1) Motivation

A) RESONANCE IONIZATION
LASER ION SOURCES
The chart of stable nuclei

284 isotopes with $T_{1/2} > 10^9$ year

Slide: M. Huyse
+ the discovery of radioactivity


\[ ^4\text{He} + ^{10}\text{B} \rightarrow ^{13}\text{N} + n \]
+ the advent of nuclear reactors

Reactors: n on U
First Isotope Separator On-Line (ISOL) experiment
Niels Bohr Institute 1951
fast n on U: Kr and Rb isotopes
Selective detection method: $\alpha$ decay

Slide: M. Huyse
+ energy increases and driver beam upgrades

Light-ion induced spallation
Heavy-ion induced fusion

Slide: M. Huyse
+ thin target and projectile fragmentation – shorter lifetimes

Projectile and target fragmentation
+ In-flight separation

Slide: M. Huysse
The modern nuclear chart

- Explaining complex nuclei from basic constituents
- The size of the nucleus: halos and skins
- Isospin dependence of the nuclear force
- Measuring and predicting the limits of nuclear existence
- Doubly-magic nuclei and shell structure far from stability
- The end of Mendeleev’s table: superheavies
- Understanding the origin of elements
- Testing the Standard Model
- Applications in materials and life sciences

> 3500 of the expected 6000 nuclei have been observed
The ISOL process

Production

Extraction/Ionization

Isotope Separation

Post acceleration or to Experiment

Fast, Efficient, Universal and Selective!
Factors influencing isotope production

\[ I = \int \sigma(E) \Phi(E, x) \rho(x) \frac{N}{A} dx \varepsilon_{\text{diff+eff}} \varepsilon_{\text{ion}} \]

- RIB intensity \([s^{-1} \mu\text{A}^{-1}]\)
- Proton beam intensity \([s^{-1} \mu\text{A}^{-1}]\)
- Target density \([\text{g cm}^{-3}]\)
- Diffusion and effusion efficiency
- Reaction cross section \([\text{cm}^2]\)
- Target mass \([\text{g}]\)
- Ionization efficiency

Production

Extraction
ISOL ion source requirements are very broad!

- Energy range $10^{-6}$ eV (10 mK) to $>\text{MeV/u}$
- Intensity $0.01 - 10^{10}$ ions/s
- Particle type: $^6\text{He}$ to $^{232}\text{R}$ (Z: 2-88, N:4-144), and molecules!
- Lifetimes: stable $\rightarrow$ micro seconds
- Charge state: mainly 1+ or 1-, or n+ for high energy beams – F. Wenander’s lectures

Clearly, not all of these requirements are fulfilled by a single ion source, we need to have many options and choose the optimal one depending on the requested case and priorities for the beam characteristics.

The operating principles of each of ISOL ion source options are presented to some extent at this school!
**Surface Ionization Process:**

*R. Kirchner: Nucl. Instr. Meth. 186, 275 (1981)*

**Surface Ion Source**
- Very simple: metal tube (line) from Ta or W
- Heated up to 2400 °C

 Ionization efficiency depends on ionization potential (and also the plasma potential inside the hot cavity - Saha Equation)

**Plasma Ion Source**
- Used for non surface-ionizing elements
- Ar or Xe plasma ignited by electrons at 130 eV

Very efficient, even for high IP elements.
Chemically unselective
Production of Exotic Nuclei

1 GeV proton beam on a lanthanum (La) target

- Mass separation
- Element selective ion source
- Note the radioactive inventory

J. Lettry, V. Fedoseev (CERN)
Fighting against unwanted isobar production and ionization to obtain $^{78}\text{Ni}$

Ni+:Ga+ ratio with surface ionization only:

$$\alpha = \frac{n_i}{n_0} = \frac{\omega_i}{\omega_0} \exp \left( \frac{\Phi - W_i}{kT} \right)$$

Ga+:Ni+ $> 10^6$!

Need to selectively increase Ni ionization efficiency

And/or suppress isobar (Cu, Zn, Ga) ionization efficiency.

Fission of U with 1 Gev protons
The Resonance Ionization Laser Ion Source

- Target
- Isotope of interest
- Laser
- Mass separation
- Extractor
- Mass separation

Laser beams

experiments

- Projectiles
- Target material
- Neutrals
- Ions

auto-ionizing state
ionization potential
Rydberg state
excited states
ground State

Isotope of interest

$^{205}\text{At}$
A) RESONANCE IONIZATION LASER ION SOURCES

2) Principle

- Photon interaction with atoms
- Atomic structure
- Electron transitions
- Ionization schemes
- Laser principles
- RIB facilities

Energy scales, units
Energy scales and units that will be used

**Wavelength, \( \lambda \):** SI unit = m  
(or \( \mu m, \) nm or Angström, \( 1 \ \text{Å} = 10^{-10} \text{m} \))

\( \lambda \) is dependent on the (refractive index of the) medium in which the wave travels.

**Frequency, \( \nu \):** SI unit = Hz (i.e., cycles s\(^{-1}\))  
(or MHz = \( 10^6 \) Hz, GHz = \( 10^9 \) Hz)

Frequency is independent of the medium.

**Energy, E:** SI unit = J,

BUT: It is hard to measure energy directly. Spectra are recorded as line intensities as a function of frequency or wavelength.

The conversion to energy appears simple: \( E = h \nu = hc/\lambda \)

But \( h \) is only known to 8 significant figures. Hence, it is convenient to introduce

**Wavenumber, a property** defined as reciprocal of the vacuum wavelength:

\[ \bar{\nu} = \frac{1}{\lambda_{vac}} \]

And whose units are universally quoted as cm\(^{-1}\) (n.b. not m\(^{-1}\))

Wavenumber is directly proportional to energy, \( E = h c \bar{\nu} \) and thus we commonly quote “energies” in units of cm\(^{-1}\).
How to describe photons

It will usually be convenient to consider light as a stream of zero rest mass particles or packages of radiation called photons with the following properties:

- **Energy**, $E = h\nu$
  
in which $h$ is Planck’s constant, $h = 6.626 \times 10^{-34}$ Js

- **Linear momentum**, $p = E/c = h\nu/c = h/\lambda$ (de Broglie)

- **(spin) Angular momentum** equivalent to a quantum number of 1:
  
  $j_{ph} = 1$ \textit{i.e.}, $|j_{ph}| = \sqrt{2}\hbar$

\textit{n.b.}, 1) photons are Bosons \textit{(i.e., obey Bose-Einstein statistics)}

2) photons have \textit{helicity} (projection of angular momentum on the direction of travel) of $\pm1$ only \textit{(i.e., not 0)}
A Prelude to Atomic Spectroscopy

17th Century: Newton demonstrates that the Sun’s white light can be dispersed into a “spectrum” of colours.

19th Century (1814) J. Fraunhofer measures dark lines in the Sun’s spectrum.

1859: Kirchhoff & Bunsen explain the dark lines in the solar spectrum in terms of absorption by elements in the Sun’s surface.

1885: J. Balmer describes the series of lines atomic hydrogen.

This discrete structure required quantum mechanics and Neils Bohr (1913)
Prerequisites for understanding how the photon interacts with atoms:

• The emission or absorption of a photon is the principal means by which an electron in an atom can increase or decrease its energy.

• An atom with all its electrons in the lowest energy configuration is said to be in the **ground state**.

• Any other electron configuration is an **excited state** of the atom.

• What factors determine the energy of the electrons in an atom?
  – Nuclear charge (coulomb): potential energy; inversely proportional to distance from nucleus.
  – Electron-electron interactions.
  – Spin-orbit interaction: electron spin/induced magnetic field interaction.
  – Understand that for a particular electron, these factors sum up to give the potential.

• How can an electron move between states?
  – Increasing or decreasing the energy of a given electron requires the absorption or the emission of a photon.
  – Energy can only be increased or decreased in **discrete** amounts which match the energy differences between one electron state (*state = combination of the factors listed above*) and the next.
  – Not all transitions between electron states are possible through the emission of a single photon, some transitions are more likely than others and some are forbidden altogether (conservation of momentum).
The atomic line spectra is an element’s fingerprint

- Electron transitions between *energy levels* result in emission or absorption lines.
- The spectral position of these lines are determined by the structure of the atom.
- Every chemical element therefore has its own unique spectral fingerprint.
- **Example:** In astronomy the chemical composition of an astronomical object is determined by observing its *absorption* or *emission spectrum*.
- The spectral lines are not absolutely monochromatic! They are actually an intensity distribution around a specific central wavelength. The width of this intensity distribution is the ‘line-width’ of the transition.
- This line-width depends various factors that will be discussed.
The atomic line spectra is an element’s fingerprint
By increasing the resolution by a factor of ~5000 a fine structure splitting of the hydrogen is observed: key evidence for the spin of the electron.

A further factor of 1000 zoom into the structure reveals finer splitting due to the coupling of the nucleus with the electronic orbital: the hyperfine structure.

The splitting of the hyperfine structure results from the presence of a permanent magnetic field associated with the nucleus and/or a non-symmetric electric field associated with a deformed nuclear charge distribution.

Note – Relevant for part 6 of this course: If we can measure the splitting of the atomic transitions with sufficient resolution it is possible to deduce the nuclear observables (magnetic and electric moments, spin and size) without any model (nuclear) dependence.
Atomic Energy Scales

<table>
<thead>
<tr>
<th>Energy scale</th>
<th>Energy (eV)</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross structure</td>
<td>1-10</td>
<td>electron-nuclear attraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electron kinetic energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electron-electron repulsion</td>
</tr>
<tr>
<td>Fine structure</td>
<td>0.001 - 0.01</td>
<td>Spin-orbit interaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Relativistic corrections</td>
</tr>
<tr>
<td>Hyperfine structure</td>
<td>10^{-6} - 10^{-5}</td>
<td>Nuclear interactions</td>
</tr>
</tbody>
</table>
Laser ion source – using this fingerprint for selective ionization

$A^+ + e^-$

$E_i \approx 4 \div 11 \text{ eV}$

$\omega_1, \omega_2, \omega_3$

$10 \text{ eV} = 124 \text{ nm photon} = 80645 \text{ cm}^{-1}$

$\omega_i(\text{laser}) = \omega_i(\text{atom}); \quad P_i(\text{laser}) \geq P_i(\text{saturation})$

$P_{\text{sat}} = \frac{\hbar \omega_i}{2\sigma_i} \times f_{\text{laser}} \times S_{\text{laser beam}}$

$P_{\text{sat}} \approx 10 \text{ mW}$

$P_{\text{sat}} \approx 100 \text{ mW}$

$P_{\text{sat}} \approx 10 \text{ W}$

$Laser power$

$1000 - 1100 \text{ Å}$
Rare isotope production methods compatible with laser ion sources

**Primary Beam**
- Light ion (1.4GeV protons)
- 60keV Ionizer
- Electromagnetic separator
- Low-energy
- High-quality

**Chemistry limits**
- \( t_{1/2} \sim \text{ms} \)
- Chemical properties

**In-Flight Fragmentation (GSI)**
- Thin target
- 1 GeV/u
- Electromagnetic Separator
- Gas Catcher + RFQ Cooler Buncher
- Low-energy
- High-quality

**Limits**
- \( t_{1/2} \sim \mu s \)
- Low intensities
A) RESONANCE IONIZATION
LASER ION SOURCES

3) History of the laser ion source
Early proposals: 1984

PROPOSAL of the Institute of Spectroscopy, Acad. Sci. USSR for experiments with ISOLDE-CERN Facility

(V. S. Letokhov and V. I. Mishin)

LASER PHOTOIONIZATION PULSED SOURCE OF RADIOACTIVE ATOMS

I. Purpose The development of a pulsed isobar-selective effective source of ions at the mass-separator inlet on the basis of the method of laser resonant atomic photoionization.

\[ \gamma_{1,2,3}^{1,2,3} = \text{pulsed} \]

\[ \gamma_{1,2,3}^{1,2,3} \approx 4 \text{cm}^{-3} \]

to act-up for collinear-beam laser photoionization spectroscopy or another application

\[ \tau_{imp} \approx 200 \text{ms} \]

\[ U = 2(1-2) \text{kV} \]

repetition rate = \(10^4 \) pps
Early proposals: 1988

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/ISOLDE
IP 50

PROPOSAL TO THE ISOLDE COMMITTEE

DEVELOPMENT OF A LASER ION SOURCE

F. Ames, E. Arnold, H.J. Kluge, Y.A. Kudryavtsev,
V.S. Letokhov, V.I. Mishin, E.W. Otten, H. Ravn,
W. Ruster, S. Sundell and K. Wendt

University of Mainz, F.R.G.,
Institute of Spectroscopy, Troitzk, USSR
and the ISOLDE Collaboration, CERN, Switzerland

Spokesman: K. Wendt
Contactman: E. Arnold

SUMMARY

Test experiments at Troitzk and Mainz have demonstrated the feasibility of step-wise multi-photon excitation and final ionization by pulsed lasers as a selective and efficient tool for the production of isobarically pure ion beams. The development of a new type of ion source based on this concept is proposed. In combination with existing targets, this will open up the way to a further extension in respect to purity and availability for a number of elements at on-line mass separator facilities. The collaboration proposes to use the CERN-ISOLDE off-line separator for tests of appropriate target ion source configurations with respect to efficiency and purity. After successful development the laser ion source shall be installed as an additional facility at the IS-3 separator.
Ionization in a hot metal cavity

Application of a high efficiency selective laser ion source at the IRIS facility


Leningrad Nuclear Physics Institute, Academy of Sciences of the USSR, Gatchina, Leningrad district 188350, USSR

Received 6 December 1990 and in revised form 25 March 1991

Demonstrated:

Yb, Nd, Ho - off-line
Ho - on-line

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 and the ISOLDE Collaboration

PPE Division, CERN, Geneva, Switzerland

Received 26 November 1992

Yb, Tm, Sn, Li - off-line
Yb - on-line
RILIS at ISOLDE-PSB

CVL lasers: $\nu_{\text{rep}}$=11.000 Hz
Oscillator + 2 amplifiers
2-3 dye lasers with amplifiers, nonlinear crystals BBO:

$P_{\text{total}} \leq 75 \text{ W}$
$P_{\text{dye}} \leq 8 \text{ W}$
$P_{2\omega} \leq 2 \text{ W}$
$P_{3\omega} \leq 0.2 \text{ W}$
Resonance laser ion sources worldwide

- **LISOL**, Louvain-la-Neuve:
  - Hot cavity
  - Rep. rate: ~10 kHz
  - Dye laser

- **GSI-LEB**:
  - Gas catcher?
  - Rep. rate: <200 Hz

- **FURIOS**, Jyväskylä:
  - Gas cell
  - Rep. rate: ~10 kHz
  - Dye & Ti:Sa laser

- **RILIS**, ISOLDE, Geneva:
  - Hot cavity
  - Rep. rate: 10 kHz
  - Dye laser

- **TRILIS**, Vancouver:
  - Hot cavity
  - Rep. rate: ~10 kHz
  - Ti:Sa laser

- **ORNL**, Oak Ridge (off-line):
  - Hot cavity
  - Rep. rate: ~10 kHz
  - Dye laser

- **ALTO**:
  - Hot cavity?

- **LISOL**:
  - Gas cell
  - Rep. rate: <200 Hz
  - Dye laser

- **SPES**:
  - Hot cavity?

- **Riken**:
  - Gas catcher?

- **TIARA**, Takasaki:
  - Hot cavity
  - Rep. rate: 300 Hz
  - Dye laser

- **updated from C. Geppert, EMIS, Deauville, 2007**
A) RESONANCE IONIZATION LASER ION SOURCES

4) Case example: Building a laser ion source at ISOLDE

i) laser/atom interaction region
   - temperature
   - geometry
   - interaction time

ii) Defining laser requirements
    - Power
    - Repetition rate
    - Beam quality
    - Tuning range
    - Linewidth

iii) Suitable laser types
    - Dye laser
    - Ti:Sa
    - Pump lasers
    - Harmonic generation

iv) Laser beam delivery
    - Transport
    - Measurement
    - Monitoring
    - Timing
    - Maintenance
Building a laser ion source at an ISOL facility such as ISOLDE

What is the optimal laser ion source configuration for ISOLDE?

Where do we put the laser ion source?

Requested features:

- Universal
- Selective
- Efficient
- Reliable
- Fast
The ISOLDE Laboratory

- New hall extension
- Control room
- Class A Radiation area
- Target area
- Separator magnets
- Experimental hall
- 1.4 GeV protons
- Fairly inaccessible due to high radiation levels
What are we trying to achieve:

Production

Extraction/Ionization

Isotope Separation

Post acceleration or to Experiment

Fast, Efficient, Universal and Selective!
What are the considerations based on what we already know about the laser ionization principle and the ISOLDE target/ion source unit:

- Harsh radiation environment (Mgray!)
- High efficiency
- Exotic, short lived isotopes
- Universality
- Reliability and stability
- Selectivity

Simplicity near target unit
Good geometric and temporal laser/atom overlap
Fast – no delay w.r.t standard ion source
Applicable to many elements
Ability to maintain optimal laser conditions for long periods
High purity ion beam, no isobars

The hot surface ion source cavity
- A good laser /atom interaction region?
The Hot Cavity Laser Ion Source

Efficiency:

\[ \varepsilon = \frac{P_{\text{Ionisation}}}{P_{\text{Ionisation}} + P_{\text{Effusion}}} \]

Selectivity = \( \frac{\text{Laser Ionization Efficiency}}{\text{Surface Ionization Efficiency}} \)

\[ \varepsilon_{\text{laser}} = 2\% - 30\% \]

\[ \varepsilon_{\text{surface}} = \begin{cases} > 5\% & \text{- alkalies} \\ = 0.1\% - 2\% & \text{- In, Ga, Ba, lanthanides} \\ < 0.1\% & \text{- others} \end{cases} \]

Lasers located ~ 18 m away

=> depends on the ionization potentials of isobar atoms
Features of the hot cavity that influence the application of RILIS:

- Effusion time \(\rightarrow\) Laser repetition rate
- High temperature \(\rightarrow\) Laser linewidth atomic transitions
- Electron emission \(\rightarrow\) Extraction efficiency
- Surface ionization \(\rightarrow\) Selectivity

Chemistry dependant: wall sticking is greater for less volatile elements but typical effusion times through the hot cavity is 100-200 μs

Thermal population of low lying excited atomic states

Surface ionization

Doppler broadening

\[ N_i \propto \exp\left(-\frac{E_i}{k_B T}\right) \]
Line broadening mechanisms:

Natural linewidth determined by the *spontaneous emission* lifetime of the state

Uncertainty principle:

\[ \Delta E \Delta \tau = \frac{\hbar}{2} \]

Natural linewidth has Lorentzian shape:

\[
\sigma = \frac{\lambda^2}{2\pi} \left\{ \frac{1}{1 + [4\pi \tau (\nu - \nu_0)]^2} \right\}
\]

FWHM = \[\frac{1}{2\pi \tau}\]

For upper state lifetime of 10 ns, \(\Delta \nu = 16 \text{ MHz}\)

When an atom is in thermal motion we get *Doppler broadening*. An atomic vapour has a Maxwell-Boltzmann distribution of velocities:

\[
P(\nu_x) \propto \exp\left(\frac{-m \nu_x^2}{2kT}\right)
\]
The velocity of the atoms Doppler shifts the absorption frequency to

\[ \nu = \nu_0 \left(1 \pm \frac{v_x}{c}\right) \]

The velocity spread leads to a Doppler broadening:

\[ \Delta \nu_D = \nu_0 \frac{\Delta v}{c} \]

\[ FWHM = \sqrt{\frac{8 kT \ln 2}{m c^2}} \nu_0 \]

Example: 0 → 38278 cm\(^{-1}\) transition

Natural linewidth: 35 MHz
Spectral linewidth:
2.4 GHz (hot cavity)
~170 MHz (crossed)

The Doppler broadening is often comparable to or greater than HFS or IS effects!
**Broadening: Hot cavity vs Gas cell**

By simulating the spectral linewidth of the 244 nm Cu transition, assuming a laser linewidth of 1.6 GHz, we can compare the effect of environmental conditions:

- **Doppler broadening**
- **Pressure broadening**

Expanding gas jet is cold and has low pressure.

Resolution in gas jet limited by laser bandwidth.
What do these conditions mean for the laser power for a non-resonant ionization step?

Typical values: \( \sigma_{\text{ion}} \approx 10^{-17} \text{ cm}^2 \)

\( \beta \approx 10^6 \text{ s}^{-1} \)

For 100% ionization of the irradiated atoms, the FLUX (1) and FLUENCE (2) conditions, which are derived from the rate equations for the optical transition, must be met:

1. \( \sigma_{\text{ion}} \cdot F \gg \beta \rightarrow \text{ionization rate} \gg \text{loss rate} \)

2. \( \sigma_{\text{ion}} \cdot \varphi > 1 \rightarrow \text{number of ionized atoms per laser interaction time (pulse)} \)

**For simplicity and to have a safe margin lets assume a laser beam area of 10 mm\(^2\) and a photon energy of 3 eV.**
From (1): Flux $F >> 10^{24}$ cm$^{-2}$s$^{-1}$
\[ \rightarrow \# \text{photons required} >> 10^{22} /s \]

But with a **pulsed** laser system:
Typical pulse length is 10 ns.

But with the limited laser interaction time **Fluence (2)** condition becomes more difficult

**Ex.: Ag ionization**

---

**Step 1:** 328.1624 nm

$P_{\text{sat}} = 1.7(4)$ mW

**Step 2:** 421.2142 nm

$P_{\text{sat}} = 10(6)$ mW

**Step 3:** 511 nm

Unsaturated!

---

3 eV photons \[ (2.33 \text{ eV} = 532 \text{ nm}) \]
\[ \gg 5000 \text{ W} \]
Impossible with CW laser !!

\[ \gg 50 \mu \text{J/pulse} \]
No problem !!

\[ > 5 \text{ mJ/pulse} \]
(>50 W at 10kHz!)
How does the degree of saturation influence the efficiency or required precision of laser tuning?

Resonant saturation parameter:

\[ S_0 = \frac{I}{I_{\text{sat}}} \]

\[ I_{\text{sat}} = \frac{\pi hc}{3\lambda^3 \tau} \]

The population of the excited state:

\[ \rho = \frac{S}{2(S + 1)} \]

where \( S \), the saturation parameter, is a Lorentzian function with FWHM \( \Gamma \):

\[ S = \frac{S_0}{1 + 4\delta^2 / \Gamma^2} \]

When the laser frequency is on resonance, i.e. when \( \delta = 0 \):

\[ \rho = \frac{S_0}{2(S_0 + 1)} = \frac{I/I_{\text{sat}}}{2(I/I_{\text{sat}} + 1)} \]
So we now understand that for efficient laser ionization we need pulsed, tunable lasers, preferably with AI or Rydberg ionization, and that each transition should be ``saturated``. *The duty cycle is also something to bear in mind.*

However, for a laser ion source the ionization efficiency is not the only important requirement, what about the *optical selectivity*? This is defined as the ratio of the probability of exciting the selected isotope to the probability of exciting other isotopes or elements.

Excitation probability of an atom in a laser beam whose frequency is tuned near resonance:

\[ P \propto \frac{1}{\delta^2 + \frac{\Gamma^2}{4}} \]

When the laser is in resonance with a selected isotope and \( \Delta >> \Gamma \),

\[ S \sim 4 \times \frac{\Delta^2}{\Gamma^2} \quad (\Delta \text{ is the atomic resonance difference between isotope of interest and a } \text{``contaminating''} \text{ isotope/element}). \]

eg. Kr isotopes, \( \Gamma \sim 6 \text{ MHz} \), \( \Delta \sim 100 \text{ MHz} \) (neighbouring isotopes): \( S \sim 1000 \)

\( \Delta \sim 10^{15} \text{ Hz} \) (krypton to bromine): \( S \sim 10^{17} \) !!!

and multi-step excitation: \( S = S_1 \cdot S_2 \cdots \cdot S_n \). But in reality \( S \) is less due to broadening 😞
Summary of laser parameters that are required:

- Difficult to saturate transitions, especially ionization step
  - pulsed lasers with high energy per pulse (mJ).
- Broadening in hot cavity
  - laser linewidth to match broadening for resonant transitions (1-10 GHz)
- Finite residence time of atoms (~100 us)
  - High repetition rate (> 10kHz)
- Large range of elements required
  - broad wavelength tuning range
- Multi step ionization
  - > 2 tunable lasers required
- Heavy reliance on laser ion source and large demand
  - Reliability and flexibility, ease of use for quick element switching
- Long distance of transmission of beams and inaccessible areas
  - good beam quality, broadband optics, reference points, monitoring
What laser types meet these requirements

**Fixed frequency**

- X-rays
- Ti:sapphire (tripled)
  - 235-330 nm
- Ne-Cu* 282-292 nm
  - 248-270 nm
- Dyes (doubled) 0.2-0.4 µm
- Alexandrite 360-460 nm
  - 360-400 nm
- InGaN 370-493 nm
- InGaAs 904-1065 nm
- InGaAs 1.27-1.33 µm
  - 1.43-1.57 µm
- Ti:sapphire 670-1130 nm
- GaAlAs 750-850 nm

**Tuneable**

- Methanol 21.9 µm
- CO₂ 2.7 µm
Ti:Sapphire laser

- Optically active component is $\text{Ti}^{3+} < 1\%$ by weight
- Host solid is sapphire ($\text{Al}_2\text{O}_3$)
- Ti interacts with solid so the $E_2, E_1$ broadened significantly. The atoms in the solid vibrate and interact with the Ti atoms.
- Gain bandwidth huge (100 THz): this enables either:
  - tunable laser (if you add frequency selective elements)
  - ultra short pulse laser *(uncertainty principle)*

![Diagram of Ti:Sapphire laser](image)
Dye laser

Rhodamine 6G

Diffraction grating as a laser cavity mirror:
Reflection maxima on axis with cavity is wavelength dependent → wavelength selective oscillation

$$d \sin \theta_m = m\lambda$$
Comparing dye and Ti:Sa lasers

<table>
<thead>
<tr>
<th></th>
<th>Dye</th>
<th>Ti:Sa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Medium:</td>
<td>&gt; 10 different dyes</td>
<td>=1 Ti:sapphire crystal</td>
</tr>
<tr>
<td></td>
<td>liquid (org. solvents)</td>
<td>solid-state</td>
</tr>
<tr>
<td>Tuning range</td>
<td>540 – 850 nm</td>
<td>680 – 980 nm</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 12 W</td>
<td>&lt; 5 W</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>~8 ns</td>
<td>~50 ns</td>
</tr>
<tr>
<td>Synchronization</td>
<td>optical delay lines</td>
<td>q-switch, pump power</td>
</tr>
<tr>
<td># of schemes developed</td>
<td>47</td>
<td>37</td>
</tr>
<tr>
<td>Maintenance</td>
<td>renew dye solutions</td>
<td>~ none</td>
</tr>
</tbody>
</table>

Harmonic generation in birefringent crystals:
Due to nonlinear response of materials to high EM field of focused lasers
Sirah Dye laser – an example of a modern commercial dye laser

“Upgrade of the RILIS at ISOLDE: New lasers and new ion beams”


- Optimized for 10 kHz EdgeWave pump
- Accept both 355 and 532 pumping beams
- Equipped with FCU (up to 2W of UV)
The RILIS Ti:Sa lasers

Pump laser: Nd:YAG (532 nm), Photonics
Repetition rate: 10 kHz
Pulse length: 180 ns
Power: 60 W

Ti:Sa lasers:
Line width: 5 GHz
Pulse length: 30-50 ns

Wavelength tuning range (6 mirror sets):
- Fundamental ($\omega$) 690 - 940 nm (5 W)
- 2nd harmonic ($2\omega$) 345 - 470 nm (1 W)
- 3rd harmonic ($3\omega$) 230 - 310 nm (150 mW)
- 4th harmonic ($4\omega$) 205 - 235 nm (50 mW)
Dual RILIS Concept

Nd:YAG

10 kHz Master clock

Delay generator

Nd:YAG

RILIS Dye Laser System

Dye 2

SHG

Dye 1

THG

Narrowband Dye

RILIS Ti:Sa Laser System

Ti:Sa 1

SHG/THG/FHG

Ti:Sa 2

Ti:Sa 3

GPS/HRS

Target & Ion Source

Faraday cup...

λ – meter

12571.486 / cm

LabVIEW based DAQ

pA – meter
Installing the Ti:Sa alongside the dye lasers

Finding space for pump laser + 3 Ti:Sa + FCUs

Frequency conversion unit

Diagram showing the setup with Ti:Sa lasers, pump lasers, and FCUs.
6 tunable lasers + 50 W @ 532 nm for ionization step, 10 kHz rep rate
Nd: YAG pumping dye or Ti:Sa lasers, with possibility of doubling to quadrupling
Atomic physics: Used to determine ionization schemes and I.P of chemical elements with no stable isotopes (e.g. polonium, astatine)
Nuclear physics: laser spectroscopy -> electromagnetic ground state properties
Available elements so far

<table>
<thead>
<tr>
<th>Periodic Table of RILIS Elements</th>
<th>PeriodicTableofRILISElements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti:Sa schemes tested</td>
<td>Dye schemes tested</td>
</tr>
<tr>
<td>Feasible</td>
<td>Released from ISOLDE target</td>
</tr>
<tr>
<td>Not released</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Available elements so far</th>
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</thead>
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<tr>
<td>Ti:Sa and Dye schemes tested</td>
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</tr>
<tr>
<td>Feasible</td>
<td></td>
</tr>
<tr>
<td>Not released</td>
<td></td>
</tr>
</tbody>
</table>

| Dye schemes tested               | Ti:Sa and Dye schemes tested |
| Feasible                         |                             |
| Not released                     |                              |

<table>
<thead>
<tr>
<th>Release</th>
<th>fromISOLDE target</th>
</tr>
</thead>
</table>
Ion beams of 16 elements were produced during 2011:

- **2573 h for on-line experiments**
- Ti:Sa system used already with 9 elements
- Some additional tests only feasible because of the ‘spare’ laser system
- Significant Ti:Sa use despite 1st year of operation and still in ‘implementation/testing phase’
Modes of RILIS operation: Dual RILIS

**Condition for dual operation:** Temporal synchronization of the two laser systems

**Ti:Sa only mode**
- 50 W Nd:YAG laser available for non-resonant ionization

**Mixed mode**
- Combination of dye and Ti:Sa

**Backup mode**
- Dye and Ti:Sa are exchangeable

- Increased efficiency due to higher laser power or optimal scheme
- Improved reliability due to redundancy / backup
- More elements are accessible due to greater tuning range/scheme database
RILIS status monitoring

Essential RILIS parameters are published to a Labview DSM. All values are accessible from the CERN technical network. RILIS monitor display is published to a website for remote monitoring.

- Power
- Wavelength
- Proton current
- Reference beam images

https://riliselements.web.cern.ch/riliselements/LASERS/
Piezo actuators for fast frequency beam fluctuations

Currently capable of stabilizing up to two beams

Beam stabilization

Stabilization of high and low frequency beam fluctuations, essential for ON-CALL RILIS

http://www.tem-messtechnik.de/MainPages/en/productsfs.htm
In-source spectroscopy of Astatine

a) Photoionization threshold: $75129(95)$ cm$^{-1}$
b) Scan for 2$^{\text{nd}}$ step transitions (at TRIUMF)
c) Verification of levels, yield measurements
d) Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP

Rydberg-Ritz formula

$$E_{\text{IP}} = \text{IP} - R \Delta M / (n - \delta)$$

$E_{\text{IP}}(\text{At}) = 75151(1)$ cm$^{-1}$

*Poster to visit!: S Rothe et al. Publication in preparation*
A) RESONANCE IONIZATION LASER ION SOURCES

5) Scheme development
   - Data sources
   - Spectroscopy
   - Saturation
   - Efficiency
Ionization scheme development

What are our options for ionization schemes?

- **non-resonant ionization**
  - $E_0$ (ground state)
  - $E_1$ (first excited state)
  - $\sigma_R \sim 10^{-12}$ cm$^2$

- **excitation of auto-ionizing states**
  - $E_1$ (first excited state)
  - $\sigma_I \sim 10^{-17}$ cm$^2$

- **ionization of Rydberg states**
  - $E_0$ (ground state)
  - $\sigma_I \sim 10^{-15}$ cm$^2$

- **ionization potential**
  - $\sim 6$ eV (5-9 eV)

R.L. Kurucz' CD-ROM 23 Atomic Line Database:
http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html
Auto-ionizing states – simplified concept

Li

3 electrons: G.S 1s^22s

Decay from the AIS is either by photon emission or by electron-electron energy transfer via the coulomb interaction: more likely if the 2 electrons share similar shaped orbits (temporal overlap) and if the energy transfer does not have to be to a discrete state - continuum

Extra loss channel → reduced lifetime of state → broader resonance
How to develop an ionization scheme

• **Literature Search**
  On-line atomic spectral line databases, published spectroscopy work.
  R.L. Kurucz’ CD-ROM 23 Atomic Line Database: [http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html](http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html)
  NIST atomic spectral line database: [http://www.nist.gov/pml/data/asd.cfm](http://www.nist.gov/pml/data/asd.cfm)

• **In-source resonance ionization spectroscopy**
  Laser frequency scans across regions of interest whilst observing the ion current as the sample is evaporated in the target or oven.

• **Saturation measurements**
  Determine whether or not efficiency gains can be achieved from an increase of power. (e.g. by optimizing the distribution of the CVL pump power).

• **Efficiency measurement**
  Total evaporation of the sample (of known mass) and integration of the ion current.

---

1 week for a simple case
2 weeks for AIS search
Case Example: Finding a new Au ionization scheme for ISOLDE RILIS using the CVL pumped Dye laser

1) We know that the ionization potential is **9.23 eV** or **74408.88 cm⁻¹** (this corresponds to the energy of 134 nm photon!)  
2) We have a pump laser with both **511 nm** or **578 nm** output:  
   - Choose **511 nm** (highest photon energy) – 19570 cm⁻¹  
   - Any excited state higher than 74409-19750 = 54659 cm⁻¹ will be within reach of the ionization potential (~1 x 182 nm photon). Therefore Min 3 steps are required.  
3) Search Kurucz database for 1st step transitions:  
   - 2 transitions from ground state, population of level at ~9161 cm⁻¹ is <1% at 2300 K  
   - roughly equal transition strength, select most convenient wavelength: 267.6 nm (requires only SHG, not THG)  
4) Search Kurucz database for 2nd step transitions from this 1st excited state to a state with a minimum energy of 54659 cm⁻¹:  
   - choose 6 most convenient transitions (578 nm pump beam)  
5) Test these 6 transitions and select, depending on the time available select the best ones as a basis for the search for AIS.

---

**Configure your search:**

- **Wavelength in nm** (vacuum wavelength below 200 nm, air wavelength above):  
  - Lower limit: 200 nm  
  - Upper limit: 500 nm  
- **Absorption oscillator strength log gf:**  
  - Minimum log gf: -4.0  
  - Maximum log gf: 4.0  
- **Energy of lower level of transition in cm⁻¹:**  
  - Lower limit: 0.0 cm⁻¹  
  - Upper limit: 10000 cm⁻¹  
- **Energy of upper level of transition in cm⁻¹:**  
  - Lower limit: 0.0 cm⁻¹  
  - Upper limit: 1000000 cm⁻¹  

Select one or more elements to search for:

- **H I**  
- **He I**  
- **He II**  
- **Li I**  
- **Na I**  
- **Ca I**  
- **K I**  
- **Ca II**  
- **Mg I**  
- **Ca III**  
- **Ca IV**  
- **Ca V**  
- **Be I**  
- **Ca VI**  
- **Ca VII**  
- **Ca VIII**  
- **Ca IX**  
- **Ca X**  
- **Sr I**  
- **Sr II**  

---
- 6 of 10 known 2nd step transitions chosen: YELLOW CVL pumping
- Non resonant ionization stage with green CVL beam
- Include a 3rd dye laser
- Scan 2 dye ranges for AIS from 3 strongest 2nd steps.
- Test ionization scheme used by E.B Saloman
Scheme figure of merit:

\[ R = \frac{I_{1+2+3}}{I_3} \]

- 5 AIS known in range
- 3 known AIS observed
- 27 new AIS

4x improvement on scheme used by E.B Saloman (\( R = 55 \))

Overall RILIS Efficiency:

\[ E \approx 3\% \]

Estimated from evaporation of 3000 nA n mass marker

Compare good schemes and study the optimal scheme: Saturation curves, efficiency measurements etc.
LARIS results – A new RILIS scheme for manganese

- Replacement of current scheme which uses the CVL green beam.

**Outcome of RIS study of Mn at LARIS:**

Many new auto-ionizing states found

Various promising Nd:YAG based schemes tested and ready for efficiency measurement at RILIS.
Calcium scheme development

a) Scans for Auto-ionization states using spare Sirah Dye laser
b) AI Transitions from two intermediate levels were observed
c) Enhancement of ionization efficiency of a factor of 4 w.r.t 50 W green beam for non resonant ionization!
d) Only possible due to the use of a TiSa for 1st step

Daniel Fink: PhD work
A) Resonance Ionization
Laser Ion Sources

6) In-Source RIS

- Sensitivity
- Isotope shift
- Hyperfine structure
How does the nuclear structure influence the atomic spectra?

The earlier discussion on atomic energy levels mainly assumed that the nucleus is POINT-LIKE and INFINITELY heavy!

The **ISOTOPE SHIFT** and **HYPERFINE STRUCTURE** are a consequence of this being untrue.

For a given element, if we examine the influence of the nucleus on the electron energy levels as we add or remove neutrons, we can determine nuclear structure changes along an isotope chain.

**QUESTION:**
What are the observables and how do we extract useful information from measuring them?
ISOTOPE SHIFT

Isotope 1

Isotope 2

The frequency difference in the electron transition between 2 isotopes of an element

CAUSED BY these properties:

Finite nuclear mass  MASS SHIFT

Nuclear Volume (not point-like)  FIELD SHIFT
Finite nuclear mass

MASS SHIFT

Infinite mass

$M_A < M_{A'}$

Nuclear Volume

FIELD SHIFT

Difference in the mean square nuclear charge radius (nuclear part)

Probability density of the electron at the nucleus (electronic part)

$\Delta v_{FS} = \frac{2\pi Z}{3} |\Delta \psi(0)|^2 \delta \langle r^2 \rangle$

Heavy Nuclei: $\Delta v/v \approx 10^{-5}$

Light Nuclei: $\Delta v/v \approx 10^{-8}$
Isotope shifts in practise

\[ \delta \nu_{IS} = \delta \nu_{MS} + \delta \nu_{FS} \]

\[ \frac{2\pi Z}{3} \Delta |\psi(0)|^2 \delta \langle r^2 \rangle \]

<table>
<thead>
<tr>
<th>Transition</th>
<th>Z</th>
<th>Element</th>
<th>NMS (MHz)</th>
<th>SMS (MHz)</th>
<th>FS (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3s-3p</td>
<td>11</td>
<td>Na</td>
<td>550</td>
<td>200</td>
<td>-10</td>
</tr>
<tr>
<td>5s-5p</td>
<td>37</td>
<td>Rb</td>
<td>70</td>
<td>&lt;20</td>
<td>-100</td>
</tr>
<tr>
<td>(6s)²-6s6p</td>
<td>70</td>
<td>Yb</td>
<td>20</td>
<td>&lt;20</td>
<td>-1500</td>
</tr>
</tbody>
</table>
HYPERFINE STRUCTURE

• Magnetic dipole interaction
• Electric quadrupole interaction

Splitting of atomic spectral lines into multiplets with separation $10^{-6}$ of total transition energy.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>$1/\lambda$ (cm$^{-1}$)</th>
<th>eV</th>
<th>$\nu$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central coulomb</td>
<td>30000</td>
<td>4</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>Fine structure</td>
<td>1-1000</td>
<td>$10^{-4}$-$10^{-1}$</td>
<td>$3 \cdot 10^{10}$-$3 \cdot 10^{13}$</td>
</tr>
<tr>
<td>Hyperfine structure</td>
<td>$10^{-3}$-1</td>
<td>$10^{-7}$-$10^{-4}$</td>
<td>$3 \cdot 10^{7}$-$3 \cdot 10^{10}$</td>
</tr>
</tbody>
</table>

Hyperfine structure arises from interaction of nuclear moments with electric and magnetic fields produced at nucleus by orbiting electrons.

\[ \vec{F} = \vec{I} + \vec{J} \]

\[ F = I + J, I + J - 1, \ldots, |I - J| \]
Summarizing the effects:

Point nucleus + Finite size of nucleus + Magnetic dipole + Electric quadrupole

Example: $J=1$, $I=3/2$

Isotope A

Isotope (A−1)

Atomic state

Isotope (A−1)

Isotope A

F=5/2

F=3/2

F=1/2

$E = -\mu B_e \cos \theta$

$E = \frac{1}{4} e Q_0 V_{JJ} P_2(\cos \theta)$

These energy shifts of may be only a few parts per million of the energy of an optical atomic transition. Optical techniques provide the sensitivity and precision required to measure these effects.
Status of laser spectroscopy

Between 1995 and 2010

Before 1995

Laser spectroscopy measurements to date

Gaps in our knowledge

Beam production associated with challenges such as target chemistry.
Atomic physics considerations
It’s a big chart


Ion resonance ionization cases

On-line Laser Spectroscopy Measurements

Future Challenges
European Laser Spectroscopy Options

- In-source: RILIS, ALTO
  - Sub 1 atom/s sensitivity
  - Wide range of elements studied (~30 currently accessible)
  - Hot Cavity and associated Doppler broadening
  - Target chemistry and release time dependence

- In-gas cell laser spectroscopy: LISOL, IGISOL
  - Relatively insensitive to chemistry
  - Access to short half-lives
  - Pressure broadening and shifts

- Collinear: COLLAPS, IGISOL, CRIS
  - High resolution (typically limited by natural linewidth)
  - Highly adaptable
Methods to measure moments, radii, spin

Lifetime of the isomeric excited state / isotope ground state

1 ps  1 ns  1 µs

γ-TDPAD on aligned beams
  g-factor
  quadrupole moment

Transient field method
  g-factor

Laser spectroscopy methods
  magnetic moment,
  quadrupole moment,
  charge radius,
  spin

β-NMR/NQR on polarized nuclei
Nuclear Magnetic/Quadrupole Resonance
  g-factor
  quadrupole moment

Fragmentation

Fusion-evaporation

ISOL methods
Gas cell laser spectroscopy

- JYFL, Leuven
  - $^{57,58,59}\text{Cu}$, $^{97,99,101}\text{Ag}$
    - T. E. Cocolios et al., PRL 103, 102501 (2009)
    - T. E. Cocolios et al., PRC 81, 014314 (2010)

- Future S3 work on stopped beams
  - N=Z line: $^{94}\text{Ag}$, $^{101,103}\text{Sn}$,
  - SHE region >Ac

- Cryogenic gas cell and fluorescence detection
  - 900/s yields, $\Gamma \sim 300\text{MHz}$
  - Possible route to probe $\mu$s half-lives

G. D. Sprouse et al., PRL 63 1463 (1989)
Using the ion source for laser spectroscopy

Collinear Spectroscopy (+ cw RIS)

Pulsed Resonance Ionization (RIS)

Low-Medium Resolution, High Efficiency

Medium-High Resolution, Lower Efficiency

Specialized High Resolution Techniques + High Efficiency


Progress in laser spectroscopy at radioactive ion beam facilities

Recent REVIEW article
\[ \mu(\text{Cu}^+) = \frac{A_{hf}(\text{Cu})}{A_{hf}(\text{Cu}^{63})} \mu(\text{Cu}^{63}) \]

First Ionization Limit
62317.4 cm^{-1}

\[ \lambda_2 = 441.6 \text{ nm} \]

40943.73 cm^{-1}

\[ \lambda_1 = 244.164 \text{ nm} \]

Atomic spin: J=1/2
Nuclear spin: I=3/2
Total spin: F=1,2

Cu: ground state

P. Van Duppen, RNB 2008
\[ \omega_c = \frac{q}{m} \cdot B \]

Unambiguous state assignment!

ME of ground state is 240 keV higher than literature value!

\[ R \approx 1 \cdot 10^7, \delta m/m \approx 4 \cdot 10^{-8} \]

\[ \Rightarrow (6^{-}) \text{ state} = gs \]

\[ \Rightarrow (3^{-}) \text{ state} = 1^{st} \text{ is.} \]

\[ 101(3) \text{ keV} \]

\[ 242(3) \text{ keV} \]

\[ \Rightarrow 1^{+} \text{ state} = 2^{nd} \text{ is.} \]

RILIS laser spectroscopy in the Pb region

- Recent developments for the spectroscopy of At isotopes

- From $A = 192$ up to $A = 218$;
- From $T_{1/2} = 33$ ms up to $T_{1/2} = 3$ yr;
- From 0.3 ion-s$^{-1}$ to over $10^7$ ion-s$^{-1}$;
- Using $\alpha$, $\beta$, $\gamma$ and ion (FC) counting.

KU Leuven

A) RESONANCE IONIZATION
LASER ION SOURCES

Reducing isobars

Isomer selectivity

Optical pumping

7) Selectivity
How to improve the selectivity of the laser ion source?

Problem – unselective ionization of isobars on hot metal surfaces.

Solution 1 – Reduce the surface ionization

Reduce temperature

Use low work function materials

Trap unwanted elements
(add chemical selectivity to the effusion process)

Solution 2 – Separate surface ions from laser ions

Repel surface ions before laser ionization

Temporal separation of laser and surface ions
Ideal selective laser ion source? Repeller and trap

K. Blaum et al., NIMB 204 (2003) 331
Implementation of such a device

Challenges:

- **High radiation**
  - radiation hard material
  - Gas extraction
- **High tension**
  - electronics in HV-cage
  - remote control
  - Amplification of rf at target
  - Feedthroughs
- **Robot**
  - Connectors
  - Stability
  - Size limitations
A feasible Laser Ion Source Trap design!

- Target
- Hot cavity
- Repeller
- RF - ion guide
- RILIS lasers
- Extractor

○ ○ ○ neutral atoms
+ + + ions of interest
2000 °C, -500 V tor, 12 Mhz, 0.5 kV, -60 kV

On-line LIST run for Mg (and Po) beams during 2012!

Daniel Fink - Poster
Robot coupling
Micro beam gating – selectivity using the laser ion pulse structure

Thinner cavity walls -> more electrical resistance -> higher voltage -> shorter bunch length of laser ions

Standard W cavity:

Thin Nb cavity:

Problem: increased complexity, reliability issues, limited gain in selectivity \(\rightarrow\) How can this concept be improved?
One step further: create a temporal focus and gate at this point

High voltage hot cavity + Field free drift region -> Temporal focus downstream with width

Resonant Ionization Laser Ion Source (RILIS) with improved selectivity achieved by ion pulse compression using in-source time-of-flight technique

V.I. Mishin, A.L. Malinovsky and D.V. Mishin

Institute for Spectroscopy Russian Academy of Sciences, 142190 Troitsk, Moscow region, Russia

Abstract. This paper describes for the first time the improved selectivity of the RILIS made possible by the time-of-flight (TOF) ion bunch compression. Brief description of the compression principles and some preliminary experimental results are presented. In off-line experiments short ion peaks of natural Li, Na, K, Tm and Yb are observed as ions leave the RILIS-TOF structure. For Tm the ion peaks of 5 μs half-height duration are detected and 1 μs peaks for Sn are predicted. In view of the repetition rate of the ISOLDE-RILIS lasers it is hoped that the selectivity of Sn isotopes production may be improved as much as 100 employing the RILIS with the TOF ion bunch compression and a gating technique.

For a 15V cavity potential, Δτ ≈ 3.5 μs for $^{100}$Sn

Selectivity = 1/(laser repetition rate × Δτ)

≈ 28

With no loss of ionization efficiency!

This technique is under development by V. Mishin, at the Institute of Spectroscopy, Troitsk
Optimizing the hot cavity materials or transfer line:

Study of low work function materials for hot cavity resonance ionization laser ion sources
F. Schwellnus a,*, R. Catherall c, B. Crepieux c, V. N. Fedosseev c, B. A. Marsh c, Ch. Mattolat a, M. Menna c, F. K. Österdahl b,1, S. Raeder a, T. Stora c, K. Wendt a

*Fabio Schwellnus, Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55099 Mainz, Germany
bKTH, Royal Institute of Technology, SE-10044 Stockholm, Sweden
cISOLDE, CERN, CH-1211 Genève 23, Switzerland

Beam purification by selective trapping in the transfer line of an ISOL target unit
E. Bouquerel, , R. Catherall, M. Eller, J. Lettry, S. Marzari, T. Stora, The ISOLDE Collaboration CERN, CH-1211, Geneva, Switzerland

Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 266, Issues 19–20, October 2008, Pages 4298-4302,
A) RESONANCE IONIZATION LASER ION SOURCES

7) Worldwide laser ion sources

- RILIS
- IRIS
- LISOL
- GANIL
- TRIUMF
- RIKEN
- JYFL
- ORNL
- ALTO
Laser Ion Sources Worldwide

- **TRILIS**: ISAC/TRIUMF
- **ISTF2**: HRI/BL/ORN
- **GISELE**: GANIL
- **ALIS**: ALTO IPN-Orsay
- **FURIOS**: IGISOL/JYFL
- **IRIS**: PNPI
- **LISOL**: CRC LLN
- **RILIS**: ISOLDE/CERN
- **SPES**: INFN
- **RISIKO**: IFP/UMZ
- **TRIGA-LIS**: KCh/UMZ
- **PALIS**: RIKEN

**Laser type**
- Ti:Sa
- Dye

**Operation**
- ON-line
- OFF-line

**Source type**
- Hot cavity
- Gas cell
- planned

Projection: Van der Grinten
Resonance laser ionization of atoms for nuclear physics

V N Fedosseev¹, Yu Kudryavtsev² and V I Mishin³

¹ CERN, Geneva CH1211, Switzerland
² Instituut voor Kern-en Stralingsfysica, K.U.Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
³ Institute of Spectroscopy RAS, Troitsk, Moscow region, Russia

E-mail: Valentin.Fedosseev@cern.ch

doi:10.1088/0031-8949/85/05/058104
IRIS (Investigation of Radioactive Isotopes on Synchrocyclotron) at PNPI (Petersburg Nuclear Physics Institute)

Gatchina, Russia

A. E. Barzakh,  
D. V. Fedorov,  
V. S. Ivanov,  
P. L. Molkanov,  
V. N. Panteleev (Head of Laboratory),  
Yu. M. Volkov

LIS (Laser Ion Source) – method of laser ionization in a hot metal cavity - invented and firstly applied at IRIS [1,2]

RIS/LIS (Resonance Ionization Spectroscopy inside a Laser Ion Source) of mass-separator of IRIS facility – in operation since 1991 at 1 GeV Synchrocyclotron of PNPI [2,3]

Targets of mass-separator: UC thick targets (from 5 g/cm^2 up to 150 g/m^2) and refractory metal targets

Isotope shifts (IS) and Hyperfine structure (HFS) for very far from beta stability isotopes of Yb, Tm, Eu, Gd and Tl have been measured at IRIS using this method [4,5,6,7]
IRIS laser set-up

Copper-vapor laser set-up:
- CVL 1 - master oscillator,
- CVL 2,3 - amplifiers,
- laser power - 40 W each,
- wavelength - 510 nm and 578 nm,
- repetition rate - 10 kHz.

Dye laser set-up:
- Dye laser 1 - narrow band (500 MHz),
- with wavelength stabilization
- and scanning control
- Dye laser 2,3 - broad band (20 GHz)
- Dye amplifiers 1,2,3,4
- Laser power - up to 10W
- (with two amplifiers)
- Wavelength range.

Mass-separator IRIS

Proton beam:
- Synchrocyclotron
- 1 GeV
- 0.1 µA
- 50 Hz

Ion beam extraction-focusing system

Target - ion source unit

Magnet

Switch-yard

Dye laser 1 (scanning)

Dye amplifier 1

BBO crystal

Lens

Prism

Wavelength stabilization and scanning control

Copper Vapor Lasers (CVL 1,2,3)

Dye laser 2

Dye laser 3

Synchronization and power control
NEW GISELE @ GANIL

GANIL Ion Source using Electron Laser Excitation

- Off line prototype for SPIRAL2
- TiSa laser, 20m transport path and hot cavity: June 2010 – July 2011

Rydberg state of Ga

3 TiSa cavities from TRIUMF
2 Tripler cavities from Mainz U.

Lecesne et al, RSI 81 (2008) 02A910

- First Ga$^+$ ion beam (+ Mainz U.)
- Target and Ion Source for SPIRAL2: UCx + RILIS
- Next beams: Sn, Zn, Y, In

ICIS 2011, 12th-16th September 2011, Giardini Naxos
Laser Ion Sources for Radioactive Beams
Nathalie Lecesne
thick target - hot cavity ISOL based radioactive ion beam facility

routine operation at the licensing limit:
100 $\mu$A p+ on $A<81$ targets (up to 50kW)
10 $\mu$A p+ on UC$_x$ targets

RIB beam schedule: Apr.-Dec. (24/7)

carbide etc. targets
metal foil targets

500 MeV p$^+$ continuous

25 mm
**Operational:**

(2004) TiSa laser based RILIS:
1st on-line beams

(2009) full off-line beam development capabilities

(2010) NSERC funded “in-source laser spectroscopy program”

(2013) 1st schedule with above 50% beamtime by T RILIS
T RILIS laser operation with GHz/wk stability

**Development:**

(2012-14) enhanced beam purity via (i) RFQ-LIS, (ii) pulse structure

(2012-2015) continued laser development

• in-source laser spectroscopy

• development of TiSa RILIS schemes

---

**TiSa laser specifications:**

**Repetition rate** 10 kHz

**Wavelength range**
- fund. 3W, 690 – 990 nm
- 2ν 500mW, 350 – 490 nm
- 3ν 100mW, 233 – 320 nm
- 4ν 100mW, 205 – 232 nm

**Tuning range**
- BRF TiSa 300 GHz
- Grating TiSa 135 THz

**Spatial beam quality** $M^2 < 1.2$

**Spectral bandwidth** 3–5 GHz

**Temporal pulse duration** 30–50 ns

---

Jens Lassen | TRIUMF Resonant Ionization Laser Ion Source
Hot-Cavity Laser Ion Source at HRIBF-ORNL

Ti:Sapphire Laser System

- Three Ti:Sapphire lasers upgraded with individual pump lasers in 2011
  - Synchronizing the pump lasers
  - Eliminating the Pockels cells
- Continuous wavelength tuning thru the fundamental spectral range
- One mirror set covers the full fundamental wavelength range

- Pulse repetition rate: 10 kHz
- Wavelength tuning range:
  - Fundamental: 715 - 960 nm
  - SHG: 359 – 470 nm
  - THG: 240 – 310 nm
  - FHG: 208 – 230 nm
- Peak laser power:
  - 2.5 Watt (fundamental)
  - 0.8 W (SHG)
  - 0.12 W (THG)
  - 30 mW (FHG @ 215nm)

- Ionization schemes for 14 elements obtained in off-line studies
  - Sn, Ni, Ge, Cu, Co, Ga, Sr, Mn, Fe, Al, Ho, Tb, Dy, Te
- Ionization efficiency for eight elements evaluated in off-line studies

<table>
<thead>
<tr>
<th>Element</th>
<th>Sn</th>
<th>Ni</th>
<th>Ge</th>
<th>Cu</th>
<th>Co</th>
<th>Ga</th>
<th>Mn</th>
<th>Ho</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>22</td>
<td>2.7</td>
<td>3.3</td>
<td>2.4</td>
<td>&gt;20</td>
<td>9</td>
<td>0.9</td>
<td>40</td>
</tr>
</tbody>
</table>

- The LIS has been installed on-line for production of RIBs
Current Status of HRIBF-ORNL

- Ionization schemes for 14 elements obtained in off-line studies
  
  Sn, Ni, Ge, Cu, Co, Ga, Sr, Mn, Fe, Al, Ho, Tb, Dy, Te

- Ionization efficiency for eight elements evaluated in off-line studies

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- The LIS has been installed on-line for production of RIBs
Leuven Isotope Separator On-Line (LISOL) Laser Ion Source

- **Delay time**: 10 - 300 ms (the same for refractory atoms)
- **Efficiency**: up to 6%
- **Selectivity**: up to 2200

- **Efficiency**: up to 6%

- **Selectivity**: up to 2200

The operational principle of the laser ion source is based on an element-selective resonance multi-step laser ionization of neutral atoms that after production in a nuclear reaction are thermalized and neutralized in a buffer gas.

- **Delay time**: 10 - 300 ms (the same for refractory atoms)
- **Efficiency**: up to 6%
- **Selectivity**: up to 2200

- **Efficiency**: up to 6%

- **Selectivity**: up to 2200

**Laser system consists of two excimer-pumped dye lasers**

- **Tunable range**: 205 - 900 nm
- **Repetition rate**: 200 Hz

80% of all elements can be ionized using LISOL laser system

- **Light ion-induced fusion evaporation reactions**
  - Co, Ni, Mn, Cr, V, Cu
- **Heavy ion-induced fusion evaporation reactions**
  - Rh, Ru, Ti, Sn, In, Ag, Ac
- **Proton-induced fission reactions**
  - Fe, Co, Ni, Cu
- **Spontaneous fission of $^{252}$Cf**
  - Rh, Ru, Mo, Pd
The dual-chamber laser ion guide

A novel concept was required to overcome losses in efficiency due to recombination of photo-ions in the buffer gas plasma caused by the cyclotron beam.

By separating stopping and laser ionization volumes

- Increased laser ionization efficiency at high cyclotron beam current
- Increased selectivity (collection of survival ions)

Selectivity ($^{94}$Rh):

Laser(ON)/Laser(OFF)

Ion Collector OFF = 450
Ion Collector ON = 2200

Yu. Kudryavstev et al., NIMB
IGISOL-4: overview of facility in 2012

- Beam from K-130 or MCC-30
- Off-line ion sources: (discharge, carbon cluster...)
- Laser ionization & gas jet LIST
- Optical manipulation in rfq
- Yield station
- Decay spectroscopy
- Collinear laser spectroscopy
- Mass spectrometry & post-trap spectroscopy
Fast Universal Resonant laser IOn Source (FURIOS) @IGISOL-4, JYFL.

- 3 × Ti:Sa lasers pumped by Nd:YAG (10 kHz)
- 1 × grating based Ti:sa laser (for continuous wavelength selection)
- 1 × pulsed dye laser pumped by copper vapour laser
- In 2012: development of narrow-bandwidth Ti:Sa system

RF hot cavity • Developments towards $^{94m}$Ag (21s)
PARasitic Laser Ion-Source (PALIS) at SLOWRI RIKEN

RIKEN fragment separator (BigRIPS)

Preliminary image

MAIN RI-Beam (~250MeV/u)

Degrader

F2 PPAC

Gas catcher cell
Argon/Helium 1atm

Ionization lasers

PALIS New Laser system
(be in the planning stage)

From Dr. Tomita Gr.
(Nagoya Univ.)

F2 chamber in BigRIPS

New differential pumping method
(fast evacuation & extraction for short-lived nuclei)

SLOWRI beams (~30keV)

SLOW RI-beams will be available in every BigRIPS experiment.

These RIs are available for PALIS

79Cu ex. example @1pnA U
LISE calc.

In Gas jet
In Gas cell
Preliminary off-line test

In Gas cell/In Gas jet Laser Spectroscopy
Recommended reading for further information


Atomic Physics. Exploration through Problems and Solutions. D. Budker, D. F. Kimball, and D. P. DeMille

Laser photoionization spectroscopy
Letokhov, Vladilen Stepanovich
Moscow, Izdatel'stvo Nauka, 1987

*The scientific career of V S Letokhov* (10 November 1939–21 March 2009)
Victor I Balykin 2012 Phys. Scr. 85 050302
B) Other laser based particle sources

- Laser Stripping of H- beams
- High charge laser ion source
- Laser particle acceleration
- Photoinjector electron source
B) Other laser based particle sources
Three-Step Stripping Scheme

- A novel approach for laser-stripping which uses a three-step method employing a narrowband laser [V. Danilov et. al., Physical Review Special topics – Accelerators and Beams 6, 053501]

Step 1: Lorentz Stripping

\[ H^- \rightarrow H^0 + e^- \]

Step 2: Laser Excitation

\[ H^0 (n=1) + \gamma \rightarrow H^{0*} (n=3) \]

Step 3: Lorentz Stripping

\[ H^{0*} \rightarrow p + e^- \]
Laser stripping (for PS2)
Summary of the workshop at SNS, 18th/19th Feb. 09

W. Bartmann, B. Goddard

PS2 Meeting, 12th March 09

Summary of the PS2-specific issues (1)

• PS2 H-Injection allowing either foil or laser stripping, using SNS concept of Adiabatic Rapid Passage (relies on frequency sweep across resonance)

• ~50 kW injected power → foil stripping still feasible but
  – laser stripping may be already advantageous with respect to losses and activation
  – also testbed for a 4 or 5 GeV mulit-MW proton driver accumulator ring

• Insertion concept is still being worked on
  – if neutralising the H- with a laser is possible at 4 GeV → very elegant scheme
  – calculations of photodissociation by CERN and SNS

• Dispersion angle tailoring seems impossible for PS2 due to resulting emittance blowup from mismatch.
Summary of the PS2-specific issues (2)

• Excitation of the n=3 state gives 8 degrees incidence angle → difficult geometry
  N=2 has much easier geometry with 47 degrees but large angular spread due to the long stripping lengths

• Compromise between micro-bunch length and momentum spread needs to be defined at the injection point depending on laser limitations
  – average laser power scales linearly with microbunch length
  – peak laser power scales linearly with momentum spread. Some work on buncher cavities in the TL is needed

• Laser requirements were presented in a table for different excitation schemes and wavelengths – it was clear that using as long a wavelength as possible gives a shallower incidence angle with the big advantage of increasing the effective laser intensity from the Doppler effect.
Characteristics relevant for the laser system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Value</th>
<th>n=2</th>
<th>n=3</th>
<th>n=3</th>
<th>n=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>1064</td>
<td>1064</td>
<td>532</td>
<td>532</td>
</tr>
<tr>
<td>Laser/H- angle</td>
<td>deg</td>
<td>47.50</td>
<td>8.39</td>
<td>99.84</td>
<td>87.69</td>
</tr>
<tr>
<td>Angular spread</td>
<td>deg</td>
<td>±0.10</td>
<td>±0.42</td>
<td>±0.06</td>
<td>±0.07</td>
</tr>
<tr>
<td>Peak power (single pass)</td>
<td>MW</td>
<td>4.5</td>
<td>1.3</td>
<td>13.9</td>
<td>43.3</td>
</tr>
<tr>
<td>Average power (single pass CW)</td>
<td>kW</td>
<td>2.25</td>
<td>0.6</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>Average power (mode-locking only)</td>
<td>W</td>
<td>71</td>
<td>20</td>
<td>220</td>
<td>681</td>
</tr>
<tr>
<td>Average power (Q_c=1000 CW only)</td>
<td>W</td>
<td>2.25</td>
<td>0.6</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>Average power (mode-locking, Q_c = 1000)</td>
<td>mW</td>
<td>71</td>
<td>20</td>
<td>220</td>
<td>681</td>
</tr>
<tr>
<td>Vertical laser beam height (1 σ rms)</td>
<td>mm</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Horizontal laser beam width</td>
<td>mm</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Laser stability</td>
<td>%</td>
<td>&lt;20</td>
<td>&lt;20</td>
<td>&lt;20</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Laser availability</td>
<td>%</td>
<td>~99</td>
<td>~99</td>
<td>~99</td>
<td>~99</td>
</tr>
<tr>
<td>Laser repetition rate (max)</td>
<td>Hz</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Includes factor 3 margin in laser power
WS outputs: laser possibilities

• KEK (Yamane):
  – Laser-H- IP is brought into B-field
    → compensation of Doppler broadening by broadening of Stark-states in the magnetic field
    → single laser frequency can excite full distribution
    → no spontaneous decay worries (direct stripping of excited H⁰)

• Continuum (Laha):
  – “Stitching” ~10 laser together to reach 1 ms macropulse
    → issues: synchronisation, overlap, cost, complexity, reliability

• LBNL (Wilcox):
  – Commercial components, where mode locked, diode pumped Nd:YAG laser with 1064 nm is used to create a 1.2ms burst with 352 MHz micro-bunch frequency
  – Amplification stages are pumped continuously for 1.2 ms, laser operating in saturation
  – The peak laser output power is 10 kW for a micro pulse of 50 ps, the average power 200 W.
  – Four mirror cavity (independent control of focus and cavity length) with a conservative build up factor of 100 is assumed, to give 1 MW circulating peak power (compare to the ~4 MW quoted for PS2, which includes a factor 3 margin)
    → issues: coupling to the cavity, radiation hardness of optical elements, thermal perturbation
    → proposed system could meet requ. of CERN and FNAL, not SNS
Laser / photon recycling issues

- Laser parameters (assuming factor 100 from recycling cavity)
  - Wavelength OK - 1064 nm easiest (Nd:YAG technology)
  - 50 ps long pulse OK (see laser characteristics)
  - 352 MHz micropulse structure OK (mode-locked pulse train)
  - Micropulse energy OK (2.5 µJ)
  - 1.2 ms macropulse not OK (fluorescence lifetime of gain medium ~270 µs)...
  - Macropulse energy and average power not impossible (1 J at 0.5 Hz for PS2)

- Recycling cavity – many issues (high power, stability, radiation, incorporation, ...)

![Diagram showing laser parameters and recycling cavity issues](image)
Laser-assisted stripping schemes I: magnet-laser-magnet

Issues:

Wiggler design, IR geometry, spontaneous decay, fringe fields, laser power, laser time structure, beam parameters, stripping efficiency...
Laser-assisted stripping schemes II: laser-laser-magnet

(Additional) issues:

Photodetachment cross-sections, laser cavities, reuse of same laser beam
Laser-assisted stripping schemes III: magnet-laser+magnet

Stripping of first e⁻ (vertical 1.8 T dipole)

Vertical wiggler
To strip H⁻ to H₀
Laser for resonant excitation

Foil 1

B ≤ 0.13 T

Foil 2

B=??? T

Excitation by laser and stripping of H₀⁻ to p⁺ in strong dipole field

Waste beam

(additional) issues:

Atomic physics in strong dipole/laser fields, Stark shifts and broadening, stripping efficiencies, IR geometry, laser power...
Conclusions

• For PS2 the possibility of laser stripping remains interesting
• High beam energy gives a variety of resonance schemes to be envisaged with optimization of laser parameters and injection geometry
• Three alternative basic schemes need further investigation and quantification
  – Magnet → laser → magnet
  – Laser → laser → magnet
  – Magnet → laser+magnet
• The workshop was extremely useful technically, in addition links were formed / strengthened with the accelerator labs, laser labs and laser industry experts; technical collaborations and common areas of work were defined
• The action plan needs follow-up (to be done by J. Galambos) and a synthesis of the outcomes and progress should be made at some time in the future
• Will arrange a first follow-up meeting with those present at PAC (SNS, FNAL, CERN)
B) Other laser based particle sources
“Options for the next-generation collider with different levels of risk and different costs:

ILC: most developed, lowest risk but high cost
High gradient klystron: medium risk with significant cost savings
Drive-beam microwave: higher risk with probably greater savings
Dielectric or Plasma acceleration: much higher risk but with vast cost saving potential”

• Laser capability improving rapidly
  – Billion $ industrial development effort
• Two acceleration approaches using lasers:
  – Laser wakefield (plasma) acceleration, i.e BELLA (10 GV/m)
  – Direct laser (dielectric) acceleration, i.e. E-163 (1 GV/m)
• Real challenges for both approaches
• Very different laser requirements
  – Both require high average power → must generate beam power
    • Laser-wakefield acceleration requires high peak laser power
  – Lasers are most efficient and cost effective near CW operation
    • CW operation is best use of expensive amplification medium
→ SLAC is pursuing direct laser acceleration with ~10,000 times lower peak power requirements ⇒ more favorable cost scaling
B) Other laser based particle sources

High charge laser ion source
Laser *Plasma* ion sources

- A pulsed laser beam is focused onto a target.
- At some position the laser frequency couples to the free electron plasma frequency (either in the material, or the formed plasma).
- In the dense plasma, ions of the target material are formed through electron impact ionization.

\[ \lambda = \frac{2\pi c}{e} \sqrt{\frac{m_e e_0}{n_e}} \]

- \( n_e = 10^{21} \text{ cm}^3 \) corresponds to 1\( \mu \text{m} \).
- Laser power density needs to be above \( 10^6 \text{ W/cm}^2 \), which is easily available with pulsed lasers.

Taken from
R. Scrivens
Ion Source lecture
Laser ion source for the LHC injector chain

- An alternative and potentially favorable route for producing ions for the LHC
- Abandoned due to reliability concerns of unproven technique
Laser Ion Source (LIS) – an Alternative?

CERN - High Current Laser Ion Source

CO₂ Amplifier
100 J, 1Hz, 15ns

CO₂ Oscillator
150 mJ, 3Hz

Target

Expanding plasma

 Extraction system 120 kV

LEBT Grized Electrostatic Lenses

Double aperture simulating the RFQ acceptance

Pierrick Fournier-2001
LIS Power Laser and Source

The Russian 100 J, 1 Hz CO$_2$ Laser Amplifier in building 363 ("Farady Cage"), being commissioned

The prototype Laser Ion Source in building 236 on a HV platform (~100 kV) to decrease space charge
Could we go the LIS Route? It’s still R&D!

With Pb25+ from LIS, one could use the PS Booster instead of LEIR if:

- Current > 5mA during ~ 5µs
- Norm. transverse rms emittance $\varepsilon_{\text{rms}} < 0.15 \mu m$
- Source stable, reliable, small jitter....

Needs other major investments

- Make an operational laser (spare parts...) + installation in Linac 3;
- A new RFQ;
- Upgrading of PSB injection and vacuum systems;
- (list not exhaustive) summing up to 10...14 MCHF

😊 A few millions cheaper than LEIR
😊 Much less exploitation cost compared to LEIR

😊 Laser will (hopefully) work this summer, but then R&D starts!
😊 We cannot afford to go the LEIR and LIS routes in parallel
😊 Even if conclusive results by end 2002, Pb to LHC not before 2009
😊 Lighter ions: speculations, needs more R&D (e.g. for gaseous elements)

LHCC Ion Workshop, K.Schindl, CERN
Not enough time to decide!  
“Conclusions on Sources and Linac 3”

ECR Sources:
♦ The present 14 GHz source could (just) do the job for Pb, In, Kr, and easily do it for Ar, O, He. Due to uncertainty of extrapolation, an upgrading to
♦ 18 GHz (+ proportional field increase) is envisaged: potential increase of ~1.5
♦ Collaboration with outside labs to achieve 28 GHz (a factor > 4 in intensity?)
♦ Even a factor 10 increase would not be sufficient for the PS Booster route

Laser Ion Source:
♦ Still a prototype in the R&D phase
♦ implementation of an operational source and other hardware would cost at least 10 MCHF, but would save resources for exploitation of LEIR
♦ Lighter ions? Much more R&D needed (which also costs scarce resources)
♦ Pb ions not ready for LHC before 2009

Conclusion: If we want to have Pb ions ready for LHC in 2008 with a reasonable confidence level, decide NOW for LEIR + (upgraded) ECR source
B) Other laser based particle sources

- Laser Stripping of H- beams
- Laser particle acceleration
- High charge laser ion source
- Photoinjector electron source
RF Photoinjectors: Operation Principle

- Production of electrons by photoemission
- Acceleration of electron beam in electric field of microwave cavity
- High field gradients possible
- High bunch charges
- Low emittance
- Short electron bunch lengths
Photoinjectors at CERN

CLIC Test Facility (CTF3):
- Drive Beam Injector
- thermionic gun
- Drive Beam Accelerator
- Delay Loop: 2
- Combiner Ring: x4

CLEX
- 2 beams test area
- CALIFES Main beam photo-injector

PHIN
- Drive beam photo-injector test stand

PHIN Photoinjector:
- UV laser beam

http://clic-study.web.cern.ch/clic-study/

<table>
<thead>
<tr>
<th></th>
<th>DRIVE beam</th>
<th>MAIN beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHIN Charge/bunch (nC)</td>
<td>2.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Macro-pulse length (ns)</td>
<td>1200</td>
<td>19.2</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>0.666</td>
<td>0.666</td>
</tr>
<tr>
<td>Bunch length (ps)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Bunch rep. rate (GHz)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1802</td>
<td>32</td>
</tr>
<tr>
<td>Macro-pulse rep. rate (Hz)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Margin for the laser</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Charge stability</td>
<td>&lt;0.25%</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>QE(%) of Cs2Te cathode</td>
<td>3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Machine parameters set the requirement for the laser

Laser System

1.5 GHz Synched oscillator
Cw pre-amplifier

3-pass amplifier
200μ in 100ns (=1.3μJ / laser pulse)

2ω

4ω

10W

Booster amplifier

320mW

3.5kW

2-pass amplifier

8.3kW

7.8kW

14.8mJ in 1.2μs

2ω

3.6kW

4.67mJ in 1.2μs

4ω

1.25kW

1.5mJ in 1.2μs (=800nJ / laser pulse)

To CALIFES photoinjector

To PHIN Photoinjector

Most optical phenomena (reflection, refraction,..) are \textit{linear}, i.e. the frequency of light remains unchanged.

- Note that wavelength may change depending on the refractive index \( n (\lambda = \frac{\lambda_0}{n}) \) of the material, but the \textit{frequency} \( \nu \) does not change.

- \( c = \nu c_0/n \), where \( c_0 = 299,792,458 \text{ m/s} \) (speed of light in vacuum) is a \textit{physical constant}.

\begin{center}
\includegraphics[width=0.5\textwidth]{image1.png}
\end{center}

\textit{Linear optics}: Color of white light, for instance, may change due to absorption of some of the spectral components. However, there is no frequency conversion – the frequency of each component remains unchanged, although the amplitude may change.

- In \textit{nonlinear optics}: frequency conversion through material nonlinearity. Requires high optical intensity (large electric field amplitude).

\begin{center}
\includegraphics[width=0.5\textwidth]{image2.png}
\end{center}
At high intensity and with a nonlinear material, the emitted wave gets distorted → harmonic frequencies are generated
Second harmonic generation

- **Second harmonic generation (SHG)**, also known as **frequency doubling**

- A special case of sum frequency generation (SFG)
  \[ \nu_3 = \nu_1 + \nu_2, \text{ with } \nu_1 = \nu_2 = \nu, \text{ and } \nu_3 = 2\nu \]

- Generated second harmonic power
  \[ P_{2\nu} \propto d_{\text{eff}}^2 P_\nu^2 L h(L) \]
  - \( d_{\text{eff}} \) = effective nonlinear coefficient of the material
  - \( P_\nu \) = fundamental power in the crystal
  - \( L \) = length of the crystal
  - \( h \) = parameter that depends on the focusing of the fundamental beam (also depends on the crystal length \( L \))

Commonly used nonlinear crystals:
- KTiOPO₄ (KTP) Visible, NIR
- LiNbO₃ Visible, NIR, short MIR
- LiTaO₃ Visible, NIR, short MIR
- β-BaB₂O₄ (BBO) UV generation
- ZnGeP₂ (ZGP) MIR