

### Introduction:

This is the second 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. Unfortunately, owing to the tight agenda of last year a workshop on topical issues could not be organized in Japan but this year we are working to provide such an opportunity. The present issue includes six status reports from the IGISOL facility of Jyväskylä, LISOL and the IGLIS laboratory at KU Leuven (including the collaborative works with  $S^3$  at GANIL), SHIPTRAP at GSI, GALS at JINR, SLOWRI at RIKEN, and KISS at KEK.

### IGLIS-NET News:

◆The construction of the SLOWRI facility at RIKEN is carried out on schedule. It consists of two gas catcher cells (RF-carpet gas cell and PALIS gas cell), two isotope separators, and some miscellaneous devices such as lasers. The majority of these devices will be installed by the end of March 2014 while offline tests will be carried out for at least half a year of 2014. Several online experiments are scheduled during the online commissioning. For the RF-carpet gas cell, a multi-reflection time-of-flight mass spectrograph will be directly connected to the cell in order to investigate impurities of the extracted beams and for direct mass measurement of short-lived RI with the “wide-band mass spectrograph mode”. The PALIS gas cell will be placed behind the F3 focal plane chamber of BigRIPS before being finally installed in the F2 chamber. During the commissioning to be performed at this location, some online resonant ionization spectroscopy experiments will be also carried out. A beam cooler-buncher setup will be installed at the SLOWRI experimental room and its commissioning will be carried out in full FY2014. Users experiments at the experimental room could be started sometime in FY2015. Some details of these components can be found in the present issue.

◆The on-line tests of the KISS/KEK were performed by using  $^{56}\text{Fe}$  and  $^{124}\text{Xe}$  beam from RIKEN Ring Cyclotron. The performance (overall extraction efficiency and selectivity) with increasing those beam intensities was investigated. Especially in the test using  $^{124}\text{Xe}$ , the target ( $^{198}\text{Pt}$ )-recoils were extracted. Although the overall efficiency achieved so far was

smaller by about one order of magnitude than expected, possible measurements of lifetime of beta-decaying Pt-like recoils are to be performed, while further developing the performance by using  $^{136}\text{Xe}$  beam.

◆The IGISOL facility at Jyväskylä succeeded in the first on-line demonstration of in-gas-cell laser ionization of radioactive  $^{58}\text{Cu}$  thermalized in a dual-chamber gas cell after being produced by a  $^{58}\text{Ni}(p,n)$  reaction. Interestingly, the selectivity increases (almost linearly) with increasing primary beam intensities (in the present case, of 18-MeV proton beam), which was investigated up to  $5\mu\text{A}$ . For better performance, a new dual-chamber with smoother inner surfaces has been constructed and is to be tested shortly. An inductively-heated hot cavity catcher for producing neutron deficient Ag isotopes, with the final goal of reaching  $^{94}\text{Ag}$  and its ( $21^+$ ) isomer, was tested; the inductive heating potential turned out to degrade considerably the mass resolving power of the mass separator. A new hot cavity cell with a modified geometry was designed and tested recently off-line, successfully addressing the beam quality issue. A new injection-locked Ti:sapphire laser setup has been applied at the University of Mainz for crossed-beam resonance ionization spectroscopy of  $^{227}\text{Ac}$  and Pu isotopes, where, especially for Ac, several ionization schemes were compared and hyperfine parameters were extracted with a precision of a few MHz. The narrow-band laser system, now injection-locked by a CW Ti:sapphire master laser (Sirah Matisse TS) at Jyväskylä, allows a broad-range wavelength tuning with an average laser output power of 4-5 W at a repetition rate of 10kHz (by a pump power up to 17W) and a line-width of about 20MHz.

◆For the GALS (GAs-cell based Laser-ionization Setup) at Dubna, the laser laboratory and control room were reconstructed and ready for installing lasers (two Dye lasers and a Nd:YAG pump laser). The GALS group devoted to the project was formed.

◆An experiment for in-gas-cell broad-band laser spectroscopy on the neutron deficient actinium isotopes,  $^{212,213}\text{Ac}$  was performed at LISOL with a final resolution of about 2.5 GHz. By using a new ionization scheme (two-step; 438nm for excitation, 435nm for ionization) and reducing the laser power of the first step down to  $3.5\mu\text{J}$ , the hyperfine structure in the transition  $^2\text{D}_{3/2} \rightarrow ^4\text{P}_{5/2}$  of  $^{212}\text{Ac}$  was successfully resolved. The full commissioning of the laser room for HELIOS at KU Leuven was completed by the end of 2013. A horn-shaped gas cell for IGLIS experiments has been designed, consisting of inlet, stopping, and ionization chambers. The new gas inlet section, in addition to a smoother surface (horn-type) of the cell, has been designed to generate a homogenous gas flow, which, according to gas flow

simulations, results in a better extraction efficiency than that observed in former gas cell designs

◆ For on-line laser spectroscopy of the nobelium isotopes (e.g.  $^{254}\text{No}$  produced and separated by SHIP/GSI) by Radiation Detected Resonance Ionization Spectroscopy (RADIS), a buffer-gas cell was developed and off-line tested with  $^{\text{nat}}\text{Yb}$  at SHIPTRAP/GSI at different argon gas pressures for optimization. In the method, for example, the ions of interest from SHIP are collected on a catcher filament, re-evaporated on-line, and then guided to radiation detectors after being resonantly ionized by laser irradiation.

#### [Workshop and Conference:](#)

◆ Three SPIRAL2 Phase1+ workshops (DESIR+S3+NFS), Mar. 25 - Apr. 1, 2014, GANIL (<http://pro.ganil-spiral2.eu/events/workshops/desir-s3-nfs>).

◆ The 7th Workshop on nuclear spectroscopy using Stopped and Slow Radioactive Isotopes (SSRI), Mar. 3-4, 2014, NRC/RIKEN, RIKEN-Wako (in Japanese) (<https://indico2.riken.jp/indico/conferenceProgram.py?confId=1411>)

#### [Recent Publications:](#)

Please look at IGLIS-NET website (<http://kekrgb.kek.jp/iglis-net/reports.html>). Some publications are grouped according to the topics defined in the IGLIS-NET framework.

#### [Prizes:](#)

◆ Volker Sonnenschein has won the 2013 LA<sup>3</sup>NET prize. Volker has made a number of important developments related to solid state laser technology applicable to RIB production and spectroscopy, supporting technology transfer via collaborative work with other leading groups, including ISOLDE, GANIL, Mainz, Leuven and RIKEN-Nagoya.

◆ Yuri Kudryavtsev (KUL) has won The Ion Source Prize "Brightness Award" in the 15th International Conference on Ion sources (ICIS'13, Sept. 9-13, 2013, Chiba, Japan) for the development of the In-Gas Laser Ionization and Spectroscopy (IGLIS) method. ([http://www.nirs.go.jp/conf/icis13/brightness\\_award.shtml](http://www.nirs.go.jp/conf/icis13/brightness_award.shtml))

*Any requests or comments about the IGLIS-NET newsletter are welcome. Please send them via [iglis-net@kek.jp](mailto:iglis-net@kek.jp).*

## Status Report (1)

### Resonance ionization spectroscopy and laser development at the IGISOL facility, Jyväskylä

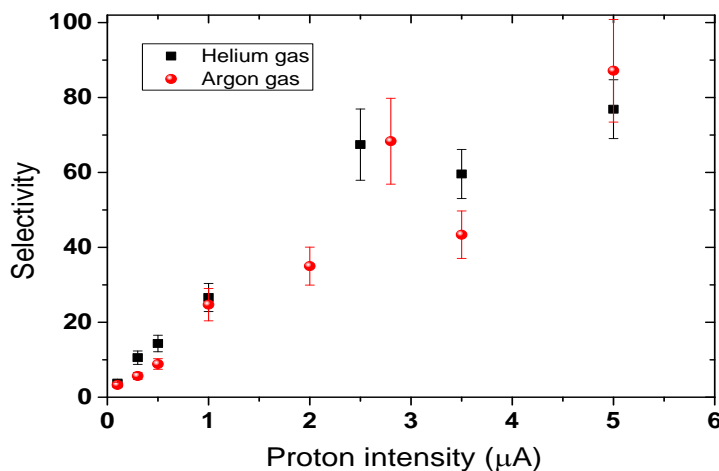
(Iain D. Moore\*, Mikael Reponen, Annika Voss, Volker Sonnenschein, Ilkka Pohjalainen, Enaam Hasan)

#### I. In-gas-cell laser ionization of $^{58}\text{Cu}$

In an important milestone, the first on-line demonstration of radioactive ion production using laser ionization was achieved in 2013. Using the dual-chamber gas cell, originally pioneered by the LISOL team at Leuven,  $^{58}\text{Cu}$  ( $T_{1/2}=3.2\text{s}$ ) was produced using a  $^{58}\text{Ni}(p,n)$  reaction with a primary beam energy of 18 MeV. A two-step ionization scheme was used – a 244.237 nm transition from the atomic ground state generated by a Ti:sapphire laser operating at 976.94nm with intracavity doubling and a final external frequency quadrupling stage, followed by an intracavity doubled Ti:sapphire operating at 441.679 nm to an AI state. In order to tune the separator to a simple spectroscopic setup (silicon and germanium detectors) the light-ion fusion-evaporation ion guide was initially used. The Si detector was used to verify the half-life of the  $^{58}\text{Cu}$  activity, the Ge detector to identify the characteristic gamma lines following the beta decay. As expected, the lasers had no influence on the activity either when He or Ar buffer gas was used. The extraction from the ion guide is simply too fast to ensure recombination of the recoil products.

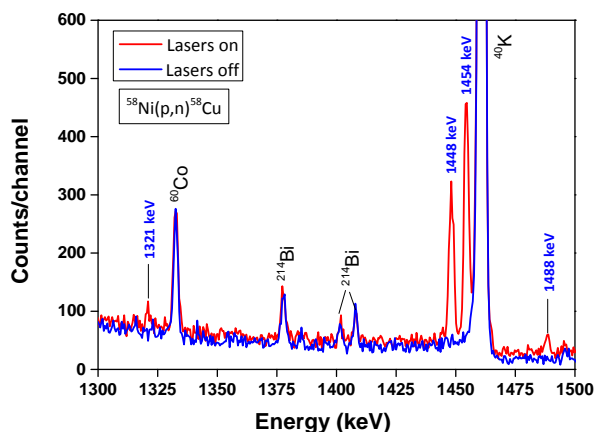
The dual-chamber gas cell was installed along with a copper filament for production of stable atoms. Both resonant steps were confirmed to be saturated, which allowed investigation into the use of different final focal length lenses. In the future each laser beam (both into the gas cell and gas jet) will have an independent telescope to optimize the RIB production for each element. The selectivity (defined as the ratio of beta activity with lasers on compared with lasers off) was studied using both helium and argon as a function of primary beam intensity, the results of which are presented in Fig. 1. At a proton beam current of 5  $\mu\text{A}$ , the absolute count rate in helium was  $\sim 7500\beta/100\text{s}$ , whereas in argon the rate was  $\sim 3500\beta/100\text{s}$ . The selectivity can be seen to be rather comparable and the general increase as a function of primary beam intensity may well reflect an increasing volume of charge density within which  $^{58}\text{Cu}$  recoil ions are neutralized and subsequently transferred to the ionization chamber for laser ionization. This differs from our earlier work on stable silver (coated on the back of a Zn target) in which the selectivity was seen to be higher in argon for all primary beam intensities. The latter work was highlighted in the 2013 IGLIS-NET newsletter. We note that during the course of these tests, problems with the cyclotron beam resulted in the primary beam being steered – this proved to be critical to the selectivity which

varied considerably.



**Figure 1.** Laser ionization selectivity for  $^{58}\text{Cu}$  in helium and argon buffer gases. The primary beam was retuned above  $3\mu\text{A}$  due to cyclotron problems. This might explain the sudden change in trend.

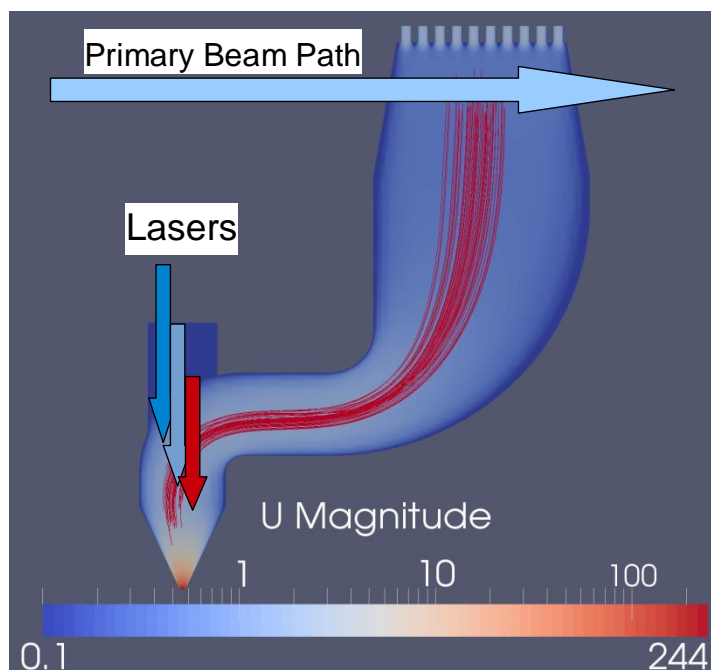
Figure 2 illustrates the gamma-ray spectrum measured just downstream from the focal plane of the mass separator, comparing the effect with lasers “on” to lasers “off”. The ion guide was operated with argon to encourage neutralization of the reaction products. An efficiency calibration of the Ge detector along with production cross section estimates (interestingly, no experimental data exist for this reaction) led to a total efficiency estimate of ~1%, comparable to the standard light ion fusion-evaporation ion guide.



**Figure 2.** Gamma-ray spectra obtained when the mass separator was tuned to  $A/Q=58$ . Lasers are tuned for resonance ionization of copper (red) and with lasers off (blue). The characteristic  $\gamma$  peaks from the  $\beta$  decay of  $^{58}\text{Cu}$  are indicated. Data was accumulated for one hour for both spectra.

## II. A new dual-chamber gas cell

While the dual-chamber gas cell was utilized successfully in the first on-line test to produce  $^{58}\text{Cu}$  (see above), alpha-recoil source efficiency measurements have indicated a rather low, ~2%, transport efficiency from the stopping region [1]. Rather similar values were also extracted from the on-line measurement. In order to investigate methods to improve the efficiency, a prototype gas cell has been constructed to investigate smoother inner surfaces and to compare computational fluid dynamic (CFD) calculations with on-line measurements. Figure 3 illustrates an example of a CFD simulation for the new gas cell which will be used in February 2014 in an on-line efficiency measurement of radioactive silver. During the same beam time, the new design will be compared with the original gas cell used in the measurement of  $^{58}\text{Cu}$  in 2013.



**Figure 3.** Computational fluid dynamics simulation for the smoother dual-chamber gas cell geometry. The simulation was performed for argon at 30 mbar, using the IT Centre for Science Ltd (CSC) cluster with the OpenFoam CFD toolbox.

[1] M. Reponen *et al.*, Nucl. Instrum. and Meth. B 317 (2013) 422.

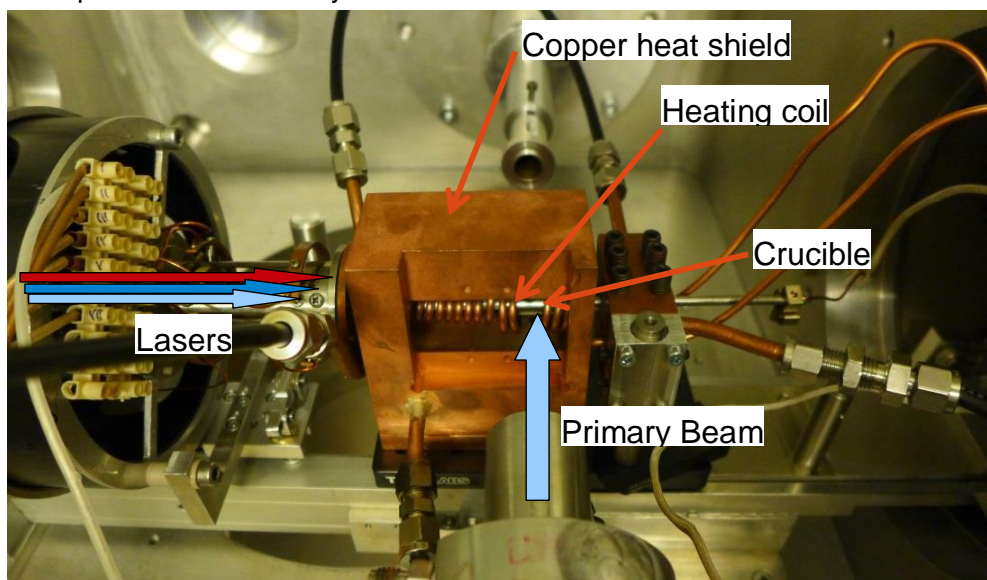
## III. Status of the inductively-heated hot cavity catcher

In the first IGLIS-NET newsletter we introduced the activities associated with a development programme whose ultimate goal is the study of the  $(21^+)$  isomer in  $N=Z^{94}\text{Ag}$ .

Extensive work by Kirchner at GSI using FEBIAD ion sources identified silver as an element exhibiting a fast release time from a graphite catcher (order of ms) and extraction efficiencies close to 50% [1]. At Jyväskylä, the concept was adopted and modified in 2010 in

collaboration with the local ECR group. An inductively-heated hot cavity catcher was constructed to overcome problems associated with the previously utilized electron bombardment heating mechanism of a FEBIAD-E source on loan from GSI, proving to be superior to the previous system. The new oven was tested at IGISOL-3 by implanting a 487 MeV beam of  $^{107}\text{Ag}^{21+}$  into the catcher. Depending on the catcher temperature and implantation depth, extraction times of between 2 and 7 ms could be measured. However, while the fast extraction of silver was confirmed, the inductive heating potential considerably degraded the beam quality resulting in a mass resolving of the separator of  $\sim 30$ .

In 2013 a new catcher was designed to address the beam quality issues. In the new geometry, shown in Fig. 4, laser ionization takes place in a 60-mm long tantalum ionization tube with a diameter of 4 mm. The tube not only increases the laser-atom interaction time but screens the photo-ions from the oscillating RF potential. Most recently, off-line tests using a sample of metallic silver have shown a considerable improvement in the mass resolving power to well beyond 200 at  $A/q=107$ . The first on-line test to probe the extraction time of the new geometry will take place in the coming months. Additionally, a new two-step ionization scheme for silver is to be investigated. The current 3-step scheme is hampered by the presence of Rydberg states around  $60945.43\text{ cm}^{-1}$  which are directly populated using the 328-nm photons used in the first resonant excitation step. This unforeseen process causes complications in the analysis of RIS measurements.

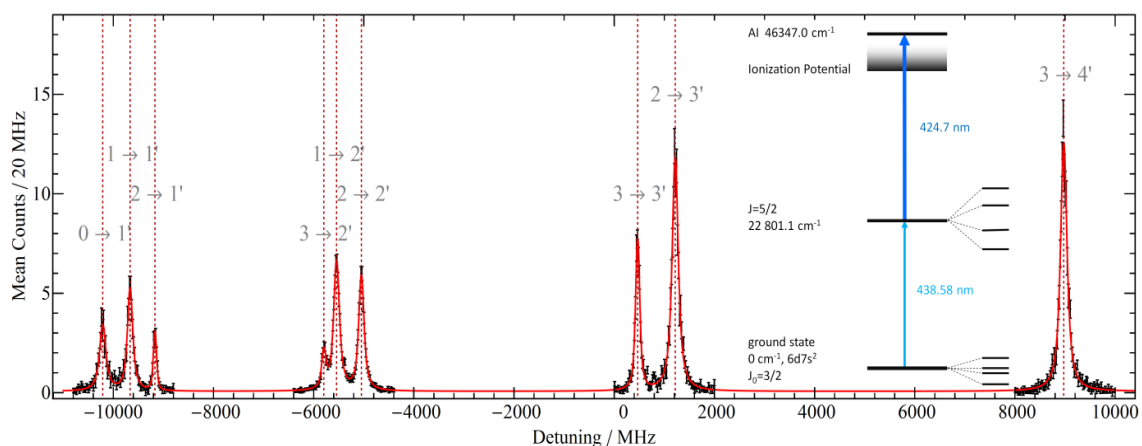


**Figure 4.** Experimental setup for the new hot cavity catcher geometry, tested off-line in December 2013.

[1] R. Kirchner *et al.*, Nucl. Instrum. and Meth. B 70 (1992) 186.

#### IV. First applications of a new injection-locked Ti:sapphire laser and improved frequency control

The injection-locked Ti:sapphire laser setup introduced in the first IGLIS-NET newsletter has been completed and characterized. In a first experiment, this laser cavity was shipped to the University of Mainz in the summer of 2013 where it was used for crossed-beam resonance ionization spectroscopy of  $^{227}\text{Ac}$  and the plutonium isotopes  $^{238,239,241,242,244}\text{Pu}$ . For actinium, several ionization schemes were compared and hyperfine parameters were extracted with a precision of only a few MHz, providing reference parameters as well as an optimal ionization scheme for a following online spectroscopy experiment at KU Leuven (LISOL). Figure 5 illustrates an example of the quality of the spectra obtained for actinium using the two-step ionization scheme highlighted. In this experiment the seed for the injection locking was provided by several external cavity diode lasers (ECDL), unlike the cw Matisse laser used in JYFL. Thus, only a limited tuning range could be provided. Nevertheless, in a first measurement of the laser linewidth using a 300 MHz confocal Fabry-Pérot Interferometer (FPI) a value of about 12 MHz was demonstrated, though at a relatively low output power of 1W, as only a 5W pump laser was available.



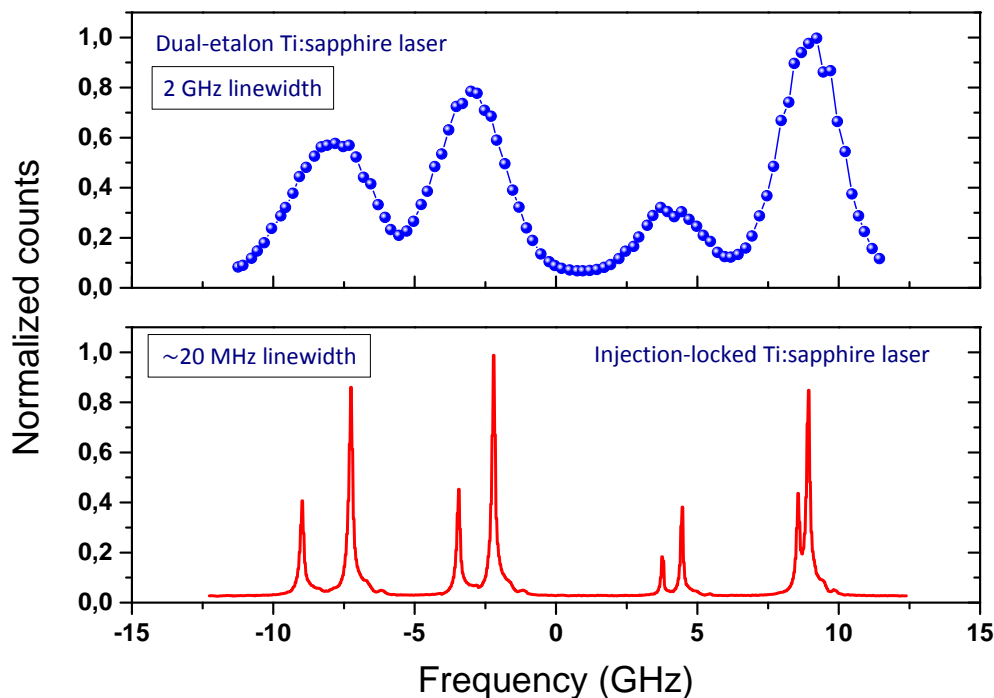
**Figure 5.** A measurement of the hyperfine structure of  $^{227}\text{Ac}$ . The transitions between the different  $F$  states are highlighted and the ionization scheme is given.

In Jyväskylä the setup has now been taken into operation using a continuous-wave (cw) Ti:sapphire master laser (Sirah Matisse TS). The cw Ti:sapphire is fiber coupled and injected into the bow-tie slave cavity. After fiber coupling up to 200 mW of cw light is available. This fairly high power as compared to the ECDL allows for a wide wavelength tuning range with high seed efficiency even when using a single broad-band mirror set. A first proof of principle measurement has been performed in an atomic beam reference cell using natural copper. The benefit of the high-resolution injection-locked system is



immediately obvious when compared to the standard pulsed laser systems, with Fig. 6 showing the clear separation of the two isotopes  $^{63,65}\text{Cu}$ .

The bow-tie resonator described in the first newsletter included planning for the addition of a pair of Brewster plates for an extended mode-hop free tuning range. These were found to be unnecessary as automatic re-locking of the cavity is reliable and fast (<50 ms) and therefore does not disturb measurements. The laser performance was characterized at a range of pump powers up to 17W, yielding an average output power of 4-5W at a repetition rate of 10 kHz, limited by the damage threshold of the mirror coatings. The linewidth was measured to be in the range of 20 MHz using a commercial FPI with a free spectral range (FSR) of 1 GHz, indicating a slight increase with pump power compared to the measurement in Mainz. Far from the gain peak of the Ti:sapphire crystal, e.g. for  $\lambda > 900\text{nm}$  or  $\lambda < 730\text{nm}$ , the seed efficiency decreases even with the high seed input powers. To address this issue a newly designed birefringent filter plate will provide additional wavelength selection, which should widen the possible wavelength range and minimize the needed input power.

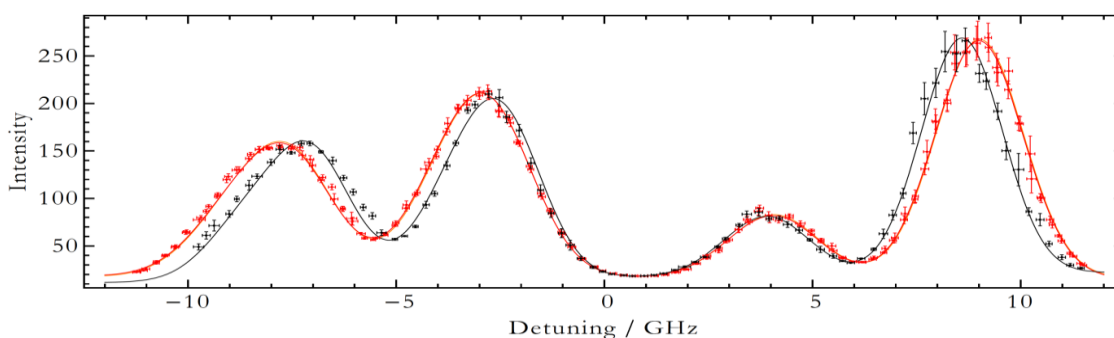


**Figure 6.** Ti:sapphire frequency scans of the hyperfine structure associated with the 244-nm transition in stable copper. With a laser linewidth of ~20 MHz, an impressive improvement in resolution is obtained and the peaks associated with  $^{63,65}\text{Cu}$  are visible.

## V. Characterization of the dual-etalon Ti:sapphire laser via Resonance Ionization Spectroscopy of copper

With the additions of the dual-etalon Ti:sapphire laser (presented in the first newsletter) and the injection-locked laser to the standard solid state laser system used for the FURIOS laser ion source, the application of higher resolution Resonance Ionization Spectroscopy (RIS) of exotic nuclei at IGISOL has become significantly enhanced. For accurate measurements of hyperfine parameters and isotope shifts it is imperative to understand and minimize any systematic errors associated with the RIS technique.

In a first test of the dual-etalon Ti:sapphire laser system for the spectroscopy of copper performed early in 2013, it was noticed that the measured hyperfine parameter values did not agree with that from published literature and deviations of up to  $7\sigma$  were seen. The primary source of the error was traced to the commercial wavemeter (High-Finesse WS6-UV) in a comparison with a Fabry-Pérot Interferometer (FPI) measurement [1]. For this purpose a simple scanning FPI was built to accurately measure the mode structure of the dual-etalon Ti:sapphire with respect to a stabilized He-Ne laser. Figure 7 shows the measured hyperfine structure of natural copper, firstly using the wavemeter (black solid line) and secondly with the calibrated FPI (red solid line). The experimental hyperfine parameter values extracted using the FPI show a significantly improved agreement with literature and error margins have been decreased to less than 1%. Further improvements to the FPI such as improved linearity and temperature stability are underway. In the future, the FPI will be used both for the injection-locked and dual-etalon laser systems for all RIS experiments. Additional comparisons against literature data, especially when using the high-resolution injection-locked laser, will be needed to ensure reliable and accurate data when finally performing on-line experiments on previously unmeasured radioactive nuclei.



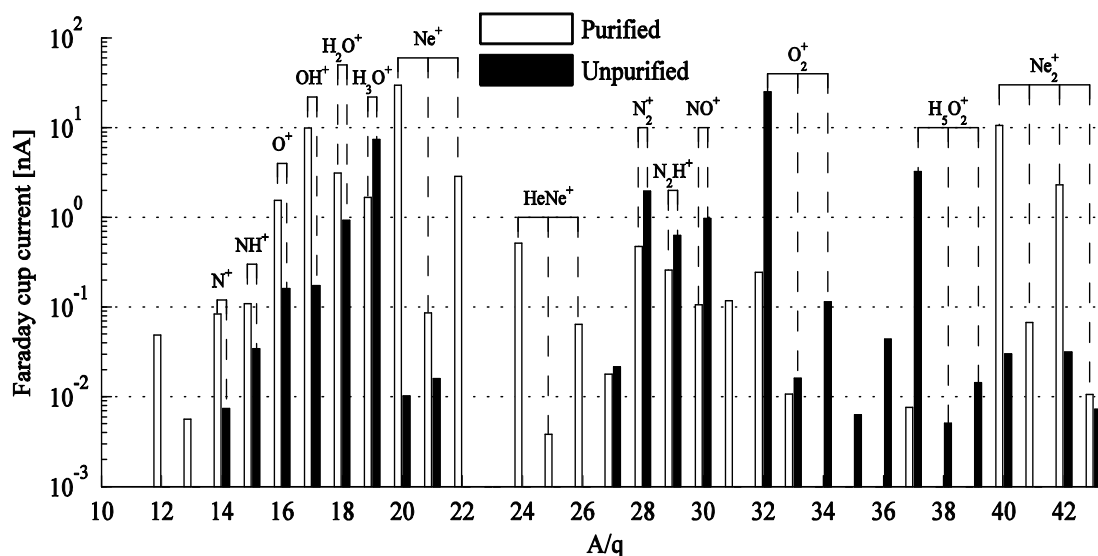
**Figure 7.** A frequency scan over the hyperfine transition of stable copper using the 244-nm atomic transition. A significant deviation is seen between the direct wavemeter measurement (black line) and the wavelength calculated from the calibrated FPI data (red line).

[1] V. Sonnenschein *et al.*, Hyp. Int. (2014), DOI 10.1007/s10751-013-1000-9.

## VI. Buffer gas purification studies at the new IGISOL-4 facility

Perhaps the most critical factor affecting the efficient use of noble gas-filled ion guides and gas catchers is the purity of the gas. Trace impurities play a crucial role in the ion survival during evacuation from the gas cell and understanding the impurity-related processes is necessary for ion guide development. The laser ion source at IGISOL-3 has been used to demonstrate the importance of the gas purity, in particular for chemically active elements [1, 2]. Impurities at the level of parts-per-million (ppm) have a significant effect on the ion guide operation by reducing the efficiency of extracting atomic ions of interest due to molecular formation. In order to prevent such losses, gas impurity levels of sub-parts-per-billion (ppb) are required.

During the upgrade to IGISOL-4 the gas purification and transport system was fully reconstructed with consideration towards a more rigorous requirement of buffer gas purity [3]. The purification of helium using liquid nitrogen-cooled cold traps was investigated and compared with unpurified gas using mass spectra obtained at the focal plane of the separator during on-line operation with the fission ion guide. Figure 8 illustrates an example of the mass spectra with and without purification.



**Figure 8.** Mass peak currents obtained on-line for purified and unpurified helium. Suggested molecular assignments are indicated.

Neon, an impurity intrinsic to the in-house recycled helium used at IGISOL, was seen to have high sensitivity to the impurity level of the gas. The mass peaks of neon and related compounds can be seen in the mass spectra only if the gas is purified, and they showed a very strong sensitivity to small changes in the operating conditions which affect the gas purity. This can be understood as the ionized neon and its compounds charge exchange irreversibly with the known helium gas impurities of  $\text{H}_2\text{O}$ ,  $\text{O}_2$  and  $\text{N}_2$ . The reaction rates are

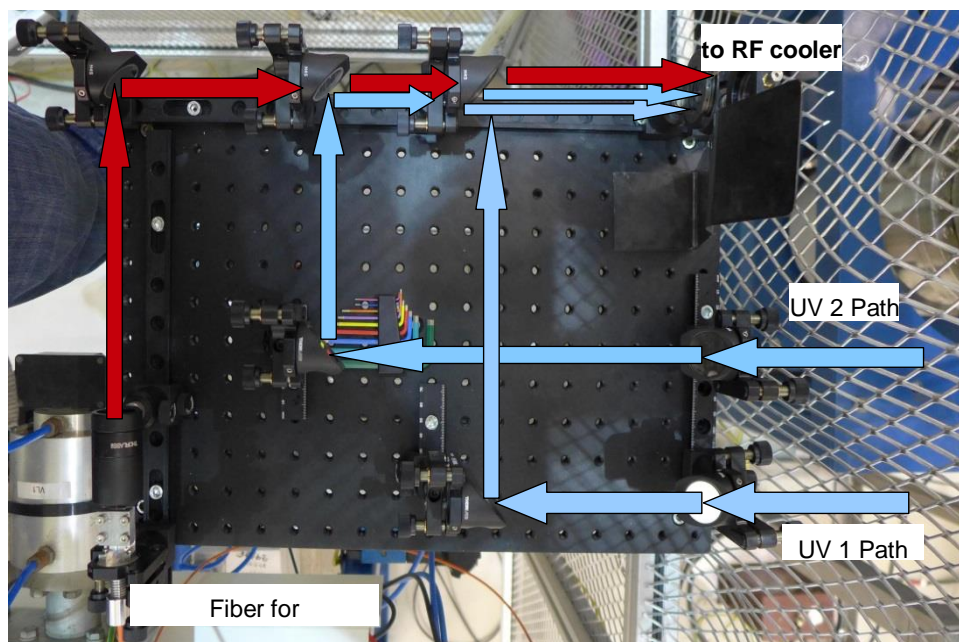
sufficiently fast such that only with impurity levels of approximately a ppb and below can the neon and related compound ions survive during evacuation from the ion guide. Due to this sensitivity, neon has become a useful indicator of gas purity conditions for all experiments at IGLISOL-4.

In addition to the neon, rich chemistry was seen between the other impurities, for example association reactions between hydronium ions and water molecules. Although a direct measurement of the absolute concentration of different impurities was not possible, the general behaviour of the mass spectra suggests that the buffer gas purity is reaching the sub-parts-per-billion level.

[1] T. Kessler, I.D. Moore *et al.*, Nucl. Instrum. and Meth. B 266 (2008) 681.

[2] I.D. Moore, Nucl. Instrum. and Meth. B 266 (2008) 4434.

[3] I. Pohjalainen, I.D. Moore *et al.*, Hyp. Int. (2014), DOI 10.1007/s10751-013-1006-3.



**Figure 9.** An optical table for coupling three laser beams into the RF cooler-buncher at IGLISOL-4.

### VII. Status of Ion Resonance Ionization Spectroscopy (IRIS)

We introduced the concept of Ion Resonance Ionization Spectroscopy (IRIS) in a RF cooler-buncher in the first IGLIS-NET newsletter. The selective ionization from the singly- to the doubly-charged state with multiple laser beams could be utilized either for access to ultra-pure ion bunches via subsequent time-of-flight gating, or to enable collinear laser spectroscopy of more favourable electronic configurations, for example in the case of yttrium. At IGLISOL-4, up to three laser beams from the pulsed laser cabin can now be

transported to the cooler-buncher using a combination of UV enhanced mirrors and optical fibers. Figure 9 shows a vertical view of the optical table set up in front of the cooler cage used to combine the three laser beams before on-axis injection into the cooler. First tests are underway in combination with the collinear laser spectroscopy programme and results will be reported in a future IGLIS-NET newsletter.

### VIII. Future projects

In addition to the aforementioned status reports from our various activities we have a number of new concepts and on-going projects which will be presented at a later stage. Two projects will briefly be highlighted in the following:

#### -Towards spectroscopy of heavy elements

In September 2013 a proposal was submitted to the JYFL Programme Advisory Committee led by members from the IGISOL-laser team and including participants from Mainz, Leuven, Manchester and Liverpool. The proposal is to initiate an exploratory laser spectroscopy study on heavy elements (in addition to our on-going interest in the study of  $^{229\text{m}}\text{Th}$ ) starting with long-lived isotopes of plutonium prepared and delivered from the Mainz research reactor. The goal is to study isotopes of  $^{236-244}\text{Pu}$  using collinear laser spectroscopy which will result in the heaviest element studied using this technique thus far. Laser resonance ionization of evaporated filament atoms in the IGISOL gas cell will be used to selectively and efficiently produce a beam of the desired isotope. Currently we are preparing to have the samples made and then delivered to JYFL.

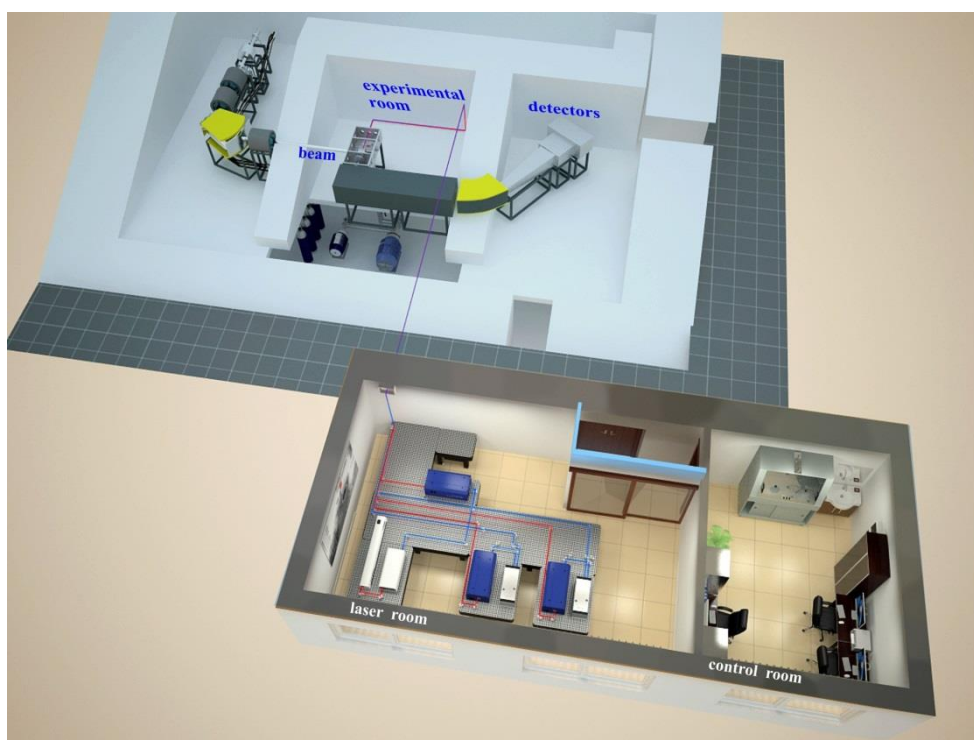
#### -Development of a gas cell for the MARA recoil separator

In a new, long-term project, efforts will combine expertise from the IGISOL group with colleagues designing a new vacuum-mode mass separator, MARA. This separator has been designed to open up a path for studies of N~Z nuclei at JYFL. In order to extend the physics opportunities with MARA, we plan to design, construct and install a gas cell to be installed at the focal plane of the separator. By allowing the mass-to-charge separated recoil products of fusion-evaporation reactions to neutralize, the application of selective laser ionization will be used to enhance the nuclei of interest which would otherwise be overwhelmed by competing fusion-evaporation channels. This project will be implemented in close collaboration with the LISOL team who are pioneering plans for the Rare Elements in-Gas Laser Ion Source and Spectroscopy at S<sup>3</sup>, REGLIS<sup>3</sup>, for SPIRAL2.

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 (KUL),  
V. Fedosseev (CERN), R. Bark (NRF, South Africa), H.A. Othman (Menoufiya Univ., Egypt))

The building of experimental setup based on the method of stopping reaction fragments in the gas and their subsequent selective resonance laser ionization is in progress at Flerov Laboratory of Nuclear Reactions, JINR, Dubna. During the last year (2013) the full reconstruction of laser laboratory and control room was performed; all engineering systems, including special ventilation, air condition and cooling systems were constructed. The GALS group devoted to realization of this project was formed. At the end of year the optical tables system supplied with laminar flow box system was installed in laser laboratory. The first lasers (two Dye lasers and one Nd:YAG pumping laser) were delivered to the lab. and will be installed very soon. More detailed information could be found on the GALS group website: [http://flerovlab.jinr.ru/flnr/gals\\_group.html](http://flerovlab.jinr.ru/flnr/gals_group.html)



**Figure 1.** The allocation of GALS setup at cyclotron U-400M FLNR is shown.

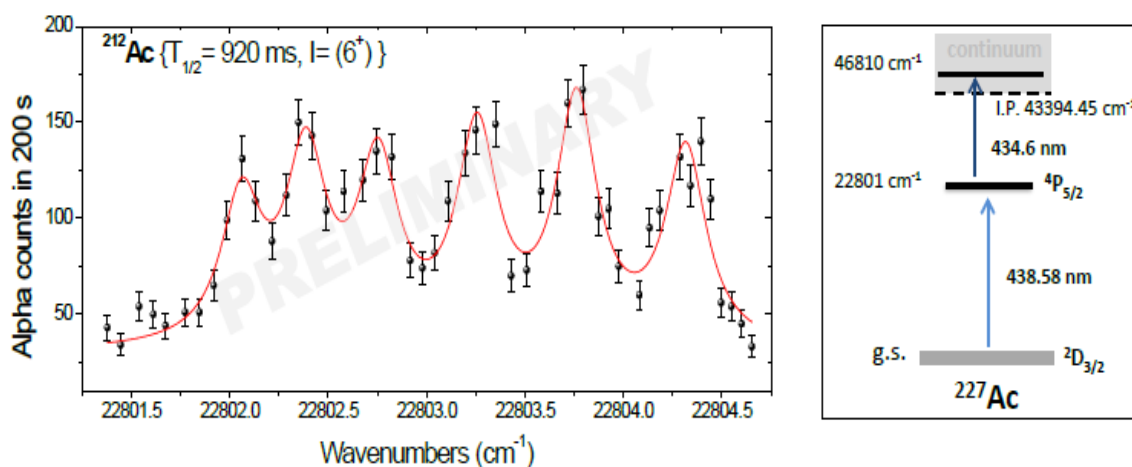
Status Report (3):In-gas laser ionization and spectroscopy (IGLIS) laboratory at KU Leuven

(Yu. Kudryavtsev\*, P. Creemers, R. Ferrer, L. Gaffney, C. Granados, M. Huyse, E. Mogilevskiy, P. Van den Bergh, P. Van Duppen (KUL), B. Bastin, D. Boilley, P. Delahaye, N. Lecesne, H. Lu, F. Lutton, J. Piot, H. Savajols, J. C. Thomas, E. Traykov (GANIL), E. Liénard, X. Flécharde (LPC-Caen), S. Franchoo (IPN-Orsay))

I. in-gas-cell laser spectroscopy of the neutron-deficient actinium isotopes at LISOL

During 2013 two days of beam time were devoted at LISOL to perform in-gas-cell laser spectroscopy on the neutron-deficient actinium isotopes. In these experiments the production of  $^{212,213}\text{Ac}^+$  was found to be similar to that in previous runs reported in [1], with a measured total efficiency of  $\sim 1\%$  for each isotope. The selectivity, however, could be improved by a factor of 6 up to a value of 30. Reduction of non-resonance actinium and of sideband formation [ $^{212,213}\text{AcO}^+$ ] was achieved after a careful gas cell conditioning process. Broadband laser spectroscopy was performed on both isotopes. The resonance linewidth for the transition  $^2\text{D}_{3/2} \rightarrow ^4\text{P}_{5/2}$  at 418 nm was reduced down to 2.5 GHz, which turned out to be still insufficient to observe indications of hyperfine structure.

A second ionization scheme, tested for the first time at LISOL, resulted in similar yields as those observed with the former ionization scheme. A number of broadband scans of the first step transition  $^2\text{D}_{3/2} \rightarrow ^4\text{P}_{5/2}$  at 438 nm were taken while reducing gradually the laser power in each of them. Two scans at 3.5  $\mu\text{J}$  (summed up in Fig. 1) showed the hyperfine structure in  $^{212}\text{Ac}$ . In a new series of online runs in 2014 we aim at performing detailed narrow-band laser spectroscopy on the neutron deficient actinium isotopes from  $^{212}\text{Ac}$  up to  $^{215}\text{Ac}$ , at the N=126 shell closure.



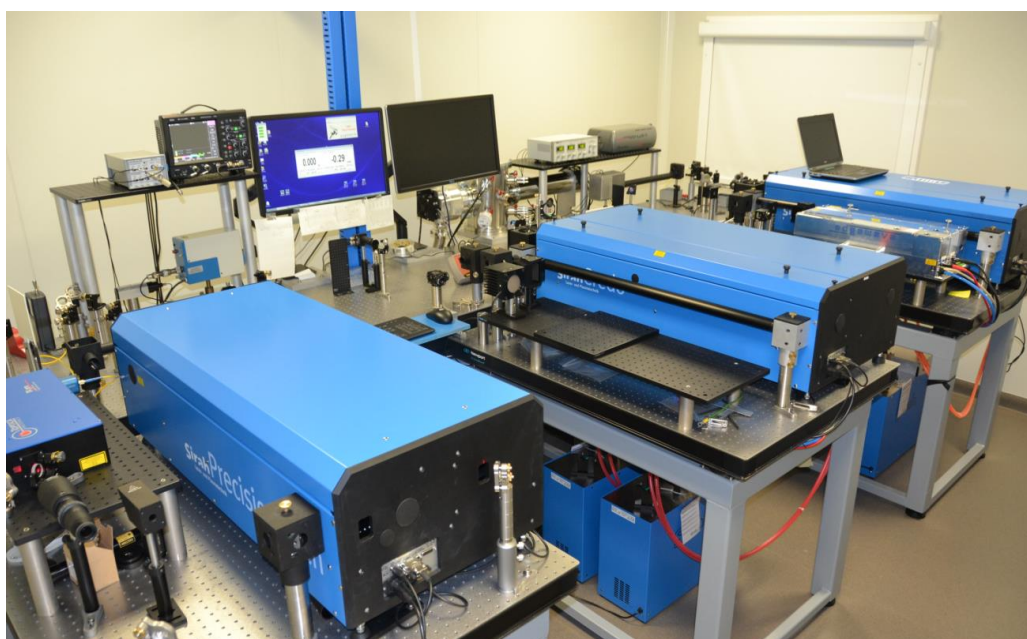
**Figure 1.** Preliminary results for the hyperfine structure of the  $^2\text{D}_{3/2} \rightarrow ^4\text{P}_{5/2}$  transition at 438 nm in  $^{212}\text{Ac}$  and the ionization scheme employed.

The results of in-gas-cell laser spectroscopy experiments on the neutron-deficient  $^{97-101}\text{Ag}$  isotopes have been recently published [2]. Magnetic dipole moments and mean-square charge radii have been determined for the first time with the exception of  $^{101}\text{Ag}$ , which was found in good agreement with previous experimental values. The reported results allow tentatively assigning the spin of  $^{97,99}\text{Ag}$  to 9/2 and confirming the presence of an isomeric state in these two isotopes, whose collapsed hyperfine structure suggests a spin of 1/2.

The results from studies performed at LISOL to identify efficient optical schemes for two-step resonance laser ionization have been recently published [3]. These schemes are available for studying exotic nuclei applying the IGLIS approach, but can also be used for resonance ionization using the hot-cavity based system.

## II. Commissioning of HELIOS at KU Leuven

The commissioning of the HELIOS lab at KU Leuven progresses satisfactorily. Despite of facing a delay in the construction work, full commissioning of the laser room was completed by the end of 2013. The laser room is kept under clean conditions and hosts the high-power, high-repetition pulse rate laser system, see figure below. The laser system already in operation consists of two solid-state Nd:YAG lasers (~15 kHz rep. rate) that pump either two dye lasers, for in-gas cell ionization and spectroscopy studies, or a dye laser and a dye amplifier in which the light of a single mode tunable diode laser is amplified, for higher resolution in-gas jet laser spectroscopy studies.

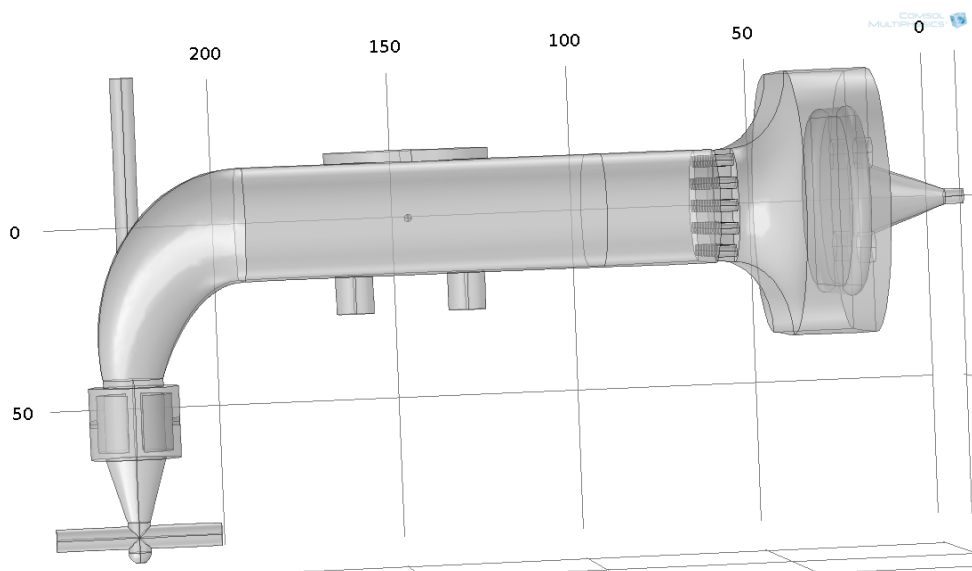


**Figure 2.** Laser system layout and atomic beam unit setup installed in the laser room of HELIOS.



### III. Horn-type gas cell

A new gas cell for IGLIS experiments has been designed. The gas cell has a horn shape and consists of three regions: inlet, stopping, and ionization chambers (see Fig. 2). In the newly added inlet region, a fast jet coming from the gas supplier stops and relaxes such that the gas homogeneously flows with a flat velocity distribution through the stopping chamber. Contours within the cell are kept smoother in the “horn” cell than in former gas cell designs. Gas flow simulations show that the optimized gas cell design allows rising the extraction efficiency from 20% (for the dual chamber kept at 500 mbar and 0.5 mm diameter exit hole) to 70% (for the horn cell at the same pressure but 1 mm exit hole diameter). On the other hand, evacuation times of about 500 ms stay unchanged in the new design. Both extraction efficiency and evacuation time can be optimized by increasing the diameter of the exit hole, which is ultimately limited by the pumping capacity of the system.



**Figure 3.** Schematic layout of the horn-gas cell. Dimensions are given in millimeters.

Plans exist to finalize the separator room this summer and start studying the gas jet formation by the end of the year.

[1] R. Ferrer *et al.*, Nucl. Instr. Meth. B 317 (2013) 570.

[2] R. Ferrer *et al.*, Phys. Lett. B 728 (2014) 191.

[3] Yu. Kudryavtsev *et al.*, Rev. Sci. Instrum. 85 (2014) 02B915.

### [Status Report \(4\):](#)

#### [In-Gas Laser Ionization and Spectroscopy at SHIPTRAP/GSI](#)

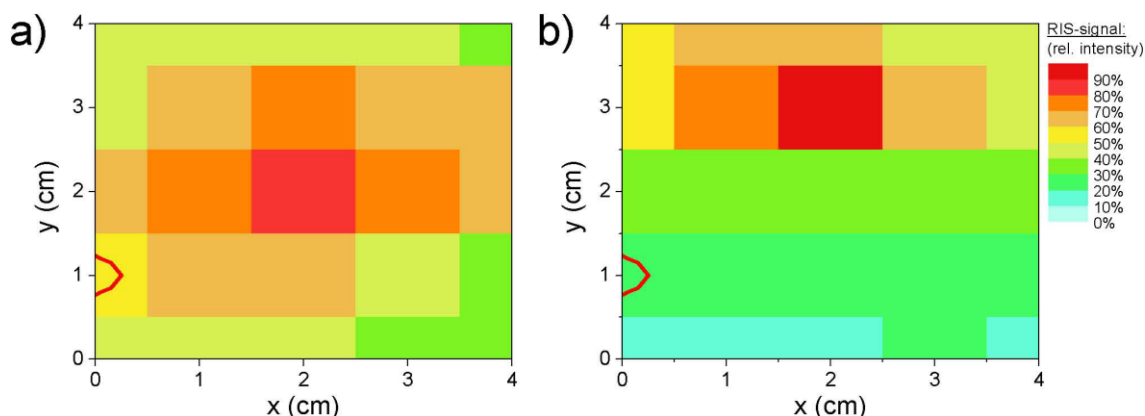
M. Laatiaoui, M. Block, F.-P. Heßberger (HIM/GSI), H. Backe, W. Lauth (JGU-Mainz), P. Chhetri, F. Lautenschläger, Th. Walther (TU-Darmstadt), and P. Kunz (TRIUMF)

#### [In-gas laser ionization and spectroscopy using catcher filaments](#)

Buffer gas stopping cells are nowadays widely used in a variety of chemistry and physics experiments. In-Gas Laser Ionization and Spectroscopy (IGLIS) in such cells has recently gained a great deal of interest especially as laser spectroscopy of exotic and heavy nuclei succeeded for the first time [1, 2]. In the region of trans-fermium elements, however, the efficiency becomes a major performance criterion of any spectroscopic technique due to the low production rates at in-flight facilities. In the nineties of the last century, laser spectroscopic investigations in the actinide region has led to the development of an efficient experimental technique, the so-called RADIATION DETECTED RESONANCE IONIZATION SPECTROSCOPY (RADRIS), for probing atomic levels of short-lived isotopes [3]. This technique is based on Resonance Ionization Spectroscopy (RIS) in a buffer gas cell with radioactive decay detection of the ionization process. A detailed description of this technique can be found in Ref. [4]. Its successful application in isotope shift and hyperfine structure measurements for americium fission isomers has made it the first choice for investigating the trans-fermium element nobelium [5].

In contrast to classical gas-catchers like used at the IGISOL (Ion Guide Isotope Separator On-Line) facility, heavy elements produced in complete-fusion reactions are first separated from the primary beam and then thermalized in ultra-high purity argon at pressures < 100 mbar. In absence of plasma conditions associated with the primary beam, a substantial fraction of the stopped recoils remain in a charged state. The ions are collected on a filament from which they are evaporated as neutrals in a spatially confined vapor cloud for subsequent laser spectroscopic investigations. This Ion-Collection-and-Re-Evaporation (ICARE) method has proven to be highly efficient in an experiment in 2006 on  $^{155}\text{Yb}$ , a chemical homologue of nobelium, where an overall efficiency of about 1% was obtained.

Since then, various studies were carried out for optimizing the ICARE method. The impact of critical experimental parameters like buffer gas pressure and filament temperature on the spatial overlap of the sample atoms with the laser beams was of particular interest. In off-line experiments, neutral atoms of  $^{\text{nat}}\text{Yb}$  were evaporated from a pulse-heated tantalum filament for subsequent two-step RIS. Mapping of the vapor cloud becomes possible by detecting the image charge, which the Yb ions induce on a detector plate while drifting inside the cell. The spatial profile of the vapor cloud has been monitored by 2D-scans, in



**Figure 1.** 2D-mapping of the Yb-vapor cloud above the filament for laser beams of 10mm diameter, a constant filament temperature of 1050°C and an argon gas pressure of 20 mbar(a) and 40 mbar (b). The first and the second excitation step were fixed to  $\nu_1 = 25068 \text{ cm}^{-1}$  and  $\nu_2 = 25028 \text{ cm}^{-1}$ , respectively. The filament is indicated by a red line located at  $(x,y) = (0.25, 1)$ . The color coded RIS-signal has been normalized to the maximum.

which the laser beams for the different excitation steps are brought to overlap within a small interaction volume in the vicinity of the filament. Figure 1 shows the landscape of the RIS-signal for different buffer gas pressures. A higher gas pressure does not only promote gas collision-induced ionization of excited atoms and, at the same time, increases the ionization efficiency, but also confines the vapor cloud into a smaller volume above the filament. The latter effect results in a drastic decrease in the overall efficiency for a reduced overlap of the laser beams with the cloud. In addition, deterioration of the efficiency may occur in the course of time for example due to chemical processes on the filament surface. Thus, on-line monitoring of the RIS-efficiency during the envisaged RADRIS experiments on the element nobelium is crucial. In experiments at SHIP/GSI planned in fall 2014, several excimer laser-pumped dye lasers will be used to search for the  $7S^2 \ ^1S_0 \rightarrow 7s7p \ ^1P_1$ -transition in  $^{254}\text{No}$  [6]. A successful resonant ionization of nobelium would then furnish a basis for further investigations like identifying high-lying Rydberg states and extracting the first ionization potential.

- [1] M. Sewtz, H. Backe, C.Z. Dong et al., *Spectrochim. Acta B* 58 (2003) 1077.
- [2] S. Rothe, A.N. Andreyev, S. Antalic et al., *Nat. Commun.* 4 (2013) 1835.
- [3] H. Backe, R.-R. Baum, B. Fricke et al., *Hyperfine Interact.* 97/98 (1996) 535.
- [4] H. Backe, P. Kunz, W. Lauth et al., *Eur. Phys. J. D* 45 (2007) 99.
- [5] H. Backe, A. Dretzke, M. Hies et al., *Hyperfine Interact.* 127 (2000) 35.
- [6] M. Laatiaoui, H. Backe, M. Block et al., *LASER 2013 Conf. Proc; Hyperfine Interact.*, doi:10.1007/s10751-013-0971-x.

### [Status Report \(5\):](#)

#### [Status of RIKEN SLOWRI project](#)

M. Wada\*, T. Sonoda, P. Schury, Y. Ito, S. Arai, I. Katayama, T. Kubo, K. Kusaka, T. Fujinawa, T. Maie, H. Yamasawa, M. Wakasugi, N. Fukuda, K. Yoshida, H. Takeda, H. Suzuki, N. Inabe (RIKEN), F. Arai, A. Ozawa (Tsukuba), H. Iimura (JAEA), H. Tomita, T. Takatsuka, Y. Adachi, T. Noto (Nagoya), T. Furukawa (Tokyo Met.), H. Wollnik (New Mexico State Univ.), A. Takamine (Aoyama), K. Okada (Sophia), Y. Matsuo (Hosei), H. Miyatake, S.C. Jeong, H. Ishiyama, I. Imai, Y. Hirayama, Y.X. Watanabe (KEK), T. Wakui, T. Shinozuka (Tohoku), F. Schneider, K. Wendt (JGU)

#### [I. Status of SLOWRI installation at RIKEN-RIBF](#)

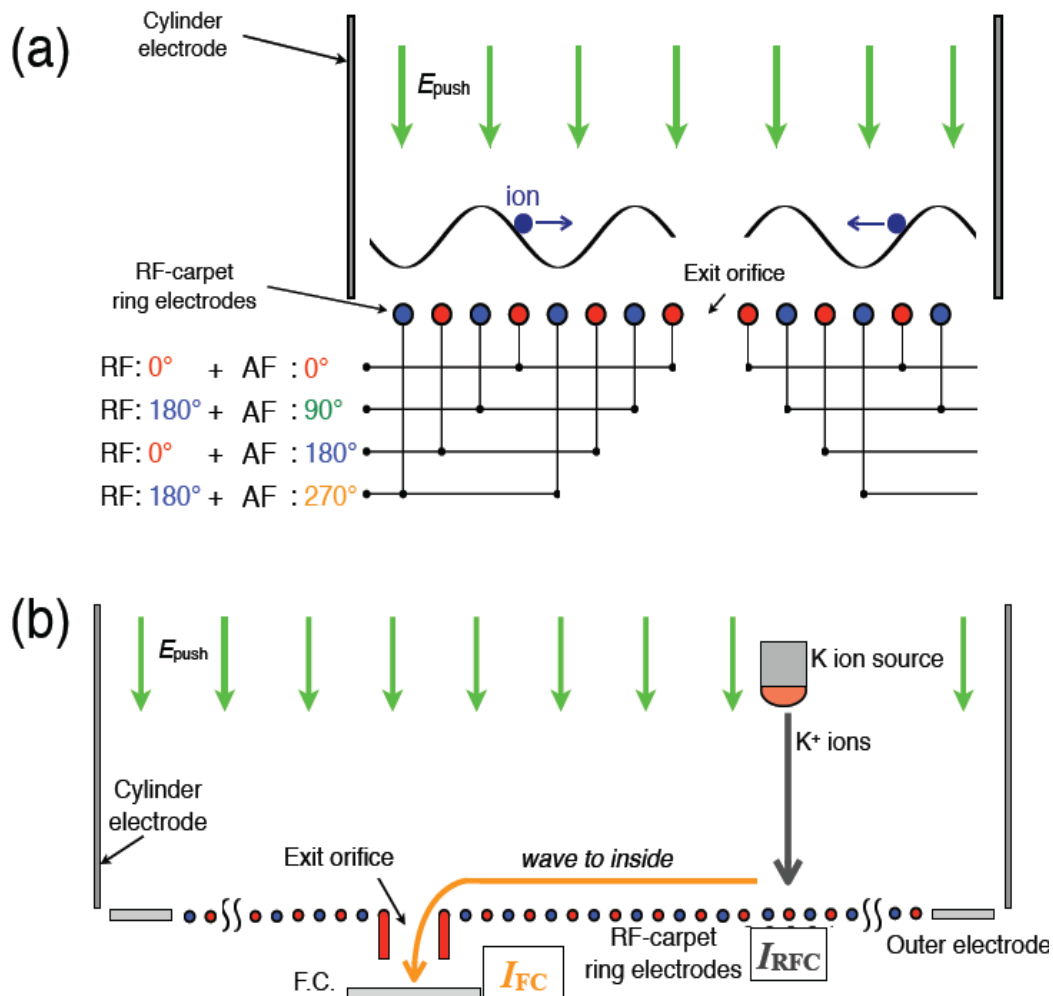
A universal stopped and low-energy RI beam facility, SLOWRI, is being installed at RIKEN RIBF. It consists of two gas catcher cells (RF-carpet gas cell and PALIS gas cell), two isotope separators, and some miscellaneous devices such as lasers. The majority of these devices will be installed by the end of March 2014 while offline tests will be carried out for at least half a year of 2014. Several online experiments are scheduled during the online commissioning. For the RF-carpet gas cell, a multi-reflection time-of-flight mass spectrograph will be directly connected to the cell in order to investigate impurities of the extracted beams. This mass spectrograph will be immediately used for mass measurement of short-lived RI with the "wide-band mass spectrograph mode". The PALIS gas cell will be placed behind the F3 focal plane chamber of BigRIPS before being finally installed in the F2 chamber. During the commissioning run at this location, some online resonant ionization spectroscopy experiments will be also carried. A beam cooler-buncher setup will be installed at the SLOWRI experimental room and commissioning will be carried out in full FY2014. Users experiments at the experimental room could be started sometime in FY2015.

#### [II. Performance of an ion surfing rf-carpet in high gas pressure for high energy RI beam gas catcher](#)

High-energy radioactive isotopes produced in-flight by fragmentation or fission can only be used in ion trap-based precision experiments after being stopped in a gas cell. Such thermalized ions can be extracted from the gas cell as a low-energy ion beam. For fast and efficient transportation and extraction of ions, guidance by electric fields in the gas cell is necessary. In this respect, an rf-carpet (RFC) method utilizing a dc potential gradient is a standard technique [1]. However, such a method is restricted by the transport time to longer half-life isotopes due to the maximum dc gradient that can be supported before electric discharges occur in the gas cell. For studies of short half-life isotopes, an RFC featuring

faster transport is required. Recently, a hybrid technique where the dc gradient is replaced by a traveling potential wave was proposed as illustrated in Fig. 1(a), called ion surfing [2]. This technique has recently been experimentally verified with a linear RFC [3].

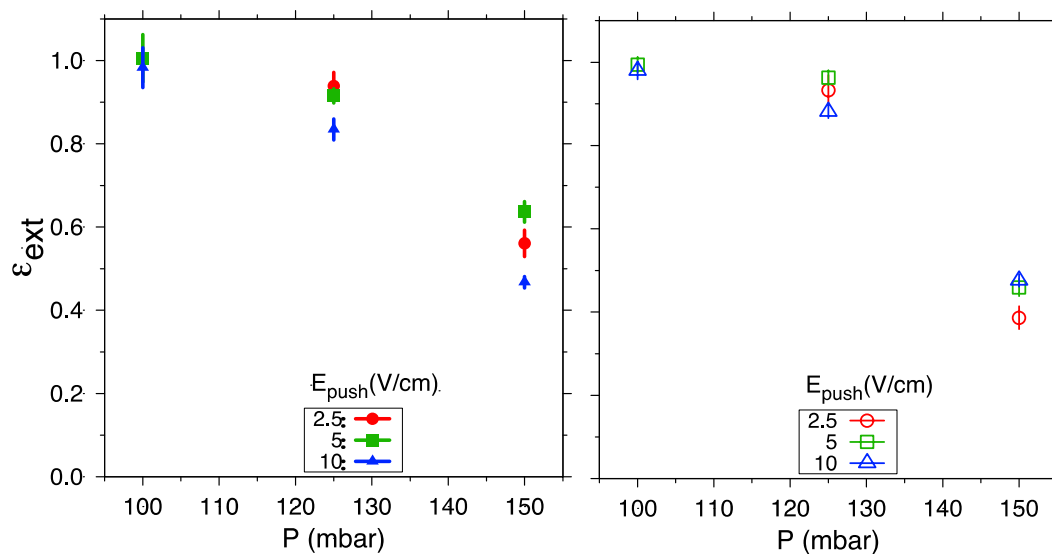
As in the standard method, rf signals are applied to the electrodes such that adjacent electrodes are 180° out of phase, creating an effective force that repels the ions from the surface. In the ion surfing method, in order to keep the ion just above the RFC surface, the repelling force needs to be balanced by a push force, created by a push electric field  $E_{push}$ . The confined ions can then be transported along the RFC surface by superimposing a weak audio-frequency (AF) signal such that adjacent electrodes are 90° out of phase, forming a traveling potential wave. Under the optimal conditions, the ion speed approaches the wave speed [2, 3]. The wave speed is determined by the AF frequency  $f_{AF}$ , the electrode pitch and the number of AF phases -- four in the case of 90° phase shifts.



**Figure 1.** (a) Concept of ion surfing with schematic of the applied rf and AF signal phases. (b) Sketch of the efficiency measurement method. The rf frequency of 8.8 MHz were used.

Recently, we have demonstrated the transport and extraction of  $K^+$  ions using a circular RFC at the He gas pressure of 20 mbar [4]. However, in the practical gas cell, gas pressure was higher. In this study, the transport and extraction of  $K^+$  ions were tested in high He gas pressure with the experimental setup shown in Fig. 1(b), using a cylinder electrode, creating a push electric field  $E_{push}$  and circular RFC with a 0.32-mm diameter orifice. The RFC consists of 245 ring electrodes, each 0.08 mm with 0.16 mm pitch. The study required the measurement of two ion currents: the current reaching the RFC electrodes (with rf off),  $I_{RFC}$  and the ion current reaching the FC,  $I_{FC}$ . The FC was biased at -10V to pull ions out from the extraction orifice.

We define the combined transport and extraction efficiency as  $\epsilon_{ext} = I_{FC} / I_{RFC}$ . Figure 2 shows the maximum  $\epsilon_{ext}$  as functions of the gas pressure  $P$  for various push electric field  $E_{push}$ . An efficiency of nearly 100% was obtained with  $P = 100$  mbar at wave speed of 51.2 m/s ( $f_{AF} = 80$  kHz) and 76.8 m/s ( $f_{AF} = 120$  kHz). It was found that efficiencies were dropped for higher gas pressure.



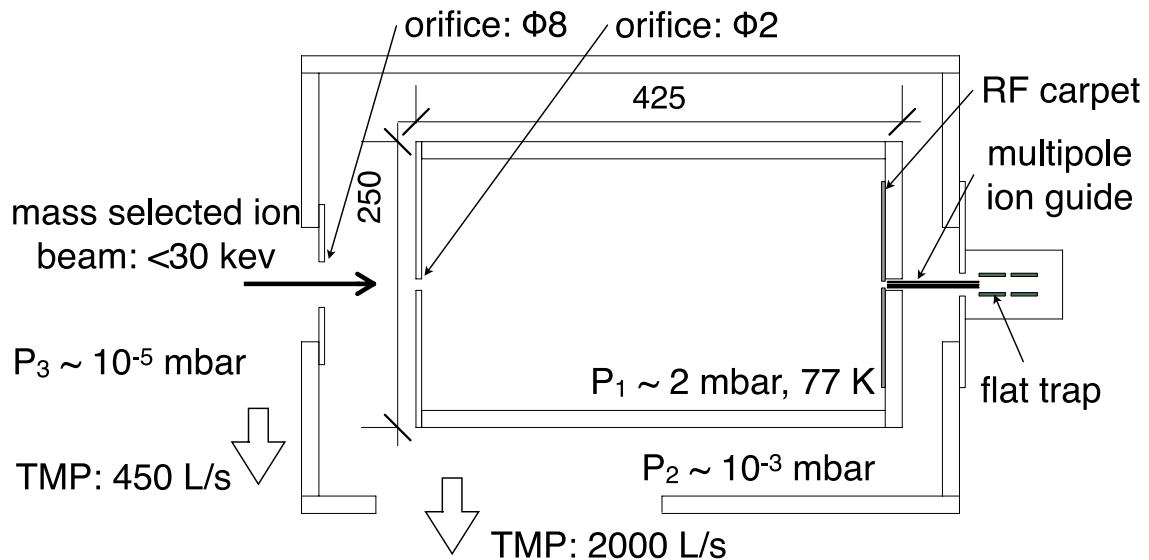
**Figure 2.** The maximum  $\epsilon_{ext}$  as a functions of the gas pressure  $P$  for each push electric field  $E_{push}$ . The wave speed was 51.2 m/s (left) and 76.8 m/s (right)

- [1] M. Wada et al, Nucl. Instr. Meth. B204 (2003) 570.
- [2] G. Bollen, Int. J Mass Spectrom. 299 (2011) 131.
- [3] M. Brodeur, et al Int. J Mass Spectrom. 336 (2013) 53.
- [4] F. Arai et al, Int. J Mass Spectrom. in press.

### III. A gas-cell ion cooler and buncher for SLOWRI

For future experiments at SLOWRI, ion cooling and bunching are indispensable for various

experiments such as collinear laser spectroscopy and all ion trap experiments. The ion beams from SLOWRI gas catchers will be continuous with an energy of 30keV. They must be decelerated and cooled in an ion trap for bunching ions. Generally, linear RF quadrupole (RFQ) traps have been used for such a purpose after electrostatic deceleration. Such systems typically use He gas at a pressure of  $10^{-2}$  mbar to cool ions in about 1-m length RFQ. Due to the limited acceptance of the RFQ, the typical efficiency is about 10% [1,2]. We propose here a new gas-cell cooler and buncher (GCCB) scheme (Fig. 3). It consists of a gas cell (GC) with an RF carpet (RFC) and a flat trap (see Fig. 3). The GCCB will be filled with He gas at up to 2 mbar -- much less than the pressure of about 100 mbar used in conventional GC -- and cryogenically cooled to the temperature lower than 77 K. According to calculations with TRIM, a stopping efficiency of almost 100% can be obtained for any 30 keV beams heavier than Li ( $Z>3$ ) once the GCCB is at least 420-mm long.



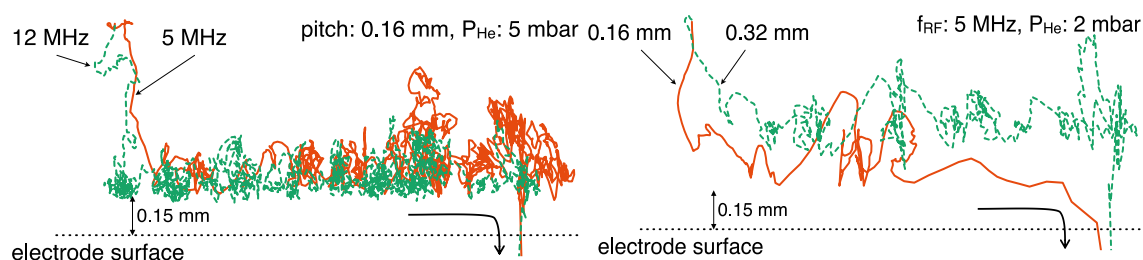
**Figure 3.** Schematic drawing of the GCCB. Continuous ion beams will be cooled in the grounded GCCB, transferred to the flat trap and extracted as a pulsed beam [3].

The RF carpet is a proven technique for efficient and fast ion transport. Recently, the so-called ion surfing method, where a traveling potential wave is superimposed on the RF, has been developed for faster transport [4]. The transport speed was as high as 75 m/s with a linear RFC [4] and an extraction efficiency of almost 100% was obtained using a circular RF-carpet [5]. However, it has yet to be used at pressures as low as 2 mbar.

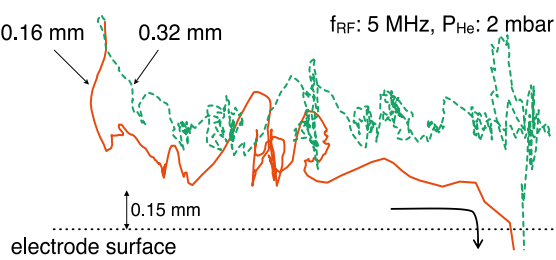
To verify the performance of the RFC at lower pressure, the extraction efficiency of the RFC was investigated with a fine-RFC which has an electrode pitch of 0.16 mm and  $0.08\text{-mm}^2$  exit hole. The experimental parameters were optimized to achieve highest efficiency using

an RF frequency of  $f_{RF} = 5$  MHz. However, when operated at 2 mbar, few ions could be extracted from the GC; at 5 mbar, the efficiency was 22%.

Simulations with SIMION indicated that the lower efficiency was the result of unstable ion motion arising from the ions moving between adjacent electrodes in fewer RF periods than required for validity of the pseudo-potential approximation (see Fig. 4). By increasing the RF frequency to 12 MHz, the simulation indicated, ion motion would become stable and a high efficiency could be achieved.



**Figure 4.** Comparison of ion motions for  $f_{RF} = 5$  MHz and 12 MHz. The dotted line indicates the level of the electrode surface.



**Figure 5.** Comparison of ion motions in 2 mbar He using 0.16 mm and 0.32 mm pitch.

Since the maximum RF frequency is, however, limited by the impedance of the RF carpet, such higher frequency is difficult to obtain; however, increasing the electrode pitch should yield a similar effect. In simulation, doubling the electrode pitch and the exit hole diameter yielded near unity efficiency with 2-mbar He for  $f_{RF} = 5$  MHz (see Fig. 5). Such a larger-pitch RF-carpet is being manufactured and will be tested soon. An offline test using 30 keV ion beam coupled to a multi-pole ion guide and the flat trap [3] will be performed in early FY2014.

- [1] F. Herfurth et al., Nucl. Instr. Meth. A469, 254 (2001)
- [2] T. Brunner et al., Nucl. Instr. Meth. A676, 32 (2012)
- [3] Y. Ito et al., Nucl. Instrum. Meth. B317, 544 (2013)
- [4] M. Brodeur, et al Int. J Mass Spectrom. 336, 53 (2013)
- [5] F. Arai, Y. Ito et al., Int. J. Mass Spectrom. (in press)

#### IV. Wide-band mass measurements with a multi-reflection time-of-flight mass spectrograph

The multi-reflection time-of-flight mass spectrograph (MRTOF-MS), first proposed more than 20 years ago [1], uses a pair of electrostatic mirrors to compress a flight path of several hundred meters (or even many kilometers in some cases) within a reflection chamber of about 1-m length. The MRTOF-MS can achieve mass resolving powers of  $R_m > 10^5$  while operating at rates of 100 Hz or more [2, 3, 4]. Recently, these devices have begun to prove



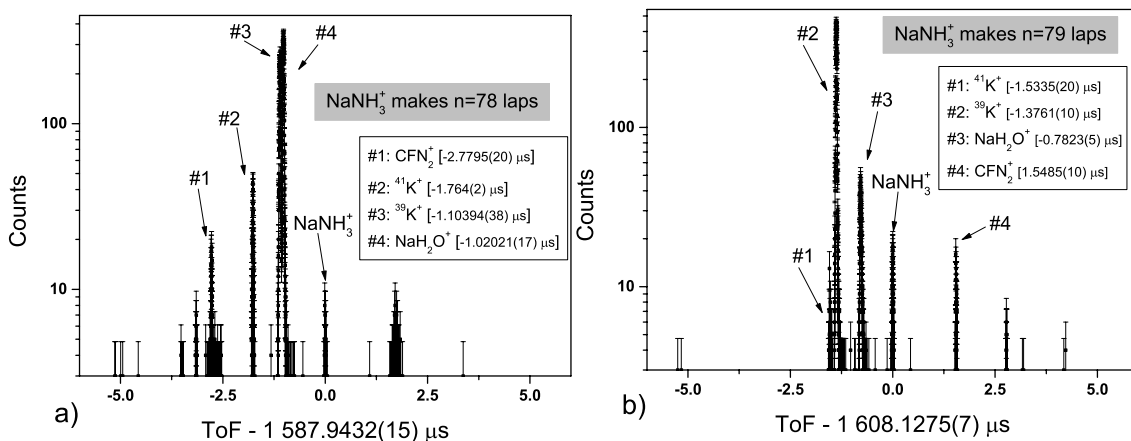
useful for online measurement of nuclear masses [5]. The technique has been demonstrated to provide mass precision of  $\delta m/m \approx 5 \times 10^{-7}$  or better.

However, the multi reflection nature of the measurement has made the analysis of rich and wide-band mass spectra difficult or even impossible. Much like runners of widely varying skill racing on a circular track, after some time ions with sufficiently differing mass-to-charge ratios make different numbers of laps and eventually cause difficulty in interpreting the TOF spectrum. By developing an analysis method to interpret such spectra, we believe the device could eventually provide wide-band measurements of nuclear masses as in the way of storage rings [6]. The device could also be useful in analytic chemistry, providing wide-band analysis much like FT-ICR Penning traps, but with greater sensitivity.

As reported [7], using a time-of-flight peak corresponding to a reference ion with known mass-to-charge ratio that makes a known number of laps in the reflection chamber it is possible to determine the mass-to-charge ratio corresponding to any other peak as

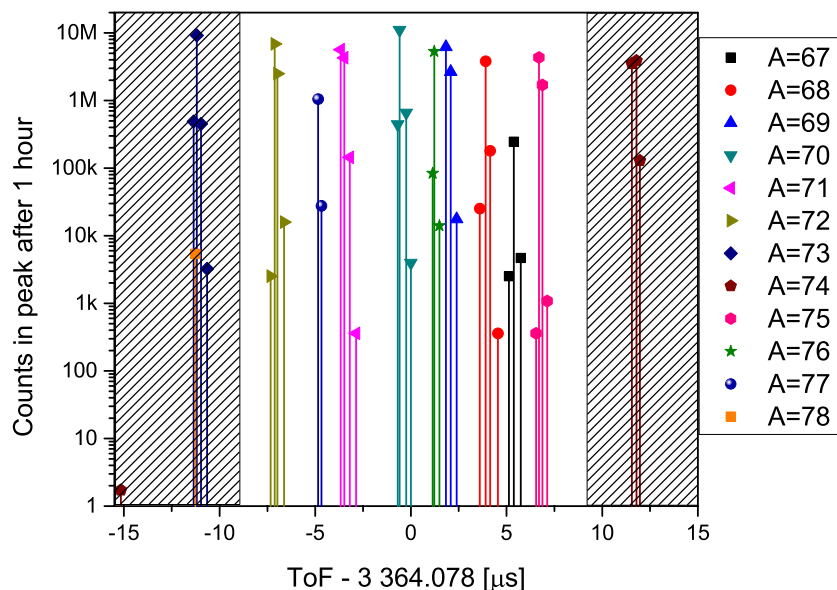
$$m_2 = m_1^{(n)} \left( \frac{\zeta + n_{m_1}}{\zeta + n_{m_1} + \Delta n} \right)^2,$$

where reference ions with mass-to-charge ratio  $m_1^{(n)}$  make  $n_{m_1}$  laps and unknown ions with mass-to-charge ratio  $m_2$  make  $n_{m_1} + \Delta n$  laps, while  $\zeta$  is a system-dependent constant; for our system  $\zeta \approx 0.686,893$ . Determining  $\Delta n$  requires a pair of spectra with different values of  $n_{m_1}$ . Using this method, it is possible to determine the mass-to-charge ratio of ions over a wide range with a relative mass accuracy of about  $10^{-6}$ , which is typically sufficient to uniquely identify the ions. Such a pair of spectra with ion identity determined is shown in Fig.6 using  $\text{NaNH}_3^+$  as a reference.



**Figure 6.** Example spectra with  $n_{m_1} = 78$  and  $79$  laps. Abscissa reflects the time-of-flight of the  $\text{NaNH}_3^+$  reference.

Once  $\Delta n$  is known, a more precise determination of the ion's mass-to-charge ratio can be determined using the time-of-flight of the reference and unknown with each undergoing the same number of laps, as previously demonstrated online for  $^8\text{Li}^+$  [8]. If there exist isobars, one isobar can be used as a reference while the others are treated as unknown masses and simultaneous accumulation of reference and unknown can be performed, removing possible drift-related errors.



**Figure 7.** Calculated spectra at SLOWRI from nuclei produced by in-flight fission of Uranium. In the hashed region, ions will experience time-dependent electric fields from extraction switch and cannot be analyzed.

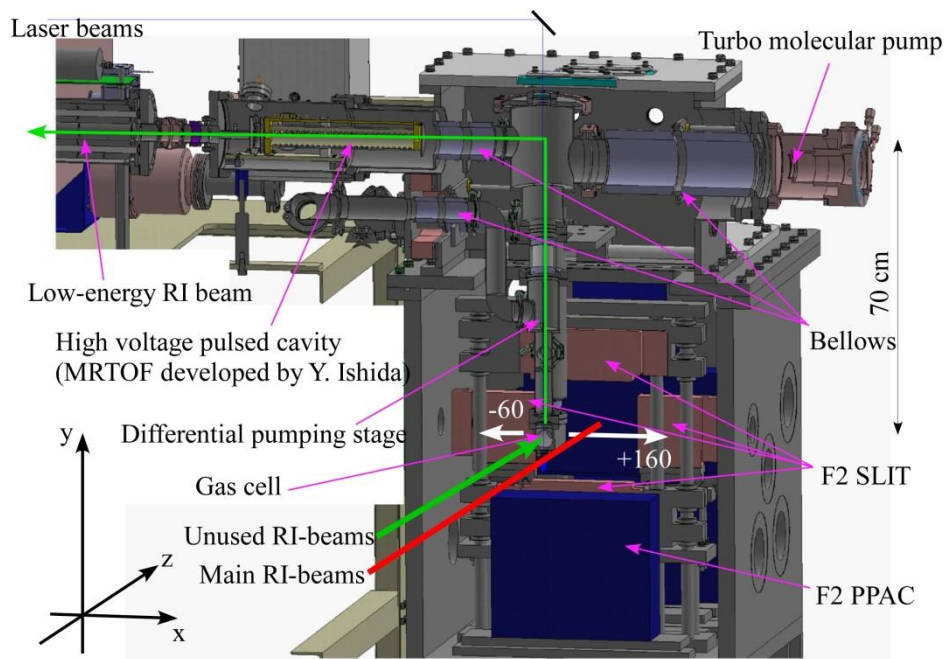
We foresee the possibility of performing such wide-band mass measurements of r-process nuclei at SLOWRI. As demonstrated in the calculated spectra shown in Fig. 7, it should be possible to measure masses of 20 or more nuclei simultaneously. This would allow the entire region from  $^{78}\text{Ni}$  to  $^{132}\text{Sn}$  to be investigated with less than 10 tunes of BigRIPS.

- [1] H. Wollnik, M. Przewloka, *Int. J. Mass Spectrom. Ion Processes* 96 (1990) 267.
- [2] P. Schury et al., *Nuclear Instr. and Methods in Physics Research B* 317 (2013) 537-543.
- [3] Y. Ito et al., *Nuclear Instr. and Methods in Physics Research, B* 317 (2013) 544-549.
- [4] W. Plaß et al., *Int. Jour. Mass Spec.* 349 (2013).
- [5] F. Weinholtz et al., *Nature* 498 (2013) 346-349.
- [6] F. Bosch and Yu. A. Litvinov, *Int. Jour. Mass Spec.* 349 (2013) 151.
- [7] P. Schury et al., *Int. Jour. Mass Spec.* 359 (2014) 19-25.
- [8] Y. Ito et al., *Physical Review C* 88, 011306(R) (2013).

## V. PARAsitic slow RI-beam production by Laser Ion Source (PALIS) system

### -Design of PALIS system

In the PALIS [1], we will restore unused RI-beams for the production of slow RI-beam by installing a laser ionization gas catcher in the vicinity of the second focal plane (F2) of the fragment separator BigRIPS. This will provide parasitic slow RI-beams for various precision experiments whenever BigRIPS experiments are in operation. The design drawing for the PALIS was almost finalized as shown in Fig. 8. More detailed design concepts can be found in Ref. [2]. The off-line and on-line commissioning test for PALIS will be started from April 2014.



**Figure 8.** BigRIPS F2 chamber implemented with PALIS system.

### -Installation of new laser system for PALIS

New laser system for the PALIS was installed. This system upgraded the laser power and repetition rate compared to those we have used, which makes reasonably enhancement for the ionization efficiency and it possible to apply a gas-jet laser spectroscopy. A room partition for the laser equipment was newly constructed having laser shield noise barriers. The room is complete with air conditioning system.

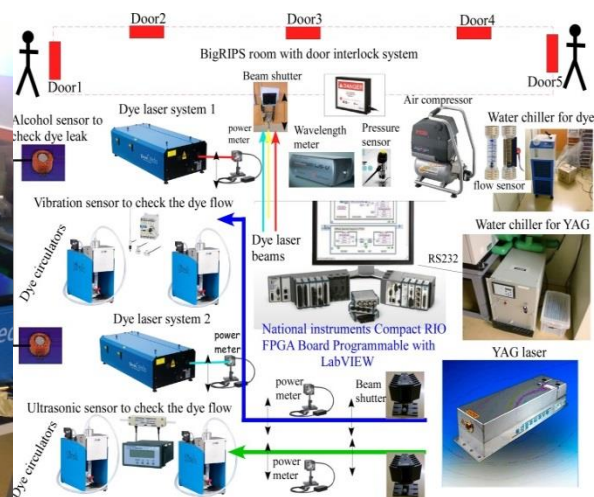
New laser components consist of two pulsed dye lasers pumped by one YAG laser. The maximum repetition rate and power for YAG laser (Edge wave) is 10 kHz and 90 W for 532 nm with a single mode, 36 W for 355 nm and 40 W for 532 nm with a multimode. Two pulsed dye lasers (Sirah) provide wide range wavelength from 215 to 900 nm with ~10 W for fundamental frequency and ~1 W for a frequency-doubled by a secondary harmonic generator. These dye lasers accept both wavelengths (355/532) from pump laser beam and

have an additional option for selecting the line width of 1.5 GHz and 6 GHz, alternately. Additionally new YAG laser (Lee) was installed for pumping Ti:Sapphire lasers. The maximum power and repetition rate is 50 W and 10 kHz respectively. An injection locked Ti:Sapphire laser operated at up to 10 kHz with a line width of 20 MHz will be installed for high precision laser ionization spectroscopy.

We confirmed that the laser system works with the specified performance. Figure 9 shows a photograph taken during new laser test at October 2013.



**Figure 9.** The photograph of new PALIS lasers: shining two dye lasers pumped by YAG laser.



**Figure 10.** Overview of interlock system with interactive modules for PALIS laser operation.

#### -Development of PALIS laser interlock system for human and machine protection

For the new laser system operation with a high-power and high-repetition-rate pump laser (i.e. 90-W YAG with 10 kHz), a laser interlock system is indispensable. Using a National instruments Compact RIO which consists of FPGA board programmable with LabVIEW, we have built an automation system by a programmable logic controller in operating all devices remotely. We installed a number of I/O modules which consist of analog and digital available from National Instruments. Figure 10 shows such interactive modules necessary for laser operation.

[1] T. Sonoda *et al.*, AIP Conf. Proc. 1104 (2009)132.

[2] T. Sonoda *et al.*, RIKEN Accel. Prog. Rep. 46 (2013) in press.

#### VI. Conceptual design of a post-accelerator for SLOWRI

As an extension plan of the SLOWRI, construction of a post-accelerator has been proposed. The radioactive ions from SLOWRI are mass-analyzed, charge-bred and injected into the post-accelerator. The post-accelerator is a normal conductive linear accelerator complex composed of an RFQ, a medium energy beam transport (MEBT) and a drift-tube linac (DT

linac). The RFQ accelerates ions with mass to charge ratio ( $A/q$ ) less than 9 from 5 to 500 keV/u. The beam from RFQ is transported to the DT linac through the MEBT. Output beam energy of the drift-tube linac is variable between 500 keV/u and 1.5MeV/u. Layout and main parameters of the post-accelerator are shown in Fig. 11 and Table 1, respectively.

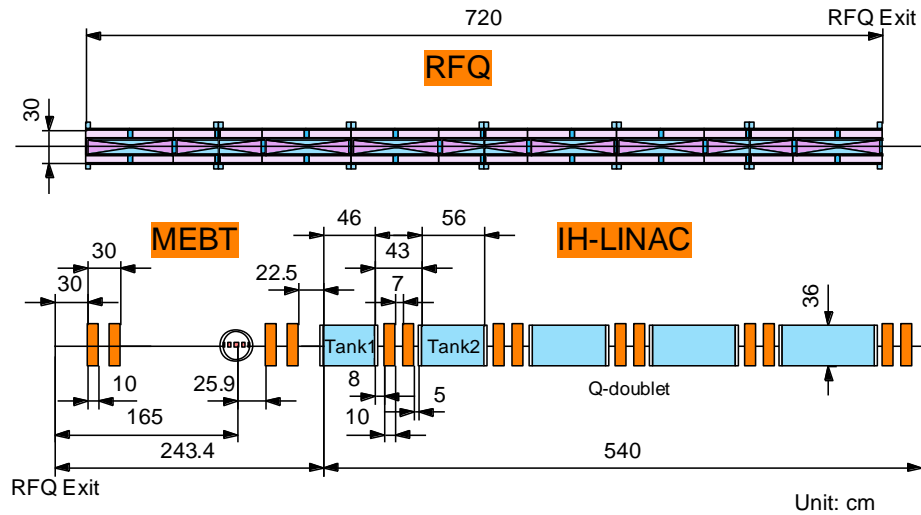


Figure 11. Layout of the post-accelerator.

Table 1. Main parameters of the post-accelerator

	RFQ	Drift-tube linac				
Structure	Split coaxial	Interdigital H				
Tank No.		1	2	3	4	5
Frequency (MHz)	79.06	158.12				
$A/q$	9	9				
Duty factor (%)	100	100				
Input energy (keV/u)	5	500	640	810	1000	1230
Output energy (keV/u)	500	640	810	1000	1230	1500
Normalized emittance ( $\pi$ cm·mrad)	0.047	0.047				
Number of cells	300	14	15	16	16	16
Bore radius (cm)	0.54	1.2	1.4	1.6	1.6	1.6
Electrode Voltage (kV)	65.1	160	180	200	220	250
Synch. Phase (deg)	-30	-25				
Cavity diameter (cm)	30	36				
Total cell length (cm)	725	46.4	56	66.7	74.2	82
Unloaded Q	6500	9150	9800	10300	11000	11400
Power loss (kW)	186	31	44	62	72	91

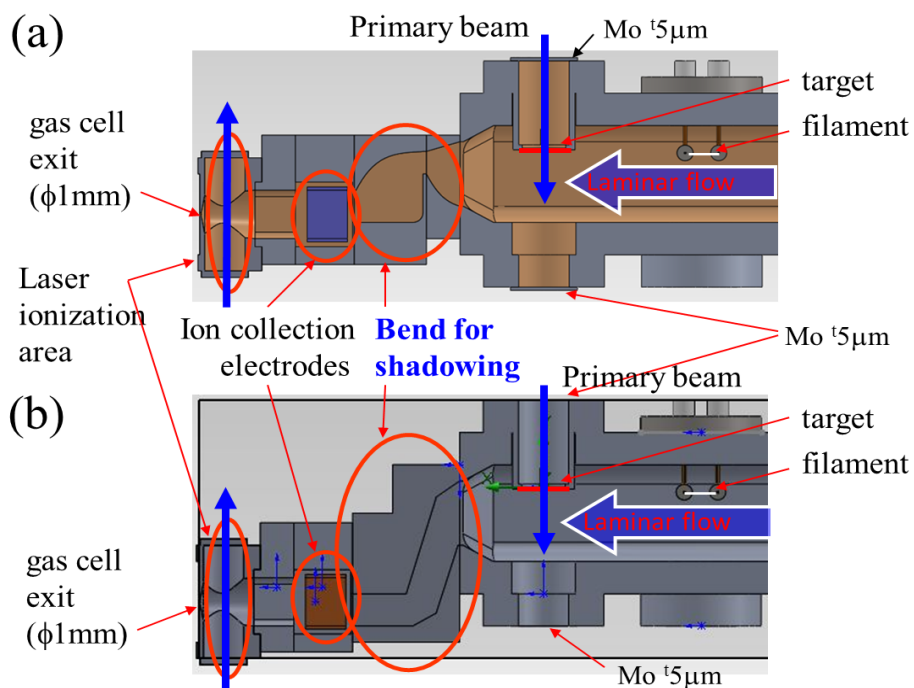
Beam simulation results are as follows: For the beam with a normalized emittance of 0.047  $\pi$  cm·mrad, transmission of the RFQ is 93.5%. Output beam emittance profile of RFQ is well matched to the acceptance profile of IH linac by means of two quadrupole doublets and a 4-gap rebuncher of quarter-wave resonator in MEBT. Transmission of the IH linac is 100%.

[Status Report \(6\):](#)[Status of KISS project](#)

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[I. Modification of bent structure for the KISS gas cell.](#)

At the on-line test performed on March, 2013, by using an energetic  $^{56}\text{Fe}$  beam of 90 MeV/nucleon from RIKEN Ring Cyclotron (RRC), we observed that the extraction efficiency and beam purity decreased with increasing the primary beam intensity (i.e. injection rate of  $^{56}\text{Fe}$ ) as reported in the first IGLIS newsletter. We assumed that the bent structure of the gas cell (Fig. 1-(a)) would not be enough to block the plasma effect induced by the primary beam in the ionization region irradiated by laser around the exit of the gas cell. For better shadowing, we modified the gas cell with a bent structure as shown in Fig. 1-(b), where the pathway is more deeply bent than in the previous cell. The flow simulation for the new structure shows that the extraction efficiency and mean-transport time from the primary beam injection region were 60% and 200 ms, respectively, which were comparable with those obtained with the previous bent structure.

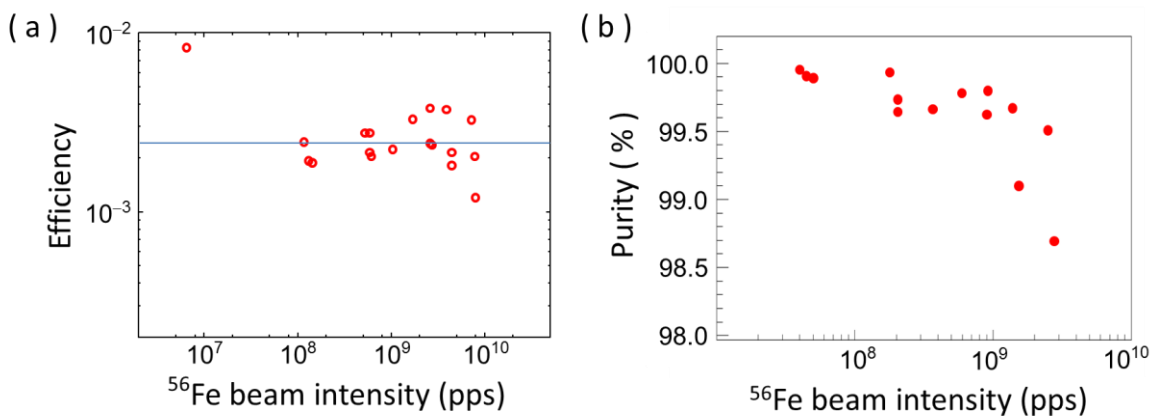


**Figure 1.** Cross sectional top view of (a) the previous and (b) new bend structures of the gas cell.

## II. On-line test using $^{56}\text{Fe}$ beam

During the last online test, we observed that the extraction efficiency for  $^{56}\text{Fe}$  increased proportionally with increasing laser power of the second step, indicating that the transition of second step was not saturated due to a lack of laser power. There might be more efficient transitions to AIS. Further efforts were paid for searching for AIS of Fe with higher transition probability. As a result of the off-line test, where neutral Fe atoms vaporized from the iron filament installed in the gas cell were ionized by the two-step laser resonance ionization and extracted as a beam which was detected by a channeltron after mass separation, a new ionization scheme involving the transition  $3d^64s^2 (J = 4) \rightarrow 3d^64s4p (J = 5) (\lambda_1 = 248.402 \text{ nm in vacuum}) \rightarrow \text{continuum} (\lambda_2 = 307.9 \text{ nm in vacuum})$  was identified. The saturation powers for the first and second step lasers ( $\lambda_1, \lambda_2$ ) were measured to be  $20 \mu\text{J/pulse}$  and  $8 \text{ mJ/pulse}$ , respectively. Although the second step corresponds to the transition to a continuum for the ionization, we suppose that the new scheme should be more efficient than that reported in Ref. [1], because the intense excimer laser for  $\lambda_2$  can provide the saturation power for the ionization transition. Here, the laser spot sizes were expanded to be about 10 mm in diameter.

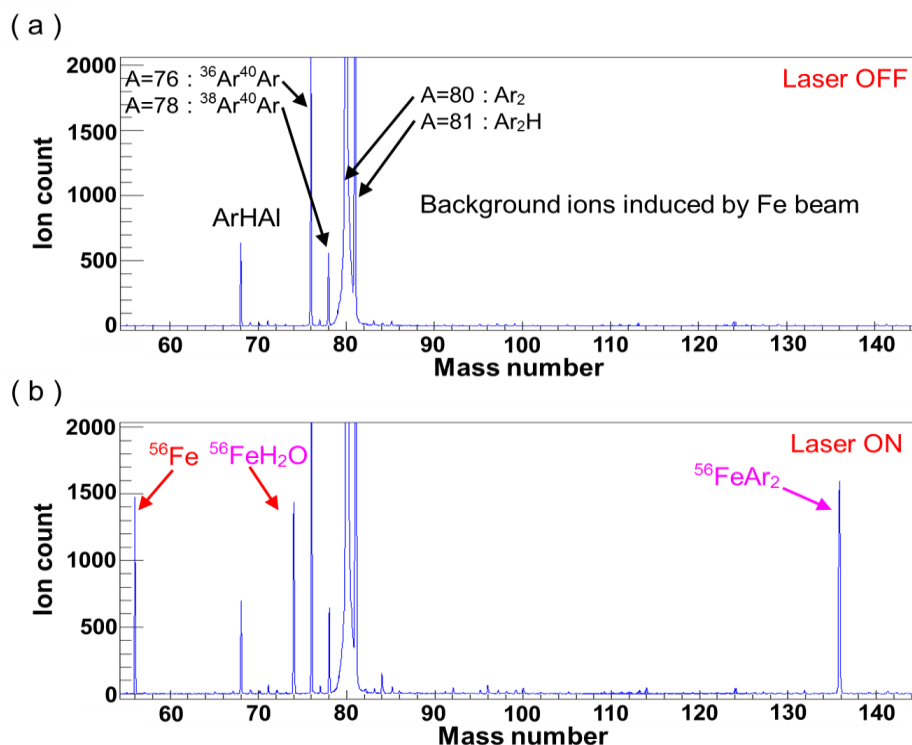
The energy of  $^{56}\text{Fe}$  beam from RRC was degraded to 1.5 MeV/nucleon in front of the gas cell by thick aluminum foils placed at about 100 mm upstream of gas cell entrance, which allows us to implant the beam at the center of the gas cell filled with argon gas at a pressure of 50 kPa. The thermalized and neutralized  $^{56}\text{Fe}$  atoms were re-ionized by the above-mentioned laser lights, extracted and detected after mass-separation. The extraction efficiency, defined as the number ratio of laser-ionized to implanted  $^{56}\text{Fe}$ , was about 0.25% as shown in Fig. 2-(a), and was almost independent on the Fe beam intensity owing to the modified bent structure of the gas cell. The obtained beam purity was better than 98% up to the Fe beam injection rate of several  $10^9$  pps. While it is only slight, the purity becomes



**Figure 2.** (a) extraction efficiency of  $^{56}\text{Fe}$  ions and (b) beam purity measured as a function of  $^{56}\text{Fe}$  beam intensity.

worse with increasing beam injection rate as shown in Fig 2-(b). However, the impurities are often associated with buffer gas ions (argon ions in the present case), and therefore are not supposed to disturb the  $\beta$ -decay lifetime measurements.

In order to look into the compositions of impurity ions, we measured mass distributions of ions extracted from the gas cell during the Fe beam injection without and with ionization lasers, respectively, as shown in Fig. 3. Figure 3-(a) shows background ions extracted from the gas cell, which are supposedly ionized by the beam injection: Dimers of argon isotopes and their compounds with hydrogen were dominant. We clearly observed laser-ionized  $^{56}\text{Fe}$  and molecular ion peaks of  $^{56}\text{Fe}(\text{H}_2\text{O})$  and  $^{56}\text{FeAr}_2$  with almost the same intensities when the ionization lasers irradiated: Laser-ionized Fe ions can be considered to transform to these sidebands just around the exit (within the evacuation time of about 10ms). The hydrogen attached to Ar molecules is the left-over residual gas in the gas cell made of SUS304; other materials are now under consideration since its residual quantity is known to strongly depend on the materials used to make the cell. The increase of molecules associated with  $\text{H}_2\text{O}$ ,  $\text{Ar}_2$  and hydrocarbons were also observed during the beam injection. Therefore, the gas cell made of the materials of low outgassing rate would be very efficient for improving the present efficiency.

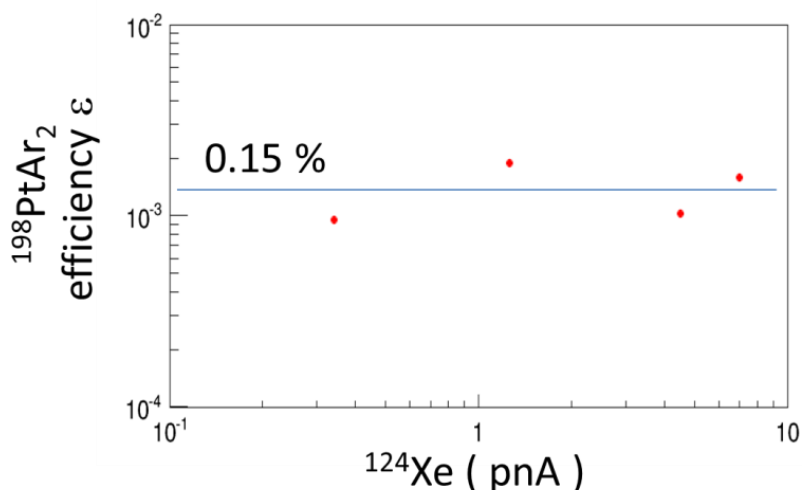


**Figure 3.** Measured mass distributions of ions extracted (a) without ionization lasers and (b) with ionization lasers during the Fe beam injection.



### III. On-line test using $^{124}\text{Xe}$ beam

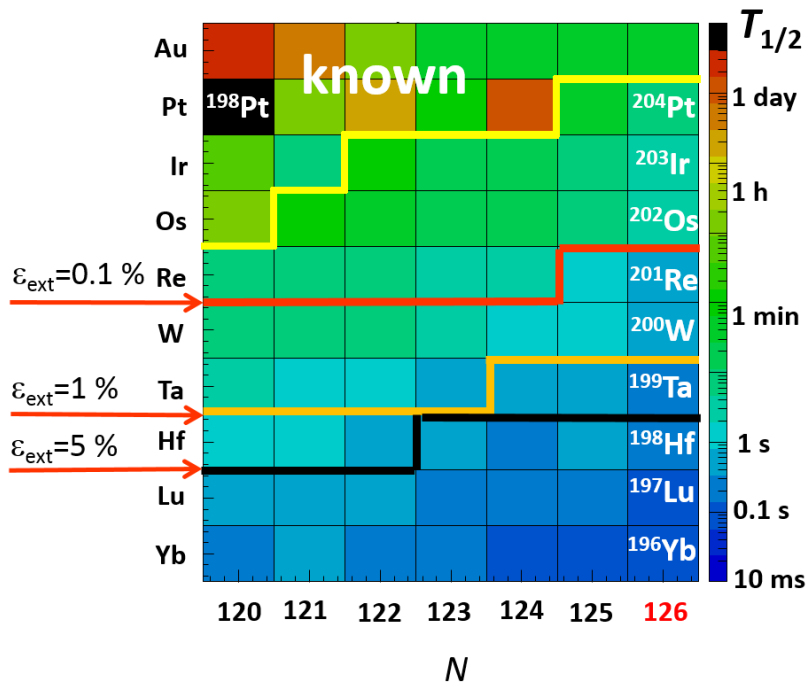
The  $^{198}\text{Pt}$  atoms recoiled out from a thin  $^{198}\text{Pt}$  target placed in the gas cell by elastic scattering of  $^{124}\text{Xe}$  beam of 11 MeV/nucleon from RRC were used to test if the performance of the KISS for heavy elements are similar to what we previously observed for iron. In the case of the  $^{198}\text{Pt}$  atoms (elastically recoiled out of the target foil), the transport time ( $\sim 200$  ms for Fe) was observed to be longer by a factor of 2 at maximum with a correspondingly broadened width. Its time structure seems to be sensitive to the flow gas pressure; e.g. close to the time structure of the laser-ionized Fe ions at half of the nominal pressure but with a reduced efficiency. The fractions of main components associated with laser-ionized Pt were 1 : 4 : 10 for  $^{198}\text{Pt}$ ,  $^{198}\text{Pt}(\text{H}_2\text{O})$ , and  $^{198}\text{PtAr}_2$ , respectively. The extraction efficiency of  $^{198}\text{PtAr}_2$  was about 0.15% which was independent on the intensity of the Xe beam, as shown in Fig. 4. Here, we calculated the number of  $^{198}\text{Pt}$  atoms stopped in the gas cell from the cross section of elastic scattering.



**Figure 4.** Extraction efficiency of  $^{198}\text{PtAr}_2$  ions as a function of  $^{124}\text{Xe}$  beam intensity.

### IV. Accessible region in the nuclear chart at KISS and further development for higher efficiency

Based on the measured extraction efficiency of 0.25% and 0.15% for  $^{56}\text{Fe}$  and  $^{198}\text{PtAr}_2$  cases, we estimated a region in the chart of nuclide accessible to the lifetime measurement of nuclei around  $N = 126$ . The red line in Fig. 5 indicates a lower boundary for the accessible region when we assumed the efficiency of 0.1%; it is feasible to measure the lifetime of more than 15 nuclei newly and access to  $^{202}\text{Os}$  (most neutron-rich in the case) by using the multi-nucleon transfer reactions between  $^{136}\text{Xe}$  beam and  $^{198}\text{Pt}$  target with the beam intensity of 10 pnA. With improved efficiencies, the accessible region would reach lighter elements accordingly.



**Figure 5.** Accessible region for lifetime measurement on nuclear chart using the  $^{136}\text{Xe}$  beam with the intensity of 10 pA for different extraction efficiency. The color codes indicate the calculated half lifetime by the KUTY model [2].

In order to estimate the feasibility more realistically, we proposed a series of experiments for efficiency development of the KISS. The R&D proposal was approved with a high priority at RIKEN NP-PAC held on 13-14<sup>th</sup> December 2013. The experiments will be performed more or less on the element-by-element base, because the efficiency appears to be element-dependent in the on-line tests performed so far. Through the experiments, we are going to address the degree of such dependency if any, and possible lifetime measurements of unknown nuclei will be performed with the developing efficiency.

[1] Y. Hirayama et al., Nucl. Instru. and Method B 317 (2013) 480-483.

[2] T. Tachibana and M. Yamada, *Proc. Inc. Conf. on exotic nuclei and atomic masses*, Arles, 763 (1995).