Journal of Physics: Conference Series

# The SPES project: An ISOL facility for exotic beams

To cite this article: G Prete *et al* 2009 *J. Phys.: Conf. Ser.* **168** 012022

# The SPES project: an ISOL facility for exotic beams

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**Abstract.** SPES (Selective Production of Exotic Species) is an INFN project to develop a Radioactive Ion Beam (RIB) facility as an intermediate step toward EURISOL. The SPES project is part of the INFN Road Map for the Nuclear Physics development in Italy and is supported by the whole Italian Nuclear Physics community and mainly by LNL and LNS the INFN National Laboratories of Nuclear Physics in Legnaro and Catania. The Laboratori Nazionali di Legnaro (LNL) was chosen as the site for the facility construction due to the presence of the PIAVE-ALPI accelerator complex, which will be used as re-accelerator for the RIBs. The SPES project is based on the ISOL method with an UCx Direct Target and makes use of a proton driver of at least 40 MeV energy and 200 microA current. Neutron-rich radioactive beams will be produced by Uranium fission at an expected fission rate in the target in the order of 1013 fissions per second. The key feature of SPES is to provide high intensity and high-quality beams of neutron rich nuclei to perform forefront research in nuclear structure, reaction dynamics and interdisciplinary fields like medical, biological and material sciences. The exotic isotopes will be re-accelerated by the ALPI superconducting linac at energies up to 10AMeV for masses in the region of A=130 amu with an expected rate on target of 109 pps.

## 1. Physics case

Starting from a nucleus on the stability line and adding successively neutrons one observes that the binding energy of the last neutron decreases steadily until it vanishes and the nucleus decays by neutron emission. The position in the nuclear chart where this happens defines the neutron drip line. It lies much farther away from the valley of stability than the corresponding drip line associated with protons, owing the absence of electrical repulsion between neutrons. The location of the neutron drip line is known only for nuclei with mass up to around 30.

The interest in the study of nuclei with large neutron excess is not only focused on the location of the drip line but also on the investigation of the density dependence of the effective interaction between the nucleons for exotic N/Z ratios. In fact, changes of the nuclear density and size in nuclei with increasing N/Z ratios are expected to lead to different nuclear symmetries and new excitation modes. While in the case of some very light nuclei a halo structure has been identified, for heavier nuclei the formation of a neutron skin has been predicted.

The evolution of nuclear properties towards the neutron drip line depends on how the shell structure changes as a function of neutron excess. This evolution has consequences on the ground state properties (spin, parity, and electromagnetic moments) and on the single-particle and collective excitations. In particular, studies of neutron-rich nuclei beyond doubly magic $^{132}$Sn are of key importance to investigate the single-particle structure above the N=82 shell closure and find out how the effective interaction between valence nucleons behaves far from stability.

New modes of collective motion are also expected in connection with the formation of a neutron skin, namely oscillations of the skin against the core, similar to the soft dipole mode already identified in the case of very light halo nuclei. Presently, neither the thickness nor the detailed properties of the neutron skin of exotic nuclei are known. This information is needed to enable a quantitative description of compact systems like neutron stars, where exotic nuclei forming a Coulomb lattice are immersed in a sea of free neutrons, a system which is expected to display the properties of both finite and infinite (nuclear matter) objects.

Despite the large number of experimental studies, so far it is still not possible to predict reliably the limits of nuclear stability or the behaviour of the Nuclear Equation of State (NEOS) at low and high baryon densities. In particular, the asymmetry term in the NEOS is largely unknown but in the region close to saturation. However, it is just this energy which plays an important role in setting the stability limits. For this reason, it is quite challenging to investigate the behaviour of nuclear matter far from stability. Although the SPES energy range is somewhat limited for studies of this kind, the neutron-rich ion beams of SPES will allow one to further extend the investigation of the NEOS along the isospin coordinate, in a region where it is largely unknown at low as well as high excitation energy.

## 2. Facility description

The basic elements of the ISOL facilities are the primary accelerator, the production target coupled to the ion source (TIS), the charge breeder (or the charge exchange system), the beam transport system and the re-accelerator. According to the requirements of the experimental needs a High Resolution Mass Spectrometer (HRMS) can be part of the transport system.

SPES is designed to have a Cyclotron as primary accelerator able to supply at least 40 MeV 0.2 mA proton beam onto a UCx direct target to produce a fission rate of about 1013 fission/s. Thus, a total beam power of 8 kW has to be managed. A surface ionization source will be used with the possibility to add a laser device to improve the purity of the ionized exotic species. For this purpose a HRMS with a mass resolution 1/20000 is also planned. To reach the charge state and ion velocity that fit the requirement for injection into the PIAVE-ALPI acceleration system a Charge Breeder and 2 High Voltage platforms (HV 250kV) will be used. The first platform will host the TIS and first stage mass separator, the second the Charge Breeder. The description of the facility is reported in the Technical Design Report at the LNL web site [1].

As the facility will handle radioactive species, special care is devoted to the radiation protection safety and several systems are added to prevent radiation hazards. A Control System will integrate in a homogeneous architecture the many subsystems necessary for the operation of the facility: from the accelerator control to the radiation and safety survey.

Several factors have to be considered to determine the intensities and the ion species available for experiment in an ISOL facility. The production of isotopes inside the primary target is the first ingredient but a crucial point, as we are dealing with radioactive species, is the target release time, i.e. the time needed by the reaction products to reach the ionization source from inside the target grains, where they are produced. The in-target beam intensity at SPES has been determined starting from the fission fragment production yield calculated with the MCNPX [2] transportation Monte Carlo code in which the target geometry is included. The following diffusion and effusion of the exotic species inside the target was evaluated with both GEANT4 [3] and RIBO [4] Monte Carlo codes. The calculations have been tuned using the available experimental data from ISOLDE, ORNL and PNPI and the complete geometry of our target has been included. Finally, source ionization and extraction, charge breeding, beam transport and re-acceleration efficiencies have to be considered. Following the literature, we assumed 1+ and N+ (charge breeder) ionization efficiencies equal to 90% (1+) and 12% (N+) for Kr and Xe, 30% (1+) and 4% (N+) for Zn, Sr, Sn, I and Cd. The typical Linac ALPI transmission efficiency is 50%.

The final estimated beam currents for the SPES facility are shown in figure 1 for some interesting species.

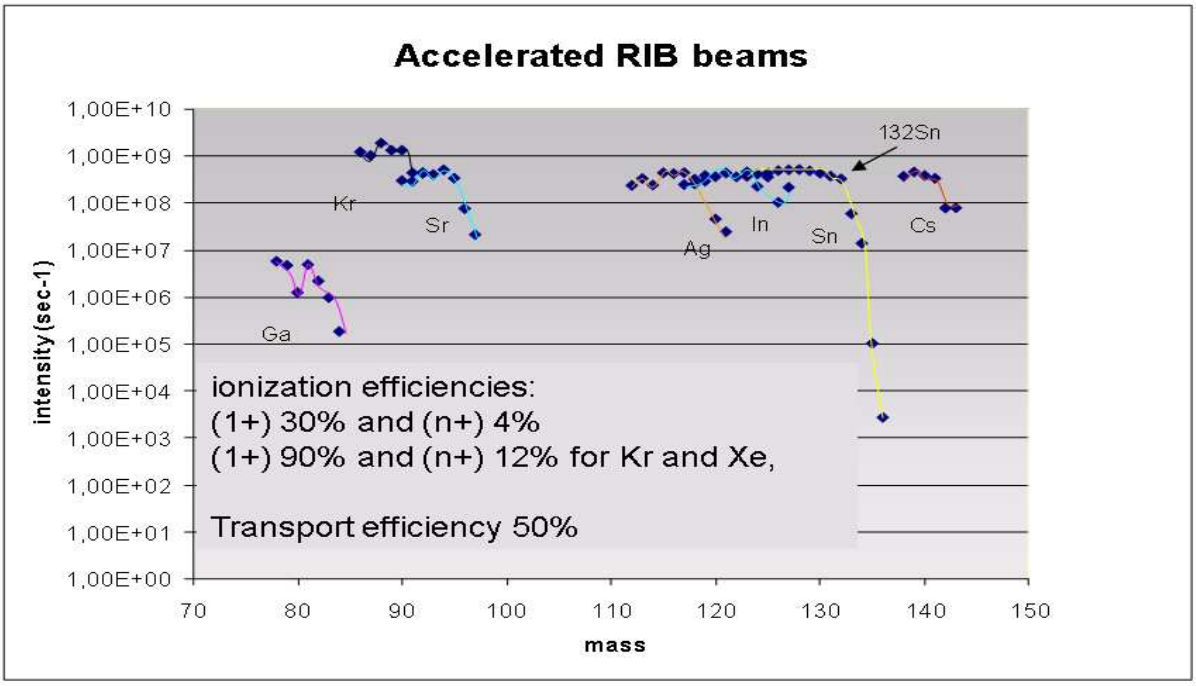


**Figure 1.** Expected on-target intensities calculated considering emission, ionization and acceleration efficiencies (see text) for different isotopes.

## 3. Proton driver

A proton driver based on a cyclotron with energy 40-50 MeV and current 0.2 mA fulfils the requirements for the SPES project as the direct target is actually designed for 8 kW power. A driver with a capability of 50 kW (70 MeV, 0.75 mA) with the possibility of a current upgrade reaching 1.5 mA and a beam power of 100kW is indeed very interesting for the development of the SPES project, as further developments of SPES will be in the direction to increase the maximum sustained power in the target, with the aim to increase the exotic beam intensity and to follow the EURISOL trend for a 100 kW direct target.

A commercial cyclotron, with characteristics which fulfill the needs for the SPES project, was recently developed by IBA: the Cyclone? 70 (C70) and it is actually in operation at the ARRONAX (Acclrateur Recherche Radiochimie Oncologie Nantes) project [5]. The cyclotron is equipped with two exit ports allowing for dual proton beam extraction; this allows at the same time RIB production and the development of applied physics based on 70 MeV proton beam of current as high as 0.5 mA.

## 4. Target system

The UCx target is made by 7 disks (each 1 mm thick and 4 cm diameter) to optimize power dissipation and release time of the fission products. The gap between the disks allows an efficient cooling of the system by thermal radiation. The total amount of the U fissile material is only 28 g.

A detailed study has been performed to evaluate the thermo-mechanical behaviour with two codes: the generally used ANSYS [6] code and one provided by ENEA [7]. Experimental tests of the target principle were performed at the HRIBF facility (ORNL-USA). The main result is that, in the adopted configuration, the target does not melt and to reach the operating temperature it is necessary to supply external power.

A strong R&D program is under development on the Direct Target subjects for material, characterization techniques and prototyping. The possibility to produce disks of carbides with the right dimensions has been proved developing and characterizing LaC and UCx pellets.

Collaborations with ISOLDE (CERN) and HRIBF (ORNL) have been established as well as participation to the EURISOL-DS Task3. A detailed discussion of the target status and development can be found in Ref. [8].

The TIS system is developed following the EXCYT and ISOLDE design. The choice of the ion source kind to be used has primarily been dictated by efficiency and secondarily by its capability of selective ionization. We consider three kinds of ion sources for SPES: the Surface Ion Source, the Forced Electron Beam Induced Arc Discharge (FEBIAD) and the Resonant Ionization Laser Ion Source (RILIS). All of these three sources are used at ISOLDE and they constitute a good reference point for further SPES goals in the ion-source development. The first version of the SPES TIS will be equipped with a Surface Ionization Source with the option to couple a Resonant Ionization Laser Ion Source as a second step in source development.

## 5. Beam transport and re-acceleration

The secondary beam line transport system will handle the radioactive beam from the output of the ionization source to the low-energy experimental area and to the re-accelerator complex. One of the main problems to operate an ISOL facility is the beam purification since the extracted species are transported according to their M/q value. Due to the low rigidity of the beam, electrostatic quadrupoles can be used to focus and transport the beam. This guarantees a reliable beam handling and a very simple procedure to set the beam transport line.

The beam extracted from the source with 50 kV extraction potential, will cross through a first stage of M/Z purification, which allows trapping the largest amount of radioactive contaminant. According to other facilities, and to satisfy the previous constraint, we plan to use a small Wien filter, placed on the first HV platform just beyond the source. Furthermore a small magnetic dipole, like in the EXCYT design, can be also used. A mass resolving power (M/?M) of 300 for this analytical magnet is acceptable. It will be followed by a 1/20000 High Resolution Mass Spectrometer (HRMS) which allows the isobar selection. To improve selection capability the HRMS shall operate at an input energy in the order of 200 keV. To fulfil this requirement the HV platform, where both target and first mass separator are mounted, is operated at 200 kV supplying 1+ beam at total energy of 250 keV.

To optimize the reacceleration, a Charge Breeder will be developed to increase the charge state to N+ before the injection of the exotic beam in the PIAVE Superconductive RFQ, which represents the first re-acceleration stage before the final injection in ALPI.

The Charge Breeder acts as a trap where the 1+ ions are stopped and re-extracted with increased charge state. To fulfil these requirements the Charge Breeder is mounted on a second HV platform operated at 250 kV; this allows to stop the incoming ions and to give the right energy to the out-coming ones. The scheme of the transport line is shown in figure 2.

The re-acceleration of the exotic species will be performed by the acceleration complex

PIAVE-ALPI. The PIAVE injector is in regular operation at LNL since fall 2006. It is based on an ECR Ion Source (placed on a 350 kV platform), and on super-conducting RFQ able to accelerate ions with A/q $\leq$ 8.5 up to 1.2 AMeV. For the SPES beams a transfer line from the Charge Breeder will be added. No main difficulties are expected as the ions coming from the Charge Breeder have similar characteristics as that ones produced in the present ECR. The ALPI acceleration capability allows to push the RIBs energy up to 10AMeV for masses in the region of A=130 amu.

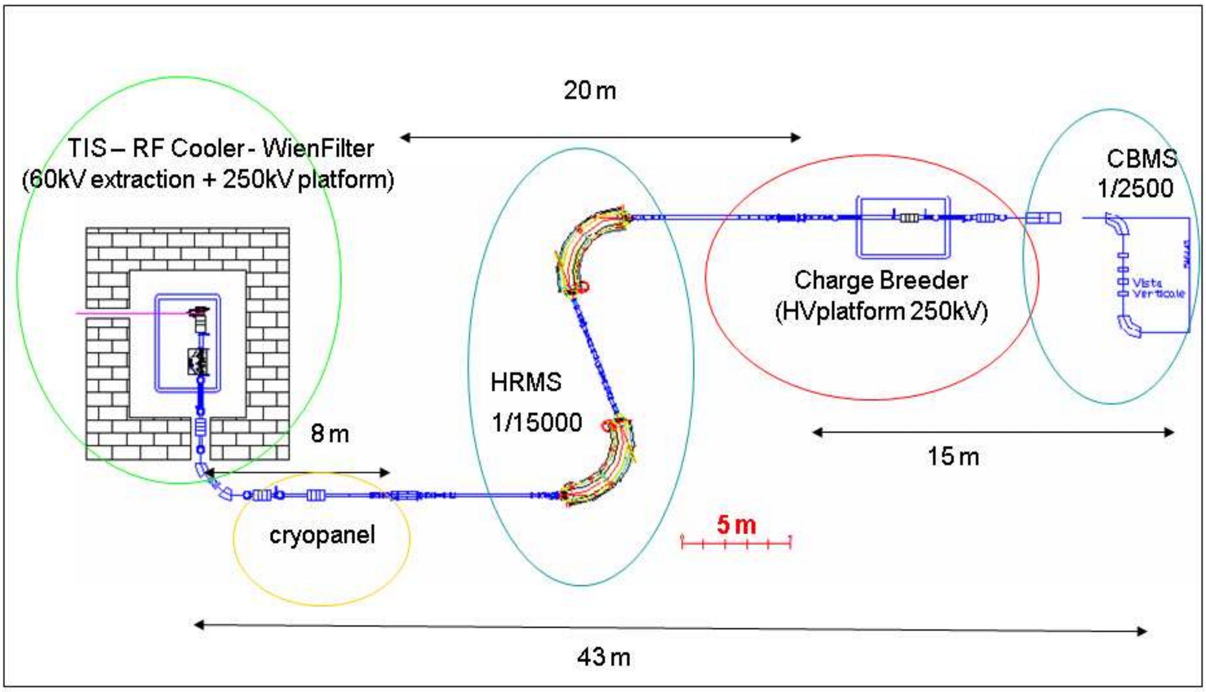


**Figure 2.** Scheme of the transport line for the SPES exotic beams. For details see the text.

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