5 ISOLDE laser ion source—status and development

Valentin Fedosseev

5.1 Introduction

Following the off-line development of the Resonance Ionization Laser Ion Source (RILIS) [1], the installation of a permanent laser ion-source at the PS-Booster ISOLDE was proposed in 1993 by the CERN–Daresbury–Leuven–Mainz–Oslo–Troitsk Collaboration as “Request for implementation and further development of the ISOLDE laser ion-source” (ISC/P47). The laser equipment was supplied from Troitsk as their contribution to the ISOLDE programme. It included three copper vapour lasers (CVL) operating in the Master Oscillator – Power Amplifier (MOPA) mode, three dye lasers, and a set of optical and mechanical components for laser beam control and focusing. The first physics run with the use of RILIS was carried out in 1994 (IS333: Neutron-rich silver isotopes produced by a chemically selective laser ion-source: test of the r-process ‘Waiting-Point’ concept). Since that time the output MOPA power increased from 40 W to 80 W by the implementation of laser tubes with higher power and a modernization of the laser power supplies. In addition, the wavelength tuning range was extended with the use of new dyes as well as by generating the second- and third-harmonic beams (Fig. 5.1).

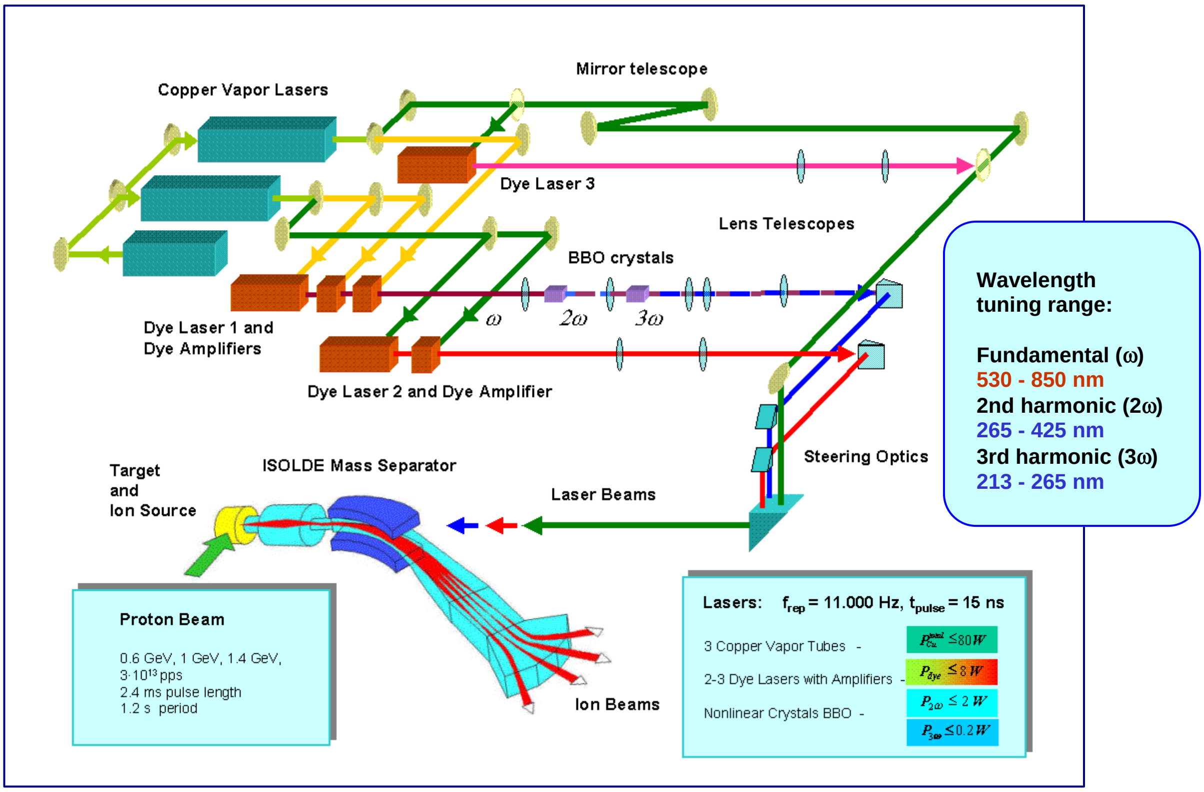

Fig. 5.1: Simplified scheme of the ISOLDE RILIS

The operation of the RILIS was provided exclusively by resources of the ISOLDE Collaboration until 1 April 2000. After the transfer of the technical part of ISOLDE to PS Division, the RILIS system became a CERN operated setup. Currently the operation of RILIS is under the responsibility of the LPE (Laser, Photocathodes and Equipment Controls) section of the AB/ATB group. During the physics runs an on-shift service of CERN staff and external specialists is traditionally supported by the ISOLDE Collaboration and by the Petersburg Nuclear Physics Institute (PNPI), where a similar laser ion source has been operated since 1989 [2]. RILIS has become the most frequently requested type of ion source within the ISOLDE community and its annual operation time has risen to the level of 1800–2000 hours.

Data on evolution of the RILIS annual operation time together with the indication of ionized elements are presented by the diagram in Fig. 5.2.

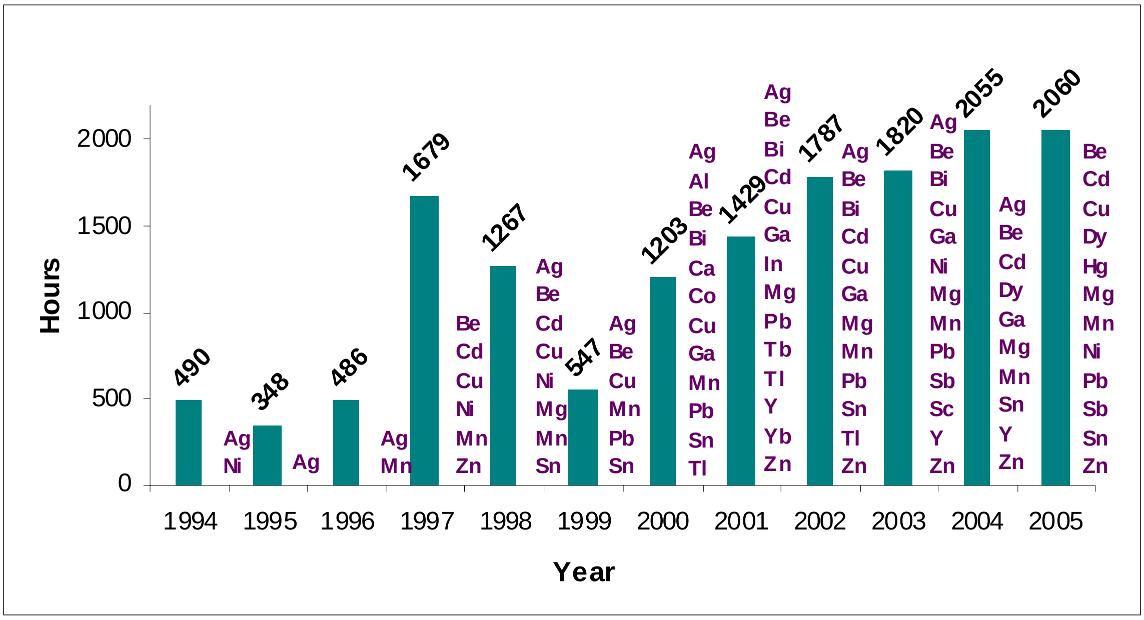

Fig. 5.2: Annual operation time of the RILIS laser setup and produced ion beams

A major upgrade and consolidation programme of the RILIS has been proposed recently to INTC with the letter of intent [3]. The main stages are

a) the upgrade and development of the RILIS laser setup with the implementation of solid-state lasers replacing the existing copper vapour lasers;

b) the development of new resonance ionization schemes by using a dedicated laser spectroscopy setup;

c) research on improvement of the RILIS selectivity by investigation of new hot cavity materials and by implementation of a so-called laser ion source trap (LIST) [4].

Extending the range of elements available at RILIS and the optimization of ionization schemes is an important direction of RILIS development. To this purpose the setting up of an independent laser spectroscopy laboratory is under way at CERN within the LPE section. It is already equipped with two sources of wavelength tunable laser radiation in the form of low pulse repetition rate Optical Parametric Oscillators (OPOs) pumped by SSL. For the resonance ionization spectroscopy, a vacuum chamber with an atomic beam source and detection system is to be added.

The hot cavity of the RILIS acts also as a surface ion source. The presence of surface ionized isobars at certain masses deteriorates the selectivity of the laser ion source. Therefore, the task of improving RILIS selectivity is very important. For the existing RILIS an optimization of the cavity construction can bring some positive results. An alternative approach to this problem has been suggested recently as a laser ion source trap (LIST). This source is based on a gas-filled linear radio-frequency quadrupole ion trap. At present the construction of LIST is under development in Mainz University and it is expected to be tested eventually at ISOLDE.

Research and development work related to RILIS is currently going on as part of the Joint Research Activity LASER in the frame of the EU Sixth Framework Programme EURONS. The equipment needed for the RILIS upgrade and the laser spectroscopy laboratory will be funded by a grant from the Knut and Alice Wallenberg Foundation (Sweden).

5.2 Upgrade and development of RILIS laser system

The RILIS laser system is old and reliant upon components that are no longer readily available. The basic equipment—the CVL and dye lasers—was manufactured 15 years ago. The stability of CVL operation has been recently improved with the replacement of the old DC high voltage power supplies by stabilized arc-protected power sources. The CVL oscillator has been entirely replaced by a new laser. A further improvement of the laser operating conditions was achieved in 2005 with the set-up of a demineralized water system for the laser cooling. Still, maintenance and operation of the RILIS requires substantial efforts. The stable performance of the RILIS setup is of great importance for the ISOLDE facility, therefore all possibilities for upgrading the RILIS lasers had to be considered in order to define an optimal way. In particular, the following scenarios were discussed:

- Replacement of the old CVL by new CVL available on the market
- Replacement of the CVL by solid-state lasers
- Creating a new fully solid-state laser system

Finally, it was concluded that it would be feasible and favourable for the improvement of RILIS functionality to implement industrial solid-state lasers (SSLs) as a replacement for the copper vapour lasers.

Currently there are two CVL beams each with average power up to 40 W, running synchronously at the pulse repetition rate of 11 kHz with a pulse duration of 15 ns. Depending on the ionization scheme, the CVL beams are split on several paths in order to pump dye lasers and dye amplifiers. In most ionization schemes one CVL beam is used for the excitation of a non-resonant transition to the atomic ionization continuum. For that the CVL beam is focused to a 3 mm diameter spot (the opening hole diameter of the ion source cavity) at a distance of 25 m from the laser setup. Actual divergence and aberrations of the CVL beam limit the power delivery efficiency to less than 50%. With the use of a green solid-state laser with similar parameters in terms of pulse rate and power, but with a higher beam quality, it is expected that the RILIS efficiency can be considerably improved.

The SSL system for RILIS will employ either two or three independent lasers operating synchronously with a relative pulse timing jitter less than 3 ns (r.m.s.) or by a single laser assembly with two or three output beams. The following beams are required from the SSL system:

Beam A (high-quality green beam for non-resonant ionization):

Pulse repetition rate	8–15 kHz
Pulse duration	10–30 ns
Output pulse timing jitter	< 3 ns
Average power (532 nm or similar)	40 W
Power stability	+/– 5% over 24 hours
Beam divergence	< 0.1 mrad after expanding to 20 mm diameter
Beam pointing stability	< 0.02 mrad after expanding to 20 mm diameter

In the present setup one CVL beam is used for pumping dye lasers. The CVL output is composed of two wavelengths—511 nm and 578 nm. This limits the wavelength range of dye lasers to 525–860 nm. By using frequency doubling and tripling techniques the tuning range is complemented by 213–420 nm. Still the gap 420–525 nm is difficult to reach. A possible way to improve the spectral range coverage is the use of a shorter (UV) wavelength for dye laser pumping.

As usual, several wavelength tuneable beams are applied for resonance ionization and one or two of those are in the yellow–red part of the spectrum where green pumping is sufficiently efficient. Therefore, a solid-state laser providing simultaneously beams at second and third harmonics would be an advantage. The beam quality for transverse pumping of dye lasers is less important, thus a multimode output is acceptable. The requirements for these beams are as follows:

Beam B (medium-quality green beam for dye laser pumping):

– Pulse repetition rate	8–15 kHz
– Pulse duration	10–20 ns
– Output pulse timing jitter	< 3 ns
– Average power (532 nm or similar)	30–40 W
– Power stability	+/– 5% over 24 hours
– Beam quality parameter M^2	1–20

Beam C (medium-quality UV beam for dye laser pumping):

– Pulse repetition rate	8–15 kHz
– Pulse duration	10–20 ns
– Output pulse timing jitter	< 3 ns
– Average power (355 nm or similar)	15–20 W
– Power stability	+/– 5% over 24 hours
– Beam quality parameter M^2	1–20

This equates to a total laser power increase from 80 W to about 100 W. The availability of a UV pump beam will enable dye laser emission across the entire visible spectral range and facilitate the generation of tuneable UV light. It will give more flexibility in the choice of optimal ionization schemes. Consequently, the RILIS efficiency will be increased.

An important requirement is a capability of all three SSLs to run synchronously with a relative light pulse jitter of less than 3 ns. For this purpose a special master clock unit for q-switching of all three lasers with precise phase and delay control is to be foreseen as part of the new laser system.

For operational and maintenance aspects, SSLs are preferred: they do not require a long preheating time, the power supply control is relatively simple, the level of electromagnetic noise is much lower with respect to CVL, and the lifetime of active elements can exceed 10 000 hours.

5.3 Development of new ionization schemes

Development of the RILIS was aimed mainly at extending the range of the elements available with RILIS. Ion beams of 26 chemical elements have been produced with the RILIS at ISOLDE during the period 1994–2005. The results of this development are summarized in Table 5.1.

Table 5.1: Ion beams produced at ISOLDE RILIS. E_i – ionization energy; $\lambda_{1,2,3}$ – optical transition wavelengths at first, second and third steps; η_{ion} – ionization efficiency.

Element	E_i (eV)	λ_1 (nm)	λ_2 (nm)	λ_3 (nm)	η_{ion} (%)	Produced isotopes, mass numbers
Be	9.32	234.9	297.3	–	>7	7, 9–12, 14
Mg	7.65	285.2	552.8	578.2	9.8	23–34
Al	5.99	308.2, 309.3	510.6, 578.3	–	>20	26–34
Ca	6.11	272.2	510.6, 578.3	–	0.45	Stable
Sc	6.56	327.4	719.8	510.6, 578.3	15	Stable
Mn	7.44	279.8	628.3	510.6	19	48–69
Co	7.88	304.4	544.5	510.6, 578.3	>3.8	Stable
Ni	7.64	305.1	611.1	748.2	>6	56–70
Cu	7.73	327.4	287.9	–	>7	57–78
Zn	9.39	213.9	636.2	510.6	4.9	58–81
Ga	6.00	287.4	510.6, 578.3	–	21	61–85
Y	6.22	414.3	662.4	510.6		Stable
Ag	7.58	328.1	546.6	510.6	14	101–129
Cd	8.99	228.8	643.8	510.6	10.4	98–132
In	6.00	303.9	510.6, 578.3	–		100–135
Sn	7.34	300.9	811.4	823.5	9	103–137
Sb	8.61	217.6	560.2	510.6	2.7	128–138
Dy	5.94	625.9	607.5	510.6	20	Stable
Tb	5.86	579.6	551.7	618.2		149
Tm	6.18	589.6	571.2	575.5	>2	Stable
Yb	6.25	555.6	581.1	581.1	15	155–178
Au	9.23	267.7	306.6	673.9	>3	Stable
Hg	10.44	253.7	313.2	626.5		Stable
Tl	6.11	276.8	510.6, 578.3	–	27	179–200
Pb	7.42	283.3	600.2	510.6, 578.3	>3	182–215
Bi	7.29	306.8	555.2	510.6, 578.3	6	188–218

The experimental work to search for ionization schemes was carried out using the existing RILIS setup at the ISOLDE on-line facility (except Yb, Tm, Sn and Ni, for which ionization schemes have been found at the Institute of Spectroscopy [5, 6] and at Mainz University [7, 8]). Since time periods for such studies have usually been limited to a few weeks of the annual winter accelerator shutdown, results obtained are not always fully satisfactory concerning the completeness of spectroscopic research and the ionization efficiency achieved. In particular, a non-resonant transition to the ionization continuum is used as the last step of atomic excitation for most schemes. Using schemes with transitions to autoionizing states could in many cases improve the ionization efficiency but the search for such transitions requires roughly an order of magnitude more time than it has been possible to allocate.

Development of ionization schemes for new elements and the optimization of schemes for available RILIS elements could be more efficient using a dedicated laser spectroscopy setup. For this purpose a laser equipment setup used for resonance ionization spectroscopy at CEA Saclay has been purchased by AB/ATB. It includes

I. **Spectra Physics Quanta-Ray PRO 230-10 –** Nd:YAG laser specified for pulse repetition rate 10 Hz with the following outputs: 1064 nm – 1250 mJ/p; 532 nm – 650 mJ/p; 355 nm – 375 mJ/p; pulse width 8–12 ns.

II. **Spectra Physics MOPO-HF –** optical parametric oscillator based on a BBO crystal pumped by 355 nm with output energy of 40 mJ (at 500 nm); signal tuning range: 450–690 nm; idler tuning range: 735–1680 nm; pulse width: 6–10 ns; linewidth: 0.075 cm^{-1}.

III. **Continuum Powerlite 7010 –** Nd:YAG laser specified for pulse repetition rate with following outputs: 532 nm – 400 mJ/p; pulse width 5–8 ns.

IV. **Continuum MIRAGE 800 –** optical parametric oscillator based on KDP or KTP crystals pumped by 532 nm with output energy of 60 mJ (at 800 nm with 300 mJ pump); signal tuning range: 720–920 nm; pulse width: 5 ns; linewidth: 0.02 cm^{-1}.

V. **Continuum UVT-1** – frequency doubler based on KDP and BBO crystals with tuning range of 360–450 nm; pulse energy - 10 mJ at 400 nm (BBO).

Thus, two sources of tuneable radiation are available. In order to study schemes with three-step resonance excitation of autoionizing states a third laser (preferably OPO) is needed. The interaction of laser beams with atoms under investigation will take place in a vacuum. The simplest way is to use a vacuum chamber with a source of atomic beam and an ion detector (secondary electron multiplier). The commonly used resonance ionization spectroscopy techniques of laser ablation and time-of-flight mass spectrometry could also be implemented. This and other laboratory equipment including laser wavelength meter, optics and opto-mechanics, electronics, etc. will be purchased during 2006–2007.

5.4 Improvement of RILIS selectivity

The selectivity of the laser ionization process itself, defined as the number of ions created when the lasers are tuned on resonance versus off resonance, is at least several orders of magnitude. In the hot cavity approach the selectivity is compromised by the presence of surface ionized elements.

It has been shown [1] that surface ionization can be reduced by using cavity materials with low work function, in particular TaC. Unfortunately, available samples of this material were rather fragile and no reliable construction of an RILIS cavity was designed. Therefore, only cavities made of tungsten and niobium have been used so far for on-line experiments with RILIS. At present, new samples of TaC and other materials traditionally used as electron emitters (LaB_6, Ir_5Ce) are available for testing. The functionality of the ion source cavities based on these materials should be initially studied using an off-line mass separator. At the ISOLDE off-line separator no lasers are installed. It is possible to carry out such tests at Mainz University, where a laser setup for resonance ionization spectroscopy is installed near the RISIKO mass-separator with a front-end capable of accepting ISOLDE target units. Some tests could also be planned at the IRIS facility in PNPI (Gatchina, Russia). Following positive results from the off-line experiments it will be possible to work on the implementation of successful solutions in the ISOLDE target–ion source construction.

A substantial gain in selectivity is expected from the new and totally different concept based on a gas-filled, linear radio-frequency quadrupole (RFQ) ion trap [4]. The idea of this so-called laser ion source trap (LIST) is to block the unwanted ions from the hot cavity using an ion repeller whilst allowing the atoms to freely expand in an RFQ trap where atoms of interest are laser-ionized with a high repetition rate laser. The first results obtained with the LIST prototype at Mainz are very promising. As the next step we propose to adapt the LIST to the ISOLDE target and front-end requirements and carry out a thorough investigation at the off-line mass separator.

5.5 Conclusion

Owing to the strong advantage in selectivity of laser ionization, RILIS is an indispensable asset for the ISOLDE users’ community. With the laser hardware in its present conditions it is practically impossible to satisfy constantly increasing demand for RILIS. The fundamental upgrade of the laser system as well as the acquisition of equipment for regular laser spectroscopy research required for RILIS development is now feasible on receipt of a grant from the Wallenberg Foundation.

For the research on selectivity improvements, the fabrication of test and prototype models of the ion source cavity as well as off-line experiments at different facilities are foreseen. The advantages of the LIST concept are to be confirmed via testing at the ISOLDE off-line mass separator.

References

[1] Chemically selective laser ion-source for the CERN-ISOLDE on-line mass separator facility. V.I. Mishin, V.N. Fedoseyev, H.-J. Kluge, V.S. Letokhov, H.L. Ravn, F. Scheerer, Y. Shirakabe, S. Sundell, O. Tengblad, the ISOLDE Collaboration, Nucl. Instrum. and Meth. Phys. Research B **73** (1993) 550.

[2] Application of a high efficiency selective laser ion source at the IRIS facility. G.D. Alkhazov, L.Kh. Batist, A.A. Bykov, V.D. Vitman, V.S. Letokhov, V.I. Mishin, V.N. Panteleyev, S.K. Sekatsky, V.N. Fedoseyev, Nucl. Instrum. and Meth. Phys. Research A **306** (1991) 400.

[3] Development of the RILIS research laboratory at ISOLDE. V.N. Fedosseev, L.-E. Berg, J. Billowes, K. Blaum, R. Catherall, J. Cederkall, D. Fedorov, G. Huber, B. Jonson, O. Launila, M. Lindroos, R. Losito, B.A. Marsh, V.I. Mishin, T. Nilsson, V.N. Panteleev, E. Tengborn, G. Tranströmer, K. Wendt, CERN INTC-2006-015 / INTC-I-065.

[4] A highly selective laser ion source for bunched, low emittance beam release. K. Wendt, K. Blaum, K. Brück, Ch. Geppert, H.-J. Kluge, M. Mukherjee, G. Passler, S. Schwarz, S. Sirotski, K. Wies, Nucl. Phys. A **746** (2004) 47c.

[5] Ultrasensitive resonance laser photoionization spectroscopy of the radioisotope chain $^{157\text{-}172}$Tm produced by a proton accelerator. V.I. Mishin, S.K. Sekatski, V.N. Fedoseev, N.B. Buyanov, V.S. Letokhov, G.D. Alkhazov, A.E. Barzakh, V.P. Denisov, V.S. Ivanov, I.Ya. Chubukov, Sov. Phys. JETP **66** (1987) 235.

[6] A new highly efficient method of atomic spectroscopy for nuclides far from stability. G.D. Alkhazov, A.E. Barzakh, V.P. Denisov, K.A. Mezilev, Y.N. Novikov, V.N. Panteleyev, A.V. Popov, E.P. Sudentas, V.S. Letokhov, V.I. Mishin, V.N. Fedoseyev, S.V. Andreyev, D.S. Vedeneyev, A.D. Zuzikov, Nucl. Instrum. and Meth. Phys. Research B **69** (1992) 517.

[7] An efficient excitation scheme for resonance ionization of tin in a laser ion source. F. Scheerer, F. Albus, F. Ames, H.-J. Kluge, N. Trautmann, Spectrochimica Acta B **47** (1992) 793.

[8] Selective laser ionization of radioactive Ni-isotopes. A. Jokinen, A.-H. Evensen, E. Kugler, J. Lettry, H. Ravn, P. Van Duppen, N. Erdmann, Y. Jading, S. Koehler, K.-L. Kratz, N. Trautmann, A. Wöhr, V.N. Fedoseyev, V.I. Mishin, V. Tikhonov, the ISOLDE Collaboration, Nucl. Instrum. and Meth. Phys. Research B **126** (1997) 95.