HIGH INTENSITY
STABLE ION BEAMS
in EUROPE

ECOS: European COllaboration on Stable ion beams

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HIGH INTENSITY STABLE ION BEAMS
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Preamble

ECOS, the European COllaboration on Stable beams, grew out of a realisation by a group of nuclear physicists that our science was developing in a way that required much more intense beams. As our understanding of the nucleus has developed, further advances increasingly require the study and understanding of more subtle aspects. Probing these requires increasing experimental ingenuity, to enable our measurements to select out the particular aspects of interest from the many other processes taking place. Over the last decade or so the emphasis has been on developing the technology to produce beams of radioactive nuclei, as this gives access to new ways of approaching these studies. This approach has lead to the building of major new facilities in Europe such as FAIR and SPIRAL2.

However there are certain areas when the key to further advance lies in having more intense beams available. These are cases where the nuclei of interest can only be produced with very small cross sections and with present beam intensities such studies are ruled out as they require unrealistically long measuring times. Many of these are detailed in the ECOS report, among them the most obvious being the study of super-heavy nuclei and drip-line nuclei. However to make serious advances in these areas requires a major advance, with beam intensity increases of a thousandfold being required.

NuPECC has supported the ECOS collaboration since its inception as a relatively small group, whose initial intention was the realisation of a new, high-intensity, stable-beam facility. As the work developed, and the realisation grew as to the scale of exciting new physics which would be accessible, so too did the size of the group. Indeed the Town Meeting held in Paris 5-6 October 2006 to discuss this report, was attended by over a hundred scientists from all over Europe. It is clear that there is great science potential in this concept and a large and active group wishing to tackle it. As well as working on the science potential, the collaboration has also explored the technical issues involved in producing high intensity beams and the challenges of developing instruments and readout systems which can operate in the high count rate environment these will produce. The required developments have turned out to be challenging, although probably achievable. This realisation has lead to a shift from the initial intention to build a dedicated new facility, to a staged approach where the technologies will be developed on the existing European network of large scale facilities. This of course has the added advantage of providing improvements to the capability of these facilities. The longer term goal of a new facility is not lost, and still remains a longer term aspiration.

NuPECC is proud of its role in supporting the ECOS collaboration and its work. Indeed this is a clear example of how NuPECC can help parts of the community to self organise to develop new ideas and bring them to the attention of the wider community. In this case the outcome has been particularly successful. Not only has a large community been able to come together to define a common interest, but out of this have come practical proposals to take the field forward through technical development projects which will now be addressed on a European level through bids within FP7. These developments will create new capabilities at the existing research infrastructures in Europe, enabling the European community to lead advances in several areas. Moreover a marker has been established for a possible future facility with even higher beam intensities. NuPECC encourages the community which has developed to continue work on this concept. If the science is strong and the technology feasible, the concept might be brought into the considerations at the time of the next Long Rang Plan.

NuPECC is pleased to publish this report on behalf of the ECOS collaboration and endorses the intention of the collaboration to develop Joint Research Activities within FP7 to realise the technology developments required to realise the exciting science which the report identifies can be done by the European nuclear physicists on our existing facilities.

Brian Fulton
Chairman of NuPECC

REPORT on
HIGH INTENSITY STABLE ION BEAMS
in EUROPE

This document is prepared by the ECOS (European COllaboration on Stable ion beams) working group, in order to describe the research perspectives with high intensity stable ion beams, to help categorize existing facilities and to identify the opportunities for a dedicated new facility in EUROPE

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I Introduction

The atomic nucleus has been studied for many years using heavy-ion accelerator facilities delivering stable ion beams with beam intensities that have increased over the years up to a few 10^{12} particles/sec along with increasingly sensitive instruments. Furthermore, small-scale low-energy accelerators have been used for the study of nuclear reactions relevant to astrophysics. Using these conventional "stable beam" facilities radioactive species are produced by nuclear reactions at energies far below or close to the Coulomb barrier, i.e. by fusion and transfer reactions, as well as deep-inelastic collisions. In this way rare nuclear phenomena have been discovered, among them super-deformation, nuclear super-fluidity, first hints for the existence of the "island of stability" for super-heavy nuclei and others, many of which are still not well understood despite intense theoretical efforts. Further experimental investigations of very weak signals typical for these rare phenomena require the development of more sensitive instruments as well as facilities capable of higher beam intensities than those available today. The correct probe, coupled with the optimal detection equipment is of paramount importance for improving the signal to noise ratio for studying nuclei close to the observation limits. The latter applies also to nuclear astrophysics investigations which do not necessarily requires experimental work deep underground. Intense heavy ion beams may be used in inverse kinematics to improve the signal to background ratios.

In recent years, the advent of a first generation of RIB facilities which continue to operate at rather low intensities (< 10^8 particles/sec) has opened up new possibilities to access still unexplored regions in the chart of nuclei. Such regions are not or not easily accessible with stable beams. Nuclear halos, shell quenching far from stability and new decay modes are some examples of the newly discovered facets of nuclear behaviour. Presently, higher intensity RIB facilities are planned and some are already under construction, though the maximum expected RIB currents in the medium-term future will only be (for a few species) of the order of magnitude of those presently available for stable beams.

In the past a sufficiently large number of facilities has been available to the European Nuclear Physics Community delivering stable heavy ion beams at energies close to the Coulomb barrier with intensities of up to a few 10^{12} particles/sec. Many of these facilities are being recognized as leading European research infrastructures. Nevertheless, the last decade has seen the phasing out of several of these facilities in Europe. Especially in the case of low-energy accelerators dedicated to nuclear astrophysics research this situation has reached a critical point. In the meantime new physics domains have emerged that require the use of higher beam intensities than available today.

NuPECC has stressed on many occasions and particularly in its recommendations for the last two 'Long Range Plans', the importance of the existing stable beams facilities for our field. Furthermore NuPECC has appointed, less the ECOS working group in order to examine the research perspectives with high intensity stable ion beams, to help categorize existing facilities and their possible upgrades and to identify the opportunities for a dedicated new facility in Europe.

This document is produced by the ECOS working group. It contains, in its first section, a highlight of many fascinating nuclear physics questions that can be better (or only) addressed with high intensity stable beams at energies close to the Coulomb barrier. From the requirements dictated by the various ‘research lines’ specifications for a desirable facility will be described in the second section together with the needed research and development for ion sources, targets, spectrometers and detection systems. This document will also present the status and capabilities of some major facilities in Europe for producing high intensity stable ion beams as well as their future developments and up-grades. The ECOS working group came to some conclusions and recommendations that will be developed in the last section.

II Research using stable ion beams

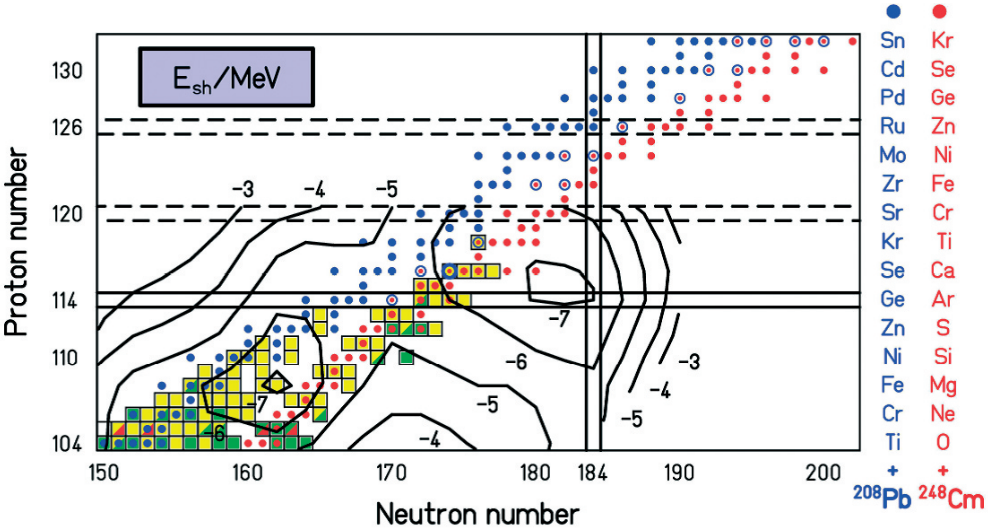
In the following, we briefly describe some of the physics questions that will be uniquely addressed with a modern high-intensity stable beam facility:

1. The quest for super-heavy nuclei

The study of nuclei at the limits of stability is one of the main challenges faced by nuclear structure physics. Often the finer details of structure are isolated and identified in the exploration of extremes. One such extreme is that of high mass and charge – the regime of super-heavy elements (SHE). The question whether an island of stability exists for nuclei beyond uranium and where the borders of such an island may lie has been at the centre of nuclear physics for nearly half a century and is still one of the most fascinating and elusive open questions in nuclear physics.

In a simple first step the liquid drop model in various parameterizations predicts the limits of stability somewhere around Z=100-106 where the long-range Coulomb repulsion between the protons overcomes the short range attraction of the strong nuclear force. Extra stability comes from the microscopic shell corrections and a lot of effort is focused on the best description and extrapolation of the mean field far from the well studied nuclei around Z=92 to those with the largest masses. Here various approaches favour different spherical proton and neutron magic numbers: The macroscopic-microscopic models predict Z=114, N=184. Calculations using self-consistent mean-field approaches broadly fall into two categories, namely relativistic and non-relativistic approaches. Within each approach a large number of parameterizations of the effective Skyrme and Gogny forces are commonly used. However, systematic comparisons show that most non-relativistic mean-field calculations favour Z=124 or 126 and N=184. In contrast, the relativistic mean-field models show an extended region of additional shell stabilization, centred mainly around Z=120, N=172.

One major challenge to experimental investigations is the increasing difficulty with which SHE can be produced. Fusion evaporation reactions are used. Two main approaches have been successfully employed here. Firstly, reactions with medium mass ion beams impinging on stable Pb and Bi targets. These reactions have been successfully employed to produce elements up to Z=112 at GSI and to confirm these experiments at RIKEN and LBNL. Using a Bi target one isotope of element 113 was recently synthesized at RIKEN. Secondly, reactions between lighter ions and radioactive actinide targets have been employed. These combinations, especially with ^{48}Ca beams, have been used to produce more neutron rich isotopes of elements from Z=112 to 116 and 118 at FLNR. The figure below summarizes the data as they are presently known or under investigation. Besides the pure discovery of these elements with highest Z, two more important observations have emerged. First, the expectation that half-lives of the new isotopes should lengthen with increasing neutron number



Ground-state shell correction energy and compound nuclei which can be reached in reactions with targets of ^{208}Pb and ^{248}Cm and stable projectile isotopes. The boxes show the isotopes in the region of heavy and SHE's, which are known or presently under investigation

as one approaches the island of stability seems to be fulfilled. Second, the measured cross-sections for the relevant nuclear fusion seem to be correlated with the variation of the shell-correction energies and fission barriers.

The immediate future of SHE research is dictated by the request for stable and radioactive ion beams of highest intensity. The compound nuclei which can be reached with beams of stable ions and two representative targets ^{208}Pb and ^{248}Cm are shown in the figure above. Using beam intensities of about 1 pμA, which are presently available for stable ions, the production rate at a cross-section of 1 pb is one atom per week. These rates or vice versa the reachable cross-section limits could be considerably increased or decreased, respectively, if beams of higher intensity were available. Improvements up to a factor of 100 are technically possible.

In order to optimally use these high intensities in experiments, separators and detection systems of highest sensitivity and precision have to be developed further. With ever improving production yields and detectors, in-beam nuclear structure studies of SHE are also making rapid progress. For No and Lr (Z=102 and 103) experiments at ANL and JYFL have enabled important information on nuclear deformation, single particle properties, and resistance against fission under rotation (see following Chapter). Finally, by establishing nuclear chemistry of elements up to hassium (Z=108) one can hope that the other discovered elements may eventually be placed in the Periodic Table according to their chemical properties.

1-a Synthesis

What we need in the future for the study of super-heavy elements are systematic measurements of highest accuracy and reliability both of the reaction processes for synthesis of these nuclei as well as of their decay properties. Concerning the reaction process the new results on the synthesis of elements 112 to 116 and 118 obtained at FLNR Dubna using actinide targets open most interesting perspectives for further investigation of isotopes at and near the double magic shell closure at N = 184 and Z = 114 to 126. Obviously, as revealed by the data, relationships exist between the stability of these nuclei which is determined by shell effects, and their production yield which increases up to 5 pb for the synthesis of element 114 and 116. The relatively long half-lives, up to minutes were measured for the most neutron rich isotopes and up to days for isotopes near N = 162, open possibilities for the application of new techniques, for example the trapping of these ions in ion traps and measurement of the masses and of other atomic and nuclear properties with high precision.

Continuation of experiments based on cold fusion reactions are of highest interest for the study of the reaction dynamics and synthesis of new isotopes and elements. The reason is that the isospin (neutron excess) of the projectiles almost continuously increases up to ^{96}Zr, which would result in the compound nucleus ^{304}122. This nucleus is located already two neutrons beyond the closed shell N = 184. Similarly, even more pronounced due to lower excitation energy than in the case of hot fusion reactions, the survival probability of the compound system should be increased by strong shell effects which result in high and wide fission barriers. However, cold fusion reactions resulting in compound nuclei at and beyond element 118 (^{86}Kr beam) are endothermic at Coulomb barrier energy with continuously decreasing (negative) excitation energy which reaches a value of −10 MeV for the reaction ^{96}Zr + ^{208}Pb. It remains one the interesting questions, how an increase of the beam energy in order to make the reaction energetically possible, will influence the cross-section.

The prerequisites for an extended program for the study of SHE's are projectile beams of highest intensity, long term stability of accelerator and detection set-up and sufficiently long irradiation times. Accelerator upgrades for experiments at Coulomb barrier energies have the primary goal to provide optimum beams for study of SHEs. No estimate is possible of the number of new elements that can be produced with a new accelerator. However, the quest to discover the existence of an island of stability and the exploration of its border lines, can be only attacked with a considerable improvement of experimental equipment.

1-b In-beam spectroscopy

For the most part, structure information has mainly been derived from the study of alpha decay fine structure. Here the selective population of states with a similar single-particle structure as the mother state has allowed studies aimed at a systematic mapping of single-particle orbitals close to the ground-state in a large number of nuclei. The main difficulty in this approach lies in the assignment of spins and parities from just the alpha decay observables such as energies and hindrance factors. The heaviest nucleus in which a direct measurement of the ground-state spin has been made is ^{253}Es. More commonly one has to rely on an evaluation of decay chains over a wide range of nuclei and comparison with the theories one wishes to constrain. Thus this method alone generally does not pin down configurations.

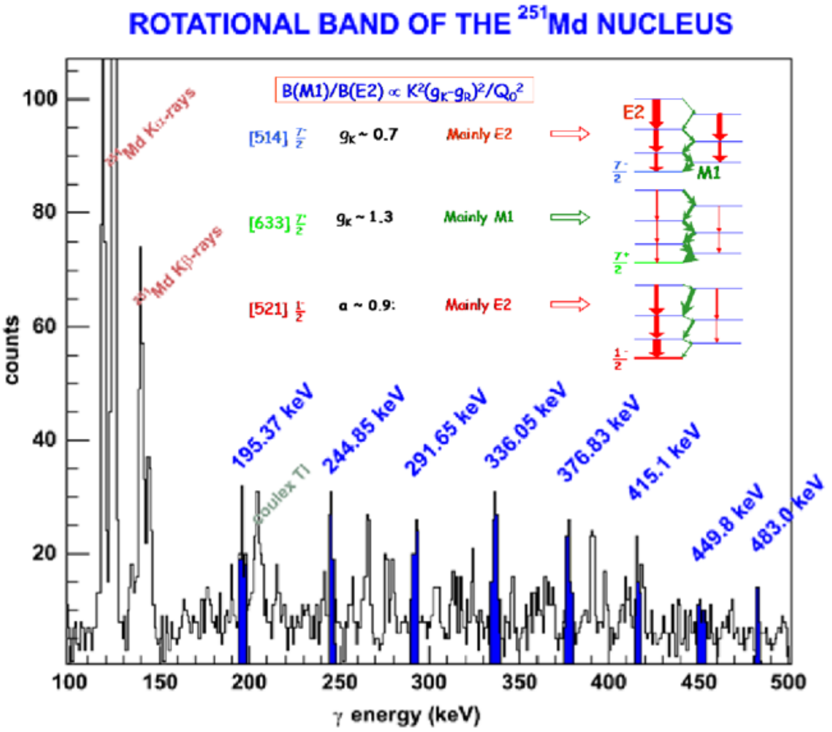
One further, indirect approach is open to the study of SHE. In the deformed nuclei around ^{254}No$_{152}$, the Nilsson orbitals, at the Fermi surface are built on single particle levels which come down in energy and lie at or close to the Fermi surface. Here the sequence of levels at a deformation $\beta_2 \approx 0.3$ probes the strongly down-sloping low-Ω levels stemming from the spherical $1i_{11/2}$ and $1j_{15/2}$ orbitals well above Z=126. Thus, the structure of the well deformed nuclei in the nobelium region will depend strongly on variations in the energies of those spherical orbitals.

In-beam spectroscopy is a powerful tool that allows deep insights into the atomic nucleus. All experiments follow the same principle: The nuclei of interest are produced and separated from unreacted beam, fission fragments and products of other reactions. At the focal plane of the separator the recoiling nuclei are identified. Prompt radiation detected at the target position is then correlated with the recoils of interest via the characteristic time of flight. This method has been successfully employed to study nuclei produced with as little as 200 nb production cross-section and today cross-sections of 20 nb allow successful experiments. An example from the study of ^{251}Md is shown in the figure below.

The largest challenge in this area is to pick the extremely rare SHE events out of a background typically $10^6 - 10^9$ larger than the signal. In addition, the decay properties of SHE's vary strongly even between neighbouring isotopes. This makes it difficult to propose an one-size-fits-all approach that only looks at the available beam intensity. The brunt of the effort has to be borne by the instrumentation that should be able to handle the data rates associated with large beam currents while retaining the high sensitivity and selectivity to pull the rare SHE events out of the background. In the following a closer look at a few representative cases may serve to illustrate the interplay between accelerator, beam, target, and detection system.

In SHE studies the main channels open in any reaction are fast fission and compound nucleus fission with cross-sections of about 1 b. The resulting fission fragments produce a large number of high energy gamma rays which the detectors array at the target needs to handle. Furthermore, the targets employed are typically Pb and Bi with low melting points and thus target wheels need to be used.

The rapid progress in the field has been achieved using tagging spectrometers such as GREAT that can detect radiation from all possible decay processes, operated alone or coupled with either a conversion electron spectrometer or a γ-ray spectrometer



In-beam gamma-ray spectrum of ^{251}Md taken with JUROGAM. A rich structure of at least one rotational band is seen. The highlighted transitions were confirmed to be in mutual coincidence. The inset shows the expected behavior of the E2 and M1 transitions in the band as a function of the single proton orbital upon which the band is built. In-beam gamma ray spectroscopy is only sensitive to the E2 transitions marked by vertical arrows in red, conversion electron spectroscopy is only sensitive to the M1 transitions (diagonal arrows, green). Only a simultaneous measurement of conversion electron and gamma-ray decays will provide the full picture.

array that measures the prompt radiation emitted following the synthesis of nuclei. Both types of in-beam spectrometer are necessary because internal conversion competes strongly with γ-ray emission in heavy nuclei, particularly for low transition energies and high multipolarities. Consequently, when detected individually, each radiation type can at best reveal only a partial picture. Future instruments such as the planned SAGE spectrometer will allow the simultaneous measurement of prompt γ rays and conversion electrons with high efficiency. This important development will be essential for obtaining a deeper understanding of such complex quantum systems.

1-c Decay studies and isomers

The best way to deduce information on the single particle structure of SHE's produced below the 1 nb level where, in-beam studies are no longer possible, is to perform spectroscopy following alpha decay at the focal plane of a separator. Since no prompt radiation is detected, high currents of several pμA can be used provided the targets withstand the thermal load. Here rotating wheels with more heat resistant compounds (e.g. PbS) can be used. The main limitation is the total rate of reaction products and background particles arriving at the focal plane. The Si implantation detectors can withstand heavy-ion implantation rates of 10 kHz for reasonable periods of time and may need to be replaced several times during a long run. This can be avoided if the suppression factor is good enough, a property which depends entirely on the quality of the separator.

In order to make the most of the rare decays all possible types of radiation (alpha, conversion-electron, gamma, X-ray, beta) need to be detected with high efficiency. The detector system at SHIP and the GREAT spectrometer are good examples of focal plane arrays with high Si pixellation and excellent efficiency for the detection of conversion-electron, X-rays and gamma rays.

Based on these estimates one would conclude that spectroscopy studies following alpha decay are possible on nuclei produced at a level of several picobarns with beam currents of several tens of pμA. It will then be possible to perform detailed decay studies on those nuclei whose production was previously possible at the level of a few atoms only.

Another way to approach the single-particle structure of the SHE is via nuclear magnetic moments studies of fission isomers. The orbitals on which these isomers, located in the second (super deformed) well at lower Z (92 –97), are built, are expected to come to the Fermi surface at higher Z.

The ordering of the single-particle orbitals in the second well will provide a possibility to test the shell model for extreme nuclear deformations and will help us better understand the structure of the SHE close to the island of stability as well. Production cross section of the order of few µb makes the nuclear moments studies of fission isomers still feasible.

1-d Coulomb and atomic excitations

With the increase of beam intensities new quantities such as the collectivity (B(E2) measurements) will also become measurable. By using inverse reactions to create the heavy residues, their Coulomb excitation at the focal plane of the separator will be possible. Coulomb excitation is achieved after separation by passing the recoiling nucleus through a high-Z foil before the implantation detectors. With a pµA beam the Coulomb excitation of nuclei produced with cross-sections down to the microbarn level becomes feasible.

Example of Coulomb excitation of ^{254}No nuclei: 50 ($4^+ \rightarrow 2^+$) electron transitions can be detected per day with a 1 pµA ^{208}Pb beam (production cross-section for ^{254}No = 3 µb, ^{48}Ca primary target thickness = 100 µg/cm^2, recoil transmission and detection of 50 %, ^{208}Pb secondary target thickness = 10 mg/cm^2, Coulomb excitation cross-section for the 4^+ to 2^+ transition = 5 b and electron detection efficiency = 40 %).

Inverse reactions also result in proper residue energies for the creation of collision induced X-rays. In the region of heavy elements the cross-sections for emission of L electrons are on the order of 10^5 barn at ion energies of 2 A.MeV. Using a properly chosen converter foil and high resolution X-rays detectors in the focal plane of a separator, the emission of L X-rays can be studied in coincidence with signals from residues subsequently implanted into a Si stop detector. Information is obtained from the X-ray energy on relativistic effects on the electron binding with increasing Z. In principle, the method can also be used for the identification of the produced nuclei.

1-e Chemical studies

Nuclear chemistry experiments were among the first which were performed at the newly built UNILAC in 1975. During the first decade the research programme concentrated on the search for SHE's in a variety of heavy-ion reactions mainly with ^{238}U and ^{248}Cm targets and projectiles ranging from ^{238}U to ^{48}Ca. In the mid-80's the emphasis shifted towards chemical investigations of the transactinide elements including nuclear reaction and nuclear structure aspects. In this extremely successful and ongoing research programme only hot-fusion reactions with actinide targets were utilized to synthesize the most n-rich, long-lived nuclides needed for chemical studies.

The first two transactinide elements are rutherfordium and dubnium (Z=104 and 105). They are placed in group 4 and 5 of the Periodic Table, as it was shown in pioneering experiments by the Dubna and the Berkeley-Livermore groups in the course of or soon after the discovery of these elements. The central question about the influence of relativistic effects on the chemical behaviour of these elements remained open and was only approached in the more recent experimental programmes. The increasingly strong relativistic effects when going to even heavier elements makes this field most thrilling for chemists. Continuous developments of new and constantly advanced techniques for many experimental facets, allowed sensitivity improvements over about four orders of magnitude from 10 nb to a few pb.

Quite naturally, because of relatively high cross-sections and long half-lives, the most detailed knowledge is now available for Rf and Db. While the GSI group started – together with the collaborating partners from Bern, Mainz and Berkeley – the first detailed investigations, the centre of gravity for studies in the aqueous phase has shifted now to experiments performed at Tokai. This was established and is continued in the course of a very fruitful GSI-JAERI collaboration. Right from the very first experiments Db and Rf showed surprising properties as compared with empirical extrapolations. Fully relativistic theoretical calculations are now able to explain many of these unexpected findings. However, we are far away from a good understanding of the chemistry of Rf and Db in a general sense.

A very large international collaboration, consisting of 16 institutes from 8 countries, joined at the GSI to perform over several years in a series of beam times all experiments which establish today's knowledge about the Sg chemistry – in the gas-phase and in the aqueous phase. They placed Sg into group 6 of the Periodic Table. Sg is the heaviest element for which information about the behaviour in aqueous solution is available and more detailed studies are in preparation. For the first time, chemistry experiments provided samples for nuclear decay studies of the most n-rich Sg isotopes ^{265}Sg ($T_{1/2}$=7.4 s) and ^{266}Sg ($T_{1/2}$=21 s).

The first chemical property of bohrium (Z=108) was investigated at the Paul Scherrer Institut (PSI), Villigen, in collaboration with the GSI group and others. The determined volatility puts BhO_3Cl into group 7 of the Periodic Table. The isotopes ^{266}Bh and ^{267}Bh were discovered and investigated in the preparation and during the Bh chemistry experiments.

One of the more recent highlights are the two Hs gas-phase chemistry experiments both performed at the GSI. The first experiment, headed by the group of PSI Villigen and University Bern, showed the formation of the volatile compound HsO_4 with typical group 8 properties. Moreover, this experiment not only provided an independent confirmation of the discovery of element 112 (by the study of the alpha decay of the grand daughter of ^{277}112) but also yielded new information on the nuclear decay properties of ^{261}Rf and ^{269}Hs and an indication for the new nuclide ^{270}Hs at N=162. Chemical and nuclear investigations of Hs are continuing.

The most recent and most exciting experimental programme is the gas-adsorption study of element 112 in comparison with Hg and Rn – presumably the two extremes in the range of possible element 112 properties. While first experiments were performed at Dubna, a much more detailed, ongoing investigation began at GSI. First results indicate that element 112 shows a significantly different behaviour compared to Hg. These experiments will be continued and will be extended to cover also the element 114 behaviour. These experiments also have the potential to independently confirm results obtained with recoil separators.

In the future, this research field will fully take advantage of the availability of higher intensity stable ion beams in Europe and will expand further.

2. Nuclear structure studies at low, medium and high-spin

Identifying and characterizing nuclear states as a function of excitation energy (E^*) and spin (I) is crucial to understand the underlying single particle and/or collective structure of the nucleus. Questions such as how different nuclear shapes and associated motions develop and disappear, how shell effects and residual interactions survive with spin and temperature and how chaos sets into the nucleus can only be answered by a study of the nuclear properties in the (E^*, I) plane. Gamma-ray emission constitutes a unique probe of the nuclear structure. In recent years, large arrays of gamma-ray detectors have been exploited at several accelerator facilities. Among many other phenomena they have allowed the discovery of super-deformation and of the first hints of hyper-deformation at the highest angular momenta a nucleus can sustain.

The third important variable which needs to be evaluated is isospin (T), related to the difference in the number of protons and neutrons. In the following, we will focus on a few selected physics topics, which will benefit most from more intense stable beams than used today. The main experimental limitations are the finite resolving power of the multi-detector arrays and the constraints on beam intensity associated with overloading their high resolution analogue electronics. Further progress can only be made by combining future 4π tracking arrays, such as AGATA, with more intense stable beams than those used today. Both components are needed if we want to answer the burning questions related to the study of discrete nuclear states at extreme spins.

2-a Exotic shapes and decay modes.

High spin states of the nucleus are accessible through fusion-evaporation reactions using heavy ion projectiles. Much progress has been achieved in investigating the evolution of nuclear structure with increasing angular momentum with advanced gamma-ray detectors: Alignment effects, band termination, shape transition and rotational damping are some of the fascinating features that can be studied in this way.

The observation of super-deformed (SD) nuclei constitutes an important confirmation of shell structure in the nucleus and the study of excitations in the SD well allows to characterization of the active orbitals and their correlations. In the past 5 years, several new regions of super-deformed nuclei have been discovered near mass number A ~ 60, 90, 110. Octupole "pear-shaped" vibrational modes have been identified in super-deformed nuclei with masses around 150 and 190 and first evidence has been found for very extended triaxial shapes near A ~ 170. In lighter nuclei, very elongated shapes in the N = Z nuclei ^{36}Ar and doubly magic ^{40}Ca provided the opportunity to study the microscopic origin of collective rotation through the detailed comparison of mean field and shell model calculations. Many unexpected and surprising phenomena have been investigated and have yet to be explained and generalised.

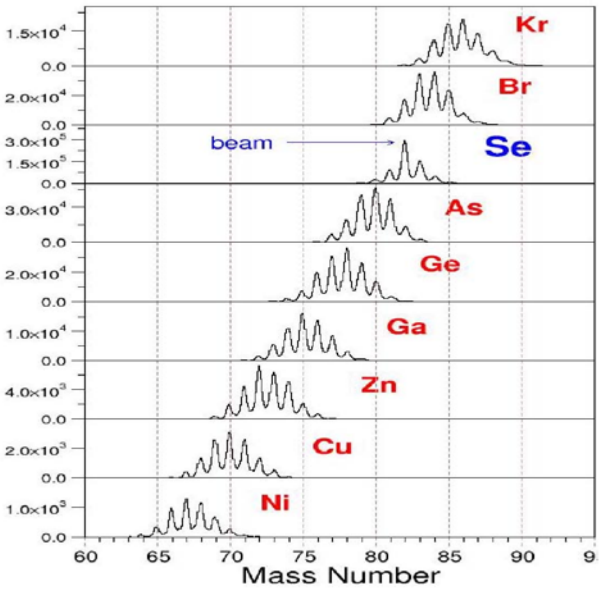
Although more than 200 super-deformed bands are known, only a handful have known spins and excitation energies. Despite intense experimental and theoretical efforts, there are still many open questions regarding the population of super-deformed states, in particular, their observed intensity, which are orders of magnitude larger than that of normally deformed states of similar spin, is still not understood. Knowing the population mechanisms of super-deformed states will certainly influence the understanding of the population mechanisms of more exotic nuclear shapes and those of very heavy nuclei.

Hyper-deformation is also strongly related to the important issue of how much spin the nucleus can sustain since in most nuclei these states are thought to be only observable at very high spins (70-80 h). In such angular momentum region they are predicted to become the lowest excited states of a given spin. However, even with today's most powerful gamma spectrometers such as EUROBALL and GAMMASPHERE, it has not been possible to populate and identify nuclear states above spin 139/2 hbar. The main experimental limitations are the finite resolving power of the multi-detector arrays and the amount of beam one can use without overloading their associated high resolution analogue electronics. Further progress can only be made by combining future 4π tracking arrays, such as AGATA with more intense stable beams than those used today.

2-b Structure of neutron-rich nuclei

One of the critical ingredients in determining the properties of a nucleus from a given effective interaction, is the overall number of nucleons and the ratio N/Z of neutrons to protons. It is the extremes in these quantities, which define the limits of existence for nuclear matter that is going to be opened up for study with present and future radioactive ion beam accelerators. High intensity beams of heavy ions can also be used to reach both proton rich and neutron rich systems where new exciting phenomena are expected to happen. The interest in the study of nuclei with large proton/neutron ratios is in the changes of the nuclear density and size, which are expected to lead to different nuclear symmetries and excitations. A relevant aspect related to changes in size and diffusivity encountered in neutron rich nuclei is the modification of the average field experienced by a single nucleon. This is a basic ingredient in the many-body theories used to describe nuclear properties. The experimental study of the single-particle levels with neutron excess is therefore very important, inducing changes in the standard magic numbers and, possibly, even the breakdown of shell gaps and magicity.

In the last few years, the use of binary reactions, quasi-elastic (multi-nucleon transfer) or deep inelastic scattering, combined with modern γ-ray arrays (GASP, Gammasphere, Euroball, etc.) with or without efficient ancillary detectors, has increased substantially the amount of information available on the structure of previously inaccessible nuclei far from stability. Due to the large number of final products it is extremely important to provide the necessary selectivity to identify the mass and charge of the produced systems. Such selectivity can be achieved combining highly segmented γ-ray detector arrays with large acceptance spectrometers.



Mass distributions at the focal plane of the PRISMA spectrometer for the different elements populated in the ^{82}Se + ^{238}U reaction at 505 MeV of beam energy.

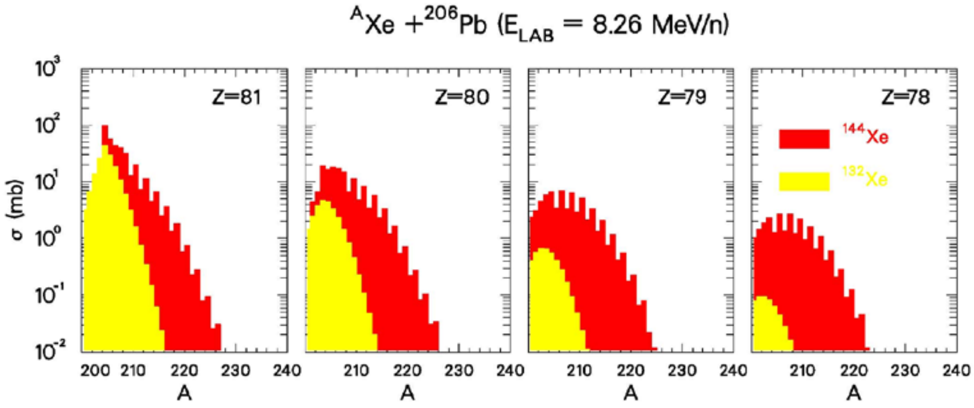
Recently a major breakthrough has been achieved with a new gamma-detector array (CLARA) dedicated to such binary reactions. The array has started operation at Legnaro National Laboratories in combination with a magnetic spectrometer (PRISMA). PRISMA is a large acceptance magnetic spectrometer for heavy ions. The use of the PRISMA spectrometer coupled to an anti-Compton gamma-ray detector array marks a step forward with respect to the previous spectroscopy studies with deep inelastic or multi-nucleon transfer reactions.

High intensity beams of stable heavy ions (like Xe, Pb or U) offer the interesting possibility to further extend our knowledge of neutron rich nuclei. The figure below shows the production of neutron rich nuclei calculated using the programme GRAZING.

Presently available beam intensities for medium or heavy beams hardly reach the value of one pnA. Even using large acceptance spectrometers and large gamma detector arrays a sensible rate of double gamma coincidences is only seldom reached for those reactions. Future perspectives in the field are therefore based on the use of high intensity (I~100 pnA) beams of stable heavy ions with large A/Z ratios (as for example Pb or U) together with new gamma-ray detectors based on gamma ray tracking (AGATA). This would push the present sensitivity limit of ~100-10 microbarn (CLARA-PRISMA) down to 1 microbarn-100 nanobarn allowing to investigate at medium and high spin very exotic neutron rich systems as for example ^{78}Ni.

2–c Structure of nuclei at and beyond the proton drip-line

The study of nuclei along the N=Z line is of special interest due to the particular symmetries between protons and neutrons that can be explored, such as proton-neutron pairing correlations, exotic deformations, coupling to the continuum for drip-line nuclei, isospin symmetry in mirror nuclei and isobaric multiplets. The structure of the nuclei along the N=Z line is also of significant astrophysical interest, as the path of the rp process of stellar burning passes through these nuclei. These studies are often linked to the use of radioactive ion beams. While this is certainly true for neutron rich isotopes, proton rich nuclei at the N=Z line can also be produced in fusion evaporation reactions with stable beams. As long as the intensity of proton-rich radioactive ion beams does not approach the pnA range, the use of very high inten-



The theoretical predictions for the production cross-sections of neutron rich nuclei using multi-nucleon transfer reactions from both ^{132}Xe and ^{144}Xe beams.

sity stable beams can be competitive in a number of well-chosen cases. Of specific interest in this context are cold reactions at even below the Coulomb barrier where only very few particles are evaporated. Under these circumstances evaporation channels involving up to two neutrons can become rather important. Since the total reaction cross-section is very small at sub-barrier energies (10 mbarn or less) a very high primary beam intensity can be used (up to pμA) leading to a larger production rate of exotic nuclei than is possible with beams from the first generation RIB facilities. An advanced detector system is required consisting of a high-efficiency Ge array and light charged particle as well as neutron detectors. In order to reach the most proton rich nuclei the quality (efficiency and sensitivity) of the neutron detector system is of utmost importance. For nuclei that can be reached by pure xn reaction channels an efficient charged particle (proton and α) anti-coincidence detector should be utilised. As an alternative a very high efficiency recoil spectrometer could be employed. In special cases a device for measuring conversion electrons is also needed.

Mirror nuclei (those with opposite proton and neutron numbers) are expected to reveal nearly identical energy level structures. This is an immediate consequence of the charge independence of the nuclear force. Therefore, the differences in energy levels with the same spin and isospin in mirror nuclei shall arise from the different contribution of the Coulomb energy, which breaks the isospin symmetry. The study of the mirror symmetry has so far been limited to light nuclei and low spins; the heaviest pair with $T_z = \pm 1$ being ^{50}Fe and ^{50}Cr. At an advanced stable beam facility with highly efficient Ge and ancillary detector systems, it would be possible to extend these studies considerably to higher masses and/or angular momenta.

Another very important issue related to the structure of proton rich nuclei is to find the origin of the coexisting nuclear shapes and exotic excitations observed in medium-mass and heavy nuclei close to the proton drip line, and to understand their relation to the fundamental interactions between the nucleons. Nuclei at the proton drip-line and beyond can be produced in fusion-evaporation reactions with stable ion beams and stable targets. The production cross-sections quickly go down when approaching the drip-line and the reaction channel of interest typically represents only a very small fraction (down to 10^{-8}) of the total cross-section. Therefore, special devices and methods are needed to resolve the weak events from the vast background. A major breakthrough was achieved recently when Ge-detector arrays (JUROGAM = 43 Compton suppressed large Ge detectors from the EUROBALL array) were combined with the RITU separator for Recoil-Decay-Tagging (RDT) experiments at JYFL. For the first time, it was shown that in-beam gamma-ray spectroscopic studies of alpha-decaying proton drip-line nuclei with production cross-sections down to approximately 20 nbarn are possible. The scientific results include first observations of excited states in 50 isotopes with Z = 52-103 involving exotic shapes.

One of the main discoveries in these studies is that the triple-shape-coexistence is common for these nuclei close to the mid-neutron shell. Most striking is the result for mid-shell Pb and Po isotopes, which reveals that the energy minima corresponding to the spherical, oblate and prolate shapes all lie within two hundred keV in excitation energy, one of them forming the ground-state. More detailed spectroscopic studies are needed to understand the origin of these and other exotic structures in proton drip line nuclei.

Flight times in recoil separators limit the search for proton emitters to cases with lifetimes longer than 1 microsecond. the extension of these studies to much shorter time scales by detecting protons directly from the target would be a revival of the methods used in the discovery of the ^{109}I and ^{113}Cs proton emitters. In the region of relatively heavy nuclei the resulting daughter nucleus of such a proton emitter is often an alpha- or proton emitter of a longer lifetime. Consequently, identification of the exotic ultra-fast proton emitter can be done by employing the RDT technique. These proton emitters give information about very weakly bound systems beyond the proton drip line.

In general, it is important to combine information extracted both from in-beam and decay studies. The beam intensity in in-beam studies is limited by the counting rates of the detectors at the target area. In case of gamma-ray detection this limit is typically 10.000 counts per second per Ge-detector. Today several projects are ongoing to develop digital front-end electronics for such detectors. It is expected that in this way the detector rate limits can be increased up to 100,000 counts per second. In terms of beam intensity this increase represents a step from approximately 10 pnA to 100 pnA on a 1 mg/cm^2 target. Such an increase will push the limit of in-beam spectroscopy down to the level of a few nanobarns in the production cross-section.

In off-beam studies of medium-heavy proton rich nuclei the maximum beam intensity is typically limited by the counting rate of the recoil detector at the focal plane of a separator. In the case of focal plane studies of heavy nuclei ($Z > 80$), where the dominant decay channel of the compound nucleus is fission, the maximum beam intensity (up to several pμA) is typically set by the durability of the target.

2-d Clusters and molecules in nuclei

Neutron rich and weakly bound nuclei show a strong tendency to clustering. This appears to be partially due to the properties of the residual interaction which can saturate better the nuclear forces in such a way that a maximum number of protons can interact with neutrons. In light nuclei this leads to the formation of shape isomers as covalent molecular structures for weakly bound systems. Since 1968 it has been realized that clustering in nuclei will become relevant for states close to the threshold for their decomposition into clusters. Nuclear clustering based on alpha particles and strongly bound substructures with N=Z has been studied since many decades. The physics of the drip-line nuclei, where single nucleon and cluster binding energies are very small, is strongly related to the clustering phenomenon observed at the single nucleon and cluster threshold in normal nuclei. The latter species have the advantage, that often the properties of the relevant states can be studied with high precision, because the experiments can be based on the recent advances in detector technologies. The existence of strongly deformed shapes in light nuclei has also been recognized to be related to clustering phenomena. Recent interest focuses on extreme deformations, in the deformed shell model these are referred to as super- and hyper-deformation. The alpha chain states in the carbon isotopes are the first examples of such structures. The structure of the strongly clustered states is very peculiar, and there are many examples which show that they can not be obtained even in the largest shell-model calculations. Theoretical approaches based on model independent calculations of nuclear properties, like the antisymmetrised molecular dynamics (AMD), are able to reproduce the extremely clustered states in light nuclei. Other approaches are developed which are based directly on a basis with clusters as centers of orbitals for single nucleons. This gives rise to multi-center molecular structures. The spectroscopy of strongly deformed shapes in N=Z nuclei has so far been the domain of charged particle spectroscopy. Various decay studies with the emission of alpha particles, ^{8}Be and heavier fragments are known, however, new detector set-ups with a combined particle-gamma detection are expected to give new insight into exotic shapes in nuclei related to clustering. For instance, the observation of the gamma-decays of these cluster states is a big challenge as their branches are expected to be rather small at these excitation energies (in the range of 10^{-5} 10^{-6} fractions of the total width) but will provide stronger evidence of their existence.

The physics of loosely bound and extremely deformed nuclear systems is an emerging field, which has been triggered in recent years by the new insights gained into the structure of exotic nuclei. The role of dedicated accelerators with stable beams becomes decisive for this field. As in the case of very heavy nuclei (new elements), the big advances are expected from dedicated and sufficiently long experiments. A stable beam facility with higher beam intensities than usually used and longer experiments, is a pre-requisite for such studies.

3. Ground-state properties.

Ground-state properties of atomic nuclei such as masses, half-lives, radii and moments are direct observables that can provide crucial information on the structure of nuclei. These properties are often well-determined for nuclei close to the valley of beta-stability but an extension of their knowledge towards extreme proton and neutron numbers far from stability is a real challenge in modern nuclear physics research. The presently operating stable beam facilities have played a key role in this endeavour, as described shortly below. In the future, such facilities will continue to make important contributions to the field. The combination of stable high-intensity light or heavy-ion beams and an ISOL or in-flight separator equipped with a gas catcher technique can provide intense and exotic beams of low-energy radioactive ions complementing the planned radioactive beam facilities. Especially, heavy-ion induced fusion evaporation reactions and light-ion induced fission reactions that employ a high-intensity driver accelerator can be truly competitive in producing neutron-deficient nuclei up to the proton drip-line above A=60 all the way up to the superheavy element region as well as in producing neutron-rich nuclei near and between the doubly-magic ^{78}Ni and ^{132}Sn. Another interesting and reachable region is located in the neutron-rich side of the nuclide chart above the fission production region. This can be reached by transfer reactions induced by neutron-rich stable beams. The experimental techniques described below are easily adaptable to highest intensities.

3-a Atomic masses

The mass is a fundamental property of a nucleus and depends on the masses of its constituent nucleons and the total binding energy. The latter is directly connected to the structure or the ground state wave function of the nucleus. From this point of view systematic mass measurements probing the variations in the binding energy at different levels of accuracy can unreveal both global and local microscopic features with changing proton and neutron numbers. Despite of their importance the accurately known atomic masses are still rather rare and already a few neutron numbers away from the valley of stability the masses are known with modest accuracies only.

Physics questions that can be investigated via mass measurements are, for example, the evolution of shell structures and appearance of new shell closures, influence of pairing between like nucleons as well as proton-neutron interaction and the role of spin-orbit interaction at extreme proton and neutron numbers. In nuclear astrophysics, the binding energies are one of the most important ingredients for reliable nucleosynthesis calculations. They affect the rates of relevant reactions and they influence the time-scale and energy production of nucleosynthesis. In high temperature conditions, they adjust the balance, which defines the process paths. Precision measurements provide important data for fundamental studies of the weak interaction. Of particular interest are the measurements related to the super-allowed beta decays, which test the CVC hypothesis and the unitarity of the CKM-matrix.

In the past accurate mass measurements applying traditional techniques, like reaction kinematics and magnetic spectrometry, were restricted to stable or almost stable nuclei. Decay studies, in principle, allow extraction of masses further from the stability, but often a poor knowledge of the mass of the daughter nucleus and complex decay schemes seriously prevent accurate mass determination. Penning trap technology has shown ability to provide high resolving power (R) and accuracy – typical values being $R=10^7$ and $\delta m/m=10^{-8}$ for medium mass ions, respectively. A pioneering work at ISOLTRAP combining the ISOL-method and Penning trap technology has extended direct precision measurements to radioactive isotopes. Since then various projects relying on ion traps have been initiated at stable beam facilities as well. In the University of Jyväskylä, another approach where Penning trap was coupled to IGISOL-separator was chosen. There the availability of refractory isotopes allows extension of detailed mass spectroscopic studies to the new regions which were not accessible at conventional facilities. As a result, around 120 atomic masses of neutron-rich fission products were recently measured with and accuracy of the order of 10 keV or better. In addition to two ISOL-based, but production-wise complementary projects, precise masses of radioactive isotopes are measured also by applying the RF-spectrometer MISTRAL at ISOLDE. Although less accurate than Penning trap method this approach has an advantage of the very short delay time, which makes it suitable for very short-lived isotopes. An excellent example of this is the recent determination of the mass of ^{11}Li which has a half-life less than 9 ms.

While the masses are important for understanding the nuclear landscape and its limits among neutron-deficient and neutron-rich nuclei they are also important in the region of the heaviest elements where the interplay between the collective structures and shell effects are important in defining the limits of existence of the heaviest elements, for example. The SHIPTRAP project at GSI is devoted to measure the masses of the heaviest isotopes produced in fusion reactions. It combines the isotopic identification and primary beam suppression by the velocity filter SHIP with the gas catcher method which stops and subsequently injects exotic heavy isotopes into the Penning trap for precision measurements. Due to the extremely efficient suppression of unwanted species this combination provides a unique approach for precision measurements of atomic masses of heaviest elements. The performance of this facility can straightforwardly be improved by the increase of the primary stable beam intensity.

European efforts in the field of precision mass measurements are closely connected to the running stable beam facilities. Despite major progress during the last few year, much work is still to be done. The existing projects, like ISOLTRAP and JYFLTRAP, should be vigorously continued and exploration of the upper part of the nuclear chart by SHIPTRAP should be pursued. Extension of these experiments farther from the valley of stability sets new requirements for the facilities. There the limiting factors are shortening half-lives and low production rates. The first problem is of experimental nature and is to be addressed by individual experimental setups. The second limitation, low production rates of exotic species is related to the performance of the production and measurement schemes but above all to the intensities of stable primary beams. It is obvious that a vast amount of new data is within reach by the intensity increase of the primary accelerator beams.

3-b Charge radii and moments

High resolution laser spectroscopy is a well-established method for measuring nuclear moments and charge radii of nuclei. The ground-state magnetic dipole and electric quadrupole moments are obtained from the observed hyperfine structures of optical transitions of the atom or ion. The nuclear spin can be deduced from the same data. Thus the valence nucleon configurations and static quadrupole shapes of ground states and even isomeric states can be deduced.

The change in the nuclear mean square charge radius between two isotopes may be deduced from the frequency difference (isotope shift) of the optical transition in the two isotopes. Nuclear shape changes along an isotope chain are clearly seen from the isotope shift systematics and nuclear shapes can be deduced even if the hyperfine quadrupole interaction is small or absent. The subtle difference in the shape parameter measured by these two methods (the moment provides the mean deformation parameter; the isotope shift gives a root mean square value) opens up the possibility of studying the proton diffuseness at the nuclear surface, which may be affected by changes in the nuclear pairing or proton binding energies.

There is therefore great potential to learn about shapes and structures of exotic nuclei provided the laser techniques have sufficient sensitivity and production rates of the nuclei are adequate. There are many variants of the general technique of laser spectroscopy which could be applied to exotic nuclei. The key requirement is that the radioactive atoms are prepared predominantly in a single atomic or ionic state with a precisely defined velocity (the Doppler broadening of the transition should be less than a part per million). In practice this means the initial reaction products must be stopped in a gas or solid catcher as part of the preparation process. The efficiency and timescale of the preparation process will determine the scope for laser measurements. To date most laser measurements have been carried out at ISOL facilities using intense light-ion beams (usually protons) to produce the nuclei. Experiments have been possible on ion beam fluxes of tens of ions per second with lifetimes down to a millisecond. This timescale encompasses many interesting isomeric systems as well as ground states out to the proton drip line and neutron-rich nuclei produced by fission.

The extraction time of ions from conventional ion sources can limit studies of the most exotic nuclei. The shortest-lived species could be provided for measurement by a combination of a recoil mass spectrometer with a gas-catcher at the focal plane. Such a technique is suitable for medium and heavy mass isotopes near the proton drip line. High intensity heavy-ion beams are required to maximise production. Key advantages over ISOL techniques is that there is no chemical dependence on efficiency, and the nuclear lifetimes that can be studied are limited only by the flight time through the separator and extraction time from the gas cell.

4. Near barrier transfer and fusion reactions

The use of stable beams with intensities one to two orders of magnitude higher than the present available ones would lead to very significant advances in the field of reaction mechanisms close to the Coulomb barrier. Below we discuss representative physics cases in the field of multi-nucleon transfer and sub-barrier fusion reactions which would benefit from the availability of such high intensity beams.

4-a Transfer reactions

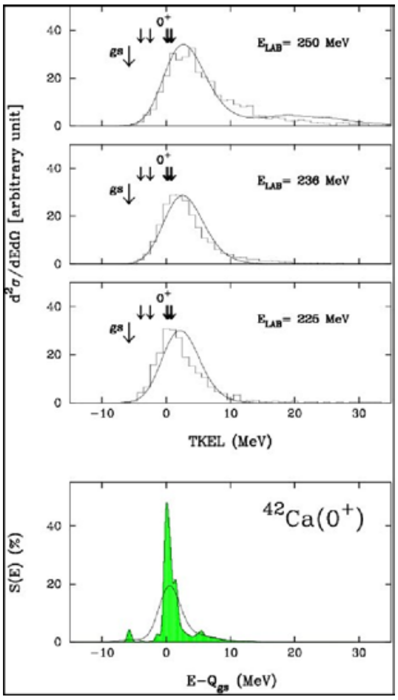
Transfer reactions between heavy ions at energies close to the Coulomb barrier provide invaluable information for both nuclear structure and reaction dynamics studies. From the stripping and pick-up of neutrons and protons one can deduce information about the shell structure close to the Fermi surface (one-particle transfer) of the two reactants or one can study nuclear correlations in the nuclear medium (multi-nucleon transfer reactions).

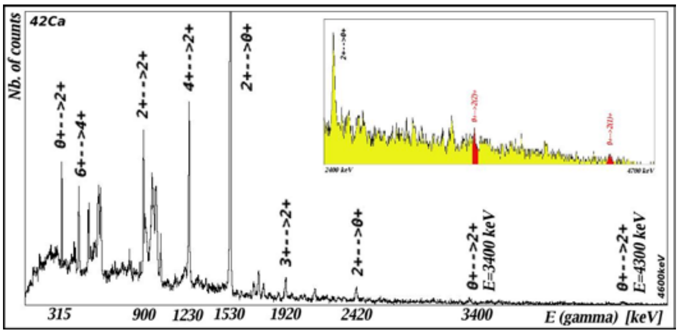
From the extensive work performed at LNL during the last years one could study detailed mass and nuclear charge yields, differential and total cross sections and total kinetic energy loss distributions of transfer products in several systems. From the comparison of experimental observables with theoretical models incorporating surface vibrations and successive transfer processes, one observes a good agreement with the inclusive data obtained for pure neutron transfer channels and for the stripping of one proton. However the calculations miss the massive proton transfer channels under-predicting the two-proton stripping by an order of magnitude. The discrepancies indicate that the theory should incorporate more complex transfer degrees of freedom. By adding to the reaction mechanism the transfer of correlated pairs of protons and neutrons, in the macroscopic approximation, and fixing the strength of the form factors to reproduce the pure -2p channel, the predictions for all other charge transfer channels become much better.

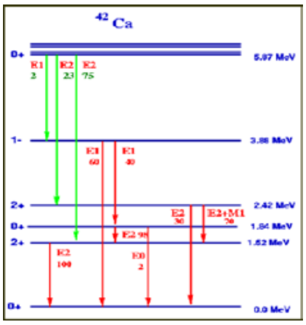
The microscopic justification for these pair transfer degrees of freedom, and, more generally, the understanding of the effect of nucleon-nucleon correlation, would be very much improved by performing experiments able to extract the strength distribution of transfer products among specific excited states. Interesting hints in this direction are coming from recent investigations on nuclei near closed shells, in particular in the ^{40}Ca+^{208}Pb, ^{40}Ca+^{96}Zr, ^{90}Zr+^{208}Pb reactions, the last two studied with the PRISMA+CLARA set-up at LNL. The Figure below (top) shows the total kinetic energy loss distributions at three bombarding energies for the two-neutron pick-up channel in comparison with CWKB calculations. The two neutron pick-up channel displays at all measured energies a well defined maximum, which, within the energy resolution of the experiment, is consistent with a dominant population in ^{42}Ca of states with excitation energy at around 6 MeV. These results are discussed in terms of two neutrons filling the $p_{3/2}$ orbital, which correspond to the main component of the excited 0^+ states interpreted as multi (additional and removal) pair-phonon states. This is also visible in the bottom part of the figure, where the strength distribution S(E) coming from large scale shell model calculations is shown. More detailed studies performed via gamma-particle coincidences (bottom part of the figure below) allowed to observe weak transitions that open the road to study these multi pair-phonon excitations.

Heavy ion reactions, though in general less selective than light ion reactions in populating specific final states, have the advantage to provide a mechanism for the transfer of multiple nn, pp, and np pairs. The transfer strength may be spread over several final states and to make detailed studies of the corresponding weak gamma decays, gamma-gamma-particle correlations are needed, in order to identify the spin and multipolarity of the interesting levels. At the same time, with the presently maximum available beam intensities in the range of few tenths of pnA extremely high statistics is required. A definite increase of primary heavy ion beam intensity, together with the availability of a wide variety of nuclear beams, which should range from closed shell, to superfluid and deformed nuclei, and the optimum use of large solid angle spectrometers coupled to powerful gamma arrays would enormously extend the knowledge in the field.

The energy region far below the Coulomb barrier is another interesting area to investigate the role of







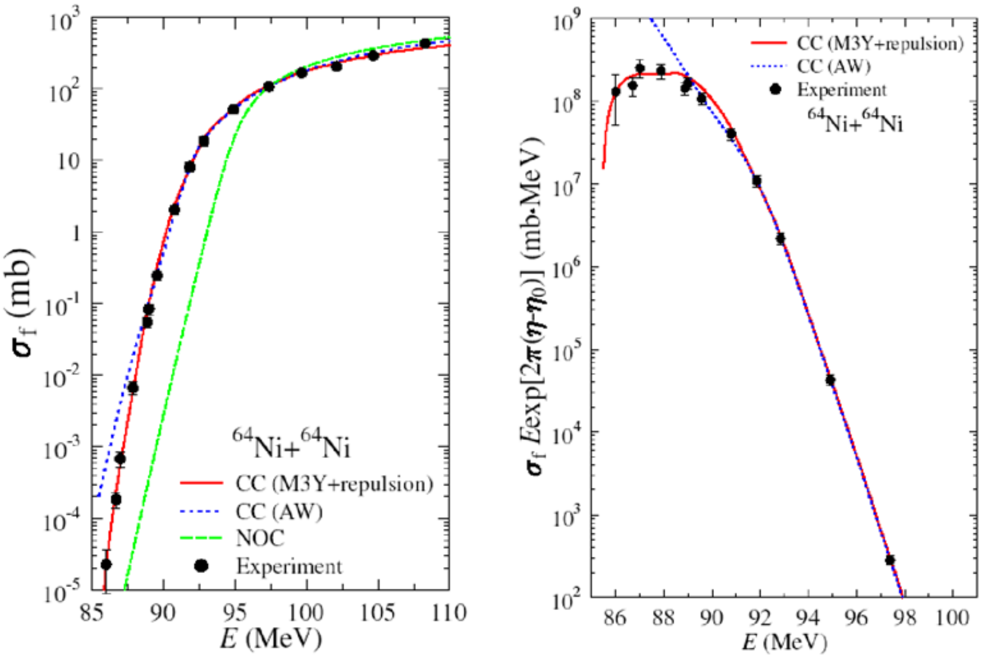
Left : experimental (histograms) and theoretical (curves) total kinetic energy loss distributions of the two neutron pick-up channel in the ^{40}Ca+^{208}Pb system at the indicated energies. The arrows correspond to the energies of 0^+ states in ^{42}Ca with an excitation energy lower than 7 MeV. Bottom panel shows the strength function S(E) from shell model calculations. *Top Right* : experimental gamma spectrum for ^{42}Ca obtained in the reaction ^{40}Ca+^{96}Zr in a recent experiment with PRISMA+CLARA. *Bottom right* : level scheme of interesting transitions.

transfer channels in determining the total reaction cross section and to study nucleon correlation in the nuclear medium. At sub-barrier energies only the extreme tail of the nucleon wavefunctions enter into play and this provides a much simpler analysis of the data. To give an hint of why it is so, we recall that the nuclear part of the inelastic form factor is well described by the derivative of the optical potential and thus has a decay length of ~ 0.65 fm, while the transfer form factors have a decay length of ~ 1.3 fm being related to the binding energies of the transferred nucleon. In the very low energy domain, the two ions probe their mutual interaction only at large distances, where the nuclear couplings are dominated by transfer processes (one particle transfer). The multi-nucleon transfer is here dominated by a successive mechanism, in fact, the collective form factor for a pair transfer mode has a decay length that mirrors the one of the optical potential and thus should play a minor role in this energy region.

The possibility to perform measurements at far sub-barrier energies depends on the availability of extremely high efficiency devices. In fact, in this energy regime, angular distributions result, in the center of mass frame, in a strong backward peaking, with a maximum at $\theta_{cm} = 180^o$ and the absolute yield gets very small. At the same time, mass and nuclear charge resolutions must be maintained at a level sufficient to distinguish the different reaction channels. In the past, few experiments in this direction have been performed making use of recoil mass spectrometers, but one or at most two particle transfer channels could be identified. With the new generation large solid angle spectrometers these efficiency problems can be now overcome, and the use of high intensity stable beams would allow to push the detection sensitivity to below the μb cross section level. At far sub-barrier energies, the Q-value distributions get much narrower and the strength for multiple particle transfer should be concentrated within a few MeV close to the ground states. This fact would allow observing, for instance, an odd-even staggering in the final yields, giving evidence of the effect of nucleon correlations. The combined use of powerful spectrometers and a definite increase of beam intensity would also allow to quantitatively probing if any (long standing problem in nuclear physics) effect like Josephson or diabolic pair transfer exists.

4-b Sub-barrier fusion

The influence of the different reaction channels in sub-barrier fusion processes is well known in literature. Nuclear structure properties like surface vibrations or nuclear rotations, and possibly, nucleon transfer channels, can strongly affect the behaviour of the fusion excitation functions. This



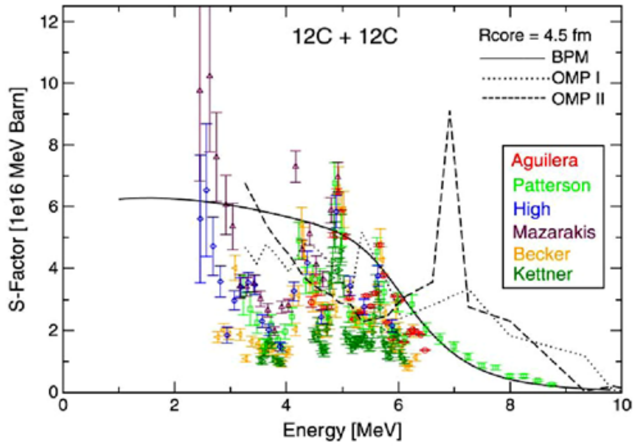
Measured excitation functions and S-factors at ANL for the indicated system compared with coupled channel calculations (CC) based on the Akyuz-Winther potential (AW) and the M3Y+ repulsion potential. The NOC curve represents the no-coupling limit.

is reflected in the large enhancements and isotopic effects seen in the fusion excitation functions. Very recently, contrary to usual expectations, it has been observed that at energies well below the Coulomb barrier the fusion cross sections are strongly hindered, namely they drop much more strongly than the prediction of coupled channel calculations. This has been seen in systems like ^{58}Ni+^{58}Ni, ^{64}Ni+^{64}Ni, ^{60}Ni+^{89}Y and is best characterized by determining the maximum in the S-factor curve of the fusion excitation function. An example is given in the figure below for a case measured in ANL (Argonne). In the most recent theoretical interpretation it has been shown that taking into account the nuclear incompressibility in the double folding model, one obtains a potential much shallower than the previous one and that is able to explain the behaviour of the fusion excitation functions in the full energy range. More into detail, it was used an M3Y nucleon-nucleon interaction that includes a direct isoscalar plus isovector part and an exchange part that is treated as a contact interaction. In addition, to simulate the nuclear incompressibility, the NN interaction is supplemented by a repulsive contact interaction. The results are shown in the same figure and the agreement obtained shows the possibility to probe the nuclear potential at very short distances. Notice that fusion cross sections need to be measured at a level of some tenths on nb, namely two orders of magnitude lower than the range usually investigated to observe isotopic effects. To reach this level of sensitivity a recoil mass spectrometer with extremely high background suppression and a focal plane gas detector system with multiple segmentation have been used. Clearly, a significant increase of beam intensity would allow to explore these sub-sub-barrier fusion phenomena even lower in bombarding energy and for a wider range of nuclear combinations.

5. Nuclear astrophysics

Nuclear astrophysics research is strongly related to nuclear structure studies: the profound impact of nuclear structure on astrophysical processes can be envisaged in many cases of stellar burning and the associated nucleosynthesis and energy production. The evolution of nuclear structure as a function of mass, deformation and isospin is of special interest in nuclear astrophysics since it determines the evolution of the nucleosynthetic mechanisms, the most characteristic one being that of the r process. Moreover, global nuclear properties like nuclear masses, level densities and deformations play a decisive role in large scale nucleosynthesis calculations.

Under these conditions, many of the research topics presented in the preceding paragraphs are of importance in nuclear astrophysics. However, they form only part of the nuclear astrophysics programme outlined in the last NuPECC Long Range Plan 2004. In this direction, the proposed high-intensity stable beam facility will be of benefit for the community of nuclear astrophysics. Such a facility will provide intense heavy-ion beams for indirect measurements, mostly based on transfer reactions or Coulomb break-up, or capture reactions in inverse kinematics. The latter technique will certainly provide a solution to the problem of reducing the beam-induced background, from which many nuclear astrophysics measurements suffer. In parallel to these techniques, the "classical" method, i.e. the acceleration of light ion beams at low energies can still provide a direct "approach" (model independent) to a variety of fundamental questions of astrophysical relevance that still remain open. Some of these cases are given below



Experimental data of the astrophysical S-factor for the $^{12}C+^{12}C$ fusion reaction and theoretical predictions (curves).

Many nuclear reactions across the periodic table play an important role in the aspects of nucleosynthesis. However, there are about 20 reactions among light nuclides which play a decisive role in the energy production: hydrogen burning via the p-p chain and CNO cycles in main sequence stars and helium burning via $3\alpha \rightarrow {}^{12}C$, $^{12}C(\alpha,\gamma)^{16}O$, $^{16}O(\alpha,\gamma)^{20}Ne$ and $^{14}N(\alpha,\gamma)^{18}F$ in red giants. These, helium burning reactions together with the $^{12}C+^{12}C$, $^{12}C+^{16}O$ and $^{16}O+^{16}O$ fusion reactions are also crucial for the evolution of a star of given mass and chemical composition, i.e. whether the star evolves into an early carbon-detonation supernova or into other supernovae of type I or type II. These H-, He- and C/O burning reactions are considered therefore as "key reactions" for nuclear astrophysics. Clearly, they need to be known with fairly high precision if we want to understand the structure and evolution of stars and galaxies. These key reactions are extremely difficult to measure using the existing facilities and instrumentation.

Example 1: The $^{12}C(\alpha,\gamma)^{16}O$ reaction has been investigated for more than 45 years (notably by Caltech, Bochum and Stuttgart) with a slow progress, where the aim of a 10% precision at the Gamow energy E_0=0.3 MeV is by far from being reached. The present low energy limit is at E_{cm}=1.5 MeV and the present uncertainty at E_0 exceeds 50%. Additional efforts with new techniques are needed to solve this problem in the future.

Example 2: The $^{12}C+^{12}C$ fusion reaction has been measured down to E_{cm}=2.5 MeV, while the Gamow peak E_0 is at 1.2 MeV; as shown in the figure above, the extrapolation to E_0 has presently an uncertainty of almost 200%.

The situation is similar for all other key reactions, where the low energy limit was determined so far by beam-induced background. The exceptions are the hydrogen-burning reactions $d(p,\gamma)^{3}He$, $^{3}He(^{3}He,2p)^{4}He$ and $^{14}N(p,\gamma)^{15}O$ (crucial for solar neutrinos and cosmochronometry) where the low-energy limit was given by cosmic-ray background: by removing this background essentially in an underground laboratory such as LUNA at Gran Sasso, Italy, we were indeed able to measure these reactions at E_0 or very close to it, thus no extrapolation was needed any more. For most other key reactions solutions have to be found to minimize first the beam-induced background in a laboratory at the earth surface.

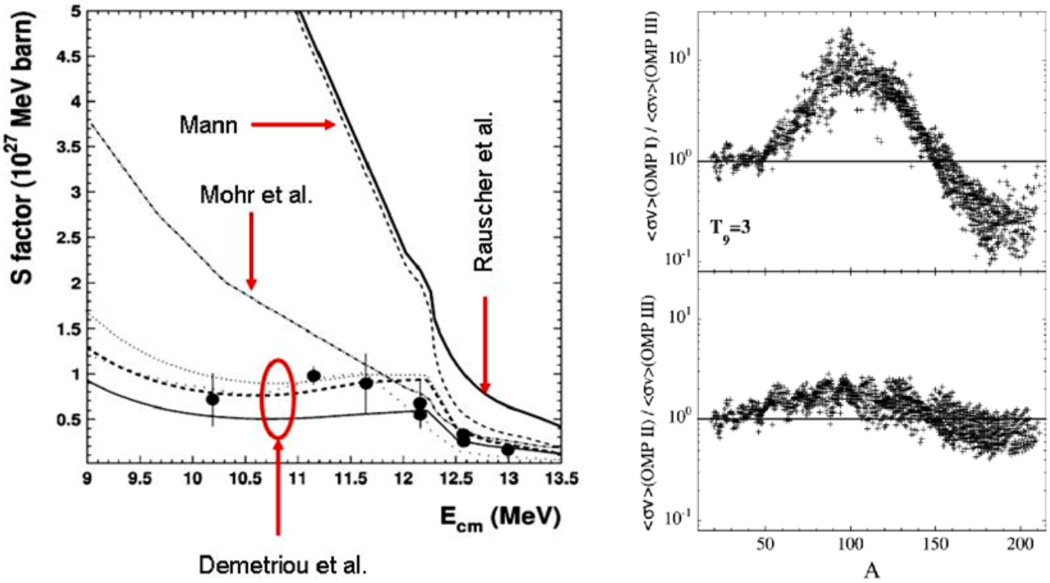
The origin in the cosmos of the so-called p nuclei is one of the most puzzling tasks to be solved by any model of heavy-element nucleosynthesis. These nuclei are by-passed by the s- and r-process pathways. To date, these nuclei have been observed only in the solar system. Understanding the synthesis of these p-process nuclei on the basis of astrophysical processes occurring outside the solar system, like e.g. in exploding supernovae (SNII) or on He-accreting white dwarves with sub-Chandrasekhar mass, which are both thought to be the most possible p-process sites, will enable us not only to understand the nuclidic composition of the solar system but also to further elucidate our fundamental picture of its creation. Abundance calculations of the p nuclei make an extensive use of the nuclear statistical model for the calculation of the rates of an extended reaction network. Comparisons with (p,γ) and/or (n,γ) cross sections indicate that these rates can be predicted within a factor of two. However, some of the very few (α,γ) data show that the reaction rates calculated using phenomenological alpha-particle optical potentials can be wrong by a factor of ten or more (see figure below). These uncertainties might be reduced substantially by putting constraints in the so far poorly known alpha-particle optical potentials at such low energies ($E<12$ MeV). It is worth mentioning that the relevant cross-section data are scarce. To achieve this goal, there exist different approaches, amongst which the direct (α,γ) measurements at sub-Coulomb energies using state-of-the art detectors is the most transparent. Detailed theoretical studies of this problem have shown that the most sensitive mass region to distinguish between different alpha-particle optical potentials is around A=100 and A=200 (see figure below).

It is a fact that nuclear astrophysics has traditionally focussed on measurements, often very time-consuming, that have been realized at small-scale low-energy accelerators with the aim to determine accurate reaction cross sections at energies as close as possible to the relevant stellar energies, i.e. around the Gamow energy E_0. So far, many nuclear reactions occurring at various evolution stages of stars have been systematically investigated and our fundamental picture of stellar evolution and nucleosynthesis has been considerably elucidated. Unfortunately, leading nuclear astrophysics laboratories in Europe (mainly in Germany, such as Karlsruhe, Stuttgart and Bochum) are already closed or will be closed in the very near future. Thus, there is an urgent need for Europe to create a new and upgraded low-energy stable beam facility (such as a high-current 5 MV tandem) with modern detection techniques (such as a crystal ball and a recoil detector setup). Such a facility will complement the present impressive efforts in Europe on the development of radioactive ion-beam facilities aiming at investigating among others the r-process nucleosynthesis. Without such a stable-beam low-energy high current facility, we will not be in position to improve our fundamental understanding of the evolution of stars.

6. Ion-ion collisions in a plasma

Motivated by two applications of energy deposition in matter by heavy ions (damage creation in materials and energy transfers in dense plasmas), a project was studied a few years ago for the im-

Left: Experimental S-factor data for the 144Sm(α,γ)148Gd reaction compared with the Hauser-Feshbach predictions using different alpha-particle optial model potentials.
Right: Ratios of calculated (α,γ) rates $<\sigma v>$ for different alpha-particle optical potentials (OMP) as a function of the mass number A.



plementation at GANIL of an experimental device dedicated to ion–ion collision experiments. Motivations for the realisation of such experiments is of great importance and should be regarded with attention in the perspective of the increase by two orders of magnitude of the available stable ion beam intensities.

As far as modifications of materials are concerned, the observed effects are mainly produced at velocities of the incident ions corresponding to the maximum of stopping power. In this velocity domain, the elementary collision processes which are at the origin of energy deposition - exchange (capture), loss (ionisation) and excitation of electrons - have typical cross-section values close to their maximum and of the same order of magnitude. While remarkable progress was made in recent years on the theoretical side, Complications made by the fact that, under these conditions, the coupling between the elementary processes has to be treated explicitly, these cross sections still cannot be accurately predicted. Such treatments cannot furthermore be properly tested using the results of ion atom collision where (out of the collision of a bare ion on an atomic hydrogen target) the presence of numerous electrons on the target atom comes to complicate the mechanisms into play. Ion-ion collision experiments appear as the only way to allow a direct comparison to test the validity of existing models and encourage the development of new models.

Concurrently, studies about the interaction of high energy heavy ions and ionised matter (dense plasmas) were developed at different places (GSI Darmstadt and IPN Orsay) in connection with research activities in the domain of fusion by inertial confinement. Experiments concerning comparison of charge states and stopping powers of heavy ions observed in plasmas with those observed in gases and solids lead to conclusive results as far as hydrogen or deuterium plasmas are considered. Their extension to plasmas of higher atomic number species leads to greater difficulties due to the fact that such plasmas contain species with different degrees of ionisation. The observed effects correspond to mean effects induced by a series of simultaneous phenomena from which it is difficult to extract quantitative information about elementary processes. Here again direct and quantitative measurements will only be possible by directly studying ion-ion collision processes.

The ideal experimental apparatus to perform such experiments would be obtained by crossing a highly stripped and charge state selected intermediate energy beam (2-20 A.MeV) with a low energy beam (produced by an ECR source for instance). The experiments would simply consist in recording, in coincidence, the change of charge states in both beams.

One should consider the opportunity offered by the high intensity beams for the study of rapid processes following high energy losses in solids. Transient species with intrinsic lifetimes, reaction or diffusion times of the order of nanoseconds to milliseconds and even more, may indeed play a very important role as precursors of permanent defects observed after electronic slowing down of high energy heavy ions in materials. Since some years now, detection and following the time evolution of such species has been demonstrated to be feasible at GANIL in the frame of a series of experiments dedicated to the study of water radiolysis. In the course of these experiments single pulse excitation with high energy carbon and argon ions has, in particular, allowed to follow the kinetics of formation and disappearance of solvated electrons.

The main limitations to the time resolution and sensitivity of such experiments are the amount of energy which can be deposited by a single pulse and the duration of that pulse. As compared to existing facilities the CSS1 and CSS2 beams at GANIL, a one order of magnitude increase of beam particles per pulse is expected from a future high intensity stable ion beam facility. The time structure is also expected to be much shorter (0.2 ns instead of 2 ns), so very rapid processes could be investigated. The high intensity stable beam facility should allow to study the time dependence of high energy loss phenomena.

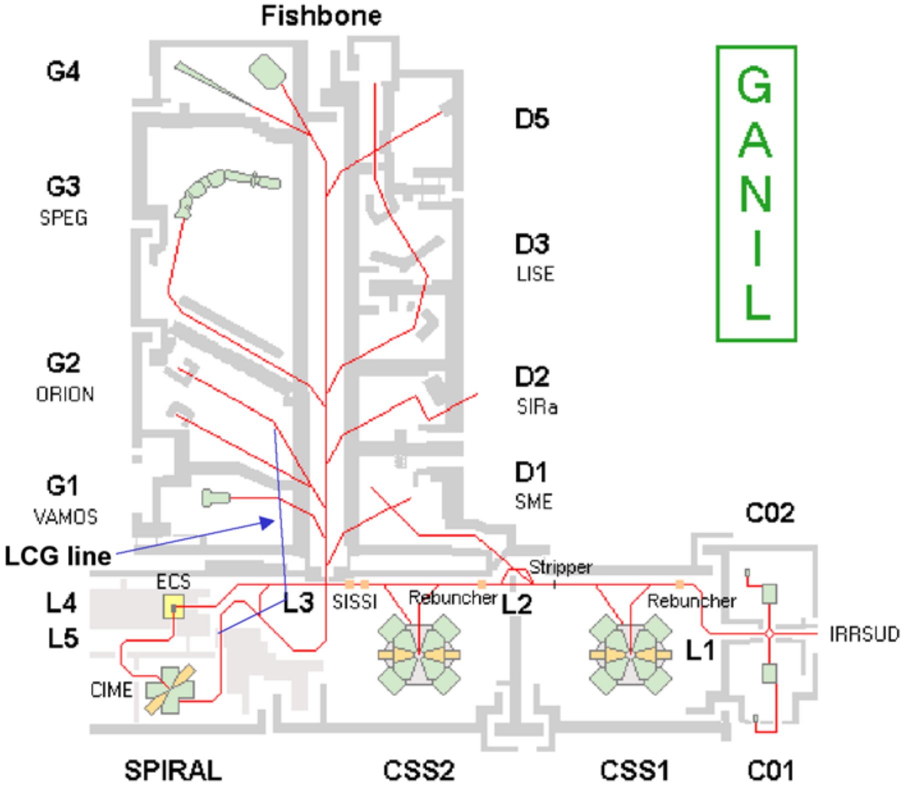
Intense quasi-continuous ion beams are of enormous interest for solid-state and materials research for cases where high-dose-rate implantations are required. There is a broad spectrum of aspects, including phase transformations, development of novel compound materials, heavy doping of semi-conductors, generation of nanostructures, commercial applications such as filter production, etc.

III Technical performance and readiness for a high intensity stable ion beam facility

The performance of the proposed high intensity stable beam facility, will provide the European low-energy physics community with a world class stable ion beam capability. This facility will benefit from the tremendous improvements that have been achieved, over the last decade, in accelerator technology making accelerators highly reliable and cost-effective to operate. The stable ion beam facility will be designed to meet the science needs outlined in the previous sections and will have capabilities beyond those presently available in Europe.

1. Existing European stable beam facilities and their up-grades

For comparison, the performances of existing major European facilities and their possible upgrade regarding high intensities are described.



Layout of the GANIL facility

1-a Status and future developments at GANIL

The GANIL facility shown in the two figures, is composed of a set of 5 cyclotrons, one of them is part of the radioactive beam facility SPIRAL, that can be used independently for stable beam production. The present GANIL facility offers a broad range of ions and energies: ions from carbon to uranium, and energies from 0.5 to 95 A.MeV, depending on the ion q/A ratio, and on the number of cyclotrons chosen for the acceleration. After the stripper, two simultaneous beams are produced, with two different charge states: one at medium energy (5-13 A.MeV), and one which is sent towards CSS2 or directly to the experimental areas. In parallel, the CIME cyclotron, designed for the acceleration of radioactive beams, can also be used for the production of stable beams, for ions ranging from carbon to xenon, with energies from 2 to 25 A.MeV, depending on the q/A ratio. All these beams can then be sent towards the different GANIL experimental areas.

The CSS1 beams can be used, in the following domain: from ^{12}C (4 to 13.5 A.MeV) to ^{238}U (4 to 8 A.MeV). The intensities range from several *p*μA for light ions to less than 1 pμA for A > 40.

The CIME cyclotron beams can range from He to Xe, with energies between 2 and 25 A.MeV depending on q/A, and with a maximum intensity of 80 pnA (mainly because of safety limitation).

There is a continuous development on new ion production methods at GANIL, and to increase existing beam intensities such as Ni, Ca, Ge, etc. Concerning Pb and U beams, an intensity increase of a factor of 5 to 10 could be considered (≈ 0.1*p*μA), using new source types (like Phoenix, Venus, etc…), and developing the high temperature oven method for uranium beam production. It is possible to increase the light gaseous ion (up to Kr) intensity on target by adding a re-buncher at the entrance of the C01 injector cyclotron. The intensity of light gaseous ions transmitted by the injector cyclotron C01 is presently limited, due to the space charge forces in the injection line. One has to keep in mind that this re-buncher would also be necessary for 0.1 pμA Pb and U beams.

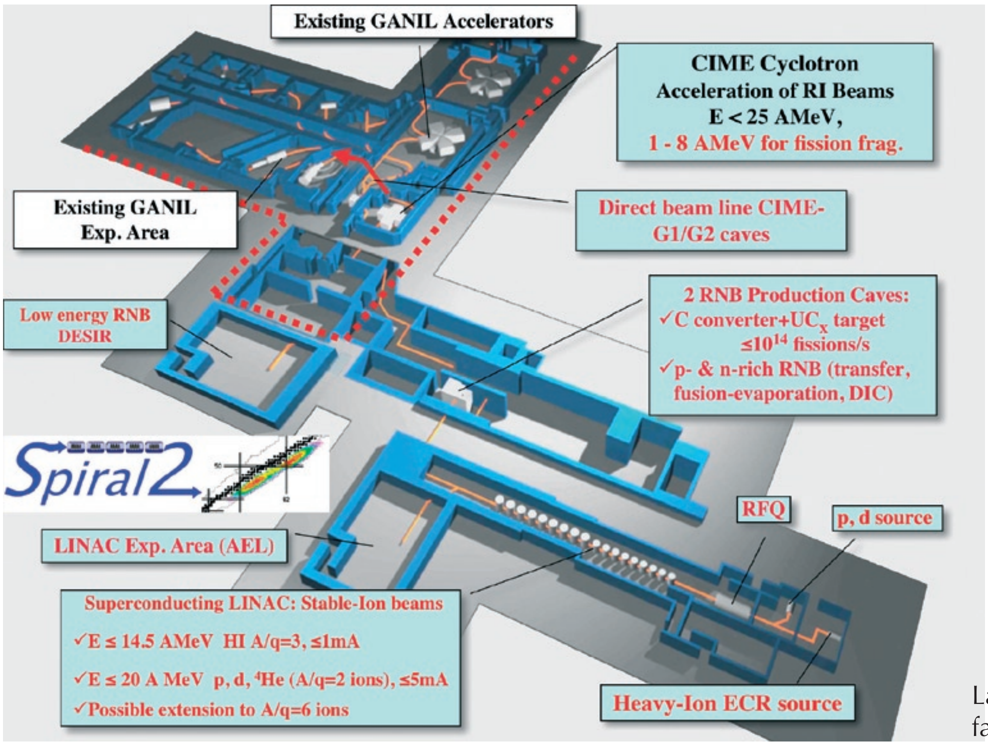
Concerning the use of parallel beams at GANIL, a design study of a direct line between CIME and the G1-G2 experimental areas is in progress. This line should be constructed in the coming years, and will give the possibility to send in the experimental areas, beams accelerated by CIME, simultaneously to beams coming from GANIL.

The SPIRAL2 facility, based on LINAG-Phase 1 study, is aimed at accelerating deuteron beams up to 20 A.MeV and 5 mA intensity, in order to produce neutrons in a carbon converter, which are then used in the fission process of an uranium carbide target, for the production of a broad band of fission products. The SPIRAL2 driver accelerator has also the capability of accelerating q/A=1/3 stable ions, up to 14.5 A.MeV and with intensities varying from few tens to few hundreds of pμA, in a first step. In a second step, a second injector will be added, in order to produce heavier ions of q/A=1/6, up to 6 A.MeV and equivalent intensities.

In a first step, light beams will be available, like O, Ne, Ar up to 1 mA. For beams like Ca, Cr, Ni, further R&D is necessary to estimate, via meas-

In the following table, are listed some beam intensities produced these last years on targets:

Ion	Energy in A MeV	Intensity in pμA
^{48}Ca^{8+}	4.5	0.5
^{58}Fe^{8+}	4.9	0.65
^{58}Ni^{9+}	4.3	0.22
^{76}Ge^{10+}	5	0.85
^{86}Kr^{12+}	4.5	0.83
^{208}Pb^{25+}	5	0.016
^{238}U^{28+}	5.5	0.003



Layout of the SPIRAL2 facility

urements, the maximum intensity achievable for q/A=1/3. This intensity is expected be at least of the order of few tens of pμA. Then, when the second stage of the SPIRAL2 project is built, heavier ions up to mass 160 will be available, with q/A=1/6. In that case also, R&D is needed to increase the intensities of the produced beams, the few tens of pμA will be available at the beginning. The construction of SPIRAL2 approved by the French government in May 2005 is in progress.

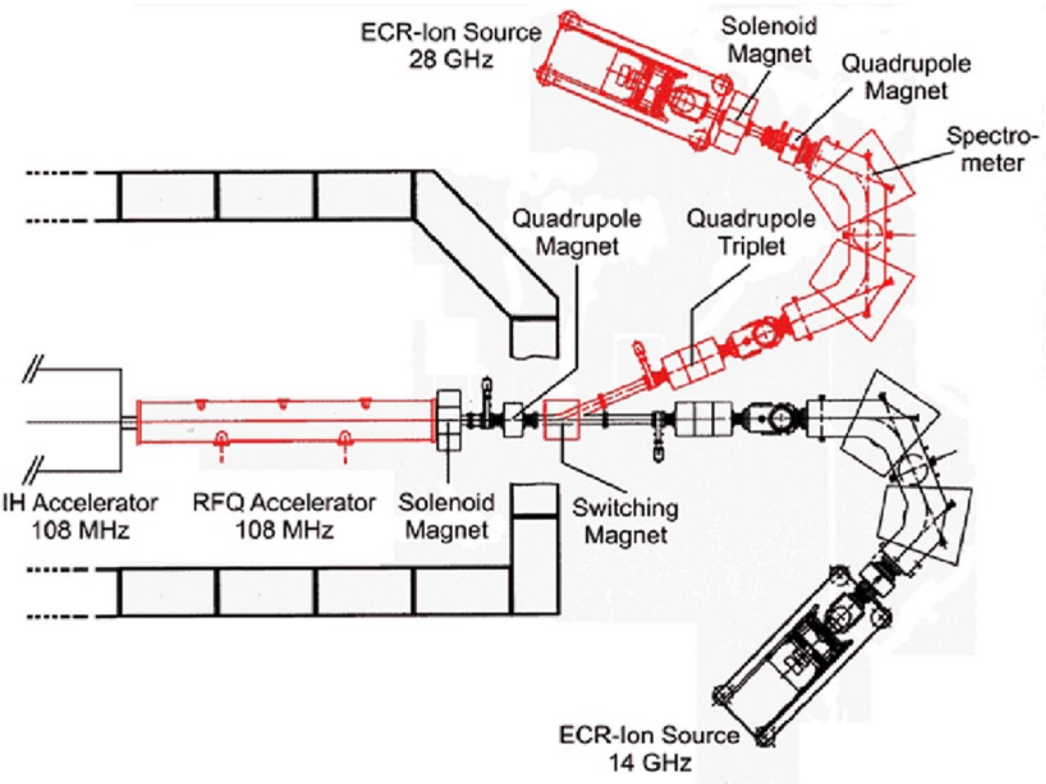
Presently, the GANIL beam time dedicated to high energy stable beam experiments, in the high energy experimental area is around 2/3 of the total time dedicated to nuclear physics, which means around 1600 hours per year. Thus, long period experiments like studies of SHE's are difficult to plan. One of the goals of the direct line G1-G2 is thus to have the possibility to send stable beams from CIME when GANIL is running, and in the future, to send for instance GANIL beams in parallel to radioactive beams produced by SPIRAL2. In that case, the number of stable beam hours will be substantially increased, and will enable long period experiments. In the presently planned scheme of the operation of SPIRAL2 three to four "4 weeks" periods (12 to 16 weeks per year) would be dedicated for the use of stable heavy ion beams of very high intensity in the dedicated experimental area, that will come in addition to the possible stable beams produced by GANIL.

1-b Status and future developments at GSI

Experiments for the investigation of phenomena, which determine the limits of stability, will always need relatively long irradiation time. This will be the case also at higher beam currents and soon after realization of the proposed upgrades. In recent years the activity of work at SHIP was concentrated on the investigation of heavy elements. This strategy will be kept in the future. However, the investigation of heavy-ion fusion reactions by SHIP is promising also in the region of lighter nuclei. Examples are the proton radioactivity, isomeric states and other phenomena. Even concentrating on reactions with beams of stable projectiles only, the demand for beam time will increase in the future.

The combination of an ECR ion-source and an accelerator capable of delivering DC beams instantaneously results in an increase of the beam intensity at minimal consumption of source material. An intensity increase by a factor of 3.5 would arise from the prolongation of the duty factor from now 28 % to 100 %. Another factor of ≈5 can be expected from the use of new generation ECR ion sources.

Three possible versions of accelerator upgrades for the GSI heavy element programme have been worked out. Specific properties, advantages and



Front end of the new high charge state injector at GSI.

disadvantages have been extensively studied. All three upgrades are based on a new high charge state injector (see figure below) consisting of a 28-GHz ECR source and improved versions of RFQ and IH-structure accelerators providing a beam energy of 1.4 A.MeV. Version 1, will use the present or upgraded Alvarez sections for further acceleration. In this version the duty factor is increased from now 28 to 50 % for medium heavy projectiles like ^{70}Zn, for example. The two other versions, represent stand alone linear accelerators, both with a 100 % duty factor. In version 2, the maximum energy is 6 A.MeV achieved by normal conducting IH structures subsequent to the 1.4 A.MeV injector. Finally, version 3 uses a superconducting linac behind the normal conducting injector resulting in a maximum energy of 7.5 A.MeV.

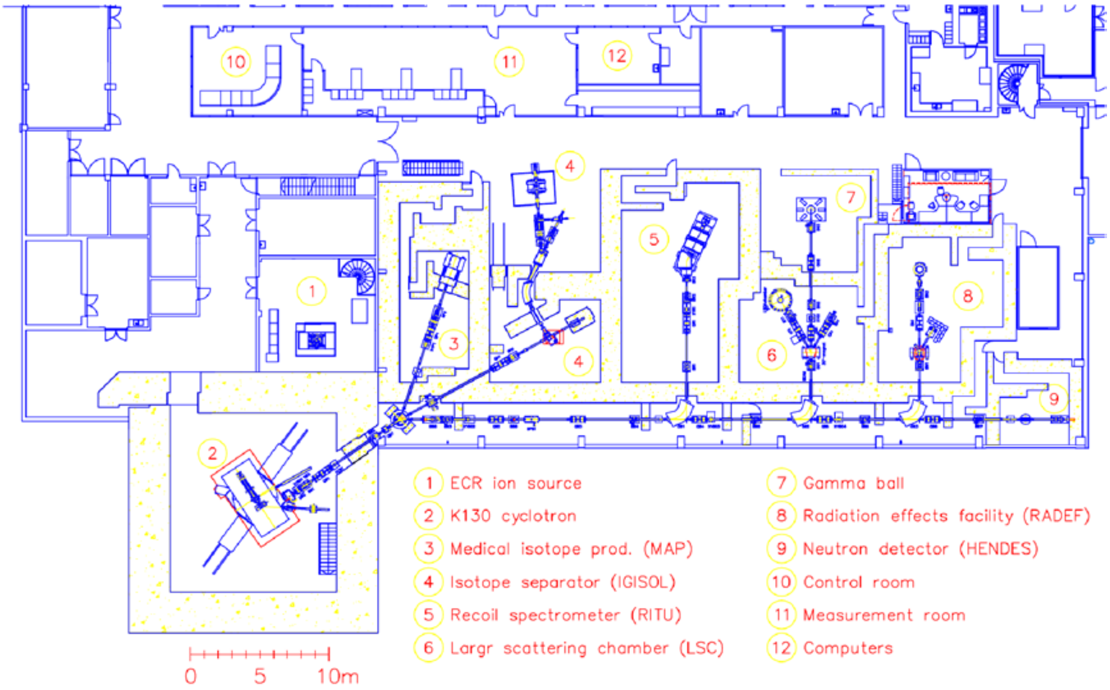
1-c Status and future developments at JYFL

The facility at the Accelerator Laboratory of the Department of Physics of the University of Jyväskylä (JYFL), Finland, consists of a K=130 AVF cyclotron equipped with two ECR ion sources for heavy ions and a multi-cusp ion source for protons. It is a relatively new facility used for nuclear physics experiments since 1994. Its reliability is reflected in the annual operation time, which during the last years has been close to 7000 hours. As a university laboratory attached to the Department of Physics it forms an ideal training site for PhD students and young researchers.

As the maximum energy for the ion beam from the JYFL cyclotron is $E/A = 130(q/A)^2$ A.MeV, the availability of various beams strongly depend on the performance of the ion sources. Heavy ions are delivered by a 6.4 GHz or a 14 GHz ECR ion source. Available and so far used beams and intensities from the cyclotron for ions with energies above 5 MeV per nucleon are as follows:

~ 1pμA	p, He, B, C, N, O, Ar
~ 100 pnA	F, Ne, Mg, Al, Si, S, Cl, Ca, Fe, Cr, Ni, Cu, Zn, Kr
~ 10 pnA	Ti, Mn, Ge, Sr, Zr, Ru, Xe

Intensities for various isotopes depend on the isotopic enrichment of the available material. Metallic beams are extracted from a furnace or a MIVOC chamber. The MIVOC method (based on the use of volatile compound) was developed at JYFL. Negative H ions for high-intensity proton beams up to 50 μA from the cyclotron are extracted from the multi-cusp source.



Layout of the accelerator facility at JYFL

The main experimental facilities using the beam time at JYFL are the RITU recoil separator with detector arrays at the target (JUROGAM Ge detector array) and the focal plane (GREAT spectrometer) and the IGISOL separator with ion traps and laser spectroscopy systems. The former uses heavy ions and is at the moment the most efficient system in the world for tagging experiments of heavy exotic nuclei. The latter mainly uses high-intensity proton beams to produce various species of cooled and bunched radioactive ion beams via fission for studies of ground-state and decay properties of exotic nuclei. Beam lines and instrumentation for nuclear reaction studies are also available. Special beam lines have been designed for various applications and test experiments.

Continuous development of the ECR ion sources is going on to improve the beam intensity at JYFL. It is done in collaboration with Argonne (ANL) and within the EURONS-JRA-ISIBHI project. In the near future the JYFL 14 GHz source will be equipped with a TWTA RF-source enabling it to run with two frequencies at the same time. A new type of magnetic multipole structure for better confinement of the ECR ion plasma will be tested. The transmission, which at the moment through the cyclotron is approximately only 5 %, will be improved by better design of the injection line.

To increase the available beam time with heavy-ion beams, a dedicated cyclotron will be constructed to deliver high-intensity light ion beams for the production of radioactive ions for IGISOL and radioisotopes for medical purposes.

1-d Status and future developments at KVI

The facility at the KVI, centered around the superconducting cyclotron AGOR, provides beams of all stable elements of the periodic table. Protons can be accelerated in the energy range 120 - 190 MeV, for ions with Q/A = 0.5 the maximum energy is 90 A.MeV, while in general heavy ion beam can be delivered in the energy range between 5.5 A.MeV and 600 $(Q/A)^2$ A.MeV.

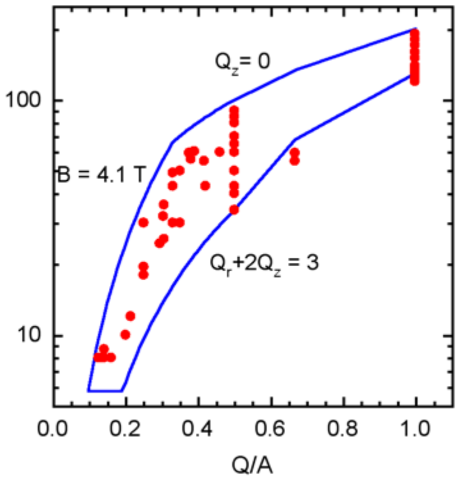
The cyclotron is equipped with a source for polarised protons and deuterons (both vector and tensor polarisation) and an ECR source for heavy ions.

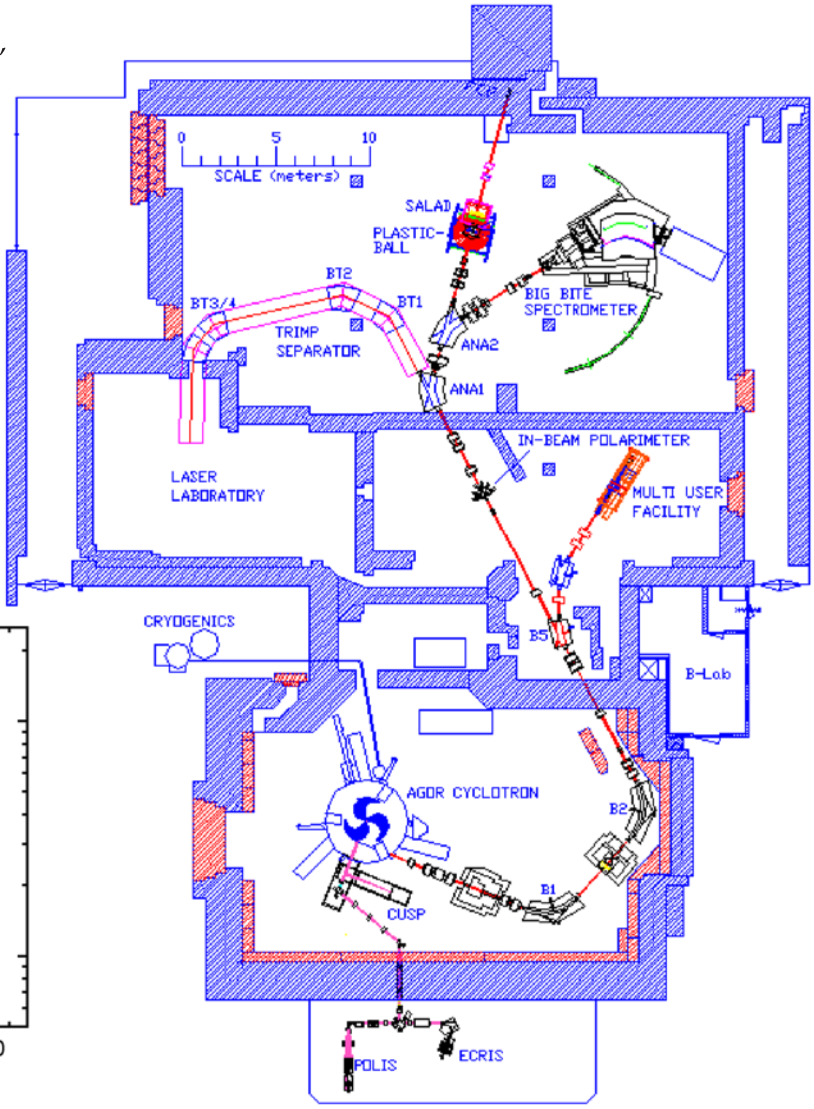
At present the intensities of heavy ion beams are in the range $10^{10} – 10^{12}$/s, depending on the mass and charge state. An upgrade programme aiming at a very significant increase of the intensities has been started. In first phase, which is planned for 2005 and 2006, the existing CAPRICE-type ECR will be replaced by an AECR-type source similar to that in Jyväskylä and the injection beam-line will be upgraded. This should increase the beam intensities for most beams by one order of magnitude, resulting in a maximum beam power of about 200 W.

In the second phase, which is planned for 2008 – 2009, a second ECR source, based on the results of R&D in the framework of EU-FP6, will be installed. The goal of this phase is increase of the intensity to at least $5 \cdot 10^{12}$ pps for all ions.

The experimental facilities at the AGOR facility are

- the TRIμP fragment separator for the production of secondary, radioactive beams. A setup for experiments with low-energy secondary beams is presently being commissioned.
- the BBS magnetic spectrometer with detection systems for light and heavy ions.
- the BINA-setup for experiments in few body physics
- a general purpose beam-line, where user-provided setups can be installed.





Operating diagram of the AGOR cyclotron indicating the energy range as a function of the charge-to-mass-ration Q/A and layout of the AGOR-facility at the KVI.

1-e Status and future developments of the Tandem-ALPI facility at LNL

ALPI is a linac for heavy ions operating at Legnaro since 1994. It consists of an array of 70 superconducting QWRs (Quarter Wave Resonators) aimed at accelerating beams, ranging from C to U, at energies around the Coulomb barrier. Many improvements were realized with respect to the original ALPI design. The low β section is equipped with bulk Nb cavities; sputtered Nb on Cu QWRs are installed in the high β section. Concerning the medium_ β section, in the last few years the previously installed medium β, Pb/Cu resonators had their superconductor layer replaced by Nb. The use of Nb for these resonators allows operating them at an average accelerating field higher than 4.4 MV/m. ALPI equivalent voltage is about 50 MV.

A large variety of beams can be accelerated to and above the Coulomb barrier. The heaviest accelerated beam being, so far, ^{127}I(21+). A list of currents and energies of some beams accelerated in 2004 is presented below.

ALPI has been used so far as a booster for a 15 MV XTU Tandem, which is devoted to ALPI injection for about 30 % of its beam time. The Tandem-ALPI complex provides about 6000 hours beam time per year to users. The use of a tandem as an injector limits both the mass (A≤100) and the beam current (I≤10-20 pnA), which can be injected into ALPI. These limits are now overcome by PIAVE, the new positive ion injector, which was commissioned in 2005 and became operational in 2006.

PIAVE includes an ECR ion source on a 350 kV platform, ALICE, two superconducting RFQs (A/q = 8.5) and eight superconducting QWRs. ALPI does not change the beam output energy by the PIAVE beam injection, but can substantially increase the beam intensity up to 100 pnA for most ions.

The available current on target is presently limited, by the authorization limits, to 30 pnA and 20 MV/m for ions heavier than Si and to 2 pnA and 26 MV/m for light ions (from C to Al): An extension to higher beam intensities can be asked as soon as we will provide the current request by the authorization tests. An accurate analysis of the required radiation shielding upgrading is necessary.

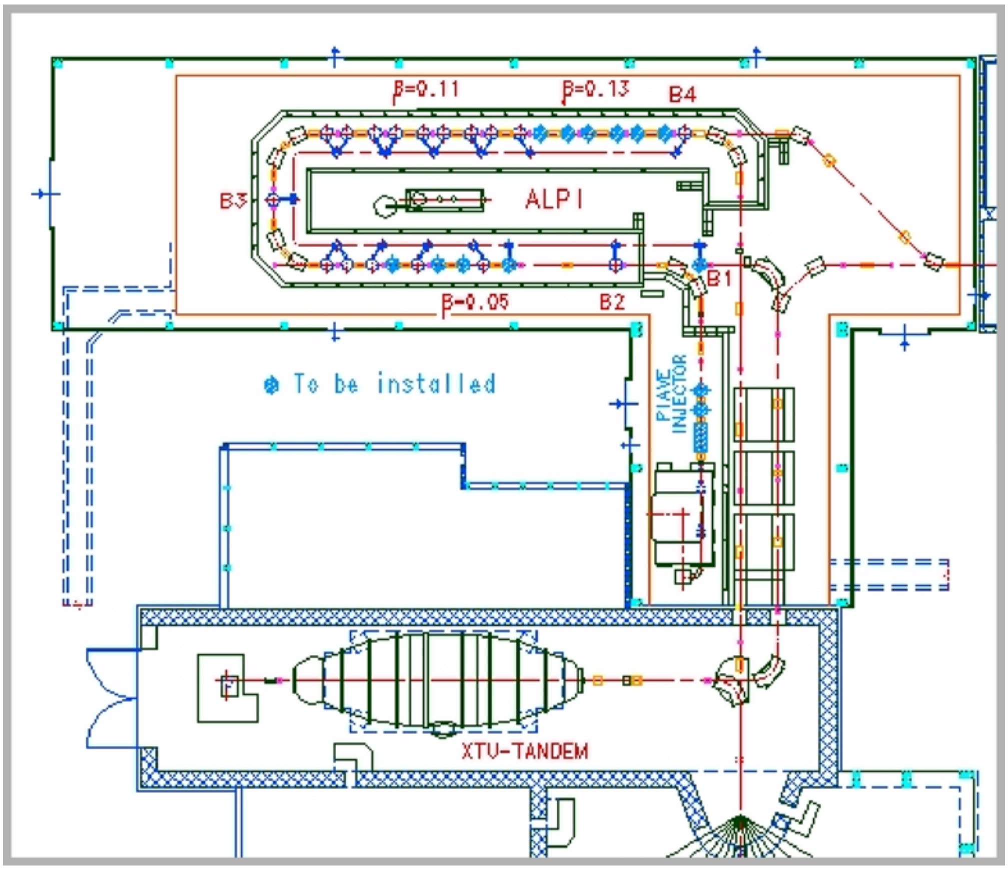
The values of ALICE output current for some ion species, tested up to now is listed below.

Improvements are foreseen, both in ion species and intensities, but the acquisition of a more updated source is necessary to saturate the current limit of the SRFQs and to reach the intensities of 100 pnA for the all ion species required by nuclear physics experiments.

When PIAVE injects into ALPI, the Tandem can continue to operate as stand-alone accelerator, sending the beam into a different experimental hall, doubling in this way the available beam time.

By the beginning of 2006, the setting up of a new ECR (funded) will allow injecting enough current in PIAVE to reach the goal of 100 pnA on target for all the required ions. As mentioned, a new authorization limit needs to be requested.

PIAVE was designed for a current I ≤ 5 µA, a value at which the space charge effect in the SRFQs



Layout of the TANDEM+ALPI facility at LNL

Ion	I [pnA] on target	Linac Transmission [%]	I target/I source	E [A.MeV]	Resonators
$^{36}S^{9+}$	6.6	24	0.37	6.25	12
$^{58}Ni^{11+}$	0.5	27	0.42	6.03	31
$^{82}Se^{12+}$	6.7	26	0.32	6.16	46
$^{90}Zn^{13+}$	3.1	30	0.27	6.17	46
$^{64}Ni^{11+}$	5.5	29	0.40	6.25	35

Beams accelerated by ALPI in 2004

is negligible. In the SRFQs, beam losses need anyway to be limited both for thermal load reasons and for avoiding superconducting surface contamination. A current limit of 100 pnA accelerated by the complex ALPI-PIAVE is achievable, but further substantial increases in the accelerated beam current can hardly be reached.

The replacement of the Pb with Nb in the superconducting QWR allowed operating ALPI resonators at average accelerating fields substantially higher than the design ALPI value. Filling the 8 cryostat places left empty would increase the ALPI equivalent Voltage by about 25%.

A new sputtering cycle of medium β resonators would certainly increase the average accelerating field up to an average value between 5.5 and 6 MV/m, values routinely obtained in the last produced sputtered resonators.

Ion	ALICE currents [pμA]
$^{16}O^{3+}$	13
$^{16}O^{6+}$	2
$^{40}Ar^{12+}$	0.2
$^{63}Cu^{11+}$	0.1
$^{84}Kr^{13+}$	0.2
$^{84}Kr^{15+}$	0.1
$^{120}Sn^{16+}$	0.04
$^{129}Xe^{18+}$	0.03
$^{132}Xe^{18+}$	0.03
$^{120}Sn^{19+}$	0.01
$^{141}Pr^{18+}$	0.03

Alice typical currents

A further increase in the available beam energy can be obtained by beam stripping in proximity of ALPI U-Bend. This will clearly reduce the beam current, although this effect can be partially compensated by acceleration of multicharge beams.
A technical design for an Advanced Exotic Ion beam Facility at LNL, named SPES, was proposed in June 2002. The project is aimed at producing neutron-rich isotopes via the fission process induced by neutrons in an UCx target material. Neutrons are generated by an intense (up to 5 pmA) primary proton and deuteron beam with energy up to 100 MeV hitting a thick C target. Secondary, high intensity beams (with A = 80-160) can be accelerated by the ALPI LINAC up to 20 A.MeV and can reach an intensity of 10^8-10^9 ions/s on target, for experiments. The facility includes a several pmA ion source, an RFQ to accelerate protons and deuterons up to 5 MV, an ISCL (Independent Phased Superconducting Linac) to accelerate the beam up to 100 MeV, a converter and a U target. The radioactive ion species are produced in an ECR source, and analysed in a high-resolution spectrometer. They are then accelerated by an array of three RFQ's, two of which are superconducting and finally by ALPI. An extraction channel after the RFQ allows delivering the 5 MeV proton beam to a ^{9}Be target for the production of high intensity neutron flux to be used in a Boron Neutron Capture Therapy (BNCT) plant for skin melanoma treatment. The ISCL linac has the possibility to accelerate ions up to a q/A ratio of 1/3. The use of ALPI as the SPES booster implies the completion of the whole ALPI cryostats (as previously mentioned) and the building of an array

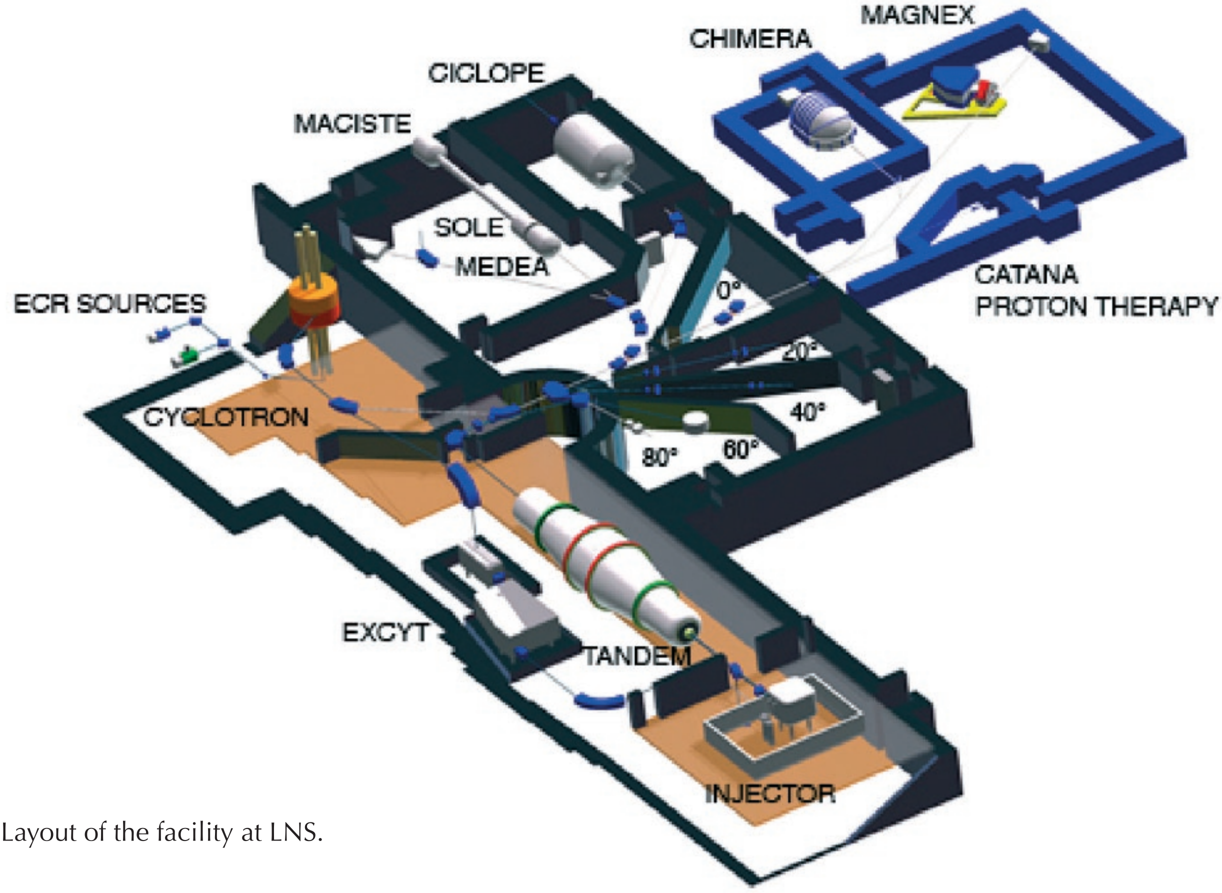
of 3 RFQs following an ECRIS at ground potential. The latter could be used as a second injector in alternative to PIAVE. The better capture efficiency of the RFQ's array (about 95%), due to the adiabatic bunching in the first RFQ, and a devoted ECRIS, can significantly improve the beam intensity injected into ALPI.

1-f Status and future developments at LNS

The study of nuclear collisions at intermediate and low energy is the main research line at the Laboratori Nazionali del Sud (LNS). In order to fulfil its scientific goals LNS mainly relies on two accelerators: an electrostatic HVEC MP Tandem, with a maximum terminal voltage of 15 MV, and a K800 Superconducting Cyclotron.

The Superconducting Cyclotron accelerates positive ions with q/A ranging from 0.1 to 0.5. Two ECR sources, one of which is a superconducting one (SERSE), are the injectors of the Cyclotron. The nominal maximum energy for q/A=0.5 is 100 A.MeV, the present operating maximum value being 80 A.MeV. For the heaviest ions the maximum energy depends upon the source performance. The present operating maximum energy for Au is 23 A.MeV, obtained accelerating the charge state 36+.

A list of the beam types developed to date is available at http://www.lns.infn.it/accelerator/beamlist.htm. Intensity is less than 1 pnA for beams requested to have a good timing quality (time peak with FWHM 1 nsec) and a large time separation (120–150 nsec). In the other cases intensity depends upon the ion species and the final energy. Additionally, particular care must be devoted to the extraction process: the cyclotron compactness implies a consistent beam loss in the first electrostatic deflector. Therefore in the last three years a concerted upgrading program has developed around the electrostatic deflectors, with the aim of extracting a light ion beam with a power of 500 watt, to be used as a primary beam for production of radioactive ion beams in the Isol facility EXCYT. Presently the maximum beam intensity for a $^{13}C^{4+}$ beam, accelerated to 45 A.MeV, is 240 pnA, corresponding to a beam power of 140 watt and to a rate of $1.5 \cdot 10^{12}$ pps.



Layout of the facility at LNS.

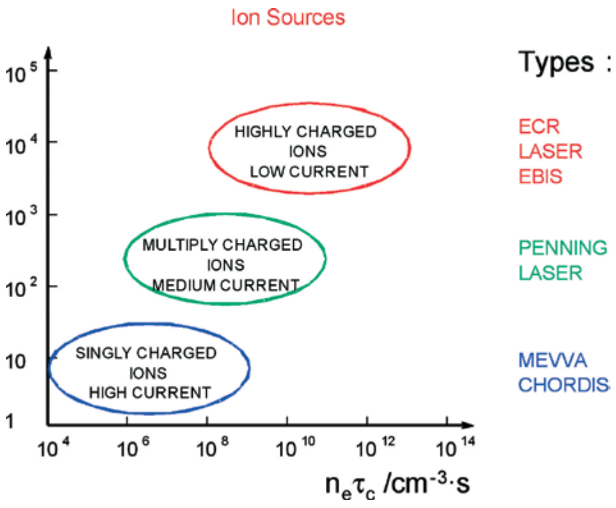
Similar values of primary beam intensity are also required for in-flight production of radioactive fragments (FRIBS). Recently a ^{20}Ne beam accelerated to 45 A.MeV, with an intensity of 60 pnA, was sent to a Be target to produce ^{18}Ne fragments to be used as projectiles in an experiment.

A significant number of interdisciplinary research lines have come up in the most recent years. Among all them, it is worth to mention the proton-therapy activity, which started several years ago as the CATANA project, and became a clinical activity in 2002, when the first patient was irradiated. Since then patients have regularly been treated, and at the same time a lot of experiments, concerning proton-therapy, have been performed.

CATANA, the first proton-therapy facility in Italy, is a collaboration between LNS, University of Catania, Azienda Policlinico of Catania; it consists of a dedicated beam line for the treatment of eye tumours by means of 62 MeV protons.

2. Future developments

An important challenge is the development of appropriate ion sources, recoil separators, target systems, instrumentation and electronics that needs to keep step with the increasing beam currents.



Typical electron temperatures and nτ – products for different ion sources

2-a Ion sources

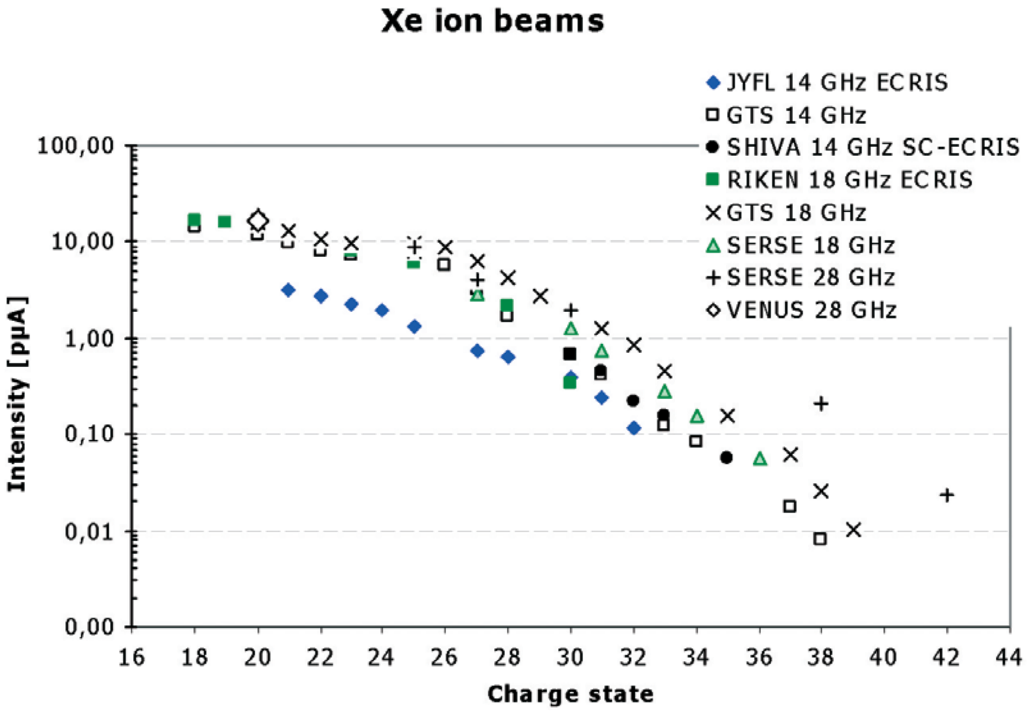
The size of an accelerator depends a lot on the charge state provided by the ion source. There are three main classes of ion sources as shown in the figure.

Only in the case of extremely high beam current needs (in the order of tens of mA) it is still necessary to start with a 1+ charge state from a discharge driven volume ion source such as CHORDIS. Another possibility would be a Metal Vapour Vacuum Arc source (MEVVA), which is used at GSI to deliver uranium beams up to 100 emA at a 4+ charge state. The Penning – type ion source was and still is a work horse at several places and can provide intermediate charge states like 10+ for uranium. The highest charge states can be provided by Electron Beam driven Ion Sources EBIS – very efficiently in pulsed mode like demonstrated at BNL, Upton, NY, USA with the new gold 32+ - injector for RHIC.

Electron Cyclotron Resonance Ion Sources (ECRIS) will continue to play a key role in the delivery of high-intensity highly charged heavy ion beams for various types of accelerators.

According to a semi-empirical scaling law for ECR ion sources, the ion beam intensity increases with the square of the applied microwave frequency. However, to properly fulfil the magnetic field scaling laws the higher microwave frequency must be combined with a stronger magnetic field. The other key factor is the power density absorbed by the ECR plasma. Consequently, powerful ECR ion sources utilise superconducting magnets to optimize electron confinement, high frequency heating to reach high electron density, efficient rf-coupling, a large plasma chamber leading to a long ion lifetime, efficient cooling of the plasma chamber and finally a high efficiency extraction system.

The maximum intensity of an ion beam extracted from a modern ECR ion source for elements available in gaseous mode can be up to 250 pμA (e.g. ^{40}Ar^{8+}). The higher the atomic number the more difficult it is to reach a certain charge-to-mass ratio. The figure below shows the performance of ECR ion sources for Xe ions (isotope enrichment close to 100 %). Extraction voltages of 10 – 20 kV have been used. Presently the most advanced ECR ion sources are VENUS, which has been built for



Xe ion beam intensities in pμA from different ECR ion sources

RIA at LBNL and SERSE at INFN-LNS in Catania. Both of them are based on the use of fully superconducting magnets and use microwave frequencies up to 28 GHz.

The next generation European ECR ion sources (MS-ECRIS: Multipurpose Superconducting ECR Ion Source and A-PHOENIX ECR source) will be designed and built by a collaboration working for the FP6-I3-EURONS-JRA-ISIBHI project. The object of this activity is to improve the performance of the ECR ion sources by a factor of ten compared to present 14 GHz ECR ion sources. This will open a new era for nuclear physics experiments.

Ion beams from gases like H, He, O, N, Ne, Ar, Kr and Xe can easily be extracted from an ECRIS (if needed, using isotopically enriched material). In the case of metallic elements the availability and the ion beam intensity strongly depend on the element. Some of them are available in the form of gaseous molecules such as CO_2, SO_2 and SiH_4. For the production of other metal ion beams a method of feeding the element into the ECR ion source plasma has to be used. The most common techniques are: evaporation ovens, sputtering and the MIVOC method.

The MIVOC method, utilizing volatile compounds, is nowadays widely used to produce metal ion beams from ECR ion sources. Such beams are Fe^{11+}; 13.6 pμA (RIKEN) from ferrocene, Ni^{11+}; 8.2 pμA (RIKEN) from nickelocene and Ti^{10+}; 4.5 pμA (JYFL) from $(CH_3)_5C_5Ti(CH_3)_3$. The method can also be used for B, Mg, Ga, Zr, Ru and W. Some of these volatile compounds (like Ti) are not available for enriched isotopes, which seriously limits the available intensity. In this case, oven techniques are preferable.

The transmission of an ECR beam through an accelerator depends on the emittance of the beam. In the case of the VENUS and the JYFL ECR ion sources emittance values of the order of 50 – 150 π mm mrad have been measured. For example, the acceptance of the K130 cyclotron at JYFL is approximately 100 π mm mrad. The emittance is related to the acceleration voltage, the mass of the ion, the charge state of the ion, the magnetic field and the ion temperature.

Higher microwave frequencies and stronger magnetic fields are needed to produce higher intensity highly-charged ion beams. However, there are many other, still unknown parameters having an influence not only on the intensity but also on the quality of the extracted ECR beam. As ionization in the ECR ion source is a complicated and not fully understood process, it is important to develop methods to determine those parameters. An example of such a method is that developed at JYFL to measure the ECR plasma potential.

In order to meet the requirements of the future experiments with high-intensity beams, further development is needed, especially in the production of metal-ion beams. Consequently, the development of ECR ion sources will be one of the most active areas in accelerator physics.

2-b Accelerators

Intense stable ion beams at high duty factors, high beam transmission and with flexible beam energies can be provided by linear rf accelerators. At low beam energies, up to few hundred A.keV, electrostatic solutions are possible. Cyclotrons can reach quite high performance, as demonstrated, for example in Dubna, GANIL and RIKEN, but show some limitations in beam intensity when compared to rf linacs.
There are many R&D activities in Europe, North America and Asia based on rf linac improvements, which will be described briefly in the following section.

In the last two decades the Radio Frequency Quadrupole (RFQ) has been established as the front end of rf ion linacs. New RFQs, operating at high duty cycle and CW, have been built using both normal conducting and superconducting (sc) structures.

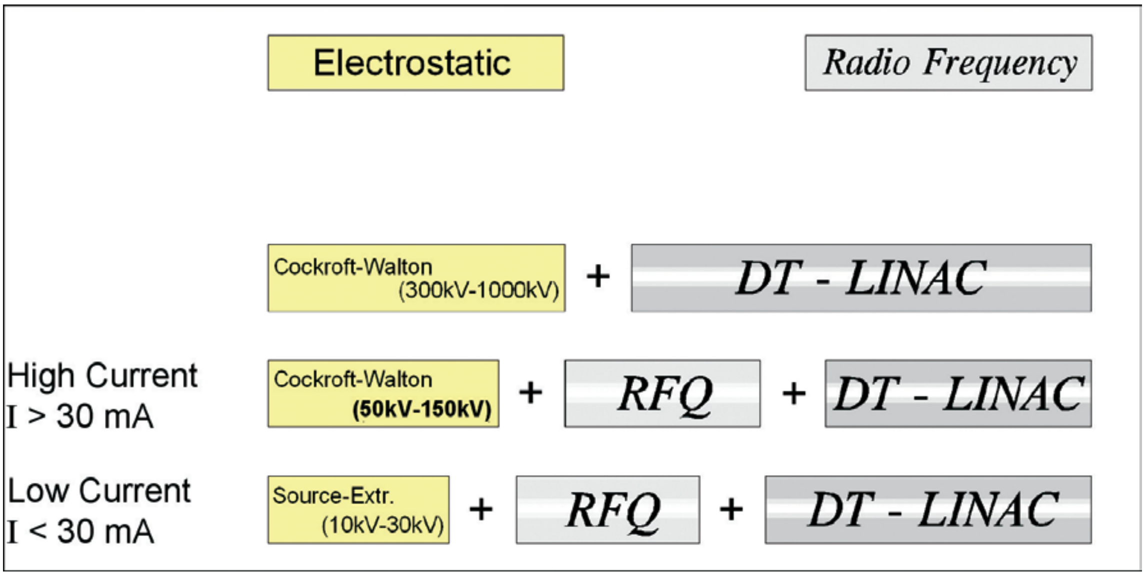
The use of the RFQs has shifted the transition between electrostatic and rf acceleration substantially towards lower energies as illustrated. The acceleration up to a few A.MeV can be provided quite efficiently by room temperature (rt) H - type – structures (IH-DTL and CH - DTL) – even for 100 % duty cycle operation.

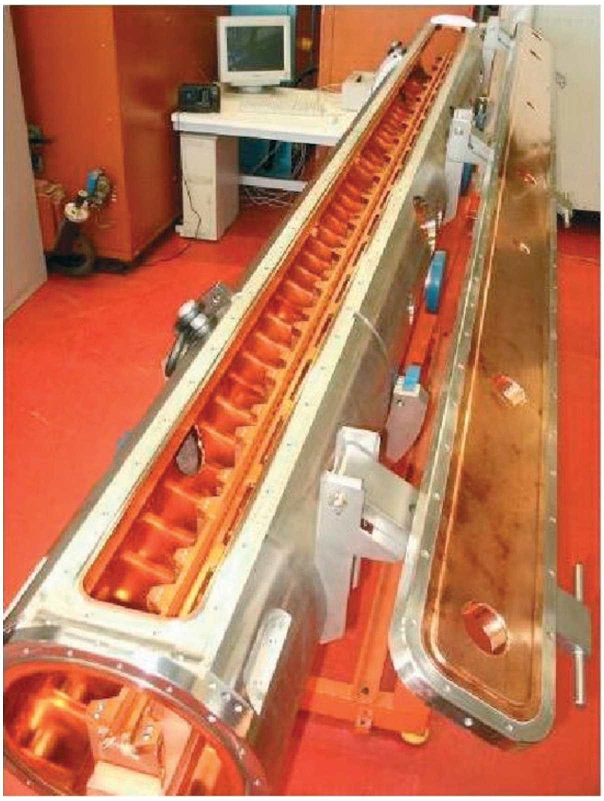
After the great success of sc linac technology both in high-beta beam acceleration and in the acceleration of low intensity low-beta beams, big efforts are now devoted at producing high performance, low and medium beta sc cavities suitable to accelerate high intensity beams. In future this will allow realizing very compact linacs, with high reliability at 100% duty cycle, and with a wide spectrum of pulsed operation modes, allowed by improved rf frequency control techniques.

Future high current linacs ask for reduced drift spaces between components to preserve beam quality. In the present design short focusing periods are obtained either with normal conducting or sc lenses.

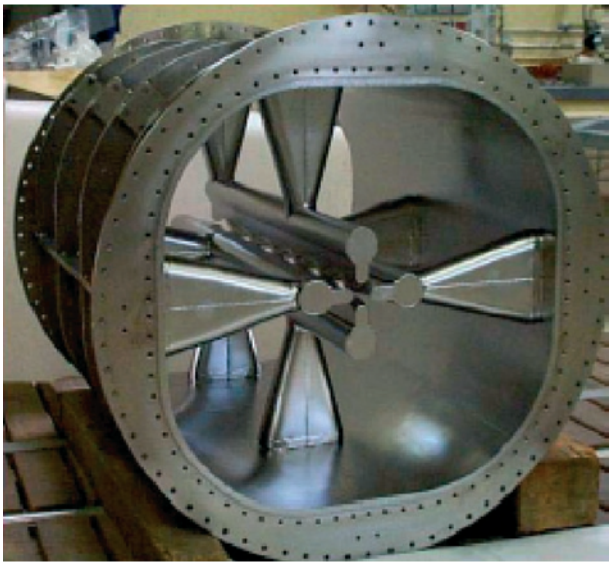
The optimum transition energy from rt to sc linac technology depends on the parameter range of

Typical electrostatic acceleration voltages made necessary by the use of an RFQ at the linac front end. At low beam currents the source extraction potential is sufficient.

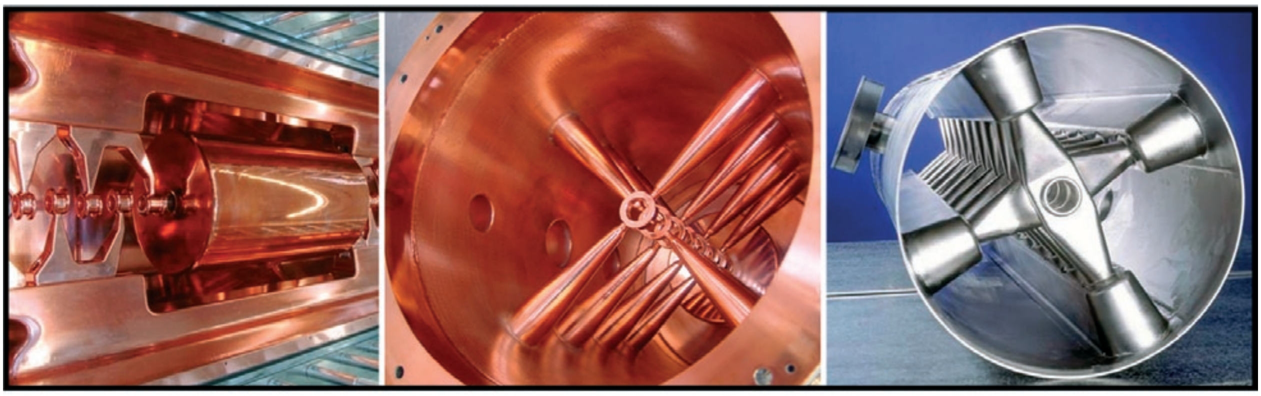




SARAF 176 MHz rt RFQ



One of the two 80 MHz sc RFQ structure operating at Legnaro



r.t. IH-DTL
W < 30 MeV
30-250 MHz

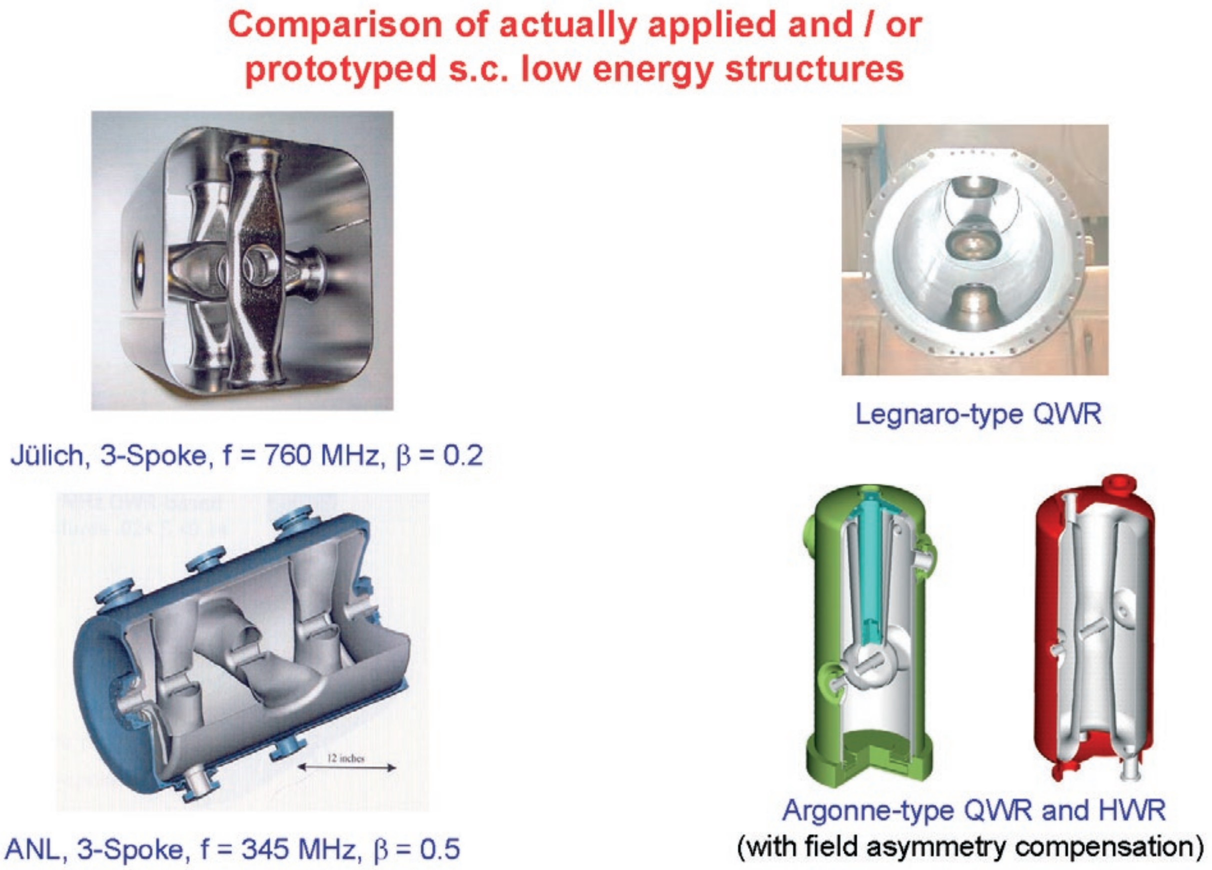
r.t. CH-DTL
W < 150 MeV
150-700 MHz

s.c. CH-DTL
W < 150 MeV
150-700 MHz

copper plated steel

bulk niobium

Examples of RFQ structures and of multi gap cavities of the H – type. They are especially suited for low beam energies up to several A.MeV. Both can be realized also with superconducting material because of their mechanical rigidity.



Two – gap cavities as used for beam acceleration already or under construction for SPIRAL II (right side) and 4-gap Spoke cavities under development (left side).

beam current, duty factor, A/q-ratio and beam energy, as well as on future progress on rt and on sc cavity development. Besides short structures multi-gap cavities of the Spoke and of the CH - type are developed now, which will further increase the efficiency of rf linacs.

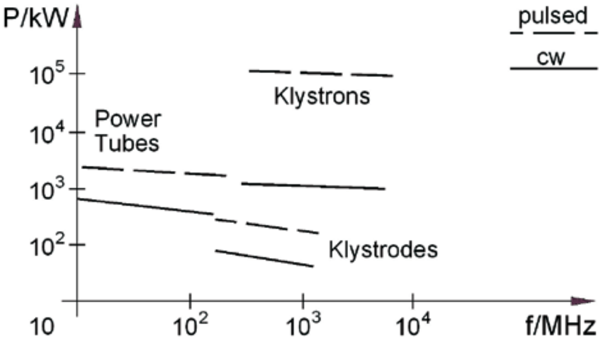
It is very important to match the linac design to commercially available rf power amplifiers as this market has changed rapidly, due to the revolution in communication technology. The figure above shows parameter limits of the rf amplifier options for the relevant frequency ranges. Especially, the power tube market has shrunk dramatically in recent years. On the other hand some powerful klystrons were developed in close co-operation between accelerator laboratories and industry, especially in the 300 to 400 MHz range. The tendency is to move towards higher operating frequencies in future whenever the beam parameters allow such a layout. Up to rf power levels of around 100 kW, semiconductor driven amplifiers are an alternative solution now to tube driven solutions in many cases.

2-c Targets

The following aspects make the development of an improved or new target necessary:

1. The use of metallic targets of lead and bismuth will not be possible at high beam intensities. Lead has a melting point of 327 °C and bismuth of 271 °C. Bismuth is used for the investigation of odd-Z elements and its lower melting point already caused a reduction of the beam intensity in recent experiments.

2. The energy-loss in the target increases quadratically with the element number of the projectile. The values are, for example, 6.2 MeV/(mg/cm^2) for 5 A.MeV argon in lead for production of fermium and 12.7 MeV/(mg/



RF power levels from commercial amplifiers. Klystrons allow for very high pulsed power levels. Klystrodes show still potential for further development in the near future.

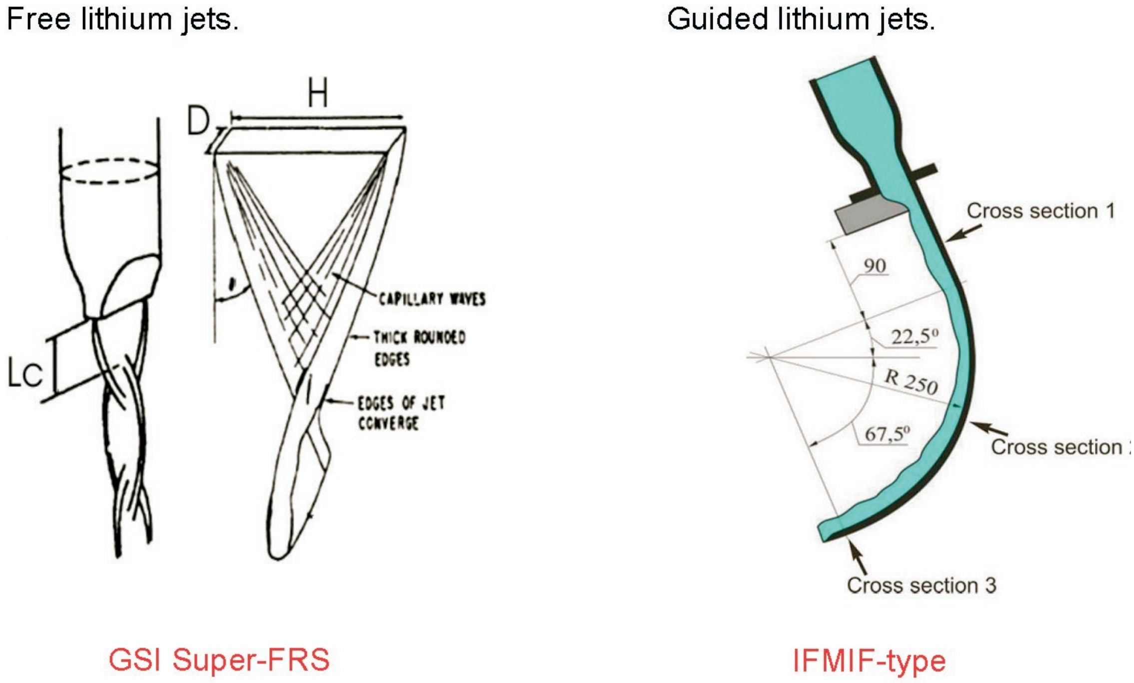
cm^2) for 5 A.MeV zinc in lead for production of element 112.

In order to use the high currents in experiments, the development of three kinds of high current targets is planned: alloys or chemical compounds of high melting point, gas-cooled targets, liquid targets and gas-jet targets.

The present target technology using target wheels which rotate with high speed through the beam can be kept also at high beam intensities, if the melting point of the material can be increased by using chemical compounds or alloys. Already successfully tested is a PbS target (melting point 1118 °C) produced by depositing the target material on a carbon backing. By heating the backing during evaporation (up to several 100 °C), the formation of a crystalline needle structure of PbS was avoided, which would result in uncontrolled energy loss of the projectiles. Using the ‘heated’ PbS target, a 1n-excitation function was measured, which was identical to the previously measured one obtained with a metallic Pb target. These targets were irradiated with ^{54}Cr beam with an intensity of up to 1.2 pμA at a 27 % duty factor without observable damage. Using a DC beam the intensity would be 4.4 pμA. Other examples of high melting point compound targets which have already been experimentally tested, are BiO$_2$ and UF$_4$. The advantage of high temperature targets is the increased radiative cooling which makes the application of more complicated gas cooling almost superfluous. However, gas cooling must be used in the case of targets of low melting point.

The cooling medium will be a stream of He, blown with low pressure (1–10 mbar) from both sides in the direction of the beam spot. The cooling effect of a gas acting on a target is well known from gas-filled separators and He-jet systems, where the currents can be increased by a factor 5–10 compared to targets in vacuum.

Scheme of target development with free and guided liquid metal jets like investigated at FZ Karlsruhe.



The gas-cooled target will be used in experiments, where the maximum current is limited by the accelerator to values of about 10 pμA and only targets of low melting point are available. The gas cooling method will be also interesting in those cases, where the target material is not available in gaseous or liquid form or where radioactive, fixed targets will be used, e.g. curium or californium.

Another advantage compared to pure gas-jet targets lies in the ion-optical properties of the separator. These are mainly determined by the mean charge state of the projectiles and reaction products escaping from the target. In a low pressure helium medium of short length the charge states of the ions escaping from the solid target will not be changed, and thus the separator properties will change compared to the presently used technique.

For the technical realization a differential pumping system has to be built using a turbo-molecular pump close to the target and two turbo pumps on either side of the target in order to reach a vacuum of 10^{-5} to 10^{-6} mbar at the exit of the accelerator beam-line and to the entrance of separator. No windows will be installed to separate the different vacuum sections.

A crucial item is also the intensity distribution of the beam across the target. Quadrupoles as ion-optical elements allow only for a Gaussian shaped beam intensity with the highest intensity in the centre region and tails at the outer areas. The former most likely melts the target in the middle and the latter causes background when hitting the target frame. The intensity distribution can be optimized using an octupole doublet in addition to the quadrupoles in the beam line in front of the target. With the use of these magnets an almost rectangular intensity distribution should be achievable.

The intensity distribution and the resulting temperature distribution across the target will be monitored by an infrared video camera. The monitor system will be developed so that it can be used also as a control of the beam current and beam position during the irradiation.

At the highest beam currents (>10 pμA) liquid or gas-jet targets become mandatory. Densities of the order of 10^{18} atoms/cm^2 are required. Gas-jet targets of this type are already in use, e.g. in experiments for investigating reactions of astrophysical interest at the University of Bochum. There helium is used as a target gas. In our case gaseous compounds of lead and bismuth will be examined. Also experiments will become possible using targets made from elements which exist only in gaseous form, like krypton or xenon. The alternative of using high temperature vapour targets was examined. This technique was rejected because of the complications due to the high temperatures needed (1500 °K) and the reduced flexibility.

2-d Recoil separators

The necessity for separator upgrades is based on the future expected ion-source and accelerator developments. Beam intensities ranging from to 6×10^{13} up to 6×10^{14} /s will become available. These currents are one to two orders of magnitude higher than used in experiments today. Therefore, the upgrade will cover primarily three items:

1. Development of compound targets of high melting point; target cooling techniques and gas-jet targets for experiments at high beam intensities.

2. Improvement of the ion-optical properties of the separator with respect to high transmission and reduced background.

3. Increase of the detector granularity and installation of an appropriate signal processing and data acquisition system.

An example of a typical separator used in experiments for the synthesis of SHE's is the velocity separator SHIP. The purpose for the upgrade of recoil separators is a further reduction of background and an increase of transmission. Using high currents, we expect that the background rate will increase more than proportional with the intensity. The reason is an unavoidable beam halo due to space charge effects. This means that with a factor of 10 higher currents the background rate on the detector will increase to more than 500 Hz on average.

A solution to considerably reduce the background will be the extension of the existing separators by post-separators consisting for example of a deflection magnet and a quadrupole doublet for focusing. The deflection angle of the magnet can be variable between 0° and 30°. In operation with the quadrupoles the deflection angle can be optimized for highest background suppression and higher transmission.

Ideal for many of the future experiments would be the development of a new separator of high mass resolution. In this case the mass number of the reaction product could be definitely determined. At extremely high resolution which would allow the separation of isobars in the case neutron deficient lighter elements, such a separator would revolutionize the investigation of proton drip-line nuclei. However, high resolution can be obtained only at the expense of reduced transmission. For example, from the several ionic charge states of the reaction products only one can be focused optimally. The others may be lost or could be used in set-ups installed in parallel. On the other hand a clean separation of isobars or the unambiguous mass identification of a nucleus is extremely important. In this case higher beam intensity compensates for the lower transmission.

The calculated transmission for asymmetric, hot fusion reactions using actinide targets is only 30 % or less. The reason is the wider solid angle covered by the relatively slow reaction products due to recoil effects from the emitted neutrons ($n \geq 3$) and scattering in the target. In order to make this reaction type better accessible an increase of the solid angle is mandatory. The design work will profit from the experience gained at the VAMOS spectrometer at SPIRAL and future separator-spectrometer S3 for SPIRAL2, GANIL. For VAMOS a large-acceptance quadrupole doublet was developed with an aperture of 200 mrad, whereas SHIP presently has a 70 mrad opening angle.

2-e Detectors, signal processing and data acquisition

The major limitation in many cases and particularly in in-beam studies remains the maximum counting rate that the detector systems can sustain in experiments using high intensity beams.

This limit has to be pushed as far as possible by the required R&D in three areas:

1. Extending detector segmentations in order to reduce as much as possible, the individual solid angle coverage.
2. R&D on throughput preamplifiers and digital electronics.
3. Development of Data Acquisition Systems capable of handling the highest rates of time stamped data without common dead time.

Which part of the experiment forms the bottleneck depends on too many specifics to be generally considered, but a few key areas are common and need to be addressed. Traditionally in-beam spectroscopy requires a gamma detection device coupled to ancillary detectors for particle and channel identification such as inner balls, neutron walls, Si detectors, recoil detectors etc. which need to be scaled with rate by more than two orders of magnitude and modern data acquisitions using triggerless techniques are required. For example, the next generation Gamma Spectrometer AGATA will boast the ability to run at a rate of more than 50 kHz per detector in ~200 detectors, a vast improvement over present devices. The developments in gamma detection, data acquisition and analysis needed to bring AGATA about are but one example of the necessary synergies that will directly benefit other detection systems.

IV Concluding remarks and recommendations

Stable beam facilities in Europe, capable of accelerating a large variety of ions at high intensity are vital for the community. They will continue to address major physics problems at the frontiers of nuclear structure and reaction studies. For the range of the physics cases outlined one can identify two categories:

1. Prompt in-beam studies at the target position: In these experiments the beam intensity is limited by the capabilities of the detectors around the target, the associated electronics and data acquisition system to distinguish and resolve correlated radiations (originating from the same event) and uncorrelated radiations (coming from two different reactions). Taking into account the ongoing and future development of highly segmented detectors, digital electronics and triggerless data acquisition systems, beam intensities in this type of experiments are unlikely to exceed few 100 pnA. We refer to them as 'medium intensity' case.

2. Studies away from the primary target: In these experiments the maximum beam intensity is dictated by the target's capability to sustain a large power deposition and by the resolving and rejection power of separators. The most advanced cooling technologies in conjunction with novel approaches to target composition as well as advances in recoil spectrometer design mean that the highest beam intensities usable in this type of experiment are of the order of 100 pμA which we refer to as 'high intensity' case.

We envisaged to take advantage of the existing stable beam facilities mainly JYFL-Jyväskylä, KVI-Groningen, LNL-Legnaro and LNS-Catania. **JYFL** is currently capable of providing up to 100 pnA of several of the stable beam species and is actively pushing the necessary ion source R&D to extend the list of available beams. **KVI** is planning an upgrade that will allow a considerable increase of the available beam intensities. **LNL** is soon expected to reach this level of beam intensities also for very heavy elements, once PIAVE will routinely replace the tandem as the injector for the ALPI linear accelerator. **LNS** is carrying out an upgrade program of the Supeconducting Cyclotron aiming for a considerable increase of the present beam intensities by reaching several hundreds of pnA.

Several low energy nuclear physics and nuclear astrophysics studies, complementary to those performed at Large Scale Facilities, will be carried out also at existing Small Scale Nuclear Facilities with unique experimental capabilities. Among those will be facilities in the Central and Southeast EC (new) countries, ie. in Athens (Demokritos), Bucharest (IFIN-HH), Debrecen (ATOMKI), Prague(Řež), Warsaw (SLCJ) and Zagreb (Rudjer Bošković Institute).

The recommendation of the committee is to ensure a strong support from both the nuclear physics community and the funding agencies for existing stable ion beam facilities not only for their accelerator system development but also for the instrumentation and experimental infrastructure that are needed to host dedicated research programmes.

Stable ion beams with the medium intensities can also be provided by the UNILAC at GSI and by either the CSS1 or the CIME cyclotron at GANIL (both separately or simultaneously). However, the committee feels that in-beam studies at medium beam intensity are but one aspect of the wide and varied research programmes at these two facilities.

It is beyond the remit of this report to make detailed recommendations for the next generation of instrumentation, indeed, specifications have to follow the physics goals of the user community. However, we recommend that the necessary advances in instrumentation must be developed in parallel to the design of the accelerator and be an integral part of a comprehensive design study.

An important challenge is the development of appropriate instrumentation that needs to keep step with the increasing beam currents. While the highest beam currents naturally are envisioned for experiments using in-flight separation techniques, the prompt spectroscopy at the target position presents its own set of challenges at currents more than one order of magnitude higher than currently used and must be considered at the same time as the upgrade of beam current.

Concerning the second category that needs the highest intensity beams, it appears clear that none of the existing, upgraded or future facilities in Europe fits the required specification.

The UNILAC upgrade will provide one order-of-magnitude greater beam intensities than available today reaching the level of tens of pμA. This is a major improvement, which will greatly enhance the programme to search for and study SHEs. The big advantage of the UNILAC will be its dedication for the SHE research field. **The realisation of this upgrade is considered highly important and the committee lends it its full support.**

LINAG, the SPIRAL2 driver is another attractive possibility as it fully matches the specification of the needed high intensity stable ion beam facility, except that it will be limited to light and medium-mass ions. The upgrade with a new RFQ suitable for heavier ions is possible but is envisaged only as a longer-term perspective. **Nevertheless, the LINAG project is recommended as a first technological step to the desired facility.** It is an important proof of feasibility and bench test for all technical issues related to very high intensity heavy ion beams. Moreover, despite its primary dedication as a deuteron accelerator driver for the production of neutron rich radioactive beams at SPIRAL2, a significant amount of beam time is foreseen to be used for the production of high intensity light and medium mass stable ion beams. This makes it ideal for typical dedicated experiments and also provides important tests with the highest intensity heavy ion beams in several physics areas such as the production and study of nuclei at and beyond the proton drip line through fusion evaporation reactions.

The use of the upgraded UNILAC and the very intense light and medium-mass beams from LINAG is an attractive medium range perspective for the community from the point of view of the physics opportunities and also from the point of view of the possibilities of testing and improving instruments and methods. **The long-term goal for a new dedicated high intensity stable ion beam facility in Europe, with energies at and above the Coulomb barrier, is considered to be one of the important issues to be discussed in the next Long Range Plan of the nuclear physics community.**

In order to be ready for this new project it is also highly important that research and development on the various related keys issues such as target, spectrometers and ion sources, electronics and data acquisition systems are initiated and organised at the European level in synergy with future RNB projects.

A low-energy (well below the Coulomb Barrier) and high-intensity stable-ion beam facility dedicated to nuclear astrophysics is seen as vitally important to improvement of our current understanding of stellar evolution and nucleosynthesis. Such a facility will complement the considerable efforts currently devoted in Europe to radioactive ion beam facilities relevant to nuclear astrophysics studies. Such a facility, built on the earth's surface, will have to meet demanding specifications if it is to resolve outstanding open questions in nuclear astrophysics. It will, also, help reveal those challenging issues that can only be met by studies in existing or future underground laboratories. In this direction, the opportunities for the development of a high-intensity accelerator at LUNA as well as in a salt mine should be thoroughly explored.