The EPIC project:
Exploiting the Potential of ISOLDE at CERN

The ISOLDE Collaboration input to the EPPS (European Particle Physics Strategy Update)

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Abstract:

The user's community of ISOLDE, CERN's radioactive ion beam (RIB) facility, has been steadily growing in the last 10-15 years, thanks to the increasing range of research fields that opened up when post-accelerated radioactive beams and more isotopes became available (see "Focus on Exotic Beams at ISOLDE: A Laboratory Portrait" [ISOLDE2017]). The demand for beam time therefore outnumbers the current production capabilities. The EPIC project takes full advantage of the recent upgrades at CERN, driven by the LHC Injectors Upgrade (LIU). In particular, the new Linac4 with its higher proton currents and the PS booster with its higher proton beam energies allow expanding the scope of ISOLDE. With a higher proton beam intensity and energy impinging on the ISOLDE target stations, significantly higher radioactive beam intensities are achieved. Additionally, this higher proton current can be divided among two target stations, constructed in such a way that parallel radioactive beams can be delivered to the many low energy (40-60 keV) and high-energy (1-10 MeV/nucleon from HIE-ISOLDE) radioactive beam experiments. This will allow doubling the amount of beam time, which is highly demanded by the continuously growing ISOLDE user's community. Furthermore, ISOLDE aims at attracting new users to take even more advantage of the increased beam time, by constructing a storage ring behind the HIE-ISOLDE post-accelerator. Thus, stored cooled exotic beams from light up to heavy short-lived isotopes will be available and open up new possibilities in the fields of astrophysics, fundamental symmetry studies, atomic physics and nuclear physics. All of these upgrades guarantee that ISOLDE remains a unique facility in Europe and even in the world, as nowhere else a proton driver with these properties is available for producing a very wide range of radioactive isotopes, nor is there a facility that has (or plans) a low-energy storage ring for short-lived isotopes, allowing unique experiments in diverse fields.

Comprehensive overview

1. Scientific Context

In recent European and American nuclear physics long-range plans [NuPECC2017 and NSAC2015], the key questions in nuclear physics research are highlighted. These are ranging from answering very fundamental questions about the origin of the elements (and thus life) to applied research by searching e.g. for efficient production methods for new radioisotopes for 'theranostics', in order to more efficiently cure a variety of cancers.

The field of nuclear physics is about why protons and neutrons can be bound together in many thousands of combinations (called 'isotopes'), thanks to the interplay between three fundamental forces in nature: the electromagnetic, strong and weak forces. While the strong force binds the UP and DOWN quarks inside the protons and neutrons, it is due to the 'effective' strong force between the protons and neutrons that the repulsive electromagnetic force is overcome and different elements and isotopes can be formed. There exists about 350 stable (or very long-lived) isotopes of about 90 elements here on earth, but more than 3500 isotopes of 118 elements have been synthesized at accelerator centers around the world. Yet, more than 6000 isotopes and an unknown amount of elements are predicted to exist, according to modern nuclear theories.

Many of these isotopes play a crucial role in astrophysical processes [Grawe2007]: nuclear reactions drive the evolution of the stars, from where chemical elements (and thus the origin of life) have emerged. One of the key-processes that led to the birth of elements heavier than iron, the so-called r-process, occurs with isotopes that contain a much higher amount of neutrons than protons. A recent "multi-messenger" observation of the gravitational wave signal (GW170817) accompanied by over 50 measurements of various astrophysical and astro-particle detectors pointed to neutron-star mergers as a highly probable site for the r-process. The physics of this observed, so-called Kilo-Nova event is however far from being understood. Many of the involved very neutron-rich isotopes have until now not been produced on earth (grey area on Figure 1, update from 2007) and we rely on nuclear theories to know their properties and to model these nuclear reaction processes (and thus the birth of new elements) in the stars.

Knowing the properties of exotic isotopes is also crucial for the next generation of experiments searching for physics beyond the standard model (BSM), such as dark matter detection, long-baseline neutrino oscillations and neutrinoless double beta decay. All these searches require accurate determination of the associated nuclear matrix elements for specific exotic isotopes, several of which are out of reach for experiments today, and for which we thus rely on the predictive power of nuclear theories.

It is therefore essential that the predictive power of modern (ab initio) nuclear theories is robustly tested against experimental observables that are measured for a wide range of the most exotic isotopes. Thanks to rapid advances in many-body methods as well as available computing power, it is since a few years possible to perform 'ab-initio' theoretical calculations for nuclei as heavy as ^{100}Sn, which paves the way to even heavier nuclei [Mor2018]. These 'ab-initio' calculations rely on effective nucleon-nucleon interactions derived from QCD, using chiral effective field theories (EFT). Such calculations give a sounder foundation to the previous generations of large-scale shell-model calculations that utilize effective nucleon-nucleon interactions based on G-matrix approaches or were derived from fitting to experimental data or to energy density functional approaches parametrized using experimental data.

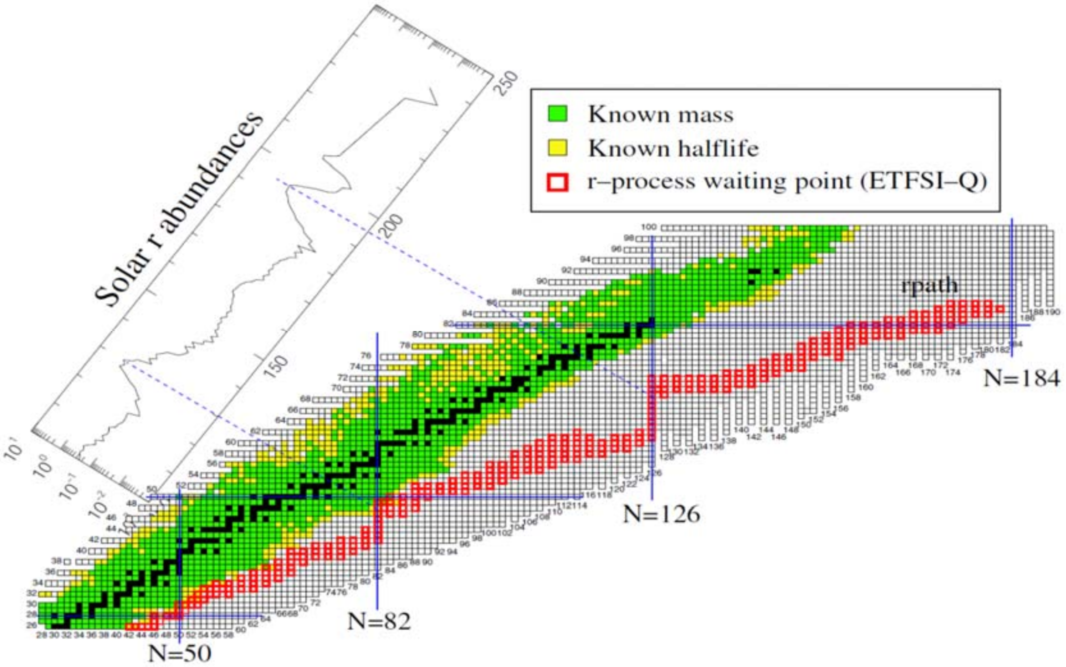


Figure 1: Calculated range of r-process paths, defined by their waiting point nuclei (red) appearing in the yet unexplored region (grey) of the nuclear chart. After decay to stability the abundance of the r-process progenitors produces the observed solar r-process abundance distribution of the elements [Grawe2007].

Transfer reactions and Coulomb excitation reactions, precision laser spectroscopy, mass measurements and detailed decay spectroscopy currently play a key role in developing and testing state-of-the-art nuclear models built on these chiral effective field theories. The majority of the isotopes that are important for testing these nuclear models are unstable and very exotic (thus very rare and difficult to produce) and they require state-of-the-art accelerator facilities to produce them in sufficient quantities.

To produce a wide range of elements (from the lightest to the heaviest) and a wide range of isotopes (from the proton drip line towards the very neutron-rich isotopes), the nuclear physics community relies on complementary accelerator facilities that are using different production methods. Table 1 gives an overview of the major European low-energy nuclear physics facilities, where highly-specialized complementary experimental techniques are used to study a wide variety of nuclear properties. Many of these experimental devices are not movable and are therefore duplicated at the facilities that provide complementary isotopic beams.

ISOLDE produces exotic isotopes with lifetimes above 5 milliseconds (the minimum time needed for the isotopes to diffuse and effuse out of the thick hot production target). The isotopes are produced by the interaction of high-energy protons from the PS Booster (currently at 1.4 GeV and 2 μA) on a primary target. It is the only facility worldwide that provides such high proton beam energies thereby allowing the production of isotopes from the very light (mass 4) up to the heavy actinides (mass 230), both neutron-deficient and neutron-rich. More than 1300 isotopes and isomers have been produced of more than 70 elements in the past 50 years of ISOLDE operation. The isotopes are being produced and ionized in a variety of target-ion source devices, tailored to the element/isotope that is needed. The RILIS laser ion source has proven to be instrumental in the production of many isotopes: it is now used for nearly 70% of all experiments. The ions are extracted from the ion source using a 40-60 kV potential, then separated by mass and sent to a variety of (low-energy) experiments in the fields of nuclear structure, nuclear astrophysics, fundamental interactions and symmetries, atomic physics, materials sciences and life sciences. Since a few years, radioisotopes have also been produced for the development of novel methods for cancer treatment (so-called 'theranostics' or 'alpha-targeted' radiotherapy). Due to the increasing demand from hospitals, the new MEDICIS facility is now available for more advanced and dedicated research on new medical isotopes production.

Since 2001, ISOLDE was the first facility to produce post-accelerated radioactive beams from the lightest to the heaviest elements, using the REX-ISOLDE accelerator, providing beams with an energy of 2.8 MeV/nucleon. That opened the research portfolio of ISOLDE to a very large new user's community: those that use reactions with radioactive beams, mostly for studies of exotic nuclear structures and for nuclear astrophysics research. Indeed, **since post-accelerated radioactive beams became available at ISOLDE, the ISOLDE collaboration has been ever growing: from 10 member countries (and about 400 users) in 2004 to 16 member countries since 2012**, when the energy upgrade of HIE-ISOLDE to 10 MeV/nucleon was agreed upon. **Now ISOLDE has more than 1300 users registered since 2015.**

Table 1: Overview of the major accelerator facilities in Europe producing radioactive beams, along with the radioisotopes that are (or will be) produced in the period 2020-2024, as well as their complementary energy ranges. Note that for GSI-FAIR we consider only the NUSTAR part of the facility (behind Super-FRS).

Facility	Isotopes	Energy range	Availability 2020-2024
ISOLDE – HIE-ISOLDE	1300 isotopes of more than 73 elements, from He to Ac (Z=89), neutron-rich and neutron-deficient. *No refractory elements*	40-60 keV 0.5,1.2,1.55,1.8,2.2MeV/u and 2.8 to 10 MeV/u	7-8 months/year (not 2020)
Jyväskylä (Finland)	Neutron-deficient isotopes and heavy elements up to No (Z=102) from fusion-evaporation, neutron-rich isotopes in mass 80 and 130 regions from ^{238}U fission, *unique for refractory elements and very short-lived isotopes (<10 ms)*	40-60 keV	9 months/year
GANIL (fragmentation)	Most isotopes from He up to ^{238}U, *including refractory elements*	50-80 MeV/u	3-6 month/year
GANIL (SPIRAL 1)	35 isotopes of 7 elements: He, N, O, F, Ne, Ar, Kr from fragmentation, ionized and reaccelerated. Upgrade: +6 new elements from 2020 Na, Mg, Al, P, Cl, K More planned in the coming years.	10-24 keV 1.2 – 20 MeV/u	1-3 month/year
GANIL (SPIRAL 2)	Neutron-deficient isotopes of most elements (including refractory and heavy elements region) from fusion-evaporation at S3	0-60 keV	After 2022
GSI - UNILAC	Super-heavy elements and n-deficient isotopes from fusion-evaporation and	1 – 10 MeV/u	2-3 months/year

	at SHIPTRAP	40 – 60 keV	
GSI – FRS	Isotopes from He up to ^{238}U from fragmentation and fission*, including refractory*	100 – 1000 MeV/u and stopped beams	2-3 months /year
GSI – FAIR (NUSTAR)	Isotopes from He to ^{238}U from fragmentation and fission (with higher primary-beam intensities), *including refractory*	100 - 1000 MeV/u 40-60 keV (LEB)	*From 2025,* 3-4 months/year
Legnaro - SPES	Very intense neutron-rich fission fragments around mass 80 and mass 130	40-60 keV Up to 11 MeV/u	From 2022 From 2023

2. Objectives

2.1 PHYSICS OBJECTIVES

Nuclei are strongly interacting many-body systems that make an astonishing variety of structures and dynamical features. Outlining and explaining them and to obtain key information on the strong interaction at work in the nuclear medium are major tasks for nuclear physics. Another task is to provide precise nuclear data for the many situations where nuclei influence processes in our Universe, from understanding of astrophysical processes to front-edge technologies e.g. in cancer treatment or time-keeping. The third task of nuclear physics research is to employ carefully selected nuclear states as laboratories for testing fundamental physics and searches for BSM physics (symmetries, new forces, …).

We will highlight here a selection of key scientific cases in the fields of astrophysics and tests of fundamental physics and symmetries, which are complementary to the research aims at other CERN facilities, and that require the suggested upgrades, as outlined in section 3. For details on the nuclear structure research goals we refer to the recent NuPECC report [NuPECC2017].

A. ASTROPHYSICS

The energies of re-accelerated beams up to 10 MeV/u excellently suit the study of astrophysical reactions. For instance, the Gamow window in the astrophysical p-process occurring during Supernovae explosions corresponds to center of mass energies of 2-6 MeV/u. This process is believed to be responsible for the production of the about 30 neutron-deficient stable isotopes that are impossible to be created by other (s-, r- or rp-) processes. The p-process involves several hundreds, mostly radioactive, nuclides forming a network of several thousand reactions. Today, only few of the relevant reactions are known for stable nuclei and the modeling of the nucleosynthesis process has to rely on theoretical calculations. The latter are uncertain by at least a factor of three. **With the storage ring installed behind the HIE-ISOLDE post-accelerator, much higher luminosity beams become available, allowing to address for the first time key reactions from the p-process**. Proof-of-principle experiments have been conducted at the ESR storage ring at GSI, where proton capture reactions on stable ^{94}Ru and ^{124}Xe were measured. Further measurements are planned at the ESR and at the low-energy storage ring CRYRING built behind the ESR (as part of FAIR-0), but due to slowing down the isotopes to astrophysical relevant energies the luminosity is often too low. In a storage ring coupled to HIE-ISOLDE, (**short-lived) isotopes can be directly injected into the ISOLDE storage ring at the required energy** and will be intersected with a high-purity internal gas target. The planned capability of the storage ring at ISOLDE will enable us to study all relevant proton- and alpha-induced reactions for the p-process. With additionally an **upgrade of the REX-(normal-conducting) part of the post-accelerator to provide the full**

energy range between 0.3 and 2.8 MeV/u, we can then also perform proton-induced reactions at the center-of-mass energies of the order of 1 MeV/u and lower, thus addressing key reactions for the rp-process of nucleosynthesis in X-ray bursts.

Another astrophysics related research program, deals with determining nuclear charge radii of mirror nuclei. **Those (proton-rich) isotopes will be produced in much higher quantities and thus be available for these detailed studies, thanks to the 2 GeV upgrade of the PSB.** Indeed, properties of finite nuclei have been shown to provide powerful constraints to the properties of nuclear matter, such as the radii of neutron stars and parameters of the equation of state [Hagen16, Brown17]. By measuring charge radii differences between mirror nuclei near the proton dripline, the slope of the symmetry energy of nuclear matter can be constrained with unprecedented precision [Brown17].

B. FUNDAMENTAL SYMMETRIES AND BEYOND STANDARD MODEL (BSM) PHYSICS

High precision measurements of low energy processes provide a powerful tool to explore our understanding of fundamental symmetries and to search for new physics beyond the standard model. While large colliders explore the intensity and energy frontiers, high-precision experiments of nuclear, atomic and molecular properties offer a complementary approach in the search of new physics [Vos15, Sev06, Saf18].

The weak interaction is described in the Standard Model as being composed of a vector and an axial-vector current. All other possible contributions have not been observed and only upper limits for their presence exist today.

Precision measurements of beta-decay processes are intensively used to probe different aspects in our understanding of the electroweak sector of the standard model, e.g, the possible existence of scalar, tensor, or right-handed current contributions to the weak interaction [Dun16], the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [Nav09,Har15], as well as to elucidate neutrino properties [Eng17,KAT10,Hay16]. **ISOLDE has played and continuous to play an important role in this field of research [Sev17]**. Because of their unique nuclear properties, the large variety of beta-decaying nuclei produced at ISOLDE, combined with complementary experimental techniques developed at this facility, offers new and unique opportunities in the study of the beta-decay process. All precision measurements performed at ISOLDE on the most exotic and most interesting isotopes such as ^{10}C, ^{22}Mg, ^{38}Ca [Sev17] are presently statistics limited and **could be significantly improved with up to a factor of 10 higher intensities, thanks to the energy and intensity upgrade of the proton beam.** This would lead to unprecedented sensitivities to non-standard scalar currents and a refined extraction of the V_{ud} element of the CKM matrix [Har15].

Non-Standard-Model contributions to the weak interaction are also searched for by the newly developed WISArD experiment, which has been successfully commissioned just before LS2. It requires an intense beams of the exotic isotopes ^{32}Ar and ^{20}Mg. The current production rate for ^{32}Ar is most likely sufficient to perform a statistically significant measurement, but systematic measurements are needed to search for apparatus and detection-set-up dependent uncertainties. **A beam intensity increase, as well as more available beam time thanks to the construction of new target stations, will guarantee that the final precision will not be dominated by systematic uncertainties**.

Measurements of parity-violation effects and Electric Dipole Moments (EDM) in nucleons, atoms and molecules can probe the violation of fundamental symmetries and probes New Physics many orders of magnitude above the TeV scale [Chu18]. Fluoride molecules, for example, have been identified as suitable physical systems with unprecedented sensitivity in these studies [Bar14, Alt18]. **ISOLDE provides unique access to radioactive molecules such as RaF, which are predicted to have the highest sensitivity to parity-violating effects [Kud14] as well as for**

EDM searches [Sas16]. The first spectroscopic properties in this system [Gar18] have been successfully measured for long-lived ^{223,224,225,226}RaF isotopes, in preparation of future studies of fundamental symmetries (EDM) and parity violation. EDM studies can also be performed using the external solenoidal spectrometer (ISS), which is currently directly coupled to HIE-ISOLDE. In the future**, using the cooled, DC-like beams extracted from the ISOLDE Storage Ring,** it will enable to measure e.g. the E3 transition moment between the parity doublet in ^{225}Ra, that promises the highest sensitivity to atomic EDM measurements on account of its nuclear pear-shape.

Another attractive, fundamental physics related research program, will focus on isomeric states at a few eV excitation energy in ^{229Th} and ^{235}U. The existence of such an isomeric state in ^{229}Th, with an excitation energy in the 10 eV range, was confirmed recently [Wen2016]. This tiny excitation energy, as compared to the total mass of the nucleus of about 229 GeV/c^2, points to an extremely fine matching of fundamental interactions acting inside this isotope, thus creating two states with different quantum numbers at nearly identical energies. A variety of applications of the isomeric state are considered, from ultra-precise nuclear clocks to searches of the variations of fundamental constants. Laser spectroscopic studies on trapped isomers are the tool for such studies. ISOLDE would be the ideal place, due to its rich experience in operating ion trapping and laser-spectroscopy setups. **A beam containing the mixture of ground and isomeric states, produced in nuclear reactions on stable ^{232}Th or ^{238}U targets, can be stored in the ISOLDE storage ring.** One may apply the dielectronic recombination (DR) process, the resonant electron capture, which is sensitive to the nuclear quantum numbers, to identify the isomeric state [Bran2013]. Furthermore, once the DR resonances corresponding to the ground and isomeric states are measured, one can use them to selectively **extract ions in the isomeric state from the storage ring for further investigations in ion traps**. The latter is possible since the atomic charge state and thus the orbit in the ring changes after an electron is resonantly captured. Moreover, ISOLDE offers unique possibilities to populate the ^{229,m}Th isomer via the beta decay of ^{229}Ac (T/2~1 h), **provided the actinium beam intensity can be increased**. This should allow to determine a more precise value of the isomer's excitation energy, necessary for the numerous laser applications through VUV spectroscopy as well as to investigate essential steps towards the development of nuclear clocks based on solid-state catchers.

2.2 TECHNICAL OBJECTIVES

A. IMPROVE EXPLOITATION OF EXISTING INFRASTRUCTURE AND INCREASE THE INTENSITY OF EXOTIC ISOTOPES. One of ISOLDE's strengths is its ability to routinely deliver high intensities of a wide range of short-lived isotopes, with half-lives down to 5 ms. This is enabled by the relatively high energy of the PS-Booster beam, unmatched at any other ISOL facility around the world. The accelerators upstream and downstream of the ISOLDE isotope production represent a sizable investment with unique capabilities. The 2 GeV, 4 μA beam from Linac-4 and the upgraded PS-Booster represents the culmination of many years of effort and investment at CERN; likewise the REX-HIE-ISOLDE linac has been built, developed and upgraded over approximately 20 years thanks to the collaboration between CERN and the ISOLDE Collaboration. A final upgrade of the REX-part of the post-accelerator will allow producing post-accelerated beams in the full energy range between 0.3 and 2.8 MeV/u, where now only a few discrete values are accessible. Accepting 2 GeV beams at ISOLDE will further distinguish ISOLDE from other ISOL facilities, currently in construction and focusing on higher beam power but lower energy driver beams.

B. MULTIPLE SIMULTANEOUS AND HIGHER QUALITY BEAMS. ISOLDE's high reliability and flexibility is one of the features that make it so attractive to its diverse research community. An upgrade of the ISOLDE targets and isotope separators would increase the overall employment of this investment for nuclear and applied research fields. Our proposal to build a new target-and-isotope-separator area would greatly improve ISOLDE's operating efficiency and flexibility, which is key to running the many short and diverse experiments that use ISOLDE beams. Beam-time for experiments would be doubled. The proposed ISOLDE upgrade includes also a modern high-resolution mass separator for routine isobar separation. This would enable a wider range of low-background and precision experiments to be carried out.

C. A NEW STORAGE RING FOR LIGHT AND HEAVY IONS coupled to the HIE-ISOLDE post-accelerator will provide a major increase in the luminosity for nuclear reactions, which is essential for the most challenging experiments. It will allow for experiments that are nowhere else in the world possible, as it is coupled to a 'low-energy' post-accelerator.

D. MEET AND EXCEED MODERN RADIO-PROTECTION STANDARDS. Increased beam intensities mean higher levels of radioactivity in the target and isotope separator areas. Construction of new target areas would permit adoption of completely new handling technologies to reduce the need for manual maintenance and repairs.

3. Methodology

The demand for beam time at ISOLDE outnumbers the current production capabilities. More than 80 approved experiments will not have been performed when LS2 starts and these experiments cannot be performed at another facility. To cope with this, as well as with the ever growing users community, the ISOLDE Collaboration proposes a next upgrade of its facilities.

The EPIC project presented here consists of a combination of upgrades of existing facilities as well as the construction of new facilities. It will transform the capacity and capability of the ISOLDE facility at CERN to deliver radioactive ion beams to a wider international community of scientists, impacting the fields of nuclear physics, astrophysics, fundamental symmetries and beyond standard model physics, materials science, atomic physics and life science.

A. ENHANCING THE PRODUCTION AND CAPABILITY OF ISOLDE is possible thanks to the increase of the driver beam energy to 2 GeV and an increase in proton intensity through the new LINAC4 driver, thus taking advantage of the LIU upgrades for the CERN Linac and Booster. The production capacity can be increased in two ways:

(a) by the installation of **new beam dumps** to cope with the higher beam powers and the installation of **new bending magnets between the booster and ISOLDE** to allow the 2 GeV beam to be sent to ISOLDE. The increase of the proton energy from 1.4 GeV to 2 GeV results in an increase of the production of short-lived nuclei, in particular those produced in the spallation process, at the limits of nuclear existence.

(b) by building **two additional new high-power target stations**. These will be used in such a way as to enable de-coupled parallel operation of the low-energy (40-60 keV) and high-energy (HIE-ISOLDE) facilities, which will double the available beam time, enabling a larger number of more challenging experiments to be performed. That is even more important in case the third component of this project is realized (a storage ring coupled to HIE-ISOLDE), as this will attract a new users community.

B. UPGRADE OF REX/HIE-ISOLDE ACCELERATOR, in order to allow re-accelerated beams in the full range of energies between 0.3 and 2.8 MeV/u by an upgrade of the 20-years old normal-conducting REX-part of the post-accelerator. This is crucial for astrophysical reaction studies relevant for the rp-process in X-ray bursts. Using the subsequent, recently commissioned superconducting HIE-ISOLDE Linac, beams can be further accelerated from 2.8 to 10 MeV/u.

C. INSTALLATION OF A LOW-ENERGY STORAGE RING at an ISOL-type radioactive beam facility will be the first of its kind and it will provide a capability for experiments with stored secondary beams that is unique in the world:

stored short-lived isotopes with lifetimes below 100 ms and high luminosity will be available for the first time. The envisaged physics program is rich and varied, spanning from investigations of nuclear ground-state properties and reaction studies of astrophysical relevance, to investigations with highly-charged ions and pure isomeric beams [Grie2012]. The storage ring might also be employed for removal of isobaric contaminants from stored ion beams and for systematic studies within the neutrino beam program. In addition to experiments performed using beams recirculating within the ring, cooled beams can also be extracted for use in external spectrometers for high-precision measurements. The ring with a circumference of about 40m will be able to store highly-charged ions with intensities up to several 10^8 ions and energies between a few 100 keV/u up to 10 MeV/u. Beam cooling is provided by an electron cooler. Storing, accumulation and separation of heavy daughter nuclei, created in nuclear gas target reactions inside the ring, should be possible to allow astrophysical experiments, which were not possible so far.

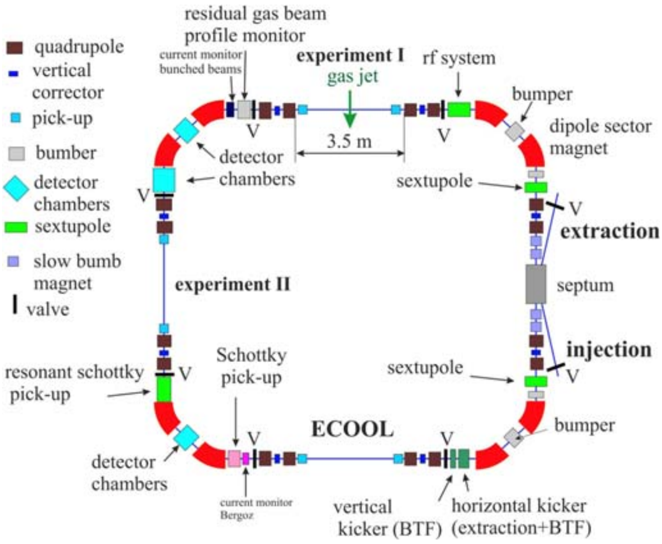
4. Readiness and expected challenges

The design and implementation of new bending magnets for the proton-beam transfer line from the BOOSTER to ISOLDE are well within CERN's technical competencies. For the **design of the new beam dumps** one can rely on the competences and experiences gained with the new beam dumps constructed at the PS-Booster within the LIU project.

The upgrade of REX/HIE-ISOLDE to obtain an energy range of 0.3MeV/u to 10MeV/u includes the replacement of the 7-GAP and 9-GAP normal conducting rf-cavities of REX-ISOLDE, as well as an upgrade of the IH-structure. It also includes the installation of a buncher/chopper which will provide the possibility of delivering micro-bunches with 100ns spacing (10MHz), instead of the natural 100 MHz frequency of the LINAC, while maintaining the beam intensity and the low background between bunches. An R&D program will be required for the buncher/chopper and for defining the best strategy for the upgrade of the rf-cavities and IH-structure. ISOLDE and CERN can build upon recent experience from the HIE-ISOLDE project for the production of 2 low-beta cryomodules, in particular for the manufacturing of niobium coated copper cavities for which CERN has gained considerable expertise. One drawback of adding two more cryomodules is the limited amount of available He-cooling power at ISOLDE: an **upgrade of the cryogenic cooling plant** should then be part of the HIE-ISOLDE upgrade project.

A lifetime of experience on ISOL-type target stations will be **beneficial to the design of the new target stations**. Similarly, ISOLDE will build upon a wealth of experience from collaborating institutes for secondary beam mass separation and beam transfer; the Ariel project at TRIUMF, Canada e.g has a considerable overlap with future beam transport objectives.

The idea of a **storage ring dedicated to post-accelerated radioactive ion beams** has been circulating for a few years [Greiser 2012]. Representatives from Max Planck Institute für Kernphysik (MPI-K), Heidelberg have proposed a new compact version (40m circumference) that maintains all the functional specifications required for the physics program with HIE-ISOLDE beams. Initial integration studies show that the so-called **ISOLDE Storage Ring (ISR)** is compatible with the ISOLDE experimental hall layout with a minimum of civil engineering modifications.



References

[Alt18] E. Altunta et al., Phys. Rev. Lett. 120, 142501 (2018), Demonstration of a sensitive method to measure nuclear-spin-dependent parity violation.

[Bar14] J. Barry et al., Nature 512, 286 (2014), Magneto-optical trapping of a diatomic molecule.

[Bran2013] C. Brandau et al., Physica Scripta T156, 014050 (2013), Probing nuclear properties by resonant atomic collisions between electrons and ions.

[Brow17] B.A. Brown, Phys. Rev. Lett. 119, 122502 (2017), Mirror charge radii and the neutron equation of state

[Chu18] T. Chupp et al., Rev. Mod. Phys. (accepted) arXiv:1710.02504, Electric dipole moment of atoms, molecules, nuclei, and particles.

[Dun16] M. Dunlop et al., Phys. Rev. Lett. 116, 172501 (2016), High-precision half-life measurements for the superallowed β+ emitter ^{10}C: implications for weak scalar currents.

[Eng17] J. Engel et al., Rep. Part. Phys. 80, 046301 (2017), Status and future of nuclear matrix elements for neutrinoless double-beta decay: a review.

[Gar18] R. Garcia Ruiz et al., "Collinear resonance ionization spectroscopy of RaF molecules" INTC-P-546 (2018).

[Grawe2007] H. Grawe et al, Rep. Prog. Phys. 70 (2007) 1525, Nuclear Structure and Astrophysics.

[Greiser2012] M. Greiser et al., Eur. Phys. J. Special Topics 207, 1-117 (2012), Storage Ring at HIE-ISOLDE: Technical Design Report.

[Hage16] H. Hagen et al., Nature Physics 12, 186 (2016), Neutron and weak-charge distributions of the ^{48}Ca nucleus.

[Har15] J.C. Hardy, I.S. Towner, Phys. Rev. C 91 (2015) 025501

[ISOLDE2017] Focus on Exotic Beams at ISOLDE: A Laboratory Portrait, special issue of J. Phys. G44 (2017) http://iopscience.iop.org/journal/0954-3899/page/ISOLDE%20laboratory%20portrait

[Hay16] A.C. Hayes, P. Vogel, Ann.Rev.Nucl.Part.Sci. 66 (2016) 219-244, Reactor Neutrino Spectra

[KAT10] KATRIN Coll., Nucl.Instrum.Meth. A623 (2010) 442-444, The KATRIN Neutrino Mass Experiment

[Kud14] A.D. Kudashov et al., Phys. Rev. A 90, 052513 (2014), Ab initio study of radium monofluoride (RaF) as a candidate to search for parity- and time-and-parity violation effects.

[Mor2018] T.D. Morris et al., Phys. Rev. Lett. 120, 152503 (2018), Structure of the Lightest Tin Isotopes.

[Nav09] O. Naviliat-Cuncic and N. Severijns, Phys. Rev. Lett. 102, 14230 (2009), Test of the conserved vector current hypothesis in T=1/2 mirror transitions and new determination of |Vud|.

[NSAC2015] The 2015 NSAC Long Range Plan for Nuclear Science https://science.energy.gov/np/nsac/

[NuPECC2017] The 2017 NuPECC Long Range Plan: Perspectives in Nuclear Physics http://www.nupecc.org/index.php?display=lrp2016/main

[Saf18] M.S. Safronova et al., Rev. Mod. Phys. 90, 025008 (2018), Search for new physics with atoms and molecules.

[Sas16] S. Sasmal et al., Phys. Rev. A 93, 062506 (2016), Relativistic coupled-cluster study of RaF as a candidate for the parity- and time-reversal-violating interaction.

[Sev06] N. Severijns et al., Rev. Mod. Phys. 78, 991 (2006), Tests of the standard electroweak model in nuclear beta decay.

[Sev17] N. Severijns et al., J. Phys. G: Nucl. Part. Phys. 44, 074002 (2017), Weak interaction physics at ISOLDE.

[Vos15] K.K. Vos et al., Rev. Mod. Phys. 78, 1483 (2015), Symmetry violations in nuclear and neutron β decay.

[Wen2016] L. v.d. Wense et al., Nature 533, 47 (2016), Direct detection of the Thorium-229 nuclear clock transition.

Addendum

1. Interested community

The users community at ISOLDE has been growing in the past 15 years, from about 500 up to **more than 1300 ISOLDE users today** (the last counting was performed by the users office in summer 2018 and includes persons registered as a user since 2015). In Fig. A1 we represent the 27 European and 16 non-European countries that have representatives in the very diverse research program of ISOLDE. The countries with more than 50 (European) and more than 10 (non-European) users are indicated in bold with their numbers given in the pie.

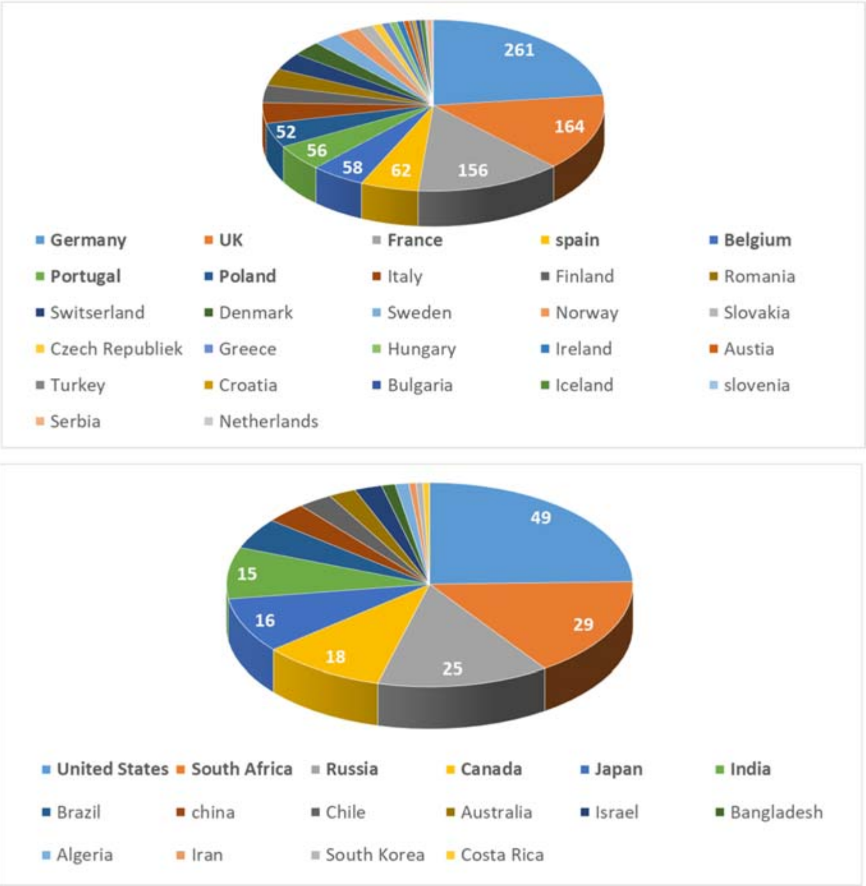


Fig. A1: The users community at ISOLDE: 1314 users registered since 2015, from 43 countries.

The ISOLDE Collaboration is organized via a MOU, in which also CERN is a partner. There are currently 16 member countries who pay a yearly membership fee, which is used for the payment of common investment and operational costs of the facility (administration, technical support to users, contribution to HIE-ISOLDE construction, support of young researcher long-term stays). Each member country has a representative in the ISOLDE Collaboration Committee (ISCC) which meets 3 times per year and agrees on common issues of the collaboration. This meeting takes place the day before each INTC meeting, where new proposals for experiments are presented. Users from non-member countries can propose experiments at ISOLDE, as a co-spokesperson of a user from a member country.

At the end of the current running period, there will be more than 80 active experiments, endorsed by the CERN research board, waiting for beam time after LS2. Those experiments are in the following fields: reaccelerated beams using HIE-ISOLDE (42), mass measurements with ISOLTRAP (4), laser spectroscopy measurements for nuclear and atomic physics research (7), decay spectroscopy studies (5), (soft, bio and hard) materials research (10), medical isotope production (3), others (10). During the LS2, the relevance of each active research program will be re-evaluated by the INTC, as some of these experiments have been endorsed more than 6 years ago.

However, as many of the beams provided by ISOLDE are unique worldwide (both in intensity and in energy and purity), most of these experiments cannot be executed elsewhere and remain relevant after LS2.

Furthermore, **with the construction of a storage ring at ISOLDE, a whole new users community will be attracted**. Groups now active at e.g. the ESR (and soon also CRYRING) at GSI-FAIR will be interested to extend their research portfolio by using the short-lived stored exotic beams at ISOLDE.

2. Timeline

The beam dump replacement, new target stations and the ISR require a significant amount of civil engineering. For the latter, once the building extension of the experimental hall is complete, the installation of the ISR will have little impact on ISOLDE operations. However, for other civil engineering work, the operational downtime of ISOLDE will be in the order of 2-3 years. To minimize the impact on operations at ISOLDE, the proposed upgrades should therefore overlap with CERN’s long shutdown periods.

There are two possibilities to address the installation of the low-beta cryomodules and buncher/chopper. The first would be to complete the installation during a long shutdown period thus having no impact on HIE-ISOLDE operations. The second would be to have a similar approach to the high-beta cryomodule installation where one cryomodule was installed in January and commissioned by June of the same year. This results in a loss of 3 months per year for HIE-ISOLDE physics but is more compliant with the manufacturing process. During this process, low-energy experiments could still be conducted at ISOLDE.

In figure 2, a schedule based on the next long shutdown at CERN, LS3, is presented.

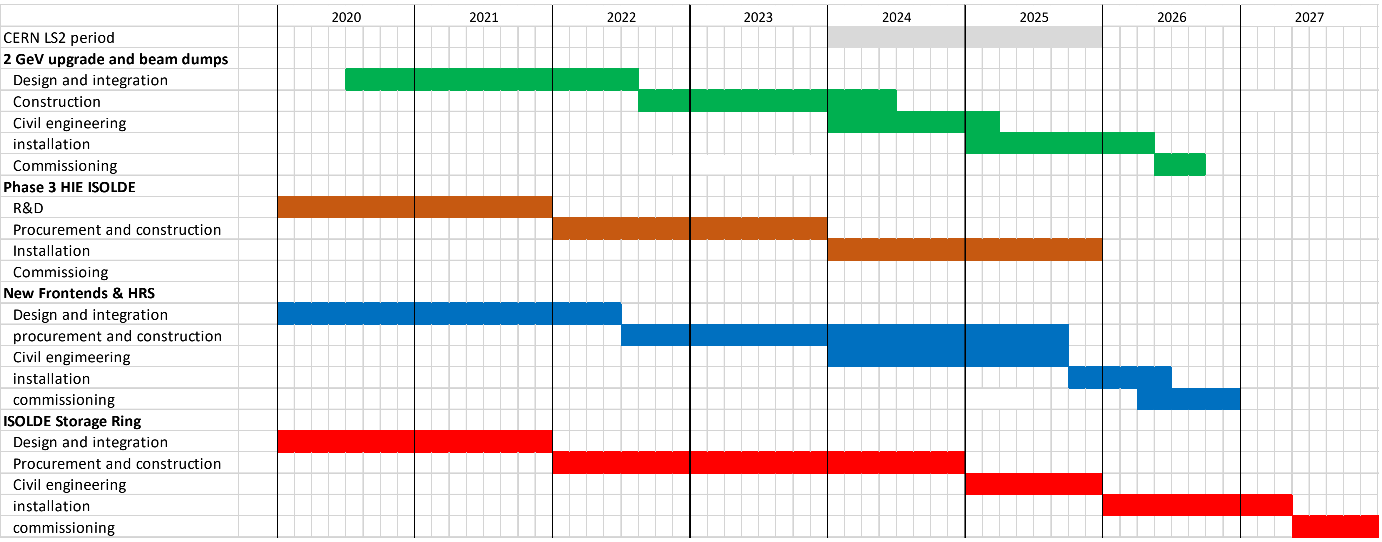


Figure 2. A proposed schedule for the EPIC project based on the CERN's long shutdown 3.

3. Construction and operational costs

Table 2 below provides an estimate of the construction costs for the EPIC project. The financial and manpower costs for the ISR are quite well defined and are partially extracted from the Storage Ring at HIE-ISOLDE TDR. Similarly, the phase 3 of HIE-ISOLDE figures correspond to those announced in the initial HIE-ISOLDE project. The beam dumps and target station figures however, require further refinement within a TDR for the EPIC project. It is worth noting that up to 100FTE can be recuperated through collaborations with institutes outside of CERN; all of whom are either working on similar aspects of the project or have an indirect interest in the R&D.

Items	Cost kCHF	FTE	Comments
Beam dumps and 2 GeV	9,000	15	Includes civil engineering for the existing beam dumps, 4 beam dumps and bending magnets
Phase 3 HIE-ISOLDE	8,000		Includes beam chopper, 2 low Beta cryo-modules and refurbishing of cooling plant
Target stations and HRS	67,000	400	2 new target stations, pre separators , HRS, RFQ Cooler, beam lines, civil engineering, shielding and cooling and ventilation, additional laser laboratory
ISR	17,000	46	Procurement of all ISR equipment and hall extension
Total	**101,000**		

Operational costs in terms of resource requirements following the implementation of the EPIC project can be divided into 4 categories; target production and characterization, machine supervisors, handling and CERN service groups.

Target production and characterization is currently done by four technicians (staff) and four senior scientists (I staff and 3 Fellows/Doctoral students). Following the implementation of the EPIC project, a doubling of target production will be needed. In terms of manpower, this relates to two more target production technicians and two more scientists for characterization. Note that the target production budget is expected to increase by approximately 50%.

There are currently six machine supervisor staff operating the facility, supported by one or two Fellows/students. At least two extra staff will be required to operate the ISR and two more to account for the overall increase in beam lines when the two additional target stations will be operational.

Remote handling of target units can be expected to increase by 50% and this should be reflected in the number of technicians required to operate the facility. This would imply a 1 FTE technician instead of the current 0.75 FTE.

The CERN service groups cover radiation protection, power converters, vacuum, cooling and ventilation, beam diagnostics etc and with the exception of radiation protection accounts for approximately 0.1 FTE per year per service. An increase of 10% in FTE and costs can be expected across all services.

These figures are an approximation and will be further refined within the TDR of the EPIC project.

4. Computing requirements

No particular.