EURISOL-DS Project

Deliverable D4/M3.2

Design of 1+ Ion Source Coupling

First Design of the Resonant Ionization Laser Ion Source

For the Multi-Mega Watt Target Station

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Abstract

The realisation of next-generation ion sources suitable for the EURISOL multi-mega-watt (MMW) target station needs exhaustive studies and developments. An exhaustive review was carried out to evaluate the capability of the ion-sources to operate under the irradiation conditions of the MMW target station. In addition, selectivity must be taken into account to avoid the spread of unwanted radioactivity out of the target-ion-source system (TIS).
These studies led to consider RILIS (Resonance Ionization Laser Ion Source) as the reference ion source for this target station.

Introduction

EURISOL is a future accelerator-based research facility using the ISOL (Isotope Separation On Line) technique to produce radioactive ion beams (RIB). The multi-mega-watt target station (MMW TS) of EURISOL is particularly dedicated to the production of nuclear beams obtained from fission induced by fast neutrons. To achieve highest yields, the neutron flux is generated by the interaction of a multi-mega-watt proton beam on a heavy metal (mercury) converter. Then the generated neutrons induce fission in dedicated Uranium Carbide targets.

The radioactive species produced from the targets are ionized, extracted and mass-separated to obtain high quality beams of isotopes. The isotopes can be delivered directly to low energy experimental facilities, or they can be post-accelerated.

The purpose of such a device is the study of exotic nuclei that is often hampered either by low intensity of these nuclei or the overwhelming presence of unwanted species in the beam. In that sense, the development of a Resonant Ionization Laser Ion Source (RILIS) to efficiently and selectively ionize these elements is of main importance for the next generation of radioactive ion beam facilities.

The popularity and demand for laser ion sources arise from the extreme isobaric purity, production efficiency and beam time structure these sources can achieve. These specifications are inherent to the technique applied for RILIS in which neutral atoms are resonantly excited by one or two consecutive steps and finally ionized by laser lights. These resonant multi-step excitation paths are unique to each particular element.

Up to now, about 80% of the elements can be ionised by RILIS. As developments continue, the list should get longer. Existing lasers already allows competitive ionisation efficiencies, from a few percent up to beyond 50%. Progress on laser technology are such that even CW lasers could be expected within the next ten years. Nevertheless, such a technology depends on demands from industry, which are so far satisfied by pulsed lasers.

Two kinds of laser production systems are in operation at ISOL facilities: dye laser systems which have been used on-line for many years at ISOLDE (CERN) [Fed00, Mis93], JYFL (Jyväskylä, Finland) [Moo05], LISOL (Leuven, Belgium) [Kud03] and at ALTO (IPN Orsay, France), and solid-state Titanium-Sapphire (Ti:Sa) laser systems that have been developed more recently and made available mainly by University of Mainz (Germany) [Yi03]. They are currently used on line at ISAC (TRIUMF, Canada) [Las09] and JYFL (Jyväskylä, Finland) [Moo05].

This report covers the first design of the RILIS which includes the laser and optical systems from the laser pump to the fission target which is 17 m away.

Description of the RILIS for EURISOL MMW station

The design is based on the option of six Uranium Carbide fission targets around the converter so six RILIS will be developed.

In parallel with the six on-line RILIS (ONL RILIS), one off-line RILIS (OFL RILIS) is dedicated to the R&D activities in order to test new schemes of transition, new dye solutions and to perform efficiency measurements.

We can see on figure 1 the six ONL RILIS and the OFL RILIS in their environment.

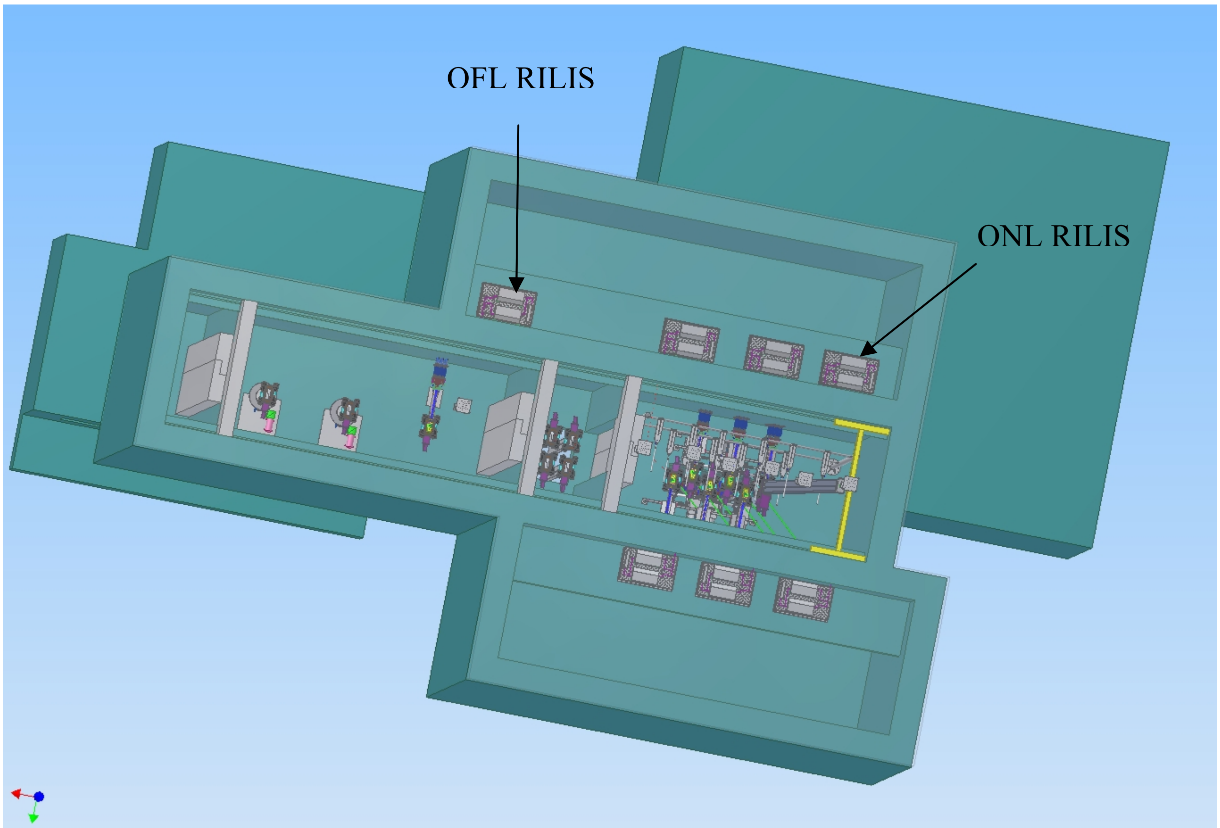

Figure 1: Layout of the 6 + 1 RILIS.

As shown on figure 2, each RILIS is composed of:

- 1 laser pump for the optical pumping of each laser,
- 2 or 3 lasers, depending on the ionization scheme chosen, to generate the excitation and the ionization step.

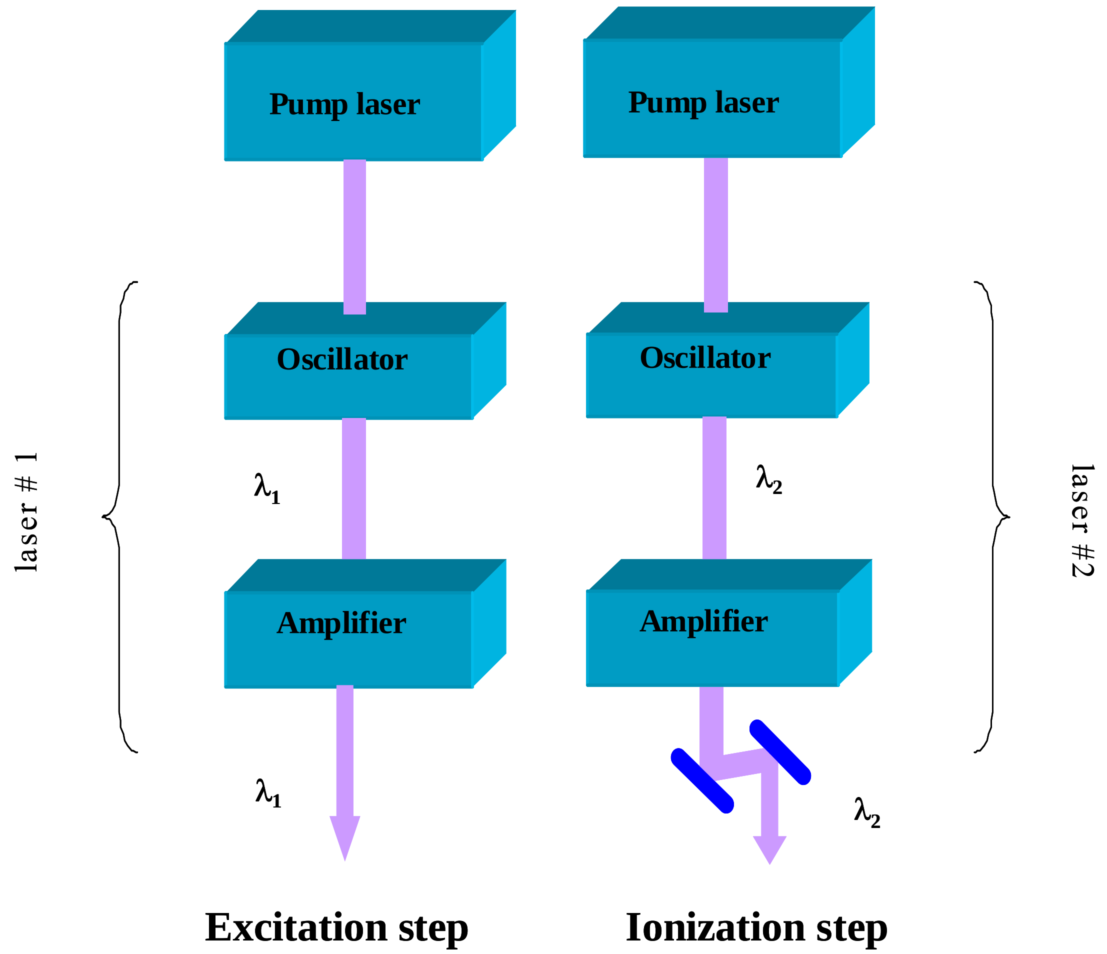

Figure 2: Basic lasers scheme of a RILIS (2 levels ionization).

Characteristics of the laser pump

Two kinds of laser pump are currently used for the RILIS:

- Diode pumped Nd:YAG laser at 532 nm,
- Copper Vapour Lasers (CVL) at 511 nm and 578 nm.

For dye laser pumping, the advantages of CVL are the short pulses delivered (20 ns) and two pumping wavelengths but an expensive price and a lack of reliability are the main disadvantages. Recent development on Nd:YAG pulse duration gave results equivalent to the CVL.

For the RILIS of the MMW TS, we need one laser pump for each laser in order to supply enough power (typically 150 W). Moreover we will apply ourselves to have the highest repetition rate and so the most important efficiency rate.

Characteristics of the lasers

Two kinds of tunable laser systems are used for the RILIS:

- Dye lasers,
- Solid-state Titanium-Sapphire (Ti:Sa) laser systems.

Dye laser and Ti:Sa do not cover the same range of wavelength. Then a complementarity can be seen between these two laser systems. Notably, the last transition to autoionizing state (AIS) or continuum does not fall for all atoms in a convenient spectral range, considering one or the other laser system. A broad spectral range where we can produce powerful and wavelength tunable laser beams is a main advantage.

The use of one or an other system influences the characteristics of the laser pump: for dye lasers, pulse length must be the smallest possible and not exceeds 80 ns; whereas pulse length must be over 80 ns to properly pump Ti:Sa lasers.

An advantage of the Ti:Sa laser is the low maintenance of the crystal compared to the dye solution. Nevertheless, the crystals have to be changed after one or two weeks of operation. This has to be considered in case of experiment exceeding such a period. The other main advantage is the absence of chemical hazard. On the contrary, for dye laser, the use of a few chemical products in accordance with safety rules may be delicate.

Currently, with dye lasers the average power on fundamental wavelengths can be quite high. It reaches 19 W for the RILIS at ISOLDE-CERN [Fed09] while Ti:Sa average power hardly exceed about 6 W. Considering the complementarity of the two laser systems, a setup combining dye and Ti:Sa lasers could cover a range of 540 900 nm with multi-Watt beams. Then second and third harmonics can be used for 210 460 nm. If the dye pump laser can generate a 355 nm beam, the range of 400 540 is covered with dye laser fundamental beam so that no spectral gaps are left. For the last transition, at ISOLDE-CERN a pump laser green beam is frequently used. In principle, the same operation is possible with Ti:Sa. So for a setup combining dye and Ti:Sa lasers, a dye pump laser could be used for the transition-to-continuum step and Ti:Sa lasers for the first or second step [Fed09].

All these arguments lead us to consider for the MMW target station a laser configuration including for each RILIS (7 in total): 4 Nd:YAG pump lasers, 2 dye lasers and 2 solid-state lasers, (Ti:Sa for example). Such a configuration allows to obtain efficiently the largest number of selective ionization schemes.

Example of the laser systems used at ALTO for the production of copper beam

The scheme used (cf. figure 3) was that developed at ISOLDE by RILIS [Kös00]: 327 nm for the excitation step and 288 nm for ionization (using an auto-ionizing state).

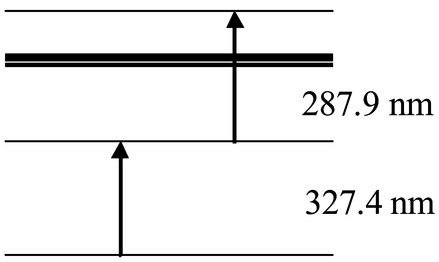

Figure 3: The 2 levels ionization scheme for Cu.

The laser system consists in a 150 W 20 kHz Nd:YAG laser at 532 nm pumping two or three dye lasers depending on the ionization scheme chosen (cf. figure 4).

To generate these two wavelengths, two commercial Lambda Physik FL3002 dye lasers are used. They both are composed of an oscillator with a preamplifier and one or two amplifiers.

The laser pump has two exits, both vertically polarized. With 60% of the total power, the first one is used for the ionizing wavelength and the remaining 40% of the second one is use for the excitation step.

To generate the 327 nm, we used DCM dissolved in DMSO at 0.32 g/l that produces a beam at 654 nm. The red is frequency doubled with a coated BBO crystal to obtain 327 nm. With 48 W of 532 nm, 2 W of red are obtained producing 100 mW of UV after the BBO crystal.

This power is sufficient to saturate the first resonant step.

For the 288 nm, we used Rhodamin 6G dissolved in methanol at 0.14 g/l producing a beam at 576 nm. The yellow is frequency doubled with a coated BBO crystal to obtain 288 nm. With 72 W of green, 10 W of yellow were obtained producing 1 W of UV.

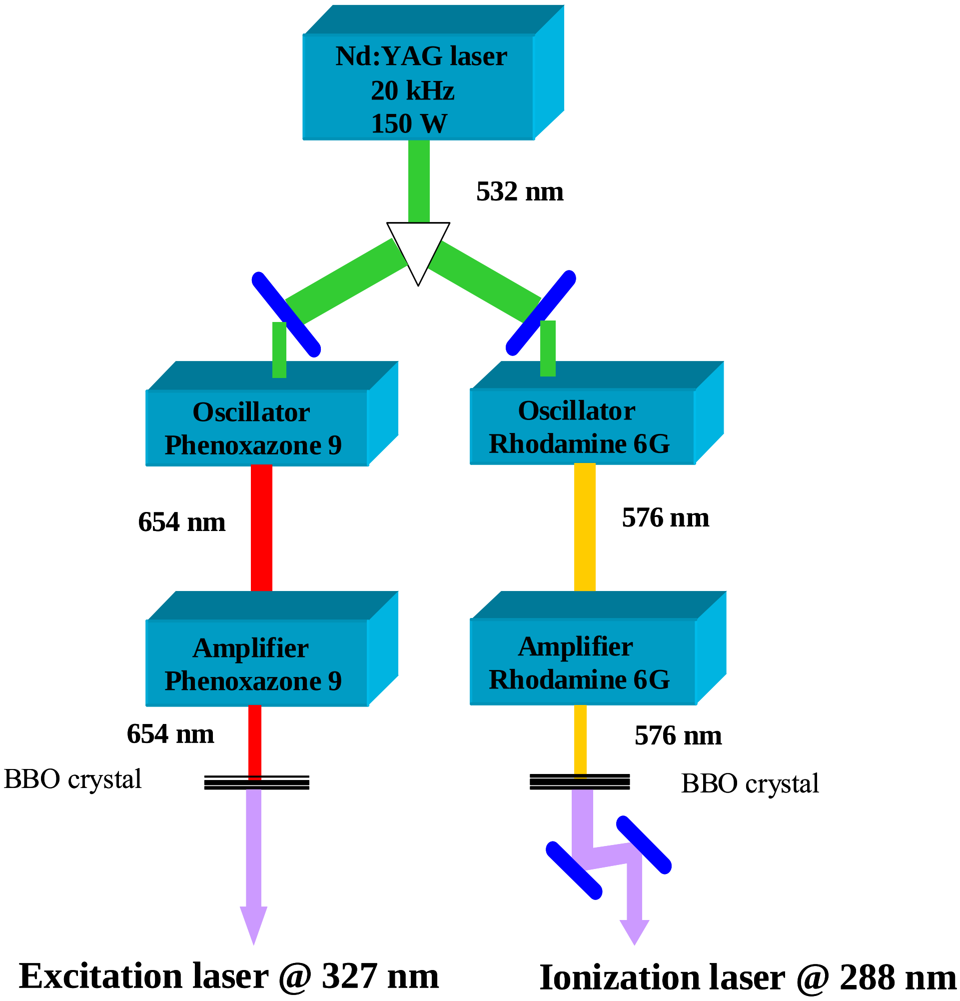

Figure 4: Laser System at ALTO for Cu beam.

After passing through a telescope behind each doubling crystal, the two beams are sent at 17 m in the ion source of ALTO as recovering two spots of 3 mm diameter.

The beam transport: a critical point

The transport of the laser beams from their production place to the ion source body is very critical, as losses in transmission might directly convert into corresponding losses in ionization efficiency, if the laser beam intensities are weak.

In addition, the final part of the path located in the area of the production cave, will not be accessible in on-line conditions. That is why the laser beam transport line has to be developed with fully automatic beam position monitoring and remote transport optics readjustment. Such a development has to take into account radiation resistance of the sensitive elements such as optical elements. For instance, the strong resistance of quartz windows must be checked for the safe operation of the MMW target station. The development also has to integrate the various safety procedures for maintenance and breakdown fixing.

Several laser beam feedback control system systems exist from New Focus© or Thorlabs© and are composed of quadrant-cells photoreceivers and mirrors controlled (x and y axis) by picomotors. The signals of the photoreceivers are analysed and if necessary, orders are sent to the motorised mirrors to readjust the position of the laser beam. It can control the position to within 10 µm.

Efficiency measurement

To estimate the efficiency, a technique consists in measuring the atom flow from the ionisation tube at a known temperature and the number of detected ions produced by the laser beams.

The atom flow was measured off-line using a quartz microbalance. A copper sample is heated and the atom flow effusing out of the ionisation cavity is deposited on a quartz crystal. The thickness of the coating is measured using the resonance of the quartz. Under a certain potential, the quartz is resonant at a certain frequency that varies with the copper deposited thickness. We measure this frequency variation that is directly linked to the number of collected atoms. This technique allows off-line efficiency measurements to be performed on new ionization schemes before utilizing them for on-line experiments.

Another other way of measuring the efficiency of the laser ion source is to implant at low energy a certain amount of a stable isotope in a metal foil. This sample is put in the ion source and the implanted atoms are heated and laser ionized. The production is measured until the sample is empty and one thus deduced the efficiency.

Ionization efficiency can also be deduced on-line for an element if the in-target yield of one of its radioactive isotopes is determined, and the target-release efficiency is known or very high. Table 3 sums up the efficiency of typical ions produced at ISOLDE (CERN) [ISO].

Elements	**Efficiency**
Be	≤ 7 %
Mg	≤ 9.8 %
Ca	≤ 0.45 %
Sc	≤ 15 %
Mn	≤ 19 %
Cu	≤ 7 %
Zn	≤ 4.9 %
Ga	≤ 21 %
Al	≤ 0.1 %
Ag	≤ 14 %
Cd	≤ 10.4 %
In	≤ 0.1 %
Sn	≤ 9 %
Sb	≤ 2.7 %
Au	≤ 0.1 %
Hg	≤ 0.1 %
Tl	≤ 21 %
Pb	≤ 3.1 %
Bi	≤ 6 %
Tb	≤ 0.1 %
Dy	≤ 20 %
Yb	≤ 15 %
Ni	≤ 6 %
Y	≤ 0.1 %

Table 3: Elements produced at ISOLDE (CERN) with RILIS technique and their efficiency

Developments on the ionisation cavity

Today's RILIS is high-performance ion source with the major advantages of selectivity, element choice and the distance of sensitive parts. For instance, at ISOLDE-CERN, 50% of all the beam time involves RILIS. However, efficient operation under the MMW target station still has to be investigated. Indeed the target thickness is one order of magnitude larger and the aimed intensities for radioactive beams are up to three orders of magnitude higher.

Concerning high-current operation, at ISOLDE-CERN, on-line RILIS shows no evidence of efficiency drop up to an extracted beam of 100 nA, and this is not an upper limit. Furthermore, even in the case of yields over 10^{14} fissions/s, pure radioactive beam intensity should remain significantly below 1 μA with RILIS, due to selective ionisation. However, total extracted beam can reach much higher intensities by the production of unwanted ions. In particular, the production of alkali ions by surface ionization can easily make up a serious beam contamination. Such a contamination is all the more severe as Rb and Cs isotopes are abundantly produced by fission. Developments on ionization cavity material have been initiated to minimize surface ionization, as well as developments on processes to trap the alkalis.

However, even if RILIS selectivity can be preserved through such developments, the important vapour from the fission target system at temperature above 2 000 °C to the ionization cavity can alter the efficient operation of the RILIS. Indeed, if the pressure in the hot ionization cavity is high, it alters the plasma confinement. In high-charge-density plasma, positive ion confinement is reduced if the electron emission is not sufficient. Material with low work function for the ionization cavity may help as long as the vapour released in the cavity does not chemically degrade the cavity surface. In addition, depending on the selected ionization schemes and the laser power, non-resonant ionization can be more or less negligible. Be it as It may, to work out a proper ionization cavity for RILIS operation with the MMW target station, extensive developments are required. Various technologic solutions are promising. For instance, for plasma confinement, electron emission can be induced by a IRENA-like system or similar options.

Acknowledgements

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