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Radiation transfer in dense edge plasmas and divertors: experimental and recent computational results

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Abstract

Divertor plasmas are a mixture of electrons, hydrogenic ions and neutrals and a radiation field. The strong mutual influence of the charged and neutral particle components is the key for establishing favourable divertor conditions, for example detached divertor scenarios. In most quantitative assessments of such plasmas the radiation field has been regarded as entirely decoupled from the particle fields, i.e., the plasma is assumed to be optically thin. However, various spectroscopic studies have shown clear signals of opacity (line absorption) effects. In order to quantify these effects we argue that already current divertor neutral particle codes, in which photons are treated as just another particle species, can be used. We apply this concept to study possible Lyman opacity effects on divertors.

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1. Introduction

Detached divertor plasmas are currently regarded as the most promising option for next generation fusion reactor experiments. It seems that a rich complexity of atomic, molecular and radiation processes, not otherwise encountered in fusion devices, control the various different detachment scenarios. Since particle, momentum and energy balances are delicately interrelated here and details of the processes and even of the configuration are essential, understanding of detachment is largely based on those computer codes which incorporate these effects in great detail ([1], chapter 16).

Whereas the key role of neutral gas transport on the overall divertor dynamics is generally accepted, the radiation field is, at least in 2D divertor modelling codes, assumed to be decoupled from the particle field: the divertor plasmas are regarded to be optically thin for the line radiation they produce (i.e.: perfect transparency, or, what is the same, zero 'opacity' is assumed).

The optical thickness $\tau = L/mfp$ (inverse Knudsen-number for photons) certainly scales linearly with $n_a L$, the product of number density n_a of radiation absorbing particles and L, the typical geometric size (average chord length) of the divertor chamber. $mfp = mfp(\nu)$ denotes the photon mean free path for photons with fixed frequency ν.

The photon mean free path at the center of a Doppler broadened line, in CGS units, is

$$mfp_\lambda = \left(5.4 \times 10^{-9}\lambda\left(\frac{\mu}{T}\right)^{1/2} n_a\right)^{-1} \approx 1.8 \times 10^{13} T^{1/2}/n_a \text{ (cm)}. \tag{1}$$

Here we have inserted $\lambda \sim 10^{-5}$ cm as a typical wavelength for Lyman lines, and $\mu = 1$, the relative proton mass. T is the temperature (eV) of the neutral atoms, n_a is their ground state density (cm^{-3}).

It is evident from this that whereas most current divertor Tokamaks may be optically thin to Lyman lines

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to a good approximation, this may not be the case for very high gas densities (C-Mod) or very large divertors (ITER). Also the neutral gas dissociation degree matters then. Such effects will lead to an enhanced degree of ionisation, reduced recombination and neutral-ion friction, due to photoexcitation and photoionisation. Quantifying them is, therefore, an essential ingredient in understanding divertor detachment.

2. Experimental evidence for opacity

Opacity effects, in particular on the resonance Lyman lines, have already been observed experimentally for dense divertor plasma conditions in various Tokamaks, in particular, see Eq. (1), for the very dense Alcator C-Mod divertor [2], and in MARFEs [3].

Spectroscopic indications of such opacity effects would be

(1) modifications of line ratios of the Balmer series, which depart from predictions of collisional radiative (CR) population models,
(2) modification of line shapes of individual lines caused by the frequency and temperature dependency in the absorption length (leading, in the extreme case, to inverted line profiles),
(3) modification of line ratios such as Lyman β over Balmer α between a Lyman line and another line with the same emitting state (e.g. the Balmer α line chosen here).

According to observations of type (3) JET divertor plasma conditions have been described as just marginally optically thick for Lyman lines [4], whereas Alcator C-Mod, with n_a as high as $\sim 2 \times 10^{14}$ shows clear evidence of strong line re-absorption [2] and major effects on the overall divertor ionisation–recombination balance.

Both other types (1) and (2) of observation are somewhat indirect.

In the first case (1) the line ratios, as predicted from collisional-radiative (CR)-models, may differ from the experimentally observed series due to (a) uncertainties in the atomic data in the CR-model, (b) because at least five contributions to each line have to be properly weighted and accounted for. There is usually one contribution from coupling to ground state atoms (ionising), one from coupling to protons (recombining), one from coupling to neutral molecules (dissociative excitation), one due to molecular ions (direct or dissociative ionisation) and finally one due to negative ions (dissociative attachment). Experimentally accessible is only sum of all these contributions, each weighted by the only poorly known relative local abundance of H, p, H_2, H_2^+, and H^-. With this uncertainty in mind opacity effects have still been concluded for divertor plasma conditions in DIII-D [5], C-Mod [2].

The most detailed, but also the most speculative observation is that of type no. (2). Laser induced flourescense at Lyman α has been employed to analyse the spectral line shape, possibly affected by a neutral gas cloud near a test limiter in TEXTOR [6]. Opacity effects have been concluded there from the typical flattening (even inversion) of the line profile. However, opacity is only one out of many possible explanations for inverted line-shapes, given the uncertainty in the various Franck–Condon energies of the excited dissociation products from hydrogenic molecules, not to mention surface effects on the atomic emitters velocity distributions.

Beyond the terse identification of opacity effects went the attempt to actually use these effects to determine, experimentally, the neutral particle density in the divertor. Using semi-analytical estimates of Lyman β line escape probability [7] of the order 0.5, the necessary Hydrogen atom density was inferred at ASDEX-U by spectroscopy. A qualitative agreement with predictive B2-EIRENE calculations, based upon the usual zero opacity assumption there, (within the considerable experimental and modelling uncertainties) was indeed found, loc.cit. This indicates that opacity effects under such circumstances are strong enough to permit spectroscopic assessment, at least along some selected lines of sight, but that these effects may not yet be strong enough significantly to influence overall neutral particle transport in the divertor.

It should be noted that, except for the clear observations of type (3), all these findings are partially based upon modelling analysis with strongly simplified (if any) configurational aspects, often resorting to rather crude escape probability estimates. On the other hand, radiation transfer is probably the best established transport mechanism of all in fusion edge plasmas (despite some uncertainties in the line broadening mechanisms), in terms of accuracy of data: the Einstein–Milne coefficients are certainly much better known than any other atomic or molecular cross section, not to mention anomalous transport of electrons and ions.

It therefore seems tempting to eliminate at least this unnecessary free parameter from the large set of modelling assumptions present in current divertor codes, by a detailed computational assessment. This is discussed in the next section.

3. Theoretical predictions

Opacity effects have been discussed as long as dense divertor conditions are considered, i.e., first estimates are historically much older than the current concepts of detached divertors. See e.g., [8] for one such early example, although there for a somewhat artificial LTE condition with neutral densities two orders of magnitude larger than nowadays observed. We do not add anything new to this, in physical terms, except that we wish to show how these effects, hitherto only qualitative, can be now quantified for far more realistic physical and configurational conditions, due to progress in 2d and 3d plasma edge modelling. Previous computational assessments have usually been based upon highly idealized, often zero dimensional approximations (so called optical escape factors in CR models) [7] or, at best, one dimensional approximations [9]. Due to the spatial gradients of neutral gas profiles in divertors, the various line broadening mechanisms and the often kinetic (non-fluid) properties of the neutral gas components in divertors a quantitative bookkeeping of radiation processes seems to require Monte Carlo photon gas simulations also for dense divertors and in MARFEs. Such procedures are already well established in many fields, e.g. in astrophysics, for low and high pressure discharges used for lighting purposes, and many others. The effort to adapt these specialized codes to typical fusion edge plasma conditions, especially configurational details, is quite considerable, but some steps have already been undertaken, e.g. with the CRETIN code [10].

In [11] we have chosen the opposite approach: the EIRENE neutral particle transport code [12], already well adapted to fusion plasma edge conditions, is extended from it's test particle (neutrals and ions) options towards photon gas simulations. The radiation transfer equation is mathematically analogue to the linear Boltzmann equation for neutral particles solved by EIRENE. Because of that most of the existing coding can be used directly for photon transport problems, with only minor modifications and without large amounts of duplicating work.

4. Kinetic neutral particle code extensions for radiation transfer

The material in this sections can be found in many textbooks, such as [13] on radiation transport in stellar atmospheres.

Here we only give a brief 'dictionary' for translating the terminology typical of radiation transport into that of neutral particle- (or also neutron-) transport.

The basic quantity of interest in photon gas transport is, usually, the specific intensity (also: 'brightness') $I_\nu = I_\nu(\vec{x}, \nu, \vec{\Omega}, t)$. It has the dimensions: energy $(\text{time})^{-1}$ $(\text{area})^{-1}$ (solid angle) $^{-1}$ $(\text{frequency})^{-1}$.

We first convert the frequency ν into an energy E, $E = h\nu$ with Planck's constant h. Then the velocity space coordinates of a single ray $(E, \vec{\Omega})$ can be transformed into the velocity vector $\vec{v}$, upon which, usually, neutral particle transport codes for fusion edge plasmas are based. In order to recover $(E, \vec{\Omega})$ from $\vec{v}$, the frequency needs to be added to the phase space of a test particle in the case of photons, $E = h\nu$, whereas for neutral atoms or molecules the mass is needed: $E = m/2|v^2|$. The state of a test-particle in EIRENE is given by m, $\vec{x}$, $\vec{v}$, E, t, hence, due to this 'redundancy in the dimensionality of the problem', it is suitable for both particles and photons.

Now we can identify the specific (radiation) intensity I_ν with the 'energy transport flux'

$$\widetilde{I} = \widetilde{I}(m, \vec{x}, \vec{v}, E, t),$$

$$\widetilde{I} = Evf(m, \vec{x}, \vec{v}, E, t) \tag{2}$$

and f is the usual particle distribution function used in neutral particle transport, and $v = c$, the vacuum speed of light.

The volumetric source function for neutral particles, for example due to plasma recombination, can be reinterpreted to become the spontaneous photon emissivity for the case of radiation transfer.

Absorption and scattering (excluding stimulated scattering) are entirely analogous in the two cases of photon gas and neutral gas simulation. Redistribution due to scattering of photons in the volume is described by the so called 'phase function', in case of neutral particles this same quantity is usually referred to as 'scattering kernel'. The extinction coefficient $\chi(\vec{x}, \nu, t)$ (also: 'opacity coefficient', or 'total absorption coefficient') in radiation transport is the inverse of the photon mean free path, and, hence, the same quantity as the 'total macroscopic cross section' $\Sigma_t(\vec{x}, E, t)$ (Dimension: $(\text{length})^{-1}$) in neutron- and neutral gas transport terminology [12].

The full, self-consistent, Monte Carlo model for neutral- and photon gas transport for divertors and MARFEs, eliminating the hitherto introduced ad hoc opacity parameters from the model, is obtained by replacing the kinetic neutral atom (ground state) transport equation (for f_1) now by a coupled set of three mathematically identical transport equations for ground state atoms $f_{\tilde{1}}$, for atoms in the upper Lyman α state, i.e., in the $n = 2$ excited state $f_{\tilde{2}}$ and for photons of the Lyman α line f_{Ly}. A typical multi-species B2-EIRENE divertor plasma simulation is a kinetic multi-species problem already, with hydrogenic, helium and impurity atoms, various molecules and molecular ions, resulting in about 20 different species treated simultaneously by the Monte Carlo code. Increasing this number by 2 seems to be tolerable in terms of CPU and storage resources on current computing platforms. A number of tests of the radiation transfer option in the EIRENE code has been carried out using analytical and semi-analytical results for highly idealized cases and for the limiting case of the photon gas in thermal equilibrium (i.e., recovering, by the Monte Carlo simulation, the Planck function) [11].

5. Results

Even if clear signatures of opacity effects can be identified in spectroscopical investigations, these effects may still be too small to be too relevance for the dynamics of the SOL. Most current experimental results on opacity effects (excluding those from Alcator C-Mod) probably fall into this category.

Fig. 1 shows the photoexcitation pattern resulting for a typical detached ASDEX-U divertor solution, as obtained from B2-EIRENE applications. The geometrical data and the plasma fields have been provided by Coster, IPP-Garching. The effect of including opacity, as compared to the standard optically thin limit, on the neutral gas is rather week. But we do recover, roughly, a population escape factor (defined in [14]) of ≈0.5 in the relevant region of the outer divertor, confirming the independent ADAS-estimates by Behringer [7].

We also see that for divertor configurations and plasma conditions similar to the ones modelled here, firstly and in particular the private flux region (PFR), and perhaps even the 'vacuum region' below the PFR, should see the strongest effect of photoexcitation (and, not yet investigated here, perhaps even of photoionisation).

In order to demonstrate that opacity can be much more significant in ITER-FEAT, then even affecting the overall divertor plasma dynamics we have, in [11], compared a typical ITER-FEAT detached divertor simulation (B2-EIRENE runs provided by Kukushkin, [15,16]), continued 'stand alone' with EIRENE with and without opacity effects. A drastic reduction of the neutral atom 'cushion' (by a factor ≈6 for the atom density) was found. Supplementing these results we show here, firstly in Fig. 2, the radiation intensity field (only the Lyman α line) as implicit in the original runs, as compared to the same field (Fig. 3) obtained after consistently coupling the radiation field with the neutral atom field. Now also the target heat load due to this radiation can be assessed. We find, for the conditions investigated so far, additional peak target heat loads below 0.5 MW/m^2. In Fig. 5 the strongly reduced field of ion-atom momentum removal (friction) was found, again as compared to to the original (optically thin) friction (Fig. 4), on which the plasma solution is based.

It is clear that for a machine of ITER-FEAT size, and for conditions in which ion-atom friction is essential (such as, most probably, for the detached state) interpretation of divertor plasma diagnostics on the basis of 2D edge modelling codes lead to different conclusions about unknowns such as anomalous transport or about the basic mechanisms for producing detachment, depending upon whether a current (optically thin) model is used, or an extended code as described here, in which the consistent radiation field is properly taken into consideration.

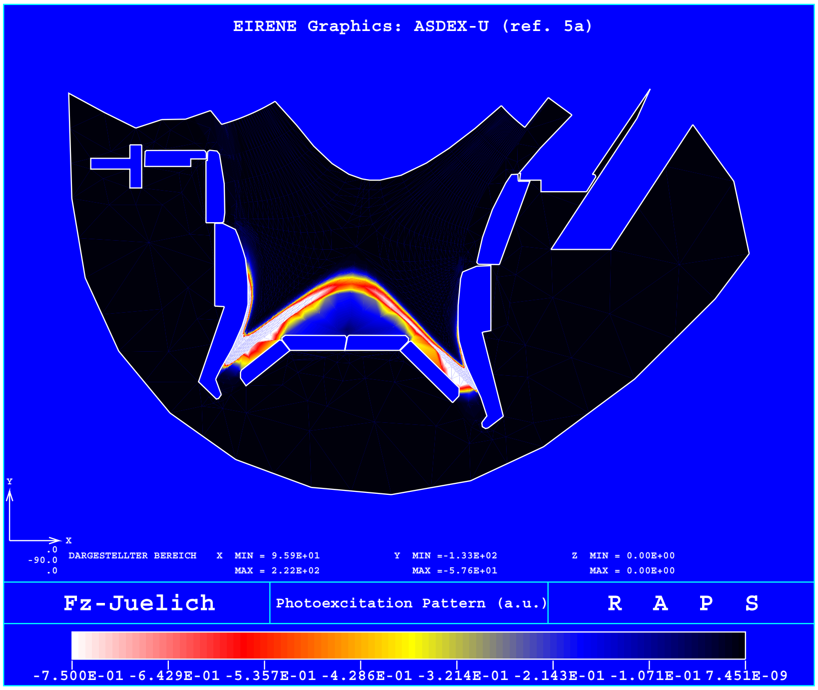

Fig. 1. Spatial distribution of photoexcitation by Lyman α in detached ASDEX-U divertor, showing main effect (if any) near the strikepoints on outer PFR.

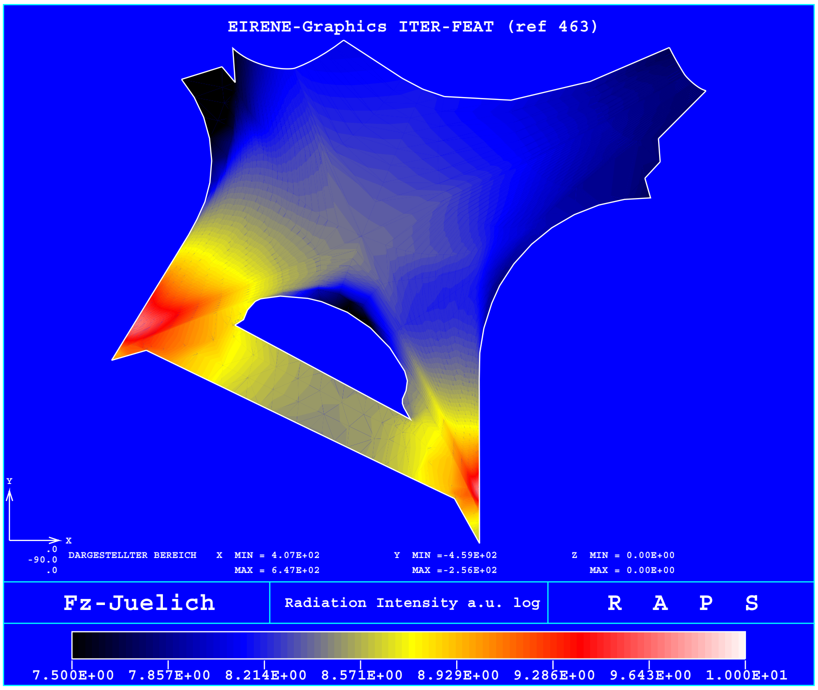

Fig. 2. Lyman α photon gas density (i.e., in other units: raditation intensity) in a detached ITER-FEAT divertor, for standard optically thin assumption.

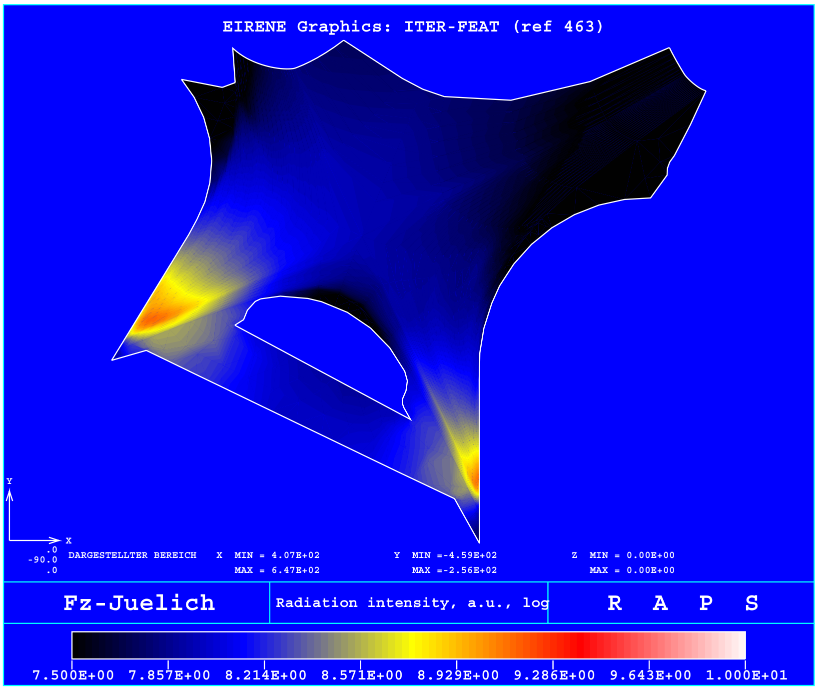

Fig. 3. Same as Fig. 3, but with consistent coupling of radiation field and neutral particle distribution.

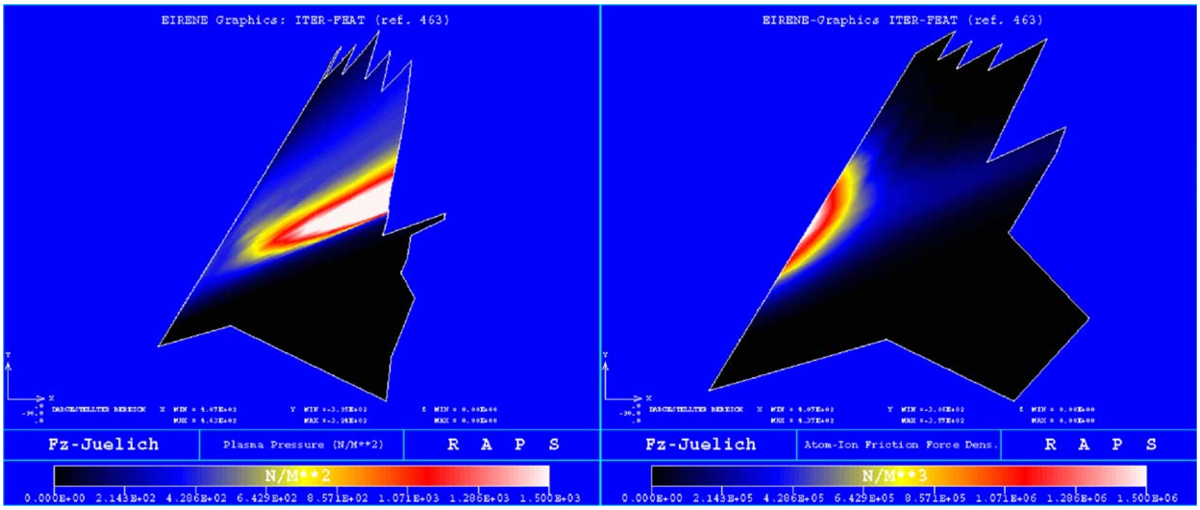

Fig. 4. Left: plasma pressure near the inner strike point (N/m^2), indicating full detachment, and, right: neutral atom-ion force density field (N/m^2), for the standard (optically thin) assumption.

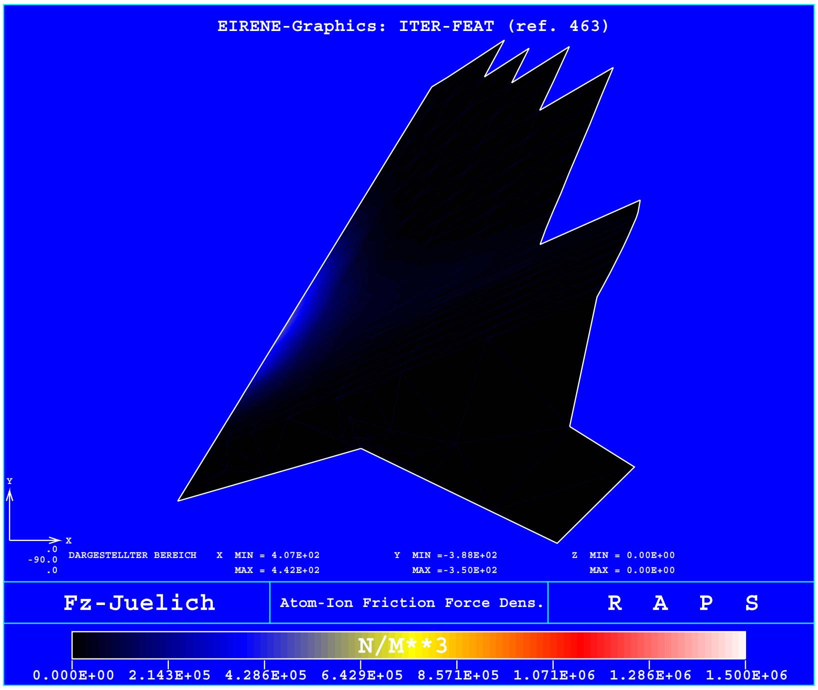

Fig. 5. Same as Fig. 4, right, but with consistent coupling between atoms and the radiation field, showing a strong reduction in neutral-ion friction due to opacity effects.

6. Conclusions and outlook

A fully parallelized 3D Monte Carlo neutral particle code for fusion edge plasma studies has been generalized to photon gas simulations (radiation transport). Doppler and Voigt broadened line emission profiles have been implemented, absorption in the volume as well as diffuse and specular reflection at surfaces could be carried over from existing coding for neutral particles. The modified collision-radiative rate coefficients for transitions to and from the upper level of the Lyman α lines and the Lyman-continuum have been added to the atomic database for the EIRENE code. The code extensions have been validated against semi-analytical results (population escape factors) for idealized cases, up to quite high opacity (optical thickness of the order 30). In first stand-alone applications the Lyman α line radiation transport has been included in a B2-EIRENE study of ITER-FEAT divertor conditions. Typically 50% of this radiation is found to be re-absorbed in the volume, 1/3 at the vessel and 10% at the divertor targets. The response of the plasma conditions (in particular the electron temperature and density fields) within the context of a fully self consistent B2-EIRENE simulation still has to be studied. Further extensions of the photon gas transport model will, most importantly, also have to address Zeeman splitting, and the issue of partial redistribution.

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