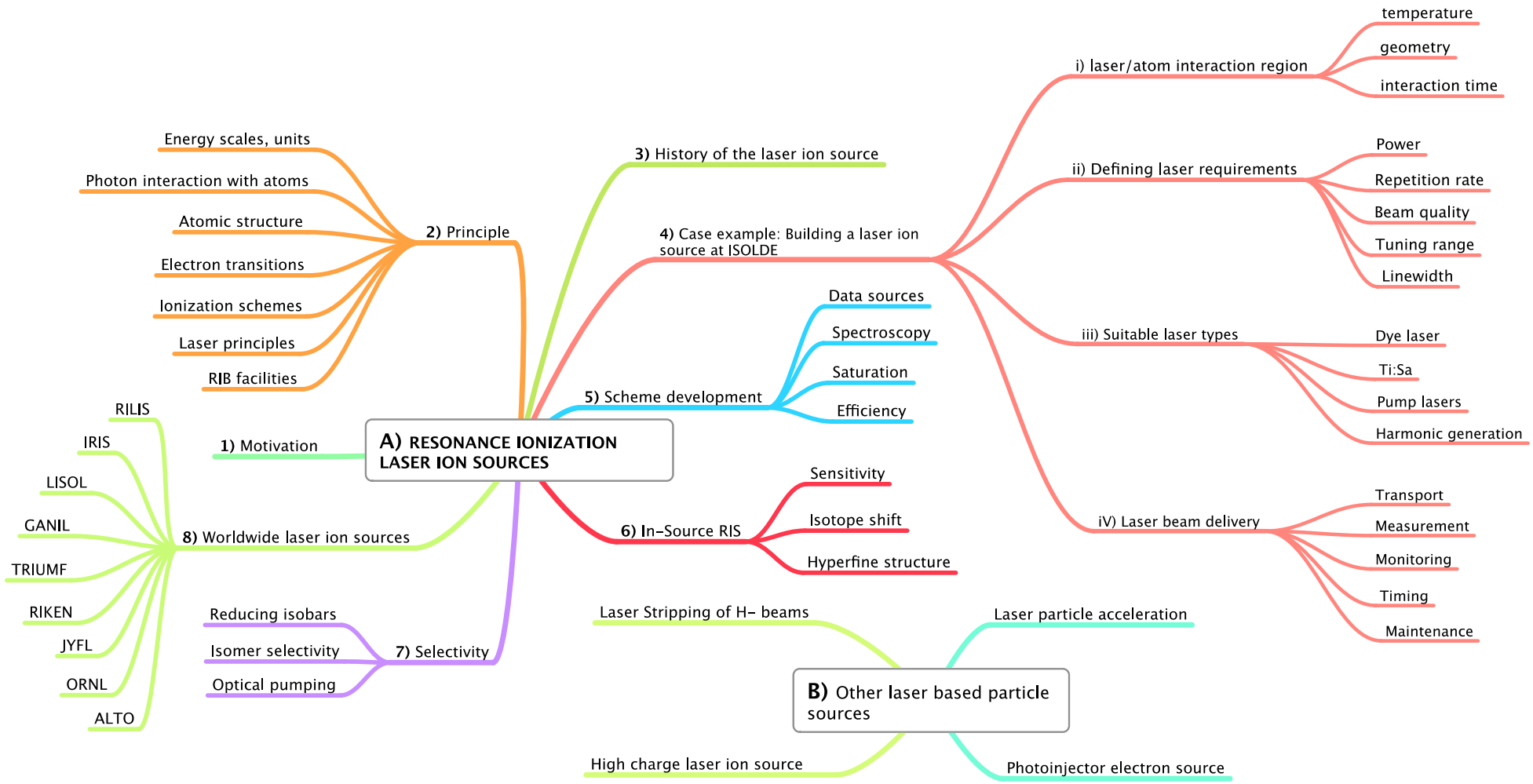
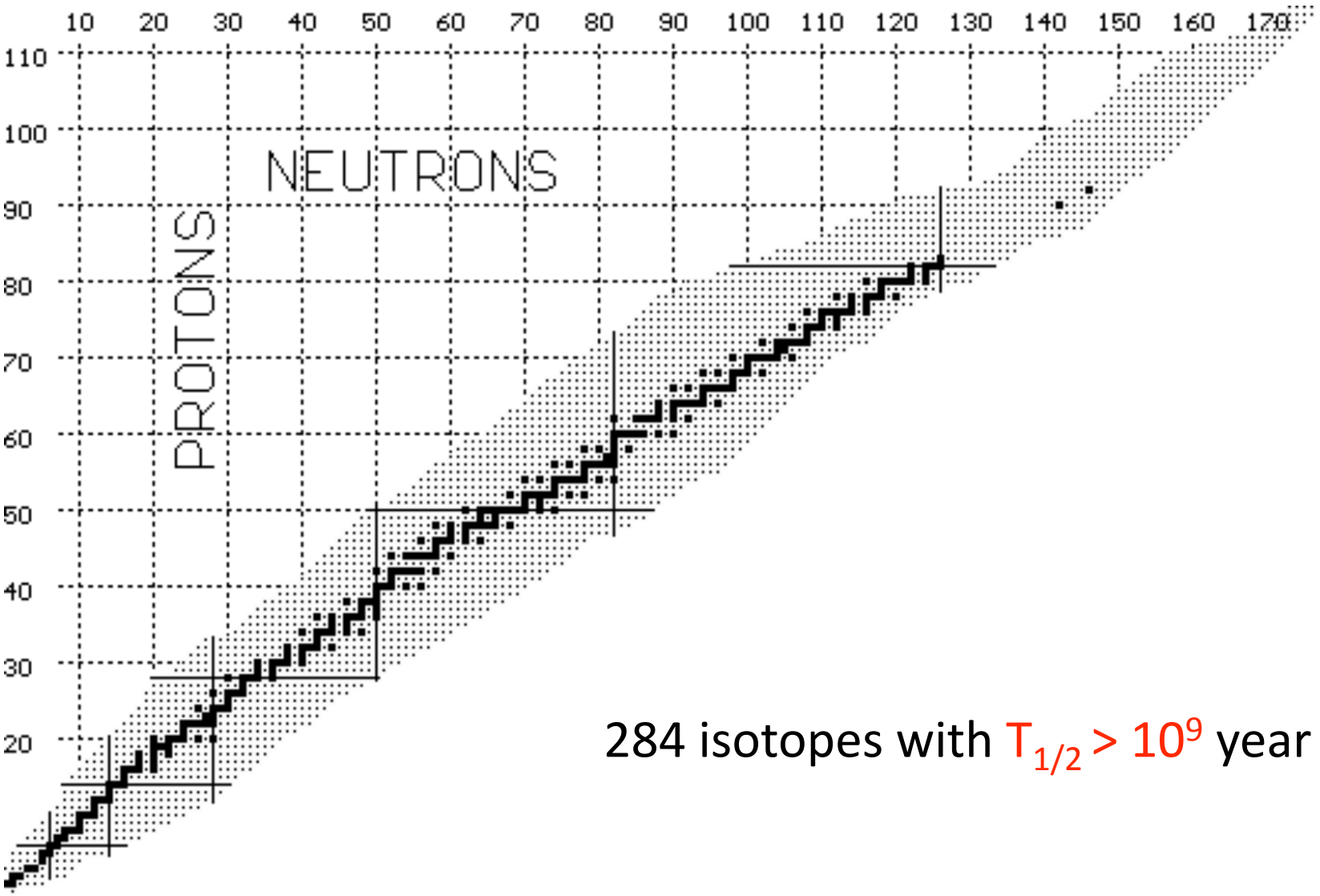
Laser Ion Sources I and II – Structure of the lectures



1) Motivation

A) RESONANCE IONIZATION LASER ION SOURCES

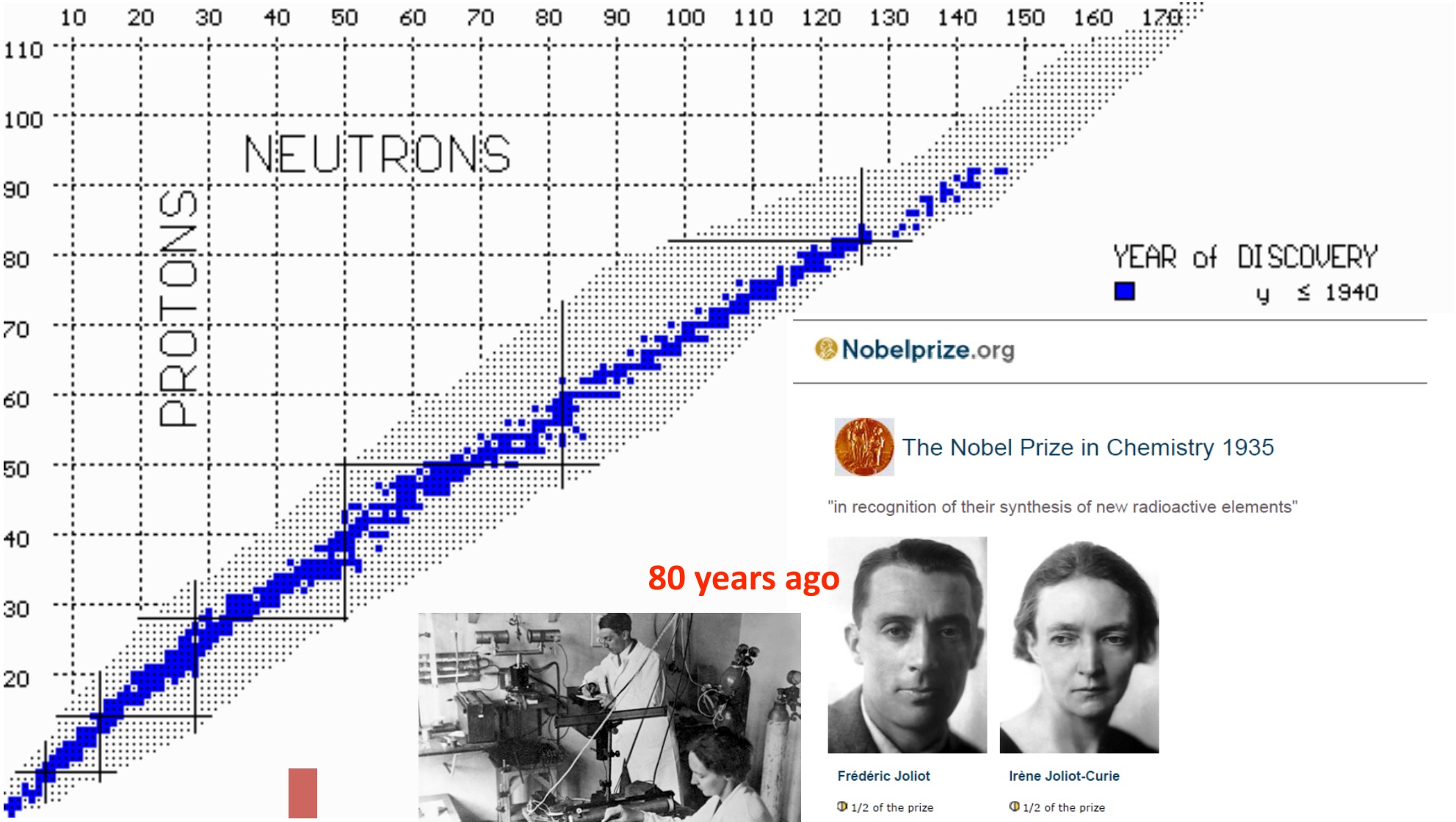
The chart of stable nuclei



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

Slide: M. Huyse

+ the discovery of radioactivity



Nobelprize.org

The Nobel Prize in Chemistry 1935

"in recognition of their synthesis of new radioactive elements"

80 years ago

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

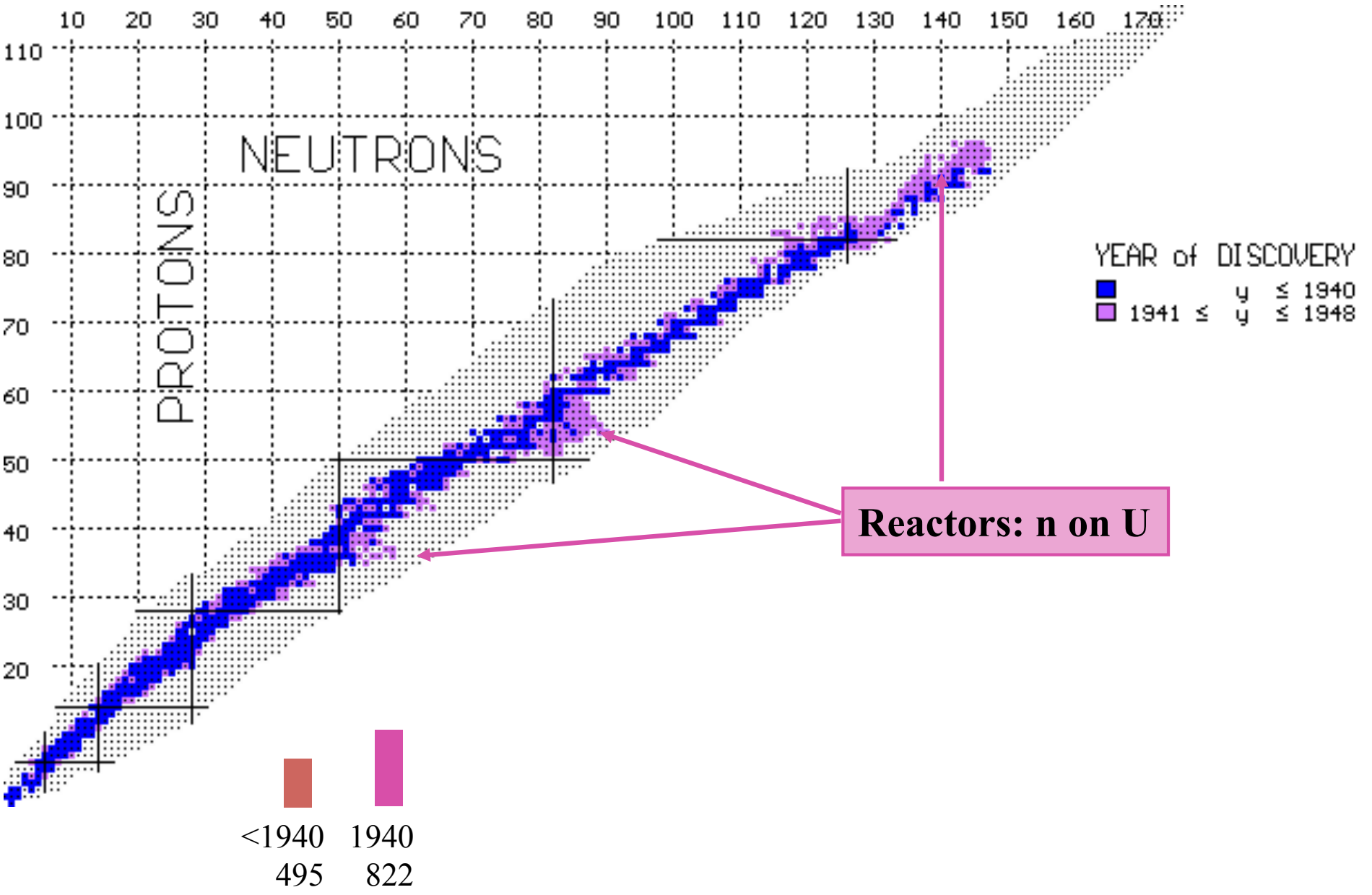
Irène Joliot-Curie
1/2 of the prize
France
Institut du Radium
Paris, France

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

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

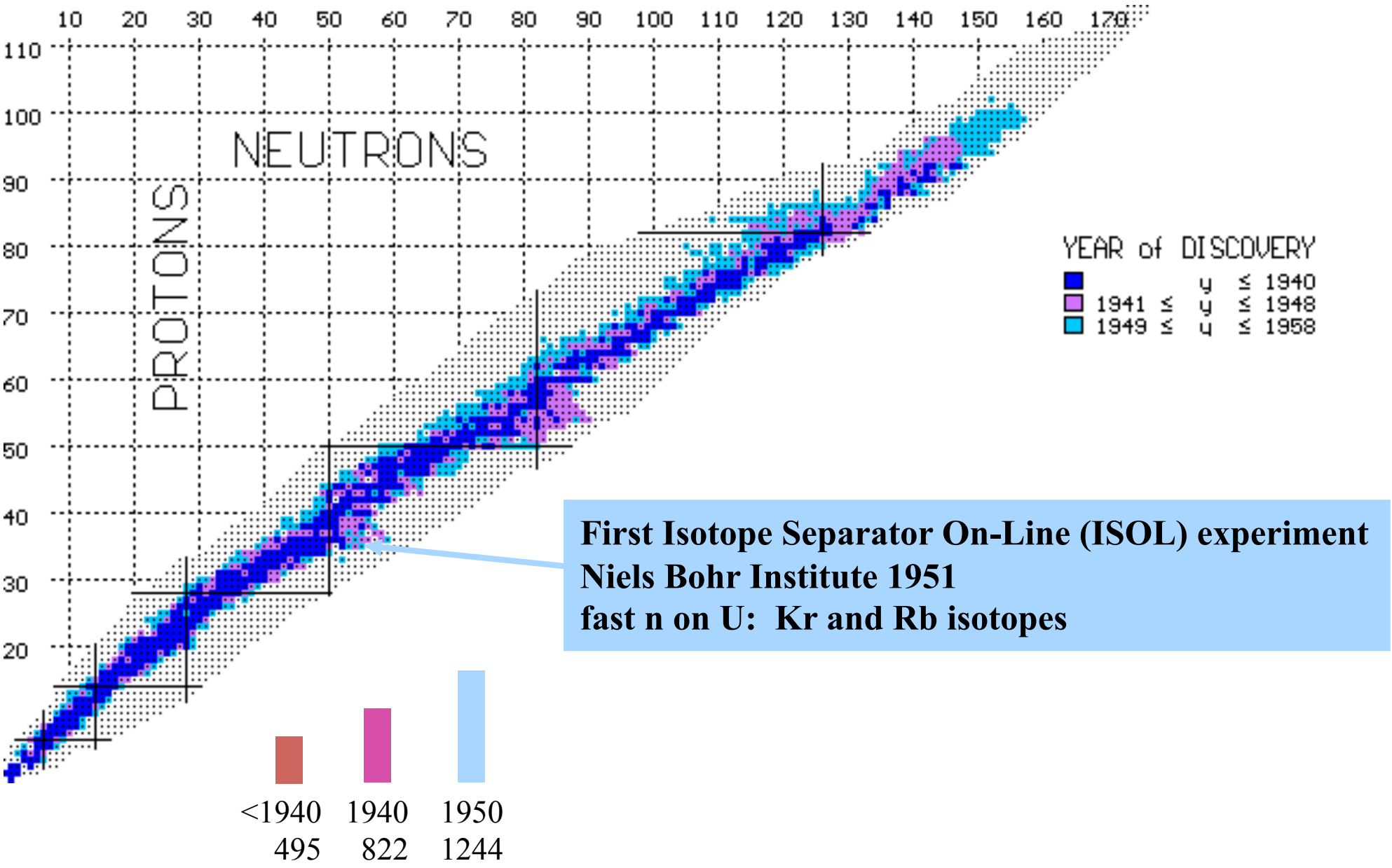
Slide: M. Huyse

+ the advent of nuclear reactors



Slide: M. Huyse

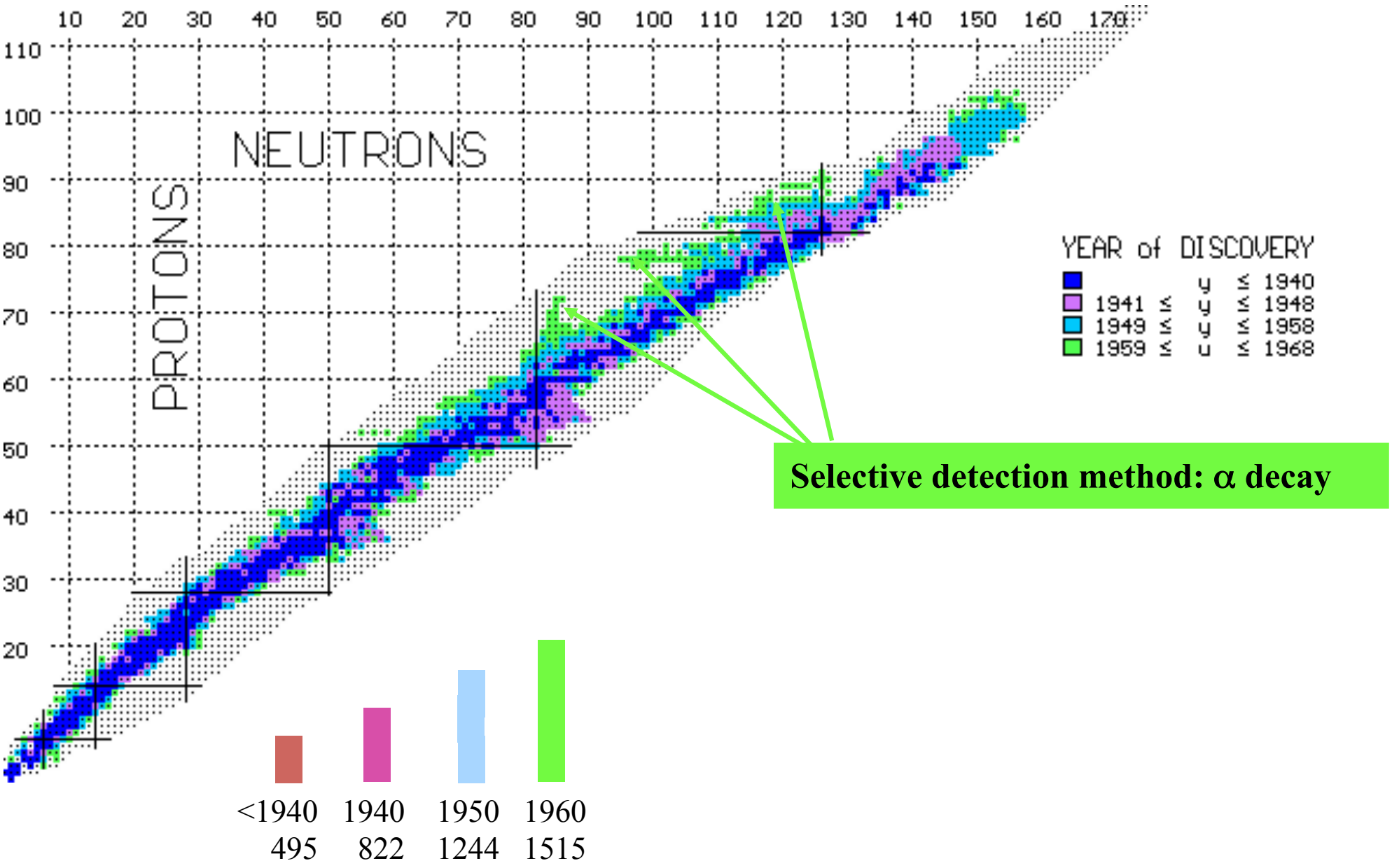
+ Early Isotope Separator On Line (ISOL) isotopes



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

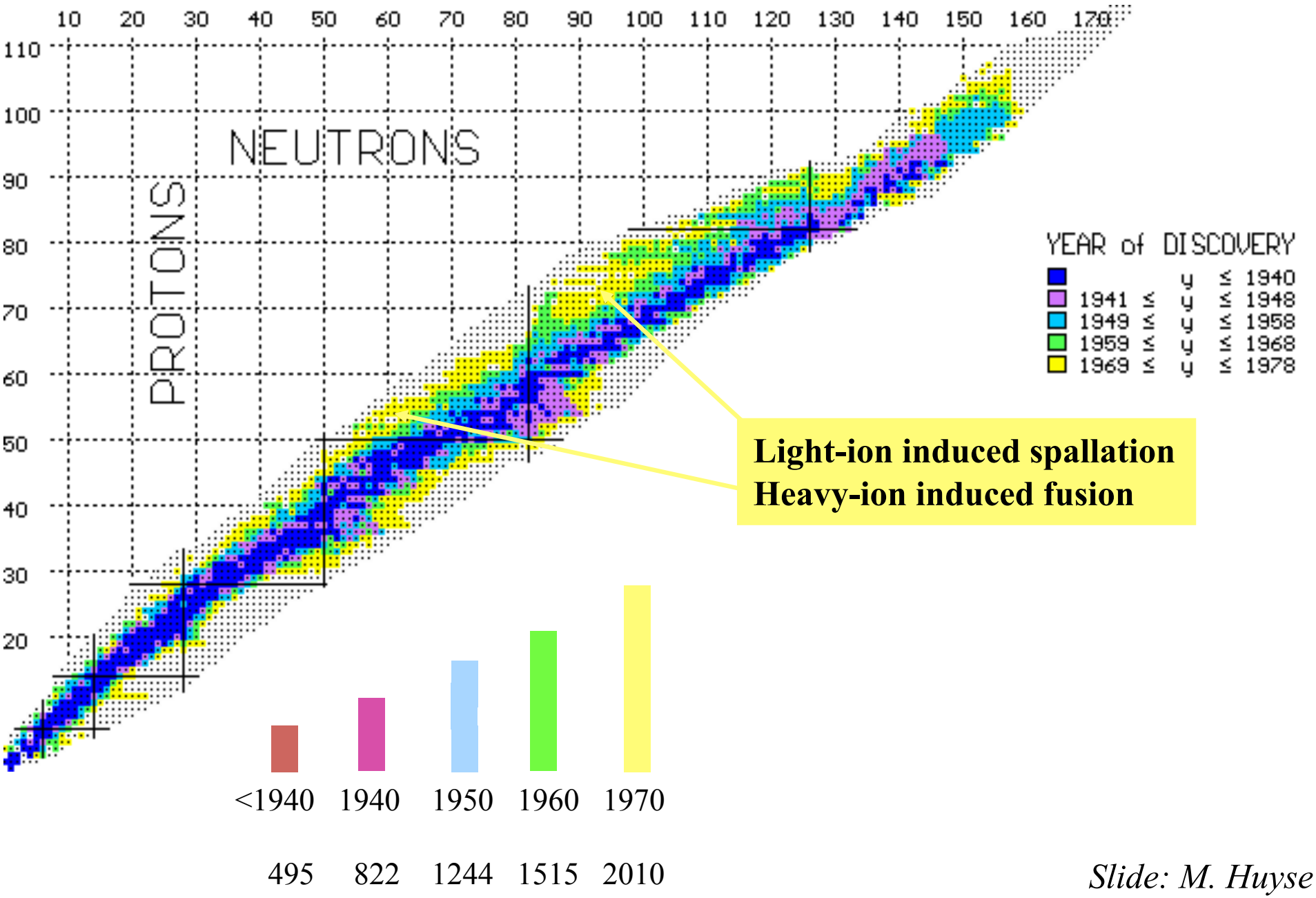
Slide: M. Huyse

+ sensitive detection methods



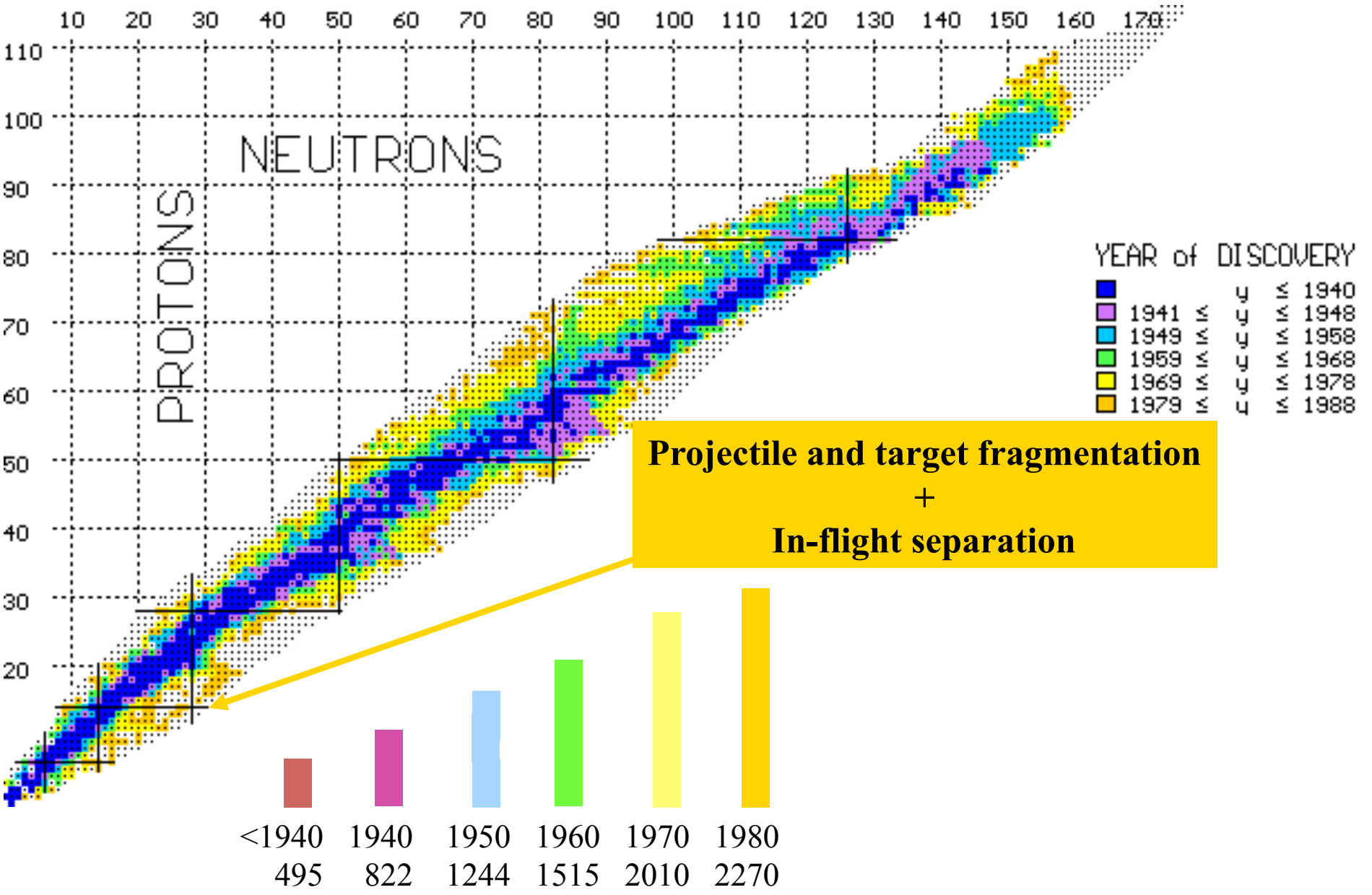
Slide: M. Huyse

+ energy increases and driver beam upgrades



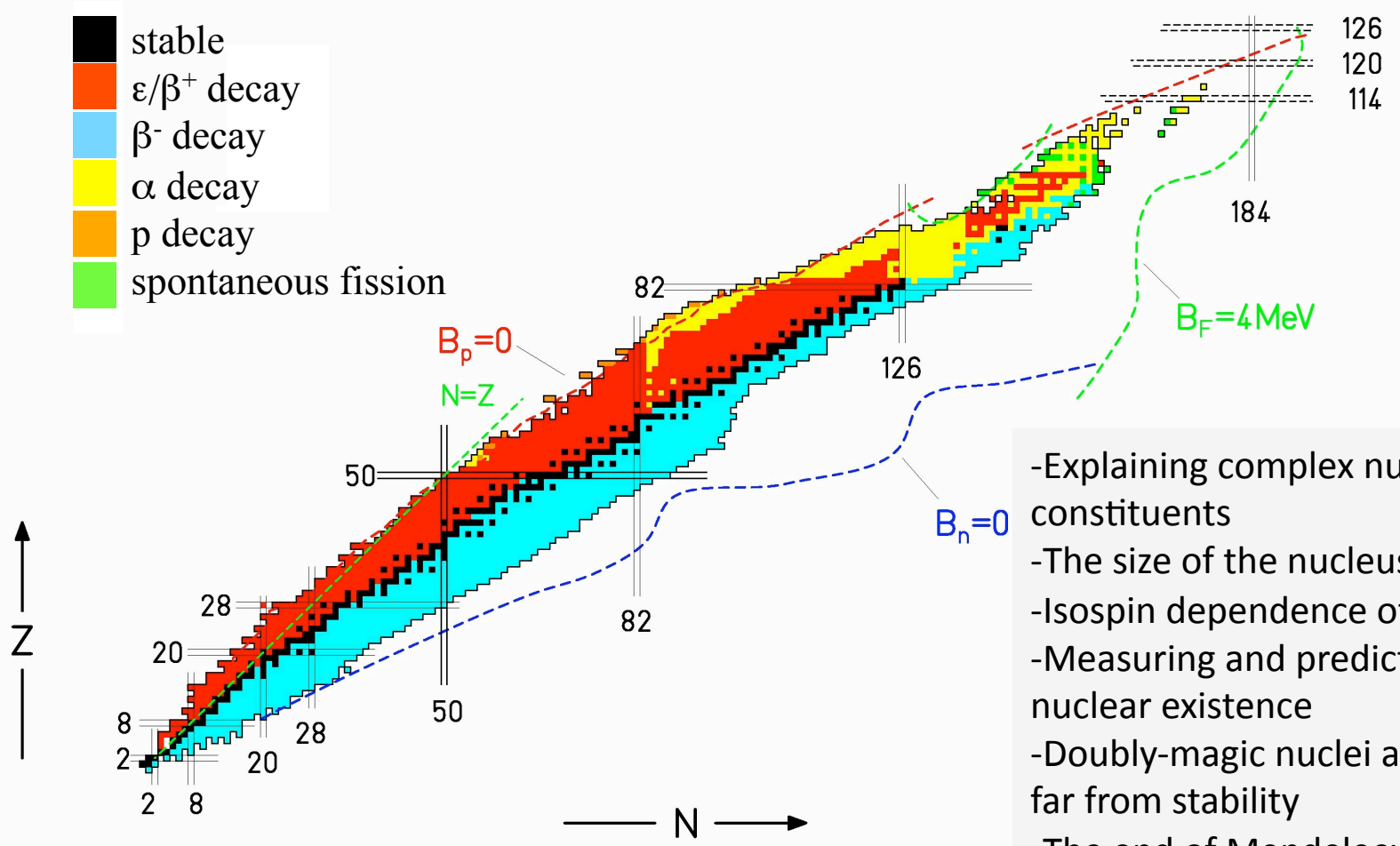
Slide: M. Huyse

+ thin target and projectile fragmentation – shorter lifetimes



Slide: M. Huyse

= The modern nuclear chart

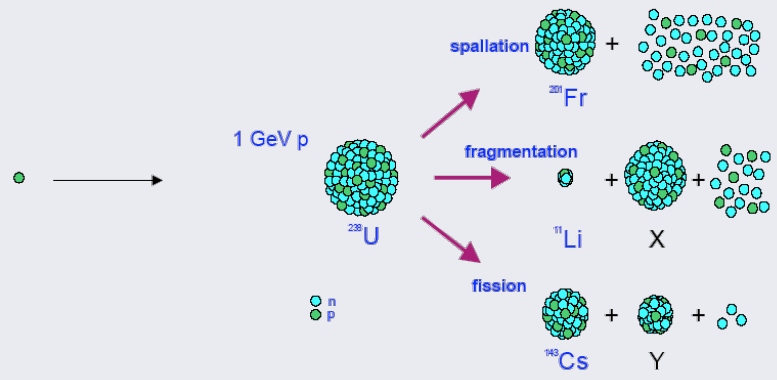


-Explaining complex nuclei from basic constituents
-The size of the nucleus: halos and skins
-Isospin dependence of the nuclear force
-Measuring and predicting the limits of nuclear existence
-Doubly-magic nuclei and shell structure far from stability
-The end of Mendeleev's table: superheavies
-Understanding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

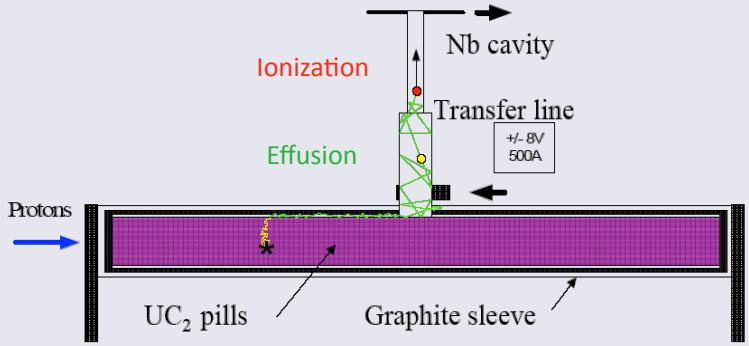
> 3500 of the expected 6000 nuclei have been observed

The ISOL process

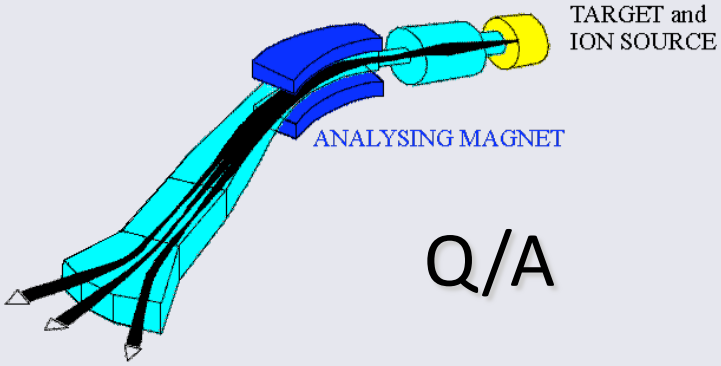
Production



Extraction/Ionization

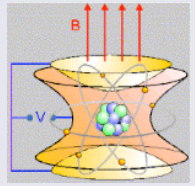


Isotope Separation

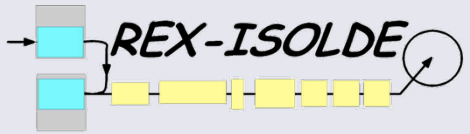


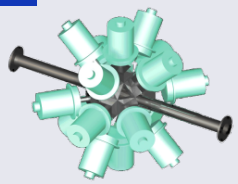
Q/A

Post acceleration or to Experiment



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

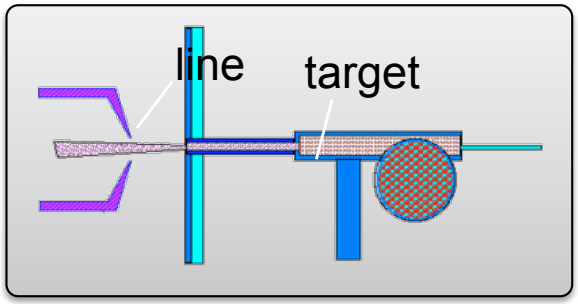
ISOL ion source requirements are very broad !

- Energy range 10^{-6} eV (10 mK) to >MeV/u
- Intensity 0.01 – 10^{10} ions/s
- 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 high energy beams –*F. Wenander's lectures*

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

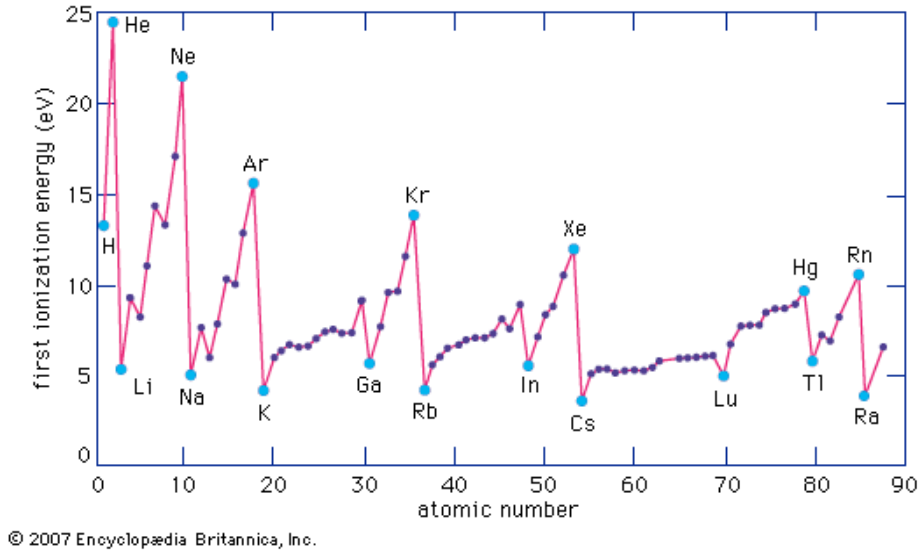
The operating principles of each of ISOL ion source options are presented to some extent at this school!

SURFACE ION SOURCE



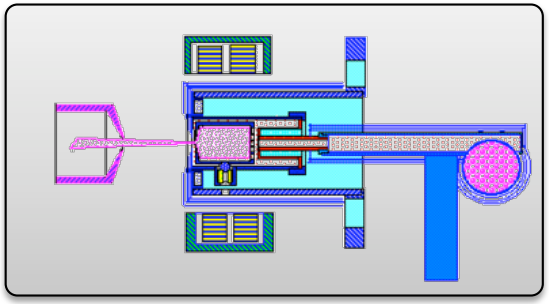
- Very simple: metal tube (line) from Ta or W
- Heated up to 2400 °C

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



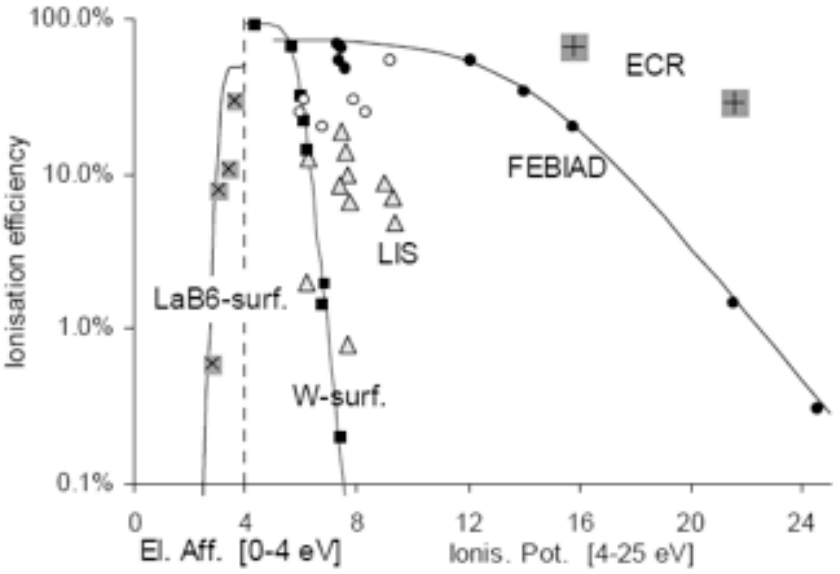
Surface Ionization Process:
R. Kirchner: Nucl. Instr. Meth. 186, 275 (1981)

PLASMA ION SOURCE



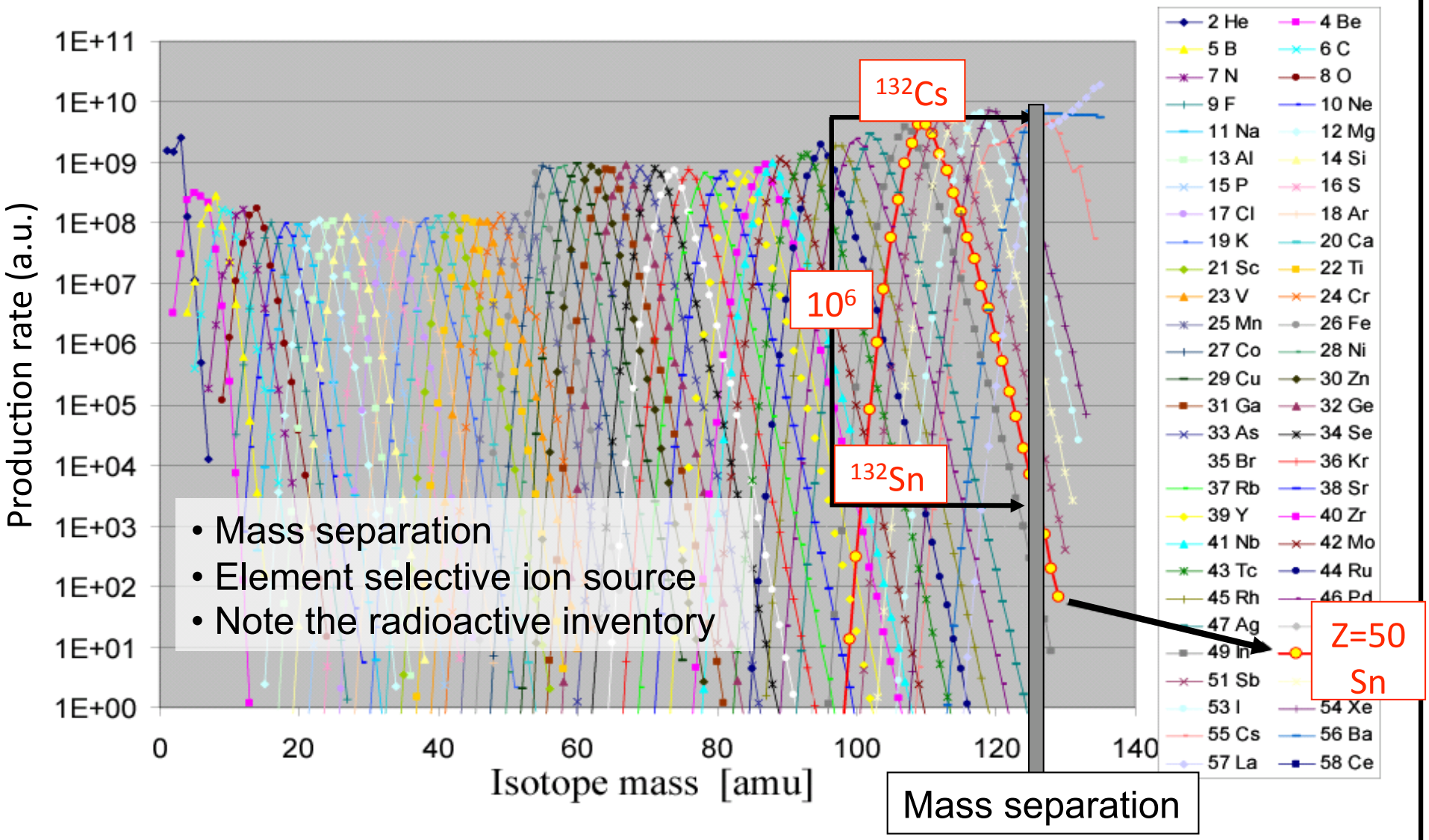
- Used for non surface-ionizing elements
- Ar or Xe plasma ignited by electrons at 130 eV

Very efficient, even for high IP elements. Chemically unselective



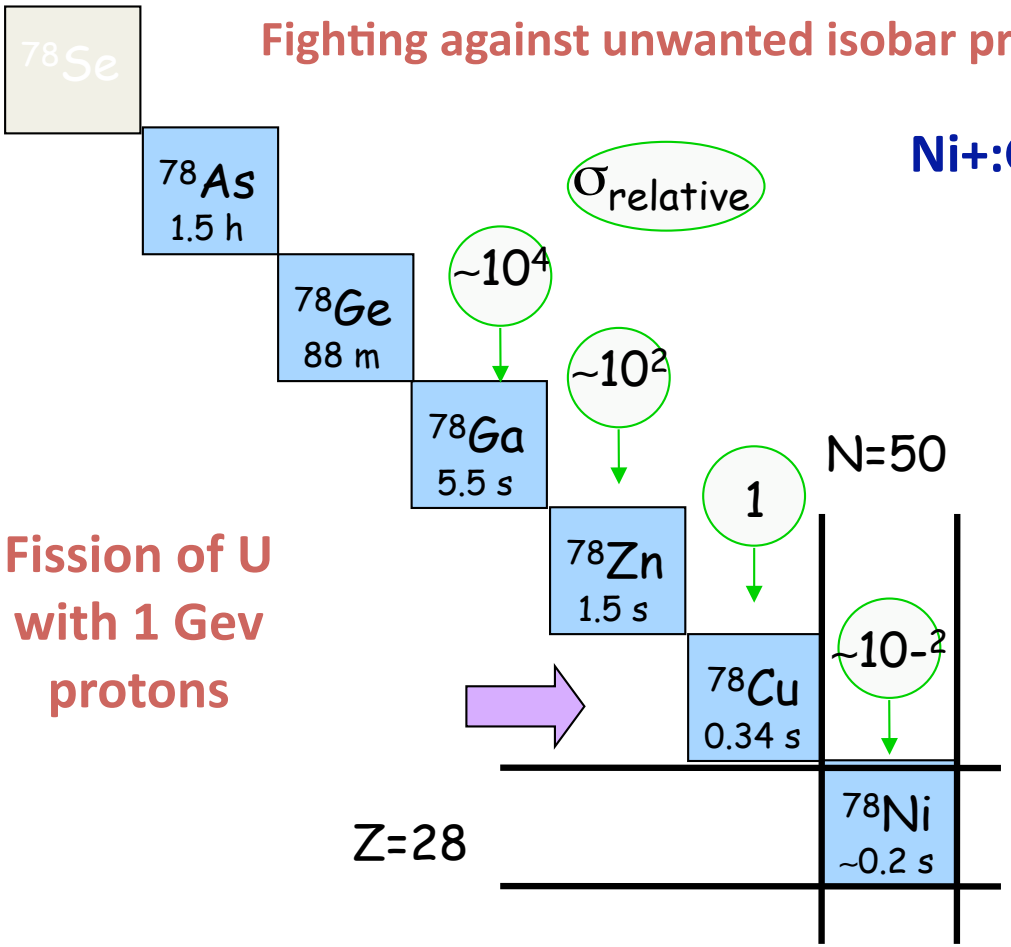
Production of Exotic Nuclei

1 GeV proton beam on a lanthanum (La) target



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:

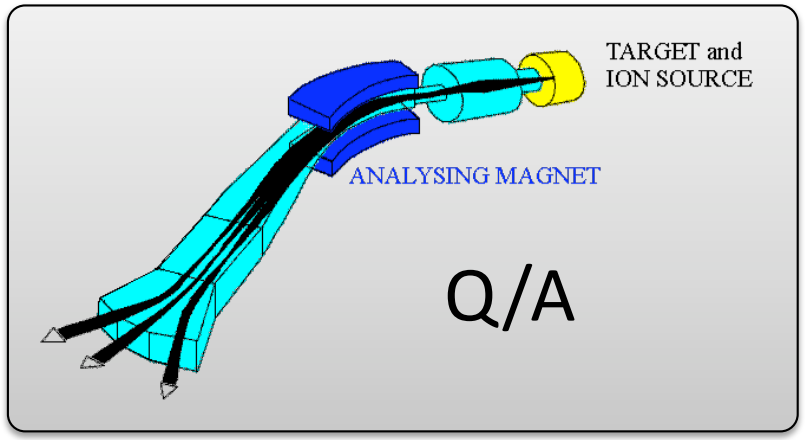
IP (Ga) = 5.99 eV IP (Ni) = 7.63 eV

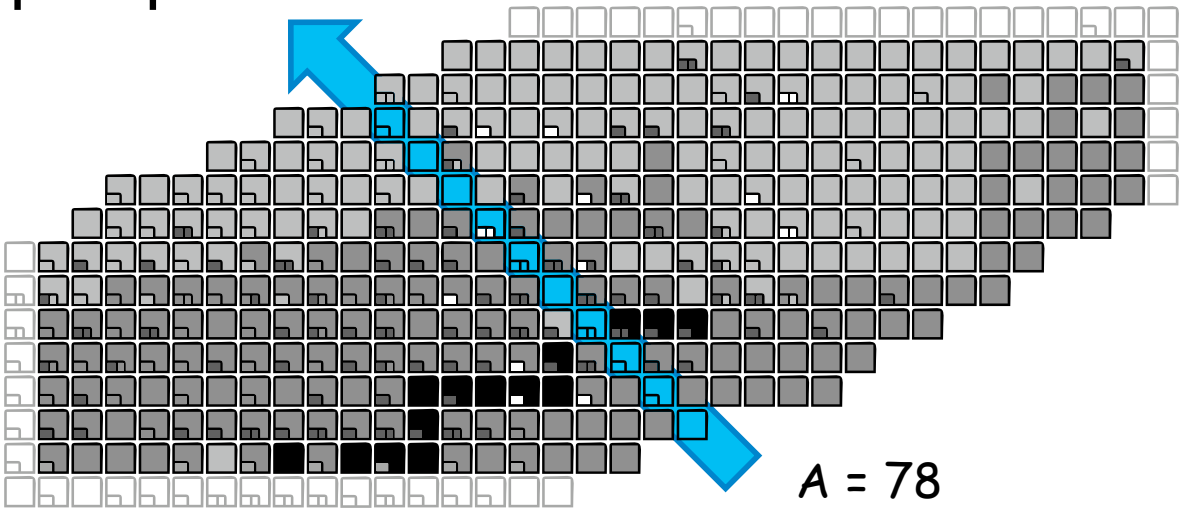
$$\alpha = \frac{n_i}{n_0} = \frac{\omega_i}{\omega_0} \exp\left(\frac{\Phi - W_i}{kT}\right)$$

Ga+:Ni+ > 10^6 !

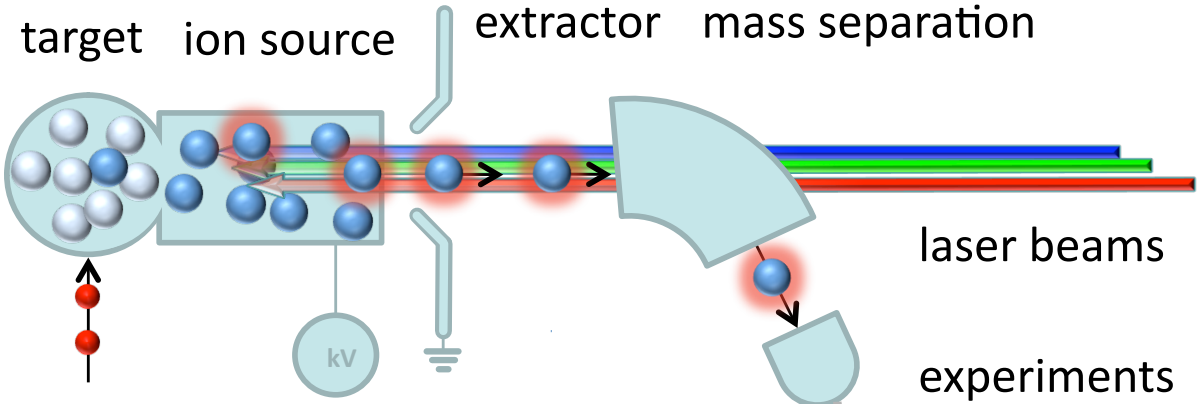
Need to selectively increase Ni ionization efficiency

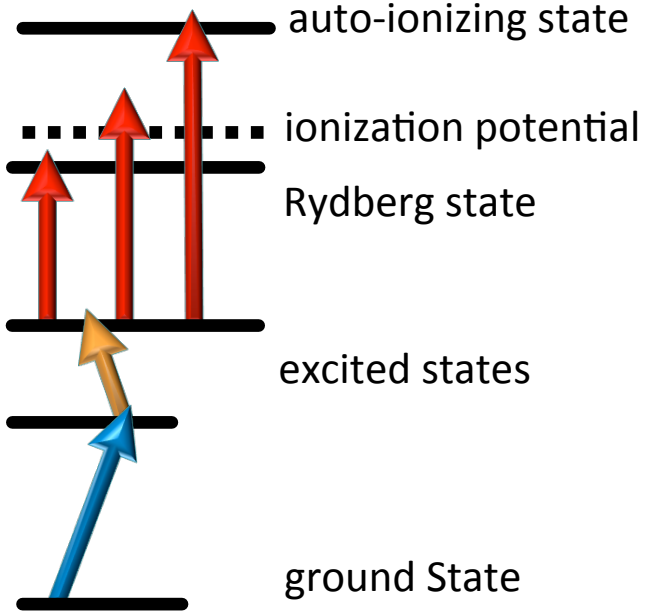
And/or suppress isobar (Cu, Zn, Ga) ionization efficiency.





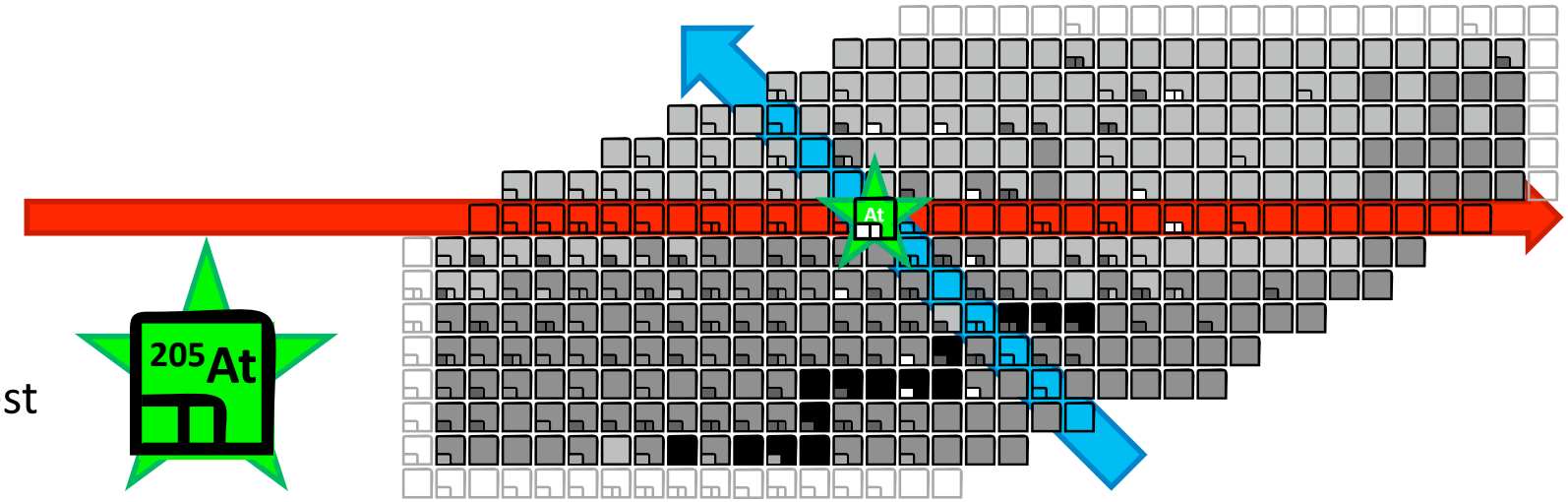
The Resonance Ionization Laser Ion Source

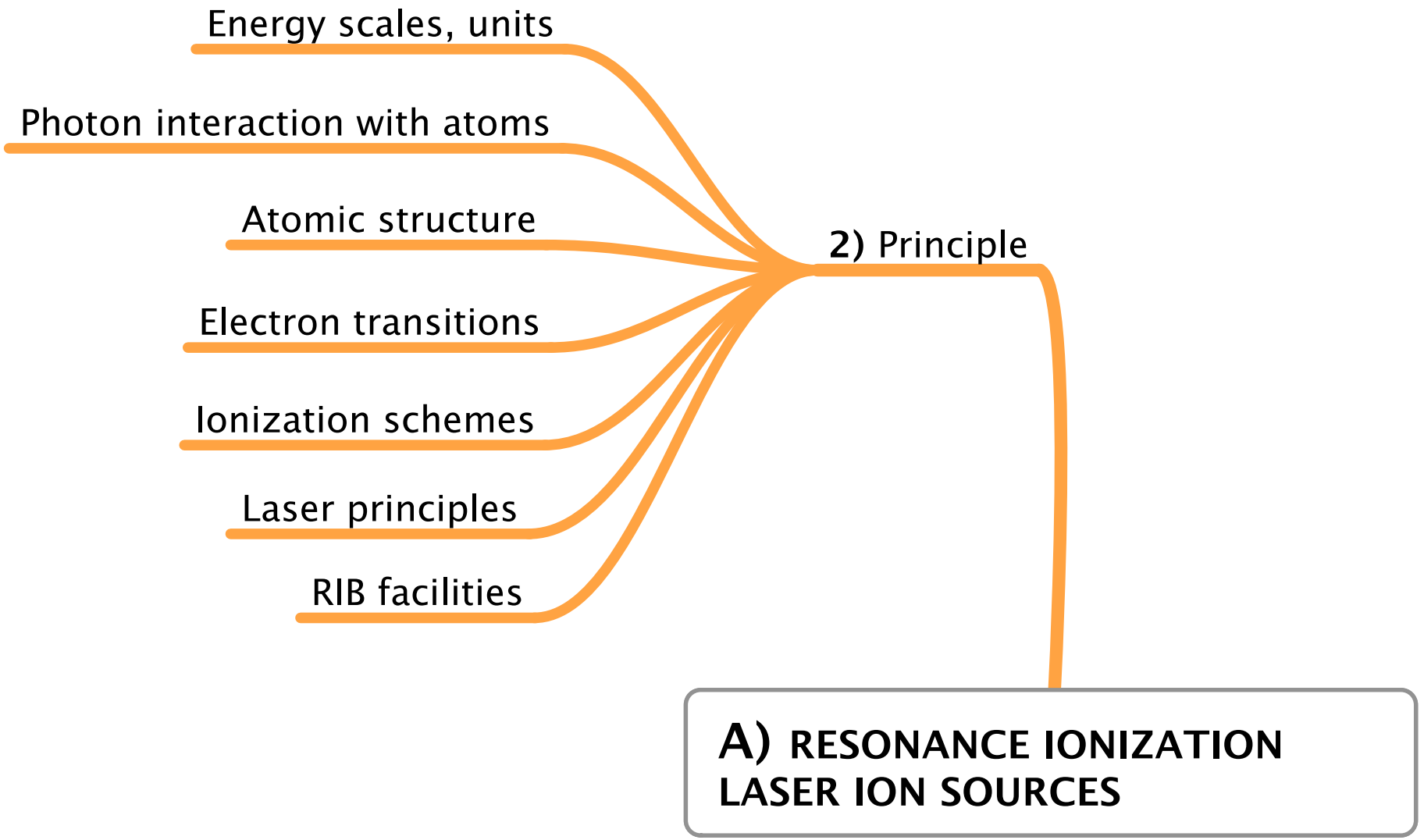




projectiles target material neutrals ions

Isotope of interest




Energy scales, units
Photon interaction with atoms
Atomic structure
Electron transitions
Ionization schemes
Laser principles
RIB facilities
2) Principle
A) RESONANCE IONIZATION LASER ION SOURCES

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})

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

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, $E = h\nu$**

  in which h is Planck's constant, $h = 6.626 \times 10^{-34}$ Js

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

Louis de Broglie
(1892-1987)

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

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

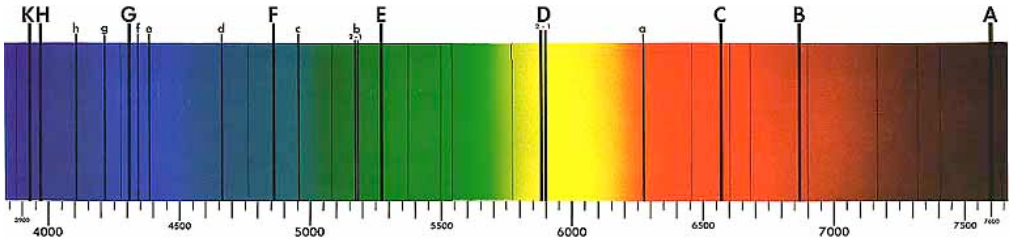
n.b., 1) photons are Bosons (*i.e.*, obey Bose-Einstein statistics)

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

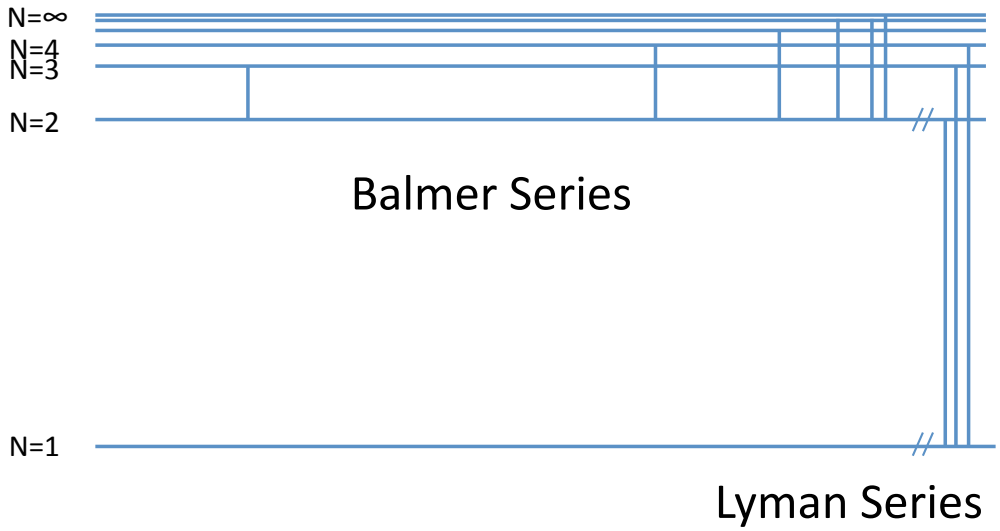
17th Century: Newton demonstrates that the Sun's white light can be dispersed into a "spectrum" of colours

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.

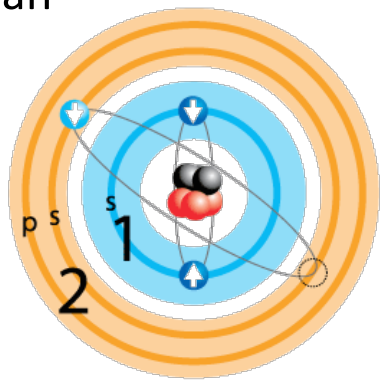
1885: J. Balmer describes the series of lines atomic hydrogen.



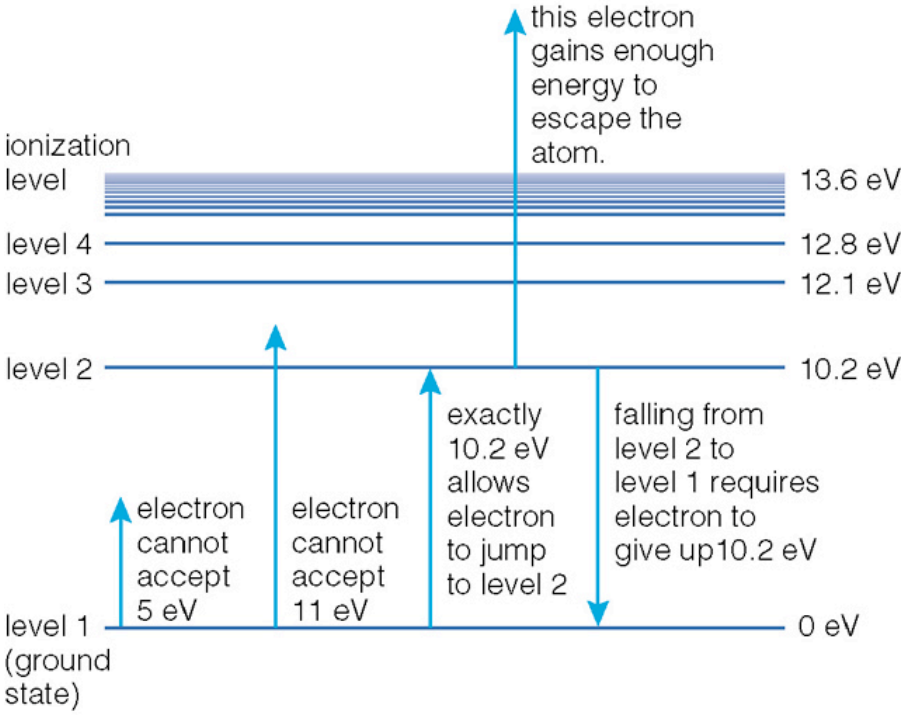
This discrete structure required quantum mechanics and Neils Bohr (1913)

Prerequisites for understanding how the photon interacts with atoms:

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

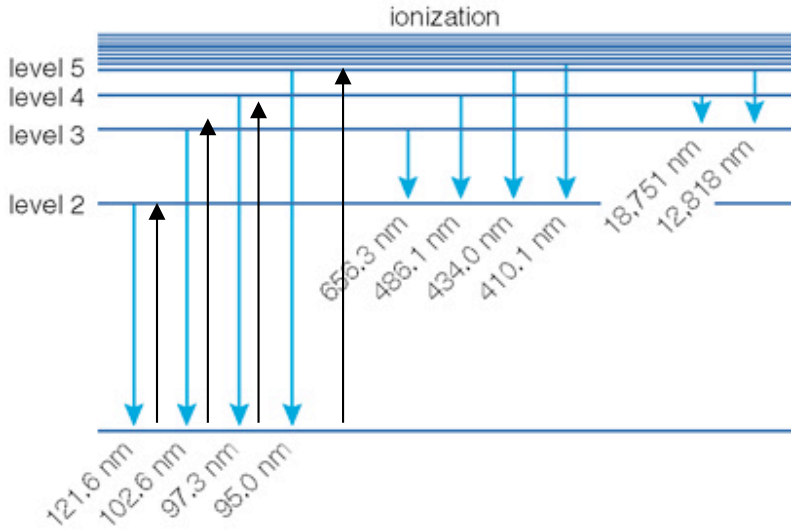


- Any other electron configuration is an excited state of the atom.
- What factors determine the energy of the electrons in an atom?
  - Nuclear charge (coulomb): potential energy: inversely proportional to distance from nucleus
  - Electron-electron interactions
  - Spin-orbit interaction: electron spin/induced magnetic field interaction
  - Understand that for a particular electron, these factors sum up to give the potential
- How can an electron move between states?
  - Increasing or decreasing the energy of a given electron requires the absorption or the emission of a photon
  - Energy can only be increased or decreased in discrete amounts which match the energy differences between one electron state (*state = combination of the factors listed above*) and the next.
  - Not all transitions between electron states are possible through the emission of a single photon, some transitions are more likely than others and some are forbidden altogether (conservation of momentum)



The atomic line spectra is an element's fingerprint

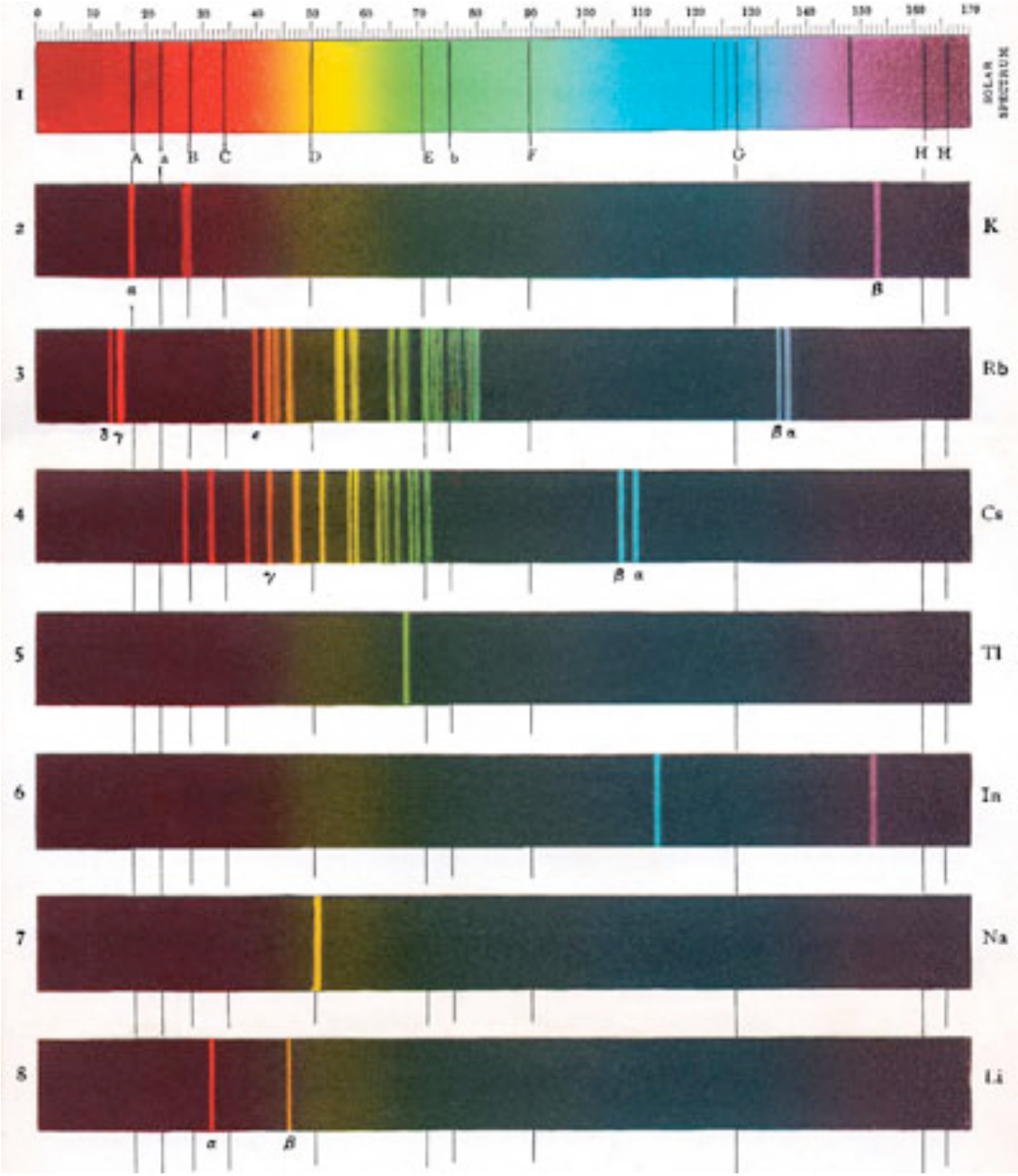
- Electron transitions between *energy levels* result in emission or absorption lines.
- The spectral position of these lines are determined by the structure of the atom.
- Every chemical element therefore has its own unique spectral *fingerprint*.
- **Example:** In astronomy the chemical composition of an astronomical object is determined by observing its *absorption* or *emission spectrum.*
- The spectral lines are not absolutely monochromatic! They are actually an intensity distribution around a specific central wavelength. The width of this intensity distribution is the 'line-width' of the transition.
- This line-width depends various factors that will be discussed.



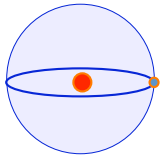
Emission spectrum of Hydrogen

Absorption spectrum of Hydrogen

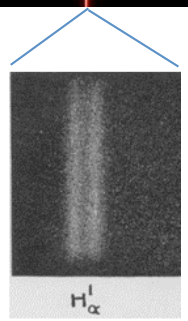
The atomic line spectra is an element's fingerprint

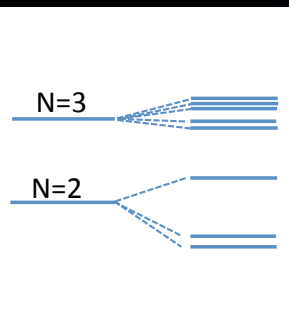


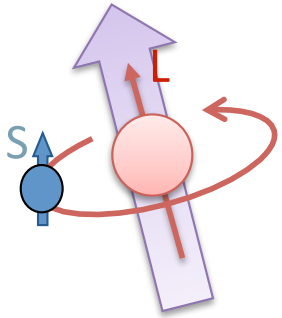
Higher Resolution



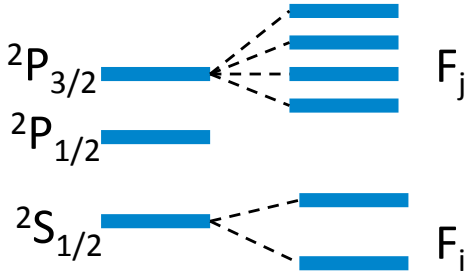
• By increasing the resolution by a factor of ~5000 a fine structure splitting of the hydrogen is observed: key evidence for the spin of the electron.



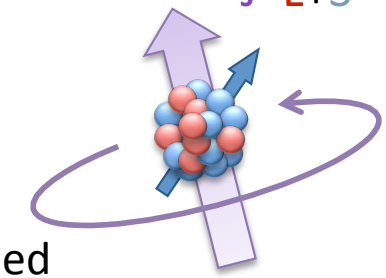




•A further factor of 1000 zoom into the structure reveals finer splitting due to the coupling of the nucleus with the electronic orbital: the hyperfine structure.

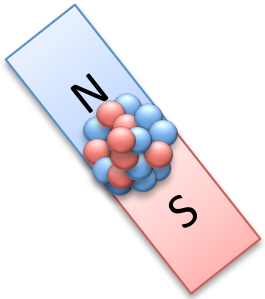


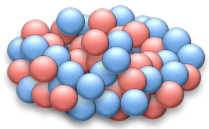
J=L+S



•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.

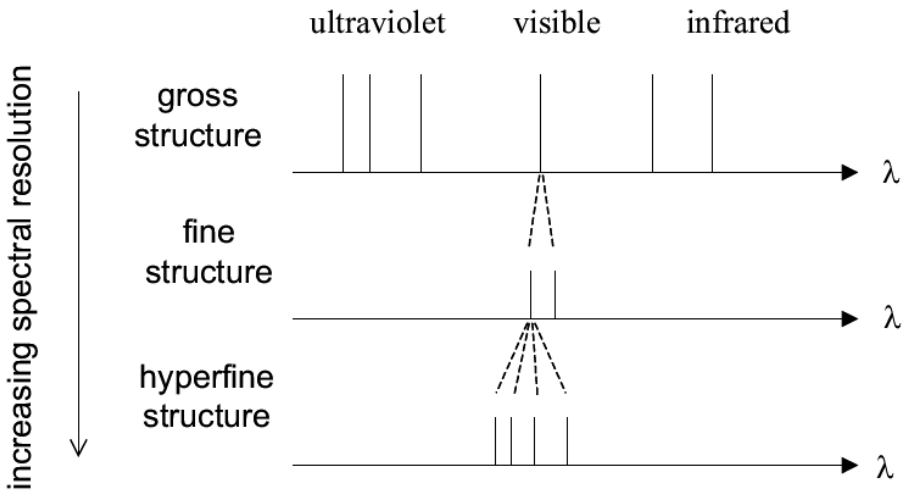
F=J+I





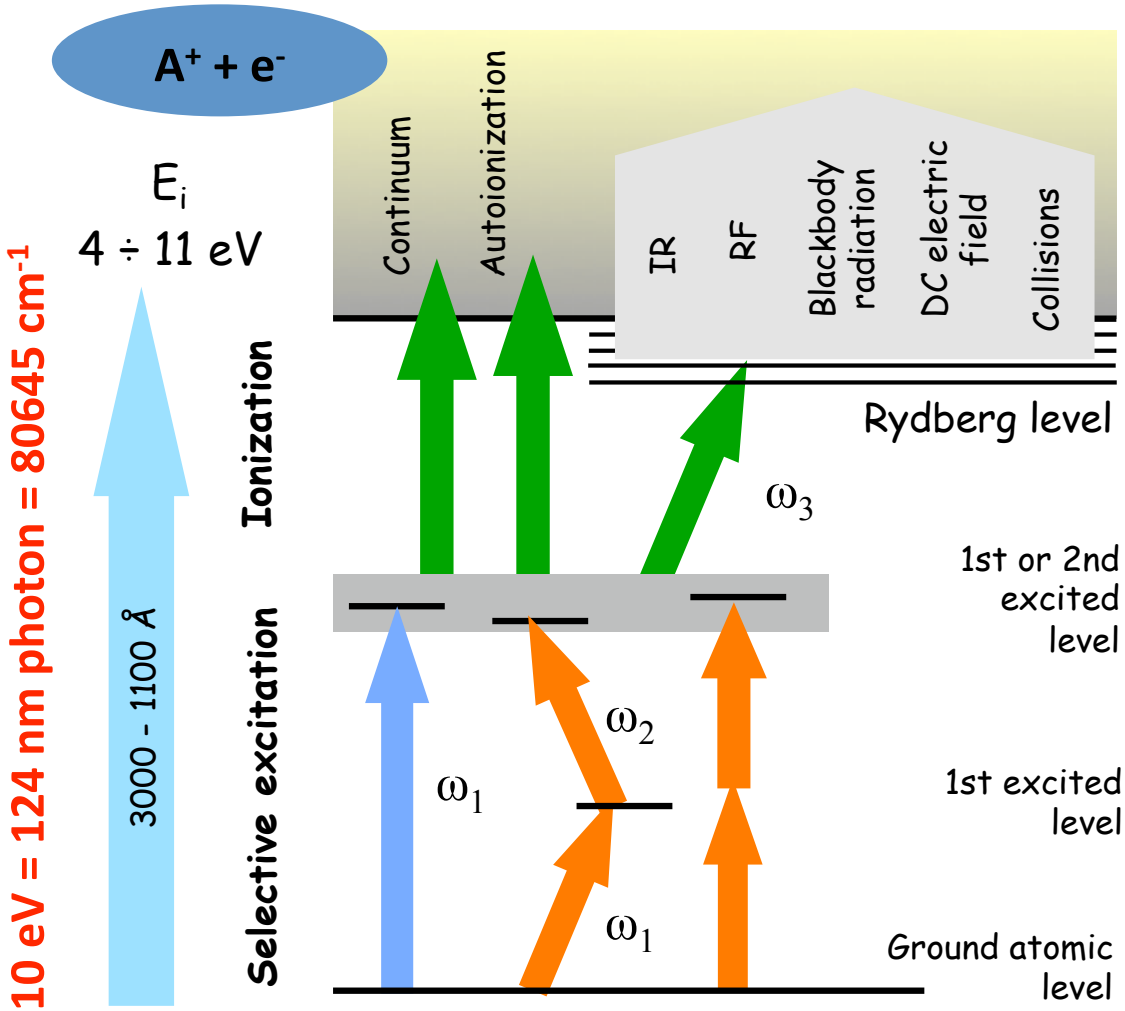
Note – Relevant for part 6 of this course:
If we can measure the splitting of the atomic transitions with sufficient resolution it is possible to deduce the nuclear observables (magnetic and electric moments, spin and size) without any model (nuclear) dependence.

Atomic Energy Scales

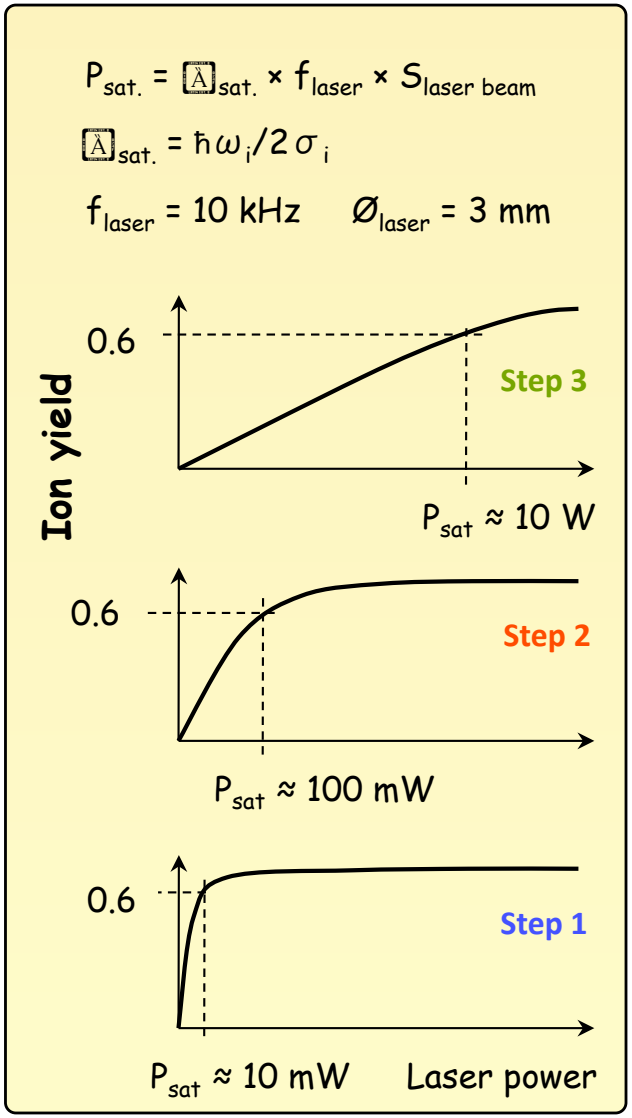


Energy scale	Energy (eV)	Effects
Gross structure	1-10	electron-nuclear attraction Electron kinetic energy Electron-electron repulsion
Fine structure	0.001 - 0.01	Spin-orbit interaction Relativistic corrections
Hyperfine structure	10^{-6} - 10^{-5}	Nuclear interactions

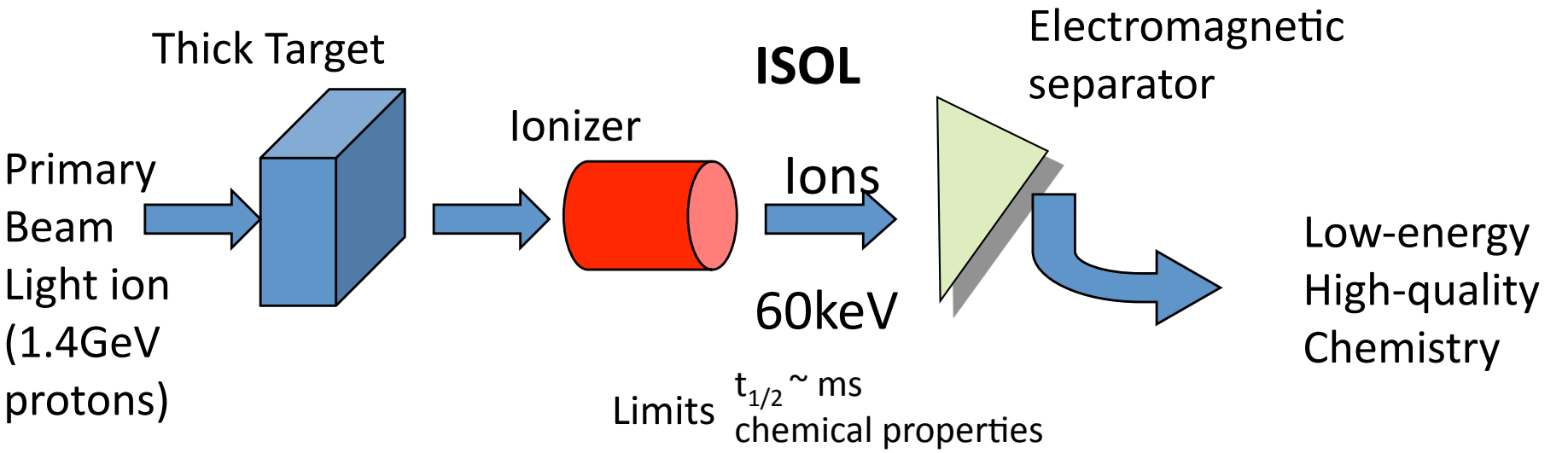
Laser ion source – using this fingerprint for selective ionization



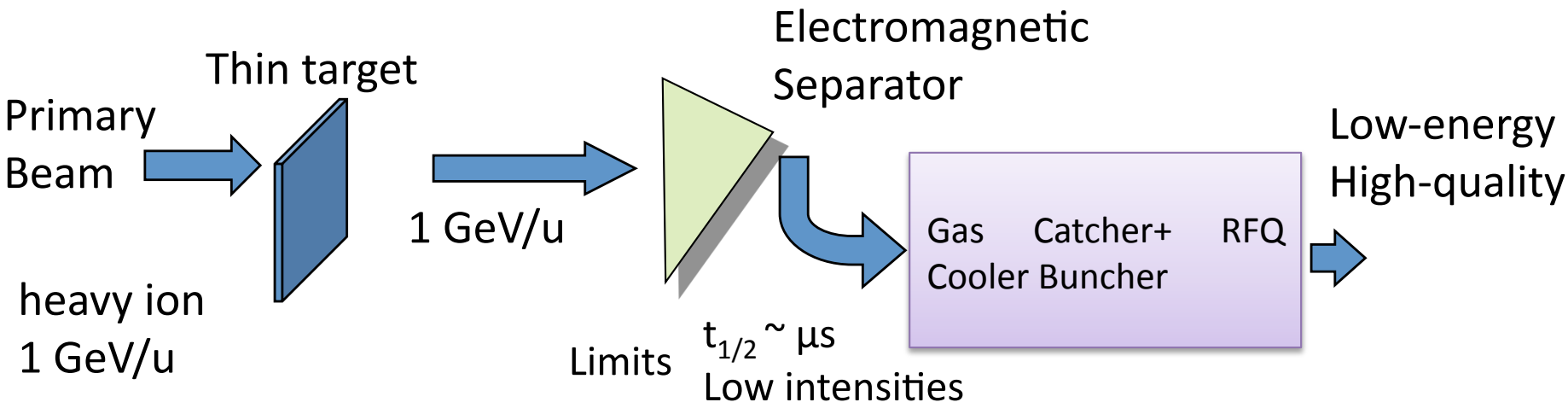
$$\omega_i(\text{laser}) = \omega_i(\text{atom}); \quad P_i(\text{laser}) \geq P_i(\text{saturation})$$

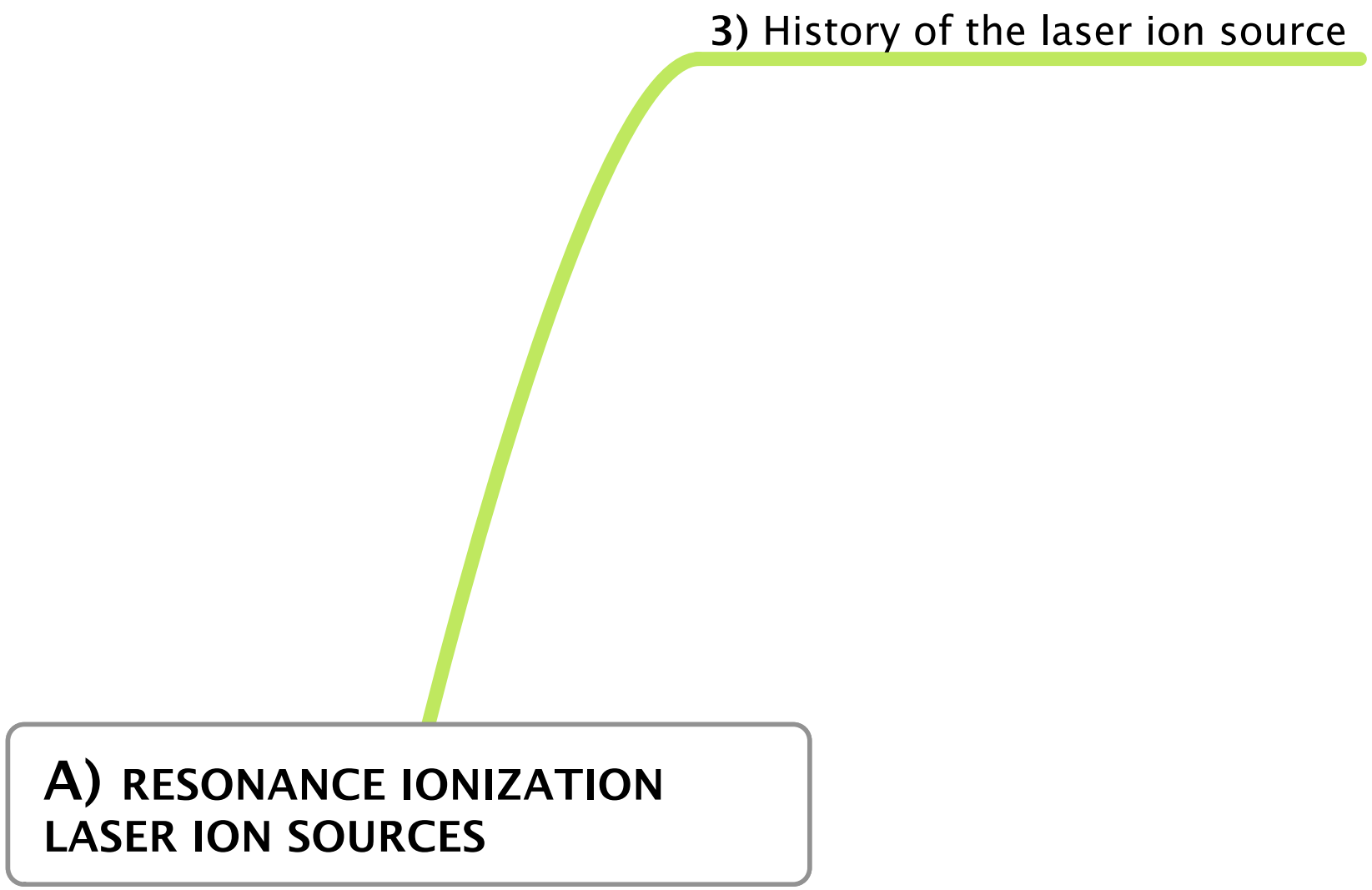


Rare isotope production methods compatible with laser ion sources



In-Flight Fragmentation (GSI)




3) History of the laser ion source
A) RESONANCE IONIZATION LASER ION SOURCES

Early proposals: 1984

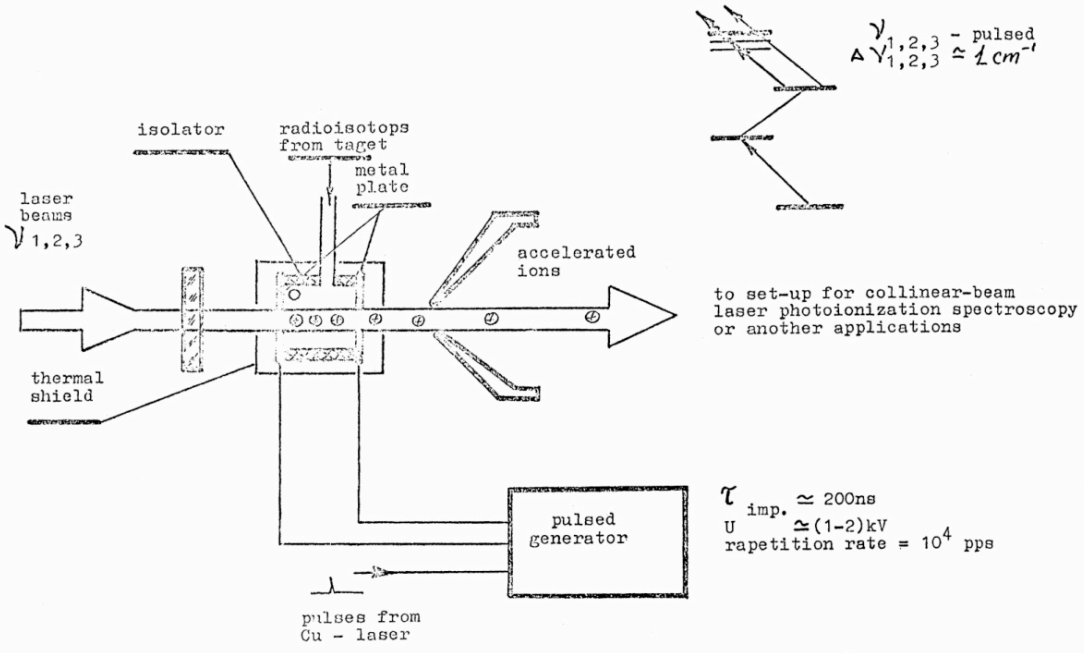
P R O P O S A L

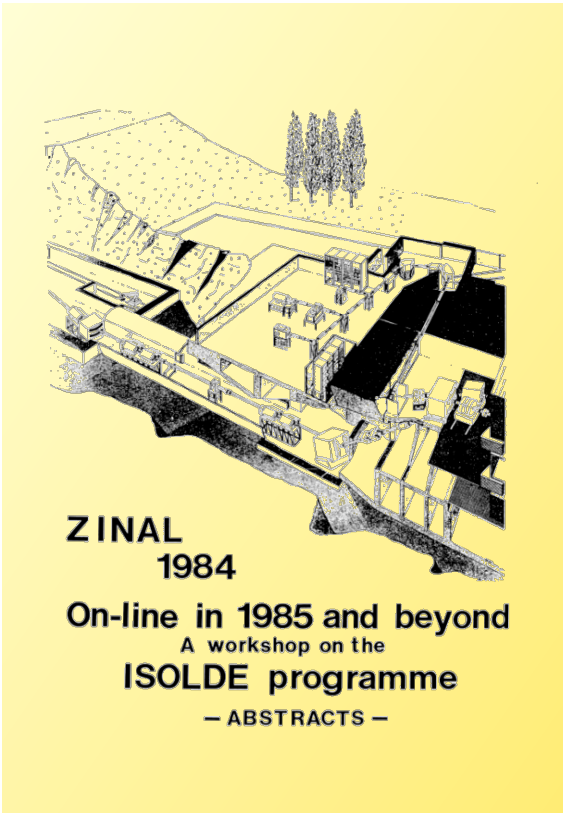
of the Institute of Spectroscopy, Acad.Sci. USSR
for experiments with ISOLDE-CERN Facility

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

LASER PHOTOIONIZATION PULSED SOURCE OF RADIOACTIVE ATOMS

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





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.

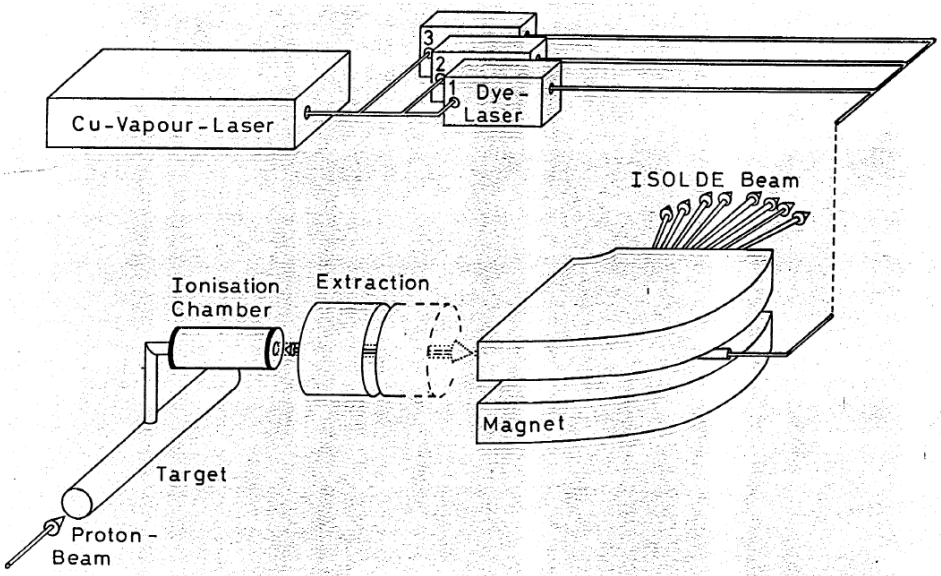
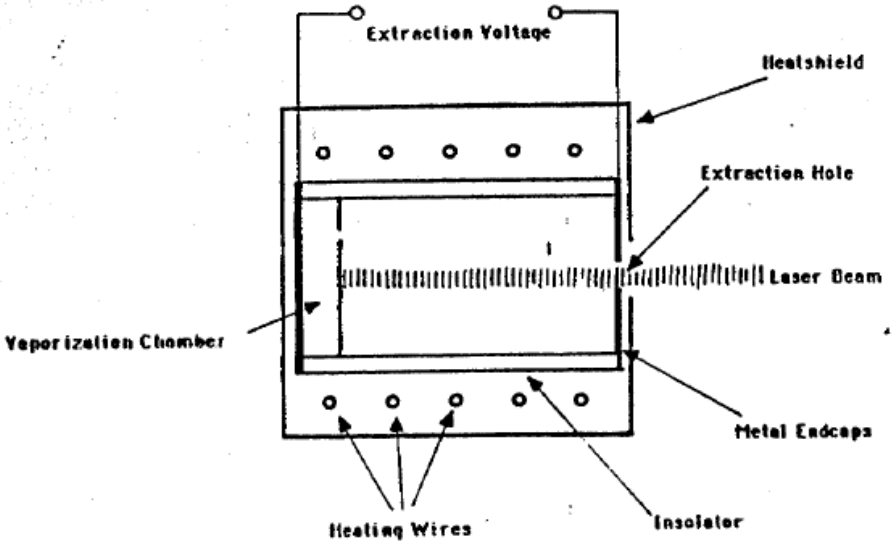


Fig. 5: General layout of the experimental set-up at the off-line separator



Ionization in a hot metal cavity

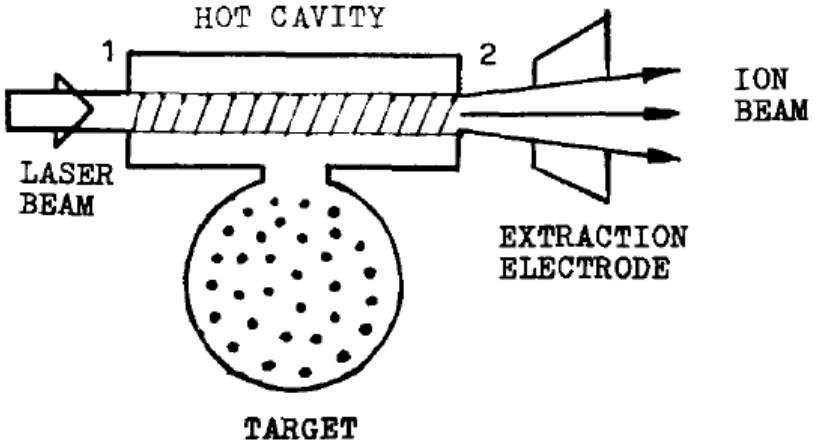
Nuclear Instruments and Methods in Physics Research A306 (1991) 400–402

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

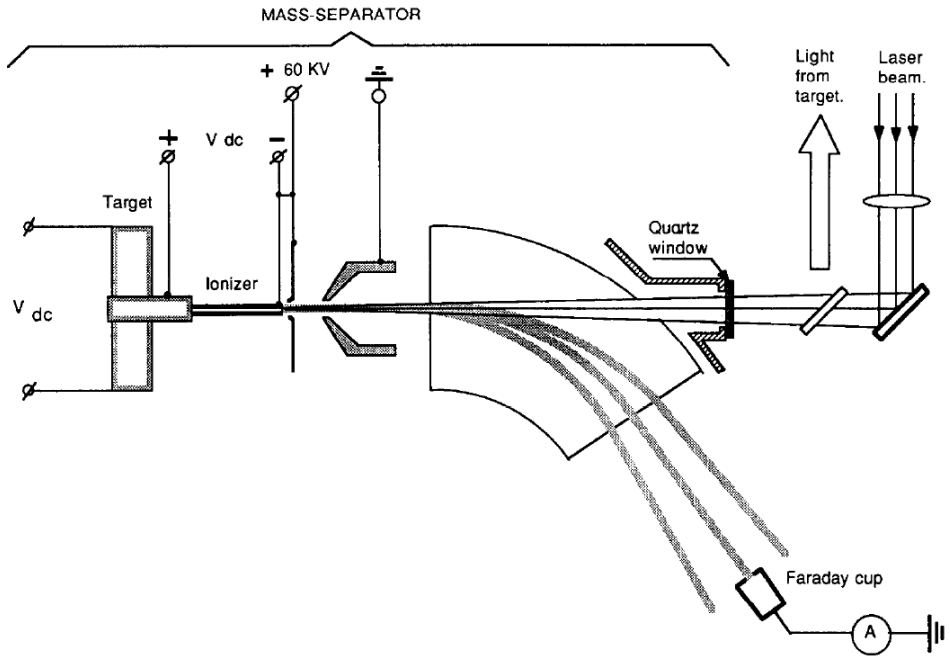
Nuclear Instruments and Methods in Physics Research B73 (1993) 550–560

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

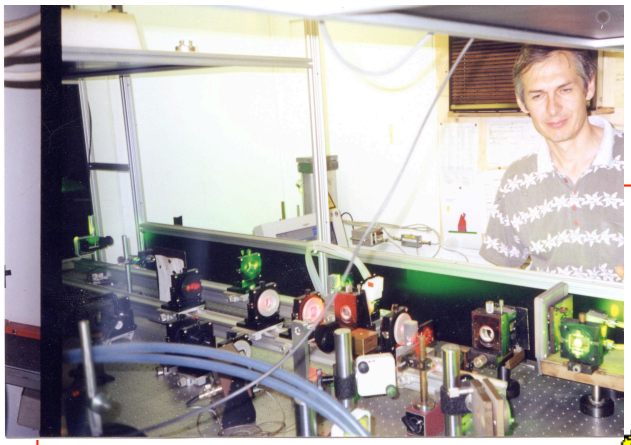
PPE Division, CERN, Geneva, Switzerland

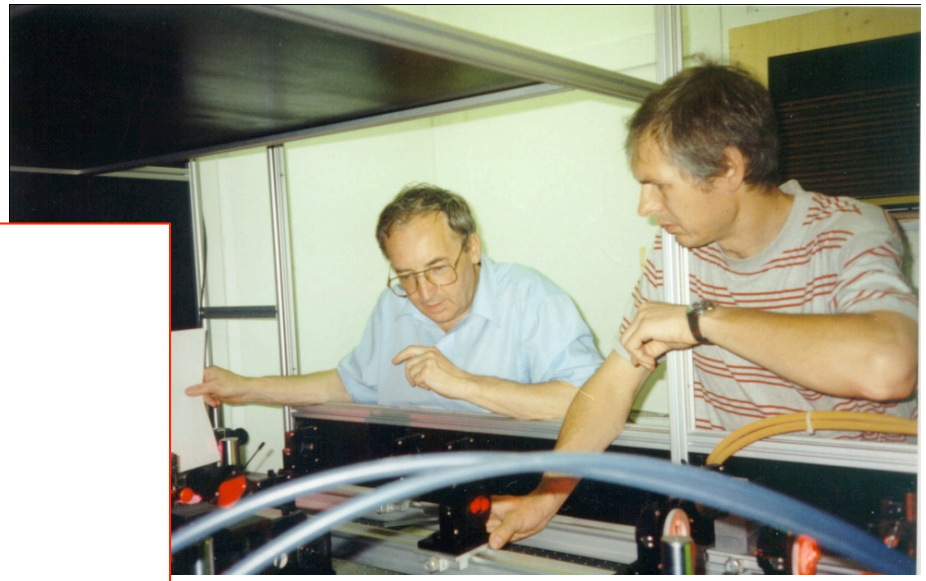
Received 26 November 1992



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

RILIS at ISOLDE-PSB





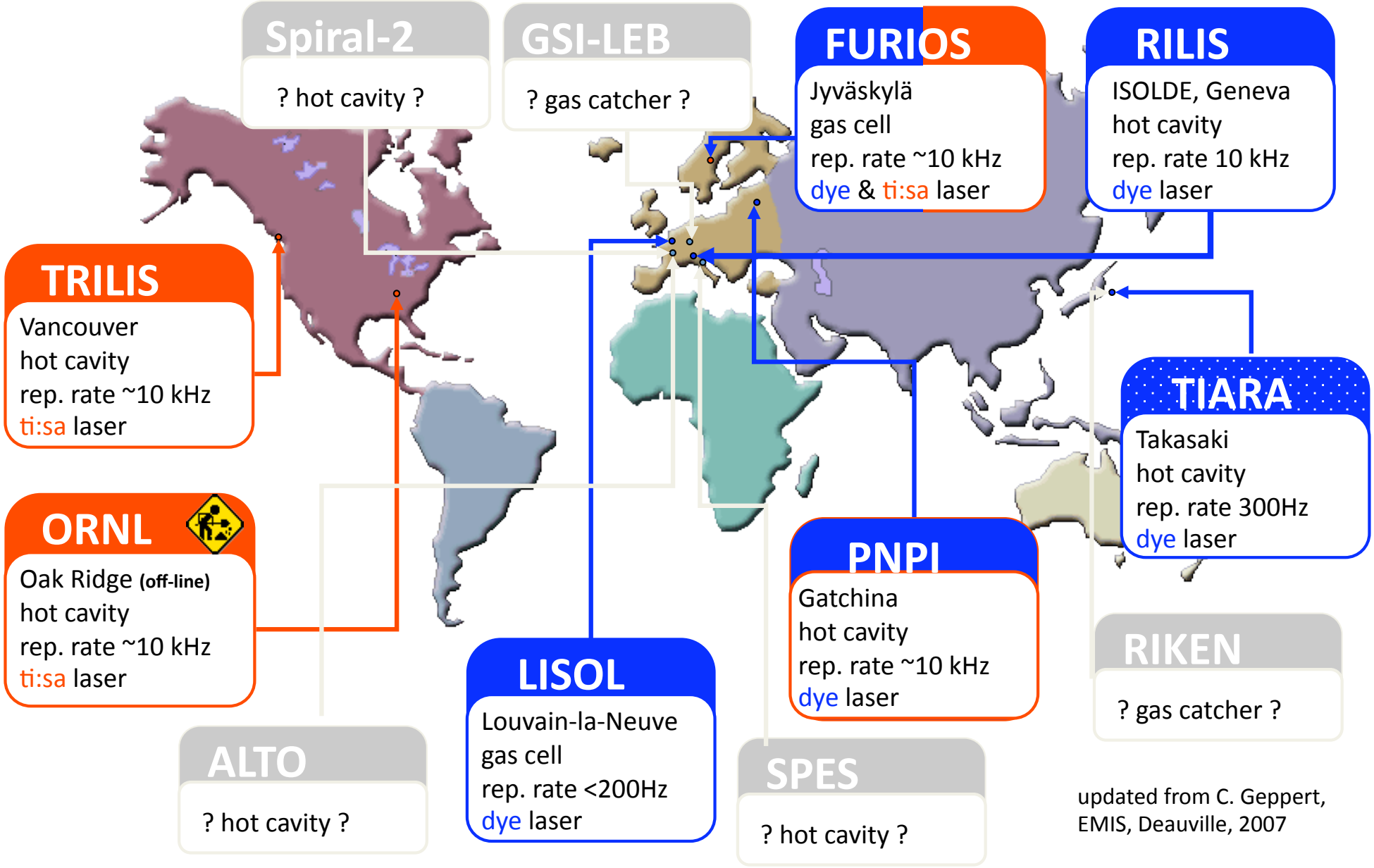
CVL lasers: ν_{rep}=11.000 Hz
Oscillator + 2 amplifiers
2-3 dye lasers with amplifiers, nonlinear crystals BBO:

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

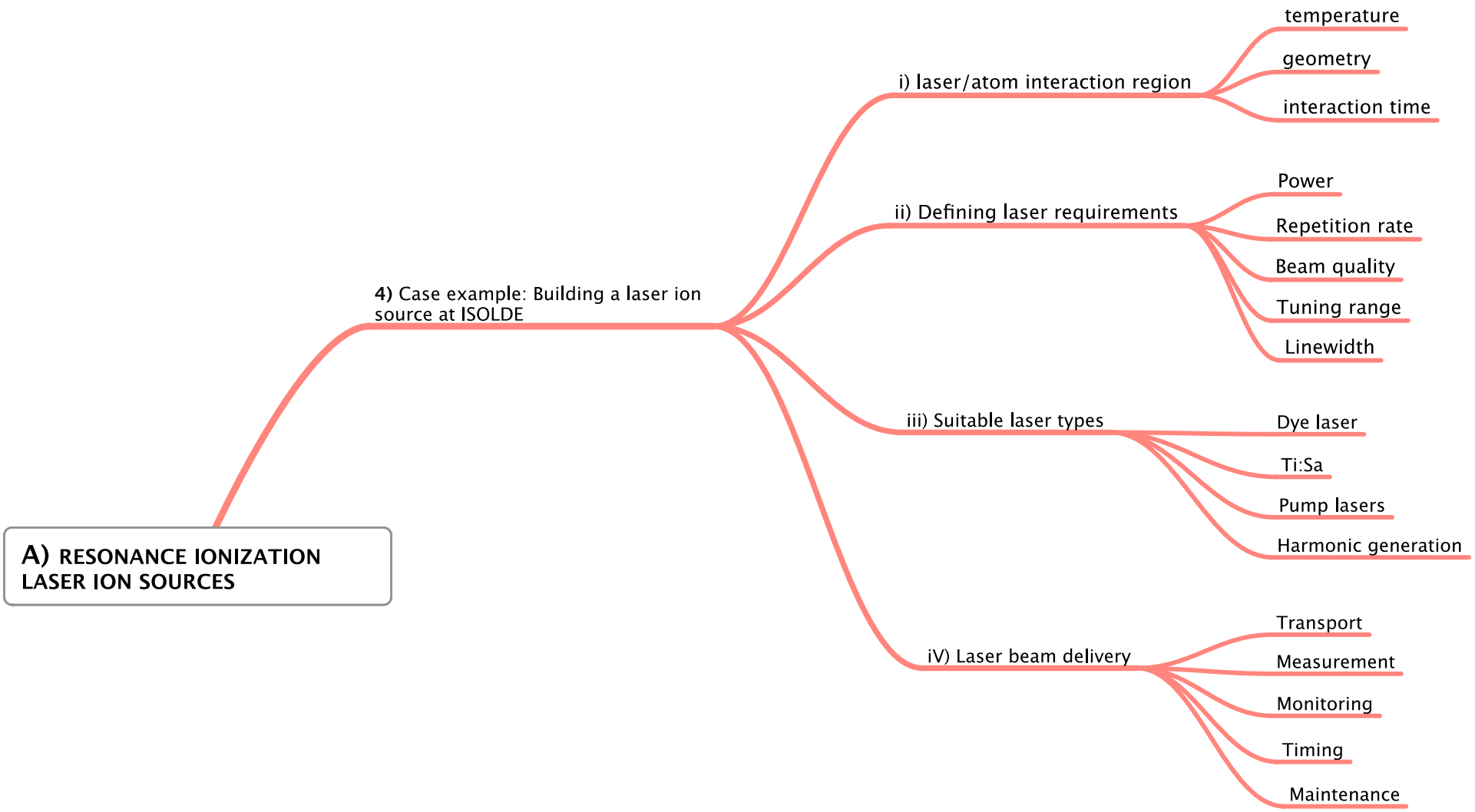
$$P_{dye} \leq 8\,W$$

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

Resonance laser ion sources worldwide

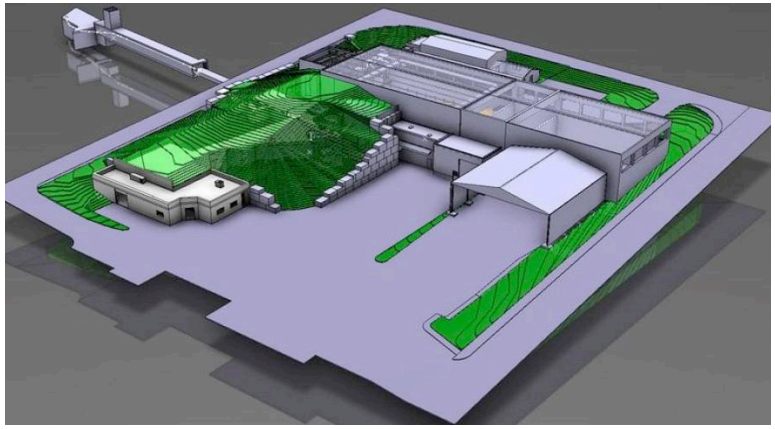


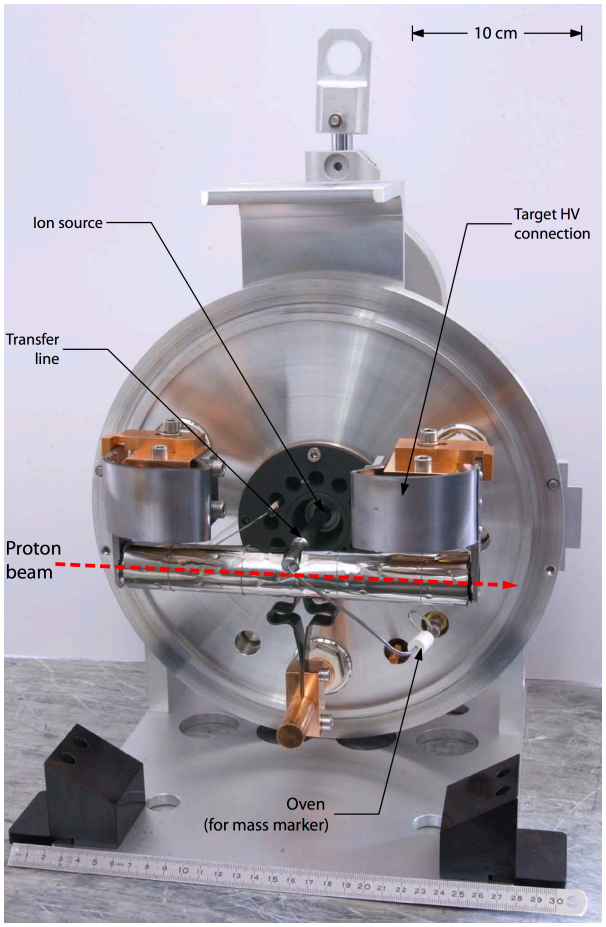
updated from C. Geppert, EMIS, Deauville, 2007


A) RESONANCE IONIZATION LASER ION SOURCES
4) Case example: Building a laser ion source at ISOLDE
i) laser/atom interaction region
temperature
geometry
interaction time
ii) Defining laser requirements
Power
Repetition rate
Beam quality
Tuning range
Linewidth
iii) Suitable laser types
Dye laser
Ti:Sa
Pump lasers
Harmonic generation
iV) Laser beam delivery
Transport
Measurement
Monitoring
Timing
Maintenance

Building a laser Ion source at an ISOL facility such as ISOLDE

Where do we put the laser ion source?

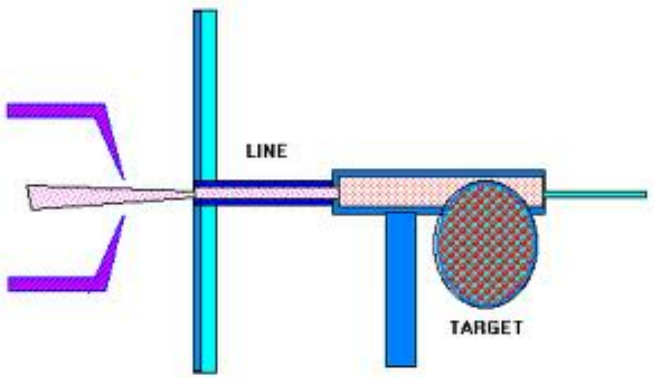




Requested features:

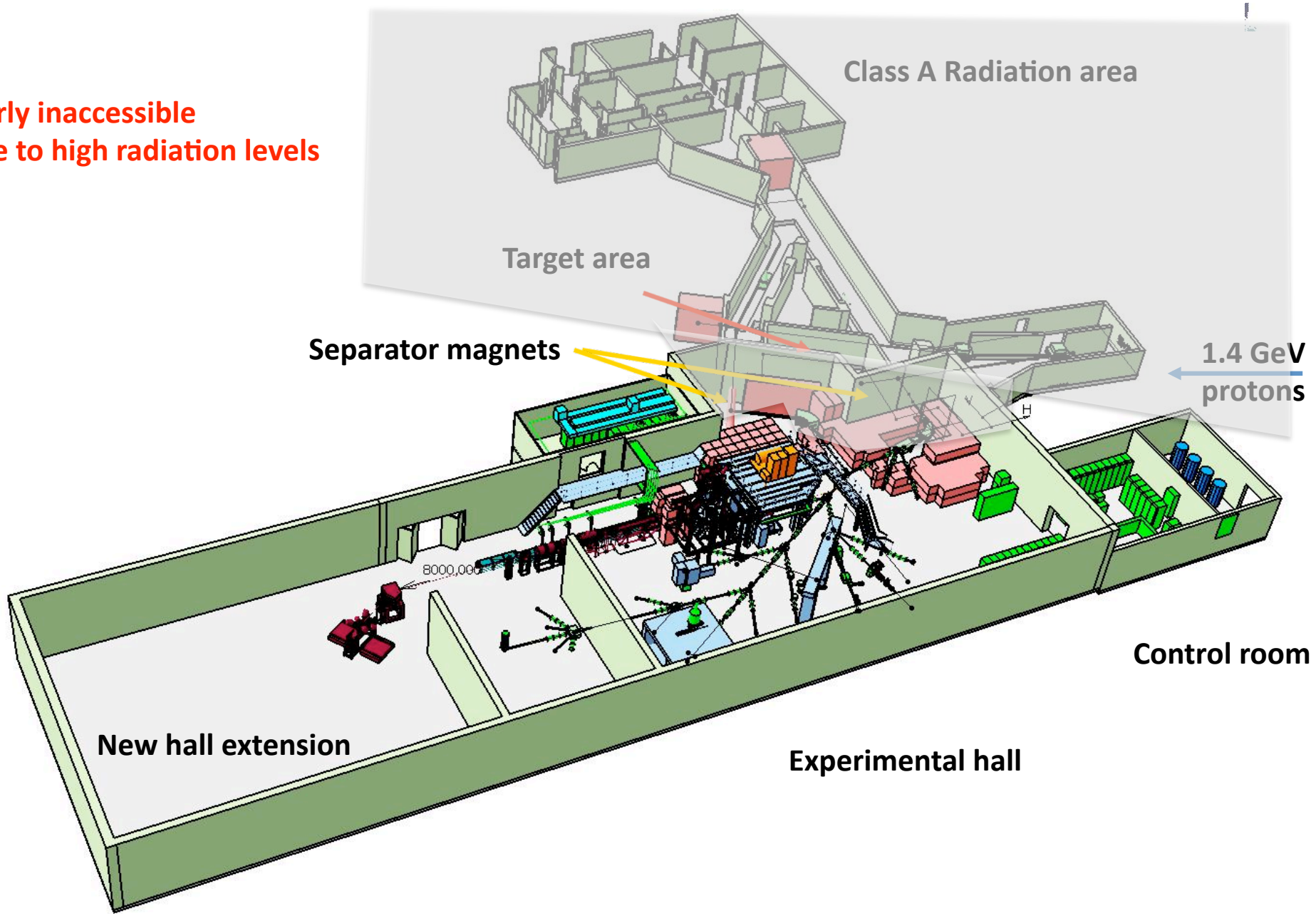
- Universal
- Selective
- Efficient
- Reliable
- Fast

What is the optimal laser ion source configuration for ISOLDE?



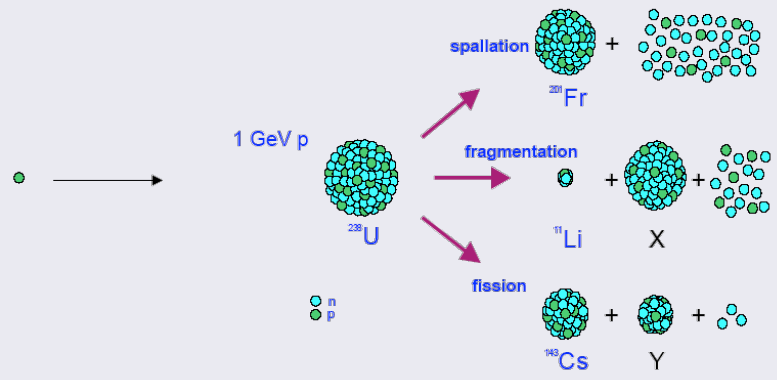
The ISOLDE Laboratory

Fairly inaccessible due to high radiation levels

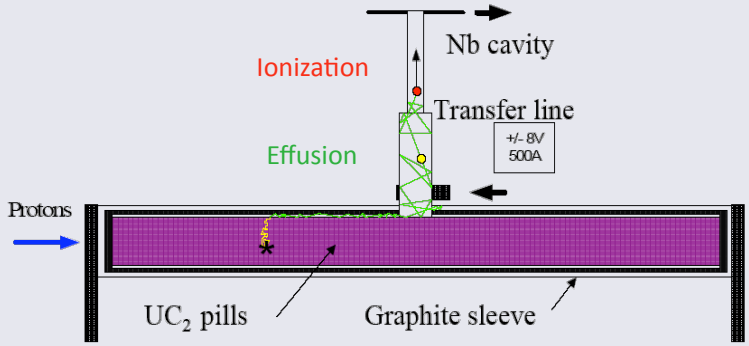


What are we trying to achieve:

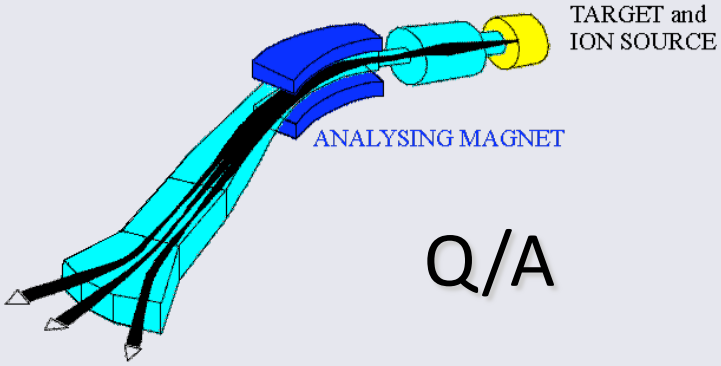
Production



Extraction/Ionization

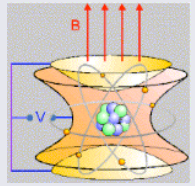


Isotope Separation

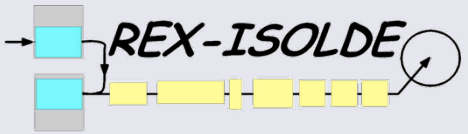


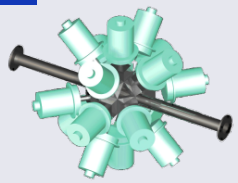
Q/A

Post acceleration or to Experiment



ISOLTRAP





Fast, Efficient, Universal and Selective!

What are the considerations based on what we already know about the laser ionization principle and the ISOLDE target/ion source unit:

Harsh radiation environment (Mgray!) → Simplicity near target unit

High efficiency → Good geometric and temporal laser/atom overlap

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

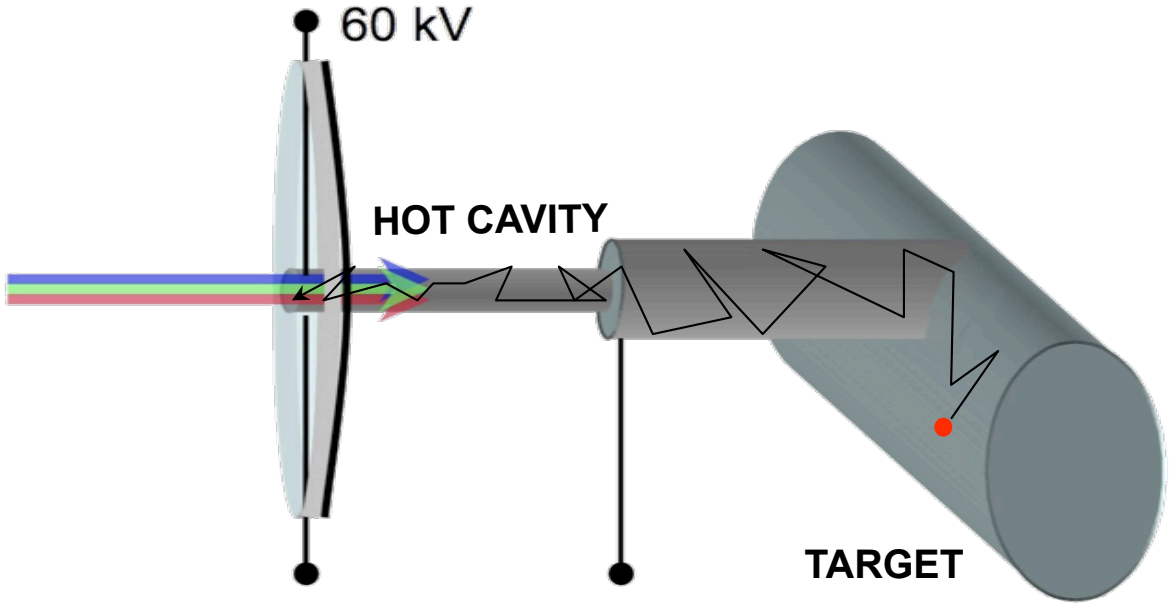
Universality → Applicable to many elements

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

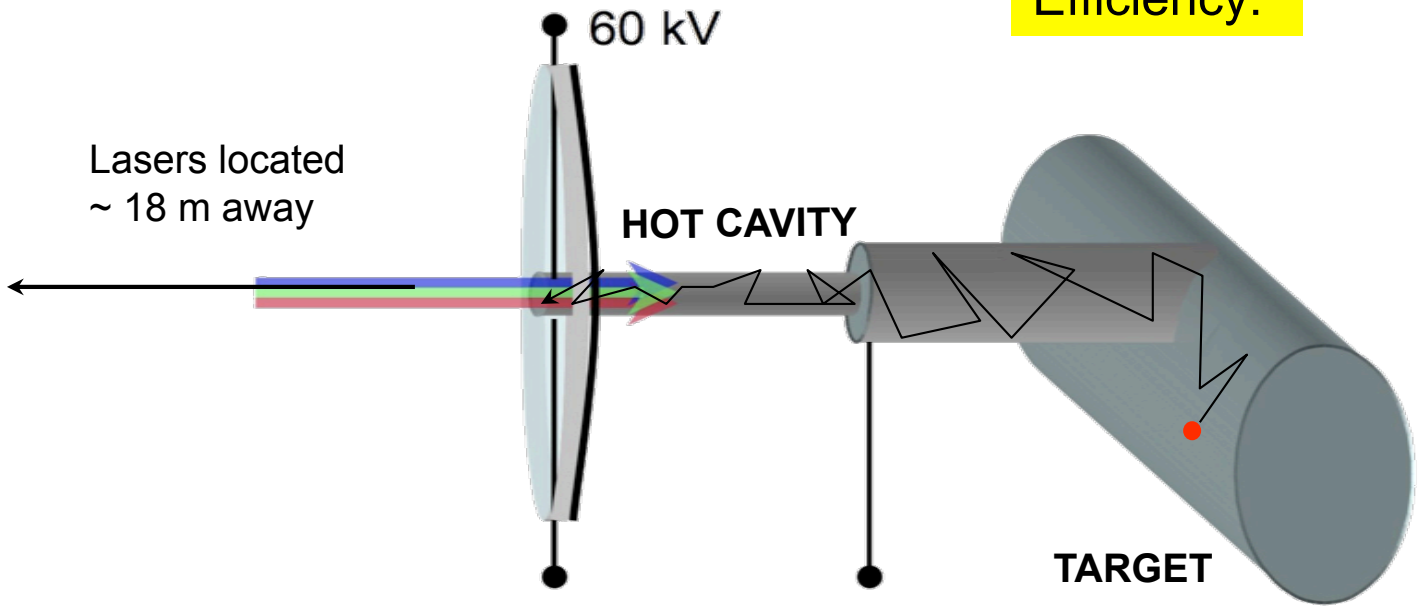
Selectivity → High purity ion beam, no isobars

The hot surface ion source cavity

- A good laser /atom interaction region?



The Hot Cavity Laser Ion Source



Efficiency:

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

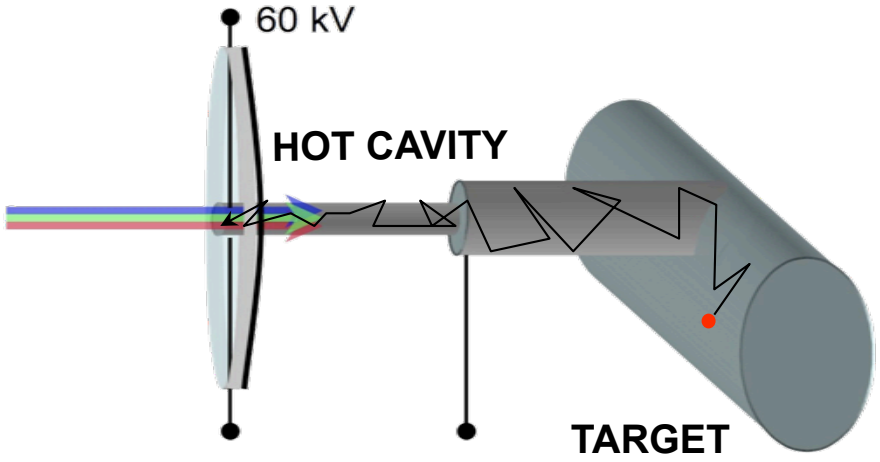
$$\varepsilon_{laser} = 2\% - 30\%$$

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

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

=> depends on the ionization potentials of isobar atoms

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



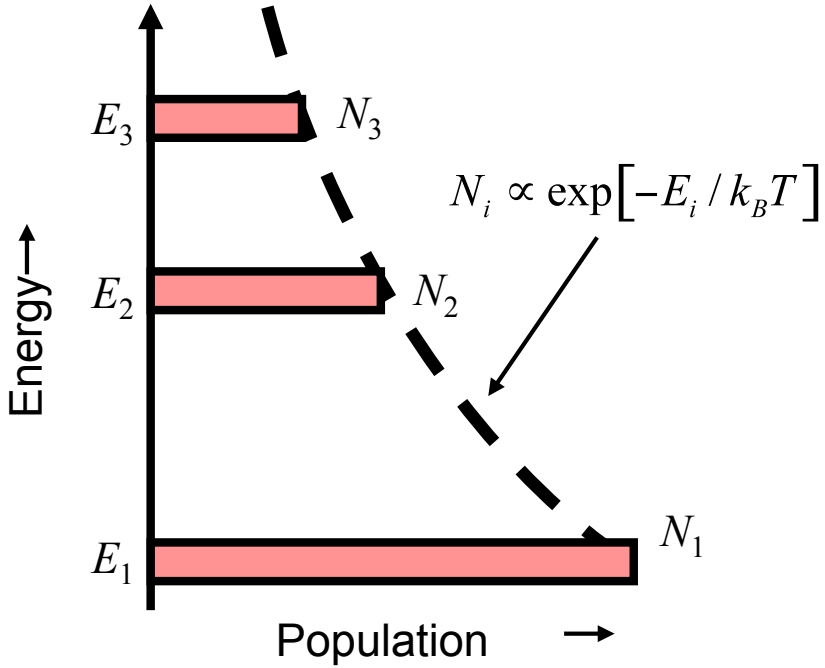
- Effusion time → Laser repetition rate
- High temperature → Laser linewidth
  atomic transitions
- Electron emission → Extraction efficiency
- Surface ionization → Selectivity

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

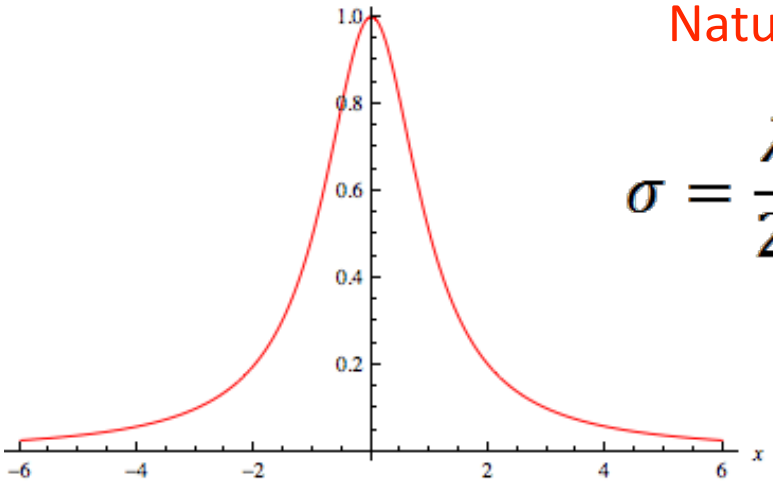


Line broadening mechanisms:

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

Uncertainty principle:

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



Natural linewidth has Lorentzian shape:

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

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

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

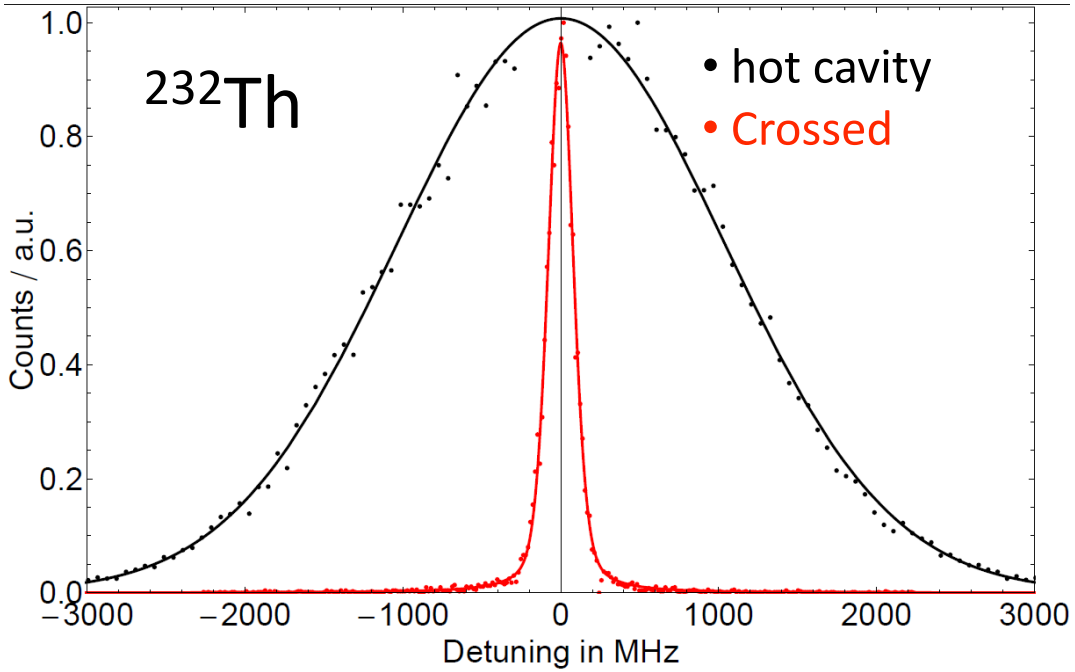
When an atom is in thermal motion we get Doppler broadening. An atomic vapour has a Maxwell-Boltzmann distribution of velocities:

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

The velocity of the atoms Doppler shifts the absorption frequency to

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

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



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

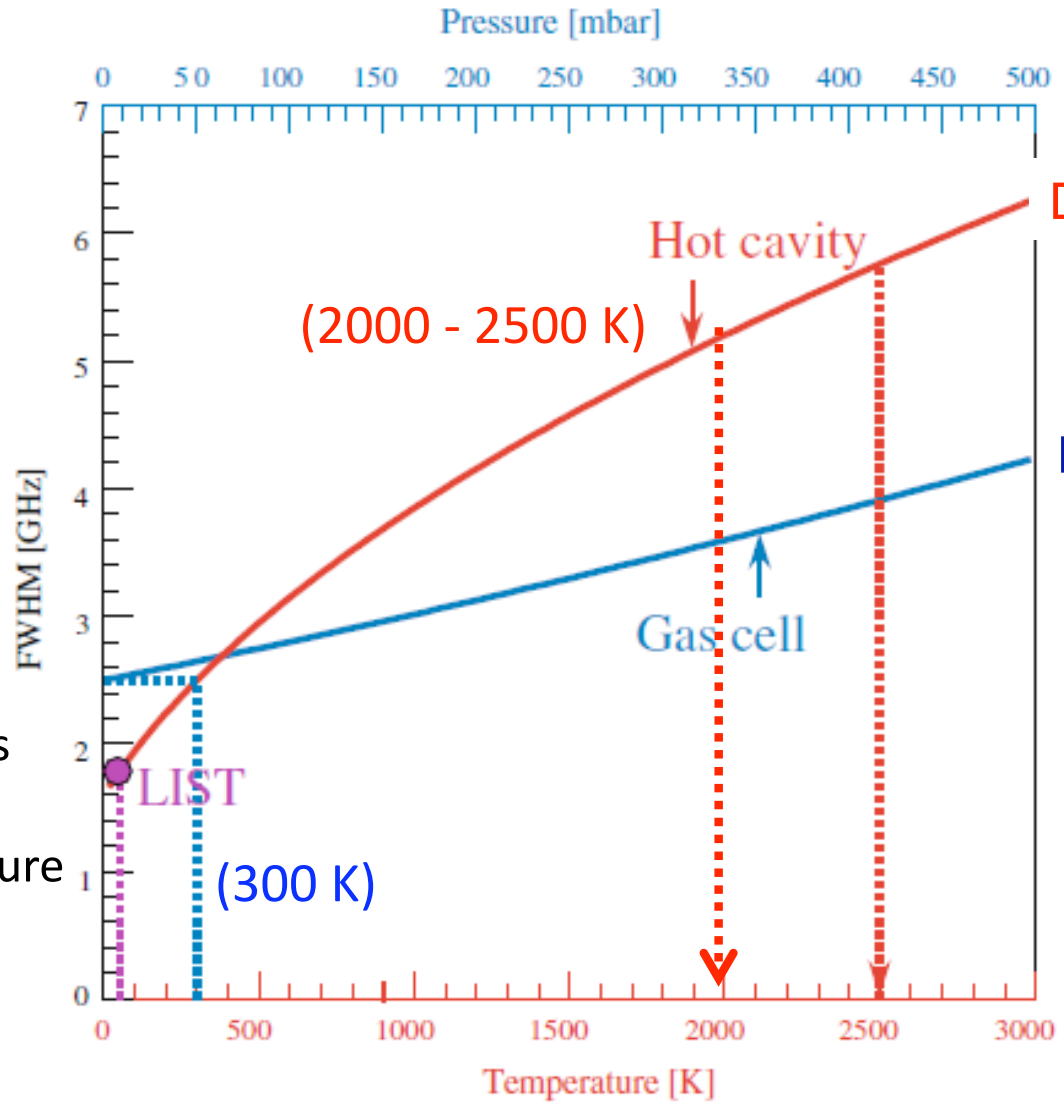
Example: 0 → 38278 cm^{-1} transition

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

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

Broadening: Hot cavity vs Gas cell

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



Doppler broadening

Pressure broadening

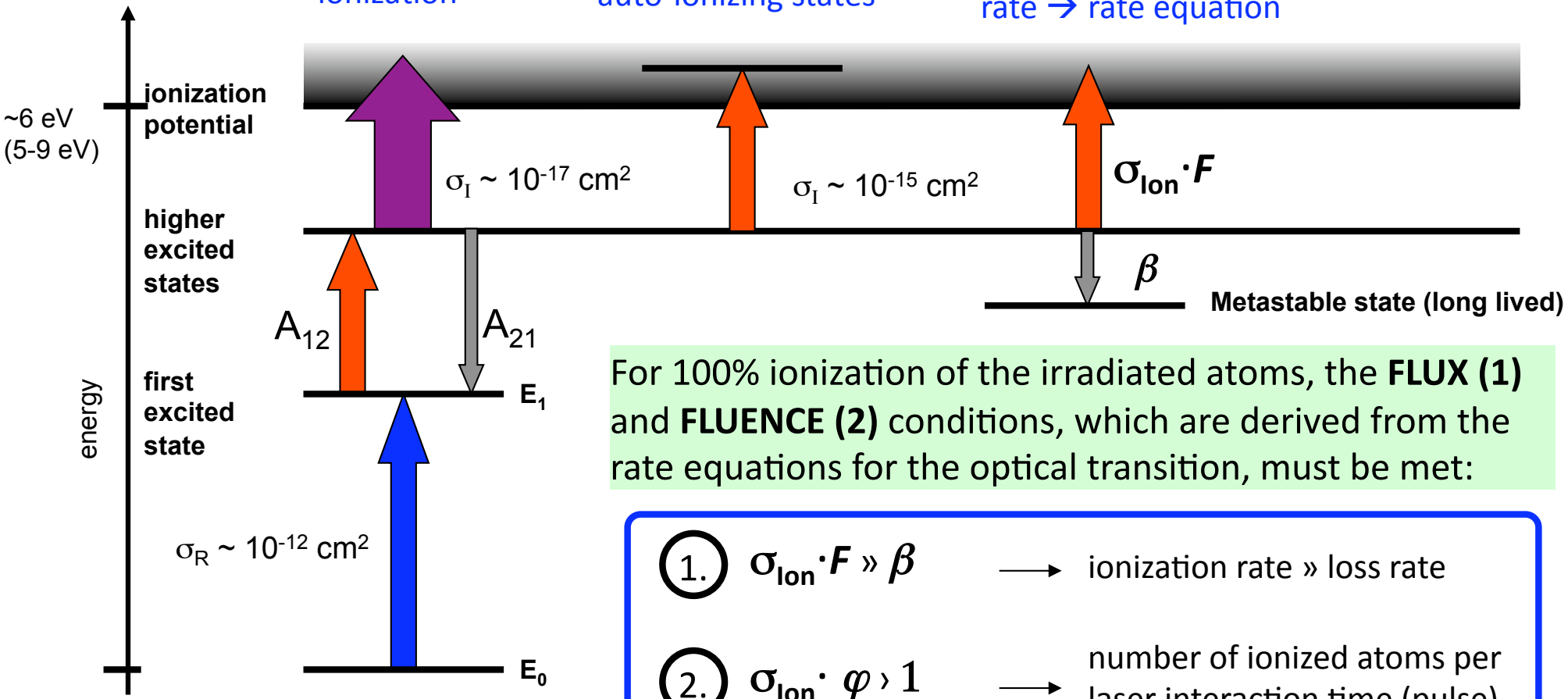
Expanding gas jet is cold and has low pressure

Resolution in gas jet limited by laser bandwidth

non-resonant ionization

excitation of auto-ionizing states

Ionization rate vs loss rate → rate equation



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. $\sigma_{Ion} \cdot \varphi \rangle 1$ ⟶ 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})

φ photon fluence (=photon flux · laser interaction time)

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

typical values:

σ_{ion} ⟶ 10^{-17} cm²

β ⟶ 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.

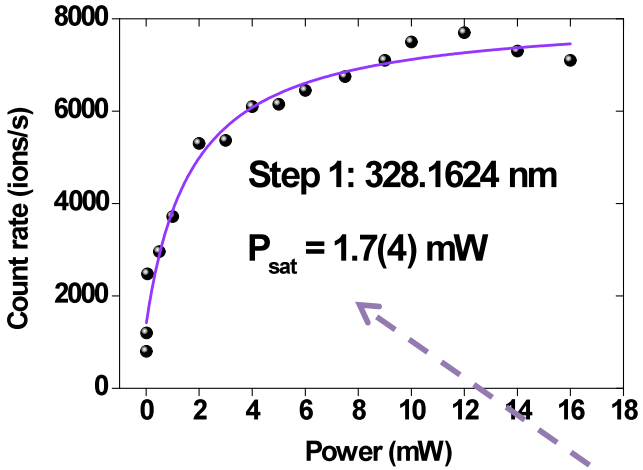
3 eV photons *(2.33 eV = 532 nm)*

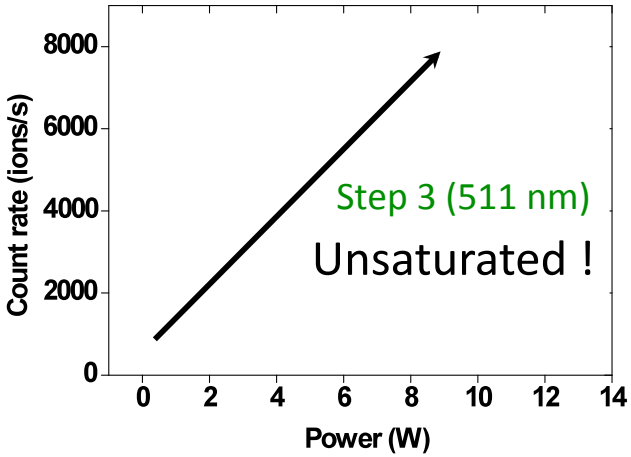
From (1): Flux F >> 10^{24} $cm^{-2}s^{-1}$
→ # photons required >> 10^{22} /s → >> 5000 W
Impossible with CW laser !!

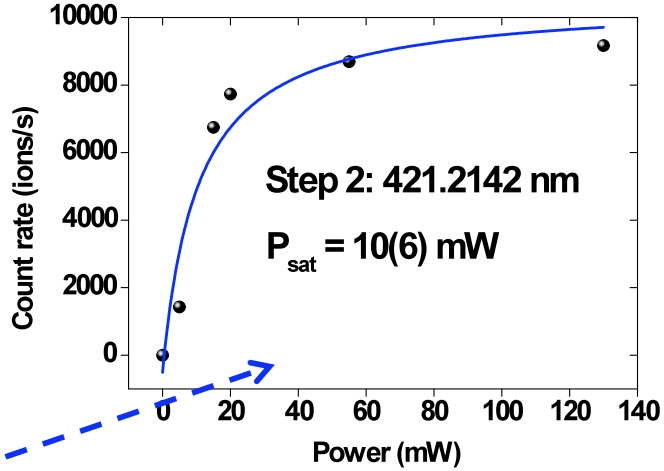
But with a pulsed laser system:
Typical pulse length is 10 ns. → >> 50 µJ/pulse
No problem !!

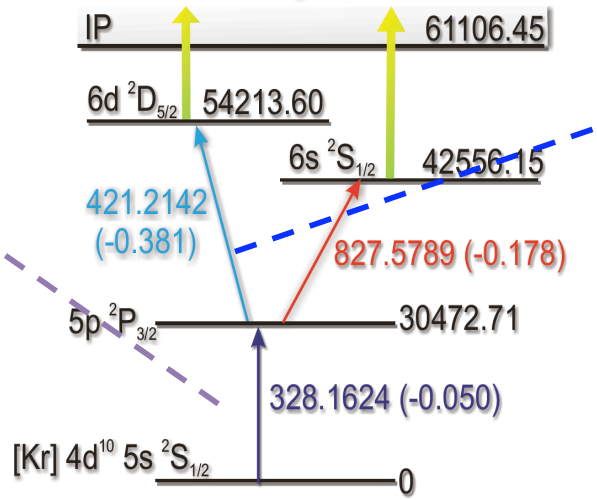
But with the limited laser interaction time **Fluence (2)** condition becomes more difficult → > 5 mJ/pulse
(>50 W at 10kHz!)

Ex.: Ag ionization









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

Resonant saturation parameter:

$S_0 = I/I_{sat}$

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

The population of the excited state:

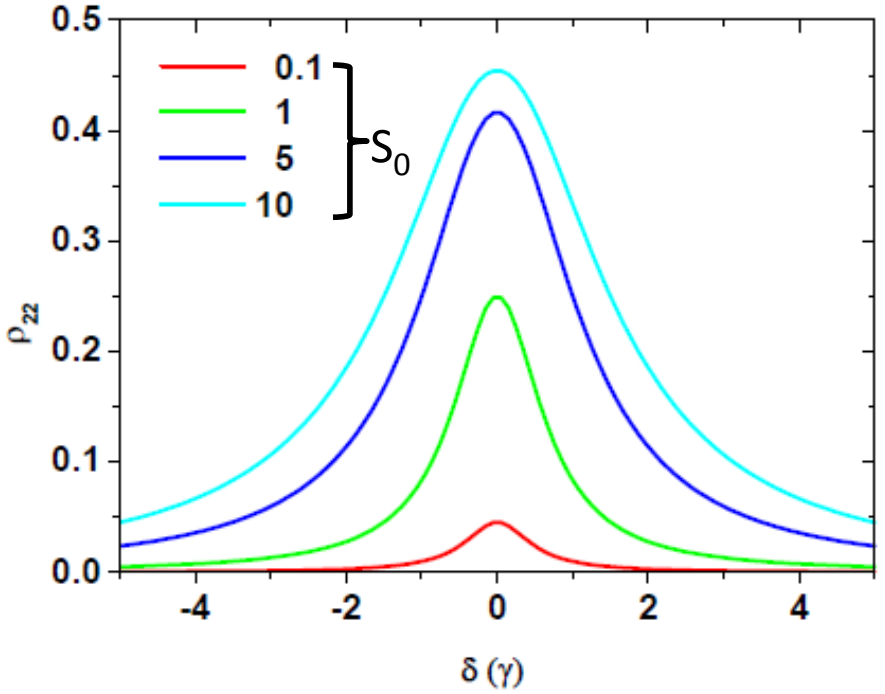
$$\rho = \frac{S}{2(S+1)}$$

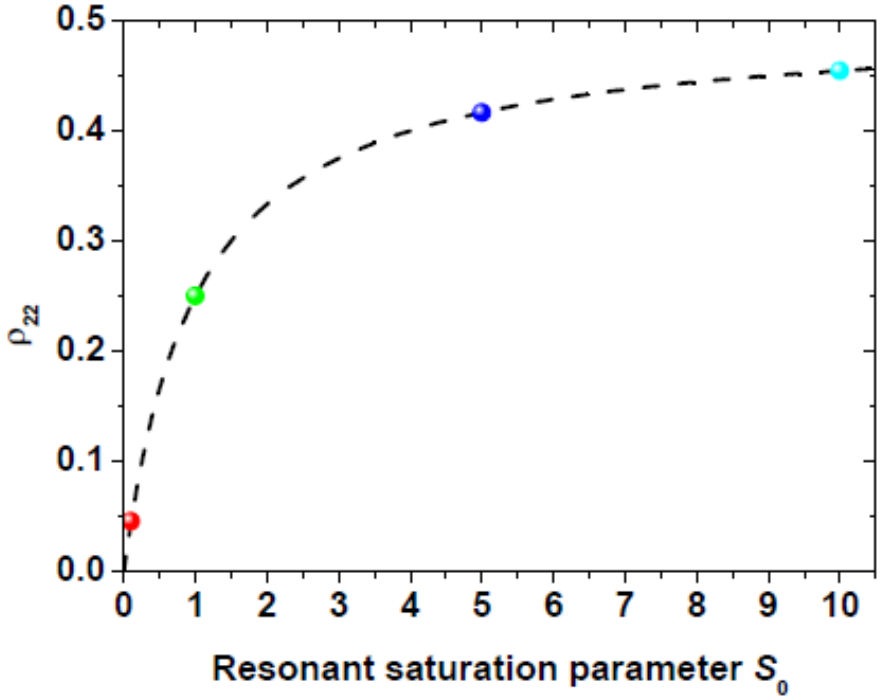
where *S*, the saturation parameter, is a Lorentzian function with FWHM Γ:

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

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

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





So we now understand that for efficient laser ionization we need pulsed, tunable lasers, preferably with AI or Rydberg ionization, and that each transition should be ``saturated´´. *The duty cycle is also something to bear in mind*.

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

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

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

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

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

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

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

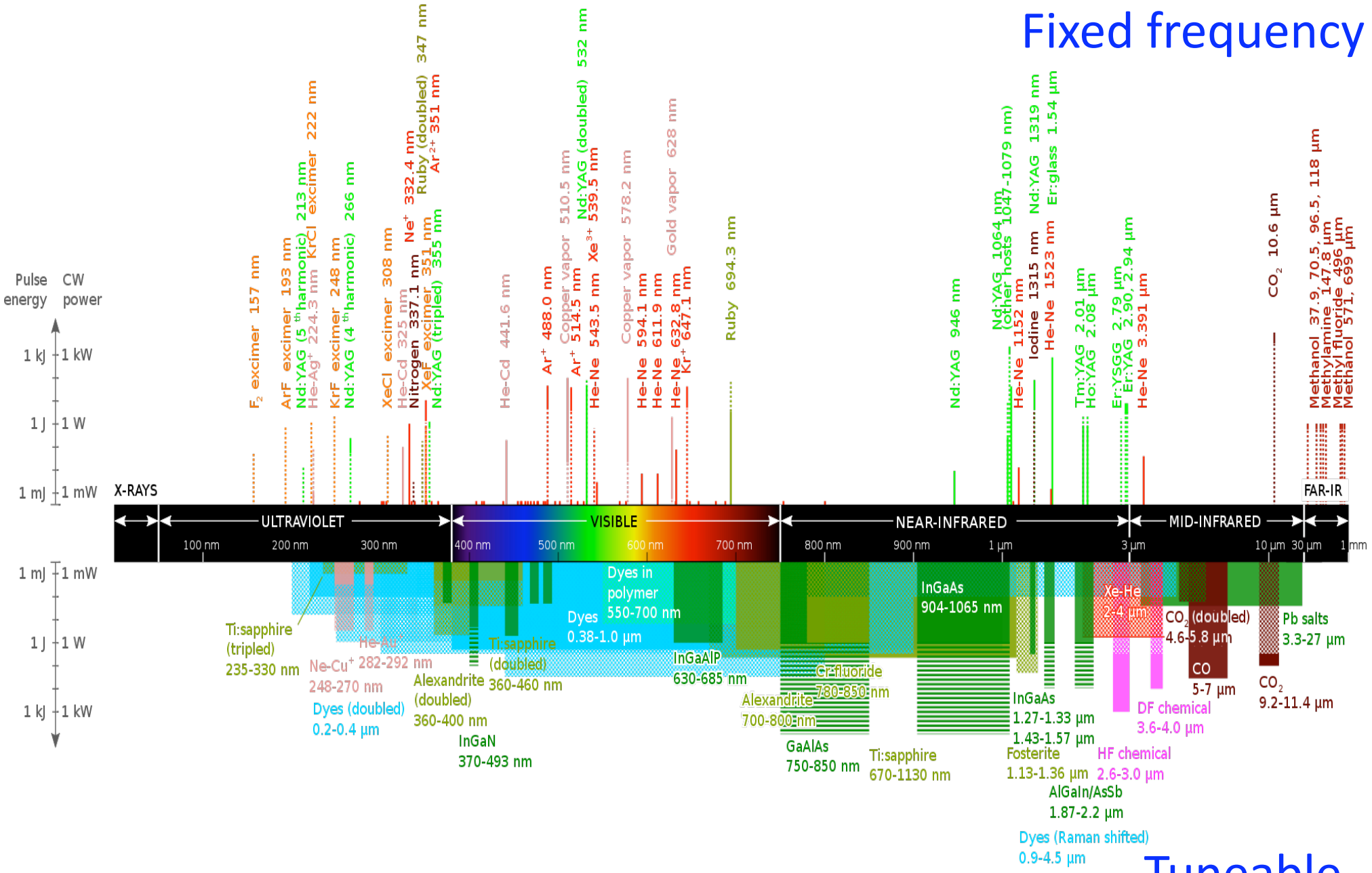
Δ ~10^{15} Hz (krypton to bromine): S ~10^{17} !!!

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

Summary of laser parameters that are required:

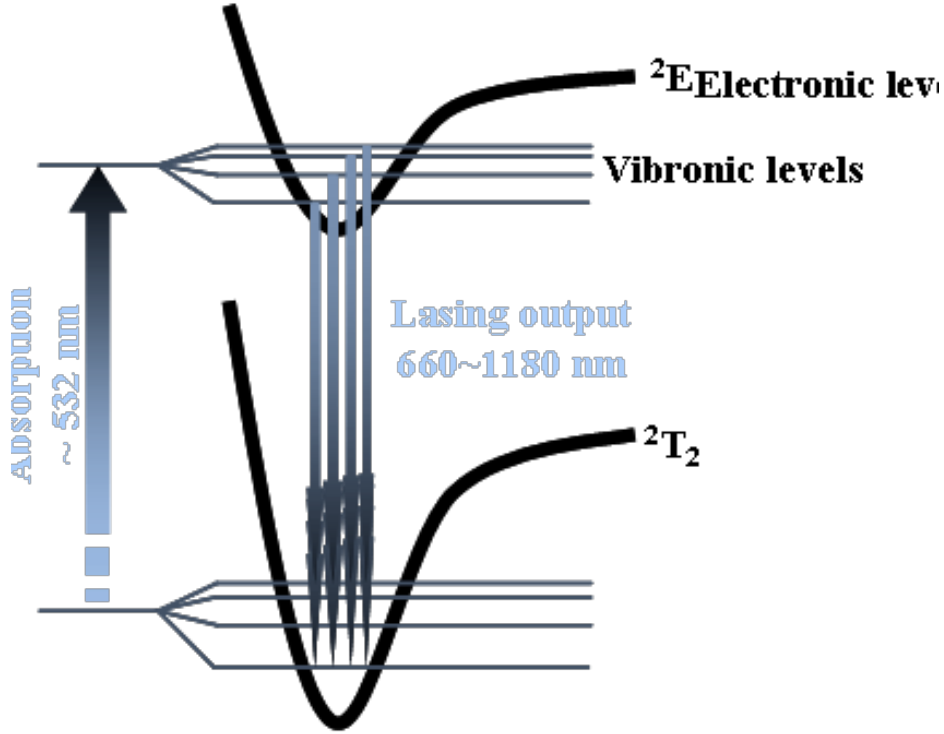
- Difficult to saturate transitions, especially ionization step
  - pulsed lasers with high energy per pulse (mJ).
- Broadening in hot cavity
  - laser linewidth to match broadening for resonant transitions (1-10 GHz)
- Finite residence time of atoms (~100 us)
  - High repetition rate (> 10kHz)
- Large 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



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)*



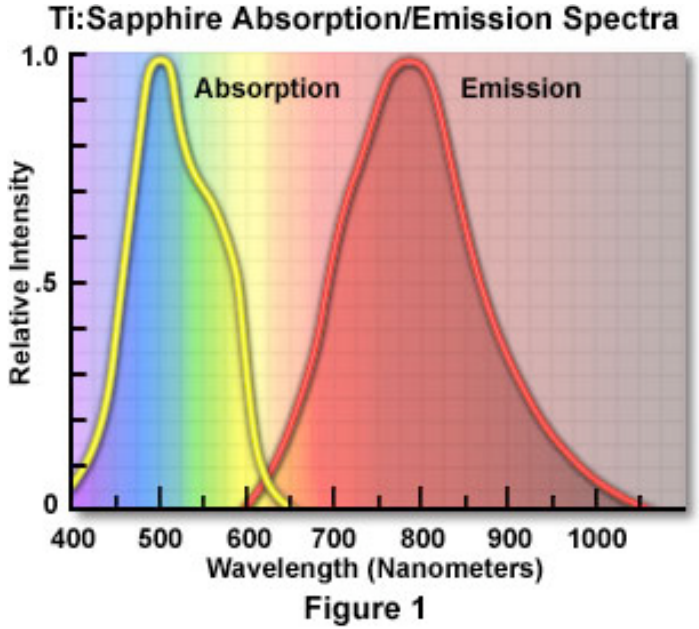
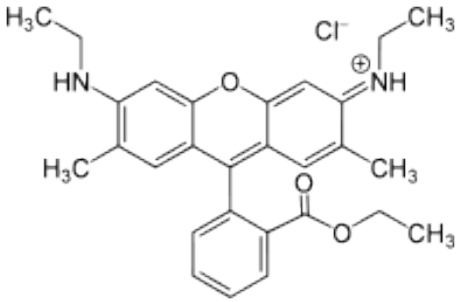
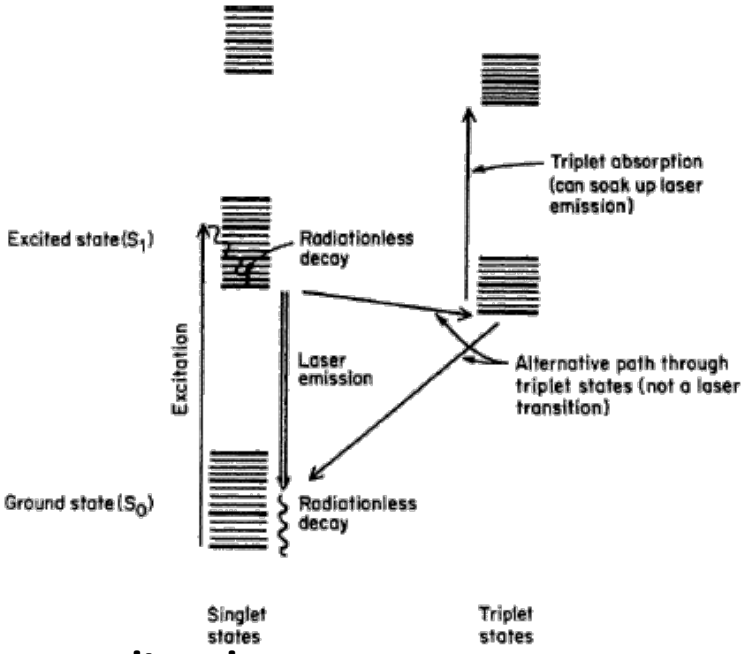


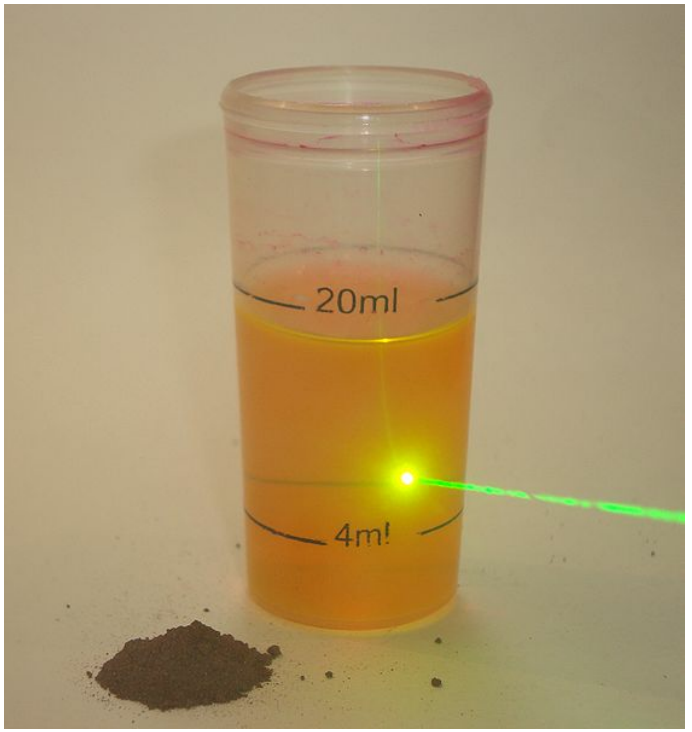
Figure 1

Dye laser

Rhodamine 6G



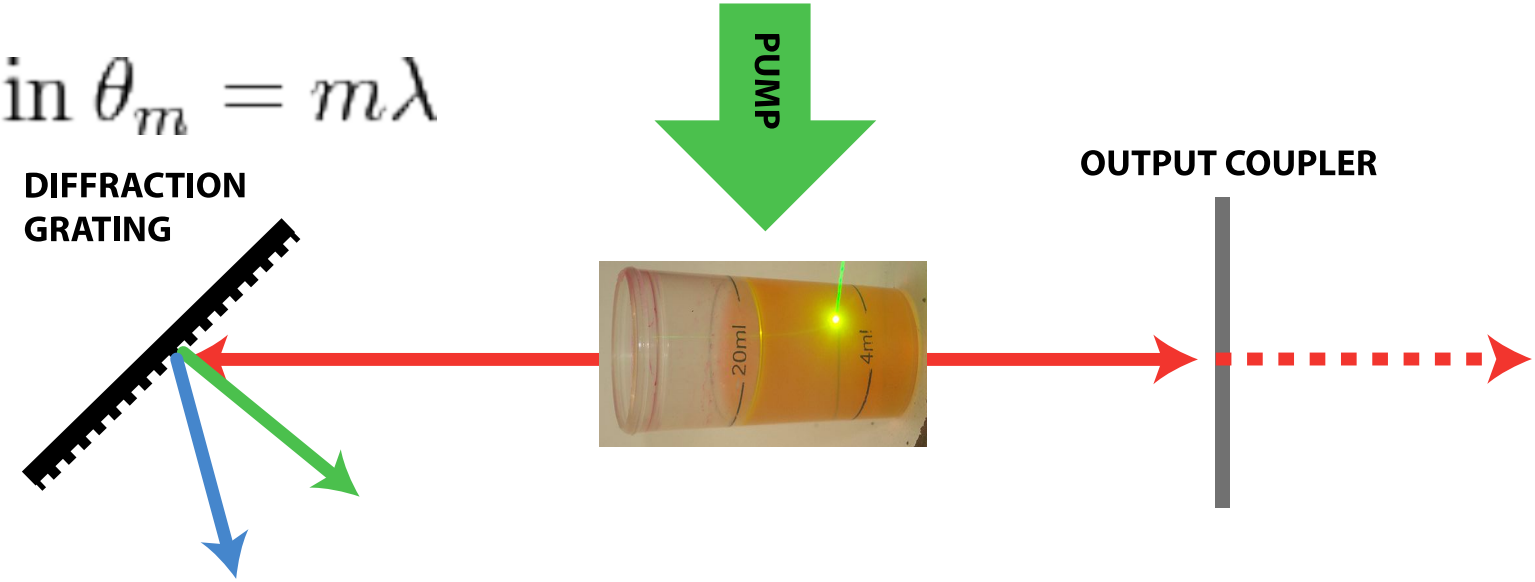




Diffraction grating as a laser cavity mirror:

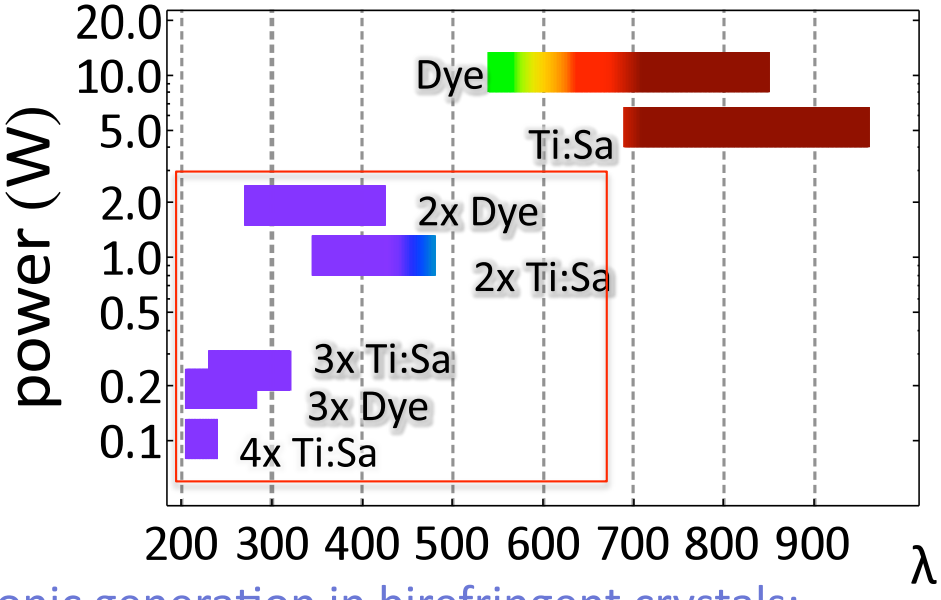
Reflection maxima on axis with cavity is wavelength dependent → wavelength selective oscillation

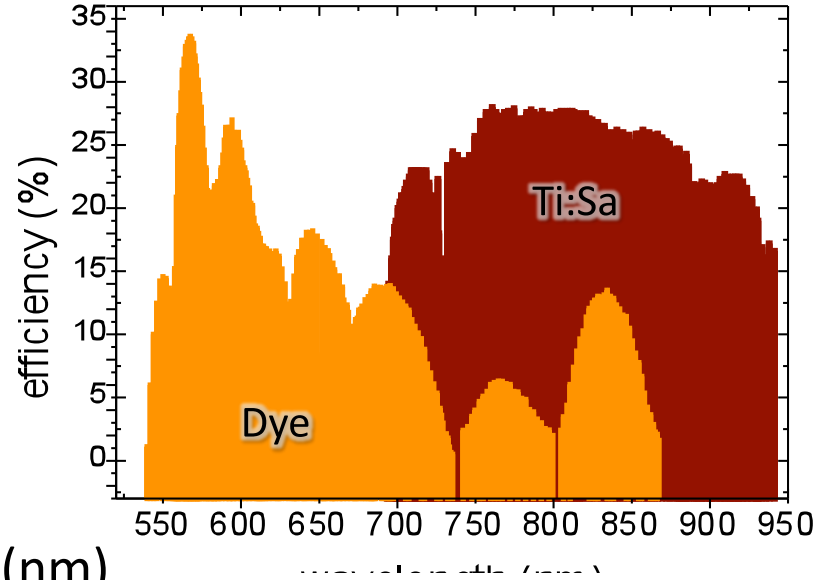
$$d \sin\theta_m = m\lambda$$



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

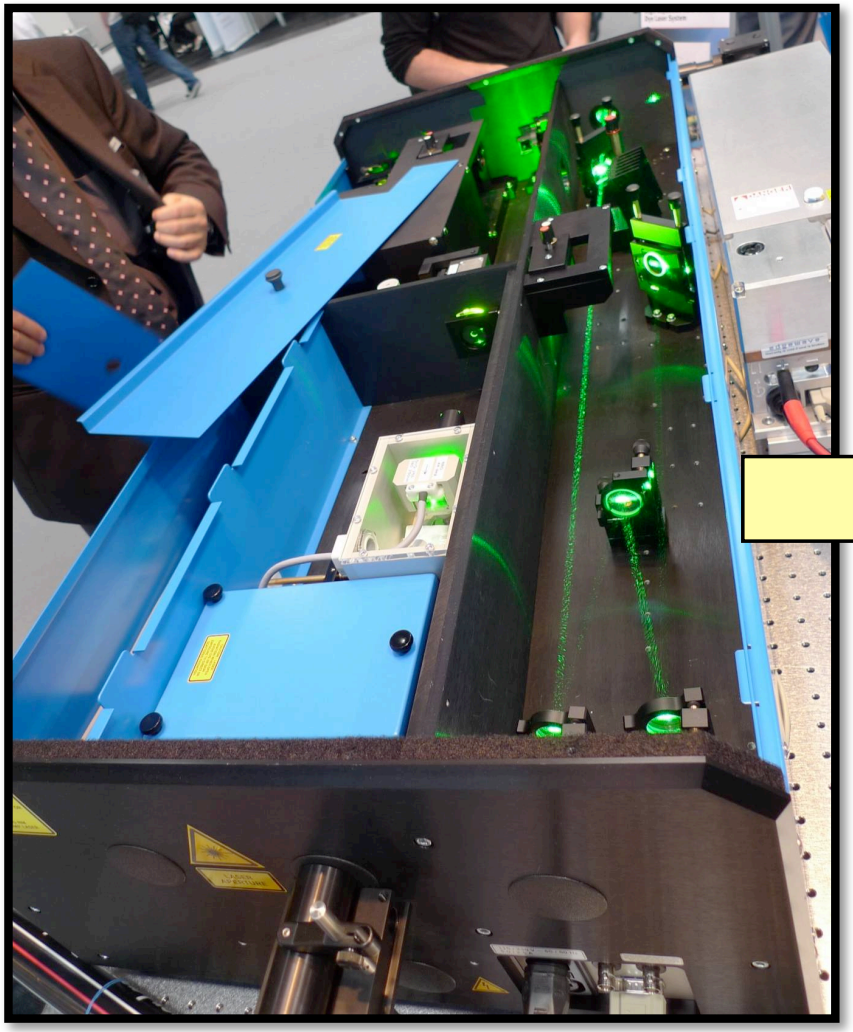


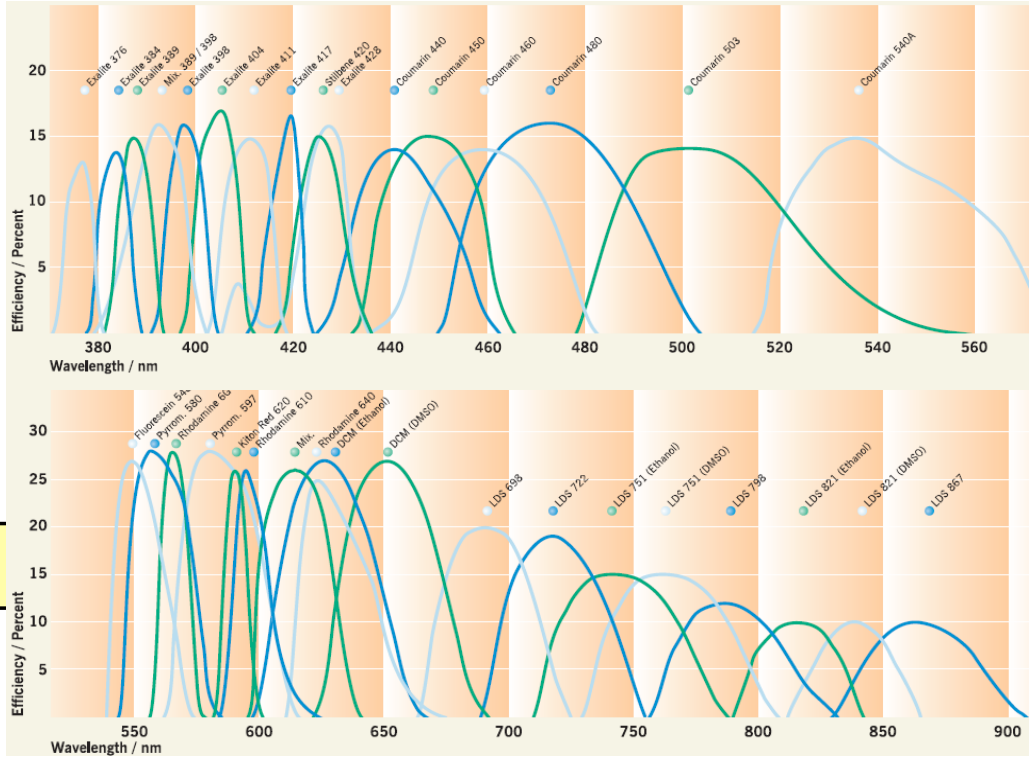


Harmonic generation in birefringent crystals:

Due to nonlinear response of materials to high EM field of focused lasers

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



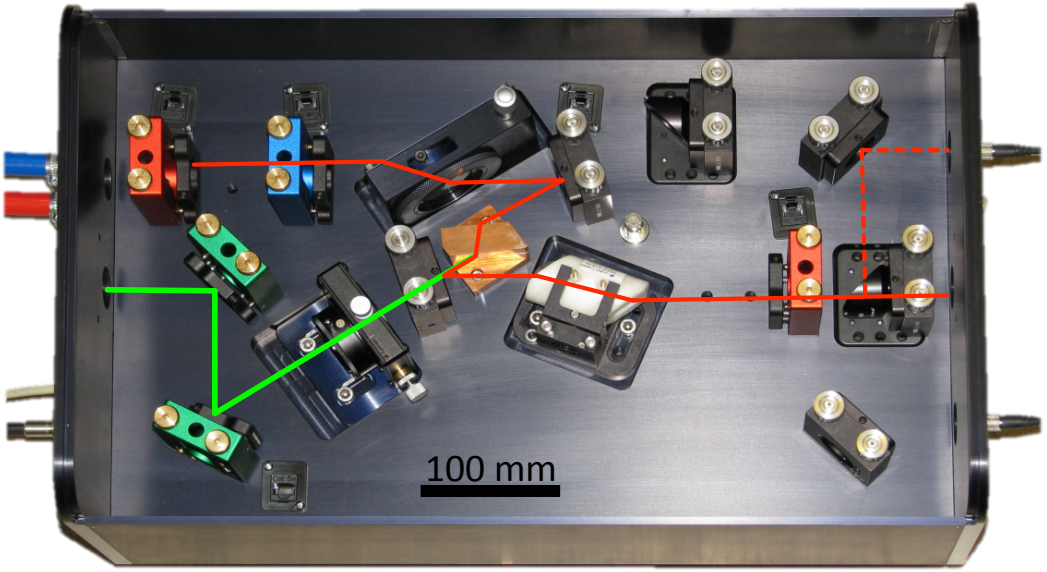


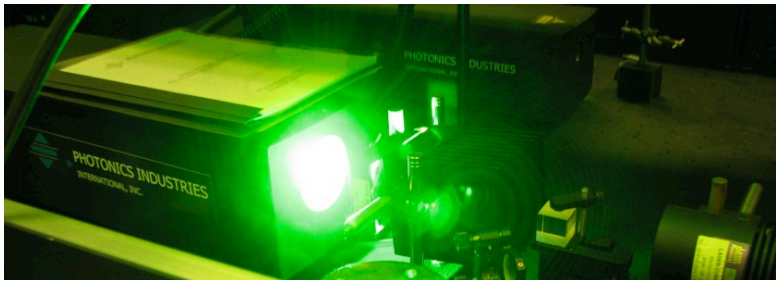
- Optimized for 10 kHz EdgeWave pump
- Accept both 355 and 532 pumping beams
- Equipped with FCU (up to 2W of UV)

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

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

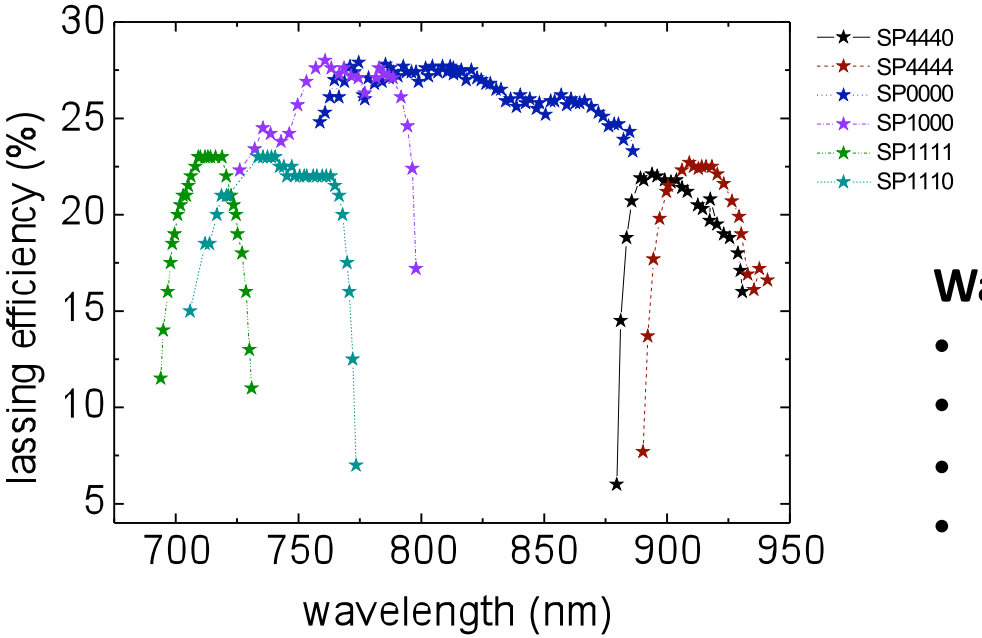
The RILIS Ti:Sa lasers





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

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



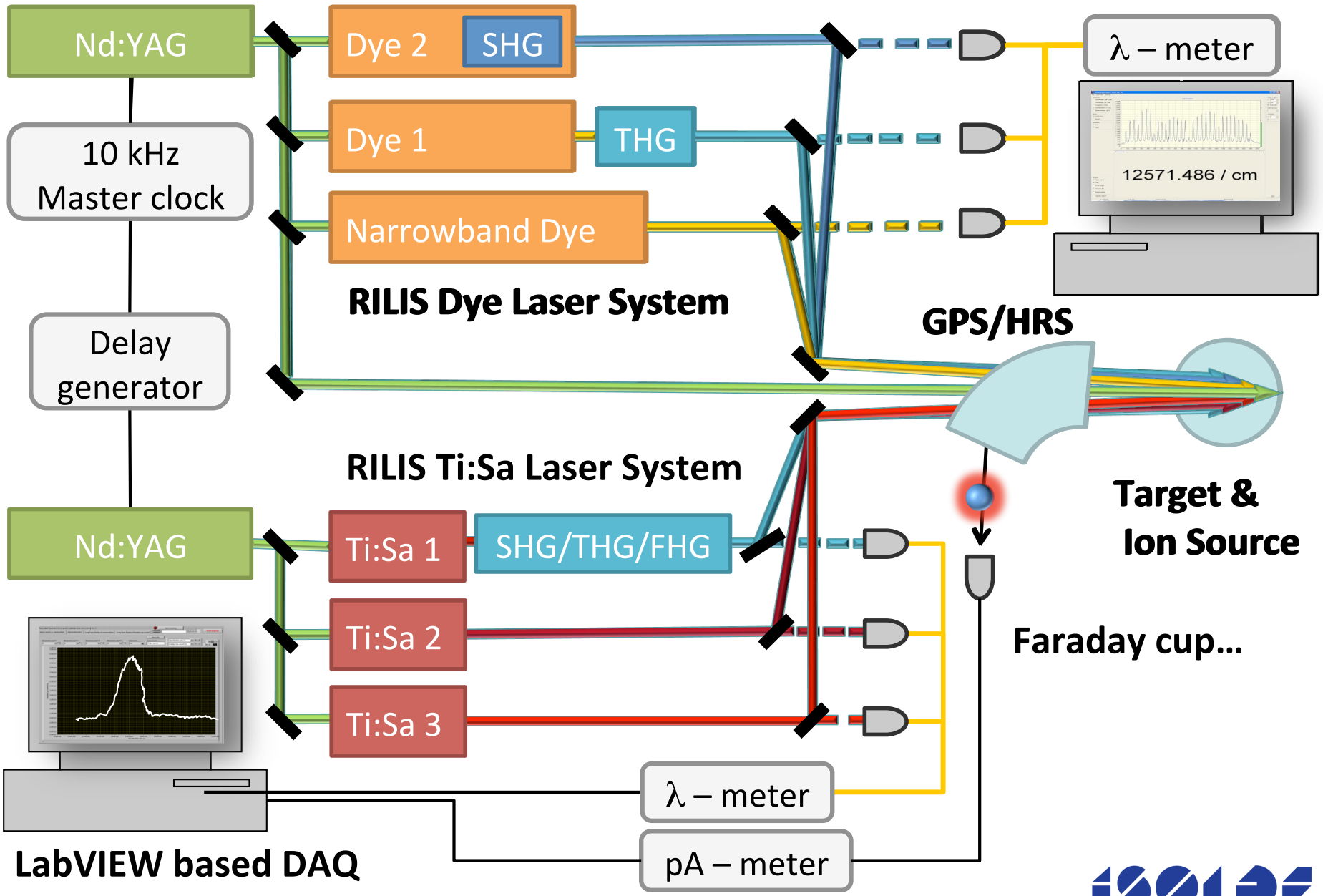
Wavelength tuning range (6 mirror sets):

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

"A complementary laser system for ISOLDE RILIS"

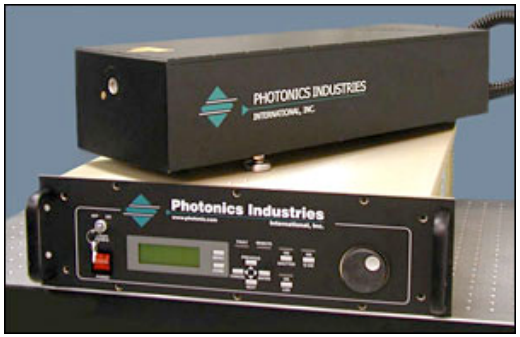
S Rothe et al: Journal of Physics: Conference Series 312 (2011) 052020

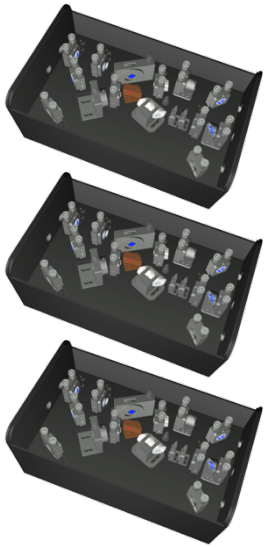
Dual RILIS Concept

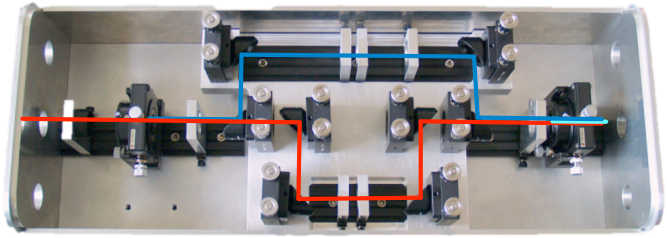


Installing the Ti:Sa alongside the dye lasers

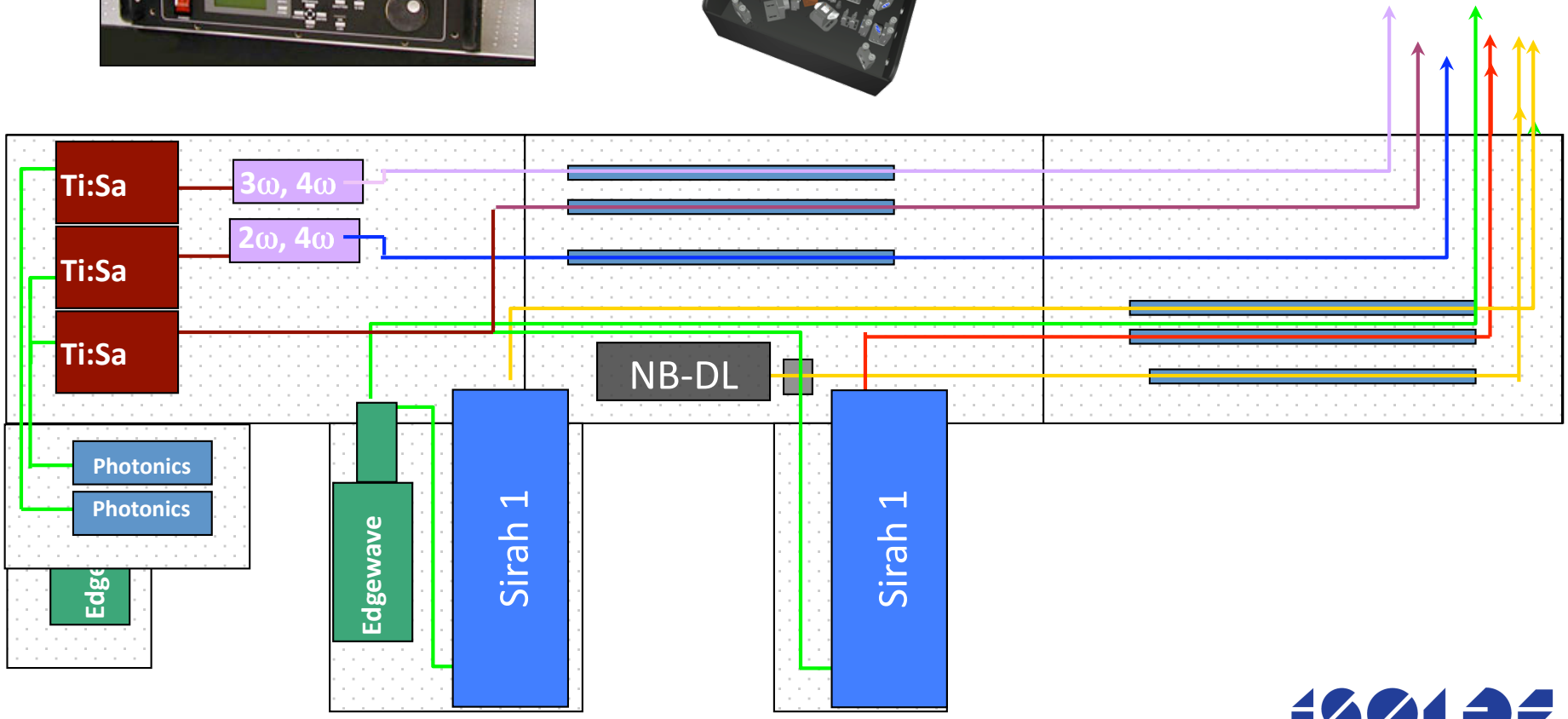
Finding space for pump laser +
3 Ti:Sa + FCUs





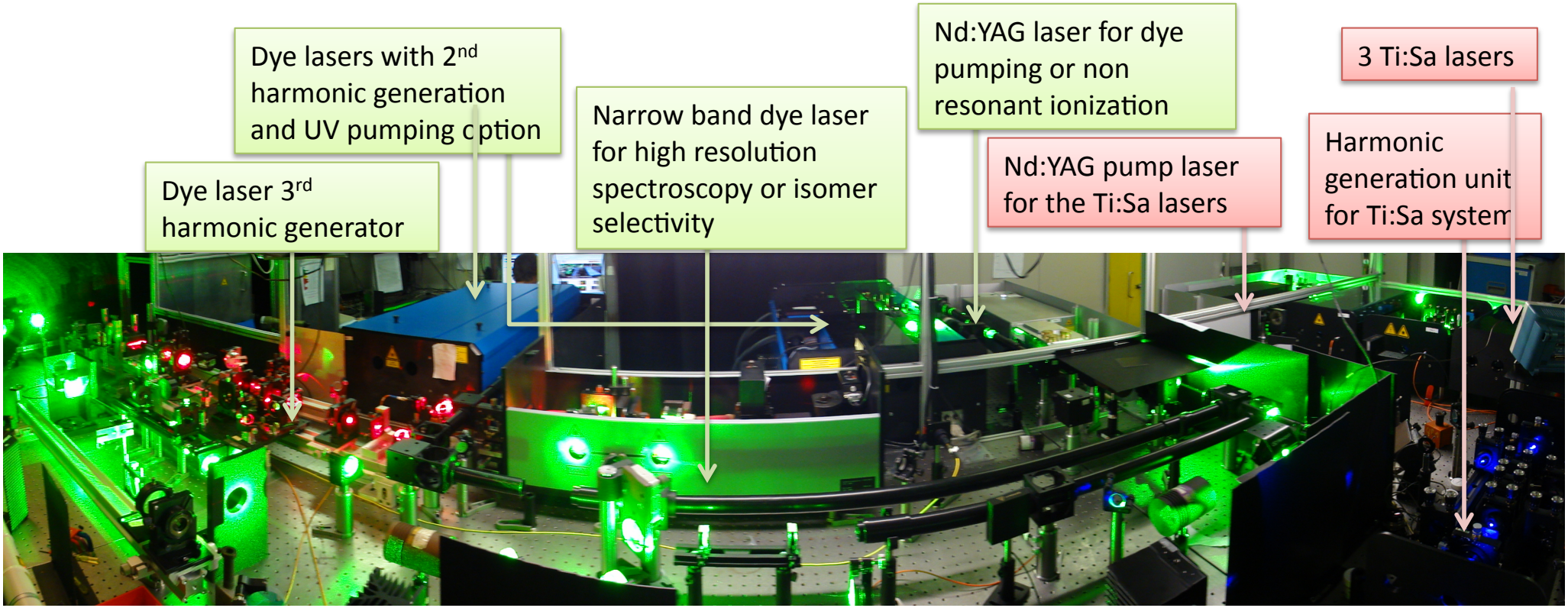


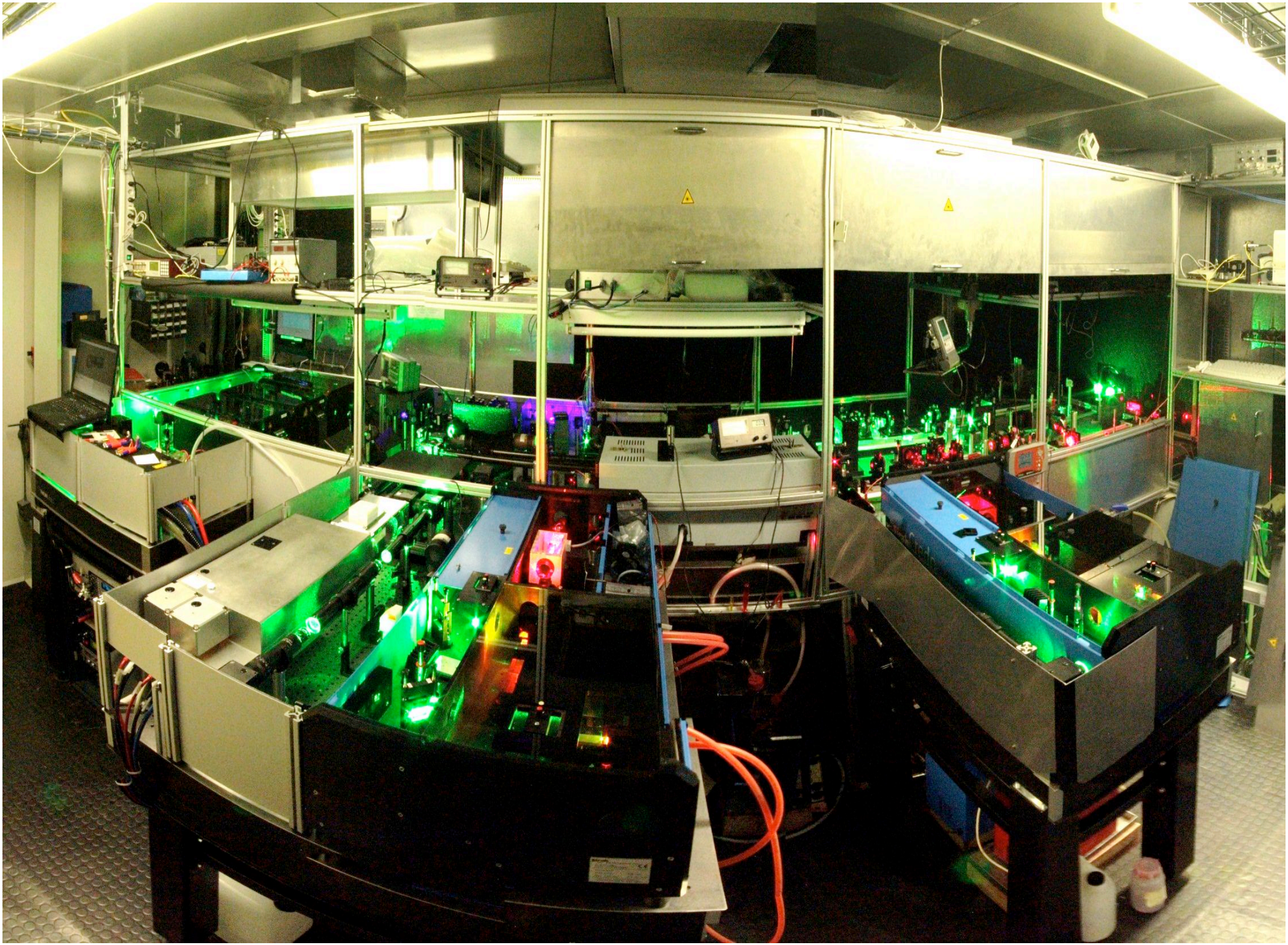
Frequency conversion unit



The actual ISOLDE RILIS setup

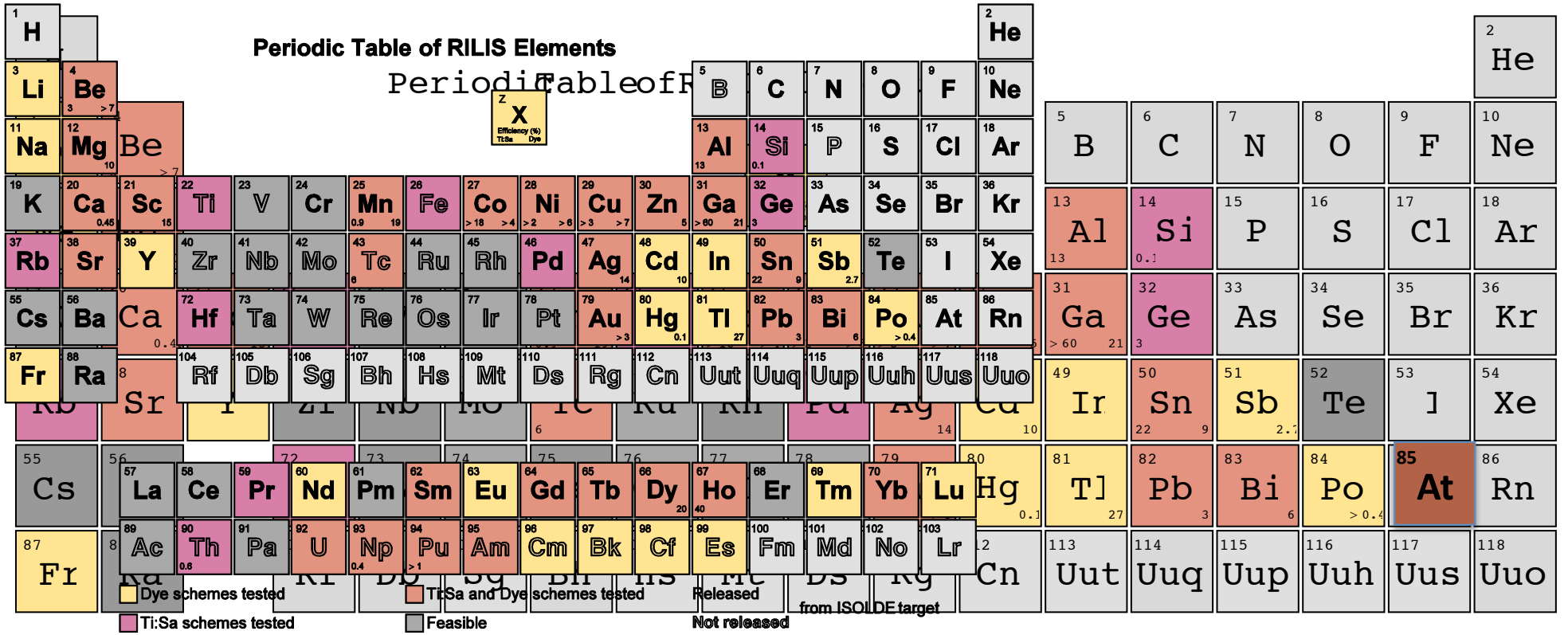
- 6 tunable lasers + 50 W @ 532 nm for ionization step, 10 kHz rep rate
- Nd: YAG pumping dye or Ti:Sa lasers, with possibility of doubling to quadrupling
- Atomic physics: Used to determine ionization schemes and I.P of chemical elements with no stable isotopes (e.g. polonium, astatine)
- Nuclear physics: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

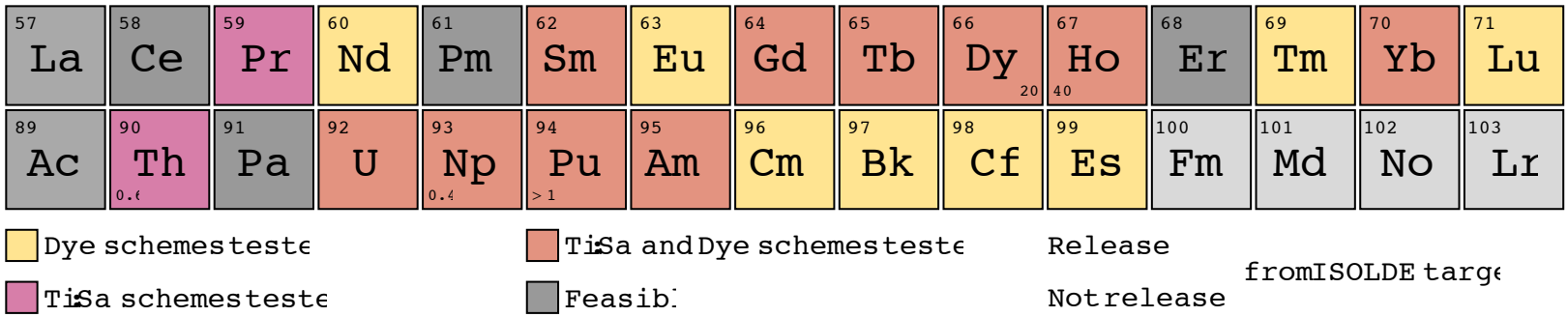




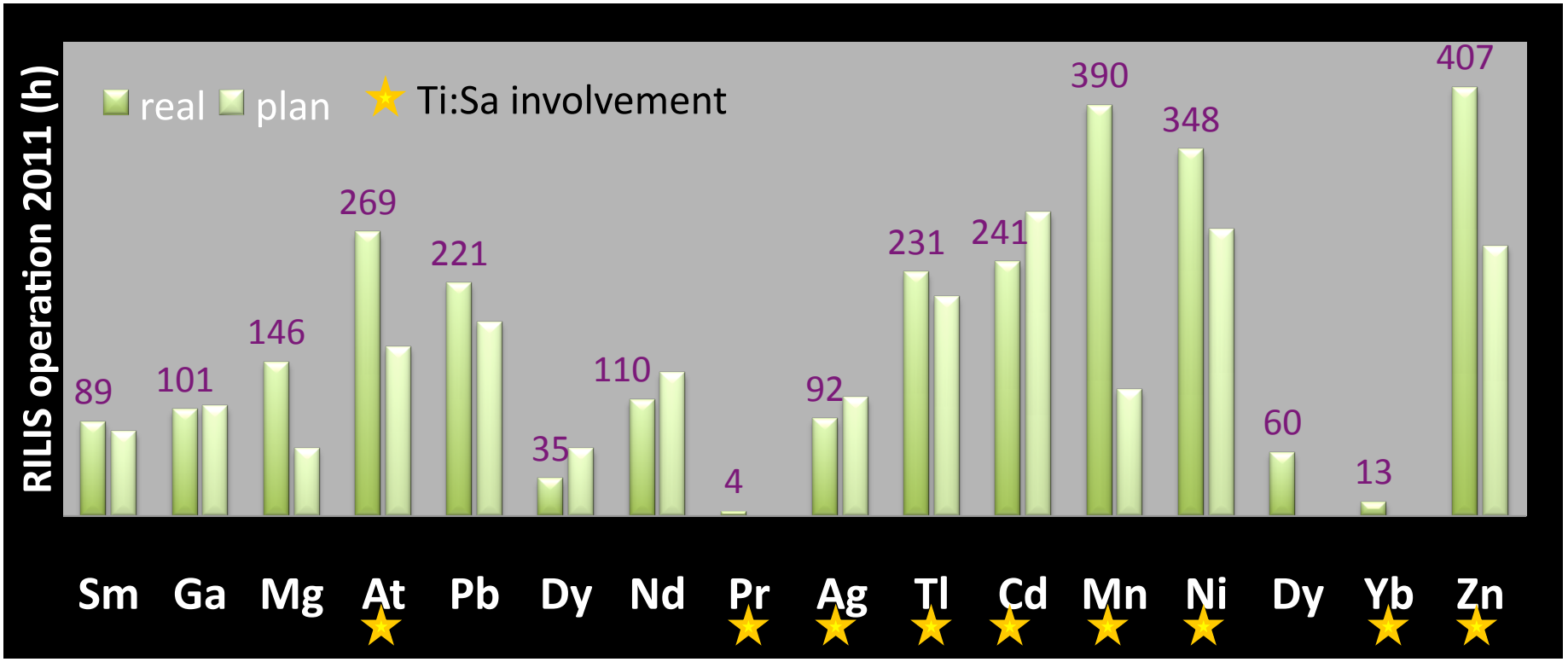

RILIS screen 1
PHOTONICS INDUSTRIES

Available elements so far





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'

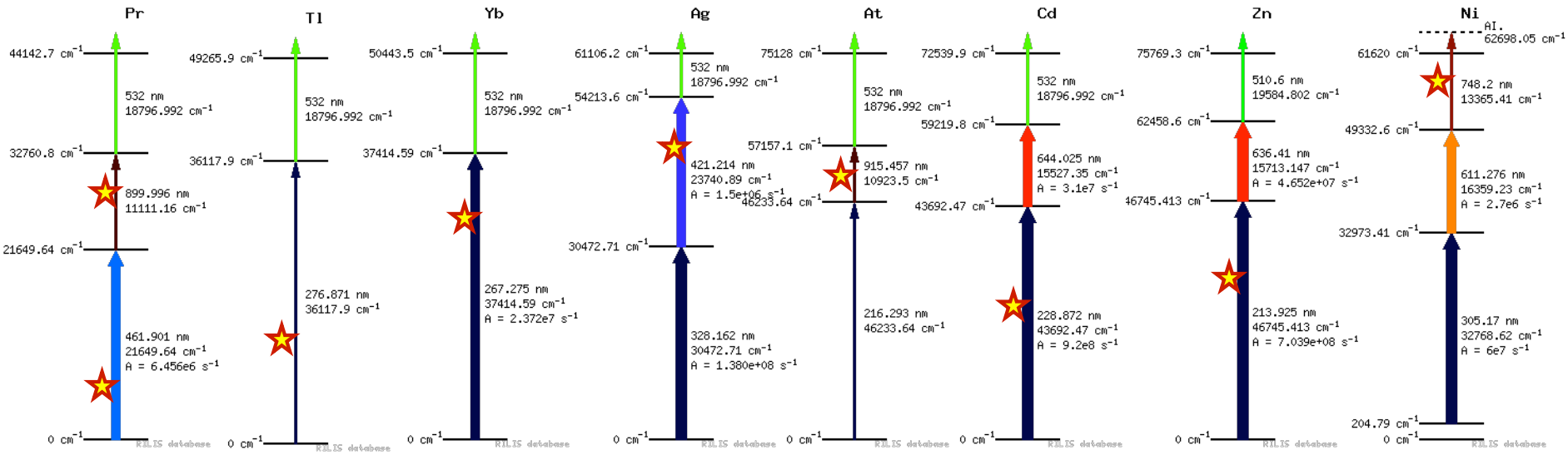
Modes of RILIS operation: Dual RILIS

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

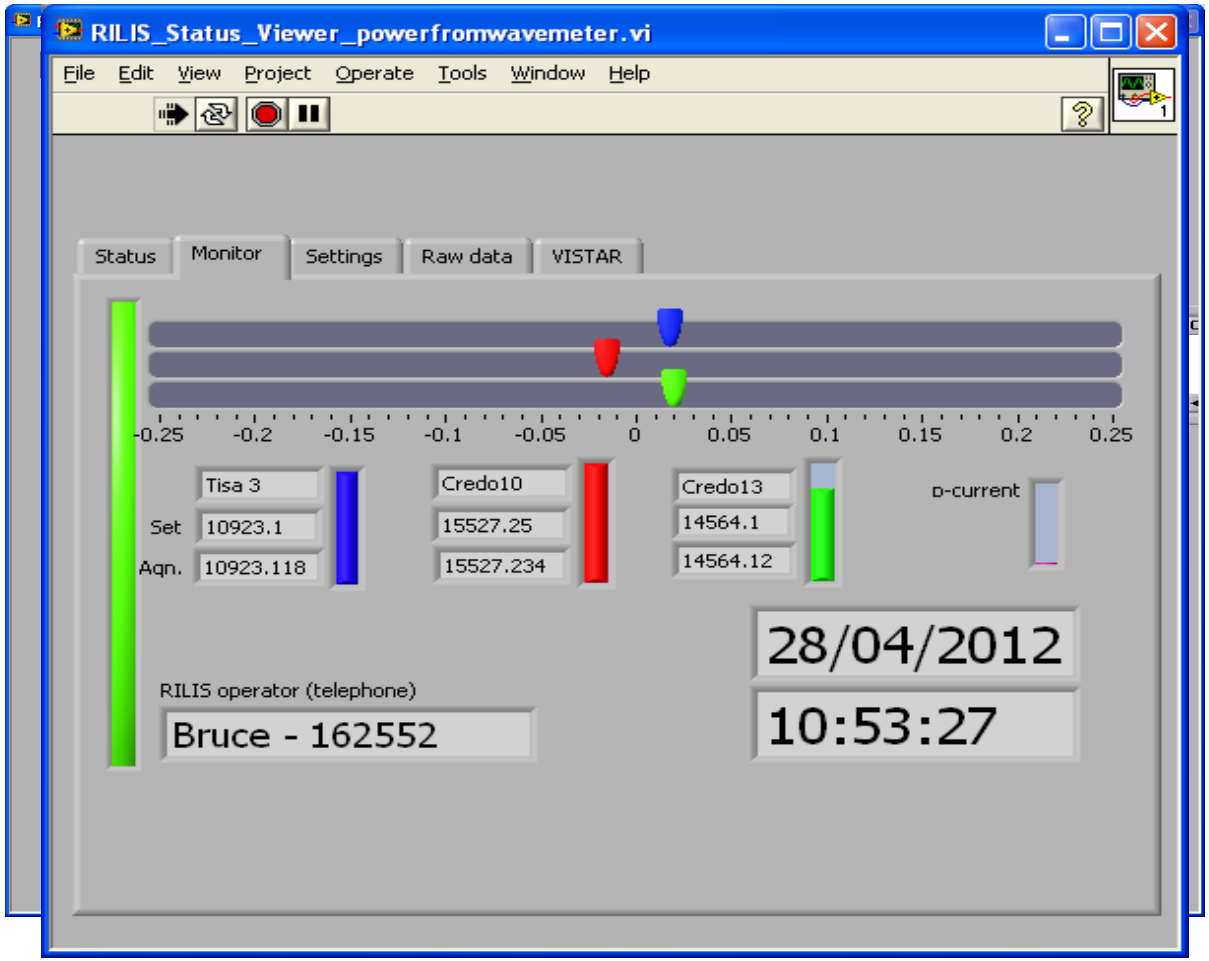
RILIS status monitoring

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

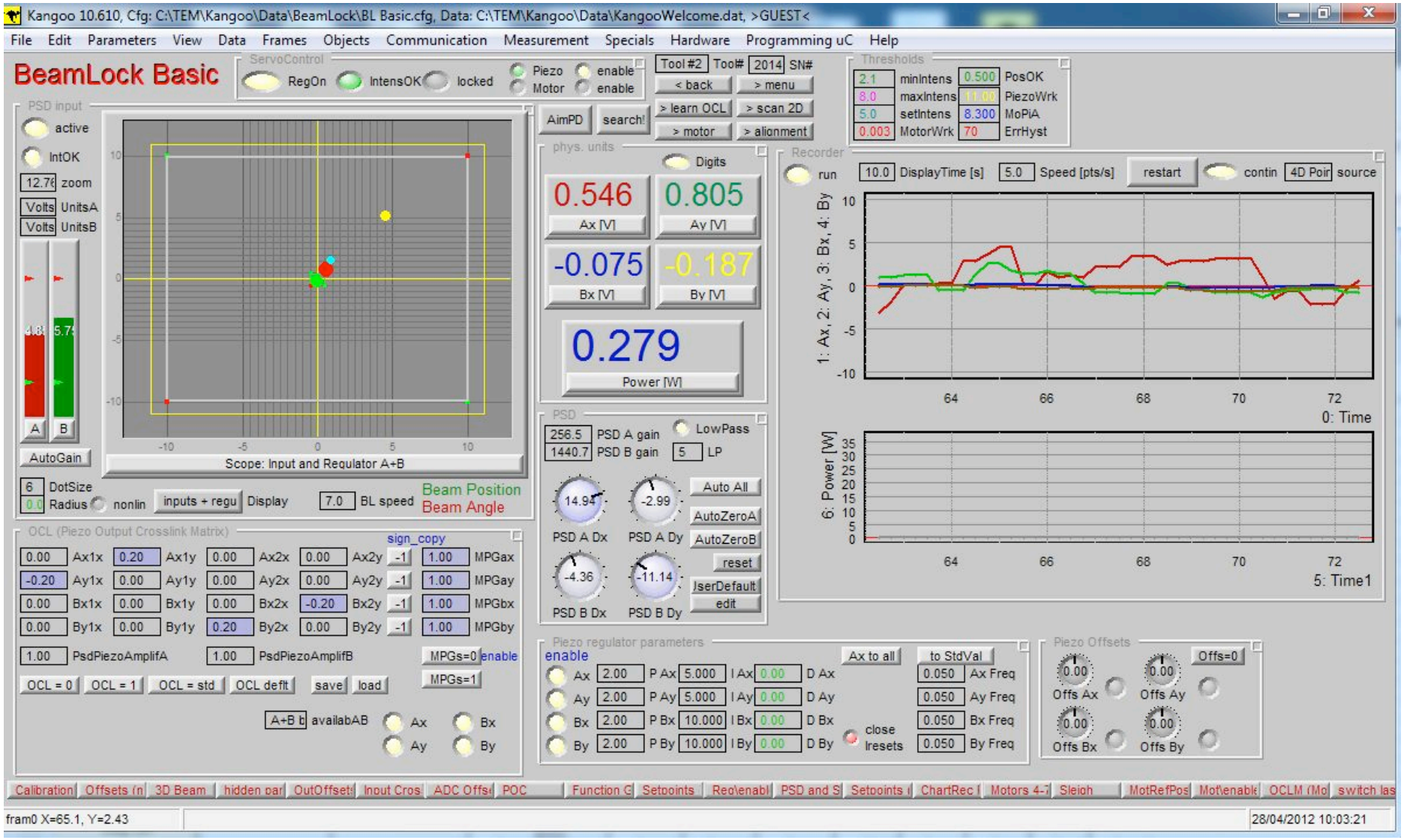
NATIONAL INSTRUMENTS LabVIEW

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



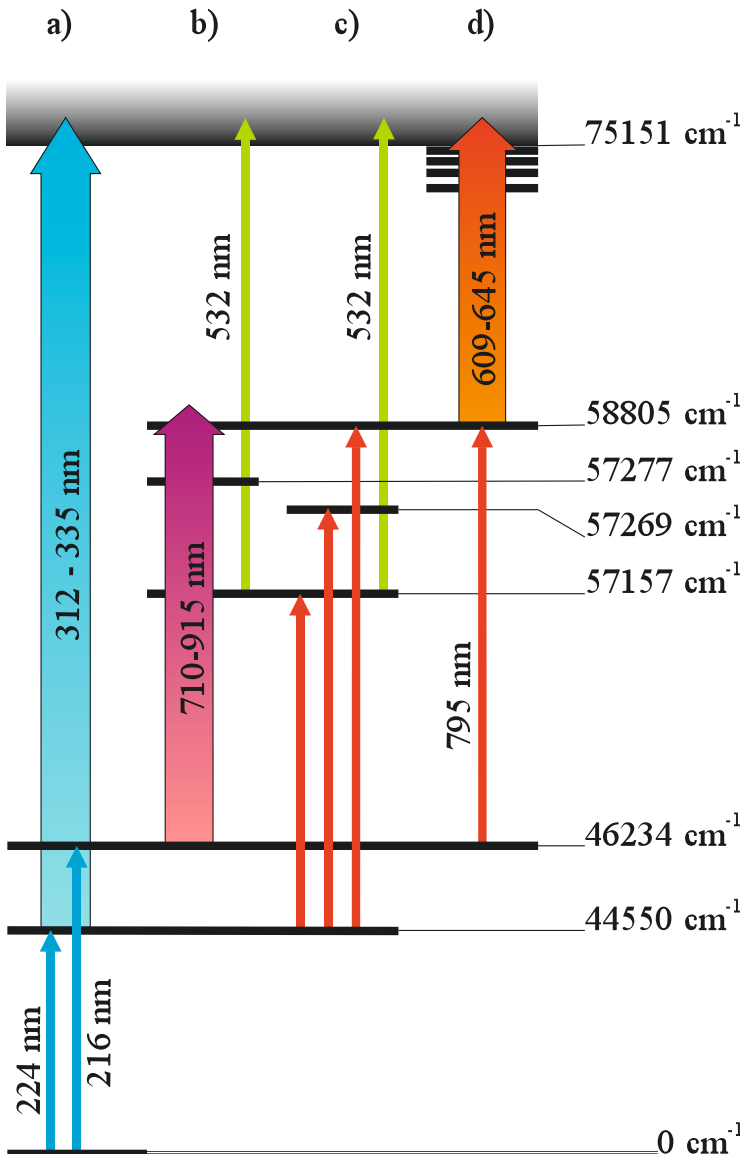
Beam stabilization

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



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

In-source spectroscopy of Astatine

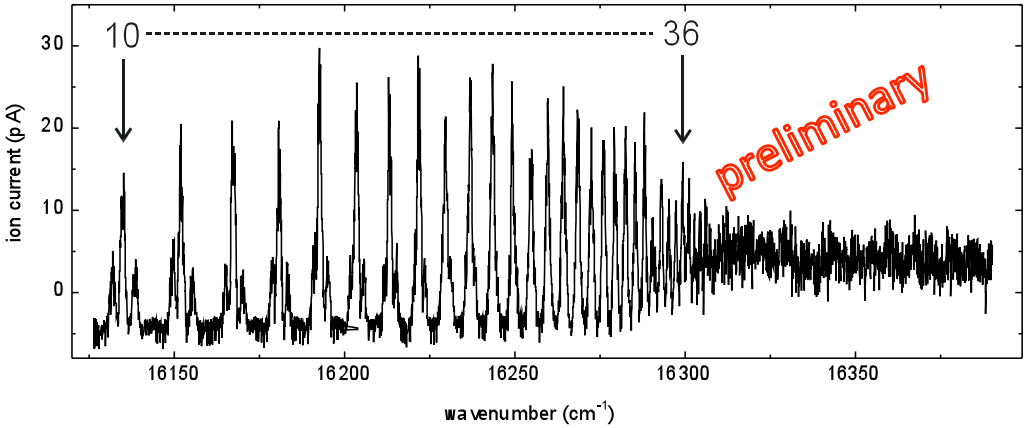


a) Photoionization threshold : 75129(95) cm^{-1}

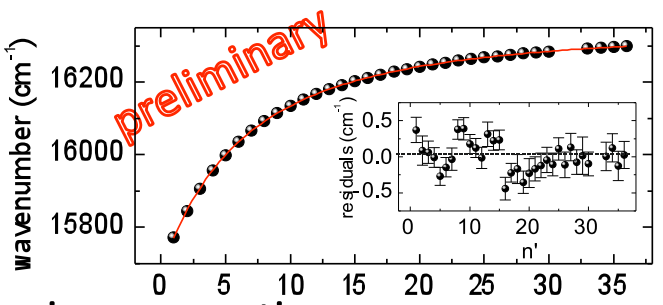
b) Scan for 2nd step transitions (at TRIUMF)

c) Verification of levels, yield measurements

d) Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP

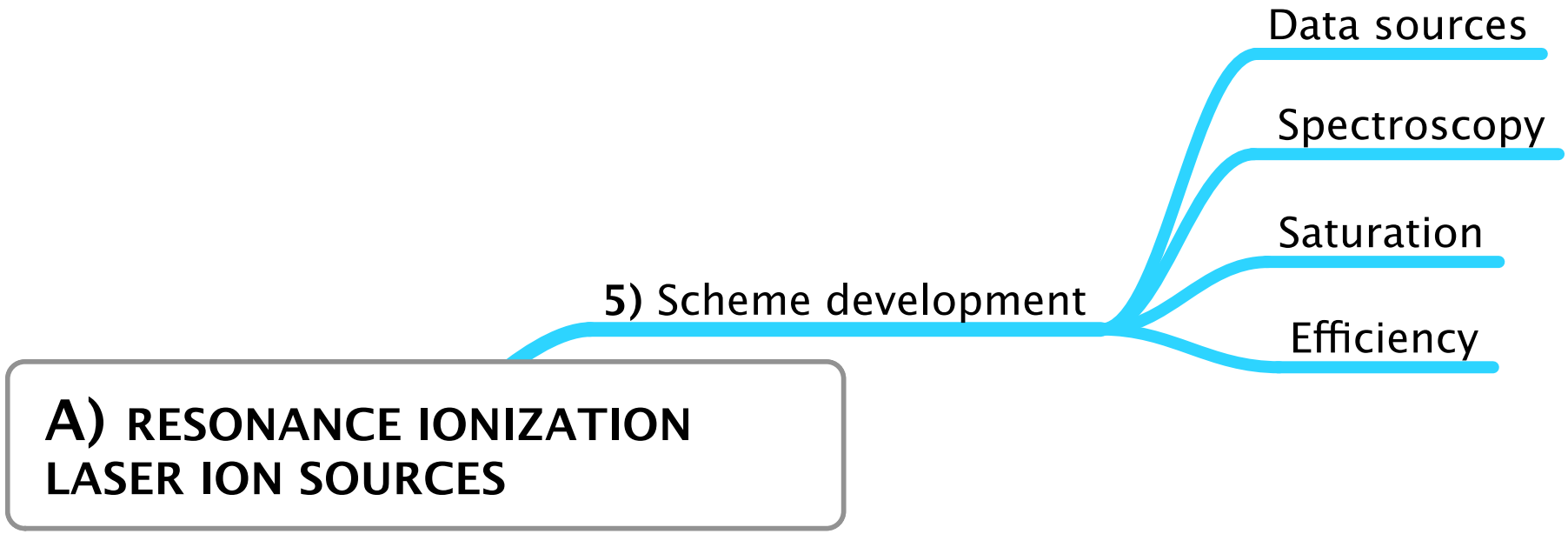


Rydberg-Ritz formula $E\downarrow n = \mathrm{IP} - \mathrm{R}\downarrow\mathrm{M} / (n - \delta$



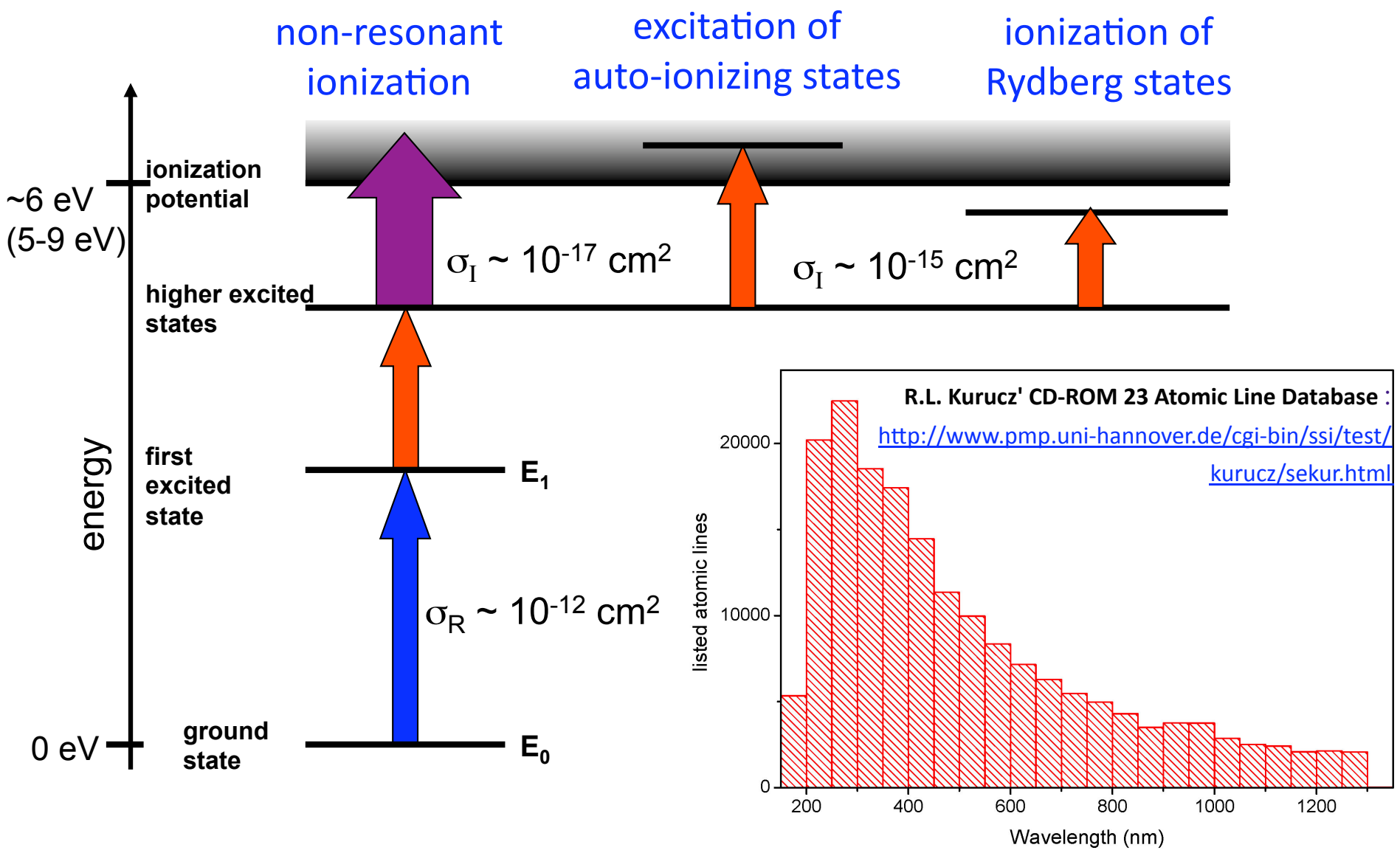
E_{IP}(At) = 75151(1) cm^{-1}

Poster to visit! : *S Rothe et al.* Publication in preparation

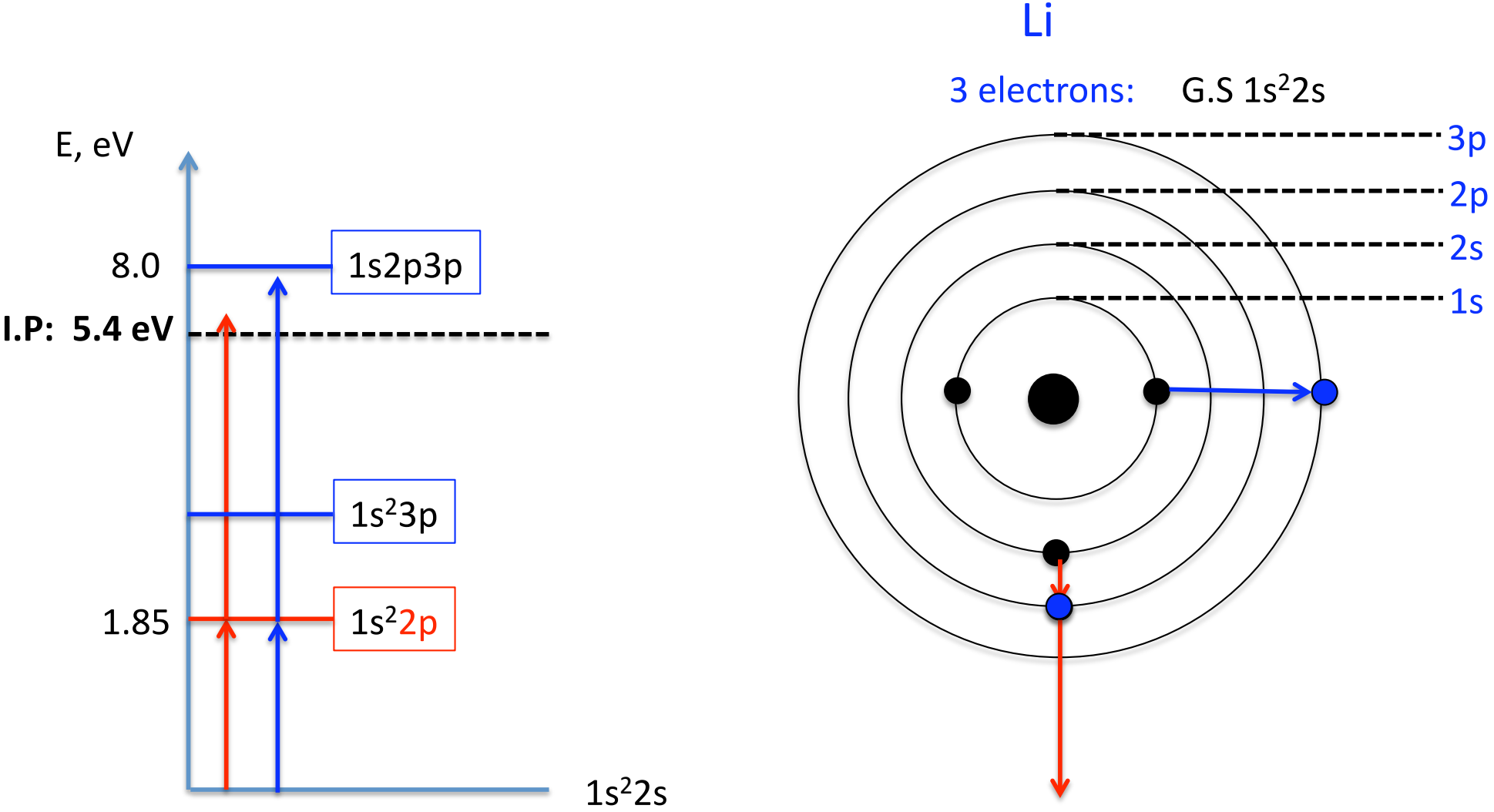

A) RESONANCE IONIZATION LASER ION SOURCES
5) Scheme development
Data sources
Spectroscopy
Saturation
Efficiency

Ionization scheme development

What are our options for ionization schemes?



Auto-ionizing states – simplified concept



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**

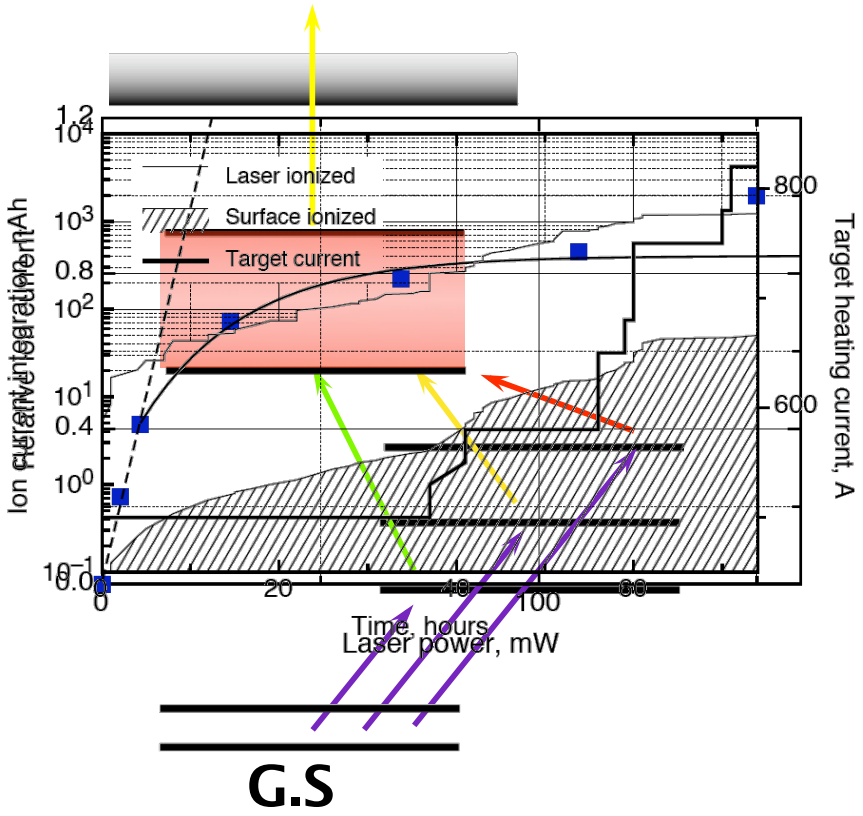
  Laser frequency scans across regions of interest whilst observing the ion current as the sample is evaporated in the target or oven.

- **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).

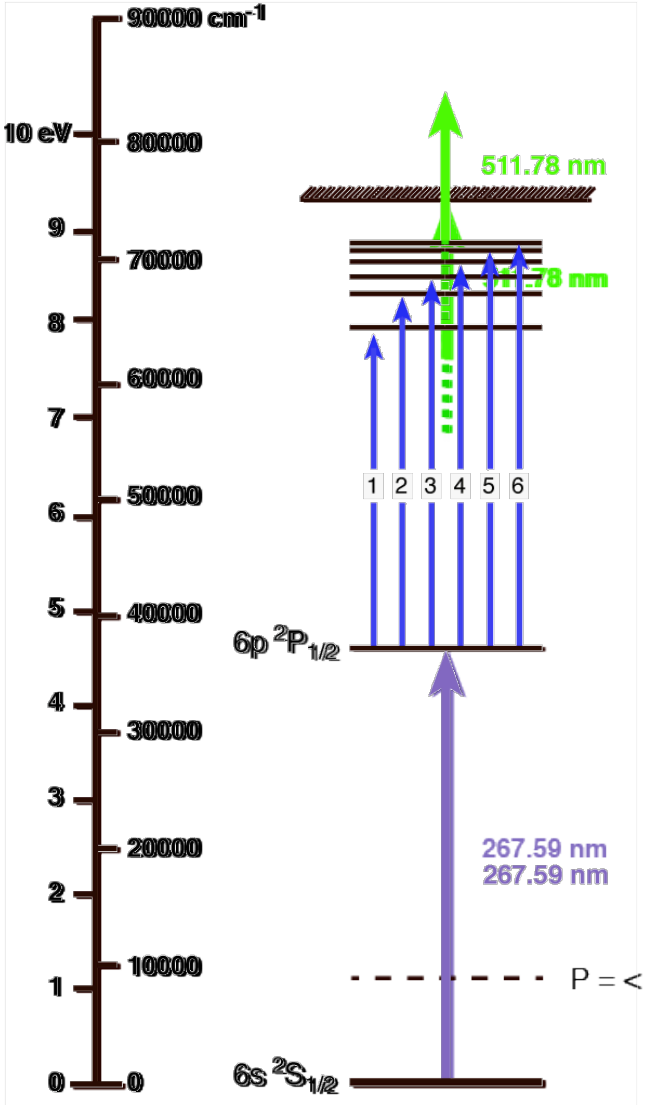
- **Efficiency measurement**

  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



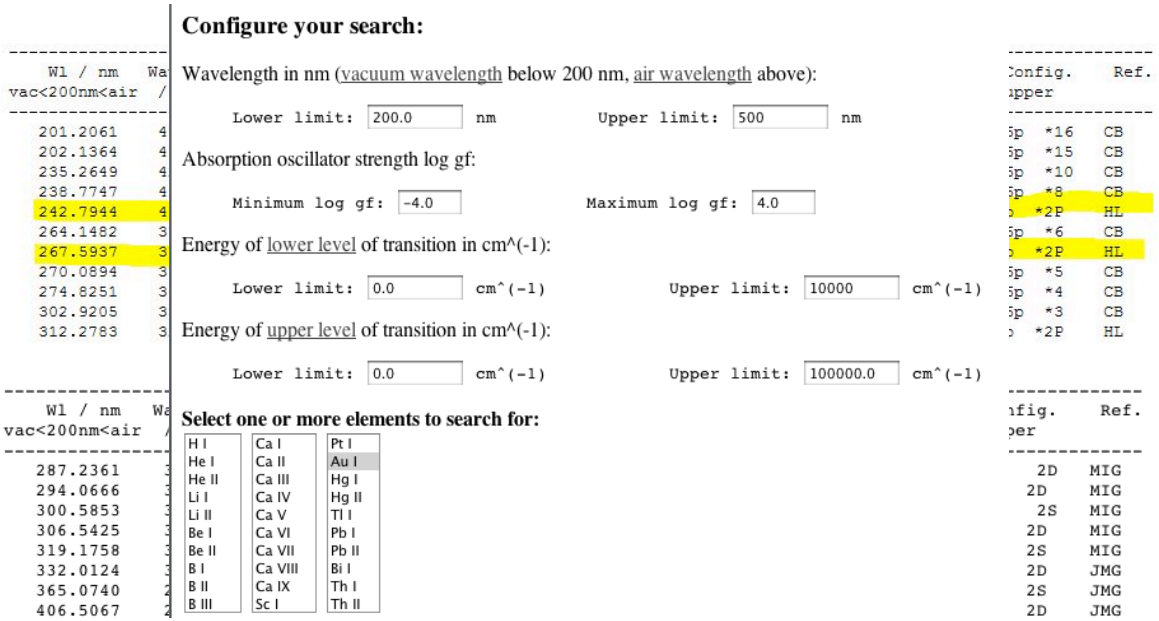
1) We know that the ionization potential is **9.23 eV** or **74408.88 cm $^{-1}$**
(this corresponds to the energy of 134 nm photon!)

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:
- *2 transitions from ground state, population of level at ~9161 cm-1 cm-1 is <1% at 2300 K*
- *roughly equal transition strength, select most convenient wavelength: 267.6 nm (requires only SHG, not THG)*

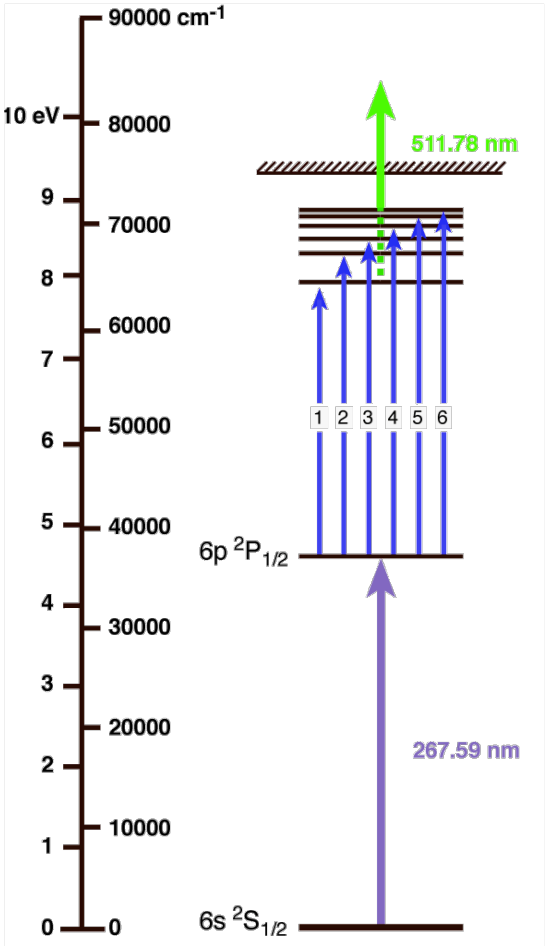
4) Search Kurucz database for 2nd step transitions from this 1st excited state to a state with a minimum energy of 54659 cm -1.
- *choose 6 most convenient transitions (**578 nm pump beam**)*

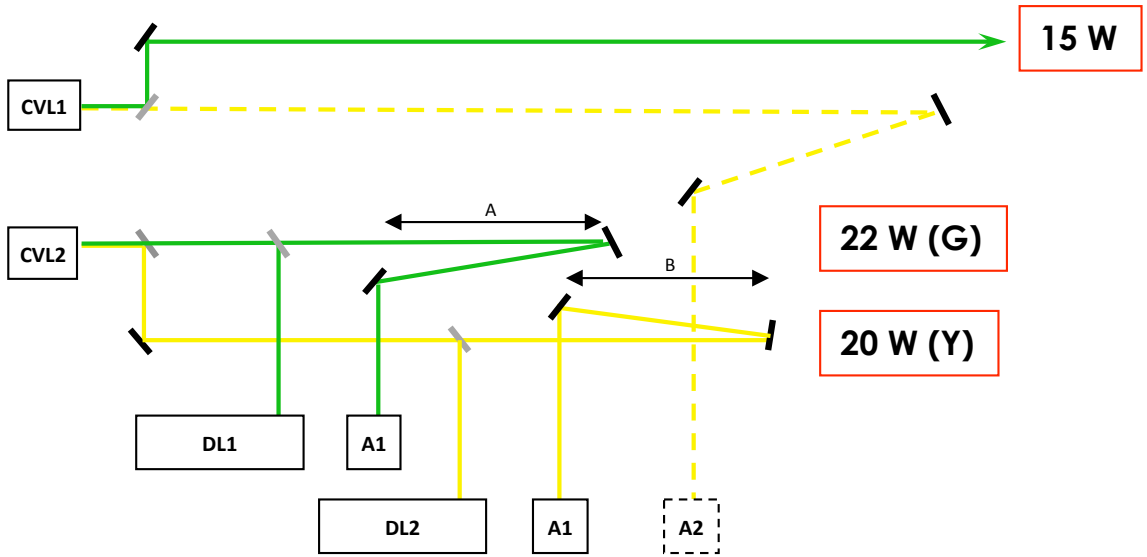
5) Test these 6 transitions and select, depending on the time available select the best ones as a basis for the search for AIS.

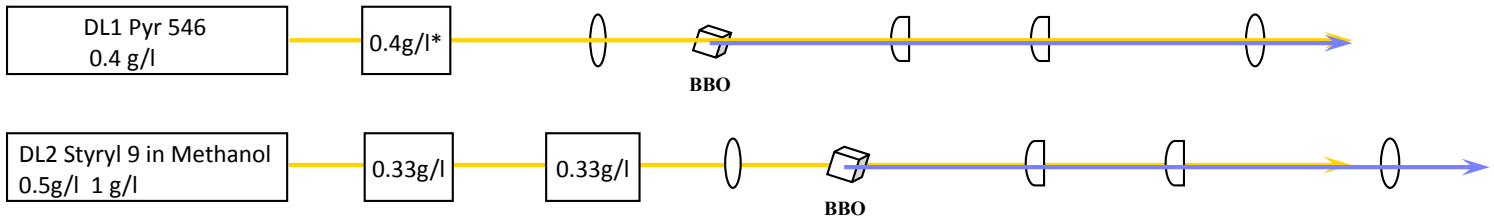


Laser setup for testing 2nd steps

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

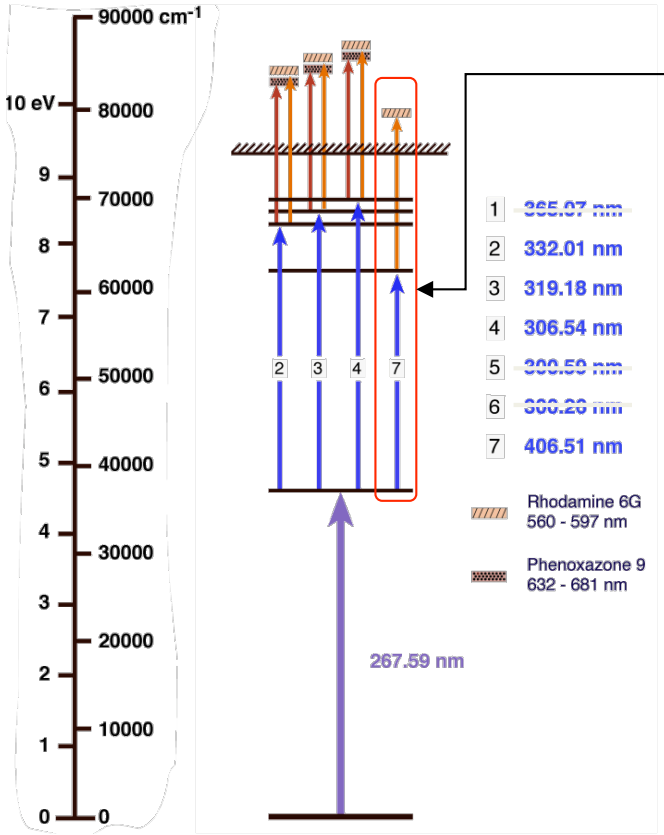


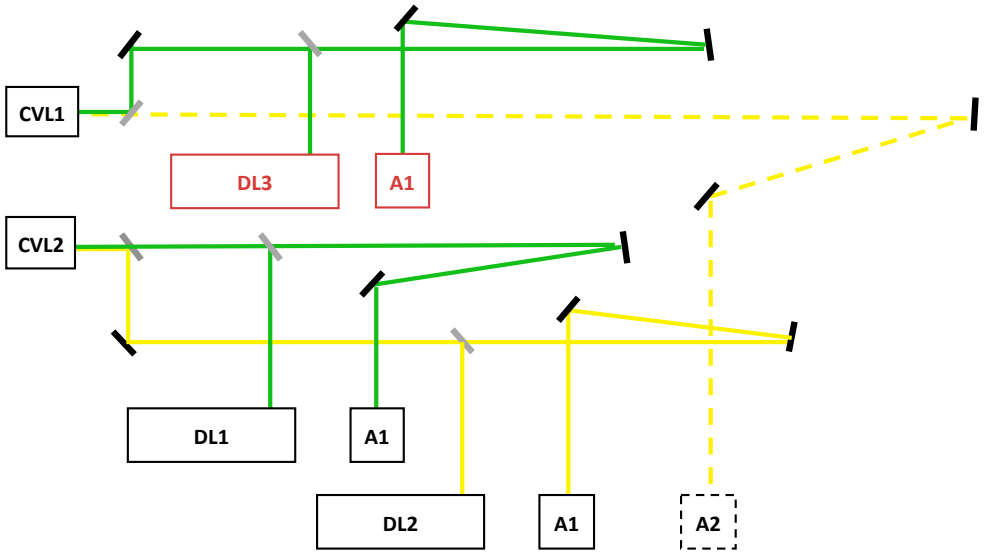


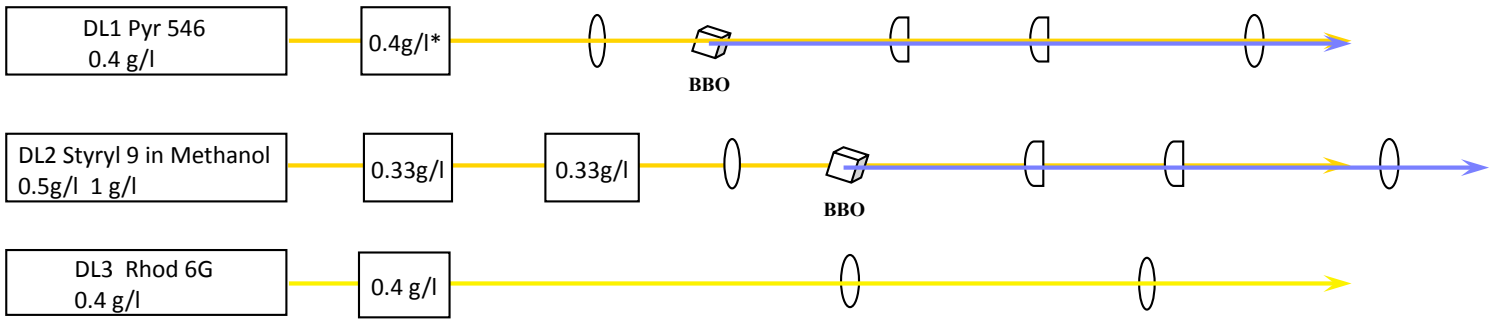


Laser setup for AIS search

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



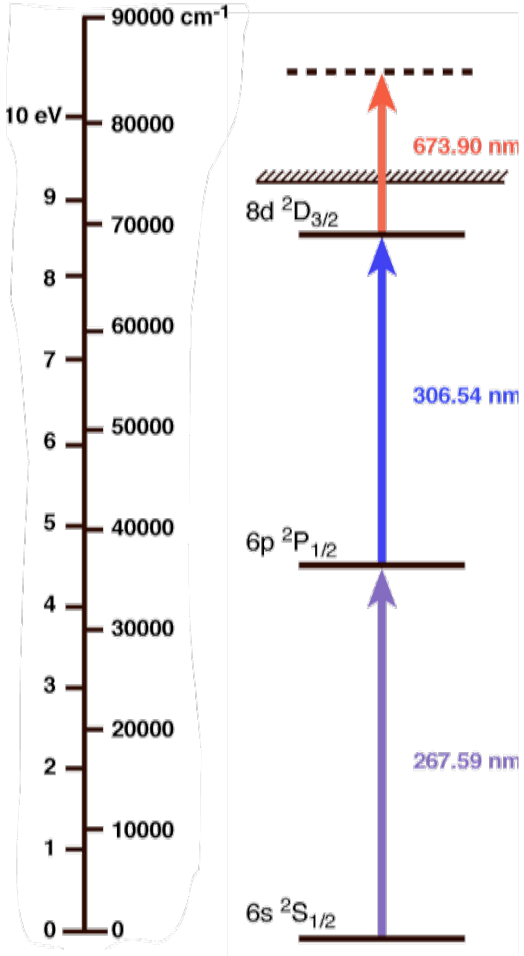


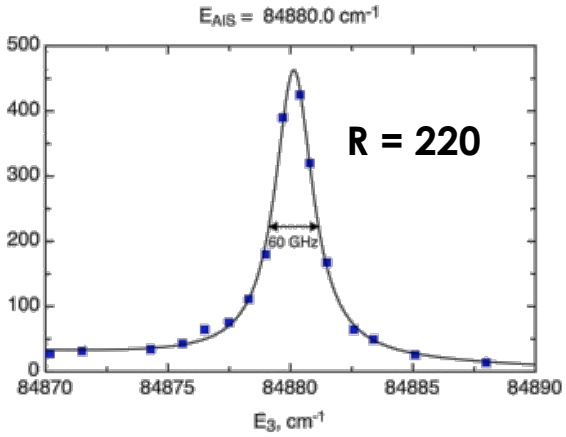


Compare good schemes and study the optimal scheme: Saturation curves, efficiency measurements etc.

Scheme figure of merit:

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



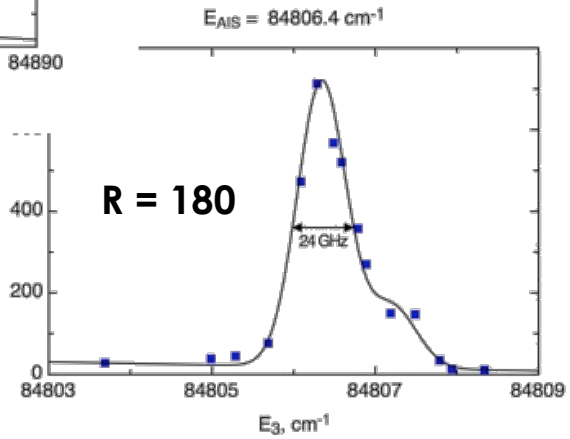


Overall RILIS Efficiency:

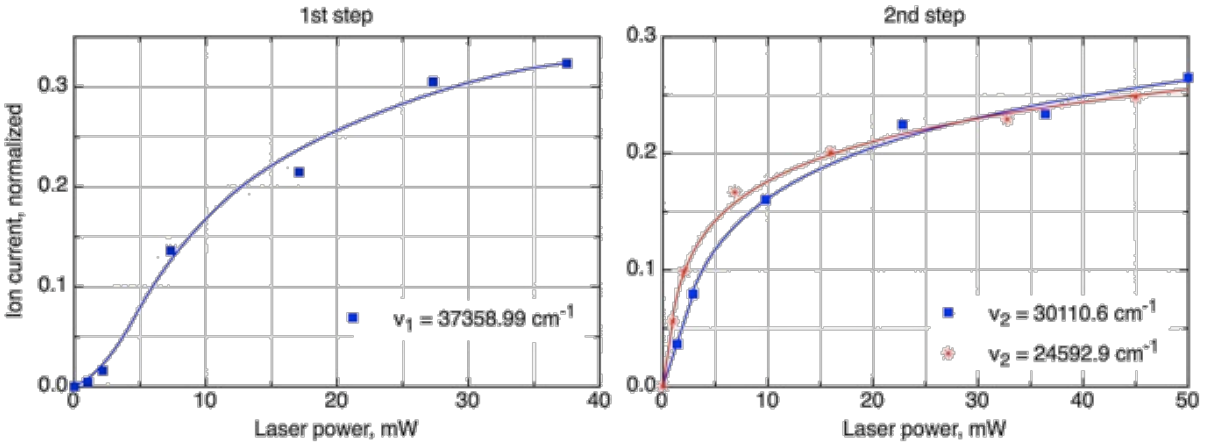
E ≈ 3 %*

Estimated from evaporation of 3000 nAh mass marker

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

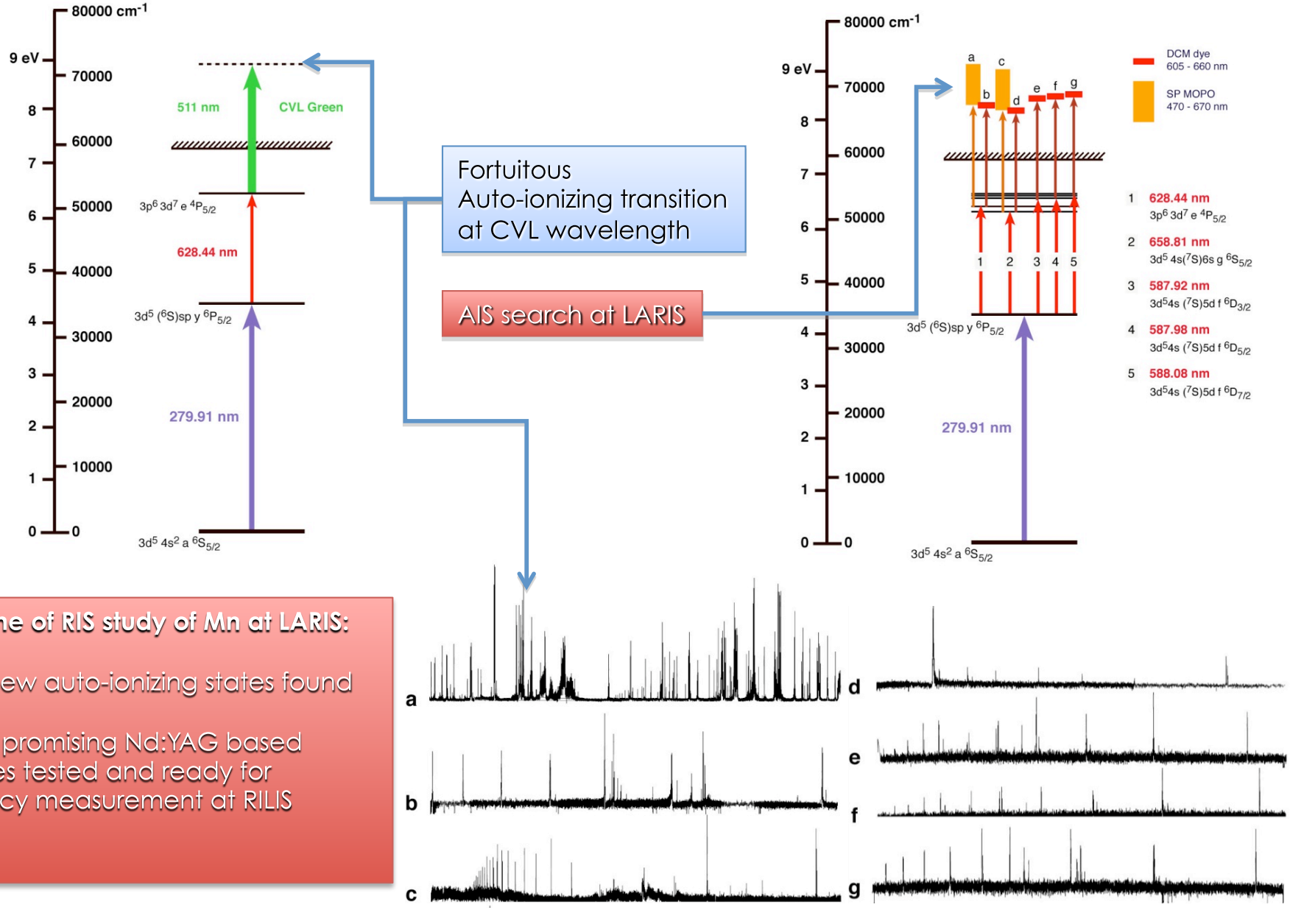


4x improvement on scheme used by E.B Saloman (**R = 55**)



LARIS results – A new RILIS scheme for manganese

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



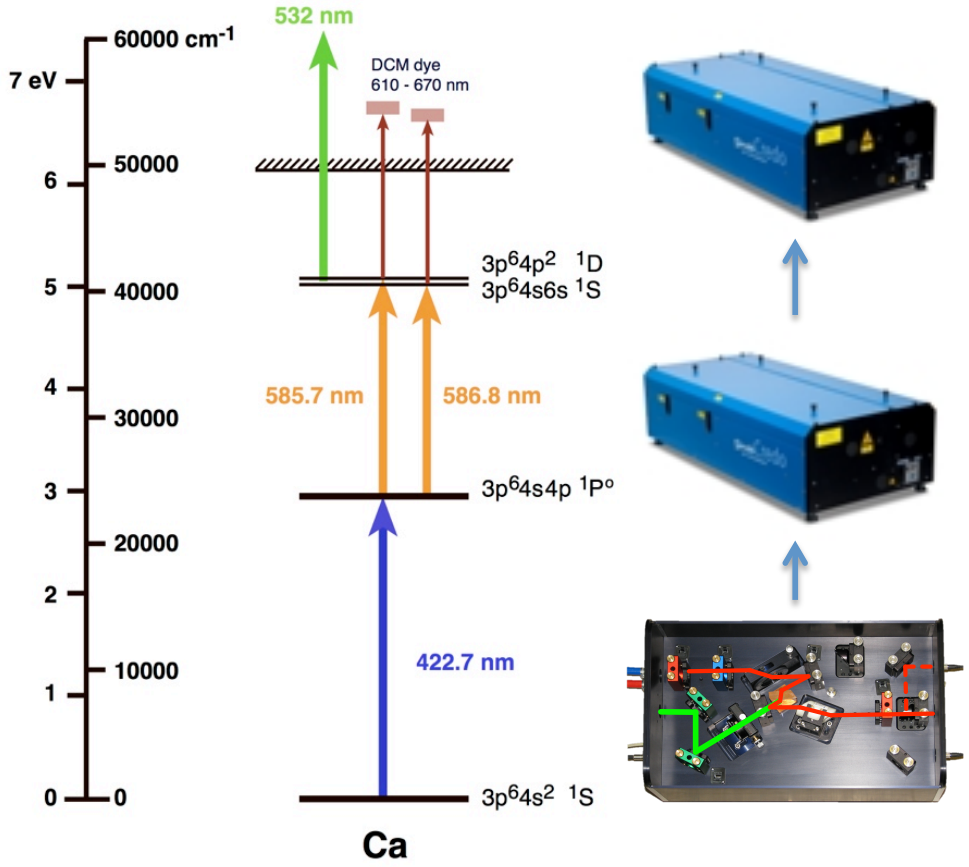
Outcome of RIS study of Mn at LARIS:

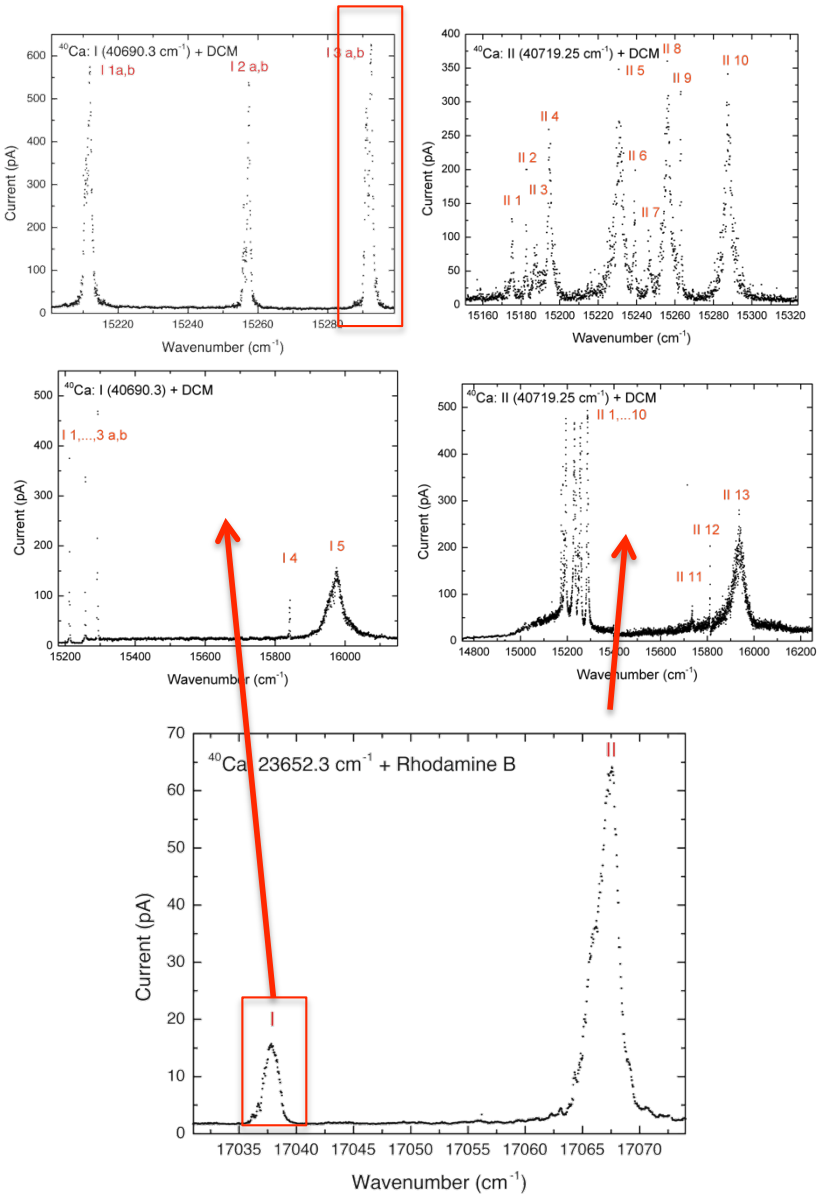
Many new auto-ionizing states found

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

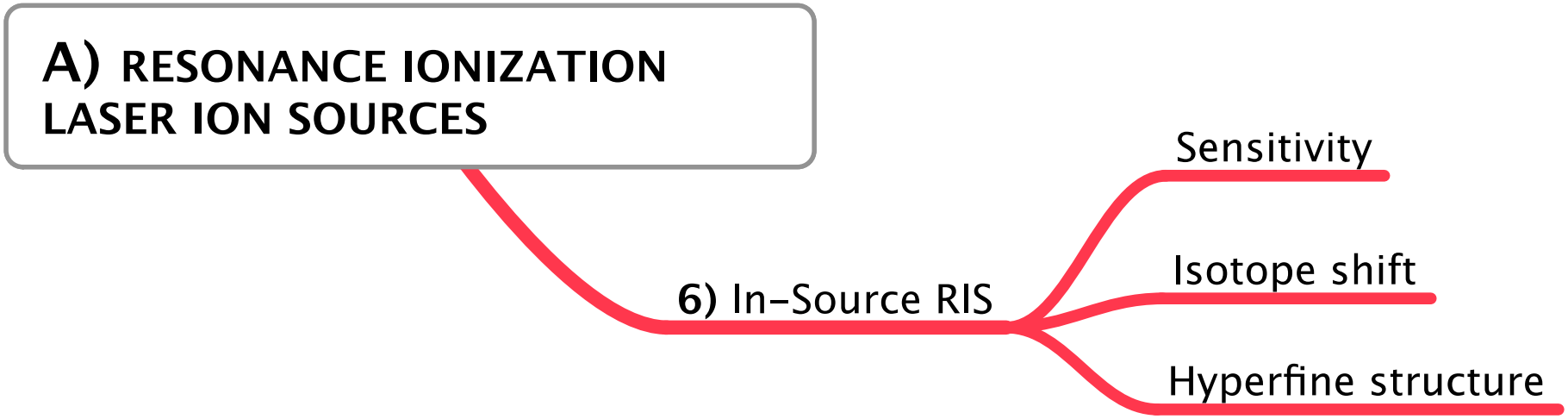
Calcium scheme development

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





Daniel Fink: PhD work


A) RESONANCE IONIZATION LASER ION SOURCES
6) In-Source RIS
Sensitivity
Isotope shift
Hyperfine structure

How does the nuclear structure influence the atomic spectra?

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

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

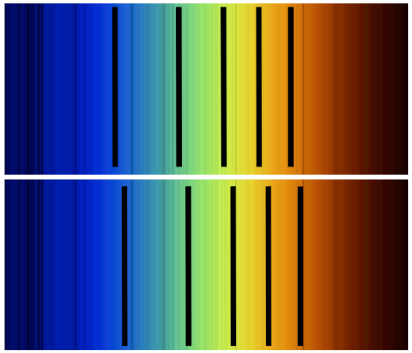
For a given element, if we examine the influence of the nucleus on the electron energy levels as we add or remove neutrons, we can determine nuclear structure changes along an isotope chain.

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

ISOTOPE SHIFT

Isotope 1

Isotope 2

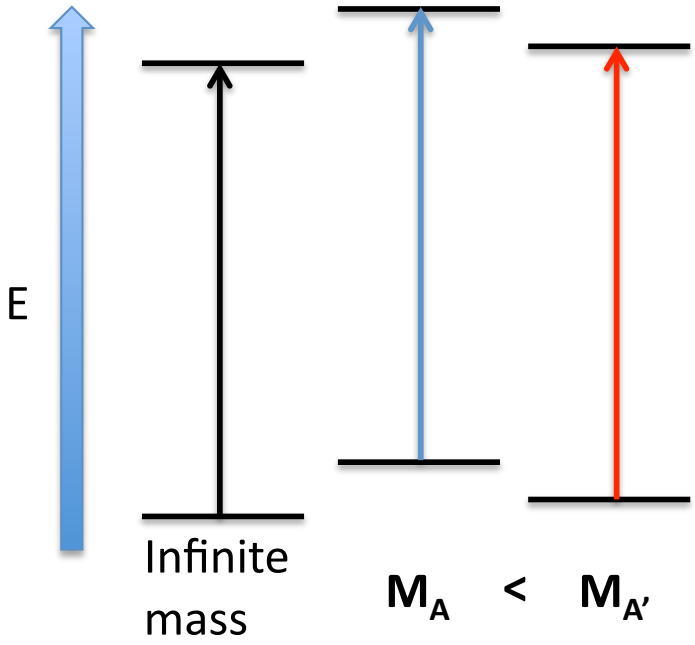


The frequency difference in the electron transition between 2 isotopes of an element

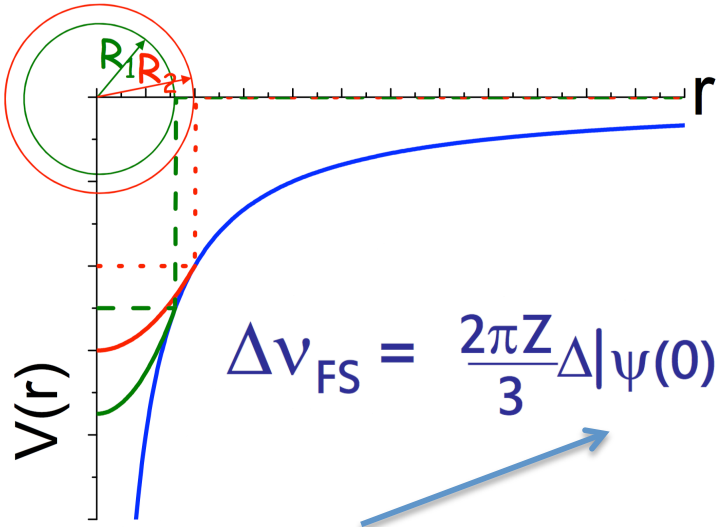
CAUSED BY these properties:

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

Finite nuclear mass — **MASS SHIFT**



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

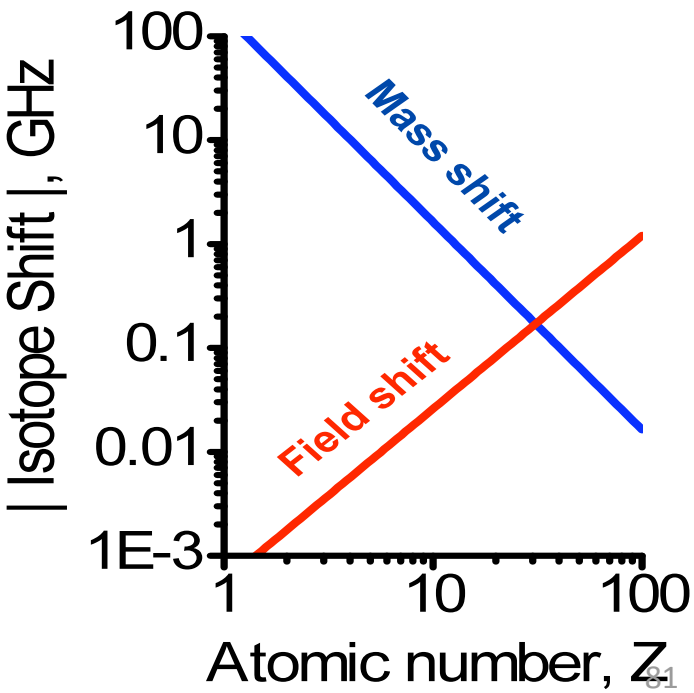
$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

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

EXPERIMENT

THEORY

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

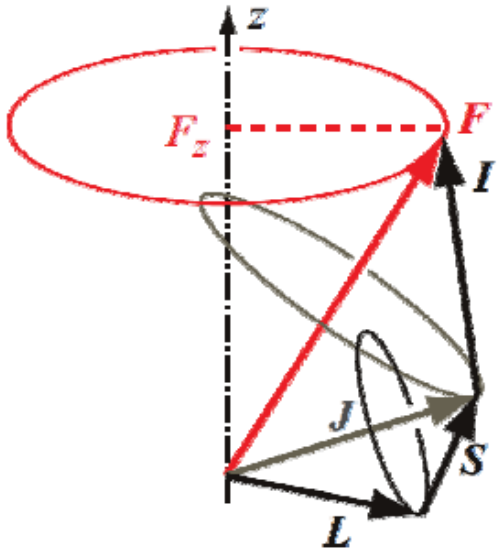


HYPERFINE STRUCTURE

- Magnetic dipole interaction
- Electric quadrupole interaction

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

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

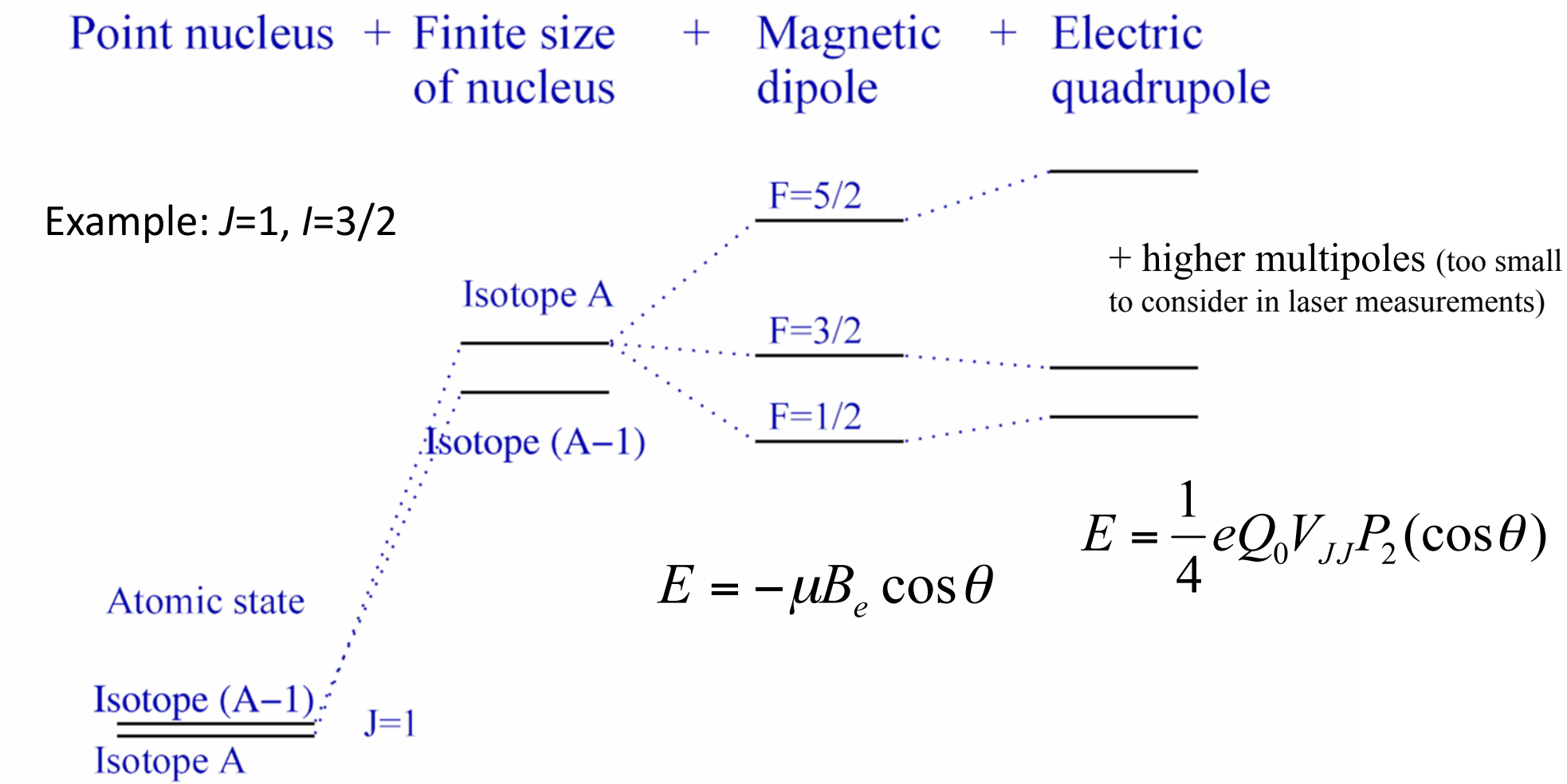


Hyperfine structure arises from interaction of nuclear moments with electric and magnetic fields produced at nucleus by orbiting electrons.

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

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

Summarizing the effects:



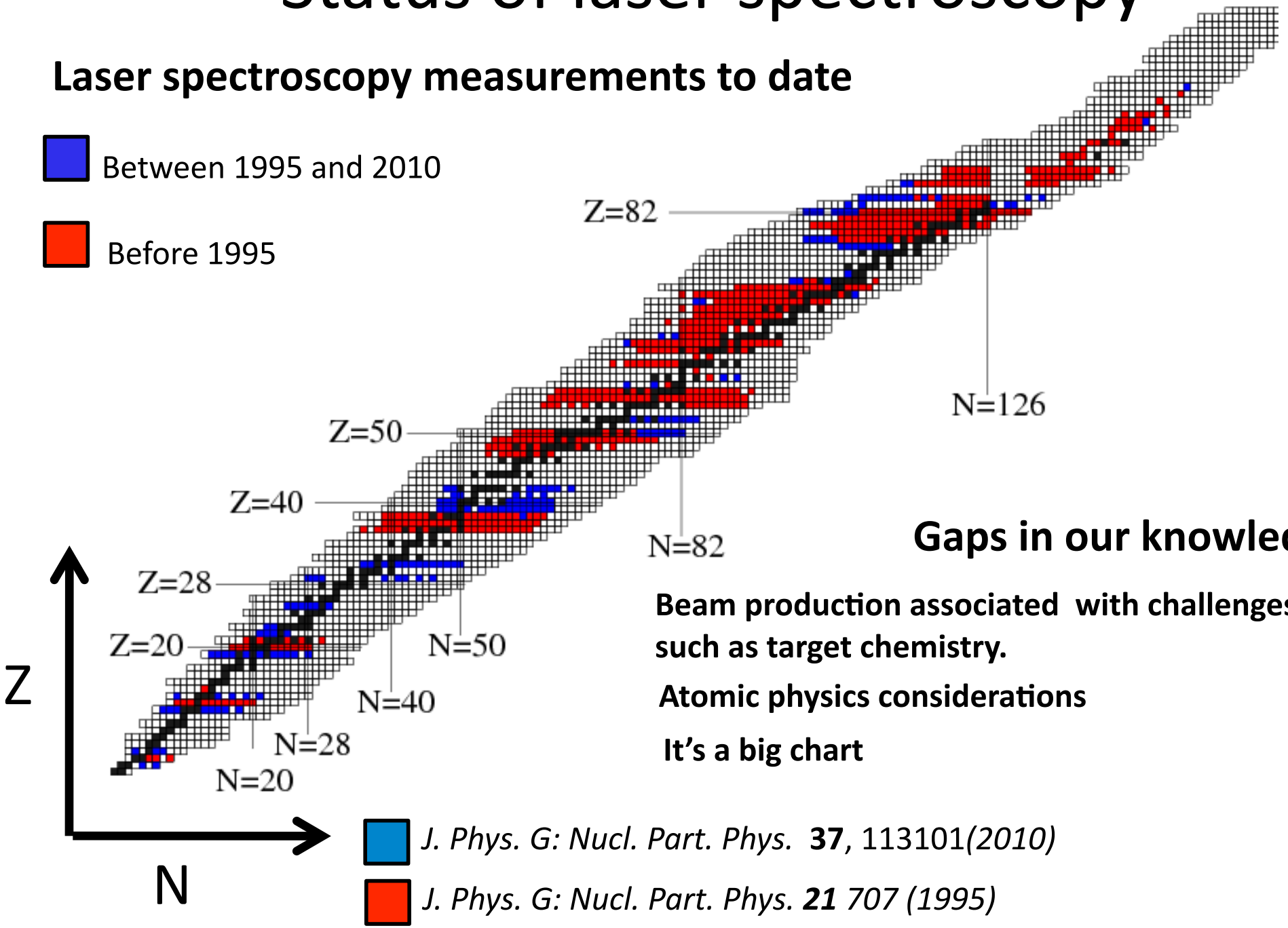
These energy shifts of may be only a few parts per million of the energy of an optical atomic transition. Optical techniques provide the sensitivity and precision required to measure these effects.

Status of laser spectroscopy

Laser spectroscopy measurements to date

Between 1995 and 2010

Before 1995



Gaps in our knowledge

Beam production associated with challenges such as target chemistry.

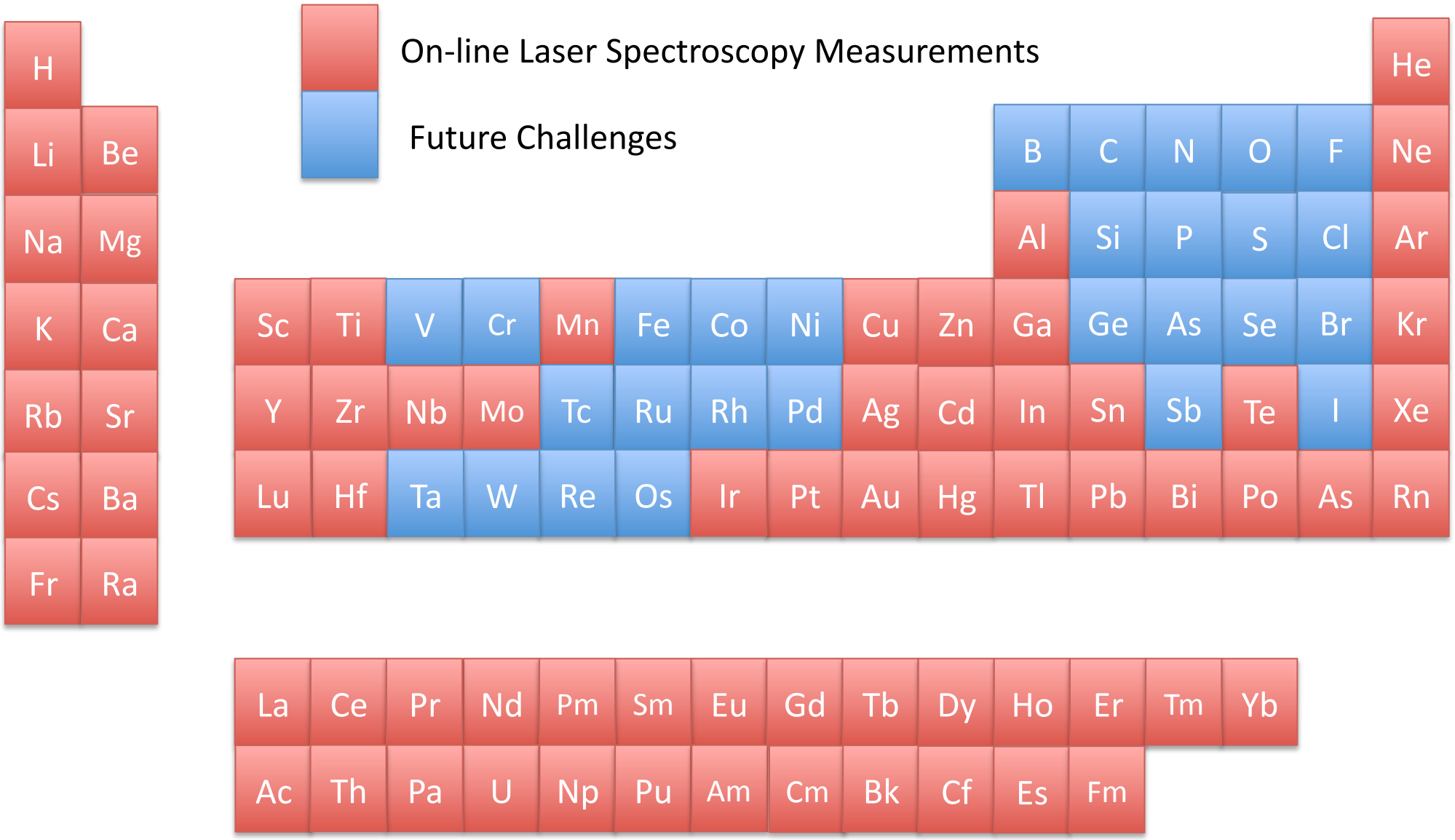
Atomic physics considerations

It's a big chart

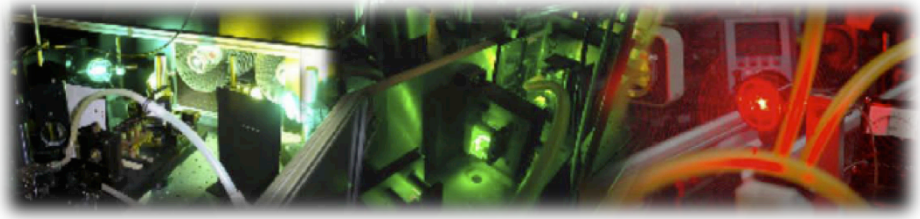
J. Phys. G: Nucl. Part. Phys. **37**, 113101*(2010)*

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

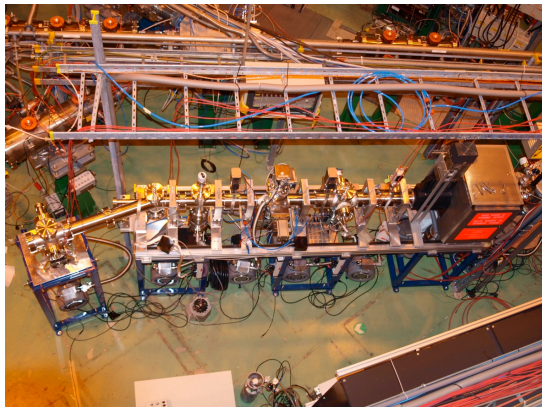
Ion resonance ionization cases



European Laser Spectroscopy Options



- In-source: RILIS, ALTO
  - Sub 1 atom/s sensitivity
  - Wide range of elements studied (~30 currently accessible)
  - Hot Cavity and associated Doppler broadening
  - Target chemistry and release time dependence
- In-gas cell laser spectroscopy: LISOL, IGISOL
  - Relatively insensitive to chemistry
  - Access to short half-lives
  - Pressure broadening and shifts
- Collinear: COLLAPS, IGISOL, CRIS
  - High resolution (typically limited by natural linewidth)
  - Highly adaptable



Methods to measure moments, radii, spin

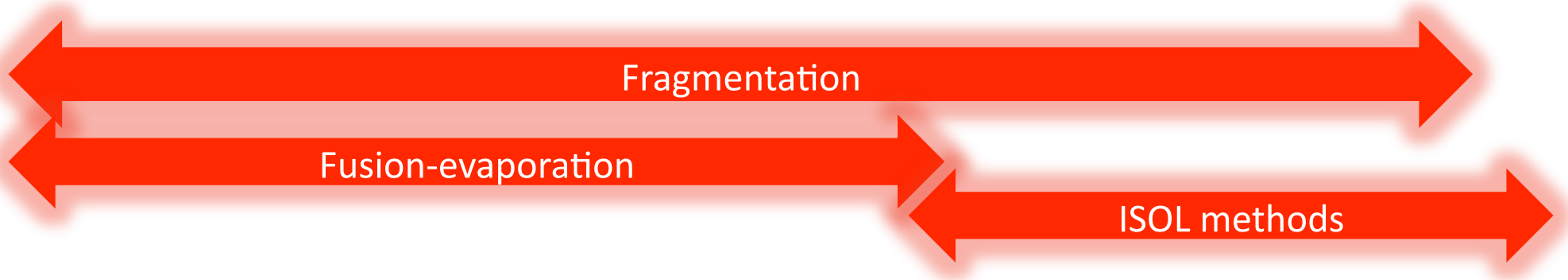
1 ps 1 ns 1 μs 1 ms 1s

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

γ-TDPAD on aligned beams
g-factor
quadrupole moment

Transient field method
g-factor

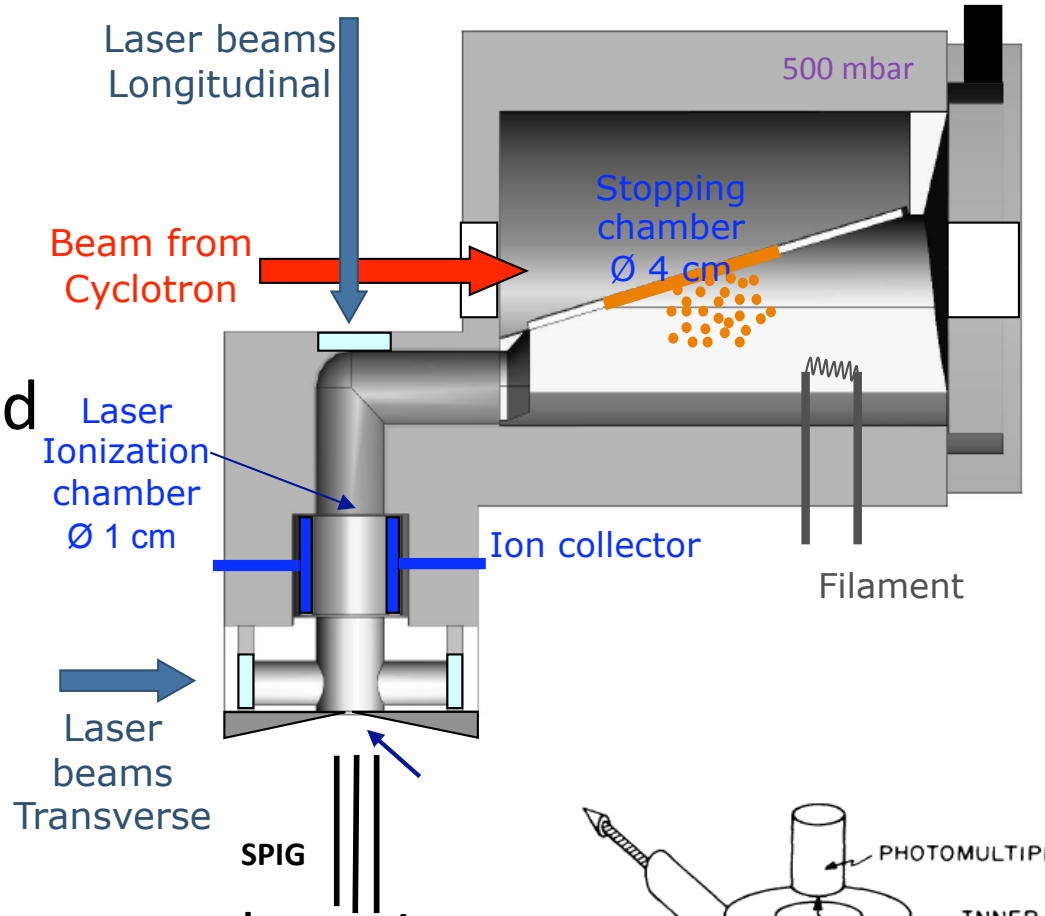
β-NMR/NQR on polarized nuclei
Nuclear Magnetic/Quadrupole Resonance
g-factor
quadrupole moment

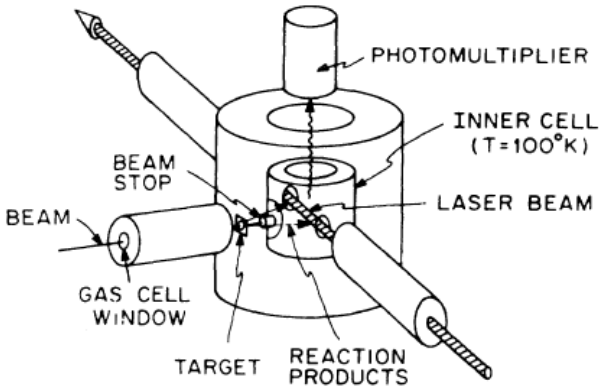


Gas cell laser spectroscopy

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

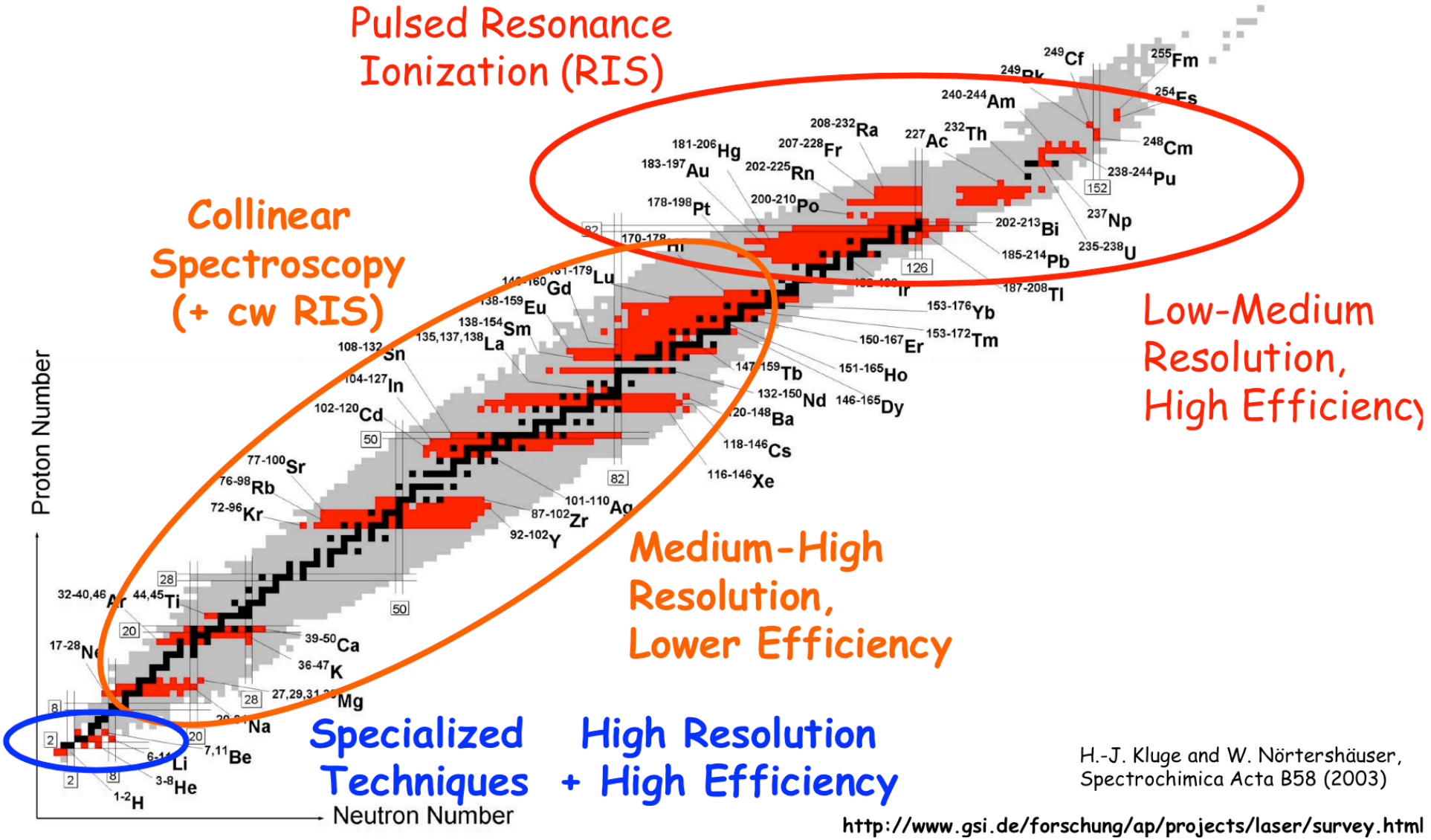
    T. E. Cocolios et al., PRL 103, 102501 (2009)
    T. E. Cocolios et al., PRC 81, 014314 (2010)
    Iain Darby Phys. Lett. B (in preparation)
- Future S3 work on stopped beams
  - N=Z line: ^{94}Ag, ^{101,103}Sn,
  - SHE region >Ac
- Cryogenic gas cell and fluorescence detection
  - 900/s yields, Γ~300MHz
  - Possible route to probe μs half-lives





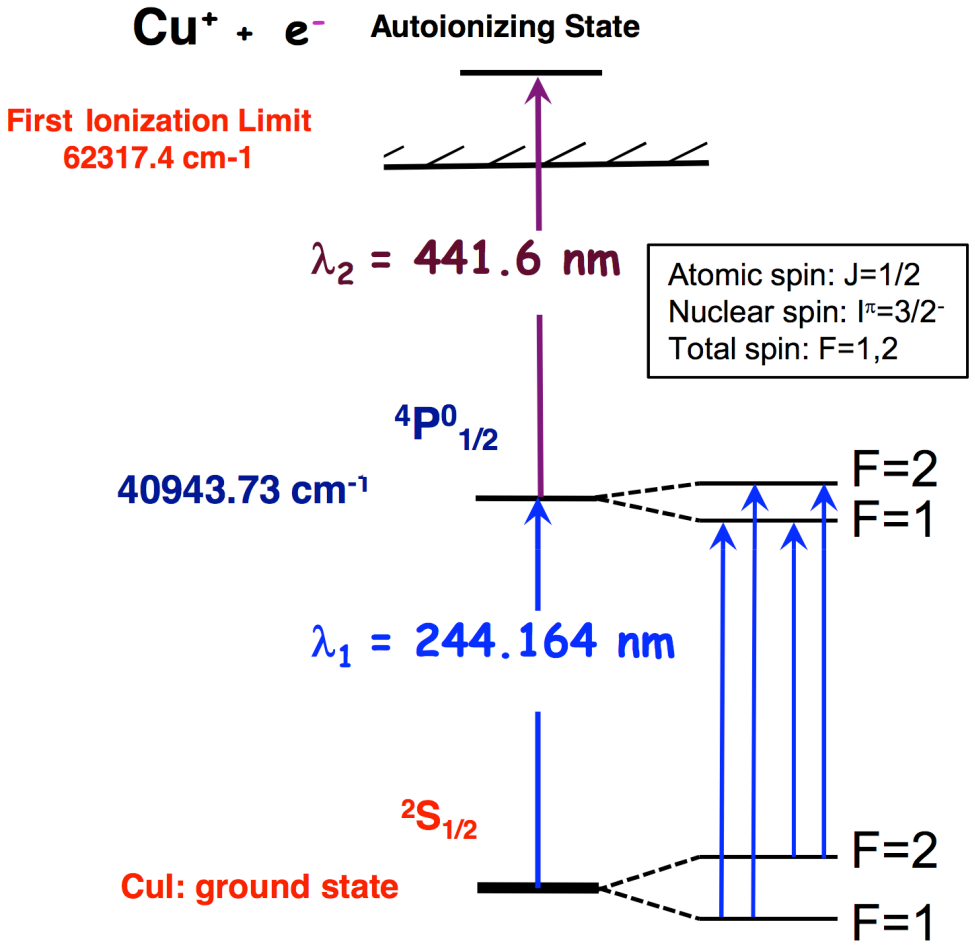
G. D. Sprouse et al., PRL **63** 1463 (1989)

Using the ion source for laser spectroscopy

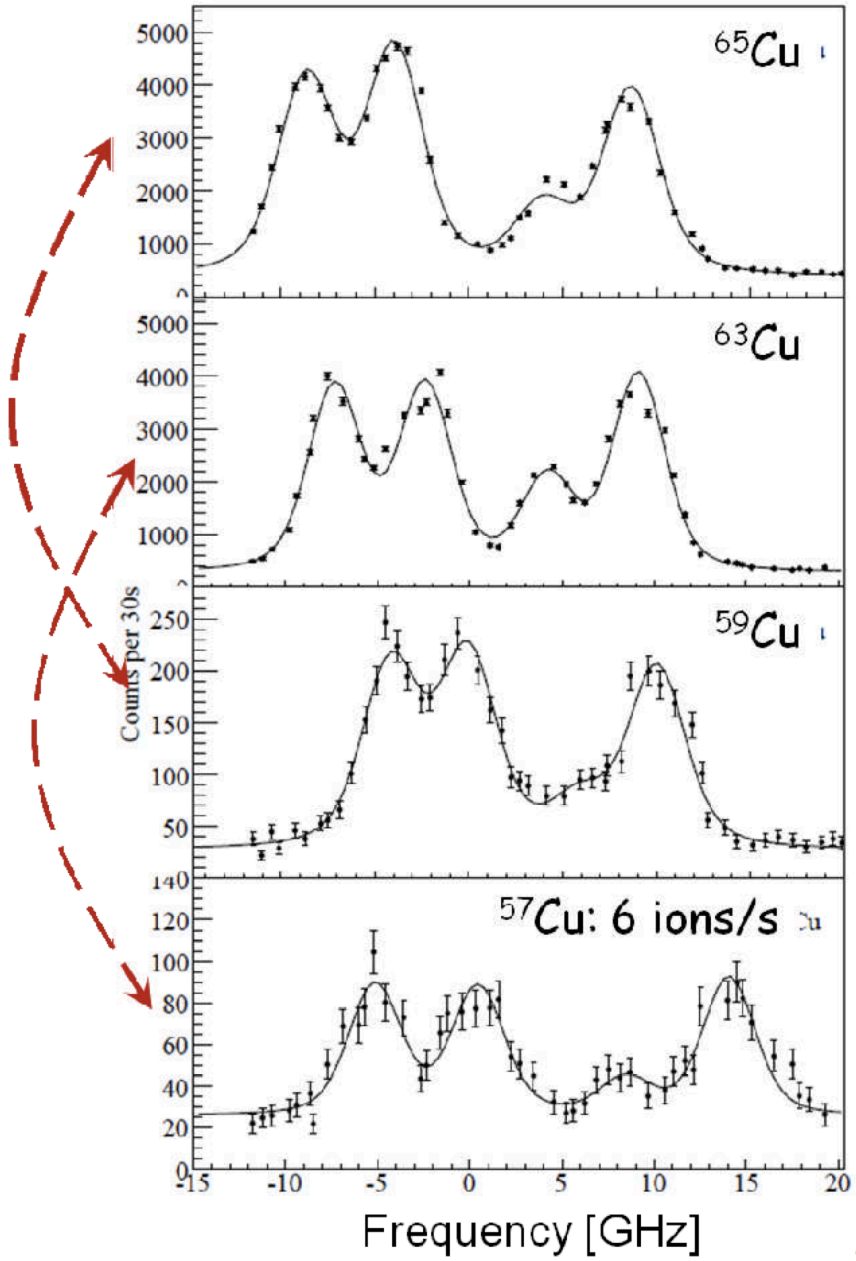


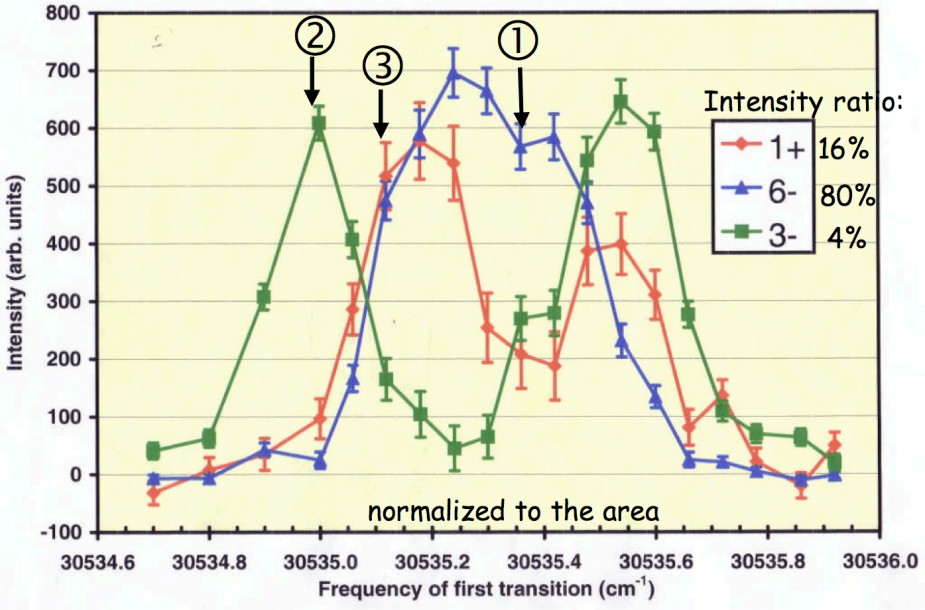
Progress in laser spectroscopy at radioactive ion beam facilities
B Cheal and K T Flanagan 2010 J. Phys. G: Nucl. Part. Phys. 37

Recent REVIEW article



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





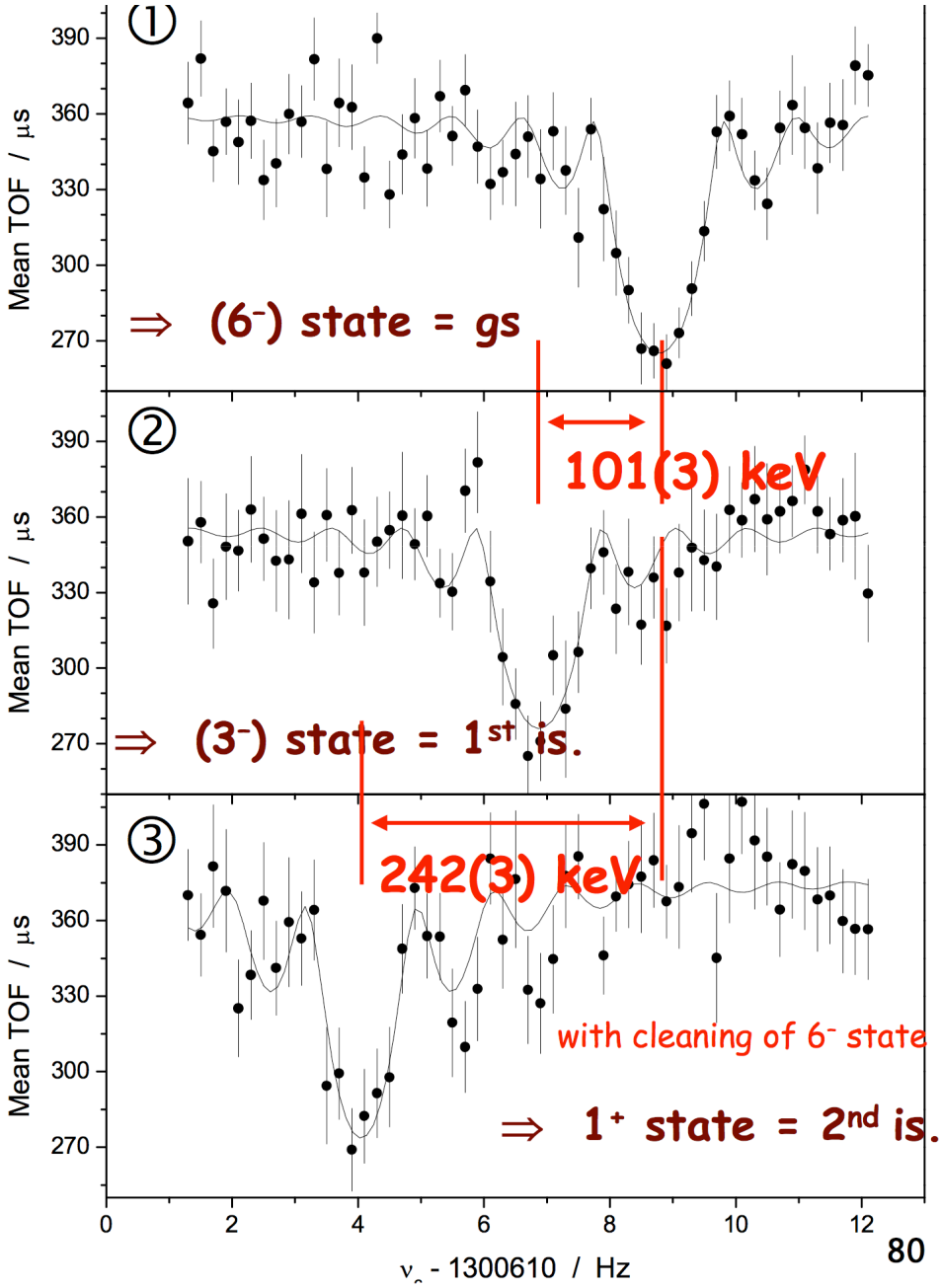
$$\omega_c = \frac{q}{m} \cdot B$$

Unambiguous state assignment!

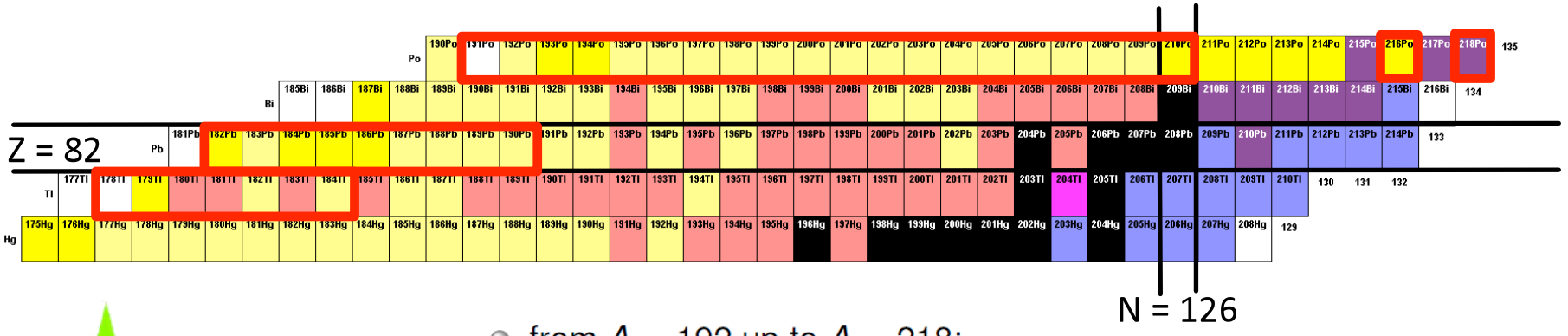
ME of ground state is 240 keV higher than literature value!

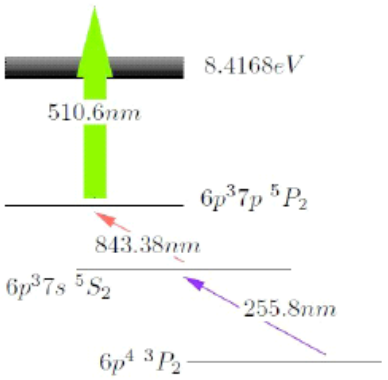
$R \approx 1 \cdot 10^7$, $\delta m/m \approx 4 \cdot 10^{-8}$

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

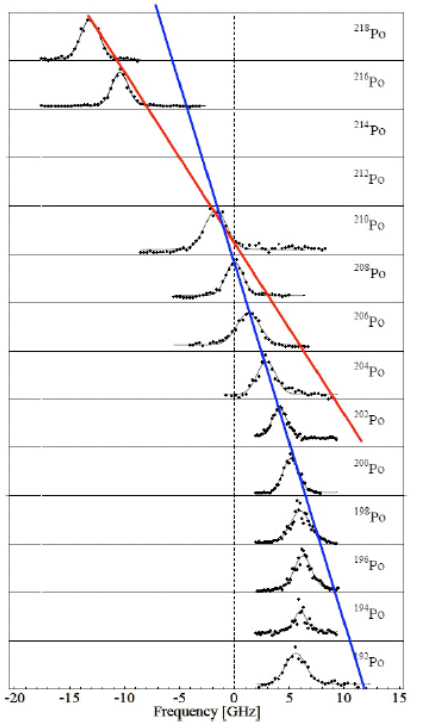


RILIS laser spectroscopy in the Pb region





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



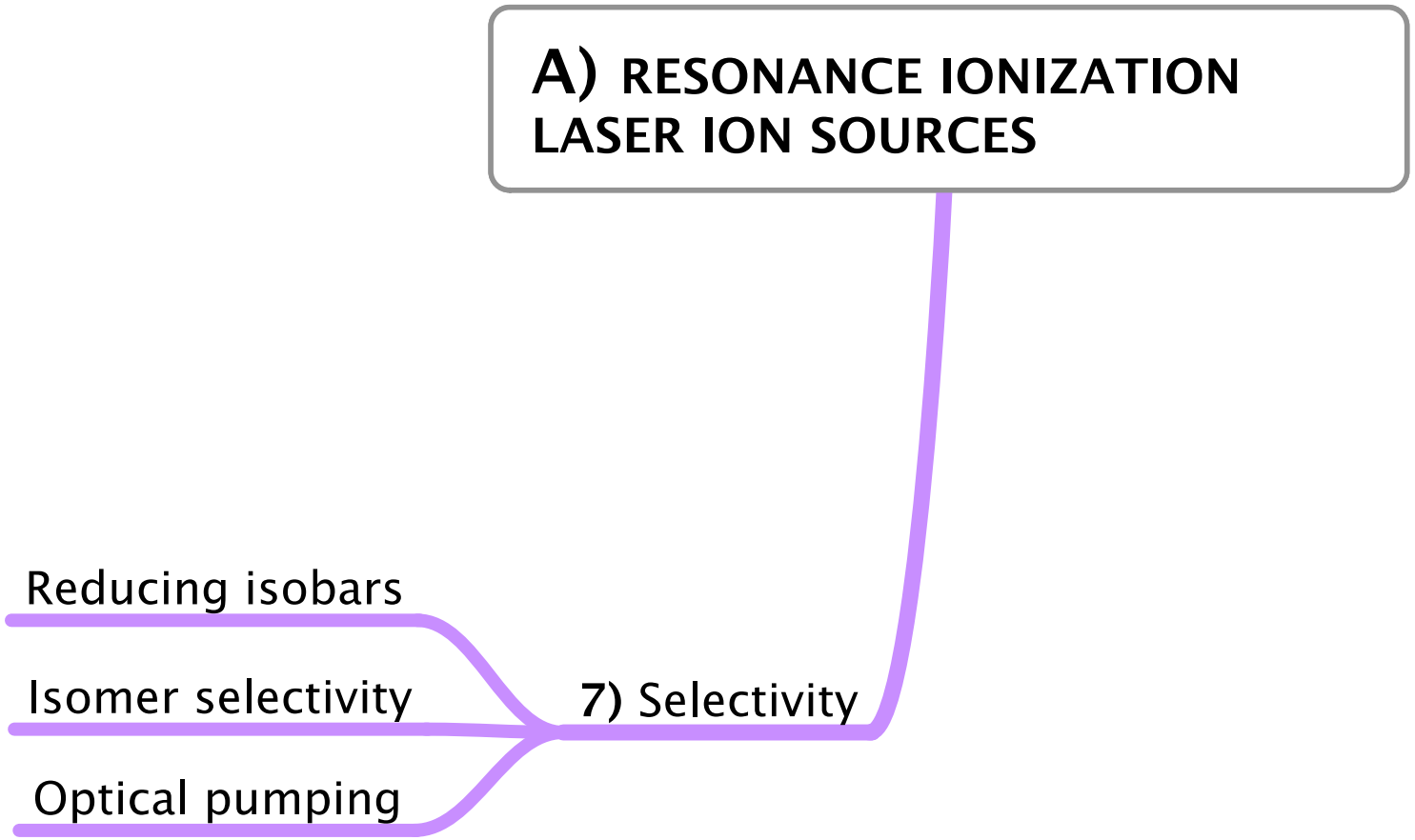
^{218}Po

^{192}Po

Recent developments for the spectroscopy of At isotopes

KU Leuven

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


A) RESONANCE IONIZATION LASER ION SOURCES
7) Selectivity
Reducing isobars
Isomer selectivity
Optical pumping

How to improve the selectivity of the laser ion source?

Problem – unselective ionization of isobars on hot metal surfaces.

Solution 1 – Reduce the surface ionization

Reduce temperature

Use low work function materials

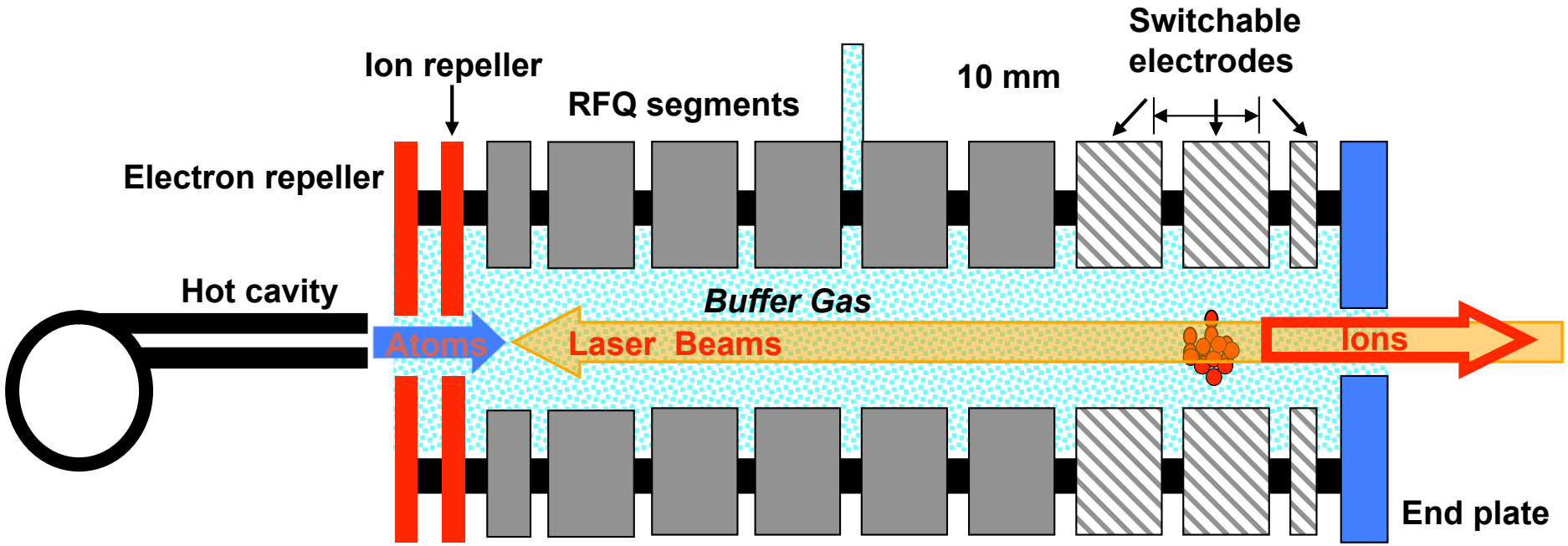
Trap unwanted elements
(add chemical selectivity to the effusion process)

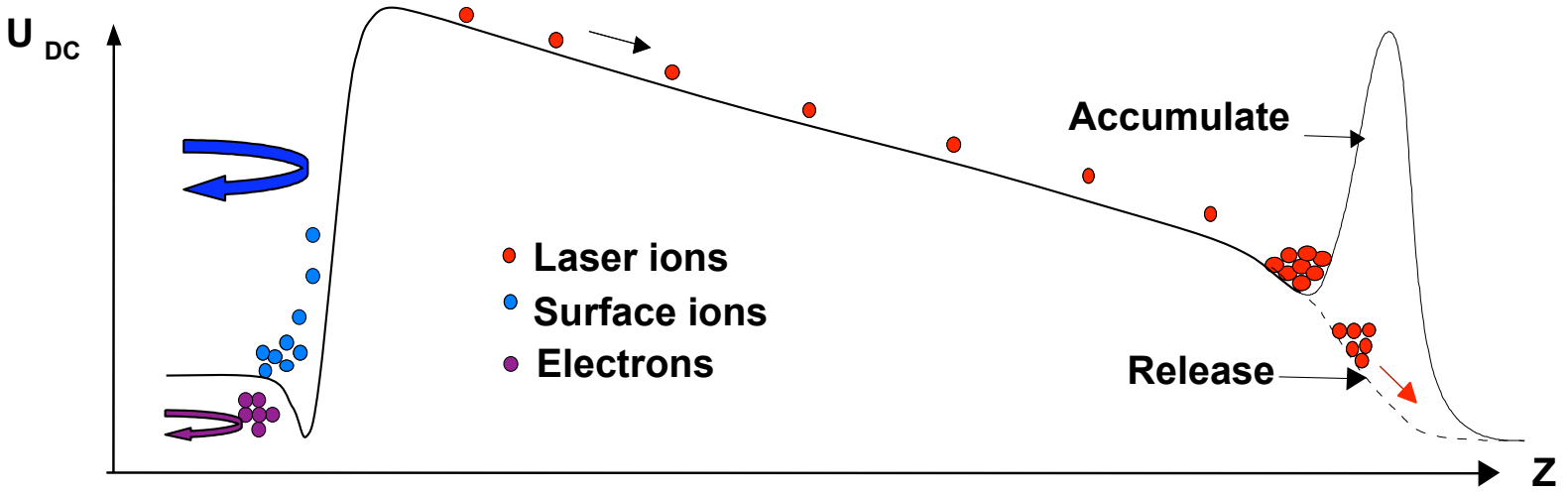
Solution 2 – Separate surface ions from laser ions

Repel surface ions before laser ionization

Temporal separation of laser and surface ions

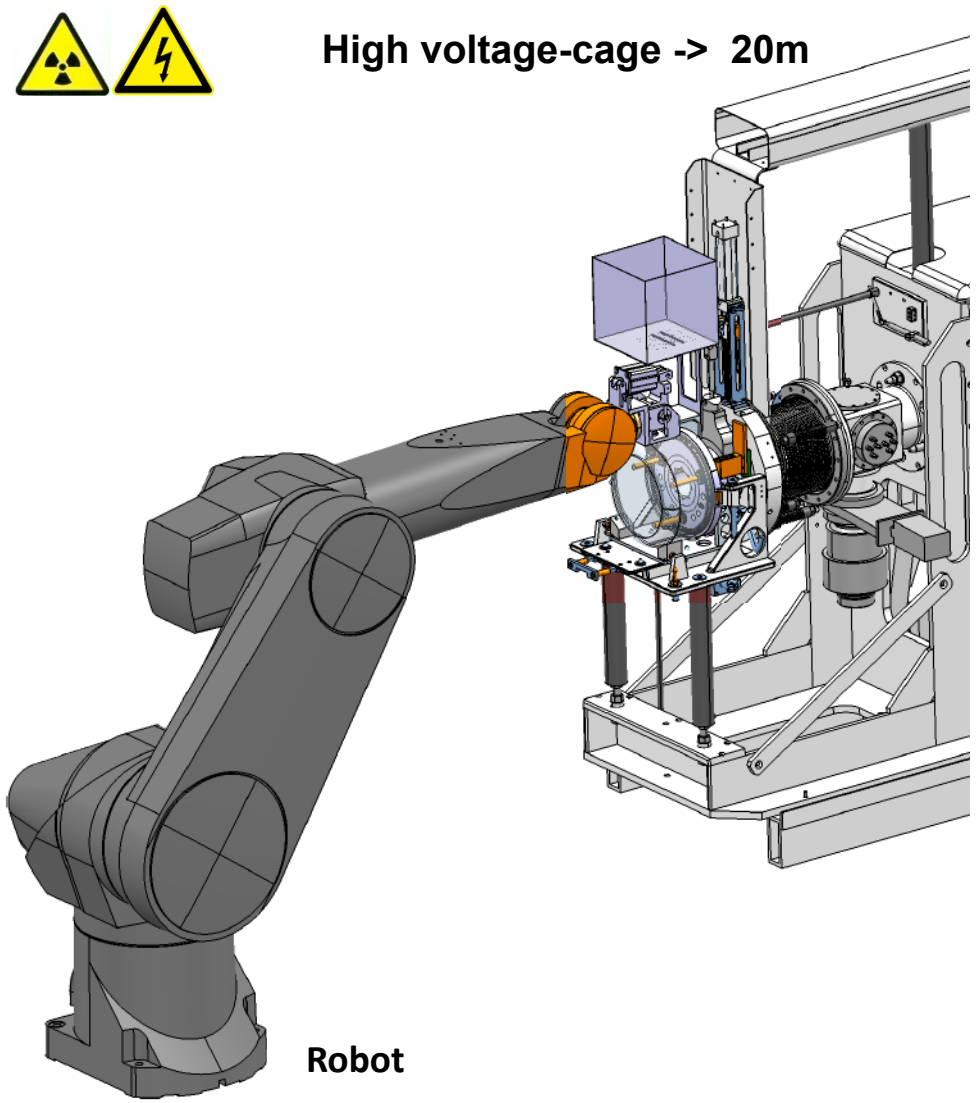
Ideal selective laser ion source? Repeller and trap





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

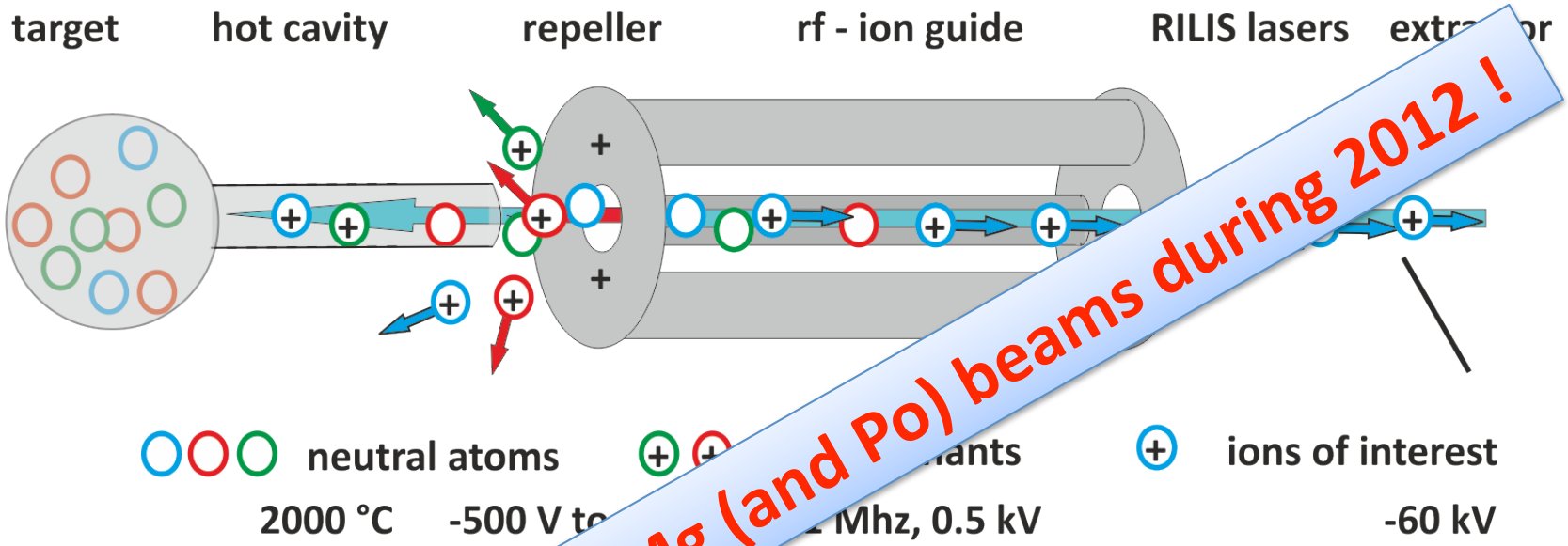
Implementation of such a device



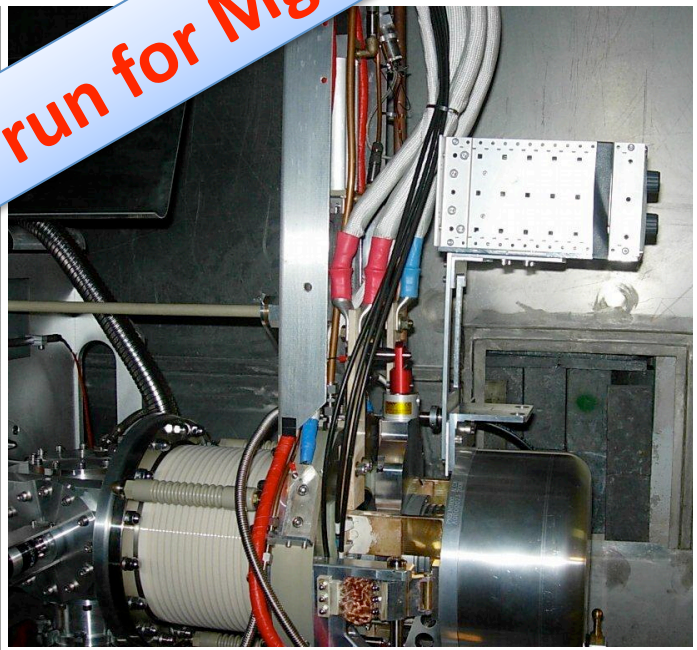
Challenges:

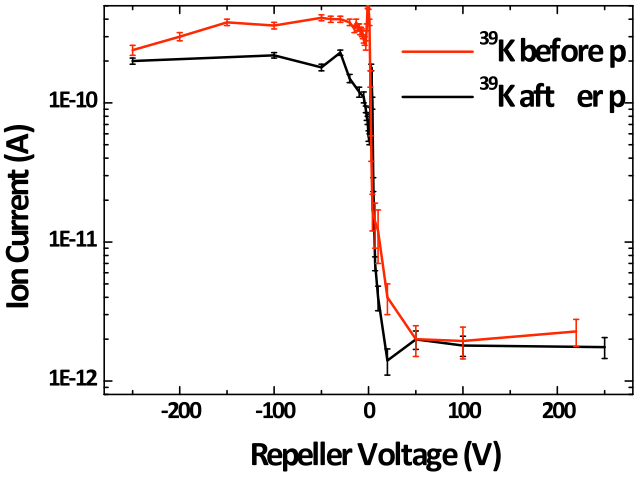
- **High radiation**
  - radiation hard material
  - Gas extraction
- **High tension**
  - electronics in HV-cage
  - remote control
  - Amplification of rf at target
  - Feedthroughs
- **Robot**
  - Connectors
  - Stability
  - Size limitations

A feasible Laser Ion Source Trap design!



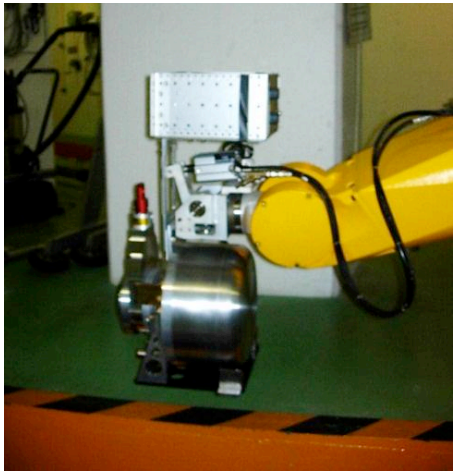
On-line LIST run for Mg (and Po) beams during 2012 !

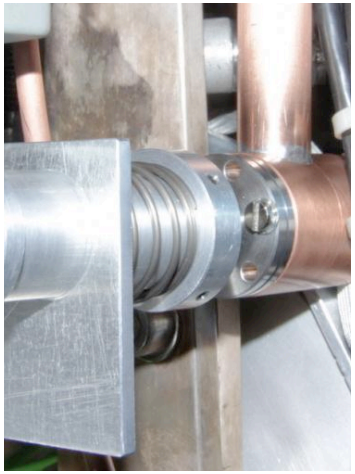


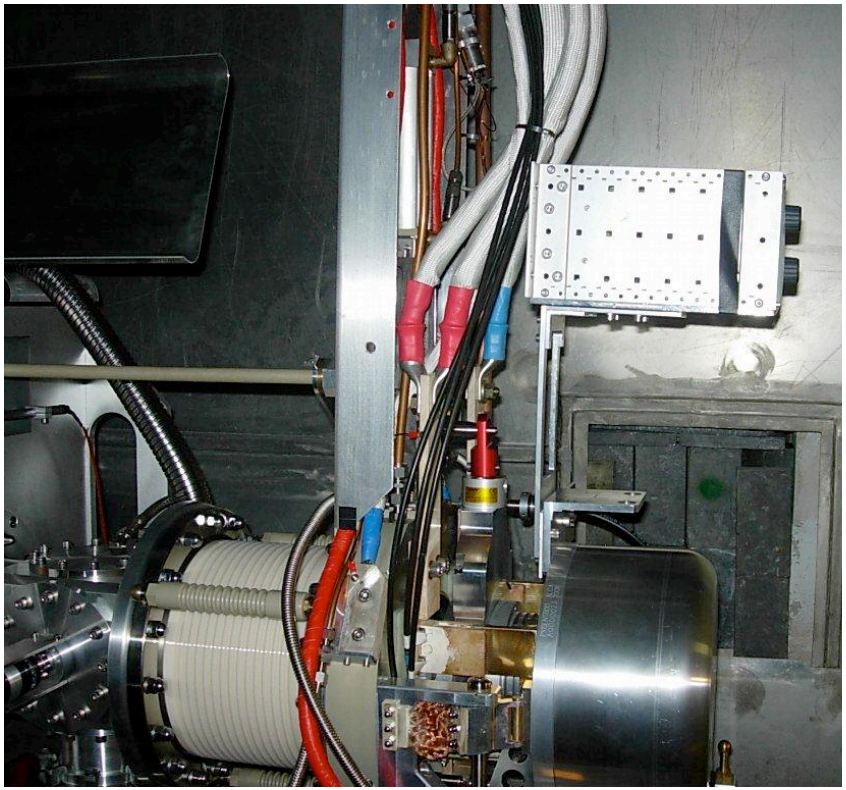


Daniel Fink - Poster

Robot coupling



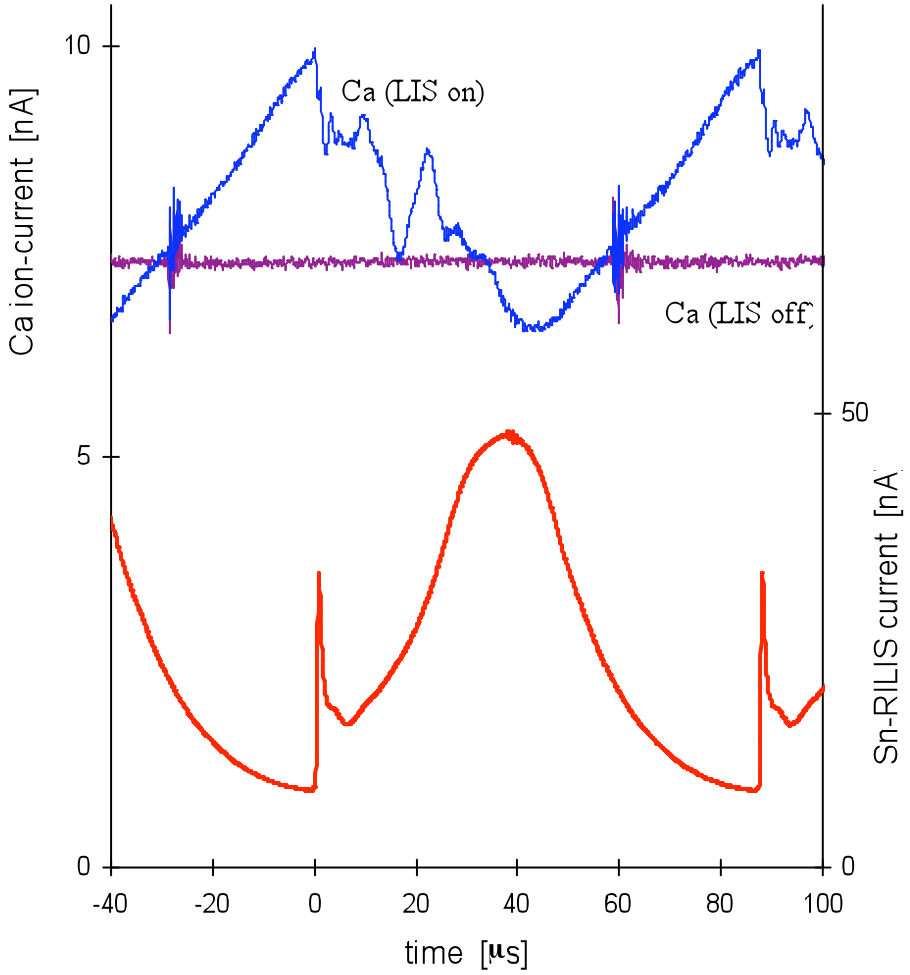




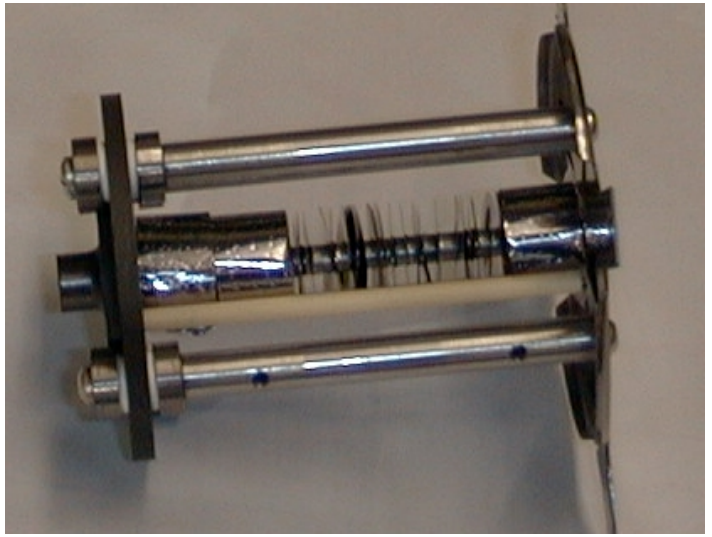
Micro beam gating – selectivity using the laser ion pulse structure

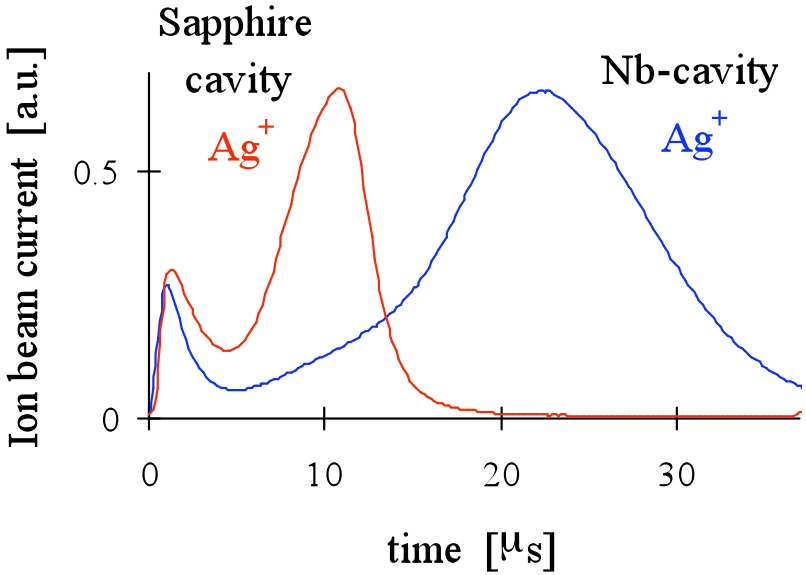
Thinner cavity walls -> more electrical resistance -> higher voltage -> shorter bunch length of laser ions

Standard W cavity:



Thin Nb cavity:





Data presented by J.Lettry at CERN Sept 2007

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

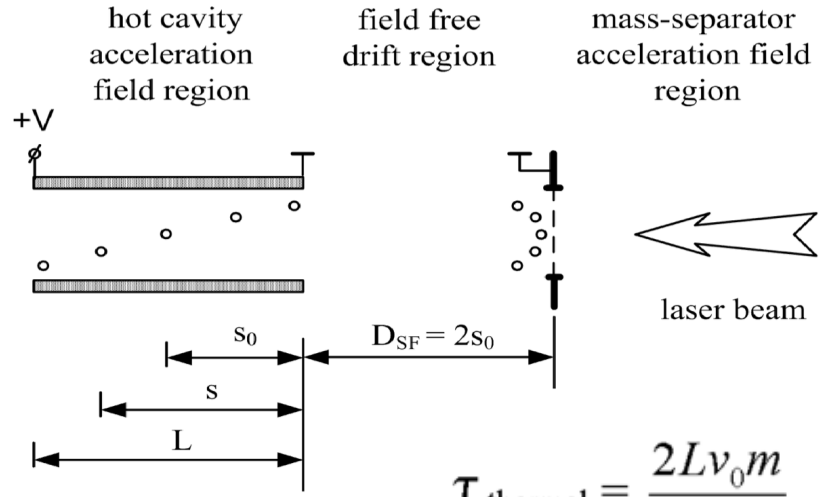
Resonant Ionization Laser Ion Source (RILIS) With Improved Selectivity Achieved By Ion Pulse Compression Using In-Source Time-of-flight Technique

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.

al distribution of atoms



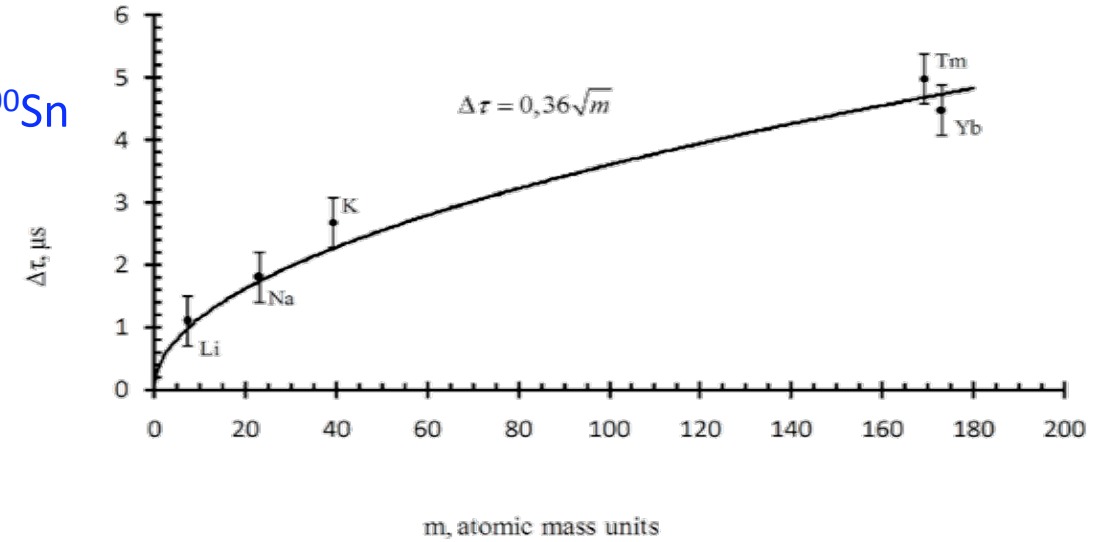
$$\tau_{\text{thermal}} = \frac{2Lv_0m}{eV}.$$

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:

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

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]

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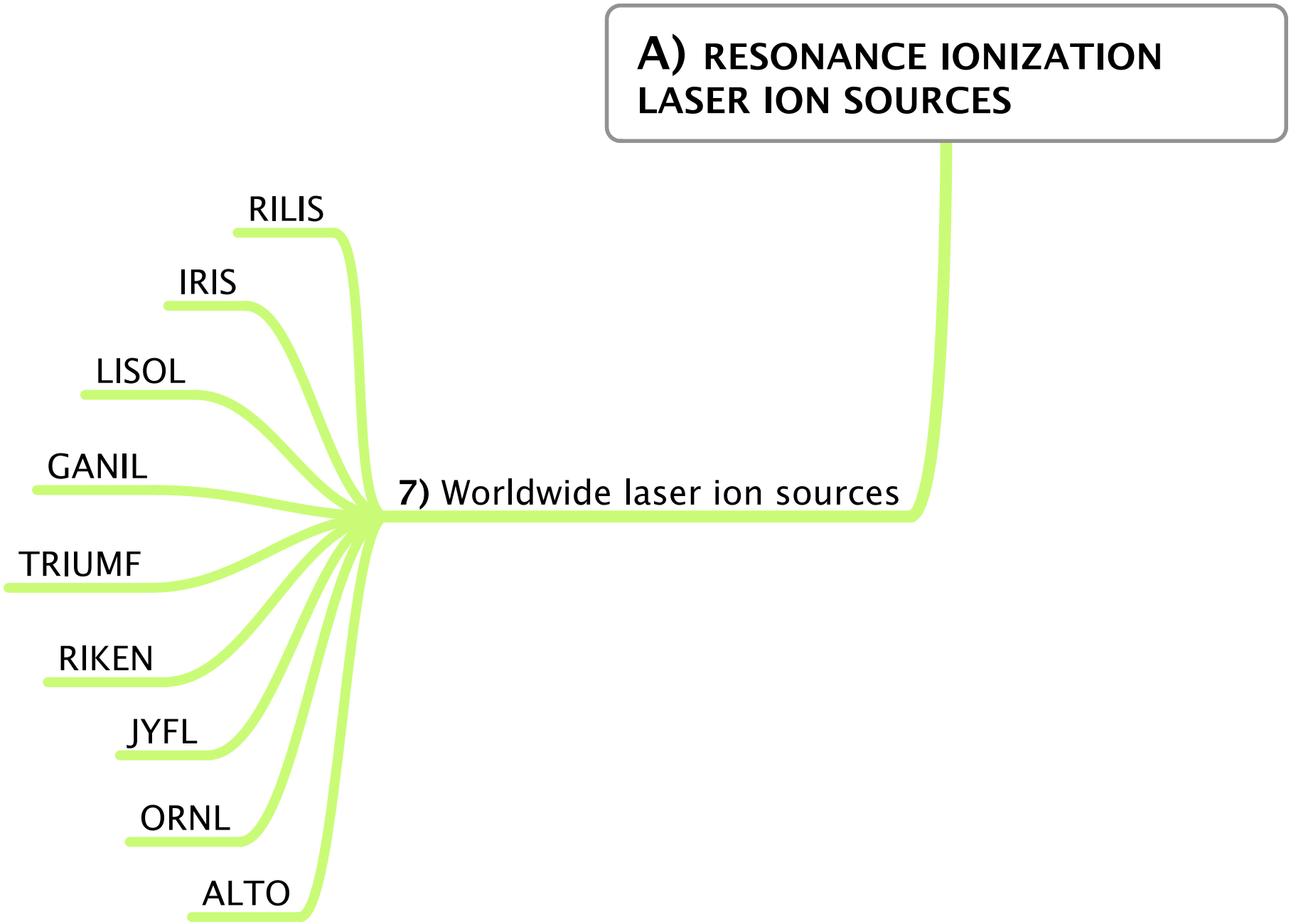
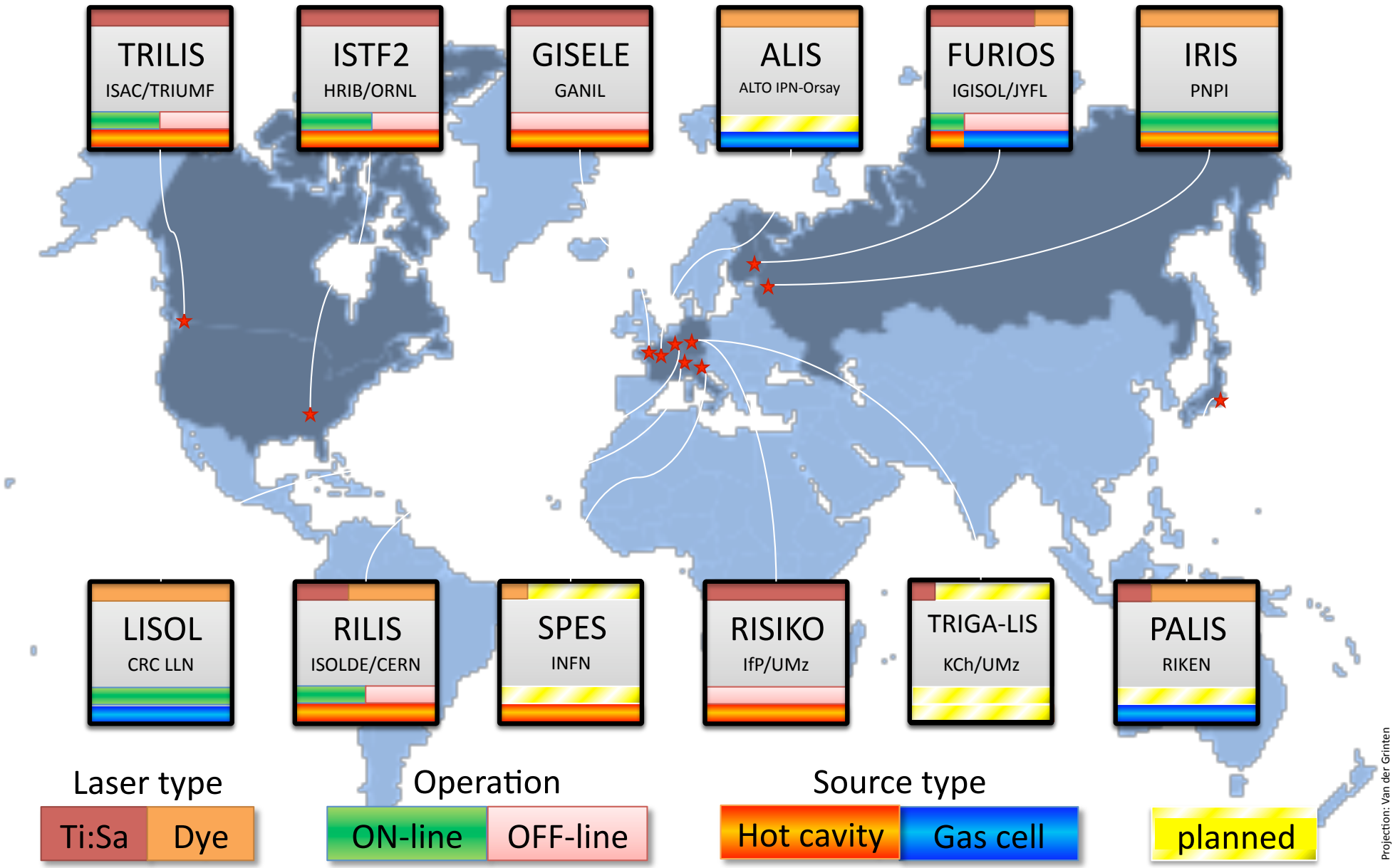
Beam purification by selective trapping in the transfer line of an ISOL target unit

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



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

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[2] Instituut voor Kern-en Stralingsfysica, K.U.Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

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

E-mail: Valentin.Fedosseev@cern.ch

	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
						et al/2003b
						rg 2011
						zov *et al*/1989a
						zov *et al*/1991
						et al/1987a
						ch *et al*/2000
						et al/1991
						zov *et al*/1992
						ch *et al*/2000
						ch *et al*/2002
						et al/1993
						rg 2011
						et al/2000
						al/1988
						et al/1989
						ath *et al*/1992
						unc *et al*/1999
						eroth *et al*/1987
						rt *et al*/1987
						al/1987a
						al/1987b
						et al/1990
						rt *et al*/1991
						unc *et al*/1992
						ge *et al*/2000
						et al/2010
						vak 2010
						et al/1992
						et al/2003b
						ch *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

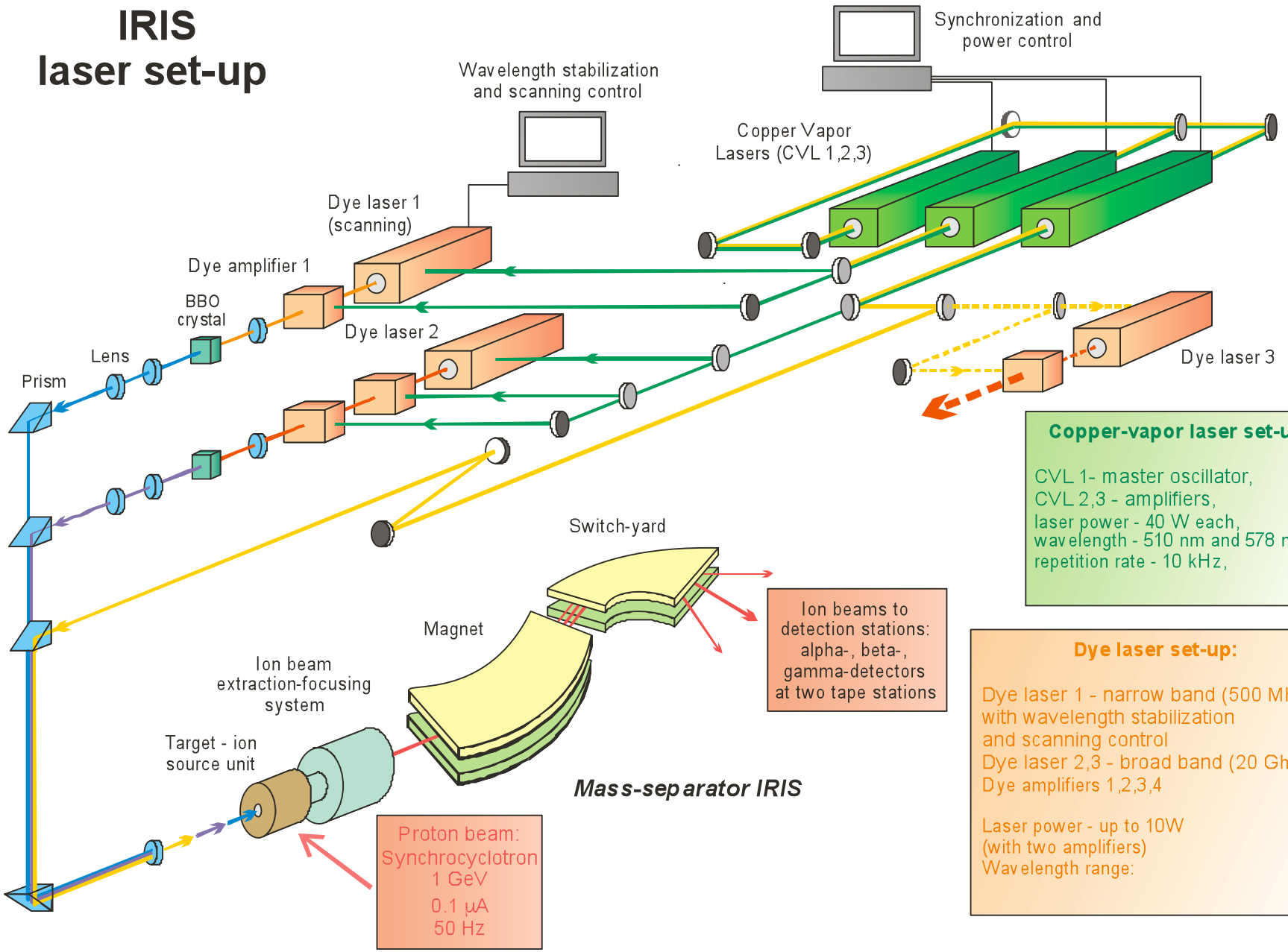
LIS (Laser Ion Source) – method of laser ionization in a hot metal cavity - invented and firstly applied at IRIS [1,2]

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



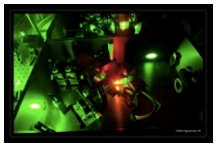
Copper-vapor laser set-up:

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

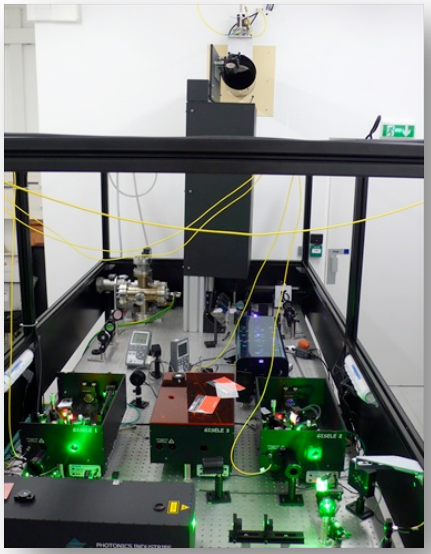
Laser power - up to 10W
(with two amplifiers)
Wavelength range:

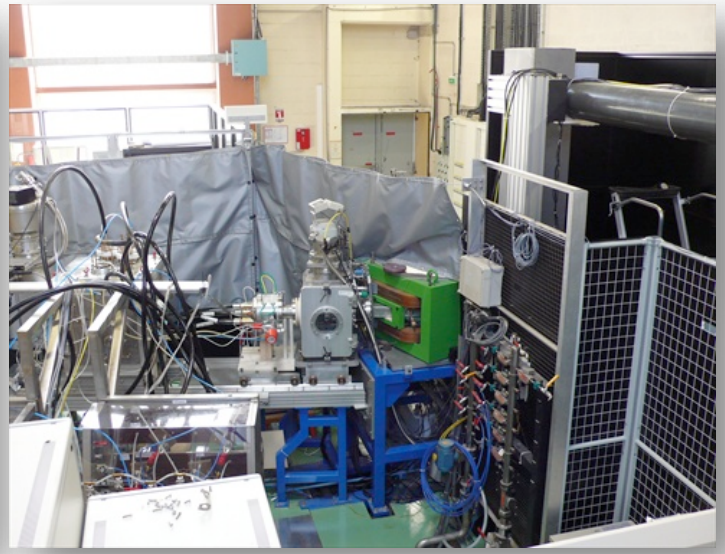


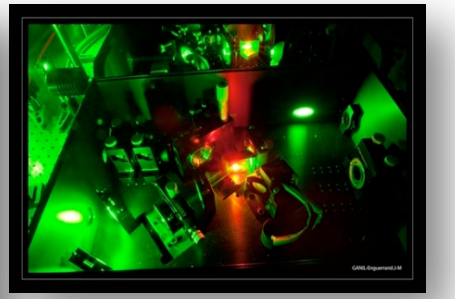
NEW GISELE @ GANIL

GANIL Ion Source using Electron Laser Excitation

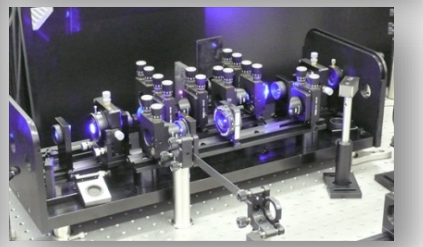
- Off line prototype for SPIRAL2
- TiSa laser, 20m transport path and hot cavity: June 2010 – July 2011





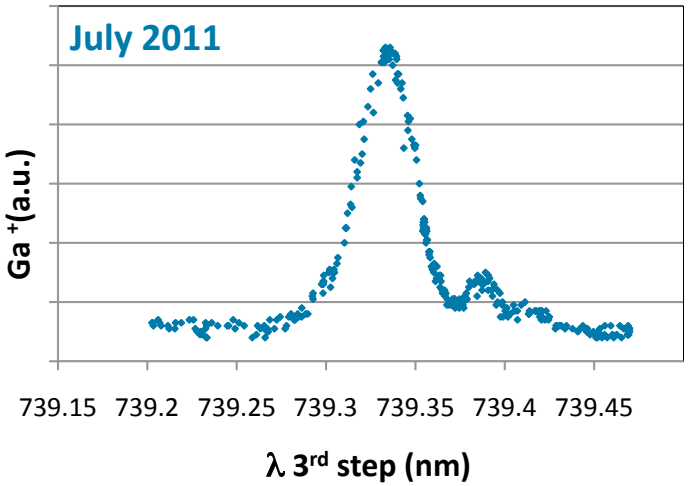


3 TiSa cavities
from TRIUMF



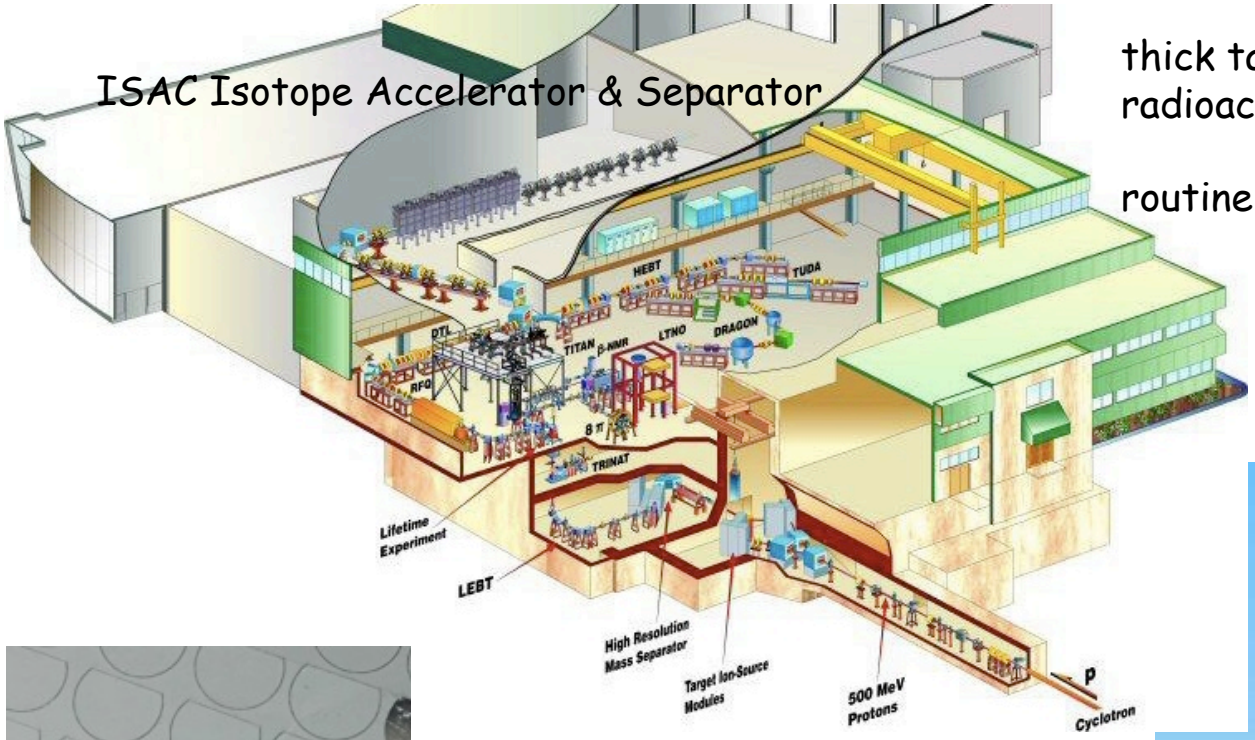
2 Tripler cavities
from Mainz U.

Rydberg state of Ga



Lecesne et al, RSI 81 (2008) 02A910

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



thick target – hot cavity ISOL based radioactive ion beam facility

routine operation at the licensing limit:

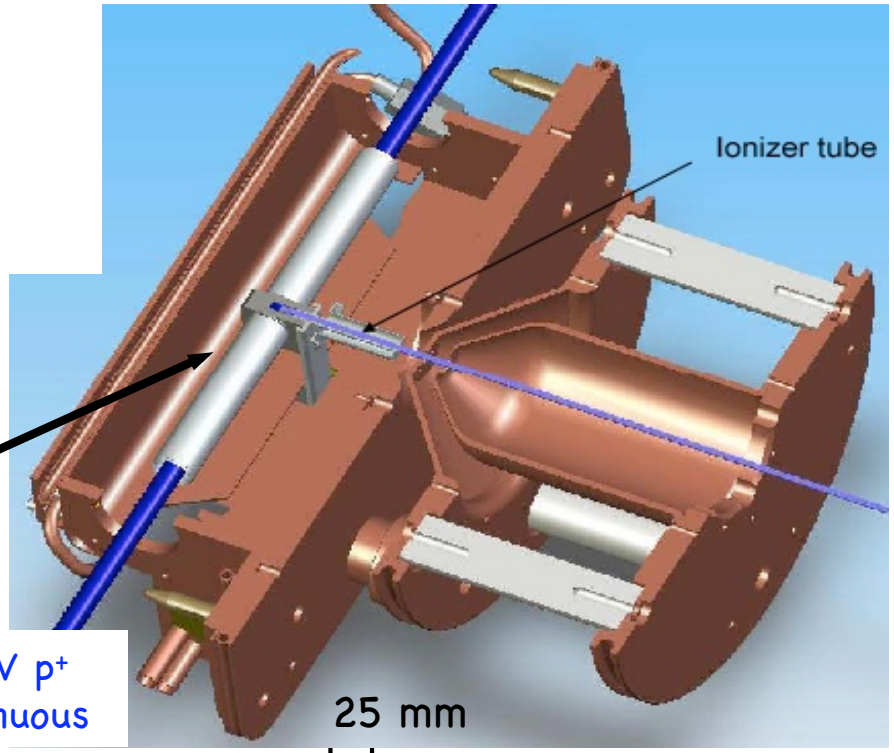
100 μA p+ on A<81 targets (up to 50kW)

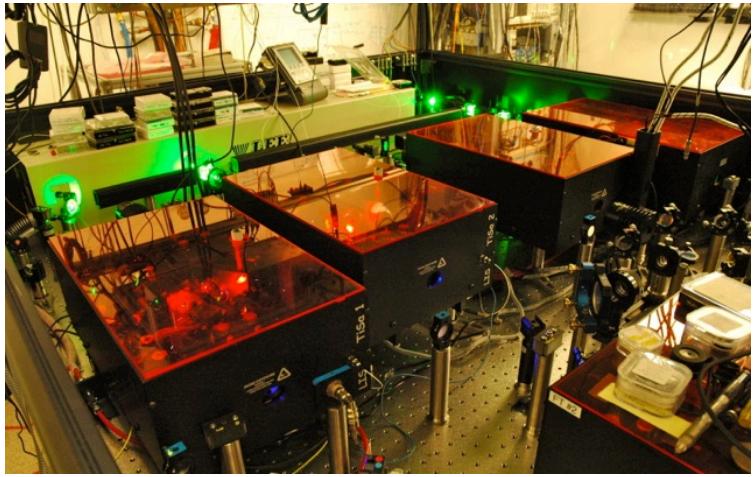
10 μA p+ on UC_x targets

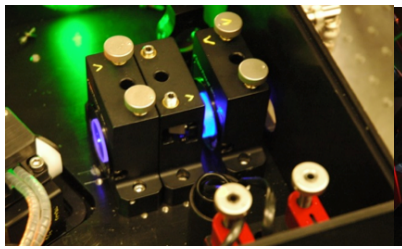
RIB beam schedule: Apr.-Dec. (24/7)

carbide etc. targets

metal foil targets







TiSa laser specifications:

Repetition rate 10 kHz

Wavelength range

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

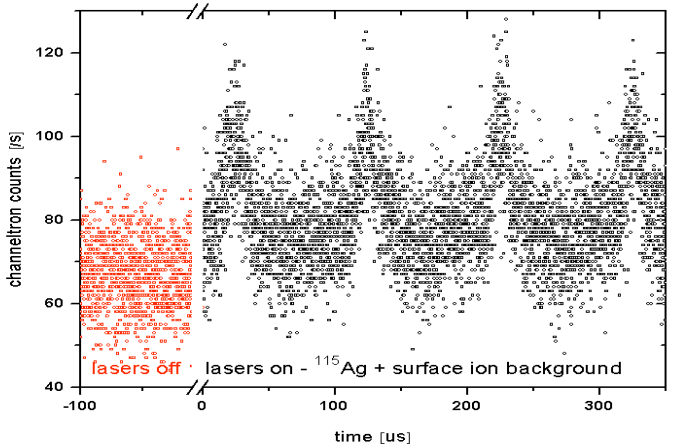
Tuning range

- BRF TiSa 300 GHz
- Grating TiSa 135 THz

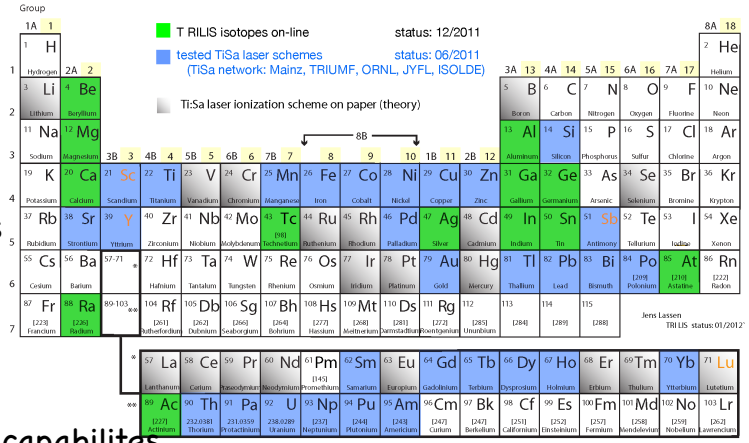
Spatial beam quality $M^2 < 1.2$

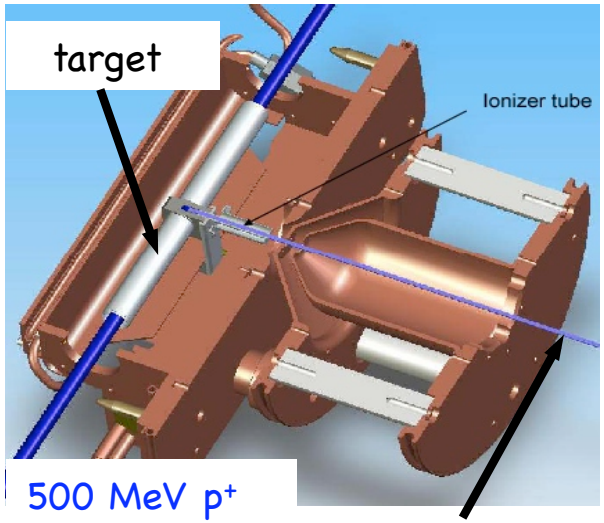
Spectral bandwidth 3–5 GHz

Temporal pulse duration 30–50 ns



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





Operational:

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

(2009) full off-line beam development capabilites

(2010) NSERC funded "in-source laser spectroscopy program"

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

Development:

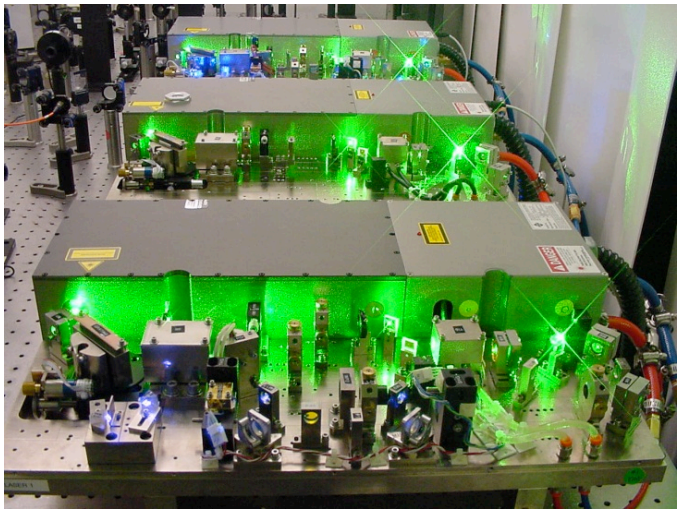
(2012-14) enhanced beam purity via (i) RFQ-LIS, (ii) pulse structure

(2012-2015) continued laser development

- in-source laser spectroscopy
- development of TiSa RILIS schemes

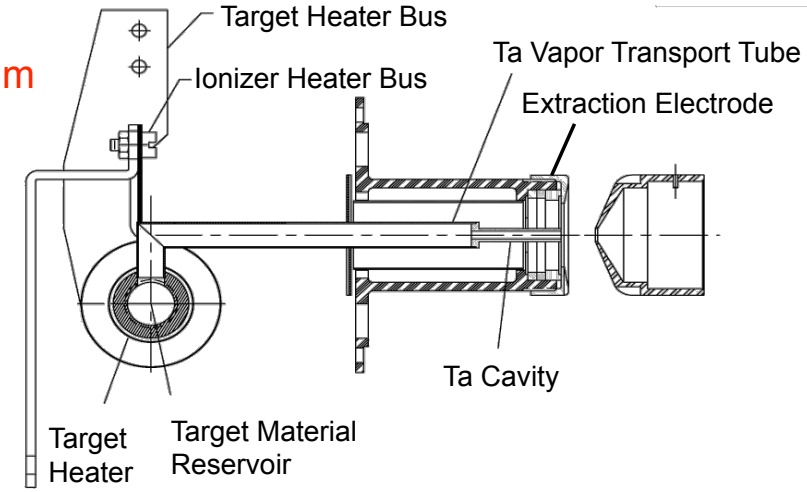
Hot-Cavity Laser Ion Source at HRIBF-ORNL

Ti:Sapphire Laser System



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

Hot cavity ionizer



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

- Ionization schemes for 14 elements obtained in off-line studies

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

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

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

Current Status of HRIBF-ORNL

- Ionization schemes for 14 elements obtained in off-line studies

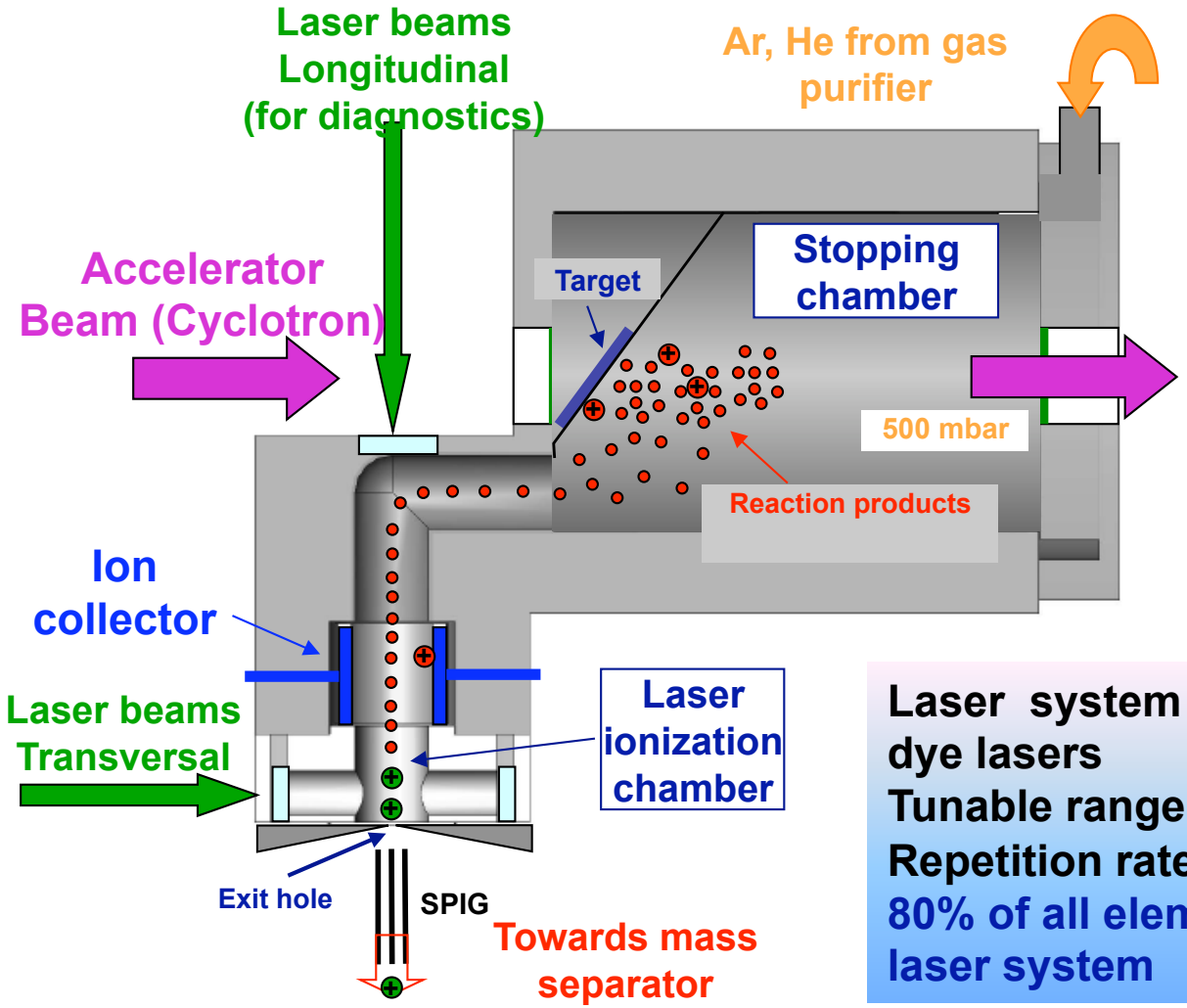
  Sn, Ni, Ge, Cu, Co, Ga, Sr, Mn, Fe, Al, Ho, Tb, Dy, Te

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

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

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

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



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

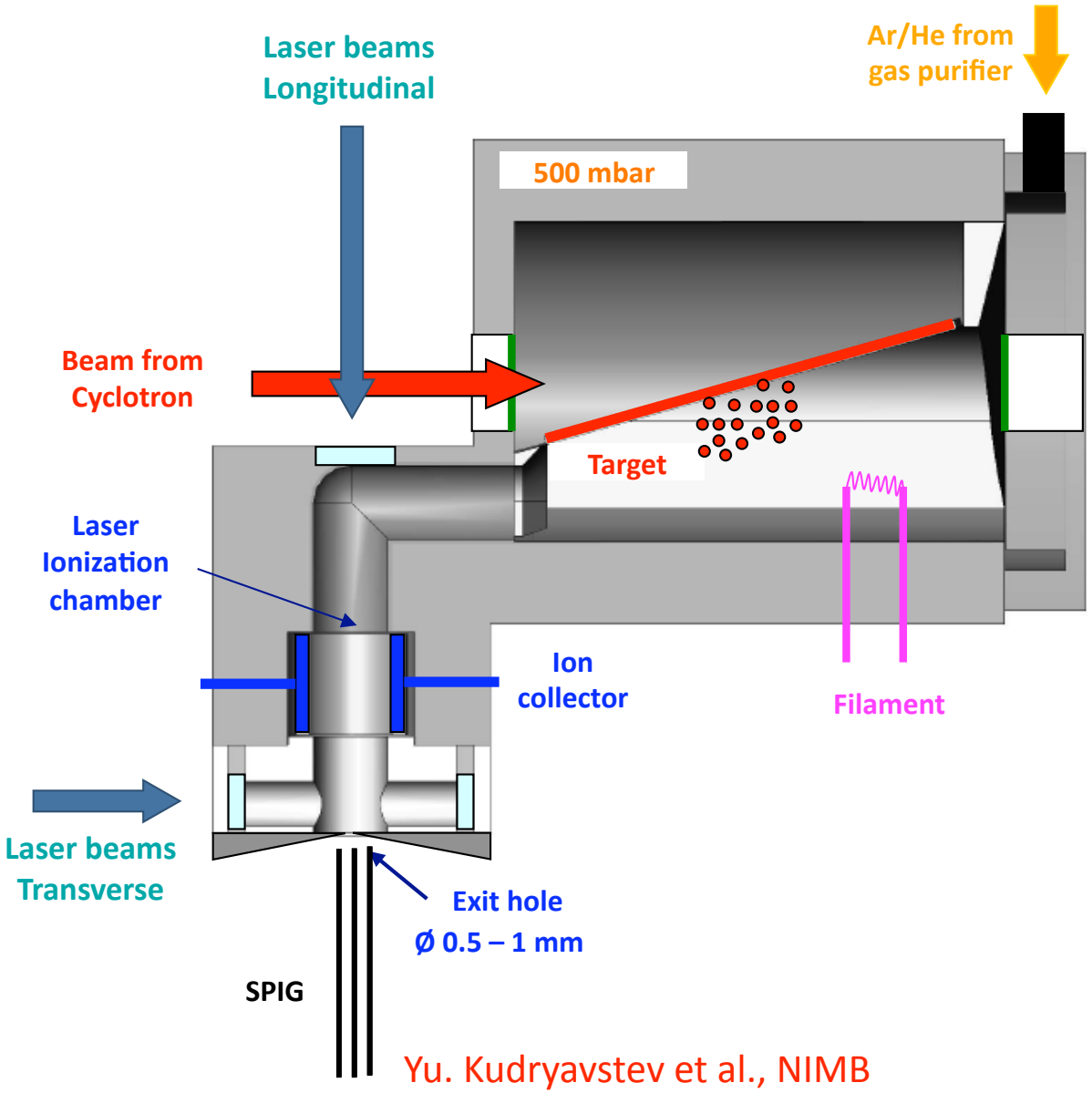
Laser system consists of two excimer-pumped dye lasers
Tunable range: 205 - 900 nm
Repetition rate: 200 Hz
80% of all elements can be ionized using LISOL laser system

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

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

The dual-chamber laser ion guide

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



Yu. Kudryavstev et al., NIMB

By separating stopping and laser ionization volumes

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

Selectivity (^{94}Rh):

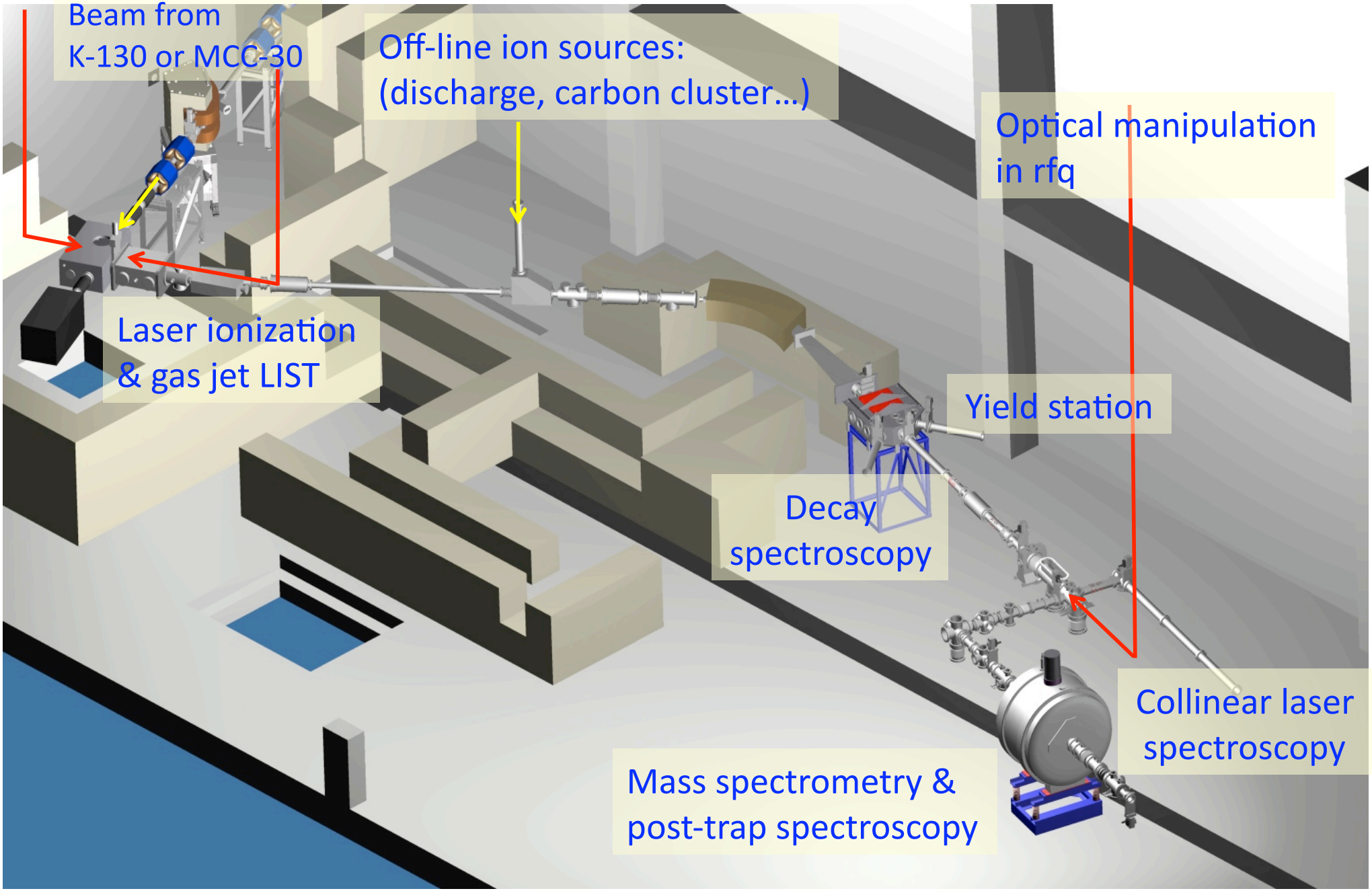
Laser(ON)/Laser(OFF)

Ion Collector OFF = 450

Ion Collector ON = 2200

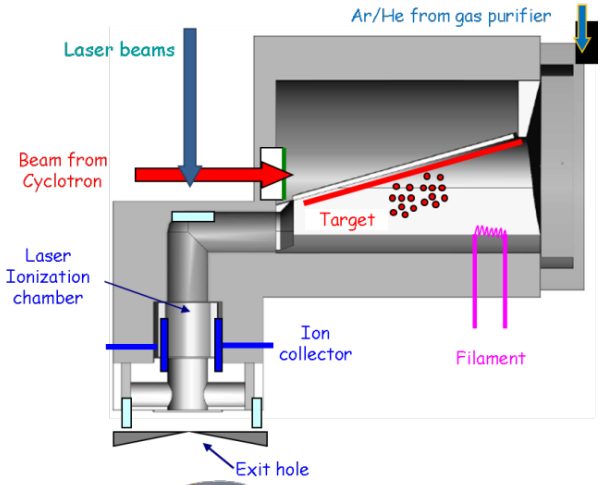
IGISOL-4: overview of facility in 2012

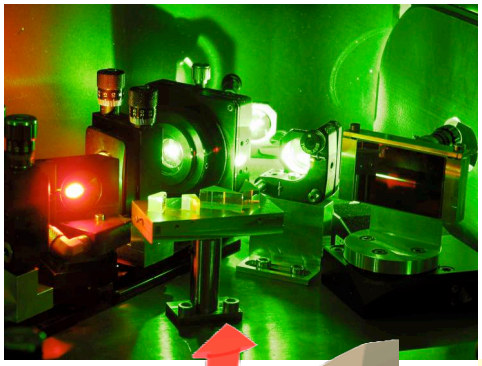
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

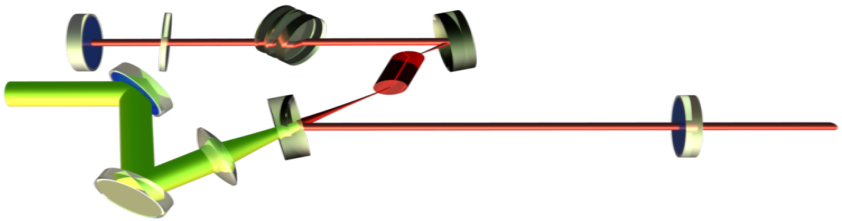


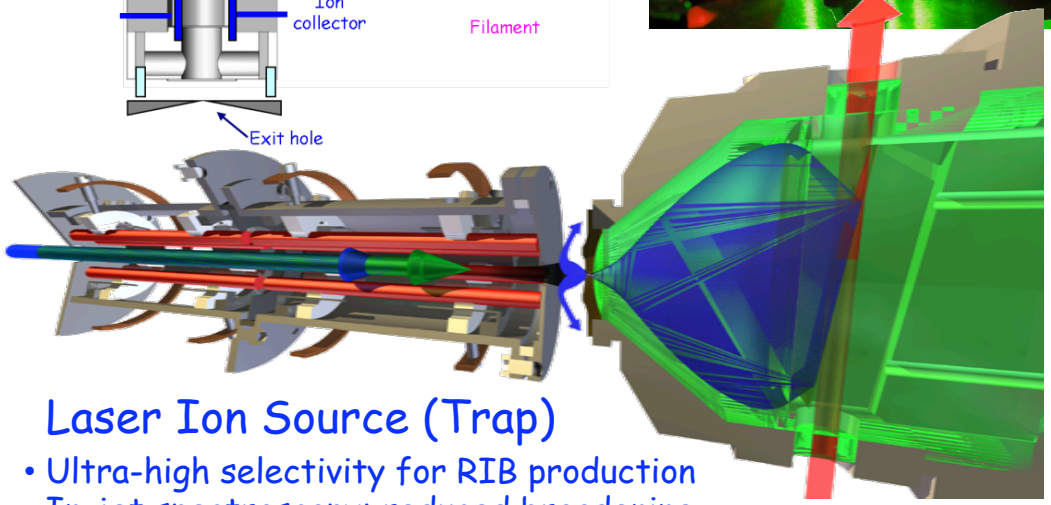
Fast Universal Resonant laser IOn Source (FURIOS) @IGISOL-4, JYFL.

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ









Laser Ion Source (Trap)

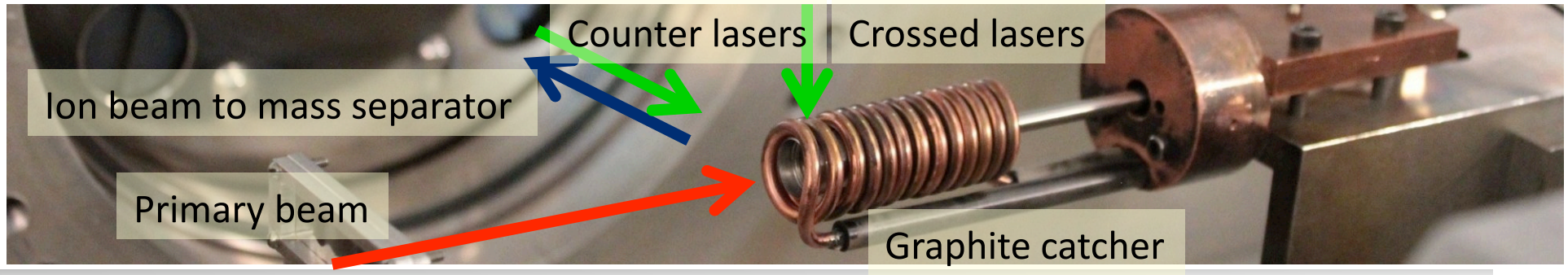
- Ultra-high selectivity for RIB production
- In-jet spectroscopy: reduced broadening

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

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

RF hot cavity

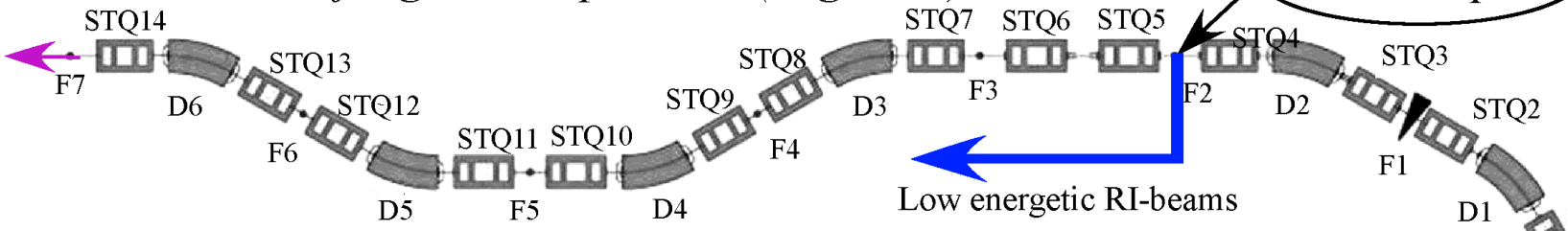
- Developments towards ^{94m}Ag (21^+)



JYFL

PArasitic Laser Ion-Source (PALIS) at SLOWRI RIKEN

RIKEN fragment separator (BigRIPS)



RIKEN NiSHiNA CENTER

Preliminary image

MAIN RI-Beam (~250MeV/u)

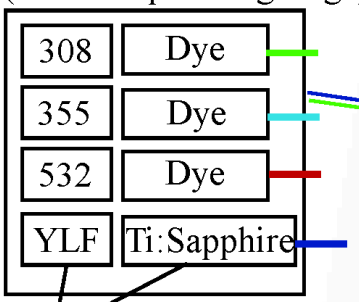
Unused RI-Beams

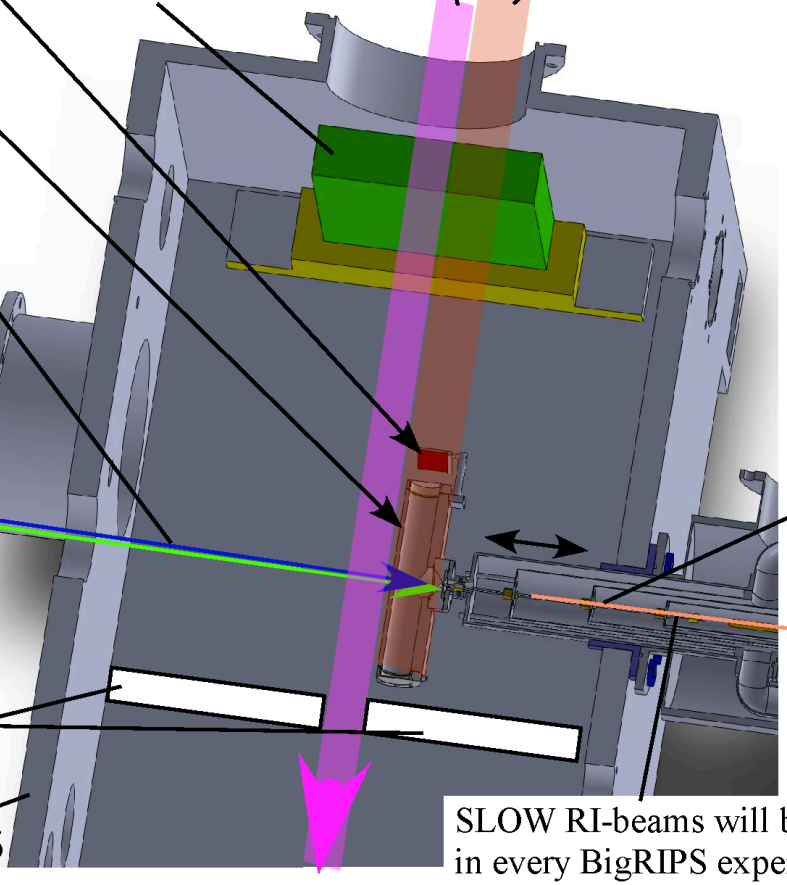
Degrader

F2 PPAC

Gas catcher cell
Argon/Helium 1atm

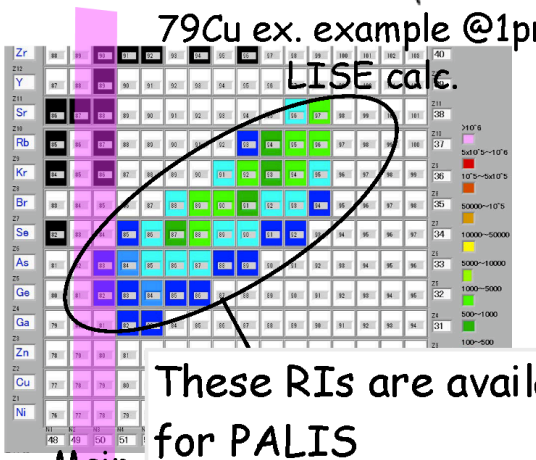
Ionization lasers





79Cu ex. example @1pnA U

LISE calc.



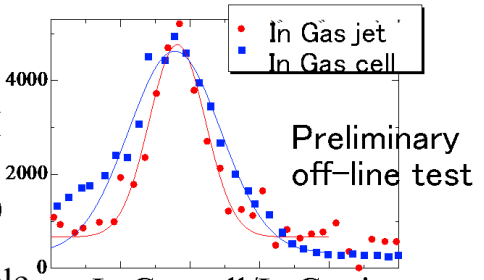
Main

These RIs are available for PALIS

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

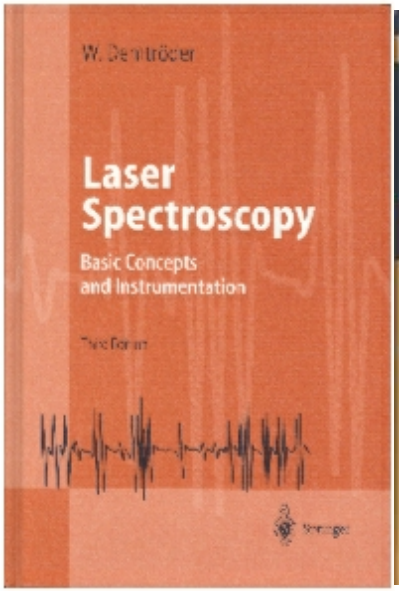
SLOWRI beams (~30keV)

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

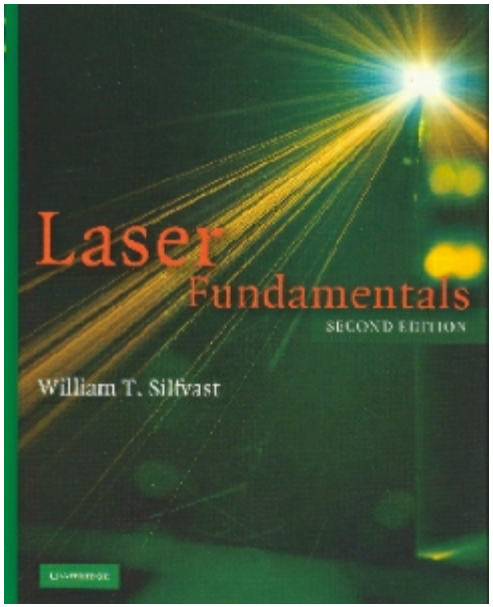


In Gas cell/In Gas jet
Laser Spectroscopy

Recommended reading for further information

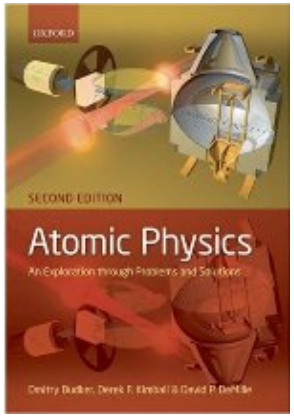


W. Demtröder, Laser Spectroscopy , 3rd Edition (Springer-Verlag, Berlin, 2003).



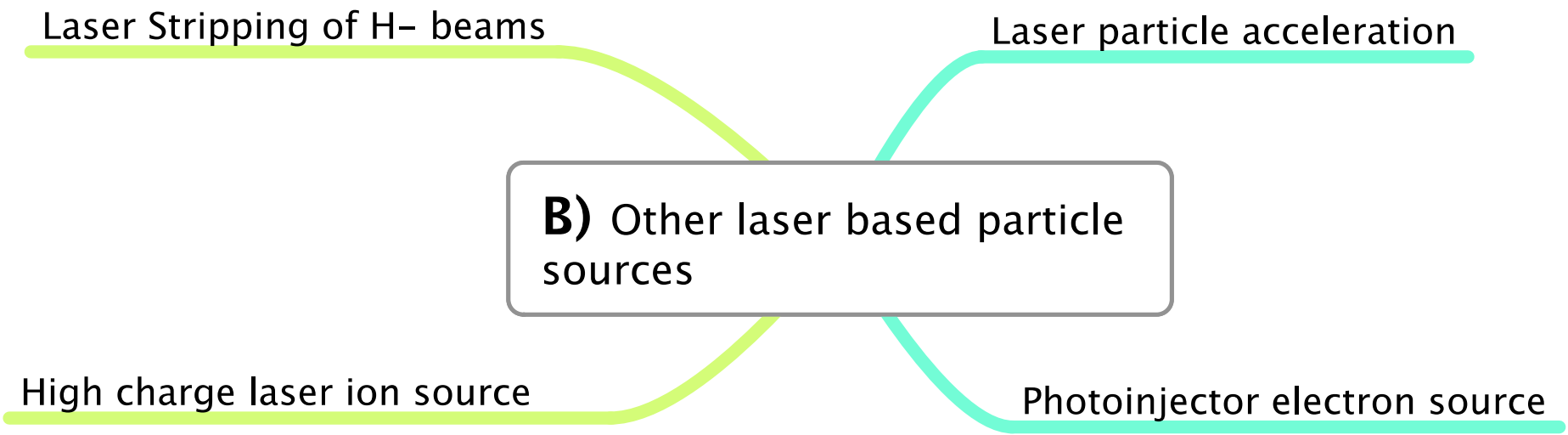
W. T. Silfvast, Laser Fundamentals, 2nd Ed. (Cambridge University, Cambridge, 2003).

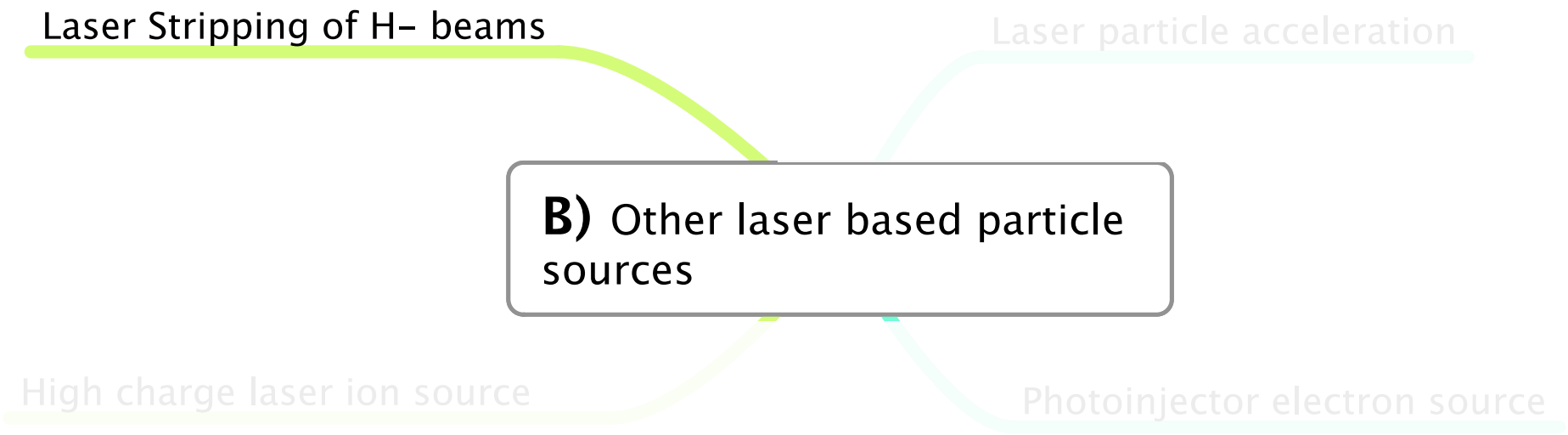
Atomic Physics. Exploration through Problems and Solutions. D. Budker, D. F. Kimball, and D. P. DeMille



Laser photoionization spectroscopy
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


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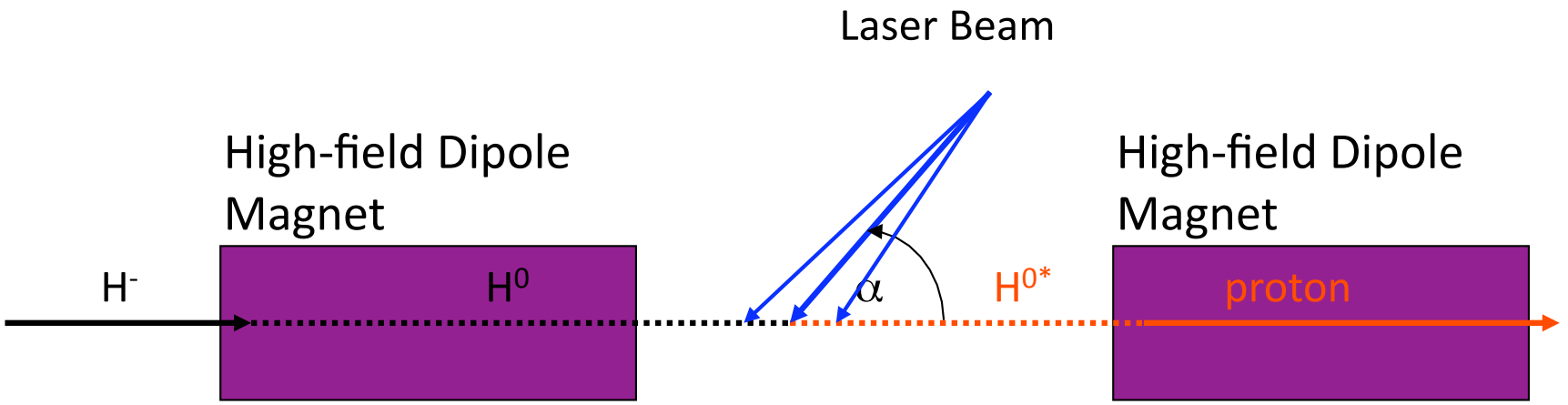
Three-Step Stripping Scheme

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



Step 1: Lorentz Stripping

$H^- \rightarrow H^0 + e^-$

Step 2: Laser Excitation

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

Step 3: Lorentz Stripping

$H^{0*} \rightarrow p + e^-$

Laser stripping (for PS2)

Summary of the workshop at SNS, 18th/19th Feb. 09

W. Bartmann, B. Goddard

PS2 Meeting, 12th March 09

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

Summary of the PS2-specific issues (1)

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

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

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

- Dispersion angle tailoring seems impossible for PS2 due to resulting emittance blowup from mismatch.

Summary of the PS2-specific issues (2)

- Excitation of the n=3 state gives 8 degrees incidence angle → difficult geometry

  N=2 has much easier geometry with 47 degrees but large angular spread due to the long stripping lengths

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

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

Characteristics relevant for the laser system

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

Includes factor 3 margin in laser power

WS outputs: laser possibilities

- KEK (Yamane):
  - Laser-H- IP is brought into B-field
    → compensation of Doppler broadening by broadening of Stark-states in the magnetic field
    → single laser frequency can excite full distribution
    → no spontaneous decay worries (direct stripping of excited H^0)
- Continuum (Laha):
  - "Stitching" ~10 laser together to reach 1 ms macropulse

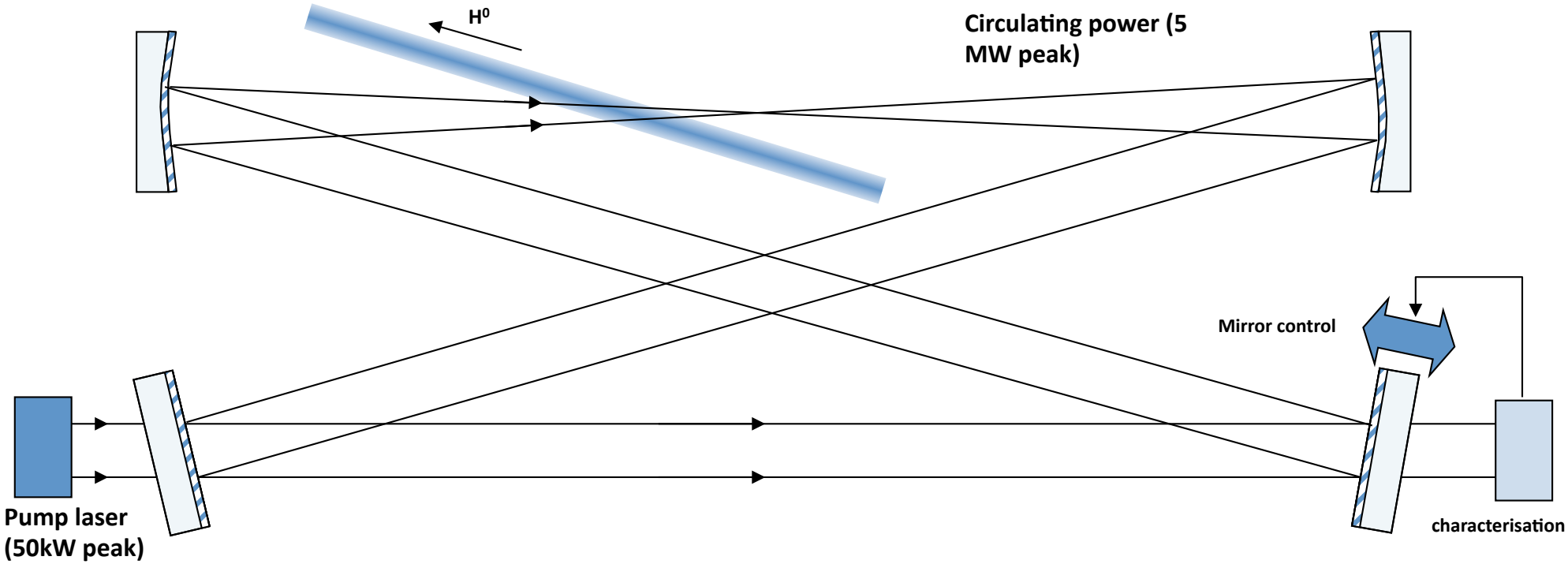
    →issues: synchronisation, overlap, cost, complexity, reliability
- LBNL (Wilcox):
  - Commercial components, where mode locked, diode pumped Nd:YAG laser with 1064 nm is used to create a 1.2ms burst with 352 MHz micro-bunch frequency
  - Amplification stages are pumped continuously for 1.2 ms, laser operating in saturation
  - The peak laser output power is 10 kW for a micro pulse of 50 ps, the average power 200 W.
  - Four mirror cavity (indepent control of focus and cavity length) with a conservative build up factor of 100 is assumed, to give 1 MW circulating peak power (compare to the ~4 MW quoted for PS2, which includes a factor 3 margin)

    →issues: coupling to the cavity, radiation hardness of optical elements, thermal perturbation

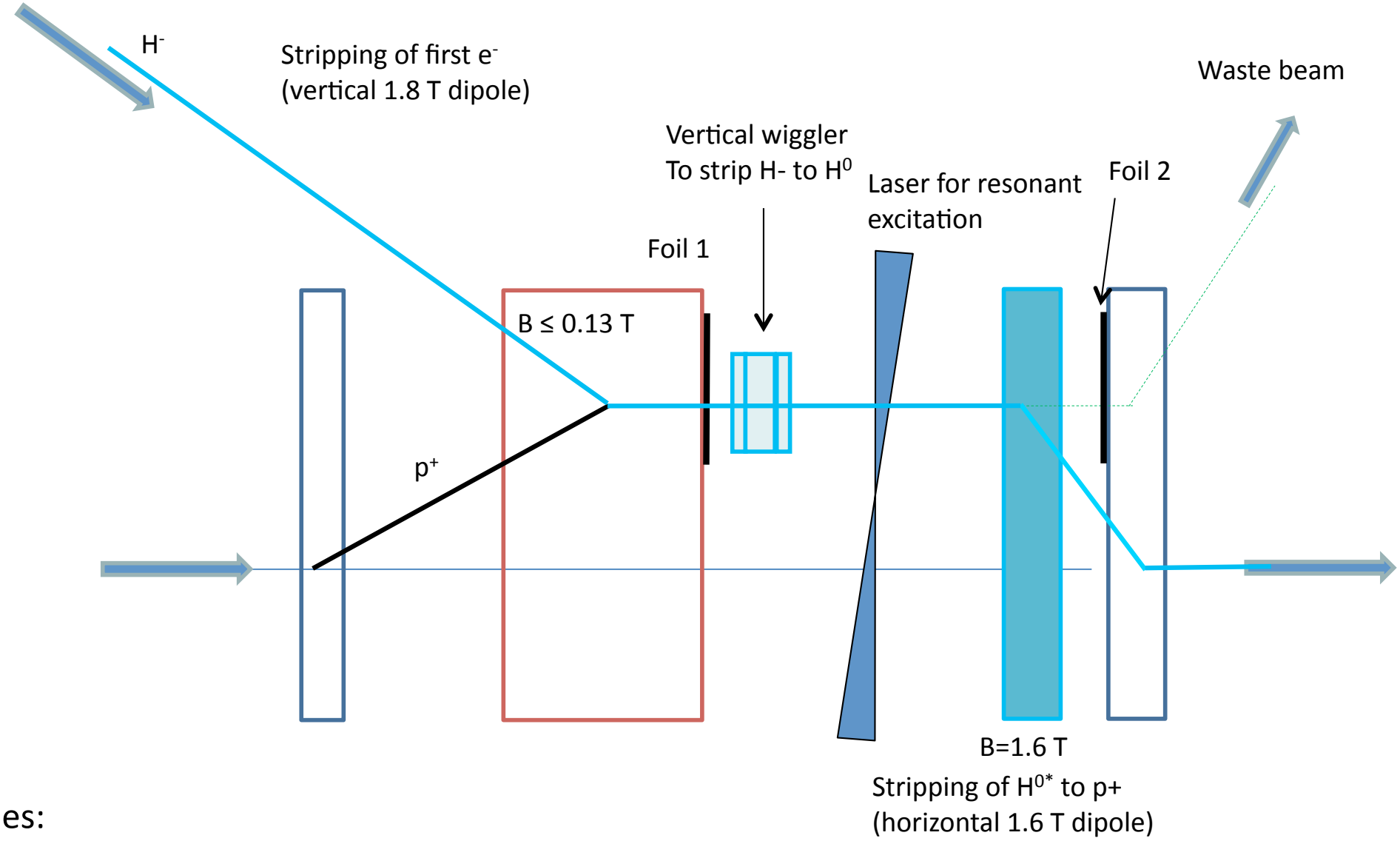
    → proposed system could meet requ. of CERN and FNAL, not SNS

Laser / photon recycling issues

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



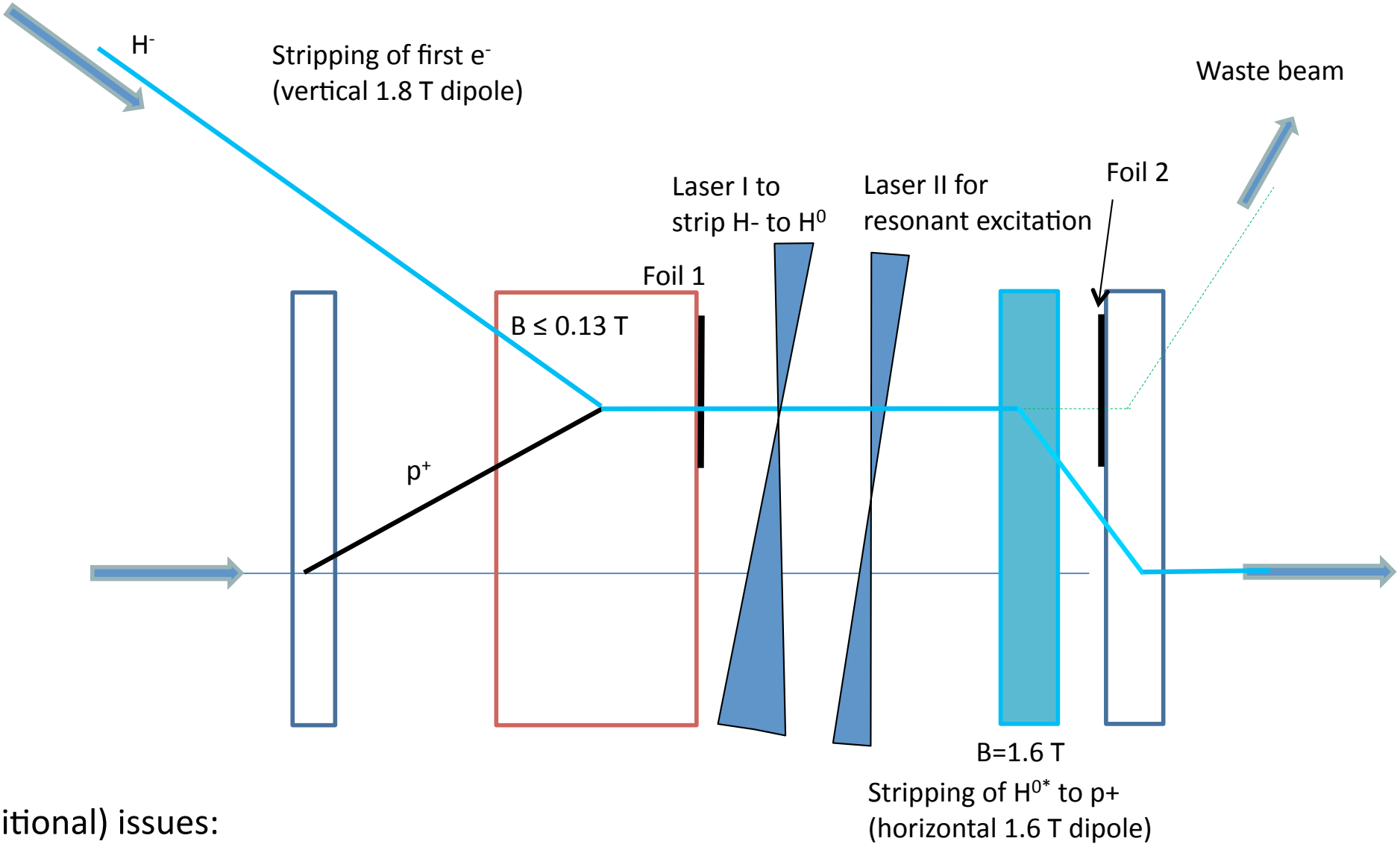
Laser-assisted stripping schemes I: magnet-laser-magnet



Issues:

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

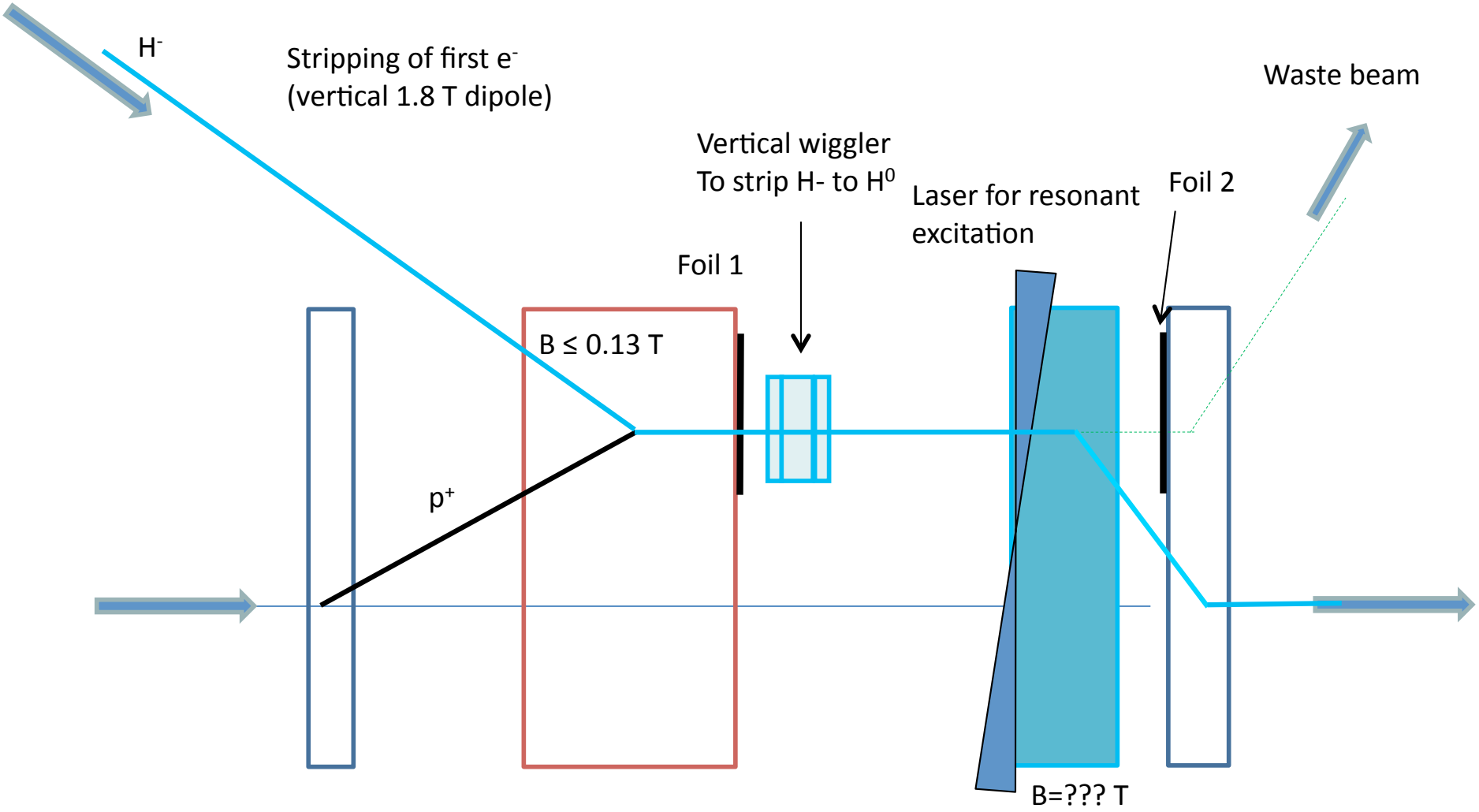
Laser-assisted stripping schemes II: laser-laser-magnet



(additional) issues:

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

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

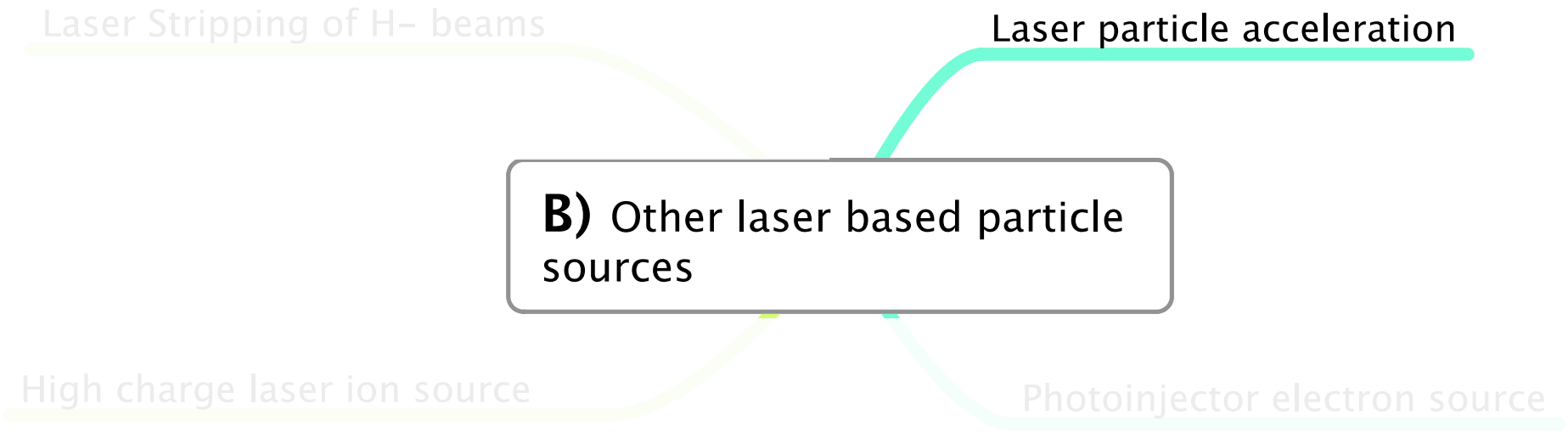


(additional) issues:

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

Conclusions

- For PS2 the possibility of laser stripping remains interesting
- High beam energy gives a variety of resonance schemes to be envisaged with optimization of laser parameters and injection geometry
- Three alternative basic schemes need further investigation and quantification
  - Magnet → laser → magnet
  - Laser → laser →magnet
  - Magnet → laser+magnet
- The workshop was extremely useful technically, in addition links were formed / strengthened with the accelerator labs, laser labs and laser industry experts; technical collaborations and common areas of work were defined
- The action plan needs follow-up (to be done by J. Galambos) and a synthesis of the outcomes and progress should be made at some time in the future
- Will arrange a first follow-up meeting with those present at PAC (SNS, FNAL, CERN)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"Options for the next-generation collider with different levels of risk and different costs:
ILC: most developed, lowest risk but high cost
High gradient klystron: medium risk with significant cost savings
Drive-beam microwave: higher risk with probably greater savings
Dielectric or Plasma acceleration: much higher risk but with vast cost saving potential"

- Laser capability improving rapidly
  - Billion $ industrial development effort
- Two acceleration approaches using lasers:
  - Laser wakefield (plasma) acceleration, i.e BELLA (10 GV/m)
  - Direct laser (dielectric) acceleration, i.e. E-163 (1 GV/m)
- Real challenges for both approaches
- Very different laser requirements
  - Both require high average power → must generate beam power
    - Laser-wakefield acceleration requires high peak laser power
  - Lasers are most efficient and cost effective near CW operation
    - CW operation is best use of expensive amplification medium

  → SLAC is pursuing direct laser acceleration with ~10,000 times lower peak power requirements ⇒ more favorable cost scaling

Laser Stripping of H- beams

Laser particle acceleration

B) Other laser based particle sources

High charge laser ion source

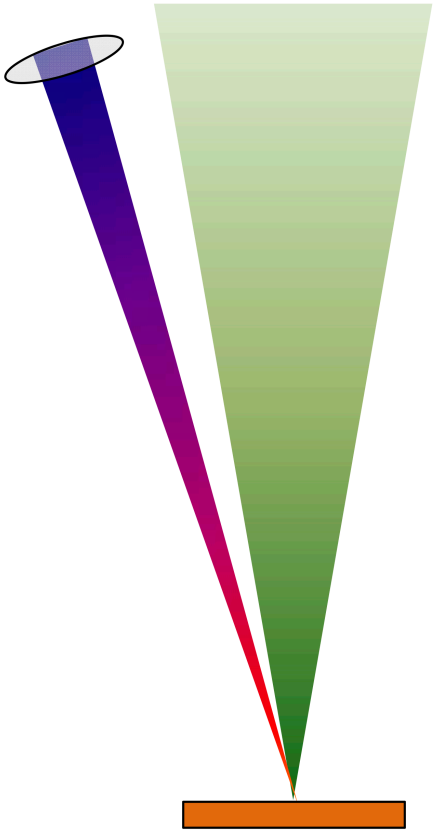
Photoinjector electron source

Laser *Plasma* ion sources

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

$$\lambda = \frac{2\pi c}{e}\sqrt{\frac{m_e \varepsilon_0}{n_e}}$$

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

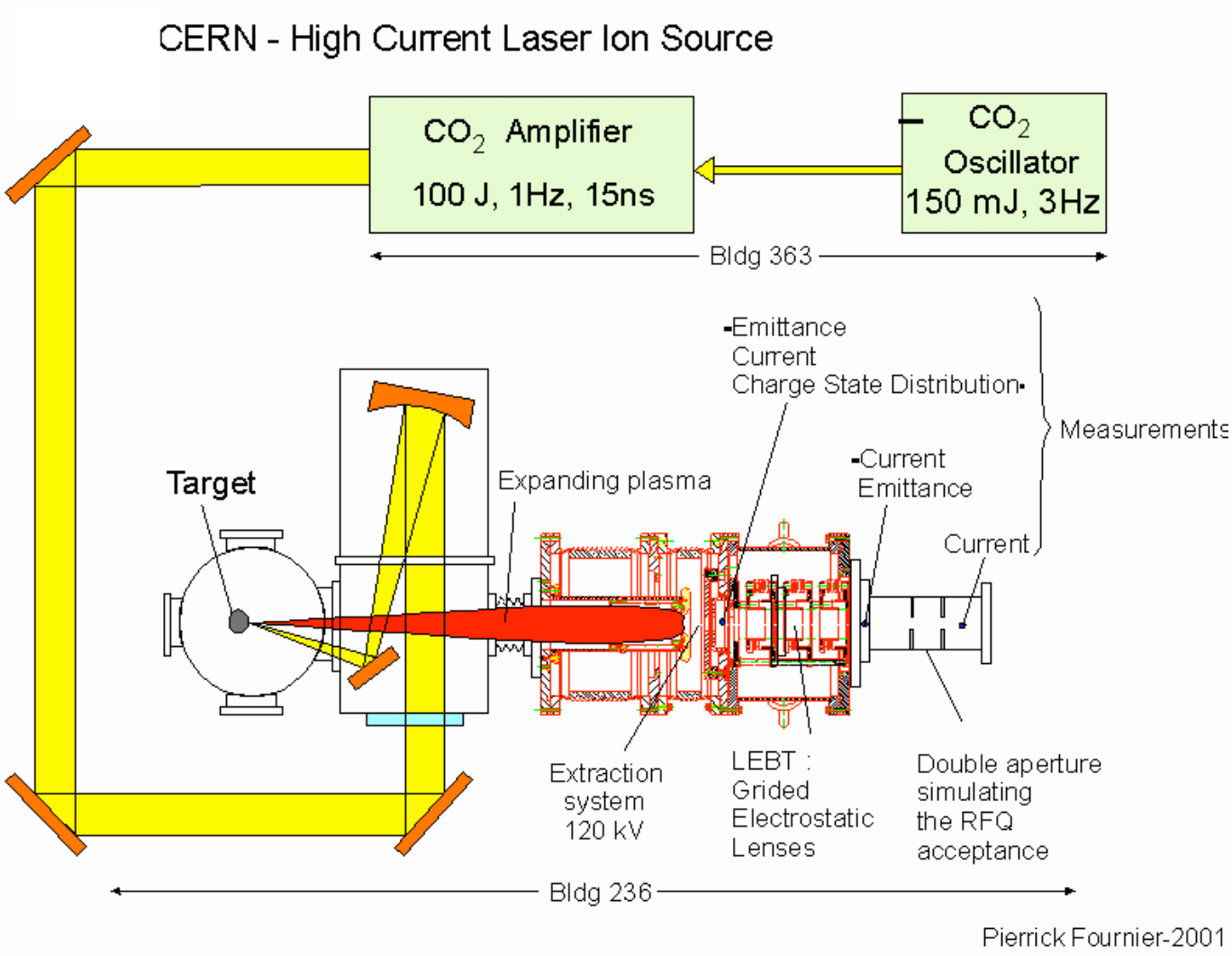


Taken from
R. Scrivens
Ion Source lecture

Laser ion source for the LHC injector chain

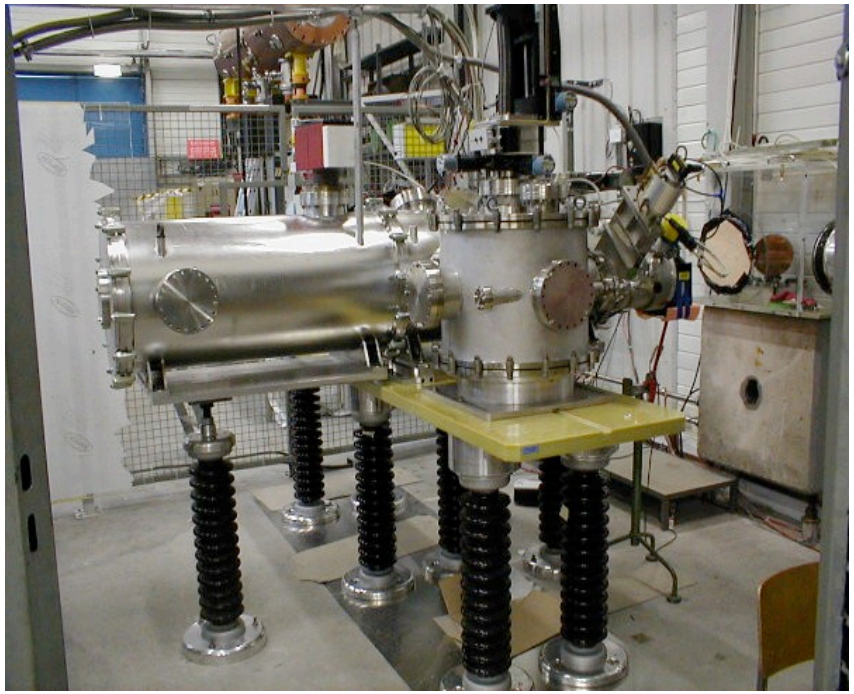
- An alternative and potentially favorable route for producing ions for the LHC
- Abandoned due to reliability concerns of unproven technique

Laser Ion Source (LIS) – an Alternative?



LIS Power Laser and Source

The Russian 100 J, 1 Hz CO_2 Laser Amplifier in building 363 (“Farady Cage”), being commissioned



The prototype Laser Ion Source in building 236 on a HV platform (~100 kV) to decrease space charge

Could we go the LIS Route? It's still R&D!

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

- Current **> 5mA** during ~ 5μs
- Norm. transverse rms emittance ε^*_{rms} **< 0.15 μm**
- Source stable, reliable, small jitter….

Needs other major investments

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

☺ A few millions cheaper than LEIR

☺ Much less exploitation cost compared to LEIR

☹ Laser will (hopefully) work this summer, but then R&D starts!

☹ We cannot afford to go the LEIR **and** LIS routes in parallel

☹ Even if conclusive results by end 2002, **Pb to LHC not before 2009**

☹ Lighter ions: speculations, needs more R&D (e.g. for gaseous elements)

Not enough time to decide!

"Conclusions on Sources and Linac 3"

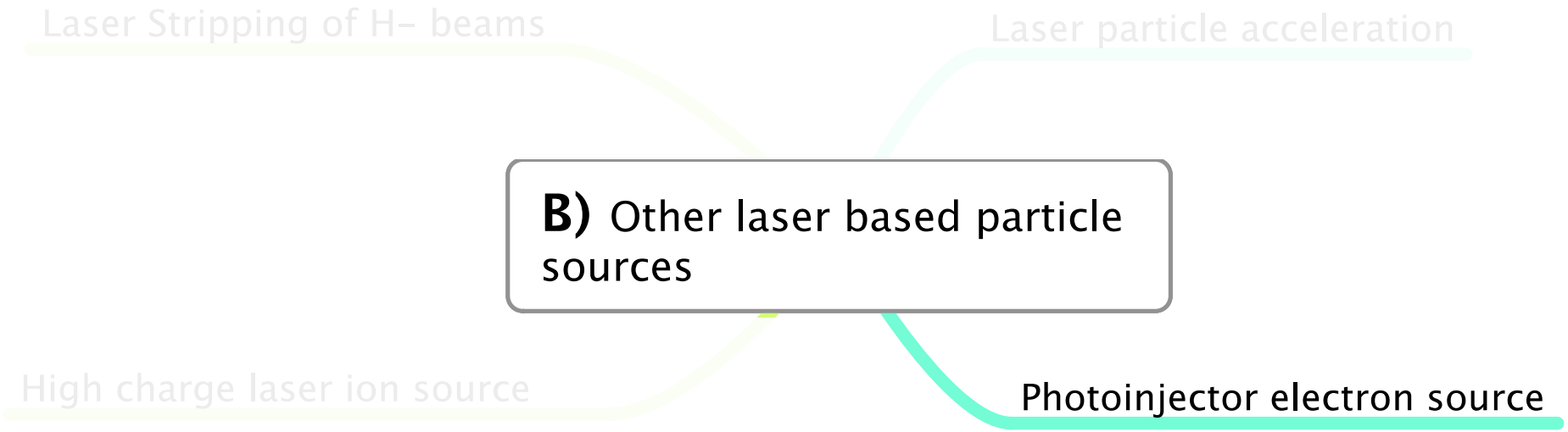
ECR Sources:

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

Laser Ion Source:

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

Conclusion: If we want to have Pb ions ready for LHC in 2008 with a reasonable confidence level, decide NOW for LEIR + (upgraded) ECR source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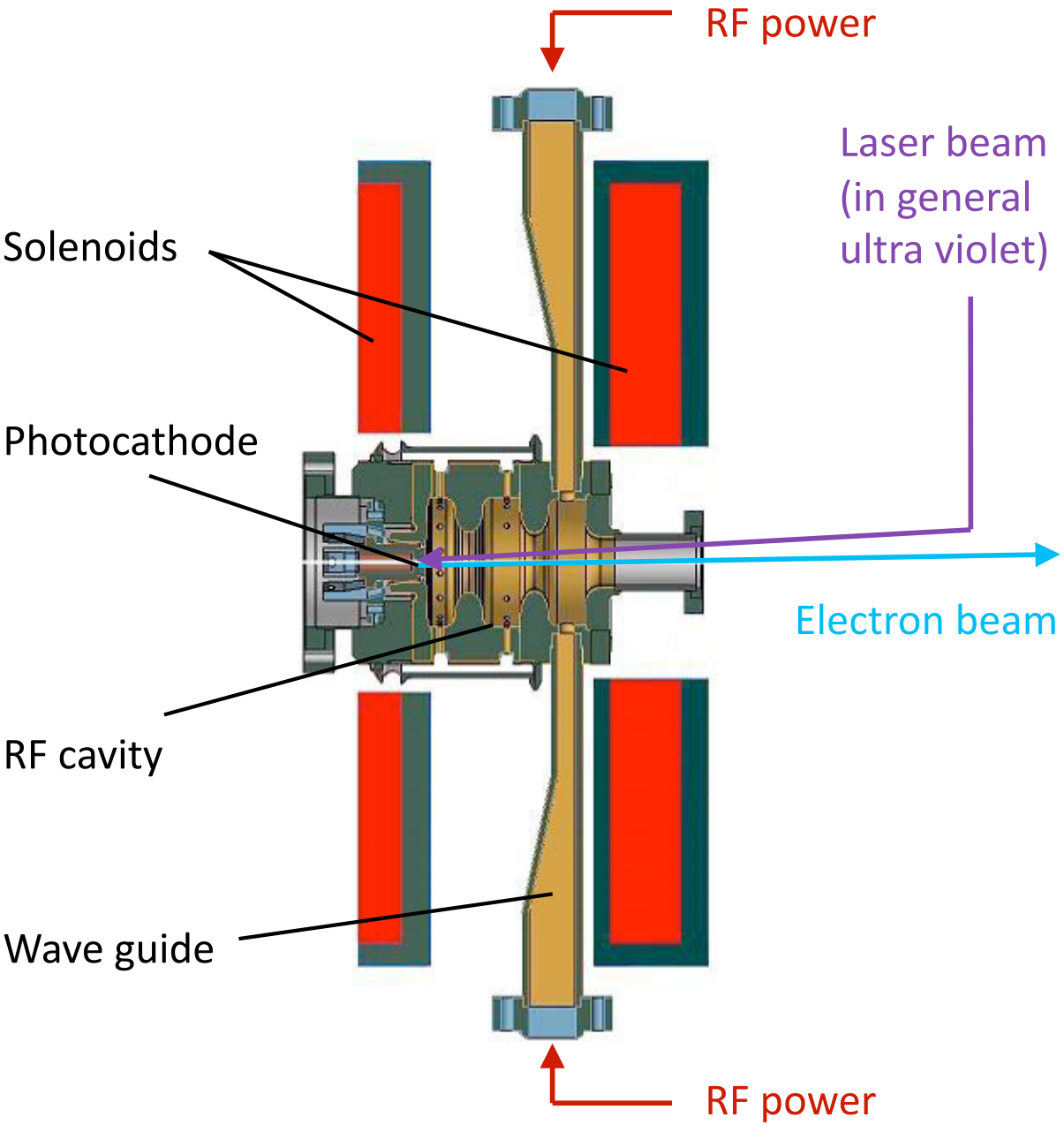
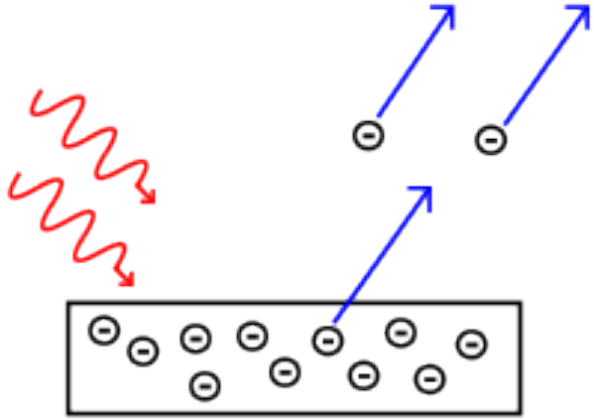
RF Photoinjectors: Operation Principle

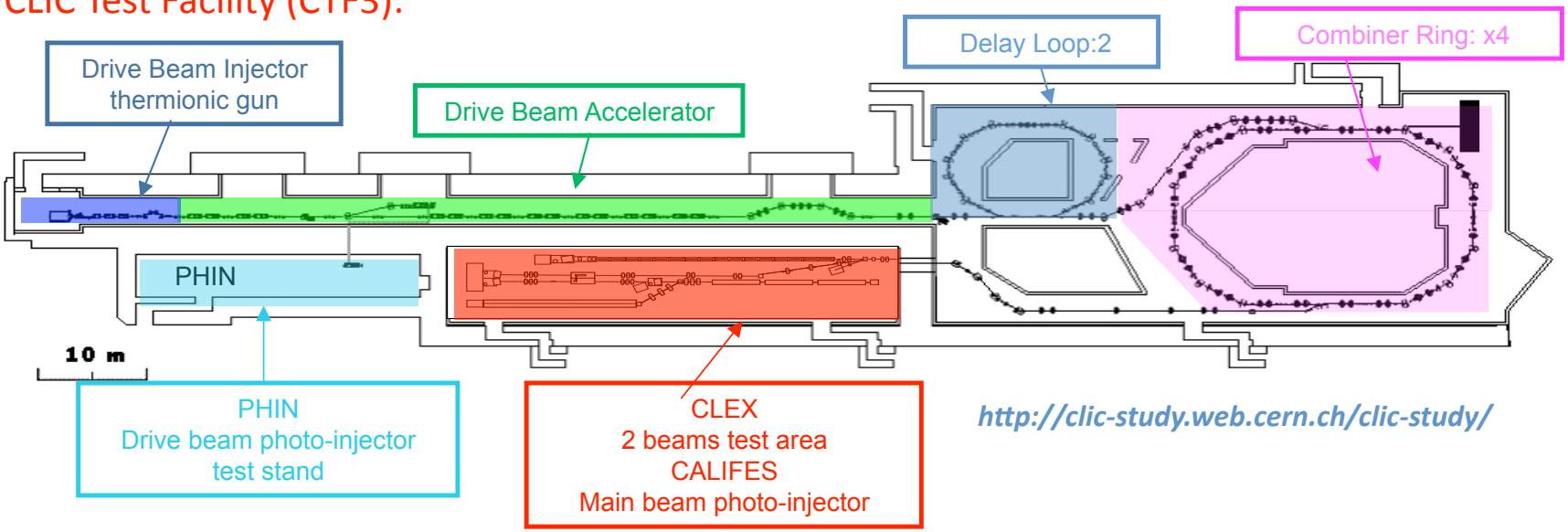




- Production of electrons by photoemission
- Acceleration of electron beam in electric field of microwave cavity
- High field gradients possible
- High bunch charges
- Low emittance
- Short electron bunch lengths

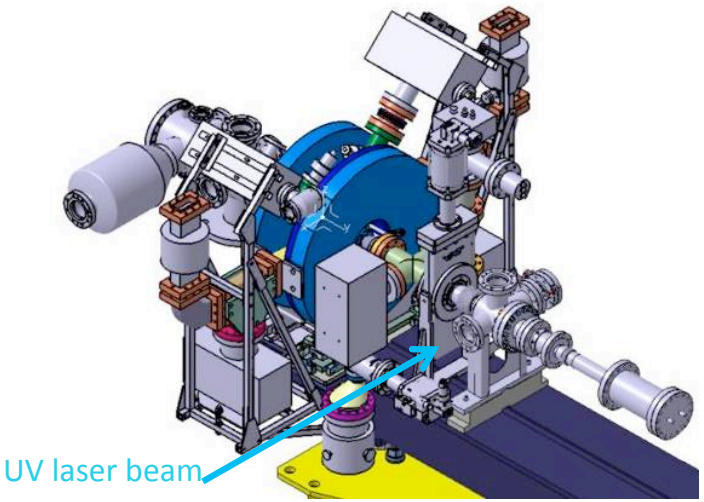
Photoinjectors at CERN

CLIC Test Facility (CTF3):



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

PHIN Photoinjector:

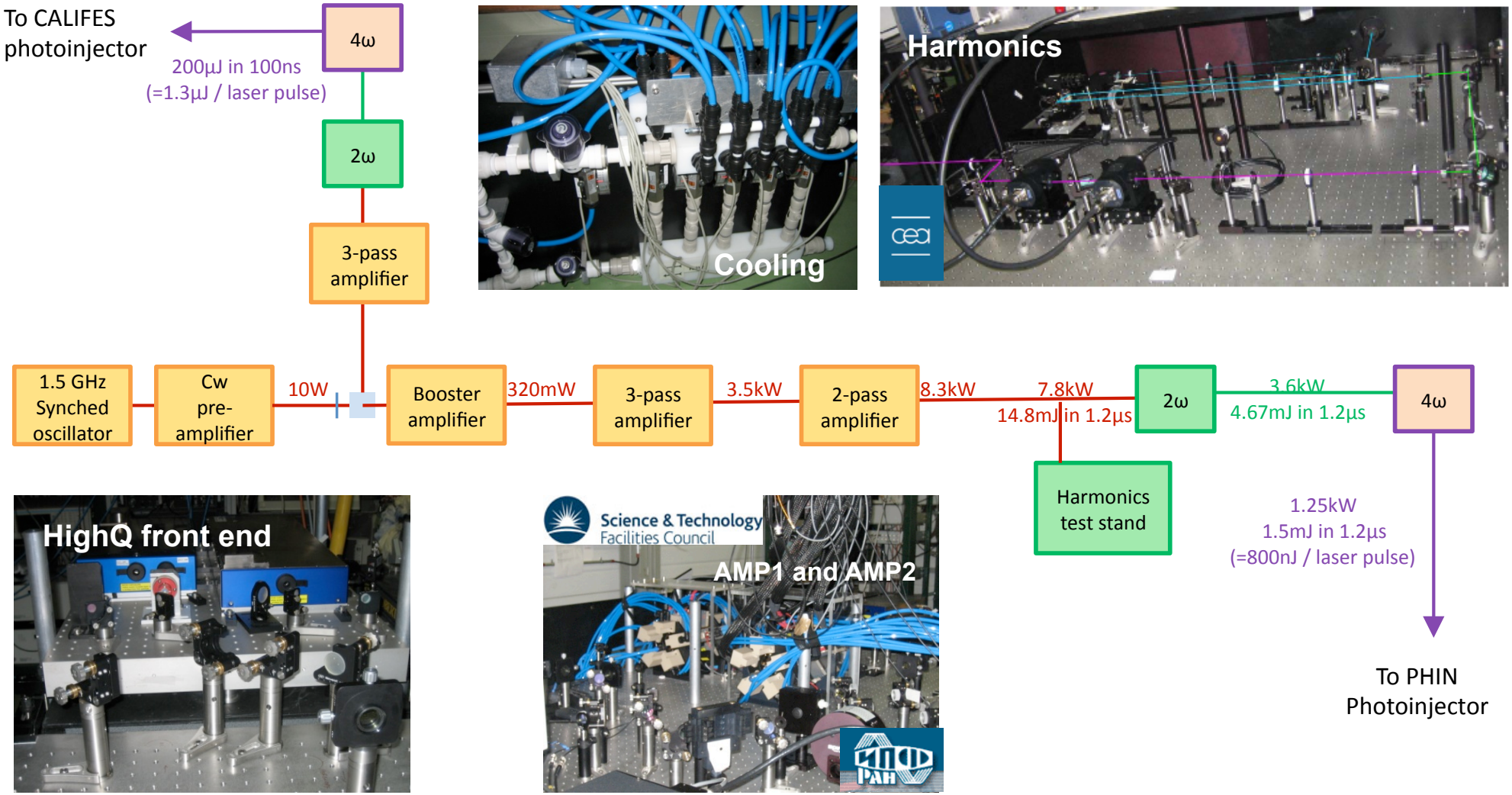


		DRIVE beam	MAIN beam
		PHIN	CALIFES
Electrons	Charge/bunch (nC)	2.3	0.6
	Macro-pulse length (ns)	1200	19.2
	Bunch spacing(ns)	0.666	0.666
	Bunch length (ps)	10	10
	Bunch rep. rate (GHz)	1.5	1.5
	Number of bunches	1802	32
	Macro-pulse rep. rate (Hz)	5	5
	Margin for the laser	1.5	1.5
	Charge stability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

Machine parameters set the requirement for the laser

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

Laser System

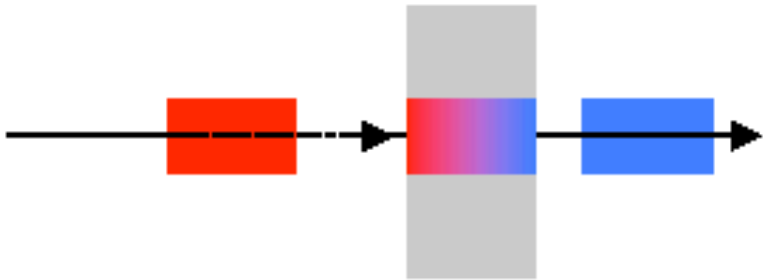


M. Petrarca et al., "Study of the Powerful Nd:YLF Laser Amplifiers for the CTF3 Photoinjectors", IEEE J. Quant. Electr. 47 (2011), p. 306.

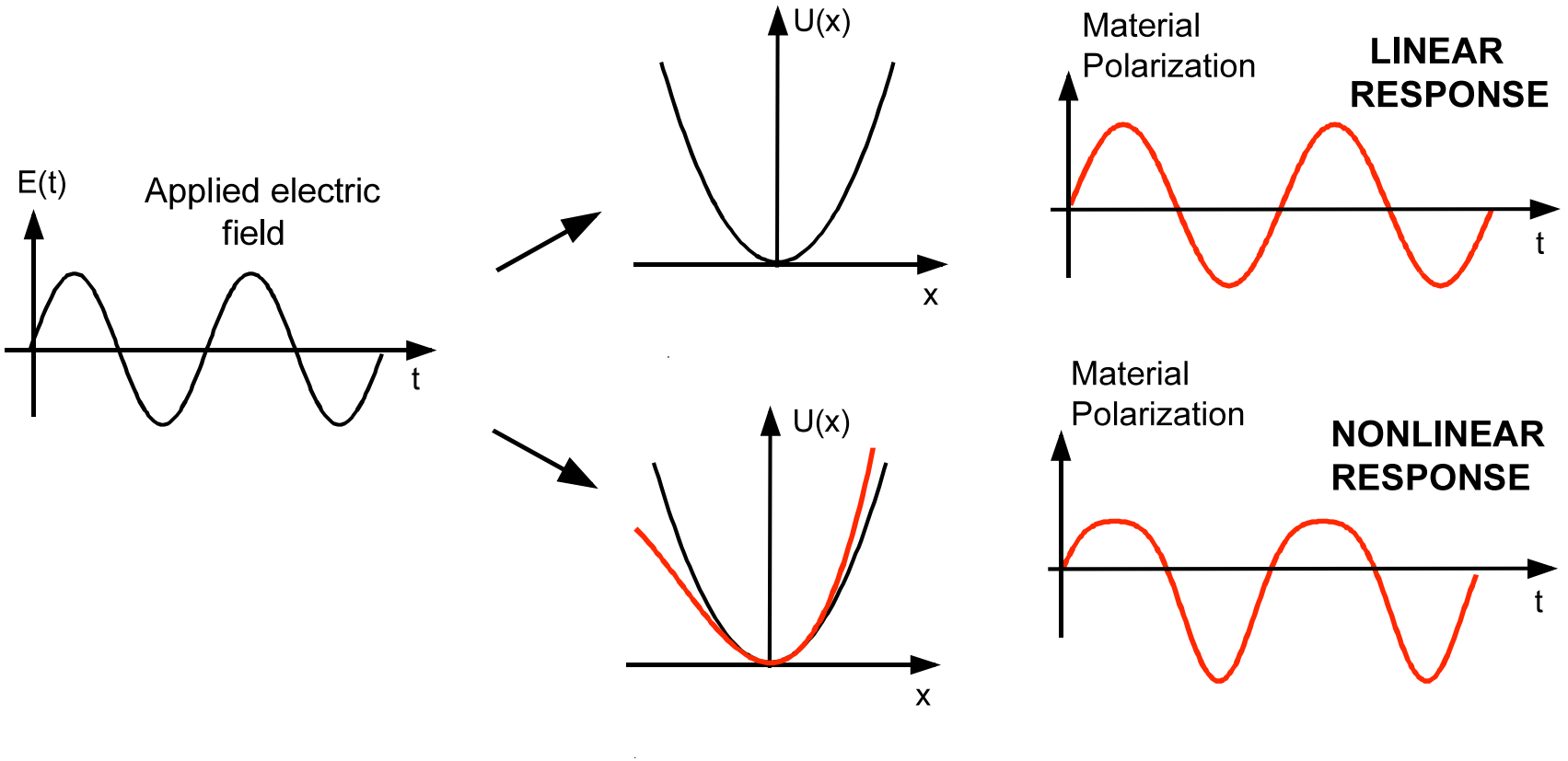
- Most optical phenomena (reflection, refraction,..) are *linear*, i.e. the frequency of light remains unchanged.
  - Note that wavelength may change depending on the refractive index n ($\lambda = \lambda_0/n$) of the material, but the frequency (ν) does not change
  - $c = \lambda \nu = c_0/n$, where $c_0 =$ 299 792 458 m/s (speed of light in vacuum) is a *physical constant*

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

- In *nonlinear optics*: frequency conversion through material nonlinearity. Requires high optical intenstity (large electric field amplitude)



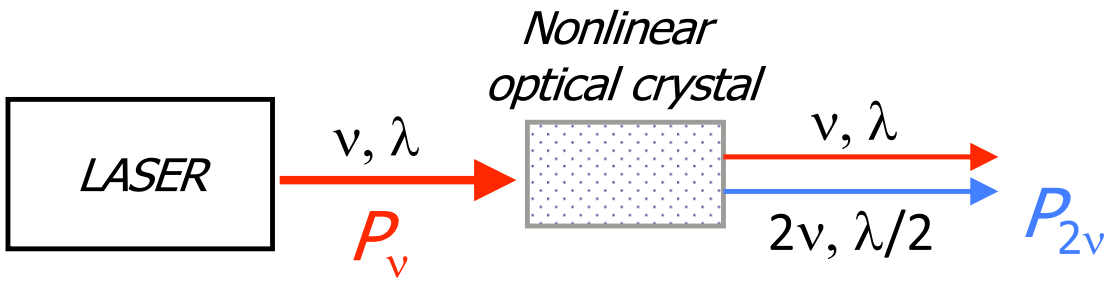
Nonlinear optics



- At high intensity and with a nonlinear material, the emitted wave gets distorted
  → harmonic frequencies are generated

Second harmonic generation

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



- A special case of sum frequency generation (SFG)

  $\nu_3 = \nu_1 + \nu_2$, with $\nu_1 = \nu_2 = \nu$, and $\nu_3 = 2\nu$

- Generated second harmonic power

$$P_{2\nu} \propto d_{eff}^2 P_\nu^2 L h(L)$$

  - d_{eff} = effective nonlinear coefficient of the material
  - P_ν = fundamental power in the crystal
  - L = length of the crystal
  - h = parameter that depends on the focusing of the fundamental beam (also depends on the crystal length L)

Commonly used nonlinear crystals

- $KTiOPO_4$ (KTP) Visible, NIR
- $LiNbO_3$ Visible, NIR, short MIR
- $LiTaO_3$ Visible, NIR, short MIR
- β-BaB_2O_4 (BBO) UV generation
- $ZnGeP_2$ (ZGP) MIR