

# Applications of the RENATE beam emission spectroscopy simulator

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## Introduction

Neutral beams can be used not only for heating and fueling the plasma but for diagnostic measurements, as well. One of these diagnostics is Beam Emission Spectroscopy that – besides for monitoring beam attenuation [1] – can be used to measure the density profile, turbulence characteristics and plasma waves [2]. The desire for an accurate and comprehensive simulation of BES diagnostics, which could be used both in the evaluation of BES measurement results and the development of new BES systems led to the birth of the RENATE (Rate Equations for Neutral Alkali-beam Technique) simulation code.

## The RENATE simulation code

As the name suggests, it was originally developed for modeling alkali-beams (lithium and sodium), but support for the more common H and D beams was also added. RENATE can calculate beam evolution in plasmas with mixed isotope content and impurity composition using either a simple quasi-stationary model [3] corrected with finite atomic level life-time, or by calculating the evolution of several atomic levels by solving the time-dependent (1) rate equations.

$$\frac{dn_i}{dt} = \sum_I n_I \left[ -n_i \left( \sum_{j=i+1}^m R_I^{exc}(i \rightarrow j) + \sum_{j=1}^{i-1} R_I^{dexc}(i \rightarrow j) + R_I^{ion}(i \rightarrow +) + R_I^{CX}(i \rightarrow +) \right) + \left( \sum_{j=1}^{i-1} n_j R_I^{exc}(j \rightarrow i) + \sum_{j=i+1}^m n_j R_I^{dexc}(j \rightarrow i) \right) \right] - n_i \sum_{j=1}^{i-1} A(i \rightarrow j) + \sum_{j=i+1}^m n_j A(j \rightarrow i) \quad (1)$$

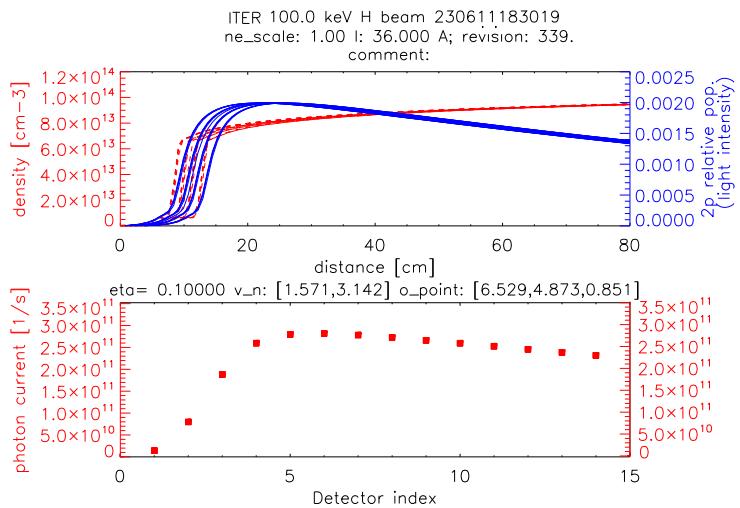
where  $n_i$  is the population of the atomic level  $i$ ,  $n_I$  is the density of species I,  $R$  denotes the rate coefficients and  $A$  denotes the Einstein coefficients. During the beam evolution calculation RENATE takes collisional excitation (*exc*), de-excitation (*dexc*), ionization (*ion*), charge exchange (*CX*) and spontaneous de-excitation processes into account.

The neutral beam itself is modeled as a set of infinitesimally thin virtual beams (beamlets), for which the beam evolution is calculated individually. This allows the handling of complex beam structures, which could have a significant effect on the measured

signal. In the case of hydrogen and deuterium, the calculation with the rate equation solver algorithm is carried out using the bundled-n approximation, taking the first 6 atomic levels into account. Atomic physics data was obtained from the IAEA ALADDIN database [4] and the Open ADAS database [5] with corrections from E. Delabie and O. Marchuk [1]. The rate equation solver of RENATE has been benchmarked against the simulation code in [6]. Comparison of RENATE results with measurements is still in progress.

Having calculated beam emissivity, RENATE has the capacity to take all the subtle geometrical effects into account. Complex beams having 3D structure can be composed from a large number of beamlets. Evolution of each beamlet in the 3D model of the tokamak geometry is calculated independently, and contributions to the observation channels is then summed up by the optical modules. Two levels of optical modules exist: the simpler module models the pinhole optics approximation while the more sophisticated one uses ray tracing through the Zemax model of the optical system. The latter method is more accurate, and can be used in the last design phase when the detailed optical design is available. The final result is the expected absolute photon current on the surface of each detector (Fig. 1).

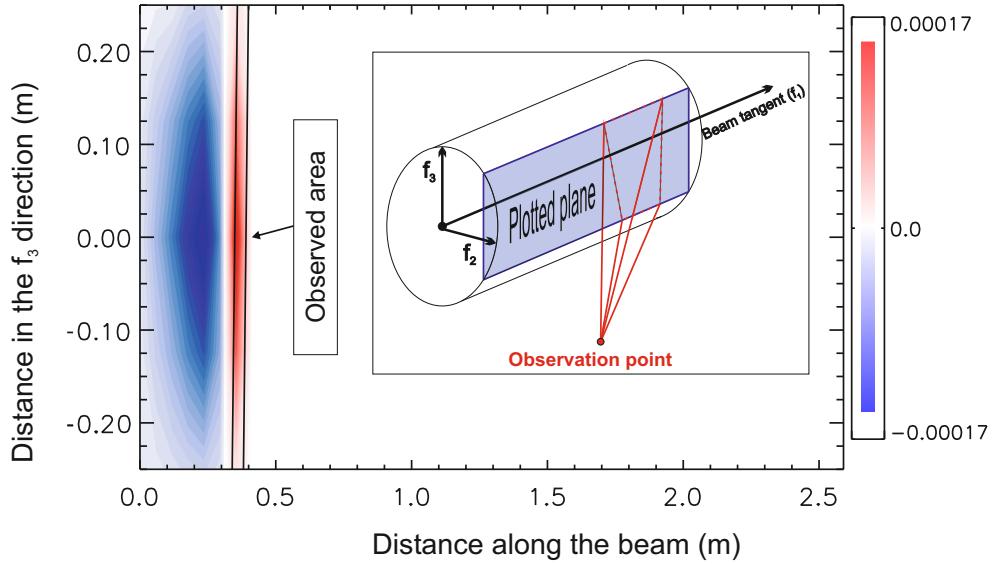
One of the main features of the RENATE simulation tool is the capability of calculating the density perturbation response matrix. This calculation involves placing small amplitude quasi Dirac delta plasma density perturbations (approximated with a spherical Gauss functions matching to the resolution of the grid size) along the beam, and computing the change in detected photon currents for each detector segment. The results are



**Figure 1:** RENATE graphical output showing the the density along the beamlets (top-red), light profiles (top-blue) and the photon currents reaching the detector surfaces (bottom)

organized into a matrix that gives the response of a chosen detector's signal to a quasi Dirac-delta perturbation at a given position (thus the matrix has 4 indices: 3 coordinate and 1 detector index). Given a sufficiently high resolution perturbation response matrix,

the BES system response to an arbitrary shaped small amplitude density perturbation can be easily calculated. A visualization of the perturbation response matrix is shown on Fig. 2.



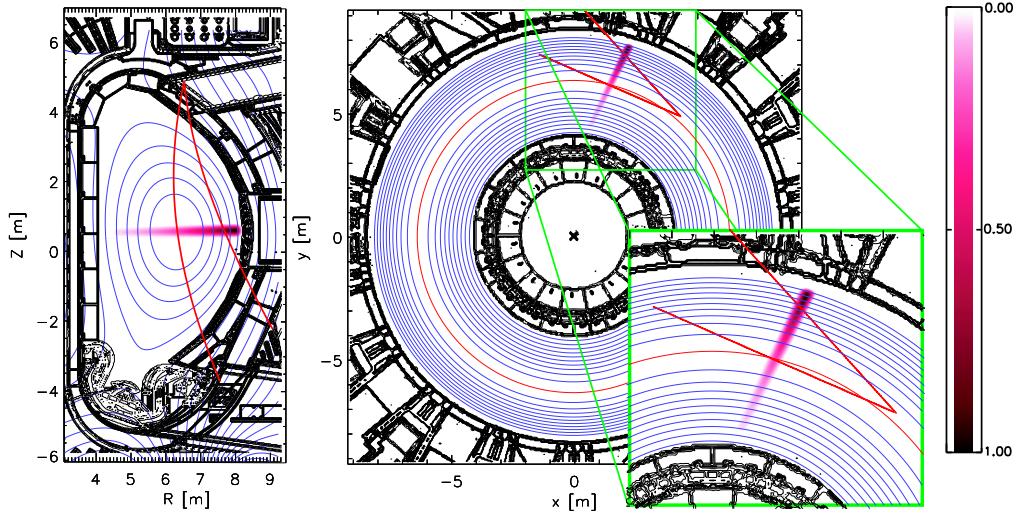
**Figure 2:** Segment of a perturbation response matrix, showing the normalized absolute response of the detector for perturbations in the given plane. The rectangular box indicates observed area of the beam.

These matrices can be either used to determine the resolution of the given BES system or to evaluate results of plasma fluctuation measurements.

### Application to ITER and KSTAR

The first demonstration of the capabilities of RENATE includes applications for ITER (Fig. 3) and KSTAR [7]. With the help of RENATE the photon currents reaching the detector surfaces can be calculated. Combined with the given detector type's characteristics these results enable the calculation of the signal to noise ratio for each detector segment. Calculating the density perturbation response matrix yields the spatial resolution of the fluctuation BES system. RENATE can also provide the poloidal and resolution for field-aligned perturbations by integrating the response matrix along magnetic field lines.

## ITER DNB



**Figure 3:** Toroidal and poloidal projections of the simulated configuration for ITER DNB, showing some structural elements, the flux surfaces, the relative emissivity and the lines of sight for  $r/a = 0.0$  and  $r/a = 0.8$  from Upper Port 3.

In the near future RENATE is to be upgraded to be able to take the wavelength dependent effects (e.g. motional Stark-effect) into account.

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