PARTICLE BEAM INDUCED LIGHT EMISSION

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Abstract:

Experiments to study the light emission from plasma produced by particle beams are presented. High energy heavy ion beam and low energy electron beam experiments are described. The electron beam technique can be used for fundamental research as well as various practical applications such as vacuum ultraviolet light sources.

Key words:

Ion beam exciation
Electron beam excitation
Excimer molecules
VUV light sources
Particle beam pumped lasers

1 Introduction

Collisional processes play a key role in plasma-based light sources. Electron collisions with mercury atoms in a low pressure discharge, for example, leads to population of excited levels of mercury. Subsequent radiative transitions lead to the emission of ultraviolet light which is converted into visible light by a wavelength-shifter to realize a regular fluorescent lamp [1]. Plasmas at atmospheric pressure, as an alternative for the well known low-power glow-discharges, have become of interest for light source- and various other applications such as plasma chemistry [2]. The collisional processes in all these discharge plasmas are based on an acceleration of charged particles, electrons or ions, in a gaseous medium by a static or pulsed electric field.

An alternative to discharge induced plasmas is discussed in this article. The main aspect of the method is to accelerate particles, electrons or ions *outside* a gas volume. A beam of projectiles is formed. The projectiles are accelerated and sent through an appropriate entrance foil into a gaseous or sometimes also a liquid medium. There they transfer their energy to the medium via collisional processes – similar to the collisions induced by internally accelerated charged particles in a discharge. However, much more energetic collisions are involved leading to the production of a cascade of secondary projectiles. Experiments using ion- and electron beam excitation and their applications will be described.

2 Ion beam induced plasmas

The first experiments which had been performed in the context of this research program were based on so called “nuclear pumped lasers” (NPL) [3]. In such a device a gas laser tube is placed inside or near the core of a pulsed nuclear reactor. Neutrons from this reactor enter the laser tube an induce fission reactions in a layer of enriched uranium which is placed inside the laser tube as a thin coating on the wall. The fission fragments emitted from this uranium layer pump an appropriate laser gas which is filled into the laser tube. The "appropriate" laser gas is an interesting aspect of such experiments from a physics point of view. Laser schemes which have been realized with nuclear pumping work mostly in the near infrared spectral region and use laser gas mixtures such as argon – xenon. The gas density can be rather high corresponding to roughly atmospheric pressure. This leads to interesting gas kinetic processes populating and depopulating the laser levels.

It had been found in this project that the excitation of dense gases by ion beams with parameters similar in particle energy and flux to fission fragments in NPLs can reproduce the results from reactor experiments avoiding the radiation hazard of a nuclear reactor. The first heavy ion beam pumped laser had been built at the Munich Tandem accelerator in 1983 [4]. It used a 100 MeV ^{32}S ion beam with about 100 W beam power for pumping a He-Ar laser. Progress in beam power at Gesellschaft für Schwerionenforschung, Darmstadt, Germany, allowed much later, in 2005, laser experiments in the ultraviolet spectral range (KrF laser 248nm) [5].

A conceptual argument for using heavy ions to pump a laser medium is the small angular scattering of the heavy projectiles with a high kinetic energy. The projectiles pump a cylindrical volume rather homogeneously. The energy transfer from the pump-beam to the medium is high due to the high stopping power values (dE/dx) which can be described by the Bethe-formula. A more fundamental aspect of the interaction of heavy ions with matter is the fact that large cross sections for multiple ionization of target species are found in single collisions. This can be explained by the Fano – Lichten model. In the light output this should lead to an enhancement of light emission which is related to ionized target species.

An overview emission spectrum of argon at atmospheric pressure is shown in Fig. 1. It covers the spectral range from 110 nm in the vacuum ultraviolet (VUV) spectral region to the near infrared (900 nm). The wavelength limits are due to the cut-off in transmission of the magnesium fluoride window (MgF_2) of the target cell at the short wavelength side and the sensitivity of the phototube at the long wavelength side. The most intense features in this spectrum are molecular emission bands in the VUV and UV. They can be assigned to so called “excimer” molecules – an acronym for “excited dimmers”. In this case these are argon molecules consisting of two argon atoms which can form bound molecules in electronically excited states. The strong emission near 130 nm is the so called second excimer continuum which is related to the first excited states decaying via photon emission to the repulsive ground state of two argon atoms [6]. The so called “classical left turning point” (LTP) emission at 155 nm is attributed to the same electronic transition but at high lying vibrational levels [7]. The so called “third continuum” is of interest in the context of ion beam excitation [8,9]. It got its name just by counting the strong emission features along wavelength axis, with the “first continuum” of argon at shorter wavelengths than the second continuum cut off here by the MgF_2 window. The spectrum also shows atomic and ionic line radiation of argon at longer wavelengths [10].

The third continuum has been studied in detail using heavy ion beam excitation [9]. It is attributed to transitions in at least singly ionized Ar_2^{*+} molecules. The short wavelength part around 190 nm is believed to be due to the decay of Ar_2^{2+} molecules. The longer wavelength part may be related to cluster formation as deduced from the time structure of the emission. Recently ion beam excited spectra could be compared with spectra recorded with electron beam excitation in the identical target gas. This comparison is shown in Fig. 2. The higher cross sections for forming ionized target species mentioned above, shows up as an enhanced intensity of the third continuum with ion beam excitation.

3 Low energy electron beam induced plasmas

Secondary electrons are formed in the slowing down process of both high energy ions and electrons, as mentioned above. Electron energies up to about 5 keV are produced e.g. in the case of 100 MeV sulfur ions [11]. These electrons contribute significantly to the collisional excitation of the target gas. Initially, to simulate such secondary electrons we have developed a novel technique in which electrons with typically 10 keV particle energy are coupled through a thin foil into dense gases. This technique is very similar to experiments performed in the late 19hundreds by P. Lenard who used aluminum foils, so called Lenard windows, to send cathode rays from a low pressure discharge into air and other gases [12]. In the experiments described here we use ceramic membranes as entrance windows for the electron beam. They are made of double layer silicon nitride and silicon oxide films with only 300 nm total thickness. The membranes are deposited on a silicon wafer as the substrate. The substrate is etched away in the areas used as free standing membranes. Quadratic foils, 0.7 mm by 0.7 mm in size, are often used as entrance windows for the electron beam. They can withstand pressure differentials of about 10 bar. The electron beams are nowadays formed by cathode ray tubes in a high vacuum part of the setup. Beams with 12 keV particle energy are routinely used and less than 20% of the beam power is deposited in the entrance foil. The effective range of the electrons in the gas is very short (e.g. ~1 mm in argon at atmospheric pressure) due to the low energy and the large angular scattering. This leads to high power densities deposited in the gas already at moderate beam currents. The ~0.5 mm^2 membrane mentioned above can handle on the order of 10 μA beam current leading to typically 0.1 W beam power. This corresponds to 100 W/cm^3 deposited in the target gas for the typical 1 mm^3 volume excited by the beam.

The application as a model system for secondary electrons has already been described in section 2 in the context of Fig. 2. Various other applications have been realized with low energy electron beam excitation of dense gases and partly also liquids. The most advanced application is the development of short wavelength light sources based on excimer molecule formation of the pure rare gases. Electron beam induced incoherent VUV light sources are now commercially available. A 12 keV electron beam is sent through a membrane into a gas cell filled with argon krypton or xenon slightly above atmospheric pressure. The electrons excite a volume of about 1 mm^3 which acts as a brilliant light source at wavelengths of 127, 150 or 172 nm, respectively. Parameters of the device are available from the manufacturer (http://www.optimare.de/cms/en/divisions/alk/alk-products/e-lux.html) and in reference [6]. The main application of the VUV light sources is photoionization in mass spectroscopy [13].

Electron beam excitation of gases and gas mixtures can also be used for fundamental research. Gas kinetic studies, in particular are possible using pulsed excitation in combination with time resolved optical spectroscopy [14]. A great advantage of the technique is that the gas density can be chosen freely from almost zero pressure up to several atmospheres without a principal change in the excitation process. Note that a gas discharge in comparison undergoes drastic changes for example from a glow discharge to an arc discharge when the gas density is increased. Similar experiments can be performed using accelerator facilities. The low energy electron beam excitation, however, has the advantage that it is available as a “table top” setup which also avoids hard x-ray due to the low acceleration voltage.

Recently the technique has also been used to study the emission characteristics of liquids which are used as fluorescent material in particle detectors in particle astro physics. Liquid scintillator material has been studied in ref. [15] and liquid argon in ref. [16] and [17]. It has also been shown that the technique can be combined with a high frequency discharge [18]. Both electron beam sustained and electron beam ignited discharges can now been realized in a table-top arrangement. A miniature electron beam pumped laser has also been demonstrated [19]. Finally, it has been demonstrated that electron beams coupled into gas at atmospheric pressure provide a way to replace radioactive ionization sources in so called ion mobility spectroscopy, a technique used for chemical analytics based on drift velocities of the analyte molecules in a stream of carrier gas at atmospheric pressure [20].

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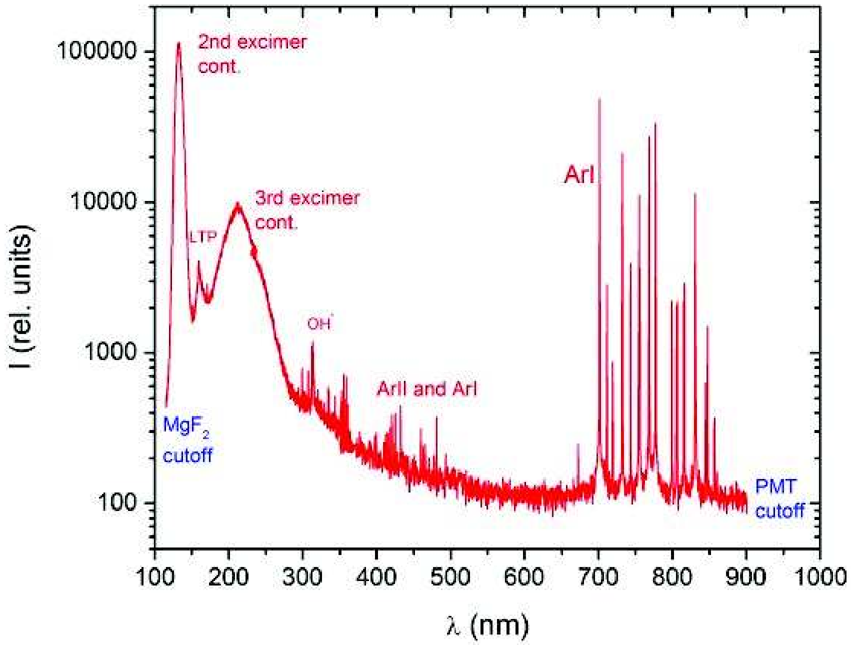
Figure Captions

Fig. 1: Overview spectrum of light emitted from argon gas at a pressure of 600 mbar over a wide spectral range from ~100 to ~1000 nm. The gas was excited by a dc 120 MeV ^{32}S beam.

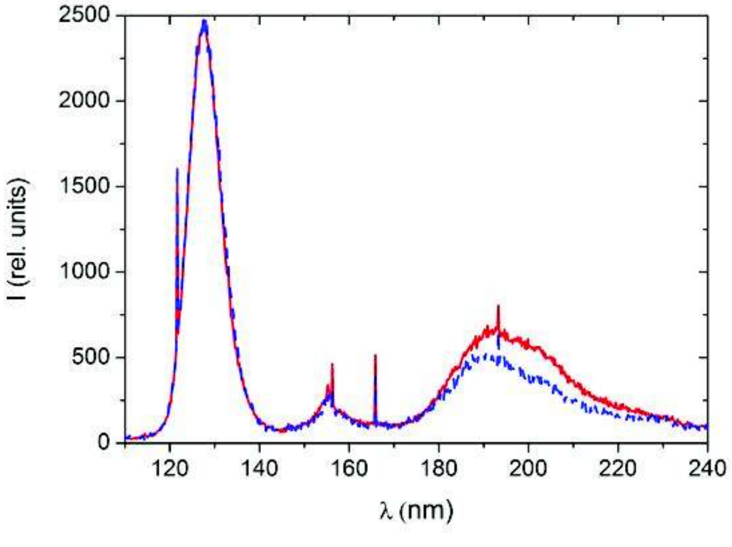
Fig. 2: Two spectra emitted from argon at 300 mbar are shown. The spectrum shown as a dashed (blue) line was recorded with 12 keV electron beam excitation and the spectrum shown with a solid (red) line was recorded with 120 MeV ^{32}S beam excitation. The difference in intensity in the so called “third excimer continuum” around 200 nm, originating from ionized target species, is attributed to direct excitation by the sulfur projectiles which have a higher cross section for forming multiply ionized target species than electrons.

Fig. 3: The three spectra shown correspond to pure electron beam excitation (A), electron beam excitation with RF power added (B), and 6 W RF excitation (C). Note the changes in the spectral shape of the emission and the logarithmic intensity scale. The RF induced spectrum matches very well with the cutoff wavelength of LiF and MgF_2 thereby representing a light source emitting with high intensity and efficiency at the shortest wavelengths possible for a setup containing optical windows.



2nd excimer cont.
3rd excimer cont.
LTP
OH
ArII and ArI
ArI
MgF_2 cutoff
PMT cutoff
100000
10000
1000
100
I (rel. units)
100
200
300
400
500
600
700
800
900
1000
λ (nm)

Fig. 1



2500
2000
1500
1000
500
0
I (rel. units)
120
140
160
180
200
220
240
λ (nm)

Fig. 2

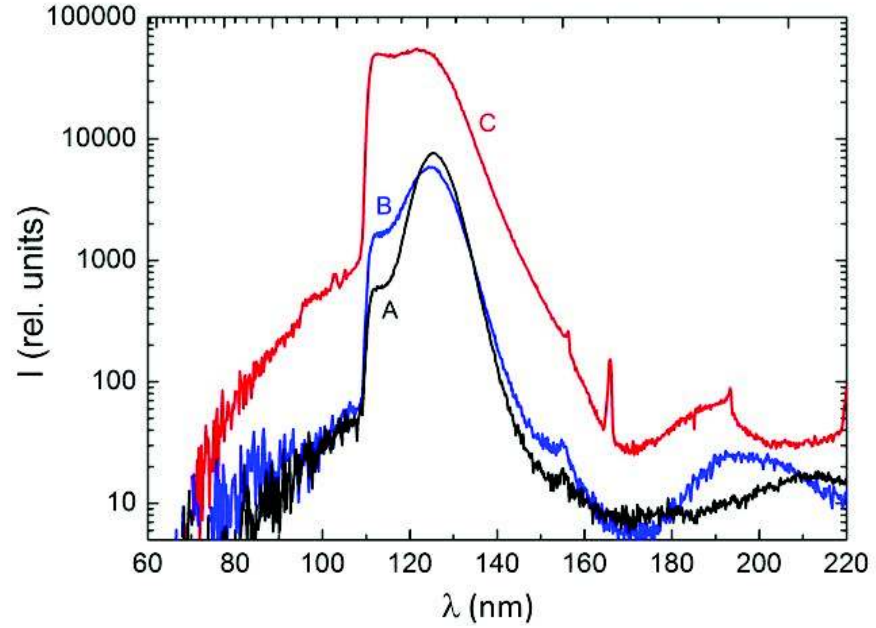

100000
10000
1000
100
10
I (rel. units)
60
80
100
120
140
160
180
200
220
λ (nm)
A
B
C

Fig. 3

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