Introduction

This is the third issue of the IGLIS-NET (In-Gas Laser Ionization and Spectroscopy NETwork) newsletter. The IGLIS-NET launched on Dec. 2012 is now constituted by 15 participating research groups and institutes. One of the main activities through the network is frequent exchanges of the communications among these participants. The issue of the newsletter periodically summarizing the status of the research activities of the participating groups is another important activity. The present issue includes five status reports from the IGISOL facility of Jyväskylä, GALS at Dubna, the S^3-Low Energy Branch collaboration (including works at the IGLIS laboratory in KU Leuven and the LISOL facility), SLOWRI at RIKEN, and KISS at KEK.

IGLIS-NET News

- The IGISOL facility at Jyväskylä succeeded in high resolution spectroscopy of natural copper with frequency determination at the 1 MHz level after a proper wavelength calibration. Using the new injection-locked Ti:Sa cavity at JGU Mainz, a number of isotope shifts of Pu were measured on two different atomic transitions with one order of magnitude increased precision compared to existing literature data and hyperfine structures of the isotopes $^{239,241}Pu$ were observed. An inductively-heated hot cavity catcher for producing neutron deficient Ag isotopes was successfully commissioned on-line by implanting a beam of $^{107}Ag^{21+}$ ions into the graphite catcher. The extraction time of Ag atoms from the catcher changed as the temperature was varied. An exploratory laser spectroscopy study on heavy elements was initiated with long-lived isotopes of Pu prepared and delivered from the Mainz research reactor, where a two-step blue-blue scheme was successfully employed and clear identification of $^{240,242,244}Pu^{+}$ ions could be seen.
- For the GALS at Dubna, the room for the laser laboratory has been prepared. The laser equipment will be installed to complete the laser part of setup, and the first test experiments on selective resonance laser ionization will be performed using the reference gas cell in 2015.
- In the S^3-LEB collaboration, $REGLIS^3$ gas cell design was updated and the specific studies of the gas cell window and the gas cell chamber are foreseen under inputs from the S^3 beam optics group. The shape parameters of the de Laval nozzle for supersonic flows of noble gases were optimized by means of simulations. Preparation studies for the flow imaging have been performed, where the planar laser-induced fluorescence technique will be used. Optimization of an S-shaped RFQ ion guide system for $REGLIS^3$ was done with high performance in simulations. The comparison between dye lasers and

Ti:Sa lasers for laser spectroscopy studies at S^3 showed the essential requirement of a dye laser system in many cases and a sufficient use of a Ti:Sa laser system in some cases with long-term stable performance. The PILGRIM, a mass reflection – Time of Flight – Mass Spectrometer which will be placed after the RFQ system, and electrostatic deflectors for injection of the radioactive beam have been optimized using SIMION. In-gas-cell laser ionization and spectroscopy on the $^{212-215}Ac$ isotopes were accomplished at LISOL with an overall efficiency of ~0.8% and an average spectral linewidth of 6 GHz. The hyperfine structure of the 438 nm atomic transition in $^{214,215}Ac$ was investigated using an injection-locked Ti:Sa cavity, where the front-end was modified to enable gas jet formation interacting perpendicularly with the two laser beams prior to the SPIG. A preliminary analysis reveals a reduction of the spectral linewidth down to ~300 MHz, which enables to extract the isotope shifts and the hyperfine parameters with a 25-fold higher precision than the former in-gas-cell spectroscopy studies.

- SLOWRI, which consists of two gas catcher cells (RF carpet gas cell and PALIS gas cell), two mass separators and long beam transport lines, is under commissioning at RIKEN-RIBF. The majority of the SLOWRI setup has been installed in FY 2014. The installation of the PALIS gas cell at the F2 chamber of BigRIPS was successfully tested. Further confirmation concerning the laser radiation, radiation shields and other issues is necessary before the final installation. The development of a new low-energy experimental facility has been begun, where a small cryogenic gas cell is used to thermalize and extract heavy radioactive ions such as super heavy elements. In the first experiment, ^{205}Fr, produced by fusion between ^{40}Ar and ^{169}Tm, was successfully extracted at the efficiency of 30%.
- Laser-ionized ^{198}Pt from the elastic scattering of ^{136}Xe beam and ^{198}Pt target was extracted as a secondary beam at KISS/KEK. The extraction efficiency of $^{198}PtAr_2^+$ was ~0.2% which was independent of the primary beam intensity. The beam purity was higher than 99.7% at the maximum primary beam intensity of 20 pnA. The unstable nucleus ^{199}Pt, which was produced in the reaction between ^{136}Xe and ^{198}Pt, was also extracted as $^{199}PtAr_2^+$ molecular ions and its lifetime was successfully measured in good agreement with the reported value. A new extraction system, which consisted of two SPIGs having different geometries, was tested off-line, and the dissociation of the molecular ions of laser-produced iridium was clearly observed.

Recent Publications

Please look at IGLIS-NET website (http://kekrng.kek.jp/iglis-net/), where the publications are grouped according to the topics defined in the IGLIS-NET framework.

Any requests or comments about the IGLIS-NET newsletter are welcome. Please send them via iglis-net@kek.jp.

Status Report (1)

Laser resonance ionization and development at the IGISOL facility, Jyväskylä

(I.D. Moore*, M. Reponen, P. Papadakis, A. Voss, I. Pohjalainen, V. Sonnenschein (JYU), S. Geldhof (University of Leuven))

I. High resolution spectroscopy studies of natural copper

The second issue of the IGLIS-NET newsletter showed a first comparison of the improvement in spectral resolution using a dual-etalon Ti:sapphire laser and the new pulsed injection-locked Ti:sapphire laser. This comparison was performed using the 244-nm transition in copper. As this demonstration still lacked a proper wavelength calibration no values for the hyperfine coupling parameters were extracted at that time for the high resolution data. The measurements on copper were repeated later in 2014, now including calibration with a scanning FPI (Toptica FPI-100-0750-1) referenced to a stabilized HeNe laser. The free spectral range of the FPI had previously been measured using saturated absorption spectroscopy on rubidium to be 0.99850(15) GHz, allowing for a frequency determination at the 1 MHz level after inclusion of remaining systematic errors due to a nonlinear scanning behaviour of the FPI.

A crossed-beams geometry with a well-collimated atomic beam source was used for the new measurements, with the results shown in Table 1 [1]. For both the ^{63}Cu and ^{65}Cu ground state a good agreement with the high precision literature values [2] was found. For the excited state parameter of ^{63}Cu as well as for the isotope shift, the new results disagree with the existing lower resolution literature data [3] by several standard deviations. Based on these results, future on-line measurements of radioactive nuclei can be relied on, though measurements with the injection-locked laser inside the gas jet have yet to be attempted at

Hyperfine coupling constants of ^{63}Cu and ^{65}Cu			
	Experiment	Literature	Dual etalon exp.
^{63}Cu A_g/MHz	5866.84(21)[116]	5866.908706(20)*	5887(20)
^{63}Cu A_e/MHz	2411.33(31)[86]	2432(8)†	2416(20)
^{65}Cu A_g/MHz	6284.85(27)[121]	6284.389972(60)*	-
^{65}Cu A_e/MHz	2582.77(28)[87]	2588(15)†	-
ΔIS^{63-65}Cu /MHz	1045.95(21)[79]	977(21)†	1090(100)

Table 1. *Results for hyperfine parameters and isotope shift of copper as well as comparison with literature values from [2](†) and [1](*). Shown for completeness is the previous result using the dual-etalon Ti:sapphire laser [4]. For the dual-etalon measurement no result is given for ^{65}Cu as a fixed ratio A_{63}/A_{65}=5.867/6.284 was used for the fit.*

the IGISOL facility.

The long lifetime of the first excited state in copper (483 ns) allows for a further improvement in resolution by delaying the ionization laser pulse with respect to the exciting laser pulse [5]. As power broadening of spectral lines is affected by the power of both lasers, a delay of the high power ionizing laser pulse significantly narrows the Lorentzian part of the line shape, while only minimally impacting the ionization efficiency. For a delay of 80 ns, the ion signal is reduced by 10% as seen in Fig. 1 however the Lorentzian linewidth decreases by a factor of 10 as shown in Fig. 2. For delays exceeding the sum of the laser pulse durations, no further reduction of the linewidth is observed.

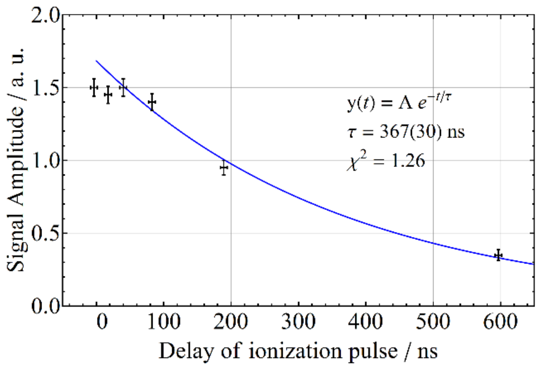

Figure 1. *Ionization efficiency dependence on Ionization pulse delay.*

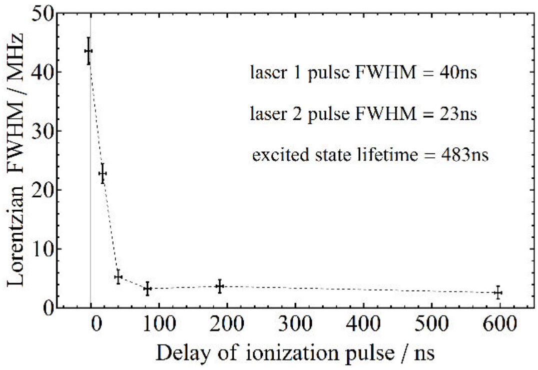

Figure 2. *Dependence of Lorentzian linewidth on ionization pulse delay.*

[1] V. Sonnenschein, Ph.D. thesis, University of Jyväskylä, 2015.
[2] H. Figger, D. Schmitt, and S. Penselin, Colloq. Int. C.N.R.S, 164:355, 1967.
[3] T. E. Cocolios, A. N. Andreyev, B. Bastin, N. Bree, J. Büscher, J. Elseviers, J. Gentens, M. Huyse, Yu. Kudryavtsev, D. Pauwels, T. Sonoda, P. Van den Bergh, and P. Van Duppen. Phys. Rev. C 81 (2010) 014314.
[4] V. Sonnenschein, I.D. Moore et al., Hyp. Int. 127 (2015) 113.
[5] R. de Groote, Master's thesis, KU Leuven, 2013.

II. Spectroscopy of the long-lived radioisotopes of plutonium

The new injection-locked Ti:sapphire cavity was also used at the University of Mainz for spectroscopy of ^{227}Ac and isotopes of plutonium [1], as well as in the recent experiment on gas jet laser spectroscopy of neutron-deficient Ac isotopes at the LISOL facility. In plutonium a number of isotope shifts were measured on two different atomic transitions with one order of magnitude increased precision compared to existing literature data [2]. Hyperfine structures of the isotopes ^{239,241}Pu were observed as well. The isotope shift data for one of the transitions is shown in Fig. 3, with a more detailed view of the hyperfine structure of ^{241}Pu given in Fig. 4.

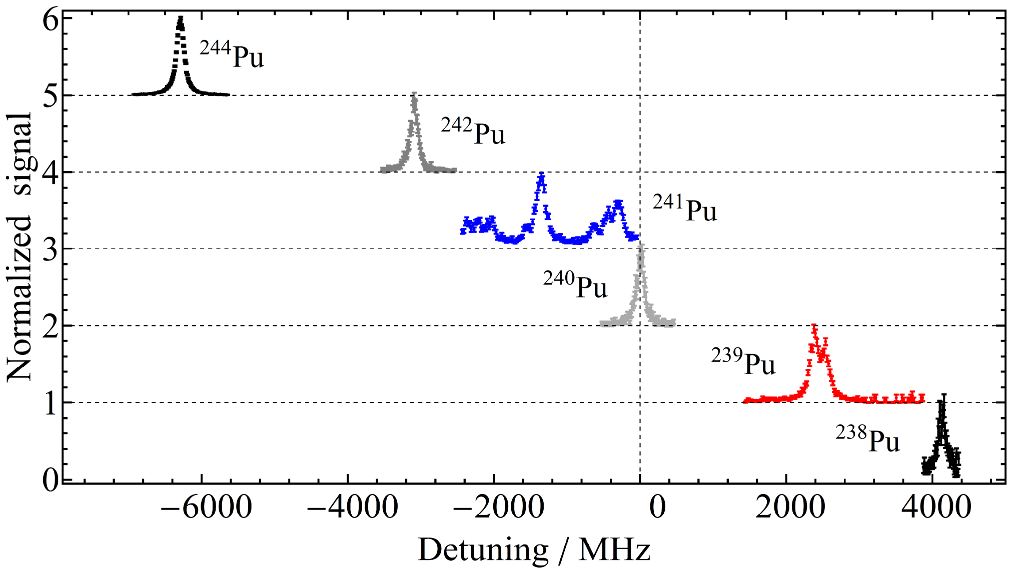

Figure 3. *Laser resonance ionization spectra observed in the plutonium isotopes. ^{240}Pu was used as the reference.*

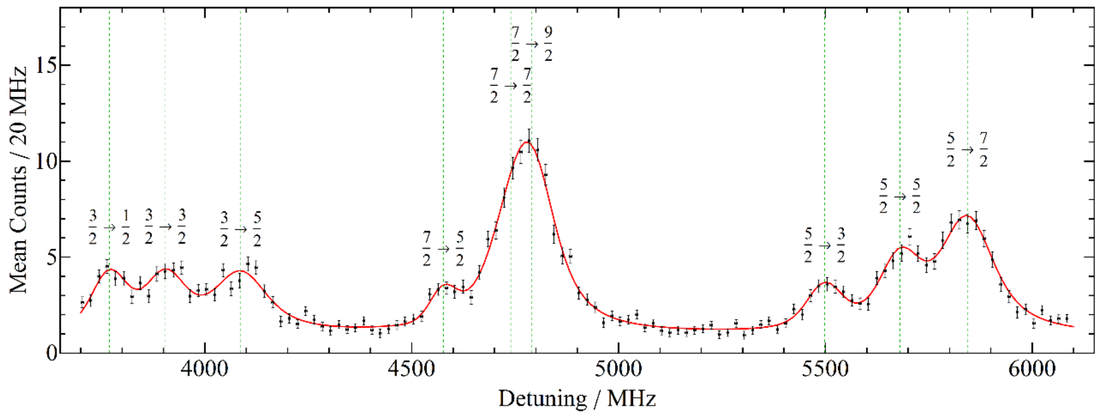

Figure 4. *Hyperfine structure of ^{241}Pu. The dashed lines mark the position of each hyperfine component and are also indicated by their respective F-F´ transition.*

Due to a strong correlation between upper and lower state hyperfine fit parameters in ^{239}Pu combined with the relatively small splittings and shifts observed in the spectra, further complementary measurements on other transitions or in the ionic species would be helpful. Such a measurement on singly-charged Pu^{+} ions is currently under preparation at the collinear laser station at IGISOL. In addition to further clarifying the current results and allowing for a comparison between the precision of the pulsed injection-locked system and a continuous wave laser measurement, Pu would be the heaviest element studied to date with the collinear technique.

[1] V. Sonnenschein, Ph.D. thesis, University of Jyväskylä, 2015.

[2] P. Kunz, Ph.D. thesis, University of Mainz, 2004.

III. Laser ionization of implanted ^{107}Ag using the hot-cavity catcher

An inductively-heated hot cavity catcher has been constructed for use at the IGISOL facility with the goal of achieving high efficiency on-line production of neutron-deficient silver isotopes and isomers using heavy-ion fusion-evaporation reactions.

In the second issue of the IGLIS-NET newsletter we described a new geometry of catcher which shielded the photo-ions from the inductive RF potential, thus dramatically improving the mass resolving power of the IGISOL mass separator. In 2014 the device was successfully commissioned on-line by implanting a beam of $^{107}Ag^{21+}$ ions from the K-130 cyclotron into the graphite catcher. By changing the angle of a degrader foil positioned in front of the catcher, the effective thickness and thus the resulting implantation depth of the Ag ions could be varied. The extraction time of silver atoms from the catcher was measured by pulsing the primary cyclotron beam while recording the mass-separated photo-ion count rate. The temperature of the graphite catcher was varied from ~1500 to 1700 K with the corresponding release times (shown in Fig. 5) changing from about 10 ms to 500 ms [1].

This first on-line experiment demonstrated the potential for the hot cavity to be used in future experiments for the extraction of short-lived exotic nuclei. In the future, a combination of reactions including ^{92}Mo(^{14}N, 2pxn)$^{104-x}$Ag and ^{64,nat}Zn(^{36}Ar, pxn)$^{101-97}$Ag will be utilized for the production and study of neutron-deficient Ag isotopes. Upon success, the goal of the hot cavity is the production of ^{94}Ag.

[1] M. Reponen, I.D. Moore *et al.*, to be submitted (2015).

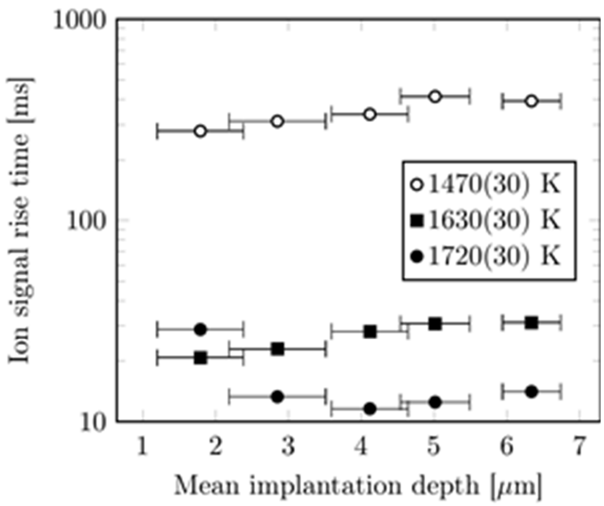

Figure 5. *Release times for different hot cavity temperatures and Ag implantation depths.*

IV. First tests of laser ionization of Pu isotopes in the IGISOL gas cell

In the fall of 2014, we initiated an exploratory laser spectroscopy study on heavy elements starting with long-lived isotopes of plutonium prepared and delivered from the Mainz research reactor. A number of filaments were obtained with different sample sizes of Pu ($^{238\text{-}240,\ 242,\ 244}$Pu) which had been electrically deposited onto Ta foils. Two null foils were also provided and were used in tests of filament heating.

The filament(s) were mounted inside a laser ion guide designed to be used for heavy-ion fusion-evaporation reactions (see Fig. 6). The dual-chamber gas cell is not required as no primary beam is involved in this work. A number of measurements were made including laser wavelength scans, mass separator scans, saturation measurements and so forth. It was seen that the three-step ionization scheme provided by Raeder [1] with an estimated laser ionization efficiency of 20% for in-source ionization in a hot cavity oven did not perform as expected in the gas cell. This may have been due to losses via gas collisions. In the end a two-step blue-blue scheme was successfully employed however further work to clarify the scheme is required.

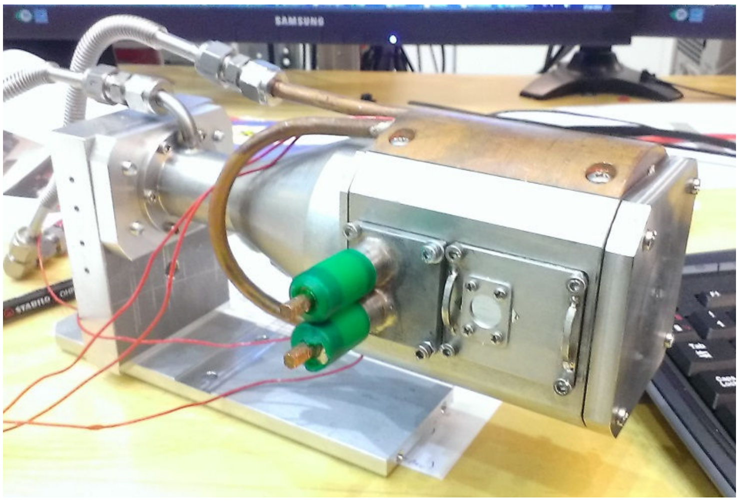

***Figure 6**. The laser ion guide used for resonance ionization spectroscopy of Pu atoms evaporated from heated filaments. The filament feedthroughs can be seen in the foreground.*

Figure 7 shows a mass scan obtained at two different heating currents, with and without laser ionization. Clear identification of $^{240,242,244}Pu^{+}$ ions can be seen (only one filament was used to focus on the more abundant isotopes in these initial tests). Additionally the effect of impurities is noticeable via the formation of plutonium oxide as well as the addition of a single hydrate. By mechanically chopping the laser beams we were also able to extract time profiles of the atomic and molecular species.

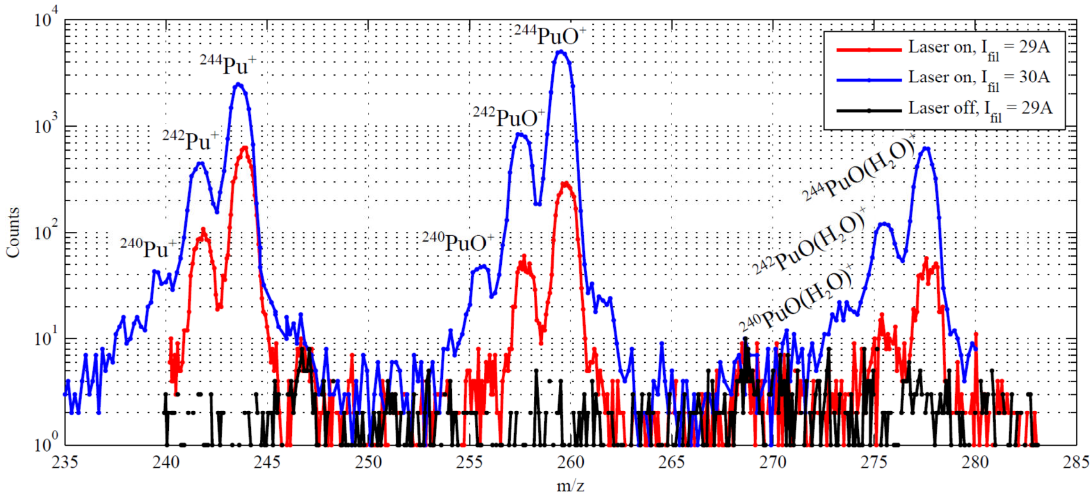

***Figure 7**. Mass scans of resonantly produced ion beams of Pu isotopes. Both atomic and molecular peaks can be clearly identified.*

This work will continue in May 2015 using a smaller gas cell in order to shorten the evacuation time. This should provide less sensitivity to molecular formation. The JYFLTRAP Penning trap will be used to identify possible molecular formation in the rf cooler-buncher as a function of bunching time. As noted above, complementary data to the injection-locked measurements is required. Thus far, no laser spectroscopy has been performed on the Pu^+ ion and therefore it is planned to use laser resonance ionization for the production of low-energy beams of Pu isotopes for the purpose of high-resolution collinear laser spectroscopy. The first collinear measurements are planned for May and if successful, Pu would be the heaviest element measurement using this technique to date.

[1] S. Raeder *et al.*, Anal. Bioanal. Chem. 404 (2012) 2163.

V. Future projects

In addition to the aforementioned status reports from our various activities we have a number of new projects. Two projects are briefly highlighted in the following:

-nuClock

JYFL has joined a consortium of six leading European research groups (the others being TU Vienna, PTB, University of Munich, Max Planck Heidelberg, Ruprecht-Karls University Heidelberg, Toptica) covering specialized expertise in the fields of atomic and nuclear physics, quantum optics, metrology, as well as detector- and laser technology, in a new proposal to develop a nuclear clock based on a unique low-energy nuclear transition in ^{229}Thorium. On 2 March 2015, the “nuClock”, collaboration received notification from the EU that the application to the Future and Emerging Technologies (FETOPEN) call in Horizon 2020 was successful. The collaboration will focus on two objectives; (i) to find clear evidence of the isomeric transition and to measure its frequency, and (ii) to develop all key components required for the operation of a nuclear clock. JYFL-ACCLAB participates as the sole large–scale facility in an effort which will last for a duration of 4 years and has secured 4 M€ in funding. JYFL has funding for a PhD student to work on this project therefore interested parties should contact I.D. Moore.

-Gamma-ray super-radiance in a Bose-Einstein condensate

A new research theme at JYFL has recently been developed in collaboration with the ultra–cold atom group of Prof. Ferruccio Renzoni, University College London. The proposed research aims to experimentally demonstrate coherent gamma–ray emission in a Bose–Einstein condensate of ^{135m}Cs isomers, produced in proton–induced fission of uranium at IGISOL. Currently, Finland has no single research group running an experimental programme in cold atom physics and thus this would be a major boost to the research community. The UK on the other hand has no facilities for the production of radioactive beams and this new research would increase its activity in the emerging field of atomic physics with radioactive atoms.

The idea is to implant mass-separated ^{135}Cs ground- and isomeric ions into an yttrium foil. Subsequent release of the atoms will be made following heating of the foil. The Cs will be laser cooled and trapped in a magneto-optical trap. Once cold, the atomic sample will be transferred to an optical dipole trap, where, by means of forced evaporative cooling, a BEC will be realized. The ^{135m}Cs condensate satisfies the requirement for coherent gamma-ray emission and the project is expected to lead to several milestones in fundamental physics.

In 2015 we were successful in obtaining a Marie Curie Individual Fellowship for a researcher to work on the new project (Luca Marmugi). Prof. Renzoni and I.D. Moore have just recently submitted a grant proposal to the Royal Society, UK, for a two year international exchange scheme.

Status Report (2)

GALS – setup for production and study of heavy neutron rich nuclei at Dubna

(V.I. Zagrebaev, S.G. Zemlyanoy*, E.M. Kozulin, Yu. Kudryavtsev (KU Leuven), V. Fedosseev (CERN), R. Bark (NRF, South Africa), H.A. Othman (Menoufiya Univ., Egypt))

The realization of the project GALS, devoted to the production and study of heavy neutron rich nuclei by multinucleon transfer reactions is in progress. The main results obtained in 2014 are following:

1. Design of the laser part of the setup has been finished. First 4 lasers (two Nd:YAG pump lasers and two Dye lasers), needed optical tables and breadboards are purchased. The room for the laser laboratory has been prepared (see Fig. 1). Ventilation and conditioning system (FRIVENT) providing cooled water and cooled laminar air fluxes was installed and commissioned. Optical tables with laminar boxes system have been installed. Laser system, control optical system etc. are delivered to the laboratory and will be installed in the beginning of 2015.

Figure 1. *Laser system of the GALS project.*

2. Design of the gas and vacuum system is finished. All the specifications of this system (pumps etc.) are defined and the corresponding contracts for supply of this equipment are under consideration.

3. Design of the mass separator (having typical mass resolution of 1500) was performed and a possibility for its allocation in the experimental room has been confirmed. Approved allocation of the whole GALS facility in experimental rooms near the hall of the cyclotron U-400M is shown in Fig. 2 in real scale.

Remaining laser equipment (diode pump laser and Dye laser, instrumentation, optoelectronics etc.) will be delivered, installed and tested during 2015. This way the laser part of setup will be completed and first test experiments on selective resonance laser ionization will be performed in 2015 using the reference gas cell.

Front end system, gas cell, ion guide, mass separator and gas purification system will be designed, purchased (partially), manufactured, and installed during 2015.

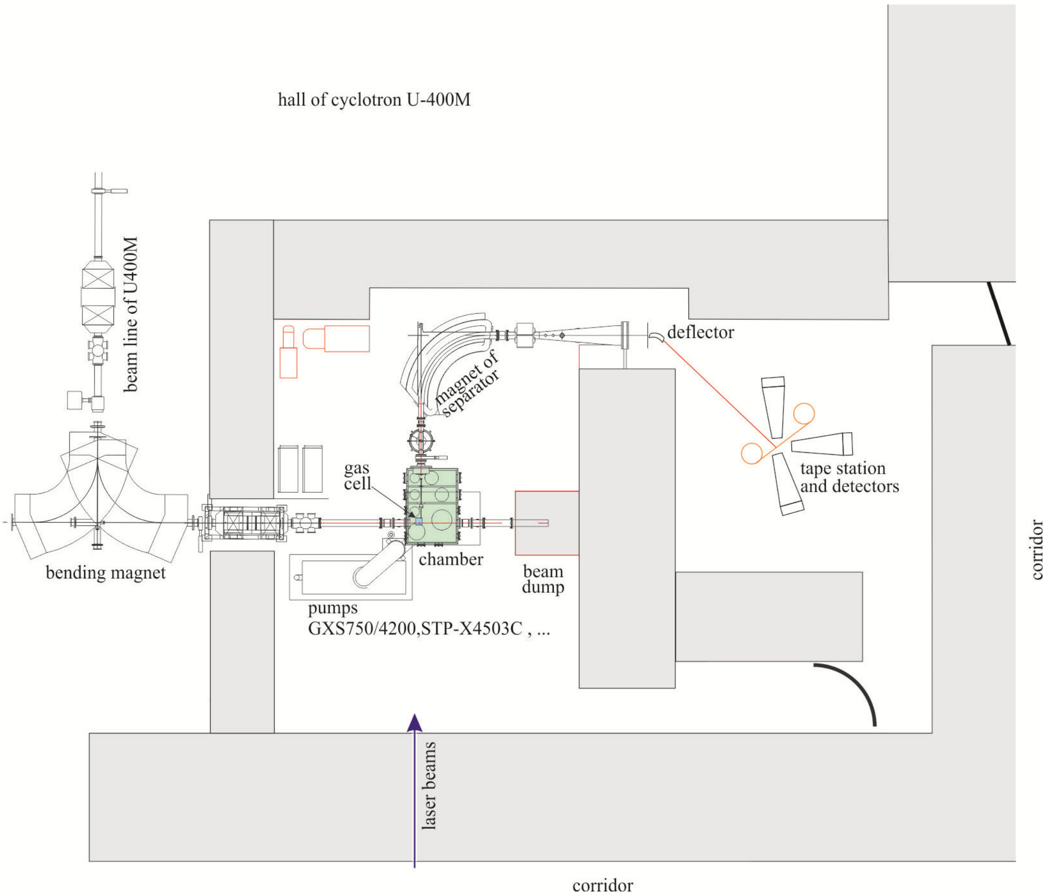

Figure 2. *Location of the GALS setup at the Flerov Laboratory in the experimental rooms near the hall of the cyclotron U400M. Gas system, mass separator, and detecting system are shown in real scale. The laser system is already installed in the room over the corridor.*

Status Report (3)

The S^3-Low Energy Branch collaboration activity

Status on the IGLIS laboratory at KU Leuven, the experimental and R&D program at the LISOL facility and the REGLIS^3 project

(P. Creemers, R. Ferrer, L. Gaffney, L. Ghys, C. Granados, M. Huyse, Yu. Kudryavtsev, Y. Martinez, E. Mogilevskiy, S. Raeder, S. Sels, P. Van den Bergh, P. Van Duppen, S. Zadvornaya (KU Leuven), B. Bastin*, D. Boilley, P. Delahaye, L. Hijazi, N. Lecesne, R. Leroy, H. Lu, F. Lutton, B. Osmond, J. Piot, H. Savajols, J.-C. Thomas, E. Traykov (GANIL), X. Fléchard. J. Lory, Y. Merrer, E. Traykov (LPC Caen), P. Dambre, P. Duchesne, S. Franchoo, O. Pochon (IPN Orsay), R. Heinke, T. Kron, P. Nauberreit, P. Schoenberg, K. Wendt (JGU Mainz), M. Laatiaoui (GSI), I. Moore, V. Sonnenschein (JYU), S. Rothe (CERN))

The following sections report on the progress of the different working groups of the S^3-LEB collaboration.

The general layout of the S^3-LEB facility as currently defined is shown in Fig. 1.

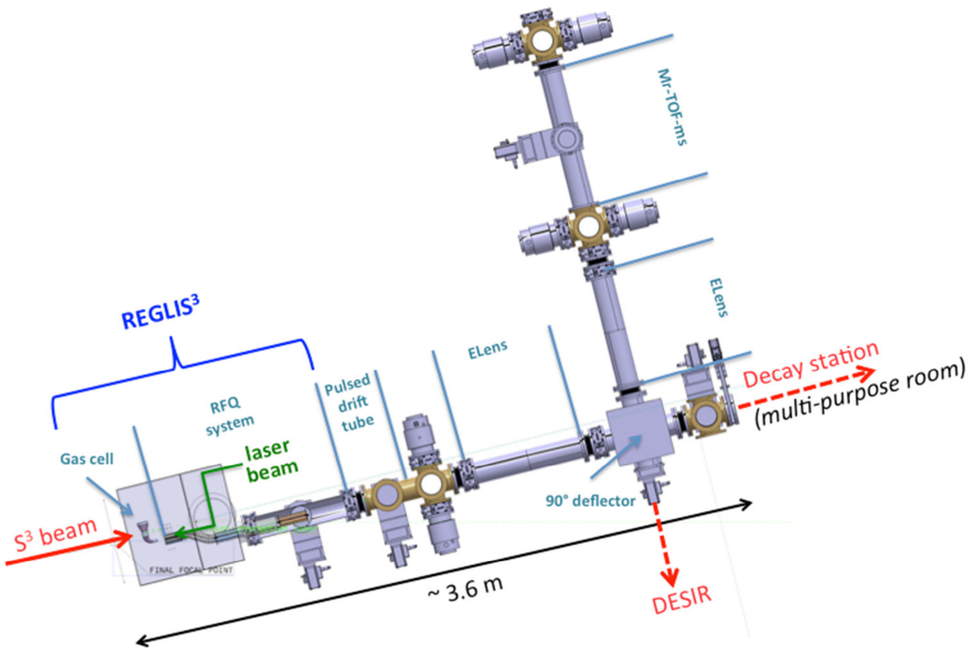

Figure 1. *The S^3-LEB general layout.*

I. The REGLIS^3 gas cell design (IPN Orsay, KU Leuven)

A first technical drawing of the REGLIS^3 gas cell has been made in January 2014 by the IPN Orsay “Mechanical Design” sector, based on propositions from KU Leuven. Improvements have been integrated in an updated design in February (see Fig. 2).

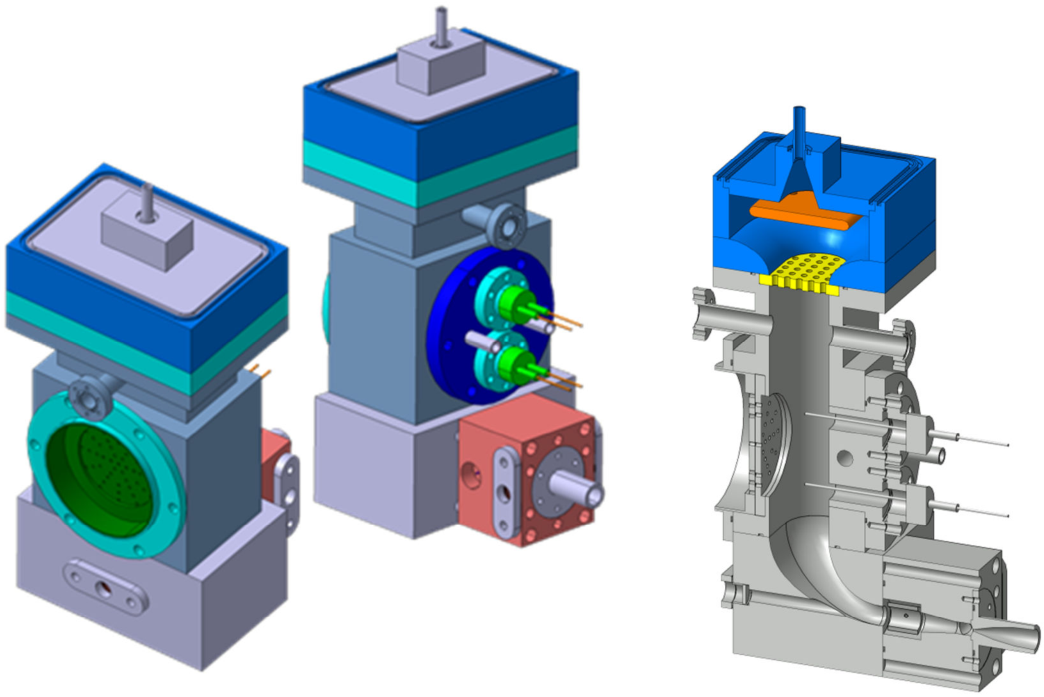

Figure 2. *Technical drawing of the REGLIS^3 gas cell (O. Pochon, IPN Orsay technical design office).*

The specific studies of the gas cell window and the gas cell chamber are foreseen in the incoming months. These studies require input from the S^3 beam optics group.

For each of the reference physics cases defined by the collaboration [1] (^{208}Pb(^{48}Ca, 2n)^{254}No, ^{197}Au(^{22}Ne, 4n)^{215}Ac, ^{58}Ni(^{50}Cr, 2p6n)^{100}Sn, ^{58}Ni(^{40}Ca, p3n)^{94}Ag and ^{24}Mg (^{58}Ni, 2n)^{80}Zr), a good knowledge of the beam envelope and the distribution (energy, angle, position) of the isotopes of interest is needed at the entrance of the gas cell for two reasons:

- to optimize the entrance window geometry of the gas cell.
- to validate the orientation of the gas cell.

The information concerning the energy and angles of the residues would help to define the nature of the entrance window and would allow more realistic gas flow calculations that could impact the gas cell body design.

A reference document, which summarizes the S^3-LEB needs in terms of beam optics calculations, has been prepared and is under validation [2].

The discussion concerning the technical possibilities for the realization of a gas cell with a shorter evacuation time has been initiated during the DESIR-S^3-NFS workshops (March 2014) and is still ongoing.

[1] R. Ferrer. et al., NIM B 317 (2013) 570.

[2] B. Bastin et al., S^3-LEB internal collaboration report, “Beam optics calculations for the S^3-LEB”, in preparation.

II. Nozzle design and jet visualization (KU Leuven)

The cooling of atoms by supersonic expansion together with the formation of a collimated low-pressure gas jet are crucial aspects for laser spectroscopy studies with an enhanced resolution on short-lived isotopes provided by S^3. A better collimation of the atomic beam will also allow obtaining an optimum overlap with the laser beams, therefore improving the ionization efficiency. The proposed way to obtain a gas jet that can meet these requirements is using a convergent-divergent (also known as 'de Laval') nozzle.

The specified Mach number M, i.e. the velocity and the temperature in the gas jet, and the buffer gas are the main parameters that define the shape of the nozzle. Therefore these parameters are being studied to find out an optimum nozzle shape.

Supersonic flows of noble gases in the 'de Laval' nozzle were studied by means of simulations using the COMSOL Multiphysics software package. The shape parameters of the nozzle for M = 7.5 (Helium gas, nozzle throat diameter = 1 mm) and M = 3.5 (Argon gas, nozzle throat diameter = 1 mm) were optimized. The profile of the former, with the colours indicating the velocity magnitude of the gas flow, is shown in Fig. 3.

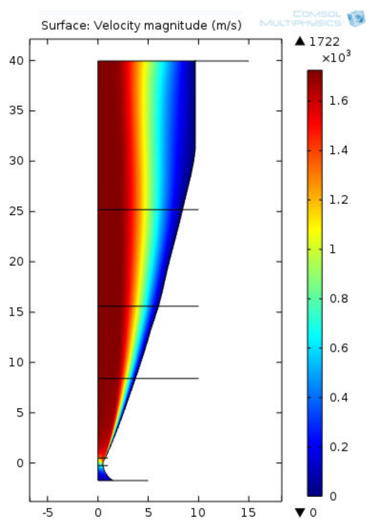

__Figure 3.__ Profile of the nozzle for a Mach number M = 7.5 (throat diameter = 1 mm, Helium gas).

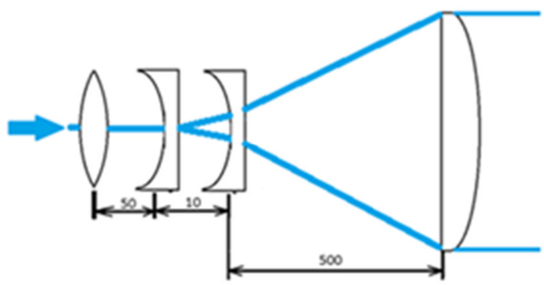

__Figure 4.__ Conversion of the laser beam into a laser sheet. The dimensions are shown in mm.

On the other hand, preparation studies for the flow imaging have been performed. For these studies the planar laser-induced fluorescence (PLIF) technique will be used. It requires the conversion of the laser beam into a laser sheet. Sheets of light were obtained recently in the IGLIS lab by using a set of spherical and cylindrical lenses as that shown in Fig. 4.

At the first stage of the experiment the PLIF technique will be applied only to vizualize the jet formed by different nozzles. This will be done by the observation of fluorescence of acetone molecules seeded into the argon gas. At the second stage the parameters of the jet such as temperature, velocity and density will be investigated by applying the PLIF technique to copper atoms seeded in the gas. This will be done by scanning a narrow band laser across the atomic resonance and monitoring the fluorescence of the copper atoms. The jet parameters will be then deduced from the Doppler shift and the shape of the resonance in different regions of the jet.

III. The RFQ system (LPC Caen, KU Leuven)

-The RFQ system prototype (KU Leuven)

An S-shaped RFQ ion guide system that will be used as a prototype for REGLIS^3 at S^3 is under development at the IGLIS laboratory in KU Leuven. The RFQ ion guides will provide optimum spatial overlap of the laser beams with the atomic gas jet formed at the gas cell nozzle, and at the same time will efficiently capture, cool and transport the photoions resulting from the resonance laser ionization process. Simulations with the commercial software package SIMION [1] were performed and led to the high-performance design shown in Fig. 5. The simulations predict a total transport efficiency of 80-100%, a 7π mm mrad beam transverse emittance at the exit of the ion guides at 2 kV extraction voltage, and a 400-900 μs time of flight through the different pressure regimes in the ion guides depending on ion-neutral collision model (Stokes viscous damping, or HS1 hard sphere collisions [1]). Technical drawings have been completed and machining of the ion guides

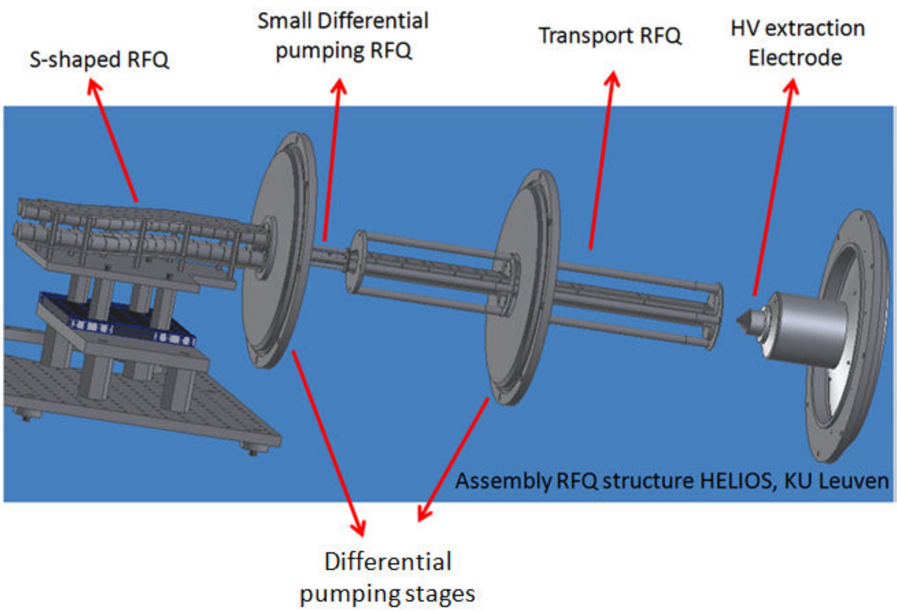

Figure 5. *Drawing of the proposed assembly of the RFQ ion guides for REGLIS^3 at S^3 which will be mounted and tested in the IGLIS lab at KU Leuven.*

has been accomplished. A cross-check and refinement of the simulations is currently being carried out considering a real neutral-ion collision potential (Ioncool [2]). The ion guides prototype will be commissioned and tested in the IGLIS laboratory at KU Leuven in the next months.

-The REGLIS^3 RFQ system (LPC Caen)

The RFQ system is intended for coupling the gas stopper cells to the detection station, the MR-TOF-MS, and the DESIR facility. The purpose of the ion guide system is to transport efficiently the laser-ionized radioactive samples from the high-pressure ionization region to a high-vacuum region while simultaneously cooling and purifying the ions of interest and finally forming bunched ion beams of low emittance. Although RFQ coolers/bunchers have been widely used in nuclear physics facilities in the last two decades and their operation is well understood, the specific conditions at the S^3-LEB (such as the incorporation of both free-expansion and collimated gas jets, the necessity of a curved RFQ cooler due to laser access, the direct coupling of several RFQs with different purposes, etc.) require extensive simulations and testing in order to choose optimal design (dimensions, shape, distances) and operation parameters (gas, pressure, potentials) of the RFQ system.

Simulations were carried out using SIMION ion optics program with two different extensions incorporating gas jets and their interactions with the ions (Statistical Diffusion Simulation and Hard Sphere collision models).In both models the same empirical equations were used describing the pressure, temperature, and velocity distributions of the atoms in the jet volume [3]. The SDS model was found to be reliable only at higher pressures (above 0.1 mbar) whereas the HS model was the preferred option although the HS simulations can be computationally heavy thus too slow at high pressures.

The first step was to simulate the behaviour of the extracted ions in a free-expansion gas jet formed at the exit of the gas cell. In addition, the interaction of the ions with the rest gas atoms was included in order to simulate properly the loading of the ions into the S-shaped RFQ cooler (SRFQ) and subsequently into a mini RFQ (mRFQ) (Fig. 6) (the latter is required for the purpose of differential pumping). An optimal combination of buffer gas, background pressure, cooling distance, and DC potentials is being investigated in this step.

There are several other important details in the design of the RFQ system which were investigated by the simulations. Among the parameters and details to be studied were the distance between the nozzle exit and the entrance of the SRFQ, the pressure of the rest gas in the chamber and eventually the addition of (helium) buffer gas in the SRFQ volume, the minimal length of the cooling section of the SRFQ for different gas pressures, the dimensions of the mRFQ (differential pumping vs. transmission efficiency), the design of the electrostatic lenses coupling the mRFQ to the quadrupole mass filter (QMF), the tuning of the QMF (transmission vs. resolving power) and the time and energy structure of the bunched beams from the RFQ buncher.

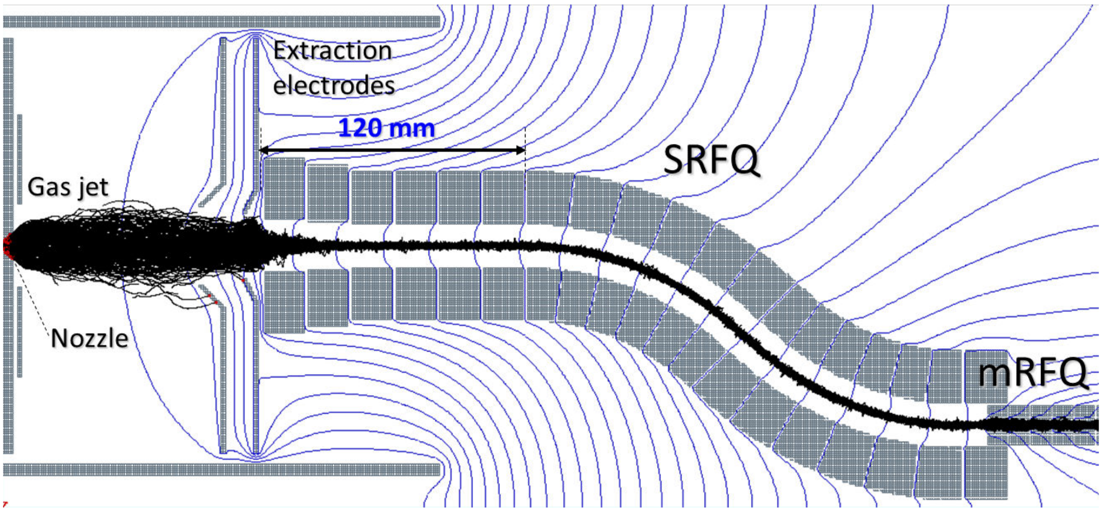

Figure 6. *A plot from a Hard Sphere SIMION simulation showing trajectories of ions (in black) influenced by the gas jet and background gas collisions. The ions are then guided by DC potentials (in blue) and confined radially by RF fields for transport through the volumes of the SRFQ and mRFQ towards a mass filter stage.*

The main simulations were completed in the beginning of 2015 estimating good transmission efficiencies : 85-90% for the gas jet – SRFQ region, 100% for the mRFQ, and around 95% for the QMF at a mass resolving power of 250 (for A = 85). The performance of the latter was extended for resolving powers of up to 1700 (A = 85) with a corresponding efficiency of 77%. The high resolving power operation may be beneficial in special cases of high contamination by neighbouring mass nuclei. After the completion of the simulations a technical design study has begun in early 2015.

[1] D.A. Dahl, Int. J. Mass Spectrom. 200 (2000) 3. Source: Scientific Instrument Services, Inc., Ringoes, NJ – SIMION (www.simion. com)

[2] S. Schwarz, Nucl. Instr. And Meth. in Phys. Research A 566 (2006) 223-243, Ioncool – a versatile code to characterize gas-filled ion bunchers and coolers (not only) for nuclear physics applications.

[3] Y. Kudryavtsev et al, NIM B 297 (2013) 7.

IV. The laser systems (GANIL, KU Leuven)

The requirements of the laser system used for spectroscopic studies at S^3 have been investigated regarding especially the proposed Day-1 experiments. For this purpose the commercial dye lasers used for offline studies at the IGLIS laboratory in Leuven and the university of Mainz Titanium:sapphire (Ti:Sa) lasers have been compared. While the more comprehensive dye laser system as well as the needed infrastructure has to be newly installed, a Ti:Sa laser system is already available at the GISELE laser laboratory, only lacking a narrowband-laser. In a short summary it can be concluded that for some cases such as actinium and tin the available Ti:Sa laser system will be sufficient for successful laser spectroscopy studies. Nevertheless, many other cases such as the level search in nobelium or the HFS spectroscopy in silver essentially require the availability of a Dye laser system. Especially the universal wavelength coverage as well as the available high power UV laser radiation makes Dye lasers indispensable for general usage. If applicable the Ti:Sa laser appeal with a maintenance free operation which allow for long-term stable performance in spectroscopy and resonant laser ionization. All in all Dye and Ti:Sa laser system complement each other and a combined laser system as it is also used at the ISOLDE RILIS will allow for the best performance at GANIL. For the complete adaptation of the existing Ti:Sa laser system, automation of few optical components is ongoing for easier wavelength scan in laser spectroscopy experiments.

V. The PILGRIM Multi Reflection – Time of Flight – Mass Spectrometer and 90° deflector (GANIL, LPC Caen)

The PILGRIM (Piège à Ions Linéaire du Ganil pour la Résolution des Isobares et la Mesure de masse) is a Multi-Reflection – Time-of-Flight – Mass Spectrometer (MR-ToF-MS) which is being developped by GANIL and LPC Caen in collaboration with the University of Greifswald. The aim of the MR-ToF-MS is the purification and mass measurement of the exotic isotopes produced by S^3-LEB, with a typical resolving power $R = 10^5$ and a relative mass accuracy of $\delta m/m = 5\times10^{-7}$ for 10 ms trapping times. It will be placed after the set of RFQs, which shall separate, cool and bunch the beam prior to the injection into the MR-ToF-MS.

The PILGRIM MR-ToF-MS has been optimized using SIMION and following the same procedure as that used in the University of Greifswald, which has developed the ISOLTRAP MR-ToF-MS presently under operation at ISOLDE [1]. The mechanical design has been done in order to allow for a simple replacement of the mirror electrodes (see Fig. 7). PILGRIM will make use of the in-trap-lift method as developed for the ISOLDE MR-ToF-MS [2].

The injection of the radioactive beam into PILGRIM will possibly be done using one or two electrostatic deflectors (Fig. 8), whose design has also been carefully optimized using SIMION not to spoil the transverse and longitudinal emittances of the ion bunches, as it is crucial to achieve high resolving powers in PILGRIM. The precise layout of the beam lines, from the RFQs to the MR-ToF-MS and then to the tape station, is under study.

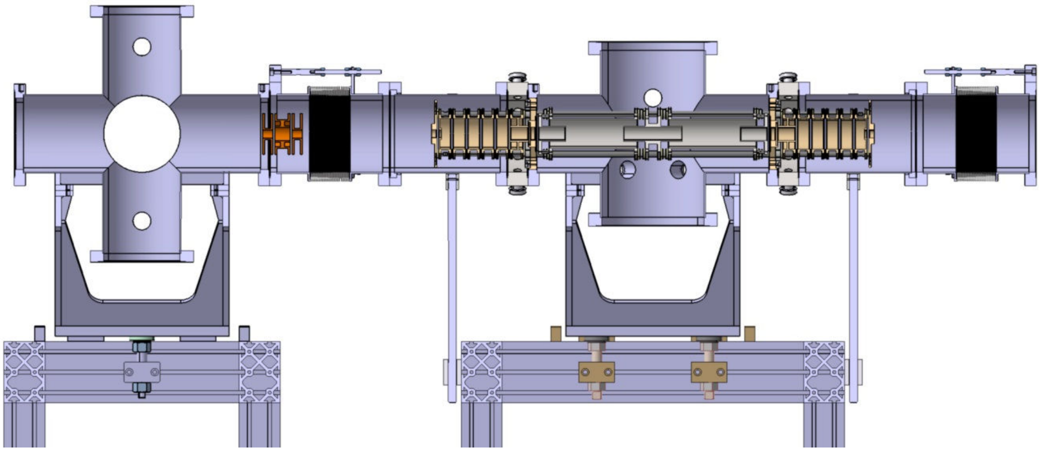

Figure 7. *3D model of PILGRIM.*

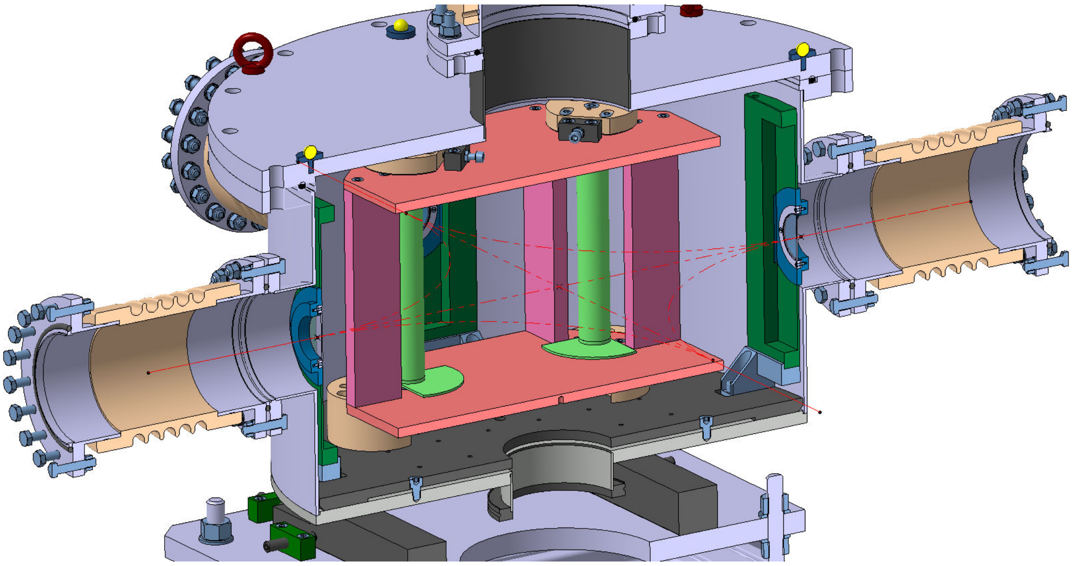

Figure 8. *90° electrostatic deflector cross section from the initial study.*

-Planning

The PILGRIM mechanical drawings are on the way to be completed. The equipment and mechanical parts will be purchased so that PILGRIM can be assembled in the first half of 2015. Off-line tests at LIRAT could be scheduled during the fall of 2015 or beginning of 2016.

The final design of the deflector shall be completed by late October. The mechanical drawings will either be done by GANIL or CENBG, and should be completed in the first trimester of 2015. A prototype could be realized by the fall of 2015 or beginning of 2016, and should be tested together with PILGRIM.

[1] R. Wolf et al, NIM A 686 (2012) 82.
[2] R. Wolf et al, Int. Journ. Mass. Spectr. 313 (2012) 8.

VI. Beam diagnostics and decay station (GANIL, LPC Caen)

-Diagnostics for optics optimization

Detectors would be first needed in order to optimize the tuning of the spectrometer, to check the beam profile (beam centered on the gas cell window) and to check the beam current stability (during experiments). Currently, a Faraday cup and an Emission Foil Emitter (placed at −363.15 mm and −238.15 mm from the PFF, respectively) have been defined as diagnostics boxes prior to the gas cell. The use of DSSD detector is foreseen when running VHE or SHE experimental campaigns, where the beam intensity would be about few pps or less. Question remains concerning the appropriateness of these diagnostics equipment (sizes suitable?). A need of details concerning the beam envelope is mandatory to their validation. The results of the beam optics calculations will reveal whether specific detectors need to be designed [1].

[1] B. Bastin et al., S^3-LEB internal collaboration report, “Beam optics calculations for the S^3-LEB”, in preparation.

-Diagnostics for S^3-LEB setup optimization

Four diagnostics points have been identified. The first one, located after the pulsed drift tube, would be composed of 4 insertions (a Faraday Cup (FC), an MCP detector and a set of 2 ‘pepper pot’-type attenuators). The second and third diagnostic points – placed at the extremities of the MR-ToF-MS – would have both two insertions (a FC and an MCP). The last one, located after the 90° deflector on the multi-purpose room beam line axis, would be also composed of a FC and an MCP.

-Decay station

The decay station is defined to be a successive combination of an alpha-decay station and a beta-decay station. It will be used to perform laser spectroscopy studies. It will help to tune the beam and lasers when the count rate is very low. It will also provide an ultimate validation of the beam identification and will be used to optimize isomeric beam ratios.

The alpha-decay station will be based on the “Windmill” system developed by the Leuven group. As for it, the beta-decay station will be based on the IBE station designed by LPC Caen for SPIRAL2-phase2. The use of the tape prototype build for SPIRAL2 is envisaged (existing structure, engines, automates…). The possibilities for funding the decay station are under investigation.

The test of the beam diagnostics tools foreseen to be used is current on going at the GISELE test bench (GANIL-ARIBE facility) with ion beams issued from a laser ion source.

VII. Ac laser spectroscopy experiments at LISOL

Following up the experimental campaign on the actinium isotopes at the LISOL facility, two more beam time periods in 2014 were devoted to investigate the hyperfine structure of the transitions at 418 nm and 438 nm. In the first run, in-gas-cell laser ionization and spectroscopy of the $^{212\text{-}215}$Ac isotopes could be accomplished with an overall efficiency (ions reaching the back-end detectors to those produced in the nuclear reaction) of ~0.8% and an average spectral linewidth of 6 GHz. The analysis of the data, still ongoing, has provided so far values for the pressure shift and broadening coefficients, as well as isotope shifts and magnetic moments of these isotopes. Input from atomic theory is required to calculate the unknown electronic factor and the specific mass shift of the investigated transitions in order to obtain information on the mean-charge radii as well.

In the second run of 2014, and final run at the LISOL facility, the front-end was modified to fit a de Laval nozzle at the gas cell exit and to enable a suitable ionization volume for the gas jet formation and ionization of the actinium isotopes. The gas jet propagated through a free-space distance of 11 mm, interacting perpendicularly with the two laser beams prior to the injection of the radioactive ion beam into the sextupole ion guide. An all-solid state narrow-bandwidth, high-repetition-rate laser system based on the amplification of a CW diode laser in an injection-locked Ti:sa cavity was used to investigate the hyperfine structure of the 438 nm atomic transition in ^{214,215}Ac. A preliminary analysis of the data obtained reveals a reduction of the spectral linewidth down to ~300 MHz. Thus, the isotope shifts as well as the hyperfine A- and B- parameters are extracted with a 25-fold higher precision in these experiments than in the former run by in-gas-cell spectroscopy studies, and additionally a better spin assignment for the N = 126 ^{215}Ac ($T_{1/2}$ = 0.17 s) nuclide can be established. Furthermore, the results show that the total ionization efficiency in the gas jet is comparable to that in the gas cell (~0.4%) and can potentially be improved up to one order of magnitude by increasing the duty cycle.

With this last campaign the LISOL facility was brought to an end after 40 years of fruitful operation.

VIII. Collaboration meetings and international network

A common workshop with the DESIR collaboration was held on March 2014 [1], where the scientific programs were discussed. During the workshop, which gathered 115 physicists, synergies concerning the scientific projects (for example: ^{100}Sn region for laser spectroscopy and mass measurements) and technical developments (such as RFQ, four-way 90° deflector, MR-TOF, laser ionization schemes…) were identified. The conference highlighted once more the importance of the coupling to DESIR. The latter is essential for experimental projects which need further beam purification techniques, for higher-resolution experiments (collinear laser spectroscopy, Penning trap mass measurements) and for more elaborate experimental set-ups (LPC trap, TAS, neutron detection).

The status of the technical developments for each S^3-LEB working groups was presented during the S^3 workshop that took place in March 2014 [2].

An MoU between the S^3-LEB partners (GANIL, IPN Orsay, KU Leuven, LPC Caen, JGU and JYU) is in preparation.

[1] http://pro.ganil-spiral2.eu/events/workshops/desir-s3-nfs/circulars/detailed-programme-desir-preliminary

[2] http://pro.ganil-spiral2.eu/events/workshops/desir-s3-nfs/circulars/detailed-programme-s3-preliminary

Status Report (4)

Status of RIKEN SLOWRI project

(M. Wada*, T. Sonoda, P. Schury, Y. Ito, M. Reponen, S. Arai, I. Katayama, T. Kubo, K. Kusaka, T. Fujinawa, T. Maie, H. Yamasawa, D. Kaji, K. Morimoto, H. Haba (RIKEN), F. Arai, A.Ozawa (Tsukuba), H. Iimura, H. Koura (JAEA), H. Tomita, T. Takatsuka, Y. Adachi, T. Noto, V. Sonnenschein (Nagoya), H. Wollnik (NMSU), A. Takamine (Aoyama), K. Okada (Sophia), H. Miyatake, S.C. Jeong, H. Ishiyama, Y. Hirayama, Y.X. Watanabe (KEK))

I. Status of SLOWRI activities at RIKEN-RIBF

A universal stopped and low-energy RI beam facility, SLOWRI, is under commissioning at RIKEN-RIBF. It consists of two gas catcher cells (RF carpet gas cell and PALIS gas cell), two mass separators, and long beam transport lines. The majority of these setups have been installed in FY 2014 and some test experiments are taking place. Vacuum evacuation of the long beam transport line has been started and baking of the beam lines is in progress. Off-line tests of the PALIS gas cell showed good differential pumping performance. Resonance ionization in a reference cell with new laser setup has been tested. Novel ion transport method with RF carpet, ion surfing method, has been tested online at GARIS-II facility for the SHE-Mass project.

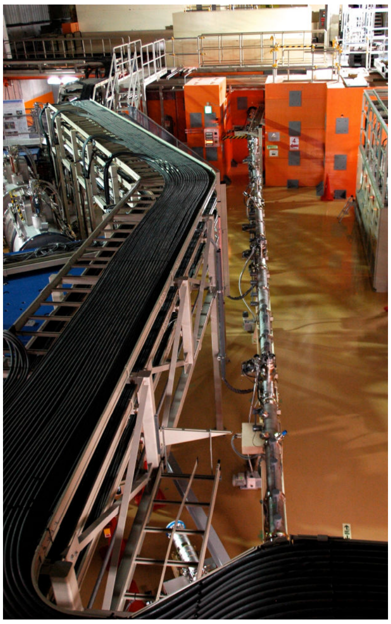

Figure 1. *SLOWRI beam transport line (left) and RFC gas cell (right).*

II. Off-line adjustment of PALIS setup for installing in BigRIPS F2 chamber

We tested installation of PALIS gas cell at the second focal plane (F2) chamber of BigRIPS. The baseplate of PALIS setup replaces the roof flange of the F2 chamber and the reproducibility of the position of the PALIS setup was confirmed to be better than 1 mm thanks to guide pins. We also confirmed that the BigRIPS detectors (two PPAC chambers and a plastic scintillator) in the F2 chamber could be replaced through two maintenance windows prepared on the PALIS baseplate --- without removing the PALIS setup. Vacuum level of the F2 chamber with PALIS setup has been tested and it showed that a pressure of 10^{-4} Pa can be achievable within a few hours of evacuation.

We still need to confirm that laser radiation does not interfere with the BigRIPS detectors, necessary amounts of radiation shields on top of the F2 chamber, and several other issues before final installation of PALIS setup.

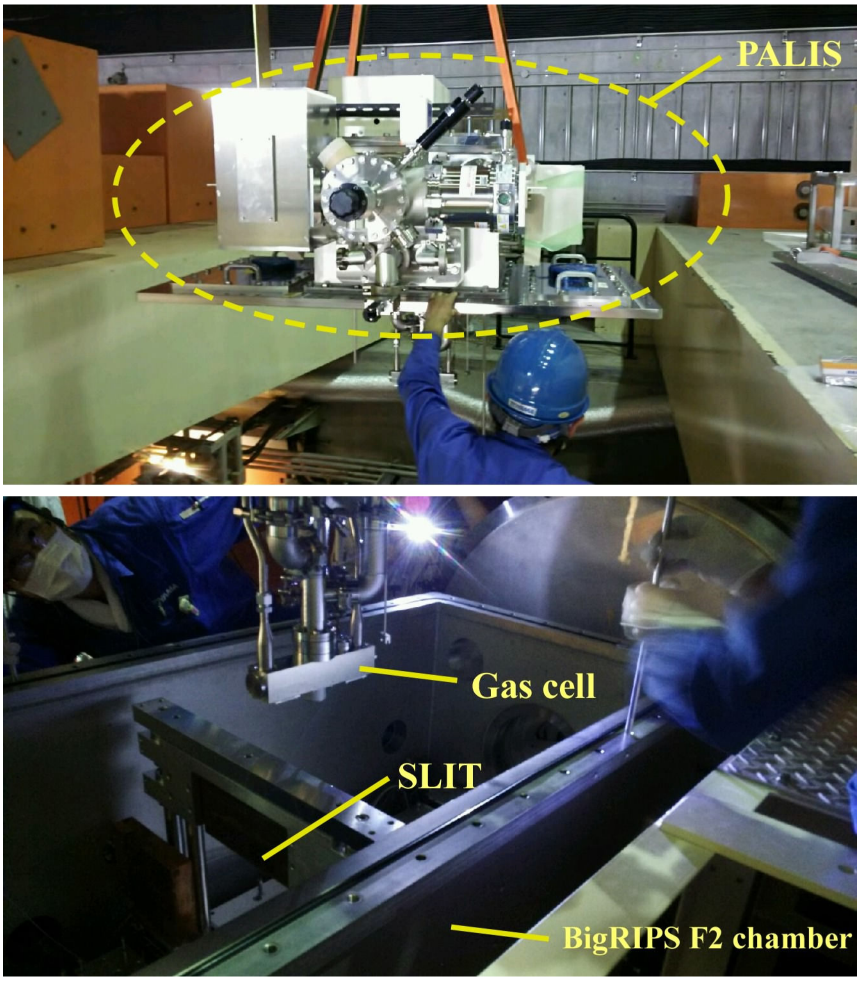

Figure 2. *Temporarily installing PALIS setup to the BigRIPS F2 chamber.*

III. First online tests of small ion-surfing RF carpet gas cell at GARIS-II

As part of SLOWRI project, we have begun development of a new low-energy experimental facility for use with heavy radioactive ion beams, such as super heavy elements, produced via fusion-evaporation reactions. This new experimental setup utilizes a small cryogenic gas cell placed after the GARIS-II separator to thermalize the heavy ions before they are transported to a multi-reflection time-of-flight mass spectrograph. A thin mylar film (2.4 μm thick) on a rotatable frame is placed before the gas cell to adjust the beam energy for the gas catcher together with the similarly thin window of the gas cell. The energy-degraded beam can be thermalized in the cell by successive ionization of He buffer gas. The thermal ions can be quickly extracted from the cell by a combination of DC electric field in the cylindrical part, and inhomogeneous RF fields and audio-frequency traveling wave fields of the ion-surfing RF carpet at the bottom of the cell. The extracted ions can be further transported by carbon-SPIG through differential pumping sections towards an ion trap.

In the first experiment, we tested total efficiency of the setup with ^{205}Fr, produced via a reaction ^{169}Tm (^{40}Ar, 4n) ^{205}Fr. Figure 3 shows the total efficiency, defined as the ratio of the number of alpha decay on a SSD placed behind the carbon-SPIG of the cell and those seen on a large SSD placed in front of the gas cell. The efficiency was nearly 30%. We have also tested with shorter-lived isotopes, ^{216}Th, ^{215}Ac, and ^{217}Pa. Although the degrader thicknesses were not optimized for these isotopes, the efficiencies were more than 10%. This performance already makes mass measurements feasible. In FY 2015, we are going to measure the masses of trans uranium elements.

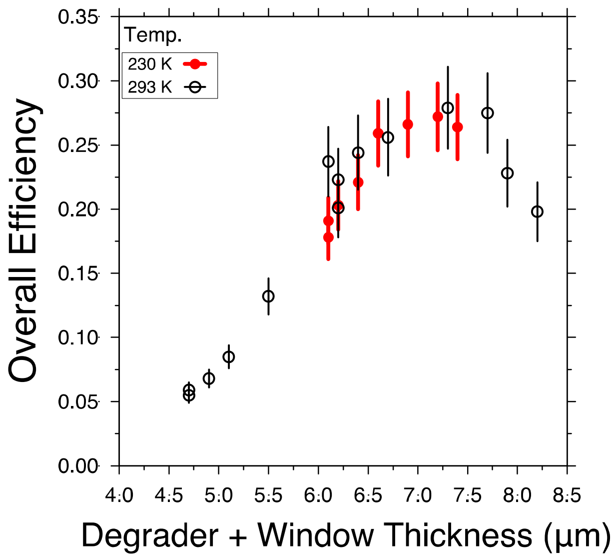

Figure 3. *Efficiency of gas cell stopping and extraction for ^{205}Fr as function of the degrader thickness.*

Status Report (5)

Status of KISS project

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I. Development of KISS

We have been developing the argon gas cell of the KEK Isotope Separation System (KISS) to study the β-decay properties of neutron-rich isotopes with neutron numbers around *N* = 126 for astrophysics research [1-3]. In the KISS, a gas cell filled with argon gas at a pressure of 50 kPa, in which nuclei produced by the multi-nucleon transfer reaction are to be stopped and collected, is essential equipment for selectively extracting the isotope of interest by using a resonant ionization technique. Using the elastic events of ^{198}Pt in the ^{136}Xe primary beam (10.75 MeV/nucleon, 20 pnA) and ^{198}Pt target (6 mg/cm^2) system, we evaluated the absolute extraction efficiency and beam purity of the KISS gas cell system. We successfully measured the lifetime of unstable nucleus ^{199}Pt extracted from the KISS as well. However the efficiency was more than one order of magnitude lower than the simulated value of 7%. We have been developing a new sextupole ion-guide (SPIG) with larger angular acceptance for increasing the extraction efficiency. For the coming β-decay lifetime measurements, we have been developing low-background of β-ray telescopes, which will be installed at this July, having background rate as low as 0.1 counts per second (cps). Further development is continued to achieve a very low background rate below 1 count per hour (cph) at the end of 2015.

[1] S.C. Jeong *et al*., KEK Report 2010-2.
[2] Y. Hirayama *et al*., RIKEN Accel. Prog. Rep. 44 (2011) 25; 45 (2012) 152; 46 (2013) 176; 47 (2015).
[3] H. Ishiyama et al., RIKEN Accel. Prog. Rep. 45 (2012) 151.

II. Extraction efficiency and selectivity of $^{198}PtAr_2^+$

^{198}Pt atoms were produced in the gas cell by elastic scattering of ^{136}Xe beam and ^{198}Pt target placed in the gas cell. Transported ^{198}Pt atoms by argon gas flow were ionized by laser resonance ionization technique and extracted as a secondary beam. The ^{198}Pt atoms were found to form the impurity molecular ions of $^{198}PtH_2^+$, $^{198}Pt(H_2O)^+$ and $^{198}PtAr_2^+$ with the relative intensities of 1, 1, and 6 to the $^{198}Pt^+$ ions, respectively. The extraction efficiency of $^{198}PtAr_2^+$ was measured to be about 0.2% which was independent of the primary beam intensity as shown in Fig. 1, owing to the bend structure of the gas cell. The extraction efficiency was defined as a ratio of detected number of $^{198}PtAr_2^+$ ions and estimated number of ^{198}Pt atoms emitted from the target by elastic scattering (17 barn). The obtained selectivity and beam purity were higher than 300 and 99.7%, respectively, at the maximum primary beam intensity of 20 pnA.

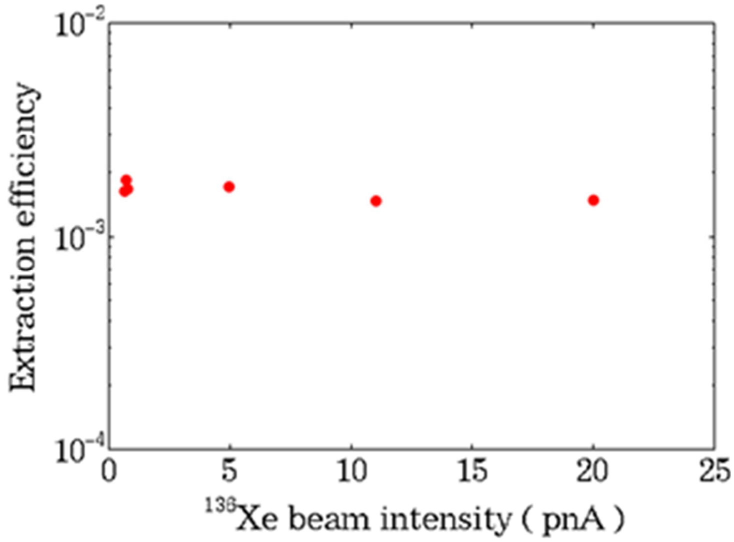

Figure 1. *Extraction efficiency of $^{198}PtAr_2^+$ molecular ions measured as a function of ^{136}Xe beam intensity.*

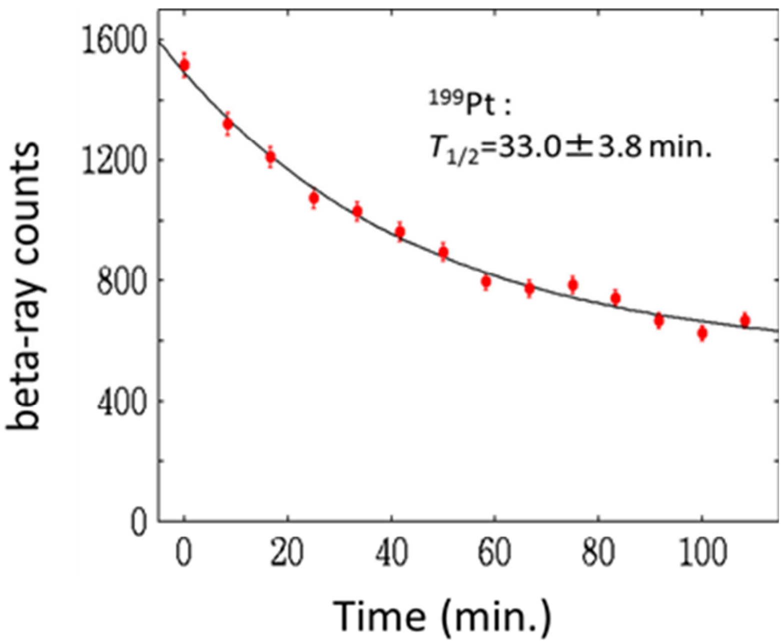

Figure 2. *Decay time spectrum of ^{199}Pt. It was measured in the time sequence of 45 min. beam-on and 120 min. beam-off.*

III. Lifetime measurement of ^{199}Pt

After the extraction of ^{198}Pt, we extracted laser-ionized ^{199}Pt ($t_{1/2}$ = 30.8(2) min.) atoms which mainly formed $^{199}PtAr_2^+$ molecular ions like ^{198}Pt. Figure 2 shows the measured decay time spectrum by using $^{199}PtAr_2^+$ molecular ions. The measured half-life of $t_{1/2}$ = 33(4) min. was in good agreement with the reported value. Thus, the molecular formation does not affect the lifetime measurement of unstable nuclei.

IV. Development of SPIG for higher efficiency

To increase the extraction efficiency, we have developed a new extraction system, which consists of two SPIGs having different geometries. The geometry of the first SPIG placed at the gas cell exit is 8 mm in diameter and 83 mm in length, and that of the second SPIG after the first SPIG is 3 mm in diameter and 118 mm in length. Two SPIGs are overlapped with the length of 1 mm at the both ends. The geometry of the second SPIG is similar to the former SPIG (3 mm in diameter and 200 mm in length) used above measurements. By increasing the inner diameter of the first SPIG, we intended to capture the laser ionized atoms emitted with a large angle from the gas-cell exit-orifice of 1 mm in diameter. We also intended to dissociate the molecular ions by applying the DC voltage between the first and the second SPIG. A relatively low DC voltage compared to the ref. [1] enables to dissociate

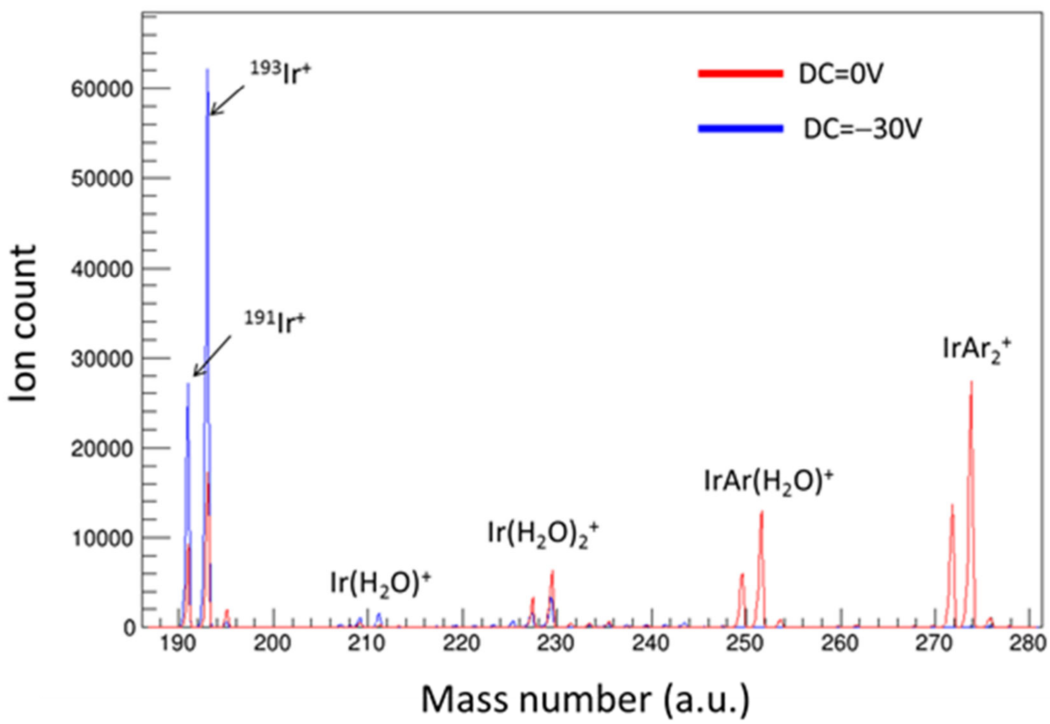

Figure 3. *Mass distributions of laser-produced iridium isotopes of $^{191,193}Ir$ and their molecular ions.*

the molecular ions at the connection point of two SPIGs, where the gas pressure is much lower than that at the gas cell exit and high mobility of ions are expected compared to the region just after the gas cell exit. Figure 3 shows the measured mass distributions using iridium filament placed in the gas cell with the pressure of 45 kPa. Here, we applied the RF fields of 150 V peak-to-peak to the two SPIGs and the V_{DC} = 0 V for the first SPIG. The red and blue lines indicate the measured mass distributions with V_{DC} = 0 V and −30 V for the second SPIG, respectively. We can clearly observe the dissociation of the molecular ions of laser-produced iridium. More than 90% of extracted laser-produced iridium was recovered as singly charged iridium ions. Considering the molecular ion formation probability in the case of platinum, the extraction efficiency would be recovered with a factor of about 1.5. The effect of the large acceptance of the first SPIG will be studied at the next on-line experiment scheduled at July 2015.

[1] Yu. Kudryavtsev et al., Nucl. Instr. and Meth. B 179 (2001) 412.

V. Development of low-background β-ray telescopes

The background rate of the β-ray telescopes used at the ^{199}Pt lifetime measurement was 5 cps without the lead shield for room background β-rays and the active shield for the cosmic rays, and 0.7 cps with the shields. Considering the extraction yields of nuclei around N = 126, we need to reduce the rate down to 0.1 cps for the lifetime measurements of

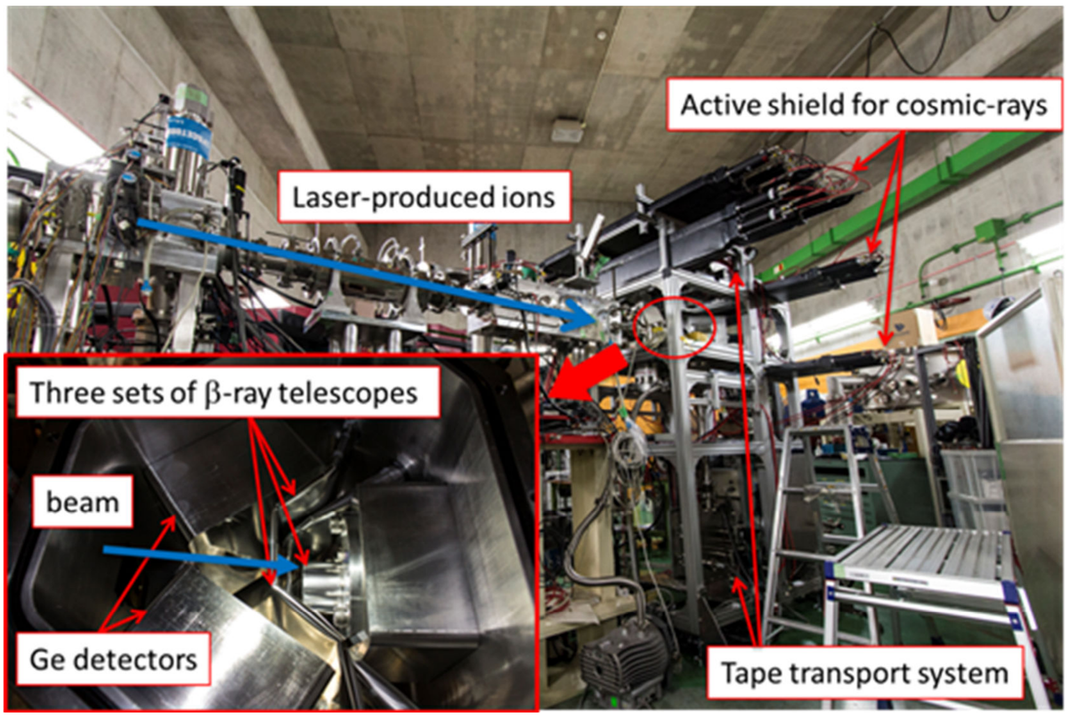

Figure 4. *Photo of the detection system of KISS.*

platinum and iridium isotopes. Our challenging goal in suppressing the rate is 1 cph for the lifetime measurement of ^{200}W. Figure 4 shows the photo of KISS detection system. Tape transport system was employed to avoid the radioactivities in the decay chain of separated nuclides under pulsed beam operation of the KISS. Inserted figure shows a detector chamber which has the three sets of two layered plastic scintillator telescopes for β-ray detections and the silk-hat flanges with thin aluminum window for Ge detectors. The newly installed telescopes with about 65% detection efficiency of 4π in the photo would achieve a low background level as 0.1 cps. The performance of new telescopes of the plastic scintillator will be studied and used for the next lifetime measurements at July 2015. In addition, we have already started to develop a gas counter system for further reduction of the background rate as low as 1 cph.