19th International Conference on Ion Sources – ICIS2021 IOP Publishing
Journal of Physics: Conference Series **2244** (2022) 012020 doi:10.1088/1742-6596/2244/1/012020

Experiments to improve the performance of the GTS-LHC ECR ion source

T Kövener, D Küchler, E Mahner, R Scrivens, A Baris, S Pfeiffer, L Mourier, W Vollenberg

CERN, CH-1217 Geneva, Switzerland

Richard.Scrivens@cern.ch

Abstract. The GTS-LHC 14.5 GHz ECR ion source provides the ion beam, which after acceleration in the ion injector complex, is injected into the LHC, as well as being sent to fixed target experiments at CERN. Two experiments have been performed on the source. The stainless steel plasma chamber has been sputter-coated with a rather thick layer of aluminium on the surface facing the plasma; and the lead micro-oven has been modified to avoid the build-up of lead-oxide on the oven outlet. Details of the changes will be given, and results of beam measurements will be shown, with particular attention on how the stability and oven-refill schedule is impacted by these changes.

1. Introduction

CERN's ion programme uses as a source an Electron Cyclotron Resonance Ion Source (ECR) constructed by CEA Grenoble in 2005 [1]. The source uses 14.5 GHz microwaves injected into a magnetic structure consisting of three normal conducting solenoids and a permanent hexapole magnet. Mostly lead ions are requested, hence the source uses a filament heated micro-oven to evaporate isotopically pure lead, as well as an oxygen support gas. The source uses the after-glow mode, where a 50 ms microwave heating pulse with a 10 Hz repetition rate is applied, after which a more than 1 ms long, high intensity pulse of highly charged lead ions is extracted. Ions are extracted with a three-electrode extraction system, with a total potential of 18.8 kV, and the Pb^{29+} is selected in a low energy spectrometer for acceleration through a 101 MHz RFQ, before further acceleration, stripping and injection into CERN Low Energy Ion Ring (LEIR). Further details on the source and previous upgrades can be found in [2], [3].

Two modifications to the source have been made recently and tested, in order to explore possible improvements in performance and long-term stability. These modifications and the results will be detailed in the following sections.

All the beam results presented in this report are for Pb^{29+}. As a source for an accelerator, the most important performance parameters are the beam intensity transported through the RFQ, and the shot-to-shot stability. The highest intensity through the RFQ does not always correspond to the highest beam intensity measured out of the source.

2. Plasma Chamber

The Linac3 source was originally designed with an aluminium (Al) plasma chamber, which has a length of 637 mm and an internal diameter of 78 mm. This was exchanged for a stainless steel (SS) version in 2010 [4], which led to an improvement in stability of the source, at the expense of needing a higher microwave power, and was less prone to damage. The lower stability of the aluminium chamber was suspected to be due to the lower rigidity of the chamber, which allowed very small leaks to develop in the O-ring vacuum sealing as the temperature varied.

To investigate if some of the benefits of lower microwave power can be recovered, an SS plasma chamber with a 20 μm thick coating of aluminium along the plasma facing surface, produced by dc magnetron sputtering in argon, denoted here as the Al/SS chamber, was tested.

The Al/SS chamber was installed for approximately 1500 hours of test running, and is compared with the beam performance reached with stainless steel chambers, at different times, in Table 1. All data from 2021 are taken with the beaked crucible oven (see next section). The beam intensity out of the RFQ is a critical performance indicator for Linac3 operation. However, this intensity is not recorded every pulse by the Faraday Cup. The source beam intensity measured with a transformer is also given, as well as the standard deviation of the intensity of all recorded pulses (averaged during the 200 μs pulse) over a 72 hour window, where pulses below 25% of the average are removed.

Concerning the Al/SS chamber test period, it is divided into two phases, the low-power (LP) phase where a microwave power of 400-600 W was sufficient for high intensity operation, and high-power (HP) phase where 1000-1500 W was required. In between these two phases, the source was very unstable. This was coincident to the microwave generator failing, which may have affected stability and lead to a 2 week pause in data. During the LP phase higher microwave powers did not lead to better source performance, whereas once the HP phase was reached, the source stability improved. Results for a new stainless steel chamber in 2021 are also given after about 200, 1000 and 2000 hours of operation and conditioning, where the first two periods correspond to the same periods after which the Al/SS chamber is assessed for LP and HP phases.

Once the Al/SS HP phase is reached, it is possible to have an intense stable beam. It was not possible to run the source in this test phase long enough to compare the performance of the source after 4000 hours of operation and regular optimization, as for the stainless steel chamber in 2018.

Figure 1 shows the beam intensity development over 300 hours, starting 200 hours after the source was ignited, for the stainless-steel, and Al/SS chambers.

Table 1. Beam performance for bare stainless steel (SS) and aluminium coated stainless steel (Al/SS) plasma chambers. Intensities given correspond to the best achieved value over approximately three days. Stdev is the standard deviation of measurements made over the assessment period of 72 hours, except (*) which was assessed over 36 hours only.

Plasma Chamber	Year	Start time for data analysis (Hours)	Source Beam Intensity Pb29+ (μA)		RFQ Beam Intensity Pb29+ (μA)
			mean	stdev	
SS	2018	4000	190	9	140
Al/SS (LP)	2021	200	190	14	140
Al/SS (HP)	2021	1000	175	10*	130
SS	2021	200	150	8	115
SS	2021	1000	150	8	115
SS	2021	2000	160	10	130

The Al coated stainless steel chamber has been analysed after dry cutting the chamber open, performing fast ion milling (with an added Pt protection layer) to expose a cross section of the material to a depth of ~50 μm and then performing secondary electron microscopy, allowing a cross-section of the chamber to be exposed, and analysed (see Figure 2 Left). Over most of the chamber surface, a layer containing Pb-O-C has been deposited on top of the Al coating. The depth of this Pb-O-C layer is variable, with a thickness up to 20 μm, with the thickest layer corresponding to the surface close to the Pb oven. The deposited Pb-O-C is mostly porous, and in all cases a thin intermediate layer of Al has formed within it. However, the three regions where the electron losses mostly occur, due to the hexapole magnetic field, are free of this Pb-O-C layer. At no location is the Al layer seen to be significantly removed. The analysis is still ongoing and will be fully reported in the future.

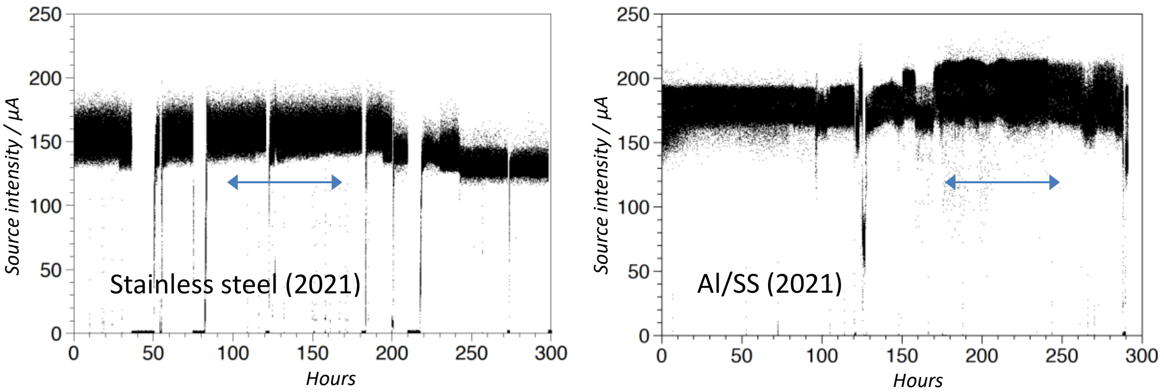

Figure 1. Source intensity of Pb^{29+} using Left: Stainless steel chamber; Right: Stainless steel chamber coated with aluminium. The arrow indicates the period used in Table 1 for the average and standard deviation of the intensity.

In summary, the Al coated plasma chamber initially provides a high intensity beam more quickly after start-up, although with poorer stability, but had a transition through a significant change in performance between 200 and 1000 hours, requiring a significant increase of the microwave power. The bare stainless steel plasma chamber starts with lower intensity, but after approximately 2000 hours its performance is very similar to the Al coated chamber. From this, we hypothesize that the Al surface initially delivers a high number of secondary electrons to the plasma, but as both chambers become coated with the Pb layer, the difference between them diminishes.

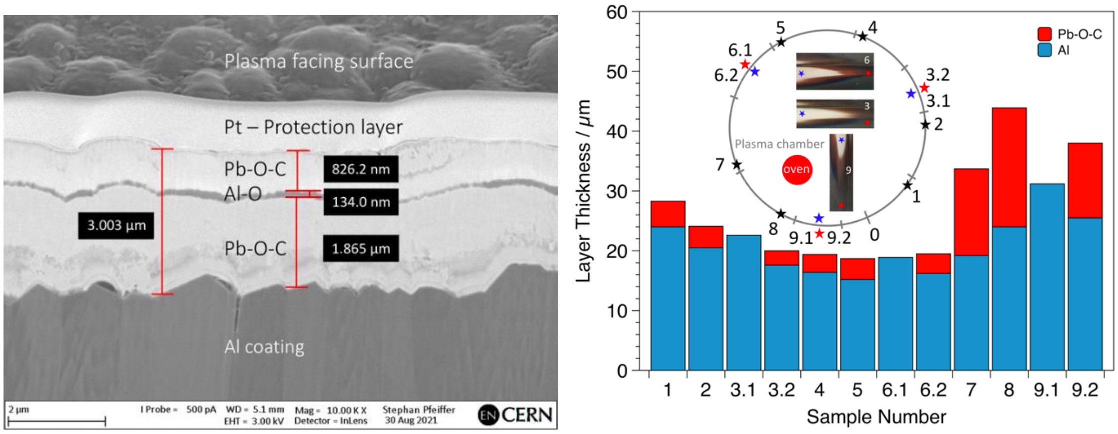

Figure 2. Left: Scanning Electron Microscope image of the Al coated plasma chamber surface, with the different surface layers marked. Right: Thickness of the Pb-O-C (red) and Al (blue) layers determined at 12 positions of the plasma chamber; samples #3, #6, and #9 were analysed at two different locations, i.e. inside visible "light" and "dark" layer areas (see insert). The oven position relative to the sample locations is marked in the insert.

3. Micro-oven

To evaporate lead into the plasma chamber of the ECR ion source a micro-oven containing an alumina crucible with the capacity of around 1.5 g of lead is used. A tantalum filament resistively heats this oven while a feedback loop stabilizes the applied heating power at a chosen level. During the operation of the source in the year 2018 and before, the applied power needed almost daily adjustment to maintain a stable beam output. After two weeks of uninterrupted operation, the oven needed a refill of the lead sample and a cleaning of its orifice, even though the crucible still contained around half of the initial lead sample.

A dedicated study to understand the reasons for the necessity of the frequent tuning and the failure mechanisms of the oven was conducted, including thermal simulations, gas flow simulations and measurements at an offline test stand [3], [5], [6]. Trials at the test stand showed the main failure mechanism to be the formation of a lead oxide blockage starting from lead condensate on the outer oven cover (also in [7]). The outcome of the study were proposals to prevent this blockage, with the least invasive being a modification of the oven crucible (see also [8]). By giving the crucible a prolongation at its orifice (for convenience called a beak), the Pb atoms no longer have a direct path towards the cover, while the crucible tip remains hot enough to prevent any condensation on itself. Figure 3 shows a thermal simulation of the conventional and the modified oven orifice. More details on the simulation model can be found in [6]. For a heating power of 8.5 W here the temperature of the crucible tip is 714 °C (without beak), 686 °C (with beak) while the outer cover only has 440 °C.

Testing with the modified crucibles at the GTS-LHC ion source started end of November 2020 and lasted all runtime of the source in 2021 so far. Here we present the experience during the longest possible operation of one lead filling with the new crucible design and compare it to the performance seen in 2018.

In order to operate the oven with the modified crucible the heating power was ramped up to 7 W. During the run the operator then adjusted the power as part of the source tuning to maintain a stable source output. In contrast to previous runs the refill of the oven was not pre-scheduled but it was operated until no further lead beam could be extracted from the source.

The longest oven fill lasted 59 days and upon inspection of the oven tip after the run no lead oxide blockage had formed. In this configuration it was possible to operate the source until the lead filling was completely consumed. Throughout the run the heating power was adjusted several times, usually in steps of 0.1 W leading to a final power of 9.1 W.

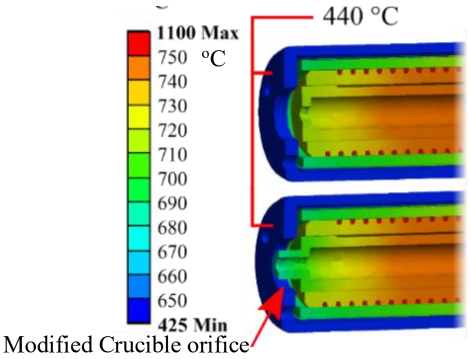

Figure 3. Simulations of the thermal profile of the micro-oven with Ansys [9]. The lower model includes the modified crucible. In both cases a heating power of 8.5 W is simulated by setting the filament temperature to 1100 °C.

Figure 4 shows the oven power and the Pb^{54+} beam current of each Linac3 pulse measured in the beam current transformer ITF.BCT25 at the end of Linac3 during the presented run, together with the same data during several refills of 2018 in a comparable timeframe (11.10.2018 - 11.12.2018), also spanning over the heavy ion run of the LHC. The red line shows the beam current requirement from the subsequent accelerator LEIR which is 30 μA of Pb^{54+}. It can be seen that Linac3 could provide the required beam output in 2021 for more than 30 days even though the delivery of beam to LEIR only started after the oven already ran for 17 days. During this time, the beam current did not drift significantly which can partly be attributed to a stable oven performance.

This experience differs from the previous operation in 2016 and 2018 where it was regularly necessary to ramp up the heating power up to 20 W during the source operation. The longest operation of one oven filling in 2018 lasted 16.8 days and on average a fill was operated for 14 days. Note that in 2018 the refills were pre-scheduled and the oven was not run as long as possible.

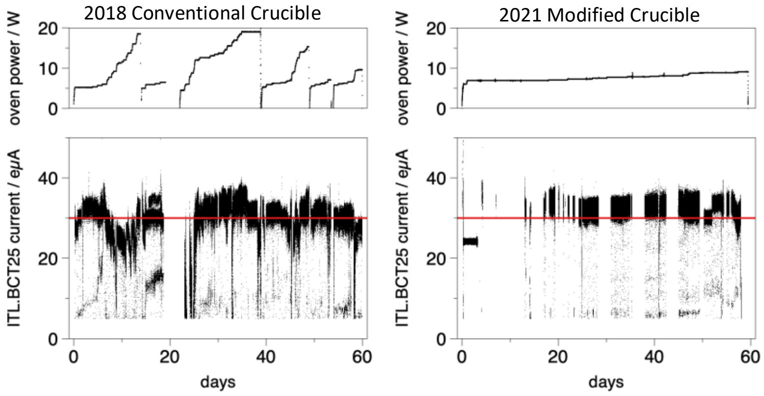

Figure 4. Plots of the oven power and the beam current measured in beam current transformer ITF.BCT25. Left: Selected timeframe of 2018 also spanning over the heavy ion run of the LHC, with six oven refills. Right: The longest run so far with the modified crucible. The red line indicates the intensity target.

In conclusion, the modified crucible successfully prevented the formation of a blockage at the oven orifice as it was expected from the previous test stand measurements. With no blockage forming, the oven could be operated until the lead sample was consumed (consumption rate 1 mg/h, in 2018 it was on average for the reference period 1.5 mg/h), which reduces the number of necessary refills or cleanings. This is promising especially considering the LHC heavy ion run that usually lasts four weeks and could be performed without having to include the downtime of an oven refill. Additionally, the oven needs less tuning as there is no closing orifice that needs to be compensated by higher vapour pressures.

References

[1] Dumas L, Hill C, Hitz D, Küchler D, Mastrostefano C, O'Neil M and Scrivens R 2006 Operation of the GTS-LHC Source for the hadron injector at CERN, *Proc. 17th Int. Workshop on ECR Ion Sources and Their Applications,* Lanzhou, China, p51
[2] Küchler D, O'Neil M and Scrivens R 2008 First experience with the operation of the GTS-LHC ion source at 18GHz, *Proc. 18th Int. Workshop on ECR Ion Sources ECRIS'08,* Chicago, Illinois
[3] Toivanen V *et al*, 2016 Recent developments with the GTS-LHC ECR ion source at CERN, *Proc. 17th Int. Workshop on ECR Ion Sources and Their Applications,* Busan, Korea, WEAO01
[4] Küchler D, Bellodi G, Lombardi A, O'Neil M, Scrivens R, Stafford-Haworth J and Thomae R 2012 Operation experience with the GTS-LHC ion source and future developments of the CERN Ion Injector, *Proc. of ECRIS2012,* Sydney, Australia, TUPP10
[5] Fichera C, Carra F, Küchler D and Toivanen V 2018 Numerical study of the thermal performance of the CERN Linac3 ion source miniature oven, *Nuclear Inst. and Methods in Physics Research, A* **901** p21
[6] Koevener T, Study of the micro oven at the Linac3 heavy ion source, Thesis, Staats- und Universitätsbibliothek Hamburg Carl von Ossietzky, Hamburg (2020), https://ediss2.sub.uni-hamburg.de/handle/ediss/8493?mode=full
[7] Koevener T, Küchler D and Toivanen V, 2018 Study of the lead evaporation from the oven of the GTS-LHC ion source, *Proc. ECRIS2018,* Catania, Italy, TUP21
[8] Koevener T, Küchler D and Toivanen V, 2020 Lead evaporation instabilities and failure mechanisms of the micro oven at the GTS-LHC ECR ion source at CERN, *Proc. ICIS2019, Lanzhou, China, Rev. of Sci. Instrum.* **91** 013320
[9] The official Ansys simulation tools website. https://www.ansys.com/