Identification of technologies developed at ISOL facilities applicable at future facilities

1. Introduction

Since the end of EURISOL-Design Study in 2009, a number of new large Radioactive Ion Beam facilities that use the ISOL technique and that share common technical challenges in Europe and elsewhere have started their construction phase. The most relevant ones are HIE-ISOLDE at CERN, SPES at Legnaro, Italy, SPIRAL2 at GANIL, France, and and ARIEL in TRIUMF, Canada. ARIEL will be operating a 50 MeV, CW, 0.5 MW electron linac, aiming at producing 10^{14} fissions/s in a refractory actinide target to deliver neutron rich radioisotope beams, and will be complemented with a more traditional 500 MeV, CW, 100 kW, proton beam sent onto an ISOL target alike ISAC II presently in operation. Two high power installations which are not dedicated to radioactive beams but which pose many similar technological challenges to EURISOL are in the advanced design phase: MYRRHA in SCK-CEN Mol, Belgium, and ESS in Lund, Sweden. MYRRHA is an ADS demonstrator. It will operate a 600 MeV, CW, 4 MW proton linac which will impact onto a liquid Pb/Bi eutectic target, part of the cooling system of the sub-critical core of a nuclear reactor. The MYRRHA project also includes plans for an ISOL facility ISOL@MYRRHA. ESS is the European spallation neutron source that will operate a "long" pulsed proton Linac of 2.5 GeV, 14 Hz, 2.8 ms, 5 MW on average, intercepting a rotating tungsten target cooled with helium gas. This rapid overview should furthermore be completed with operational feedback obtained from SNS in Oakridge, the American neutron spallation source operating a pulsed 1 GeV, 1 MW proton linac onto a liquid mercury loop target.

In view of the elements obtained from these different radioactive beam and high power facilities, different key elements of the EURISOL facility need to be specifically addressed in the coming 5 to 10 years. In this report we give an overview of the technical developments achieved during the ENSAR contract, which are relevant for EURISOL and for future ISOL facilities in general. Most of these developments were carried out in the participant laboratories of the EURISOL-NET network: CERN/ISOLDE, CNRS/IPN Orsay-ALTO, GANIL, INFN/LNL and LNS and JYFL Jyväskylä. They were presented and discussed during two technical workshops organized by the EURISOL NET network at CERN in June 2011 and in Jyväskylä in May 2013 as well as at the two EURISOL town meetings which took place in Lisbon (October 2012) and Orsay (October 2014). Some of the technical work presented here was performed in the framework of JRA02 ACTILAB of the ENSAR contract. Studies were also supported by other FP7 contracts: the EMILIE project in the framework of the NUPNET ERA-NET (project Number 202914) and the TIHPAC WP9 of the TIARA preparatory phase (project number 261905).

2. Neutron Converter Developments

Converters which produce neutrons from initial charged particle beams are an essential component of high power ISOL facilities. Solid converters are in use at ISOLDE and being developed at GANIL for SPIRAL2. Within the EURISOL Design study, the target complex was one of the key elements of the EURISOL facility, which was the subject of intense design work and preliminary prototyping. The 4 MW mercury converter was to be set up in a target station where it would be utilised in conjunction with a uranium target to create exotic isotopes by rapid fission. The converter was based on a circulating metal loop exposed to direct proton beam irradiation. First prototypes were developed and tested off-line, from which relevant experience was gained. At the present stage, several issues are yet to be addressed, such as the impact of beam irradiation parameters on the liquid metal loop operation. Likewise, the target development will necessitate further research in the field of heat exchange with liquid metal, irradiation, corrosion and fatigue testing of materials.

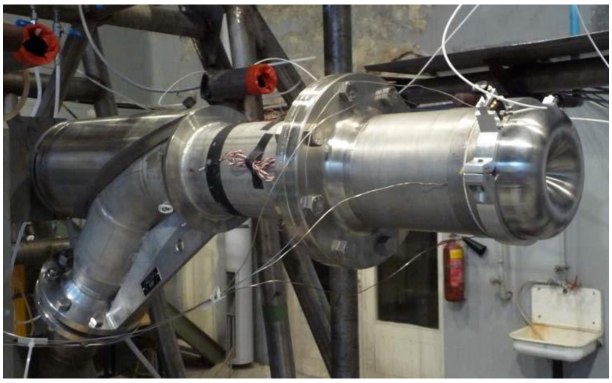
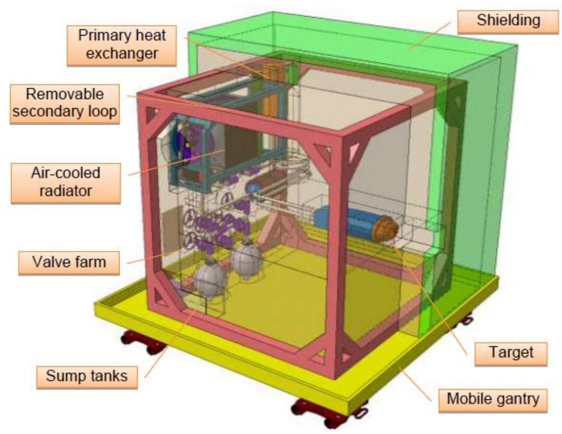
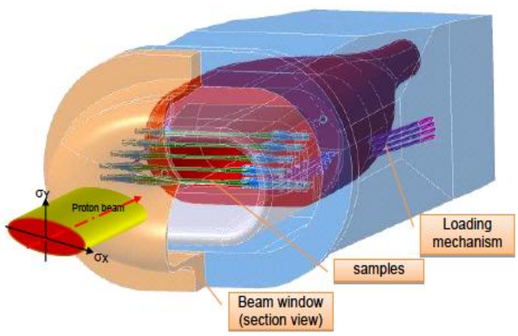


Fig.1*: EURISOL liquid metal neutron converter target on test stand at IPUL*

Achieving the design of the full-scale target for EURISOL will require several partial tests: first of sub-components (e.g. beam window), irradiation at lower power, through to instrumentation tests, and finally full-scale tests. In order to better ascertain the needs for testing a high-power target, various existing and projected facilities have to be examined and their characteristics evaluated.

Within the framework of the WP9.1 task of the TIARA project (CERN deliverable), the design of a facility able to test materials under high irradiation doses has been proposed as it will result in many possible applications in different areas of interest to science [1]. Concentrating a high neutron flux over a small volume will be of interest to material studies, fundamental physics or radiopharmaceutical production. By sufficiently shielding the facility, an implementation in existing dedicated laboratories can be envisaged, which prioritises safety in order to fulfil rapidly regulatory requirements.





Neutron Converter for SPIRAL2

The design of the SPIRAL2 solid neutron converter has been described in detail in [2]. The neutron converter is conceived as a high speed (400 turns/min) rotating graphite wheel operating at peak surface temperature of 1850 °C. It has about 10.000 hours lifetime, this is more than 4 working periods, after which the wheel must be replaced. The motor drivers are submitted to an integral dose about 10^6 Gy every working period and have to be replaced every year. The graphite gaskets have to be replaced at every disassembling of the Neutron Converter Module. The cooling panels, delay window and other mechanical components are submitted to a relatively low radiation rate and the accumulated damage is in the order of 1 dpa per 10.000 hours of operation. Their replacement may be planned after reaching the 5 dpa of damage.

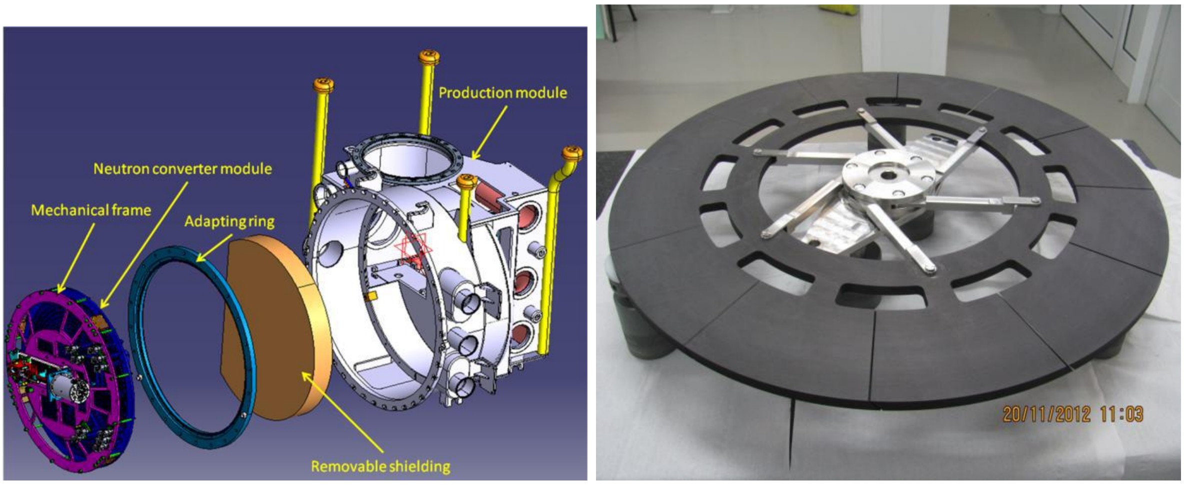


Fig.2*: 3D View of the neutron converter and a picture of the 50 kW graphite prototype target*

More recently, the Ta-DW (Delay Windows is a beam protection device) prototypes were designed, constructed and tested with the corresponding electronic system for performing the experiments [3]. The measurements were carried out using an EBW adapted to the scope. The Ta-plate traversing time was measured using 60kV e-beam, 170mA and 4 mm diameter, for 80kW/cm2. The experiment was performed at three different Ta-plate temperatures: 50 ºC, 300 ºC and 500 ºC.

In order to carry out the maintenance of the NCM, a dedicated tool has been designed and constructed. Mechanical tests for assembling and disassembling have been done [4].

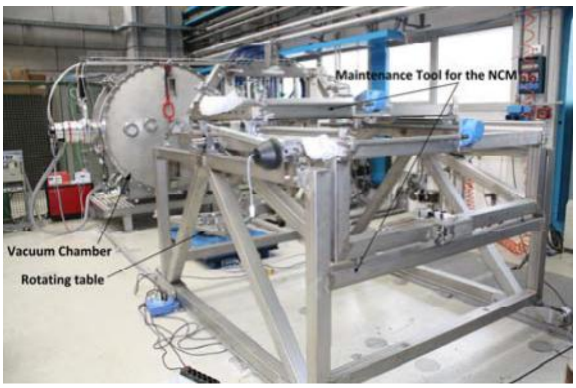


Fig.3*: Tool for the maintenance of the NCM*

3. Target Material Studies

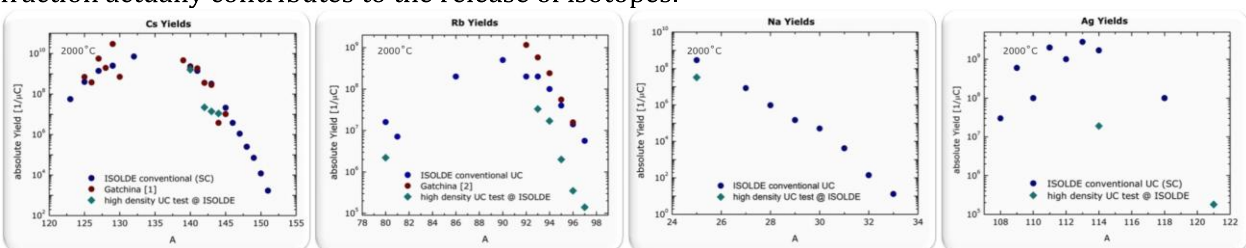
The improvement of radiation hardness and release properties of ISOL targets are essential to increase the beam intensities and scientific output of ISOL facilities. Vigorous related R&D, particularly concerning sub-micron structured target materials, are performed at CERN-ISOLDE, INFN-LNL and IPN-Orsay. This has already been witnessed using solid targets with nanostructures, and should be translated to the most important class of Uranium carbide targets within the WP8 in FP7-ENSAR. If the gain of at least one order of magnitude is confirmed for the most exotic isotopes, this would pose the question as whether a MW-class primary beam power is still required to meet the EURISOL physics goals, with implications on cost, site selection decision and safety aspects. In line with the precedent results, an important prototype tests is foreseen in 2014 on a liquid metal target loop equipped with a diffusion chamber. This should indicate if isotope release properties can be improved by fragmentation of the molten metal into thin droplets.

A final axis of development consists in the production of beams of refractory elements that were until then not accessible by the ISOL method. Such beams are available by fragmentation of the post-accelerated (non-refractory) secondary radioisotope beams within EURISOL-DS. The method consists in the release of the refractory elements through volatile molecule formation and subsequent break-up in the ion source cavity, either by laser light or by electron impact.

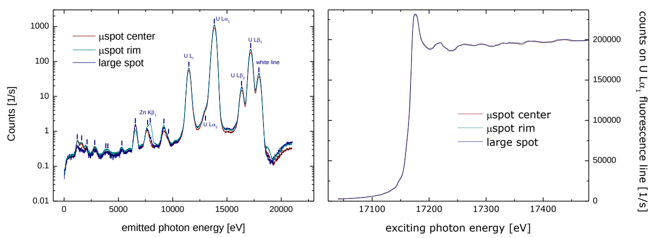
CERN-ISOLDE Facility

Activities at CERN-ISOLDE involve the exploration of new kinds of material synthesis, on-line tests of recent types of actinide targets and finally comprehensive studies of structural, crystallographic and chemical evolution during target operation.

Within the FP7-ENSAR Joint Research Activities (JRA), ACTILAB a well-defined fine-grained Uranium Monocarbide with high density (12.7 g/cm^3) was studied online in a standard ISOLDE target geometry. The measured yields from the high density UC target at ISOLDE are comparable to the ones gained in Gatchina [5,6] after correcting for geometry and proton intensity. But despite its large thickness (241 g/cm^2) this target was found to deliver comparable absolute yields for the studied isotopes of Cs, Rb, Fr, K, Na, and Ag (partly shown in the charts below) compared to conventional ISOLDE UCx targets with smaller thickness (45 g/cm^2)[7]. This observation indicates, that in the case of the high-density material only a small fraction actually contributes to the release of isotopes.



To achieve better knowledge about the influence of the material's microscopic structure on the release properties advanced spectroscopic techniques are applied, both before and after proton irradiation while operation of the material in a target unit. In that way first tests using μ-spot extended X-ray absorption fine-structure spectroscopy have been successfully performed on the high-density material, reveling the chemical and crystallographic details on the μm-scale (see the X-ray fluorescence spectra (left) and the EXAFS spectra (right) below).



R&D on new target materials showing better release properties of radioisotopes has been carried out within the HIE-ISOLDE project,. It has been shown in previous studies that purposeful modification of the grain size down to 50 nm and porosity content can significantly change effusion and diffusion properties of the material, which leads to better isotope release more intense beams [8]. Potential future target material samples of SiC and Al_2O_3, with a tailor-made microstructure using the ice-templating technique, have been subjected to proton-beam bombardment at ISOLDE and CERN's HiRadMat facility [9]. These samples have undergone several tests to characterize and evaluate their structure after irradiation.

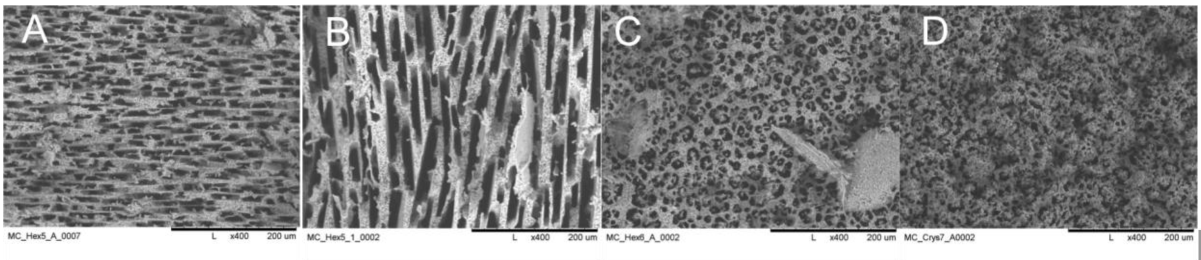


Fig.4: *SEM images of ice-templates green bodies of the same powder sub- ject to different parameters modifications listed in Table 1: (A) fast-freezing; (B) slow-freezing; (C) addition of ZRA - honeycomb-like structure; (D) over- loaded slurry [9].*

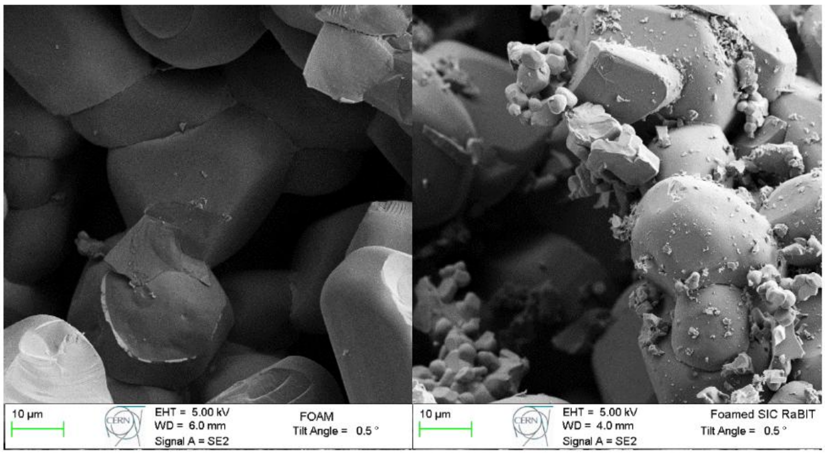


Fig.5: SEM analysis of the samples irradiatied with RaBIT at 5000x before (left) and after irradiation (right) [10]

On line tests using NaF:LiF binary system as a target material for the production of ^{18}Ne have been performed with an operation time of ~50h and a post irradiation inspection shows that the integrity of the container was preserved. This target unit is a prototype built in the past months at ISOLDE in the framework of the EURISOL Beta Beams project. The aim is to produce (anti-)neutrino beams from the decay of beta active ions circulating in a storage ring. The chosen beta emitter ion pair is $^{6}He/^{18}Ne$ and the need for production is of about $6\cdot 10^{13}$ ^{6}He and $1\cdot 10^{13}$ ^{18}Ne ions per second. The production of ^{6}He has been verified using the isotope separation on-line (ISOL) method with 1.4GeV proton beam onto a tungsten neutron converter located close to a thick BeO target. On the other hand, the production of the required $1\cdot 10^{13}$ ^{18}Ne /s was harder to accomplish. In this context a proposal where ^{18}Ne is produced via a high power molten salt loop was presented but needed to be verified therefore the molten salt unit was tested on-line and then analysed after the run.

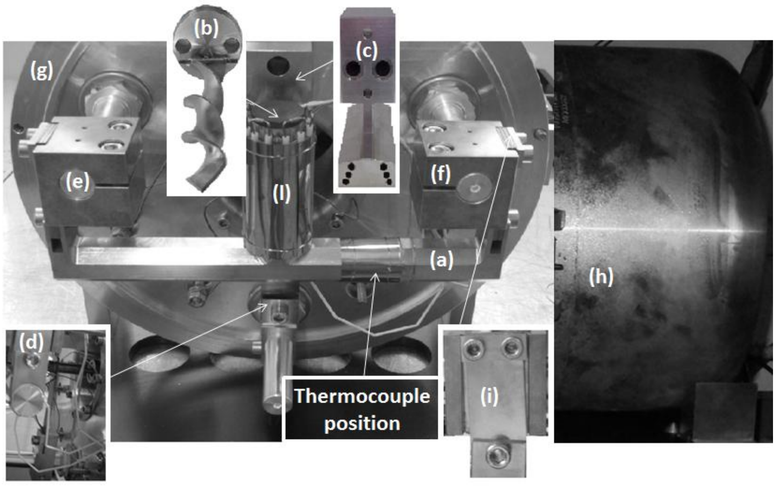


Fig.6: NaF:LiF Molten Salt Target unit before irradiation [11]: (a) Container; (b) Helical Transfer Line; (c) Cold Line;(d) Ion Source; (e) Feed through; (f) Connection Block; (g) Flange; (h) Vessel; (i) Electrical Connection; (l) Screen.

Within the LIEBE project (LIquid Lead-Bismuth Eutectic Loop for EURISOL), the partner institutions (CEA, CERN, IPUL, PSI, SCK-CEN, SINP) are collaborating on the development and online tests of a high-power LBE loop target, to be operated at ISOLDE in 2015. Some activities related to beam instrumentation, post-irradiation analysis and licensing are yet to be funded.

INFN-Legnaro, SPES Project

The SPES project at Laboratori di Legnaro of INFN (Italy) is concentrating on the production of neutron-rich radioactive nuclei by the Uranium fission at a rate of 10^{13} fission/s. The Radioactive Ion Beams (RIB) will be produced by the ISOL technique using an 8kW proton beam that induces fission on a Direct Target.

The most critical element of the SPES project is the Multi-Foil Direct Target which consists on seven UCx discs of 40 mm diameter each, and about 1 mm thickness. Up to day, the SPES target represents an innovation in term of capability to sustain the primary beam power. The design is carefully oriented to optimise the radiative cooling taking advantage of the high operating temperature of the ISOL target (up to 2200^{o}C).

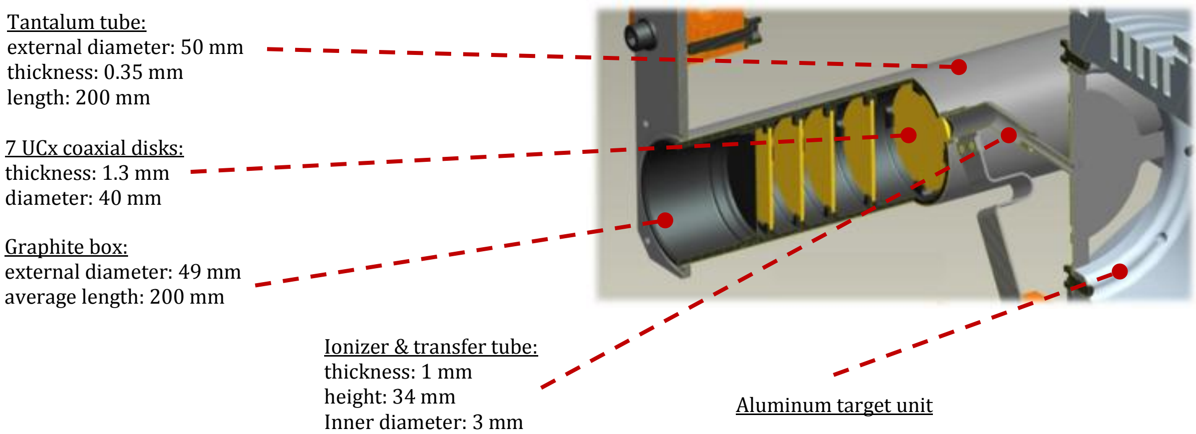


***Fig.7**: Layout of the SPES Target-Ion Source device (A. Andrighetto, proceedings of EU-ITN CATHI Final Review meeting, Barcelona, September 22-26, 2014)*

New developments on the fabrication, characterization, and on-line testing of uranium carbide targets have also been reported. In particular, the yield measurement performed at HRIBF (ORNL), using the SPES UCx target prototype irradiated by a 40 MeV, 50nA proton beam, but also much recently at IPNO (2013) and iTHEMBA (May 2014).

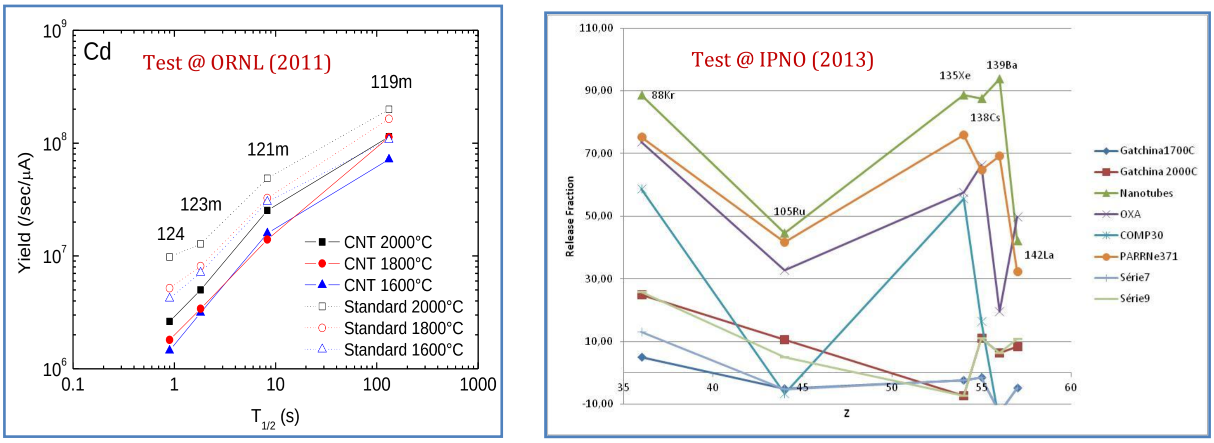


***Fig.8**: Release Efficiency Studies (A. Andrighetto, proceedings of EU-ITN CATHI Final Review meeting, Barcelona, September 22-26, 2014)*

IPN-Orsay, ALTO Facility

The Institut de Physique Nucléaire Orsay (IPNO) is strongly involved in the study of actinide targets for the production of neutron rich radioactive beams by the ISOL method (isotope separation on line) through active collaborations. IPNO has taken part in EURISOL-DS and is currently in charge of UCx target developments within the SPIRAL2 project. An efficient collaboration has been set up with the Sciences Chimiques material laboratory of the University of Rennes (France). A MoU is being established between IPNO and Legnaro (Italy) within the SPES project. Experimental work is performed within the MoU existing between IPNO and Triumf (Vancouver, Canada). Lastly but not the least, IPNO is an active partner of both the ENSAR ActILab project and the EURISOL-NET working group.

Having already developed various prototypes of UC materials, IPNO is in charge of coordinating the “Synthesis of new actinide targets” task within the FP7-ENSAR Joint Research Activities (JRA), ACTILAB. The aim of the work pursued at IPNO is to increase the target density while improving the release properties. Different precursors are studied for the carboreduction process (uranium oxide and oxalate) along with the arc melting process of uranium and graphite. In parallel, studies on the electrochemical treatment of UCx material are starting in order to deal with the disposal of the targets. So far, different new targets have been investigated at IPNO, including binders for pressed powders, sol-gel synthesis in complex fluids and nanostructures. The laboratory also participated in the release tests at Isolde of the new dense UC target previously tested at Gatchina.

In the framework of SPIRAL2, IPNO has started an exhaustive R&D program on uranium carbide targets, focusing on the synthesis of porous material having high uranium concentration. This R&D program is carried out in collaboration with the group “Sciences Chimiques” of Rennes University. In particular, the feasibility of an experimental setup for characterizing the release of fission products from different samples has been demonstrated. This setup has been used to compare the release kinetics of different prototype materials at 1200°C and 1550°C. The results obtained so far bring to light that many parameters of influence have to be taken into account to well control the synthesis process. To further investigate rapidly some of these parameters, systematic measurements are planned with lanthanum as a substitute of uranium.

Furthermore, a specific R&D program has been initiated to produce the best beams of rare earth nuclei using a fluorination technique. Physicochemical properties of the involved elements have been studied to synthesize suitable pellets containing rare earth. Two experimental campaigns have already been achieved successfully at the off-line isotope separator. Further tests and analysis are in progress.

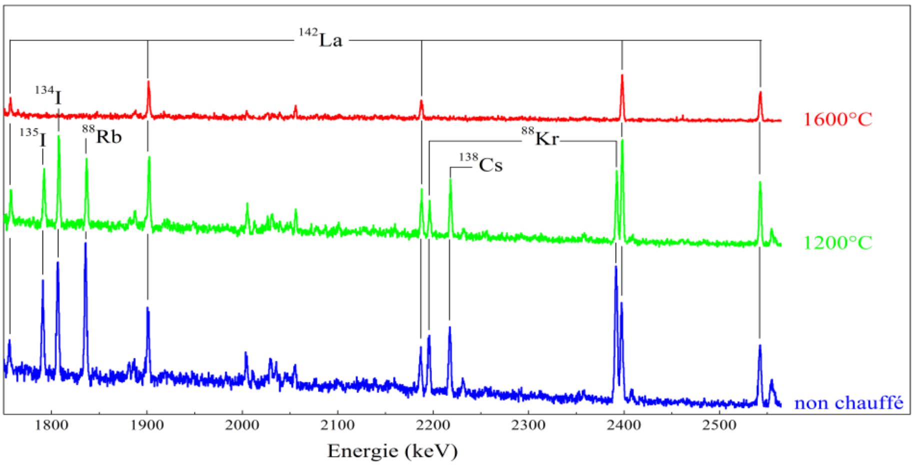


***Fig.9**: Release properties of various prototypes of UC_x pellets at 1600 °C (courtesy of E. Cottereau et al., proceedings of Eurisol-Net meeting at CERN, June 27-28, 2011)*

4. Ion Source Developments

Ion source developments useful for the EURISOL concept have been ongoing in several laboratories participant in the EURISOL NET network. FEBIAD type, ECR and Resonant Ionization Laser Ion Sources (RILIS) have been studied. The LIST ion source which leads to a large improvement of the beam purity delivered by a Laser ion source has also been implemented.

Irena Ion Source of FEBIAD type developed at IPN Orsay

During the EURISOL-DS, a plasma ion source was designed to operate specifically in a high radiation environment such as the one considered in the MW target station. The tests achieved on the first designed prototype have validated the IRENA concept. Tests on a second prototype could be achieved only at an extraction voltage at 20 KV due to various technical issues. Due to the difficulty in the manufacturing process, the strip structure of the anode used in the first prototype was modified into a grid one. In addition, 3D Thermal simulations were carried out using the NX-IDEAS code to improve the temperature homogeneity all along the cathode at high temperature. Off-line tests of the second prototype have shown very competitive performances in comparison to the classical plasma ion source Febiad-MK5 commonly used nowadays at the ALTO facility at IPN Orsay. These tests are still in progress to get the best configuration for the production of radioactive nuclear beams on-line.

R&D on RILIS sources

The development of laser ionization schemes using dye and/or Ti:sapphire laser technology is critical to the selective and efficient production of RIBs. Such work is often distributed among a number of laboratories and the data is then accumulated and shared within the laser community. In particular, the known excited atomic states of heavy elements are often limited to the first state in a possible 2- or 3-step ionization scheme. Indeed, even basic chemical information such as the ionization potential (IP) may be missing completely. In a recent highlight, four institutes were involved in a measurement of the first ionization potential of astatine, determined via laser ionization spectroscopy on a series of Rydberg states. Astatine is the rarest naturally occurring element on earth. The new value serves as a benchmark for quantum chemistry calculations of the properties of astatine as well as for the theoretical prediction of the ionization potential of the heaviest homologue, super-heavy element 117. This research was carried out in the framework of the PREMAS JRA in ENSAR.

In order to perform high-resolution spectroscopy of high-Z elements, efforts are underway to address the limitation due to the laser bandwidth, which for solid state systems may be several GHz. Such intrinsic resolution severely hampers the ability to resolve hyperfine structure and thus to gain access to fundamental nuclear structure information. Similarly, the ability to produce pure isomeric beams is hindered. A relatively simple way to reduce the laser line width is by the addition of a second etalon into the cavity. At LISOL in Louvain this has been demonstrated on the dye laser system and utilized on stable copper isotopes. Similarly, a dual-etalon system is now in operation for Ti:sapphire lasers at both JYFL and ISOLDE.

The main directions of present and future RILIS development are: extension of the range of available ion beams, increasing the ionization efficiency and improvement of selectivity. Due to the RILIS upgrade a substantial progress has been achieved in first two directions. A tremendous improvement of ionization selectivity has been reached via implementation of the Laser Ion Source Trap (LIST) in collaboration with Mainz University. Although the ionization efficiency with LIST was found 20 times less than that of RILIS, the suppression of surface ions by up to 4 orders of magnitude was demonstrated. This enabled in-source spectroscopy study of polonium isotopes which were heavily contaminated by francium isobars in conditions of the standard RILIS approach.

The work on improvement of LIST performance is continuing. In particular, the observed selectivity reduction for certain isotopes caused by in-trap ionization via nuclear decay is addressed by using thinner rods for the LIST rf-quadrupole structure. The study of the time structure of LIST ion beams is on-going at Mainz University. Gating of the ion beam synchronously with the laser pulses would further increase the selectivity of ionization. The experiments with LIST coupled to UCx-target made evident the effect of high ion load on the efficiency of ion extraction from the hot cavity. This is to be taken into account for considering an optional use of the LIST in the ion-guide mode when the laser ions created inside the hot cavity (as in the standard RILIS scheme) are extracted. However, the LIST mode of operation should provide an efficient extraction of ions created inside the LIST RFQ structure. In the standard RILIS cavity the extraction is provided by the penetrating external high voltage field of the mass separator and by a weak gradient of the internal cavity potential due to the dc heating. Although at typical regimes of ISOLDE targets these fields seem sufficient to compensate the charge load effect, it could become a limiting issue for applications of RILIS (and surface) type ion sources at the high current ISOL facilities. Therefore the development of ion sources with higher internal filed is important. This can be achieved by constructing cavities with higher electrical resistance in the longitudinal direction. Recently a high resistance ion source cavity made of crystalline graphite has been reported. The R&D on high resistance graphite cavities for RILIS is started at CERN within the target and ion-source development programme.

The RIALTO (Resonant Ionization at ALTO) is the on-line laser installation built at the ALTO facility in Orsay in 2011 to provide radioactive beams obtained selectively by a multistep photo-ionization. It has been validated in fall 2011 with the production of stable and radioactive Ga beams. In addition to providing beams for experiments RIALTO will provide an additional test bench for R&D of RILIS sources.

While surface and plasma sources will continue for many years to provide beams at ISOL facilities, RILIS sources are the most promising technique for developing pure beams. Important progress has been achieved during the ENSAR contract, in particular in the framework of the PREMASS JRA. All ISOL facilities are now running or considering a RILIS. For EURISOL inherent limitations on achievable beam intensities will still have to be overcome.

5. Beam Manipulation

The beam purity is an important parameter for the success of experiments with ISOL beams. Despite the progress made with RILIS and LIST sources described in the previous section, contaminants still often remain in the beam after exit from the ion source. Therefore High Resolution Mass Spectrometers (HRMS) are often an important component of ISOL facilities. In the case of post accelerated beams it is necessary to increase the charge state of the ions in order to maximize the post acceleration energy and efficiency. Charge breeding is done using either an EBIS or an ECR ion source. Vigorous R&D for both methods is ongoing and will be reported in the following.

High Resolution Mass Spectrometers

The production of the most exotic isotopes is generally accompanied by a high contamination by the less exotic isobars of longer half lives. Powerful selection methods are mandatory. The important criteria are the selectivity: the capability to separate the ions of interest from contaminants; the efficiency to keep the maximum of the ions of interest and the rapidity. Three types of separators can be envisaged: magnetic spectrometers (HRMS), MR-TOF devices and Penning traps. HRMS are the fastest while Penning traps have the highest selectivity. A simple dipole will separate neighboring mass units but will be incapable of separating isobars. Most systems currently in use (HRS at ISOLDE) or planned for future facilities (SPES, SPIRAL2 for example) use 2 dipoles and theoretical mass resolving powers of 20000 or greater are obtained. However high resolution separation requires on the one hand cold beams and on the other a good control of the high order aberrations of the system. Studies performed at GANIL for the SPIRAL2/DESIR HRS show that corrections of aberrations up to the fifth order allow to obtain a resolution of around 30000. In that case a beam of ^{132}Sn would contain 13% of ^{132}Sb. The addition of a penning trap downstream from the HRMS would provide a completely pure beam.

Multi-reflection time-of-flight (MR-ToF) mass analyzers are among the most recent developments in mass spectrometry and manipulation of low energy (keV) ion beams. They offer highest mass resolving power on the order of $R=m/\Delta m$=100,000 on short time scales of a few tens of milliseconds. Therefore, they are ideally suited as, e.g., mass analyzers of short-lived ion beams, mass purifiers in combination with a fast ion selector and high-precision mass spectrometers. Although conceptually developed and tested already in the early 1990s, the application to radioactive ion beams was achieved only recently. Several groups have developed MR-ToF devices for nuclear physics investigations; in particular in Europe the FRS-ioncatcher group at GSI and the ISOLTRAP collaboration at ISOLDE/CERN. This type of device is now under development at many other radioactive ion-beam facilities. In combination with fast ion deflector, e.g. a Bradbury-Nielsen gate, the MR-ToF separated species can be selectively addressed for further transfer to a subsequent experimental step. So far at ISOLTRAP, a contamination suppression of four orders of magnitude has been reached. The purified bunches can, e.g., be used to supply Penning traps for high-precision mass measurements or any other investigation. For example, the MR-ToF MS will offer a fast alternative for trap-assisted decay-spectroscopy experiments at ISOLTRAP, where currently the purification is performed by Penning-trap mass separation. The MR-ToF device can also be used as a mass spectrometer of its own right which is very fast and sensitive, i.e. can be applied to nuclides of short half-lives (down to a few milliseconds) which are available with only very low yields – even a few counts of the ions of interest are sufficient. Such MR-ToF mass separators are no doubt a tool of the future.

Charge Breeding

Charge breeding, which transforms the charge state of radioactive beams from 1+ to an n+ charge state prior to post-acceleration, is a key technology which has to overcome the following challenges: high charge states for high energies, efficiency, rapidity and purity. During FP6 the two techniques of ECR and EBIS charge breeding were compared and were found to be complementary. However they still require dedicated R&D: ECRIS are capable to charge breed large intensities (>>10^{10} pps) for moderate charge states, but suffer from low efficiency for condensable elements. In contrast, EBIS sources provide high charge states, but are limited in capacity (<10^{10} pps) and are pulsed devices which complicate event detection especially for in-beams experiments. The EMILIE project, initiated within the NuPNET FP7 Era-net contract, aims to combine efforts for the improvement of both techniques, for their optimal use in the future EURISOL facility. The two main goals of the project, which runs for 4 years from 2012 to 2015 and involves 8 European laboratories, are to test and upgrade the Phoenix ECR charge breeder and to build an EBIS beam debuncher.

The parameters which can be optimized for the ECR charge breeder include
–MW coupling simulations and new plasma chamber
–Hot sources and wall recycling
–Reproducibility of results and magnetic field optimization
–Multiple frequency heating

Up to now optimization of charge states and capture efficiencies have been carried out with double frequency heating and gas mixing using molecular beams (CO) and light ions. Extensive studies of the 1+ beam capture process are underway. Off-line tests of these improvements will be realized at LPSC Grenoble up to September 2015.

For many applications, in particular EURISOL, it is important to provide a continuous post accelerated beam while an EBIS charge breeder is inherently pulsed. This was the motivation to develop within the Emilie project a buffer Paul trap to be placed downstream from the EBIS device. It will use the energy spread of the beam extracted from the EBIS and a slow extraction in order to provide a pseudo CW beam. The trap will include RF for radial confinement of A/Q = 4, DC potentials on the segments for longitudinal phase space manipulation and UHV (P< 5 10^{-11} mb) for avoiding recombination. The design was completed in 2012 at CNRS-LPC Caen, and simulations with the SIMION code have been performed at GANIL. The machining and assembly of the debuncher is done and the electronics are purchased and being tested. Tests with singly charged ions at LPC Caen and multiply charged ions at GANIL are planned for 2015-2016. With the EMILIE program a major step has been accomplished to eliminate one of the main drawbacks of the EBIS charge breeder which delivers higher charge states and purer beams than its ECR counterpart.

Additional work is ongoing at CERN/ISOLDE (and at Brookhaven National Laboratory in the USA) in view of improving the beam intensity handled by an EBIS breeder by the implementation of a High Energy Current Compression Gun (HEC^2). A protoptype gun was designed by BNL and built by CERN and installed at the test stand at BNL. A record current for a high compression beam was obtained but many technological challenges remain, which should be addressed in the coming years.

6. Superconducting Linear Accelerator Technology

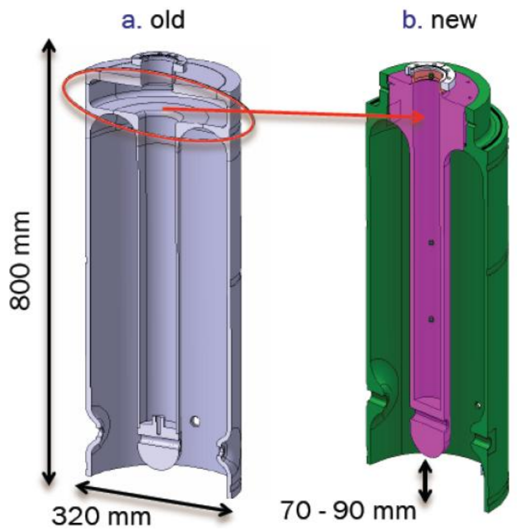
Advances in RFQ systems and superconducting accelerator cavities are necessary for the realization of the HIE-ISOLDE and SPIRAL2 projects and later for EURISOL, for both proton driver and heavy ion post-accelerator. Vigorous R&D for both accelerating structures is on-going and will be reported in the following.

CERN

The technology of Nb sputtering on copper was selected for the Quarter Wave Resonators (QWR) needed for HIE ISOLDE project [12] at CERN, where it had been invented [13], and originally developed for the LEP cavities [14]. More specifically this choice made reference to the sputtered QWR developed at INFN-LNL for the ALPI linac [15]. The state of the art SRF surfaces made at CERN were magnetron sputtered Nb films on elliptical cavities (for LEP and for future Linac Colliders), while in the case of the quarter wave resonators for heavy ions, different in shape, bias diode sputtering was optimized and is used at INFN-LNL [16].

The HIE-ISOLDE specification calls for an average surface resistance of 65 nΩ at 6 MV/m accelerating field, corresponding to the performance achieved in the best ALPI cavities. This is quite challenging in consideration of the much larger surface of the HIE-ISOLDE resonator (a factor 2.5), with the consequent higher risk of spurious defects on the substrates. On the other hand, the lower operating frequency (101 MHz vs. 160 MHz) and the use of clean rooms for cavity preparations should provide some safety margin.

Work at CERN to establish a complete production chain for Nb sputtered QWR started in 2008 [17]. By the end of 2009 the chemistry, coating and RF testing infrastructures were operational, the first prototype cavity had been produced, and it was ready to be coated. A first design relying on rolled sheets and extensive electron beam welding was initially adopted (with 4 prototypes built) for the early phases of the program. In a second time a new version, based on machining from bulk with minimal number of EB welds, was produced and 3 prototypes were manufactured. The shape of the helium reservoir was also modified. As a result, the sensitivity to the helium pressure fluctuations was decreased by two orders of magnitude down to 0.02 Hz/mbar. A detailed report on the copper substrates is in these proceedings [18,19].



Design Parameter	Value
f_0 (MHz)	101.28
β_g (%)	10.3
E_{acc} (MV/m) = V_0/L_a	6
L_a (m)	0.3
R_{shunt}/Q_0 (Ω)	550
E_{peak}/E_{acc}	5.6
H_{peak}/E_{acc} (G/(MV/m))	100
Q_0 (at 6 MV/m, P = 10 W)	5 X 10^8
$\Gamma = R_s Q_0$ (Ω)	31
U/E^2_{acc} (mJ/(MV/m))^2	210
T (K)	4.5

***Fig.10**: HIE-ISOLDE high-beta Copper substrates: left) rolled and welded prototype; right) bulk machined prototype (inner conductor shown in magenta);*

In recent years much effort has been put into the optimisation of the coating process. The latest cavities went up to 6 MV/m at 7 W, 30% above the design goal. More details on the diode coating procedure at CERN are given in [20,21,22]. The evolution of the RF performance in vertical cryostat at 4.5 K is displayed in Figure 2 below. The level of performance reached so far is sufficient to start the series production, but work will continue in order to secure more margins and cover possible performance losses from the vertical tests to the Linac operation.

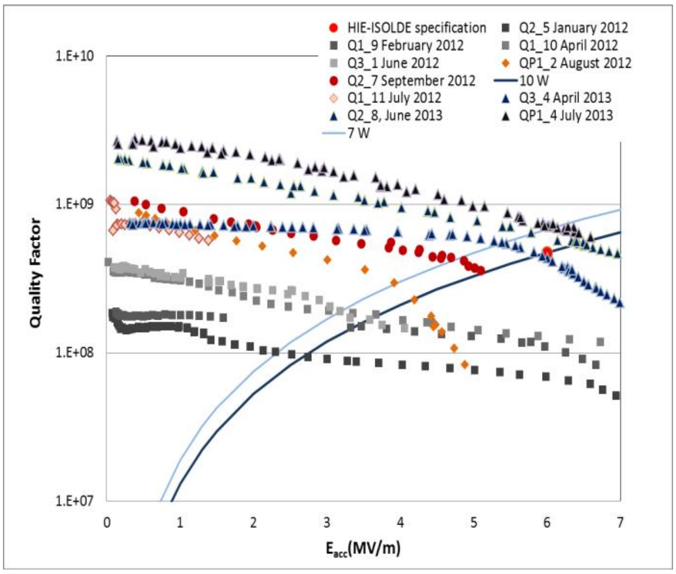


Fig.11: Q vs. E_{acc} curves of bias diode coated cavities [23]

GANIL-SPIRAL2

The SPIRAL2 extension of the existing GANIL facilities, which is under construction, will extend the exotic particle productions of the present GANIL complex towards heavier elements [24,25]. The driver is required to accelerate in CW mode, proton beam (5mA, 33MeV), deuteron beam (5mA, 40MeV) or heavy ions (1mA, 14.5MeV/nucleons). It will be made of two dedicated ion sources, a single RFQ, and 2 families of superconducting quarter wave resonators. Extensive R&D and prototyping has been carried out over the last few years which have lead to the successful validation of the SPIRAL2 RFQ. This has been a joint effort between GANIL, CEA-Saclay, INFN-LNS in Catania and IN2P3-LPSC Grenoble.

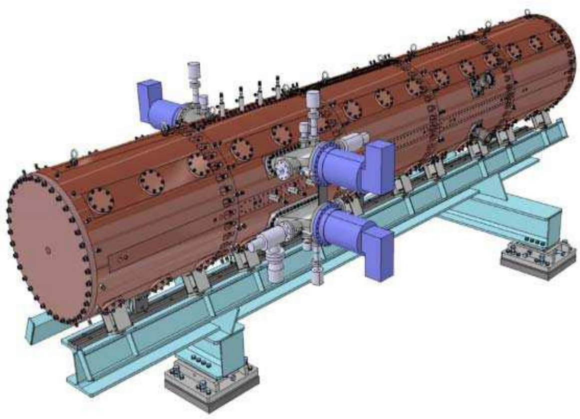


Fig.12a: SPIRAL 2 RFQ prototype cavity[25] ***Fig.12b:*** Artistic view of the final SPIRAL2 RFQ [25]

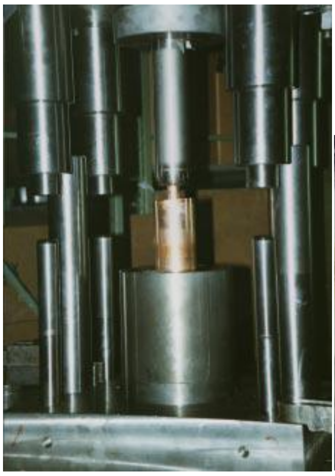
INFN-Legnaro

The INFN-LNL laboratory is one of the leading centers in the development of low-beta superconducting cavities, including superconducting RFQs. The successful operation of the ALPI Linac at INFN- LNL and the adoption of the Nb/Cu at CERN for the HIE-ISOLDE cavities has demonstrated the feasibility of using large-scale copper accelerating cavities coated with a thin superconducting niobium film.

New techniques have been developed to minimize the resonators construction cost, like spinning of multi-cell cavities, modular design of quarter wave resonators and niobium sputtering on copper: these technologies have reached a high level of performance and reliability. However high energy gradients remain unachievable when using thin films. The main limit of the Nb/Cu cavity is the Q-slope, that makes the Q-factor to decrease at high accelerating fields. The SRF community supposes that it is possible to eliminate, or decrease, the problem of Q-slope with higher quality films of sputtered niobium. Development work has taken place at INFN-LNL in order to improve the film quality by modifying or completely changing the magnetron coating configuration starting from three main ideas (this is being implemented on a HIE-ISOLDE high-beta QWR prototype copper cavity):

- making niobium atoms impinging perpendicularly the substrate surface;
- promoting the effect of plasma bombardment of the growing film in order to remove impurities weakly bonded to the surface;
- increasing the sputtering area and the plasma ionization efficiency in order to increase the sputtering rate.

INFN-LNL has been developing and testing different cavity machining techniques among which the spinning process is an interesting alternative among all seamless technologies. The cavity is straightforwardly spun from a circular blank by a cold forming process and no intermediate annealing is required. The actual procedure for prototype spinning foresees a fabrication rate on the order of one resonator per day, but it can be increased to several times that rate.



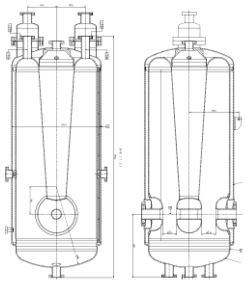
The laboratory is also investigating three other fabrication methods: forward flow-turning, and both direct and reverse deep-drawing [26].

IPN-Orsay

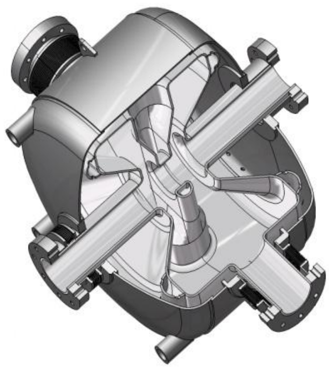
The R&D activity is mainly focused on the conception of accelerators and the associated systems (ion sources, accelerating cavities, RF equipment, cryogenic systems…). It is based around SupraTech, a technological platform dedicated to the research and developments on superconducting cavities for the future high power and high energy particle accelerators. The platform provides all necessary equipments to prepare, condition, assemble and test superconducting cavities for the superconducting technology based projects in which the IPNO is involved.

Since 2010, the development of the platform has been pushed further on with the installation of a new experimental hall dedicated to cavity cryogenic tests. This new experimental facility increases the cavity test capability and will give the possibility to especially test complete cryomodules at 352 and 704 MHz thanks to the concentration, in one area, of the RF power sources and the high cryogenic power capacity down to 1.8 K.

- **SPIRAL2**: IPNO is committed in the conceptual design and construction of the Spiral2 facility, this includes: Beam dynamics and commissioning; Cryomodules B of the high energy part and Beam Position Monitor (BPM); Cryogenic plant and FEBIAD ion source and UCx production target.



- **MYRRHA Project**: IPNO is coordinating the MAX project which is pursuing the R&D on this ADS-type accelerator, specifically focusing on the MYRRHA LINAC (600 MeV, 4 mA) with sufficient detail and an adequate level of confidence in order to initiate in 2015 its engineering design and subsequent construction phase. The main scientific results obtained by the IPNO team during the first part of the project are the following: Fine-tuning of the accelerator layout; Preliminary design of the MYRRHA Spoke cryomodule and experiments using the 700 MHz beta 0.5 prototypic accelerating module installed in IPNO and developed during the previous FP6 EUROTRANS programme.



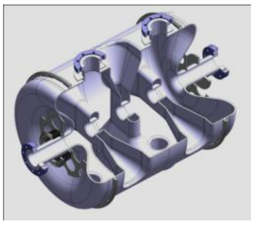
- **ESS Project**: IPNO is actively participating to the ESS accelerator, especially the superconducting part, through two main tasks: the design of all components (spoke cavities, couplers, tuners and cryomodule) composing the intermediate energy section of the linac and the study of the cryomodule for the two families of elliptical cavities. For the different linac sections, several cryostat configurations and solutions are being studied in order to optimize cryogenic performances, physical lengths, assembly easiness, alignment accuracy, mechanical stability and costs.

- **SPL Project**: In the frame of the extra contribution of France to CERN, IPNO was involved in the Superconducting Proton Linac cryomodule studies. It is an R&D effort aiming at developing key technologies for the construction at CERN, of a multi-megawatt proton linac, based on state-of-the-art SRF technologies. It would serve as a driver for new physics facilities such as neutrino and radioactive ion beam facilities. One of the main short term objectives is the testing, by 2014, of a string of four 704 MHz β=1 elliptical cavities, made of bulk niobium and operating at 2 K in a machine-type cryomodule to provide an accelerating field of 25 MV/m. Conducted by CERN and in partnership with CEA/Saclay, IPNO is in charge of the design and construction of the 2K cryomodule and the assembly (cryostating) tooling.

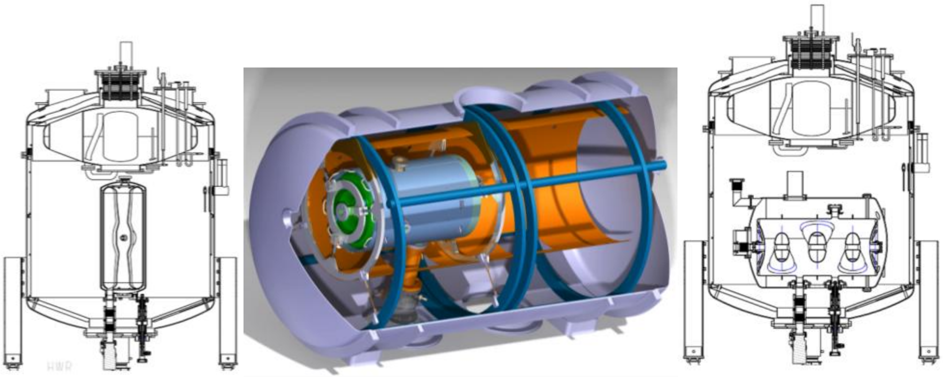
- **RF Power Source SPARE**: The LINAC projects which are under construction or going to be built in the coming years (FAIR, LINAC4, ESS) or under design (MYRRHA, EURISOL) have some common needs in terms of high RF power sources. Up to 2010, there was no technology available in Europe for such RF power sources. In addition, such RF power stations are required for testing and validating several accelerator key components at full power. In this context, IPNO is setting up an RF power test station able to deliver a peak RF power of 2.8 MW (1.5 ms, 50 Hz or 3 ms, 14 Hz) at the required frequencies of these accelerators (352 MHz and 704MH).

- **Digital Low Level RF**: Within the framework of the European research programs EUROTRANS and EURISOL on High Intensity Proton Accelerators, and particularly for the R&D on superconducting Spoke cavities, a Digital Low Level Radio Frequency system has been developed at IPNO in collaboration with LPNHE. This system is used for the control of the phase and the amplitude of the accelerating field in an SRF cavity. Several tests at ambient temperature and 4.2 Kelvin have been performed at low power (up to 300W) allowing to develop the test bench and the acquisition and supervision system. The work focuses on the test results of the second version of the digital board with its acquisition and supervision system. Tests of the complete system have been performed at high power (up to 10kW) in cryomodule conditions for the SPIRAL2 cavities (@ 88MHz).

- **EURISOL**: In the framework of the European project EURISOL (European Isotope Separation-On-Line facility), a prototype multi-spoke superconducting cavity (352 MHz, β = 0.3) was developed and optimized by IPN Orsay.



- **TIARA**: IPNO coordinated WP9, a technical Work Package dedicated to the study of two specific test infrastructures relevant to EURISOL and other high power accelerators: a low beta superconducting (SC) versatile horizontal test cryostat (IPNO main activity) and a test infrastructure for high power targets (CERN main contribution). Since the project started in January 2011, the main activity of WP9 was dedicated to study the European user's needs and requirements for testing low beta SC cavities in order to define specifications for the cryostat. Based on this analysis, a conceptual design of the cryostat has been produced.



SC RF developments is very active in Europe (and worldwide), and more recently for low beta cavities. Many projects are under study or construction and drive intense R&D programs on such accelerating structures with potential for real technological synergies between them:

- IFMIF-LIPAC (CEA, CIEMAT): characterization of materials with intense neutrons flux (10^{17} n/s) for the future Fusion Reactor DEMO (~150 dpa). Based on two CW 40 MeV deuterons SC linac, 125 mA each.
- ESS (17 EU countries): SRF Technology from 90 MeV to 2 GeV, for spoke and double-spoke cavities, elliptical cavities
- SPL (CERN, CEA, IPN-Orsay): elliptical cavities.
- MYRRHA (EU-FP7): for spoke and elliptical cavities.

SC RF technology for accelerators:

- Is a technology of choice for high power acceleration / high duty cycle, thanks to intrinsic efficiency and its maturity gained over the past 25 years.
- Can efficiently accelerate high (and low…) power ion beam starting from a few MeV/u (starting at $\beta \sim 0.05$)
- The type of cavity and implementation in the accelerator needs to be carefully chosen according to beam specifications and requirements: range of b, beam current, variety of beam species to accelerate, final energy, reliability, upgradability, … and cost !
- The cavity type or design IS NOT the whole story: coupling the power to the beam, tuning the cavity, preparing the cavity (dust is a tough and invisible enemy !), integration in a cryo-module are even more potential sources of problems.

7. Conclusions

An ultimate ISOL facility such as EURISOL holds broad scientific promise but represents a formidable technological challenge. The concentration of ISOL facilities in Europe is unique in the world, and coordination of their development work will strengthen Europe's technological excellence. All major European ISOL installations that are research infrastructures (ALTO, EXCYT (LNL-LNS), SPIRAL (GANIL), ISOLDE and IGISOL (JYFL)) are helping to lay the groundwork for the future "ultimate" ISOL facility EURISOL which aims to integrate all European ISOL activities at the horizon of the 2020 decade. EURISOL will encompass the progress being achieved today in many areas at the existing facilities, and the R&D which will be performed at the intermediate generation facilities (HIE-ISOLDE, SPES and SPIRAL2). These facilities will provide a ground for development and testing of many of the technological solutions outlined in the reports from the EURISOL Design Study.

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