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Modell-aided design and interpretation of beam emission spectroscopy measurements on fusion devices

Ph.D. thesis booklet

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Introduction

Fusion energy production focuses on harnessing energy from controlled deuterium-tritium fusion reactions. The high required impact energies and the high probability of elastic Coulomb collisions necessitates a hot thermal medium of roughly 10^8 K for fusion ignition [1]. At these temperatures, the fuel mixture is in a fully ionized plasma state, which is confined by magnetic fields of magnetic confinement devices such as the tokamak or the stellerator. The fusion output is strongly determined by the performance and behavior of the confined plasma region, which is subject to micro turbulence and other transport phenomena. The last closed flux surface and attached to it the scrape-off layer (SOL) not only set boundary conditions for the confined plasma region, and therefore the core transport mechanisms, but also connect the confined plasma to the plasma facing components. The latter indicates a role similar to an exhaust system for the confined plasma and causes intense heat and particle loads on plasma facing components driven by SOL turbulence and transient magneto-hydrodynamic phenomena. The study and measurement of turbulent timescale phenomenon requires well localized and fast measurement methods [2, 3].

Beam emission spectroscopy (BES) is a commonly used active plasma diagnostics method in fusion energy research for the study of plasma density. The method relies on a high energy, mono-energetic neutral beam, which can be a diagnostic beam composed of light alkali metals, such as lithium (LiBES) or sodium (ABES), or heating beam composed of hydrogen or its isotopes (DBES) injected into the plasma. Collisional processes between beam atoms and plasma particles excite and subsequently ionize the beam atoms, which emit characteristic radiation collected by a dedicated observation system. The observation system features a narrow band optical filter to remove the background plasma emission and a fast detector with high quantum efficiency. The detected emission profile is used for plasma density profile and density fluctuation inference. The diagnostic system features spatial and temporal resolutions of cm and μs, respectively, enabling it to resolve turbulence timescale events. Fast BES measurements are features on nearly every fusion device facilitating measurements of SOL, edge or core plasma turbulence, flows and transient density perturbations [4, 5].

The modelling of BES diagnostics is an important aspect for measurement interpretation and density inference. Numerous BES modelling codes and synthetic diagnostics exist with various scope and complexity. They all compute the beam evolution based on a collisional radiative model. The simpler approach computes the beam attenuation and the emission by means of beam stopping and emissivity coefficients. Such methods are more suitable for gradually changing plasma profiles. A more complex method relies on solving a rate equation system, which determines the electron population density on all relevant excited atomic states along the beam, from which the emission is computed, realizing a more reliable method in case of fluctuating density fields. The rate equation system handles the reduced rates for various beam atoms with plasma particle collisions, such as electrons, main ions and various impurities, accounting for impact ionization, excitation and charge exchange, where appropriate. Another varying aspect in BES modelling is the handling of the beam and observation geometries, which range from 1D beam and line of sight considerations, through 3D beam and pinhole optics considerations to ray tracing approaches. The persistent challenge lies in the application of the right BES code with the required level of detail to fulfill the specific modelling task [6-8].

Motivation

My work was driven by the need to develop novel methods suited for modeling aided measurement interpretation, optimization and performance parameter trade-off navigation of BES systems and turbulence timescale synthetic diagnostics aimed at first principle plasma model validation.

Spatial localization of density fluctuations is a paramount information for any BES driven fluctuation study, which is difficult to obtain as the emitted information is spatially delocalized due to magnetic field alignment with lines of sight and atomic physics processes. Previous works feature various approximations for the spatial localization [9, 10]. In this work an exact calculation method for spatial localization is proposed and demonstrated.

BES synthetic diagnostics are commonly used to estimate expected performance parameters of proposed BES diagnostic systems by optimizing specific design and engineering parameters. The performance enhancement considerations are unique for each proposed BES system needing to tackle different trade-off challenges imposed by the optimization process. To help navigate such performance trade-offs, I aimed to develop a general methodology applicable to any proposed BES concept.

Synthetic diagnostics are becoming a useful tool for the study and validation of first principle plasma physics models by placing the output of the plasma models into almost identical frames of reference as the actual measurements against which the validation process occurs [11, 12]. My aim was to create a fluctuation BES synthetic diagnostic that can account for all BES measurement artefacts that alter the measurement statistics and has the capability to validate turbulent timescale measurements against experimental ones.

Neutral particles at the edge of the plasma have generally not been deemed relevant in fusion research. Research in recent years has shown the SOL neutrals to have a significant impact on SOL behavior and therefore affect core plasma performance as well [13, 14]. My aim was to expand existing collisional radiative models to include beam atom with neutral gas collisions in order to assess the impact neutral particles have on the beam evolution process.

Methodology

During the course of my PhD work I have used a large number of existing methods and tools to develop the synthetic BES diagnostic features highlighted in the Motivation section.

RENATE

A fully 3D BES synthetic diagnostic developed by the fusion group of the Institute for Nuclear Techniques at the Budapest University of Technology and Economics. RENATE features a direct collisional radiative model that calculates the rate equation system. It models hydrogen, deuterium, tritium, lithium and sodium beam materials, collisions with electrons, protons and an averaged impurity species. The collisional radiative model accounts for impact projectile ionization, charge exchange, excitation and spontaneous transitions [6].

The code features a fully 3D beam model and a 3D observation model based on pinhole optics. The beam and observation modelling occurs within a realistic magnetic geometry computed from EFIT. RENATE was the main focus of current PhD work and subject to various developments related to BES synthetic diagnostics modelling.

Simulation of Spectra

Simulation of Spectra (SoS) is BES modelling code developed by Mannfred von Hellermann at Forschungzentrum Jülich, Germany. The code uses a beam stopping and emissivity coefficients derived from collisional radiative model to compute the emission along the beam. Based on the magnetic geometry and beam velocity as well as the observation angle, SoS calculates the Stark splitting of the emission lines and returns the Doppler shifted BES emission spectrum for heating beams. The beam geometry is 3D elliptic Gaussian profile, while the observation geometry is a simple 1D line of sight. SoS possesses the capability to compute various aspects of plasma background emission by estimating continuum radiation and line radiation in the wake of the beam [7]. SoS was used in the thesis for narrow band optical filter design in order to ensure most BES emission to be observed, most of the background emission to be excluded.

Signal performance indicators

During the optimization process, the BES performance parameters were assessed and optimized by adjusting the design parameters. The primary performance parameters featured in this work are as follows:

- **Beam penetration** is defined as the distance along the beam from the last closed flux surface to the emission peak. This measure is especially relevant for diagnostic beams, as they are less able to spatially localize detected fluctuations beyond that point. This feature is computed by RENATE.
- **Signal to Background Ratio (SBR)** is given by the fraction between BES emission and background emission and determines how distinguishable detected BES light is from the background. The SBR is derived from spectrally integrating filtered BES and background emission computed from SoS.
- **Signal to Noise Ratio (SNR)** is related to the photon count reaching the detector surface. The noise in BES diagnostic systems is determined mostly by photon statistics and electronic noise. The photon current was calculated using RENATE.
- **Spatial localization** corresponds to the volume where density fluctuations cause detected light fluctuations. The spatial localization also foreshadows spatial size of density fluctuations the system can resolve. The spatial localization and resolution was calculated with RENATE.

Turbulence codes

For the validation effort of first principle plasma physics codes, the HESEL 2D, four-field, energy-conserving fluid model was used. HESEL is a SOL turbulence code, developed at DTU Denmark and mainly models the evolution of density filaments in the SOL. The model is derived from the Braginskii equations, which describe quasi-neutral plasma. The code computes the time evolution of low frequency, interchange driven turbulence on a 2D slab located at the outside midplane and perpendicular to the magnetic field. HESEL models the density, ion and electron pressure as well as the generalized vorticity. The slab has a periodical boundary condition on the upper and lower sides, while Dirichlet and Neumann boundary conditions exist at the inner and outer radial boundaries, respectively. The domain is split into an edge and a SOL regions where the magnetic fields lines are closed and open, respectively. The open field lines are assumed to end at the divertor.

For demonstrating the effect of neutral particles on the beam evolution process and their impact on turbulence perception the nHESEL variant of the before mentioned model was used, which as an addition also evolve the neutral particle density besides the plasma density.

HESEL and nHESEL were coupled to RENATE and functioned essentially as density and temperature profile generators for repeated RENATE beam evolution calculations [16, 17].

Statistical tools for synthetic diagnostic validation

A significant aspect of current work was the validation exercise of the HESEL turbulence code against experimental BES measurements, where the fluctuating HESEL density and temperature fields were processed by the newly developed RENATE turbulence synthetic diagnostics. The following synthetic and experimental statistical characteristics were compared:

- **Auto Power Spectral Density** is the absolute value squared of the Fourier transforms of the signals, which tells the power of each frequency component.
- **Skewness and Kurtosis** are higher signal moments which describe the asymmetry of the signal amplitude distribution and the “tailedness” of the signal amplitude distributions, respectively [3].
- **Event identification** is a method that allows for the selection of local peaks within the measurement signal larger then typically 2-3 times the signal standard deviation from the signal mean [3]. Further statistical analyses were subsequently conducted determining various event features, such as frequency or amplitude distribution.

Classical trajectory Monte Carlo method

The classical trajectory Monte Carlo (CTMC) is a non-perturbative method that classically deals with particle collisions. The method computes the probabilities for various collision outcomes and derives cross-section values. The CTMC method featured in current work was developed by K. Tőkési at Atomki Debrecen. In this work, a four body approximation was applied for the modeling of collisions between beam atoms with neutral particles. The interactions between the colliding particles is governed by the Coulomb force and described by a set of non-relativistic Newtonian equations [18].

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New Scientific Results

The new scientific results of my work on the enhancement and exploitation of synthetic BES diagnostics are summarized in the following thesis statements:

T 1. I have developed a fluctuation response method applicable to beam emission spectroscopy (BES) diagnostics that measures the spatial localization of plasma density fluctuations by generating the light response of the BES system to plasma perturbations, which account for all relevant localization effects. The method computes the light responses to small, localized plasma density and temperature fluctuations, elongated along the magnetic field line, realizing a fluctuation response function that characterizes the fluctuation sensitive areas for each detector [**P9**]. I utilized the method by calculating the effective spatial resolution for the EAST Li-BES and DBES observation systems, contributing to their design considerations [**P3**]. I also used the method on the JET Li-BES observation geometry in support of data interpretation by demonstrating positive and well-localized fluctuation response close to the separatrix [**P7**].

T 2. I have developed a comprehensive methodology using synthetic diagnostics to assess the capabilities and performance of beam emission spectroscopy (BES) diagnostic concepts, primarily focusing on trade-off resolution impacting penetration depth, spatial resolution, signal to noise ratio, signal to background ratio and observation geometry location. I used fluctuation response and emission smearing calculations to determine the ideal observation geometry and Na as beam material for scrape-off layer W7-X ABES diagnostic system while navigating the trade-off between spatial resolution and penetration depth [**P4**]. I used the Simulation of Spectra and the RENATE BES synthetic diagnostics to calculate the signal to noise and signal to background ratios for the proposed ITER pedestal and core fluctuation BES systems. By performing filter optimisation, I derived a relation between the expected SBR and SNR to navigate the performance trade-off between them [**P8**]. I developed a method that calculates locations of ideal observation positions on the first wall based on beam and magnetic geometries. The method minimizes the fluctuation sensitive areas and navigates the trade-off between radial and vertical resolutions. The method was applied to the proposed JT-60SA LiBES and DBES diagnostic systems [**P1**, **P2**].

T 3. I created a novel beam emission spectroscopy synthetic diagnostic to study and validate turbulence-timescale first principle plasma physics codes. The synthetic diagnostic includes the precision modelling of all relevant BES measurement features such as 3D beam, 3D observation and 3D magnetic geometry data and stochastic noise modelling accounting for all relevant noise sources. I have coupled the synthetic BES diagnostic to the HESEL turbulence code and successfully determined the effect of BES measurement artefacts on filament detection. Furthermore, a successful validation was undertaken between ASDEX-Upgrade LiBES experimental and synthetic BES measurements of HESEL plasma simulations [**P5**, **P10**]. Finally, I have used the synthetic diagnostic to predict the detection of SOL filaments with the ITER pedestal observation geometry [**P8**].

T 4. I expanded the existing rate equation solver of the RENATE beam emission spectroscopy synthetic diagnostic to include beam atom and neutral gas collisional interactions such as collisional excitation, de-excitation and ionisation. I showed the classical trajectory Monte Carlo method to be suitable for the generation of new BES-relevant atomic physics data by validating to experimental ionisation cross-sections [**P6**]. I estimated the additional beam attenuation expected as a result of the inclusion of neutrals in the scrape-off layer and beam ducts [**P6**]. Coupled to the nHESEL neutral-capable SOL turbulence code, I showed significant emission to be induced by beam with neutral gas interactions for close to equal plasma and neutral densities. The far SOL turbulence observation with synthetic BES was thus shown to be dominated by neutral dynamics rather than filament dynamics [**P11**].

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