Final Technical Report for the DOE Grant No. DE-FG02-99ER54523: "USXR Based MHD, Transport, Equilibria and Current Profile Diagnostics for NSTX"

PI: Dr. Michael Finkenthal

Department of Physics and Astronomy

The Johns Hopkins University

Baltimore, MD 21218

June 2009

(Re-submitted on September 21, 2012)

Period I: 1999-2002

During the first period of our research on the NSTX tokamak at Princeton Plasma Physics Laboratory, the JHU Plasma Spectroscopy/Diagnostics Group concentrated on topics related to *particle transport* and *impurity content* in the tokamak discharge. However, instead of using the conventional spectroscopic methods based on line emission, we implemented a set of filtered diode *Ultra-soft X-ray arrays* (USXR) which enabled time resolved imaging of the plasma, which as we shall see, enabled – in time – to provide information not only about the impurity content and impurity charge state distribution in the NSTX tokamak. The first stage of research was achieved by combining the spectrally broad but spatially resolved data with single-chord, high resolution spectra provided by a spectrometer developed by the Hopkins group. The very promising results of these first experiments (see Stutman et al. in *Proceedings of the 28th EPS*

Conference on Controlled Fusion and Plasma Physics, 2001, ECA, Vol. 25A, p.445) led us to propose to DOE in 2002 a multipurpose ‘integrated diagnostic package’ which could be used by other alternative magnetic confinement experiments besides tokamaks (see our publication on this theme in *Review of Scientific Instruments*, 74, 2003, p.1982). In addition to the study of intrinsic impurities, small amounts (<1%) of Ne had been periodically puffed in higher temperature NSTX plasmas and the 2-D distribution of the He-like and H-like Ne charge states was mapped using the arrays. This enabled the monitoring of the particle transport over most of the plasma volume. The results indicated that the particle transport in the core was near the neoclassical limit, implying thus that the turbulent transport is low. L and H-mode plasmas were studied in *transport scaling experiments* (we reported on these results at the 29th EPS Meeting in June 2002 and at the APS Meeting the same year). Another very important result was related to the electron thermal transport we begin to measure and which was found to be very high in our preliminary experiments (we did extend these measurements in the next cycle of our research; see below). Using the USXR in a ‘multi-color’ configuration (i.e. filtering the X-rays at various energies) we could study also the evolution of the electron temperature profile on a sub millisecond scale.

Period II: 2003-2006

During this second period of our reported research we extended the use of the ultrasoft X-ray (USXR) arrays to *MHD, electron transport and plasma equilibrium* studies as well as to *current profile* diagnostics. In addition, we developed associated computational and physics analysis tools to be used in the investigation of MHD and transport in NSTX.

More specifically, we defined our research goals during this second period as follows:

1) Completion of the poloidal USXR imaging system for multi-spectral tomographic capability on NSTX and development of tomographic algorithms and codes for routine analysis of the data (the results were reported in an Invited Talk by Kevin Tritz at the *45th Annual Meeting of APS* in October 2003)
2) Application in collaboration with a research group from the Frascati ENEA Research Center in Italy of a 2-D Micro-Pattern Gas Detector (MPGD) and of the USXR systems to the estimate of the central safety factor (The results obtained with the second proposed diagnostic development were reported by Pacella et al. in *Nuclear Instruments and Methods in Physics Research* A 508 (2003) and *Rev. Sci. Instr*. 74 (3) same year)
3) The study of the XUV properties of Transmission Gratings, the design and construction of a prototype, time and space resolved, Transmission Grating (TG) based spectrometer for impurity content studies (see Blagojevic et al. and Finkenthal et al. (in the same year), in *Rev. Sci. Instr*. 74).

As stated above, the first goal was the completion of the poloidal USXR imaging system for tomographic capability on NSTX and development of tomographic algorithms and codes for routine analysis of the USXR data. An AXUV diode based, re-entrant vertical array was designed and built, eliminating thus the vignetting problem encountered by the old, out-of-vessel diode arrays. This enabled developing and applying for the first time tomographic techniques on NSTX and detailed studies of the 1/1 MHD activity, which is persistent in high beta discharges.

Our results (see above quoted Tritz talk and his subsequent paper), showed a remarkable agreement between the structure of the 1/1 kink mode obtained by USXR tomography and that obtained by using a magnetic flux surface based emissivity model. Our tomography code showed nevertheless that in order to reconstruct perturbations with m > 1 in NSTX a much large number of chords than those available to us would be needed.

As electron transport became more and more clearly a major issue for the ST development path, we further focused our research on this topic, by initiating the first perturbative electron transport studies and experiments at NSTX. The initial results, obtained using the USXR diode system in the ‘multi-color’ configuration (see Delgado-Aparicio et al. in *Plasma Phys. and Contr. Fusion*, 49 (2007), p. 1245) in order to ‘propagate’ the T_e profiles in between the Thomson scattering time points, indicate that the electron response to natural (e.g., Type I ELM) or induced (e.g., Li pellet) perturbations of the Te profile, is also very fast. Also, during the present grant cycle the ‘two-color’ poloidal USXR system consisting of horizontal and vertical arrays of AXUV diodes has been improved through the addition of a re-entrant vertical viewing array, which eliminated the vignetting problems encountered with out-of-vessel vertical arrays. The entire USXR system was also upgraded to 600 kHz data acquisition rate, while a good part of it to very-low noise current preamplifiers. This enabled for instance, radial localization of fast and transient MHD activity, such as TAE and Energetic Particle Modes (EPM). The completion of the system also enabled studying the application of tomographic algorithms for reconstruction of mode structure mentioned above.

The second development in the area of XUV imaging was based on a Micro-Pattern Gas Detector (MPGD). As mentioned, this research was performed in collaboration with the FTU Group (ENEA, Frascati). Its primary goal was to explore the possibility of using and MPGD as detector in a tangential USXR system designed to constrain the *reconstruction of the plasma current profile*. We tested this possibility by comparing an image of the plasma core recorded at high energy (E > 3 KeV) with EFIT predictions. Also, we performed fast T_e fluctuation measurements, enabled by the intrinsic MPGD energy resolution.

In synergy with our Advanced Diagnostic Research, we tested on NSTX during this second research period, a prototype USXR multi-chordal (imaging) spectrometer for the 10-300 Å range, based on a free-standing transmission grating, or TG. We presumed that such an instrument which offers a broad spectral coverage and most importantly, accurate and reliable photometric calibration will be well suited for the task of a survey spectrometer needed for the modeling of the USXR emission profiles. As we shall see in the next Section, the assumption proved to be correct.

Period III: 2007-2009

For the third research period we proposed:

1) Upgrades and modifications of the existent (at the time) poloidal diode systems
2) A number of ‘multi-color’ optical soft-X-ray systems for core and edge diagnostics of electron temperature, perturbations in transport and MHD studies.

3) An imaging TG Survey spectrometer for the 10-300A range having r/a =1/12 spatial resolution and 0.25 millisecond integration time (extension of the prototyping work done in the previous research cycle).

The fully implemented multi-energy soft X-ray (ME-SXR) systems during this period of research brought a much expanded contribution towards the understanding of the ST physics, in particular in the electron transport areas. They also helped identify issues that are of interest *for the entire fusion program*, such as a possible relation between shear Alfven activity and electron transport (see D. Stutman et al., Correlation between Electron Transport and Shear Alfven Activity in NSTX Experiment, *Phys. Rev. Lett*., 102, (2009), 115002). We have also built and operated successfully the Transmission Grating Imaging XUV spectrometer, as well as the earlier built poloidal USXR system. The ME-SXR technique consists in simultaneously imaging the soft X-ray emission from the same plasma volume in multiple energy ranges. Fast, space resolved information about the electron temperature or impurity density profile is then obtained through forward modeling of the line integrated emission profiles, or through analysis of the Abel inverted emissivity profiles. In the past grant cycle we implemented on NSTX a tangential ME-SXR diagnostic consisting of an 'optical' SXR array, that has filters with cutoff energies at E>0.5 keV, E>1.5 keV and E> 2.5 keV. The 'optical' array design includes an efficient and fast SXR converter, followed by fiber optic light guides and multichannel light amplification. The existing tangential ME-SXR array measured the plasma between R~85 cm and R~147 cm, with ~4 cm spatial resolution and ~10 kHz bandwidth. The earlier installed poloidal USXR arrays could also be filtered with similar cutoff energies and are used in conjunction with the tangential system, especially in order to measure with high speed and sensitivity the core and peripheral MHD activity.

The tangential Transmission Grating Imaging Spectrometer (TGIS) was developed in support of the ME-SXR diagnostics. This instrument provided space resolved XUV (~10-300 A) impurity spectra that can be used to further constrain the ME-SXR modeling and improve its accuracy. The main advantage of this type of instrument consisted in its simplicity and stability of its photometric calibration. The discussed device was a 'hybrid' design that incorporated in addition to the transmission grating also a compact, image intensifier based, ME-SXR camera. The TGS had around 5 cm spatial resolution and recorded the plasma emitted signal throughout the entire discharge. The device viewed a region including the neutral beam, thus enabling to measure the emission of low-Z impurities also in the core. The relatively modest signal-to-noise ratio obtained was due to the low diffraction efficiency of the grating.

During this last grant cycle, our group developed two main applications of the ME-SXR technique. The first consisted in simultaneously imaging the emission from different charge states of a medium-Z injected impurity, in order to perform more accurate impurity transport measurements. For instance, using Neon injection and the E>0.5 keV and E >1.5 keV cutoff energies in the ME-SXR array, the spatial and temporal evolution of the He- and H-like charge states could be discriminated from that of the fully stripped species. In conjunction with measurements of the total radiated power and with the Thomson data this put a strong constraint on the particle transport modeling. The background emission was subtracted using reproducible, consecutive shots. The second application of the ME-SXR technique consisted in measuring the Te profile on fast (sub-ms) time scales. Since the ECE technique is not applicable in the low field

ST, the SXR substitute is valuable. While the ‘two-color’ SXR technique was used for Te estimates since the early days of fusion research, we found that by including intermittent normalization to the Thomson Te profile, its accuracy and resolution could be greatly improved. In essence, through detailed modeling of the ratios of the line-integrated multi-energy profiles, or of the ratios of the Abel inverted emissivity, one can follow in time the evolution of the Te profile with high temporal and spatial resolution and with several percent accuracy.

The ME-SXR modeling accounts for both line and continuum emission and requires approximate impurity fractions as a constraint. For a low-Z impurity dominated plasma the technique is little sensitive to variations in the impurity content. Also, having more than one Te sensitive ratio substantially increases the accuracy in the Te profile fitting. For plasmas contaminated by a high-Z impurity such as iron, there are temperature ranges where the sensitivity to relative impurity fractions is increased. However, with a judicious choice of cutoff energies, the use of three or more energy bands enables to discriminate the presence of high-Z contamination as well as to correct for its spectral effect. As above mentioned, improved accuracy was obtained when an additional spectral constraint, such as space and time resolved XUV line spectra was introduced. We estimate that due to its robustness and simplicity this technique is also of value for the *Burning Plasma* effort.

As mentioned often in this report, the main contributions of our group to NSTX research focused during the years on transport topics. However, the transport behavior of the ST offered some surprises: while in high power H-modes (the basic operational scenario of the ST path) the ion thermal transport was found to be near neoclassical, the electron transport appeared to be highly anomalous. This rapid electron transport in turn leads to a progressive flattening of the Te profile in NSTX as the beam power is increased. To try to validate the unusual transport picture arising from the power balance, we turned to perturbative experiments. The particle diffusivity in high power H-modes was measured through dedicated experiments using Ne injection. The results of these experiments indicate central particle diffusivity of the order of 1 m2/s; the particle transport is with good approximation in the neoclassical range, throughout most of the radius. The neoclassical trend is also supported by the B^2 dependence of the diffusivity, observed in field scaling experiments. This suggested that anomalous transport associated with low-k turbulence is likely suppressed in NSTX H-modes. Indeed, our GS2 calculations have shown that the growth rates of all low-k instabilities are well below the ExB shearing rates (see Luis Delgado Aparicio et al., *Nuclear Fusion*, 49, (2009), 085028). The pinch velocities included in the modeling of the experimental results, indicate a change of sign, from inward at low field, to outward at high field. This was a very puzzling result to be further investigated, since the NCLASS code predicts outward velocities in both cases.

Another apparently surprising observation we made was related to the high particle diffusivity at the periphery of the NSTX H-mode plasma (several m2/s at r/a>0.8), where a strong particle transport barrier was supposed to exist. This exceeded even the typical level of anomalous particle transport in the conventional tokamak H-mode. However, the inspection of the NCLASS prediction indicated this might have been in fact a neoclassical effect: the high edge q-values typical of the ST (q_{95}~8-10), combine with the high collisionality in the cold and dense NSTX periphery (Te~0.2 keV, ne~6 10x13/cc), to make rapid neoclassical transport. In order to probe in a similar manner the electron transport as well, we used shallow injection of Li pellets to perturb the edge Te profile. The Te perturbation was then measured using the ME-SXR diagnostic and the technique of normalization of the SXR Te to the Thomson profile, a few ms prior to the injection time. The evolution of the SXR Te profile following the pellet injection in a high power H-mode indicated rapid propagation of the cold pulse up to the plasma axis in about 2 milli-seconds. The deterioration of the central electron transport with increasing beam power was also confirmed through these perturbative studies: in a series of experiments in which the beam power was varied at fixed q-profile, a large difference was observed between the cold pulse propagation at high and moderate power.

Further investigation of electron transport changes with power lead us to the formulation of an important hypothesis, concerning one of the outstanding questions in electron transport for all aspect ratio devices: What drives transport in flat temperature regimes, where the micro-instability drive is absent, since ∇gradTe~0 ? Our hypothesis, which we plan to check out in further experiments on NSTX is as follows: first, the very large gap between the electron thermal and ion particle diffusivity in the central NSTX plasma seems to indicate electron loss along stochastic field lines. Secondly, since the only constituent having substantial gradient inside r/a≤0.4 is the fraction of non-thermal beam ions, we advanced that it is this component that drives electron transport, likely through the creation of small scale magnetic islands. Lastly, we assumed that the islands must be arising from the persistent shear Alfven MHD activity driven by the fast ions. Using beam stepping experiments a potential correlation was indeed found between central electron transport and global Alfven (GAE) activity. Preliminary theoretical estimates show that the measured GAE fluctuation levels can lead through micro-island formation and stochastic transport, to core values comparable to the experiment. If further verified, this mechanism can have profound implications for the whole fusion research.

Lastly, another line of research where our ME-SXR diagnostic proved essential was the investigation of the connection between the response of electron transport to perturbations and the severity of ELM effects. Using the ME-SXR technique we compared the response of the plasma to pellet induced edge perturbations in two types of discharges: plasmas exhibiting 'giant' Type-I ELMS and having up to 40% dWtot, and plasmas characterized by regular Type-I ELMs, with only 4-10% dWtot. The results quite convincingly demonstrated that the main difference between the two levels of ELM effects is in the response of the electron thermal transport to the edge perturbation. In addition, the correlation of the ME-SXR fast Te measurements with the measurement of high-k fluctuations and with micro-stability calculations, suggested that the increase in electron transport in the Giant ELM case was due to the crossing of the critical gradient for the ETG stability.

In conclusion, the ME-SXR diagnostic and technique proved very valuable for studies of particle and electron transport in the core NSTX plasma. Since the present system (end of 2008) working on NSTX is significantly limited as concerns the spatial resolution both in the edge gradient region and in the core gradient region, in order to answer some of the key physics questions uncovered during our research, spatial resolution around 1 cm would be desirable for the edge gradient region and around 2 cm, for the core gradient region. Moreover, the present system is limited as concerns signal levels at low temperature: good SNR measurements are obtained only in regions where Te exceeds approximately 150-200 eV. Due to the modest temperature in the peripheral NSTX plasma, this limit corresponds about to the top of the H-mode pedestal. These limitations, evident in the fast Te measurements lead to uncertainties in the peripheral diffusion coefficient inferred from experiment. In order to include the NSTX edge in the ME-SXR measurements, one will have both to (1) *significantly increase the spatial resolution* and (2), *to decrease the cutoff energy to the tens of eV range*.