CERN hadron sources: status and innovation overview

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Abstract. The CERN accelerator complex is served by several different types of hadron sources, producing both high- and low-intensity negative H^- beams, highly charged positive stable ions, but also transforming low-charge radioactive ions to higher charges before post-acceleration. Apart from the operational sources, research and development is carried out at dedicated test stands for H^- production and pre-acceleration, ECRIS oven experiments and general EBIS development. In this paper, we will report on the performance and the latest development related to the sources. Efforts to enhance the theoretical understanding of the source physics will be briefly reviewed.

1. Introduction

The high-energy proton-proton collisions at the Large Hadron Collider (LHC) make up CERN's most high-profile experimental program. Nonetheless, CERN's accelerator complex as a whole provides the basis for a sprawling physics program involving different particle types with energies ranging from some keV to several TeV. The low energies are necessary for particle trapping, e.g. for the production of antihydrogen at the Antiproton Decelerator (AD), while in-ring and fixed-target collisions in most cases require higher energies. Although the primary particle type at CERN is protons, used either as the experimental collision-particle itself, or, as primary driver beam for production of exotic particles types, also different types of heavy ions belong to the standard particle assortment. In addition to stable ions, production of a large variety of radioactive ions and post-acceleration to a few MeV/u is part of CERN's experimental program.

The broad R&D program for ion sources at CERN aims first and foremost at assuring stable operational conditions in conjunction with highest performance of the sources, but also to extend their capabilities in order to pave the way for new physics opportunities. Within the last couple of years, the H^- source for LINAC4 has become operational but future requirements already impose continued studies to improve the source performance further. A low-intensity H^- source for the Extremely Low ENergy Antiproton (ELENA)) ring at the AD, initially foreseen to only be employed during the commissioning phase, will most likely become a permanent installation, so stability issues therefore need to be addressed. Likewise, an improvement of both the long-term and shot-to-shot stability of the Electron Cyclotron Resonance Ion Source (ECRIS) at LINAC3 is desirable. Finally, enhanced performance of the Electron Beam Ion Source (EBIS) charge breeder at REX/HIE-ISOLDE is requested in order to expand the physics reach. In the following sections, an overview of the performance and development programs of these four sources will be given.

However, first a brief homage to CERN's former proton workhorse: the duoplasmatron source providing protons for the 50 MeV LINAC2. Over the lifespan of 40 years, more than 700 million of proton pulses with a length up to 150 μs and with an instantaneous current of >200 mA were produced. Over the last two years of operation, amounting to >12000 h, the source was only inoperative for 6.5 h due to faults. At the end of 2018, with the start of long shutdown 2 (LS2), the exploitation of LINAC2 was discontinued, and the baton as principal linear accelerator at CERN was handed over to LINAC4.

2. LINAC4 H^- source

In the LINAC4 injector, H^- ions are now being accelerated to a final energy of 160 MeV before undergoing charge-exchange injection into the four rings of Proton Synchrotron Booster. From a 2 MHz caesiated RF source, the ions pass a 1.8 m low-energy beam transport section before being accelerated to 3 MeV in a 3 m-long 352.2 MHz Radio Frequency Quadrupole (RFQ). The repetition rate is 0.83 Hz, although operation at 2 Hz is possible.

The present source version, IS-03b, features a two-stage extraction system, where the co-extracted electrons are dumped onto the puller-dump electrode at an energy of ~10 keV, before the ions are further accelerated to 45 keV. The multi-cusp field has been removed as no significant difference in transverse emittance, required power and efficiency through the RFQ could be noted compared to having the multi-cusp present. The hole diameter of the plasma electrode has been enlarged from 6.5 mm to 7.5 mm, resulting in a larger transmission through the RFQ. Furthermore, the source is now exclusively operated in surface production mode, making use of caesiation to increase the H^- simultaneously, as the ratio of extracted e^- to H^- is reduced. The continuous low-flow caesiation is attained by keeping the caesium oven at 60 °C, while the transfer line stays at 80 °C to avoid cold spots.

2.1. Source performance and reliability

Being the main driver for the CERN accelerator complex, a very high reliability of >99% is requested, and a pulse-to-pulse stability of 2% (peak-to-peak) is specified after the LINAC. During 2021, the source availability has been 99.9%, with the gas system being the main reason for the short interruptions. The measured fluctuation of the source current amounts to 0.9% (1 σ), where half of the instability is due to RF power variations. The operational source, installed in May 2020, provides a beam current of 35 mA, of which 27 mA is transmitted through the RFQ, as well as through the remaining LINAC. Normally, the e^-/H^- ratio is below 4, while a peak RF power of 20-25 kW is required for generating this current. An autopilot acts on the RF power level, basing its adjustment on the current of the previous 10 extracted pulses. Similarly, the autopilot restarts the HV power converters automatically after trips and monitors the e^-/H^- ratio, which is a signature for the source caesium status. The occasional manual tuning focusses mainly on the RF pulse shape, the gas injection settings and the caesiation system temperatures. Since it was installed last year in the Linac4 tunnel, this source has been vented twice for a gas valve exchange - a preventative action performed every 4 months that takes 24 hours from beam stopped to beam back. In spite of the good reliability, two spare units that have been caesiated and tested, are stored under N_2 atmosphere.

2.2. Test stand activities

The layout of the LINAC4 test stand is identical to the on-line machine, although without a pre-chopper and with an emittance meter replacing the diagnostics tank and an acceptance mask at the position of the RFQ. The test stand is used for validation of spare units, source development and studies, as well as for target material irradiation studies, as endoscopic analysis of the LINAC4 RFQ showed signs of damage and degradation on the vanes.

The beam formation symmetry of the IS-03b H^- source operated in plasma caesiated surface mode is broken by the magnetic filter field inducing a left-right charge drift, and by radial asymmetry resulting from the combination of ions created in the plasma volume and those produced and directly extracted from the active caesiated surface. The goal of the beam formation studies is to provide detailed experimental evidence to validate the ONIX simulation, which serves as input for the IBSimu beam tracking, without the use of "free" plasma parameters. Optical emission spectroscopy serves to calibrate the ONIX plasma, while beam emittance spectroscopy, emittance and profile measurements contribute to distinguish asymmetries induced by beam optics from those of the meniscus ion-density distribution. For details see refs. [1],[2].

As a complement to the emittance meter, an installed set of four separated plates with square holes followed by a Faraday cup, acts as a compact "mask" that reproduces the transverse acceptance of the RFQ. Particle tracking has shown a good transmission agreement, although the mask overestimates the transmission slightly due to the ignorance of the longitudinal acceptance of the RFQ. Tests with the ISO-03 source exhibit a saturation in transmitted current at around 43 mA, while the RFQ only transmits 32 mA at most. The reason for the discrepancy is under investigation and may be due to a lack of space charge neutralization near the RFQ entrance.

2.3. Modified source extraction design

The present version of the H^- source is capable of providing a beam current of 27 mA, measured after the RFQ reliably. However, this value is below the goal of 45 mA to be provided for operational use from 2023 onwards. A large transverse beam emittance compared to the RFQ acceptance is believed to be the main obstacle. The source is using an electron dump design with a low impact energy since 45 keV electrons in the early tests with a DESY source type caused immediate damage to the dump. As the 2018 ion source review committee discouraged the use of pure volume mode operation in favour of caesiation, the anticipated amount of co-extracted electrons will be low, thereby again opening up for ion extraction options with higher electron beam dump energy, that should be beneficial for the emittance of the H^- beam.

For these reasons, a simplified extraction geometry has been studied where the intermediate puller-dump and Einzel lens are being suppressed [3]. In the geometry, now being 6 cm shorter, the 45 keV electrons are deflected onto a dedicated dump. The simulated peak power density is <100 W/mm^2 for <80 mA co-extracted electrons. A sketch of the design with the associated beam simulation is shown in Fig. 1. Initial experiments at the test bench resulted in a 52 mA extracted beam from the source, with 94% transmission through the RFQ mask. The measured normalized emittance is ~0.3 mm.mrad (1 σ) in both planes. Inspection of the source after a few weeks of operation did not reveal any trace or damage on the puller electrode nor on the electron dump made of INERMET(c).

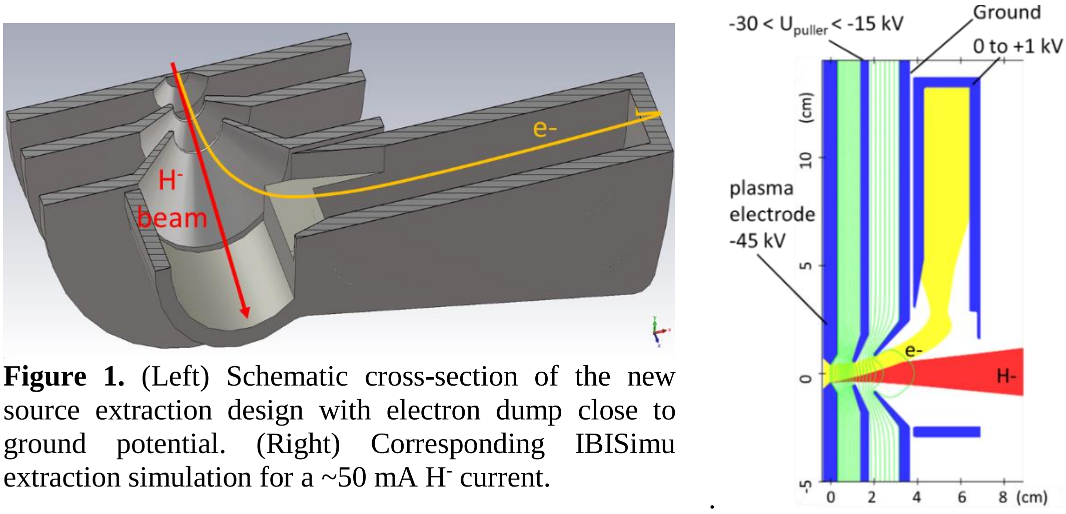

Figure 1. (Left) Schematic cross-section of the new source extraction design with electron dump close to ground potential. (Right) Corresponding IBISimu extraction simulation for a ~50 mA H^- current.

3. ELENA H^- source

ELENA is a compact ring that has been installed to complement the AD antimatter factory at CERN. With this recent adoption, the injected antiprotons can be decelerated from 5.3 MeV down to 100 keV and further cooled, before being expulsed to the experimental setups and thereby enhancing the trapping efficiency by two orders of magnitude compared to using degrader foils at AD extraction beam energy. For commissioning purposes of the ring and subsequent electrostatic transfer lines towards experiments, a local H^- source is connected to the ELENA ring. Using H^- particles with 100 keV, the antiproton beam at extraction energy can be mimicked. The source can provide higher intensity and more frequent injections than possible with the antiprotons from AD, which operates with a 110 s cycle time. In addition, it has facilitated progress with the commissioning phase also in the absence of antiprotons during LS2.

The H^- ion source was granted to the ELENA project as an in-kind contribution from the Jülich Forschungszentrum, Germany, and installed in 2015 at CERN. The multi-cusp volume-type source operates with a continuous arc discharge as well as H_2 gas injection. The pulsed beam structure is attained by rapid switching of the puller electrode potential. Details about the design of the source are found in ref. [4].

3.1. Source performance and recent improvements

Results from the initial time of operation include H^- pulses with a current of 50 to 100 μA and a length of a few μs. Since then, new important observations have been collected, facilitated by improved beam instrumentation. A recently installed Pearson 5753 wide-band beam current transformer (BCT) allows for single-shot measurements of the extracted beam, where the previous BCT required averaging over several pulses due to low sensitivity. With this, observations from pick-up elements in the ring of an intra-pulse instability that will be discussed below, could be confirmed. The introduction of an annular aluminum-doped scintillation screen (Chromox AF995R) in front of the BCT, in conjunction with a triggered digital camera and narrowband filter (694±5 nm), has permitted trajectory surveillance of the extracted particles. This tool has been essential for increasing the understanding of a slow transverse drift of the beam.

After long-standing reliability problems of the HV transformers (both of solid-state and oil-based types), -100 kV can now regularly be applied. Nonetheless, to reduce the risk of sparks inside the transformer, the HV is pulsed from -60 kV to -100 kV just in advance of the ion pulse.

3.2. Intra-pulse instability and transverse beam drift

The fast (about 1 MHz) intra-pulse instability, occurring for nominal operational parameters results in a poor intensity stability of the H^- beam injected into ELENA, as the acceptance window is around 650 ns. Numerous efforts, laid out in ref. [4], have been performed to identify the reason for the instability. Especially noteworthy is the observation of a stable proton pulse if the voltage configuration of the source is inversed. The intra-pulse instability is therefore understood to originate in the actual H^- production region, located after the magnetic filter region and therefore not easily visible on most of the external signals available, although the exact mechanism is presently unknown. The remedy is to either operate the source with a low arc voltage close to plasma extinction (~ 25 V), yielding a very stable although low extracted current, or by increasing the H_2 gas flow significantly (from 1.5 to 5 sccm).

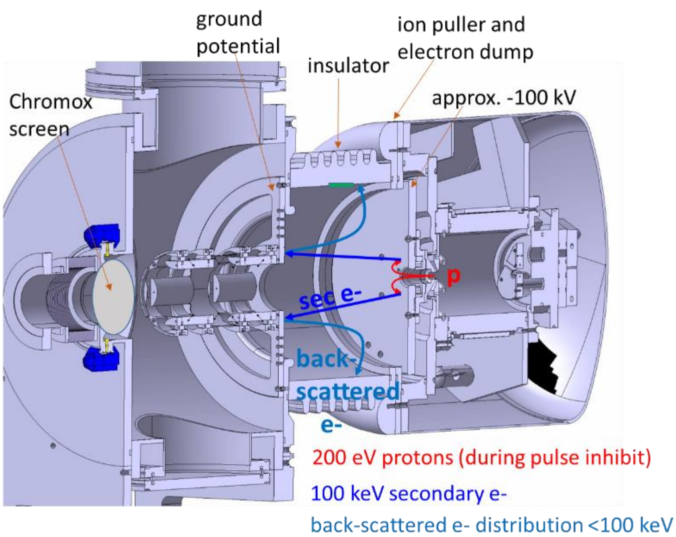

Figure 2. Low-energy protons escaping the ion puller and electron dump electrode are believed to create secondary electrons when reflected backwards onto the copper surface. The secondary electrons gain velocity and reach the ground electrode with an impact energy of nearly 100 keV. A large fraction of these electrons may backscatter at an energy of several ten keV, and will then be deflected onto the non-shielded main insulator and there build up a charge capable of steering the ion beam.

In addition, a slow drift of the beam position has been observed in the ring, and the cause of the orbit drift has been tracked back to the ion source assembly. On the previously mentioned scintillator screen, a vertical movement of the focused beam spot of up to 10 mm can be observed. The movement is sporadic (hours-days-weeks) and occurs over some minutes. Moreover, it can be provoked by applying higher negative voltage (-250 V or more) onto the electron dump during the H^- inhibiting phase. The beam position cannot be reestablished by switching off the plasma, nor by lowering the HV, only by venting the source or leaving it switched off for a night or longer. After careful exclusion of other causes, we believe the reason is a charging-up phenomenon of the HV insulator, not being shielded from the beam region (see Fig. 2 caption for a qualitative argument). Simulations support the findings and a modification of the insulator shielding is foreseen.

4. LINAC3 ECR ion source

The heavy ion beams, either used in LHC for high energy collision experiments or at the Super Proton Synchrotron North Area for fixed-target experiments, originates from the GTS-LHC ECR ion source. The produced highly charged ions are accelerated in LINAC3 to 4.2 MeV/u before being stripped in a carbon foil to even higher charge states and thereafter injected into the Low Energy Ion Ring (LEIR), where they are accumulated, cooled, and accelerated to provide intense beams for physics.

4.1. Source design and performance

The 14.5 GHz ECRIS is based on the original Grenoble Test Source, although with the addition of a center coil and a stronger Halbach-style 36-piece permanent magnet; operation commenced in 2005. The source operates in afterglow mode, with a 10 Hz RF heating cycle at 50% duty factor, and produces a typical pulse length of ~1 ms. At an energy of 2.5 keV/u, the desired charge state is selected in a spectrometer before injection into an RFQ cavity, which selects 200 µs of the pulse for acceleration. From two micro-ovens at the back of the source's plasma chamber, lead vapor evaporates into the plasma that is sustained by additional injection of oxygen gas. Delivered beams, their method of production and achieved intensities are summarized in Table 1.

Intensity and stability are key parameters for the beam. Therefore, throughout the years, several studies have been performed on the source, and it has undergone various modifications. For instance, operation at 18 GHz and at nearby frequencies of 14.5 GHz has been tested, as well as double-frequency injection using a TWTA (12-18 GHz) in addition to the 14.5 GHz. The extraction system has previously been modified with the addition of an Einzel lens and increase of the downstream beam pipe aperture. Operational experience shows that some of the source instabilities can be linked to the oven performance, hence modifications of the design have been studied over a longer period, both at the operational source, but primarily at a dedicated oven test stand. Below, the latest studies and alternations to the source are briefly introduced. For more details see refs. [5],[6].

Table 1. Beams produced in the ECRIS and their typical pulse intensity after charge selection in the spectrometer.

Beam	Intensity (µA)	Method	Year
$^{208}Pb^{29+}$	~170	Oven	All other years
$^{40}Ar^{11+}$	~100	Gas	2015
$^{129}Xe^{22+}$	~160	Gas	2017

4.2. Micro-oven investigations

The two oven crucibles are loaded with approximately 1.5 g enriched ^{208}Pb each, and resistively heated with a tantalum filament. The oven power is adjusted manually to attain an optimal and stable extracted beam current. In the past, oven refills and orifice cleaning were rescheduled every 2 weeks, as at that point, a high heating power (20 W) was required, or the oven orifice was blocked. Approximately only 1/3 of the lead had then been consumed. MolFlow+ simulations showed that 50% of the emitted lead vapor impinged on the relatively cold tantalum cover and in combination with the buffer gas oxygen, a lead oxide blockage at the tip of the oven disrupted the operation (see Fig. 3, left). With the addition of a so-called beak at the orifice of the ceramic crucible, interception of the lead vapor by the oven cover can be avoided, while the beak is still at a sufficiently high temperature to avoid condensation on itself. The design was supported with thermal simulations, and the first results have demonstrated an oven life-time of 59 days without any blockage (see Fig. 3, right). It still remains to consistently reproduce the long life-time.

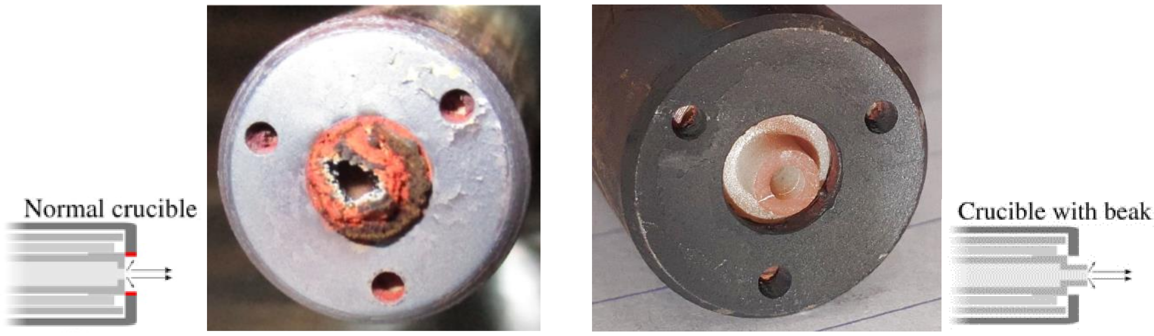

Figure 3. (Left) Lead oxide blockage of the exit hole on the old oven design. (Right) No blockage after 18 days operation using the beak modification.

4.3. Other recent ECRIS studies

Aluminum in combination with oxygen are believed to create a layer on the plasma chamber with high secondary electron yield. However, the original plasma chamber made of aluminum had to be replaced in 2010 by a stainless steel chamber due to plasma stability and mechanical lifetime issues. Thereby, the rigidity increased at the cost of slightly reduced beam intensity and a factor of 3 higher required injected RF power. To reclaim the favorable plasma surface condition, while maintaining the mechanical strength, a stainless steel chamber has been coated with a 20 μm thick Al layer using cylindrical DC magnetron sputtering. After insertion at the GTS-LHC source, a very high lead intensity is rapidly attained, and the optimum RF power is only 400-600 W. The pulse-to-pulse stability is, however, slightly worse than for a stainless steel chamber, and after 6 weeks the RF power is back at its nominal value of 1000-1600 W. No aluminum was detected in the extracted beam. A post-mortem analysis of the removed and cut open chamber demonstrated a build-up of a lead oxide layer at chamber regions that are not constantly bombarded by loss electrons.

With the aim of decoupling the influence of the plasma meniscus shape on the beam Twiss parameters, and thereby allowing for increased flexibility in the tuning of the beam into the charge state spectrometer, a moveable extraction puller has recently been implemented. This allows for an external remote manipulation of the axial position of the puller, in unison with the intermediate electrode, of ±10 mm around the nominal setting. The initial tests have not yet demonstrated a higher extracted beam current and they will be continued.

On-going is also data extraction of the source settings in relation to extracted beam current, using clustering analysis. The goal is to identify reoccurring patterns, and link setting clusters with source performance, with the ultimate aim to automatically adjust the settings. Initial analysis suggests that more observables are necessary, and therefore a real-time optical spectroscopy to detect the lead vapor density is under implementation.

5. Charge breeding at REXEBIS

In difference to the above discussed sources, the EBIS at the radioactive nuclear beam facility REX/HIE-ISOLDE is not producing ions but performing charge breeding, that is transforming externally injected 1+ ions to n+, before passing on the ion bunch to a post-accelerator via an A/Q-spectrometer. The radioactive ions in question are spanning the full nuclear chart. In fact, REXEBIS has charge bred ions ranging from $^{6}He^{2+}$ to $^{228}Ra^{53+}$ during its 20 years of operation, covering 134 isotopes from 34 elements, and provided beam time at more than 200 occasions.

5.1. Non-adiabatic electron gun

REXEBIS, with its relative moderate electron beam parameters, belongs to the first generation radioactive charge breeders. Recent development has focused on the upgrade of the electron beam properties in the trapping region of the EBIS. A higher electron current density is desirable as the charge breeding time can be reduced, thereby permitting experiments access to short-lived ions and operation of the post-accelerator at a higher repetition rate, which in turn results in a lower instantaneous particle rate of the extracted bunches. With the introduction of an immersed electron gun making use of a non-adiabatic (NA) magnetic element, in combination with a cathode placed at a low field of 700 Gs, a significantly higher current density has been obtained. By placing the NA element on the descending phase of the electron beam oscillation, the cyclotron motion can be reduced, and thereby a ripple-free laminar beam can be produced, even for magneto-immersed guns positioned in a field with only a few hundred Gs and with cathode emissions exceeding 20 A/cm^2 [7].

5.2. Commissioning results from the non-adiabatic electron gun

During the commissioning campaign, a gun perveance of 0.87 μA/V$^{3/2}$ was measured, to be compared to a simulated design perveance of 0.73 μA/V$^{3/2}$. In spite of electron gun simulations indicating an enlargement in the radial oscillations with an increased deviation from the optimum electron current of 500 mA, an electron beam with a current ranging from a few mA to 420 mA could be transmitted with low losses (<150 μA). To be noted: the gun has constantly been operated in the thermionically limited regime due to inadequate emission, while the simulations were performed in the Child-Langmuir regime. The main part of the electron losses reaches the outer drift tube in front of the suppressor electrode, and it is presently believed to be caused by elastically reflected or back-scattered electrons from the collector region.

The charge breeding efficiency, i.e. the conversion efficiency of the injected 1+ ions to the desired charge state n+ is of paramount importance due to the scarcity of the radioactive ions, and was therefore carefully investigated. Measurements showed an efficiency matching the one of the original electron gun, in spite of operating at a lower electron beam current than foreseen. In fact, observations, for instance the efficiency-independence on the electron beam current, indicate that the emittance of the pulsed injected 1+ beam can be larger than the acceptance of the EBIS electron beam, while still capturing a large fraction of the injected ions. Tangible results include breeding efficiencies of approximately 30% for $^{23}Na^{9+}$, $^{39}K^{17+}$ and $^{205}Tl^{53+}$. These high values are attained thanks to closed atomic shell configurations (Na and K), and an ionization potential approaching the electron beam energy for the Tl case. Measurements of the global efficiency, i.e. the sum of all charge states leaving the EBIS, show values of 65-85%, independent on the confinement time. This points towards an excellent survival rate of the injected ions. Furthermore, the efficiency seems unrelated to the ion mass, suggesting that the magnetic field of the solenoid has no visible influence on the 1+ ion acceptance. See Fig. 4 for a selection of breeding efficiencies into a single charge state and Fig. 5 for global efficiency values.

Another important aspect is the vacuum level inside the trapping region, as with an increased electron beam current, higher outgassing rates may be expected from the gun and collector regions. Broad range A/Q-spectra have therefore been used to measure the rate of ions created from residual gas in the trapping region, and from those partial pressures of various gases have been calculated. A total pressure inside the trapping region of ~$3 \cdot 10^{-11}$ mbar has been found, with neon gas streaming from the Penning trap being the dominating constituent. At this pressure, <20% electron beam neutralization is reached after 300 ms breeding time.

The electron beam current density in the ion trapping was determined by recording the charge state evolution in REXEBIS for various elements and for varying beam currents, and using external ion injection as well as neutral gas-injection. The effective current density was thereafter deduced by fitting the measured charge state evolution with predictions of a simple theoretical model, including electron-impact ionization and radiative recombination, but excluding charge exchange and evaporative losses, as the two latter could be proven to have limited influence on the result. Apart from arriving at an effective current density of 265 A/cm^2 to 424 A/cm^2 for a 300 mA electron beam current, the investigation revealed strong dependence on the ion mass and breeding time, as well as difference between gas and externally injected ions.

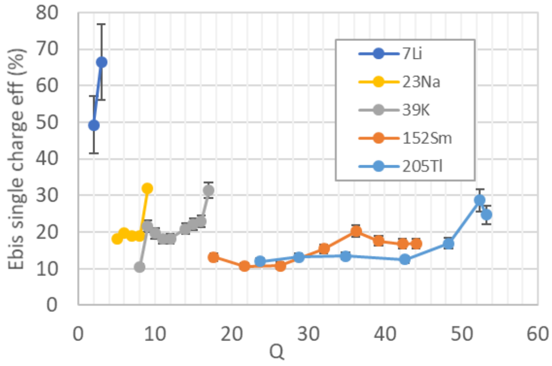

Figure 4. EBIS breeding efficiency into a single charge state with a 200 mA electron beam.

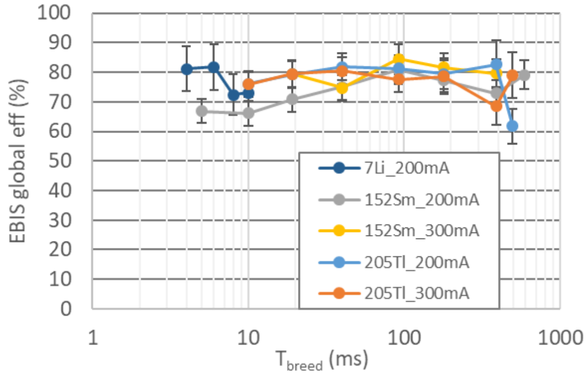

Figure 5. EBIS global efficiency for a selection of elements and different electron beam currents.

To shed light on the varying effective current densities, the axial energy spread of the trapped ions was probed and fitted to Maxwell-Boltzmann distributions. For all cases studied, the equivalent holding voltage $k_B T_{ion}/q$ did not exceed 40 V, and one can therefore assume strongly suppressed ion escape and evaporative cooling. The high and large variation in current density may therefore be explained by a non-uniform current density profile.

In order to sustain an operational electron current of more than 300 mA, we intend to test a novel scandium-doped dispenser-type cathode developed at Beijing University of Technology, from which a current density of 30 A/cm^2 at 950 °C, for more than 2000 h continuous operation, has been reported. For a detailed analysis of the commissioning results, see ref. [8].

6. Acknowledgments

The presented work is the result of common efforts within the Beams Department. The EBIS related work has been supported by the Research Foundation - Flanders, through the Big Science project Nr. G0C2813N. This work has also been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 05E15CHA).

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