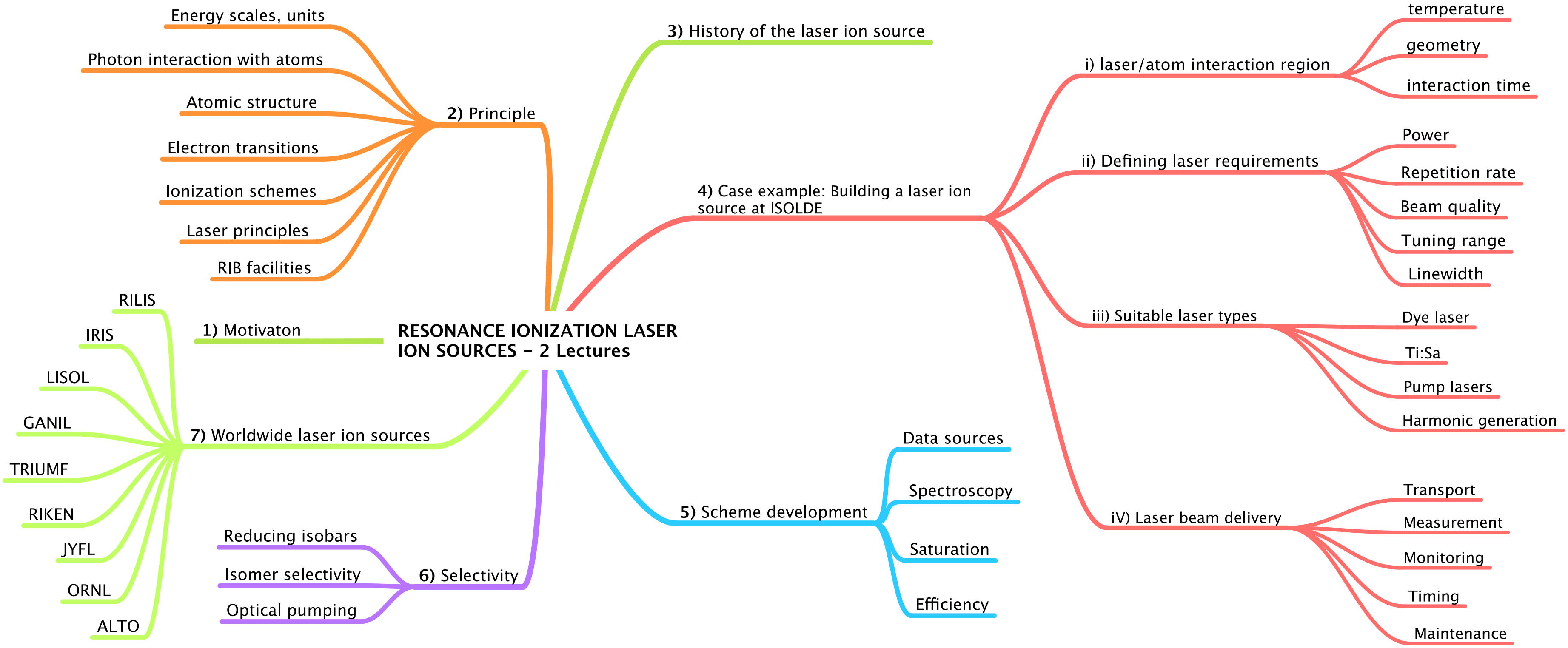
Laser Ion Sources I and II – Structure of the lectures



RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

- **1)** Motivaton
- **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)** Selectivity
  - Reducing isobars
  - Isomer selectivity
  - Optical pumping
- **7)** Worldwide laser ion sources
  - RILIS
  - IRIS
  - LISOL
  - GANIL
  - TRIUMF
  - RIKEN
  - JYFL
  - ORNL
  - ALTO

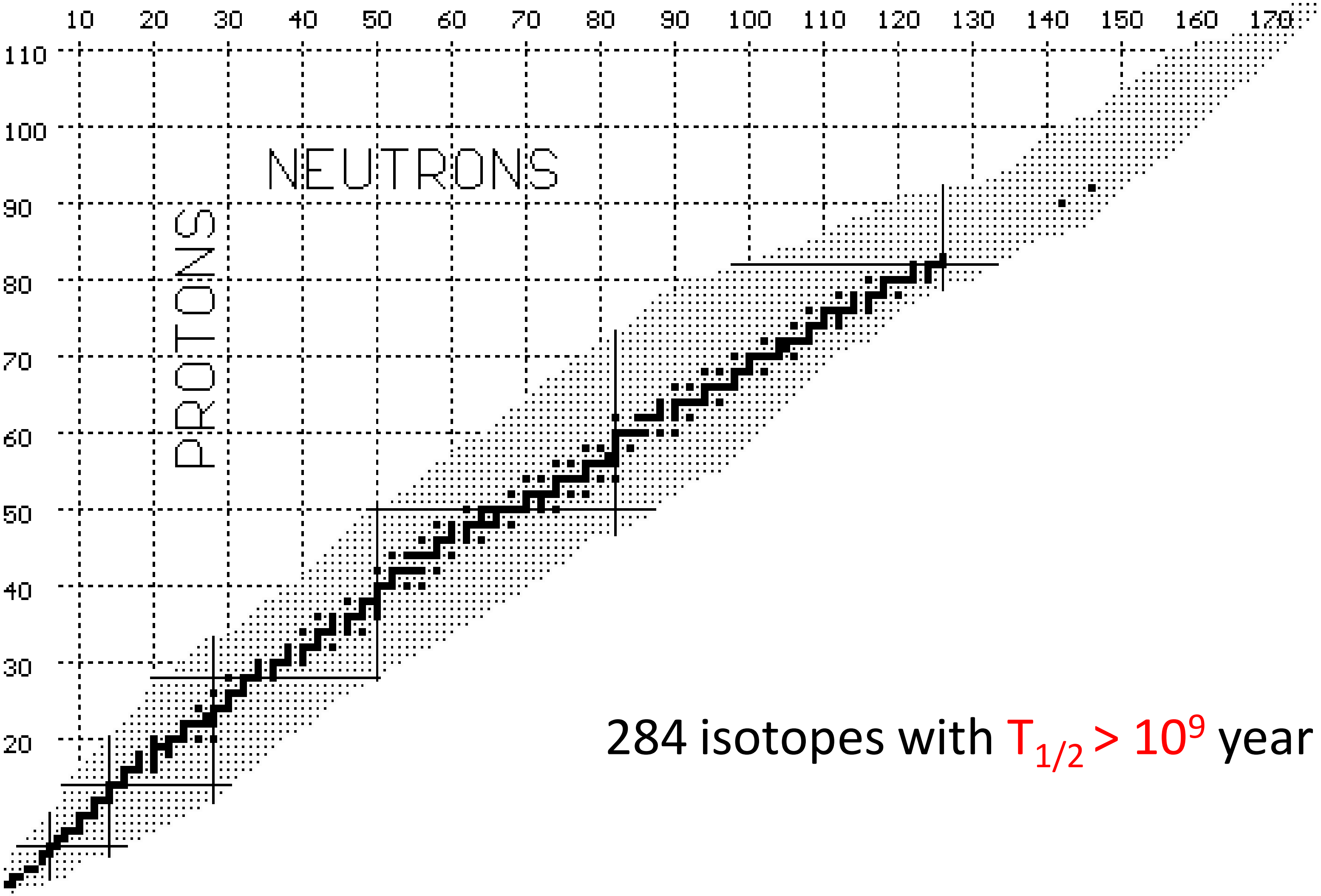
School on laser applications, GANIL, October 2012

Bruce Marsh CERN EN-STI-LP

1) Motivaton

RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

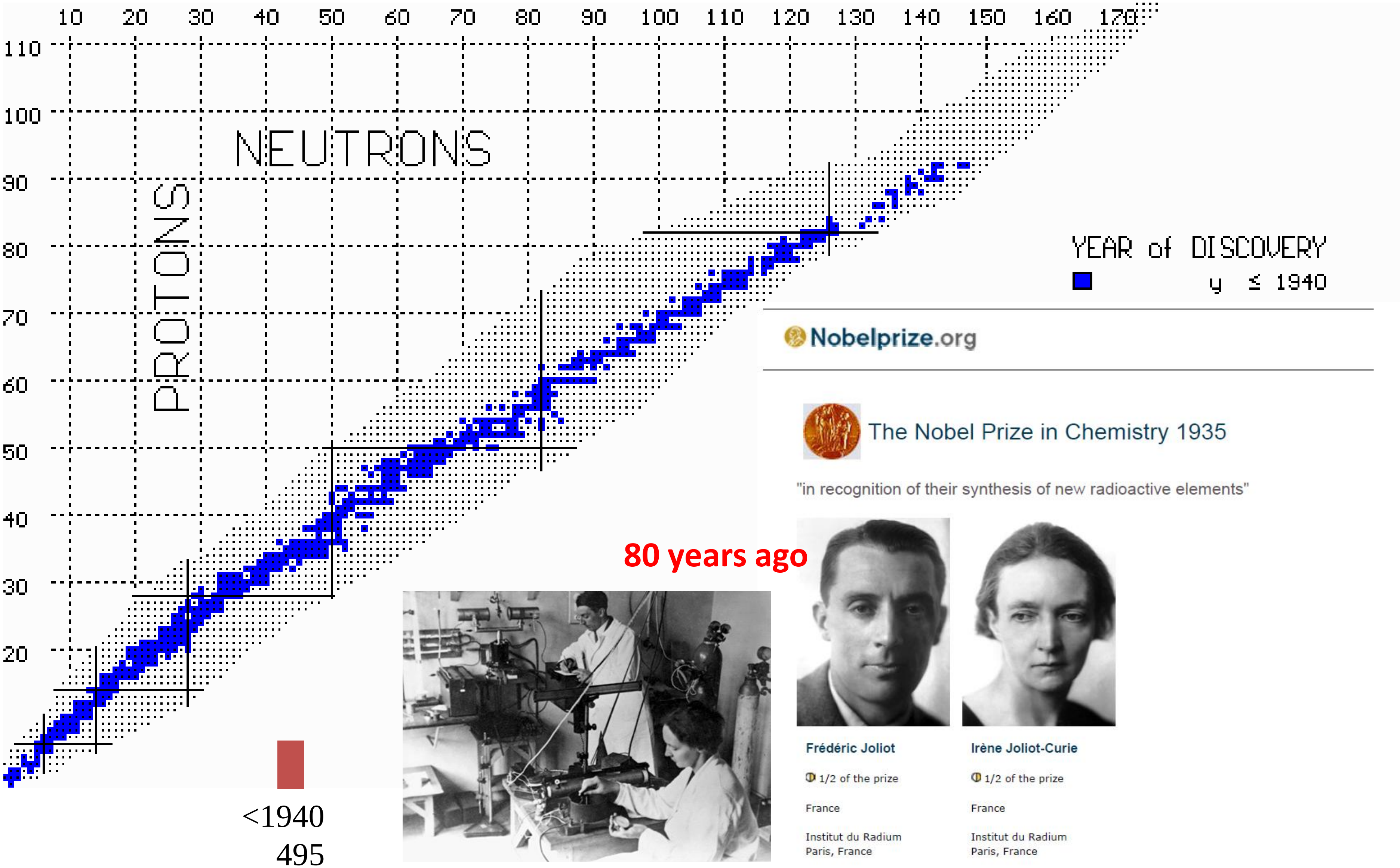
The chart of stable nuclei



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

Slide: M. Huyse

+ the discovery of radioactivity



80 years ago

Nobelprize.org

The Nobel Prize in Chemistry 1935

"in recognition of their synthesis of new radioactive elements"

Frédéric Joliot
1/2 of the prize
France
Institut du Radium
Paris, France

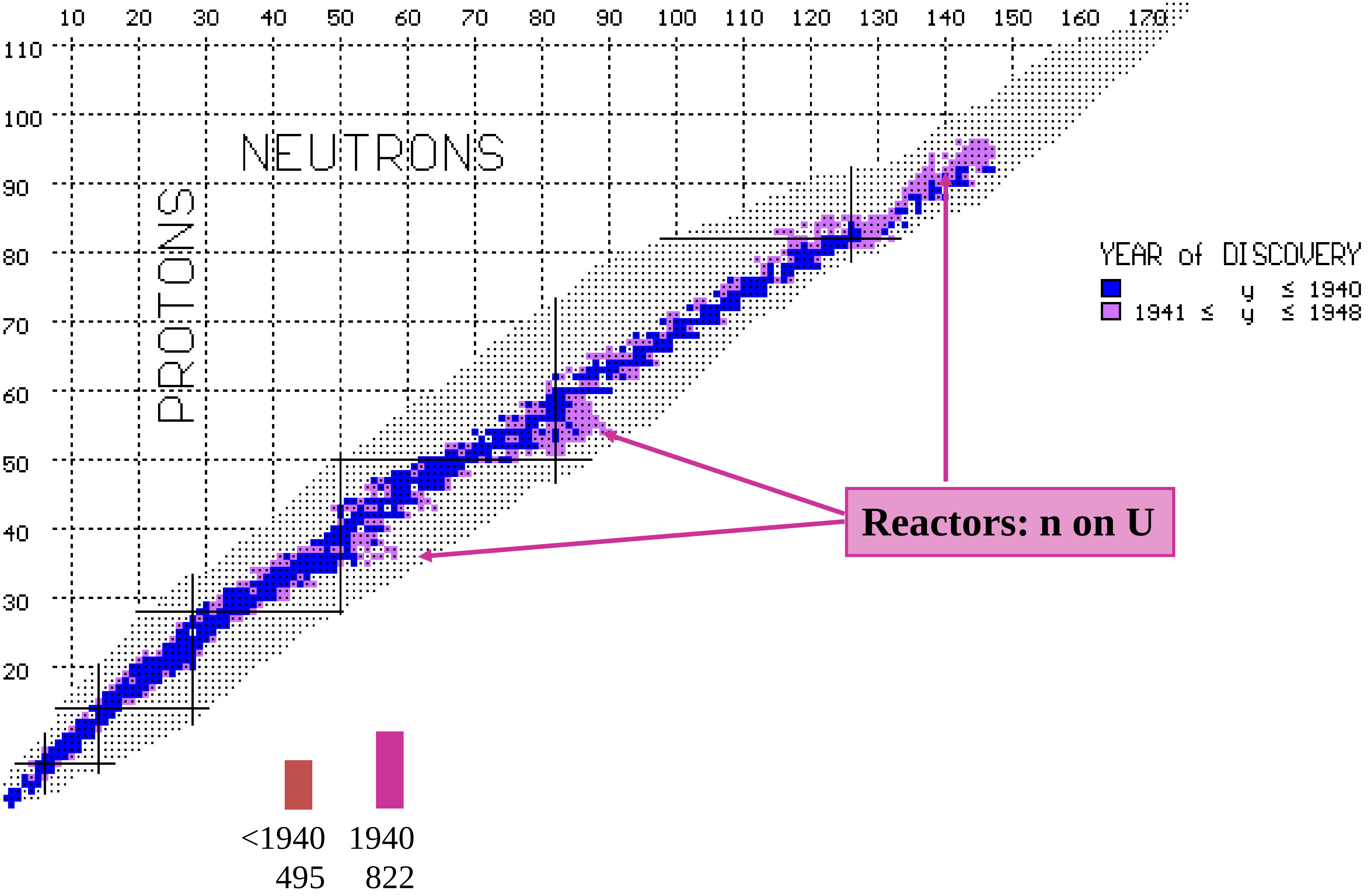
Irène Joliot-Curie
1/2 of the prize
France
Institut du Radium
Paris, France

Curie I, Joliot F. Artificial production of a new kind of radioactive element. Nature 1934;133:201–2.

$^{4}He+^{10}B \Rightarrow ^{13}N+n$

Slide: M. Huyse

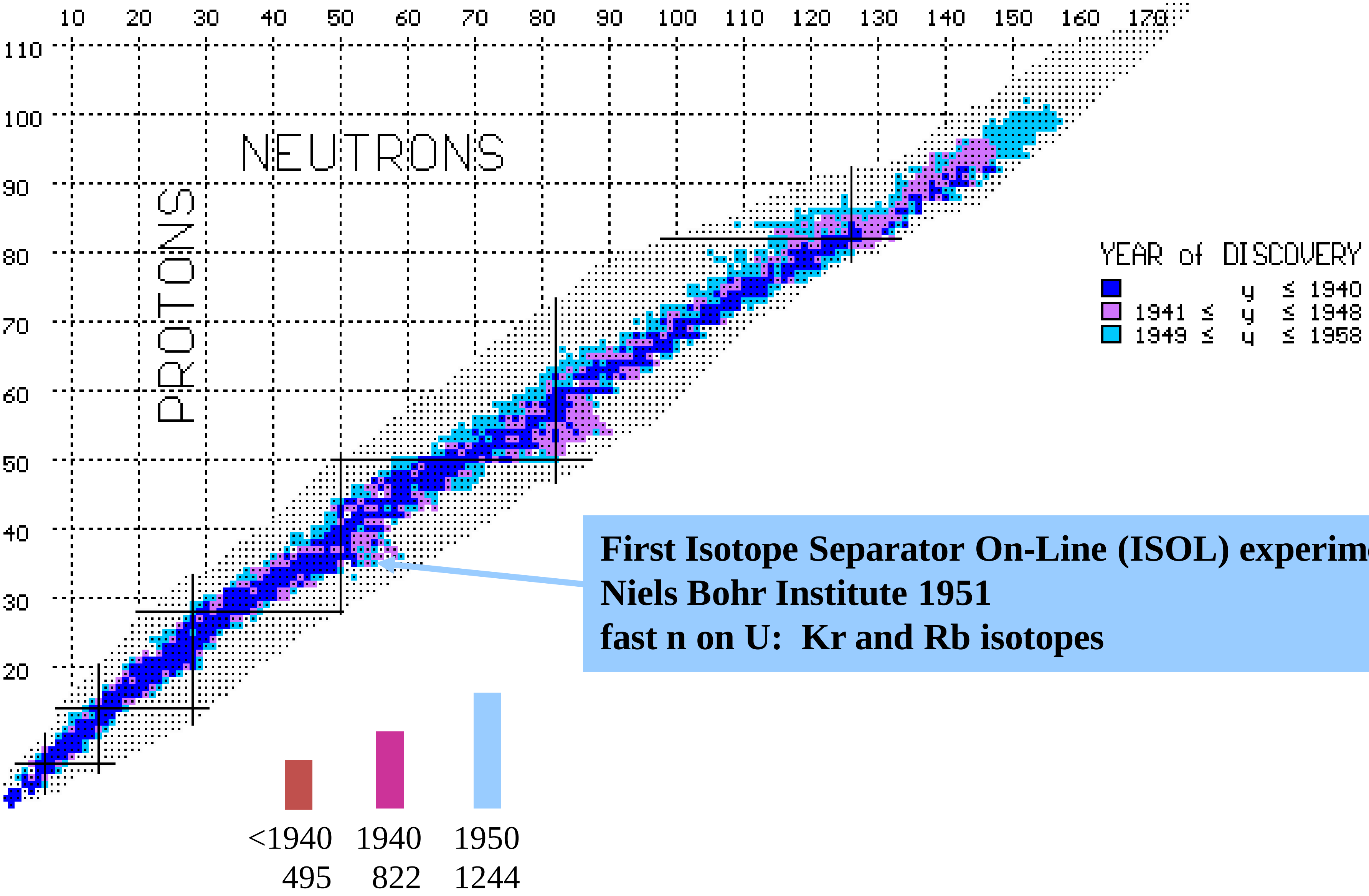
+ the advent of nuclear reactors



Reactors: n on U

Slide: M. Huyse

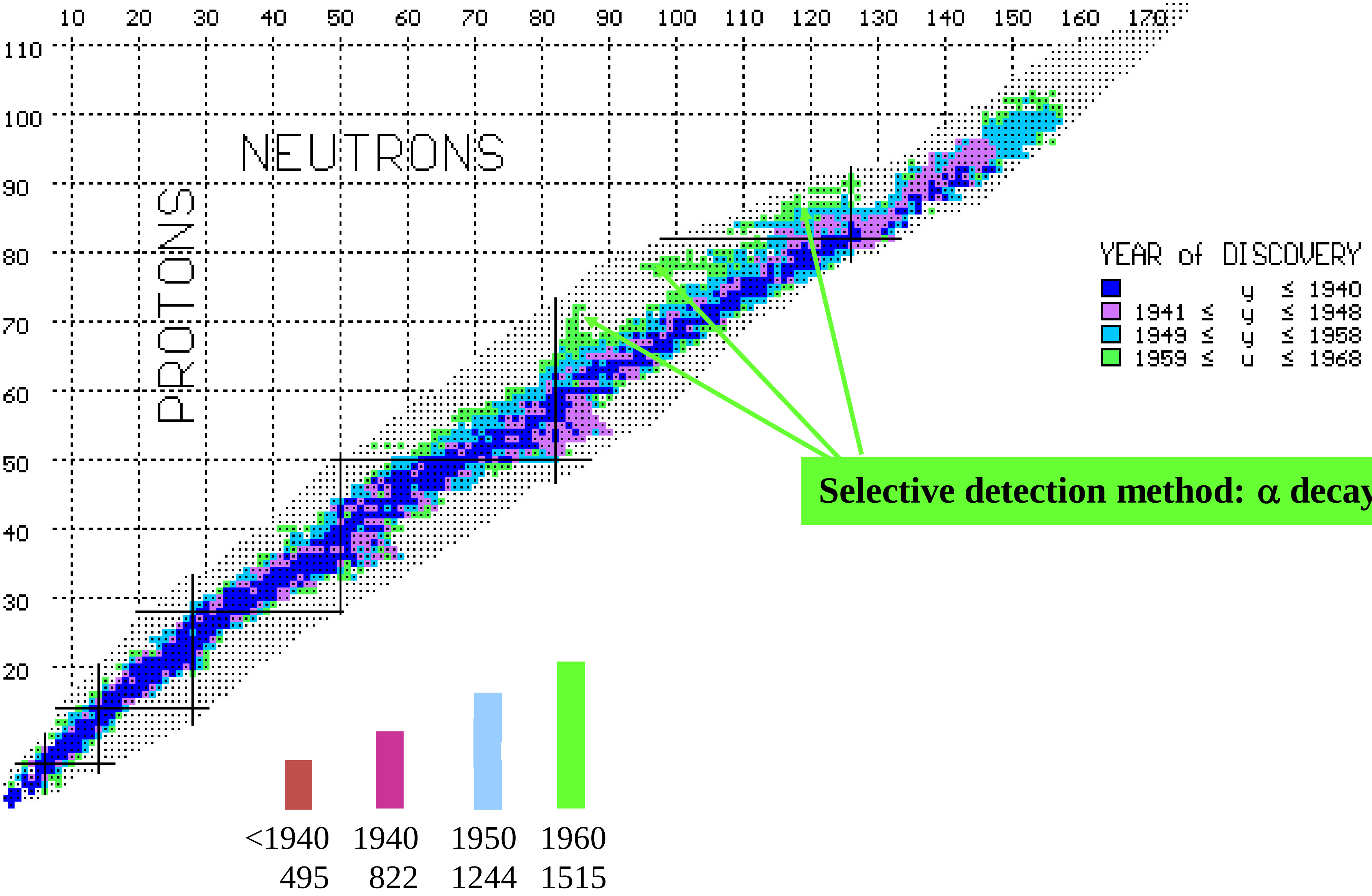
+ Early Isotope Separator On Line (ISOL) isotopes



First Isotope Separator On-Line (ISOL) experiment
Niels Bohr Institute 1951
fast n on U: Kr and Rb isotopes

Slide: M. Huyse

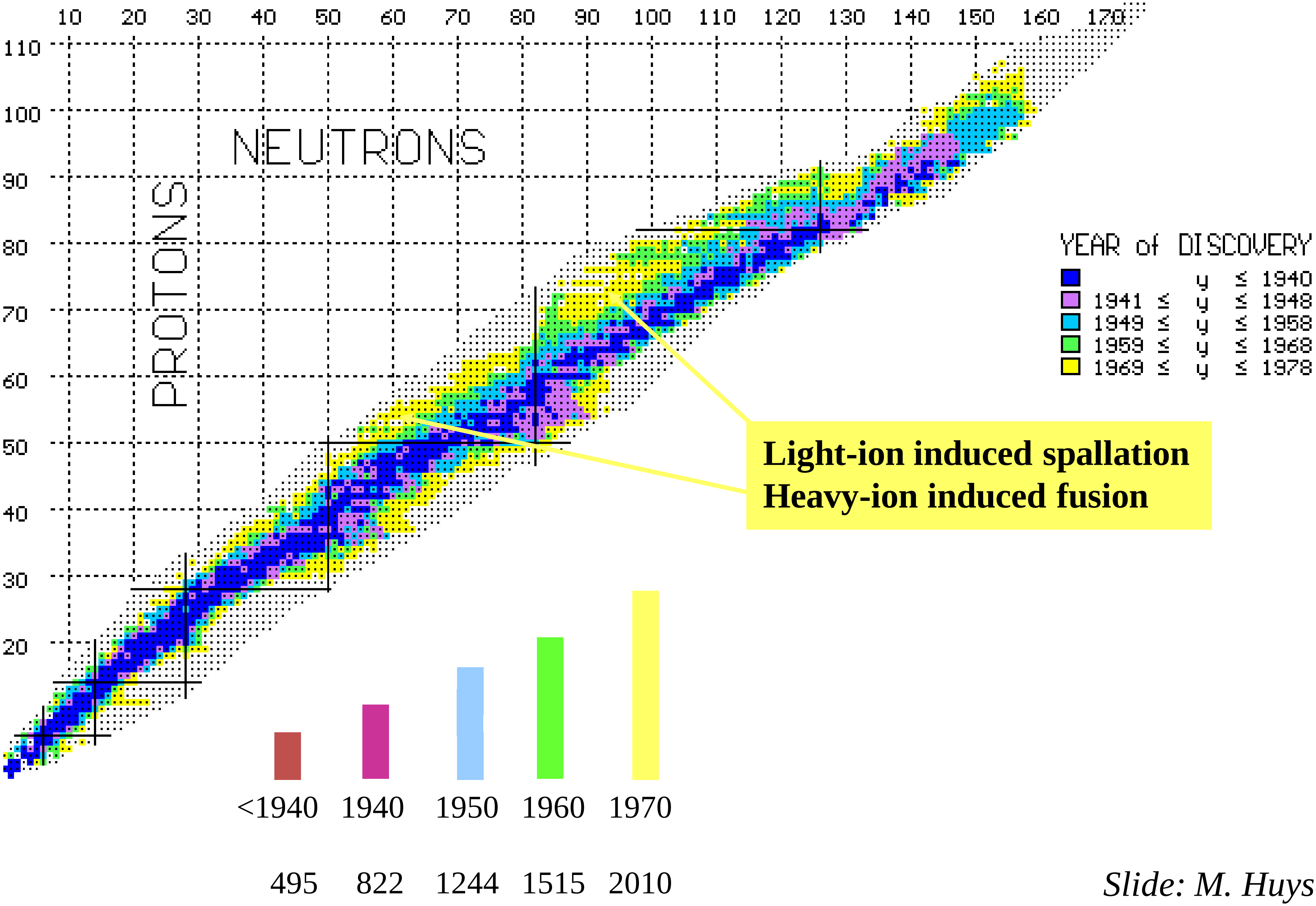
+ sensitive detection methods



Selective detection method: α decay

Slide: M. Huyse

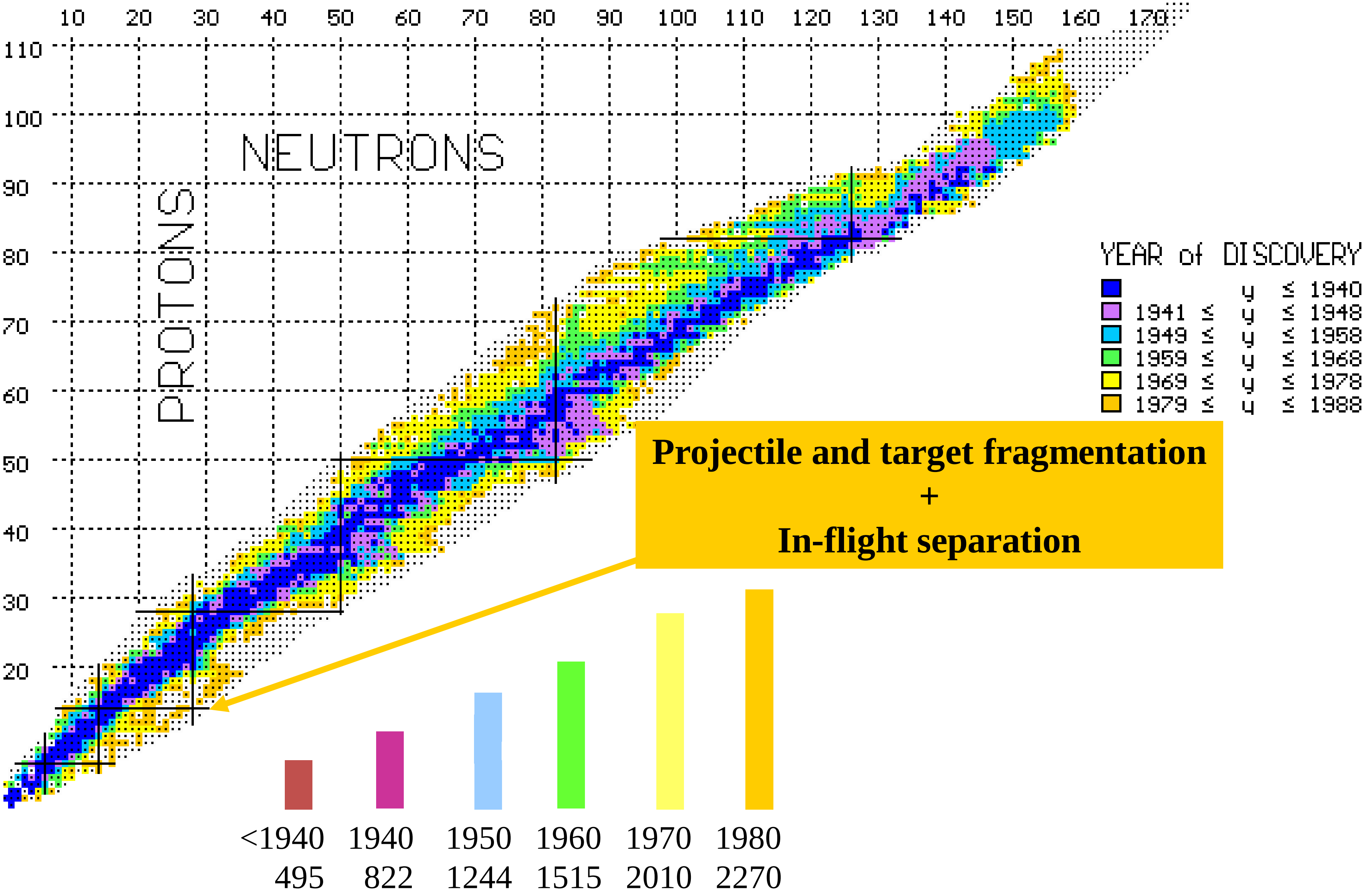
+ energy increases and driver beam upgrades



Light-ion induced spallation
Heavy-ion induced fusion

Slide: M. Huyse

+ thin target and projectile fragmentation – shorter lifetimes



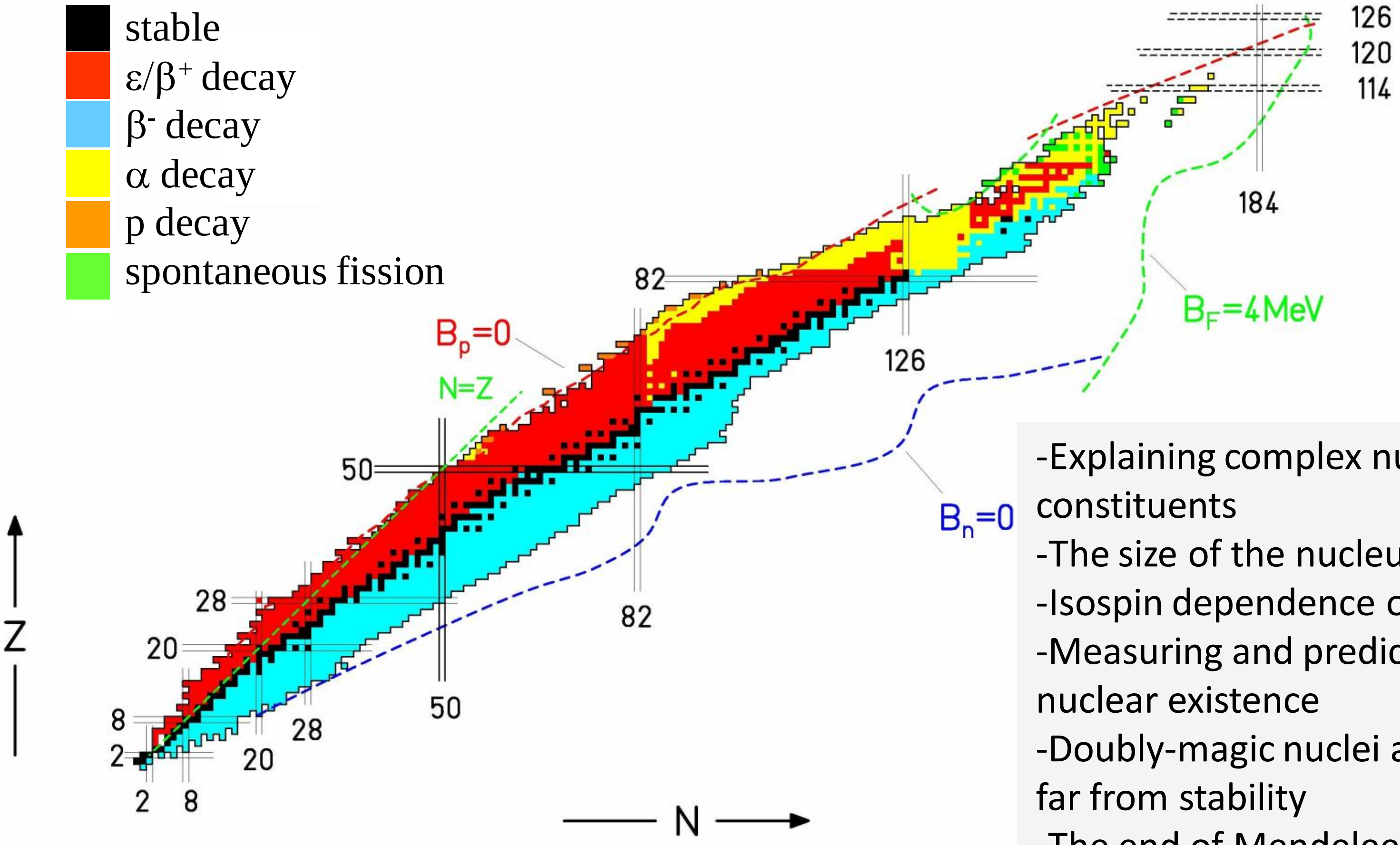
Projectile and target fragmentation

+

In-flight separation

Slide: M. Huyse

= The modern nuclear chart

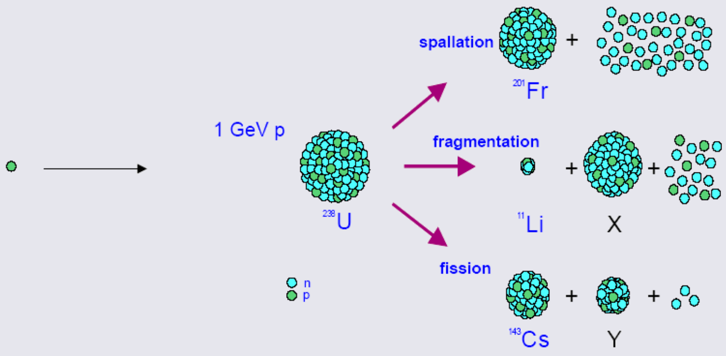


-Explaining complex nuclei from basic constituents
-The size of the nucleus: halos and skins
-Isospin dependence of the nuclear force
-Measuring and predicting the limits of nuclear existence
-Doubly-magic nuclei and shell structure far from stability
-The end of Mendeleev’s table: superheavies
-Understanding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

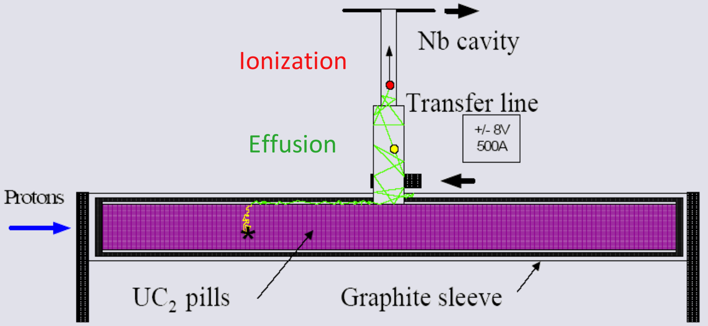
> 3500 of the expected 6000 nuclei have been observed

The ISOL process

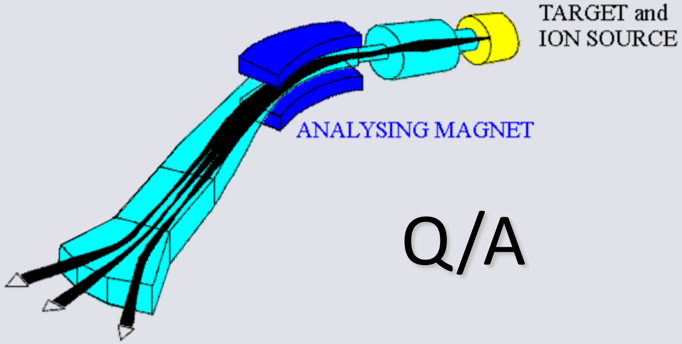
Production



Extraction/Ionization



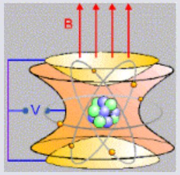
Isotope Separation



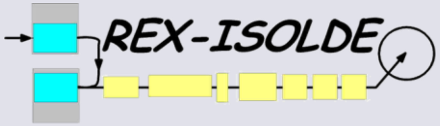
Q/A

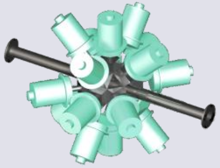
Post acceleration
or to Experiment

Collaps
Collinear Laser Spectroscopy



ISOLTRAP





Fast, Efficient, Universal and Selective!

Factors influencing isotope production

RIB intensity [s^{-1} μA^{-1}]

Proton beam intensity [s^{-1} μA^{-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

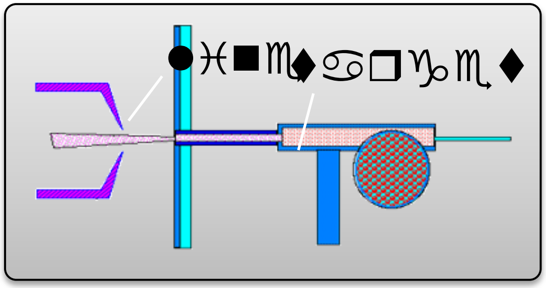
Production | Extraction

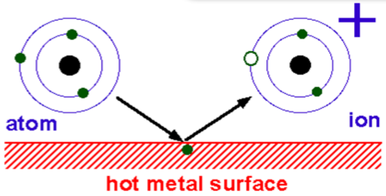
ISOL ion source and beam requirements are very broad !

- Energy range 10^{-6} eV (10 mK) to >MeV/u
- Intensity 0.01 – 10^{10} ions/s
- Selectivity, efficiency, universality!
- Particle type : ^{6}He to ^{232}R (Z: 2-88, N:4-144), and molecules!
- Lifetimes: stable → micro seconds
- Charge state: mainly 1+ or 1-, or n+ for post acceleration

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.

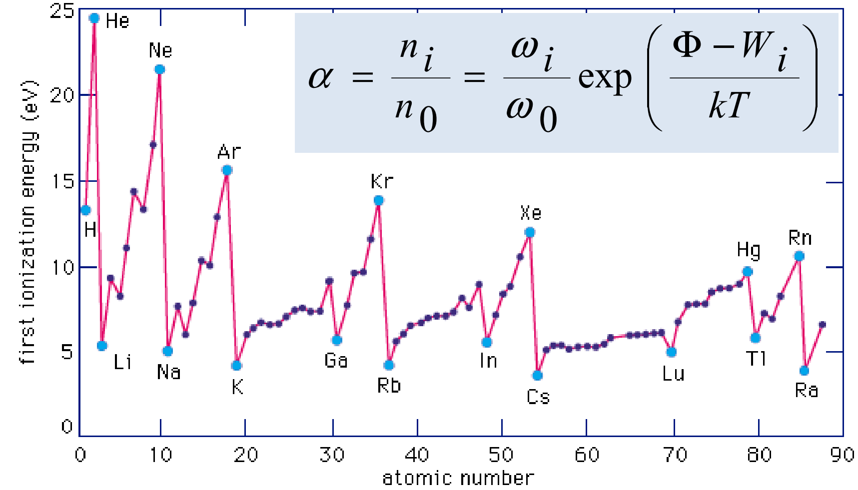
SURFACE ION SOURCE





- 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)*



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

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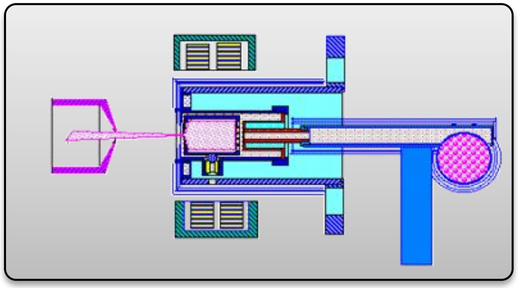
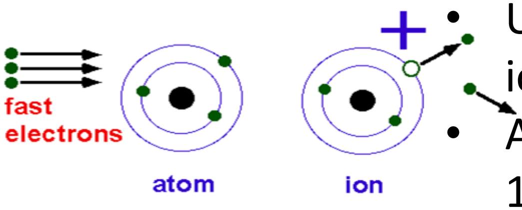
Surface Ionization Process:

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

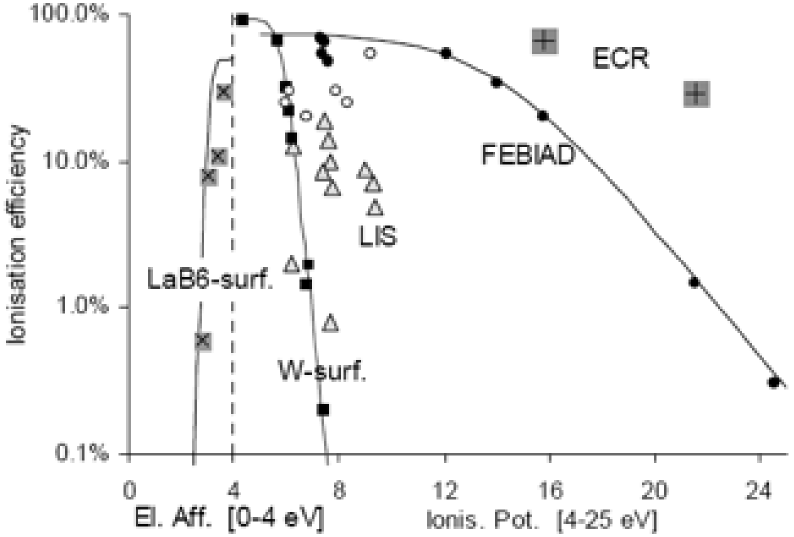
PLASMA ION SOURCE





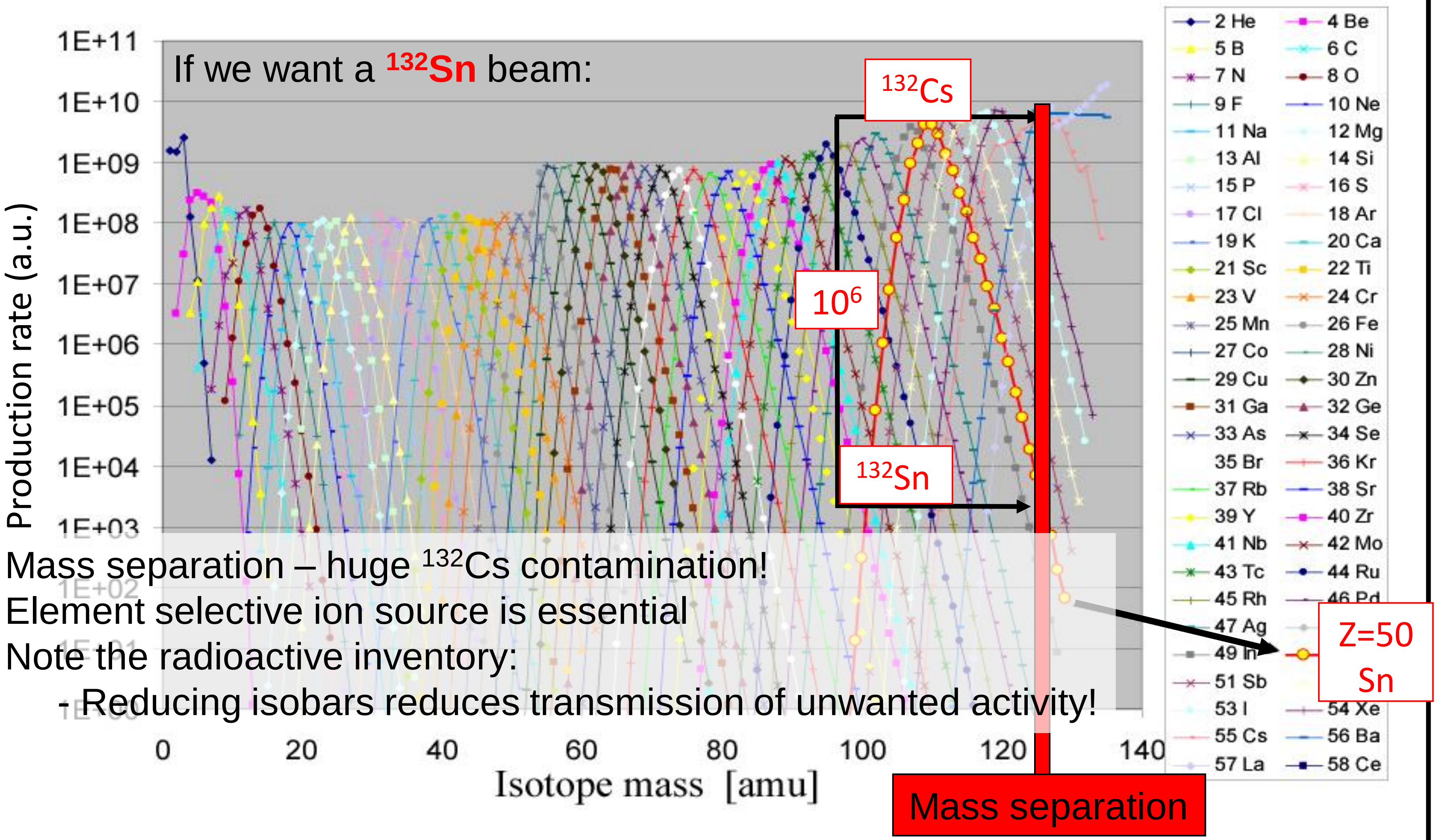
- Used for non surface-ionizing elements
- Ar or Xe plasma with 130 eV electrons

Very efficient, even for high IP elements. Chemically unselective



Production of Exotic Nuclei: Beam purity requires element selectivity

Isotope production for a 1 GeV proton beam on a lanthanum (La) target

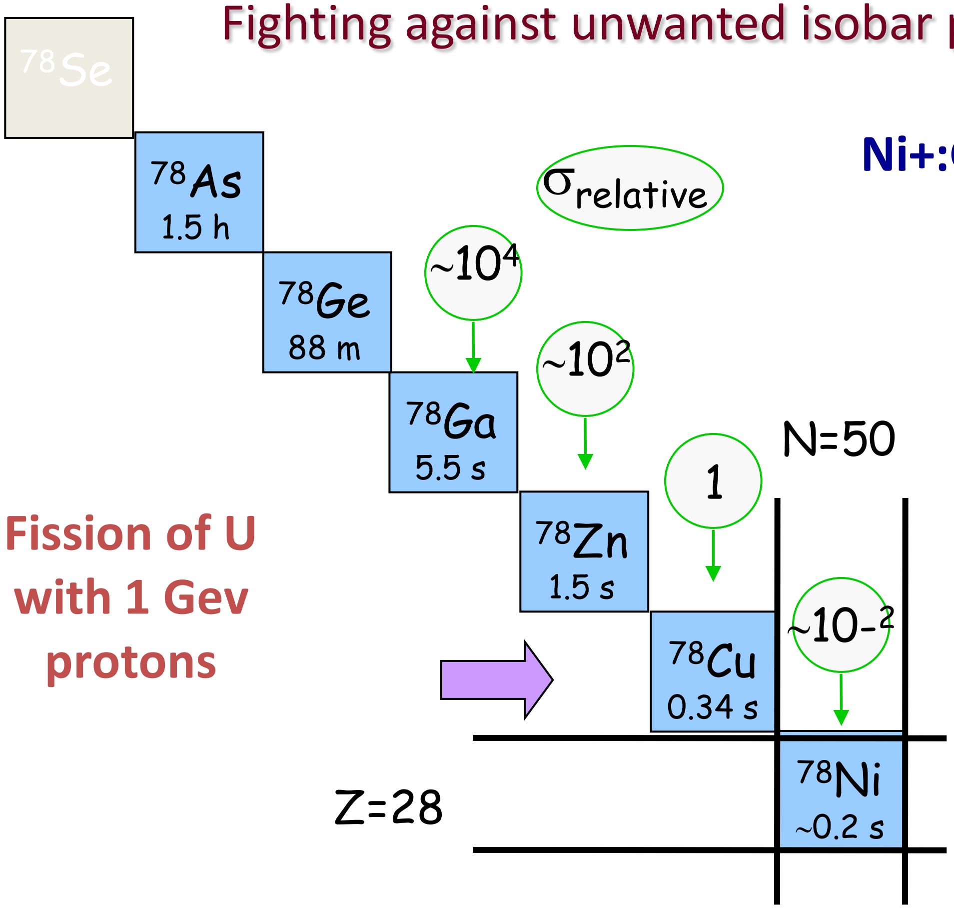


If we want a ^{132}**Sn** beam:

- Mass separation – huge ^{132}Cs contamination!
- Element selective ion source is essential
- Note the radioactive inventory:
  - Reducing isobars reduces transmission of unwanted activity!

J. Lettry, V. Fedoseev (CERN)

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



Fission of U with 1 Gev protons

Ni+:Ga+ ratio with surface ionization only:

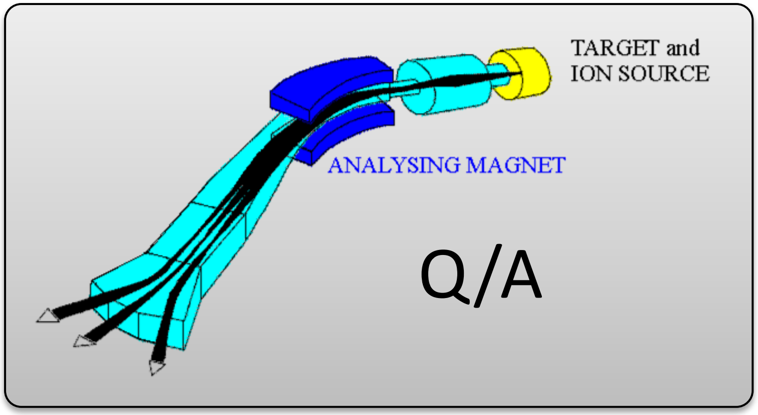
IP (Ga) = 5.99 eV IP (Ni) = 7.63 eV

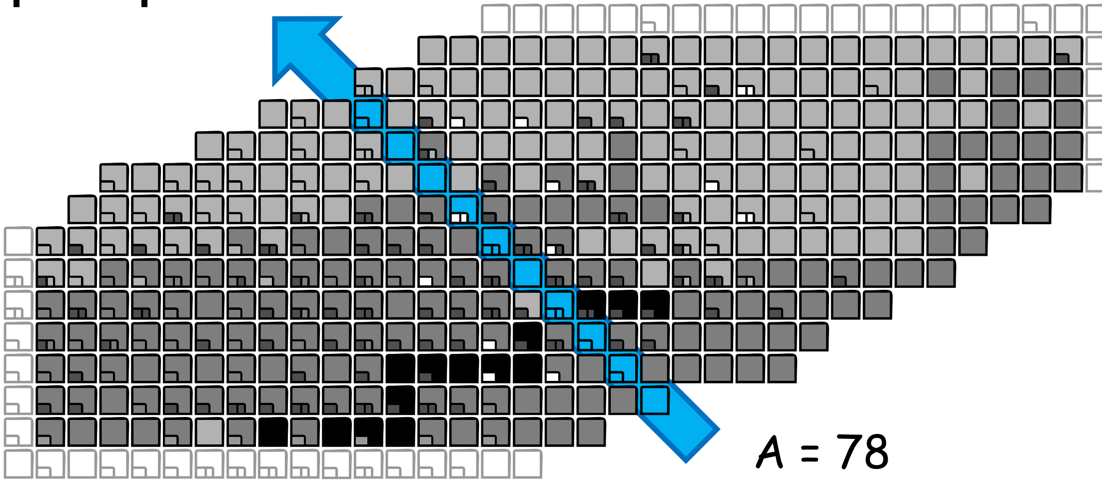
$$\alpha = \frac{n_i}{n_0} = \frac{\omega_i}{\omega_0}\exp\left(\frac{\Phi - W_i}{kT}\right)$$

Ga+:Ni+ > 10^6 !

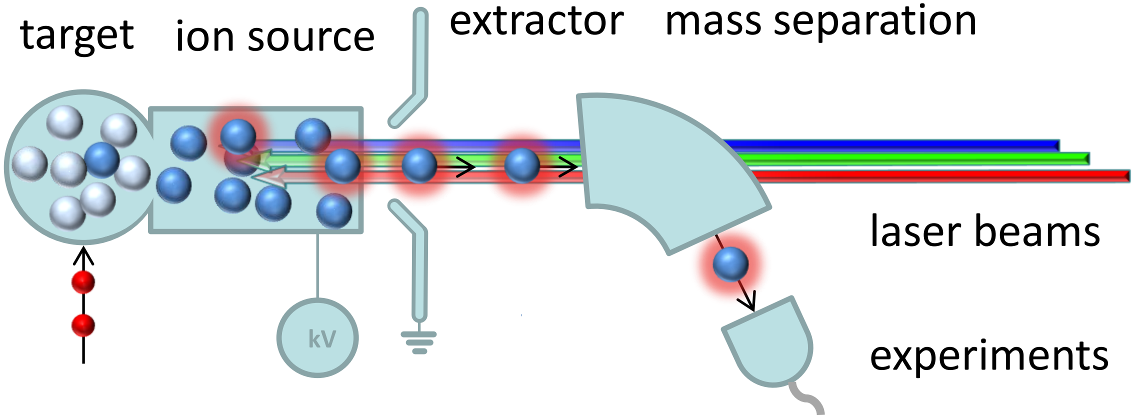
Need to selectively increase Ni ionization efficiency

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





The Resonance Ionization Laser Ion Source



target

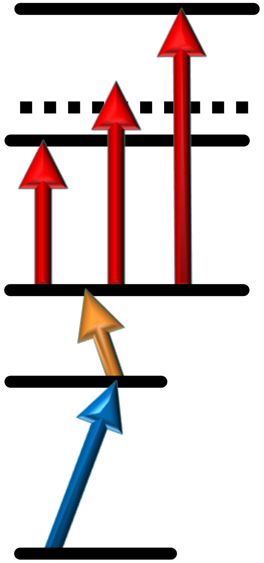
ion source

extractor

mass separation

laser beams

experiments



auto-ionizing state

ionization potential

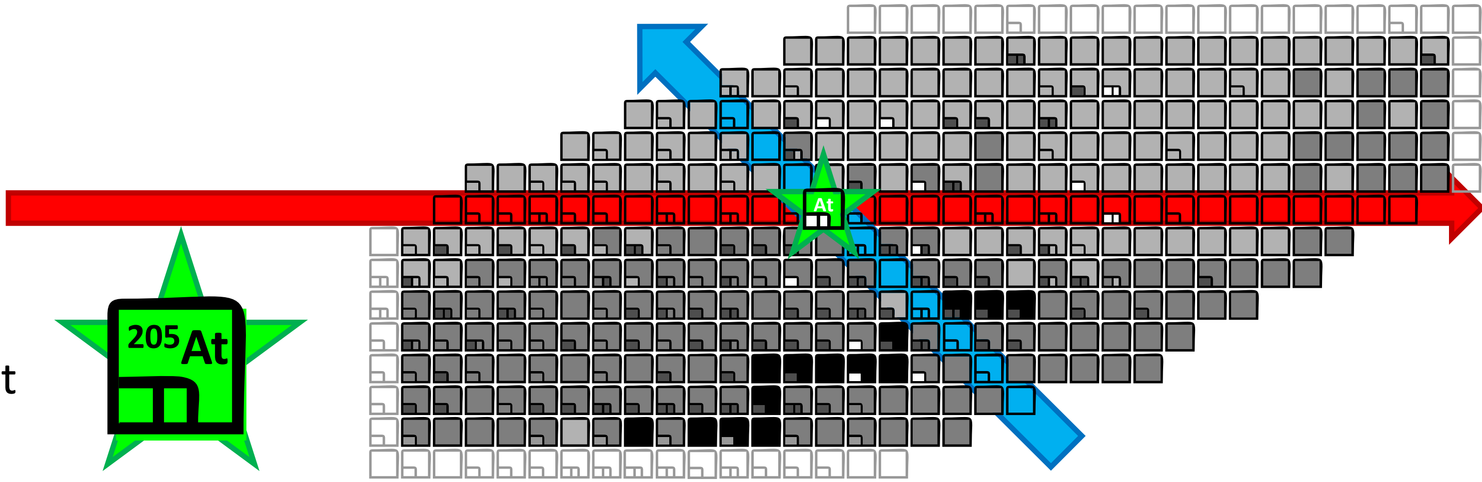
Rydberg state

excited states

ground State

● projectiles ● target material ● neutrals ● ions

Isotope of interest



RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

- 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 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:

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:

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

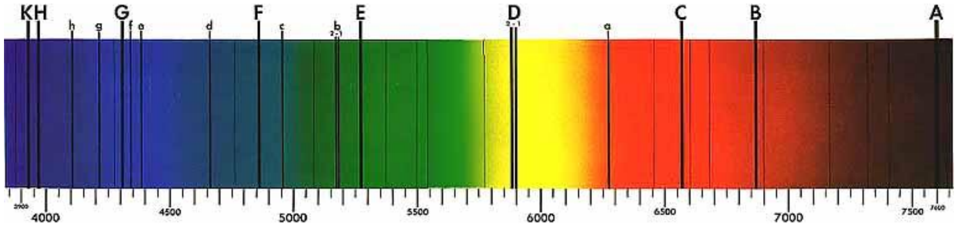
n.b., 1) photons are Bosons (*i.e.*, obey Bose-Einstein statistics)

2) photons have *helicity* (projection of angular momentum on the direction of travel) of ±1 only (*i.e.*, not 0)

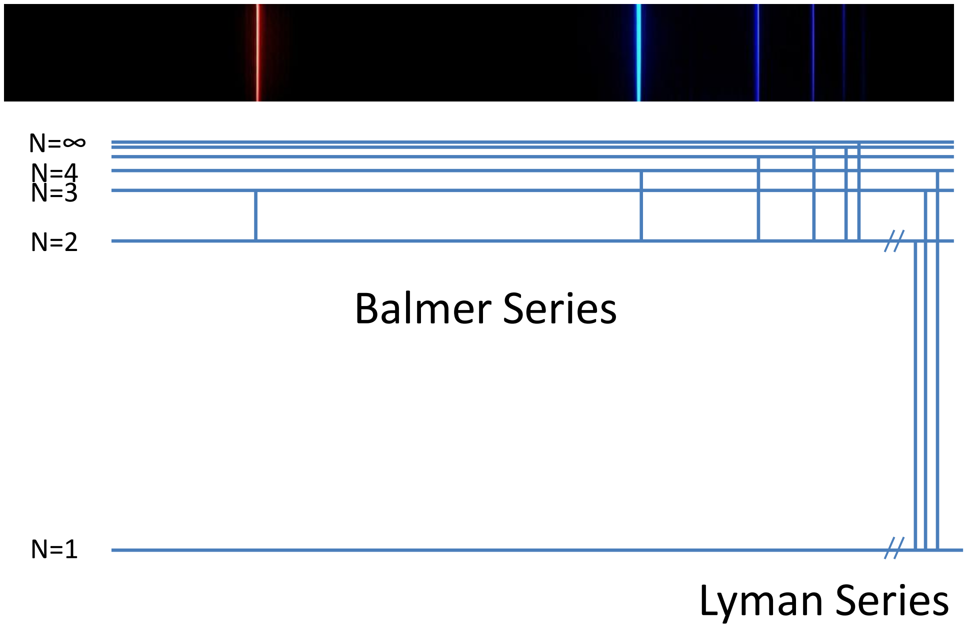
A Prelude to Atomic Spectroscopy

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.



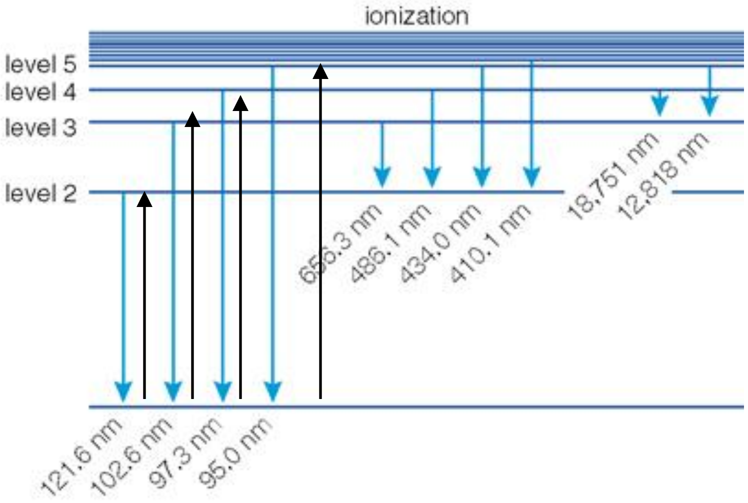
1859: Kirchhoff & Bunsen explain the dark lines in the solar spectrum in terms of absorption by elements in the Sun’s surface.
1885: J. Balmer describes the series of lines atomic hydrogen.



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

The atomic line spectra is an element’s fingerprint

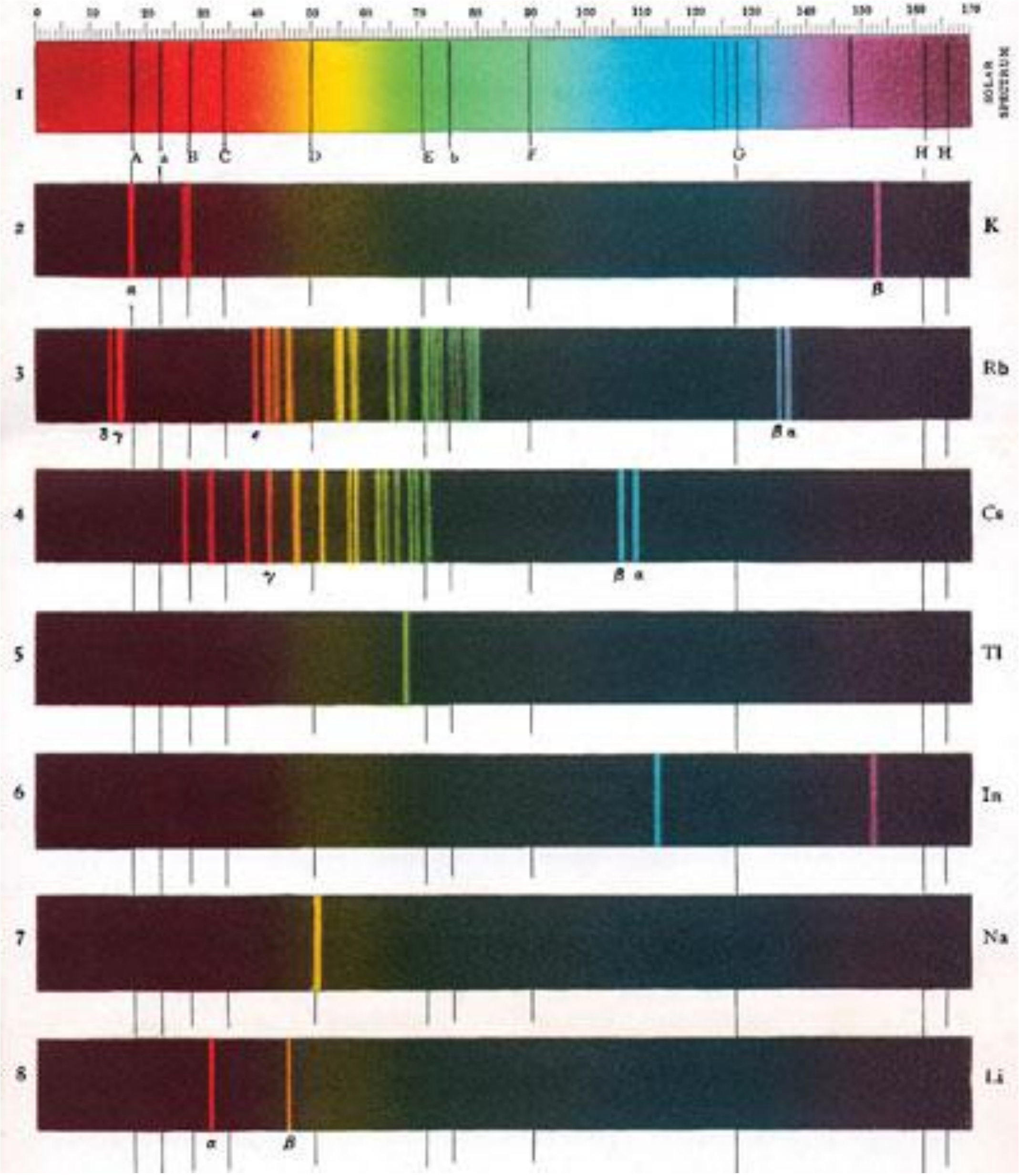
- Electron transitions between *energy levels* result in emission or absorption lines.
- The spectral position of these lines are determined by the structure of the atom.
- Every chemical element therefore has its own unique spectral *fingerprint*.
- **Example:** In astronomy the chemical composition 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.



Emission spectrum of Hydrogen

Absorption spectrum of Hydrogen

The atomic line spectra is an element’s fingerprint

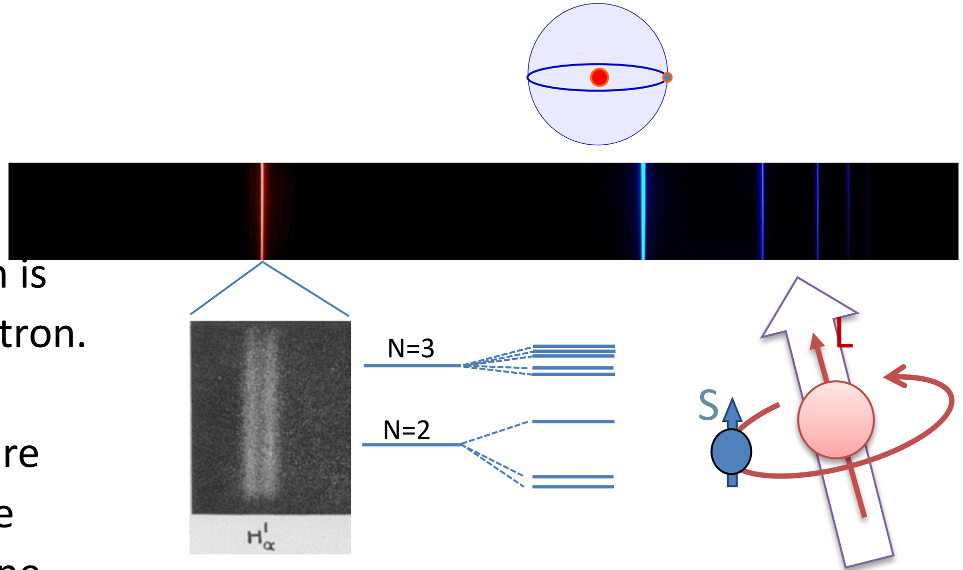


Higher Resolution

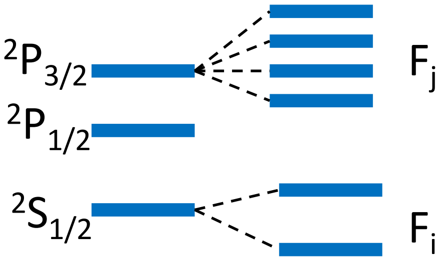
- By increasing the resolution by a factor of ~5000 a fine structure splitting of the hydrogen is observed: key evidence for the spin of the electron.

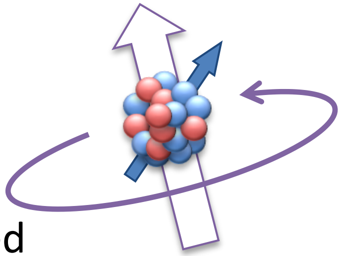
- A further factor of 1000 zoom into the structure reveals finer splitting due to the coupling of the nucleus with the electronic orbital: the hyperfine structure.

- 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.

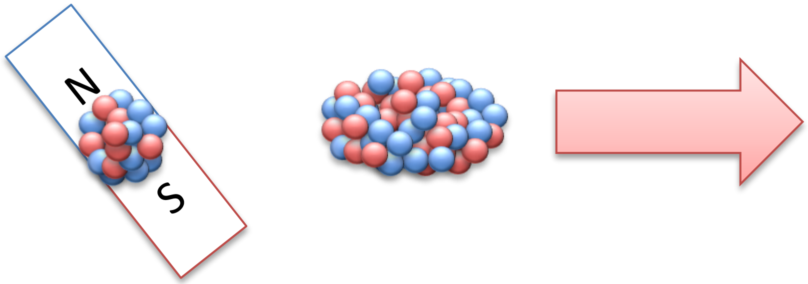


J=L+S



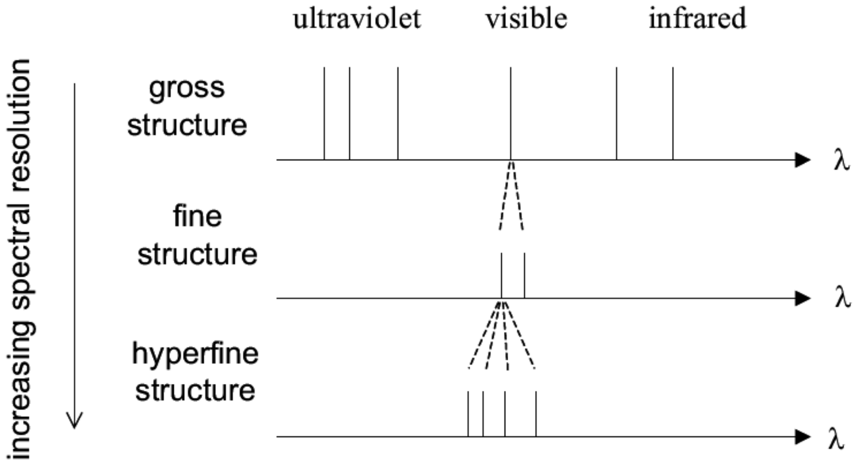


F=J+I



Note – Relevant for part 5 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.

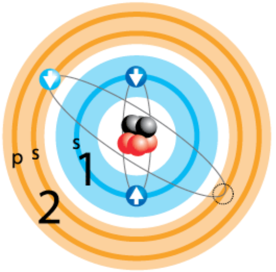
Atomic Energy Scales



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

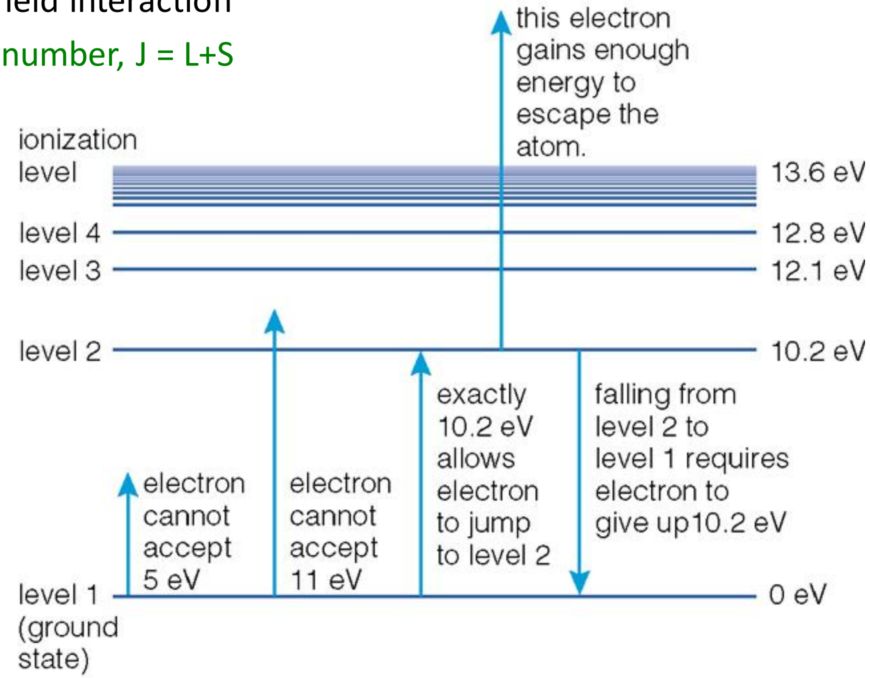
How can a photon affect the electron configuration?

- 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 excited state in an atom?
  - Nuclear charge (coulomb): potential energy: inversely proportional to distance from nucleus
    → **Principal quantum number, n** (1, 2, 3….)
  - Electron-electron interactions → (spin alignment s=±1/2; multiplicity: 2S+1)
  - Electron orbital angular momentum → L (labelled, S, P, D, F for 0,1,2,3)
  - Spin-orbit interaction: electron spin/induced magnetic field interaction
    →Total (orbital + spin) angular momentum quantum number, J = L+S

- 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)



Describing an electronic energy level

- The Term Symbol for LS coupling

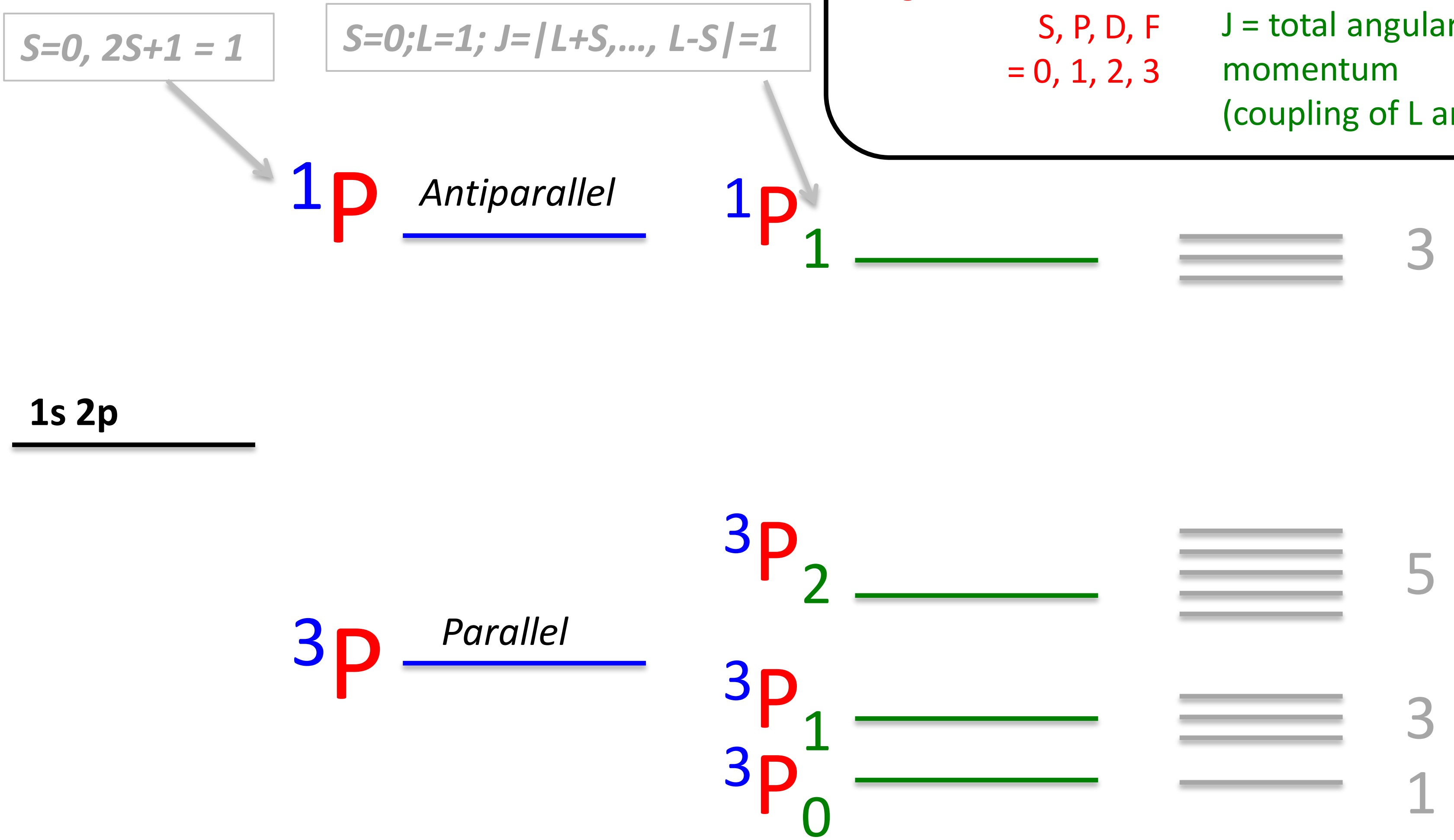
Term symbol

Multiplicity = 2S+1

$^{3}P_{2}$

L, total orbital angular momentum
S, P, D, F
= 0, 1, 2, 3

J = total angular momentum
(coupling of L and S)



S=0, 2S+1 = 1

S=0;L=1; J=|L+S,…, L-S|=1

1s 2p

^{1}P *Antiparallel*

^{3}P *Parallel*

$^{1}P_{1}$ 3

$^{3}P_{2}$ 5

$^{3}P_{1}$ 3

$^{3}P_{0}$ 1

Electron configuration

Electronic spin Correlation 2S+1

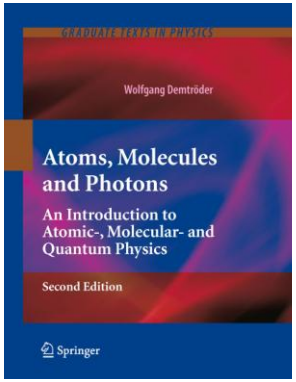
Different L, S combinations

Magnetic coupling of L and S

Spin-Orbit coupling, unique J

States (2J+1)
Degenerate without external field

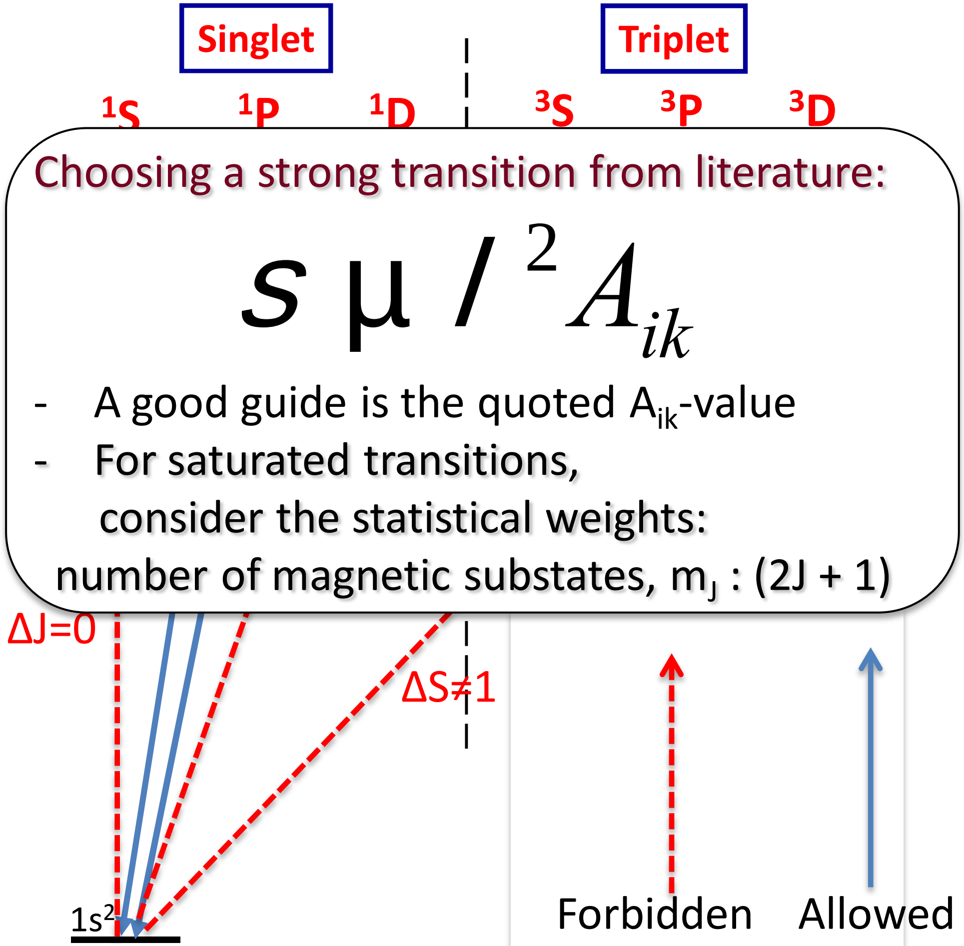
Selection rules for atomic transitions



It is not enough to ensure only energy conservation:

- Conservation of angular momentum
- Obey symmetry rules.

The origins of the selection rules are described in most atomic physics textbooks



Choosing a strong transition from literature:

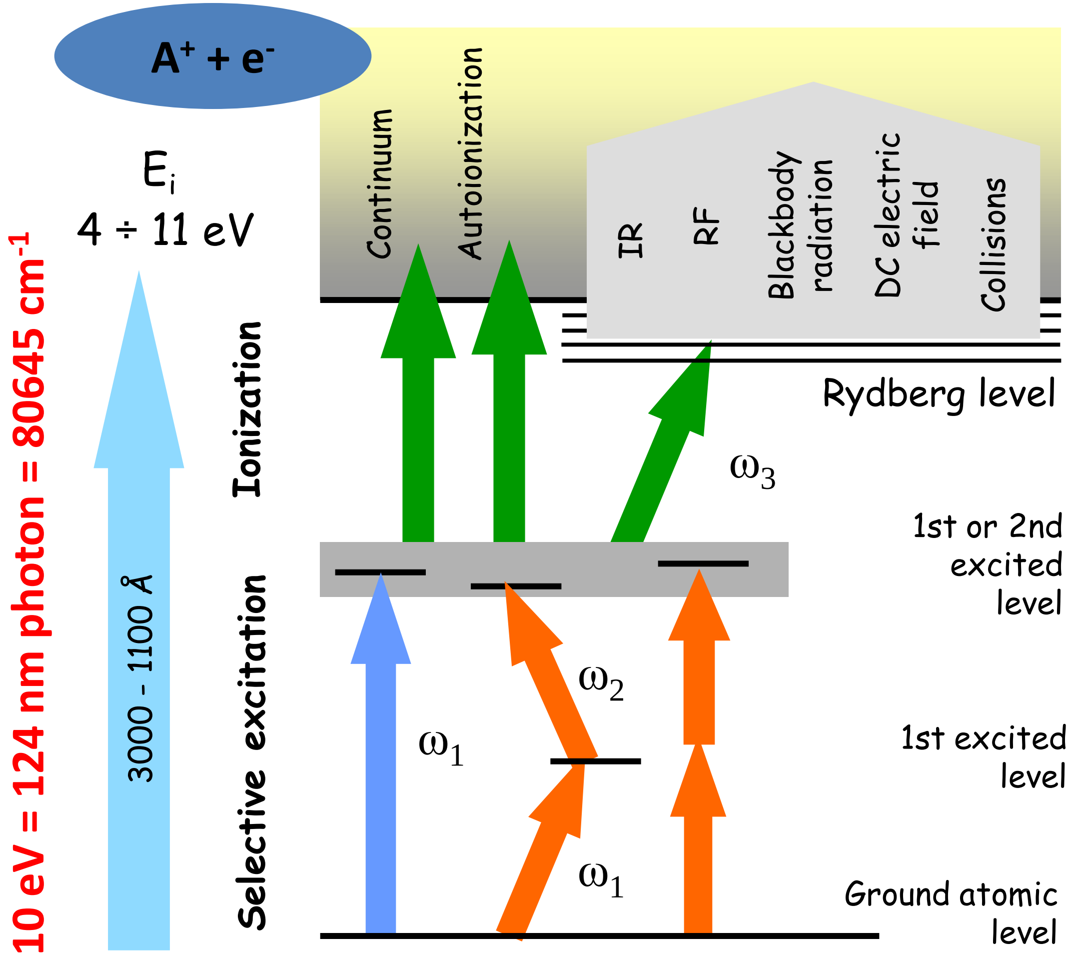
$$s\ \mu\ /\ ^{2}A_{ik}$$

- A good guide is the quoted A_{ik}-value
- For saturated transitions, consider the statistical weights:

number of magnetic substates, m_J : (2J + 1)

Selection rule	Remark
$\Delta l = \pm 1$ for one-electron systems	Strictly valid
$\Delta L = \pm 1$ for multi electron systems with $\boldsymbol{L}$-$\boldsymbol{S}$-coupling	Gerade levels are solely combined with ungerade levels
$\Delta M = 0, \pm 1$	$\Delta M = 0$: linear polarized light $\Delta M = \pm 1$: σ^+ or σ^- circularly polarized light
$\Delta S = 0$	Valid for light atoms. Exceptions for heavy atoms with large spin-orbit coupling (weak Intercombination lines)
$\Delta J = 0, \pm 1$	$J = 0 \rightarrow J = 0$ is forbidden

Laser ion source – using this fingerprint for selective ionization

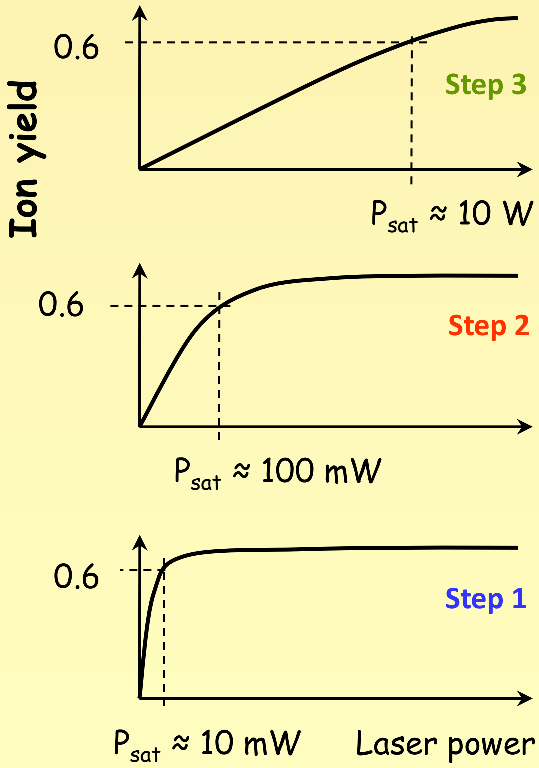


$\omega_i(\text{laser}) = \omega_i(\text{atom})$; $P_i(\text{laser}) \geq P_i(\text{saturation})$

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

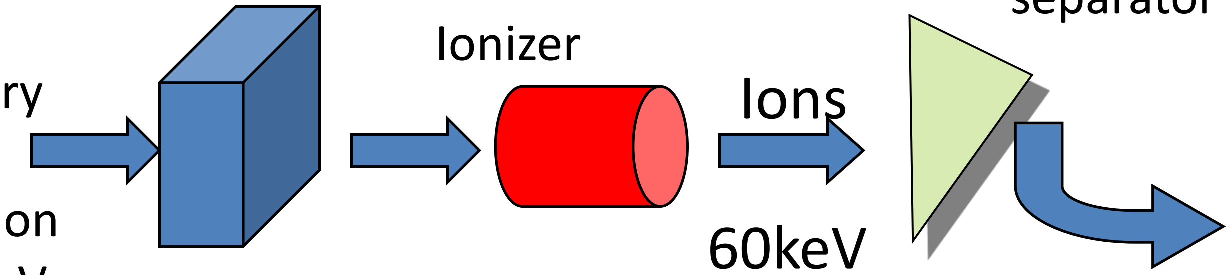
$\mathcal{E}_{sat.} = \hbar\omega_i/2\sigma_i$

$f_{laser} = 10$ kHz $Ø_{laser} = 3$ mm



Rare isotope production methods compatible with laser ion sources

ISOL



Primary
Beam
Light ion
(1.4GeV
protons)

Thick Target

Ionizer

Ions

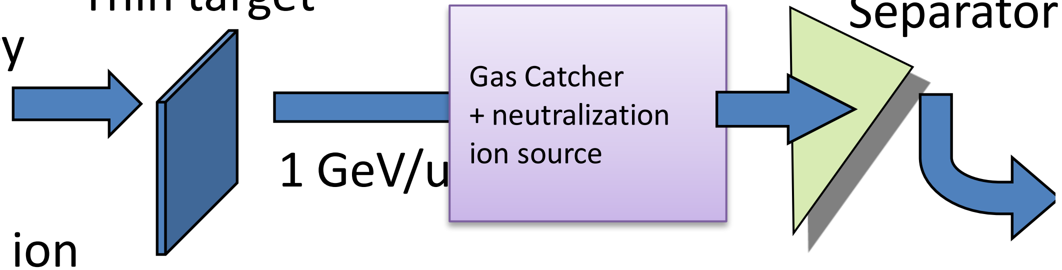
60keV

Electromagnetic
separator

Low-energy
High-quality
Chemistry

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

In-Flight Fragmentation (GSI)



Primary
Beam

heavy ion
1 GeV/u

Thin target

1 GeV/u

Gas Catcher
+ neutralization
ion source

Electromagnetic
Separator

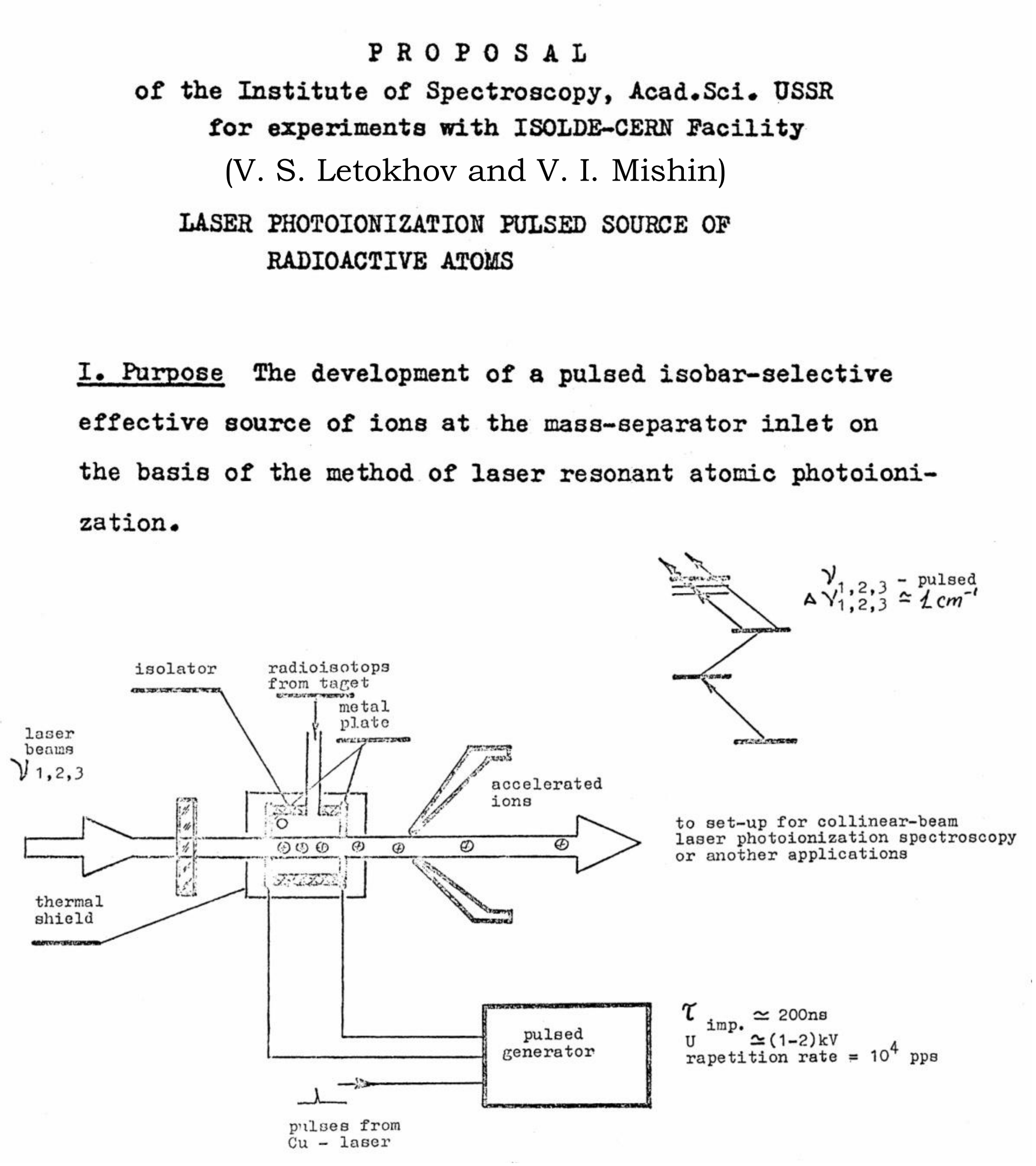
Low-energy
High-quality

Limits $t_{1/2}$ ~ µs
Low intensitie

3) History of the laser ion source

RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

Early proposals: 1984

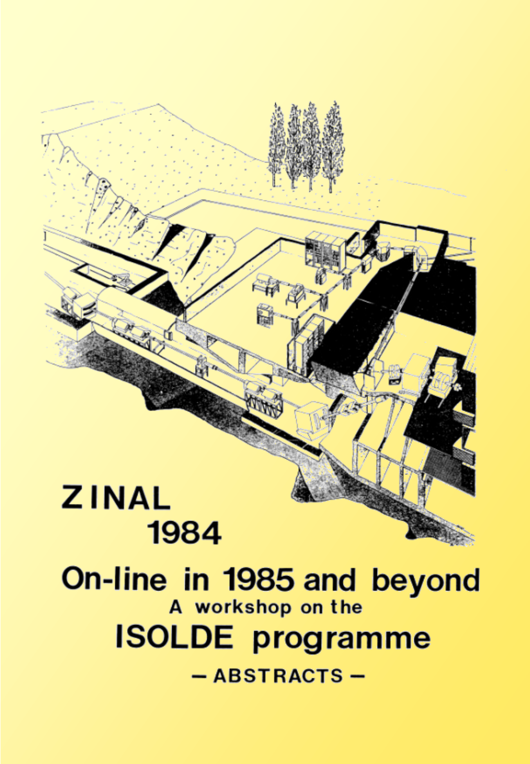


PROPOSAL

of the Institute of Spectroscopy, Acad.Sci. USSR
for experiments with ISOLDE-CERN Facility
(V. S. Letokhov and V. I. Mishin)

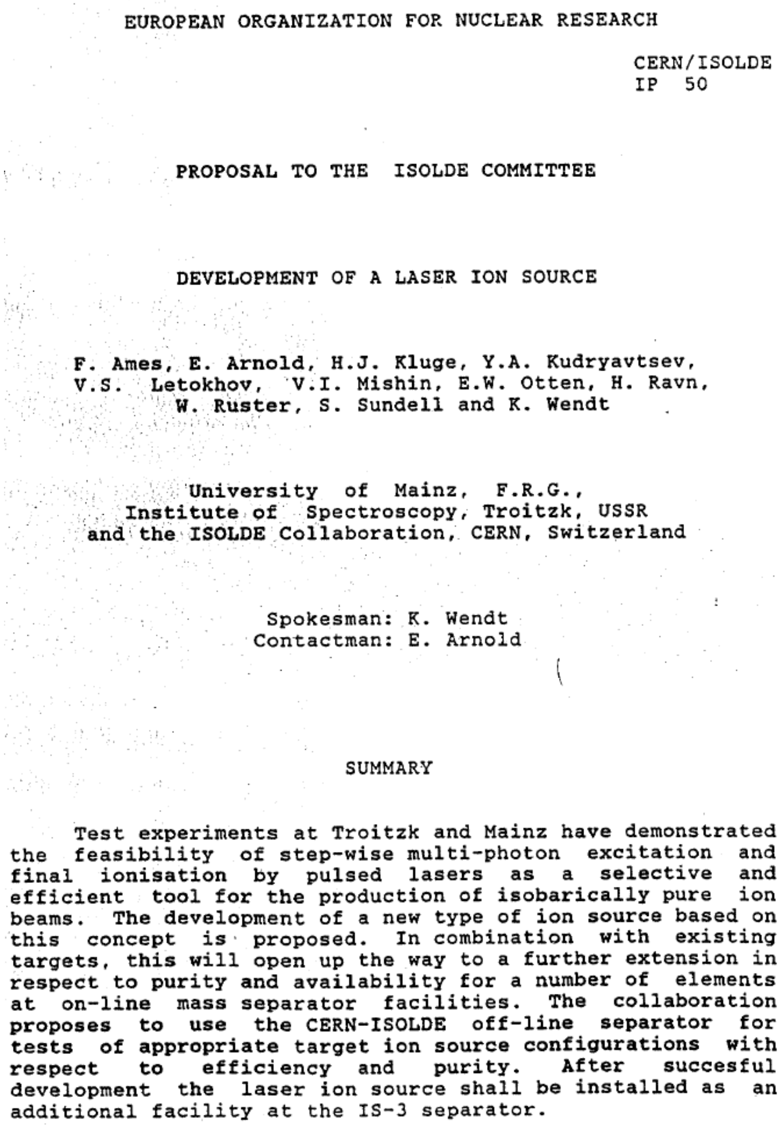
LASER PHOTOIONIZATION PULSED SOURCE OF
RADIOACTIVE ATOMS

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.



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.

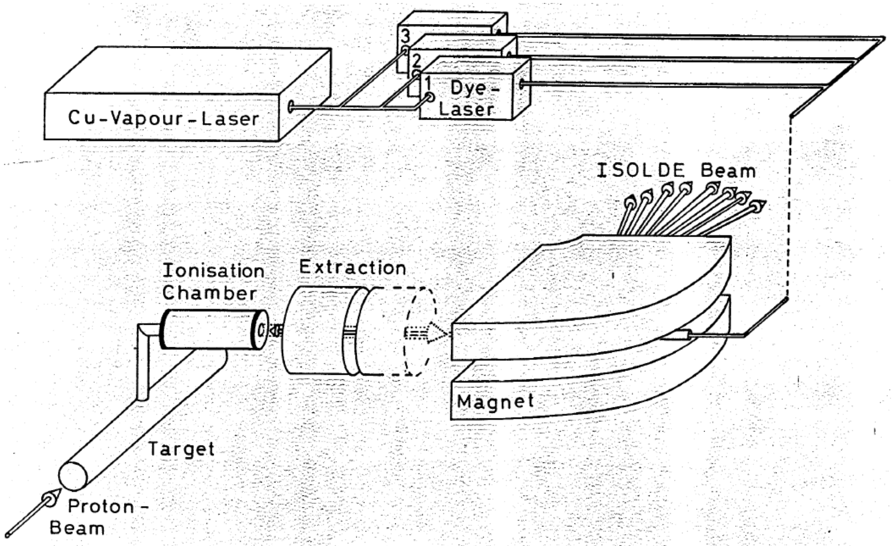
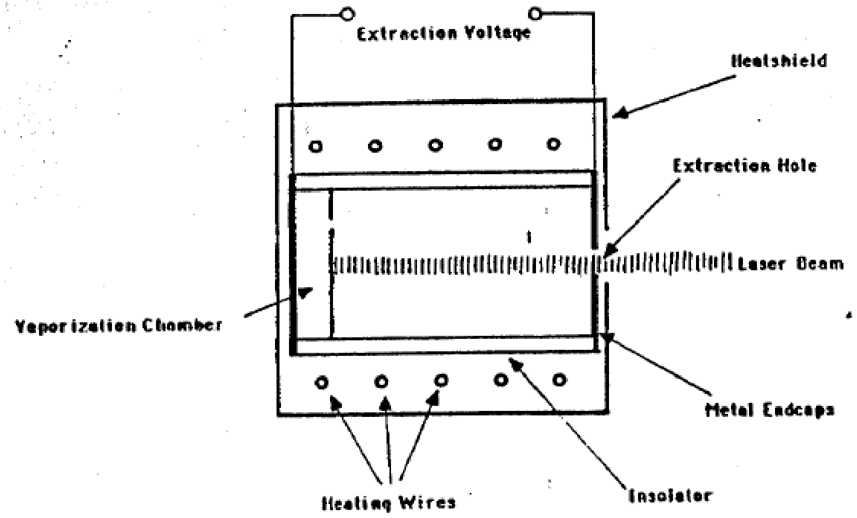


Fig. 5: General layout of the experimental set-up at the off-line separator



Ionization in a hot metal cavity

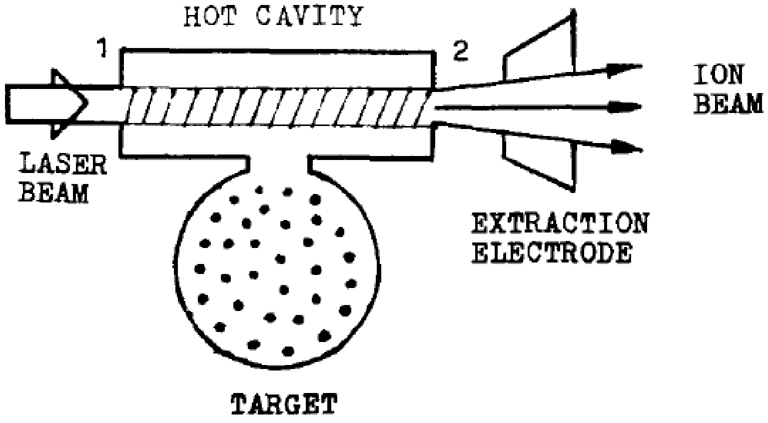
Nuclear Instruments and Methods in Physics Research A306 (1991) 400–402

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

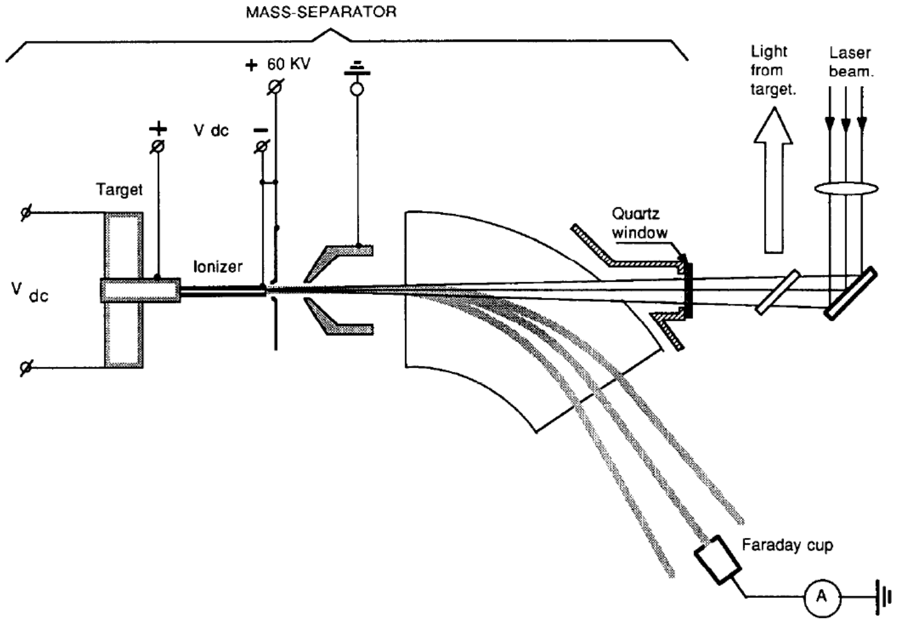
Nuclear Instruments and Methods in Physics Research B73 (1993) 550–560

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

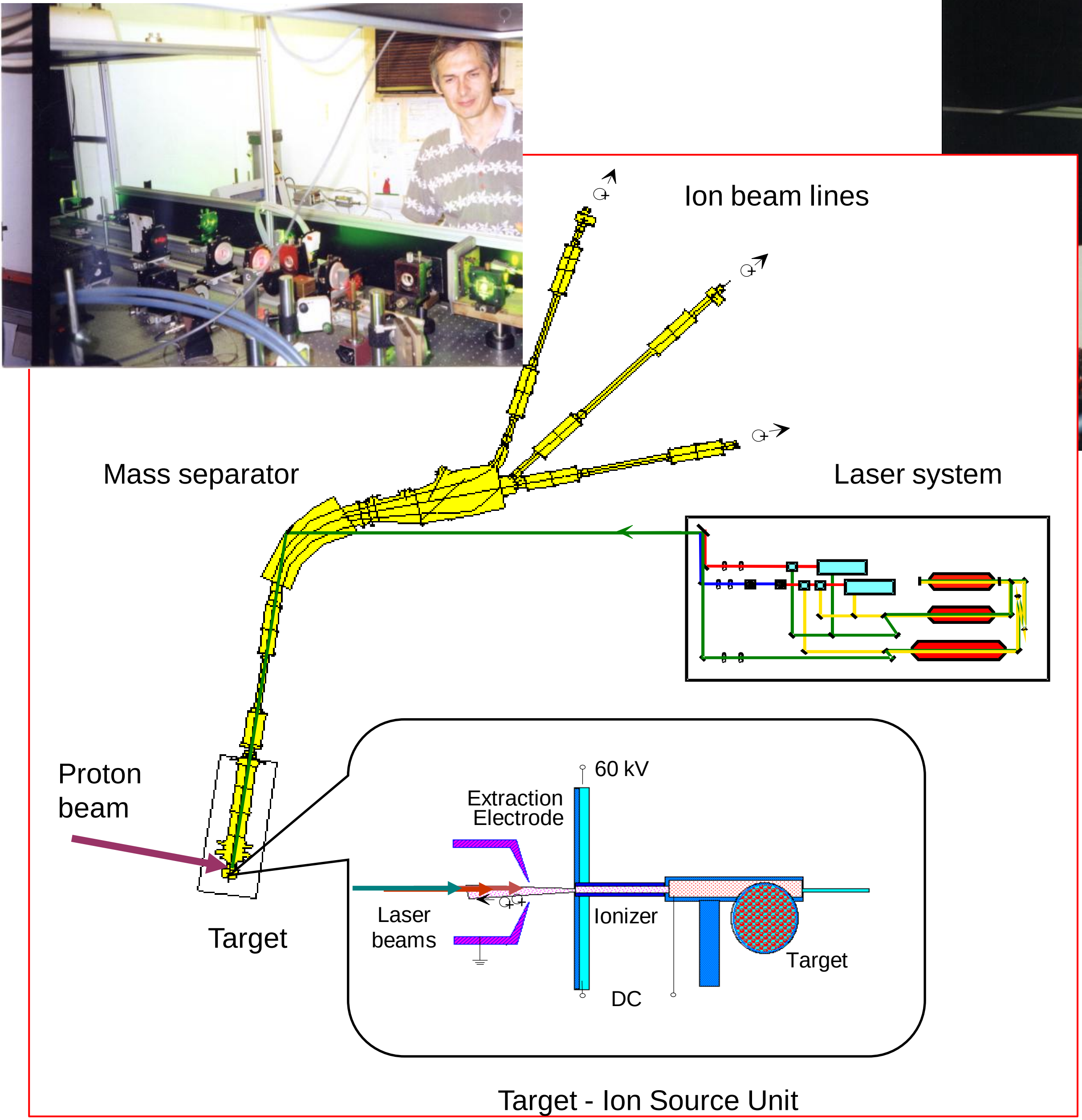
PPE Division, CERN, Geneva, Switzerland

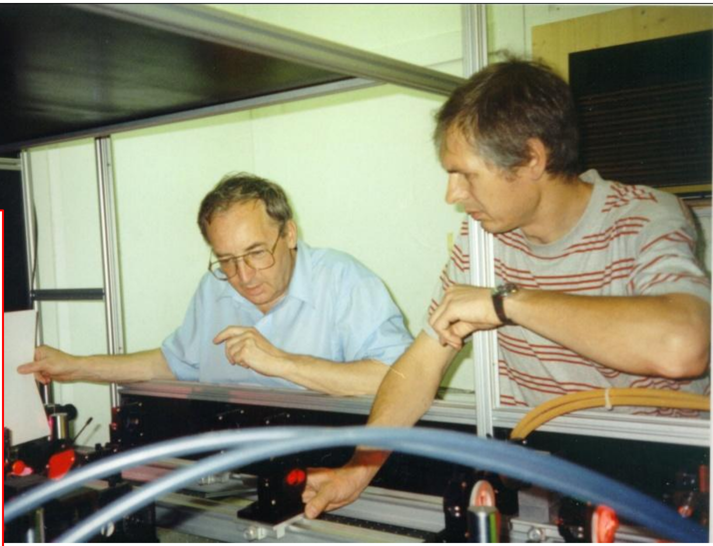
Received 26 November 1992



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

RILIS at ISOLDE-PSB





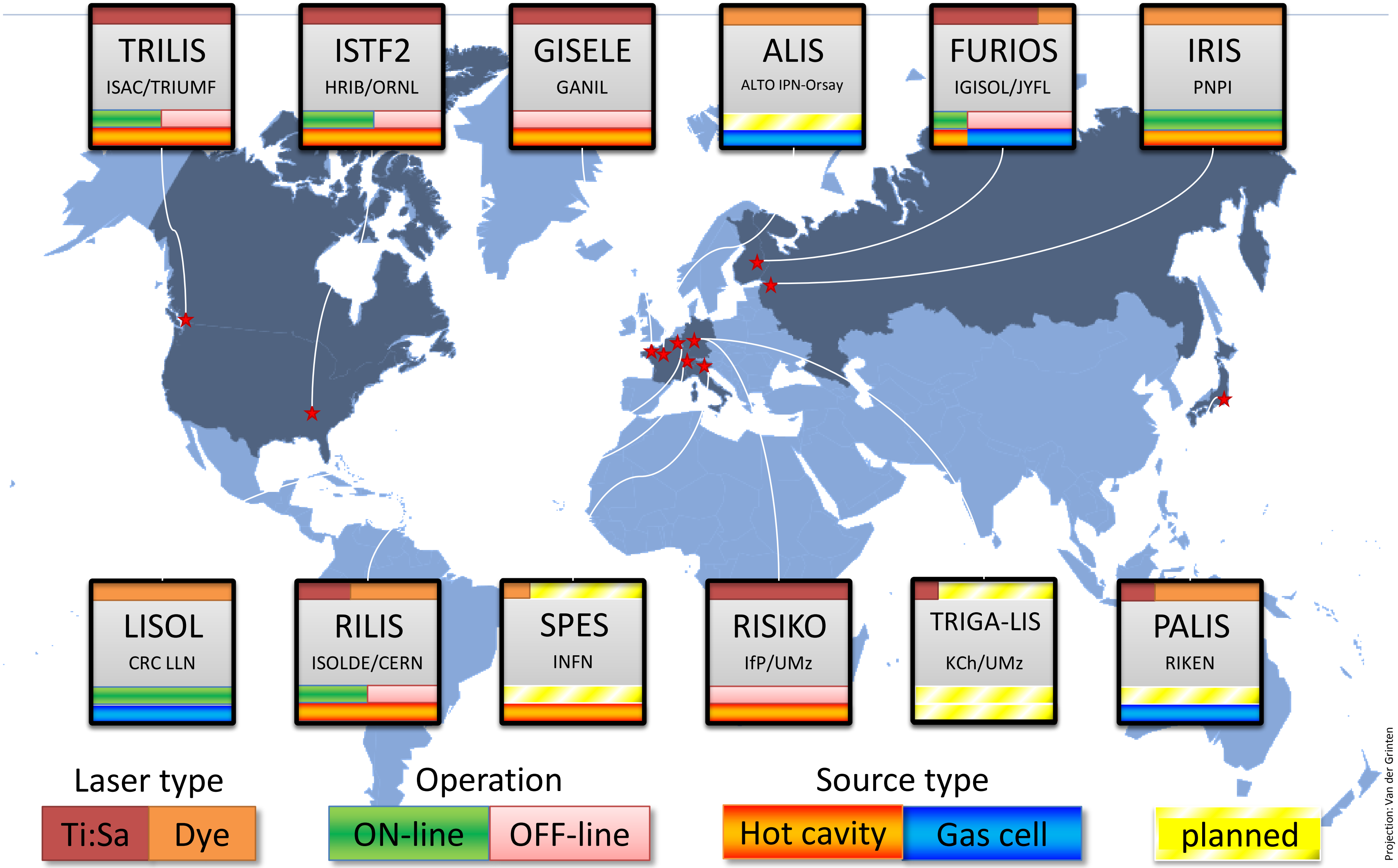
CVL lasers: ν_{rep}=11.000 Hz
Oscillator + 2 amplifiers
2-3 dye lasers with amplifiers,
nonlinear crystals BBO:

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

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

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

Resonance Ionization Laser Ion Sources Worldwide



TRILIS
ISAC/TRIUMF

ISTF2
HRIB/ORNL

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

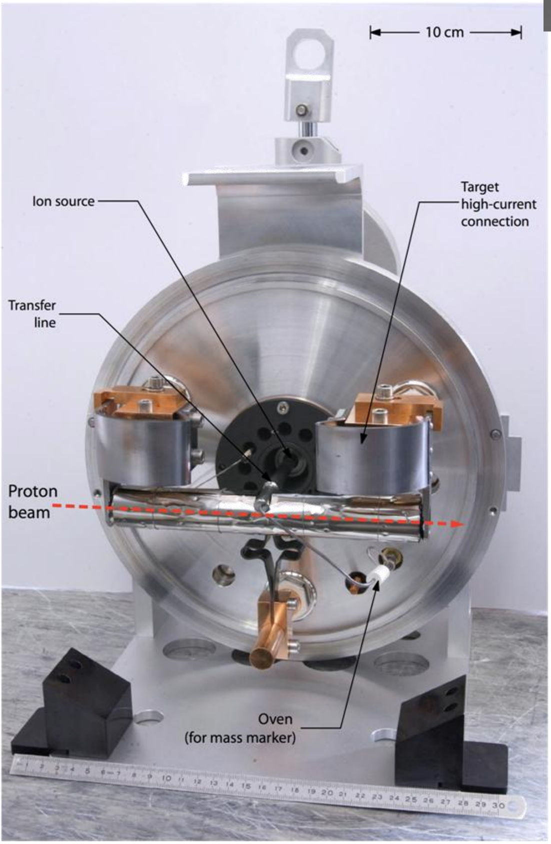
Slide: S. Rothe

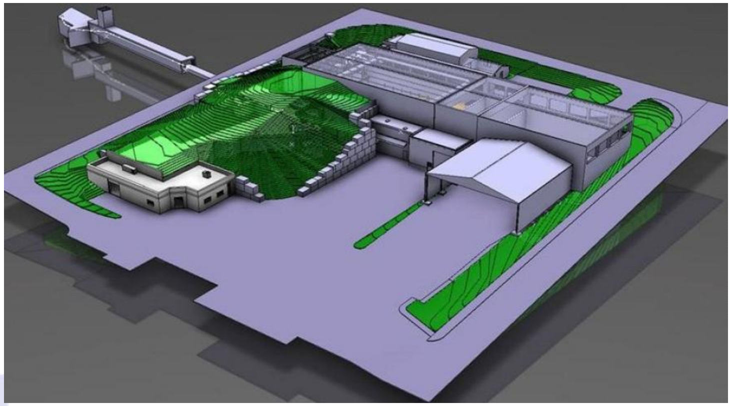
RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

- **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

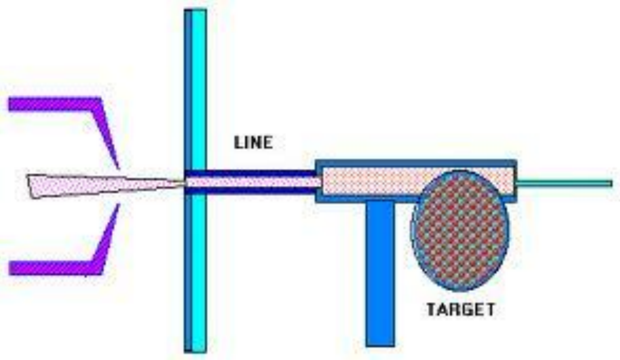
What is the optimal laser ion source configuration for ISOLDE?





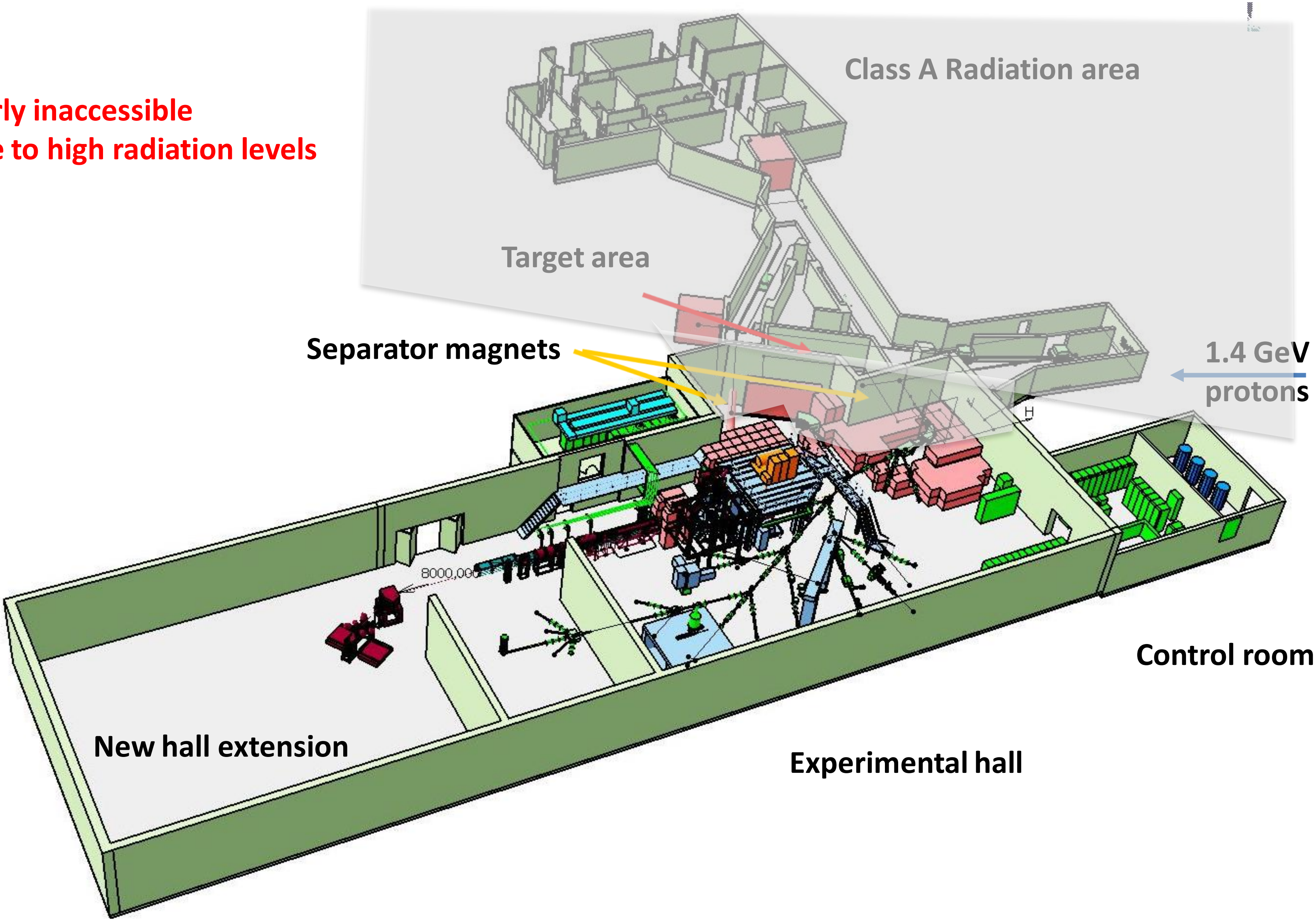
Requested features:

- Universal
- Selective
- Efficient
- Reliable
- Fast



The ISOLDE Laboratory

Fairly inaccessible
due to high radiation levels



Class A Radiation area

Target area

Separator magnets

1.4 GeV protons

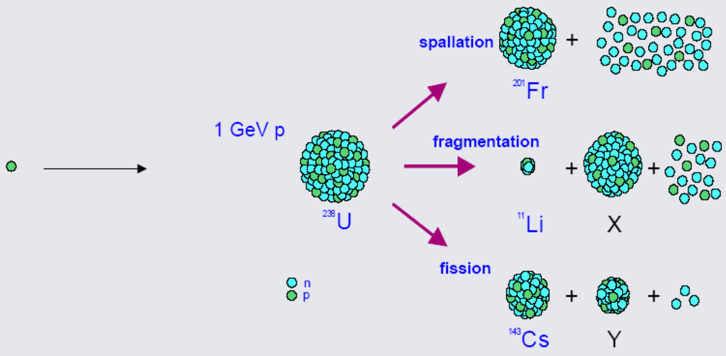
Control room

Experimental hall

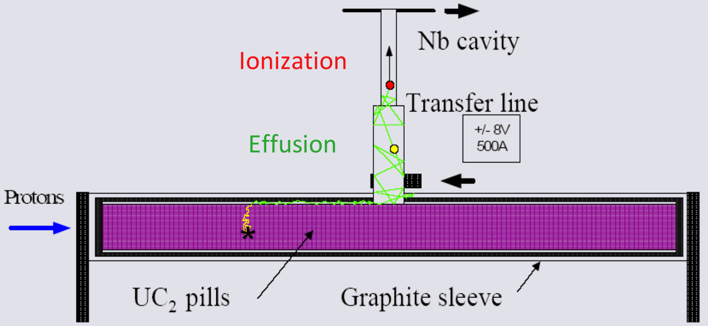
New hall extension

What are we trying to achieve:

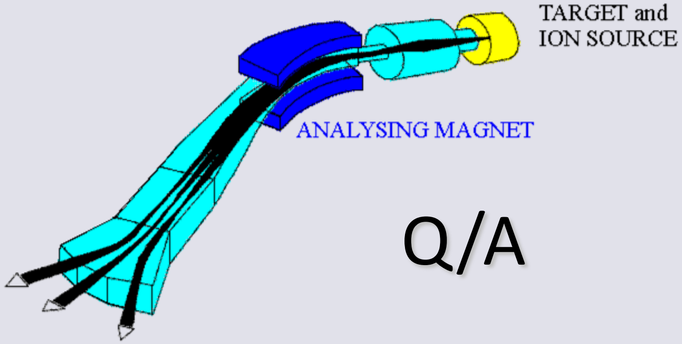
Production



Extraction/Ionization

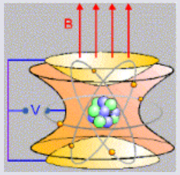


Isotope Separation



Q/A

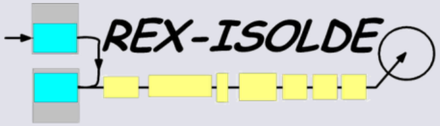
Post acceleration or to Experiment

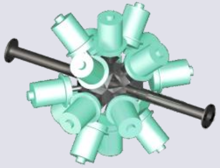


ISOLTRAP

Collaps

Collinear Laser Spectroscopy





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

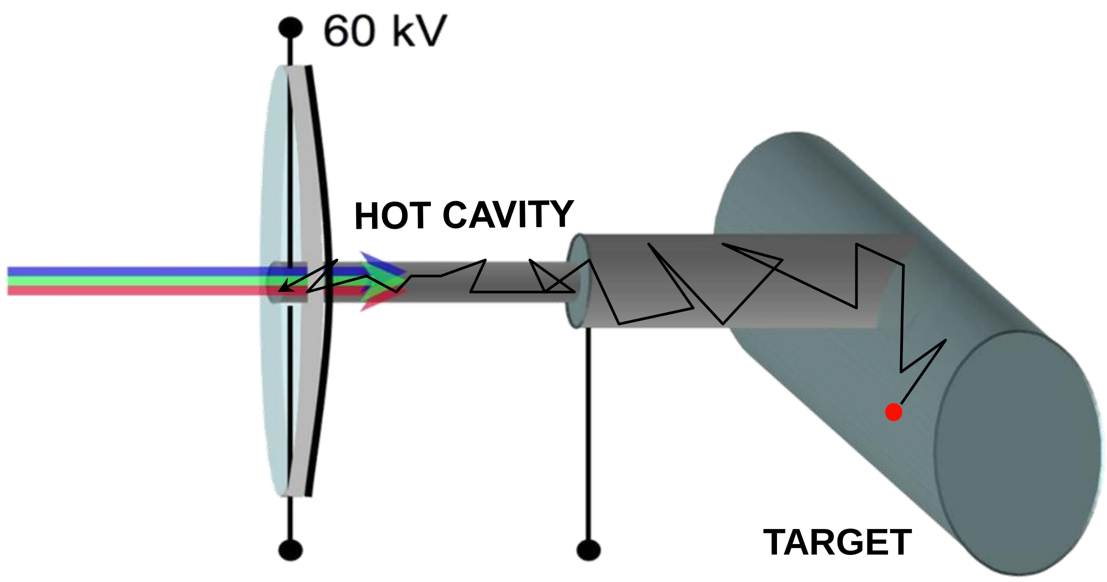
Universality → Applicable to many elements

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

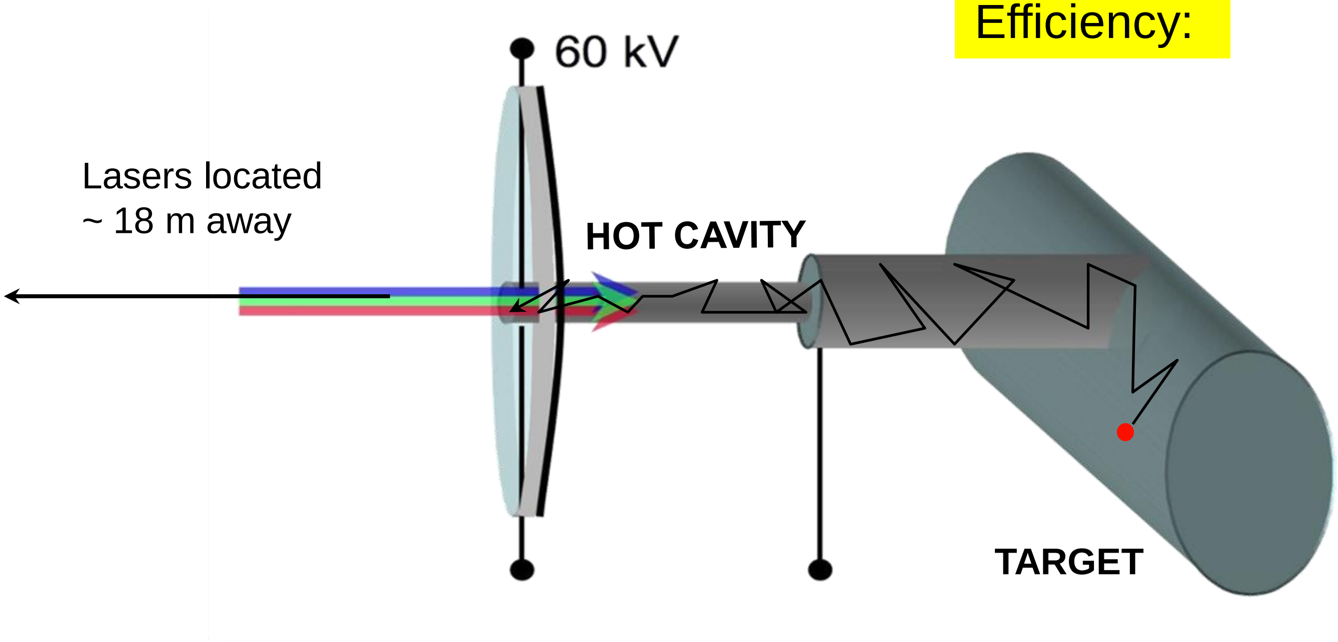
- A good laser /atom interaction region?



The Hot Cavity Laser Ion Source

Efficiency:

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



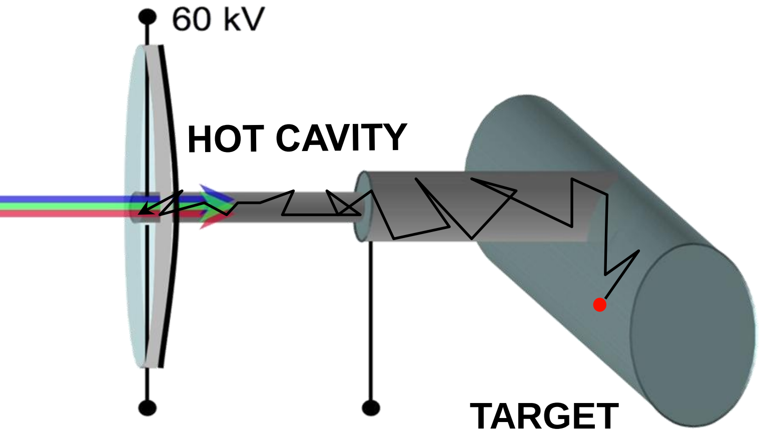
$\varepsilon_{\text{laser}}$ **= 2% - 30%**

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

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

=> depends on the ionization potentials of isobar atoms

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



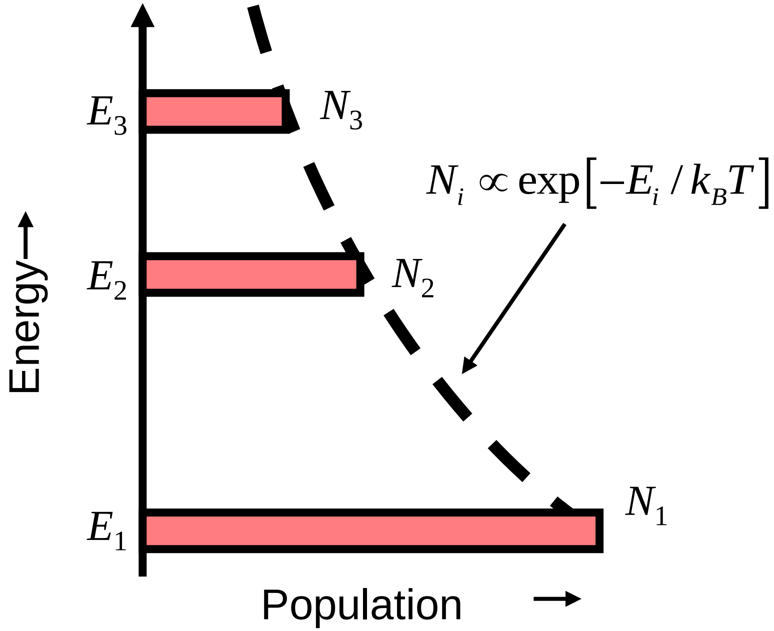
- Effusion time → Laser repetition rate
- High temperature → Laser linewidth atomic transitions
- Electron emission → Extraction efficiency
- Surface ionization → Selectivity

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



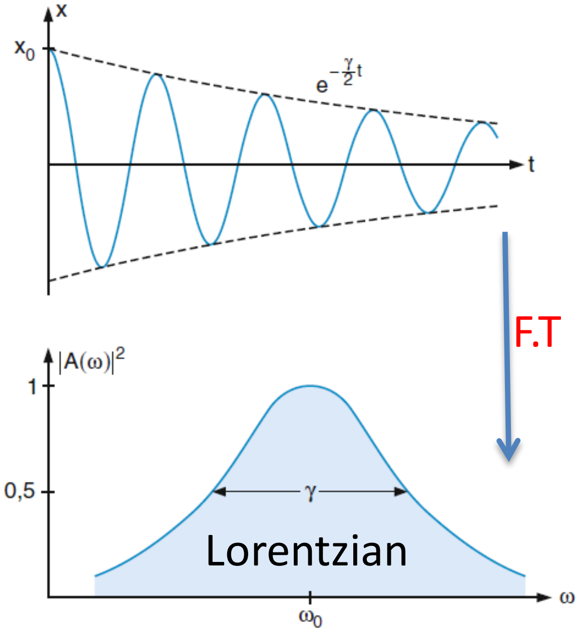
Broadening mechanisms: Natural Linewidth

Uncertainty principle:

$$\Delta E \Delta t = \frac{\hbar}{2}$$

Determined by the *spontaneous emission* lifetime of the state

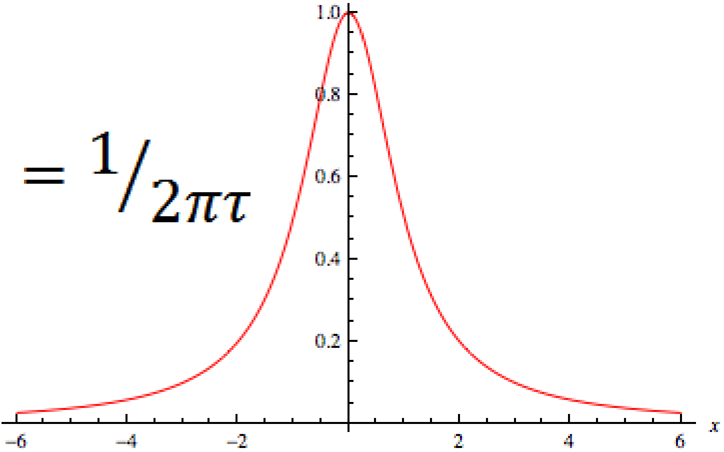
Classical analogy: treat the excited electron as a damped harmonic oscillator



Natural linewidth has Lorentzian shape:

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

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



EXAMPLE

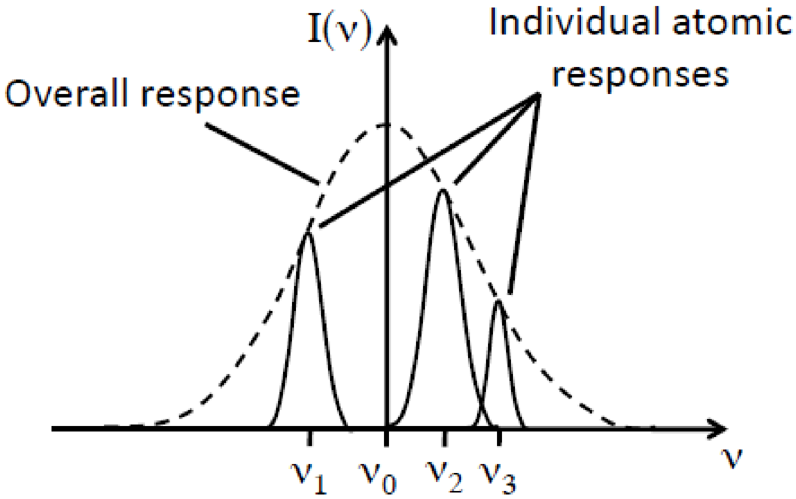
Na D-line 3P1/2 → 3S1/2 transition with a sponteneous emission lifetime of 16 ns

$$Natural\ linewidth, \delta_n = 10^{-9}/16\times 2\pi \approx 10\ MHz$$

Doppler broadening

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

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



$\delta\nu_{D\ \mathrm{is}}$ proportional to $\nu_{0,}$ $T^{1/2}$, $m^{-1/2}$

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 therefore leads to a broadening:

$$\Delta\upsilon_D = \upsilon_0 \frac{\Delta v}{c}$$

The result is a Gaussian distribution with

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

or

$$dn_D = 7.16\times10^{-7} n_0\sqrt{T/m}\ \ (Hz)$$

EXAMPLE

Na *(m = 23g/mol)* D-line 3P1/2 → 3S1/2 transition with a sponteneous emission lifetime of 16 ns;
λ = 589.1 nm ; T = 500 K; $\delta\nu_n$=10 MHz

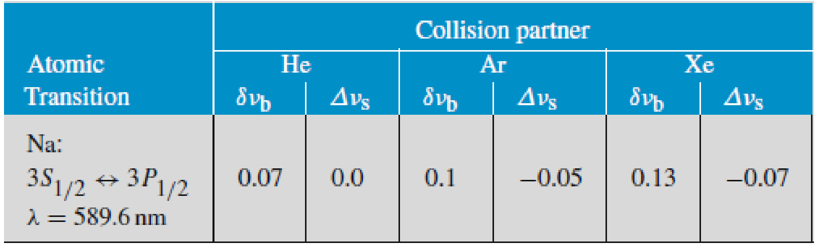
$$dn_D = 7.16\times10^{-7}\times(c/(539.1\times10^{-9})\times\sqrt{500/23} = 1.7\,GHz$$

The Doppler broadening is often comparable to or greater than HFS or IS effects!

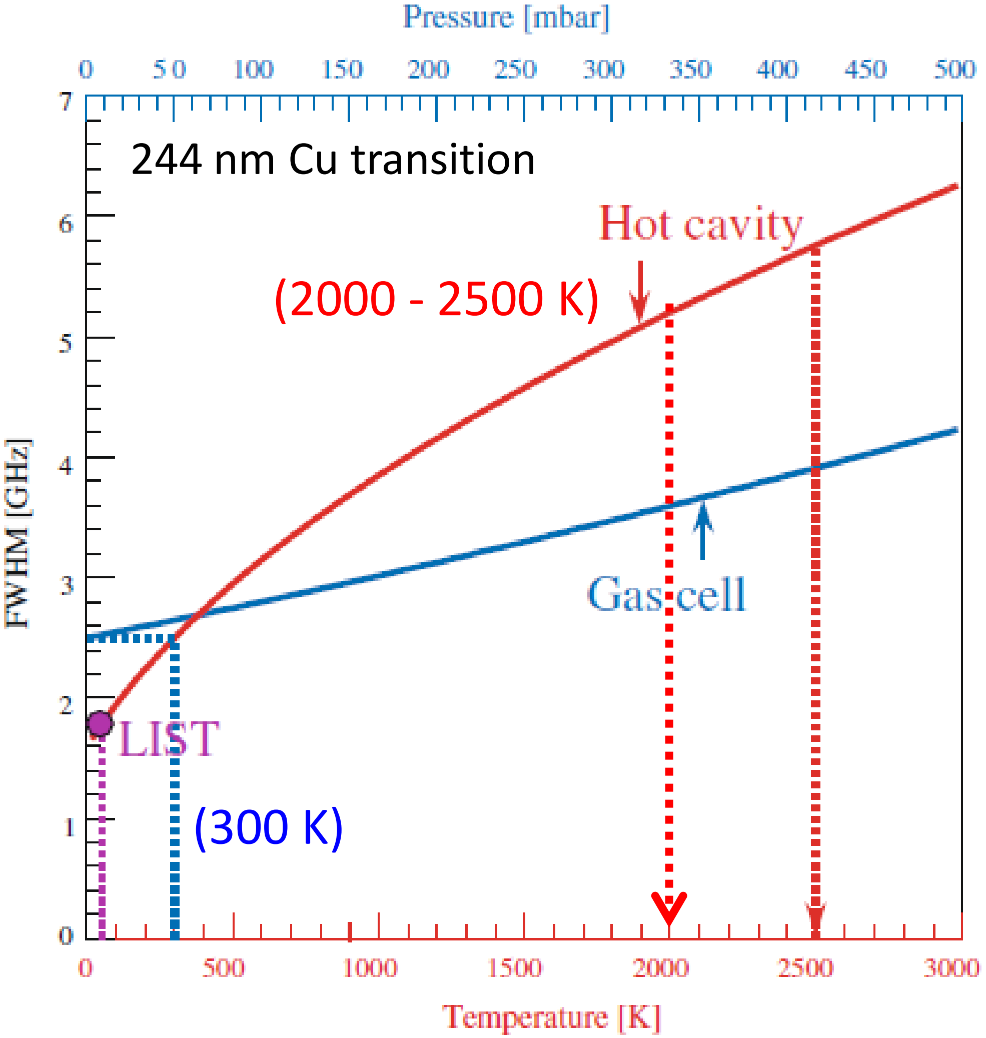
Pressure or collisional broadening: Hot cavity vs Gas cell

At high pressure both elastic and inelastic collisions occur

elastic	inelastic
Phase changes	energy loss (damping)
Frequency shift $\delta\nu_s$	Shorter lifetime
	Broadening, $\delta\nu_b$



Atomic Transition	Collision partner					
	He		Ar		Xe	
	$\delta\nu_b$	$\Delta\nu_s$	$\delta\nu_b$	$\Delta\nu_s$	$\delta\nu_b$	$\Delta\nu_s$
Na: $3S_{1/2} \leftrightarrow 3P_{1/2}$ $\lambda = 589.6$ nm	0.07	0.0	0.1	−0.05	0.13	−0.07



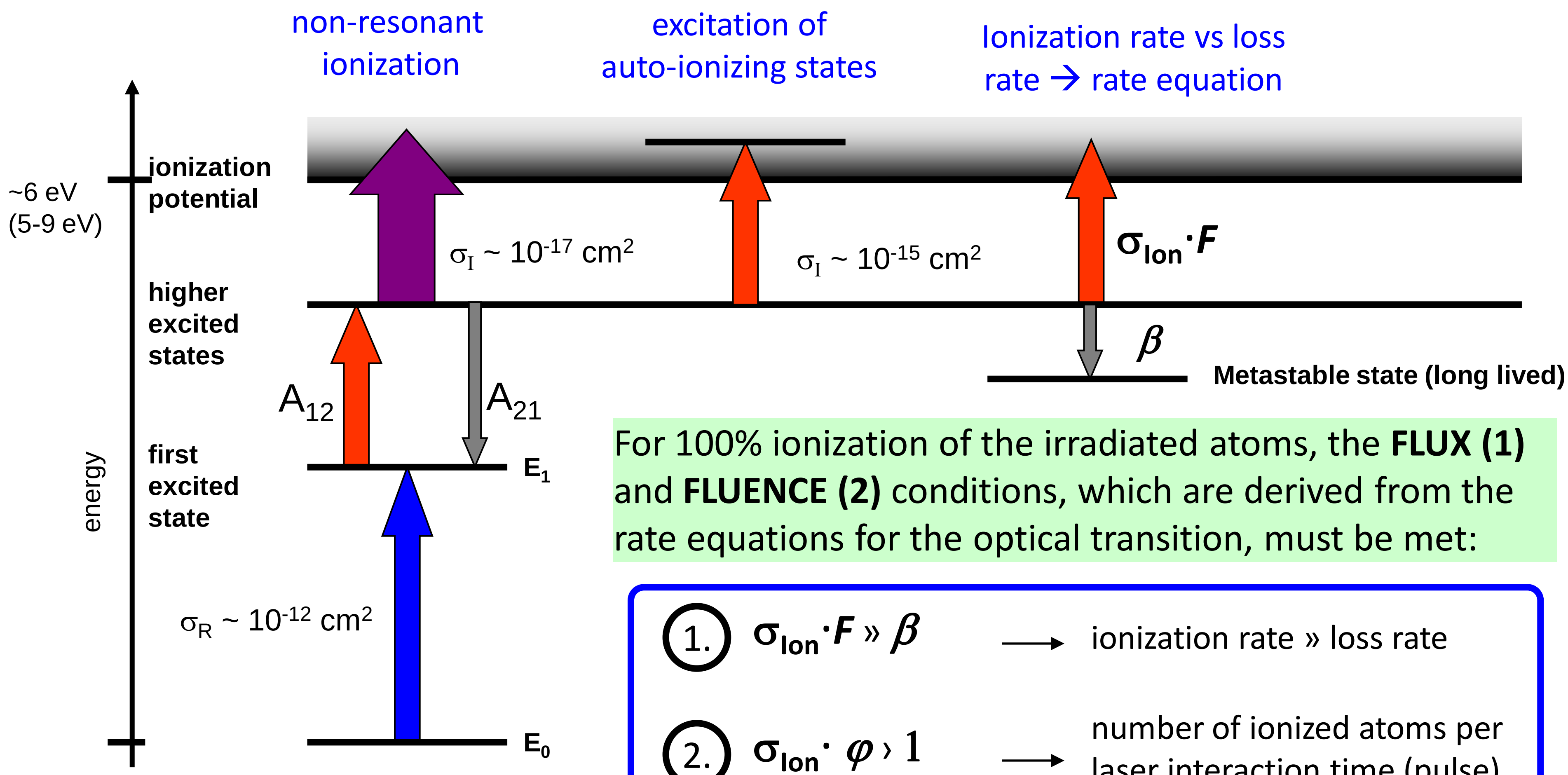
Doppler broadening

Pressure broadening

Ionization outside the gas cell:

Expanding gas jet is cold and has low pressure

Resolution in gas jet limited by laser bandwidth



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

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

σ_{Ion}	ionization cross section (non-resonant) (cm²)
β	loss rates to (metastable) states etc, state dependent
F	photon flux ($cm^{-2}\ s^{-1}$) *(photons per unit area per second)*
φ	Fluence = Flux **x** interaction time) *(photons per unit area*)

What do these conditions mean for the laser power for a non resonant ionization step?

typical values:

$\sigma_{ion} \longrightarrow 10^{-17}$ cm²

$\beta \longrightarrow 10^{6}\ s^{-1}$

For simplicity and to have a safe margin lets assume a laser beam area of 10 mm² and a photon energy of 3 eV.

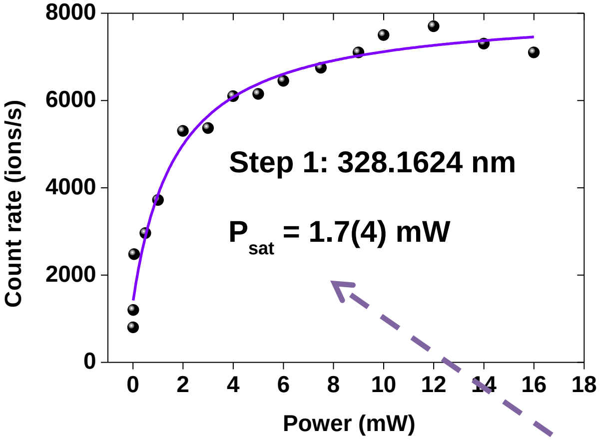
3 eV photons *(2.33 eV = 532 nm)*

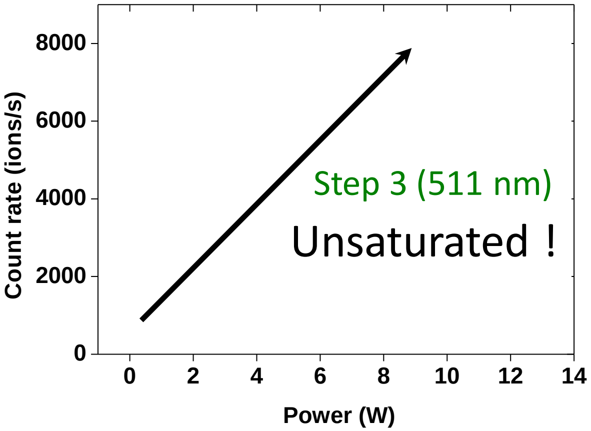
From (1): Flux F >> 10^{24} $cm^{-2}s^{-1}$
→ # photons required >> 10^{22} /s → >> 5000 W
Impossible with CW laser !!

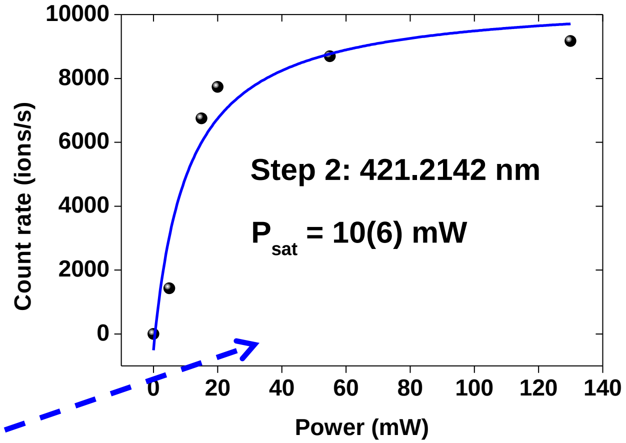
But with a pulsed laser system:
Typical pulse length is 10 ns. → >> 50 µJ/pulse
No problem !!

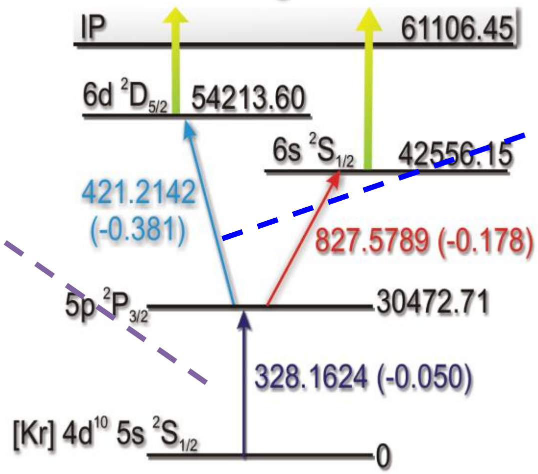
But with the limited laser interaction time **Fluence (2)** condition becomes more difficult → > 5 mJ/pulse
(>50 W at 10kHz!)

Ex.: Ag ionization







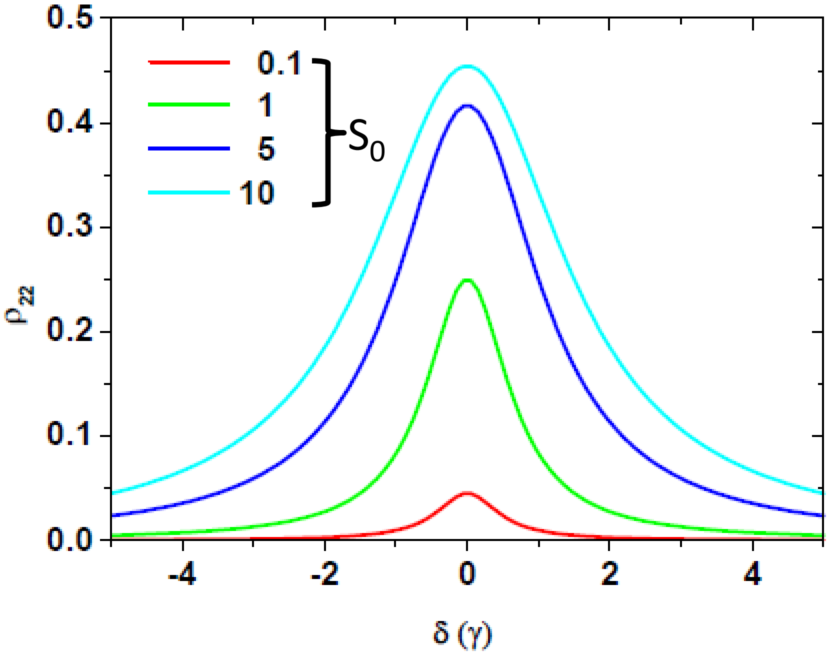


How does the degree of saturation influence the efficiency or required precision of laser tuning ?

Resonant saturation parameter:

$S_0 = I/I_{sat}$

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



For Doppler free laser spectroscopy

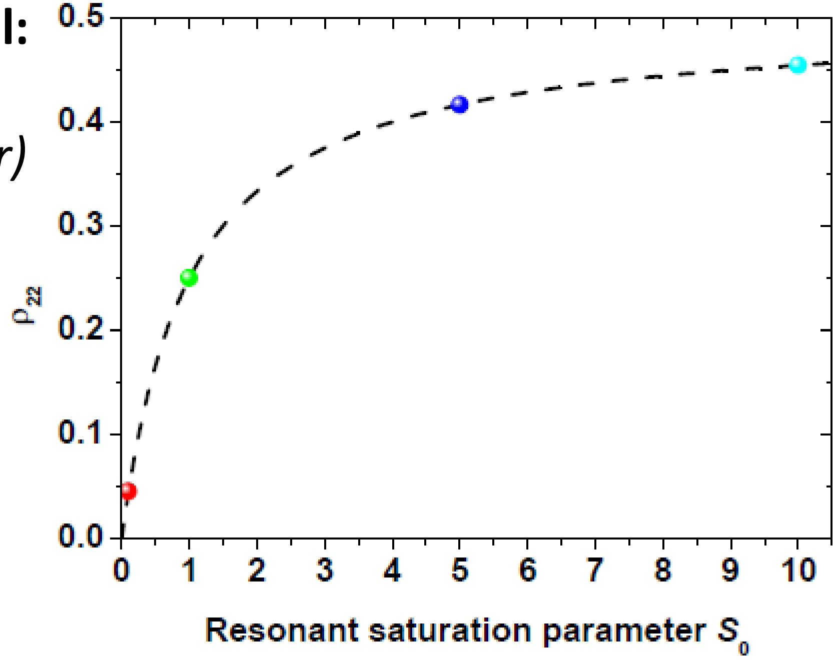
(Lecture by J. Billowes):

Saturation/efficiency trade off

For RILIS efficiency in Hot Cavity or Gas cell:

Saturation is preferred

(unless we aim for isomer separation – later)



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).

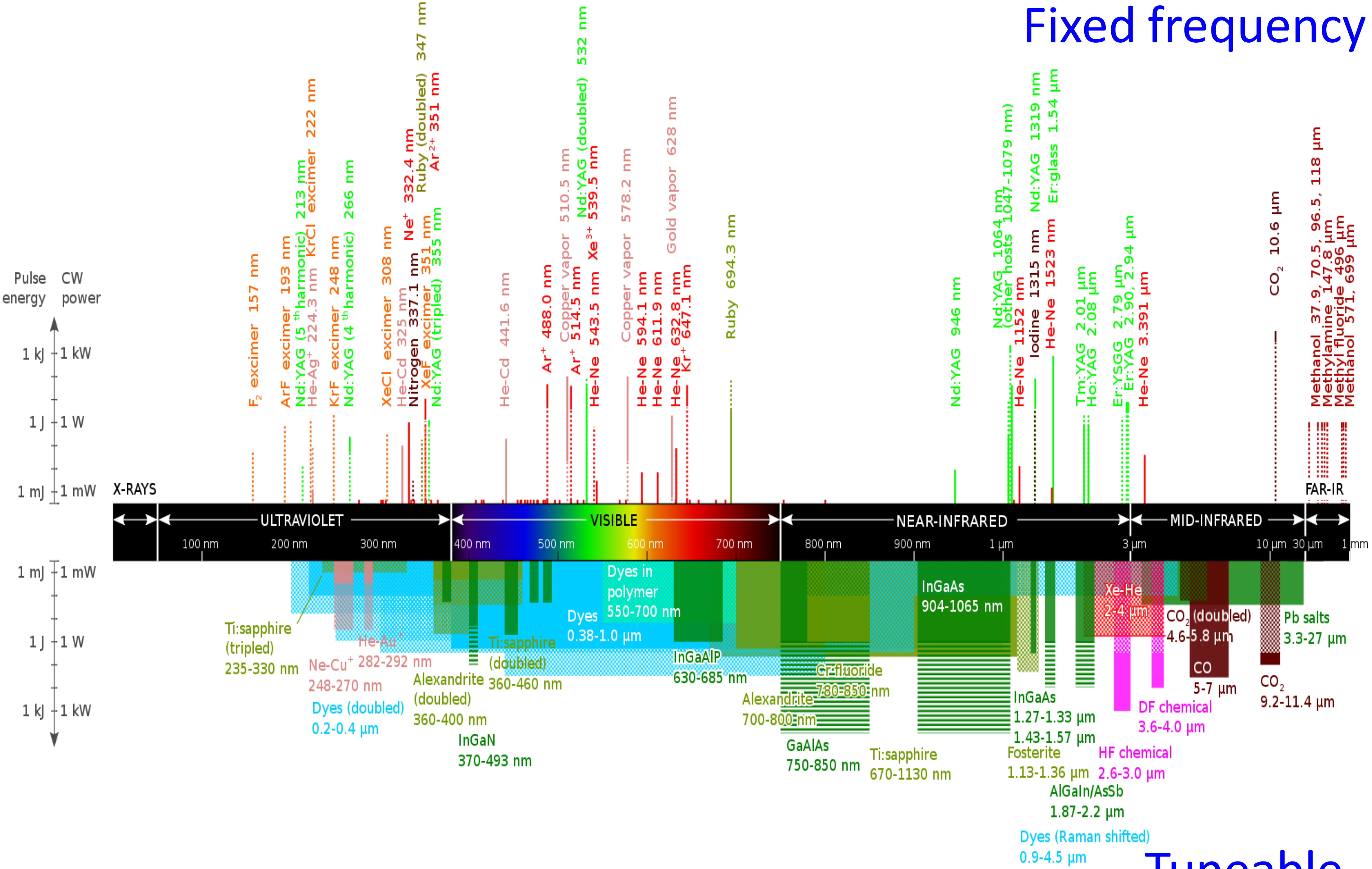
eg. Mg isotopes, Γ ~6 MHz, Δ ~100 MHz (neighbouring isotopes): S ~1000
Δ ~10^{15} Hz (Mg to Ca): S ~10^{17} !!!

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

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

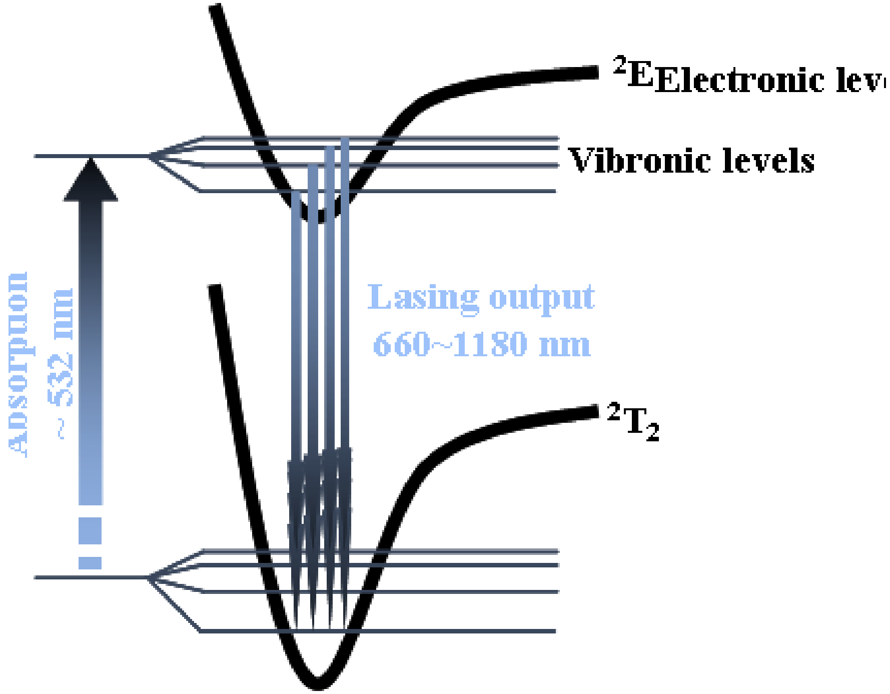


Fixed frequency

Tuneable

Ti:Sapphire laser

- Optically active component is Ti^{3+} *<1% by weight*
- Host solid is sapphire (Al_2O_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)*



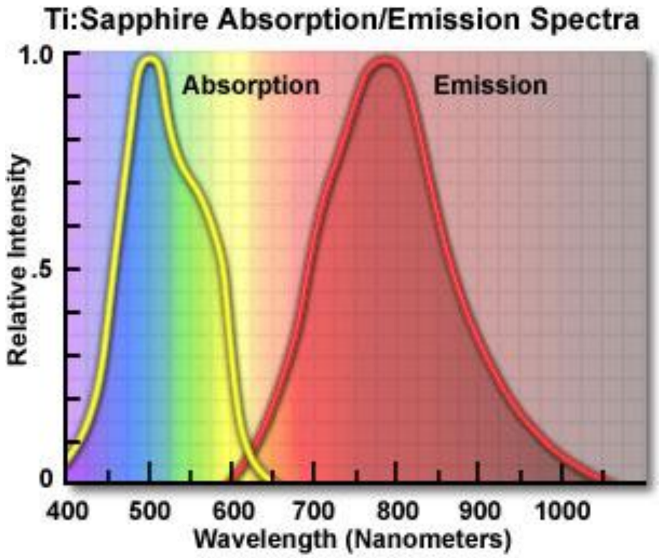
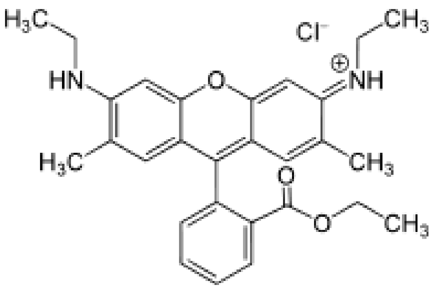
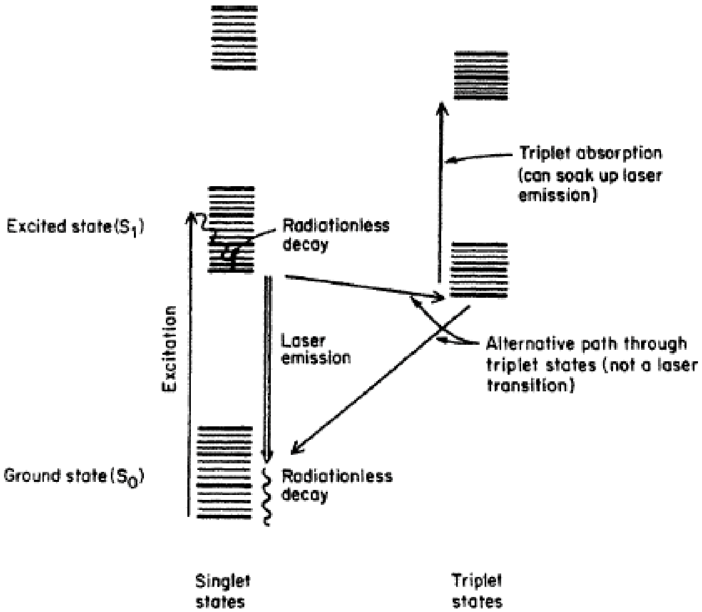


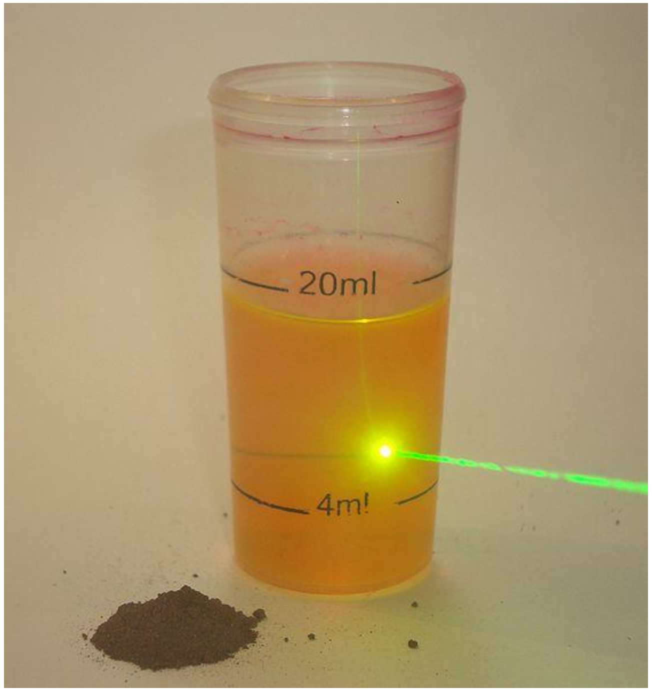
Figure 1

Dye laser

Rhodamine 6G



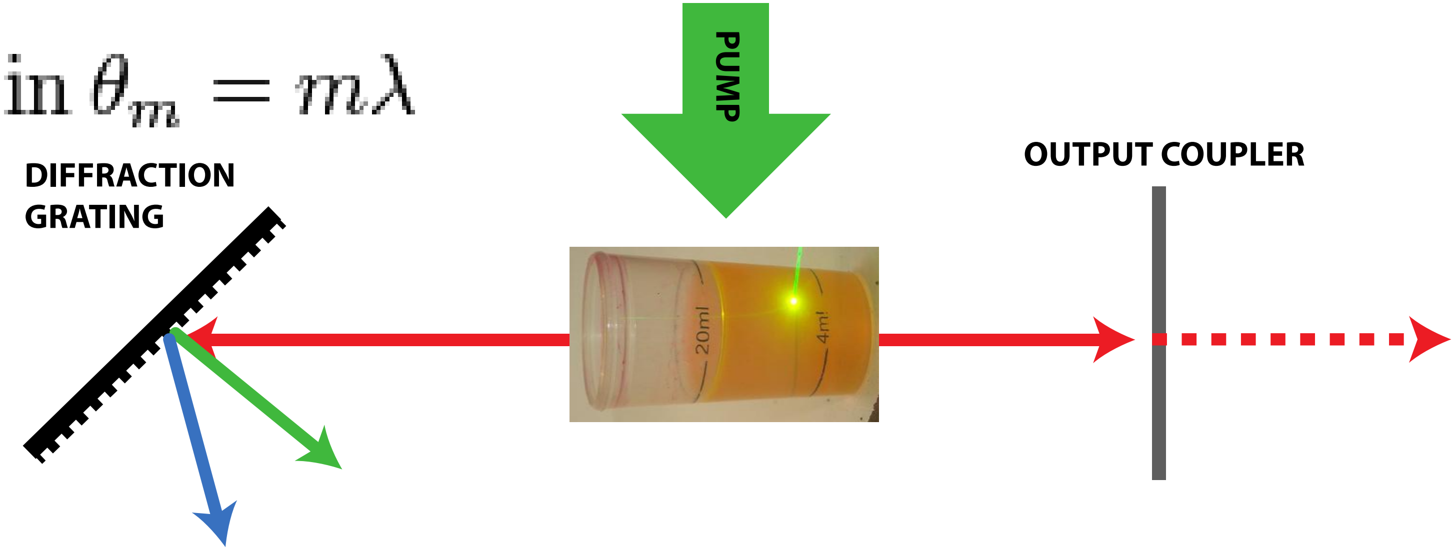




Diffraction grating as a laser cavity mirror:

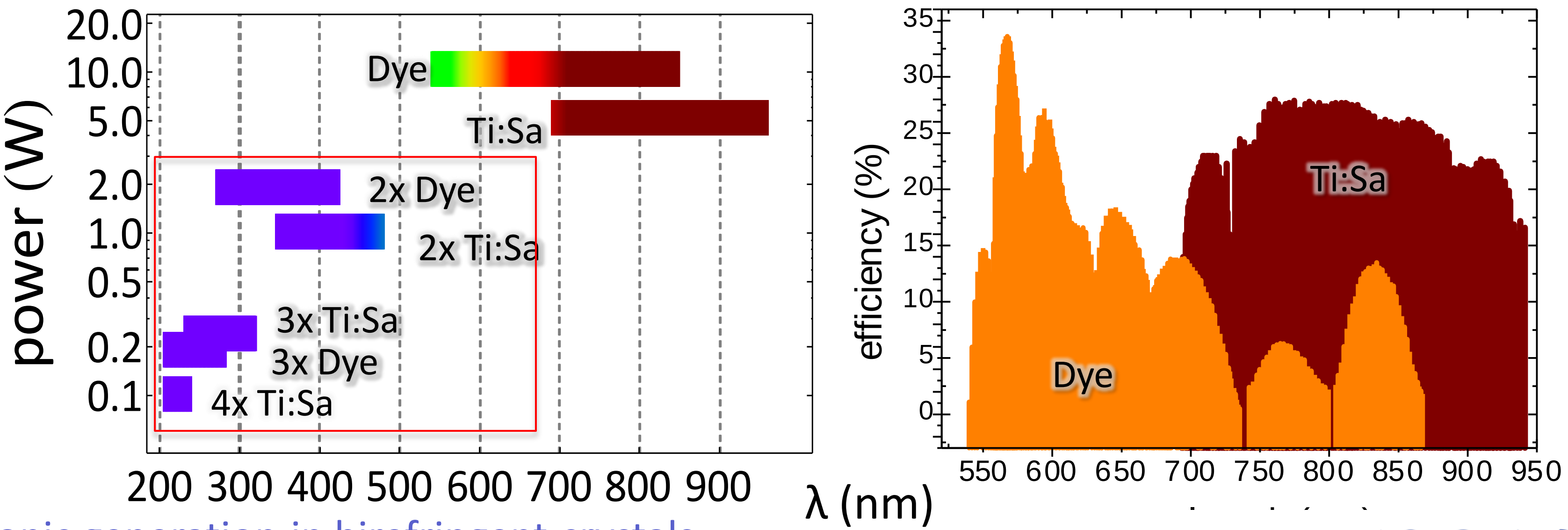
Reflection maxima on axis with cavity is wavelength dependent → wavelength selective oscillation

$$d\ \sin\theta_m = m\lambda$$



Comparing dye and Ti:Sa lasers

	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 ☺



Harmonic generation in birefringent crystals:
Due to nonlinear response of materials to high EM field of focused lasers

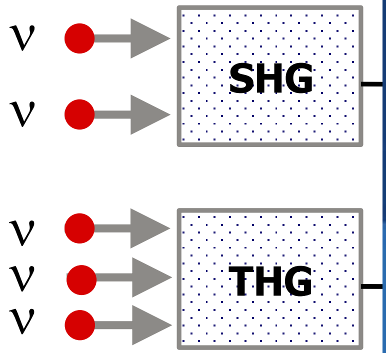
Multiple harm

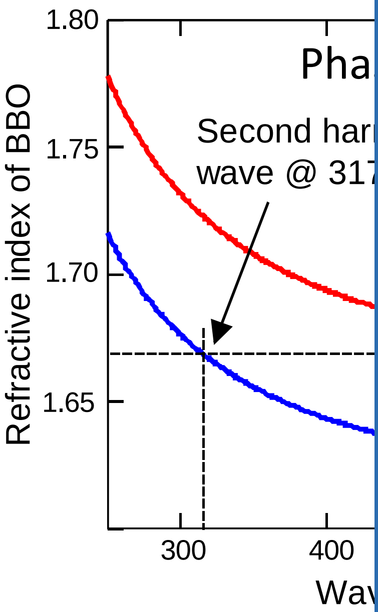
uning range

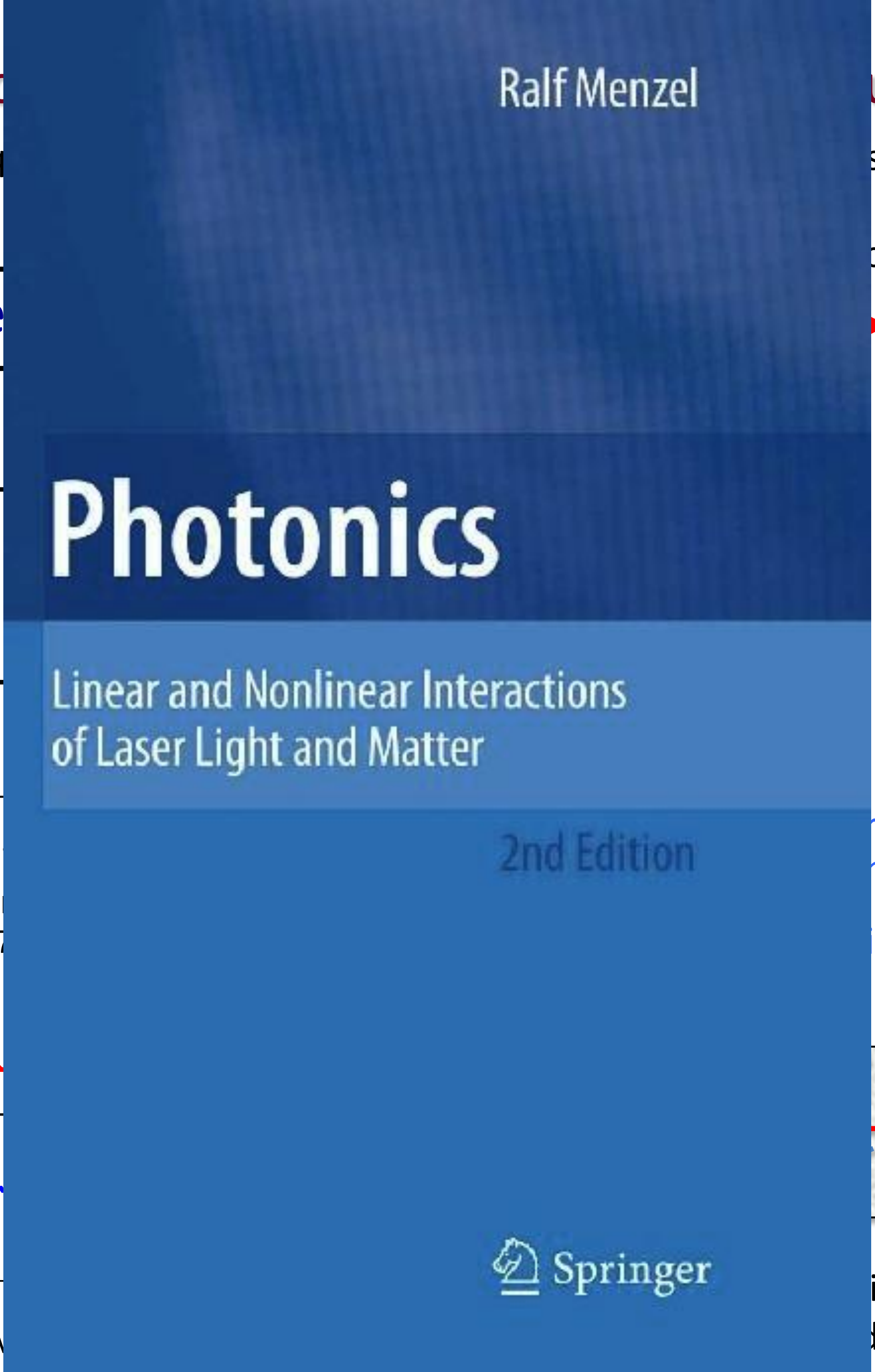
Most first excited steps req

ssible with 532 nm pumping

Harmonic gene







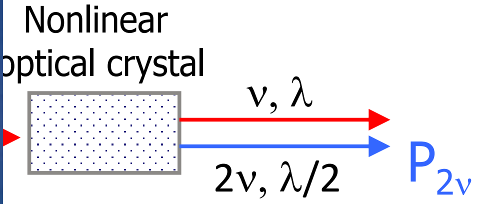
Ralf Menzel

Photonics

Linear and Nonlinear Interactions of Laser Light and Matter

2nd Edition

Springer



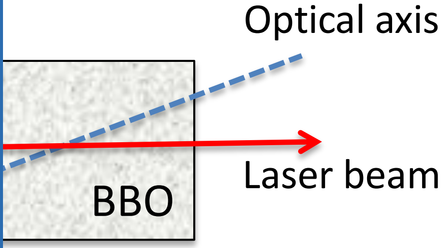
$h(L)$

Parameter related to fundamental beam focusing

ystal length

nental power in crystal

inear coefficient



ials have different

d angular acceptances

Multiple harmonic generation – Practicalities for a RILIS use.

Many non-linear materials exist with greatly varying physical and optical properties.

Material requirements

- Low absorption at required wavelengths
- High damage threshold (GW cm^{-2})
- High non-linearity coefficient, $\underline{d_{eff}}$
- Phase matching at room temperature

Good options

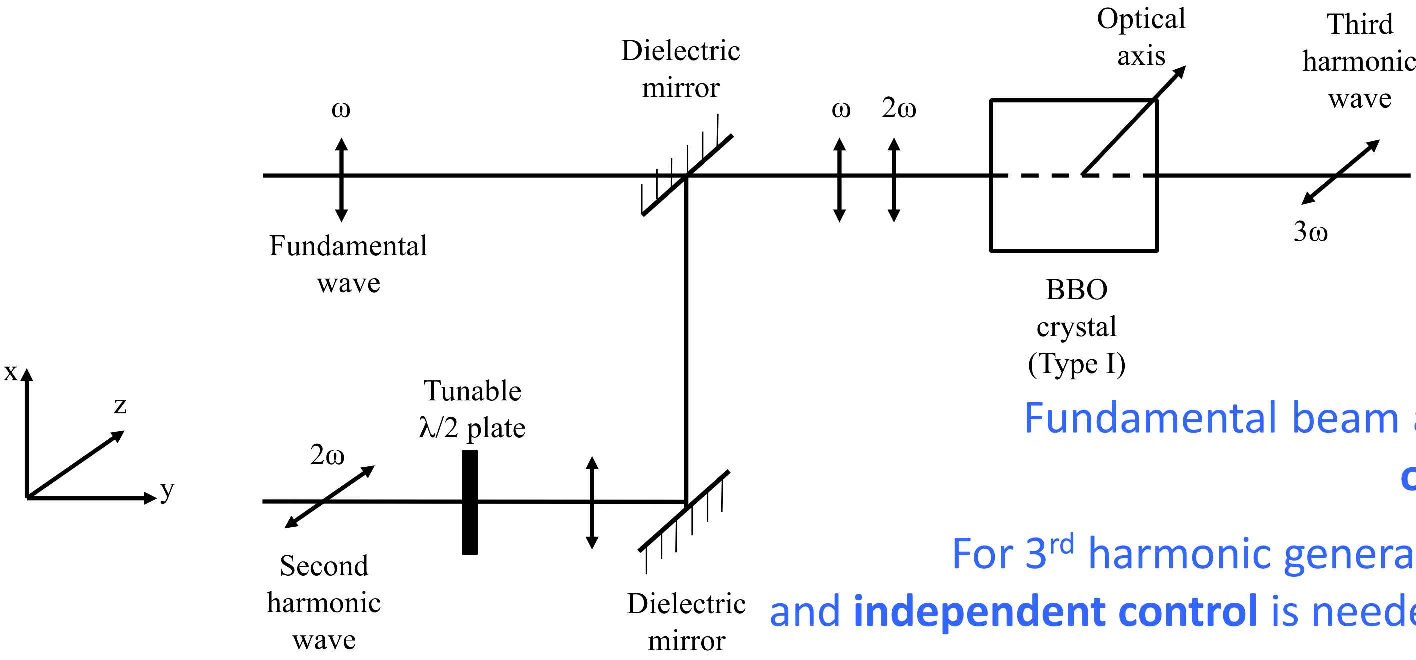
beta-barium-borate
BBO

bismuth borate
BiBO

lithium triborate
LBO

Issues to consider

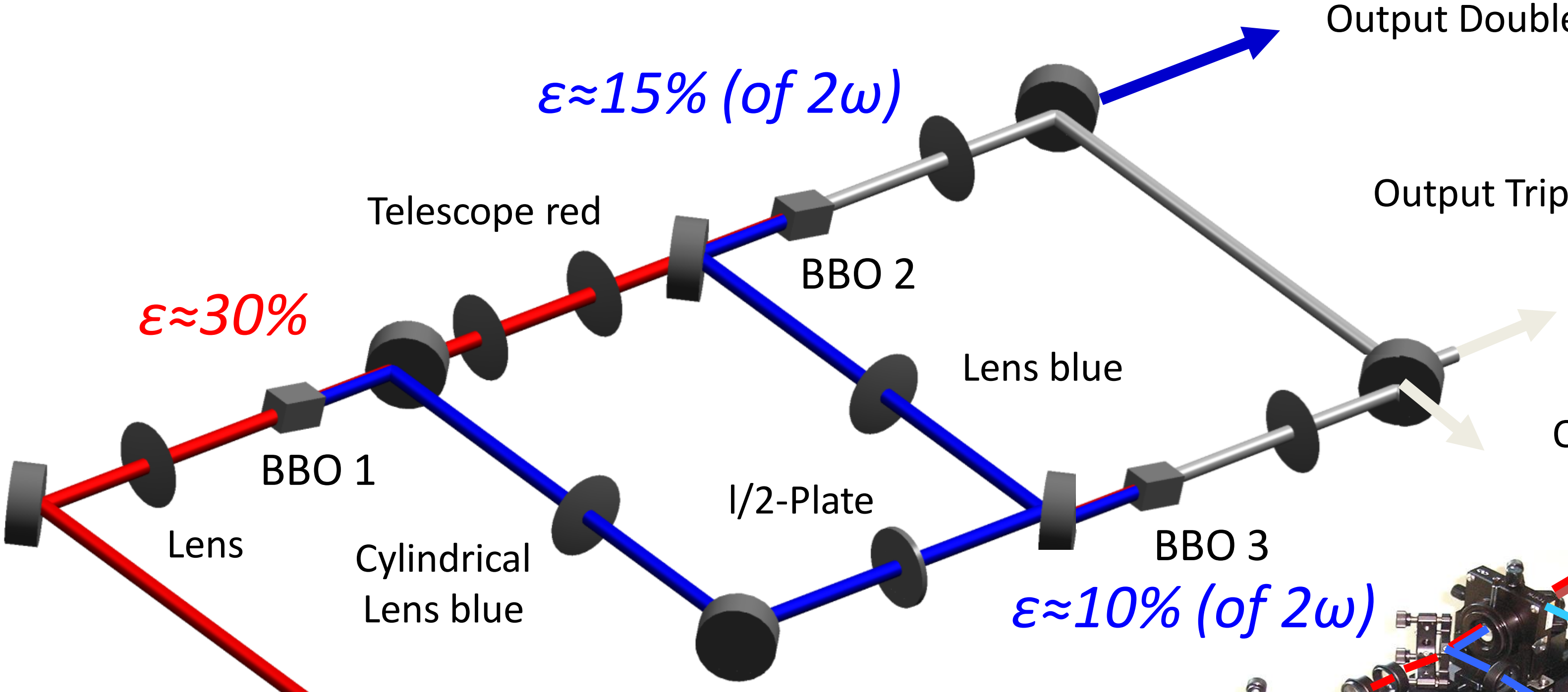
- Efficiency (<20 %)
- Dispersion→Walk-off
- Elliptical beam output
- Beam transport
- Care of optics

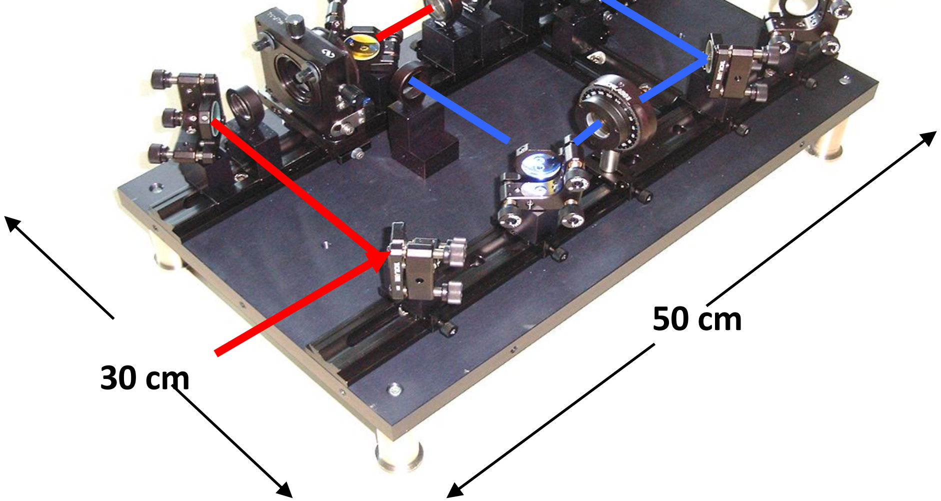


Fundamental beam and 2nd harmonic have **orthogonal polarization**

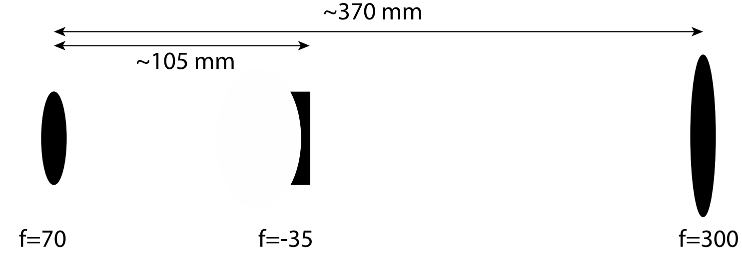
For 3rd harmonic generation, **equal polarization** and **independent control** is needed for each input beam

Frequency conversion unit – Mainz University design



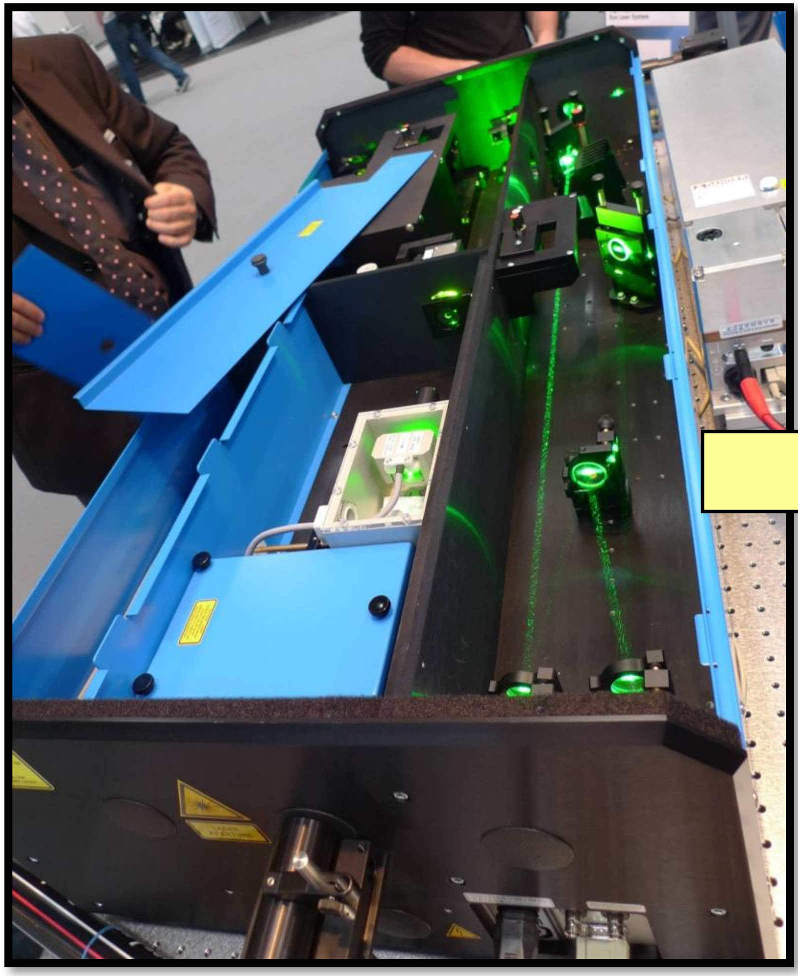


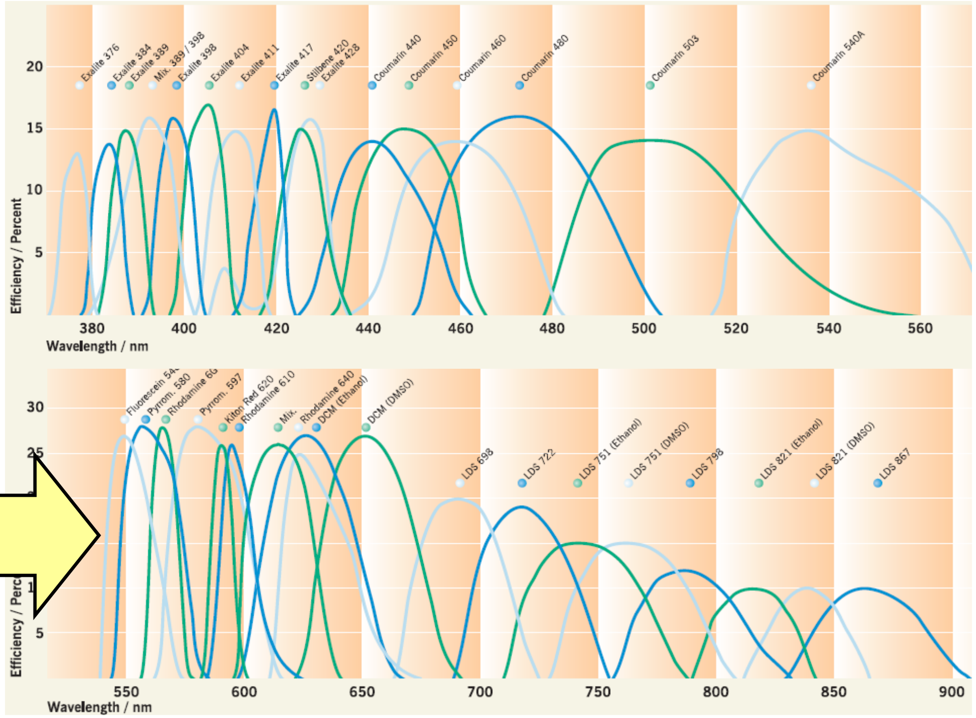
Cylindrical lens telescope is required:



For short wavelengths (<240nm) try to avoid small spot sizes on optics : Negative lens

Sirah Dye laser – an example of a modern commercial dye laser



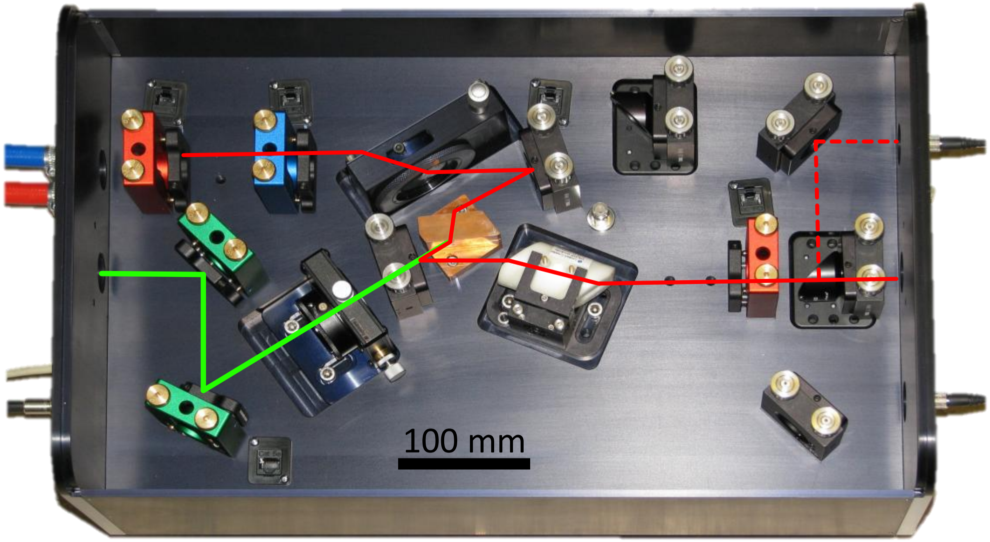


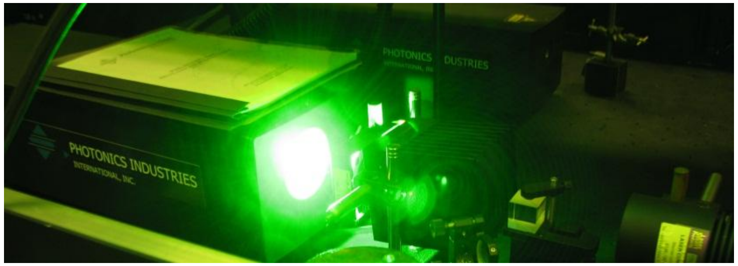
- **Optimized for 10 kHz EdgeWave pump**
- **Accept both 355 and 532 pumping beams**
- **Equipped with FCU (up to 2W of UV)**

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

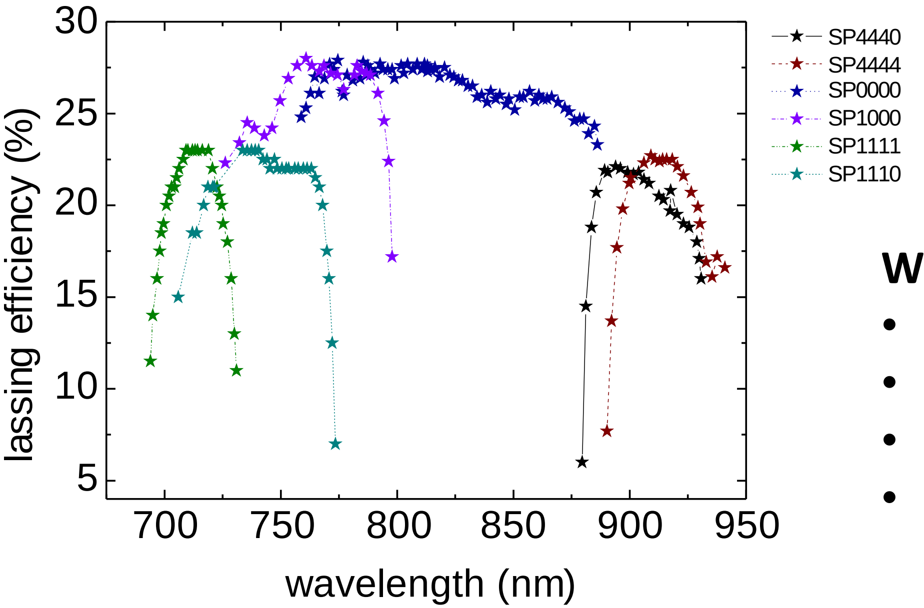
V. Fedosseev et al: Rev. Sci. Instrum. 83, 02A903 (2012)

The RILIS Ti:Sa lasers





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



<u>Ti:Sa lasers:</u>
Line width: 5 GHz
Pulse length: 30-50 ns

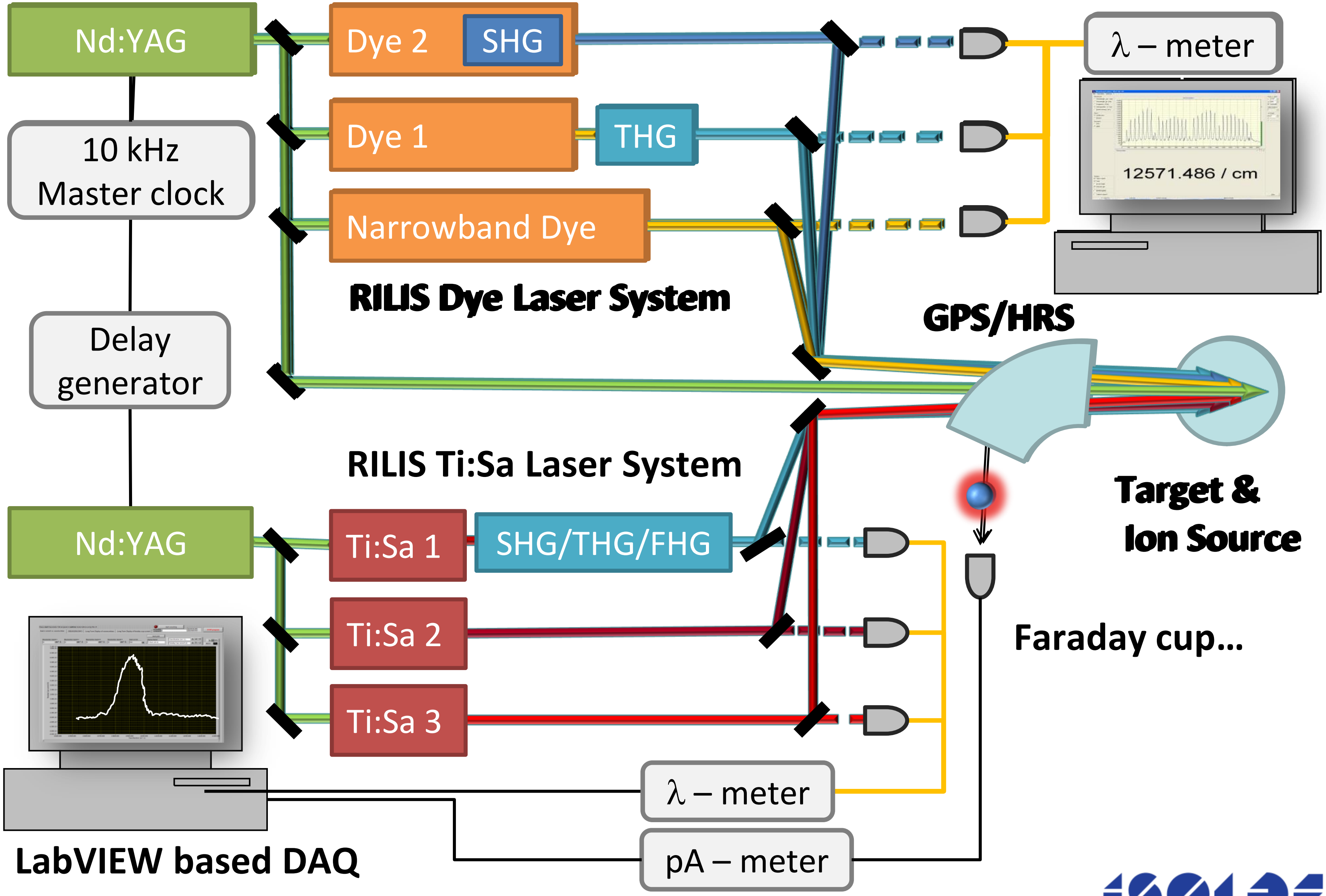
Wavelength tuning range (6 mirror sets):

- Fundamental (ω) **690** - **940** nm (5 W)
- 2nd harmonic (2ω) **345** - **470** nm (1 W)
- 3rd harmonic (3ω) **230** - **310** nm (120 mW)
- 4th harmonic (4ω) **205** - **235** nm (120 mW)

"A complementary laser system for ISOLDE RILIS"

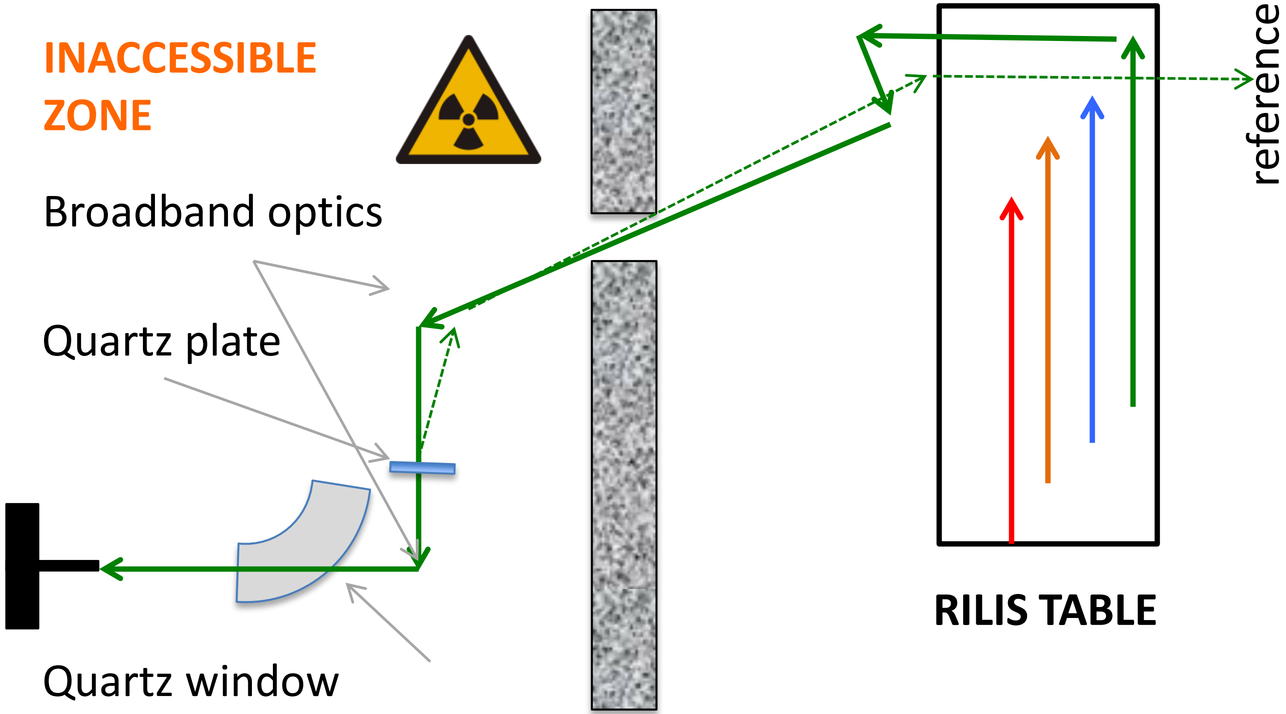
S Rothe et al: Journal of Physics: Conference Series 312 (2011) 052020

Dual RILIS Concept



Practical issues for beam transport

- Up to 4 laser beams to transport to the target (through bending magnet of mass separator)
- 2 different targets located ~20m away through considerable concrete shielding
- Air flow / temperature changes
- No access to mass separator or target area
- Small laser interaction region (3mm) – tube diameter
- Timing issues – optical delay lines



INACCESSIBLE ZONE

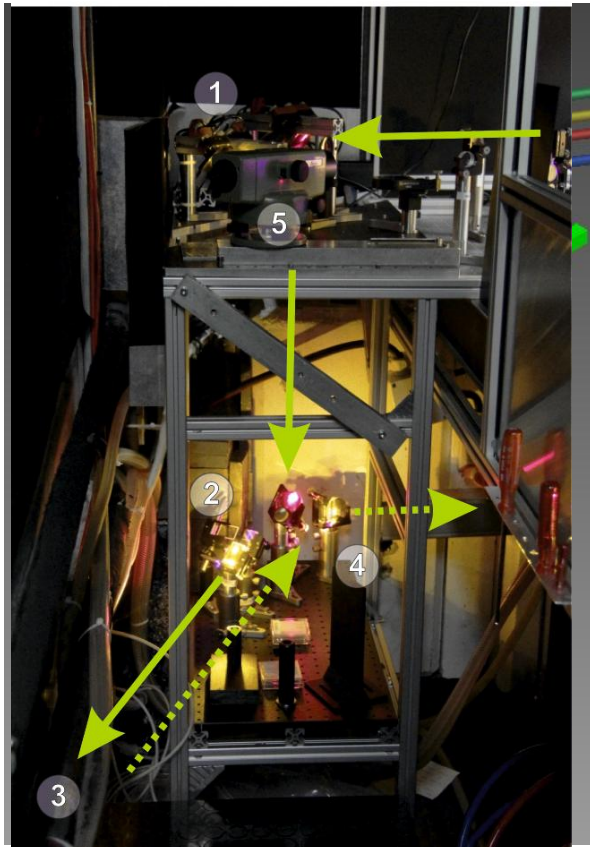
Broadband optics

Quartz plate

Quartz window

RILIS TABLE

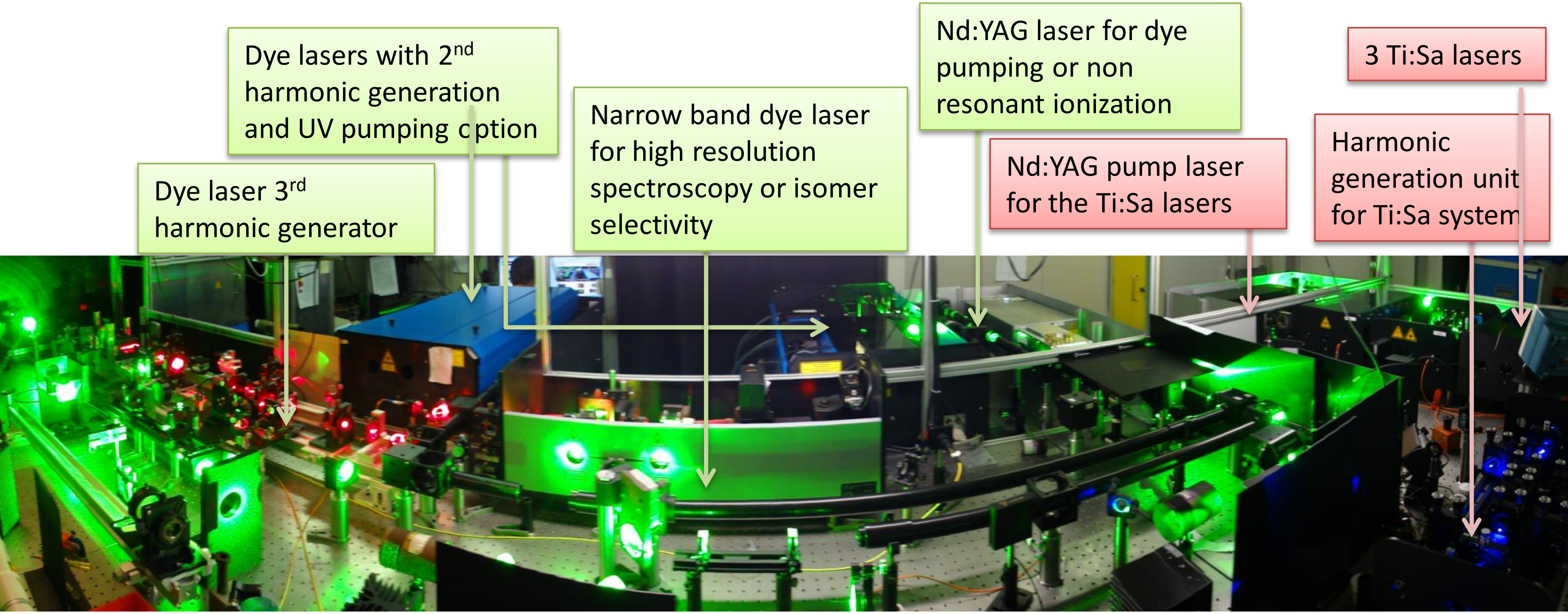
reference



Upgraded HRS launch system for ISOLDE RILIS (PhD thesis of S. Rothe)

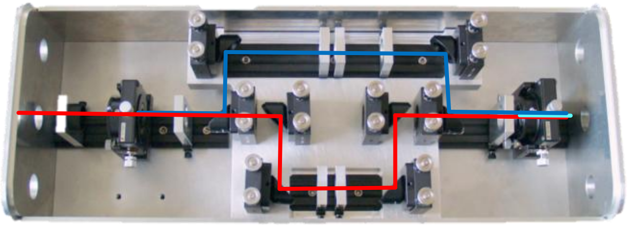
The actual ISOLDE RILIS setup

- 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

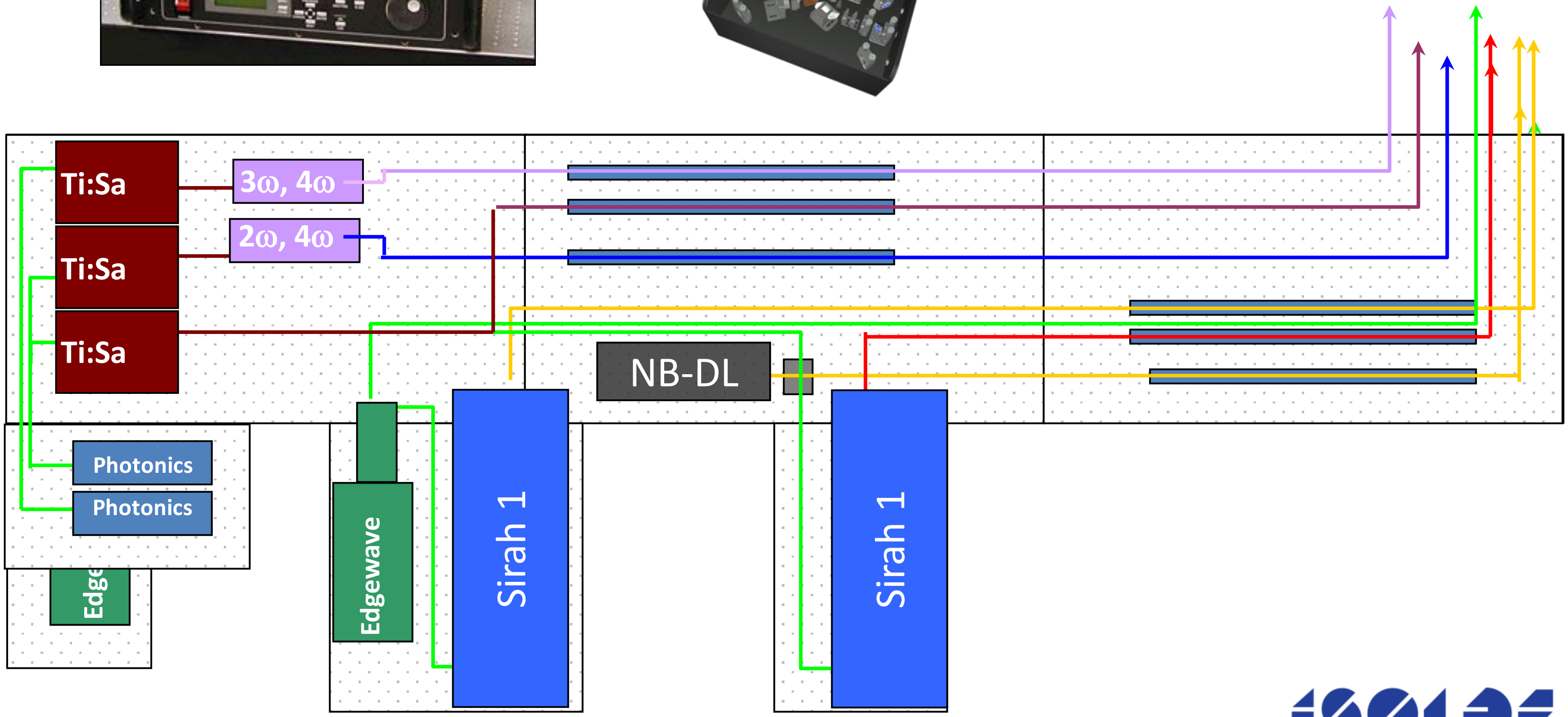


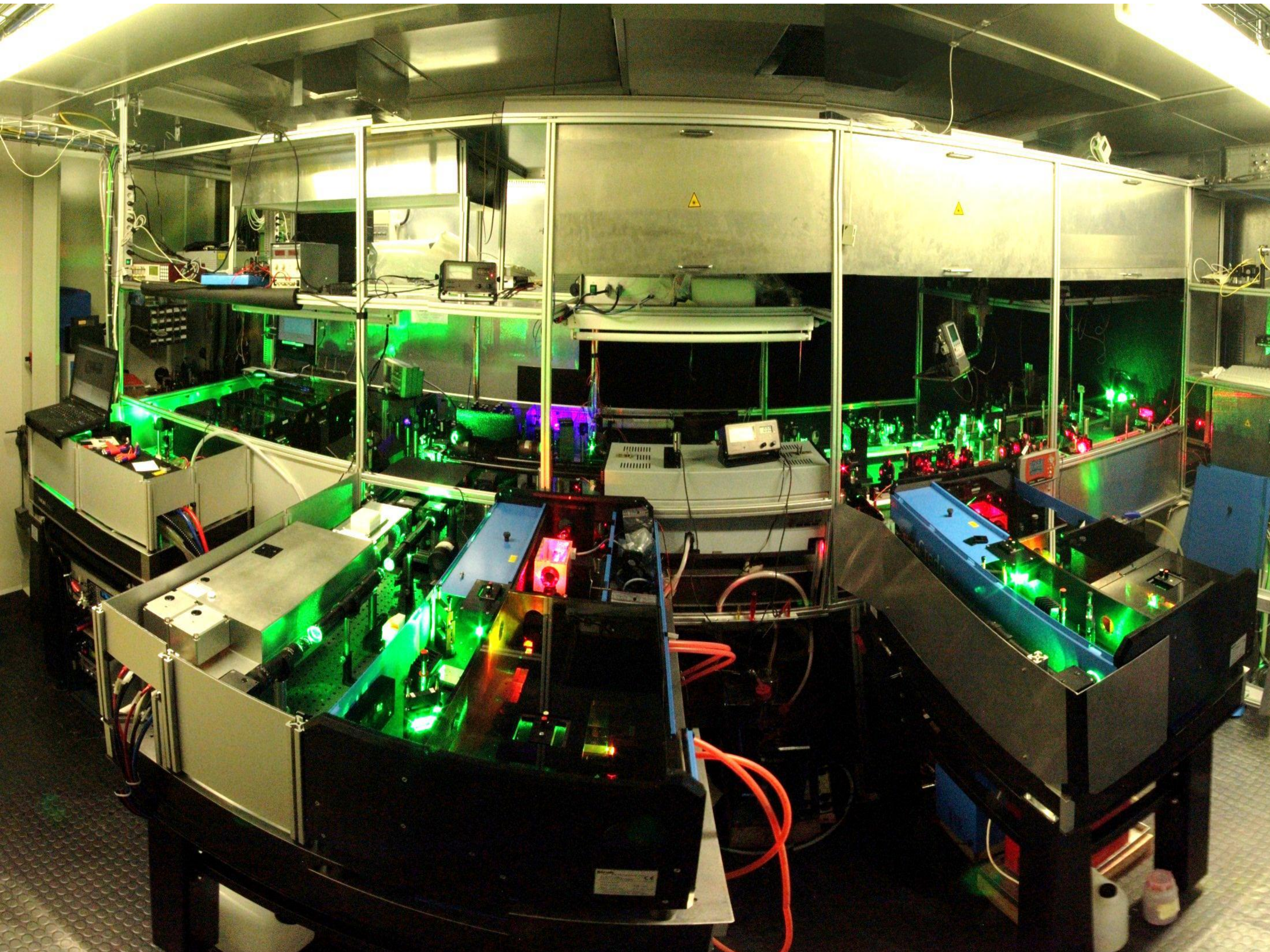
Arranging the Ti:Sas alongside the dye lasers

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



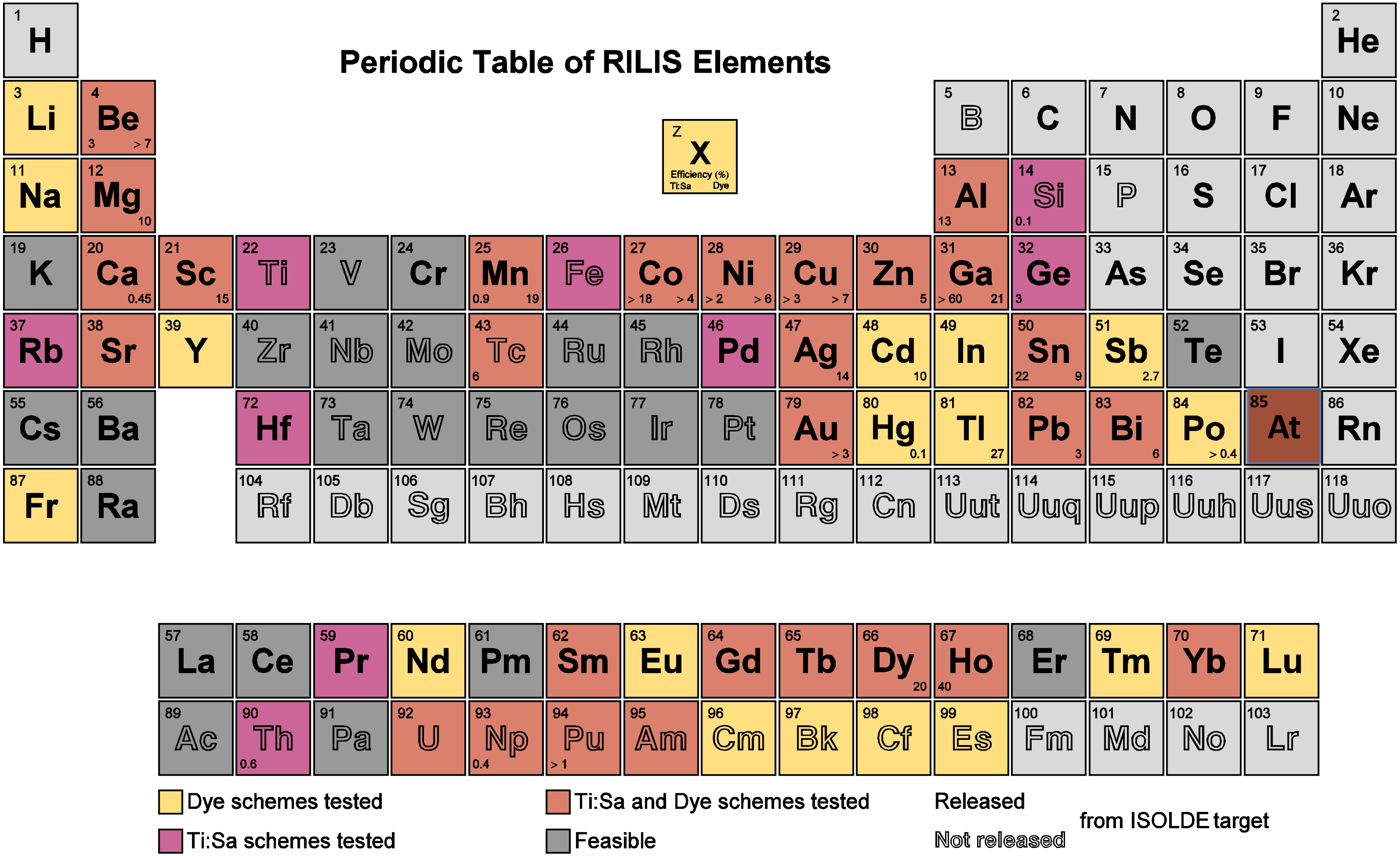
Frequency conversion unit






RILIS-screen 1
12571.858 / cm
Shuttle
PHOTONICS INDUSTRIES INTERNATIONAL, INC.

Available elements so far



Periodic Table of RILIS Elements

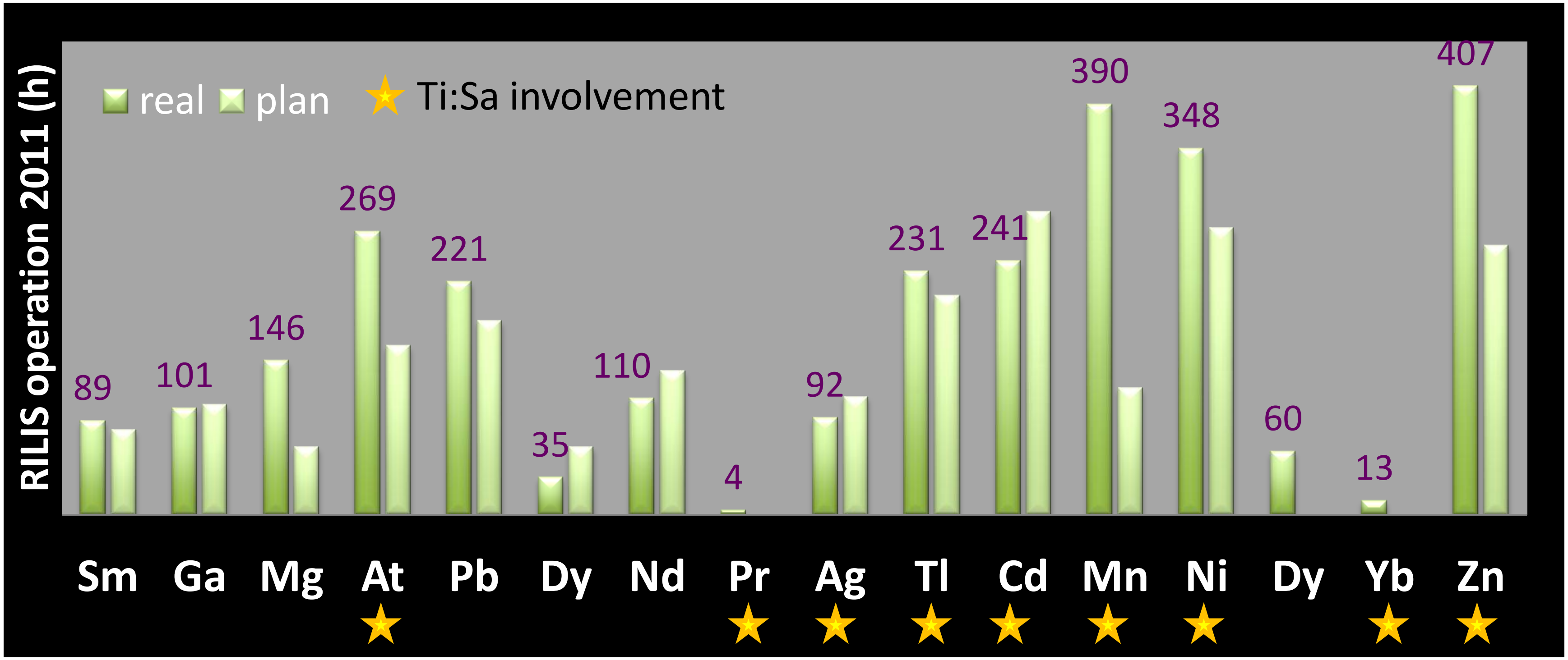
Z X
Efficiency (%)
Ti:Sa Dye

1 H																	2 He
3 Li	4 Be 3 > 7											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg 10											13 Al 13	14 Si 0.1	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca 0.45	21 Sc 15	22 Ti	23 V	24 Cr	25 Mn 0.9 19	26 Fe	27 Co > 18 > 4	28 Ni > 2 > 6	29 Cu > 3 > 7	30 Zn 5	31 Ga > 60 21	32 Ge 3	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc 6	44 Ru	45 Rh	46 Pd	47 Ag 14	48 Cd 10	49 In	50 Sn 22 9	51 Sb 2.7	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au > 3	80 Hg 0.1	81 Tl 27	82 Pb 3	83 Bi 6	84 Po > 0.4	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy 20	67 Ho 40	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th 0.6	91 Pa	92 U	93 Np 0.4	94 Pu > 1	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

🟨 Dye schemes tested
🟥 Ti:Sa and Dye schemes tested
🟪 Ti:Sa schemes tested
⬛ Feasible

Released
Not released
from ISOLDE target

Recent RILIS 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'

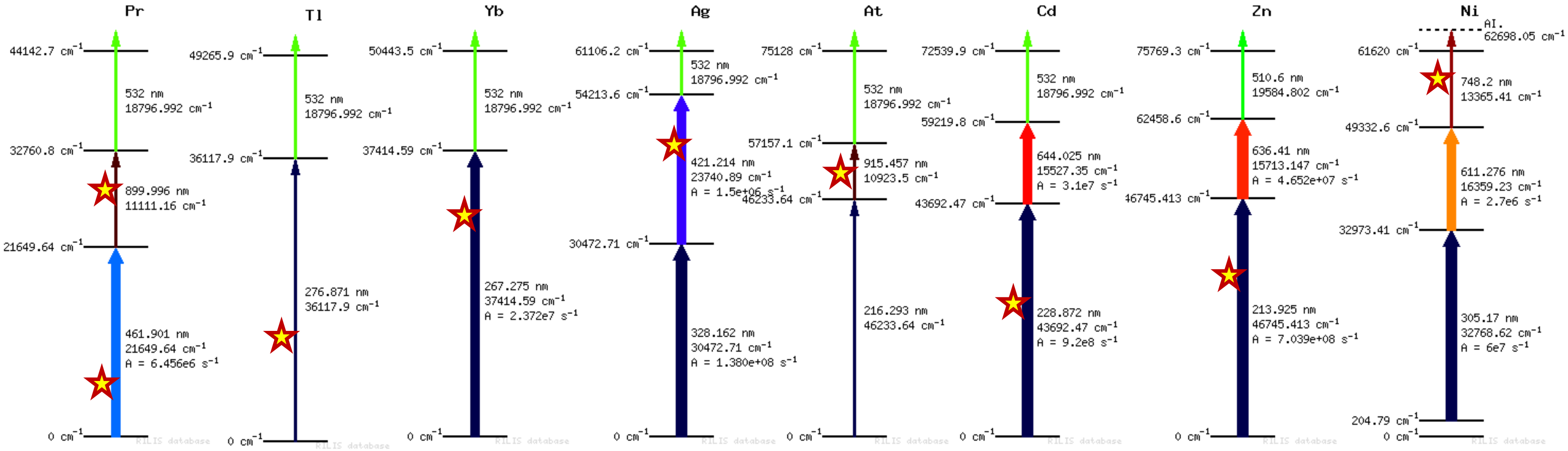
Modes of RILIS operation: Dual RILIS

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

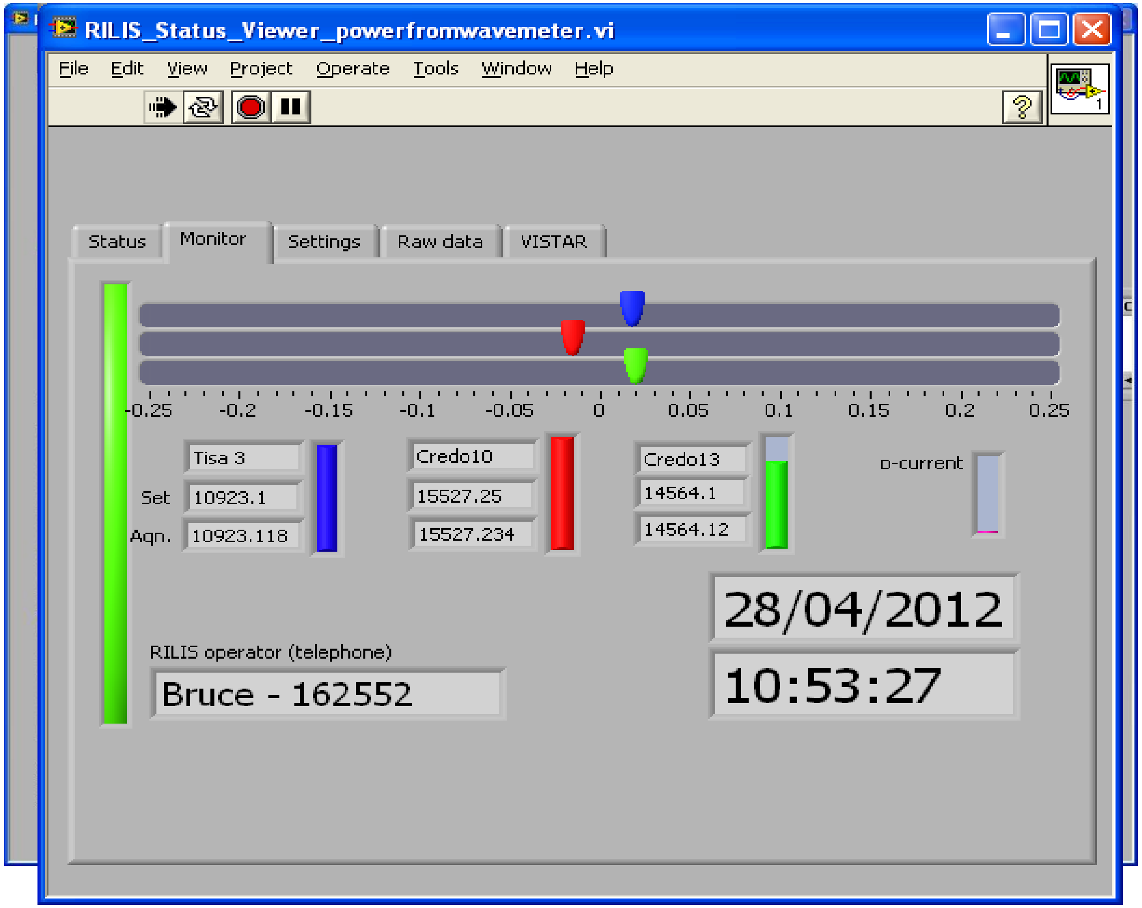
RILIS status monitoring

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

NATIONAL INSTRUMENTS LabVIEW

https://riliselements.web.cern.ch/riliselements/LASERS/



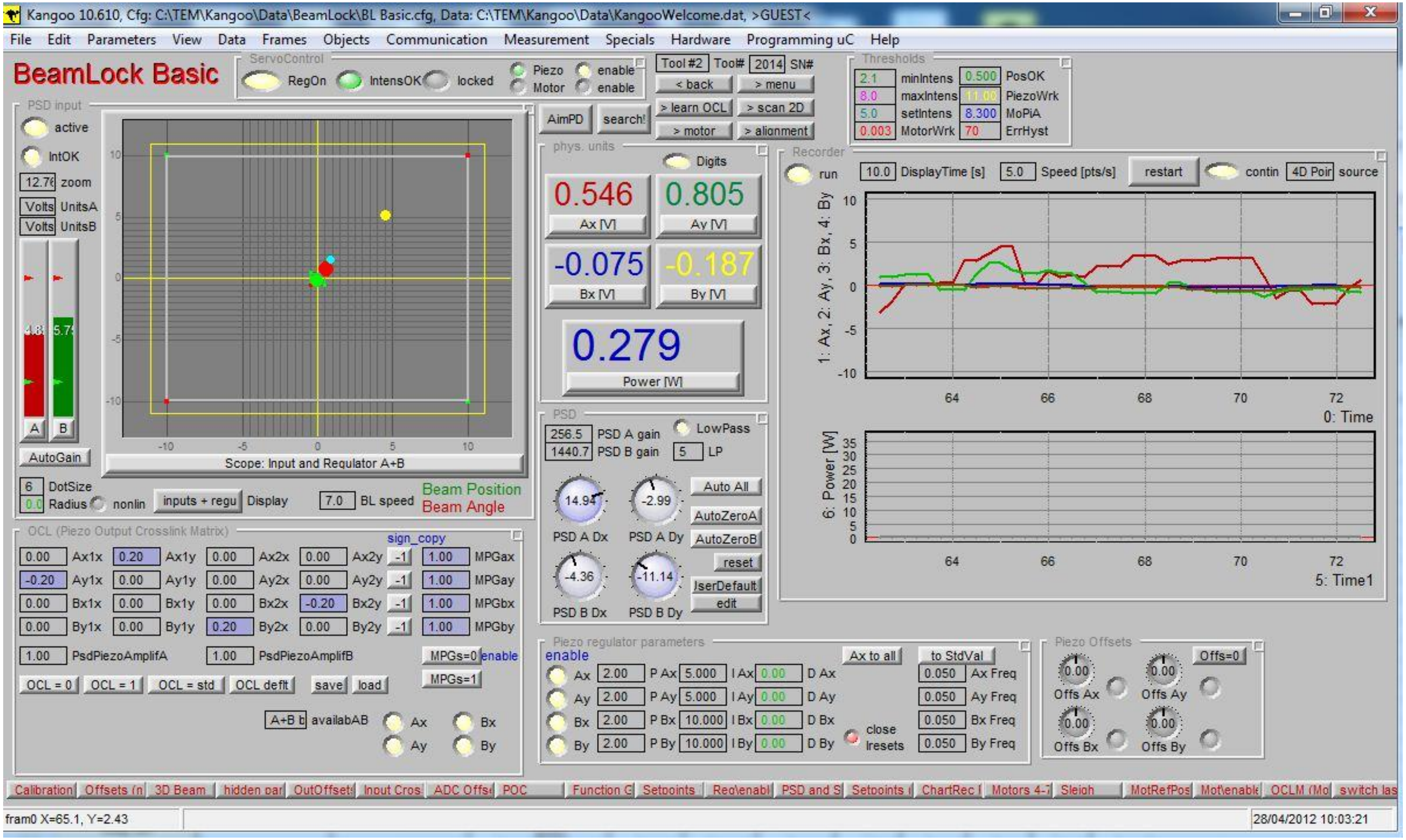
	Tisa 3	Credo10	Credo13
Set	10923.1	15527.25	14564.1
Aqn.	10923.118	15527.234	14564.12

RILIS operator (telephone)
Bruce - 162552

28/04/2012
10:53:27

Beam monitoring and stabilization

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



Kangoo 10.610, Cfg: C:\TEM\Kangoo\Data\BeamLock\BL Basic.cfg, Data: C:\TEM\Kangoo\Data\KangooWelcome.dat, >GUEST<

Tool #2, Tool# 2014 SN#

Thresholds:

2.1	minIntens	0.500	PosOK
8.0	maxIntens	11.00	PiezoWrk
5.0	setIntens	8.300	MoPiA
0.003	MotorWrk	70	ErrHyst

12.76 zoom
Volts UnitsA
Volts UnitsB
A 4.81, B 5.75
6 DotSize
0.0 Radius
nonlin
inputs + regu Display
7.0 BL speed

0.546 Ax [V]
0.805 Ay [V]
-0.075 Bx [V]
-0.187 By [V]
0.279 Power [W]

10.0 DisplayTime [s]
5.0 Speed [pts/s]
4D Point source

256.5 PSD A gain
1440.7 PSD B gain
5 LP
14.94 PSD A Dx
-2.99 PSD A Dy
-4.36 PSD B Dx
-11.14 PSD B Dy

0.00	Ax1x	0.20	Ax1y	0.00	Ax2x	0.00	Ax2y	-1	1.00 MPGax
-0.20	Ay1x	0.00	Ay1y	0.00	Ay2x	0.00	Ay2y	-1	1.00 MPGay
0.00	Bx1x	0.00	Bx1y	0.00	Bx2x	-0.20	Bx2y	-1	1.00 MPGbx
0.00	By1x	0.00	By1y	0.20	By2x	0.00	By2y	-1	1.00 MPGby

1.00 PsdPiezoAmplifA
1.00 PsdPiezoAmplifB
A+B b availabAB: Ax, Ay, Bx, By

	P	I	D	Freq
Ax	2.00	5.000	0.00	0.050
Ay	2.00	5.000	0.00	0.050
Bx	2.00	10.000	0.00	0.050
By	2.00	10.000	0.00	0.050

Offs Ax 0.00, Offs Ay 0.00, Offs Bx 0.00, Offs By 0.00

fram0 X=65.1, Y=2.43
28/04/2012 10:03:21

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

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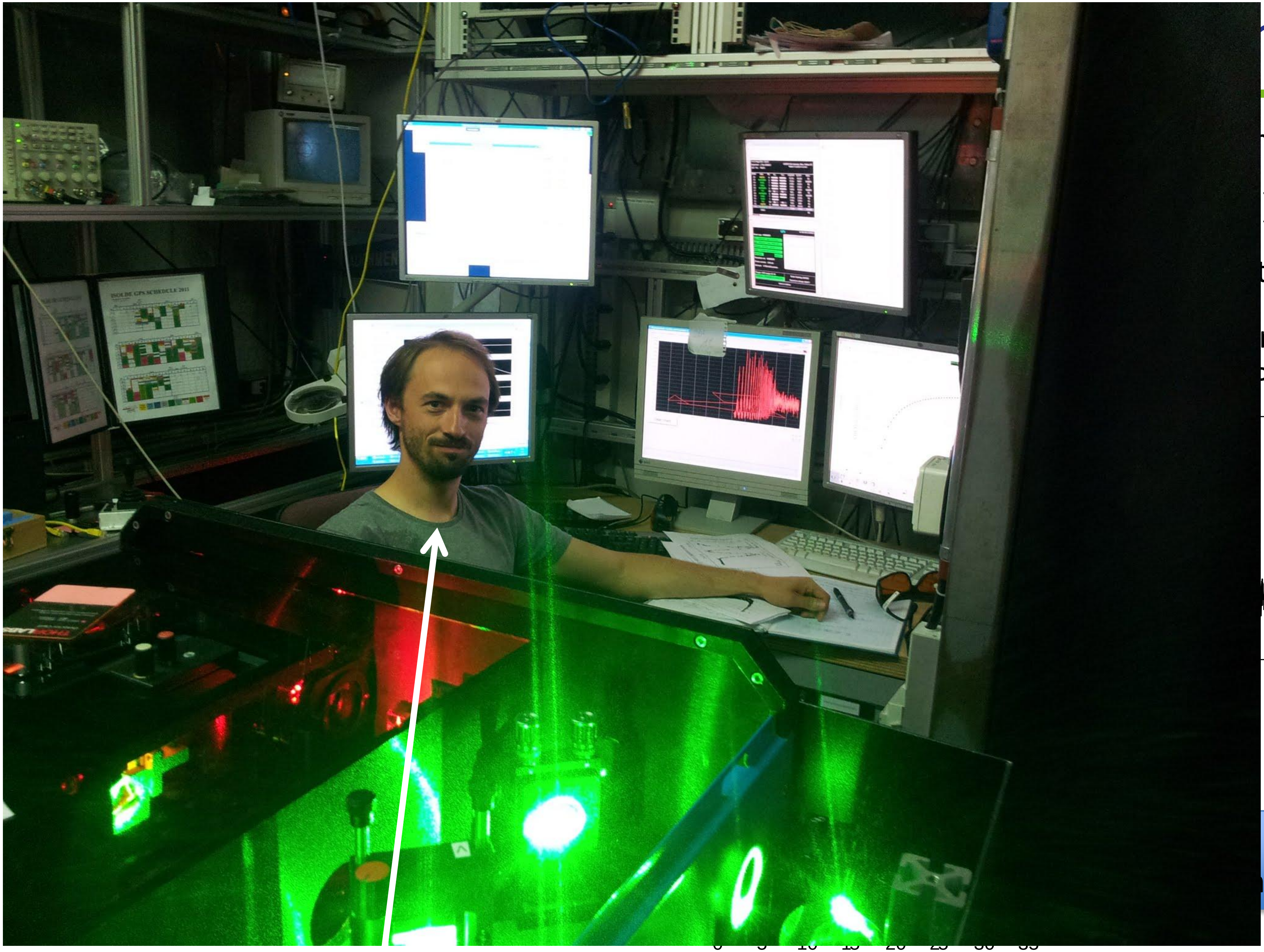

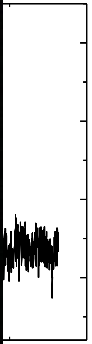

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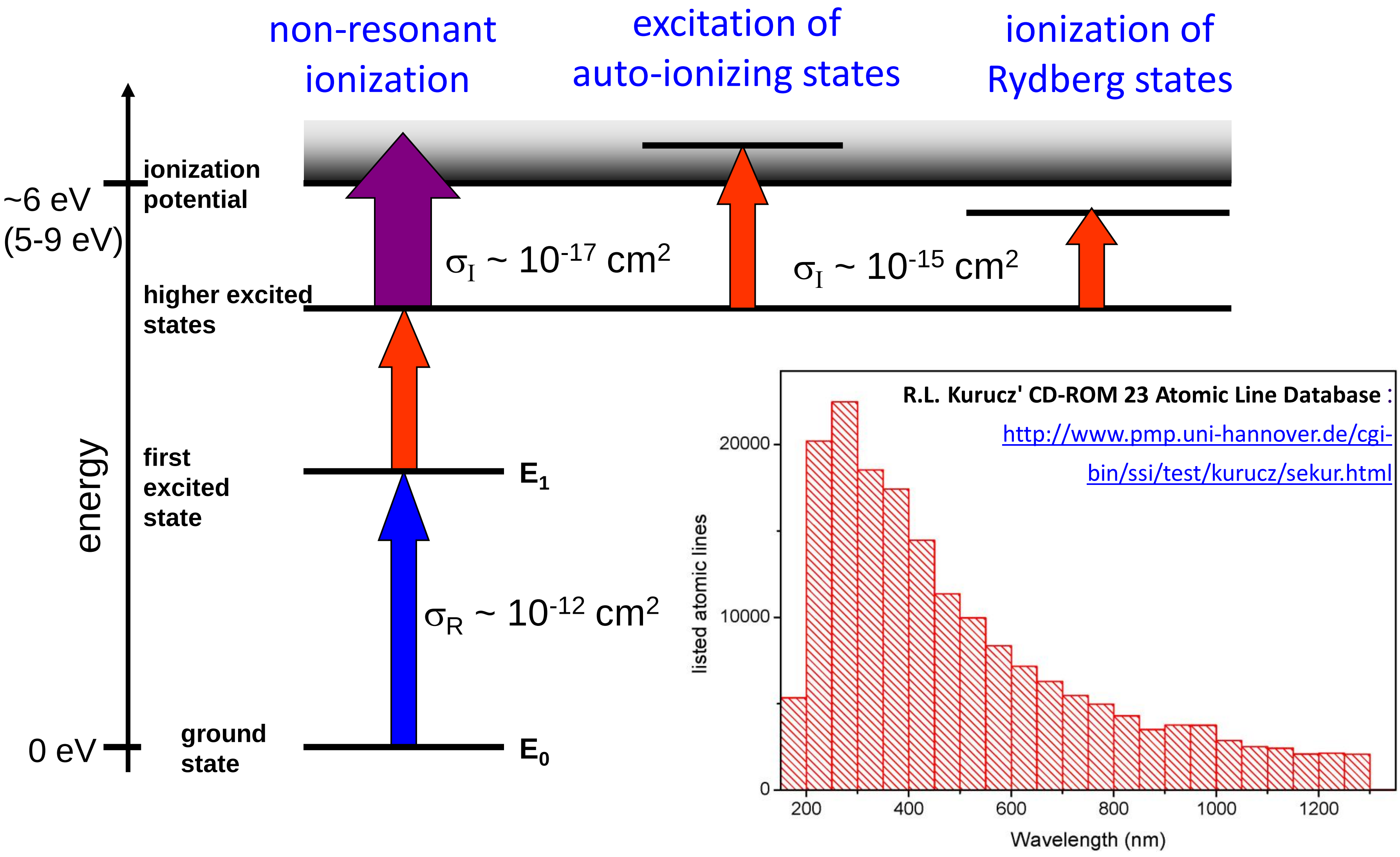
Prize winner: *S Rothe PhD Thesis and* Publication to Nature Comms.

RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

- **5)** Scheme development
  - Data sources
  - Spectroscopy
  - Saturation
  - Efficiency

Ionization scheme development

What are our options for ionization schemes?



non-resonant ionization

excitation of auto-ionizing states

ionization of Rydberg states

ionization potential

~6 eV (5-9 eV)

higher excited states

first excited state

ground state

0 eV

energy

E_1

E_0

$\sigma_I \sim 10^{-17}$ cm^2

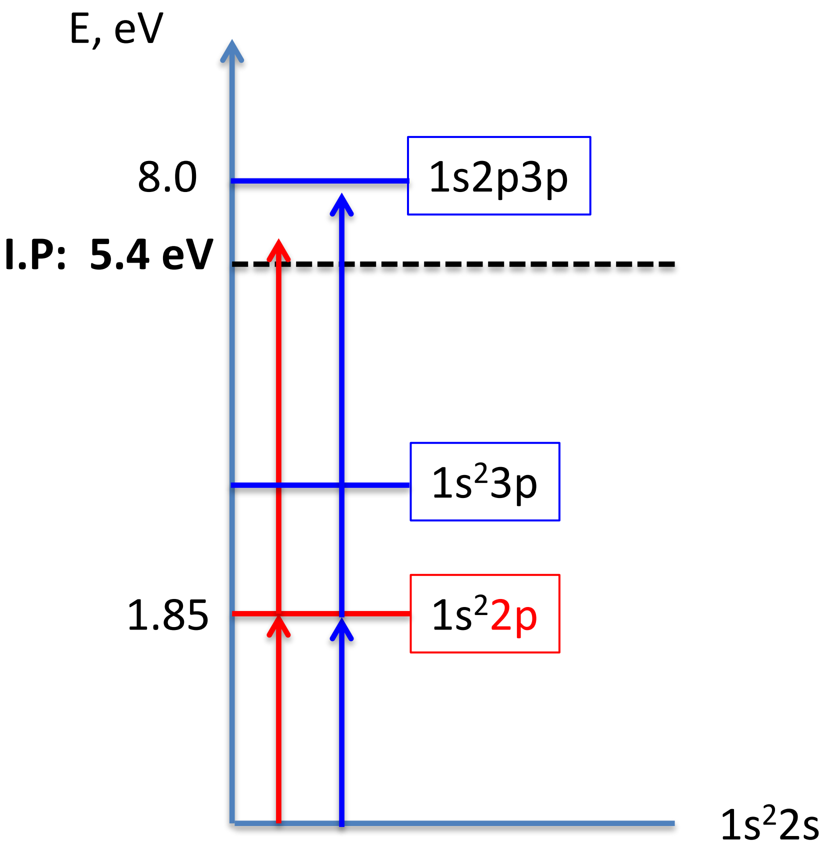
$\sigma_I \sim 10^{-15}$ cm^2

$\sigma_R \sim 10^{-12}$ cm^2

R.L. Kurucz' CD-ROM 23 Atomic Line Database :

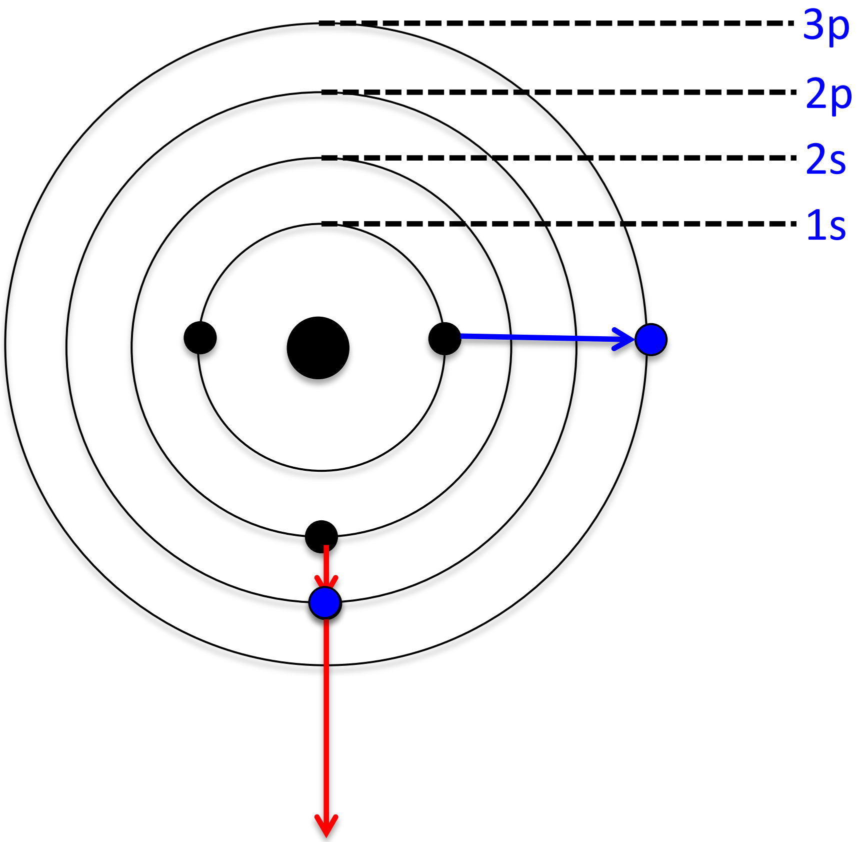
http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html

Auto-ionizing states – simplified concept



Li

3 electrons: G.S 1s^{2}2s



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

  NIST atomic spectral line database : http://www.nist.gov/pml/data/asd.cfm

- **In-source resonance ionization spectroscopy**

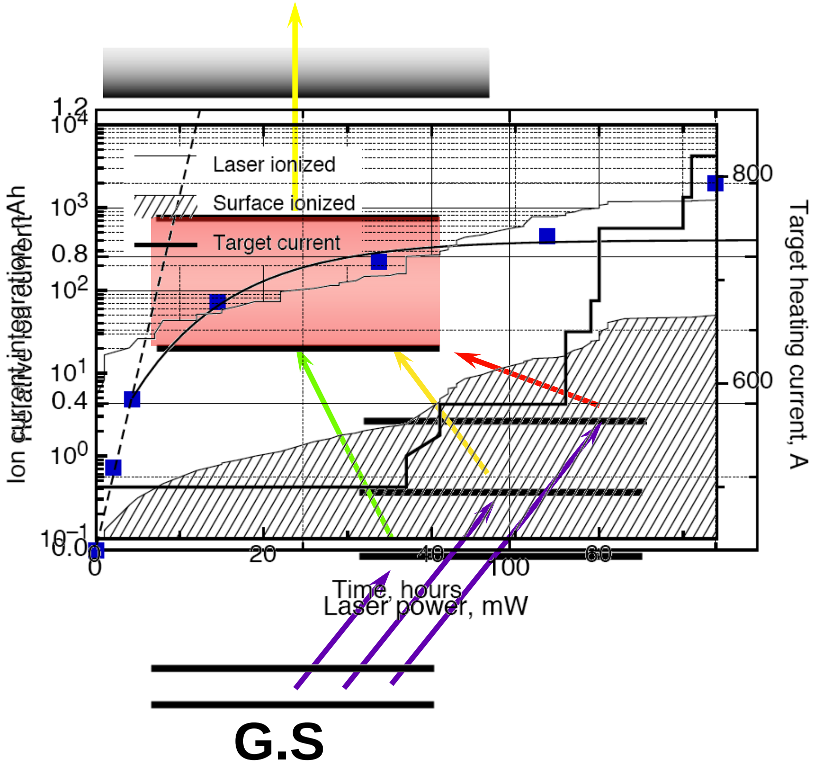
  Laser frequency scans across regions of interest whilst observing the ion current as the sample is evaporated in the target or oven.

- **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.



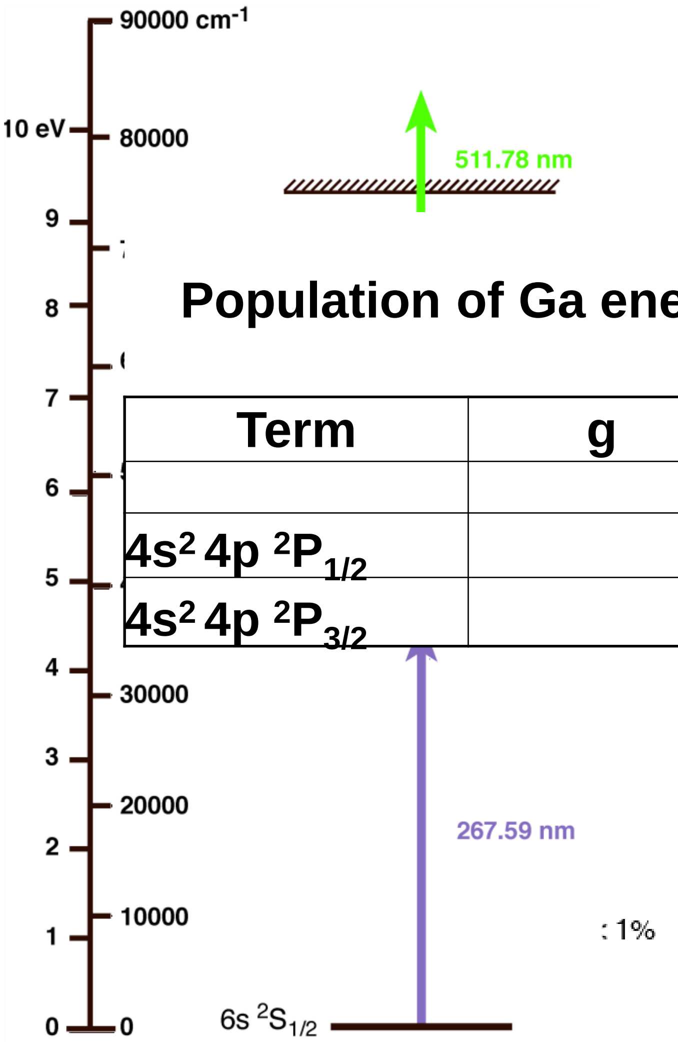
1 week for a simple case
2 weeks for AIS search

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!)

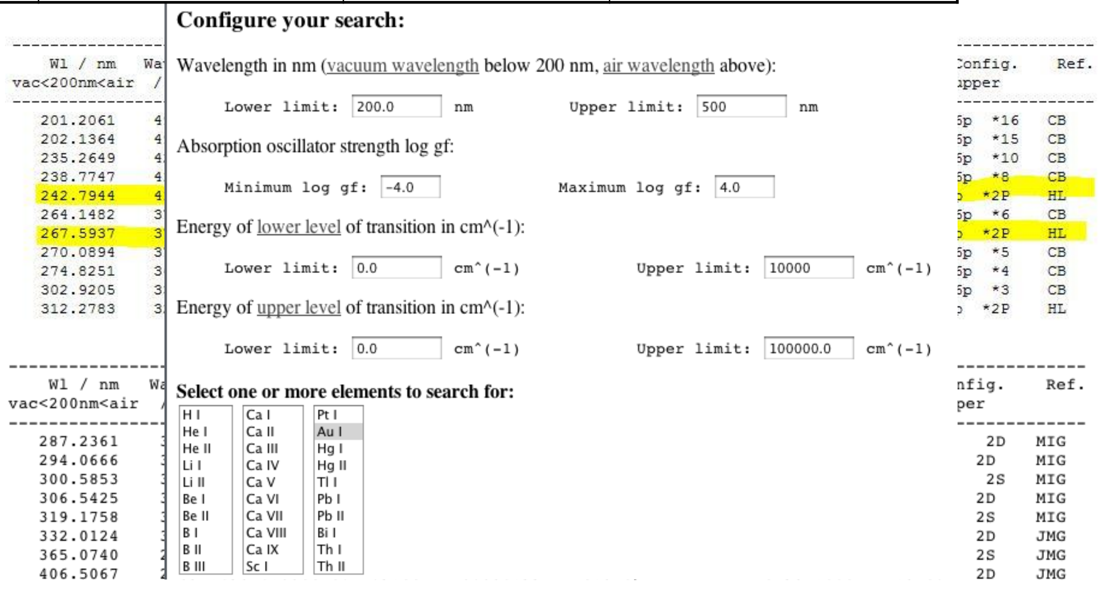
2) We have a pump laser with both **511 nm** or **578 nm** output:
- *Choose 511nm (highest photon energy) – 19570 cm^{-1}*
- *Any excited state higher than 74409- 19750 = 54659 cm^{-1} will be within reach of the ionization potential (~ 1 x 182 nm photon). Therefore Min 3 steps are required.*

3) Search Kurucz database for 1st step transitions:



Population of Ga energy levels at T= 2300K

Term	g	E, cm-1	$ge^{-E/kT}$	Population
$4s^2\,4p\ ^2P_{1/2}$	2	0	2	**45.6%**
$4s^2\,4p\ ^2P_{3/2}$	4	826	2.385860659	**54.4%**



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	Ca I	Pt I
He I	Ca II	Au I
He II	Ca III	Hg I
Li I	Ca IV	Hg II
Li II	Ca V	Tl I
Be I	Ca VI	Pb I
Be II	Ca VII	Pb II
B I	Ca VIII	Bi I
B II	Ca IX	Th I
B III	Sc I	Th II

```
-----------------
    Wl / nm   Wa
vac<200nm<air  /
-----------------
   201.2061    4
   202.1364    4
   235.2649    4
   238.7747    4
   242.7944    4
   264.1482    3
   267.5937    3
   270.0894    3
   274.8251    3
   302.9205    3
   312.2783    3
```

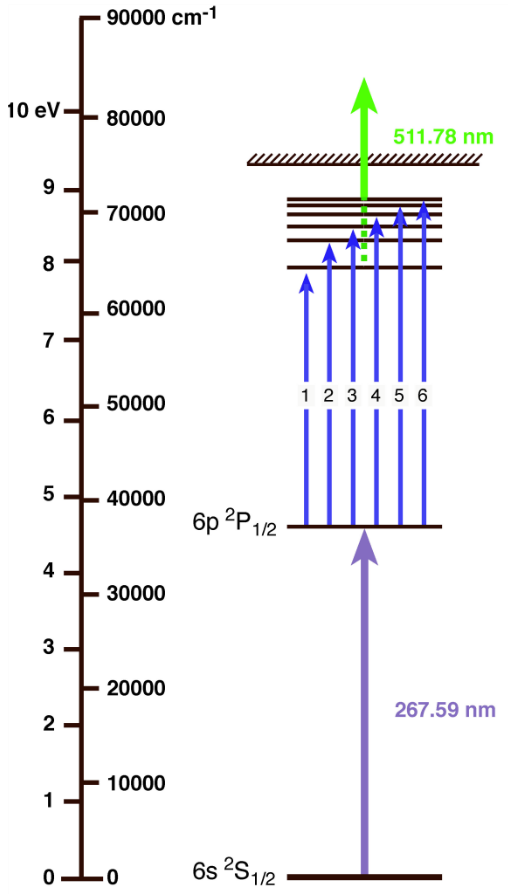
```
---------------
Config.    Ref.
upper
---------------
5p  *16   CB
5p  *15   CB
5p  *10   CB
5p  *8    CB
 *2P      HL
5p  *6    CB
 *2P      HL
5p  *5    CB
5p  *4    CB
5p  *3    CB
 *2P      HL
```

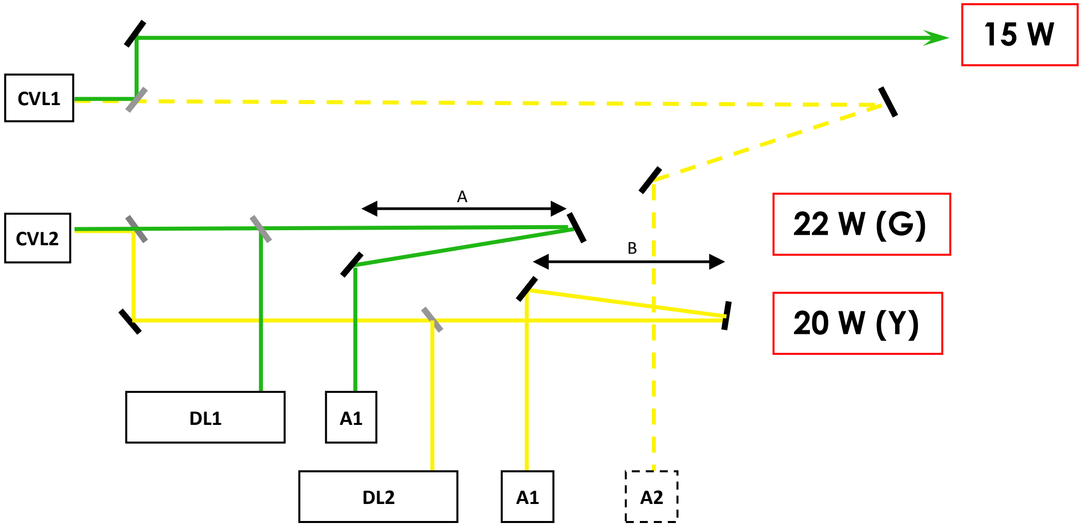
```
-----------------
    Wl / nm   Wa
vac<200nm<air  /
-----------------
   287.2361
   294.0666
   300.5853
   306.5425
   319.1758
   332.0124
   365.0740
   406.5067
```

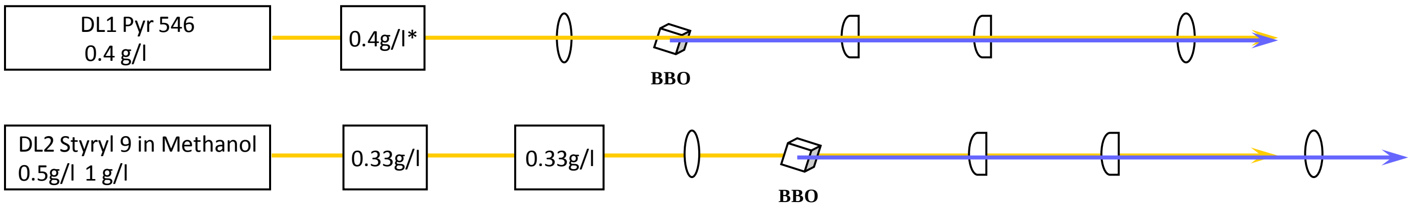
```
--------------
nfig.    Ref.
per
--------------
   2D   MIG
  2D    MIG
   2S   MIG
  2D    MIG
  2S    MIG
  2D    JMG
  2S    JMG
  2D    JMG
```

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

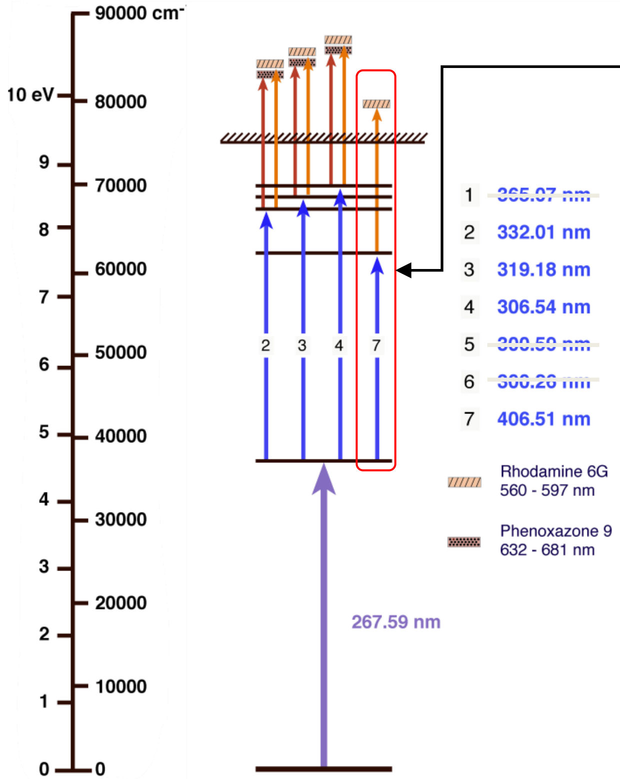


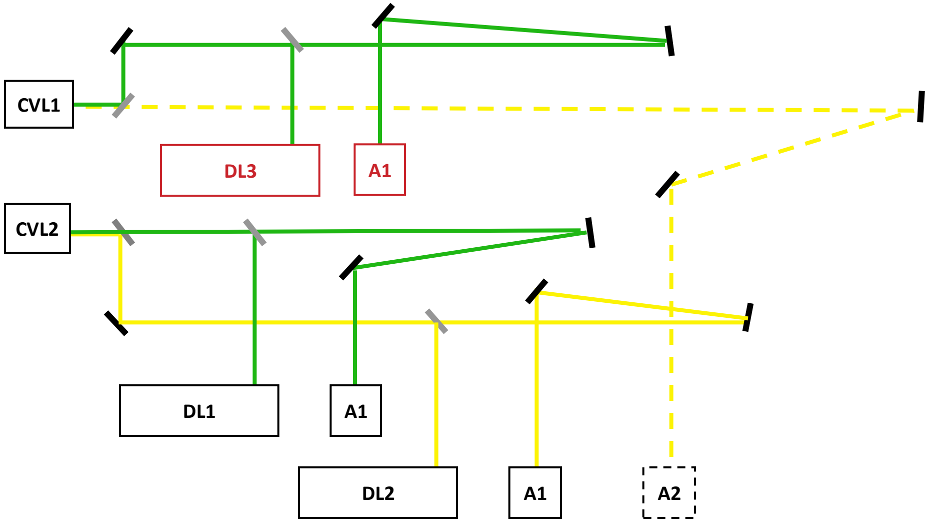


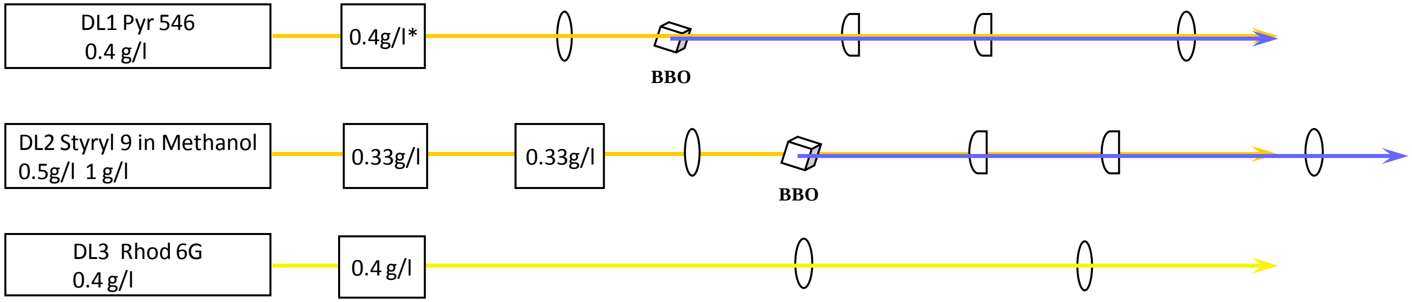


Laser setup for AIS search

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



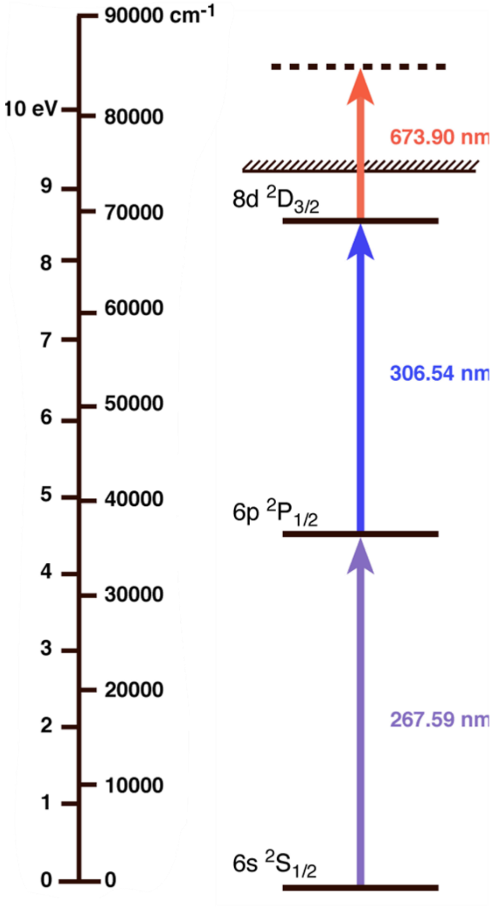


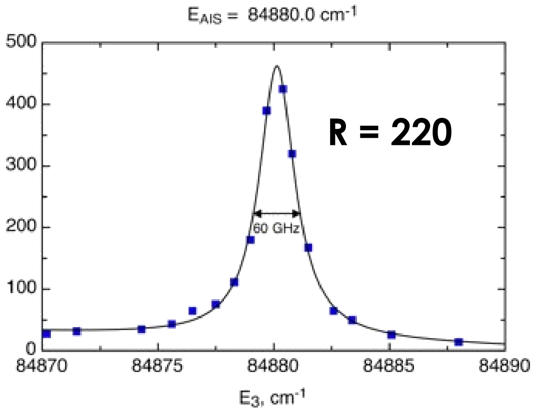


Compare good schemes and study the optimal scheme: Saturation curves, efficiency measurements etc.

Scheme figure of merit:

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





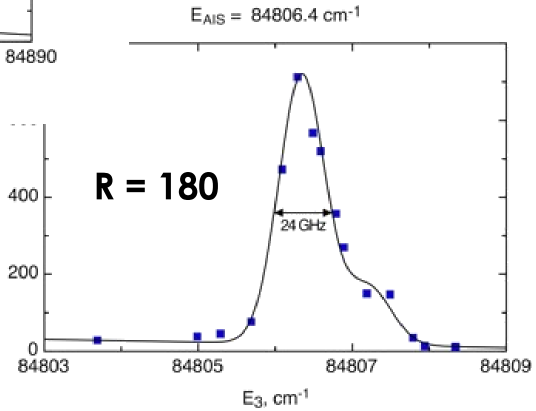
R = 220

Overall RILIS Efficiency:

$E \approx 3\ \%$*

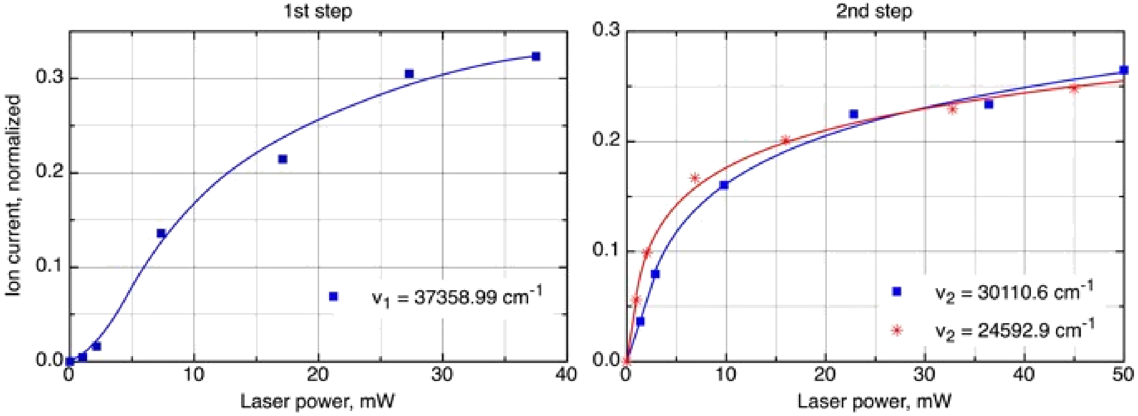
Estimated from evaporation of 3000 nAh mass marker

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



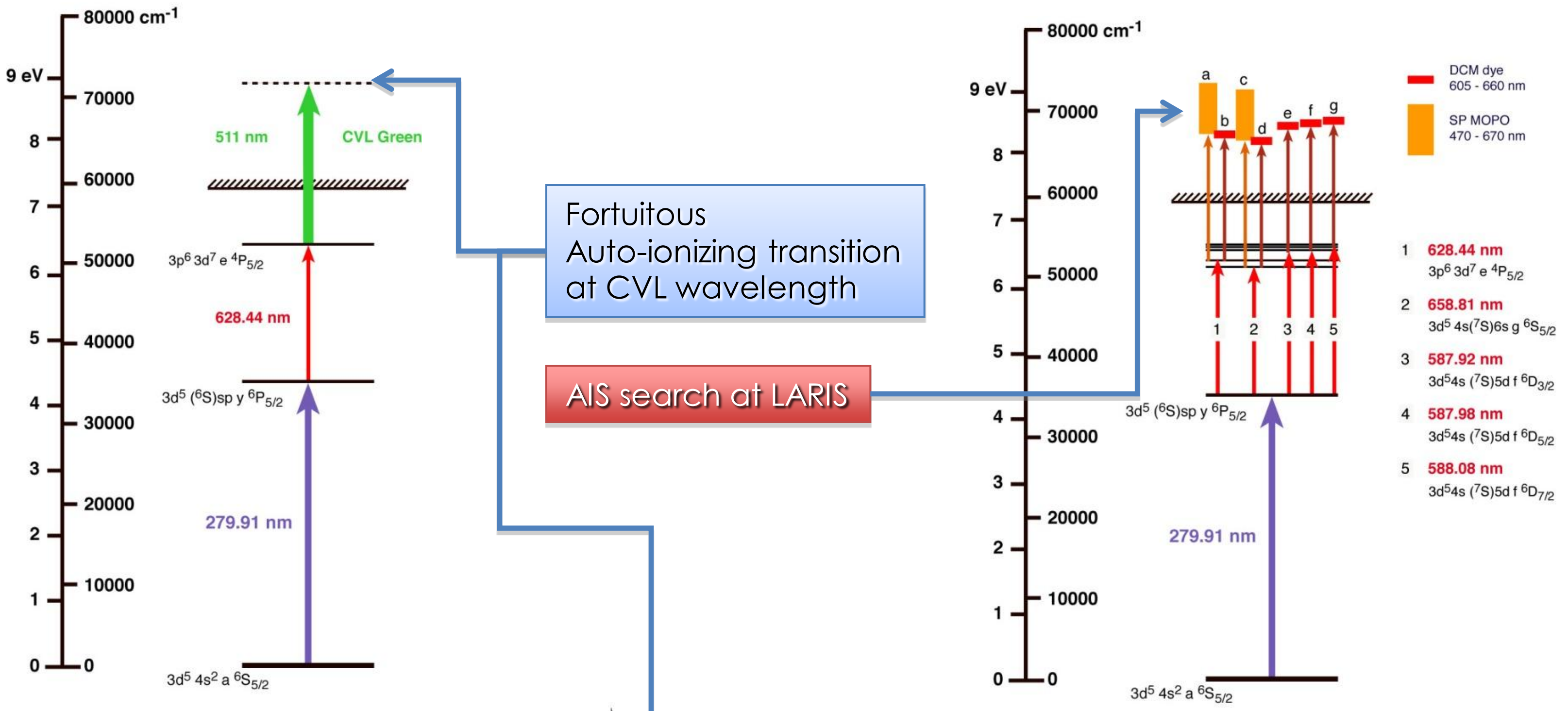
R = 180

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



Change of laser system → A new RILIS scheme for manganese

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



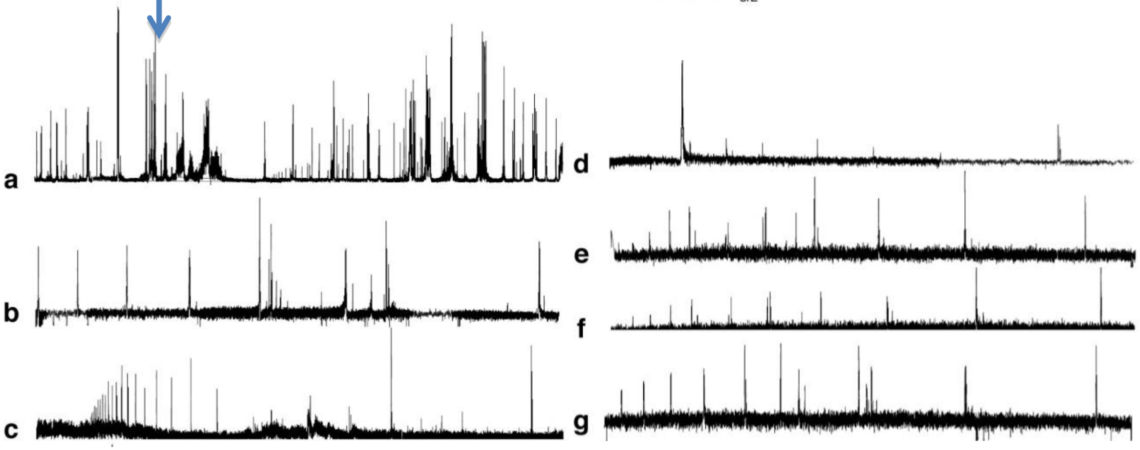
Fortuitous
Auto-ionizing transition
at CVL wavelength

AIS search at LARIS

Outcome of RIS study of Mn at LARIS:

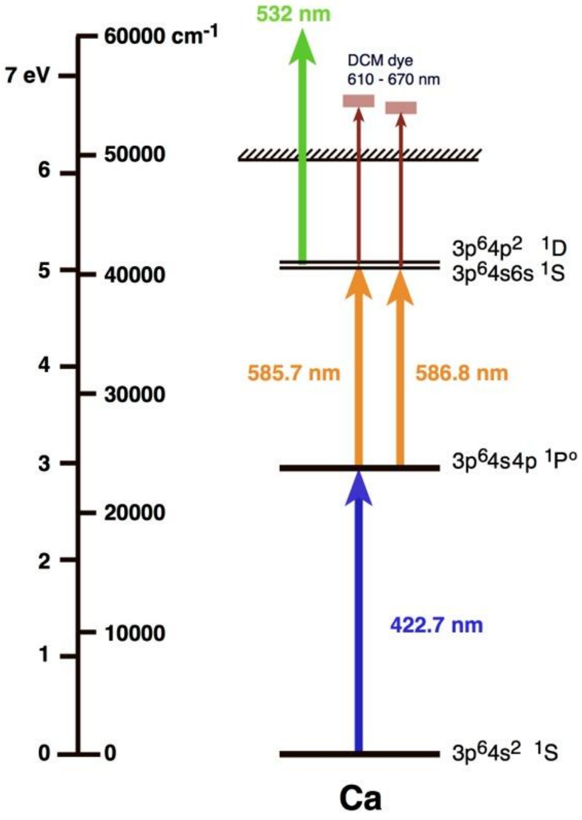
Many new auto-ionizing states found

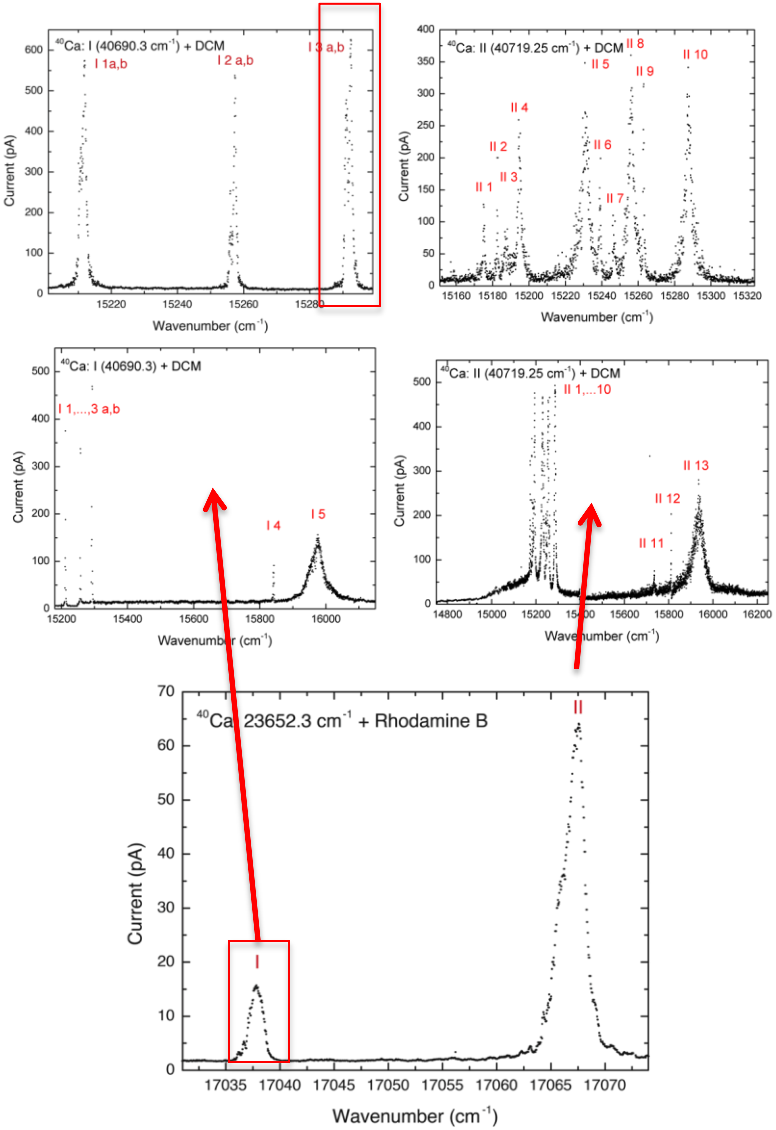
Various promising Nd:YAG based schemes tested and ready for efficiency measurement at RILIS



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





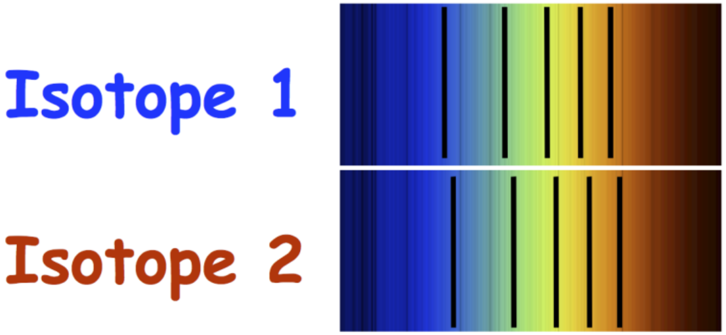
Daniel Fink: PhD work

RESONANCE IONIZATION LASER ION SOURCES – 2 Lectures

- **6)** Selectivity
  - Reducing isobars
  - Isomer selectivity
  - Optical pumping

How do nuclear properites influence the selectivity of the laser ion source?

ISOTOPE SHIFT



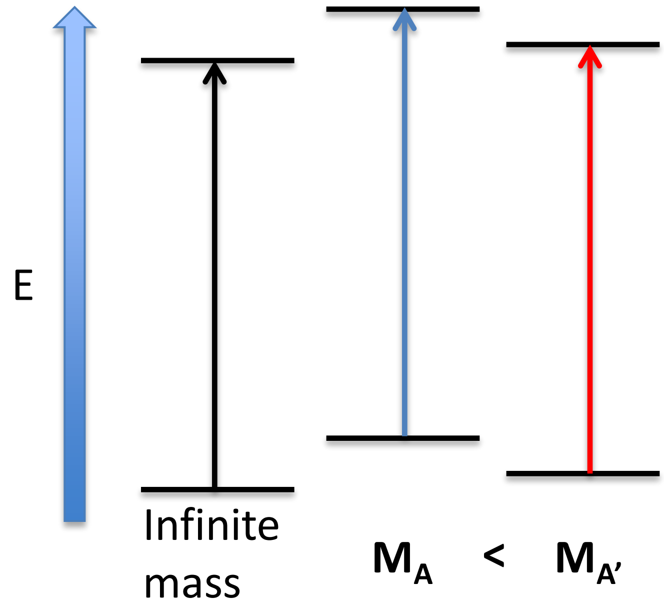
The frequency difference in the electron transition between 2 isotopes of an element

CAUSED BY these nuclear properties:

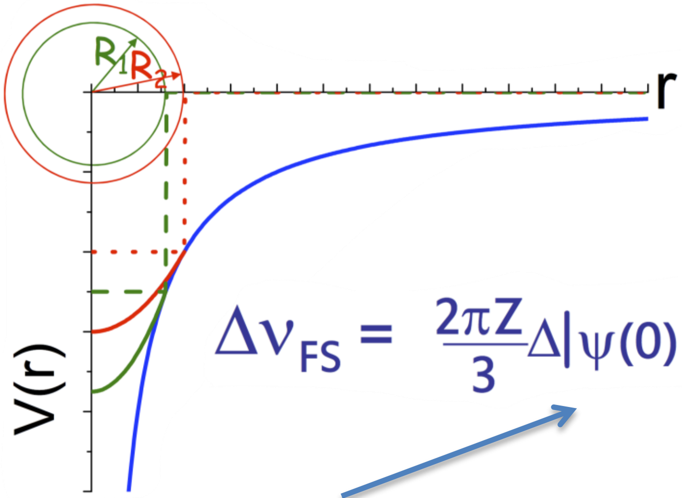
Finite nuclear mass **MASS SHIFT**

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)

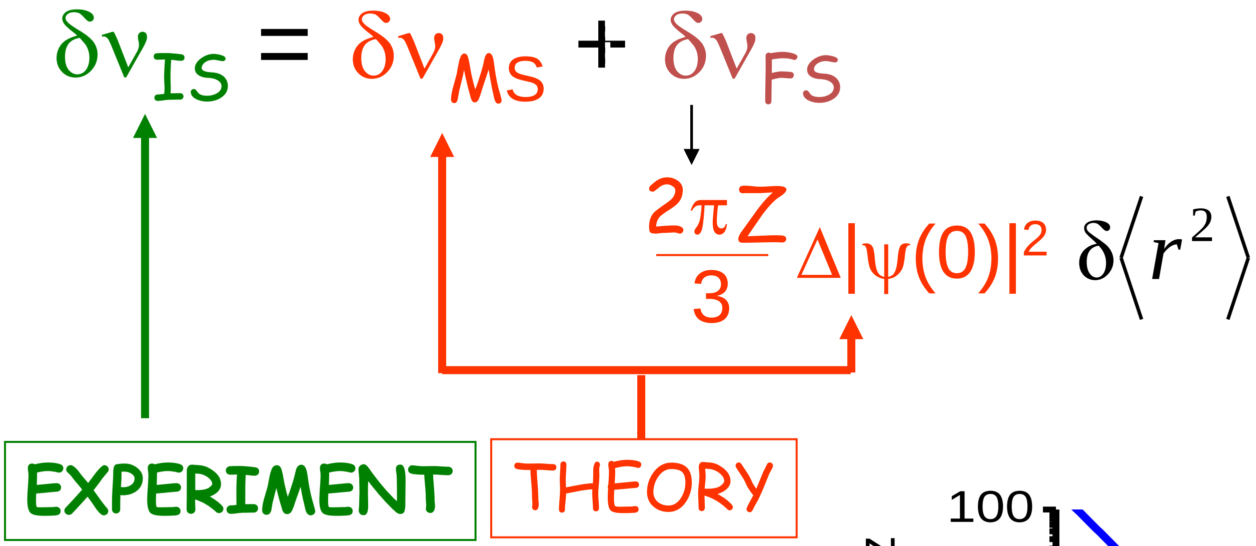
Difference in the mean square nuclear charge radius

(nuclear part)

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

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

Isotope shifts in practise



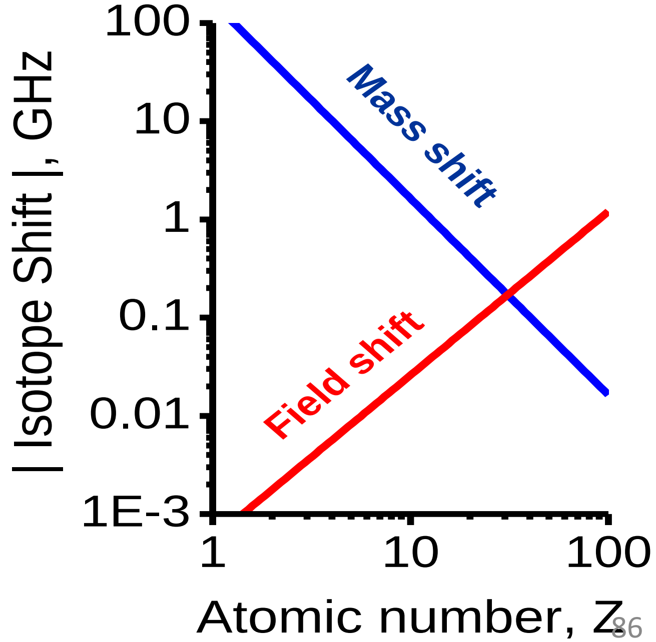
$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

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

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

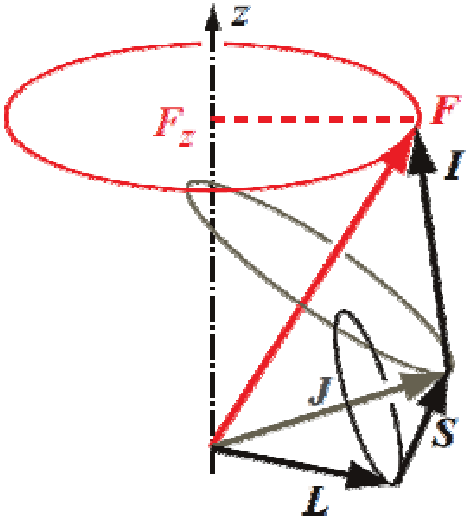


HYPERFINE STRUCTURE

- 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.

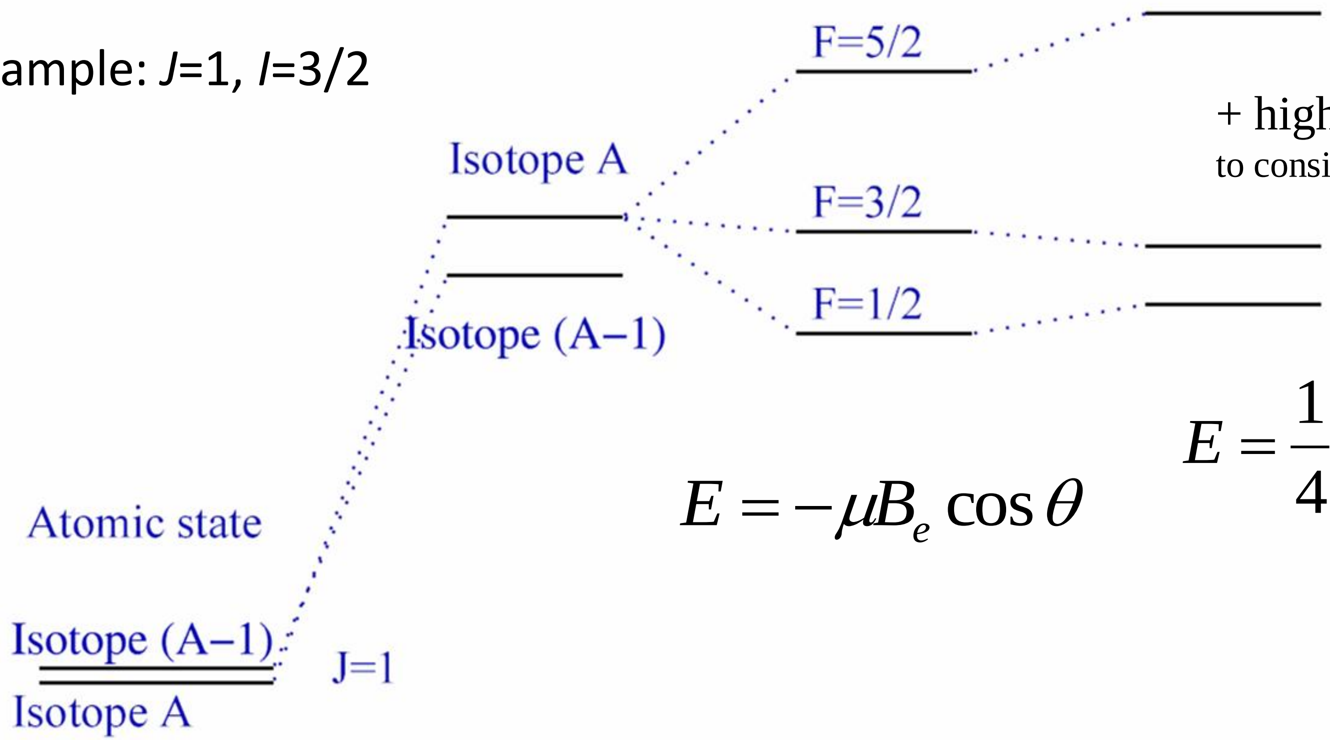
$$\vec{F} = \vec{I} + \vec{J}$$

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

Summarizing the effects:

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

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



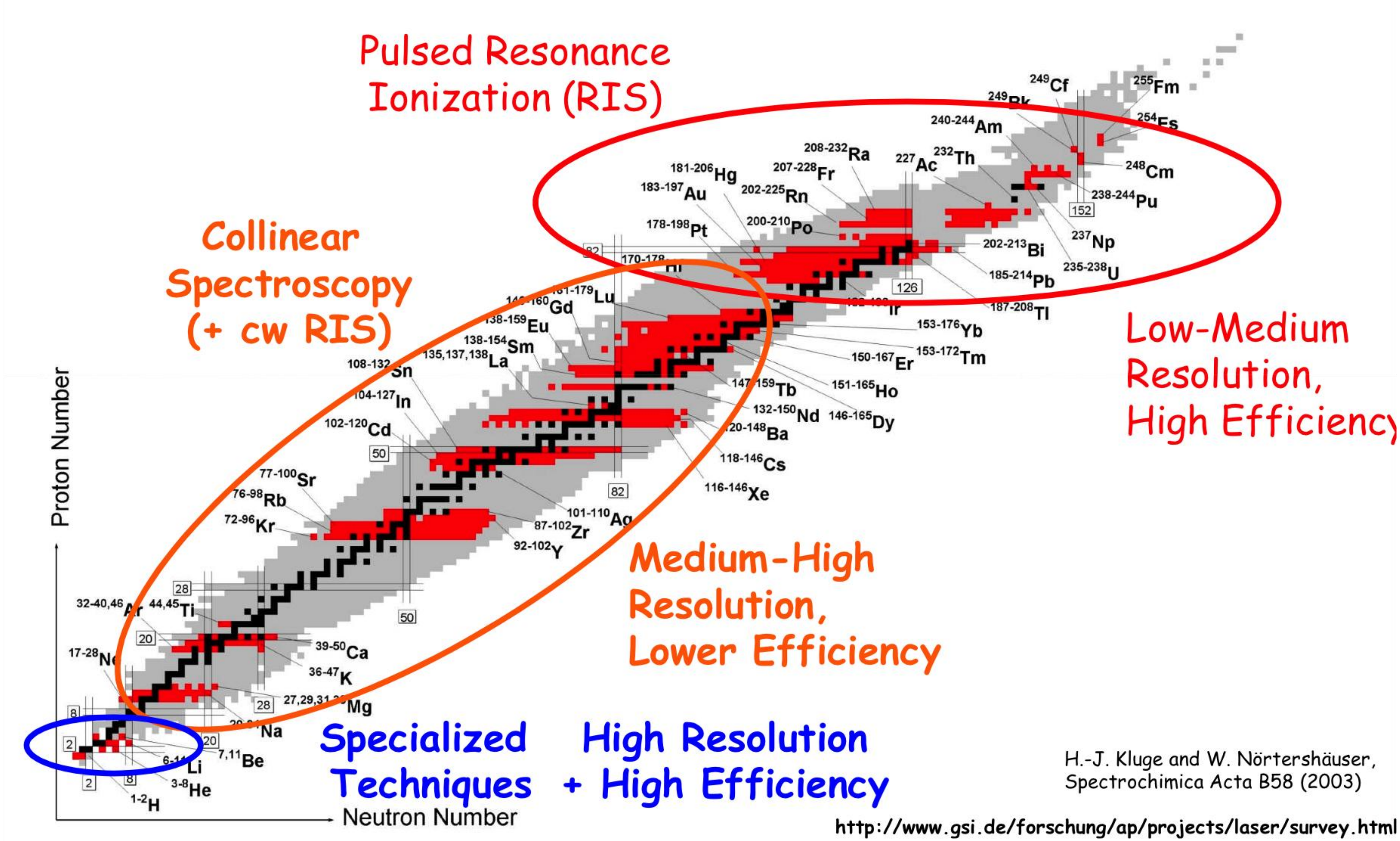
+ higher multipoles (too small to consider in laser measurements)

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

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

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.

Various techniques for different parts of the nuclear chart



Pulsed Resonance Ionization (RIS)

Collinear Spectroscopy (+ cw RIS)

Low-Medium Resolution, High Efficiency

Medium-High Resolution, Lower Efficiency

Specialized Techniques

High Resolution + High Efficiency

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

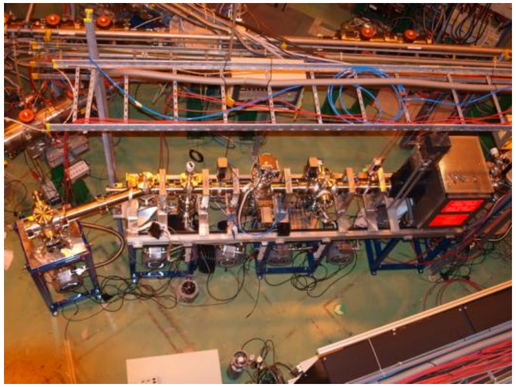
http://www.gsi.de/forschung/ap/projects/laser/survey.html

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

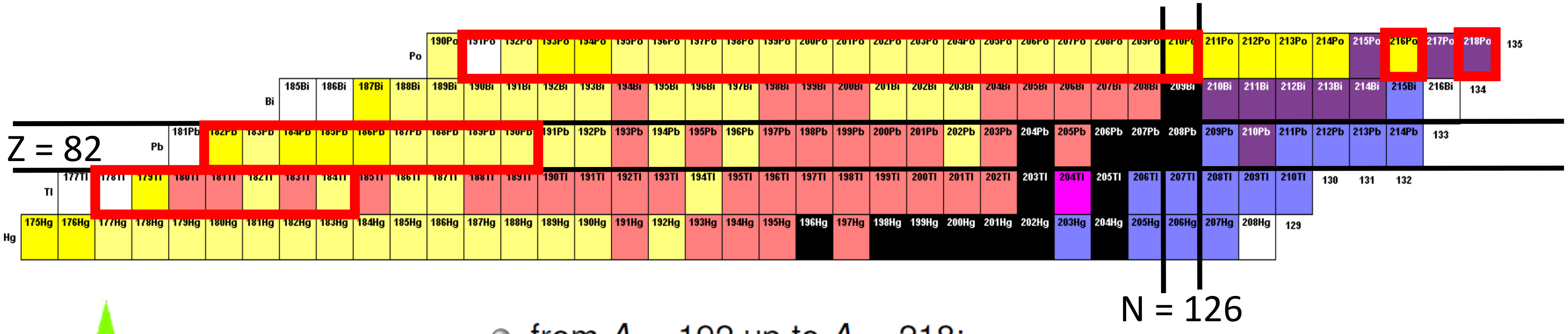
Recent REVIEW article

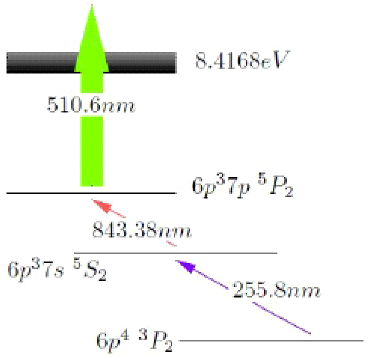
European Laser Spectroscopy Options

- 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

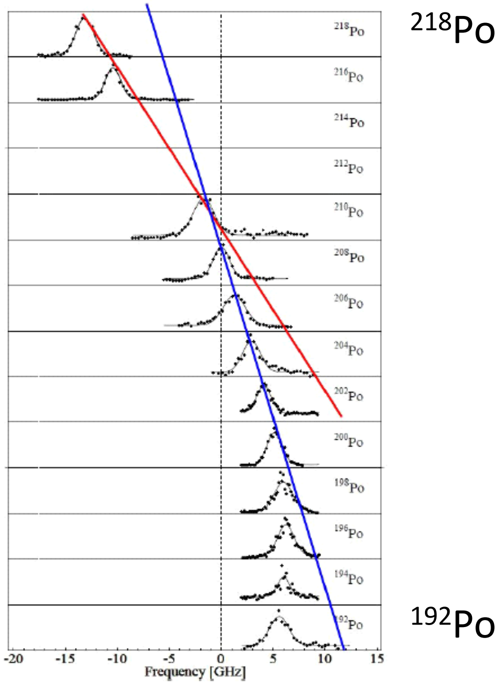


RILIS laser spectroscopy in the Pb region





- 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.

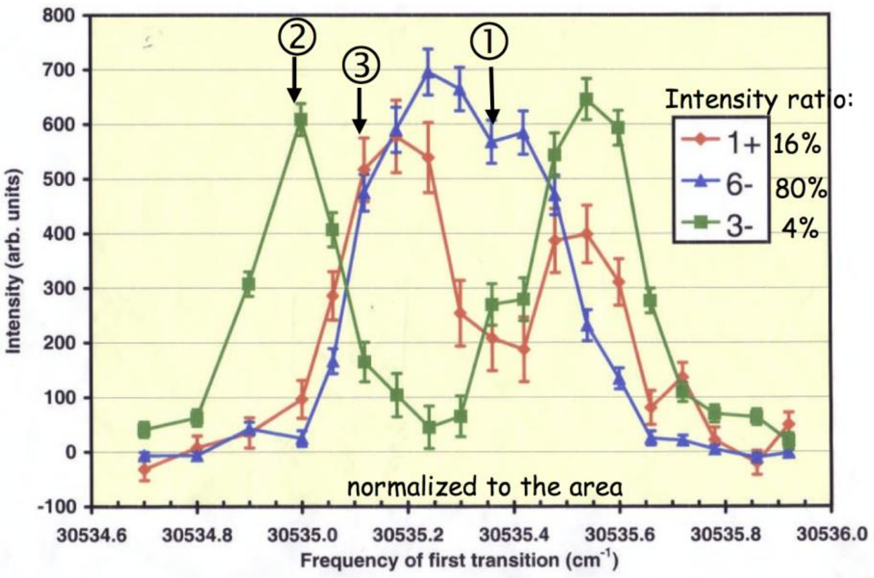


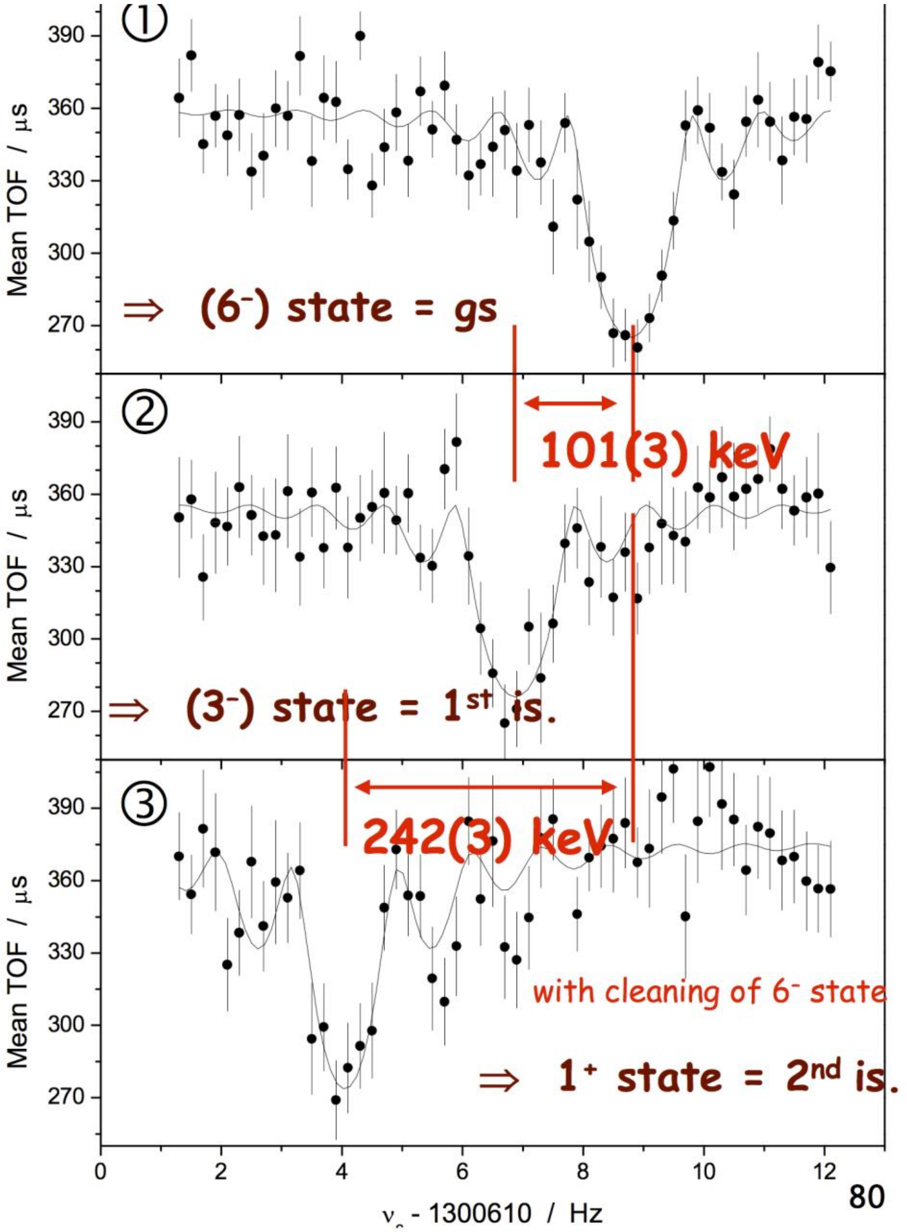
Recent developments for the spectroscopy of At isotopes

KU Leuven

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

Using the Cu HFS for **isomer selective** ionization





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

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).

How to improve the isotope 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

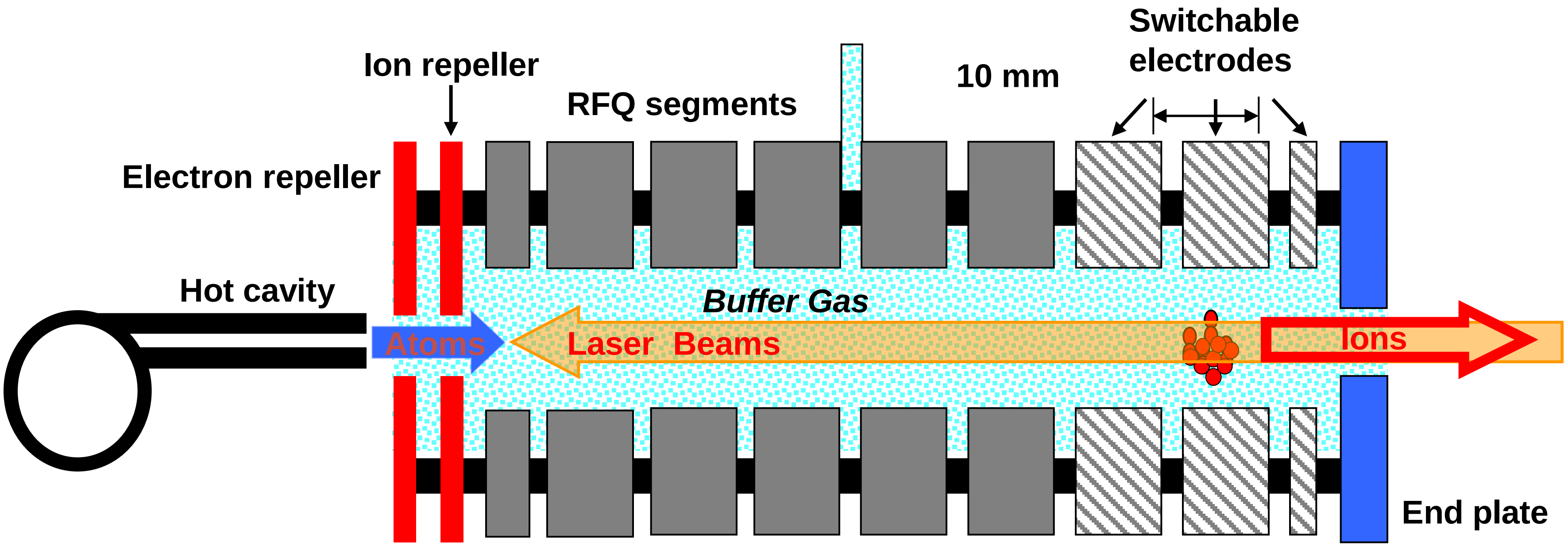
Trap unwanted elements
(add chemical selectivity to the effusion process)

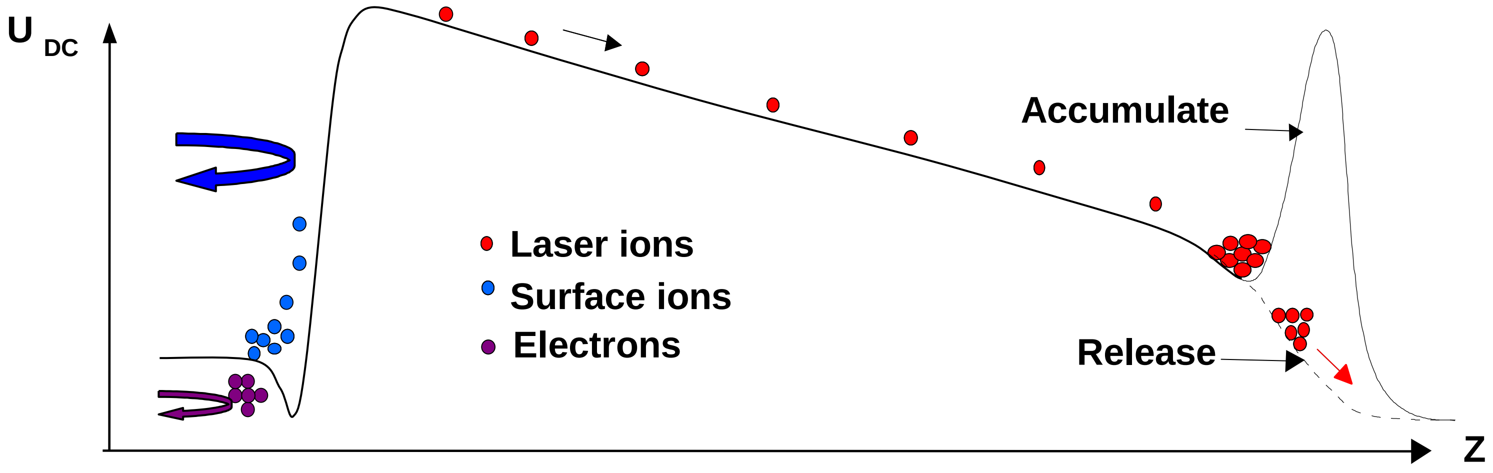
Solution 2 – Separate surface ions from laser ions

Repel surface ions before laser ionization

Temporal separation of laser and surface ions

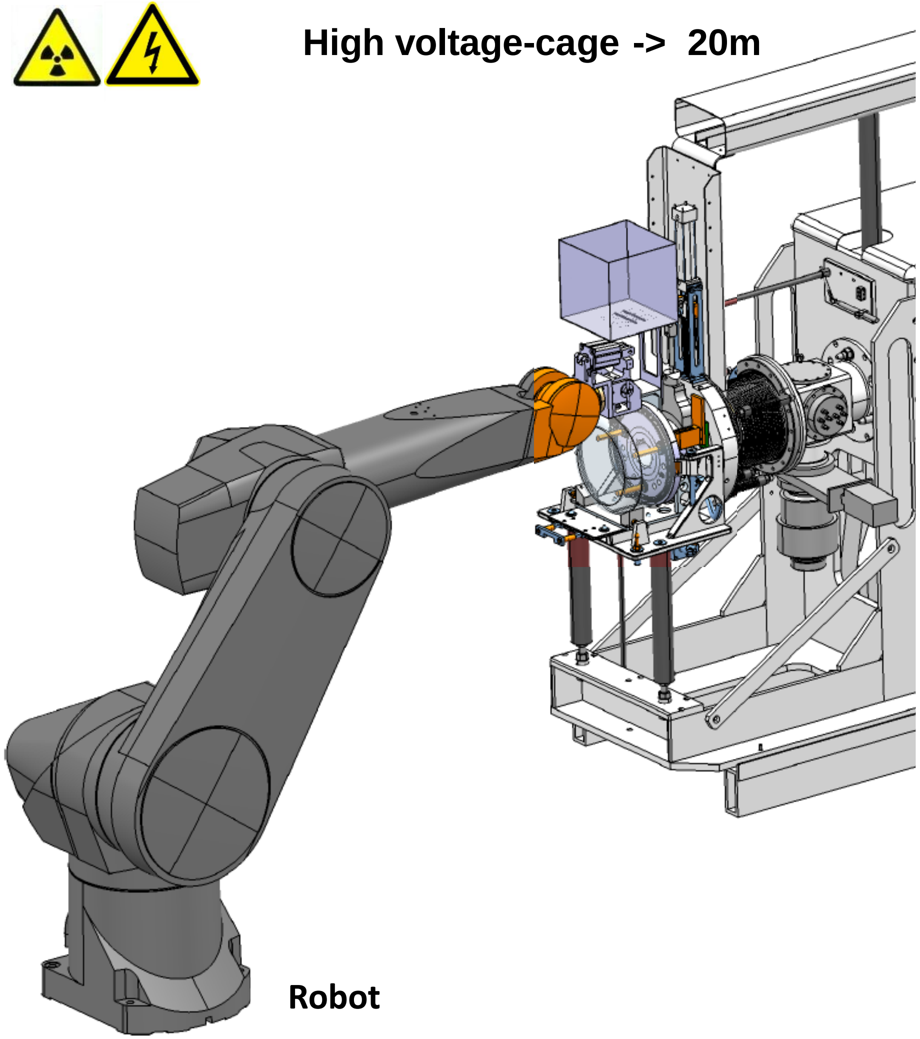
Ideal selective laser ion source? Repeller and trap





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

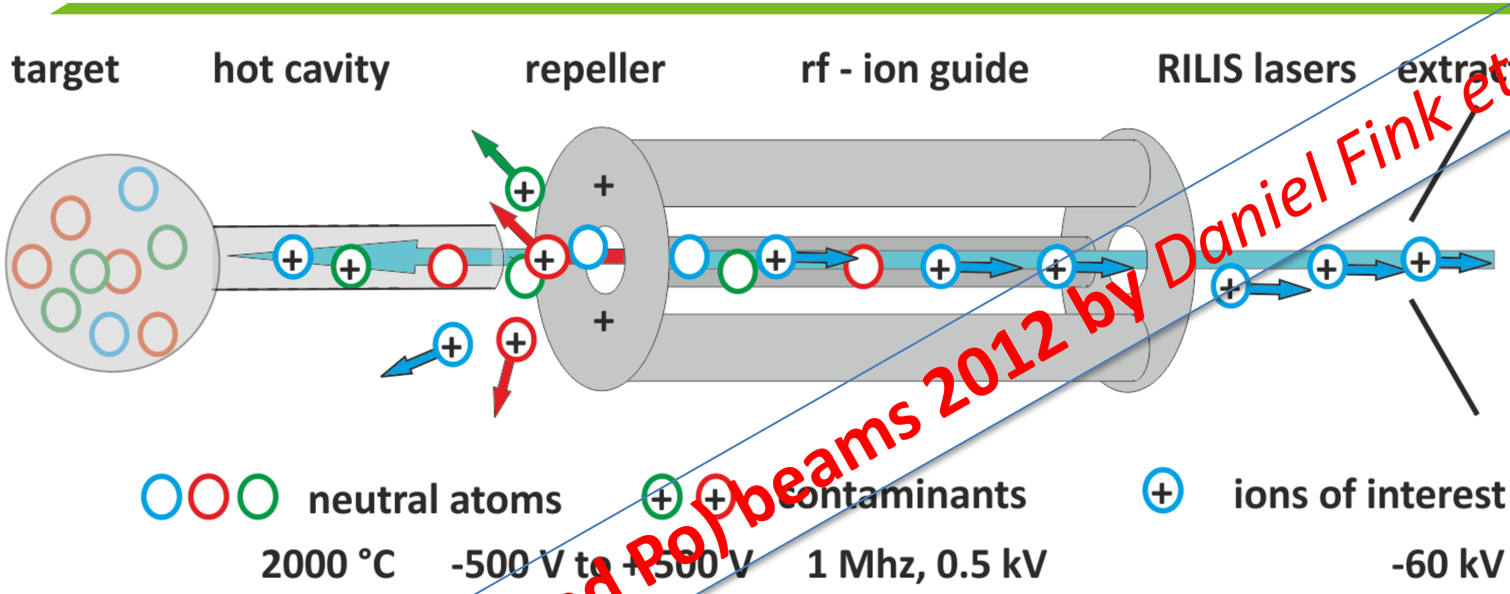
Implementation of such a device



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

⊕⊕ contaminants

⊕ ions of interest

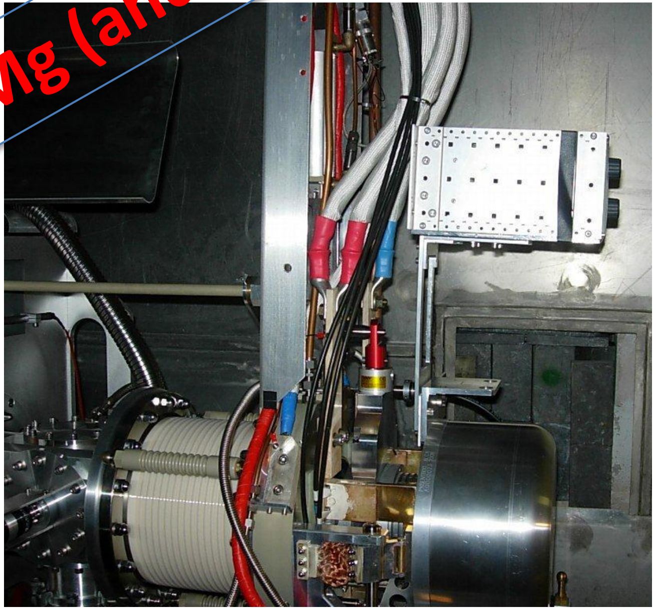
2000 °C

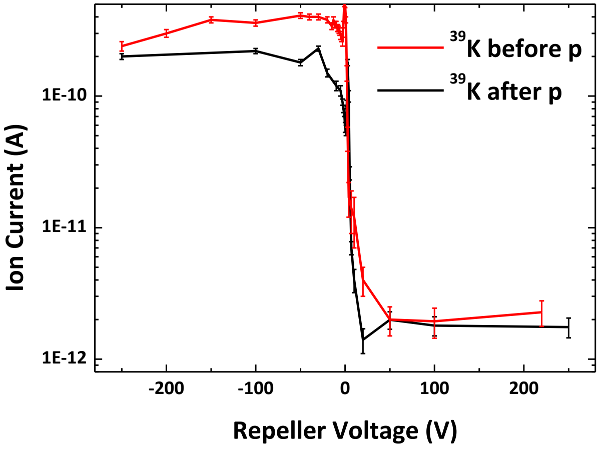
-500 V to +500 V

1 Mhz, 0.5 kV

-60 kV

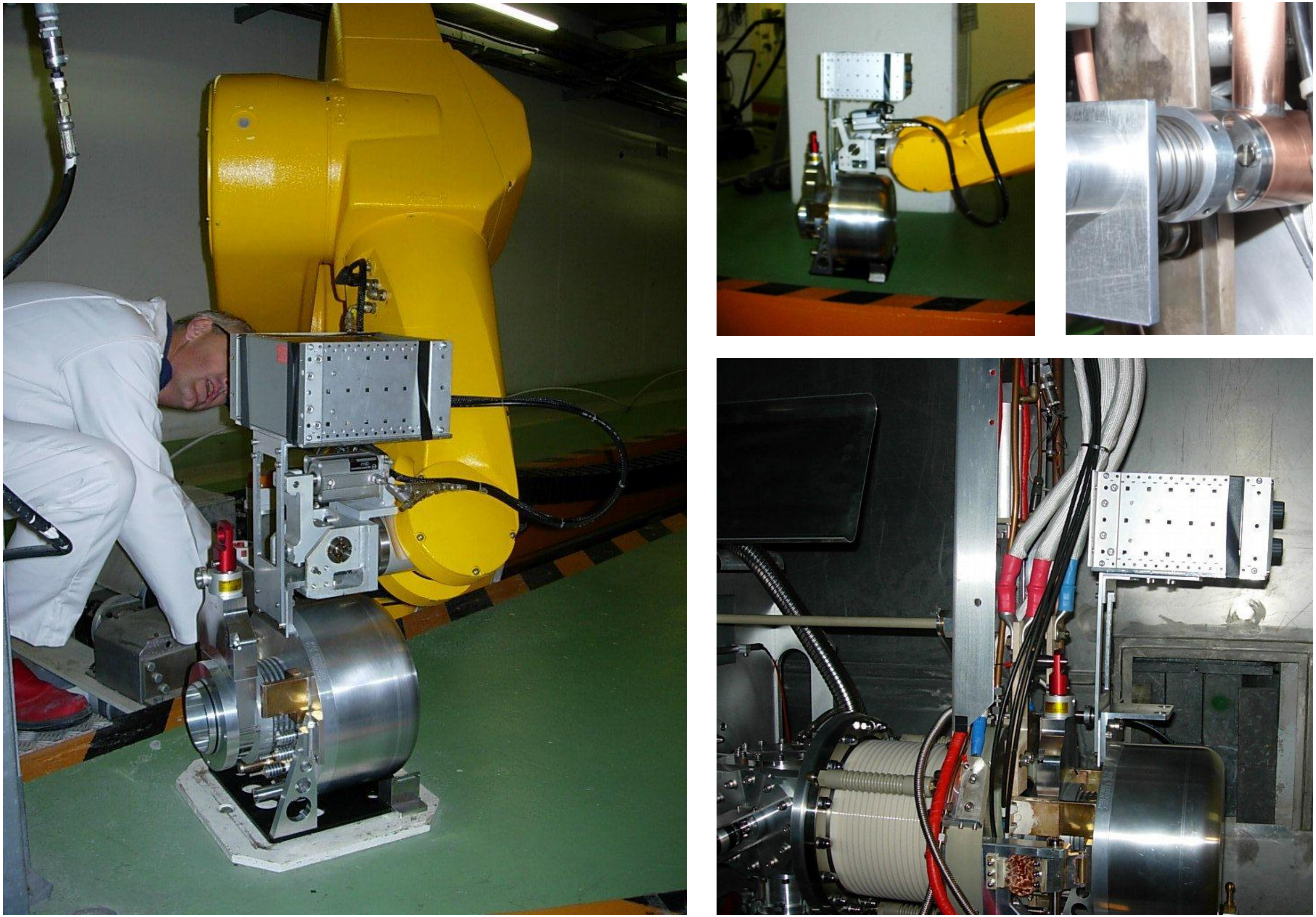
On-line LIST run for Mg (and Po) beams 2012 by Daniel Fink et al!





Daniel Fink - Poster

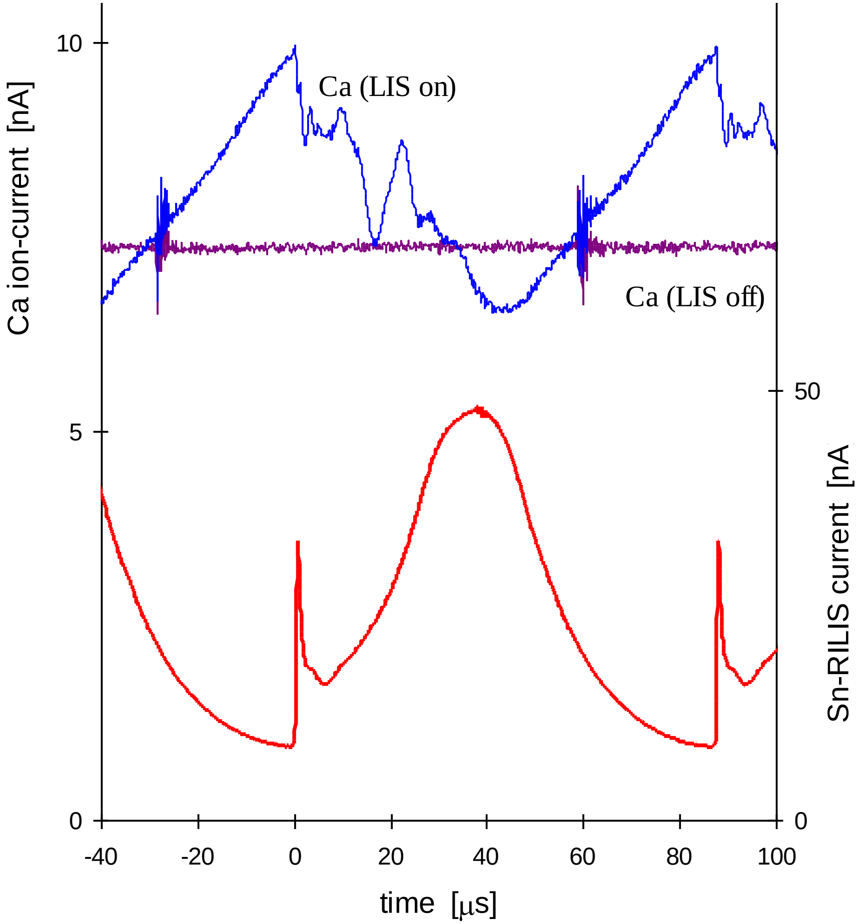
Robot coupling



Micro beam gating – selectivity using the laser ion pulse structure

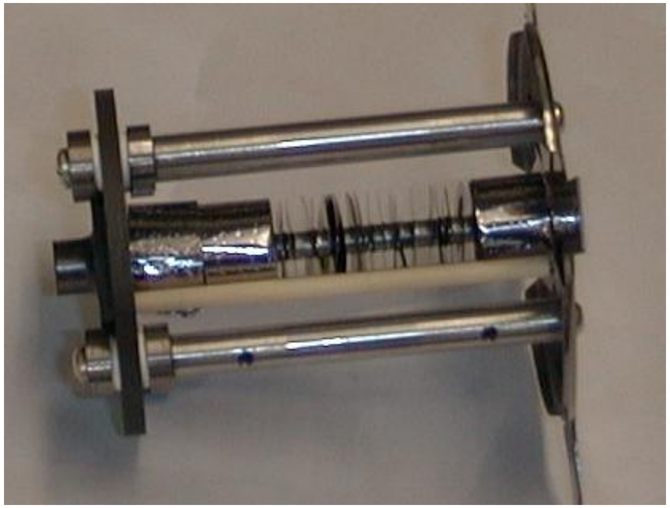
Thinner cavity walls -> more electrical resistance -> higher voltage -> shorter bunch length of laser ions

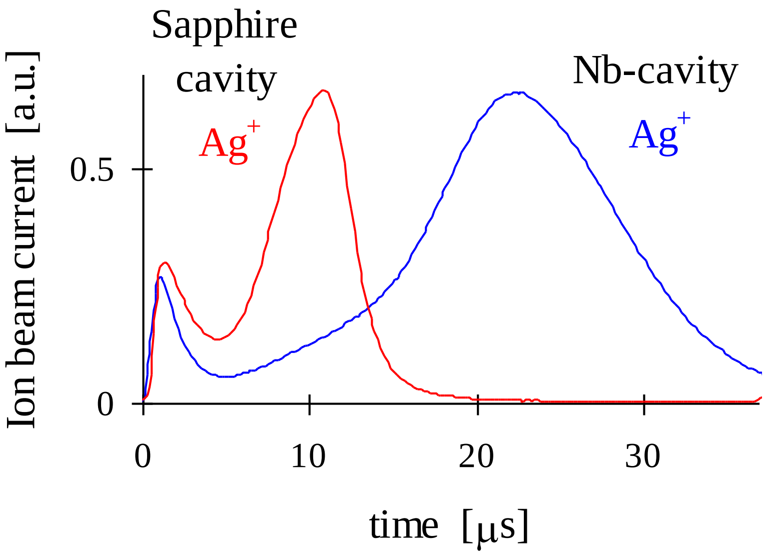
Standard W cavity:



Data presented by J.Lettry at CERN Sept 2007

Thin Nb cavity:



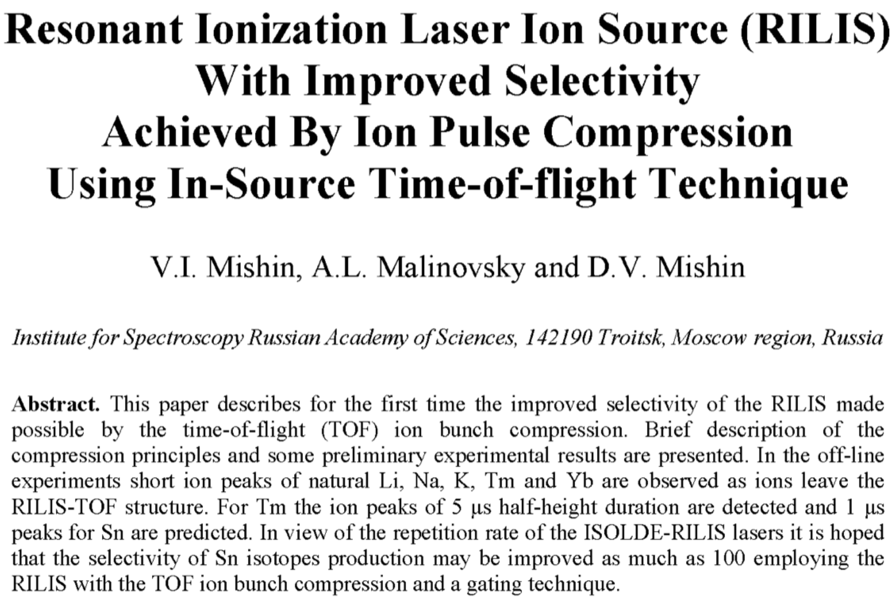


Problem: increased complexity, reliability issues, limited gain in selectivity → How can this concept be improved?

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

al distribution of atoms

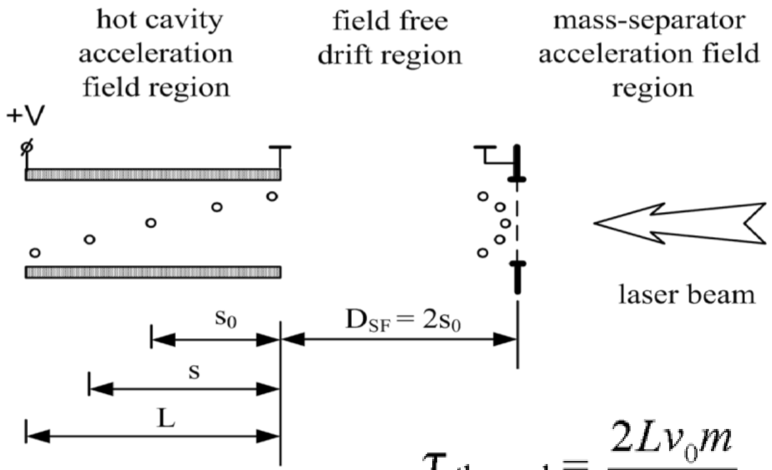


Resonant Ionization Laser Ion Source (RILIS) With Improved Selectivity Achieved By Ion Pulse Compression Using In-Source Time-of-flight Technique

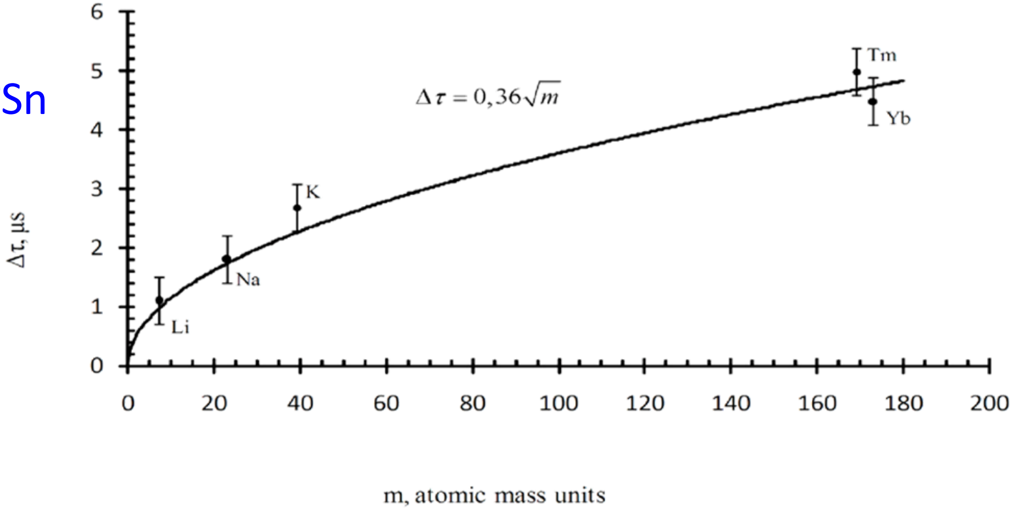
V.I. Mishin, A.L. Malinovsky and D.V. Mishin

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 the 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.



$$\tau_{\text{thermal}} = \frac{2Lv_0 m}{eV}.$$



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

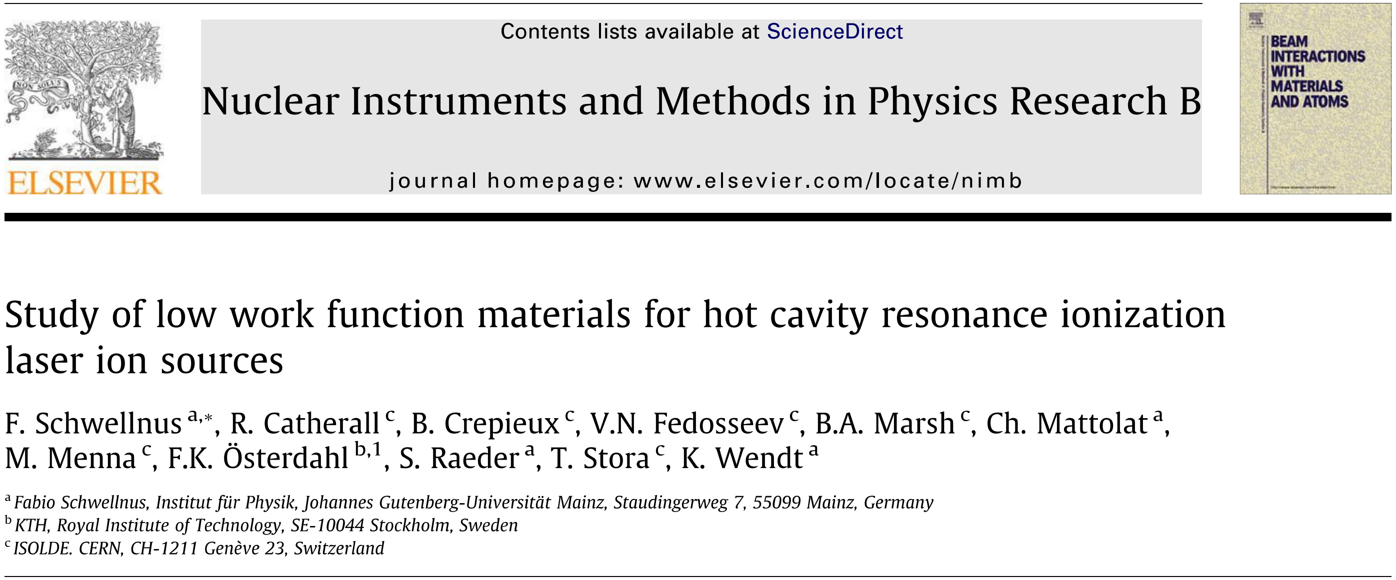
Selectivity = 1/(laser repetition rate x Δτ)

≈ 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:



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journal homepage: www.elsevier.com/locate/nimb

BEAM INTERACTIONS WITH MATERIALS AND ATOMS

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]

[a] *Fabio Schwellnus, Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55099 Mainz, Germany*
[b] *KTH, Royal Institute of Technology, SE-10044 Stockholm, Sweden*
[c] *ISOLDE. CERN, CH-1211 Genève 23, Switzerland*

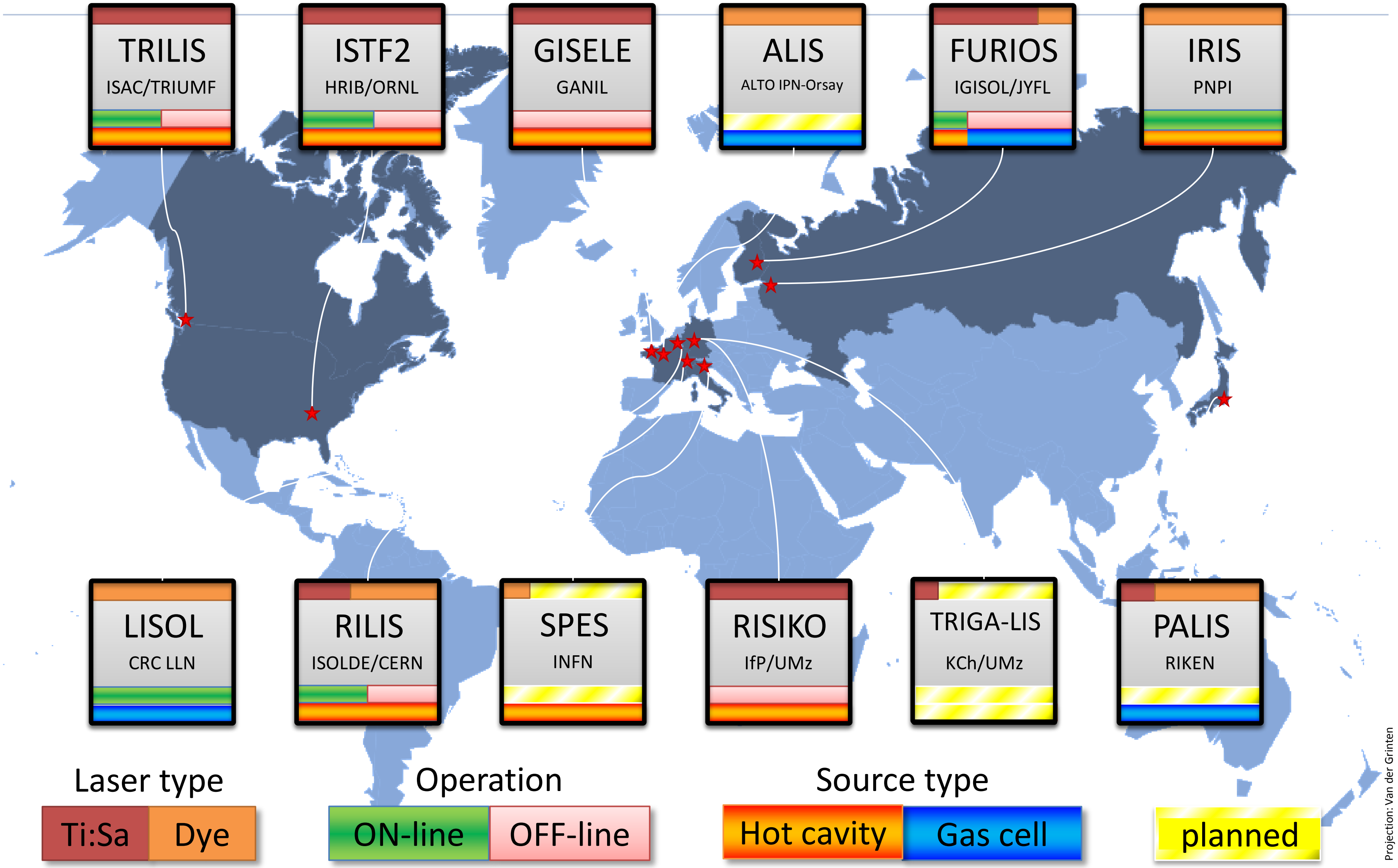
Beam purification by selective trapping in the transfer line of an ISOL target unit
E. Bouquerel, , R. Catherall, M. Eller, J. Lettry, S. Marzari, T. Stora, The ISOLDE Collaboration
CERN, CH-1211, Geneva, Switzerland

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
HRIB/ORNL

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

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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[3] Institute of Spectroscopy RAS, Troitsk, Moscow region, Russia

E-mail: Valentin.Fedosseev@cern.ch

	Z	Scheme	A	Technique	Facility	Reference
Li	3	Four-step-C	8, 9	ABT	UNILAC/GSI	Ewald *et al* 2004
			8–11		ISAC/TRIUMF	Sánchez *et al* 2006
Be	4	Two-step-A	7, 10–12, 14	HC RILIS	ISOLDE/CERN	Köster *et al* 1998
		Three-step-C	10–12		ISAC/TRIUMF	Prime *et al* 2006
		Two-step-A	9–12			Lassen 2011
Mg	12	Three-step-C	23, 27–34	HC RILIS	ISOLDE/CERN	Köster *et al* 2003b
			22			Mukherjee *et al* 2004
			21			Krämer *et al* 2009
		Three-step-C	21, 23, 27, 28		ISAC/TRIUMF	Lassen *et al* 2009
		Three-step-A	20, 21, 23–35			Lassen 2011
Al	13	Two-step-C	26, 28–34	HC RILIS	ISOLDE/CERN	Köster *et al* 2003b
		Two-step-C	26		ISAC/TRIUMF	Prime *et al* 2006
			26, 28, 29			Lassen *et al* 2009
			30–31			Lassen 2011
Ca	20	Three-s				
Mn	25	Three-s				
Fe	26	Two-st				
Co	27	Two-st				
Ni	28	Three-s				
		Two-st				
		Two-st				
Cu	29	Two-st				
		Two-st				
		Two-st				
Zn	30	Three-s				
Ga	31	Two-st				
		Two-st				
		Two-st				
Ge	32	Three-s				
Sr	38	One-st				
Tc	43	Three-s				
Ru	44	Two-st				
Rh	45	Two-st				
		Two-st				
Ag	47	Three-s				
			107m, 122–129			Kratz *et al* 1998
			101–108, 110–129	HC RILIS	ISAC/TRIUMF	Fedoseyev *et al* 2000
		Three-step-C	129–130			Kratz *et al* 2005
			98–107, 109–117			Lassen *et al* 2009
		Two-step-C	97–101	GC RILIS	LISOL/LLN	Darby (to be published)
Cd	48	Three-step-C	131, 132	HC RILIS	ISOLDE/CERN	Hannawald *et al* 2000
			98–105, 107, 109, 111, 115, 117–132			Köster *et al* 2003b
			129–133			Kratz *et al* 2005
In	49	Two-step-C	100–108	HC RILIS	ISOLDE/CERN	Köster 2002a
			132–135			Dillmann *et al* 2002
		Two-step-C	108, 110, 112, 116		ISAC/TRIUMF	Lassen 2011
Sn	50	Three-step-A	101–103, 108	HC RILIS	UNILAC/GSI	Fedoseyev *et al* 1995a
			109–111, 113, 117, 119, 121, 123, 125–137		ISOLDE/CERN	Fedoseyev *et al* 2000
			136–138			Walters *et al* 2005
			105–110, 113, 117, 119, 121, 123, 125, 128–138			Köster *et al* 2008
		Two-step-A	125–132	ABPL		Le Blanc *et al* 2002
		Three-step-A	107–111, 113, 121	HC RILIS	ISAC/TRIUMF	Lassen 2011

	Z	Scheme	A	Technique	Facility	Reference
Sb	51	Three-step-C	128–138	HC RILIS	ISOLDE/CERN	Fedosseev *et al* 2008
			137–139			Arndt *et al* 2012
Te	52	Three-step-C	120, 122–136	ABPL	ISOLDE/CERN	Sifi *et al* 2006
Pr	59	Three-step-C	136, 140	HC RILIS	ISOLDE/CERN	Gottberg 2011
Nd	60	Three-step-C	132, 134–141	ABT	IRIS/PNPI	Letokhov *et al* 1992
			138, 139, 140	HC RILIS	ISOLDE/CERN	Gottberg 2011
Sm	62	Three-step-A	138–143, 145	ABT	IRIS/PNPI	Mishin *et al* 1987b
			140–143	HC RILIS	ISOLDE/CERN	Gottberg 2011
Eu	63	Three-step-A	145–150	ABT	IRIS/PNPI	Alkhazov *et al* 1983
			141–144			Fedoseyev *et al* 1984
			155–159			Alkhazov *et al* 1990a
			138–145			Letokhov *et al* 1992
			137–139, 141–144	HC RILIS		Barzakh *et al* 2004
Gd	64	Three-step-A	146, 148, 150	ABT	IRIS/PNPI	Alkhazov *et al* 1988
			143, 145, 146	HC RILIS		Barzakh *et al* 2005
						zov *et al* 1990b
						r *et al* 2003b
						erg 2011
						zov *et al* 1989a
						zov *et al* 1991
						n *et al* 1987a
						kh *et al* 2000
						z *et al* 1991
						zov *et al* 1992
						kh *et al* 2000
						kh *et al* 2002
						n *et al* 1993
						erg 2011
						y *et al* 2000
						al 1988
						g *et al* 1989
						ath *et al* 1992
						anc *et al* 1999
						neroth *et al* 1987
						rt *et al* 1987
						al 1987a
						al 1987b
						d *et al* 1990
						rt *et al* 1991
						anc *et al* 1992
						ge *et al* 2000
						v *et al* 2010
						yak 2010
						et al 1992
						r *et al* 2003b
						kh *et al* 2012
						yev *et al* 2002
			184–203, 205, 209–215			Köster 2002b
			183–203, 215			Köster *et al* 2003b
			182–190			Seliverstov *et al* 2006
Bi	83	Three-step-C	188–208, 210–218	HC RILIS	ISOLDE/CERN	Köster *et al* 2003b
Po	84	Three-step-C	193–198, 200, 202, 204	HC RILIS	ISOLDE/CERN	Cocolios *et al* 2008
			192–210, 216, 218 (even)			Cocolios *et al* 2011
			191–203, 209, 211 (odd)			Seliverstov *et al* 2012
At	85	Three-step-C	198, 199, 212, 217, 218	HC RILIS	ISAC/TRIUMF	Lassen 2011
		Two-step-C	197–202		ISOLDE/CERN	Rothe *et al* 2012
		Three-step-C	193–205, 217			
		Three-step-R	205			
Fr	87	Two-step-C	221	HC RILIS	ISAS[a], Troitsk	Andreev *et al* 1986b
		Two-step-R	221			Andreev *et al* 1987
Ac	89	Two-step-A	212, 213	GC RILIS	LISOL/LLN	to be published
			225	HC RILIS	ISAC/TRIUMF	Lassen 2011
Th	90	Two-step-C	230	RIMS	LANL[b], USA	Johnson and Fearey 1993
		Three-step-A	228–230		Mainz University	Raeder *et al* 2011b
Np	93	Two-step-A	237	RIMS	Mainz University	Riegel *et al* 1993
		Three-step-A				
Pu	94	Three-step-A	239–242, 244	RIMS	Mainz University	Ruster *et al* 1989
Am	95	Three-step-R	243	RIMS	Mainz University	Erdmann *et al* 1998

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

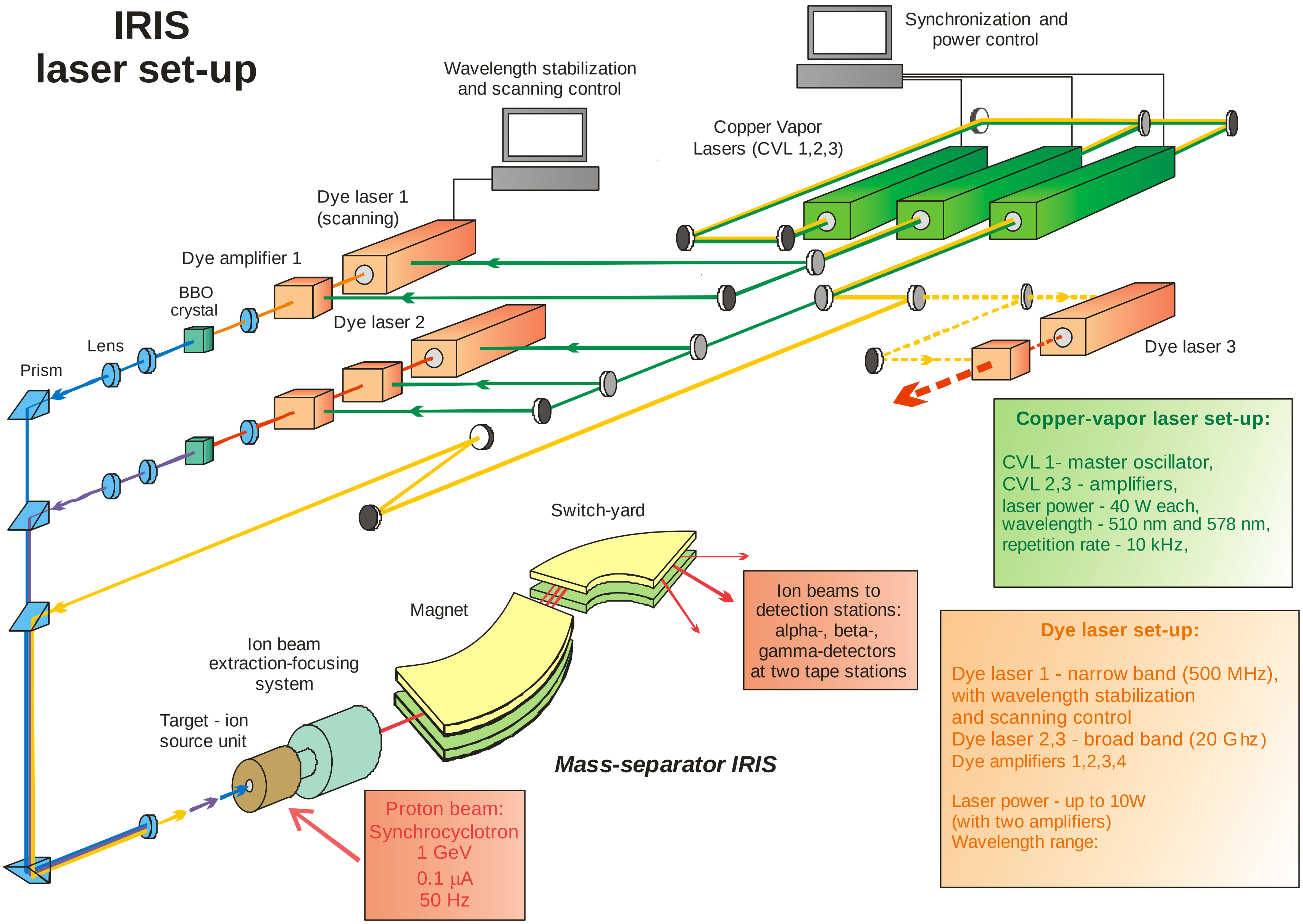
LIS (Laser Ion Source) – method of laser ionization in a hot metal cavity - invented and firstly applied at IRIS [1,2]

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



Synchronization and power control

Wavelength stabilization and scanning control

Copper Vapor Lasers (CVL 1,2,3)

Dye laser 1 (scanning)

Dye amplifier 1

BBO crystal

Dye laser 2

Lens

Prism

Dye laser 3

Switch-yard

Magnet

Ion beam extraction-focusing system

Target - ion source unit

Mass-separator IRIS

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

Proton beam:
Synchrocyclotron
1 GeV
0.1 µA
50 Hz

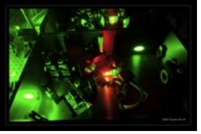
Copper-vapor laser set-up:

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

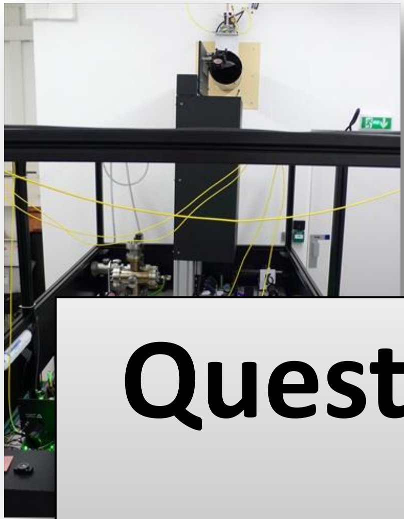
Laser power - up to 10W
(with two amplifiers)
Wavelength range:

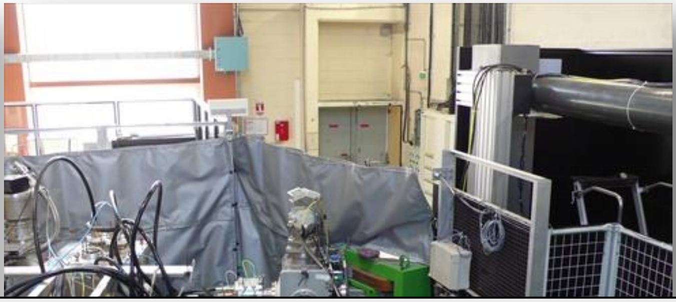


NEW GISELE @ GANIL

GANIL Ion Source using Electron Laser Excitation

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

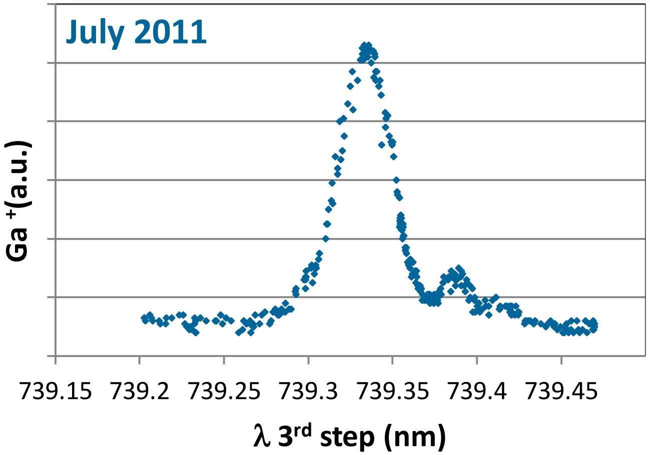




3 TiSa cavities from TRIUMF

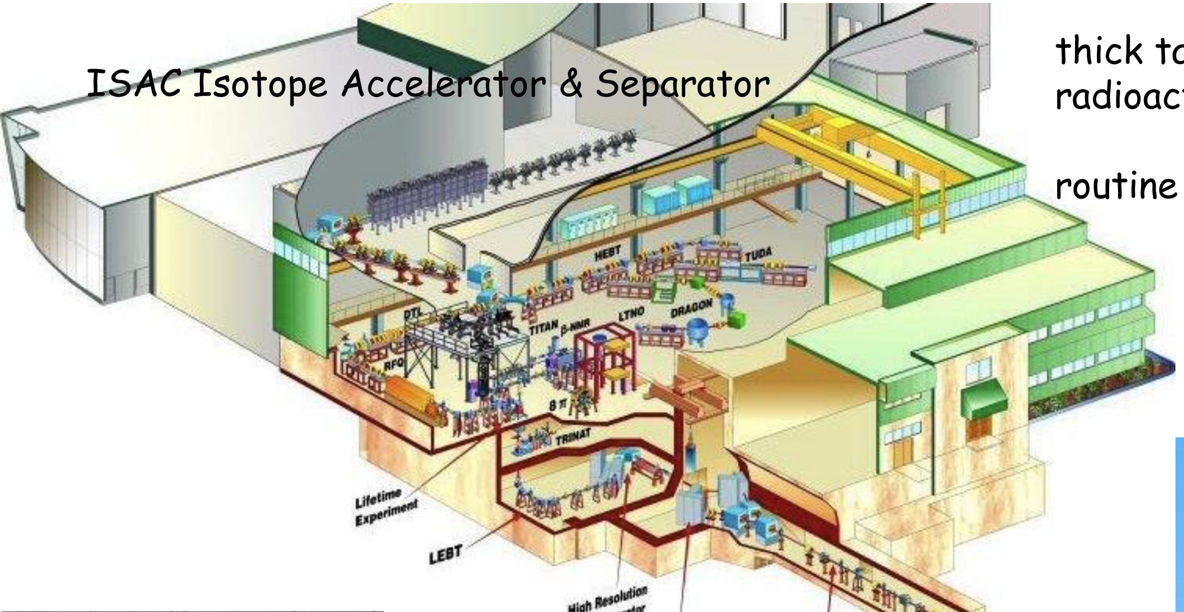
Questions? Ask Nathalie Lecesne or Marica Sjodin!

U.



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

ISAC Isotope Accelerator & Separator



thick target – hot cavity ISOL based radioactive ion beam facility

routine operation at the licensing limit:

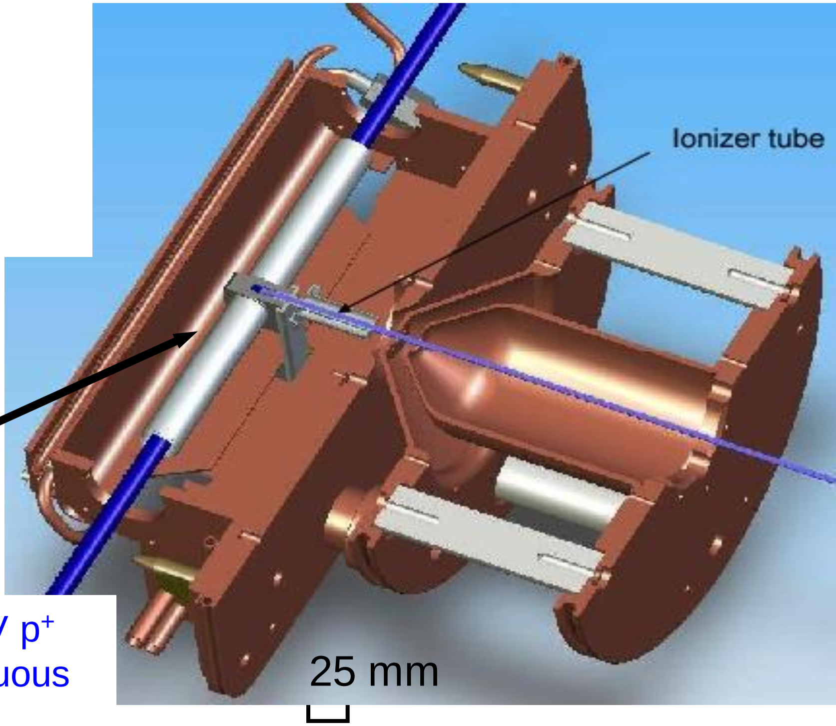
100 μA p+ on A<81 targets (up to 50kW)
10 μA p+ on UC_x targets

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

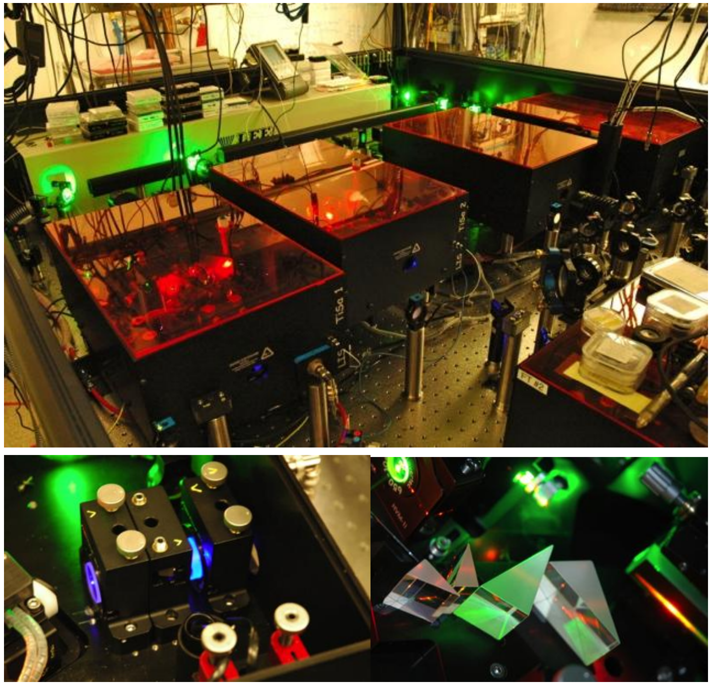
carbide etc. targets

metal foil targets

target



500 MeV p^+
continuous



TiSa laser specifications:

Repetition rate 10 kHz

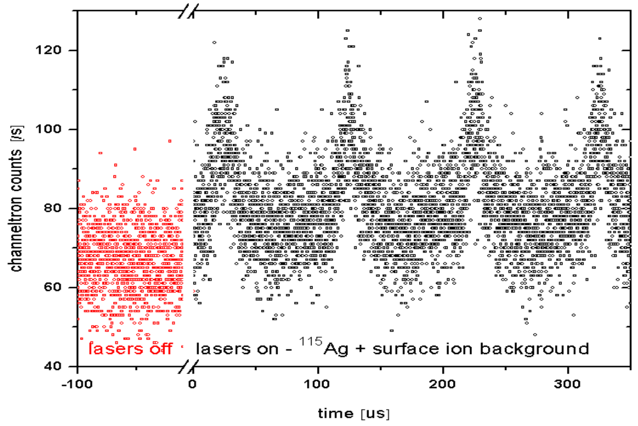
Wavelength range
- fund. 3W, 690 – 990 nm
- 2ν 500mW, 350 – 490 nm
- 3ν 100mW, 233 – 320 nm
- 4ν 100mW, 205 – 232 nm

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

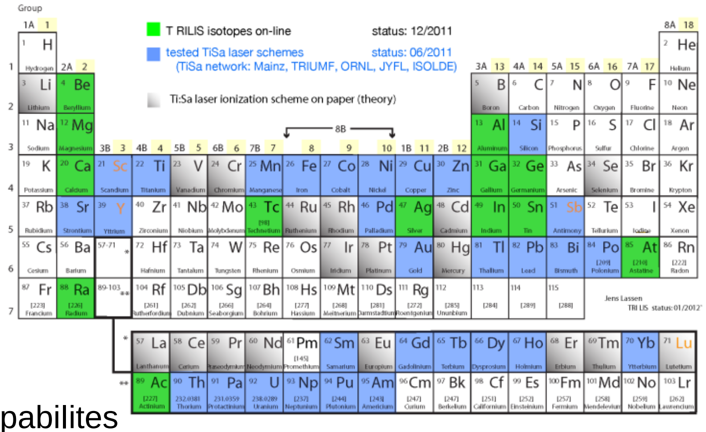
Spatial beam quality $M^2 < 1.2$

Spectral bandwidth 3–5 GHz

Temporal pulse duration 30–50 ns



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



🟩 T RILIS isotopes on-line status: 12/2011

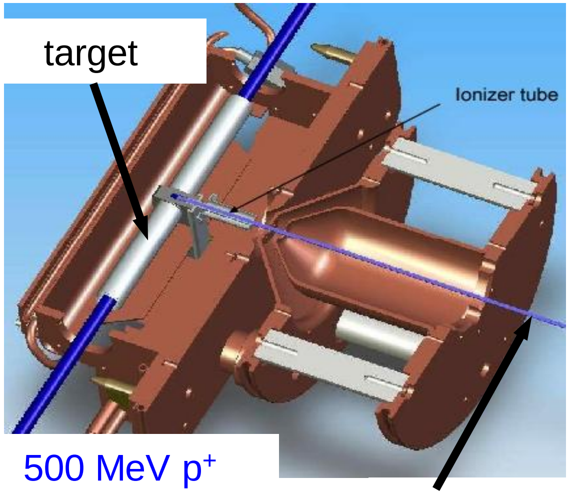
🟦 tested TiSa laser schemes status: 06/2011
(TiSa network: Mainz, TRIUMF, ORNL, JYFL, ISOLDE)

▨ Ti:Sa laser ionization scheme on paper (theory)

Group	1A 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	8B 8	9	10	1B 11	2B 12	3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1	1 H Hydrogen																	2 He Helium
2	▨ 3 Li Lithium	🟩 4 Be Beryllium											▨ 5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3	11 Na Sodium	🟩 12 Mg Magnesium											🟩 13 Al Aluminum	🟦 14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
4	19 K Potassium	🟩 20 Ca Calcium	🟦 21 Sc Scandium	🟦 22 Ti Titanium	▨ 23 V Vanadium	▨ 24 Cr Chromium	🟦 25 Mn Manganese	🟦 26 Fe Iron	🟦 27 Co Cobalt	🟦 28 Ni Nickel	🟦 29 Cu Copper	🟦 30 Zn Zinc	🟩 31 Ga Gallium	🟩 32 Ge Germanium	33 As Arsenic	▨ 34 Se Selenium	35 Br Bromine	36 Kr Krypton
5	37 Rb Rubidium	🟦 38 Sr Strontium	🟦 39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	🟩 43 Tc [98] Technetium	▨ 44 Ru Ruthenium	▨ 45 Rh Rhodium	🟦 46 Pd Palladium	🟩 47 Ag Silver	▨ 48 Cd Cadmium	🟩 49 In Indium	🟩 50 Sn Tin	🟦 51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
6	55 Cs Cesium	56 Ba Barium	57-71 *	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	▨ 77 Ir Iridium	▨ 78 Pt Platinum	🟦 79 Au Gold	▨ 80 Hg Mercury	🟦 81 Tl Thallium	🟦 82 Pb Lead	🟦 83 Bi Bismuth	🟦 84 Po [209] Polonium	🟩 85 At [210] Astatine	86 Rn [222] Radon
7	87 Fr [223] Francium	🟩 88 Ra [226] Radium	89-103 **	104 Rf [261] Rutherfordium	105 Db [262] Dubnium	106 Sg [266] Seaborgium	107 Bh [264] Bohrium	108 Hs [277] Hassium	109 Mt [268] Meitnerium	110 Ds [281] Darmstadtium	111 Rg [272] Roentgenium	112 [285] Ununbium	113 [284]	114 [289]	115 [288]			

*	▨ 57 La Lanthanum	▨ 58 Ce Cerium	▨ 59 Pr Praseodymium	▨ 60 Nd Neodymium	61 Pm [145] Promethium	🟦 62 Sm Samarium	▨ 63 Eu Europium	🟦 64 Gd Gadolinium	🟦 65 Tb Terbium	🟦 66 Dy Dysprosium	🟦 67 Ho Holmium	▨ 68 Er Erbium	▨ 69 Tm Thulium	🟦 70 Yb Ytterbium	▨ 71 Lu Lutetium
**	🟩 89 Ac [227] Actinium	🟦 90 Th 232.0381 Thorium	🟦 91 Pa 231.0359 Protactinium	🟦 92 U 238.0289 Uranium	🟦 93 Np [237] Neptunium	🟦 94 Pu [244] Plutonium	🟦 95 Am [243] Americium	96 Cm [247] Curium	97 Bk [247] Berkelium	98 Cf [251] Californium	99 Es [252] Einsteinium	100 Fm [257] Fermium	101 Md [258] Mendelevium	102 No [259] Nobelium	103 Lr [262] Lawrencium

Jens Lassen
TRI LIS status: 01/2012



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

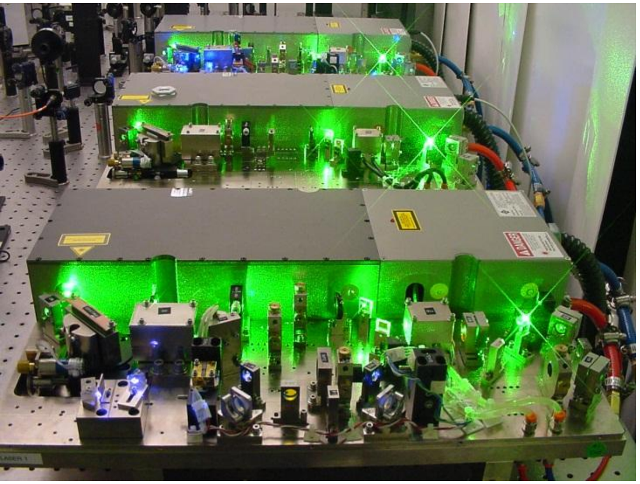
Development:

(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

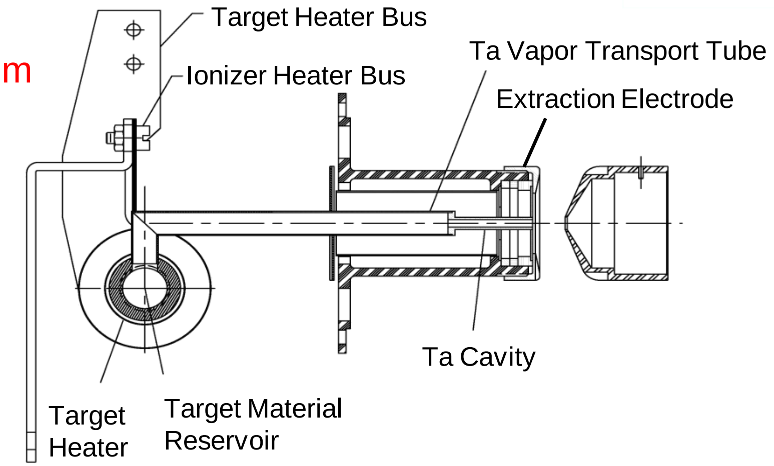
Hot-Cavity Laser Ion Source at HRIBF-ORNL

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

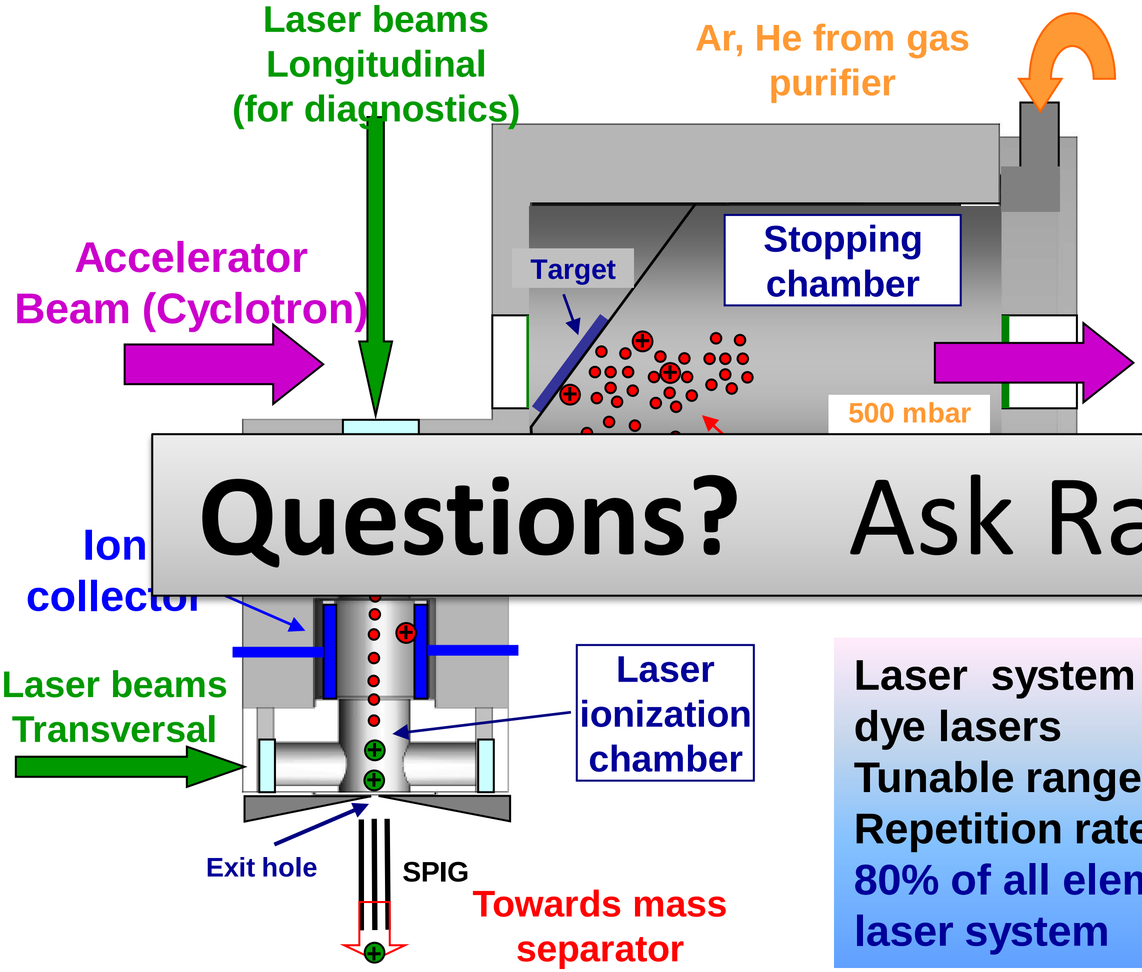
  Sn, Ni, Ge, Cu, Co, Ga, Sr, Mn, Fe, Al, Ho, Tb, Dy, Te

- 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

^{2}Cf

Questions? Ask Rafael Ferrer!

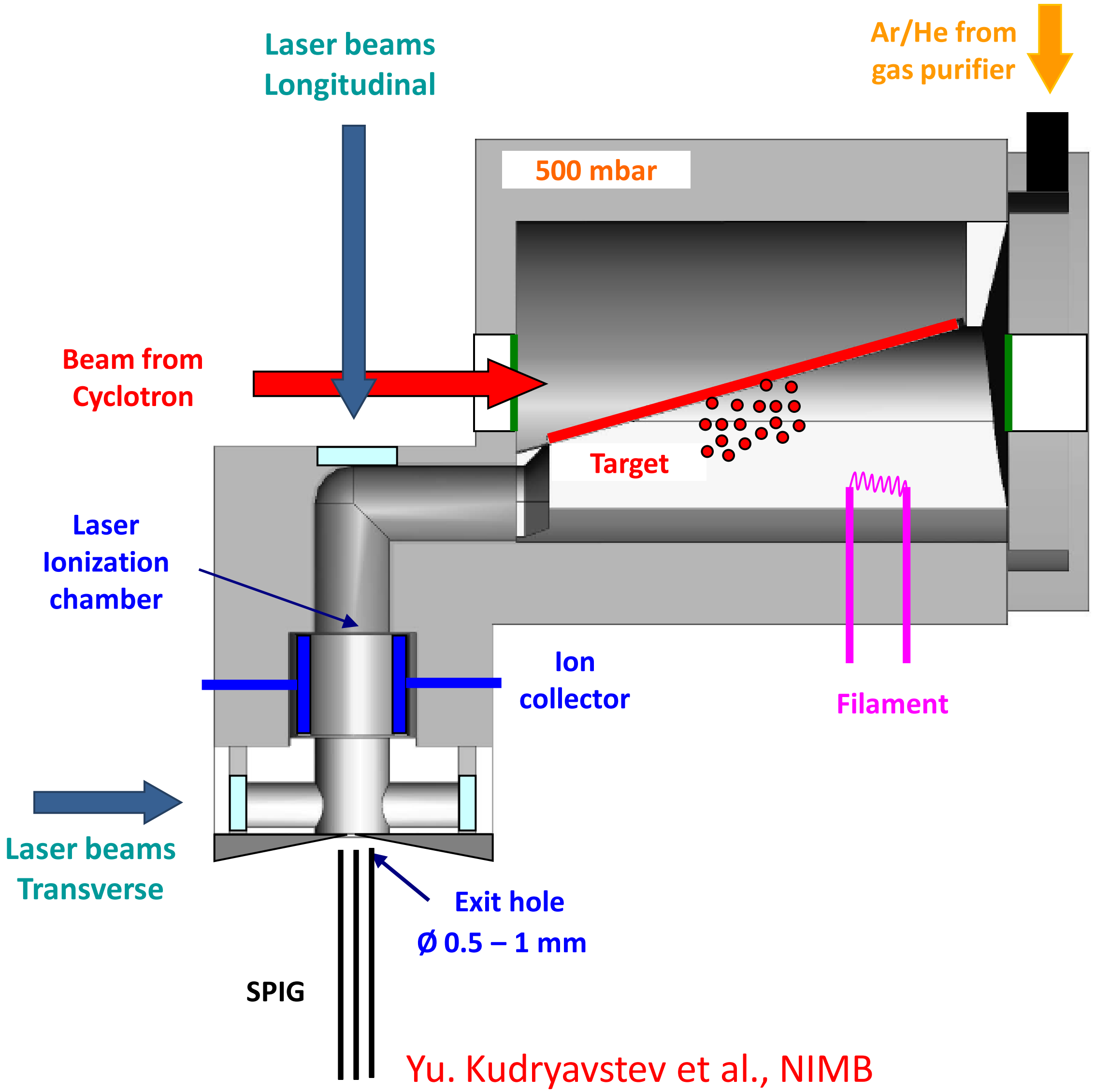
Laser system consists of two excimer-pumped dye lasers
Tunable range: 205 - 900 nm
Repetition rate: 200 Hz
80% of all elements can be ionized using LISOL laser system

- 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)

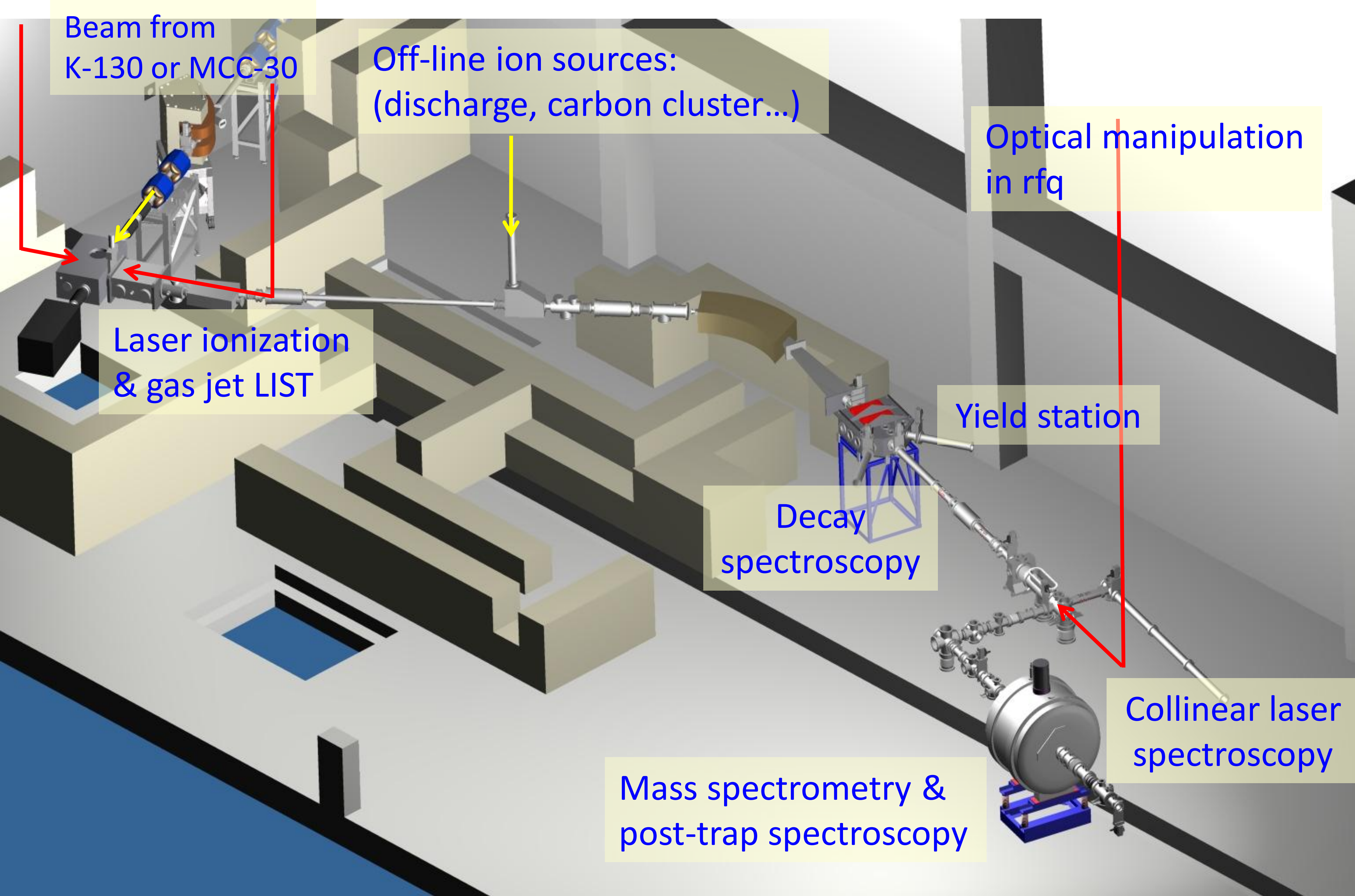
Selectivity (^{94}Rh):

Laser(ON)/Laser(OFF)

Ion Collector OFF = 450

Ion Collector ON = 2200

IGISOL-4: overview of facility in 2012



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

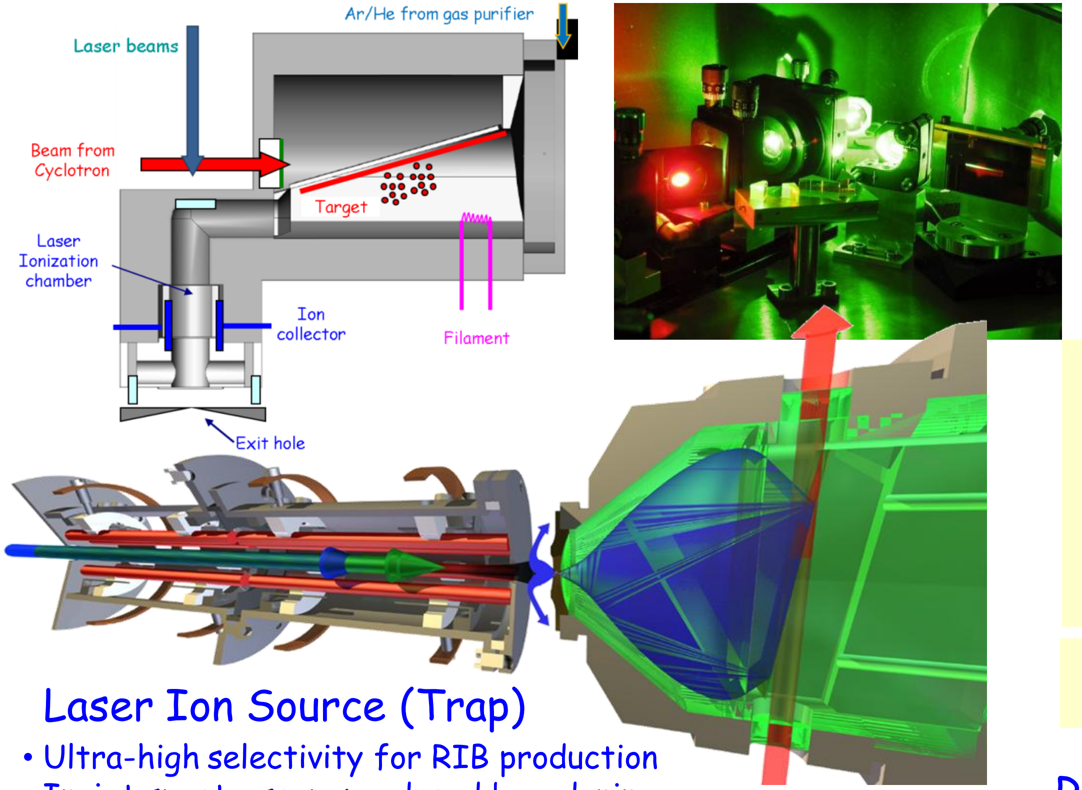
Decay
spectroscopy

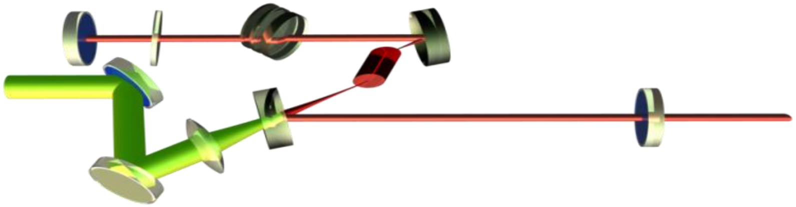
Collinear laser
spectroscopy

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

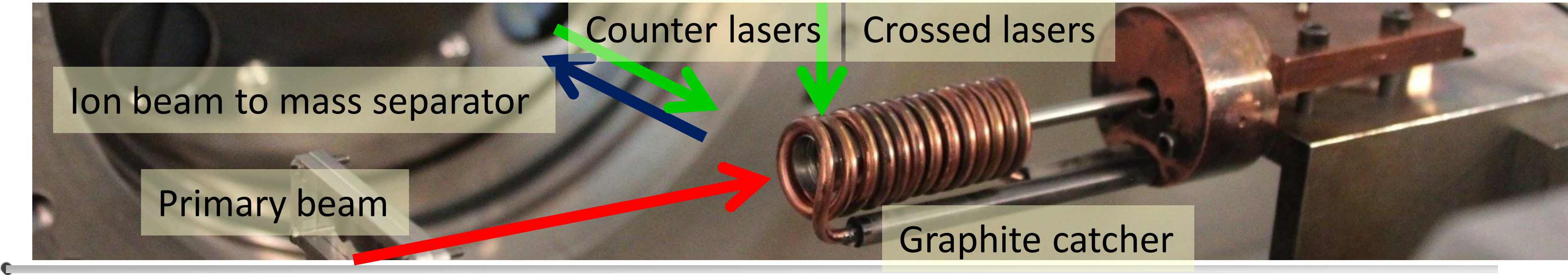
- In 2012: development of narrow-bandwidth Ti:Sa system

Laser Ion Source (Trap)

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

RF hot cavity

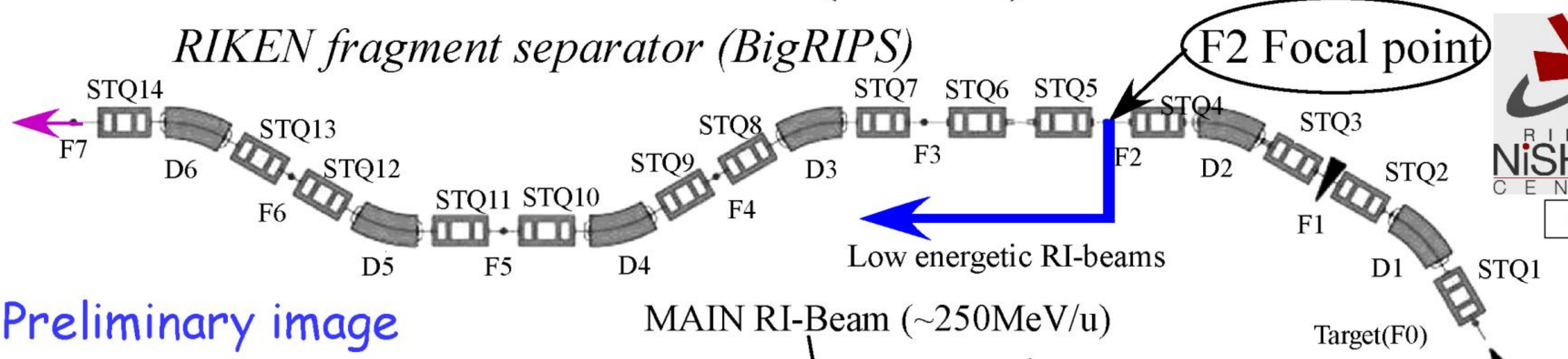
- Developments towards ^{94m}Ag (21$^+$)



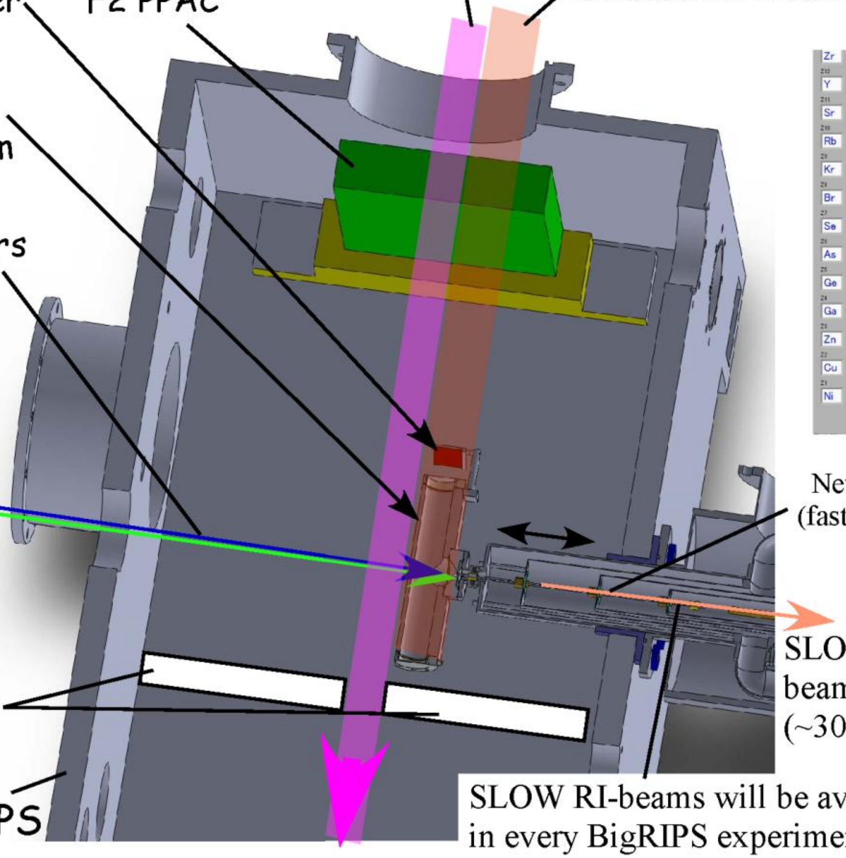
PArasitic Laser Ion-Source (PALIS) at SLOWRI RIKEN

RIKEN NiSHiNA CENTER

RIKEN fragment separator (BigRIPS)



Preliminary image



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

PALIS New Laser system
(be in the planning stage)

308	Dye
355	Dye
532	Dye
YLF	Ti:Sapphire

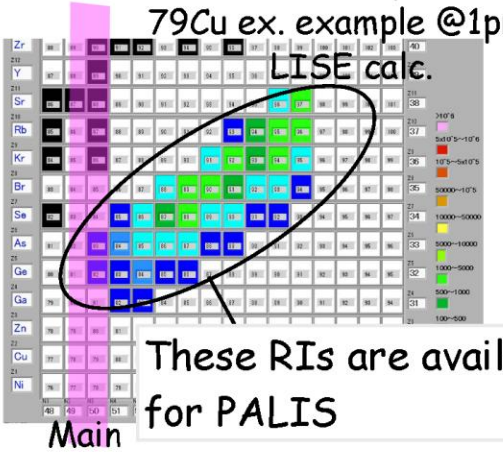
From Dr. Tomita Gr.
(Nagoya Univ.)

F2 chamber in BigRIPS

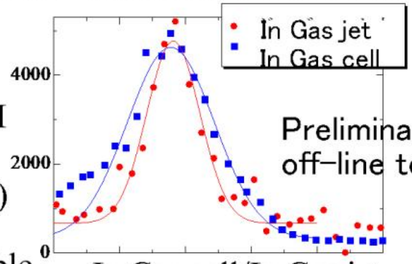
SLOW RI-beams will be available in every BigRIPS experiment.

79Cu ex. example @1pnA U

LISE calc.

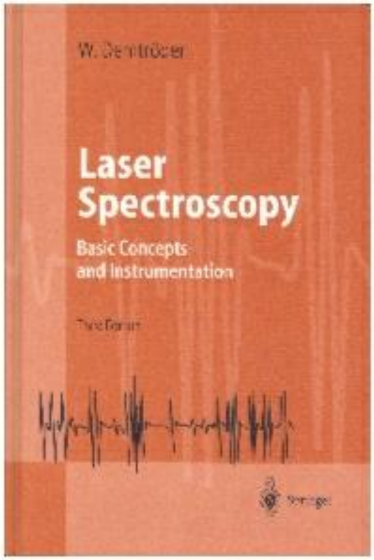


These RIs are available for PALIS



In Gas cell/In Gas jet
Laser Spectroscopy

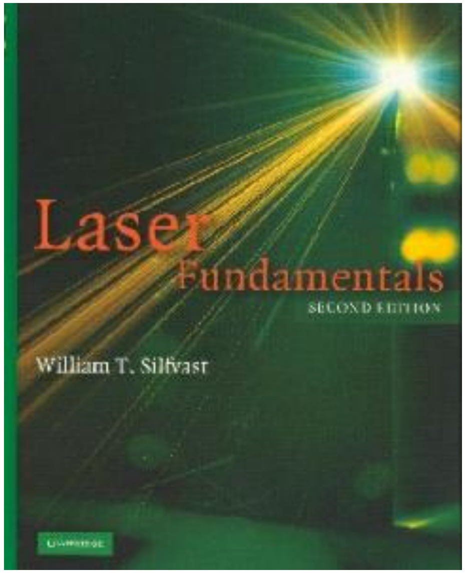
Recommended reading for further information



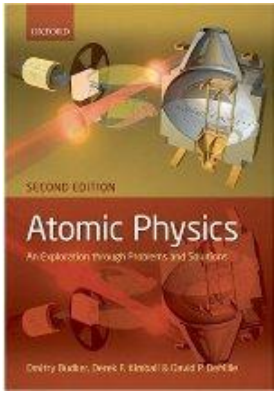
W. Demtröder, Laser Spectroscopy , 3rd Edition (Springer-Verlag, Berlin, 2003).

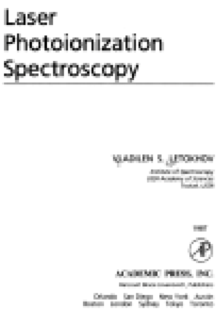
W. Demtröder:
Atoms, Molecules and Photons
(Springer-Verlag, Berlin, 2003).

W. T. Silfvast, Laser Fundamentals, 2nd Ed. (Cambridge University, Cambridge, 2003).



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



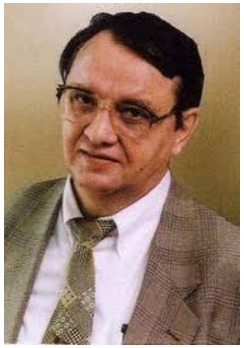


Laser
Photoionization
Spectroscopy

VLADILEN S. LETOKHOV

ACADEMIC PRESS, INC.

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

Introduction to study task: *Ionization scheme development*

*Consider two RILIS laser installations (**A** and **B**) located at different RIB facilities. For each installation choose a suitable element from the list provided and build up a feasible (preferably optimal) laser ionization scheme using the atomic spectral line databases that are available online:*

R. L. Kurucz database: http://www.cfa.harvard.edu/amp/ampdata/kurucz23/sekur.html
NIST database: http://physics.nist.gov/PhysRefData/ASD/lines_form.html

Hf, Re, Kr, Rn, Rb, Na, Gd, Cr, Ge, Pd

Choose 2 different elements (one for each facility).

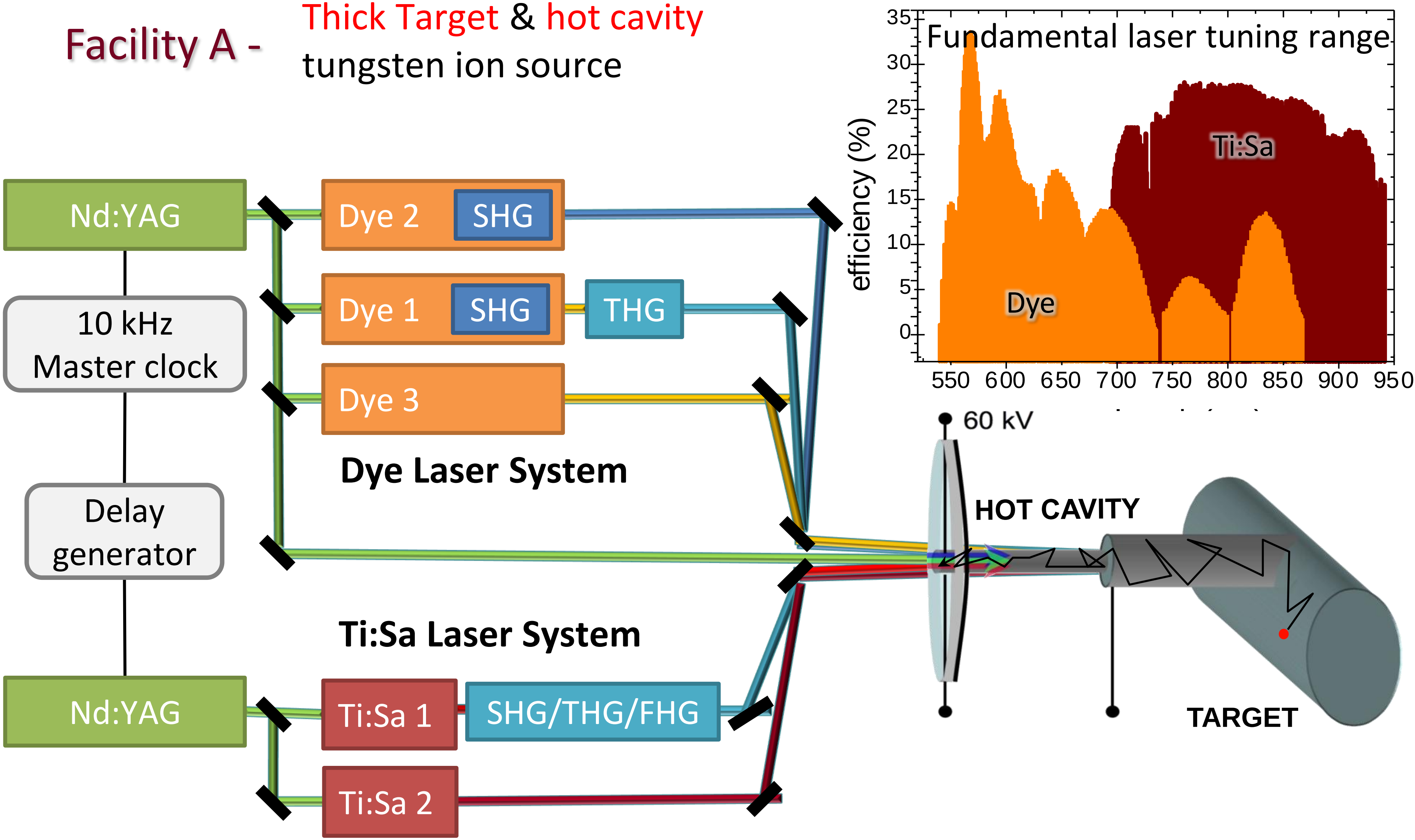
You need to choose a suitable element for the particular facility and laser capabilities:

Vapor pressures; release from target?; other ionization mechanisms; ionization potentials

Try to create a suitable scheme based on laser capabilities and ionization conditions:

Low lying excited states; laser efficiencies; tuning range; harmonic generation issues

Facility A - Thick Target & hot cavity tungsten ion source



Nd:YAG

10 kHz Master clock

Delay generator

Nd:YAG

Dye 2 SHG

Dye 1 SHG THG

Dye 3

Dye Laser System

Ti:Sa Laser System

Ti:Sa 1 SHG/THG/FHG

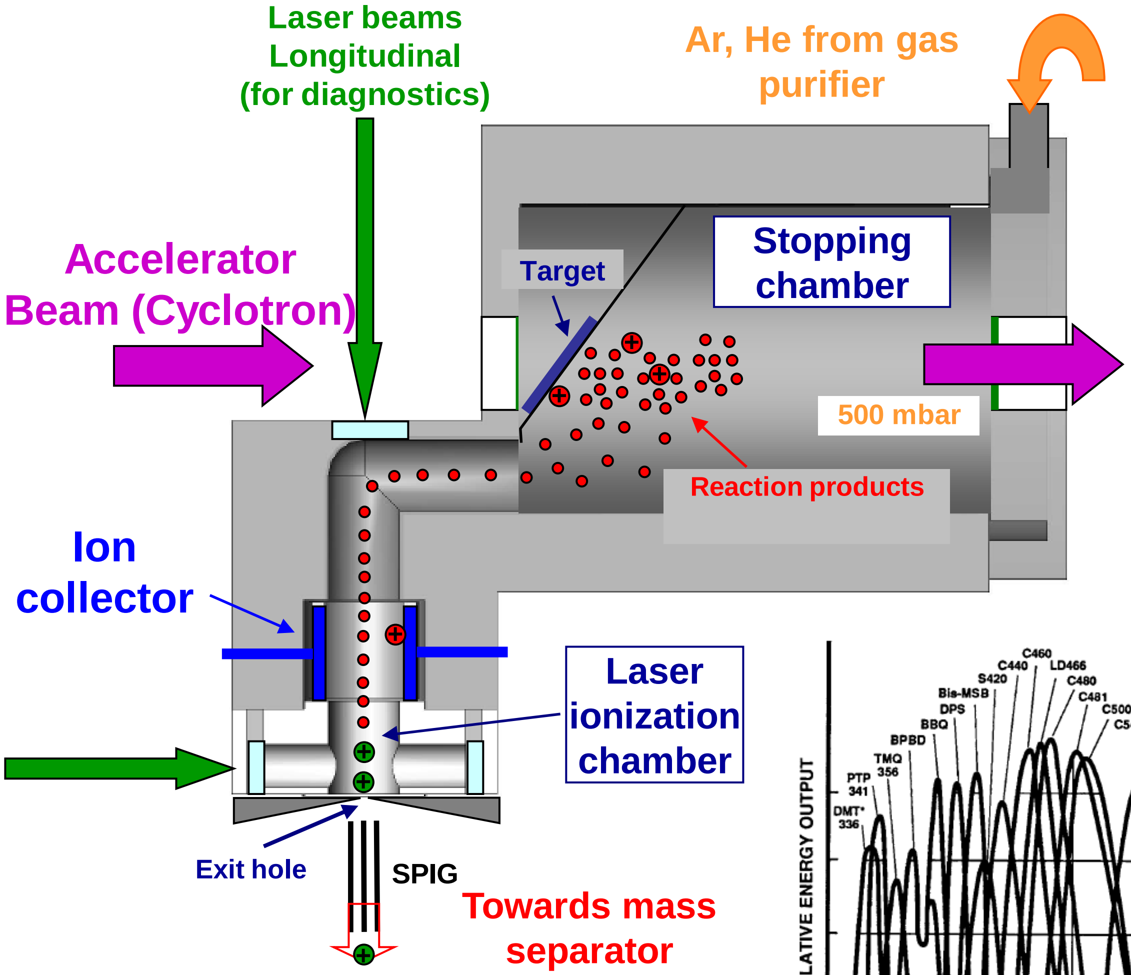
Ti:Sa 2

60 kV

HOT CAVITY

TARGET

Facility B - Thin Target & gas cell ion source



Laser system consists of 2 excimer-pumped dye lasers

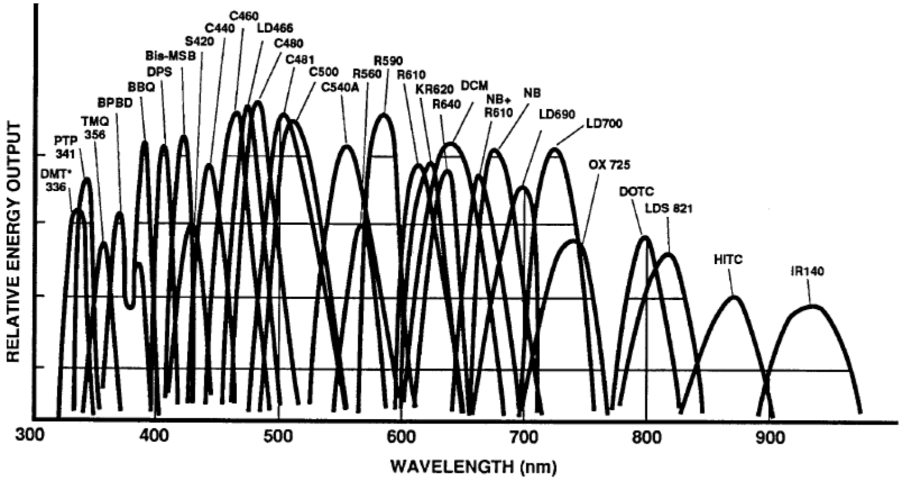
Fundamental range:

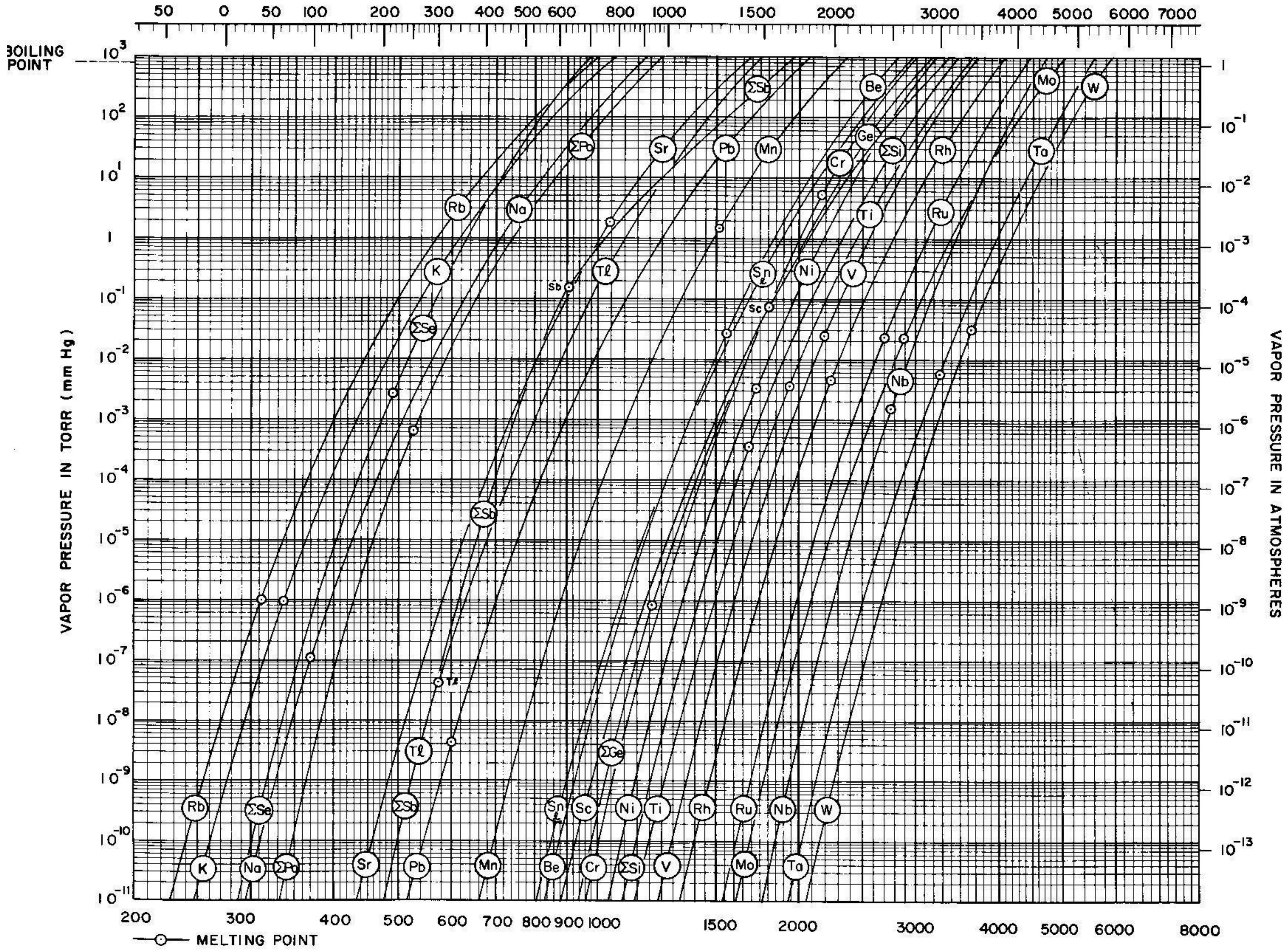
310 - 900 nm

Optional 2nd harmonics

Using nonlinear crystals

Repetition rate: 200 Hz




50
0
50
100
200
300
400
500
600
800
1000
1500
2000
3000
4000
5000
6000
7000
BOILING POINT
10^3
10^2
10^1
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
VAPOR PRESSURE IN TORR (mm Hg)
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
VAPOR PRESSURE IN ATMOSPHERES
200
300
400
500
600
700
800
900
1000
1500
2000
3000
4000
5000
6000
8000
MELTING POINT
ΣSb
Be
Mo
W
ΣPo
Sr
Pb
Mn
Ge
ΣSi
Rh
Ta
Cr
Rb
Na
Ti
Ru
K
Tℓ
Sb
Sn
Ni
V
Sc
ΣSe
Nb
ΣSb
Tℓ
Tℓ
ΣGe
Rb
ΣSe
ΣSb
Sn
Sc
Ni
Ti
Rh
Ru
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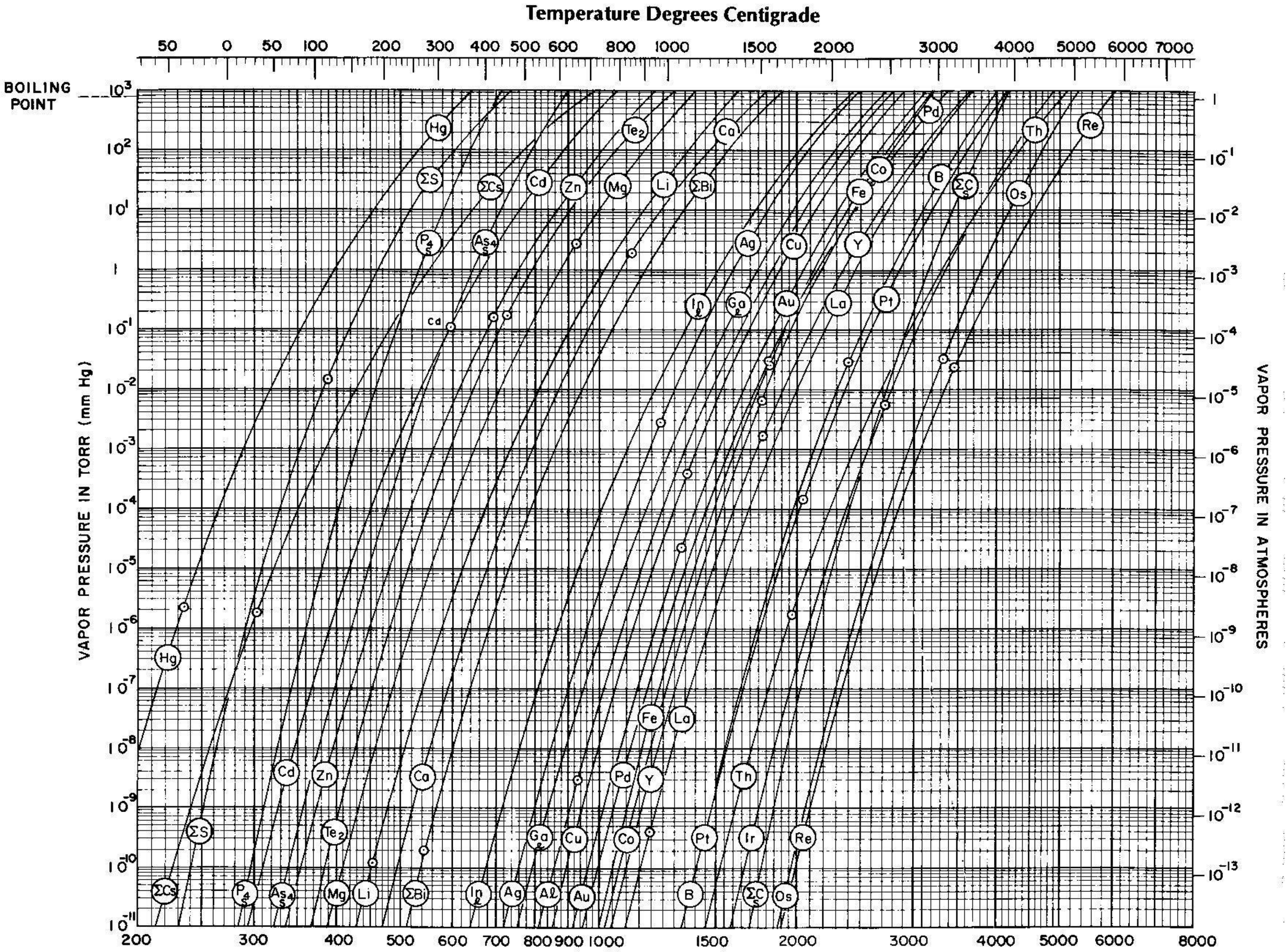
V
Mo
Ta

VAPOR PRESSURE CURVES OF THE ELEMENTS



Bonus task: *Harmonic generation configuration*

If your ionization scheme requires harmonic generation, suggest a suitable nonlinear crystal type and configuration for your laser configuration.

If possible download and use the free SNLO software for crystal selection:

http://www.as-photonics.com/snlo