Fast Simulation of Local Radiation Fields for Synthetic Diagnostics

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Introduction

The development and validation of algorithms for plasma control in tokamaks requires the simulation of the dynamic signals from plasma diagnostics. A Synthetic Diagnostic (SD) is a computational module which simulates the measurements made by a diagnostic as well as the signals sent over the real-time network used for control. The computed signals should be sufficiently realistic to be applied for plasma discharge scenario planning and analysis. Typically, simulation of the signals requires the use of resource-intensive Monte-Carlo or ray-tracing codes using detailed 3D models which take many hours of CPU time for a single time slice making simulations of evolving plasma unacceptably long and expensive. For the cases when the impact of the sources on the diagnostic signal is additive over the spatial distribution, it is possible to use an approach based upon Green's functions. We describe a technique based on this concept. The technique is applicable to dynamic simulations of diagnostic signals for a range of neutron and optical diagnostics in tokamak plasmas. Here we describe the method applied to the Divertor Neutron Flux Monitor (DNFM) [1] SD as an example.

Method description

For additive radiation sources the task for a detecting signal, F_d, produced by a distributed source of radiation, S, can be reduced to the calculation of the kernel of an integral equation:

$$F_d = \hat{H}_d S = \int k G_d S dV, \qquad (1)$$

where the kernel

$$G_d = \hat{H}_d \, \delta, \qquad (2)$$

is the analog of a Green's function of the inverse operator $\hat{H}_d^{-1}$, δ is the delta-function, and k is a constant converting the units. Equation (2) can be solved numerically with the function G_d computed by Monte-Carlo or ray-tracing techniques on a particular spatial grid. The proposed Green's-Function of Radiation Field (GFRF) method comprises a few steps: 1) the choice of the finite reference spatial grid with a certain number of nodes, R_i, Z_j, α_k; 2) the calculation of the basic matrix for the Green's function with dedicated software (typically time-consuming

comprehensive commercial codes) and the contribution to the signal at the location of the detector, $G_{dijk} = G_d(R_i, Z_j, \alpha_k)$ from unit sources located at each node of the chosen grid, $\delta(R_i, Z_j, \alpha_k)$; 3) the approximation of the data from step 2 to build a function which transfers the volumetric neutron source to the output signal of the detector, $G_d(R,Z,\alpha)$ using the basic matrix G_{dijk}. The accuracy of the derived approximation should be checked by comparison with comprehensive simulations in some additional nodes, and if necessary the number of nodes should be increased and the steps repeated unless the desirable accuracy has been reached. Thus, finally we can calculate the flux density at the location of the detector by integrating any time evolving intensity $S(R,Z,\alpha,t)$ of a radiation source using just volume integration, $F_d(t) = \int S(R,Z,\alpha,t)G_d(R,Z,\alpha)dV$ without extra time consuming calculations by more comprehensive codes.

For the case of the DNFM, the neutron source distribution is 2D $S(R,Z,t)$, and the signal, F_d is the neutron flux or fission rate in the U-235 and U-238 detectors. The functions $G_d(R,Z)$ (figure 1) for both types of detectors were calculated by the MCNP code [2] with the C-lite ITER model which computes realistic neutron fields taking into account the ITER geometry and materials (figure 2)[3].
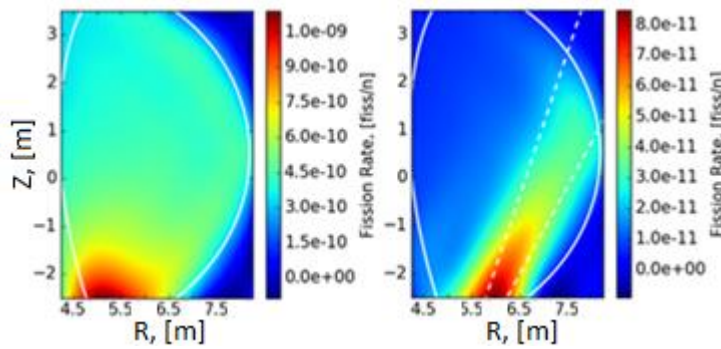

Figure 1. Green's function for fission rate in DNFM detectors (U-235 50 mg – left, U-238 500 mg – right). Solid line- separatrix, dashed lines- boundaries of the sector of direct view
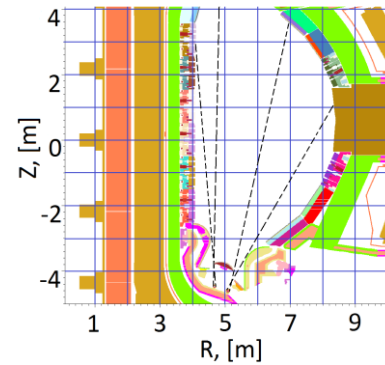
Figure 2. ITER C-lite model with DNFM and sectors of direct view

Choice of the reference grid

To keep the accuracy of simulations of the signal prescribed by the design requirements to the diagnostic, the choice of the reference grid should take into account the dependence of the contribution on the distance to the radiating ring, plasma shape and the neutron source profile evolution [4] and the Green's functions anisotropy of the neutron shielding (figures 1,2,3).
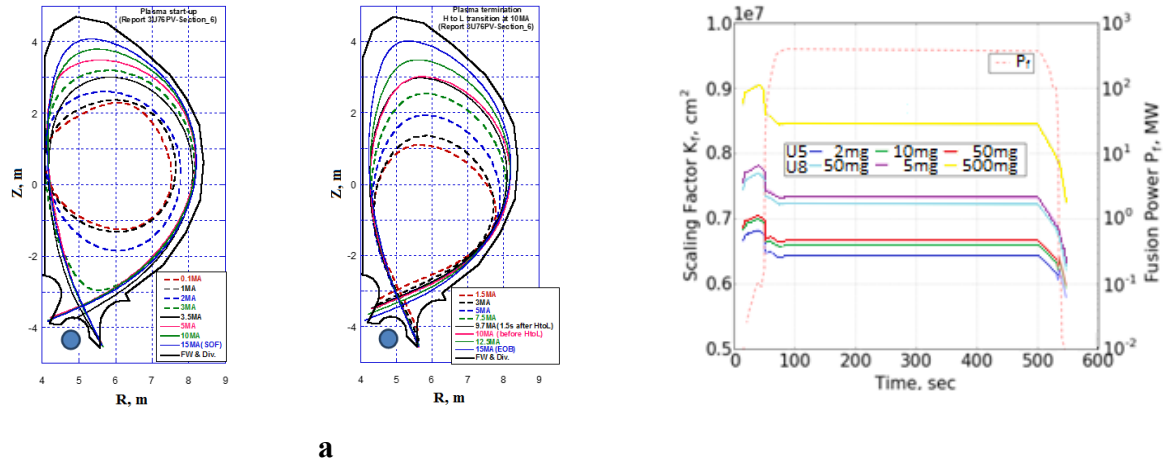
a

Figure 3. Evolution of plasma shape (a), fusion power, P_f, and scaling factor, $K_f=P_f/\mathcal{F}_d$ (b) for baseline scenario [4]. $\mathcal{F}_d$ is the neutron flux density at the location of a detector.
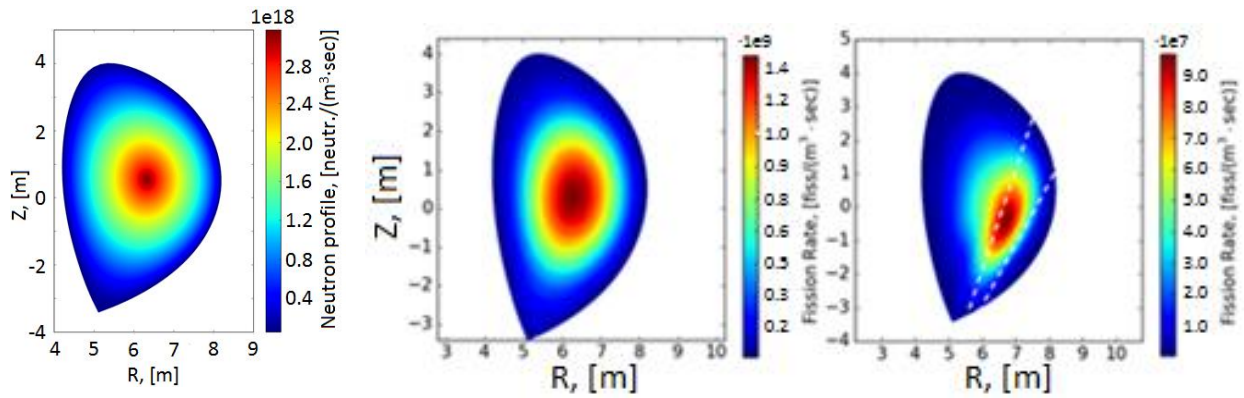

Figure 4. Maps of relative neutron source $S(R,Z,t)$ (left) and its relative contribution $S(R,Z,t)G_d(R,Z)$ to signals at DFNM detectors (U-235 50 mg – middle, U-238 500 mg – right) for baseline scenario $P_f = 500$ MW [4].

The value of the grid step for the basic grid used for interpolation of the kernel's function was optimized with extrapolation algorithms by Richardson [5, 6]. The optimal grid step size was found to be $\Delta R = \Delta Z = 50$ cm.

The accuracy test was carried out for ITER $P_f = 500$ MW 15 MA DT standard plasma scenario. The accuracy of the Richardson Extrapolation was estimated by comparison with values of the neutron flux Φ and fission rate R_f in the DNFM detectors computed by the GFRF method and with results of an MCNP simulation from a volumetric plasma source. The difference of predictions is within 2%. The product $S(R,Z,t)G_d(R,Z)$ (figure 4) reveals the contribution to the DNFM response from different parts of the plasma volume for the baseline scenario.

Summary and discussion

Applications of the GFRF technique described in this paper have enabled a reduction in the computational time needed to calculate synthetic diagnostic signals from dozens of hours of parallel computations by the MCNP code to less than a second of CPU time. The

GFRF approach is used to create the DFNM SD module compatible with the ITER Integrated Modelling & Analysis Suite (IMAS) [8]. Note that the Ray Tracing Transfer Matrix proposed for simulations of the divertor impurity monitor (DIM) system [7] can be easily transformed into the basic kernel G_{ij} and be used for simulations of the synthetic D_α signal using a simulated radiation source density distribution. The kernel's basic matrix G_{ij} and base RZ-grid approach are recommended for the creation of other synthetic diagnostics for ITER in the framework of IMAS [8]. The approach could be applied for creation of SDs for IMAS such as Radial Neutron Camera, Vertical Neutron Camera, Neutron Flux Monitor and many others. For collimated measurements with sufficient number of detectors the basic kernel matrixes can be used for reconstruction of the spatial distribution of the sources radiation from the detected signals (see [8]).

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