Modeling and characterization of a high-power X-ray gas absorber.

A. Martín Ortega[1], A. Lacoste[2], S. Béchu[2], A. Bès[2], T. Minea[3]

[1] *ESRF, Grenoble, France*

[2] *LPSC, Grenoble, France*

[3] *LPGP, Orsay, France*

Introduction: The design and commissioning of brighter X-ray sources like free-electron lasers and 4th generation synchrotrons requires new techniques to deal with the growing heat load of the optical elements [1]. A gas absorber reduces the heat load by absorbing the photons with lower energy while being transparent to the high energy ones. The advantages of such a device are the possibility of continuously modify the X-ray absorption and the reduced cooling requirements, limited to the chamber walls. However, the power absorbed heats up the gas, increasing locally the temperature and decreasing the gas density, therefore reducing the total X-ray absorption [2, 3]. To correctly predict the final power absorption it is necessary to take into account all the processes triggered by the initial photoionization, which result in a fraction of the absorbed power dissipated by other means that heat transfer.

Model: The model developed for the gas absorber reproduces the ionization by the X-ray beams and subsequent diffusion and recombination of the particles, with Argon as the working gas. The algorithm of the model is represented in figure 1. The initial photo- and Auger electron population is calculated analytically, and a Monte Carlo model simulates the evolution of this electrons population. Each electron interacts with the background gas, cold electron population and electrical field, but not with other fast electrons. This assumes that the fast electron population (keV to 100 eV) is only a small fraction of the total population, therefore it has a negligible fast electron-fast electron interaction probability. Ionization and excitation of the background gas are calculated, as well as

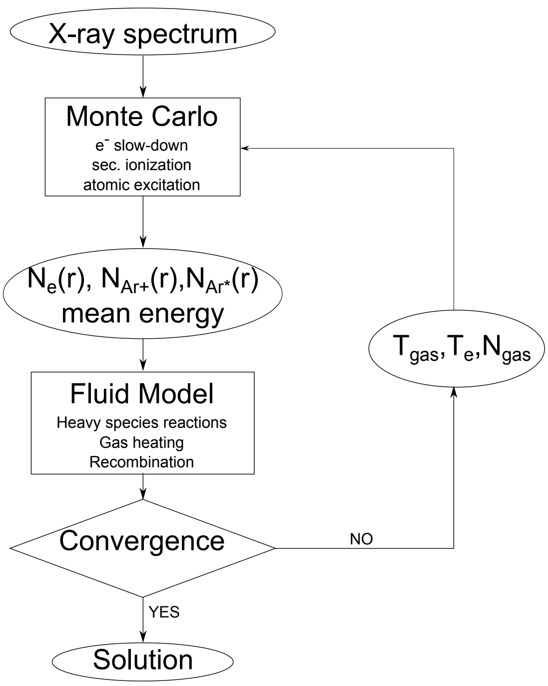

Figure 1: Algorith of the gas absorber model. The model cycles between the Monte Carlo and the Fluid model until convergence is achieved.

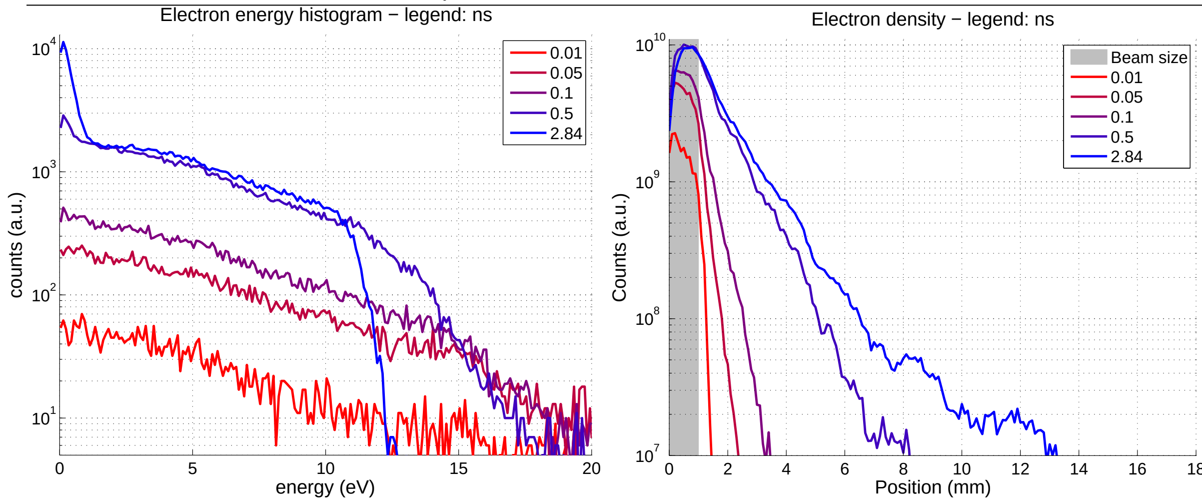

Figure 2: Electron energy distribution (left) and spatial distribution (right) at different simulated times. Gas pressure 100 mbar Ar, X-ray beam size 2x2 mm, absorbed power ~180 W/m

inner-shell and multiple ionization [4, 5]. After a time of typically 1-2 ns, all the electrons have and energy smaller than the excitation energy; a longer simulation will not change the number of ions and excited states generated. At this point, the results of the Monte Carlo model (electron energy and spatial population, excited and ionized atoms population) are projected over a 1D radial dimension and used as the source for the mass, momentum and energy conservation equations, which are solved together with the Poisson equation using the FEA analysis software COMSOL. The equations are solved for the following species: Ar, Ar^+, Ar_2^+, Ar_3^+, Ar^{+2}, Ar_2^*, Ar(4s) and Ar(4p). This model follows the fluid models applied to atmospheric pressure discharges as in [6] and [7]. The radiation trapping of the resonant levels is taken into account as a longer effective lifetime of those levels. The resulting gas density profile, electrical field and electron population are used as inputs by the Monte Carlo simulations in the next loop of the algorithm. The iterations continue until convergence in the gas density, and therefore in the X-ray absorption, is reached. The simulation of the absorber in the axial direction is made by stacking several 1D discs, each of them simulated independently but with the same gas pressure and with a progressively more attenuated X-ray beam.

Results: The proposed model is applied to a gas absorber of 50.8 cm length and 18 mm radius, with Argon as a working gas and at a pressure ranging between 100 and 400 mbar. The output of the Monte Carlo part of the model (figure 2) shows an electron population depleted above 15 eV after a time of 2.8 ns and essentially confined around the X-ray beam. These distributions are taken as the input for the fluid mode, which gives the stationary particle distribution and gas temperature and density as a function of the position (figure 3). Also from the fluid model

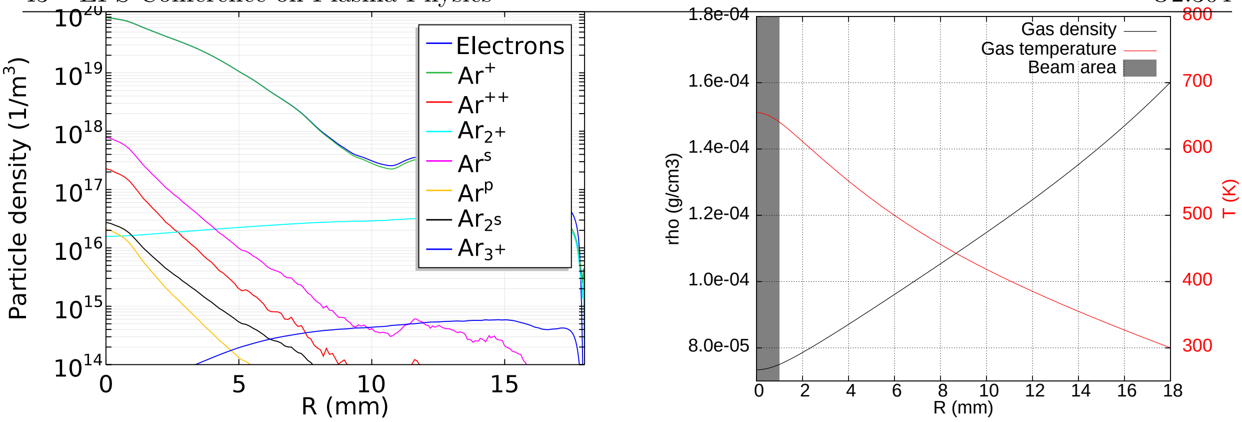

Figure 3: Equilibrium species concentration (left) and gas density and temperature (right) for 100 mbar Ar, 2x2 mm X-ray beam size and absorbed power ∼180 W/m

we obtain the plasma potential, 4 V at the center, and the electron temperature, only ∼0.22 eV. This is consistent with other experiments on plasmas created by photon beams, in which the absence of an accelerating electric field results in a fully thermalized electron population [8]. Most important is the fact that, for the same case as in figure 3, 100 mbar Ar and ∼180 W/m of power absorbed, 79% of power (142.2 W/m) is lost as visible and UV radiation and only the remaining 21% (37.8 W/m) becomes actual heating power.

To validate the model results, the excited states density profiles are compared with those obtained by OES and TLAS, and the power absorbed with the experimental one, measured with a calorimeter. The optical measurements were performed at 12.6 cm from the entrance window of the gas absorber and in perpendicular to both the X-ray beam and the laser beam (for TLAS) or the line of sight (for OES). The TLAS was performed at a wavelength of 772.38 nm, corresponding to the Ar($1s_5$) metastable state, while the OES was performed with several transition lines between the Ar(2p) and Ar(1s) states. Both OES and TLAS show an almost identical profile (figure 4 left), with a peak concentration at the center quickly decaying outside the X-ray beam region. The model results, on the other hand, reproduces the confinement of particles around the X-ray beam but underestimates their density far from this region, decaying faster than in the experimental case. As for the power absorption results (figure 4 right), one see that simulated and experimental values are quite close to each other; the maximum deviations is just above 10%. This means that, even if the description of the plasma can be improved, the power balance of the model and the total heating power are accurately calculated. Future improvements on the plasma properties may come from an accurate description of the radiation trapping, from the consideration of a non-Maxwellian electron distribution and from the separate simulation of every energy level within the Ar(4s) and Ar(4p) blocks. The accurate description of the gas

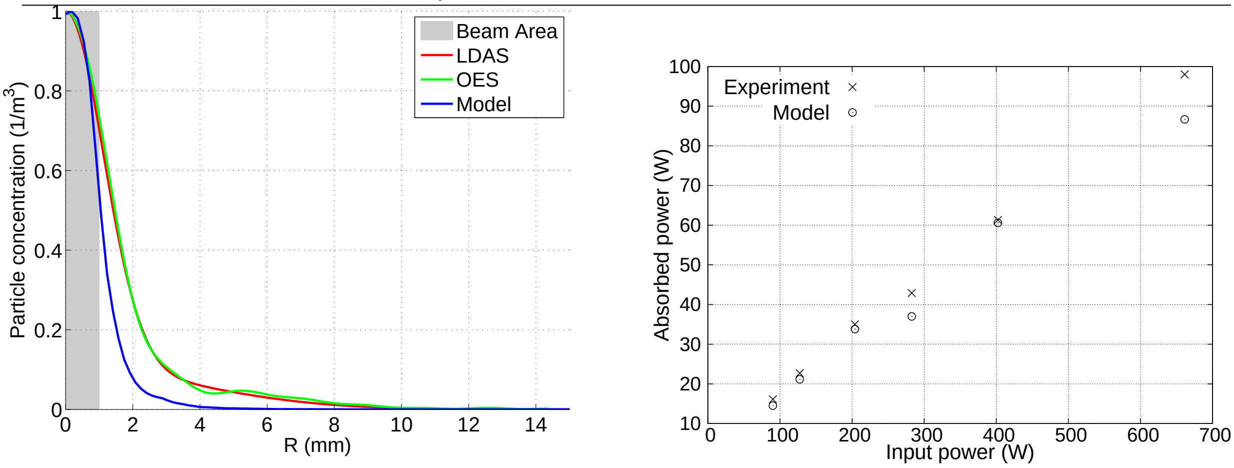

Figure 4: **Left:** OES and TLAS normalized profiles vs. simulated profile, with Ar at 200 mbar, X-ray beam size of 2x2 mm and an absorbed power of 160 W/m. **Right:** experimental vs. simulated power absorption for different power inputs and 200 mbar of Ar pressure.

heating and power absorption, on the other hand, indicates that the model can me used to hel in the design and operation of high power X-ray gas absorbers.

Summary and conclusions: A combined model using Monte Carlo and fluid models is proposed for the simulation of ans X-ray gas absorber. The results of the model show a plasma confined around the X-ray beam region with a cold electron population (∼0.25 eV) and a small plasma potential (∼8 V) for the range of pressures and power absorbed studied. The comparison with the experimental results shows an active plasma region slightly less confined in the experiment than in the model. The reproduction of the power absorption measurements enables the use of this model as a predictive tool for the design and operation of gas absorbers.

We acknowledge the contribution of Nader Sadeghi of the LiPhy, Carsten Detlefs and the rest of the ID06 staff of the ESRF during the performance of the experiments and Manuel Sánchez del Río and Yves Dabin for useful discussions. Also we acknowledge the contribution of the Reseau des Plasmas Froids by the use of the Laser Diodes for TLAS.

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