Numerical investigation of non-homogeneous ECR plasma opacities assuming an external black-body radiation

M. Bezmalinovich[1,2], G. Emma[3,4], G. Finocchiaro[3,4,6], G. S. Mauro[4], M. Mazzaglia[4],
B. Mishra[3,4], E. Naselli[4], A. Pidatella[4], D. Santonocito[4], G. Torrisi[4], A. Galatà[5], A. Saltarelli[1,2],
S. Simonucci[1,2] and D. Mascali[4]

[1] *Università degli studi di Camerino, Camerino, Italy*

[2] *INFN, Sezione di Perugia - Perugia, Italy*

[3] *Università degli studi di Catania, Catania, Italy*

[4] *INFN, LNS - Catania, Italy*

[5] *INFN, LNL - Legnaro, Italy*

[6] *CSFNSM, Catania, Italy*

Abstract The PANDORA project aims at measuring, for the first time, plasma opacities which are relevant for the interpretation of the emerging kilonova transient from the coalescence of compact binary objects and strongly dependent on the freshly synthesized *r*-process elements' abundance. In this work, we numerically estimated the electron densities and temperatures of the non-homogeneous laboratory electron cyclotron resonance (ECR) plasma under non-local thermodynamical equilibrium conditions through a particle-in-cell (PIC) code. Moreover, by means of the population kinetics code suite FLYCHK and including an input black-body radiation, we have investigated on the argon plasma (Ar) opacity, along 1-D line of sight. Finally, we studied the behaviour of the outcoming intensity as impacted by the opacity arising from both radiation-perturbed and unperturbed plasma, according to the population levels distribution of the excited Ar atoms.

Introduction Compact binary mergers as of neutron stars or neutron star-black hole aroused a great interest in the scientific community because of the peculiar neutron fluxes of such systems, which place them among the possible candidate as major producers of heavy elements through the rapid neutron capture nucleosynthesis process (r-process). In addition, other physical phenomena are correlated to the coalescence event, like gravitational waves and electromagnetic (EM) counterparts emitted from radio to gamma. Among the EM counterparts, the one linked to the visible range (VIS) is known as kilonova (KN), a light-curve which lasts from $\sim$ 1 day up to $\sim$ weeks after the merger. The KN [5] is an electromagnetic isotropic thermal transient powered by the β-decay of heavy neutron-rich nuclei, produced beyond ^{56}Fe (A$\geq$70) through the *r*-process, which form the plasma ejecta all around the merger, with expected plasma temperatures and densities of $\sim$ 1-2eV and $\sim 10^{12} cm^{-3}$ in its early-stage KN phase.

Method survey Since plasma ejecta is an evolving environment, composed by layers of materials and powered by the radiation, the PANDORA (Plasma for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry) project [1] aims at providing first-of-its-kind measurements concerning the matter-radiation coupling, resembling the KN early-stage scenario within in-laboratory ECR plasma. To support the design and to better address experimental measurements, it is fundamental to develop a numerical code, which takes into account the non-homogeneity and the anisotropy of the in-laboratory plasma, extrapolates the values of temperatures and densities from the medium, and finally estimate the attenuation property that affects a radiation passing through the plasma regions of interest (ROIs), in terms of the opacity [2] and the thermodynamic characteristics of the medium. A detailed scheme is presented in Figure 1.

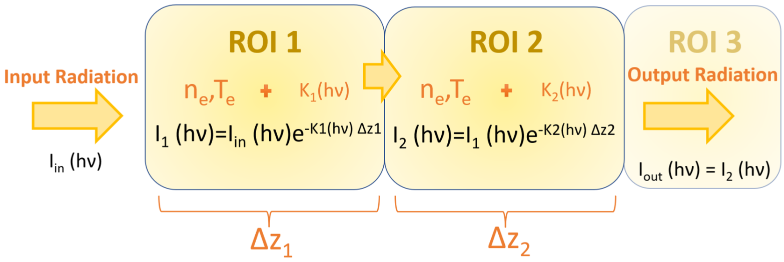

Figure 1: Scheme of the model. The attenuation of an input radiation (from left) is studied upon crossing several ROIs of the plasma with peculiar absorption (opacity) coefficients depending on the layered density and temperature.

Numerical model A numerical analysis of electron plasma dynamics through a PIC code [3], collecting electrons in different ROIs according to the same mean energy content has been performed along 1-D line-of-sight as an easier model to start with. The different ROIs of the plasma are reported in Figure 2.

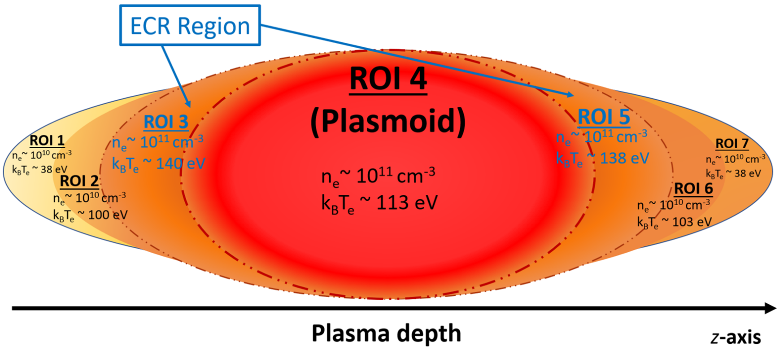

Figure 2: Representation of the plasma subdivision in ROIs

By analytically fitting the electron energy distribution via a Maxwell-Boltzmann function, plasma electron density and temperature from each ROI have been extracted and the results are shown in Table 1.

ROI	ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6	ROI 7
n_e [cm^{-3}]	1.1×10^{10}	6.3×10^{10}	1.2×10^{11}	1.4×10^{11}	1.3×10^{11}	7.1×10^{10}	2.1×10^{10}
k_BT_e [eV]	38	100	140	113	138	103	47

Table 1: Electron density and energy associated to each ROI

Absorption coefficient and opacity Since the goal of our analysis is to extrapolate the opacity outcoming from the stratified plasma, we used temperatures and densities reported in Table 1 as input parameters to the population kinetics code FLYCHK [4], a powerful tool to model the plasma composition in terms of the ion charge-state distribution and level population. FLYCHK takes into account the electron temperature, the density, as well as the ions species to simulate and gives as output synthetic spectra concerning the emissivity and the absorption coefficient, the latter defined as (1):

$$\alpha(\nu) \propto N_l \left(1 - \frac{N_u g_l}{N_l g_u}\right) \phi(\nu) \quad (\mathrm{cm}^{-1}) \tag{1}$$

where $\phi(\nu)$ is a Voigt function, N_u (N_l) stands for the upper (lower) level population correlated to VIS transitions, and g_u (g_l) represents the level degeneracy. The opacity κ (cm^{2}g^{-1}) is connected to the absorption coefficient by the eq. (2):

$$\alpha(\nu) = \kappa(\nu) \cdot \rho_{\mathrm{element}} \,. \tag{2}$$

$\rho_{\mathrm{element}} = \frac{n_e \cdot M_{element}}{N_A}$ (gcm^{-3}) is the density defined as the ratio between the element molar mass $M_{element}$ and the Avogadro number N_A, times the numerical density n_e. Due to the direct dependence on upper and lower level electron population as shown in equation (1), a detailed investigation associated to the electrons is required to estimate the absorption coefficient, hence the opacity.

Ar opacity investigation Assuming the thermodynamic results reported in Table 1 and the model summarized in Figure (1), we numerically estimated the Ar plasma opacity by means of FLYCHK using an input external black-body radiation of a temperature $T_{rad} = 8000$K (i.e., photon flux $\sim 10^{25} s^{-1} m^{-2}$), within the VIS range [1.75,3.18]eV. If we consider only a precise region of the plasma, like the ECR as shown in Figure 3 (a), it can be seen that the presence of the radiation shifts the opacity to lower values, increasing the transparency of the medium. The external radiation excites the electrons and thus, when there is an equal distribution of electrons between the states (i.e., the emission is equal to the absorption), the ratio $\frac{N_u}{N_l} \sim 1$. From this, and according to eq. (1), the absorption coefficient (hence the opacity) drops to small values. If the radiation is not sufficiently high (or absent) to excite the particles, the lower state N_l will be full filled of atoms and consequently opaque. However, both temperature and density affect the opacity. The plasma opacity increases upon increasing the electron density, as expected from eq. (1) and as can be seen in figure 3(b), i.e., by comparing ROI3 vs. ROI4. In addition, the peculiarity between the external and the ECR regions can be traced back to the temperature: the external region has a lower temperature than the one in the ECR region, and as a result low levels are occupied.

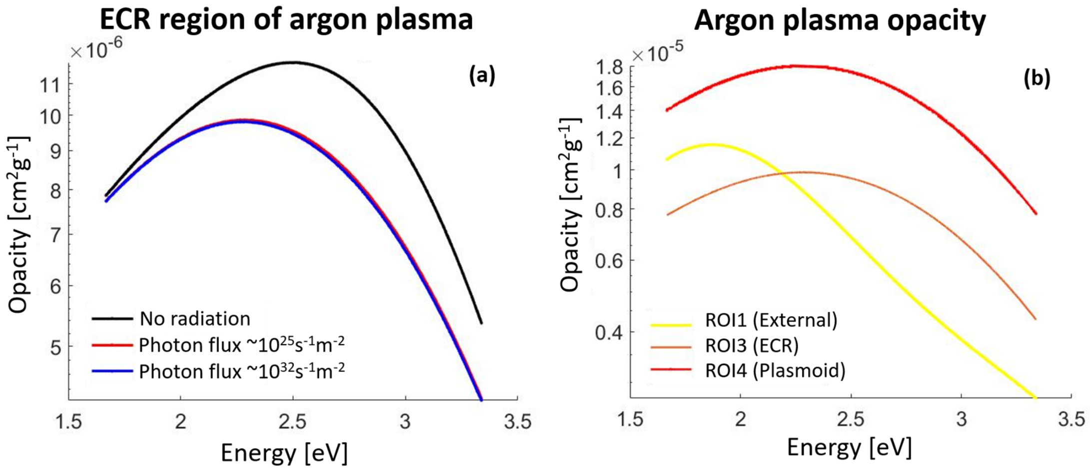

Figure 3: Graphs of the Ar opacity as a function of the energy for three different photon fluxes in the ECR region (a) and Ar opacity behaviour in different plasma regions (b).

Conclusions In this work we presented an analysis of a numerical simulated plasma based on the identification of different ROI which were characterized in therms of electron density and temperature. The Ar opacity investigation showed that the external radiation impacting the medium amplifies the transparency of the plasma, shifting its values from $\kappa \sim 10^{-4} cm^2 g^{-1}$ to $\kappa < 10^{-5} cm^2 g^{-1}$. Mainly future improvements will consist in extending the 1-D investigation to a 3D analysis and applying the stratification technique to in-laboratory plasma, in order to support direct opacity measurements and benchmark the results to the theoretical KN scenario.

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