Designing an Effusion Cell for Molecular Beam Experiments

DESY Summer Student Project Report
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1. Project motivation and background

The possibility to produce ultra-short laser pulses and tune their properties has enabled experimental studies of electron and nuclear dynamics occurring at time-scales ranging from femtoseconds to attoseconds (10^{-15}-10^{-18} s) [1,2]. Typically these experiments require ultra-high vacuum and techniques for preparing the system under investigation (e.g. atom, molecule, or cluster) in a position where it can be illuminated by the pulsed laser beam. It is also sometimes desirable to be able to cool the atomic/molecular system of interest. For these purposes a molecular beam source or a pick-up cell, respectively can be used. It was the purpose of this project to design an experimental apparatus that could serve both as an effusion and a pick-up cell for this kind of experiment.

2. Fullerene effusion cell

One way to bring the system of interest in the laser beam is to create a molecular beam which crosses the laser beam path. For this purpose a beam source, such as an effusion cell, is necessary. An effusion cell is essentially a gas container with a small orifice through which the gas particles (atoms of molecules) can escape. If this hole is much smaller than the mean free path of the gas particles inside the cavity, the escaping particles will rarely collide with each other and will have a velocity distribution given by Maxwell's velocity distribution function. In this case one speaks of an effusive beam. If no significant external forces are present, one can also assume that the particles travel on straight paths from the opening cell. The intensity of the effusive beam (particles/s m^2) depends on the source parameters, such as pressure and temperature of the gas and mass of the particles, as well as on the distance from the source.

Depending on the kind of molecular beam one wants to study, the gas can be fed into the effusion cell with a gas inlet or put into the chamber in a liquid or solid state and evaporated/sublimated by heating. The latter method is applicable to fullerenes, which are solid at room temperature.

The first factor which was considered in the design of the effusion cell was the expected power consumption. Estimates of the required power were made using Stefan-Boltzmann's law

$$P = jA = \varepsilon\sigma T^4 A$$

with the surface area of the oven, *A*, the emissivity of the surface, *ε*, and the operational temperature of the cell, *T*, as parameters. The oven was chosen to be in the shape of a hollow cylinder 50mm long, with an outer radius of 10.5mm, inner radius of 7.5 mm, and an outer thread 1mm deep. The thread was intended to accommodate the heating wire. The results of the preliminary calculations are shown in table 1. After the completion of these estimates of the required power, a market study was carried out to ascertain what heating elements are compatible with the required power rating for the oven.

Table 1. Radiative loss calculated for various grey bodies with a surface area equal to that of the effusion cell (39.9cm^2) at 1070K

Surface type	Emissivity, ε	Power/Watts
Black body	1,00	299,99
Aluminium	0,10	30,00

Weathered stainless steel	0,85	254,99
Polished stainless steel	0,08	24,00
Stainless steel type 301	0,55	164,99
Tantalum	0,20	60,00

Heating wires capable of delivering 440W for this oven (approx 210W per meter wire length, over a total length of 2.09m) were available.

The power that would be required in the worst-case scenario (perfect black body effusion cell) was about 65% of this value. It was desirable to have more extra power available (~100% of the worst case), in order to ensure that the oven will be able to reach the desired heating temperature without difficulty. For this reason it was decided to include thermal shielding in the design of the effusion cell and to use a suitable low-emissivity material to cover the surface of the cell.

Thermal shielding, which is essentially another layer of material enclosing the cell, reduces the radiative power loss of the cell by reflecting, or by absorbing and reradiating, some of the radiation that reaches it from the cell back to the cell. When the thermal shielding is included, the radiated power is no longer given by Stefan-Boltzmann's law, but by a modified expression. For a system made up of two long coaxial cylinders with radii r_1 and r_2 ($r_2 > r_1$) and emissivities ε_1 and ε_2, respectively, and assuming diffuse reflection from the surfaces of both cylinders, the expression for the power radiated by the system into the surrounding space reads:

$$P \approx \sigma T_1^4 \frac{A_1 \varepsilon_1}{1 + r_1 \varepsilon_1 (1 - \varepsilon_2) / r_2 \varepsilon_2}$$

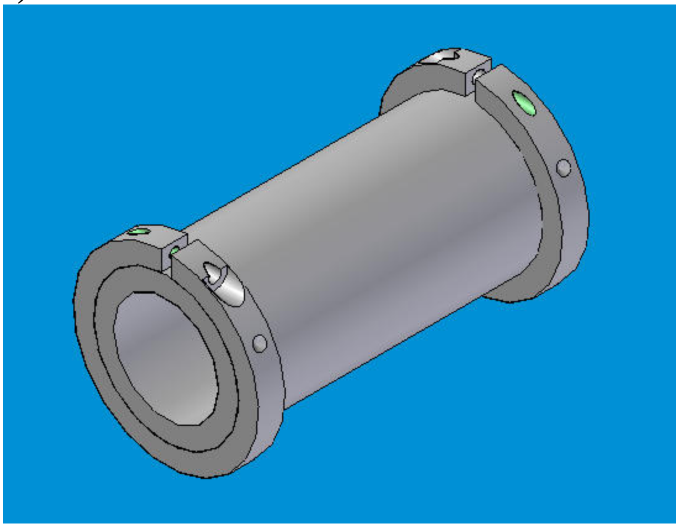
where T_1 is the temperature of the inner cylinder and the approximately equal sign is included because the contributions from the ends of the cylinders have been neglected. It is clear from this expression that a low emissivity of the shield is important for decreasing the power consumption of the effusion cell. A smaller radius of the shielding cylinder also contributes to lower power consumption.

With these considerations taken into account, the following effusion cell design was decided upon (fig. 1). A cylinder (with the abovementioned dimensions) made of Al_2O_3, a ceramic with a high heat conductivity, heated by means of a wire wound around it, was to be wrapped in tantalum foil (0.1mm thick, $\varepsilon = 0.2$) and encased in a somewhat larger steel cylinder which serves as support and thermal shielding. Tantalum was chosen for its low emissivity, chemical stability, and high melting point. The chemical stability of its surface guarantees that the emissivity changes little even after operating the oven at a high temperature.

Caps were mounted on the two ends of the steel support cylinder. The molecules inside the oven effuse through an orifice in one of the caps of the steel support cylinder. The cap on the other side is blind.

In order to collimate the beam, a circular disk with a hole (1mm diameter) in the center was attached to one of the caps (also with a circular opening of 1mm) of the support cylinder at a distance of about 10mm from the plane of the cap. This configuration results in a beam divergence of about 0.2 radians (11°).

a)



b)

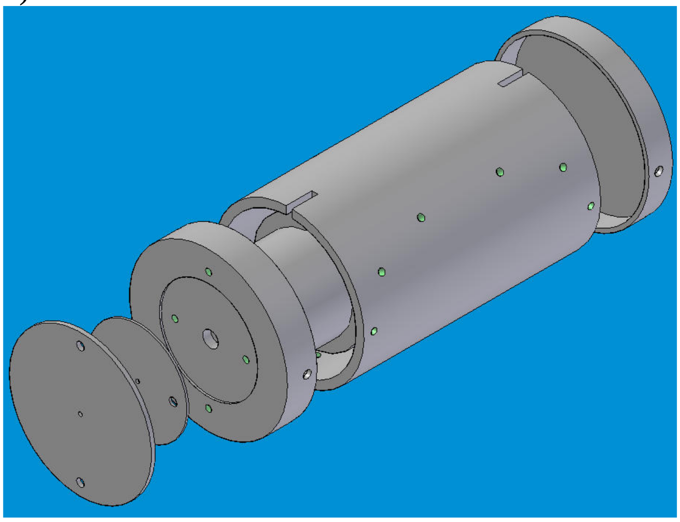


Figure1. a) SolidEdge drawing of the inner Al_2O_3 cylinder and the rings intended to hold the tantalum foil wrapped around it; **b)** the inner and outer cylinders with caps and collimation disk visible

It was further required to allow for adjustment of the distance between the effusion cell and the laser beam. This was done by allowing the effusion cell to slide on a long plate to which it was attached by means of screws (Fig. 2). To minimize the heat loss by conduction between the oven and the plate on which it was attached, buffer blocks of insulating MACOR ceramic were included between the two at the four attachment points.

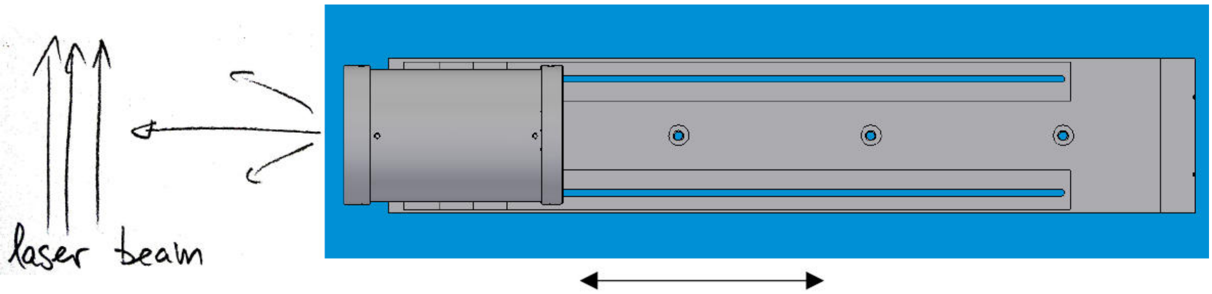


Figure 2. The effusion cell will be mounted on a long plate which will allow the distance between the cell and the laser beam to be varied

In addition, the effusion could be adapted for pick-up (doping) experiments. This functionality is achieved by replacing the caps mentioned above with others, which have openings with 4mm diameter, and allow for instance small liquid helium droplets to fly through the oven and pick up molecules on their way to the laser beam. This kind of experiment is of interest because many of the phonon modes which would exist in the molecules at the temperature of the oven are frozen out when the molecules are picked up by the LH droplets. This leaves the molecules in well defined states and is advantageous for the subsequent analysis of the dynamics. An overview of the complete design is shown in figure 3.

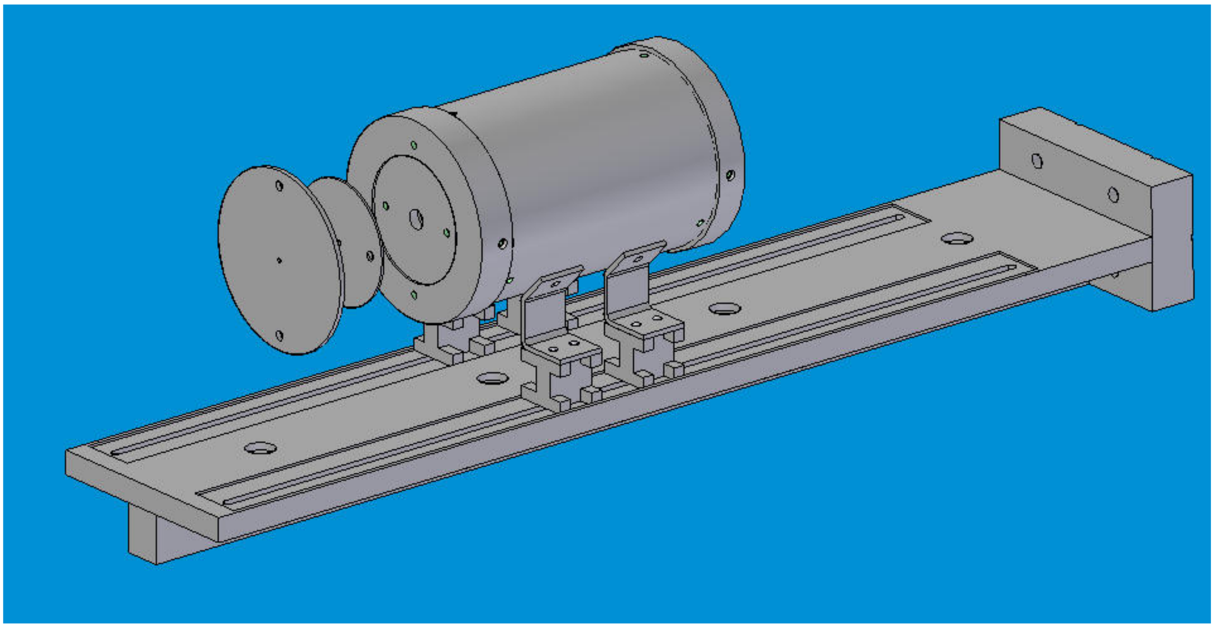


Figure 3. Complete effusion cell with collimator discs and support plate; collimator discs will be attached to the cylinder cap via screws (not shown)

3. LabView graphical programming

The purpose of this part of the work was to create LabView virtual instruments which can be used to control and monitor a temperature controller remotely. In the present project software was developed for communication with a CryoVac TIC 304 MA, a tempereature controller used in the production of droplets for the pick-up experiments mentioned above. A similar program may in principle be used to control a temperature controller for the effusion cell. LabView is a popular visual programming package.

The CryoVac TIC 304 MA can be used to control the temperature of a cryostat assembly and maintain it at a given set point. It does this by monitoring the temperature in the cryostat via a silicon diode and regulating the supply voltage of a heating coil accordingly. The apparatus is also capable of controlling the rate of flow of cooling liquid (liquid helium in this case) through the system, but this capability is not employed in the present experimental setup. The cryostat system is used to create liquid helium droplets and other clusters by rapidly cooling different gases to temperatures down to a few Kelvin.

Programs were created and tested which can be used to:

- monitor the temperature and voltage readings of the two temperature sensors
- monitor the current heater voltage
- monitor and set the current temperature setpoint
- log the above data to a file
- adjust the PID values of the temperature controller

- adjust the heater settings (voltage ranges)
- enter new calibration constants for the two temperature sensors

The preliminary tests of the software which were carried out in the laboratory were successful.

References

[1] T. Pfeifer et al. *Rep. Prog. Phys* 69 (2006) 443-505
[2] F. Krausz, M. Ivanov. *Rev. Mod. Phys.* 81 (2009) 163