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# STUDY OF THE LEAD EVAPORATION FROM THE OVEN OF THE GTS-LHC ION SOURCE

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*Abstract*

The GTS-LHC ECR ion source at CERN provides heavy ion beams for the chain of accelerators from Linac3 up to the LHC and the SPS fixed target experiments. During the standard operation the oven technique is used to insert lead into the source plasma to produce multiply charged lead ion beams. Many years of experience show that some of the source instabilities can be linked to the oven performance. The evaporation seems not to be constant and when the oven reaches its maximum power, an indication that a refill is required, often half of the original lead sample is still present inside the oven crucible.

A dedicated study of the oven using an offline test stand as well as thermal and gas dynamics simulations intends to help to identify the reasons for these experimental observations. The goal is to find design modifications to stabilize the evaporation rate and to prolong the oven runtime. This contribution presents the latest results of the study.

## INTRODUCTION

At CERN a number of experiments, in particular the heavy ion runs at the Large Hadron Collider (LHC) rely on a consistent supply of lead ions delivered by the GTS-LHC ion source [1]. This source uses ovens (schematically depicted and described in Fig. 1 (a)) to produce the lead vapour which is then ionized. The produced ions are then injected into the LHC injector chain starting with Linac3. The oven technique is a widely used method to evaporate substances that are solid at room temperature into the plasma chamber of an ion source. The necessary temperature for such an oven depends on the vapour pressure of the evaporated material. Especially lead has a high gas pressure at relatively low temperatures, which makes the evaporation inside a heated oven a natural choice. During a normal run the oven's power is initially ramped up to a suitable value to initiate the lead evaporation and then it is increased slowly throughout the operation to maintain a sufficient evaporation rate. The adjustment is done manually by the source expert as the evaporation rate differs between individual oven fills. Reaching 20 W, which usually happens after two weeks of operation, indicates the end of the runtime as the oven does not maintain a stable evaporation rate any longer and the oven can not be heated up more without damaging the filament or other oven elements. The general experience though is, that after each run the oven crucible still contains approximately half of the original lead sample. This is an indication that there might be room to improve the oven runtime when it is understood what causes the drop of the evaporation rate.

To understand the limitation of the oven runtime and the link between input parameters and the evaporation rate, a dedicated offline oven test stand (OTS) is used, that provides several diagnostic tools to study the oven in a source like environment. Figure 1 (b) shows the main parts of the test stand. To monitor the evaporation rate of the oven, an INFICON quartz crystal deposition detector is used [2]. A shutter in front of the sensor that is only opened at predefined times protects the sensor and extends the crystal life time. Visual observations can be made through a vacuum window and K-type thermocouples allow temperature measurements on the outer cover of the oven.

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## BEHAVIOUR IN OXYGEN ATMOSPHERE

One candidate for a mechanism that limits the runtime of the oven is clogging. It is regularly observed after a two weeks run of the Linac3 ion source that the oven tip is clogged with a formation of material that appears to be lead oxide. As the GTS-LHC ion source uses oxygen as a buffer gas within the plasma chamber it can be assumed that the formation might be due to a chemical reaction between the lead and the oxygen. The oven test stand was used to reproduce and study this behaviour. The clogging was not observed during previous experiments in the OTS, when the oven was operated in vacuum ($< 1.0 \times 10^{-7}$ mbar), or in nitrogen. When oxygen is injected into the vacuum system, the formation of lead oxide is observed at the tip of the oven. A thermovalve controlled by a feedback loop from the vacuum gauge stabilized the total pressure inside the OTS at $1.0 \times 10^{-5}$ mbar over the duration of the run. The oven was ramped to a sufficient evaporation rate, based on prior experiences on the test stand. During the measurement the oven power was then only adjusted when the signal on the deposition sensor dropped notably. Throughout the experiment the oven tip was photographed to document the formation of the blockage. Figure 2 shows the evaporation rate during the run together with four pictures of the oven tip taken at different times indicated in the plot. Mainly three characteristics could be observed:

- The evaporation rate at a constant power level is decreasing over time. To maintain a relatively constant

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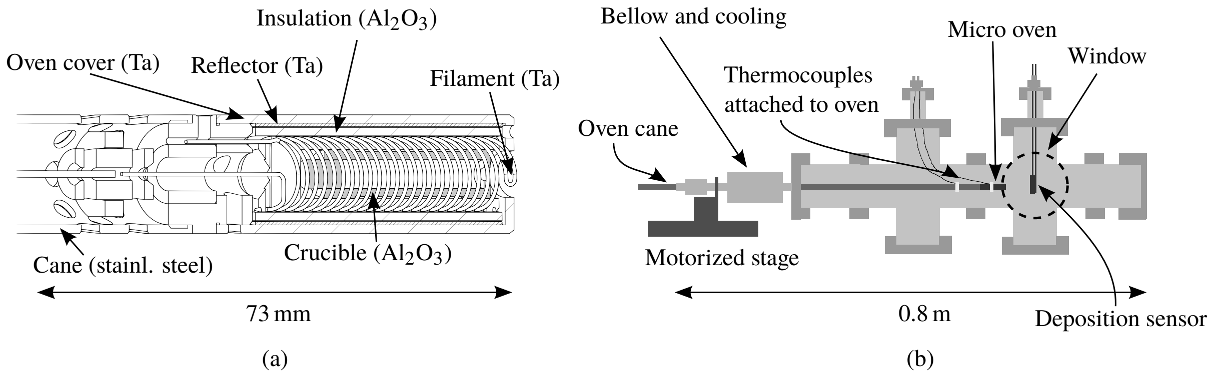


Figure 1: (a) Drawing of the micro oven of the GTS-LHC ion source at Linac3. The alumina crucible containing the lead sample rests inside an alumina structure. A tantalum filament around this structure is heating the crucible. The outer layers serve as thermal insulation. (b) Schematic of the oven test stand. The oven is on the tip of a cane that is used to insert the oven into the chamber. A window next to the oven tip allows visual observation while a deposition sensor measures the evaporation rate. The OTS is evacuated with a turbo-molecular pump and a thermovalve (not depicted) allows a stable atmosphere of a selected gas. A similar graphic is also presented in [3].

output the oven power needs to be increased periodically.

- A blockage at the oven tip was forming that finally blocks the oven completely.
- The measured evaporation rate clearly suggests that its final decrease is due to the complete blockage of the oven tip.

The pictures C and D in Fig. 2 show the transition from a still open to a completely blocked oven. In the time between the pictures the evaporation rate drops to almost zero. Around 14 days after the evaporation started, the blockage closed completely, which compares well with the experience at the operational ion source. Increasing the heating power up to 20 W did not remove the lead oxide formation and could not restore the former evaporation rate. Additionally to the lead oxide blockage that can be seen in the photos of Fig. 2, remaining unoxidised lead could be found inside the oven and behind the blockage. Most likely it was evaporated from the crucible and then deposited on the inner side of the blockage.

It is though noted that the lead oxide formation at the end of the experiment appeared to be bigger than the formations that can usually be observed in the Linac3 ion source. This might be due to a higher oxygen pressure in the experiment than in the real source. However reducing the pressure one order of magnitude already results in no oxide formation at all. Another possible factor, that might influence the formation and thereby the appearance of the oxide blockages in the source is the presence of plasma in front of the oven.

As picture A in Fig. 2 shows, the first decrease in the evaporation rate at a stable power level is not caused by the growing blockage but needs to be explained differently. One possible explanation are regions of differing temperatures within the crucible of the oven. As the vapour pressure and thereby the evaporation rate depends on the temperature, a redistribution of the lead sample for example by consuming material in the evaporation process could lead to decreasing evaporation rates. Thermal simulations, presented in [4], predict temperature differences of several tens of degrees Celsius between the end and the tip of the crucible, depending on the total temperature of the oven.

## GAS JET GEOMETRY

Observing the build up of the lead oxide at the oven tip gives information about the formation mechanism. Photo A in Fig. 2 shows droplets of lead condensate inside the opening of the oven cover at a time when no oxide is present yet. This hints that the first step in the oxide build up is the condensation of lead vapour at the oven cover. For the condensation to take place the vapour needs to hit those oven parts in significant amounts. Understanding the geometry of the gas flowing out of the crucible can help to understand the reason for the blockage build up and how to mitigate this problem. To find the appropriate way to model the system the gas flow regime needs to be identified, which depends on the present pressures and system dimensions. The Knudsen number $K_n$ is a common coefficient that is used to determine the flow regime. It is the ratio of the mean free path of a gas particle, $\lambda$, to the characteristic length of the system, $l$ [5].

$$K_n = \frac{\lambda}{l} \,. \tag{1}$$

The mean free path can be estimated from the temperature $T$ and present gas pressure $p$ assuming an ideal gas [6].

$$\lambda = \frac{k_B T}{\sqrt{2}\pi\sigma^2 p} \,. \tag{2}$$

Here $k_B$ is the Boltzmann constant and $\sigma = 360\,\mathrm{pm}$ the diameter of the lead atoms. An assumption for the upper limit of the lead gas pressure at a given temperature inside the crucible can be made using the vapour pressure, $p_v$, of lead, which can be derived from an empiric formula given in [7]:

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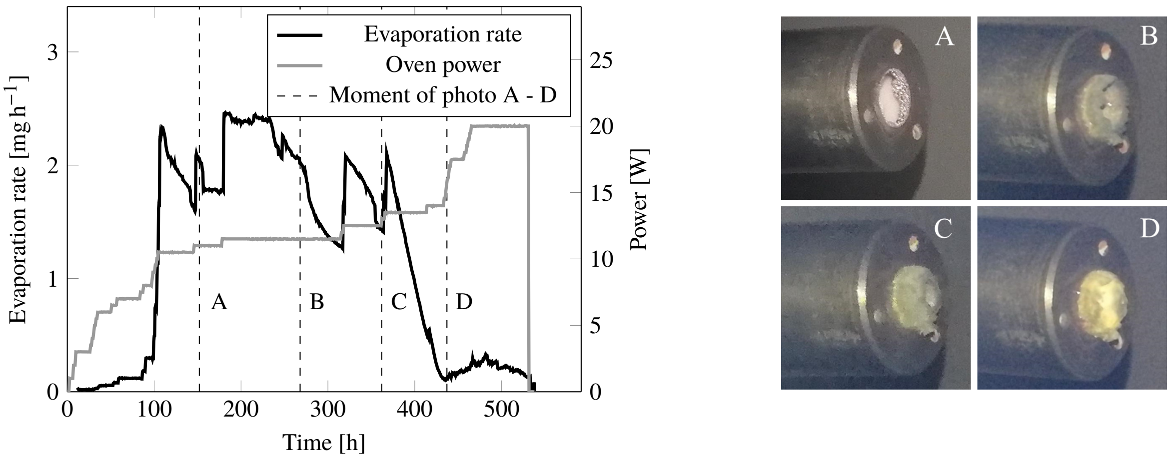


Figure 2: The plot depicts the evaporation rate and the heating power during a heating cycle. The rate was measured every 30 min for 70 s. To convert the deposition signal into an evaporation rate, the total amount of evaporated lead was measured based on the weight of the lead sample at the beginning and the end of the measurement. The dashed lines in the plot indicate the times at which the photos of the oven tip, presented on the right, were taken.

$$\log p_v = 5.006 + A + BT^{-1}, \quad (3)$$

where $A = 5.643$ and $B = -9701$ are coefficients giving the measured vapour pressure of liquid lead in Pa when the temperature $T$ is inserted in K.

The characteristic length in Eq. (1) depends on the geometry of the system. Inside the crucible it is the crucible diameter with $l = 3.4$ mm. Using these estimations the Knudsen num-ber ranges from 96 for $T = 600$ °C to 0.2 for $T = 900$ °C which are realistic temperatures in the crucible, following measurements presented in [4]. It follows that inside the cru-cible the flow regime is either molecular flow ($K_n > 10$) or Knudsen flow ($10 > K_n > 0.1$), which is a transition regime between free molecular flow and the behaviour of a contin-uum. In the Knudsen flow the probability of intermolecular interaction is similar to the one of molecule-wall interactions. At the tip of the crucible the pressure drops rapidly due to expansion of the gas, thereby enhancing the mean free path of the gas particles. It can be assumed that due to the low pressures the lead atoms outside of the crucible propagate without significant interaction between them in all relevant distances (1 mm to 300 mm) in front of the oven i.e. in free molecular flow. One consequence of this regime is that a gas jet will not bend around obstacles and no gas will get to regions behind one. In the oven test stand this can e.g. be observed in the form of shadows with no lead deposition on test stand parts that are behind the deposition detector. In the molecular flow regime the particle trajectories only depend on the surrounding geometry and not the amount of other particles present, which makes it possible to simulate the geometry of the gas jet without precisely knowing the actual pressures in the system.

### *Oven gas jet simulation with Molflow+*

The program Molflow+ [8] allows the simulation of gas dynamics in the molecular flow regime with ray tracing and Monte Carlo calculations. It was used to analyse the particle distribution in the gas jet coming from the oven. The calculated Knudsen numbers show that the validity of the simulation is better outside of the crucible than inside. The simulation is 3 dimensional and contains a model of the oven starting at the inner end of the crucible. Figure 3 shows the geometry and how the particles are tracked through the system. The liquid lead distribution within the crucible during oven operation is not known and not modelled. The simulated particles are simply launched from the inner back wall of the crucible, which resembles a vertical liquid lead surface within the crucible.

One prediction following from the gas jet geometry is the signal reduction of the deposition sensor, when the oven is moved away from the sensor while maintaining a constant evaporation rate. For this the amount of simulated test particles going through a virtual aperture is counted after the simulation ran for a certain amount of time. The position and the diameter of the aperture is chosen to resemble the deposition detector. If the distance to the oven is increased, the amount of test particles traversing the aperture should reduce at the same rate as the signal of the deposition detector does. As shown in Fig. 1 (b) the oven cane is inserted into the test stand through a feedthrough that features a bellow with a motorized stage. This way the oven's distance to the detector can be changed while the oven is operated. Figure 4 shows the result of a measurement where the signal of the deposition sensor was recorded at different distances to the oven and normalized to the maximum signal.

The measurement shows good agreement with the simulation and it can be assumed that the predictions of the jet geometry outside of the oven are close to the real jet. Using the Molflow+ model it can be studied how much of the lead particles exiting the crucible hit the oven parts that showed condensation and later the formation of lead blockages. These are predominantly the front parts of the

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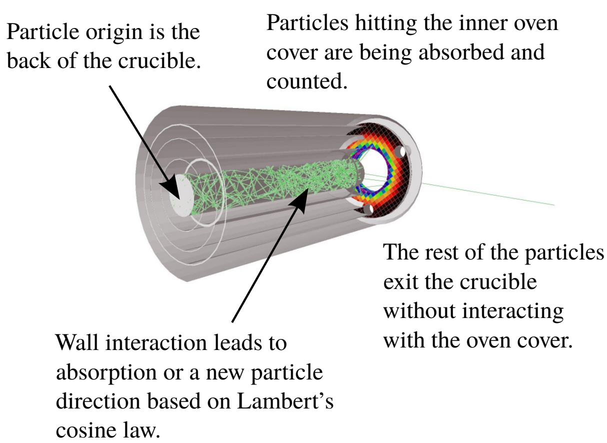


Figure 3: The 3D Molflow+ model to simulate the vapour jet geometry when the molecular flow regime is assumed. Every particle originates from a surface, here the back wall of the crucible inside the oven, starting with a random direction based on Lambert's cosine law. The particle is tracked to the next wall and when its not being absorbed it gets a new direction again based on the cosine law. A detailed description can be found in the Molflow+ documentation [8].

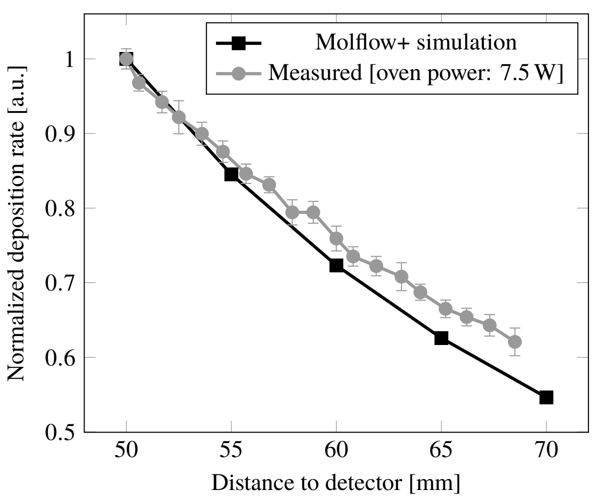


Figure 4: Deposition detector signal at different distances between the oven tip and the detector. Molflow+ predicts a reduction of the signal due to the jet diverging. To compare the deposition rate to the prediction the values are normalized to be one at the distance of 50 mm. The plotted error bars for the measured values show the standard deviation of the detector signal that was averaged over 70 s for each data point.

outer oven cover. Here the simulation predicts that approximately 50 percent of the particles exiting the crucible hit the outer oven cover instead of propagating undisturbed into the plasma chamber (The parts can be seen in Fig. 3). Optimizing the oven geometry by using the model to lower this percentage might be a way to reduce the effect of oxide blockages on the endurance of the oven. The fraction of gas condensing into lead droplets is however unknown and not described by the simulation.

## OUTLOOK

This paper presents experiments and simulations to understand the effect of lead oxide blockages on the oven runtime. The measurement implies that reducing them could help to enhace the oven runtime. Observation at the oven test stand and simulations imply that the formation is caused by the direct lead gas exposure of the outer oven cover. As the gas jet geometry is well described by a Molflow+ model, this model can be used to study geometry changes to enhance the percentage of gas atoms that propagate freely from the crucible into the plasma chamber. Besides the blockages the evaporation rate stability of the oven might also be affected by the temperature profile of the crucible. To study the thermal characteristics of the oven an ANSYS model was developed which is presented in [4] and [3]. The thermal simulations show that the crucible temperature decreases towards its tip. As mentioned this might be a cause of unstable evaporation rates besides the formation of oxide blockages. From the presented studies two goals for the design optimization follow, which can interfere with each other:

- A more homogeneous temperature distribution in the crucible.
- Less lead deposition on the outer oven cover.

To even the temperature distribution within the crucible additional layers of insulation at the oven tip between the crucible and the outer cover are a possible approach. But it needs to be examined whether they could become a new source of blockages. One example for a modification that might have a positive effect in decreasing the lead oxide formation on the outer oven cover is an elongation of the crucible at its front. However this could lead to a less uniform temperature profile in the crucible and thereby less stable evaporation or even blockages within the crucible itself as radiation could transport more heat out of the thermal insulation. The oven test stand allows to test the effects of different design modifications and whether they lead to improvements or not.

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