EURISOL JRA, ICBT subtask

Milestone MS14.1 "Experiments for the optimal breeder configuration"

Introduction

Charge breeding systems for radioactive ions based on Electron Beam Ion Source (EBIS) are inherently complicated in design and operation. The low transverse ion injection acceptance of the EBIS in conjunction with higher injection efficiency for injected pulsed beams impose the use of a preparatory stage between the 1+ ion source and the EBIS. The ion preparation, i.e. emittance cooling and bunching of the cw beam from the ISOL-stage, can take place in either a Penning trap or an RFQ cooler-buncher, both featuring buffer-gas cooling. The REX-ISOLDE charge breeding system is based on the former type. Apart from complicated operation, Penning traps and RFQ cooler-bunchers have limited space-charge capabilities, in the order of 1E8 ions/bunch. For a EURISOL facility with an expected high radioactive ion production rate, the preparatory stage may set a limit on the current throughput, as the EBIS space-charge capacity is higher for used designs. Thus, the question has been if the preparatory stage can be suppressed and so-called direct ion injection into the EBIS be employed.

Experimental tests

It has previously been shown that single charge-state breeding efficiencies in excess of 5% can be obtained at REX-ISOLDE [1,2]. This is a significant increase compared to previously reported sub-percent efficiencies at other setups. For the REX-ISOLDE cases the ion current was however limited (<500 pA) and only medium to heavy mass ions (e.g. K+, Rb+ and BaF+) were used, which are easier to trap into the electron beam than light ions.

The tests for the EURISOL JRA were performed at the REX-ISOLDE low-energy stage during two experimental campaigns in November 2016 and May 2017 [3]. At these occasions molecular CO+ beams were utilized, as charge breeding of carbon is also of interest for future cancer treatment facilities. The beam intensities, now up to 8 nA, were injected continuously over the outer barrier into the EBIS. After collection and charge breeding, the outer barrier was rapidly lowered and the charge bred carbon was extracted.

The optimal charge breeding efficiency for cw injection was found to be a factor 2.5 lower than if pulsed injection is used. For an accumulation/breeding time of 30 ms, the breeding efficiency decreased with a factor 2 when the injected current was increased from pA level up to 7.5 nA (see Fig. 1), and a further decrease is to expect for even higher injected currents. For a longer accumulation/breeding time of 100 ms, the decrease was a factor 4. The potentials of the outer barrier and the trapping region were varied for different injected currents as this affected the efficiency.

The decrease in efficiency as function of injected ion current is in part related to changed injection conditions. When the trapping region becomes partially space-charge compensated during the accumulation/breeding period, the voltage difference between the trapping region and the outer barrier changes and therefore also the probability for trapping of ions that are ionized from 1+ to 2+ during the injection round-trip within the trap. Furthermore, with increased space-charge compensation ions with high energy are lost from the trap. This is particularly pronounced for cw injection as the ion energy is high compared to the lowest voltage barrier, which is the outer barrier in this case. Ideally, the trapping and outer barrier potentials should be varied continuously during the accumulation/breeding cycle in order to optimize the trapping condition, while minimizing the ion boil-off. This functionality is not included in the control system though and could therefore not be tested during the experiment.

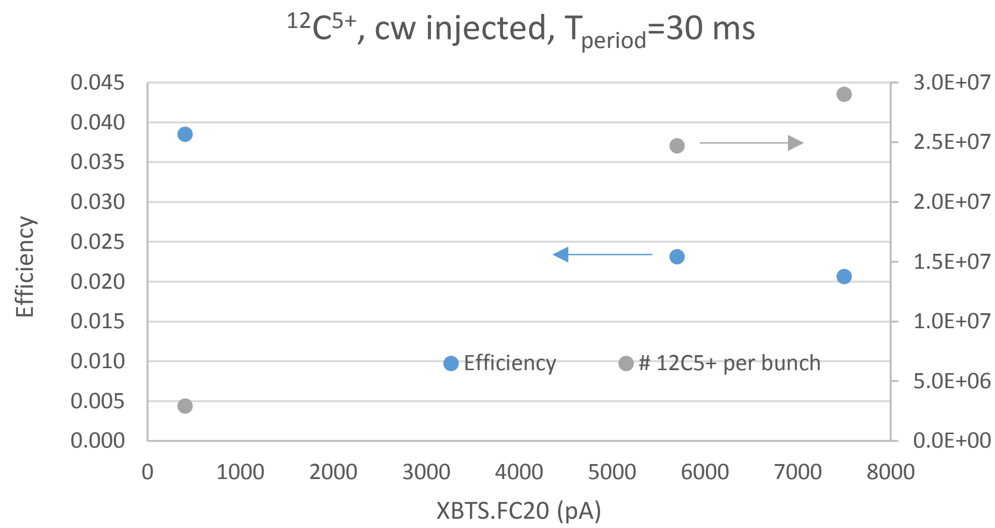

Figure 1. Charge breeding efficiency for $^{12}C^{1+}$ to $^{12}C^{5+}$ for cw injection into the EBIS as function of injected current. The charge breeding time was optimized. Also shown in the plot is the amount of ions extracted per bunch from the EBIS.

Longer accumulation times give rise to higher ion energy caused by electron-ion heating. Thereby part of the ions are lost over the electro-static barrier. This effect may not be problematic for post-accelerators where a relatively high A/Q (>4) can be accepted.

When extrapolating the breeding efficiencies to very high injected beam currents, it was found that only a fraction of the electron space-charge is occupied. For gas ionization one expect that a 50% neutralization (k=0.5) is achievable, while in this measurement series the k-value was one order lower. The main difference is the high injection energy (a few 100 eV per charge) of the externally injected ions compared with gas ionization (typically a few 10 eV per charge).

Summary

The breeding efficiency for carbon, injected as CO+ molecule is at least a factor 2.5 lower for cw injection compared to pulsed injection. A similar ratio has been found for other elements. Recent high ion-current tests at the REX-ISOLDE low-energy stage have shown that the charge breeding efficiency is decreasing with higher beam intensities when cw injection into the EBIS is used. Hence, even though the poor transmission through the Penning trap for high beam currents is circumvented, the overall efficiency does not improve by the use of cw injection into the EBIS. *A preparatory cooling stage is therefore still recommended, although instead of using a Penning trap, a simpler RFQ cooler-buncher is advised.* The case is further strengthened by the fact that even charge breeding systems designed for cw injection, such as the MSU-NSCL EBIT, later added a cooler-buncher in order to improve the breeding efficiency.

To address the increased ion currents expected from EURISOL, where the space-charge limitation in the cooler-buncher will pose problems, the charge breeding repetition rate has to be increased as the number of ions per bunch is inversely proportional to the repetition rate. Shorter charge breeding times is attained by increasing the electron current density inside the EBIS. The MEDeGUN electron gun design [4] aims to increase the current density by a factor 15, and thereby reduce the charge breeding time with a similar value, compared to the present 100-150 A/cm2 at REXEBIS.

References

1. F. Wenander et al, “The REX-ISOLDE charge breeder as an operational machine”, Rev. Sci. Instrum. 77 03B104 (2006).

2. F. Wenander, “Charge breeding of radioactive ions with EBIS and EBIT”, JINST 5 C10004 (2010).

3. J. Pitters, M. Breitenfeldt and F. Wenander, “Charge breeding of CO+ beams at REX-ISOLDE”, Proc. from ICIS 2017, accepted for publication in AIP proceedings.

4. M. Breitenfeldt et al., “MEDeGUN commissioning results”, Proc. from ICIS 2017, accepted for publication in AIP proceedings.