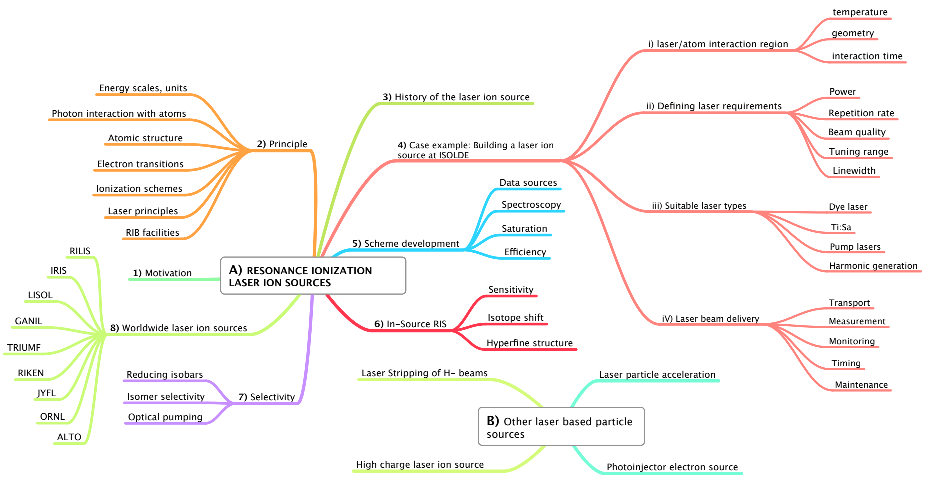
Laser Ion Sources I and II – Structure of the lectures



- **A)** RESONANCE IONIZATION LASER ION SOURCES
  - **1)** Motivation
  - **2)** Principle
    - Energy scales, units
    - Photon interaction with atoms
    - Atomic structure
    - Electron transitions
    - Ionization schemes
    - Laser principles
    - RIB facilities
  - **3)** History of the laser ion source
  - **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
  - **5)** Scheme development
    - Data sources
    - Spectroscopy
    - Saturation
    - Efficiency
  - **6)** In-Source RIS
    - Sensitivity
    - Isotope shift
    - Hyperfine structure
  - **7)** Selectivity
    - Reducing isobars
    - Isomer selectivity
    - Optical pumping
  - **8)** Worldwide laser ion sources
    - RILIS
    - IRIS
    - LISOL
    - GANIL
    - TRIUMF
    - RIKEN
    - JYFL
    - ORNL
    - ALTO
- **B)** Other laser based particle sources
  - Laser Stripping of H- beams
  - Laser particle acceleration
  - High charge laser ion source
  - Photoinjector electron source

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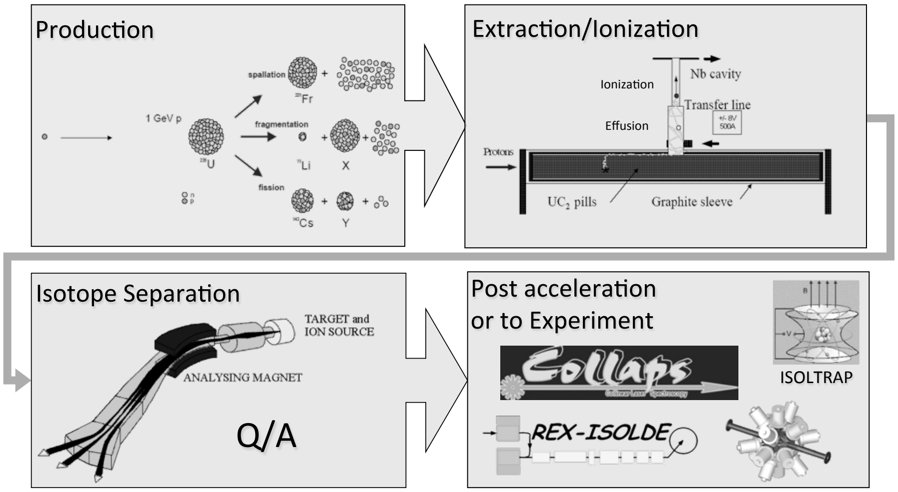
1) Motivation

A) RESONANCE IONIZATION
LASER ION SOURCES

The ISOL process



Fast, Efficient, Universal and Selective!

Factors influencing isotope production

RIB intensity $[s^{-1}\ \mu A^{-1}]$

Proton beam intensity $[s^{-1}\ \mu A^{-1}]$

Target density $[g\ cm^{-3}]$

Diffusion and effusion efficiency

$$I = \int \sigma(E)\Phi(E,x)\rho(x) {}^{N}\!/_{A}\, dx\, \varepsilon_{diff+eff}\,\varepsilon_{ion}$$

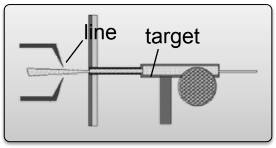
Reaction cross section $[cm^2]$

Target mass [g]

Ionization efficiency

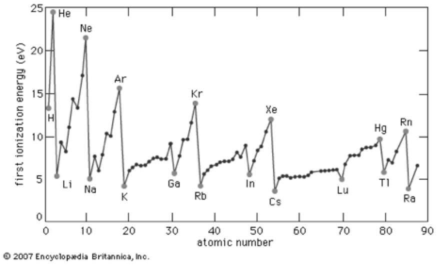
Production | Extraction

SURFACE ION SOURCE



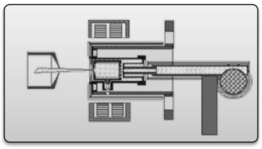
- Very simple: metal tube (line) from Ta or W
- Heated up to 2400 °C

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



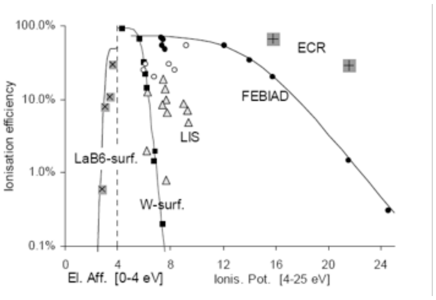
Surface Ionization Process:
R. Kirchner: Nucl. Instr. Meth. 186, 275 (1981)

PLASMA ION SOURCE



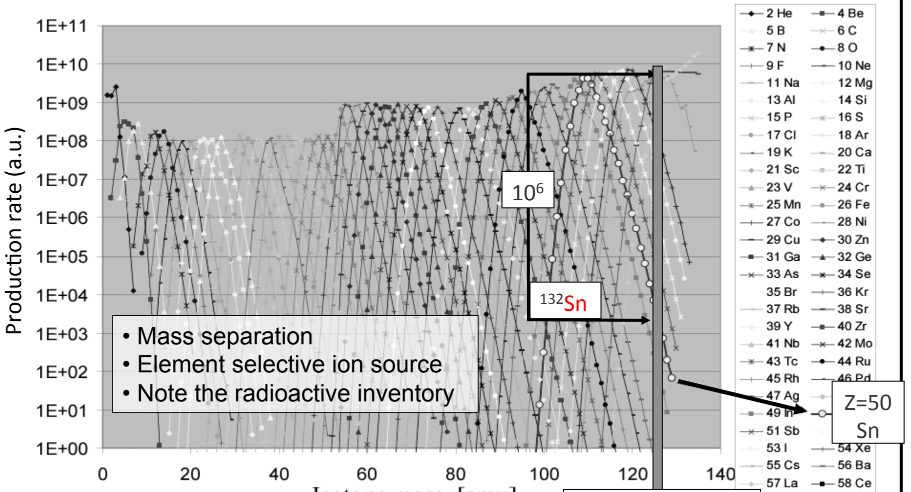
- Used for non surface-ionizing elements
- Ar or Xe plasma ignited by electrons at 130 eV

Very efficient, even for high IP elements. Chemically unselective



Production of Exotic Nuclei

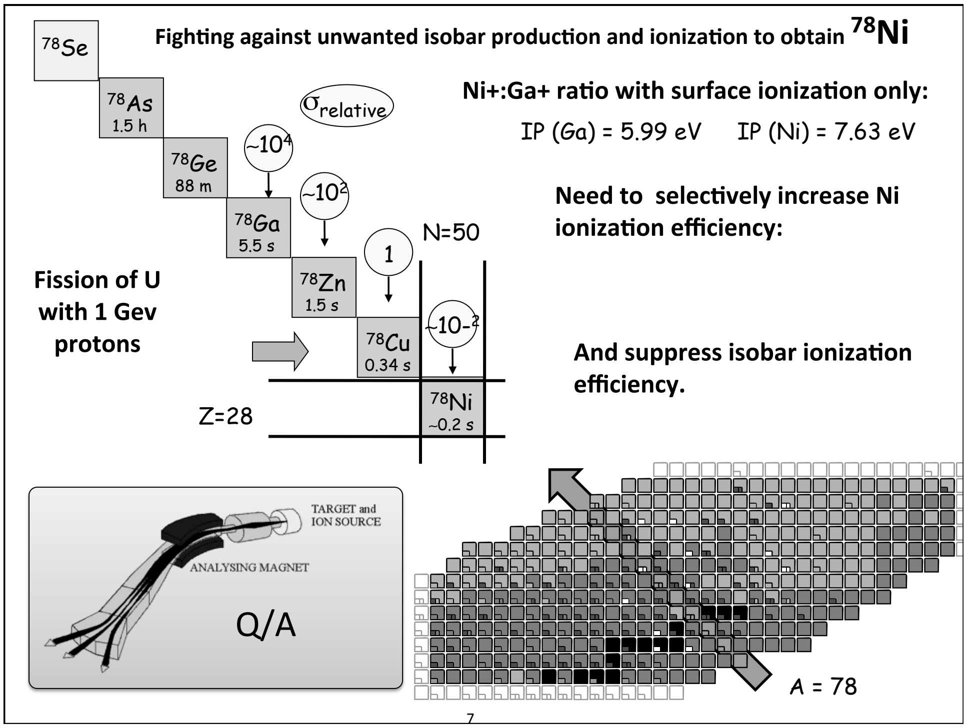
1 GeV proton beam on a lanthanum (La) target



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

Mass separation

J. Lettry, V. Fedoseev (CERN)



Fighting against unwanted isobar production and ionization to obtain ^{78}Ni

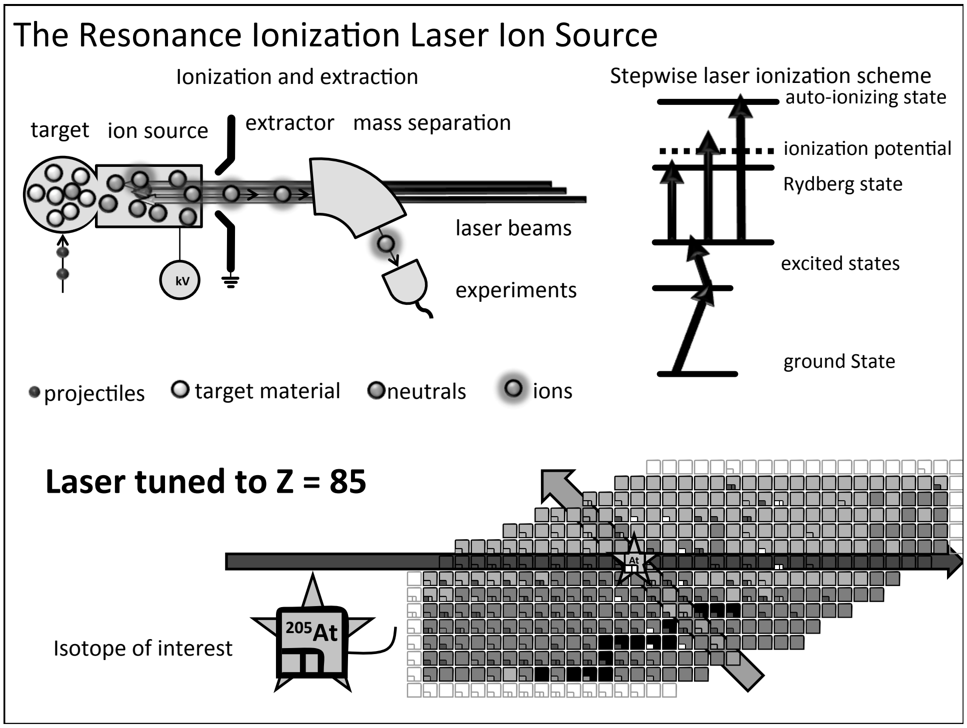
Ni+:Ga+ ratio with surface ionization only:

IP (Ga) = 5.99 eV IP (Ni) = 7.63 eV

Need to selectively increase Ni ionization efficiency:

And suppress isobar ionization efficiency.

Fission of U with 1 Gev protons



The Resonance Ionization Laser Ion Source

Ionization and extraction

Stepwise laser ionization scheme

Laser tuned to Z = 85

Isotope of interest

A) RESONANCE IONIZATION LASER ION SOURCES

2) Principle

- Energy scales, units
- Photon interaction with atoms
- Atomic structure
- Electron transitions
- Ionization schemes
- Laser principles
- RIB facilities

Energy scales and units that will be used

Wavelength, λ: SI unit = m [or μm, nm or Angström, 1 Å = 10^{-10} m]

λ is *dependent* on the (refractive index of the) medium in which the wave travels

Frequency, ν: 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: $\mathbf{E = h\nu = hc/\lambda}$

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: and whose units are universally quoted as **cm^{-1}** (*n.b.* not m^{-1})

$$\boxed{\bar{\nu} = \frac{1}{\lambda_{vac}}}$$

Wavenumber is directly proportional to **energy,** $E = hc\bar{\nu}$ and thus we commonly quote “energies” in units of cm^{-1}.

How these units describe the photon

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:


Max Planck
(1855-1947)

- **Energy, *E= h*ν**
  in which *h* is Planck's constant, *h* = 6.626 x 10^{-34} Js
- ***Linear* momentum, *p = E/c =* h*ν*/c = *h/*λ** (de Broglie)


Louis de Broglie
(1892-1987)

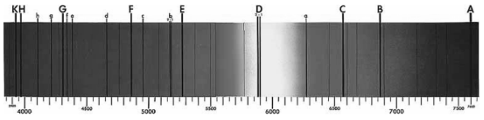
- ***(spin) Angular* momentum** equivalent to a quantum number of 1:

$$\boxed{j_{ph} = 1 \quad i.e., \quad \left|\underline{\mathrm{j}}_{\mathrm{ph}}\right| = \sqrt{2}\hbar}$$

n.b., 1) photons are Bosons (*i.e.*, obey Bose-Einstein statistics)
2) photons have *helicity* (projection of angular momentum on the direction of travel) of ±1 only (*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



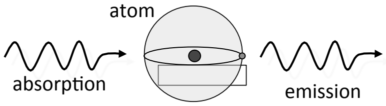
19th Century (1814) J. Fraunhofer measures dark lines in the Sun's spectrum.

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.

Balmer Series

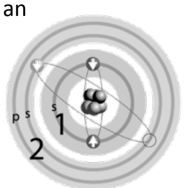
Lyman Series

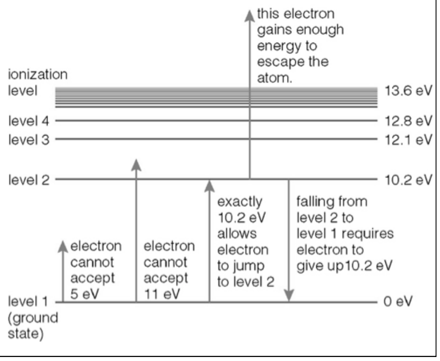
This discrete structure required quantum mechanics and Neils Bohr (1913)



Prerequisites for understanding how the photon interacts with atoms:

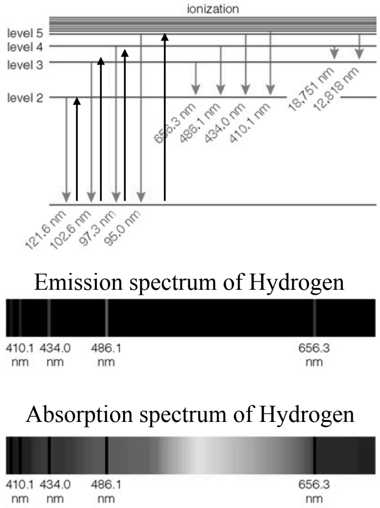
- The emission or absorption of a photon is the principal means by which an electron in an atom can increase or decrease its energy
- An atom with all its electrons in the lowest energy configuration is said to be in the ground state. ⟶
- Any other electron configuration is an excited state of the atom.
- 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.



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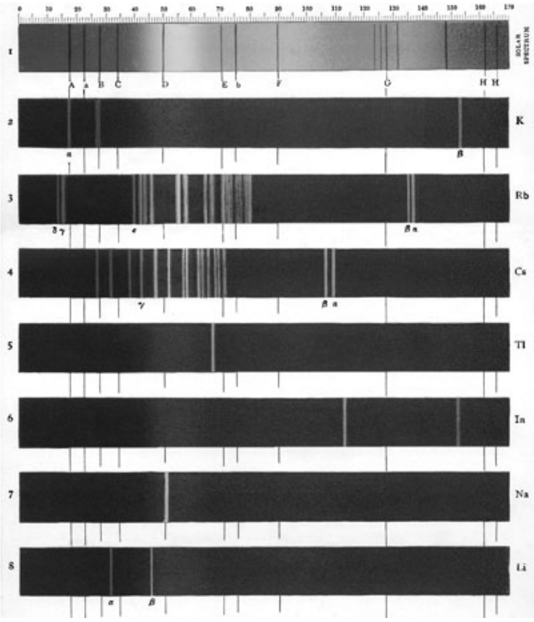
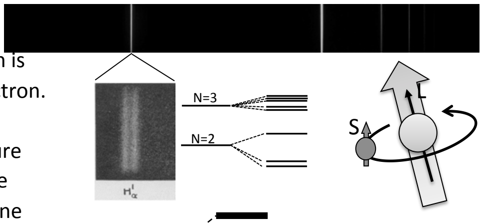
The atomic line spectra is an element's fingerprint

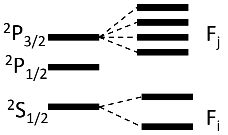


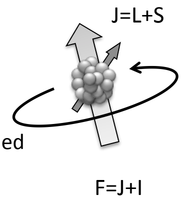
Higher Resolution

- 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.

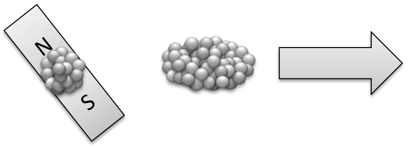


- A further factor of 1000 zoom into the structure reveals finer splitting due to the coupling of the nucleus with the electronic orbital: the hyperfine structure.



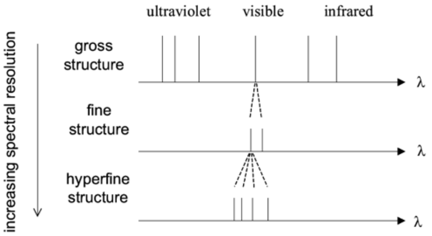


- The splitting of the hyperfine structure results from the presence of a permanent magnetic field associated with the nucleus and/or a non-symmetric electric field associated with a deformed nuclear charge distribution.



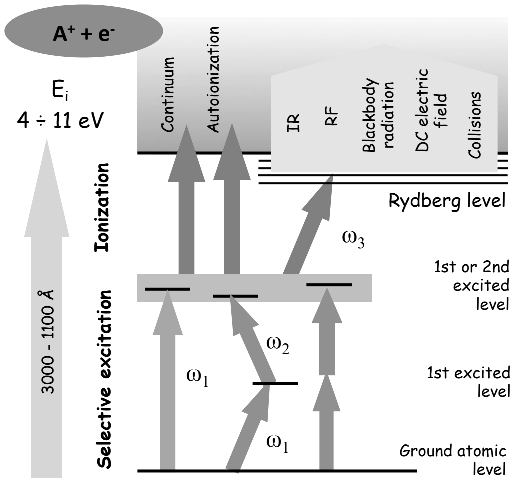
Note – Relevant for part 6 of this course:
If we can measure the splitting of the atomic transitions with sufficient resolution it is possible to deduce the nuclear observables (magnetic and electric moments, spin and size) without any model (nuclear) dependence.

Atomic Energy Scales



Energy scale	Energy (eV)	Effects
Gross structure	1-10	electron-nuclear attraction Electron kinetic energy Electron-electron repulsion
Fine structure	0.001 - 0.01	Spin-orbit interaction Relativistic corrections
Hyperfine structure	10^{-6} - 10^{-5}	Nuclear interactions

Laser ion source – using this fingerprint for selective ionization

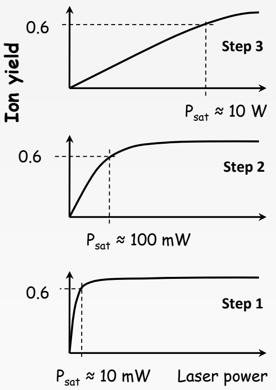


ω_i(laser) = ω_i(atom); P_i(laser) ≥ P_i(saturation)

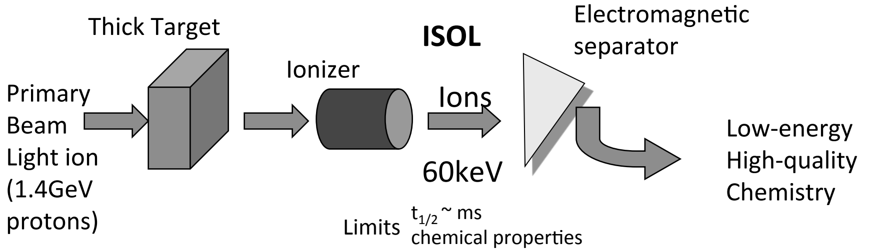
$P_{sat.} = \mathcal{E}_{sat.} \times f_{laser} \times S_{laser\ beam}$

$\mathcal{E}_{sat.} = \hbar\omega_i / 2\sigma_i$

f_{laser} = 10 kHz $Ø_{laser}$ = 3 mm



Rare isotope production methods compatible with laser ion sources



ISOL

Thick Target

Primary
Beam
Light ion
(1.4GeV
protons)

Ionizer

Ions

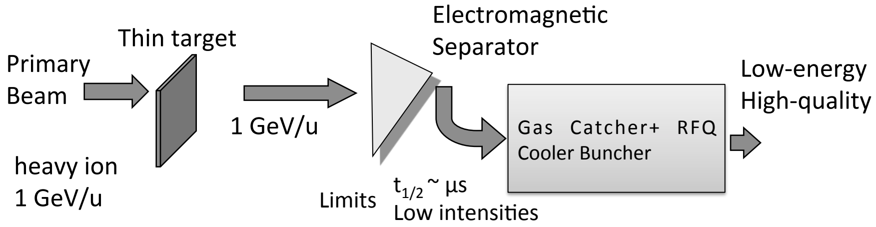
60keV

Electromagnetic
separator

Low-energy
High-quality
Chemistry

Limits $t_{1/2}$ ~ ms
chemical properties

In-Flight Fragmentation (GSI)



Primary
Beam

Thin target

heavy ion
1 GeV/u

1 GeV/u

Electromagnetic
Separator

Gas Catcher+ RFQ
Cooler Buncher

Low-energy
High-quality

Limits $t_{1/2}$ ~ µs
Low intensities

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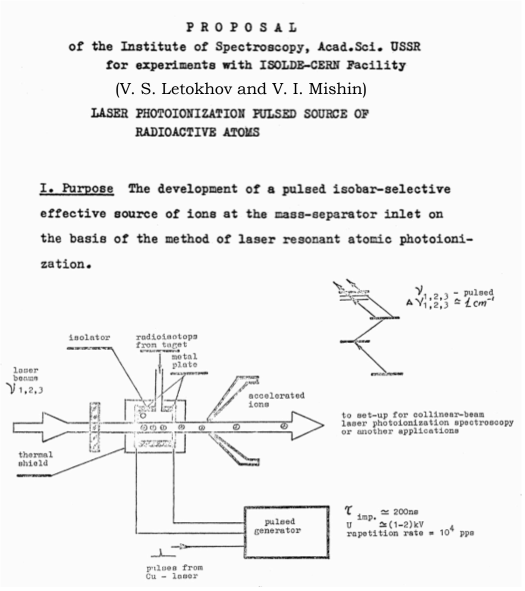
3) History of the laser ion source

A) RESONANCE IONIZATION LASER ION SOURCES

Early proposals: 1984



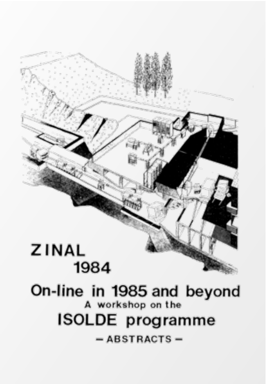
P R O P O S A L

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

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

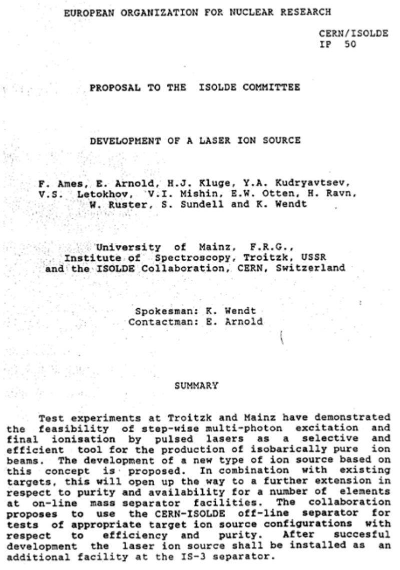
LASER PHOTOIONIZATION PULSED SOURCE OF RADIOACTIVE ATOMS

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.



ZINAL
1984
On-line in 1985 and beyond
A workshop on the
ISOLDE programme
— ABSTRACTS —

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 ionisation 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 succesful development the laser ion source shall be installed as an additional facility at the IS-3 separator.

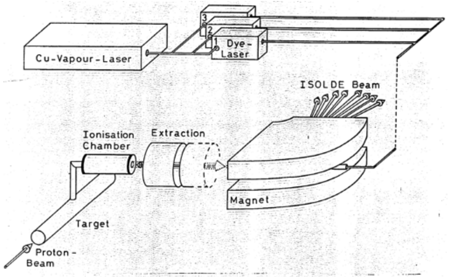
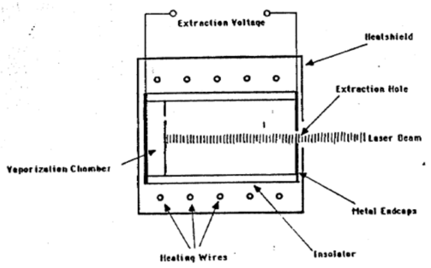


Fig. 5: General layout of the experimental set-up at the off-line separator



Ionization in a hot metal cavity

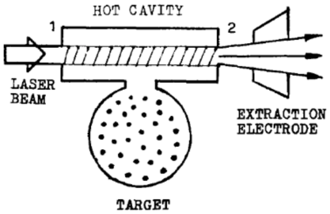
Nuclear Instruments and Methods in Physics Research A306 (1991) 400–402

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 [1], V.I. Mishin [1], V.N. Panteleyev, S.K. Sekatsky [1] and V.N. Fedoseyev [1]

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

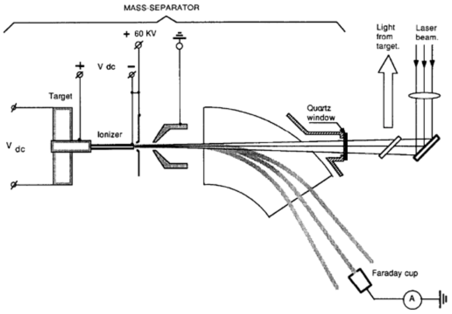
Nuclear Instruments and Methods in Physics Research B73 (1993) 550–560

Chemically selective laser ion-source for the CERN–ISOLDE on-line mass separator facility

V.I. Mishin [1], V.N. Fedoseyev [1], H.-J. Kluge [2], V.S. Letokhov [1], H.L. Ravn [3], F. Scheerer [2], Y. Shirakabe [4], S. Sundell [3], O. Tengblad [3] and the ISOLDE Collaboration

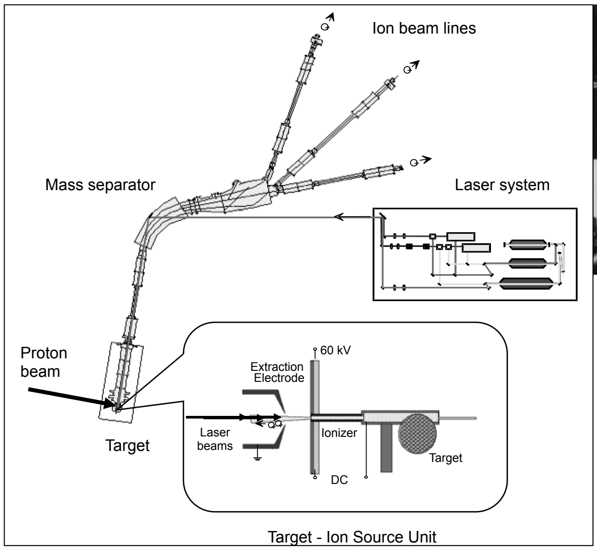
PPE Division, CERN, Geneva, Switzerland

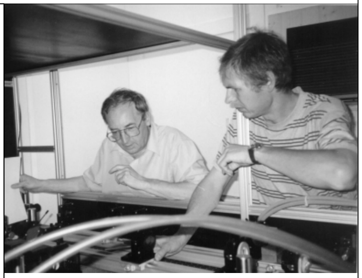
Received 26 November 1992



Yb, Tm, Sn, Li - off-line
Yb – on-line

RILIS at ISOLDE-PSB





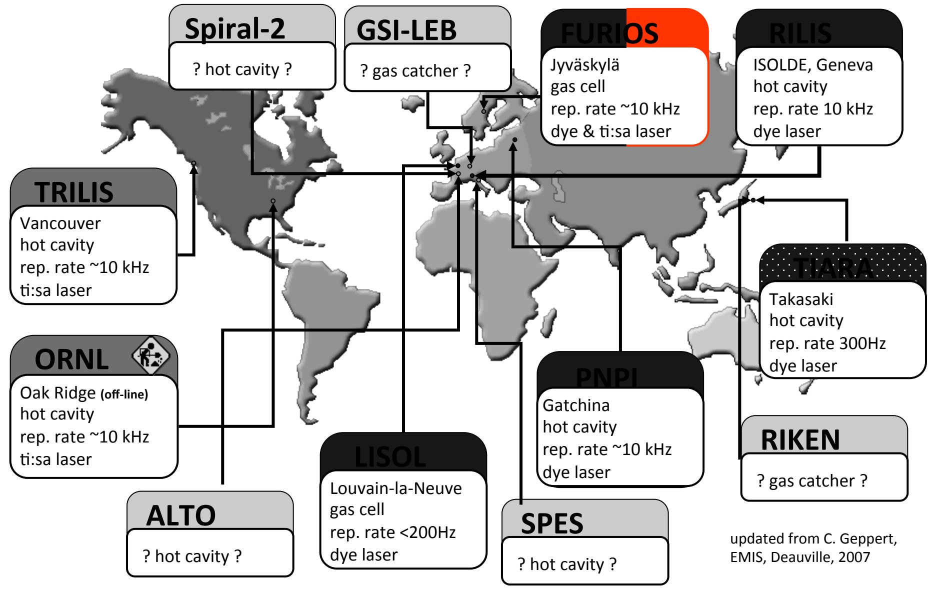
CVL lasers: ν_{rep}=11.000 Hz
Oscillator + 2 amplifiers
2-3 dye lasers with amplifiers,
nonlinear crystals BBO:

$$P_{Cu}^{total} \le 75\ W$$

$$P_{dye} \le 8\ W$$

$$P_{2\omega} \le 2\,W \qquad P_{3\omega} \le 0.2\,W$$

Resonance laser ion sources worldwide



Spiral-2
? hot cavity ?

GSI-LEB
? gas catcher ?

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
ti:sa laser

TIARA
Takasaki
hot cavity
rep. rate 300Hz
dye laser

PNPI
Gatchina
hot cavity
rep. rate ~10 kHz
dye laser

LISOL
Louvain-la-Neuve
gas cell
rep. rate <200Hz
dye laser

RIKEN
? gas catcher ?

ALTO
? hot cavity ?

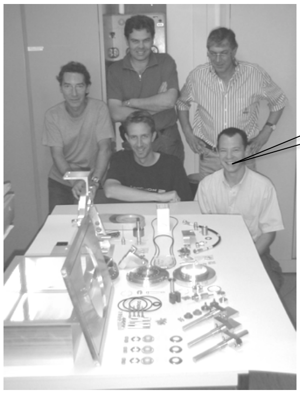
SPES
? hot cavity ?

updated from C. Geppert,
EMIS, Deauville, 2007

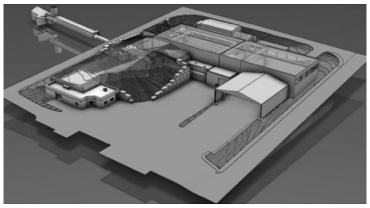
A) RESONANCE IONIZATION LASER ION SOURCES

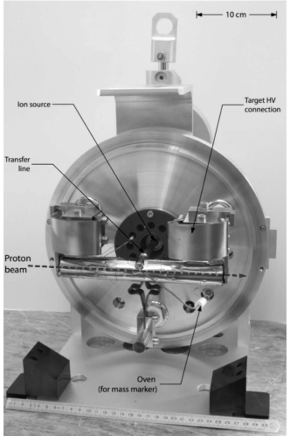
- 4) Case example: Building a laser ion source at ISOLDE
  - i) laser/atom interaction region
    - temperature
    - geometry
    - interaction time
  - ii) Defining laser requirements
    - Power
    - Repetition rate
    - Beam quality
    - Tuning range
    - Linewidth
  - iii) Suitable laser types
    - 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



Where do we put the laser ion source?

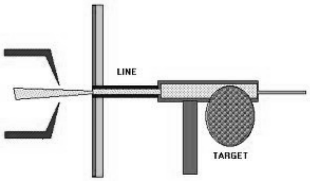




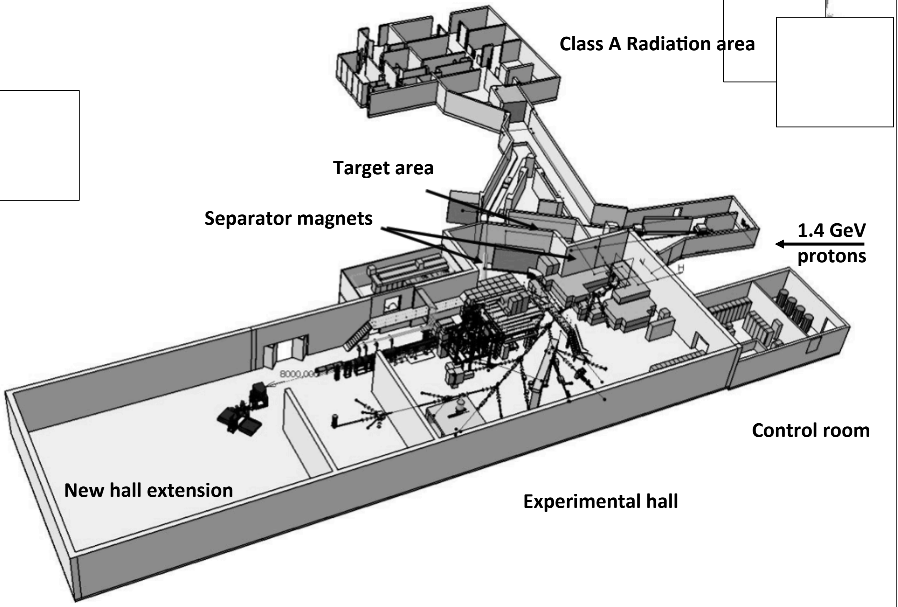
Requested features:

- Universal
- Selective
- Efficient
- Reliable
- Fast

What is the optimal laser ion source configuration for ISOLDE?



The ISOLDE Laboratory



Class A Radiation area

Target area

Separator magnets

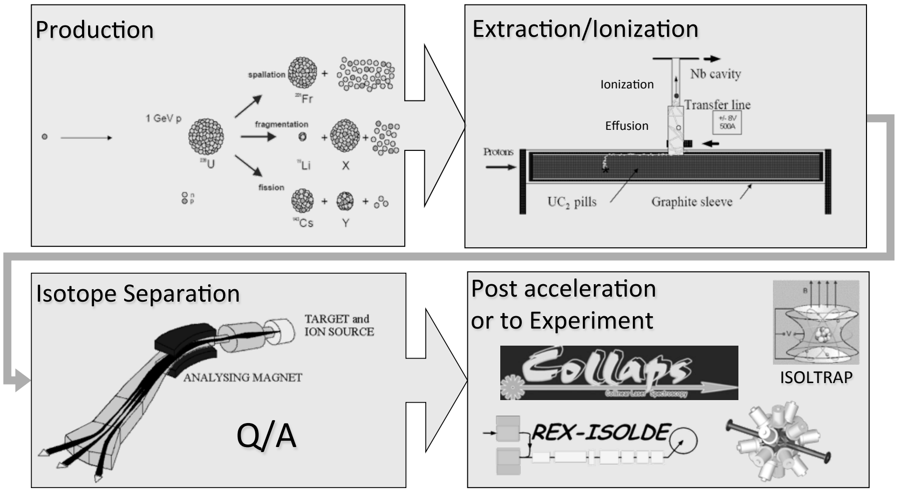
1.4 GeV protons

Control room

New hall extension

Experimental hall

What are we trying to achieve:



Production

Extraction/Ionization

Isotope Separation

Post acceleration
or to Experiment

Q/A

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!) → Simplicity near target unit

High efficiency → Good geometric and temporal laser/atom overlap

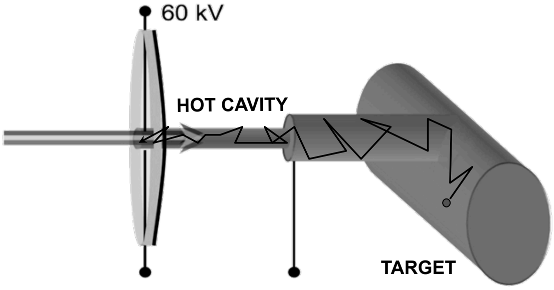
Exotic, short lived isotopes → Fast – no delay w.r.t standard ion source

Universality → Applicable to many elements

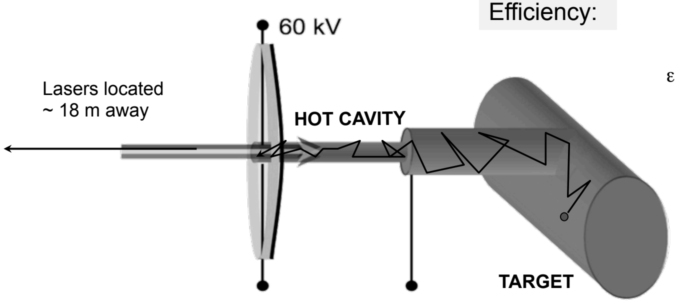
Reliability and stability → Ability to maintain optimal laser conditions for long periods

Selectivity → 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:

$$\varepsilon = \frac{P_{Ionisation}}{P_{Ionisation} + P_{Effusion}}$$

$$\varepsilon = \frac{\nu_{rep}\,\varepsilon_{ion}}{\nu_{rep}\,\varepsilon_{ion} + \frac{2dv}{3L^2}}$$

ε_{laser} **= 2% - 30%**

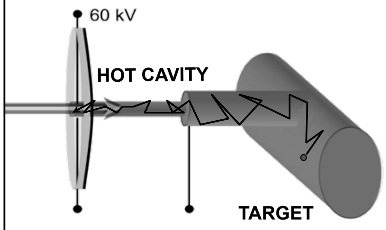
$$\text{Selectivity} = \frac{\text{Laser Ionization Efficiency}}{\text{Surface Ionization Efficiency}}$$

=> depends on the ionization potentials of isobar atoms

$\varepsilon_{surface}$

> 5%	- alkalies
= 0.1% -2%	- In, Ga, Ba, lanthanides
< 0.1%	- others

Features of the hot cavity that influence the application of RILIS:



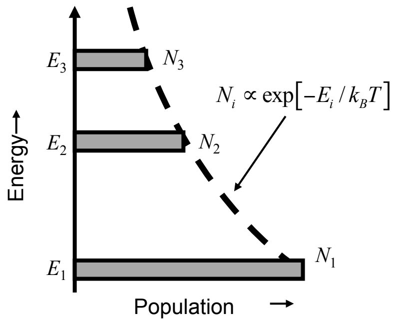
- Effusion time → Laser repetition rate
- High temperature → Laser linewidth atomic transitions
- Electron emission → Extraction efficiency
- Surface ionization → Selectivity

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

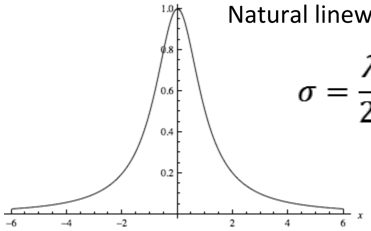
Thermal population of low lying excited atomic states

Surface ionization

Doppler broadening



→ Line broadening mechanisms



Natural linewidth has Lorentzian shape:

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

$$FWHM = {}^{1}\!/_{2\pi\tau}$$

For upper state lifetime of 10 ns, Δν = 16 MHz

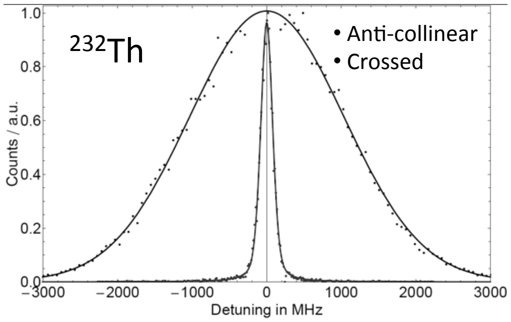
When an atom is in thermal motion we get Doppler broadening. An atomic vapour has a Maxwell-Boltzmann distribution of velocities:

$$P(v_x) \propto exp\left({}^{-mv_x^2}\!/_{2kT}\right)$$

The velocity of the atoms Doppler shifts the absorption frequency to

$$\upsilon = \upsilon_0\left(1 \pm \frac{v_x}{c}\right)$$

The velocity spread leads to a Doppler broadening: $\Delta\upsilon_D = \upsilon_0\,\frac{\Delta v}{c}$



$$FWHM = \sqrt{{}^{8kTln2}\!/_{mc^2}}\ \ \nu_0$$

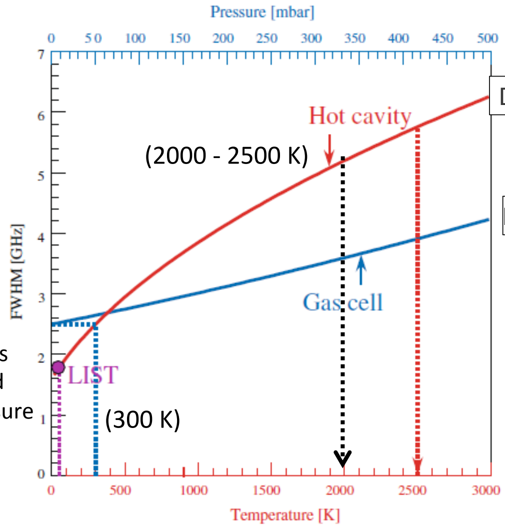
Example: 0 → 38278 cm^{-1} transition

Natural linewidth: 35 MHz
Spectral linewidth:
2.4 GHz (anticollinear)
~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:



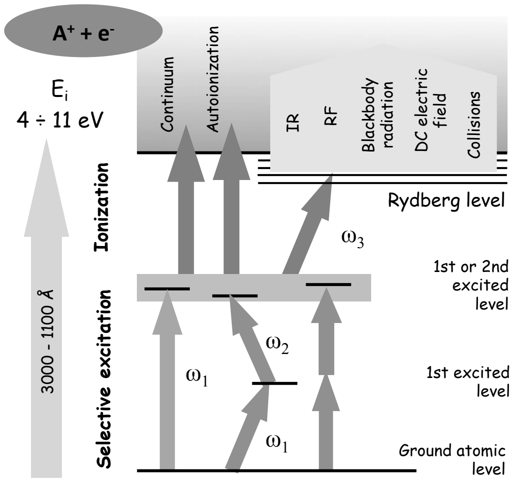
Doppler broadening

Pressure broadening

Expanding gas jet is cold and has low pressure

Resolution in gas jet limited by laser bandwidth

Laser Resonance Ionization of Atoms

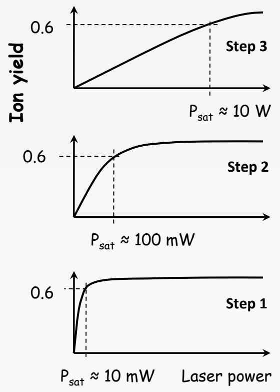


ω_i(laser) = ω_i(atom); P_i(laser) ≥ P_i(saturation)

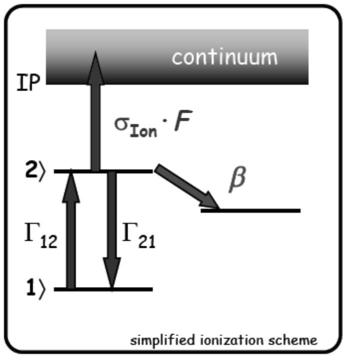
$P_{sat.} = \mathcal{E}_{sat.} \times f_{laser} \times S_{laser\ beam}$

$\mathcal{E}_{sat.} = \hbar\omega_i/2\sigma_i$

f_{laser} = 10 kHz $\varnothing_{laser}$ = 3 mm



How do we achieve efficient laser resonance ionization?



The conditions for 100% ionization of atoms irradiated by a laser is deduced from rate equations for population of different levels. This leads to two conditions:

① $\sigma_{Ion} \cdot F \gg \beta$ $\longrightarrow$ ionization rate » loss rate

② $\sigma_{Ion} \cdot \varphi > 1$ $\longrightarrow$ number of ionized atoms per laser interaction time (pulse)

σ_{Ion}	ionization cross section (non-resonant) (cm^2)
β	loss rates to (metastable) states
F	photon flux ($cm^{-2}\ s^{-1}$)
φ	photon fluence (=photon flux · laser interaction time)

What do these conditions mean for the laser power?

<u>typical values:</u>

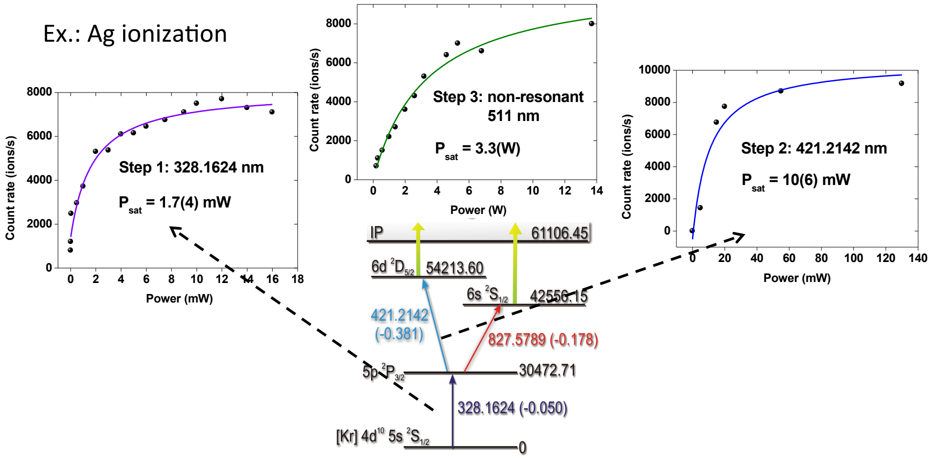
$\sigma_{ion} \longrightarrow 10^{-17}\ cm^2$
$\beta \longrightarrow 10^{6}\ s^{-1}$

Lets assume a laser beam area of 1 mm^2 and a photon energy of 3 eV.

From 1: Flux F >> $10^{23}\ cm^{-2}s^{-1}$ $\xrightarrow{\text{3 eV photons}}$ >> 500 W
→ # photons required >> 10^{21} /s Impossible with CW laser !!

But with a pulsed laser system: $\longrightarrow$ >> 5 µJ/pulse
Typical pulse length is 10 ns. No problem !!

Ex.: Ag ionization



Resonant saturation parameter:

$S_0 = I/I_{sat}$

$$I_{sat} = \frac{\pi h c}{3\lambda^3 \tau}$$

The population of the excited state:

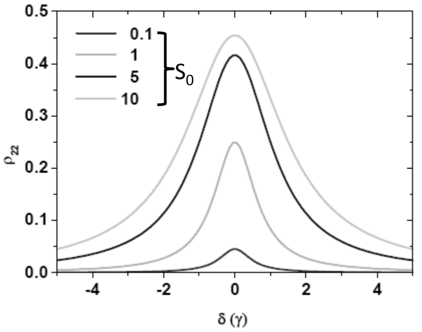
$$\rho = \frac{S}{2(S+1)}$$

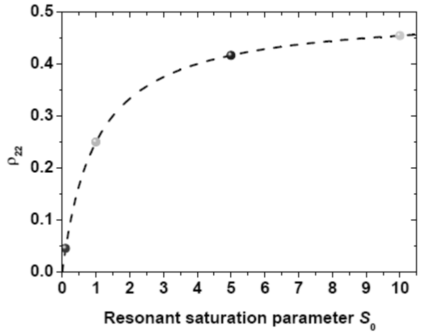
where *S*, the saturation parameter, is a Lorentzian function with FWHM Γ:

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

When the laser frequency is on resonance, i.e. when δ=0:

$$\rho = \frac{S_0}{2(S_0+1)} = \frac{I/I_{sat}}{2(I/I_{sat}+1)}$$





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 Δ>>Γ,

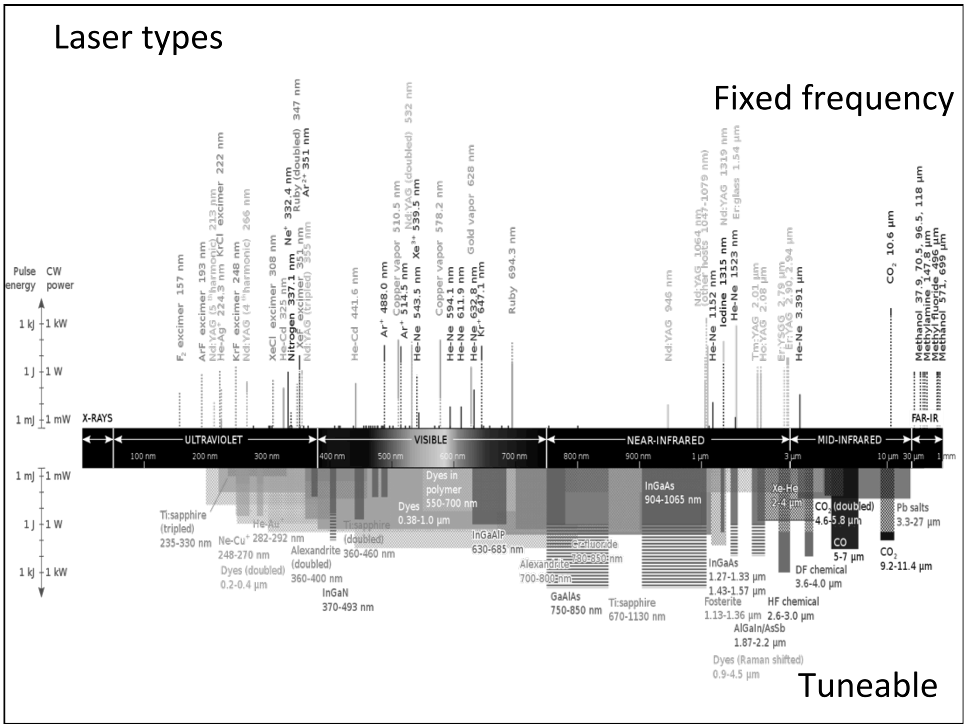
$$S \sim 4 \times \frac{\Delta^2}{\Gamma^2}$$

(Δ is the atomic resonance difference between isotope of interest and a ``contaminating´´ isotope/element).

eg. Kr isotopes, Γ ~6 MHz, Δ ~100 MHz (neighbouring isotopes): *S* ~1000

Δ ~10^{15} Hz (krypton to bromine): *S* ~10^{17} !!!

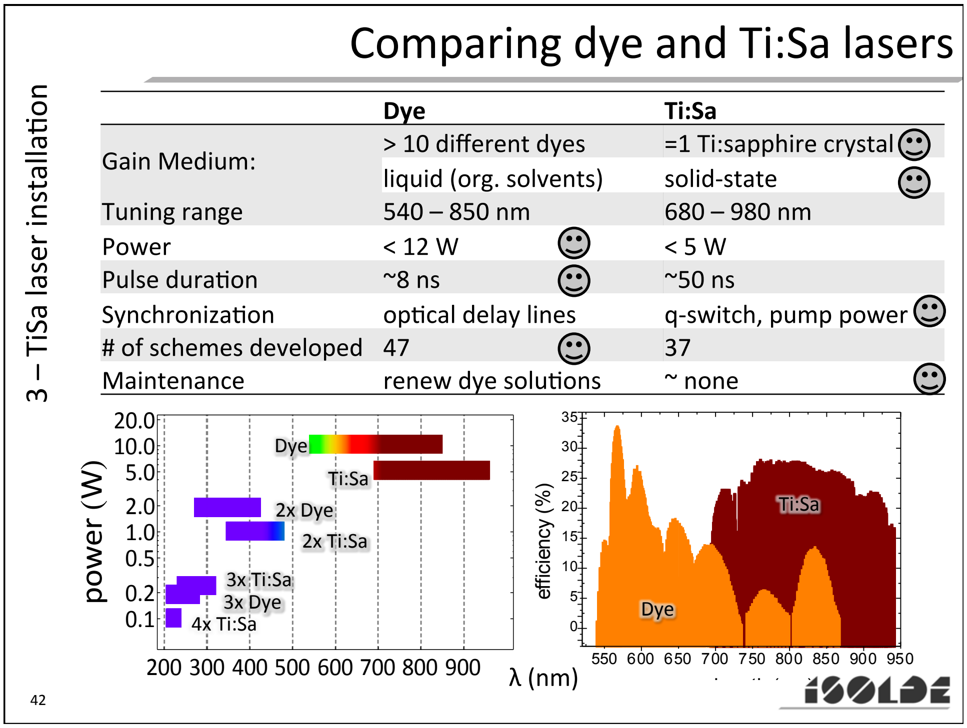
and multi-step excitation: $S = S_1 \cdot S_2 \ldots \cdot S_n$. But in reality *S* is less due to broadening ☹



Laser types

Fixed frequency

Tuneable



Comparing dye and Ti:Sa lasers

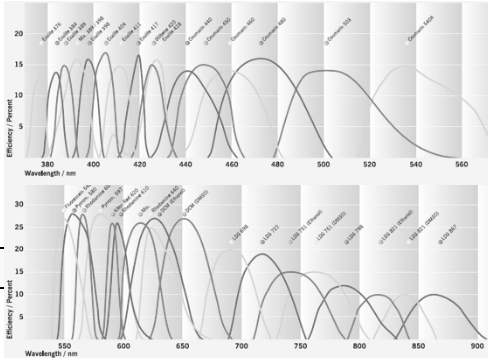
3 – TiSa laser installation

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

Sirah Dye laser

2 – Dye laser upgrade

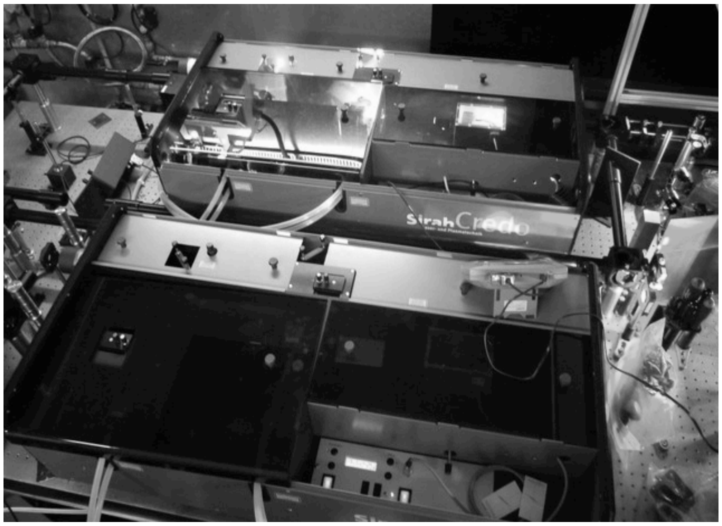
Old RILIS dye laser

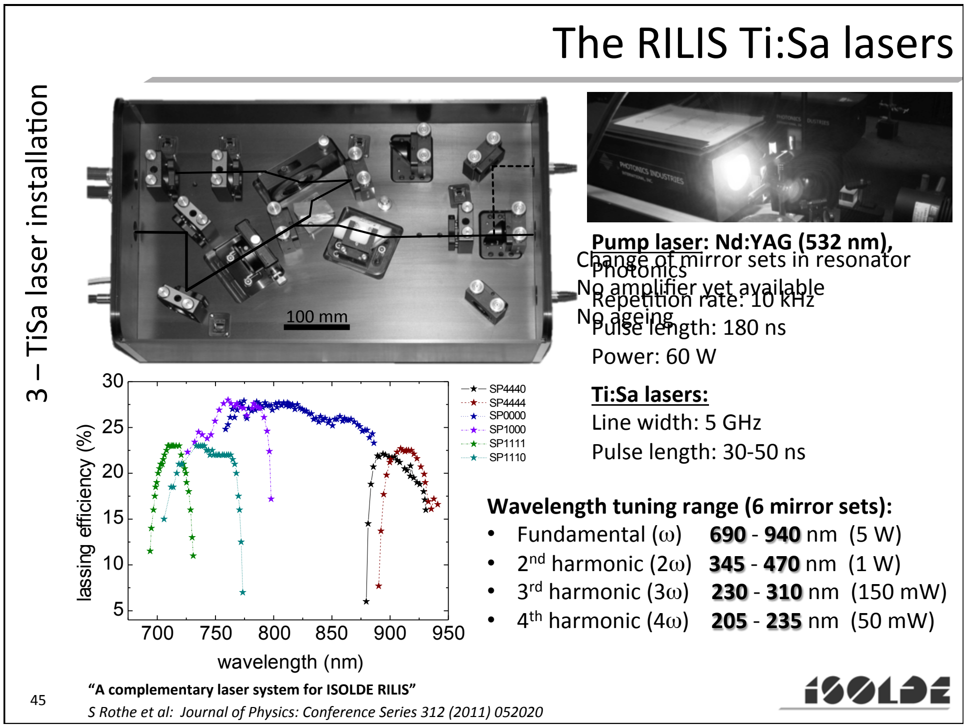


- Optimized for 10 kHz EdgeWave pump
- Accept both 355 and 532 pumping beams
- Equipped with FCU (up to 2W of UV)

“Upgrade of the RILIS at ISOLDE: New lasers and new ion beams”
V. Fedosseev et al: Rev. Sci. Instrum. 83, 02A903 (2012)

Sirah Dye laser





The RILIS Ti:Sa lasers

3 – TiSa laser installation

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

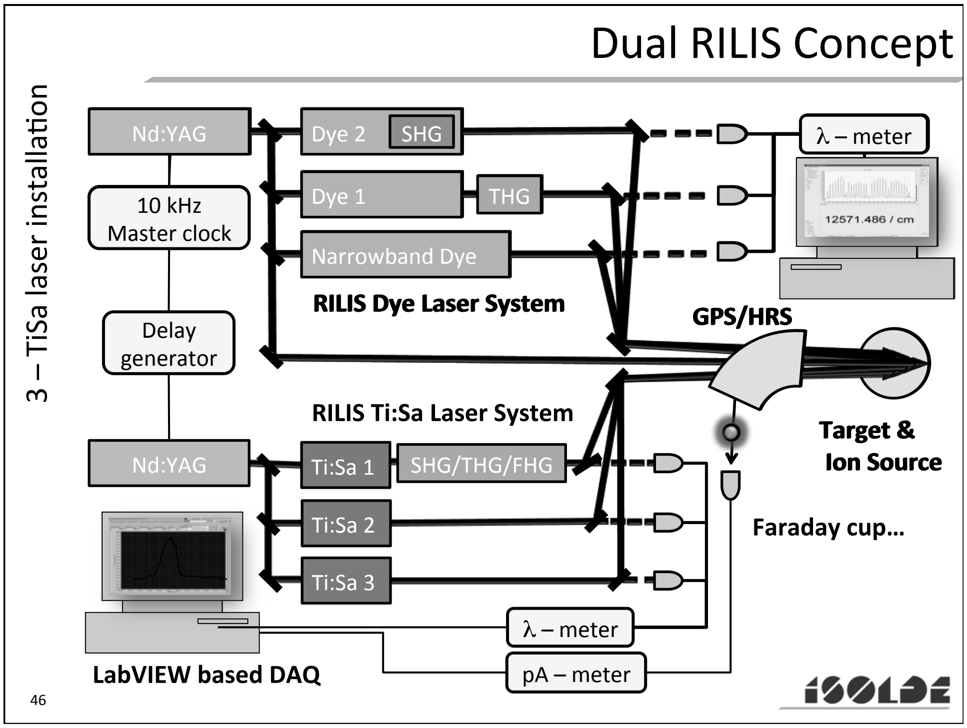
Change of mirror sets in resonator
No amplifier yet available
No ageing

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

Wavelength tuning range (6 mirror sets):

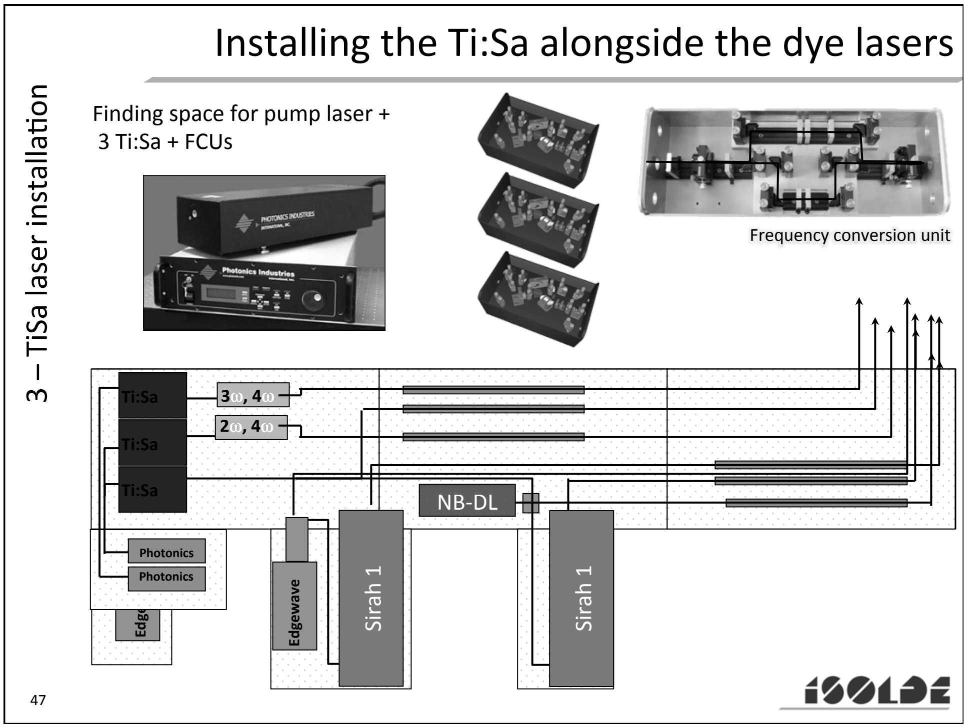
- Fundamental (ω) **690** - **940** nm (5 W)
- 2nd harmonic (2ω) **345** - **470** nm (1 W)
- 3rd harmonic (3ω) **230** - **310** nm (150 mW)
- 4th harmonic (4ω) **205** - **235** nm (50 mW)

"A complementary laser system for ISOLDE RILIS"
S Rothe et al: Journal of Physics: Conference Series 312 (2011) 052020



Dual RILIS Concept

3 – TiSa laser installation



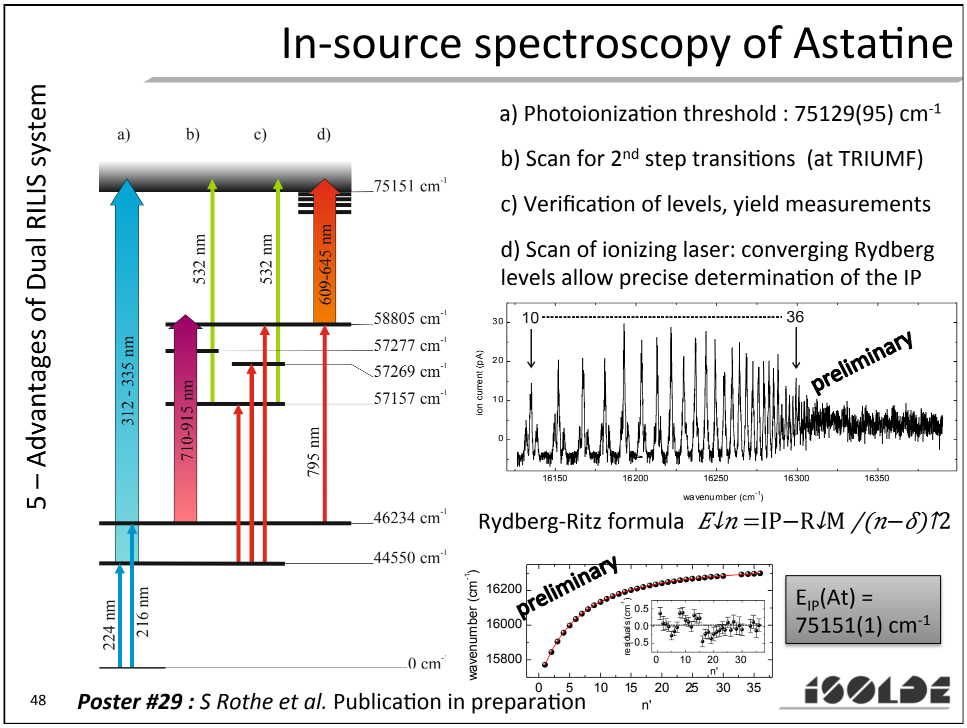
Installing the Ti:Sa alongside the dye lasers

3 – TiSa laser installation

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

Frequency conversion unit

47



In-source spectroscopy of Astatine

5 – Advantages of Dual RILIS system

a) Photoionization threshold : 75129(95) cm^{-1}

b) Scan for 2nd 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 $E_n = \mathrm{IP} - \mathrm{R}_\mathrm{M}/(n-\delta)^2$

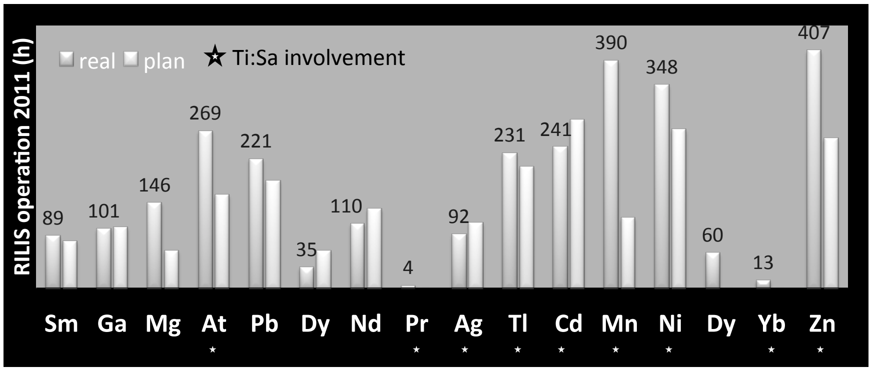
$E_{IP}(At) = 75151(1)\ \mathrm{cm}^{-1}$

48 **Poster #29 :** *S Rothe et al.* Publication in preparation


RILIS screen 1

Ti:Sa involvement in RILIS operation

4 – TiSa laser operation



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'

New modes of RILIS operation: Dual RILIS

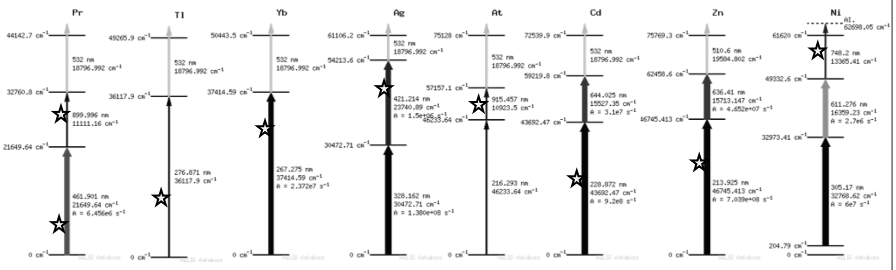
5 – Advantages of Dual RILIS system

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

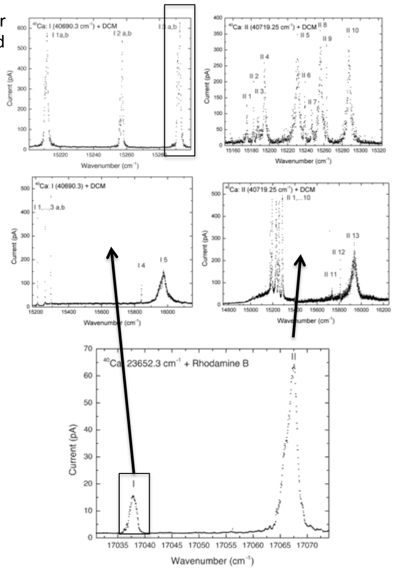


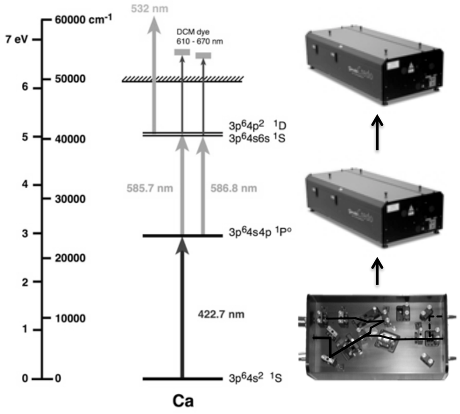
- Increased efficiency due to higher laser power or optimal scheme
- Improved reliability due to redundancy / backup
- More elements are accessible due to greater tuning range/scheme database

Calcium scheme development

5 – Advantages of Dual RILIS system

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



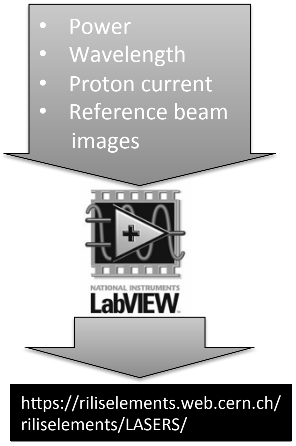


Daniel Fink: PhD work

RILIS status monitoring

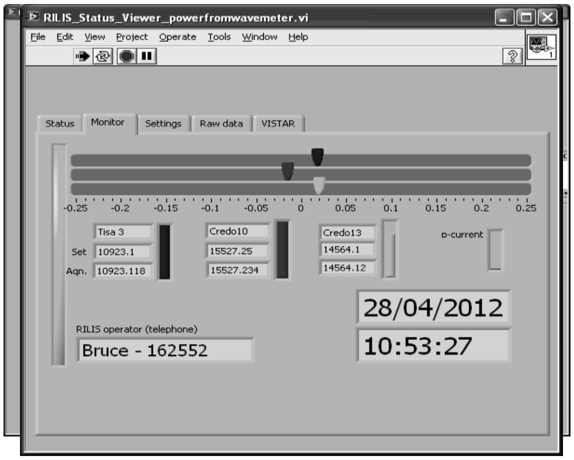
Other technical improvements

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/



	Tisa 3	Credo10	Credo13
Set	10923.1	15527.25	14564.1
Aqn.	10923.118	15527.234	14564.12

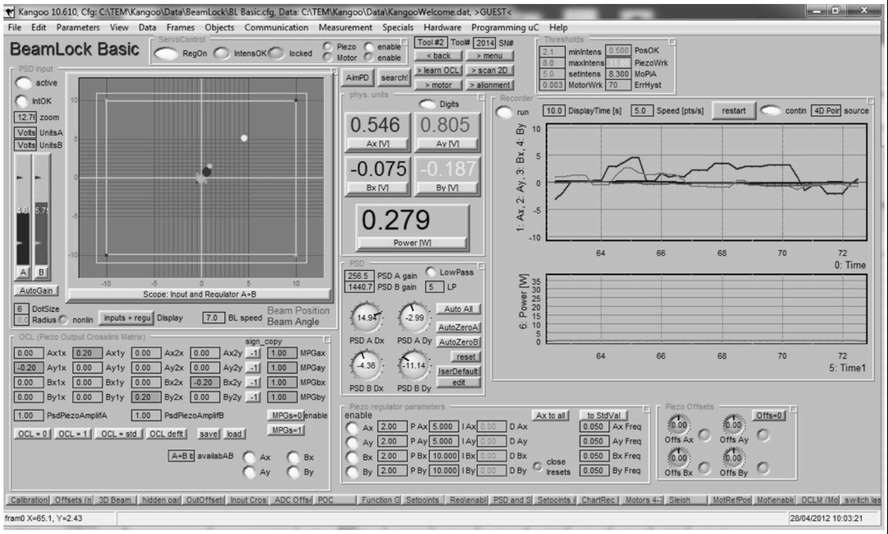
RILIS operator (telephone)
Bruce - 162552

28/04/2012
10:53:27

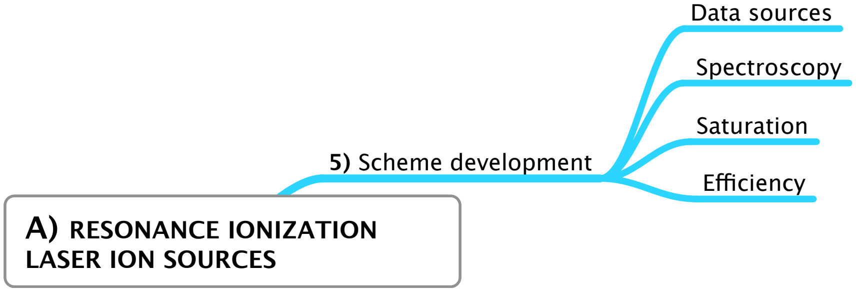
Beam stabilization

Other technical improvements

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



http://www.tem-messtechnik.de/MainPages/en/productsfs.htm



A) RESONANCE IONIZATION LASER ION SOURCES

5) Scheme development

Data sources

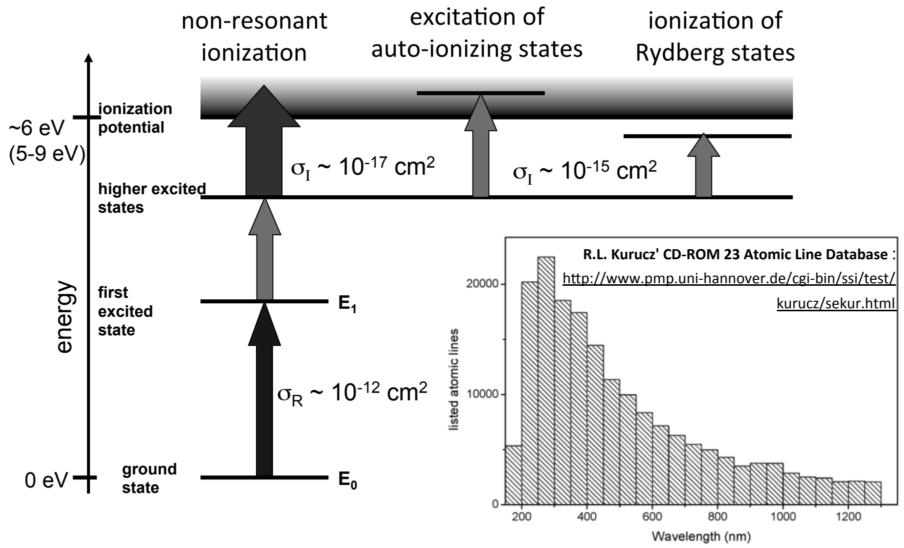
Spectroscopy

Saturation

Efficiency

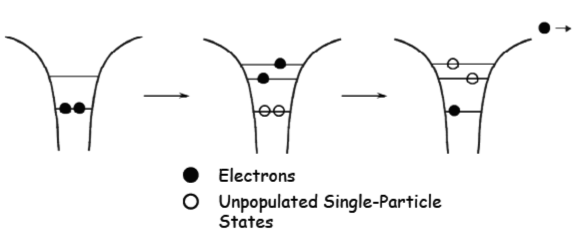
Ionization scheme development

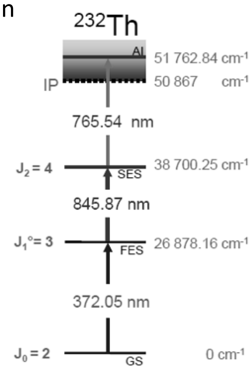
What are our options for ionization schemes?



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

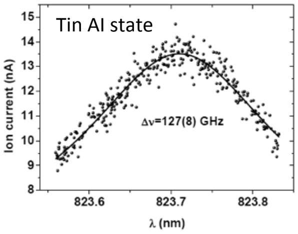
Preferred method - Auto-ionization by two-particle excitation

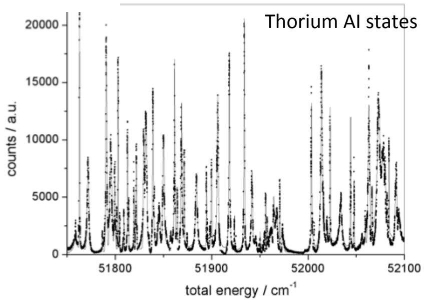




AI states are **discrete states** which lie **above the ionization** threshold of the atom and are thus *embedded in the continuum*

Due to the fast ionization mechanism the AI often exhibits a huge FWHM value (see below)

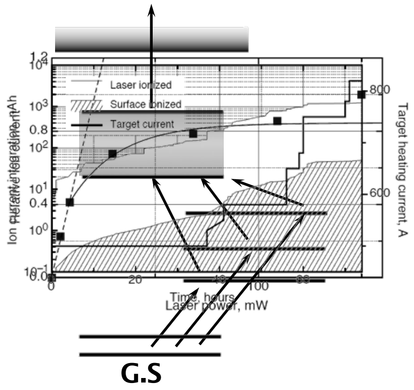




How to develop an ionization scheme

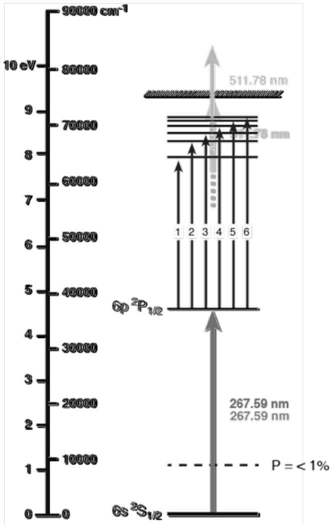
- **Literature Search**
  On-line atomic spectral line databases, published spectroscopy work.
  R.L. Kurucz' CD-ROM 23 Atomic Line Database : http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html
  NIST atomic spectral line database : http://www.nist.gov/pml/data/asd.cfm

- **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



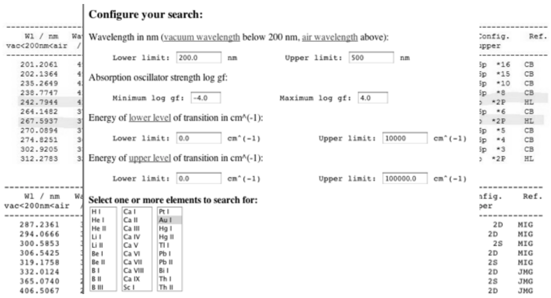
1) We know that the ionization potential is **9.23 eV** or **74408.88 cm** $^{-1}$
(this corresponds to the energy of 134 nm photon!)

2) We have a pump laser with both **511 nm** or **578 nm** output:
- *Choose 511nm (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 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: 200.0 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: 100000.0 cm^(-1)

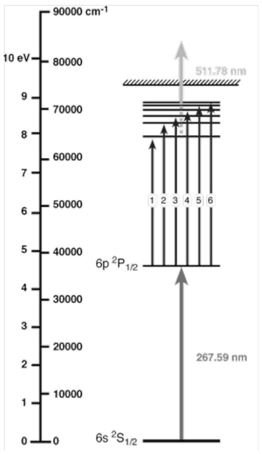
Select one or more elements to search for:
H I, He I, He II, Li I, Li II, Be I, Be II, B I, B II, B III
Ca I, Ca II, Ca III, Ca IV, Ca V, Ca VI, Ca VII, Ca VIII, Ca IX, Sc I
Pt I, Au I, Hg I, Hg II, Tl I, Pb I, Pb II, Bi I, Th I, Th II

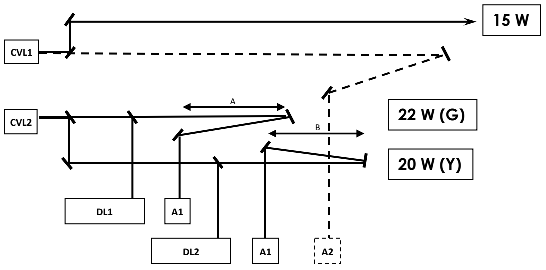
```
   Wl / nm
vac<200nm<air
---------------
   201.2061
   202.1364
   235.2649
   238.7747
   242.7944
   264.1482
   267.5937
   270.0894
   274.8251
   302.9205
   312.2783

   Wl / nm
vac<200nm<air
---------------
   287.2361
   294.0666
   300.5853
   306.5425
   319.1758
   332.0124
   365.0740
   406.5067
```

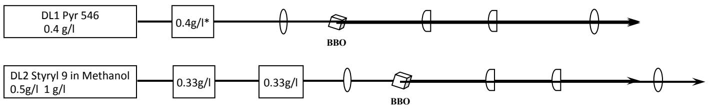
```
      Ref.
-----------
 *16   CB
 *15   CB
 *10   CB
 *8    CB
 *2P   HL
 *6    CB
 *2P   HL
 *5    CB
 *4    CB
 *3    CB
 *2P   HL

      Ref.
-----------
 2D   MIG
 2D   MIG
 2S   MIG
 2D   MIG
 2S   MIG
 2D   JMG
 2S   JMG
 2D   JMG
```

Laser setup for testing 2nd steps

- 6 of 10 known 2nd step transitions chosen: **YELLOW CVL pumping**
- Non resonant ionization stage with green CVL beam

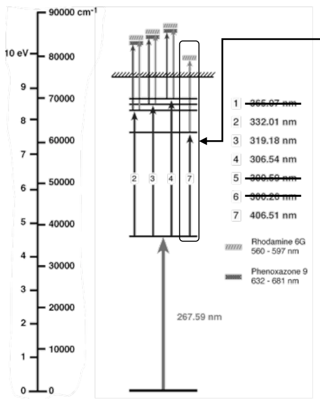


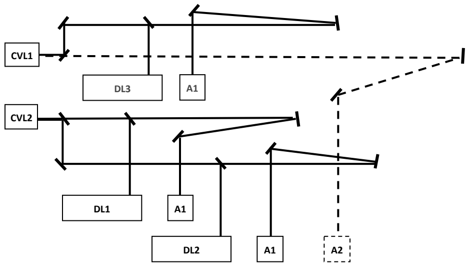


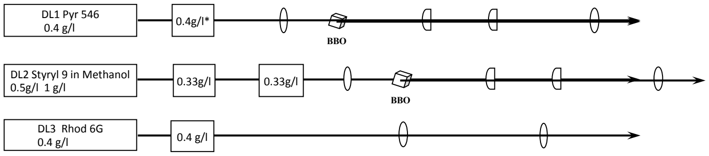


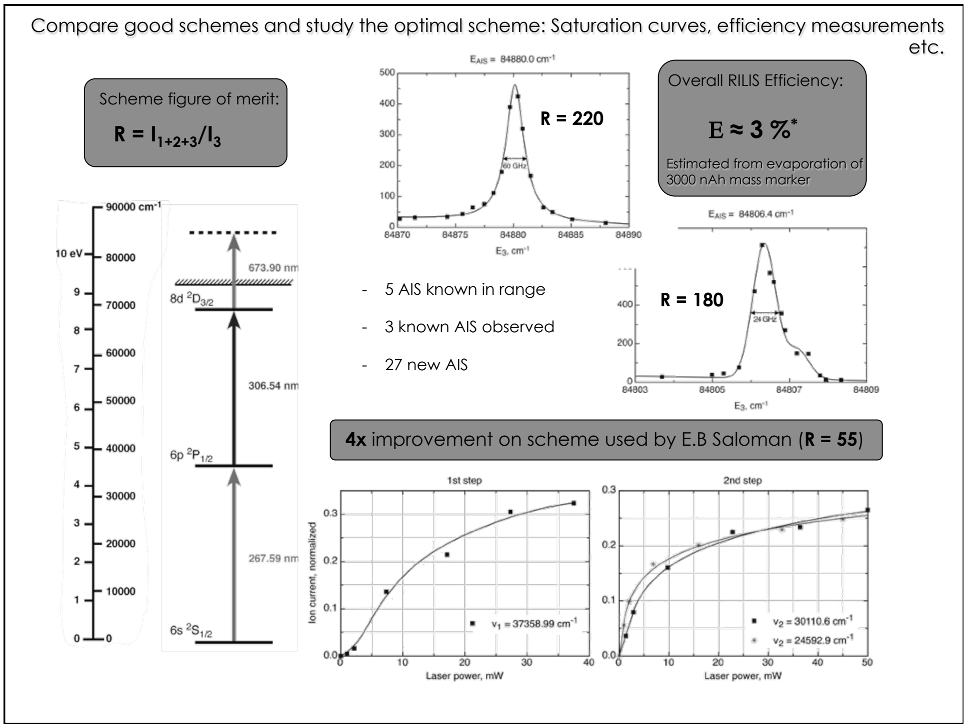
Laser setup for AIS search

- Include a 3rd dye laser
- Scan 2 dye ranges for AIS from 3 strongest 2nd steps.
- Test ionization scheme used by E.B Saloman









Compare good schemes and study the optimal scheme: Saturation curves, efficiency measurements etc.

Scheme figure of merit:

$R = I_{1+2+3}/I_3$

Overall RILIS Efficiency:

$E \approx 3\ \%^*$

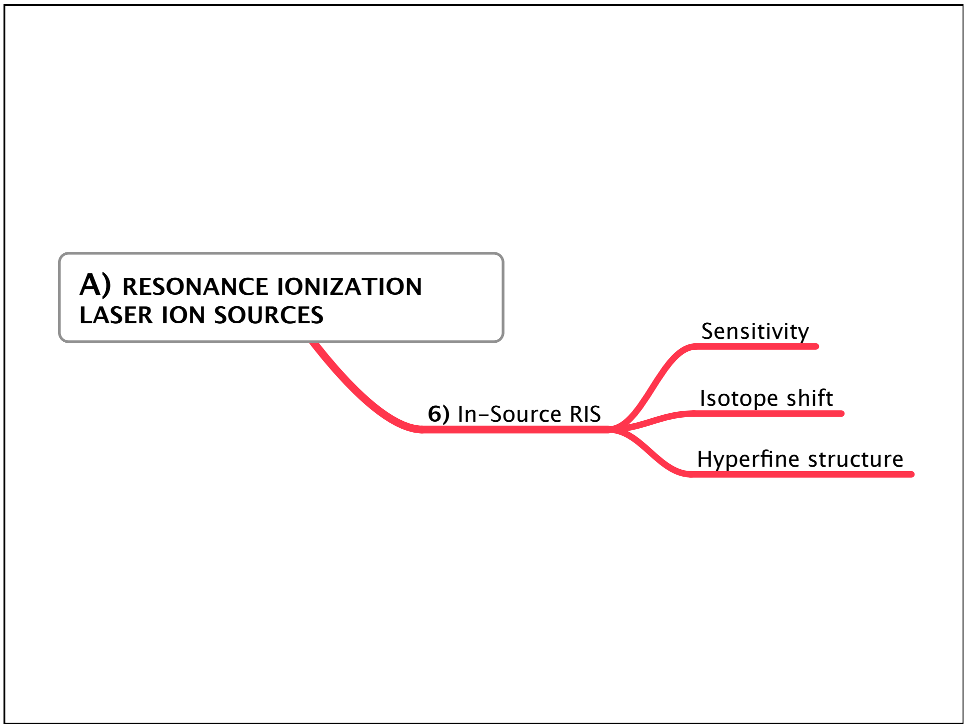
Estimated from evaporation of 3000 nAh mass marker

R = 220

R = 180

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

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



A) RESONANCE IONIZATION LASER ION SOURCES

6) In-Source RIS

Sensitivity

Isotope shift

Hyperfine structure

How does the nuclear structure influence the atomic spectra?

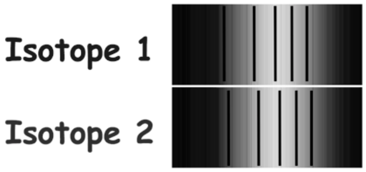
The earlier discussion on atomic energy levels mainly assumed that the nucleus is POINT-LIKE and INFINITELY heavy!

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



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

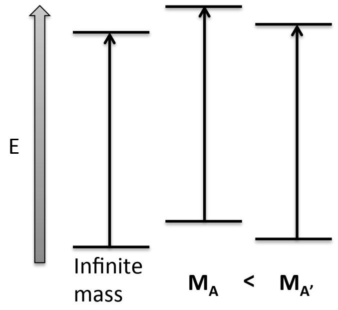
CAUSED BY these properties:

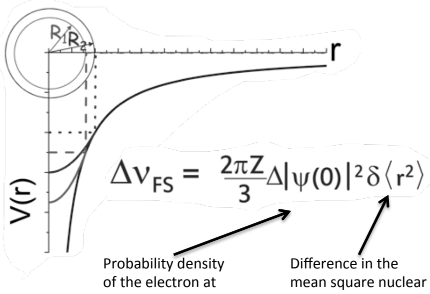
Finite nuclear mass **MASS SHIFT**

Nuclear Volume (not point-like) **FIELD SHIFT**

Finite nuclear mass MASS SHIFT

Nuclear Volume FIELD SHIFT





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

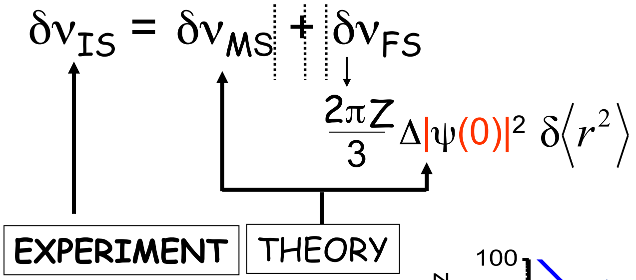
Probability density of the electron at the nucleus (electronic part)

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

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

Light Nuclei: $\Delta\nu/\nu \approx 10^{-8}$

Isotope shifts in practise

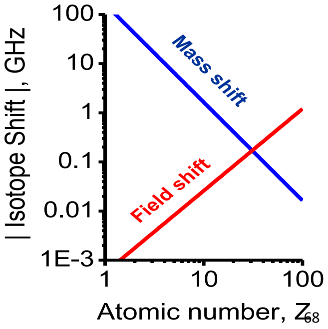


$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

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

EXPERIMENT THEORY

Transition	Z	Element	NMS (MHz)	SMS (MHz)	FS (MHz)
3s-3p	11	Na	550	200	-10
5s-5p	37	Rb	70	<20	-100
$(6s)^2$-6s6p	70	Yb	20	<20	-1500

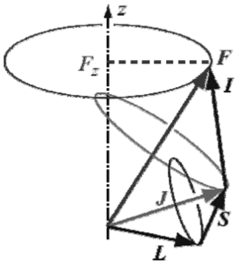


HYPERFINE STRUCTURE

- Magnetic dipole interaction
- Electric quadrupole interaction

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

Interaction	$1/\lambda$ (cm^{-1})	eV	ν (Hz)
Central coulomb	30000	4	10^{15}
Fine structure	1-1000	10^{-4}-10^{-1}	$3\cdot10^{10}$-$3\cdot10^{13}$
Hyperfine structure	10^{-3}-1	10^{-7}-10^{-4}	$3\cdot10^{7}$-$3\cdot10^{10}$



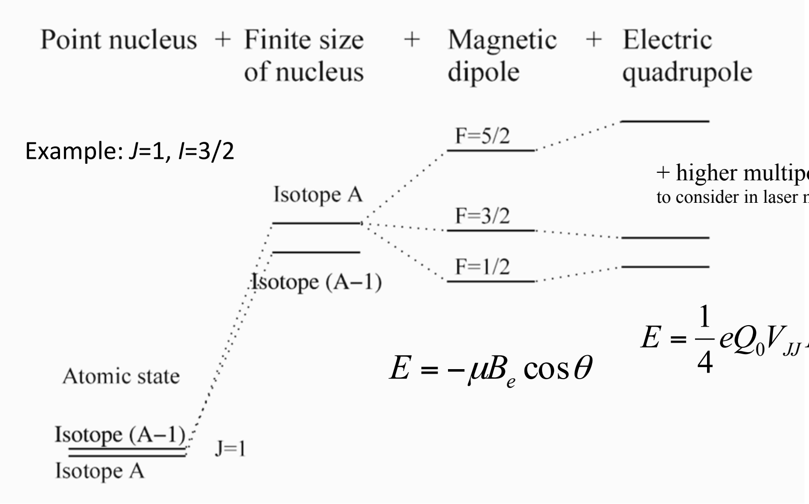
Hyperfine structure arises from interaction of nuclear moments with electric and magnetic fields produced at nucleus by orbiting electrons.

$$\vec{F} = \vec{I} + \vec{J}$$

$$F = I + J, I + J - 1, \dots, |I - J|$$

Summarizing the effects:

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



+ higher multipoles (too small to consider in laser measurements)

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

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

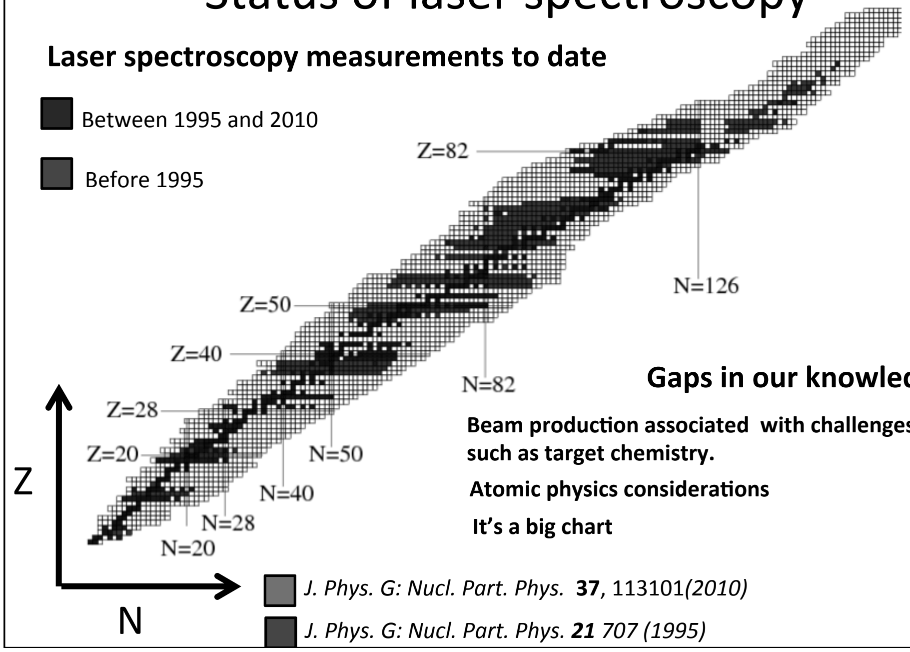
These energy shifts of may be only a few parts per million of the energy of an optical atomic transition. Optical techniques provide the sensitivity and precision required to measure these effects.

Status of laser spectroscopy

Laser spectroscopy measurements to date

■ Between 1995 and 2010

■ Before 1995



Gaps in our knowledge

Beam production associated with challenges such as target chemistry.

Atomic physics considerations

It's a big chart

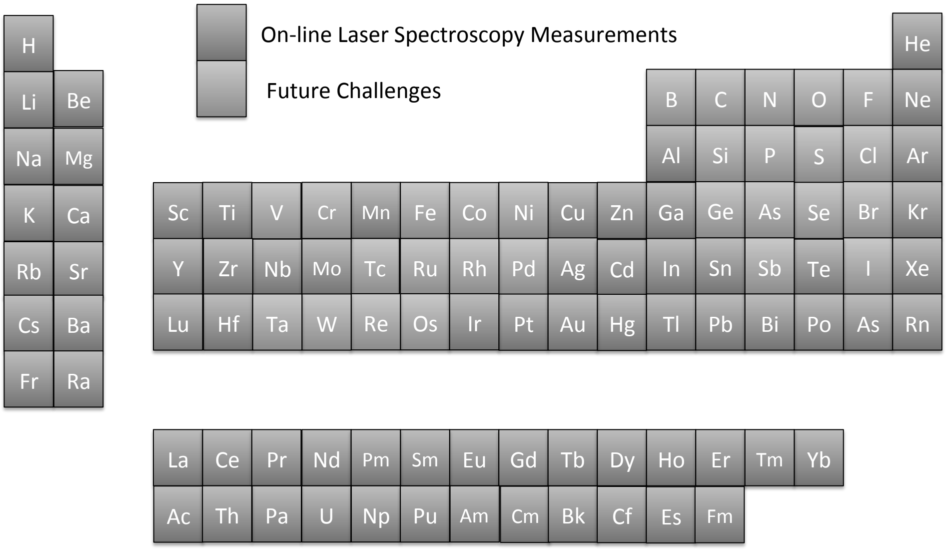
■ *J. Phys. G: Nucl. Part. Phys.* **37**, 113101*(2010)*

■ *J. Phys. G: Nucl. Part. Phys.* ***21** 707 (1995)*

Ion resonance ionization cases

■ On-line Laser Spectroscopy Measurements

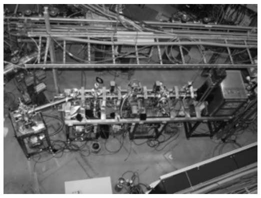
■ Future Challenges



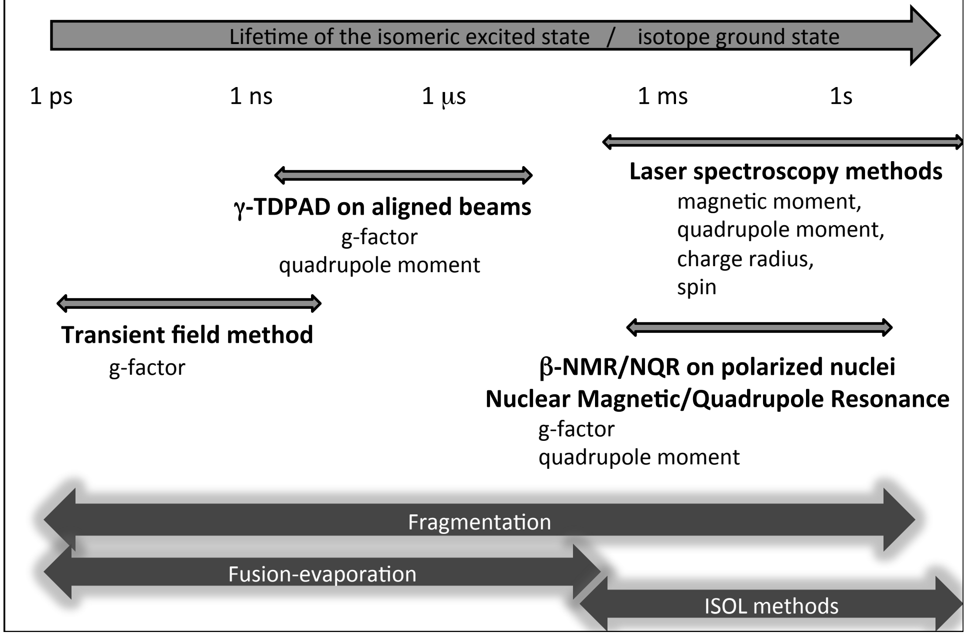
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	As	Rn
Fr	Ra																
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb		
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm				

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 1 ms 1s

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

γ-TDPAD on aligned beams
g-factor
quadrupole moment

Transient field method
g-factor

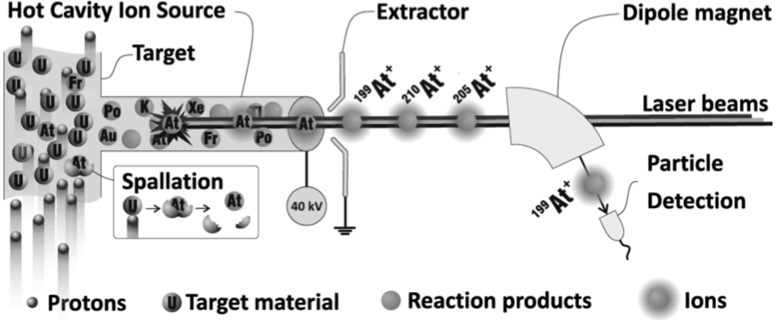
β-NMR/NQR on polarized nuclei
Nuclear Magnetic/Quadrupole Resonance
g-factor
quadrupole moment

Fragmentation

Fusion-evaporation

ISOL methods

In-source laser spectroscopy



•Need to satisfy the Flux and Fluence conditions in order to saturate transitions and maximise efficiency.

•Short duration pulsed lasers (10-20ns) with ~1-10mJ per pulse. EASY

•CW Laser> 500W (and tight focus) just to saturate the first step. DIFFICULT

G. D. Alkhazov et al., NIM B69 (1992) 517
U. Koester et al., Nucl. Phys. A 701 (2002) 441c
V.N. Fedoseev *et al.*, NIM B266 (2008) 4378

~100mW at 10kHz for resonant steps
~1-5W at 10kHz for quasi resonant steps
~10-20W at 10kHz for non-resonant steps

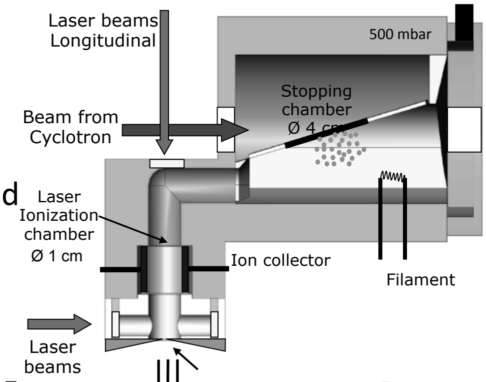
Talk by Bruce Marsh **Sebastian Rothe**

Gas cell laser spectroscopy

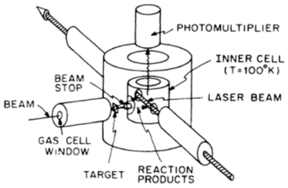
- JYFL, Leuven
  - ^{57,58,59}Cu, ^{97,99,101}Ag

T. E. Cocolios et al., PRL 103, 102501 (2009)
T. E. Cocolios et al., PRC 81, 014314 (2010)
Iain Darby Phys. Lett. B (in preparation)

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

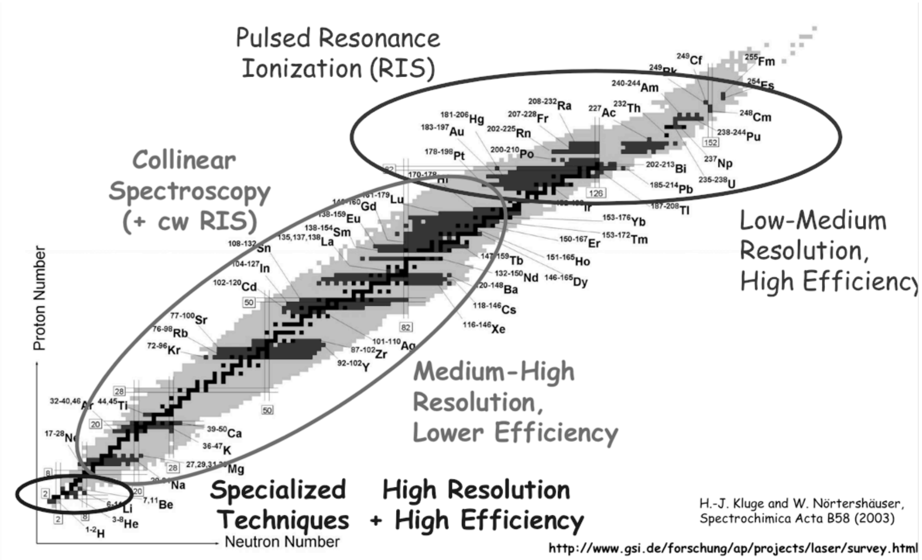


- Cryogenic gas cell and fluorescence detection
  - 900/s yields, Γ~300MHz
  - Possible route to probe μs half-lives



G. D. Sprouse et al., PRL **63** 1463 (1989)

Using the ion source for laser spectroscopy

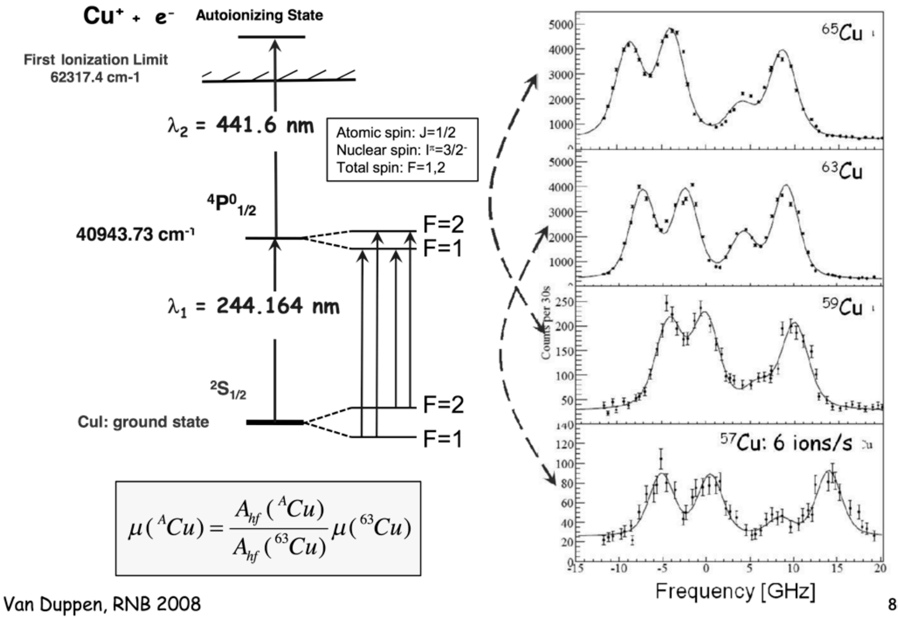


H.-J. Kluge and W. Nörtershäuser, Spectrochimica Acta B58 (2003)

http://www.gsi.de/forschung/ap/projects/laser/survey.html

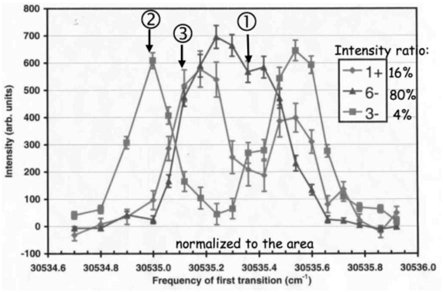
Progress in laser spectroscopy at radioactive ion beam facilities
B Cheal and K T Flanagan 2010 J. Phys. G: Nucl. Part. Phys. 37

Recent REVIEW article



$$\mu({}^{A}Cu) = \frac{A_{hf}({}^{A}Cu)}{A_{hf}({}^{63}Cu)}\mu({}^{63}Cu)$$

P. Van Duppen, RNB 2008



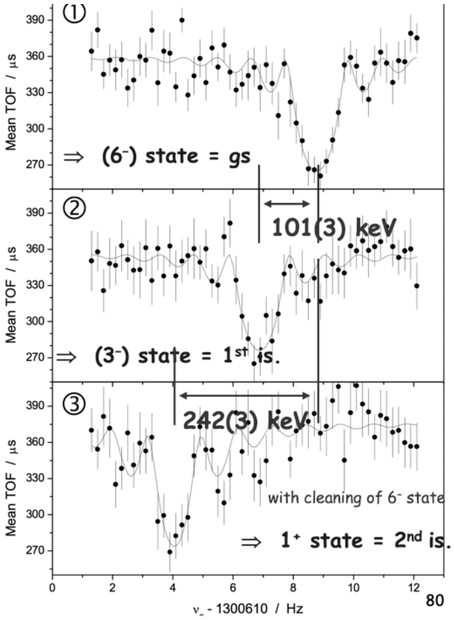
$\omega_c = \frac{q}{m} \cdot B$

Unambiguous state assignment!

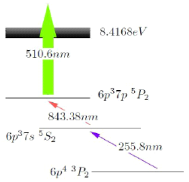
ME of ground state is 240 keV higher than literature value!

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

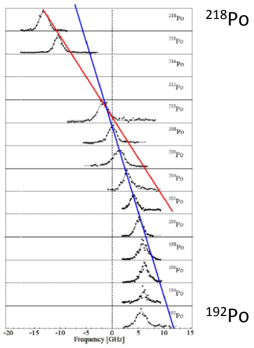
J. Van Roosbroeck et al., Phys. Rev. Lett. 92, 112501 (2004).



RILIS laser spectroscopy in the Pb region



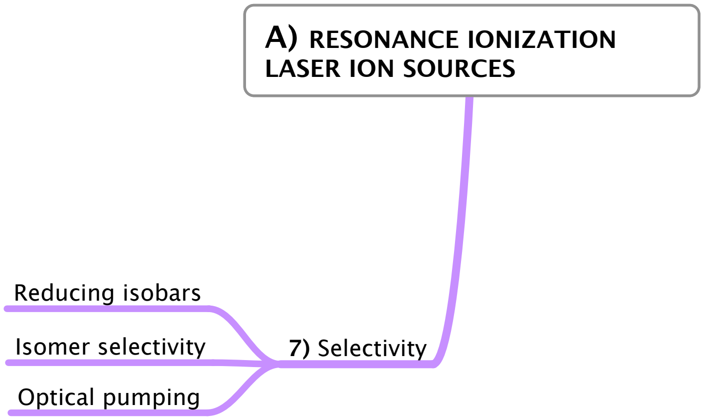
- from $A = 192$ up to $A = 218$;
- from $T_{1/2} = 33$ ms up to $T_{1/2} = 3$ yr;
- from 0.3 ion·s^{-1} to over 10^7 ion·s^{-1};
- using α, β, γ and ion (FC) counting.



Recent developments for the spectroscopy of At isotopes

KU Leuven

T. E. Cocolios *et al.*, Phys. Rev. Lett. 106, 052503 (2011)



A) RESONANCE IONIZATION LASER ION SOURCES

7) Selectivity

- Reducing isobars
- Isomer selectivity
- Optical pumping

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

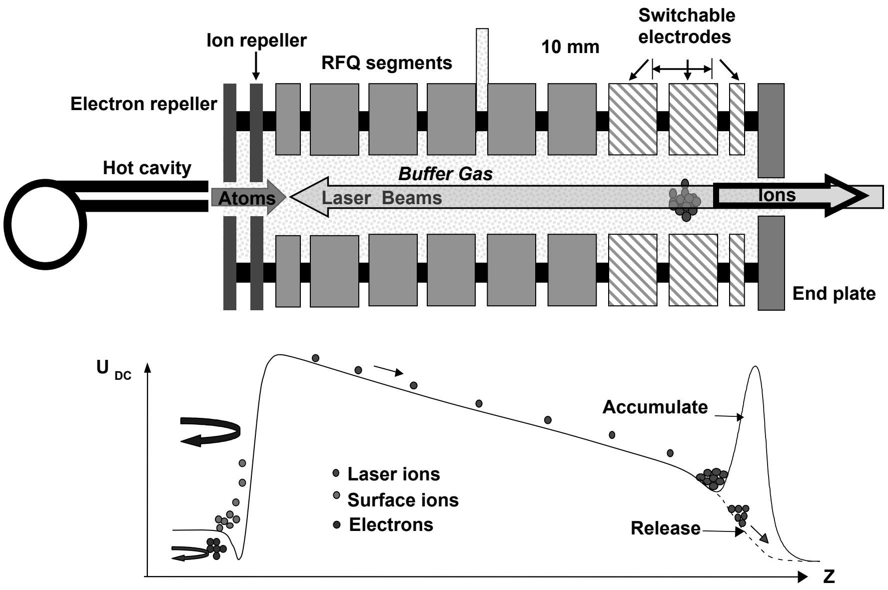
Trap unwanted elements
(add chemical selectivity to the effusion process)

Solution 2 – Separate surface ions from laser ions

Repel surface ions before laser ionization

Temporal separation of laser and surface ions

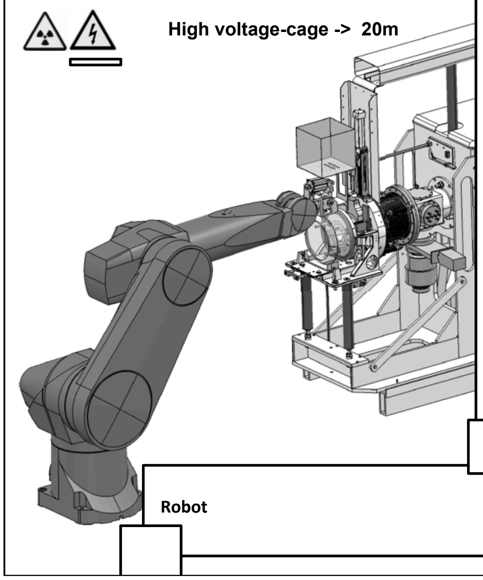
Ideal selective laser ion source? Repeller and trap



83

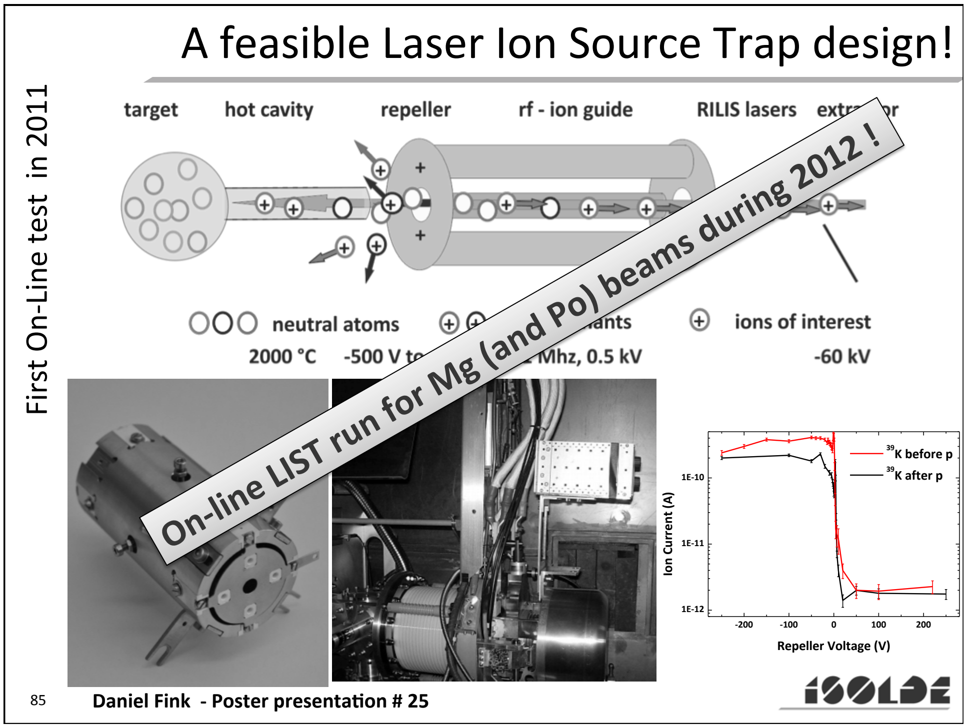
K. Blaum et al., NIMB ***204*** *(2003) 331*

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

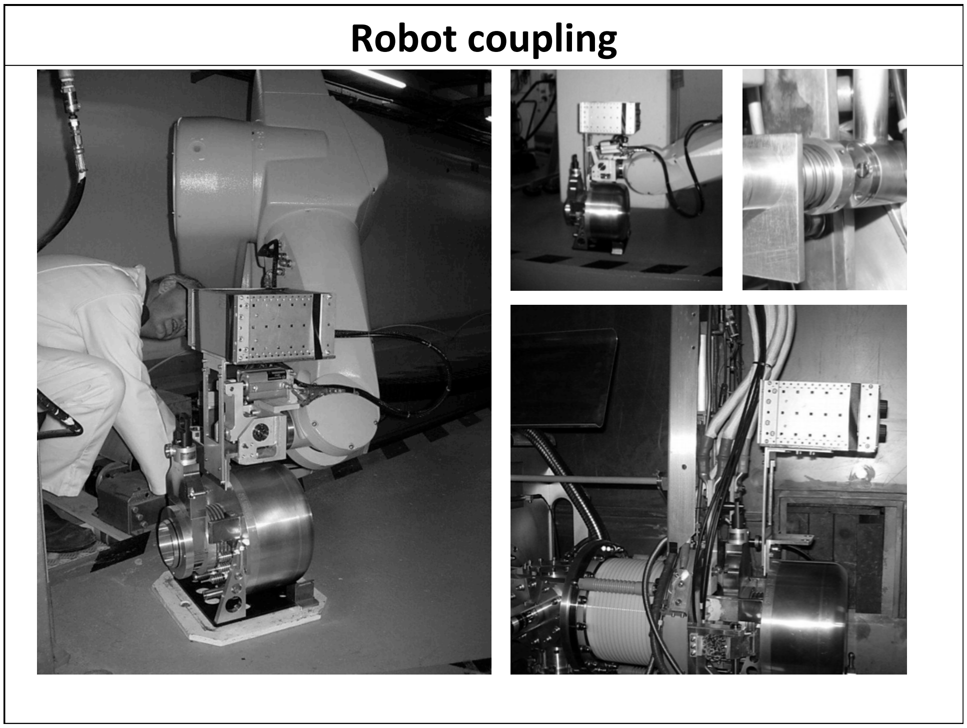


A feasible Laser Ion Source Trap design!

First On-Line test in 2011

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

Daniel Fink - Poster presentation # 25



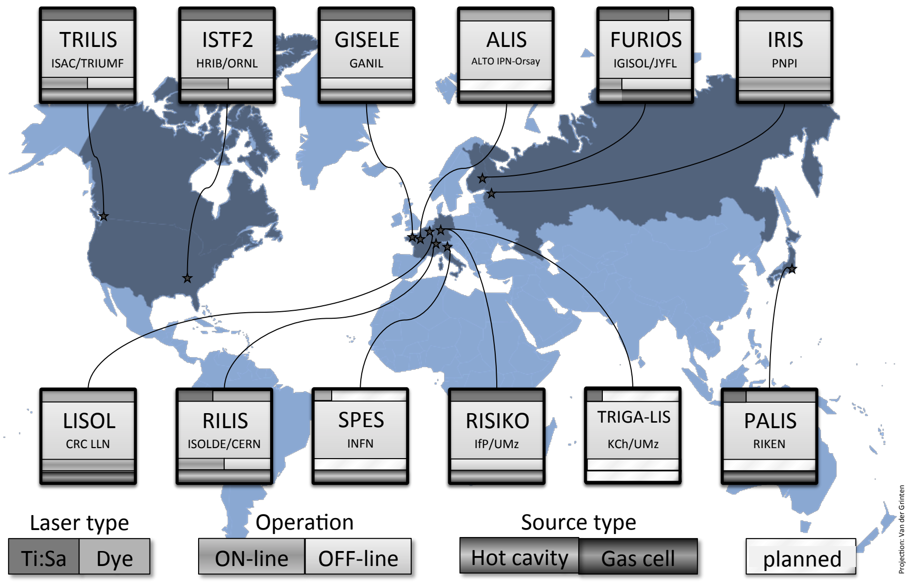
Robot coupling

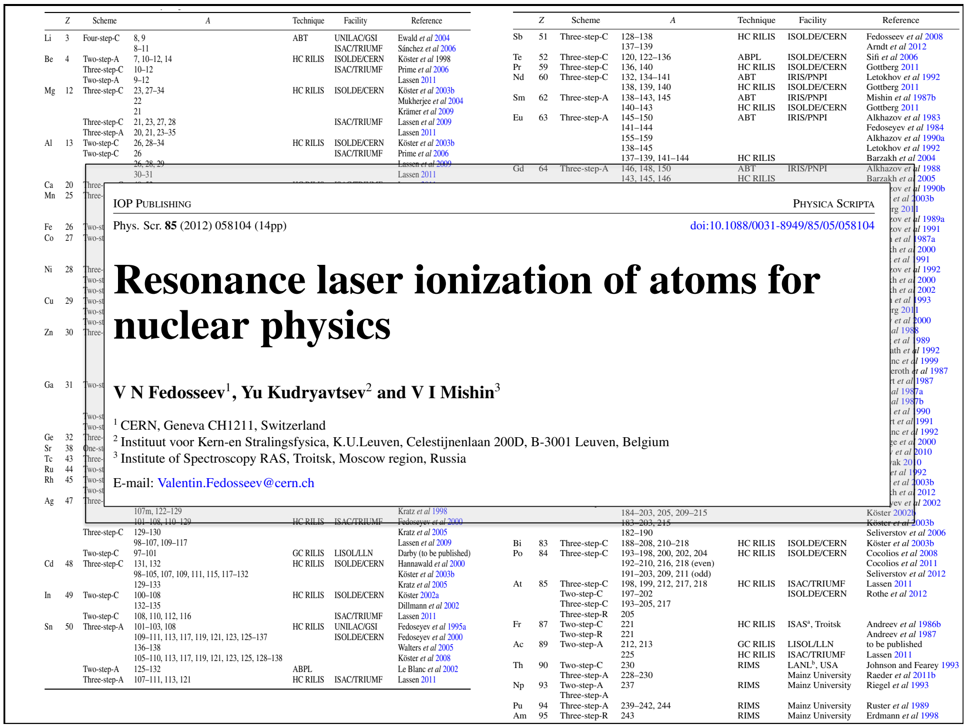
A) RESONANCE IONIZATION LASER ION SOURCES

7) Worldwide laser ion sources

- RILIS
- IRIS
- LISOL
- GANIL
- TRIUMF
- RIKEN
- JYFL
- ORNL
- ALTO

Laser Ion Sources Worldwide





IOP PUBLISHING PHYSICA SCRIPTA

Phys. Scr. **85** (2012) 058104 (14pp) doi:10.1088/0031-8949/85/05/058104

Resonance laser ionization of atoms for nuclear physics

V N Fedosseev[1], Yu Kudryavtsev[2] and V I Mishin[3]

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[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

IRIS (Investigation of Radioactive Isotopes on Synchrocyclotron) at **PNPI** (Petersburg Nuclear Physics Institute)

Gatchina, Russia

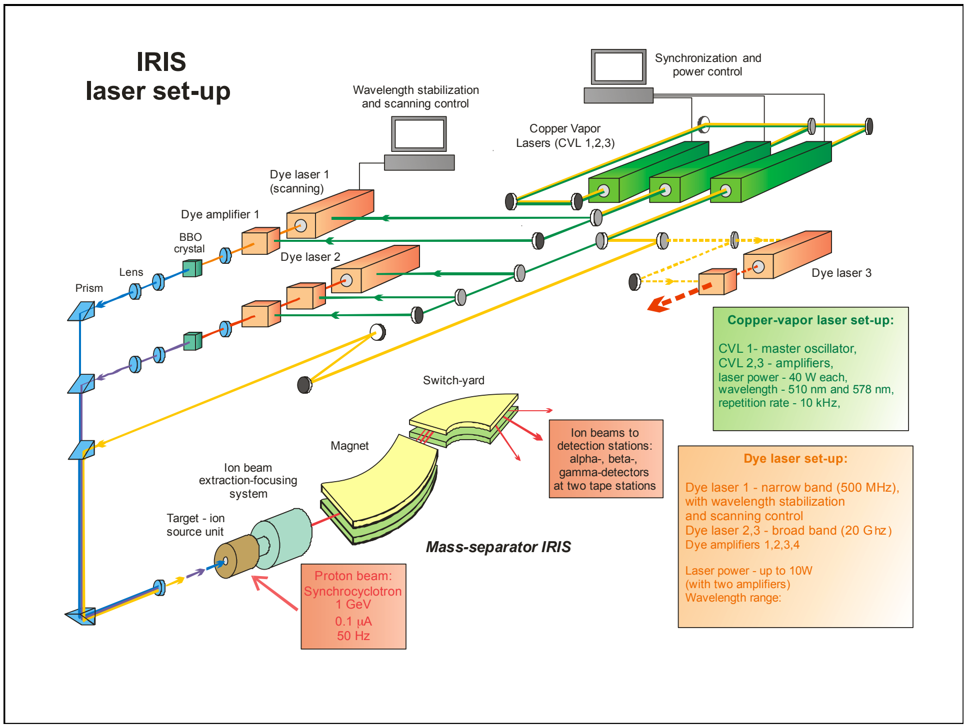
A. E. Barzakh,
D. V. Fedorov,
V. S. Ivanov,
P. L. Molkanov,
V. N. Panteleev (Head of Laboratory),
Yu. M. Volkov

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

Ion beams to detection stations: alpha-, beta-, gamma-detectors at two tape stations

Proton beam: Synchrocyclotron 1 GeV 0.1 µA 50 Hz

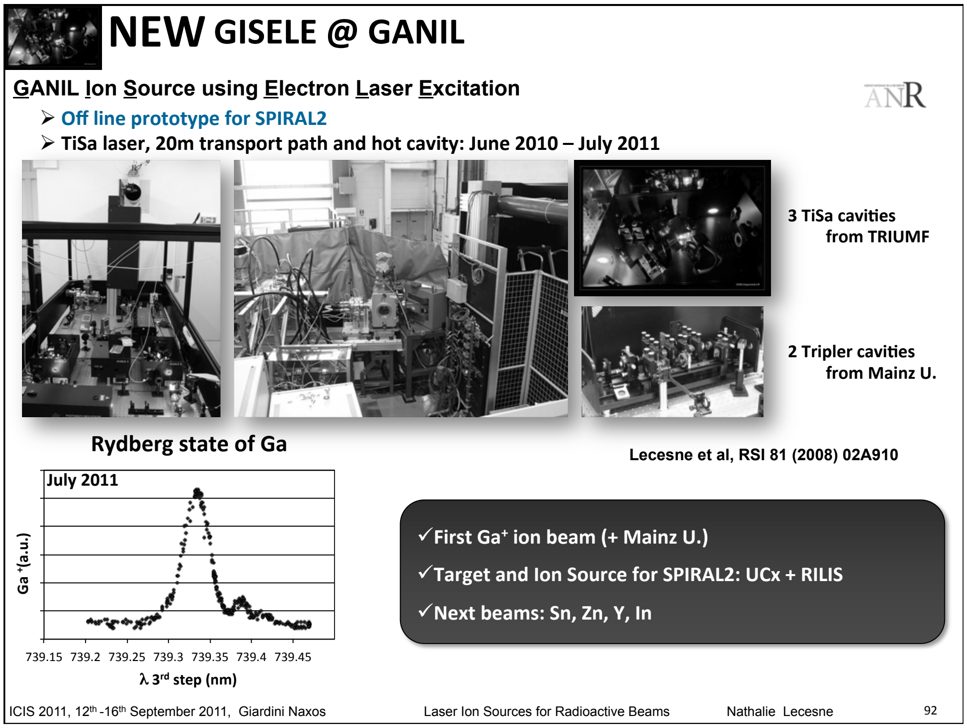
Copper-vapor laser set-up:

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:



NEW GISELE @ GANIL

GANIL Ion Source using Electron Laser Excitation

ANR

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

3 TiSa cavities from TRIUMF

2 Tripler cavities from Mainz U.

Rydberg state of Ga

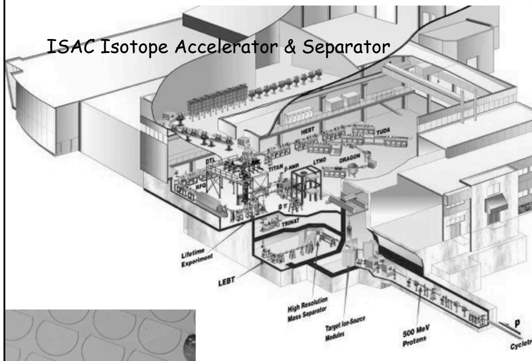
Lecesne et al, RSI 81 (2008) 02A910

- ✓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 92

TRIUMF Canada's National Laboratory for Particle and Nuclear Physics

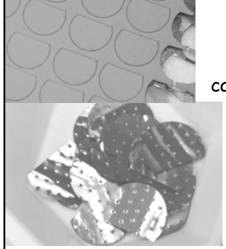
Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada



thick target – hot cavity ISOL based
radioactive ion beam facility

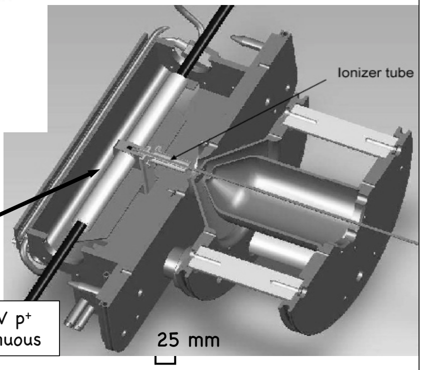
routine operation at the licensing limit:
100 μA p+ on A<81 targets (up to 50kW)
10 μA p+ on UC_x targets

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



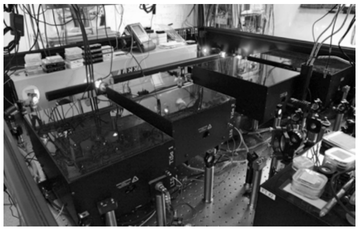
carbide etc. targets

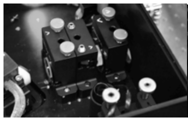
metal foil targets



Jens Lassen | TRIUMF Resonant Ionization Laser Ion Source

TRIUMF TiSa RILIS (T RILIS) status & outlook





TiSa laser specifications:
Repetition rate 10 kHz

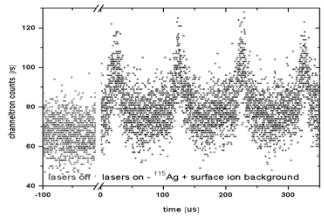
Wavelength range
- fund. 3W, 690 – 990 nm
- 2ν 500mW, 350 – 490 nm
- 3ν 100mW, 233 – 320 nm
- 4ν 100mW, 205 – 232 nm

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

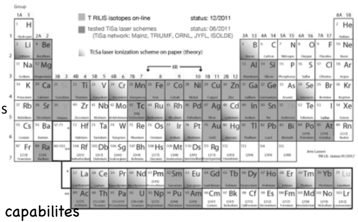
Spatial beam quality $M^2 < 1.2$

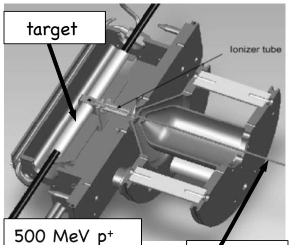
Spectral bandwidth 3–5 GHz

Temporal pulse duration 30–50 ns



yield database: http://www.triumf.info/facility/research_fac/yield.php





Operational:
(2004) TiSa laser based RILIS:
1st on-line beams
(2009) full off-line beam development capabilites
(2010) NSERC funded "in-source laser spectroscopy program"
(2011) 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

Jens Lassen | TRIUMF Resonant Ionization Laser Ion Source

Hot-Cavity Laser Ion Source at HRIBF-ORNL

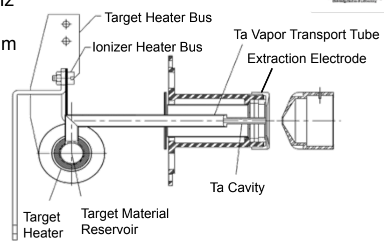
Ti:Sapphire Laser System

- 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)

Hot cavity ionizer



- 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

- 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

Element	Sn	Ni	Ge	Cu	Co	Ga	Mn	Ho
Efficiency (%)	22	2.7	3.3	2.4	>20	9	0.9	40

- 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

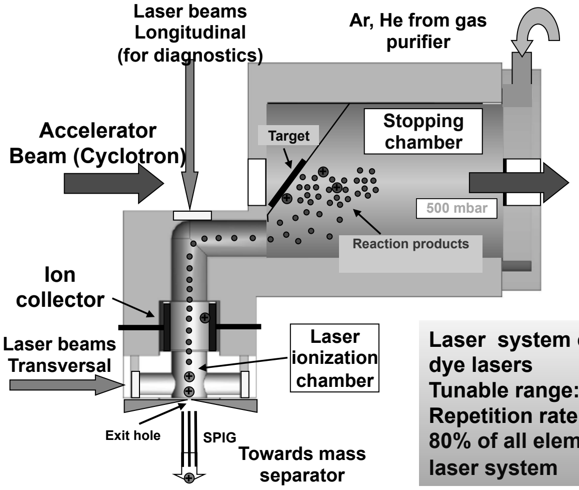
  Sn, Ni, Ge, Cu, Co, Ga, Sr, Mn, Fe, Al, Ho, Tb, Dy, Te

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

Element	Sn	Ni	Ge	Cu	Co	Ga	Mn	Ho
Efficiency (%)	22	2.7	3.3	2.4	>20	9	0.9	40

- The LIS has been installed on-line for production of RIBs

Leuven Isotope Separator On-Line (LISOL) Laser Ion Source



- 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

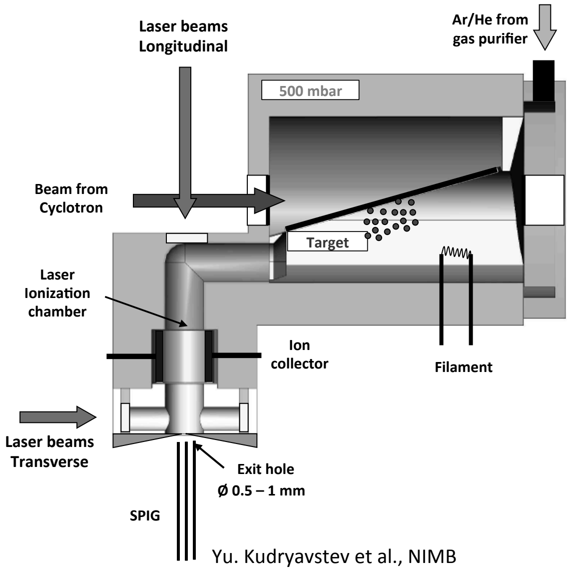
Laser system consists of two excimer-pumped dye lasers
Tunable range: 205 - 900 nm
Repetition rate: 200 Hz
80% of all elements can be ionized using LISOL laser system

- Delay time: 10 - 300 ms
(the same for refractory atoms)
- 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.

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.



Yu. Kudryavstev et al., NIMB

By separating stopping and laser ionization volumes

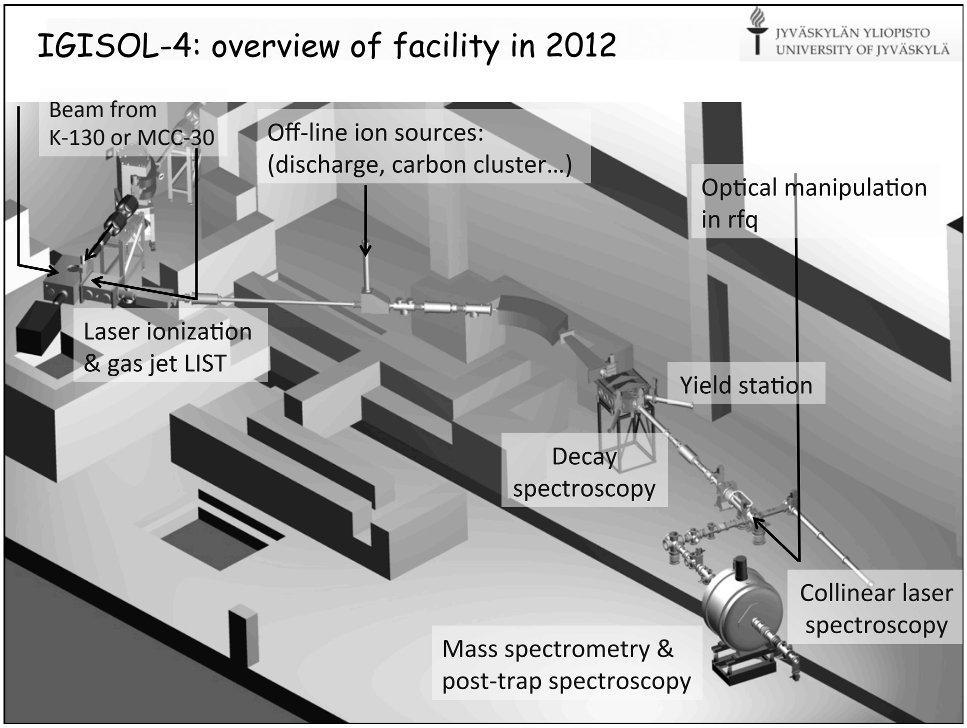
- Increased laser ionization efficiency at high cyclotron beam current
- Increased selectivity (collection of survival ions)

Selectivity (^{94}Rh):

Laser(ON)/Laser(OFF)

Ion Collector OFF = 450

Ion Collector ON = 2200



IGISOL-4: overview of facility in 2012

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Beam from
K-130 or MCC-30

Off-line ion sources:
(discharge, carbon cluster…)

Optical manipulation
in rfq

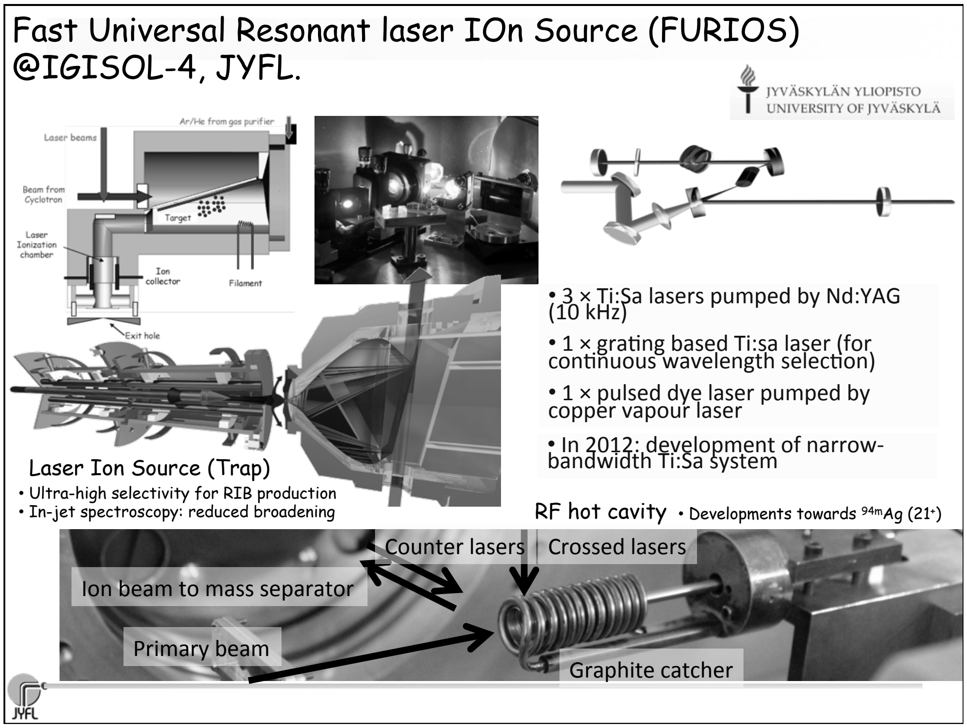
Laser ionization
& gas jet LIST

Yield station

Decay
spectroscopy

Collinear laser
spectroscopy

Mass spectrometry &
post-trap spectroscopy



Fast Universal Resonant laser IOn Source (FURIOS) @IGISOL-4, JYFL.

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

- 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

Laser Ion Source (Trap)

- Ultra-high selectivity for RIB production
- In-jet spectroscopy: reduced broadening

RF hot cavity

- Developments towards ^{94m}Ag (21^{+})

Counter lasers

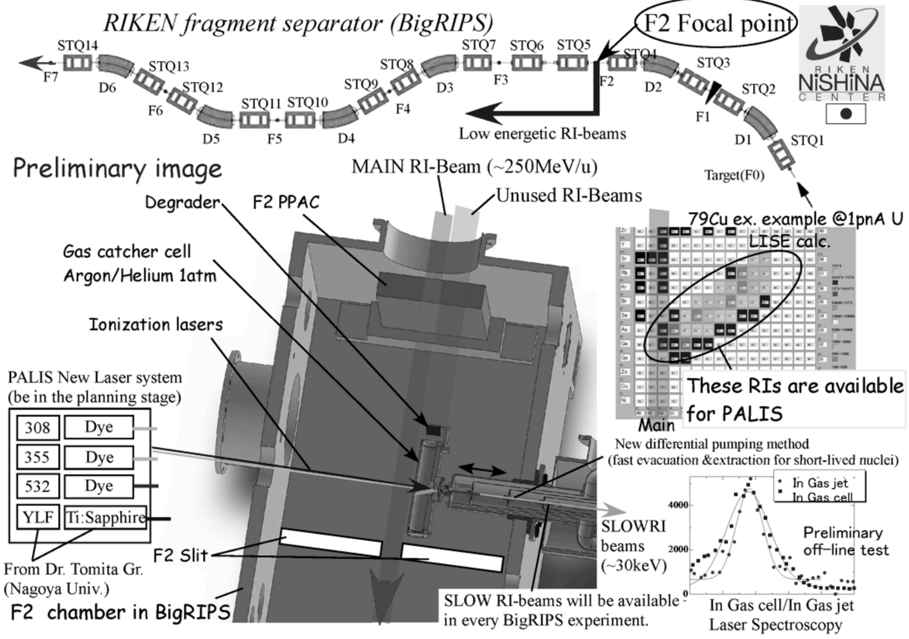
Crossed lasers

Ion beam to mass separator

Primary beam

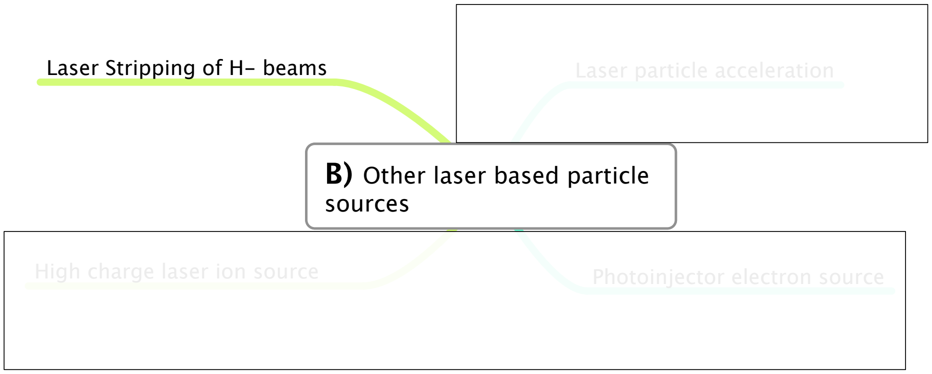
Graphite catcher

PArasitic Laser Ion-Source (PALIS) at SLOWRI RIKEN



B) Other laser based particle sources

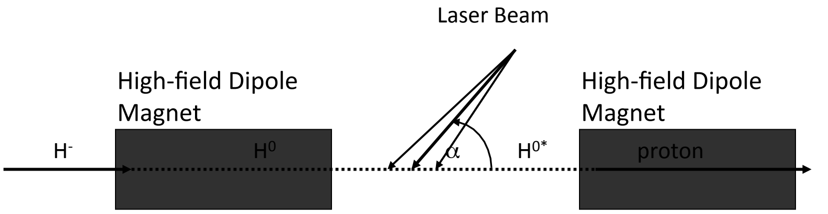
- Laser Stripping of H- beams
- Laser particle acceleration
- High charge laser ion source
- Photoinjector electron source



B) Other laser based particle sources

Three-Step Stripping Scheme

- Anovel 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

https://wiki.ornl.gov/events/lahbsa/default.aspx.

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

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

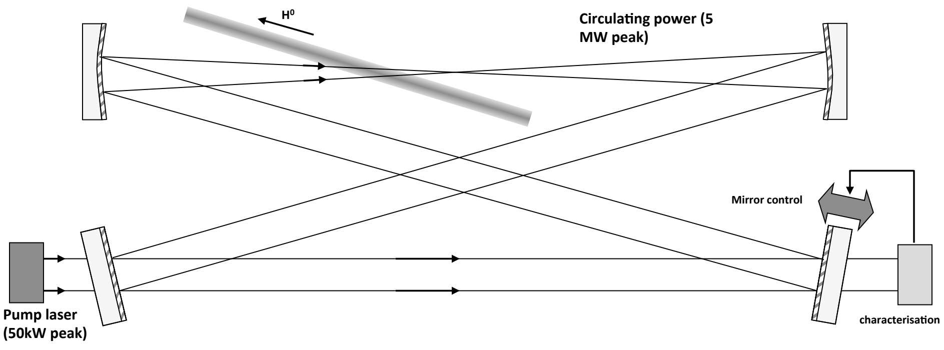
Includes factor 3 margin in laser power

WS outputs: laser possibilities

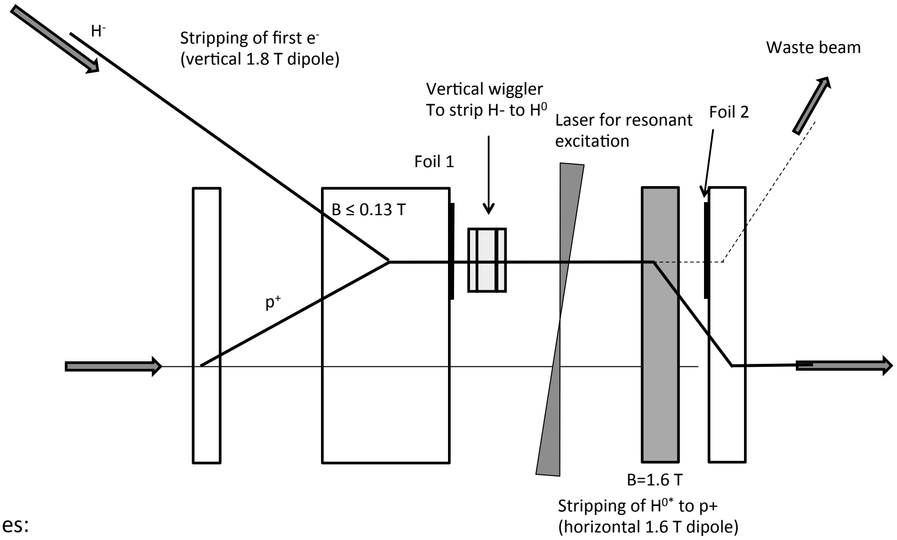
- KEK (Yamane):
  - Laser-H- IP is brought into B-field
    - → compensation of Doppler broadening by broadening of Stark-states in the magnetic field
    - → single laser frequency can excite full distribution
    - → no spontaneous decay worries (direct stripping of excited H^0)
- Continuum (Laha):
  - "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 (indepent 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, …)



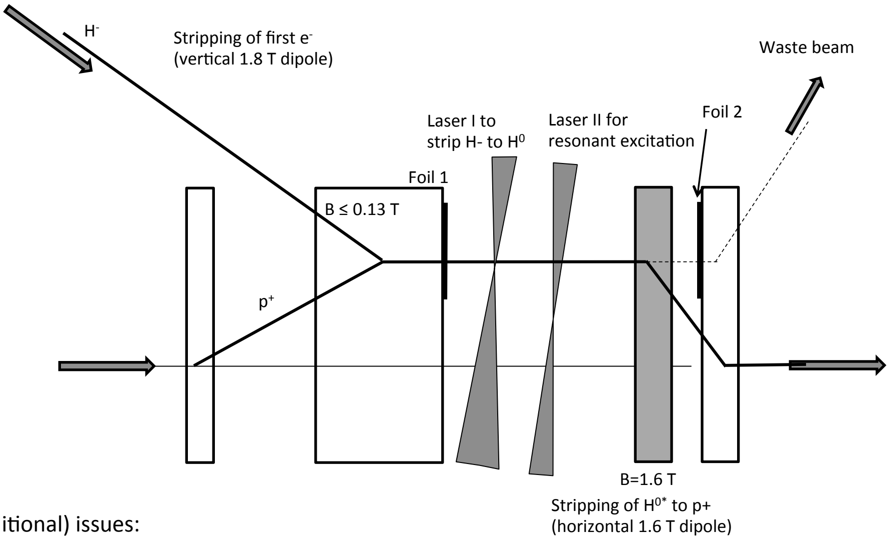
Laser-assisted stripping schemes I: magnet-laser-magnet



Issues:

Wiggler design, IR geometry, spontaneous decay, fringe fields,
laser power, laser time structure, beam parameters, stripping efficiency…

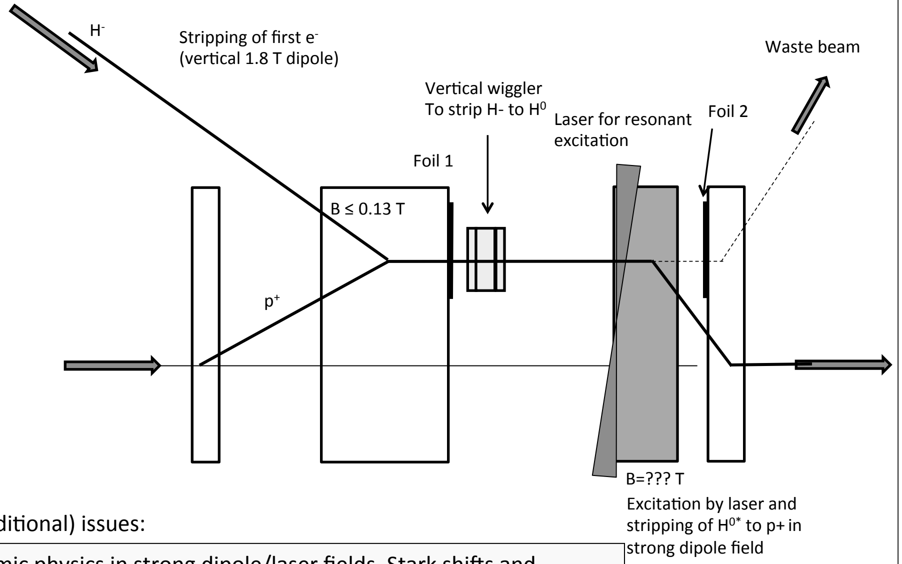
Laser-assisted stripping schemes II: laser-laser-magnet



(additional) issues:

Photodetachment cross-sections, laser cavities,
reuse of same laser beam

Laser-assisted stripping schemes III: magnet-laser+magnet



(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

- Laser Stripping of H– beams
- Laser particle acceleration
- High charge laser ion source
- Photoinjector electron source

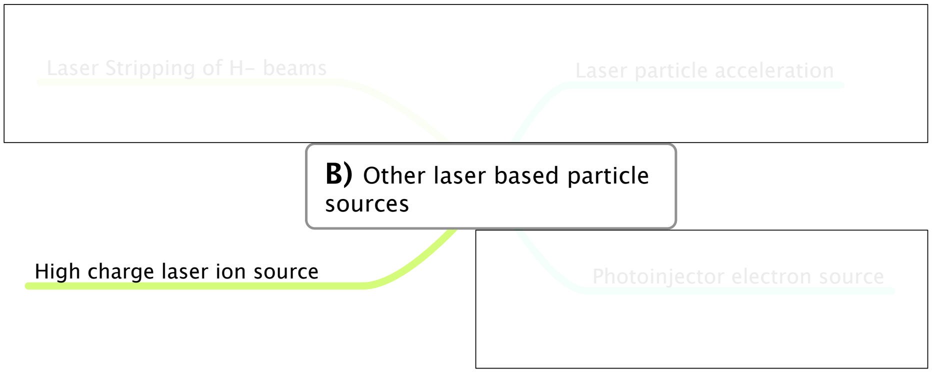
Many options for the next-generation collider with different levels of risk and different costs

- 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 potential for much lower costs

High Gradient Acceleration with Lasers

- 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



Laser Stripping of H- beams

Laser particle acceleration

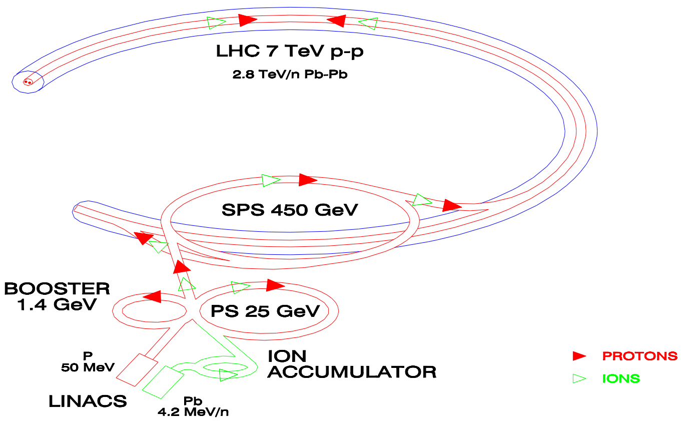
B) Other laser based particle sources

High charge laser ion source

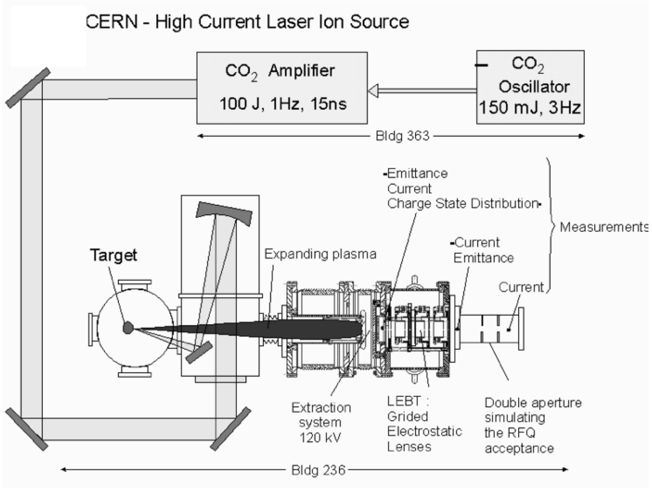
Photoinjector electron source

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



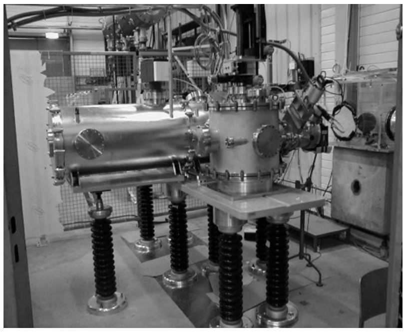
Laser Ion Source (LIS) – an Alternative?



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 **$\varepsilon^*_{\mathrm{rms}} < 0.15\ \mu\mathrm{m}$**
♦ 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)

Conclusions on Sources and Linac 3

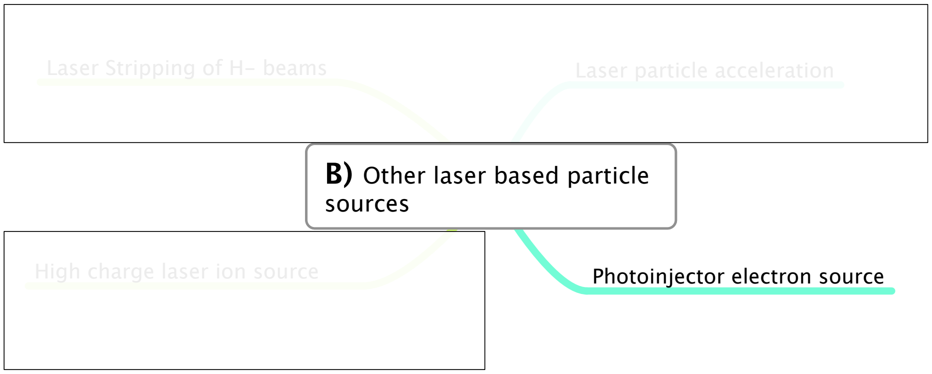
ECR Sources:

- ♦ 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

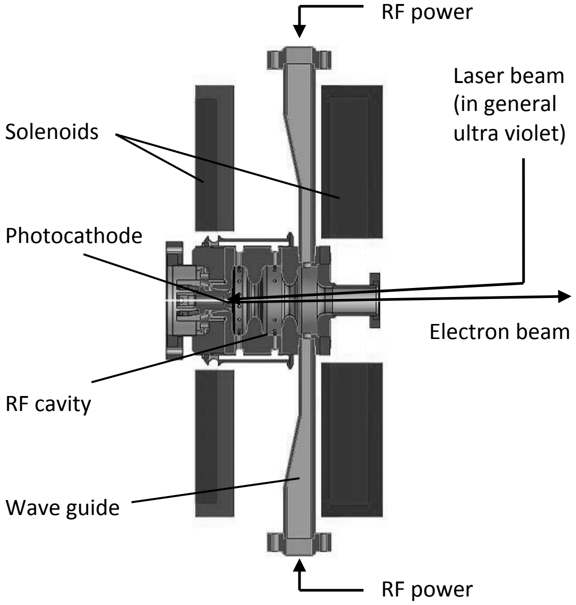
Laser Stripping of H- beams

Laser particle acceleration

High charge laser ion source

Photoinjector electron source

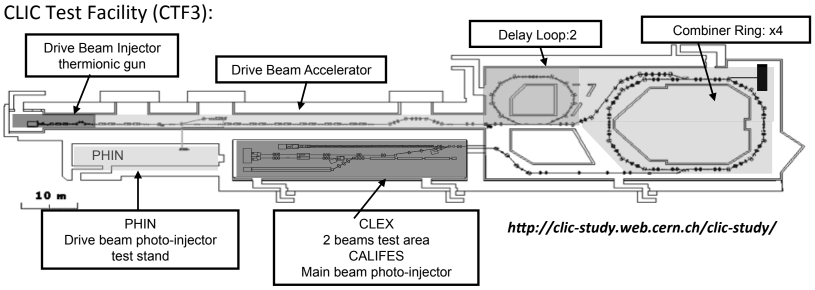
RF Photoinjectors: Operation Principle



- 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

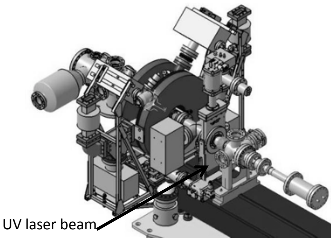
Photoinjectors at CERN

CLIC Test Facility (CTF3):



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

PHIN Photoinjector:

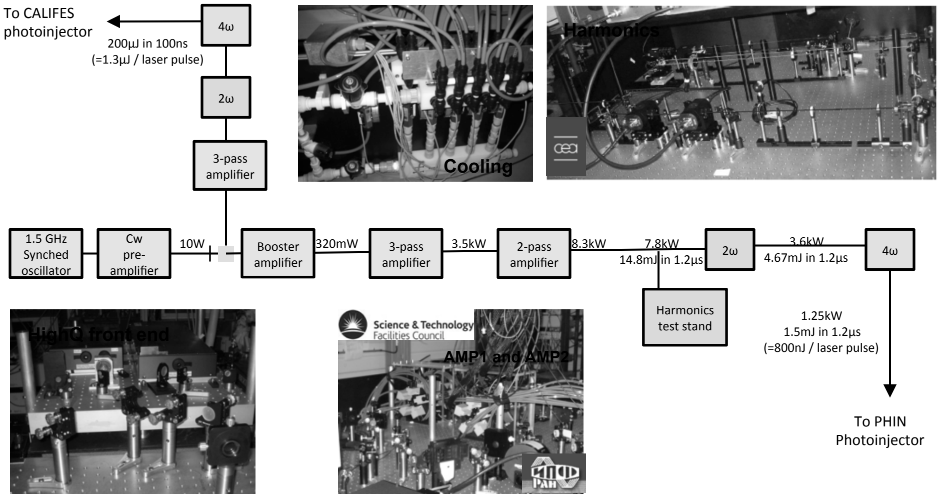


		DRIVE beam	MAIN beam
Electrons		**PHIN**	**CALIFES**
	Charge/bunch (nC)	2.3	0.6
	Macro-pulse length (ns)	1200	19.2
	Bunch spacing(ns)	0.666	0.666
	Bunch length (ps)	10	10
	Bunch rep. rate (GHz)	1.5	1.5
	Number of bunches	1802	32
	Macro-pulse rep. rate (Hz)	**5**	5
	Margin for the laser	**1.5**	1.5
	Charge stability	**<0.25%**	<3%
	QE(%) of Cs2Te cathode	**3**	0.3

Machine parameters set the requirement for the laser

H. Braun et al., “The Photo-Injector Option for CLIC: Past Experiments and Future Developments”, Proc. of PAC’01, Chicago (2001), p. 720.

Laser System



M. Petrarca et al., “Study of the Powerful Nd:YLF Laser Amplifiers for the CTF3 Photoinjectors”, IEEE J. Quant. Electr. 47 (2011), p. 306.