Advances in the SPES Project and its ion source systems

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Abstract

SPES (Selective Production of Exotic Species) is an INFN project to develop a Radioactive Ion Beam facility as an intermediate step toward the future generation European ISOL facility EURISOL.

The aim of the SPES project is to provide high intensity and high-quality beams of neutron-rich nuclei to perform forefront research in nuclear structure, reaction dynamics and in interdisciplinary fields like medical, biological and material sciences.

It is based on the ISOL method with an UCx Direct Target able to produce 1013 fission/s by proton induced fission in the UCx target. The development of new target ion source systems for the SPES facility is currently in progress at Legnaro National Laboratories. In this context the study of ion sources and their performance in terms of ionization efficiency and transversal emittance is a crucial point in order to maximize the available yields, particularly for short-lived isotopes. In this work preliminary off-line measurements for the SPES surface, plasma and laser ion sources are presented.

The SPES project

SPES is a new mid-term ISOL facility dedicated to the production of neutron-rich beams. It is an INFN project involving the two national laboratories, LNL and LNS and other INFN sites in Italy. The project consists of a proton driver, a 70 MeV cyclotron with two exit ports for a total current of 750 μA, an UCx ISOL target and ion-source, a beam transport system with a high resolution mass selection and the superconductive PIAVE-ALPI accelerator complex in operation at LNL that will be used as radioactive beam re-accelerator.

A 40 MeV 200 μA proton beam, delivered by the cyclotron, impinges on the uranium carbide target, the neutron rich isotopes produced as fission fragments with a rate of 10^{13} fission/sec, are extracted by the ion source, mass separated and sent via proper beam lines to the PIAVE-ALPI re-accelerator. The re-acceleration stage with the superconductive linac ALPI qualifies the project in terms of good quality of beams (intensity and energy spread) and in the final energy which is sufficient to perform nuclear reactions close to the Coulomb barrier between medium-heavy mass ions. The uranium carbide targets have been already developed and represent an innovation in terms of capability to sustain the primary beam power.

The ions, extracted in a 1+ state with different ion sources, depending on the kind of isotope, will be transported in ALPI, with a benefit from the experience gained in LNS (Catania) with the EXCYT project, which will be taken as a reference for the optimization of the various magnetic elements and diagnostics. To fit the proper entrance parameters for beam re-acceleration with the linac, an RFQ-cooler and a Charge Breeder are planned. The design and construction of the Charge Breeder will be made in collaboration with SPIRAL2.

With the high intensity beams delivered by SPES, a challenging and broader range of studies in nuclear spectroscopy and reaction mechanism will be performed. Interesting areas where new data will be collected are those in the very neutron rich regions, where shell evolution is an issue. Effects of how the pairing interaction is modified in the nuclear medium will receive significant inputs by measurements of multi-nucleon transfer reactions to specific nuclear states. Effects of rotational damping in the decay of high energy levels, for instance the dynamical dipole emission, will be studied by changing the N/Z of projectile and target. Sub-barrier fusion processes will make use of proper neutron rich to investigate the tunneling process in presence of very positive Q-values, an issue interesting also for astrophysics.

As the cyclotron can supply two beams at the same time, a second independent facility can be operated. Interest has been already shown up by other communities. In particular, the high intensity proton beam could be used to produce innovative radioisotopes for nuclear medicine as well as neutrons in a wide energy spectrum, which, in turn, is interesting for measurements of neutron capture reactions of astrophysical interest.

The SPES layout is shown in figure 1; the ISOL facility is located in the white area, housing the cyclotron proton driver, the two RIB targets, the High Resolution Mass Spectrometer (HRMS) and the transfer lines. Two laboratories for applied physics and other applications are planned, which makes use of the Cyclotron proton beam.

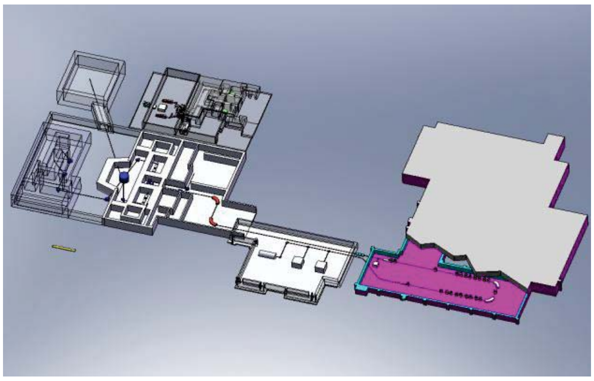

Fig. 1 The lay out of the SPES ISOL facility and connection to the re-accelerator.

The Target Ion-Source system

The interaction of the proton beam with the UCx target will produce fission fragments of neutron-rich isotopes that will be extracted by thermal motion and ionized at 1^+ charge state by a source directly connected with the production target.

The hot-cavity ion source chosen for the SPES project was designed at CERN (ISOLDE) [9]. The conceptual design is shown in figure 2.

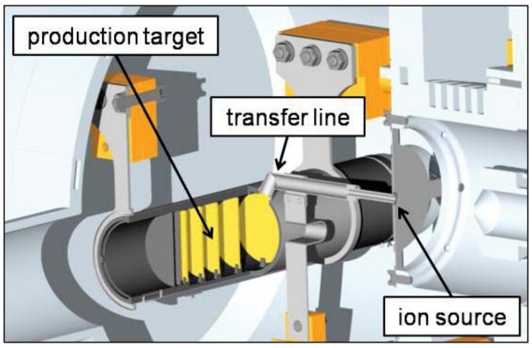

Fig. 2 Conceptual design of the SPES production target system.

The source has the basic structure of the standard high temperature RIB ion sources employed for on-line operation. The ionizer cavity is a W tube (34 mm length, 3 mm inner diameter and 1 mm wall thickness) resistively heated to near 2000°C. The isotopes produced in the target diffuse in the target material and after that will effuse through the transfer tube (its length is approximately equal to 100 mm) into the ionizer cavity where they undergo surface, plasma or laser ionization. Ideally those atoms should be ionized +1, then extracted and accelerated to 30-60 keV of energy and after that injected in the transport system. For alkalis and some rare earth elements high ionization efficiencies can be achieved using the surface ionization technique. The halogens have too high ionization levels and must be ionized by plasma ionization source. For most part of the others elements, the laser resonant photo-ionization, using the same hot cavity cell, is a powerful method to achieve a sufficient selective exotic beams. This technique is under study in collaboration with the INFN section of Pavia. To produce the large part of the possible beams three class of ion sources are under development at SPES: the Spes Surface Ion Source (SSIS), the Spes Plasma Ion Source (SPIS), the Spes Laser Ion Source (SLIS). In Figure 5 the areas of application of the different sources are shown.

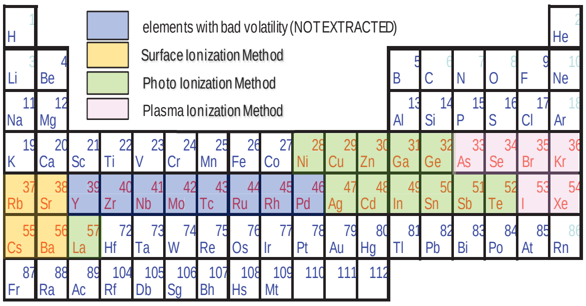

Fig. 5 The main isotopes that will be ionized and extracted in the SPES project.

An extensive simulation of the target behaviour for thermal and release properties is at the bases of the target-ion-source design. Experimental work to bench mark the simulations was carried out in collaboration with HRIBF, the Oak Ridge National Laboratory ISOL facility (USA).

Surface and Plasma ion sources

With the aim to characterize both SSIS and SPIS, a dedicated test bench delivering stable ion beams has been manufactured at LNL [2]. It is composed of three functional subsystems: the ion source complex, the beam optics subsystem and the diagnostic subsystem. In the first one 25 kV of potential difference between the ion source and the extraction electrode allows the ion beam generation. The aforementioned ion sources and the main accessories needed for their functioning and testing are shown in figure 1. During the tests both the ion sources were accurately positioned inside a vacuum chamber able to guarantee pressure levels between 10^{-5} and 10^{-6} mbar.

The SSIS is the first ion source tested at LNL for the SPES project: it is able to produce efficiently +1 ions for the elements with ionization potential smaller than 7 eV, mainly for the alkali and the alkaline earth metals (such as Rb, Cs, Sr, Ba). Efficiency values higher than 50% can be reached with this device. The SSIS is at present similar to the ISOLDE/CERN MK1 surface ion source. It is composed of a W tubular ionizing cavity (length, external diameter and internal diameter equal to 34, 5 and 3.1 mm, respectively) connected on one side to a Ta support and on the other one to the Ta transfer line [3]. The oven device represented in figure 1 is constituted by a 250 mm long Ta tube, with external and internal diameters of 2 and 1 mm, respectively; at one end a calibrated solution of the requested element is placed and hermetically sealed in, whereas the other end is connected to the transfer line and thus to the ion source. During operation the SSIS and the transfer line are resistively heated at temperature levels close to 2000°C. An independent power supply heats in a similar way the oven, allowing the atoms of interest (introduced with the calibrated solution) to effuse towards the ion source.

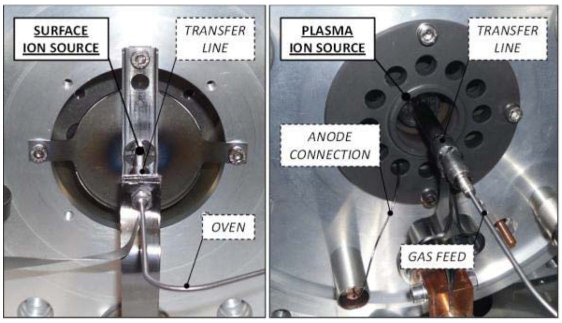

Fig. 3. The SPES Surface Ion Source (SSIS) and the SPES Plasma Ion Source (SPIS).

The SPIS (based on the principle of the FEBIAD ion source [6]) is the second source tested at the LNL test bench. It is a particular version of the ISOLDE/CERN MK5 source [4], a non selective device able to ionize a large spectra of elements, in particular noble gases. The main differences of the SPIS respect to the MK5 source are the following: the discharge chamber and the anode cylinder are made of tantalum instead of molybdenum, and the anode is electrically insulated thanks to three small cylinders made of Al_2O_3, avoiding the usage of BeO_2. In addition the SPIS is not thermally insulated by external molybdenum screens and the parts composing the cathode are connected by TIG welding instead of electron beam welding. A Ta wire connects the anode to the power supply used to increase its electrical potential respect to the rest of the source. The Ar beams provided for the preliminary study of the SPIS were produced thanks to a constant and regular Ar gas flow. It enters the vacuum chamber by means of a calibrated leak and then flows through a thin Ta tube in the direction of the Ta transfer line.

Ionization efficiency test

The test bench described in the previous paragraph is still under development. In particular the mass separator is not installed yet and it is not possible, at present, to select a particular mass and an ion charge state. In this context accurate ionization efficiency measurements cannot be performed. Waiting for more detailed sets of measurements to perform in the next future, some preliminary ionization efficiency estimations were done for Cs using the SSIS. Taking advantage of SSIS's selectivity and capability to produce exclusively singly charged ions, beam contaminants could be reduced to negligible quantities and the beam current monitored by the Faraday cup could be rapidly converted into an ion flux. Ionization efficiency for Cs was measured using calibrated Cs samples housed inside the oven (see figure 3). To perform this kind of measurement the SSIS's temperature was rapidly increased up to 2100°C. Then the oven was heated, allowing the Cs sample to vaporize, while the ion current was continuously recorded until the sample completely evaporated out of the source. The ionization efficiency was calculated as the ratio of the integrated number of detected ions to the total number of atoms in the calibrated sample. Some background tests (performed installing the oven without Cs sample and integrating the ion current) showed that contaminants can be considered negligible. An ionization efficiency value of about 51% was obtained, by far lower than the theoretical value of 95% calculated using the well known Saha-Langmuir equation [7]. This discrepancy (reported in other similar works [7]) seems to be strictly linked to the high volatility of Cs. In fact a considerable fraction of the Cs atoms could be lost during the positioning of the sample inside the oven and during the heating procedure, before the tungsten cavity is hot enough to ionize the atoms. During the tests the ion beam current was always kept between 1 and 3 µA. The extraction voltage ($V_{extraction}$) was fixed at 25 kV. Accurate ionization efficiency measurements (using the new Wien filter) for both SSIS and SPIS, will be performed in the next future.

Emittance measurements

Emittance measurements for the SSIS and the SPIS were made following the same approach proposed in [2]. In particular the root-mean-square (RMS) emittance for both SSIS and SPIS was monitored varying the extraction electrode position. Results are reported in figures 4 and 5. For both ion sources the minimum RMS emittance value was detected at about 75 mm of distance between the extraction electrode and the source extraction hole. The aforementioned results confirm data reported in [2] and [8].

During the SSIS emittance measurements a Cs beam of intensities between 350 and 400 nA was provided. A current of 360 A was set to heat the transfer line and the ion source. For the SPIS emittance tests a 1 μA Ar beam was kept stable for all the measurement time. The cathode current and the anode voltage (V_{anode}) were set to 330 A and 150 V, respectively. A current of 5 A was adopted to feed the anode magnet. For all the emittance measurements $V_{extraction}$ was fixed at 25 kV.

Numerical simulation of the ion beam extraction and emittance calculation for the Spes Plasma Ion Source

With the aim to study the SPIS beam extraction system, a set of numerical simulations has been done using the 3D Particle-in-Cell code named “F3MPIC”: it is a brand new electrostatic and electromagnetic code recently developed at CISAS for plasma simulations in complex geometries [5]. F3MPIC works in time domain, moving particles inside a volumetric mesh composed by tetrahedra. The tracking of particles inside the tetrahedra is done using a fast priority-sorting algorithm. Both charged and not-charged species can be simulated. Static and dynamic electromagnetic interactions among charged particles are treated consistently. At each time step the charge and the current densities obtained from particle motion is weighted on the vertex of the tetrahedra, and then the Poisson equation of Electrostatics, or the full set of Maxwell equations, are solved by means of the finite element method. The interaction of charged particles with neutral species is treated using the Monte-Carlo-Collision method.

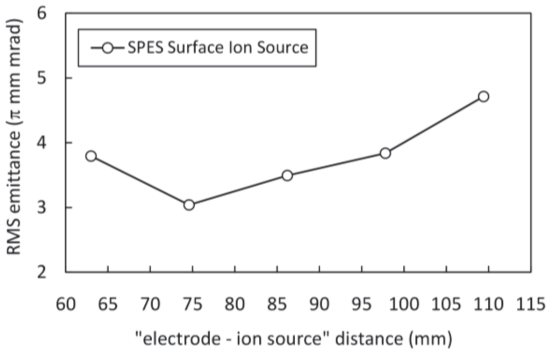

Fig. 4. Measured RMS emittance for the SPES Surface Ion Source.

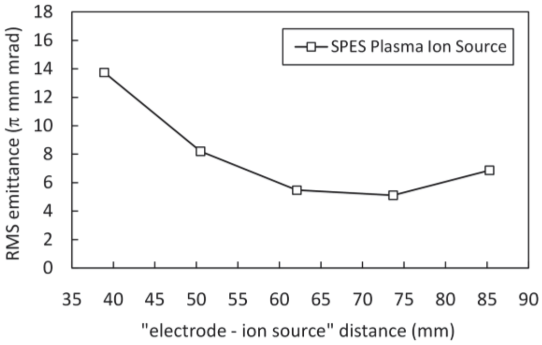

Fig. 5. Measured RMS emittance for the SPES Plasma Ion Source.

The SPIS has been numerically simulated with F3MPIC, using a two-species plasma of single-ionized Ar ions plus electrons. Both plasma species are treated in kinetic conditions, with typical time scales regulated by the fastest electrons species, corresponding to time-steps below the nano-second time scale. The equilibrium of the extracted Ar beam is then reached on time scales greater than 600 nano-seconds. Ions and electrons are generated inside the volume of the anode, with initial temperatures of T_i = 300 K and T_e = 1.0 eV. Ions are extracted by the potential difference of 25150 V ($V_{extraction}$+V_{anode}) between the anode and the extraction electrode. Figure 6 shows the simulation of the extracted ion beam in stationary conditions. Particle numerical diagnostic has been placed on a control surface after the electrode, where the electric field is small and the ion beam has already formed. Here the positions and velocities of particles have been recorded in order to obtain the beam properties of interest, in particular the RMS emittance.

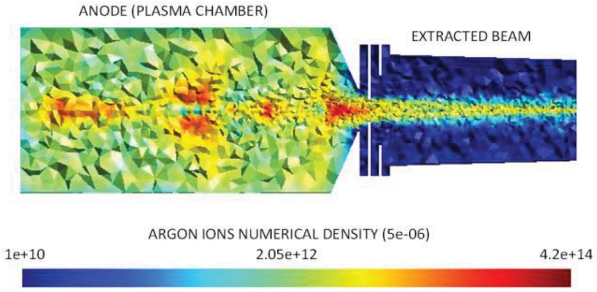

Fig. 6. Simulation of the SPIS extracted ion beam.

With the purpose to validate the code with experimental data, the RMS emittance for an "electrode – ion source" distance ($d_{extraction}$) of 38 mm was calculated; a value of 16.8 π mm mrad was obtained, in good agreement with the correspondent experimental value (13.7 π mm mrad, see figure 3). New simulations are in progress at CISAS to scan more values of $d_{extraction}$. Once the SPIS F3MPIC model will be validated in a more complete way, it will be used to optimize the beam extraction of the SPES ion sources.

Laser ion-source studies

At Spectroscopy Laser Laboratory of Chimica Generale in Pavia University studies about Aluminum laser photoionization were made using Optogalvanic Signal (OGE) in Hollow Cathode Lamp (HCL). We investigated two kinds of OGE signals: the slow or thermal and fast one, both obtained with a commercial Aluminum HCL manufactured by ISTC. The laser ionization path for Aluminum is the one color, two steps selective photoionization arising from laser wavelengths closed to 308 nm [10].

Pavia experimental setup

The Pavia experiment (figure 7) involves one Lambda Phisyk LPD 3002E dye laser pumped by 10 Hz Quanta System flash lamp frequency doubled Nd:YAG laser .

Fig. 7. Pavia Experimental setup.

The tunable dye laser radiation, once duplicated with a second harmonic generator Potassium Dihydrogen Phosphate crystal (KDP) in order to achieve the proper wavelength, is focused into the HCL through a 10 cm focal lens. Both optogalvanic signals are picked-up from the lamp power supply circuit. In these particular kind of set-up the HCL is used as atomic source. The atoms of Aluminum loaded into the cathode are sputtered by the atoms of the plasma which sustain the lamp discharge. Once sputtered, Aluminum atoms are available for spectroscopic investigations, while the power supply electric field separates charges when created and allows to collect OGE signals. In order to record the signals we use a boxcar averager and a USB6009 National Instruments datalogger to digitalize and store data on pc.

Pavia signals and results

Two kinds of signal are collected from these measurements.

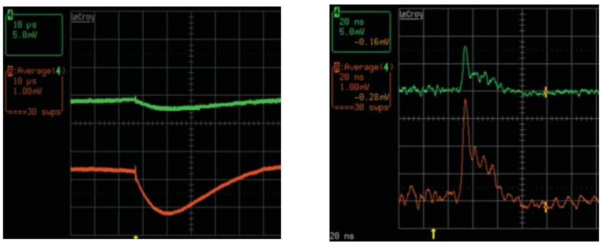

Fig. 8. Left: slow (10 μsec/div; 5 mV/div) OGE Right: fast (20 nsec/div; 5 mV/div) OGE.

1) Thermal or “slow” optogalvanic signal:

The laser resonant radiation is absorbed by the Aluminum atoms, modifying the Boltzmann distribution of electronic levels and in tens of microseconds a new momentary Boltzmann equilibrium holds up, including the ionization one. A change of discharge impedance occours, indeed. If laser radiation wavelength is off resonance its energy is not absorbed and the collected signal is zero. Temporal behavior of the signal is reported in figure 2, left.

2) “fast” optogalvanic signal:

In the particular case of Aluminum, two steps absorption of the laser radiation near 308 nm wavelength brings atoms to ionization. The first resonant absorbed photon excites the atom while the second one, with the same energy, ionizes the excited atom. In this phenomenon, electrons are immediately available as carries instantaneously modifying the lamp impedance, hence producing a signal. Ionization process persists tens of nanosecond following the laser pulse duration. Example of this signal is reported in figure 2, right. The “fast” OGE signal[4] is observable not only with Aluminum. The same process can also take place in other elements, with different colors and steps ionization schemes, as spectroscopic investigations suggest.

Photo-ionization in LNL hot cavity

The Aluminum ionization path verified in the HCL System can be used also in the framework of the SPES project in order to provide Aluminum ionization in a hot cavity.

In Legnaro we performed Aluminum ionization using the LPX200 excimer laser by Lambda Phisyk, charged with XeCl gas, lasing around 308 nm wavelength. The spectrally inhomogeneous laser radiation overlaps the absorption line of aluminum and tests are going on to control is selective photoionization occours. The Legnaro set-up (figure 9) involves the SPES front end apparatus. A small tantalum tube (oven) is charged by a calibrated amount of Aluminum and it is directly connected to the hot cavity of SPES system.

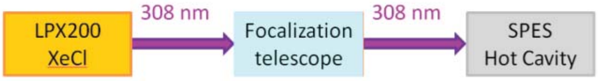

Fig 9. Legnaro Experimental Setup

Once heated the oven to 2000 °C it evaporates atoms of Aluminum which reach the hot cavity and are ready for ionization. Laser radiation, delivered by a focusing telescope 6 meter far away, enters in the 3 mm diameter hot cavity producing ionization. Ionized atoms are extracted by means of the 25 kV high voltage extractor and they are collected by a faraday cup.

Legnaro signals and results

The Faraday Cup (FC) current is the result of the ionization process in the hot cavity. In the normal operation of the front end system, the FC is inserted directly in front of the extractor, collinear to the ion beam after a quadrupole and an electrostatic lenses system.

In order to allow laser radiation to reach the hot cavity, it is mandatory to displace the FC from the laser beam propagation axes. The quadrupole and electrostatic lenses allow to collect anyway a signal. Figure 10 represents this setup: the red arrow symbolizes the laser beam path straight to the ion source, the green arrow indicates the ion beam path towards the faraday cup. Variations in the laser pulse energy or in the laser repetition rate directly affect the faraday cup current. These variations are proof of laser photoionization. The figure 11 represents the variation of the faraday cup current produced by the sweep in the frequency of the of the laser pulses (a) and the variation produced by two energy pulses set (b).

At the Pavia Spectroscopic Lab., we investigated atomic Aluminum absorption lines

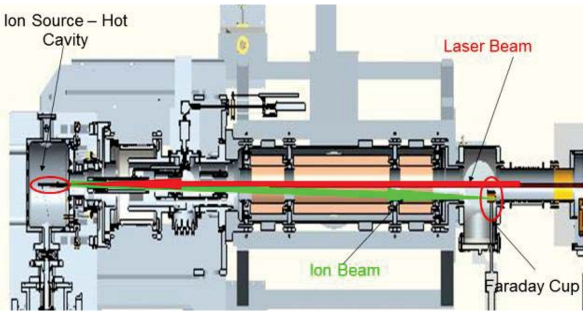

Fig. 10. Laser beam path (red) toward hot cavity vs Ion beam path (green) toward off center FC.

using tunable laser. Thanks to OGE signals a simple way in view of better understanding the spectral properties of photoionization on Aluminum atoms was pursuit with success. In Legnaro INFN National Lab, first laser photoionization was obtained with excimer XeCl laser, covering a possible ionization path for Aluminum. The results in the measured ion beam current allows to conclude that under laser action a ionization process takes place in the SPES hot cavity even if a complete system characterization is nowadays not possible. Further investigations using a mass separator will certify the selectivity of laser photoionization on Aluminum despite others atomic species present in the hot cavity, permitting ionization and transport efficiency measurements.

Acknowledgments

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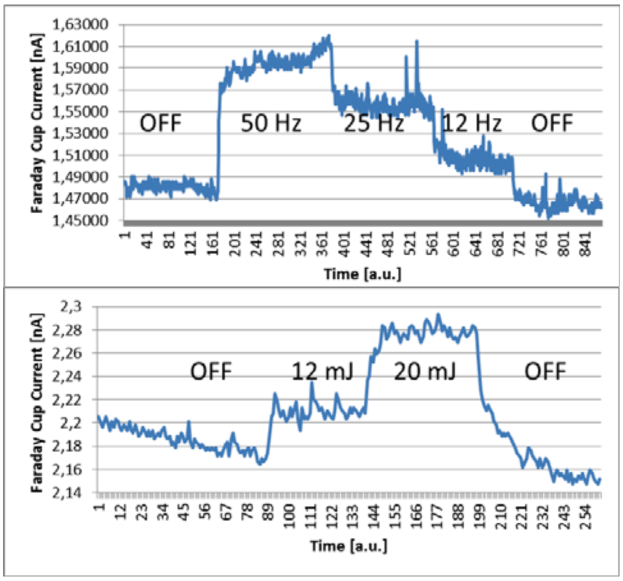

Fig. 11. Faraday cup current signal of ion collected under laser action in a) proportional to several repetition rate value, b) proportional to several energy pulse value.

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