THE FIRST STEPS TO EURISOL*

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On behalf of the EURISOL Design Study

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Following the results and recommendations of the EURISOL RTD conceptual design study performed within FP5, the EURISOL Design Study `http://www.eurisol.org` aims to carry out detailed engineering-oriented studies and technical prototyping work for the next-generation ISOL Radioactive Ion Beam (RIB) facility in Europe. Such a world-class facility, complementary to the "in-flight" FAIR facility being constructed at GSI, is expected to come into operation in the next decade. It would provide unique world-class research opportunities in nuclear physics, nuclear astrophysics and other applications of radioactive beam science. The Design Study addresses the major technological problems which are expected to arise in the creation of a facility able to provide exotic ions in quantities which are orders of magnitude higher than those currently available anywhere else in the world. A feasibility study into the use of the EURISOL facility for the production of pure electron-neutrinos is an integral part of the design study, the so-called "beta-beam" proposal. Synergies which exist between the proposed infrastructure and other European ISOL developments — MAFF, HIE-ISOLDE, SPES, and SPIRAL2 — will be exploited to mutual advantage. Twenty institutes within Europe take part in the design study as full participants, with an additional 20 in Europe, North America and Asia collaborating in the project. In this Design Study the members of the collaboration provide specific technological expertise on superconducting linear accelerators, high-power targetry, RIB production, ion sources and beam manipulation, radiation safety and nuclear instrumentation.

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1. Introduction

Radioactive Ion Beams (RIBs) can be produced either by the ISOL (Isotope Separator On-Line) method or by the complementary "in-flight" method. The new infrastructure EURISOL [1], the next-generation ISOL RIB facility in Europe, aims at the provision of high intensity beams of radioactive nuclei with variable energy, from a few keV to greater than 100 MeV/u. These beams of exotic ions will be orders of magnitude more intense than those currently available. EURISOL will provide a facility for research that addresses the major challenge of the fundamental understanding of nuclear structure in terms of the underlying many-body interactions between hadrons. Descriptions of nuclei having more than a few nucleons are semi-phenomenological in origin and cannot be reliably applied to nuclei far from stability. It is therefore crucial to measure the properties of nuclei at the extremes of stability such as the evolution of shell structure, $T = 0$ and $T = 1$ pairing, and collective phenomena such as halo effects and pygmy resonances. EURISOL also aims at understanding the universe through its history of stellar activity and galaxy formation where nuclear reactions play essential roles. In particular, in the violent maelstrom of explosive processes such as novae, X-ray bursters and supernovae the heavy elements are made in complex networks of reactions (r- and rp- processes) on unstable nuclei and beta decays. To understand these processes quantitatively and identify the astronomical sites where they occur requires a wealth of information on unstable nuclei. EURISOL, with its broad range of beams, will allow us to study many of the key reactions. Further applications of EURISOL to fundamental tests of the Standard Model, to the application of unique probes for surface science and condensed matter studies, and to other fields can be found in an early conceptual design report for EURISOL [2]

Another capability of EURISOL is the beta-beam facility, which will address the main challenges of neutrino physics: the measurement of the mixing angle θ_{13} of the Maki–Nakagawa–Sakata–Pontecorvo matrix (a fundamental parameter of the standard model of interactions) and the search for CP violation in the lepton sector. These measurements, which require intense neutrino beams of defined flavour accompanied by large detectors located at a distance corresponding to the maximum of the observed oscillations, will provide the key ingredient of leptogenesis scenarios for explaining the matter–antimatter asymmetry in the universe.

The EURISOL facility will provide a uniquely broad range of radioactive ion beams with intensities on average three orders of magnitude larger than current ISOL installations and with unrivalled flexibility in final energy between a few eV and more than 100 MeV/u. In this energy domain, unmatched beam quality will be offered so that our knowledge of nuclei far out towards the drip-lines can approach the precision of that of the stable nuclei. This advancement of performance compared to present-day ISOL facilities will be accomplished through major technical breakthroughs concerning several key components: primary beam power of 5-MW protons of 1-GeV energy; a direct target accepting up to 100 kW beam intensity; a multi MW target station based on Hg liquid proton to neutron converter and UCx production target; a CW linear post-accelerator for heavy ions delivering a continuous choice of energies up to 150 MeV/u. This will also permit fragmentation of the RIBs to produce even more exotic, neutron-rich nuclei. The main objectives of the Design Study is to demonstrate the feasibility of these components, and to design, construct and test prototypes for the most technically challenging parts. This will overcome the main limiting factors for carrying out cutting-edge research at the present ISOL facilities: the driver beam intensity, the target and ion-source technology and safety related issues and the energy of the post-accelerated beams. At present the first two limit the intensity and 'exoticity' of the available beams, while the third limits the scope of the research methods that can be utilised. It is expected that EURISOL will provide, for example, final intensities of approximately 10^9 pps of ^{11}Be or 10^{12} pps of ^{132}Sn after post-acceleration. The schematic layout of the EURISOL facility which shows the main components (driver accelerator, production targets, post accelerator and experimental areas) is displayed in Fig. 1.

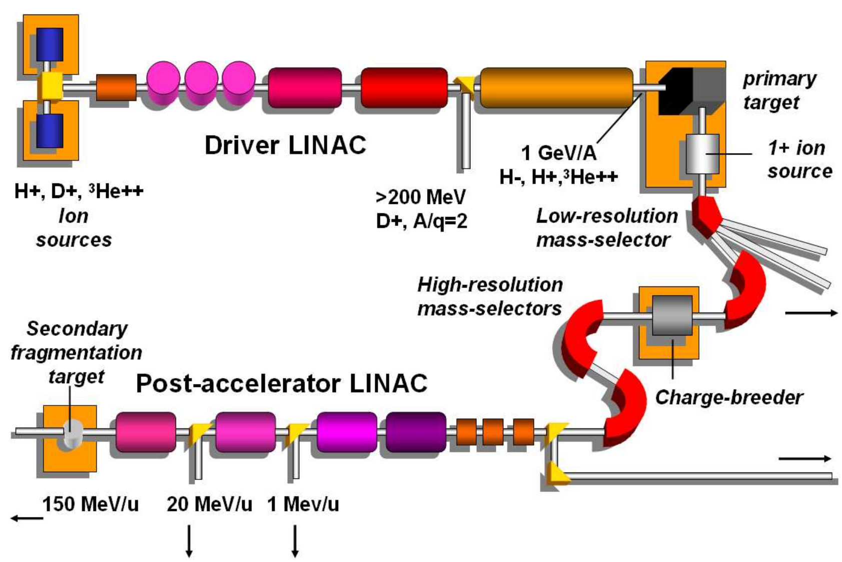

Fig. 1. A possible schematic layout for a EURISOL facility.

In total forty research institutions from twenty-three countries are participating in and contributing to this Design Study. These laboratories and universities have the technical and scientific expertise necessary for the construction of EURISOL and will eventually benefit from the research opportunities offered by the facility. The accelerator laboratories Louvain-la-Neuve, CERN (REX-ISOLDE and HIE-ISOLDE), GANIL (SPIRAL1 and SPIRAL2), INFN Legnaro (SPES), INFN-LNS (EXCYT), and MLL Munich (MAFF) will contribute from their experiences learnt from the development of existing or planned mid-term RIB projects at these laboratories, and in turn will benefit from the EURISOL R & D programme. Laboratories with existing and proposed ISOL facilities in Canada and the US — TRIUMF, ORNL, ANL, and MSU — will also contribute to the EURISOL design study.

2. Objectives of the Design Study

The work of the Design Study has been divided into a number of tasks devoted to research and development in the various aspects of the facility, summarised in figure 2.

The EURISOL 5th framework report [2] concluded that linear accelerators are the best option for both the driver and the post-accelerator. The driver should be optimised for the acceleration of (up to) 5 mA of 1 GeV protons, but heavy ion acceleration capability for $A/q = 2$ and possibly

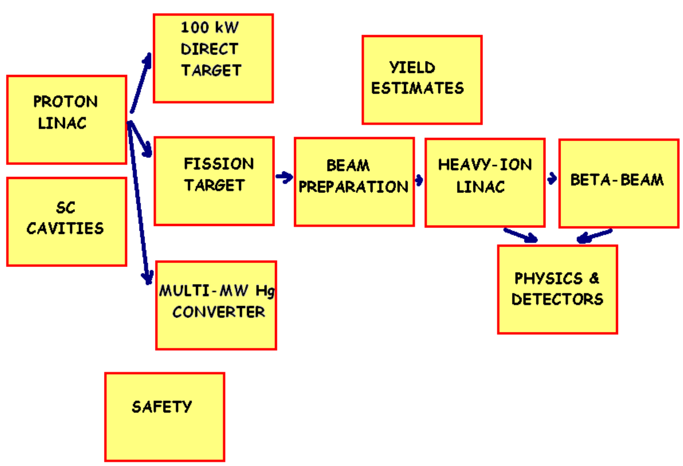

Fig. 2. Scheme of research and development tasks within the EURISOL Design Study.

$A/q = 3$ should be considered. No accelerator today is capable of such proton beam intensity in CW mode. Two R & D items that have high priority are the construction of complete prototype accelerator cryostat with low-β elliptical SCRF cavities and the development of prototypical spoke, quarter wave and re-entrant cavities with associated auxiliary RF components. The post-accelerator must accelerate heavy ions up to uranium at energies reaching 100 MeV/u or greater, in which the necessary development of SC cavities and RF systems is necessary. The accelerator-related tasks are:

Proton accelerator. This task will define a complete linac design with detailed beam dynamics studies and optimisation including complete beam loss calculations. While the SC linac design in the section above 100 MeV will benefit from previous work and development for accelerators which are under construction (SNS), the 5–100 MeV (superconducting) section will require an innovative design including novel low-β cavity and cryomodule technology, and beam dynamics schemes.

Heavy ion accelerator. This task will provide a complete design of a linac with emphasis on low beam losses and meeting the user requirements. Several types of RFQ will be studied (both room temperature and superconducting) and a detailed comparison of the various solutions will be reported. An operational prototype of the room temperature cavity and the injection beam line including buncher will be built and compared with SC options, and innovative diagnostic systems for very low intensity beams will be developed.

Cryomodule development. Research on SC cavities for linacs is actively being pursued in many laboratories throughout Europe where the emphasis is on high energy components. The aim of this task is to develop and build prototypes of the most promising cavity designs for the low and intermediate energy part of the proton driver linac, which could also be used in the heavy ion accelerator. A fully equipped modular cryostat (*i.e.* with tuner and coupler) which could be adapted for the testing of any cavity type will be constructed, and a complete versatile cryomodule, able to accept 3 SC cavities of several geometries (HWR, spoke, *etc.*) will be delivered.

In order to be able to benefit fully from the unmatched beam power delivered by the driver accelerator, the design of innovative target stations accepting large beam intensities and exhibiting fast release times is crucial. These targets must be coupled to efficient and selective 1+ ion sources. The centrepiece of the EURISOL target array should be a 5-MW target station for the production of fission fragments, in which neutrons will be generated in a liquid-mercury primary target. Design and testing of a large, high power fission target with solid converter and a spallation target, which both allow efficient release and cooling, is also necessary. Therefore three target-related tasks are included in the Study:

Multi-MW target station. The objective is to perform the technical preparative work and demonstration of principle for a high power (5-MW) target station for production of beams of fission fragments using the mercury proton-to-neutron converter target and cooling technology similar to those under development by the spallation neutron sources, accelerator driven systems and the neutrino factories. This high power target that will make use of innovative concepts of advanced design can only be done as a common effort of several European laboratories within the three communities. In this study emphasis is put on the most EURISOL-specific part which is the compact window-free Hg converter target. A prototype mercury loop will be constructed and tested.

Fission target. This task will encompass the R & D and prototype construction necessary to define the engineering concept and technical choices for the module containing a few kg UCx target and ion source assembly. A new kind of high-density UCx will be investigated. For one selected element the optimal fission target material, containment material and ion source will be chosen based on production cross section, heat conductivity, diffusion coefficient and desorption enthalpy. The use of a high-Z solid converter target will also be considered. Because the high radiation level generated by the next generation facilities, new kinds of ion sources (*e.g.* Nitschke and electron bombardment) will be investigated.

Direct target. The objective of this task is the development of target and ion source units for a wide variety of radionuclides that can accommodate 100 kW power from a beam of protons or heavier ions. This is a factor of 4 greater than is achieved at present for a few special cases of target material and design. Four challenging and representative cases are selected: an actinide target, a metal foil target; an oxide powder or oxide fibre target, and a molten-metal target. Included in the oxide target sub-task will be the development of a target system suitable for ^{6}He and ^{18}Ne production required for the beta-beam.

As a linear accelerator offers no charge and mass selectivity, beam preparation before injection into the post-accelerator is a major challenge, and therefore a dedicated *beam preparation* task will be implemented. This task will encompass mainly mass separation and charge breeding, and bring these techniques to a significantly higher level than available today at ISOL facilities. In this task beam transport, mass separation and ion cooling and bunching will be studied; charge-state manipulation methods will be tested in order to achieve breeding efficiency of more than 50% in one charge state; and a high-intensity pulsed 60 GHz ECR ion source for rapid ionisation of light noble gas radioactive ions (especially He and Ne) will be designed and prototype built suitable for the beta-beam project.

The envisaged increase by several orders of magnitude of the RIB intensities means a drastic increase of the radioactive inventory and corresponding radioprotection related issues. Safety aspects of the future RIB production targets will become decisive in limiting the beam intensities, in selecting the production method and materials, and in the final cost of the facility. The *safety and radioprotection* task aims to provide quantitative evaluation of the major safety and radioprotection questions. This task will investigate the handling of targets and in particular the disposal of spent targets. Major efforts will be concentrated on the high-power (5-MW) target station, which clearly poses the most important radioprotection problems.

The scope of the science addressed by EURISOL is strongly dependent on the beam intensities delivered. Therefore a task devoted to *beam intensity calculations* is aiming to establishing standard calculation procedures and codes, which are currently lacking, to facilitate comparison of various technical solutions. This task will be essential in assessing the importance of having a driver with heavy ion capability. Further novel ideas to be explored are: the benefit of a secondary fragmentation scenario and the assessment of the role of secondary reactions in single and two-stage targets.

A **physics and instrumentation task** is selecting a limited number of original experiments spanning the different fields in which major scientific breakthroughs are expected from EURISOL. Through detailed simulations, the innovative instrumentation necessary to perform these experiments will be defined, which will influence the layout of the EURISOL experimental areas. Feedback will be given to the more technical tasks, in order to promote compatibility between the beam characteristics and the scientific goals. This task also ensures continued interest and involvement of the broader scientific community, including theoreticians, in the Design Study.

The **beta-beam aspects** task is exploring the possibility of creating intense single flavour electron neutrino beams through beta-decay of RIBs in a high-energy storage ring (Fig. 3). The resulting neutrino beam, emitted along the straight sections of the decay ring, will be aimed towards a large water Cherenkov detector located far away. The facility will be able to search for CP violation down to small θ_{13} mixing angles ($< 1^\circ$) and in conjunction with a "superbeam" search for CPT or T violation, and the injection of a semi-continuous beam into a storage ring, bunching and space charge and lattices will be studied in detail. A high-energy injection and stacking scenario for the decay ring will be further developed and tested.

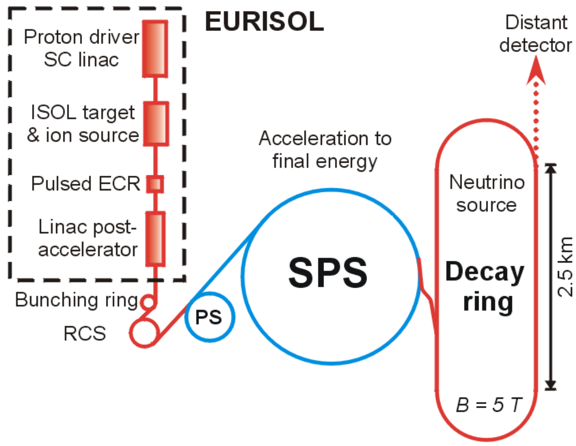

Fig. 3. Scheme of producing pure electron neutrino beams, the β-beam concept [4].

3. Recent developments

During the first 18 months of the study much preparatory R & D work has taken place in the various tasks of the Design Study. The impact of each part of the facility on the other parts has also been closely studied and has led to several important conclusions. This will give direction to the future planning of the facility.

One such important conclusion is that studies on radioactive beam intensity calculations [3] has revealed that *driver* beams having higher energy than 1 GeV will produce spallation products with Z far away (up to 20 units) from the target atomic number. This would efficiently bridge many of the gaps in RIB production that would otherwise be there from ISOL production from 1 GeV protons. In this respect, a 2 GeV ^{3}He beam is as efficient as a 2 GeV proton beam. In addition, a medium-energy deuteron (100–200 MeV) beam would bring higher energy, forward focused neutrons and thus make more efficient use of a secondary ^{238}U target and give rise to different mass and charge distributions of the fission products than the proton spallation scheme. For the driver accelerator, a preliminary design for a 5 MW, 1 GeV proton LINAC has concluded that, for an additional cost of 20%, one can provide accelerated beams of 2 GeV ^{3}He, 250 MeV deuterons and heavier ions with $A/Q = 2$ up to 125 MeV/u. The acceleration of H$^-$ followed by magnetic or laser stripping would enhance the multi-user capability of the facility for CW-proton beams.

The driver beam characteristics have a major impact on the design of the 100 kW direct targets and the multi-MW target station. In the latter case its performance in terms of energy deposition, n-flux distribution and spallation product yields) has been investigated by varying parameters such as particle beam (protons *vs* deuterons), energy (1–3 GeV), and the beam profile. The effect of using various densities of uranium carbide material on production yields and releases of specimen radioisotopes is also being assessed. A comparison of the performance of a mercury-jet configuration with a closed mercury loop similar to the SNS and ESS neutron spallation targets has concluded that the closed loop technology comes close to the performance of the Hg-jet, but there is significant gain in terms of ease of engineering, particularly for the design of the fission target.

Discussions between the tasks devoted to beam preparation, post- acceleration and physics & instrumentation have concluded that the best scientific exploitation requires the post-accelerator to be divided into several energy regimes. These would be: a very low energy accelerator (< 1 MeV/u) for astrophysics and solid state physics applications; a linac for Coulomb barrier applications (up to 20 MeV/u) and a high energy linac. The last should provide a maximum energy of 150 MeV/u for ^{132}Sn and should have branches for different energy ranges in separate experimental halls. The beta-beam injector (100 MeV/u ^{6}He and ^{18}Ne), which requires very high instantaneous beam currents, should be a separate accelerator. In order to ensure that there will be simultaneous availability of different radionuclides for multiple users, the post accelerators will be injected from separate low energy lines (including the pre-separator beam cooler, high resolution mass separator and charge breeder) from at least two primary targets.

4. Summary

The EURISOL Design Study has, after 18 months, made good progress in addressing the major technological problems which are expected to arise in the creation of an ISOL radioactive ion beam facility able to provide exotic ions in quantities which are orders of magnitude higher than those currently available.

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