Dissertation Report

Modell-Aided Design and Interpretation of Beam Emission Spectroscopy Measurements on Fusion Devices

PhD Dissertation by Asztalos Örs Dissertation

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Summary: This dissertation describes computational tools that comprise the RENATE code developed by the author that allow for design optimization and data analysis interpretation from beam-emission-based (alkali or hydrogenic beams) diagnostics for measuring plasma density in magnetically confined fusion plasmas at high spatiotemporal resolution. Such measurements are critical to measure density and fluctuations therein to understand the characteristics of turbulence, and related behavior to validate models of such phenomena and allow for accurate prediction of their impact in fusion devices such as ITER. The RENATE code develops and applies synthetic diagnostics that calculate emission from beams made from lithium and sodium, as well as hydrogenic isotope beams often used for heating and fueling plasmas.

The dissertation then describes details of designs of BES systems for ITER, JT-60SA and other experiments. The dissertation is very comprehensive and addresses multiple systems associated with the generation of the beams and the optical system required to collect and measure the emitted photons. I note that the dissertation is very well-written, well-organized and very dense with scientific content. Figure quality is generally very good.

Chapter 1 provides and introduction and overview of nuclear fusion reactions, the potential benefits of fusion energy to address climate change, and the tokamak and stellarator magnetic confinement configurations, and a brief summary of major tokamak and stellarator experiments used in this analysis, and provides an outline of the dissertation.

Chapter 2 highlights active beam spectroscopy systems, diagnostic physics concepts and measurement applications, including sources of neutral particles to spectrometers, and lists actual systems implemented at fusion programs around the world. The rate equations used to calculate photon emission from multiple plasma species and implemented in the RENATE code are described, along with the multiple excited atomic states and the geometry concepts used to evaluate light collection and signal strength. Sources of emission, both from the desired active sources, as well as passive or background sources are described. Applications of BES systems to measurement of edge phenomena such as blobs and filaments in the SOL are described, along with several simulation codes, including the HESEL code to be used later in this study. Limitations of BES systems, including frequency range and finite observation volume are mentioned, including greater noise encountered at higher frequencies.
The author may wish to be aware of another BES system implemented on the HL-2A tokamak:
https://aip.scitation.org/doi/full/10.1063/1.5039350
https://aip.scitation.org/doi/full/10.1063/5.0101806

Chapter 3 describes details of the spatial point spread function calculations and the various contributions to spatial smearing, including optical, geometric, and atomic physics components. The impact of the density profile on sensitivity is presented, including the offset of the center-ofmass of the Fluctuation Sensitive Area from the optical line of sight. Example calculations for the EAST LiBES, DBES and (vertical injection) JET LiBES are shown as comprehensive examples.

It wasn't clear how the collection optics are being treated in the 3D geometry. Is the full optical throughput, with a light cone focusing on the neutral beam, but with finite extent considered, as this will naturally further enlarge the FSA relative to using line-of-sight "pencil beams". Faster, higher throughput (lower f/#) optics will naturally collect more light but at the expense of varying doppler shift across the optical elements and increasing FSA size.

Also, DBES systems can suffer from impacts of very large edge/boundary turbulence (ñ/n>20%) attenuating the beam (slightly), which is then detectable downstream, deeper in the plasma, as an out-of-phase fluctuations, which can rival or exceed that of the local fluctuations in the core. Has this been considered in the full model? The assessment indicates that, unlike alkali beams, there is little impact downstream for DBES systems.

Chapter 4 evaluates the performance of BES systems in terms of SNR, SBR, spatial resolution for W7X, ITER and JT-60SA using the RENATE code, considering geometry, energy, current of the alkali or diagnostic (respectively) neutral beams. The overall design process considers mutiple performance and design parameters and signal properties in the evaluation. It is concluded that an Na alkali beam is more suitable (than an Li beam) for SOL/divertor island measurements on W7-X, and that an APD and MPPC detectors would yield the highest performance (SNR) for ITER core & pedestal measurements, but that SBR would be low; the large ITER background reduces SBR significantly. The JT-60SA analysis shows relatively low performance for LiBES, but an innovative toroidal view could allow for 2D measurements near the edge; the core DBES has good signal and spectral separation but poor spatial resolution due to geometry limitations. Multiple alternative viewing geometries/locations on other beams are identified that have favorable PSF and SNR parameters.

Could a fast high efficiency (e.g., transmission grating based) spectrometer be used for largely unshifted beam emission, e.g., in the ITER core, to better filter out the recycling light and allow for spectral isolation of the desired by un-doppler shifted (but spread out spectrally via the motional stark effect sigma and pi components) and improved signal-to-noise compared with interference filters that have limits to the sharpness of spectral cutoff?

Might fluctuations other than turbulence, e.g., from MHD, Alfven eigenmodes, still be usefully diagnosed in the ITER core with the poor (large) FSAs?

Chapter 5 applies a set of full synthetic BES diagnostics to compare experimental measurements from AUG LiBES to simulation data from the HESEL code, showing how finite spatial resolution blurs some features but enables observation of key dynamics. The impact of photon current on measurability of skewness, kurtosis showing degradation at low signal. It also performs comparisons of APSD, filament shape and blob frequencies with modest success. Finally HESEL simulations of ITER are evaluated. See question below.

Chapter 6 assesses the impact of neutrals in the boundary area on BES diagnostics and their interactions with SOL turbulence using a classical trajectory Monte Carlo code. It determines the impacts of neutrals in the beam ducts and plasma edge, which act to non-negligibly attenuate the beam and excite beam emission through collisions for higher neutral densities. Application and simulation with the neutral HESEL, nHESEL, code is presented. It also tantalizingly suggests the possibly of neutral density measurement via beam emission, which would itself be an extremely valuable measurement for plasma boundary/SOL physics.

Chapter 7 summarizes the thesis, highlights major results, and **Chapter 8** lists the 4 Thesis statements on: 1) Spatial resolution of beam-based diagnostics; 2) trade-offs and optimization of beam-based diagnostic designs; 3) model validation using synthetic diagnostics; 4) neutral effects of beam-based measurements.

Scientific Content: The author is clearly well prepared to perform independent scientific research. The author has worked collaboratively, building on diagnostic and modeling work by previous scientists and extended it significantly through development and application of the RENATE code. The work described fills a needed gap in research capability by facilitating direct quantitative comparison of measurements with advanced simulations of this phenomena, such as SOL filament and blob characteristics. The publication record as first or contributing author is sufficient, in line with an exceeding that of many new PhDs.

Overall assessment: The breadth and depth of this research and dissertation document are of very high scientific quality, and I judge that the doctoral thesis fulfils the requirements for a PhD dissertation set forth by the Doctoral School and that the thesis is suitable for public defense.
Questions:

1) This work comprehensively addresses fluctuation diagnostic design optimization. On the topic of detectors, however, little attention is paid to the noise contributions beyond photon noise, especially that of electronics, preamplifiers, etc. This is finally addressed in Chapter 5 on synthetic diagnostics; however, it doesn't appear to suffice for optimal detector choice, which is critical. Fully optimized, low noise, high gain (cooled) preamplifier electronics and noise therein, can change the decision of optimal detector choice, while subpar electronics may favor high-gain detectors (e.g., APDs), though these have other drawbacks. The topic of excess noise factors in APDs isn't addressed. Can the best decisions on detector choice be made with these tools?
2) Consider the value of the thermal charge exchange emission for diagnosing fluctuations in plasma density. The edge recycling emission is non-local and a complicating background that needs to be spectrally removed, but does the charge exchange emission intensity from neutral beam on thermal hydrogenic ions enhance the overall useful signal and thereby enhance the ability to measure plasma fluctuations w/DBES? All filter designs appear to isolate and largely eliminate this emission.
3) The qualitative and quantitative comparisons of HESEL with synthetic and noisy synthetic signals is assessed as reasonably good, yet does not appear adequately address significant discrepancies between experimental and simulated quantities such as APSD, PDFs, etc. Can the author provide better justification for the positive assessment of the comparisons?
4) Can the author consider the potential value, strengths, and tradeoffs of a Lyman-alpha-based (n=2-1, lambda~121 nm) DBES system, in terms of signal strength, spatial resolution, diagnostic complexity, and feasibility?