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Radioactive beams at REX–ISOLDE: Present status and latest developments

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Abstract

The ISOLDE charge breeder and post-accelerator REX has been operational for more than 5 years and is now routinely delivering beams to nuclear physics experiments. An overview of the present performances of the machine and a number of recent developments and tests of beam purification techniques are presented in this paper.
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1. Introduction

REX employs a unique combination of a superconducting Penning trap (REXTRAP) and an electron beam ion source (REXEBIS) to charge breed radioactive ion beams from ISOLDE to a suitable mass-to-charge ratio for post-acceleration. This allows for a short (10 m), energy variable, linac to be employed to provide post-accelerated radioactive beams at energies up to 3 MeV/u. The machine has been described in detail elsewhere [1] so only a short summary is given here. The semi-continuous, singly-charged radioactive ion beam from ISOLDE is first injected into REXTRAP which is used to accumulate, cool and bunch the beam. A combination of an energy-loss buffer gas and transverse RF field is used to cool down the ions [2]. The ion bunch is then injected into the EBIS where it is confined radially by the potential well from the electron beam, and captured longitudinally by the electrostatic potential barriers. In the EBIS the ions are charge bred to the desired charge state. The ion bunch is extracted in a short pulse with a small transverse emittance (∼10 π mm mrad, 90%) at an energy of 5 keV/u (linac input energy). The beam is then passed through a mass separator with a resolution of approximately 150, sufficient in most cases to separate the radioactive beam from residual gas beams from the EBIS. Finally, the beam is injected into the linac which is composed of an RFQ injector and six accelerating cavities (IH structures and split ring resonators) which operate at 100 MHz, except for the last structure which operates at 200 MHz.

2. Performance and beam properties

REX has been operational since 2001 and is now routinely delivering beams for physics. Radioactive beams of 53 isotopes covering twenty different elements have been post-accelerated. Beams ranging from Li to U can now be charge bred to mass-to-charge ratios ranging from $A/q = 2.5$ to 4.5. A list of the radioactive ion beams accelerated so far is presented in Table 1. In each case the energy and the breeding time are indicated, and where available, a charge breeding efficiency is given. The beam energy was measured using the bending magnet at the end of the linac

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Table 1
Charge states, energies, breeding times and total efficiencies for all radioactive ion beams post-accelerated at REX–ISOLDE so far

Isotope	Charge state	Energy (MeV/u)	Breeding time (ms)	Efficiency (%)	Year
8Li	3	3.15	18	2.6	2006
9Li	2	2.60	6	4.7	2002, 2003, 2004, 2005
11Li	3	2.90	6	4.1	2004
10Be	3	2.93	15	5.0	2006
11Be	4	2.92	25	5.0	2005, 2006
12Be	4	2.25	18	2.8	2005
17F	5	2.60	18	7.5	2004, 2007
24Na	7	2.30	15		2002
25Na	6	2.30	15		2001, 2002
26Na	7	2.30	15		2001, 2002
27Na	7	2.30	15		2002
28Na	9	2.30	15		2002
29Na	8	2.30	15		2002
28Mg	9	2.15	16		2004
29Mg	9	2.75	28	7.5	2006
30Mg	7	2.70	16		2002, 2003, 2004
31Mg	9	2.75	28	7.5	2006
32Mg	9	2.85	16		2003, 2004
68Ni	19	2.83	98	3.5	2005
67Cu	19	2.99	68	12	2006
68Cu	19	2.83	98	8.5	2005
69Cu	20	2.97	98	9.5	2005, 2006
70Cu	19	2.83	98	8.0	2005
71Cu	20	2.95	98	8.8	2006
73Cu	19	2.88	68	5.1	2006
74Zn	20	2.90	78	1.5	2003, 2004
76Zn	20	2.90	78	1.5	2003, 2004
78Zn	21	2.90	78	1.5	2004
80Zn	21	2.79	78	9.1	2006
70Se	19	2.85	58	3.3	2004, 2005
88Kr	21	2.19	70	1.8	2003, 2005
92Kr	22	2.19	98	1.3	2005
96Sr	23	2.87	120	2.0	2007
122Cd	30	2.85	148		2004
124Cd	30	2.86	248	9.6	2004, 2006
126Cd	31	2.85	248	9.6	2004, 2006
108In	30	2.83	198	3.5	2005
106Sn	26	2.85	98	5.8	2006
108Sn	26	2.85	98	4.3	2005, 2006
110Sn	27	2.80	98	4.4	2004, 2005
138Xe	34	2.85	198	2.4	2005, 2006
140Xe	34	2.84	198	6.0	2005
142Xe	34	2.83	198	2.9	2005
144Xe	34	2.70	198	8.7	2006
140Ba	33	2.84	171	4.5	2007
142Ba	33	2.84	168	5.0	2007
148Ba	35	2.84	230	1.5	2007
148Pm	30	0.30	38		2004
156Eu	30	0.30	38		2003
153Sm	30	0.30	30		2002
184Hg	43	2.85	170	1.7	2007
186Hg	43	2.85	170	1.7	2007
188Hg	44	2.85	170	1.7	2007

Note that the total efficiency includes trapping efficiency, charge breeding into the required charge state and transmission through the REX separator.

and is accurate within approximately ±2%. The breeding times refer only to the time the ion bunch spends inside the EBIS. A cooling time normally equal to the breeding time (but not shorter than 20 ms) should be added to obtain the total hold-up time. The charge breeding efficiencies quoted throughout this article include trapping, charge breeding and transmission efficiency through the consecutive separator but not the transmission from ISOLDE to REX (usually greater than 90%) and the linac transmission. These efficiencies, however, should be taken with some caution as: they have not all been measured in a standardised way (some have been measured directly with radioactive beams while others with stable pilot beams), they can have large error bars (this is especially true for older values), in some cases they do not correspond to optimal values (choice of a short breeding time to obtain a faster repetition rate for example). Indeed, in most cases these efficiencies were recorded during real physics runs with limited set-up times. For further details the reader is encouraged to contact the authors or consult the REX–ISOLDE website [3].

The charge breeder was originally designed for isotopes with $A < 50$ and is in principle limited to low intensity beams (limited by the Penning trap capacity, due to space charge effects). However, recent tests showed that $^{238}U^{52+}$ can be charge-bred with a 4.3% efficiency for a 498 ms breeding time. Furthermore, beams of 3 nA of $^{7}Li^{+}$ have been injected into the trap and charge breed to $^{7}Li^{3+}$ with 1.8% efficiency. This clearly demonstrates the versatility of the technique.

With the present accelerator, beams can be delivered at energies ranging from 300 keV/u (RFQ energy) to 3 MeV/u. The energy can be varied continuously above 1.2 MeV/u by switching on consecutive resonators and increasing the accelerating voltage. The linac is designed for a maximum mass-to-charge ratio of 4.5. However, in practice the maximum energy (3 MeV/u) can only be obtained for mass-to-charge ratios below 3.5 due to the limited RF power available for the last cavity. This means that the effective maximum energy at $A/q = 4.5$ is reduced to approximately 2.8 MeV/u. In the case of light ions, energies slightly higher than 3 MeV/u can be reached e.g. 3.15 MeV/u for $^{8}Li^{3+}$. Heavy ions with mass-to-charge ratios larger than 4.5 can also be delivered but only at RFQ energy (300 keV/u) e.g. $^{153}Sm^{28+}$. The linac maximum energy as a function of mass-to-charge ratio is shown in Fig. 1. Beam requests are most often for the highest possible energy, indicating the need for an energy upgrade of the linac. The linac transmission is typically between 70% and 90%. This is limited by emittance growth in the linac and dispersion in the bending magnet due to the energy spread. For this reason the transverse emittance has recently been measured in an effort to optimise the beam transport through the machine. Emittances were measured at different energies with a beam of Ne^{5+} using a slit-grid emittance meter located approximately 1 m after the experimental target position on the second beam line (i.e. about 2.5 m after the last quadrupole). Contrary to previous emittance measurements [4], these measurements were done with a relatively low intensity

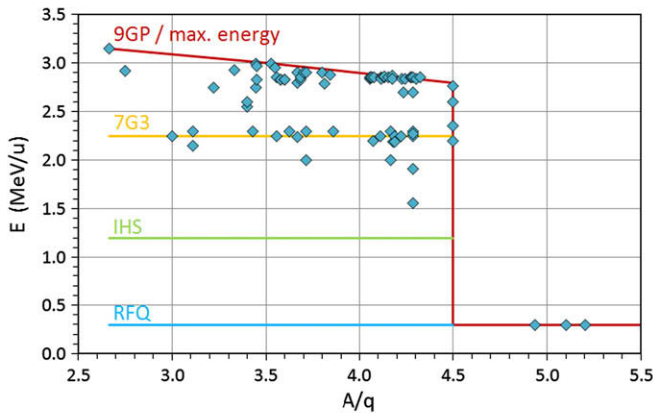

Fig. 1. Maximum linac energy as a function of mass-to-charge ratio. The diamonds correspond to the radioactive ion beams listed in Table 1.

beam (few 100 pA) so the measured emittances represents well typical radioactive ion beams at REX (where the EBIS electron beam trap is not neutralized by the ion beam). Normalised RMS emittances of 0.040 and 0.051 π mm mrad were measured at 1.2 and 2.2 MeV/u, respectively. The emittances were found larger in the horizontal direction than in the vertical direction due to energy dispersion in the bending magnet. The emittance and energy spread at 2.2 MeV/u are shown in Fig. 2.

The length of the extracted ion pulse from the EBIS is also an important parameter for the experiment. In the case of intense beams, or beams requiring long breeding times, it can be interesting to increase the ion pulse length to avoid dead time in the data acquisition system. In a recent test it has been shown that the pulse length can be extended from a typical value of 50 μs to more than 400 μs using a new extraction scheme. This length is only limited by the RF pulse of the accelerator (1 ms) and can in principle be further increased. This so-called "slow extraction" has already been used in several physics runs. A plot of normal and slow extraction pulses can be seen in Fig. 3.

3. Beam purification techniques

A key aspect for most experiments performed at REX is the beam purity. The Resonant Ionisation Laser Ion Source [5] and the molecular sideband technique [6] are now widely used at REX. In the last year a number of new techniques have been tested to remove contaminants from the beam. Among them, a test was carried out to use REXTRAP as a high resolution mass separator. In normal operation REXTRAP is only used for cooling and bunching of the ion beam. The transverse RF excitation is used to couple the reduced-cyclotron and magnetron motions. This is mass dependant and parasitic species can therefore be eliminated at this stage. However, this is not sufficient to separate ions with very close masses. In the newly tested scheme an extra step is introduced after the cooling phase where the ion cloud is shifted out with a mass-independent dipolar RF excitation and only the

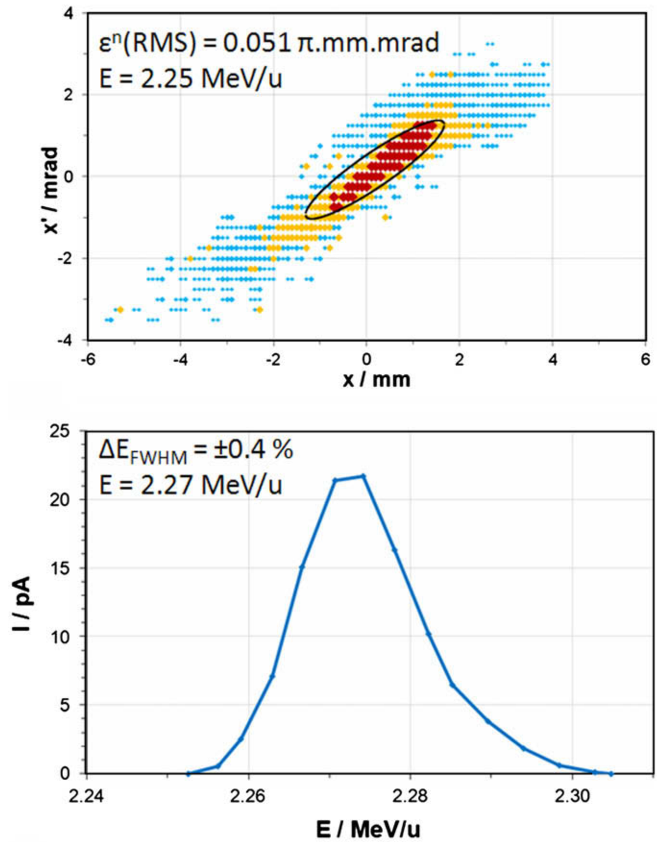

Fig. 2. Transverse emittance (top) and energy spread (bottom) for accelerated REX beams. The emittance was measured in the vertical plane with a 420 pA beam of Ne^{5+} behind the bending magnet after the linac.

desired species is re-centred using quadrupolar excitation. This is depicted in Fig. 4. Similar mass purification techniques are already in use at other ion trap experiments but have never been tried at REXTRAP. A resolving power of up to 3×10^4 has been achieved. Such a mass purification technique would in principle be relatively easy to set up, however, the technique implies a longer trapping time ($\sim$100 ms) and a lower efficiency since ions can not be collected during the cleaning period. More evaluation with radioactive beam is needed to validate the method and to establish the suppression factor. As an example, separation of stable CO^+ and $N_2{}^+$ molecular ions is shown in Fig. 5.

Another technique widely used at REX is electron stripping. Stripper foils can be inserted in the beam between the linac and the last bending magnet to remove contamination from radioactive beams. Different elements will, depending on the Z of the element, be stripped to different charge states permitting separation of the isotopes in the bending magnet. For example, carbon foils of 50 μg/cm^2 thickness have been employed to remove $^{22}Ne^{6+}$ from $^{11}Li^{3+}$ beams. In this case the efficiency was very high since Li is fully stripped and Ne is mostly pushed to higher charge states. In other cases the suppression factor is limited due to the charge state distribution, for instance for $^{8}Li^{3+}/^{16}O^{6+}$. For such cases a new technique has recently been tested

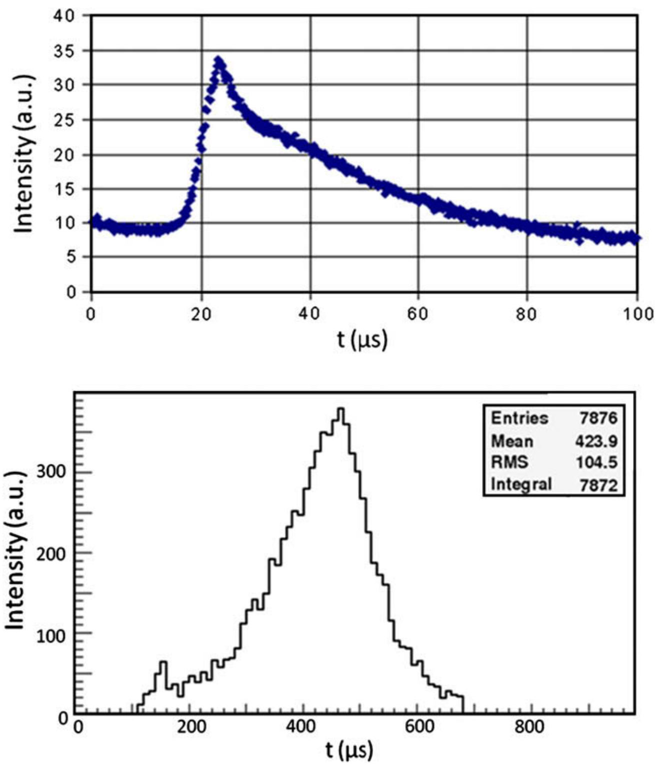

Fig. 3. Pulse shape of extracted beams from the EBIS. Top: normal extraction. Bottom: slow extraction mode.

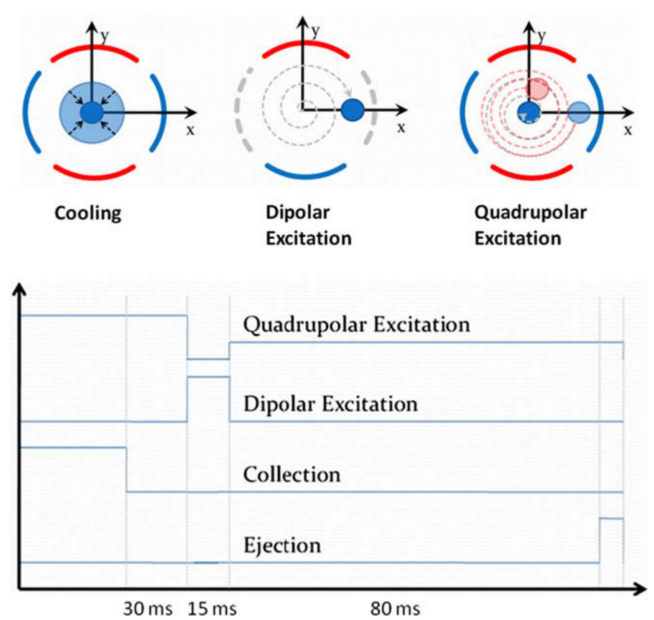

Fig. 4. Top: Trap operation cycle for mass separation. The ion bunch is cooled down with a strong quadrupolar excitation, thereafter shifted off-centre with a mass-independent dipolar excitation. Finally, only the selected mass is slowly re-centred with a weak quadrupolar excitation. Bottom: Time structure and relative length of each step.

making use of the energy selectivity of the linac. In this case, a second very thin carbon foil (4 μg/cm^2) is inserted between the RFQ and first IH cavity. At this energy, 300 keV/u, stripping is not very efficient and most of the ^{16}O ions remain in the 6+ charge state, but the stripping foil introduces a differential energy loss between ^{16}O and ^{8}Li (proportional to Z^2) which prevents ^{16}O ions from being transmitted through the linac. It has been shown that the suppression factor can be increased by a factor 4, as illustrated in Fig. 6. The technique is of course restricted to cases of relatively intense beams, as the intensity can be significantly reduced in the cleaning process.

The beam purity can be monitored at REX using the Miniball gamma array or a Bragg detector located after

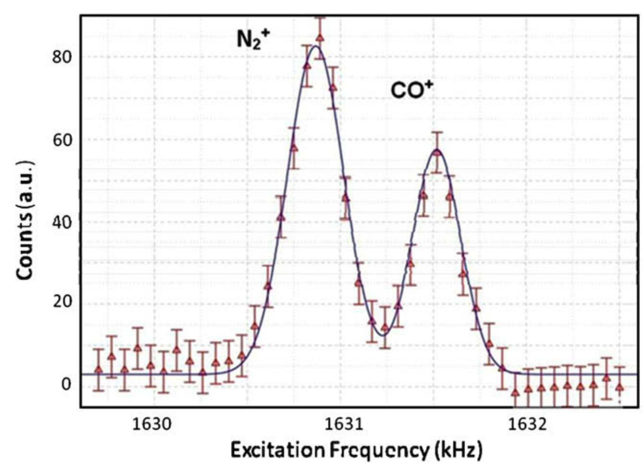

Fig. 5. Excitation resonance spectrum showing the separation of two stable isobaric molecular ions. The injected beam intensities were approximately 2 pA of $^{28}N_2^+$ and 1.5 pA of $^{28}CO^+$ and the efficiency reached was approximately 12%.

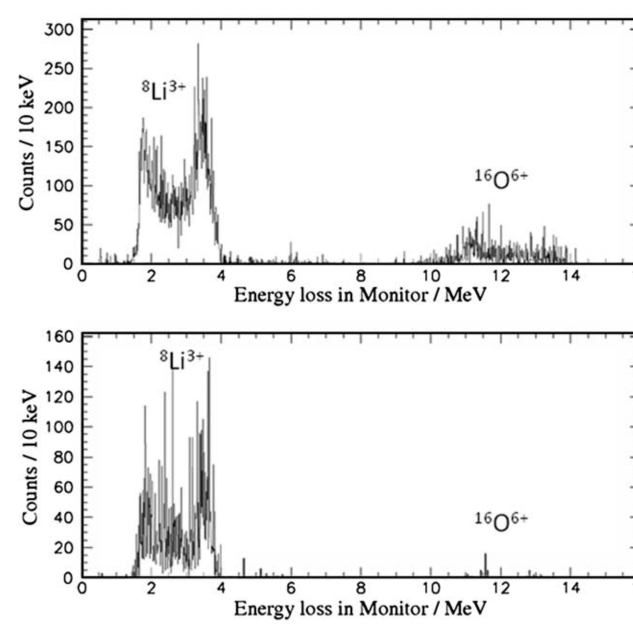

Fig. 6. Relative intensities of ^{8}Li (left peak) and ^{16}O (right peak) at the experimental station without low energy foil (top) and with a 4 μg/cm^2 foil inserted after the RFQ (bottom).

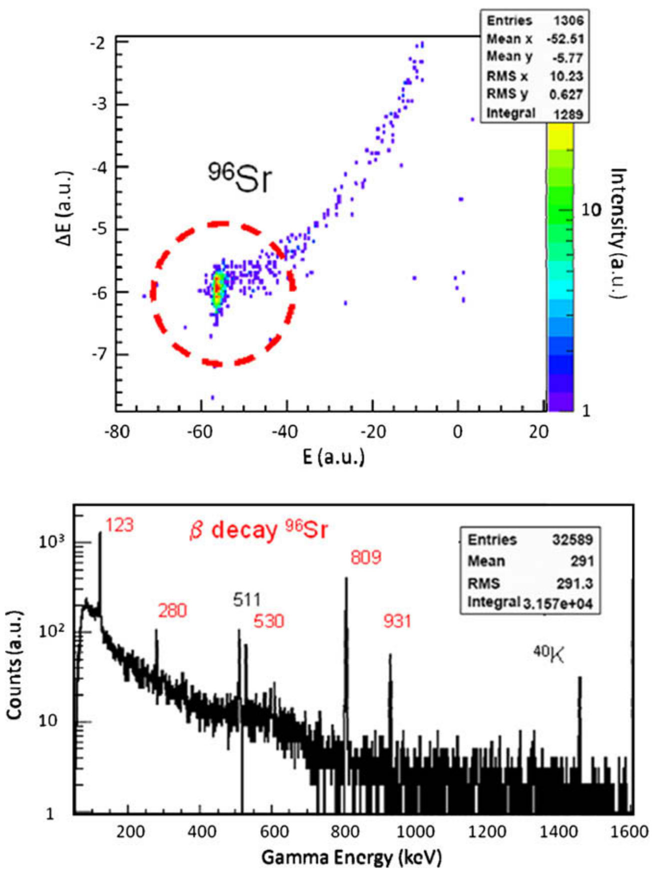

Fig. 7. An example of beam monitoring at Miniball for a beam of ^{96}Sr extracted as a molecular beam (SrF^+) from ISOLDE to avoid isobaric contamination. Top: Bragg spectrum showing the beam composition. Bottom: gamma spectrum of the beam stopped on a thick target in the centre of Miniball.

the experimental target. The gamma spectrum of projectiles stopped in the Miniball target can be used to identify radioactive contamination while stable beam contamination can be monitored with the Bragg detector. An example is shown in Fig. 7.

4. Limitations and radioprotection issues

Strict rules are of course enforced at ISOLDE to ensure that the personnel is not exposed to dangerous doses of radiation. Because of the low intensity of ISOLDE beams (10^3–10^8 s^{-1}) and the limited throughput of the charge breeder, radioprotection is normally not an issue at REX. So far only one experiment have suffered from beam intensity limitation due to radiation limits in the hall. In the rare cases where a high radioactive current (>50 pA) can be produced at ISOLDE, the radiation level is monitored at specific locations (hot spots) mainly near REXTRAP where most of the losses occur (50%). Long lived isotopes or isotopes with long-lived daughters are avoided to limit the permanent contamination along the machine and to avoid background build-up near the experimental target. Another concern is the high level of X-rays produced by the linac itself, in particular by the last cavity which is operated at a higher RF power. This cavity is shielded with a 10 mm thick lead box. This is sufficient to maintain the radiation level below allowed limits in the hall but this is not enough to remove totally the background at Miniball in the low energy gamma region (<300 keV). This situation has been improved after the extension of the experimental hall, which allowed for Miniball to be moved further away from the linac and for extra shielding to be installed.

5. Upgrade and future projects

In the last few years more than one hundred shifts (8 h) of radioactive beams were delivered yearly for nuclear physics experiments at REX. Nevertheless, to meet the requests of a wider experimental programme making full use of the vast range of isotopes available at ISOLDE, higher beam energies and intensities are required. An upgrade plan of REX focuses on three main points [7–9]. First of all, an installation of an RFQ cooler and buncher between the HRS separator and REX post-accelerator allows CW beam injection into the EBIS. Secondly, a staged installation of a new linac reaching eventually 10 MeV/u will boost the ion energy. Finally, an upgrade of the REXTRAP and REXEBIS facilitates higher intensity and faster breeding times.

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