughput spectrometers and high quantum efficiency CCD detectors. The system is envisioned to have some 75-100 spatial channels covering the ITER plasma. Currently, to achieve sufficient beam penetration for MSE measurements, a beam energy > 500 keV/amu is necessary. One of the ITER heating beams is therefore anticipated for this measurement. The radial electric field (E_r) can affect the interpretation of the MSE measurements. By using two viewing directions both the E_r and the q profiles can be obtained.

2.2 Charge Exchange Recombination Spectroscopy (CXRS)

Active Charge Exchange Recombination Spectroscopy (CXRS) is used in most of the present fusion experiments as a proven tool for local measurements of the main ions in the plasma. The ion species encompass the helium ash, as well as ions sputtered from the plasma wall(C, Be, …), ions seeded into the divertor region (N, Ne, Ar, Kr,…) and also ions representing the bulk background (H, D, T). A comprehensive diagnostic coverage of intrinsic and seeded impurities is essential for any self consistent plasma simulation and prediction of plasma performance (high fusion yield, confinement, and impurity control). Real time ion temperature and rotation analysis from CXRS based on neural networks has proven to be a viable tool for active plasma control, for example, disruption prevention in optimized shear conditions. In particular, for the assessment of local helium ash densities CXRS will play a key role for future fusion devices such as ITER.

The feasibility of CXRS for ITER relies on the extrapolation of present-day devices to the conditions expected for ITER. One fundamental limitation is the detectability of a weak CX signal against a strong background of plasma continuum radiation. A second limitation is the accuracy by which local neutral beam densities can be established in order to derive absolute ion densities from the extracted active CX signals. The second problem can be approached either by experimental data from Beam Emission Spectroscopy (BES)[4]or calculated from beam attenuation codes making use of electron and ion density profiles. The latter includes both bulk and impurity ions. The importance of having a well characterised diagnostic neutral beam in order to obtain accurate measurements of impurity densities from the CXRS measurements almost demands the presence of the BES diagnostic to provide the local beam density and the active volume of the diagnostic neutral beam.

In the plasma core, the CXRS diagnostic measurements are made by observing the visible spectral lines from the Charge exchange recombination process with the diagnostic neutral beam, which is currently planned for 100 keV/amu. CXRS visible spectroscopy is used to obtain the local ion density , ion temperature, and toroidal rotation of the plasma by observing the CXRS visible transitions with absolutely calibrated spectrometers which view the diagnostic heating beam. In the intersecting viewing volume between the neutral beam and the spectrometer sightlines, the CXRS reaction produces visible transitions, which are transmitted via fiber optics to spectrometers with holographic gratings and high quantum efficiency CCD detectors. The system is envisioned to have some 75-100 spatial channels covering the ITER plasma.

The CXRS diagnostic design, based on the current thinking for a 100 keV/amu diagnostic neutral beam, has good signal to noise levels and should provide high quality measurements of the needed physics parameters. Recent optimizations of viewing geometry and spectroscopic equipment have led to even more favorable signal to noise levels, which are compatible with extrapolations from existing CXRS diagnostics on today's fusion devices. Fundamental limitations at high plasma densities introduced by non-linear error propagation in neutral beam calculations can be counteracted by further progress and simultaneous measurements of beam parameters with BES.

2.2.1 Helium Ash Measurements using CXRS

The understanding of helium accumulation and/or removal of helium ash from the core plasma is fundamental for future burning plasma devices such as ITER since the helium ash must be continuously removed from the plasma core to prevent the dilution of the DT fuel and concomitant quenching of the burn. Currently, ORNL and PPPL in collaboration with JET scientists are providing a CXRS Helium Ash Detection System for JET's next DT experimental campaign. The CXRS Helium Ash Diagnostic for ITER would utilize spectrometer/CCD camera combinations which can each provide up to 30 spatial channels per spectrometer that cover the region from the magnetic axis out to the separatrix. This would provide very detailed spatial ion temperature and helium density profile measurements in H-mode plasmas and important profile measurements in the vicinity of internal transport barriers (ITBs). To provide 30 spatial channels (1mm optical fibers) will require high resolution spectrometers with holographic gratings (high photon efficiency at 4686Å for He^{2+}[4-3] charge exchange line). The spectrometers would be of the type made by Kaiser Optical, USA. Each spectrometer would accommodate 30 fibers (30 spatial locations). Each spectrometer is equipped with a frame transfer back-illuminated CCD detector (QE = 90%) and interface to the data archival system . The detectors currently are manufactured by Princeton Instruments and PixelVision, USA. These spectrometer and detector combinations currently have higher detection efficiencies and photon throughput than similar systems manufactured outside the US. It is currently estimated that some 20 spectrometer and CCD detector combinations would be required to meet ITER needs for the BES and CXRS needs. With the current diagnostic neutral beam geometry and viewing lines anticipated for ITER good signal to noise values are found for Helium Ash measurements during burning plasma experiments.

2.3 Beam Emission Spectroscopy (BES)

Measurements of fluctuations of key plasma parameters (e.g., density, temperature, potential) are essential to characterising and more thoroughly understanding plasma turbulence and its associated anomalous transport, one of the central outstanding scientific issues in the fusion energy sciences. Turbulence arises from microinstabilities driven by density and temperature gradients inherent to magnetically confined plasmas. This turbulence is believed to be largely responsible for the high levels of cross-field radial transport of particles, energy and momentum observed in tokamaks. As such, it is essential to obtain turbulence measurements to characterise, understand, and mitigate this largely undesired turbulent transport and ultimately to be able to predict the magnitude of such turbulent transport in future fusion devices, like ITER.

To obtain two-dimensional measurements of density fluctuations in the confined regions of hot plasmas, the Beam Emission Spectroscopy (BES) diagnostic system has been utilised on a number of US tokamaks, such as DIII-D, NSTX, etc. The BES diagnostic system measures local, long wavelength density fluctuations by observing the fluorescence of the ITER diagnostic neutral beam. BES measures density fluctuations by observing the Doppler-shifted D_{α} emission. Fluctuations in the light emission intensity are proportional to the local density fluctuations that depend on the local plasma density, temperature, beam energy and Z_{eff}. The optical viewing sightlines are deployed so that they are nearly tangent to a magnetic flux surface at the intersection point with the neutral beam volume to achieve good radial and poloidal resolution.

Light is collected onto a bundle of silica fibers. The fibers relay the light to remotely located high throughput holographic grating spectrometers (Kaiser Optical, Inc. - USA) and detectors. Signals are typically digitized at 1MHz. Around 100 sightlines are anticipated for the present configuration.

3.0 Reason for the US to take on the Active Spectroscopy Diagnostics

The Active Spectroscopy diagnostics (MSE, CXRS, and BES) were first conceived and developed in the U.S. and presently most of the innovation in these diagnostics is coming from the U.S. For example, the newest innovations include development of low magnetic field MSE, poloidal rotation, BES imaging, and CXRS He Ash measurements on JET. The US program has historically been at the forefront of development and implementation of active spectroscopy diagnostics for fusion research and by providing these diagnostics for ITER, the US could maintain this lead role in diagnostic development.

These diagnostics (MSE, CXRS, and BES) all require a diagnostic beam which is used in conjunction with the measurements, but they also require a very detailed knowledge of the beam and its geometry. Each of these diagnostics also utilizes the same types of spectrometers, detectors, and similar light collection optics. These common factors for these 3 diagnostics make it an ideal package for US participation. The US currently has a number of unique spectrometer designs with high photon throughput and detectors with quantum efficiencies of > 95%. These spectrometers and detector systems are currently faster and have higher detection efficiencies than are currently available in Europe and Japan. Utilizing traditional spectrometers and optics for these active spectroscopy diagnostics, it is estimated that some 70 spectrometers and detectors would be needed. Utilizing several innovations in US spectrometer designs with multiple entrance slits, this number could be reduced by about 50%. These spectrometer innovations are already being implemented by ORNL and PPPL, in a Helium Ash measurement on JET which is currently ongoing. Maintaining the absolute calibrations of these diagnostics is a labor intensive effort and reducing the number of active spectrometer systems to be calibrated is a key consideration.

These 3 diagnostics (MSE, CXRS, and BES) can supply a wealth of physics information about the performance of ITER plasmas. By being involved in all 3 systems, the US could provide a lead role in providing important physics information to the burning plasma physics community and ITER team.

4.0 Diagnostics R&D

One of the major R&D activities for the optical systems of MSE, CXRS, and BES is mirrors and reflectors. Mirrors are used to bring light from the tokamak and relay it to the lens systems where the light is focused on individual fibers or fiber bundles. The mirrors will be subject to intense UV radiation, neutron heating, particle fluxes arising from charge exchange atoms and in particular be subjected to the deposition of material eroded from the divertor, first wall and shield structure. Work is ongoing to select appropriate mirror materials, as well as find acceptable shutter and baffle arrangements that have been found to be successful on present day machines. Optical windows are also a concern, but much work is already underway to address this issue.

Another area of R&D will be the appropriate choice of optical fibers. Because the optical path in the material is much longer, radiation induced absorption and radioluminescence are significant. At high levels of irradiation, embrittlement can occur. Continued work on the optical transmission of fibers in an ITER environment will be needed to determine the best fibers for the active spectroscopy applications.

Some 30 spectrometers and CCD detectors are anticipated for the ITER active spectroscopy diagnostic packages. MSE, CXRS, and BES all require detailed calibrations of the spectrometer systems. Calibrations of these instruments is a very manpower and time intensive process. Innovative calibration techniques and spectrometer multiplexing for ITER will be needed to assure the highest quality measurements during ITER operation. Innovative R&D will be required to continue to work at reducing the number of spectrometers and improving the techniques for calibration of the diagnostics.

5.0 Benefits to US Fusion Program

The US should take the lead in the R&D, design, and implementation of the ITER active spectroscopy diagnostics. The US lead in this program will maintain the present lead in diagnostic capability. It is likely to lead to increased international collaboration opportunities (e.g., on JET and DIII-D) for testing of advanced spectrometer and optical detection systems. The results will be available for implementation on present and planned US experiments, thereby providing direct benefits to the US program.

Finally, major US participation in physics experiments on ITER will be much more likely if the US is responsible for a major contribution in the ITER diagnostic effort . US national laboratories have seen in the past that hardware and diagnostics delivered to international machines (e.g., RF antenna to Tore Supra, pellet injector to JET, CXRS to JET and TEXTOR) have led to substantial US participation in experimental programs using the equipment. In addition, US theory support will be needed during the design, construction, and operation of the diagnostic system as the design and operating scenarios are refined.

6.0 US Expertise, possible program participants

The US has the expertise to define the physics requirements of the Active Spectroscopy Diagnostics and to solve the technical issues. Several of the most active laboratories in the active spectroscopy area are listed below, however there are many other University and industrial partners that may choose to join this effort.

General Atomics	CXRS, MSE, BES
Oak Ridge National Laboratory	CXRS, BES
Princeton Plasma Physics Laboratory	CXRS, MSE, BES
Lawrence Livermore National Laboratory	MSE

University of Wisconsin	CXRS, MSE, BES
Nova Photonics, Inc.	MSE

7.0 Summary

Utilizing the combined efforts of the US National Laboratories, Universities, and Industry, the US has the capability to design, fabricate and deliver an active spectroscopy diagnostic system to ITER. This diagnostic package will provide access to a wealth of burning plasma physics information that will be used to evaluate the performance of ITER and provide further information that will be directly applicable to the fusion program, as it proceeds toward the next step of a DEMO power plant.