1-D plasma X-ray radiation code as a first step for developing the fusion diagnostics

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Abstract. A computer code named RayX has been developed for W7-X for checking the performance of a spectroscopy system and optimizing individual parts, like detectors and filters. This specialized software tool makes it possible to investigate the influence of a geometrical configuration of the diagnostic systems on the intensity and shape of the spectra, as well as to simulate emission from different discharges characterized by widely varied electron temperature and density profiles. Simulation results presented in this work provided the necessary information for the concept of the PHA measurement system which is under designed for W7-X.

1. Introduction

High temperature plasma, apart from electrons and hydrogen isotopes, contains also an impurity ions which have significant influence on fusion plasma properties. It makes the monitoring of impurity density very important and diagnostics for such a measurements must be present in today's fusion devices.

The pulse height analysis (PHA) diagnostics is designed for identification of the line radiation from all relevant impurities (with exception of elements lighter than nitrogen) and to determine their concentration in the hot plasma core. The slope of the hydrogen and low-Z continuum radiation is used to determine the central electron temperature. The intensity of the continuum radiation along with additional spectroscopic data allow to assess Z_{eff} values in the plasma center.

To design the PHA diagnostic system special numerical code, named RayX has been developed [1]. It is equipped with modules that are responsible for simulation of soft X-ray emission, from specific plasma sources like tokamaks or stellarators. Moreover, it is able to incorporate components of the tested detectors.

2. Description of the X-ray module

Emission of the X-ray from plasma seems to be a very great task as a whole. In order to simulate a full range of mechanisms several elements responsible for such an emission should be taken into account. There are free-free emission (bremsstrahlung); free-bound emission (recombination radiation); bound-bound emission (line radiation); de-excitation after radiative recombination (additional mechanism for free-bound emission); de-excitation after dielectronic recombination (additional mechanism for free-bound emission); electron impact excitation (additional mechanism for bound-bound emission); de-excitation after CX recombination. For the detector test purpose the most important are the first three of these components and in RayX these elements are implemented.

In the case of free-free emission, radiation is emitted by free electrons, which are accelerated in the electric field of charged particles. Both, the initial and final states of the electron are free. This explains its continuous spectrum. If the free electrons are scattered by the plasma ions, the bremsstrahlung emission energy E*ff* per unit frequency ω, the temporal interval *dt* and unit volume *V*, averaged over the Maxwell velocity distribution:

$$\frac{dE_{ff}}{d\omega dt dV} = \sum_j \frac{16}{3}\left(\frac{2\pi}{3}\right)^{1/2}\left(\frac{e^2}{4\pi\varepsilon_0 c}\right)^3 \frac{n_e n_j Z_j^2}{m_e^{3/2}(k_B T_e)^{1/2}} \overline{G}_{ff} e^{-\frac{\hbar\omega}{k_B T_e}} \qquad (1)$$

where it is summed over all species of ions; m_e , v , Te are the electron mass, velocity and temperature, $\hbar\omega$ is the emitted photon energy, n_j is the ion density with the charge Z_j , and G*ff* is the Maxwell-averaged Gaunt factor.

Recombination radiation differs from bremsstrahlung in the final state of the electron, which is bound. Radiative recombination emission term is represented by the equation similar to that for bremsstrahlung:

$$\frac{dE_{ff}}{d\omega dt dV} = \sum_j \frac{16}{3}\left(\frac{2\pi}{3}\right)^{1/2}\left(\frac{e^2}{4\pi\varepsilon_0 c}\right)^3 \frac{n_e n_j Z_j^2}{m_e^{3/2}(k_B T_e)^{1/2}} e^{-\frac{\hbar\omega}{k_B T_e}} \times \\ \times\left[\frac{\chi_{j-1}}{k_B T_e}\overline{G}_{fb}(n)\frac{\xi}{n^3} e^{-\frac{\chi_{j-1}}{k_B T_e}} + \sum_{\mu=n+1}^{\infty}\overline{G}_{fb}(\mu)\frac{Z_j^2\chi_H}{\mu^2 k_B T_e}\frac{2}{\mu} e^{-\frac{Z_j^2\chi_H}{k_B T_e}}\right] \qquad (2)$$

where χ_{j-1} is the ionization potential of the final ion with charge j -1, n is the main quantum number of this state, $\xi = 2n^2$ is the total number of places in the shell with the main quantum number n, and $G_{fb}(\mu)$ is the Gaunt factor for the recombination to the nth shell. The spectrum of radiative recombination has a continuous character.

Line radiation originates in the transitions of electrons between the bound states of atoms or ions according to the following formula:

$$\frac{dE_{bb}}{dt dV} = 2.56\cdot 10^{-22}\, n_e n_Z \sum_j f_j \overline{G}_{ex} \frac{(E_{ph,j}/kT_e)^{1/2}}{kT_e^{3/2}} E_{ph,j} \qquad (3)$$

where: *fj* is an oscillator strength, G_{ex} is averaged Gaunt factor for bound-bound emission, n_e, n_Z are electron and ion densities, T_e is the electron temperature and $E_{ph,\mathrm{j}}$ is energy of the X-ray photon.

As it is well seen, all equations are dependent on electron temperature and density. Such parameters are related to geometry of device. RayX code was written in such a way that it includes real plasma profiles and is universal because it can be used both for tokamak and stellarator.

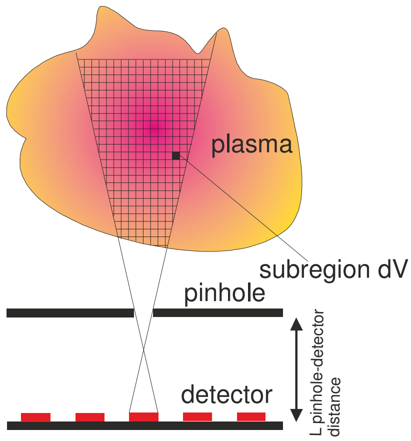

Fig.1 *Scheme of the computation idea.*

The main idea used in the calculations is based on numerical integration of X-ray emission for the cone of the detector view which is a function of the device and plasma geometry (among others: the detector and pinhole sizes, the distance between them and some mechanical obstacles present inside the plasma region). The whole region of integration is divided into small subregions where the constant value of the temperature, ion and electron concentration are assumed. The scheme of the concept is shown in the fig.1.

Based on these assumptions code has possibly to take into account a diagnostic geometry which includes distance between plasma and pinhole as well as pinhole and the detector, various pinhole sizes as well as some types of detectors (back illuminated, front illuminated, etc.). Additionally, simulations could also take into account the type and thickness of the used filter.

Using RayX code it is possible to check the influence of the pinhole size, detector size, location of each diagnostic components, time of the data acquisition as well as the type and filter thickness on recorded spectra. In fig.2 the exemplary data sheet which includes diagnostic's geometry is presented.

In the code the hydrogen has been chosen as a background plasma. There is a choice to use carbon, nitrogen, oxygen and iron as an impurities elements with given percentage (see fig.2 right).

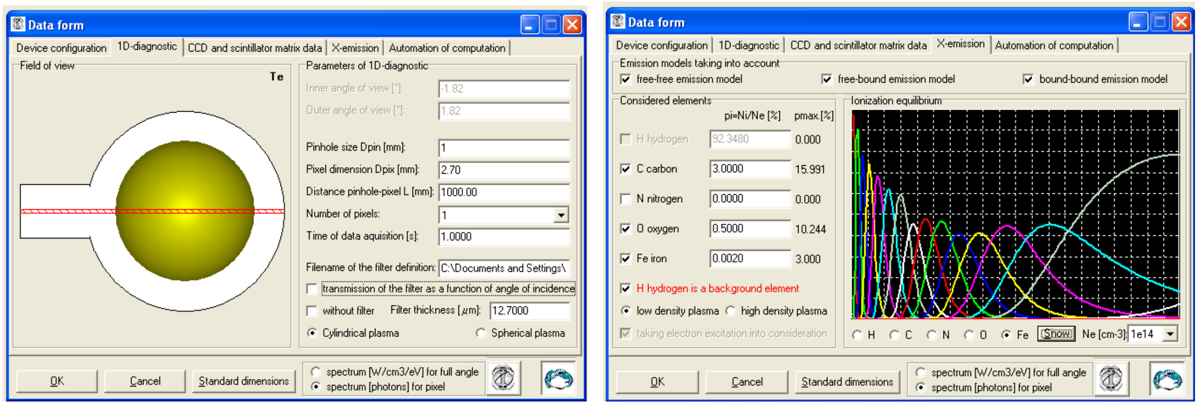

Fig.2 *Exemplary data sheet which includes geometry of diagnostics, acquisition time and type and thickness of the used filter (left) as well as plasma contamination (right) .*

For analyzing of the impurities, code simulates the real composition of the ions charge, according to the temperature and concentration profile of the plasma. For this purpose coronal model of ions equilibrium was used. It was assumed that ionization is realized mainly by interaction between atoms or ions and electrons while recombination is realized by interaction of ions and electrons.

As an output date the RayX code produced information about photons reaching the detector as well as currents and charges generated inside the detector. Additionally, code can provide information about photons energy spectra recorded by applying the filter.

3. Conclusion

A simple code for checking the performance of a spectroscopy system and optimizing individual parts, like detectors and filters in fusion devices has been presented. The code includes coronal model of ions equilibrium. It was used for develop PHA system on W7-X [2] which will be tested in the first phase of stellarator operation.

Acknowledgment

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