Laser spectroscopy on nuclear ground states for charge radii and moments. Some new developments

Thanks to: Jon Billowes, Paul Campbell, Iain Moore, H.-J. Kluge

For a review up to 2002, see:
H.-J. Kluge and W. Nörtershauser , Lasers for Nuclear Physics,
Spectrochim. Acta B 58 (2003) 1031

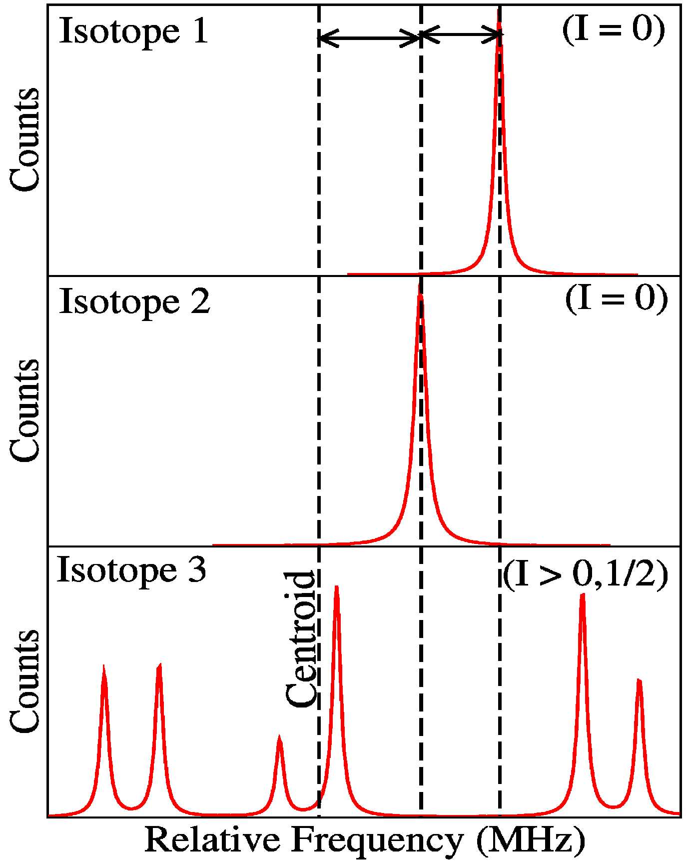
Laser Spectroscopy

The nucleus is not a point charge –
the atomic energy levels are perturbed
by the electric and magnetic fields
at the nucleus (part per million effects)

Investigation of

- Hyperfine structure
- Isotope shifts
- Isomer shifts

provides **model-independent** data…



Optical techniques provide the sensitivity and precision required
to measure these effects.

Isotope Shift (IS)

Mean Square Charge Radii

$$\delta\langle r^2\rangle^{AA'}$$

Hyperfine Structure (HFS)

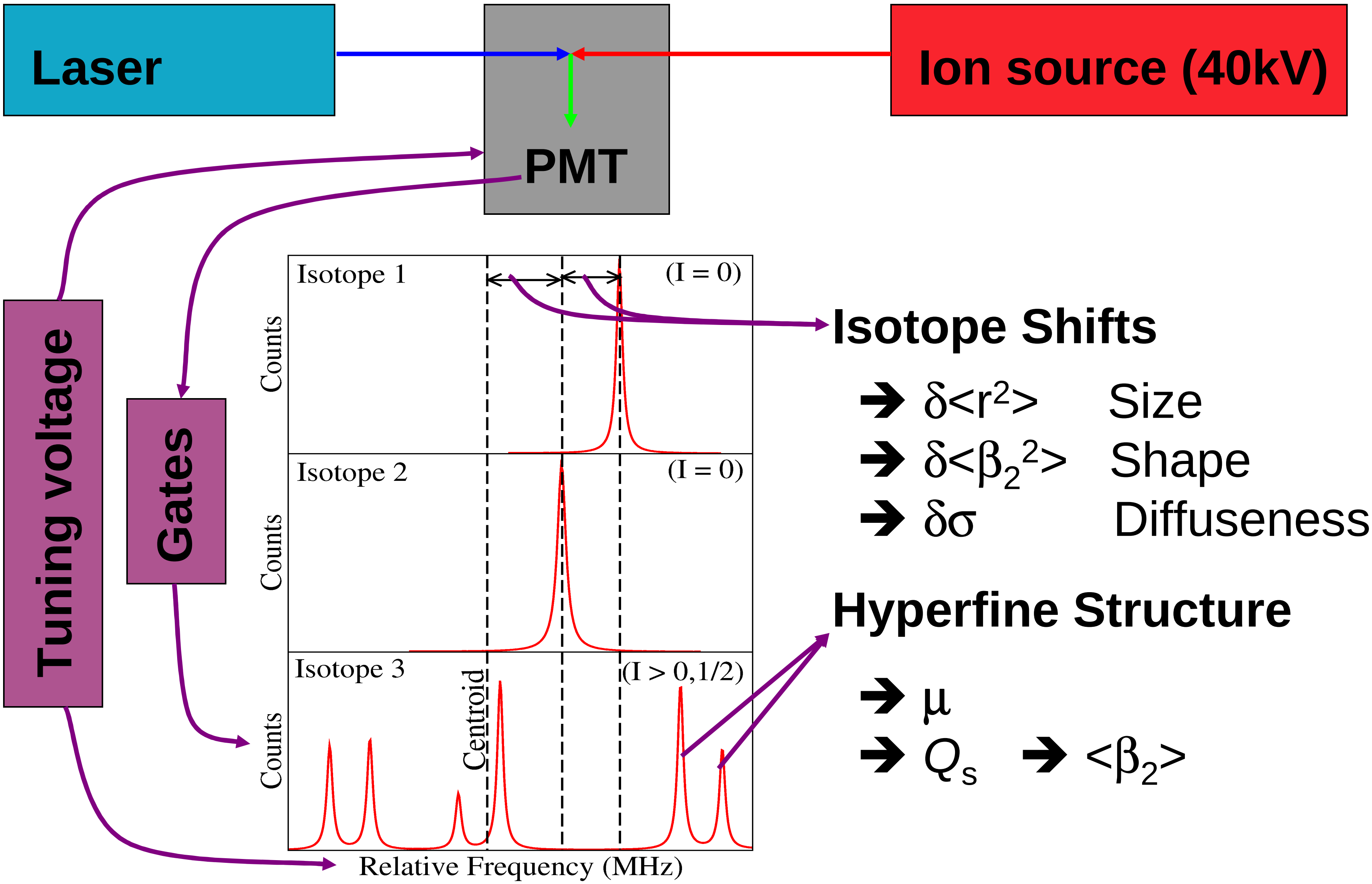
Nuclear Spin I
Magnetic Dipole Moment μ_I
Electric Quadrupole Moment Q_s
Hyperfine Anomaly

Sample preparation is crucial…..
Nuclear reaction products must be slowed and thermalized quickly, efficiently, universally and selectively.

Thermal or discharge ion source + isotope separator

Gas stoppers and beam coolers

Introduction to laser spectroscopy



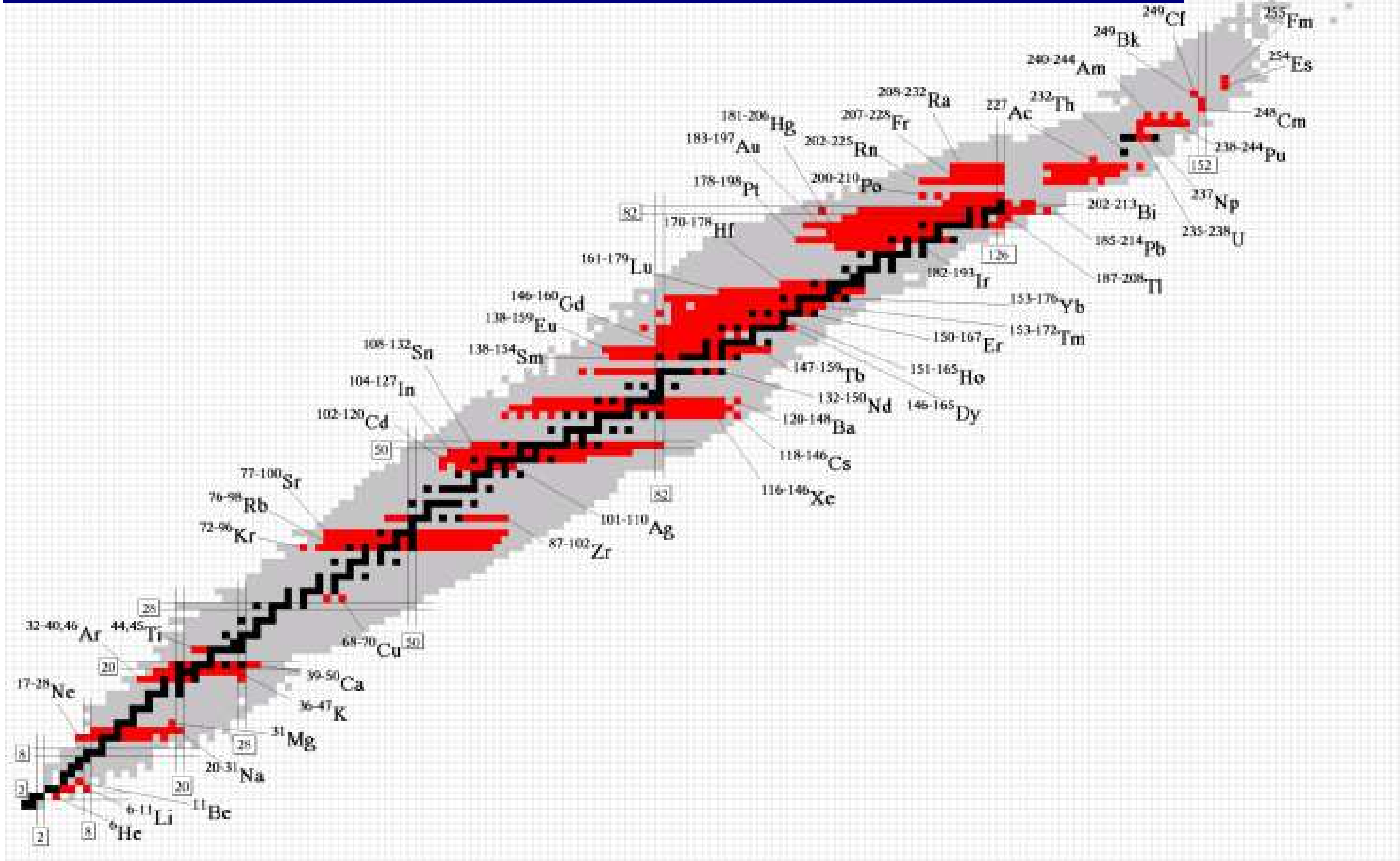
Isotope Shifts

➔ $\delta\langle r^2\rangle$ Size
➔ $\delta\langle\beta_2^2\rangle$ Shape
➔ $\delta\sigma$ Diffuseness

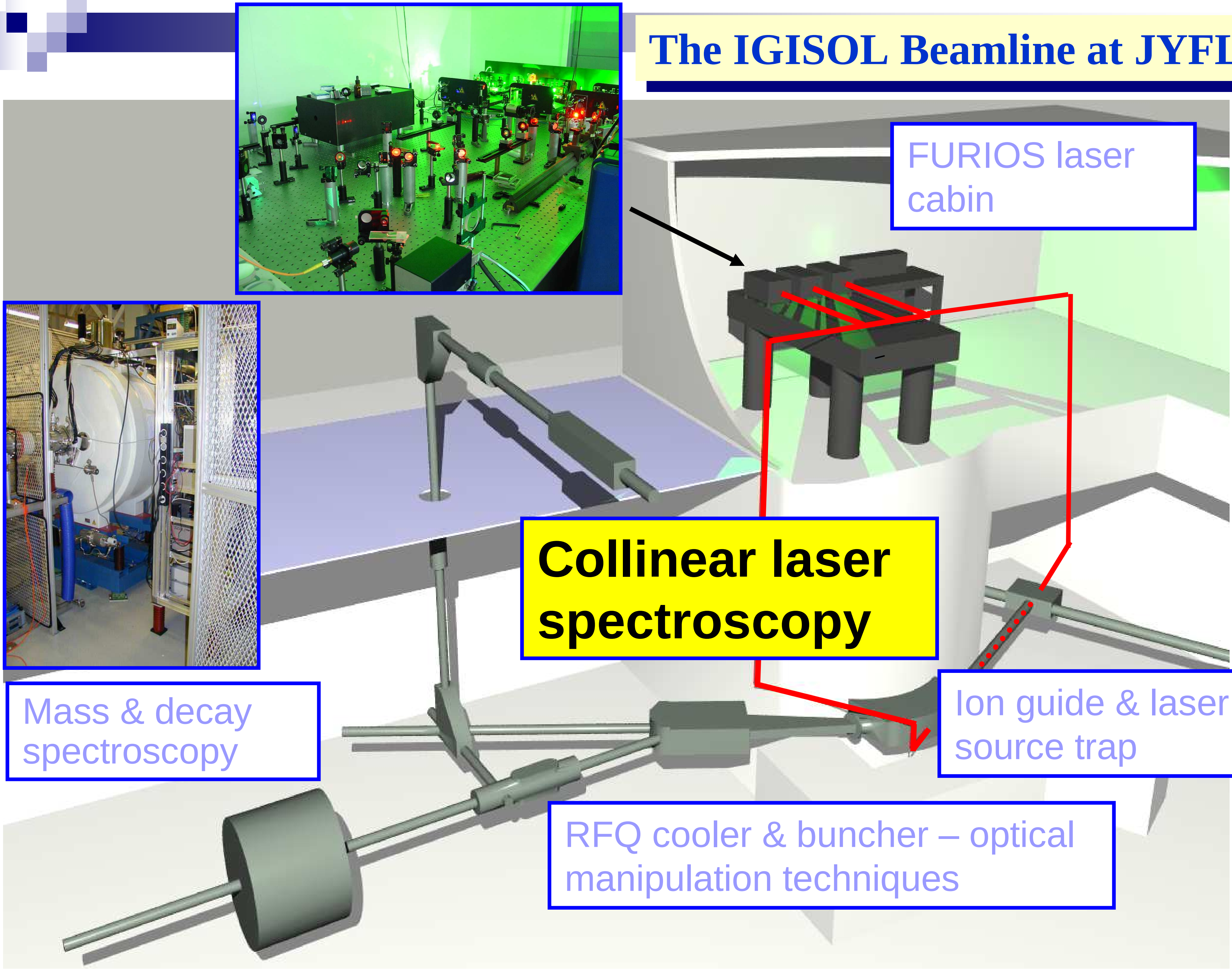
Hyperfine Structure

➔ μ
➔ Q_s ➔ $\langle\beta_2\rangle$

Present status of laser spectroscopy measurements



The IGISOL Beamline at JYFL



FURIOS laser cabin

Collinear laser spectroscopy

Mass & decay spectroscopy

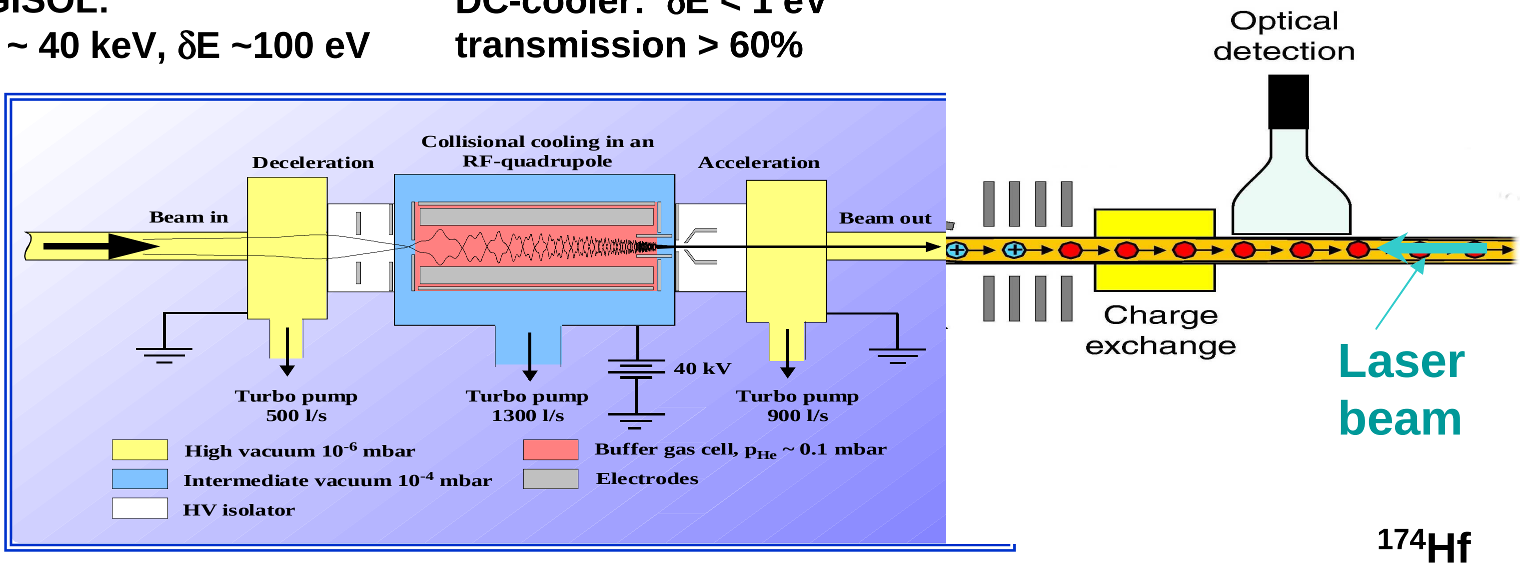
Ion guide & laser ion source trap

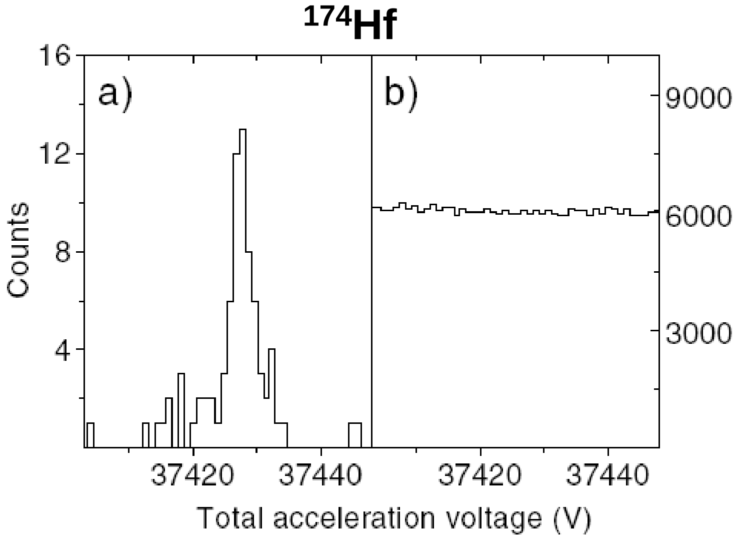
RFQ cooler & buncher – optical manipulation techniques

COLLINEAR LASER SPECTROSCOPY WITH BUNCHING

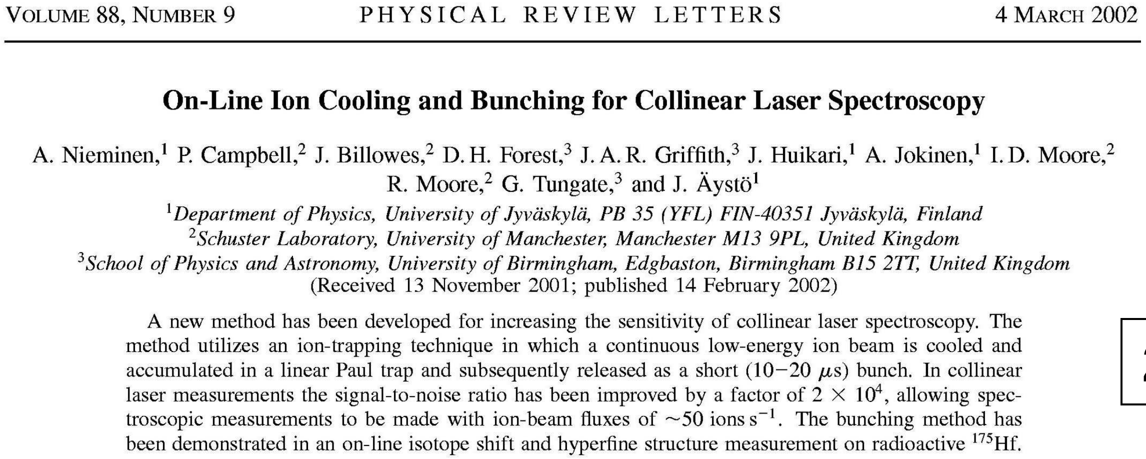
IGISOL:
E ~ 40 keV, δE ~100 eV

DC-cooler: δE < 1 eV
transmission > 60%





Buncher:
Accumulation time 10 ms - 10 s


VOLUME 88, NUMBER 9 PHYSICAL REVIEW LETTERS 4 MARCH 2002

On-Line Ion Cooling and Bunching for Collinear Laser Spectroscopy

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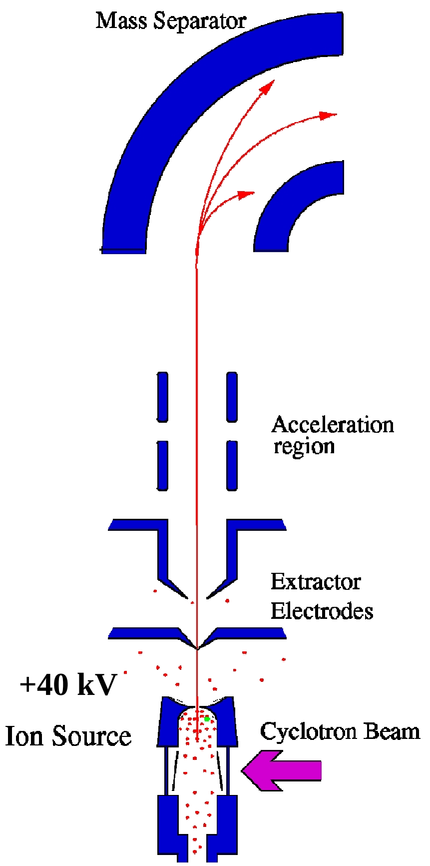
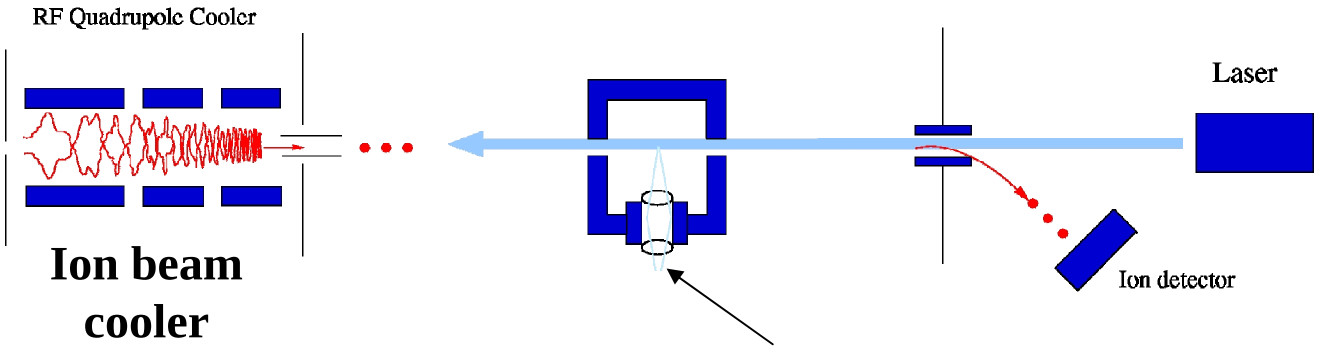
(Received 13 November 2001; published 14 February 2002)

A new method has been developed for increasing the sensitivity of collinear laser spectroscopy. The method utilizes an ion-trapping technique in which a continuous low-energy ion beam is cooled and accumulated in a linear Paul trap and subsequently released as a short (10–20 μs) bunch. In collinear laser measurements the signal-to-noise ratio has been improved by a factor of 2×10^4, allowing spectroscopic measurements to be made with ion-beam fluxes of ~ 50 ions s^{-1}. The bunching method has been demonstrated in an on-line isotope shift and hyperfine structure measurement on radioactive ^{175}Hf.

$2 \cdot 10^4$ improvement of SNR !

Cooler advantages





Ion beam cooler

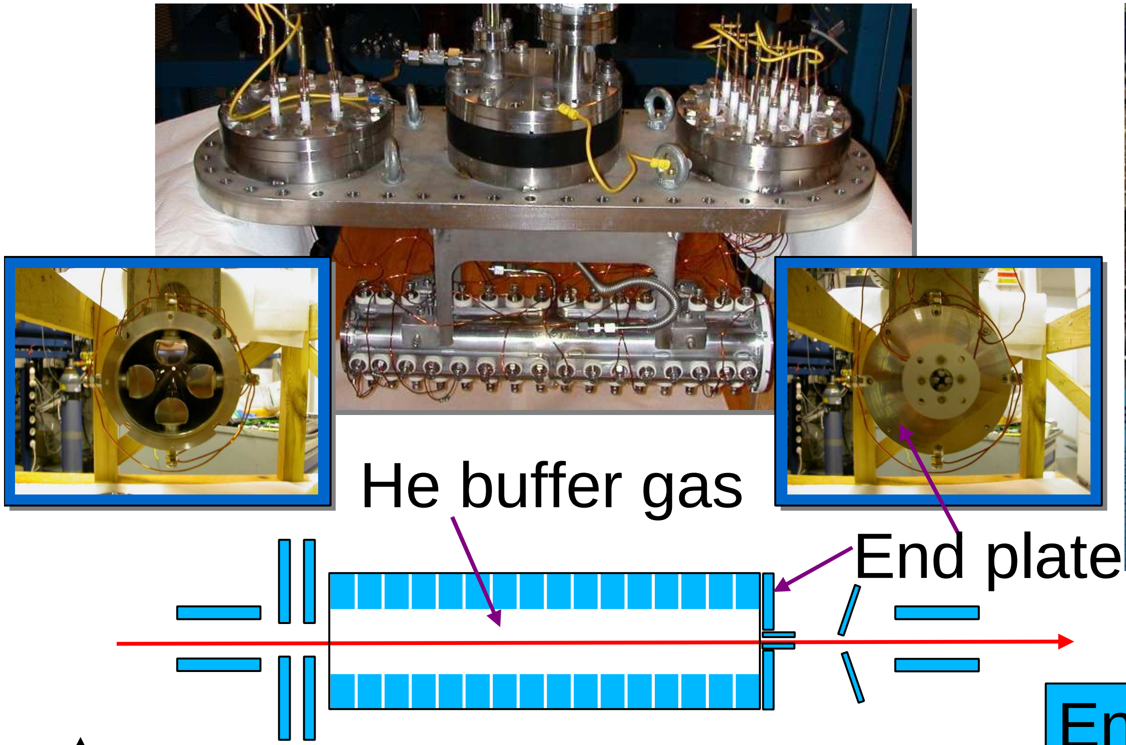
Light collection region

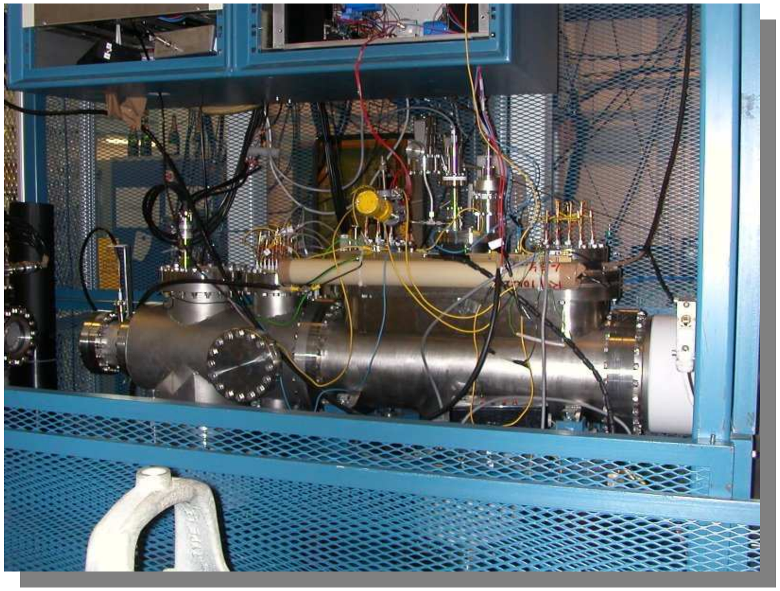
(Laser resonance fluorescence)

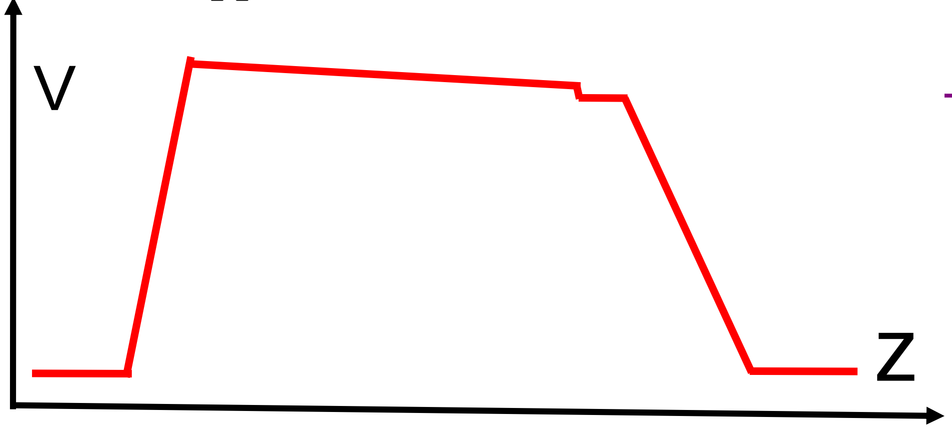
Collinear Beams Laser Spectroscopy

- → **Reduces energy spread of ion beam (100eV → 1eV)**
- → **Improves emittance of ion beam**
- → **Trap and accumulates ions – typically 100 - 500 ms**
- → **Releases ions in a 10 μs bunch**

Cooling for laser spectroscopy







Energy spread: 100→1 eV

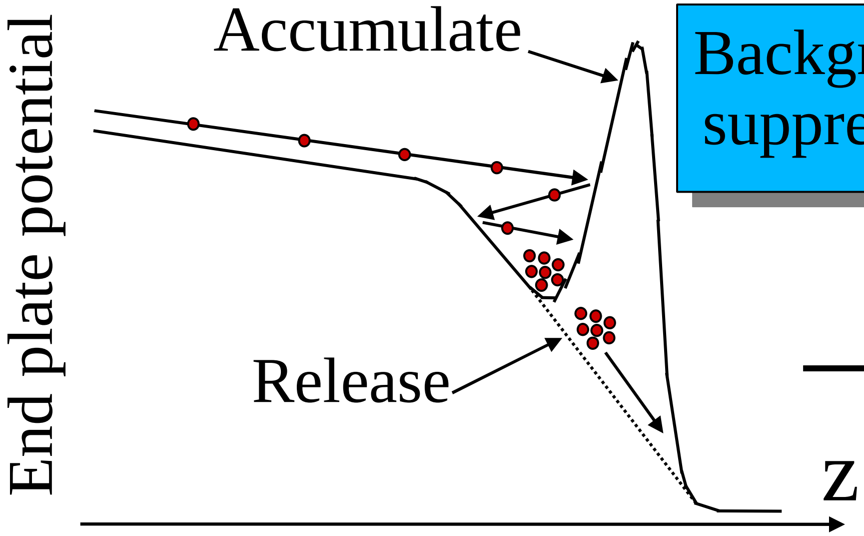
→ Less spectral broadening

Emittance: →3 π mm.mrad

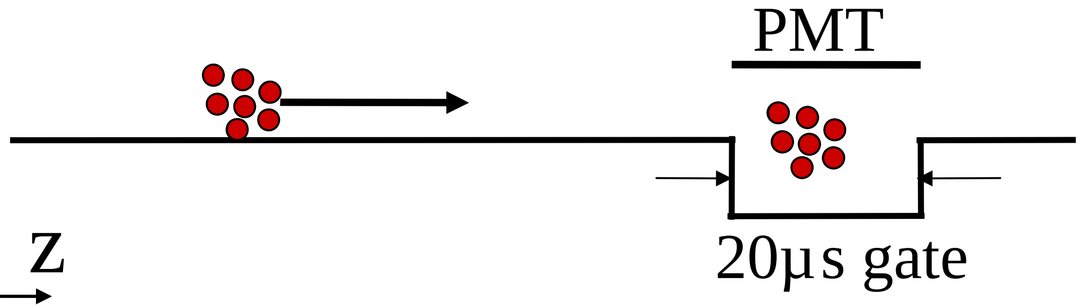
→ Better laser-ion overlap

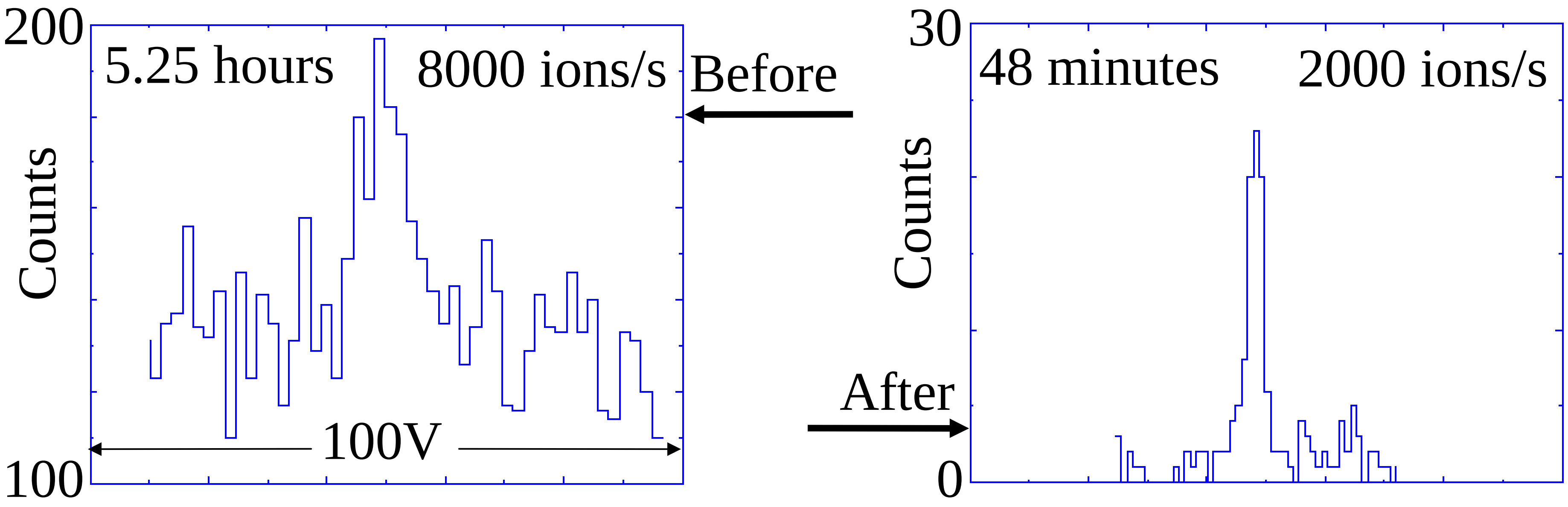
→ Reduced peak skewing

Bunching for laser spectroscopy



$$\text{Background suppression} = \frac{\text{eg. 200ms accumulation}}{20\mu\text{s gate width}} \sim 10^4$$





Some recent highlights – but first an older measurement

Zr charge radii measurement at IGISOL

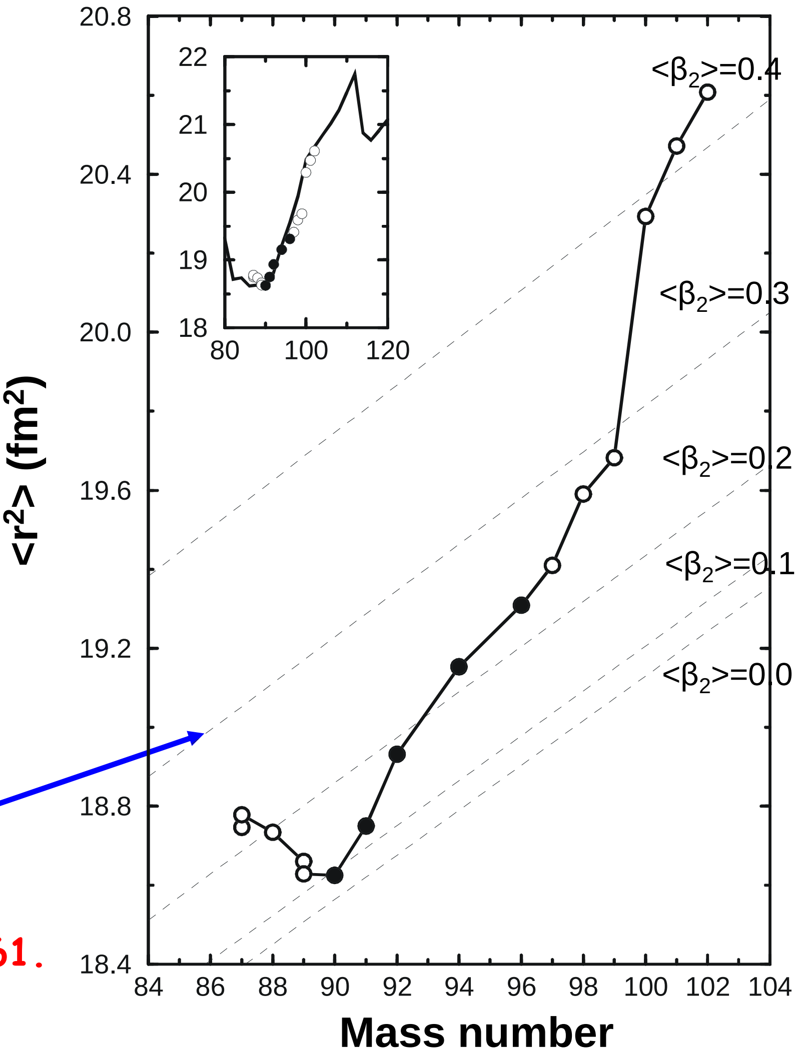
$^{96\text{-}102}$Zr

~ 3000 ions/s ^{100}Zr
~ 500 ions/s ^{96}Zr

Deformed nucleus

$$\langle r^2\rangle = \langle r^2\rangle_0\left(1+\frac{5}{4\pi}(\langle\beta_s^2\rangle+\langle\beta_3^2\rangle+...)\right)$$

Spherical nucleus



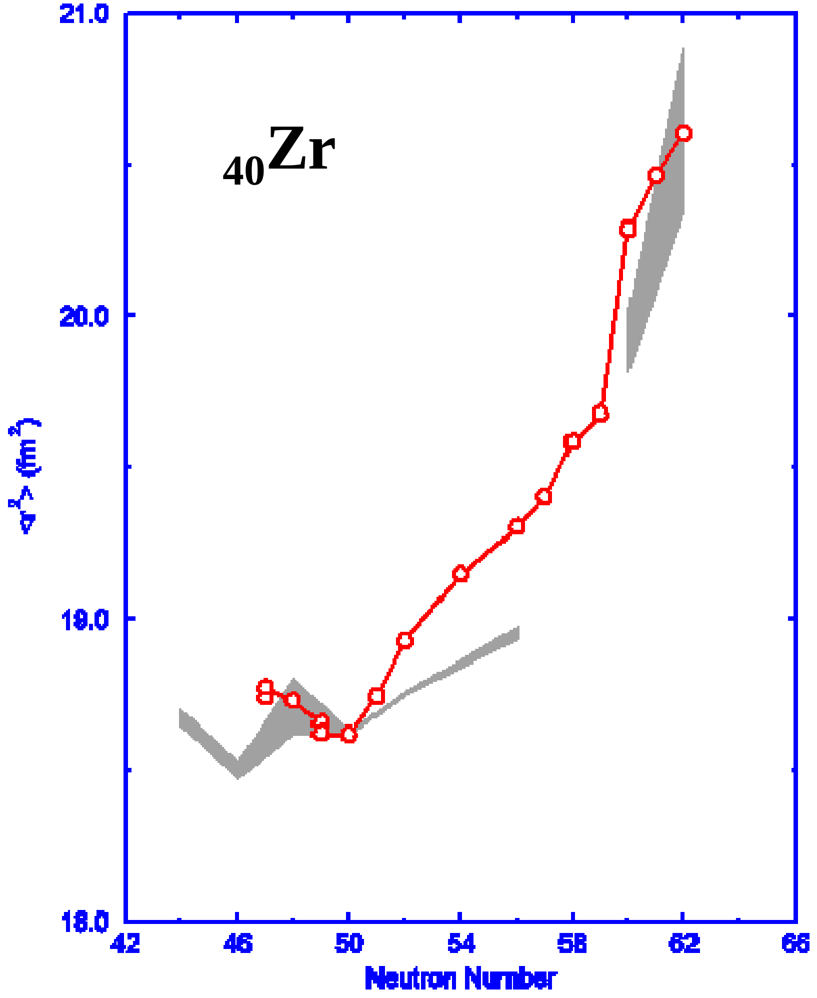
Droplet model

Myers & Schmidt, Nucl. Phys. A410 (1983) 61.

P. Campbell *et al*., Phys. Rev. Lett. 89 (2002) 082501

Radii predictions for $_{40}$Zr from B(E2) values

(Very similar to $_{38}$Sr behaviour)

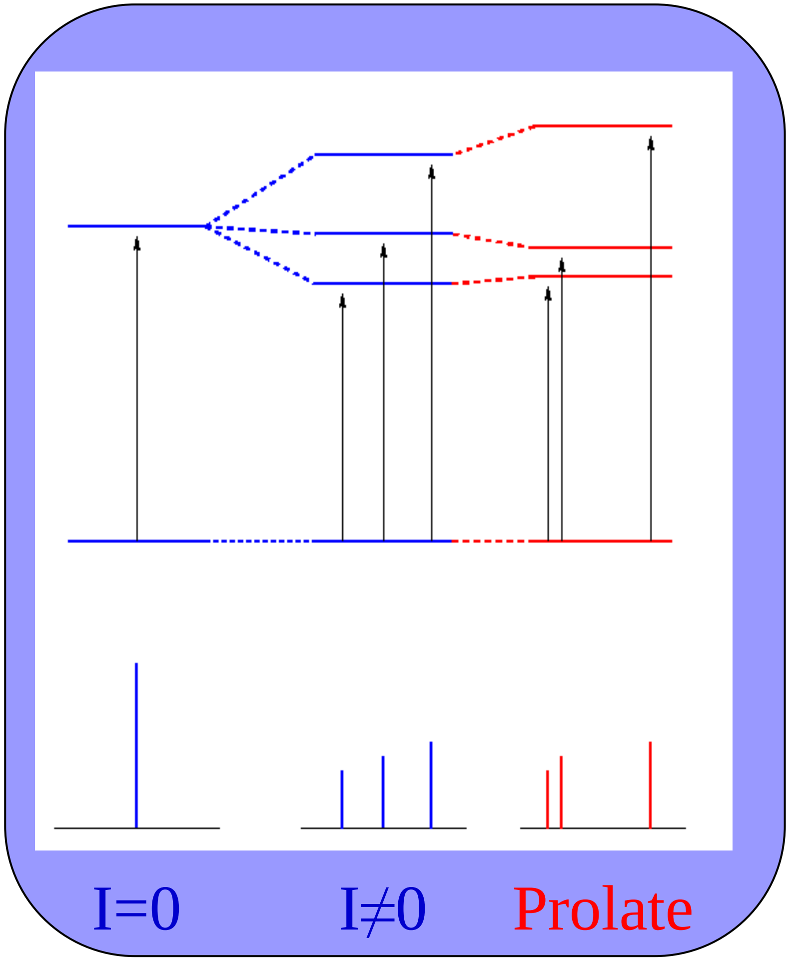


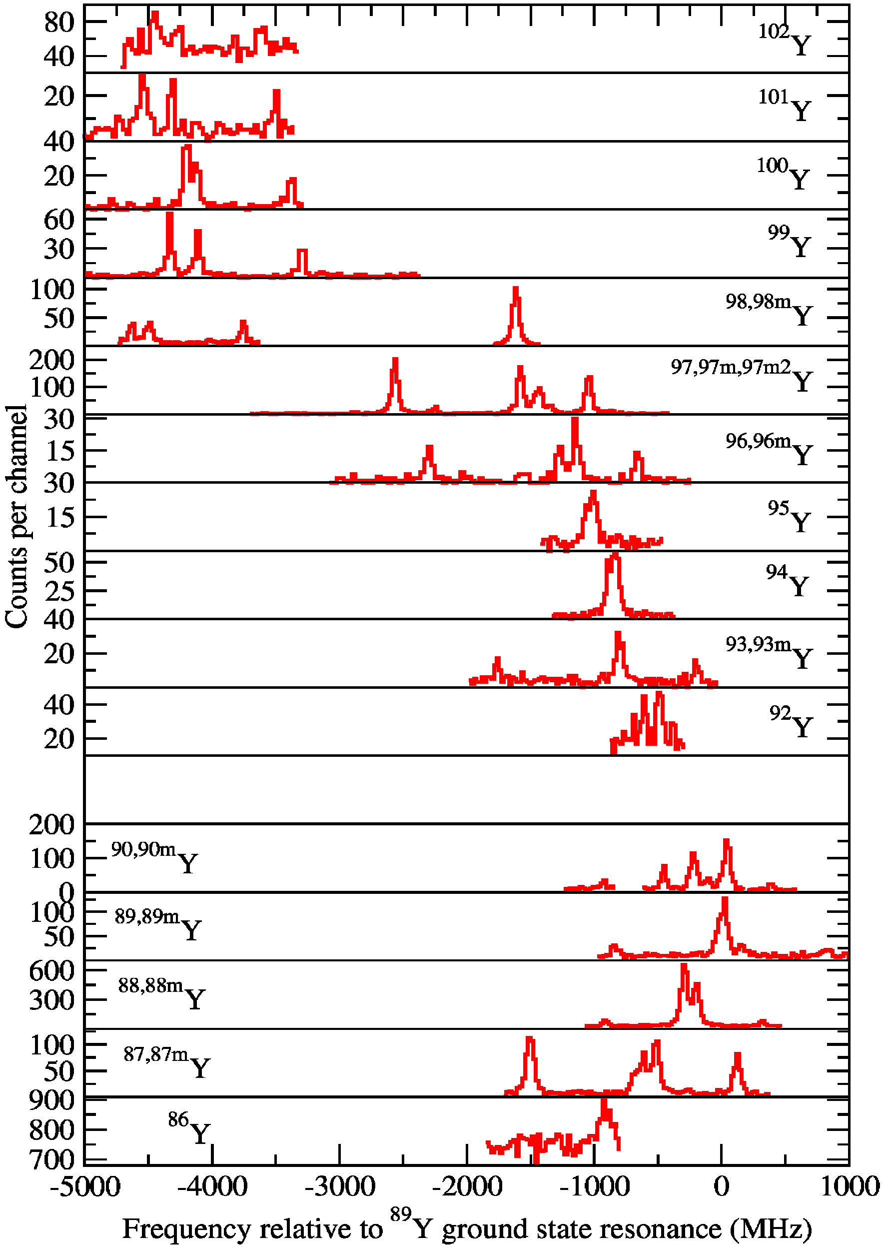
$$\langle \beta_\lambda^2 \rangle = \left(\frac{4\pi}{3ZeR_0^\lambda} \right) \sum_f B(E\lambda; J_{gs} \to J_f)$$

Big discrepancies between B(E2) measurements and charge radii. But for A=96 to 100, nuclear spins are either 0 or ½: NO measureable quadrupole moments…..

….look at yttrium (+isomers).

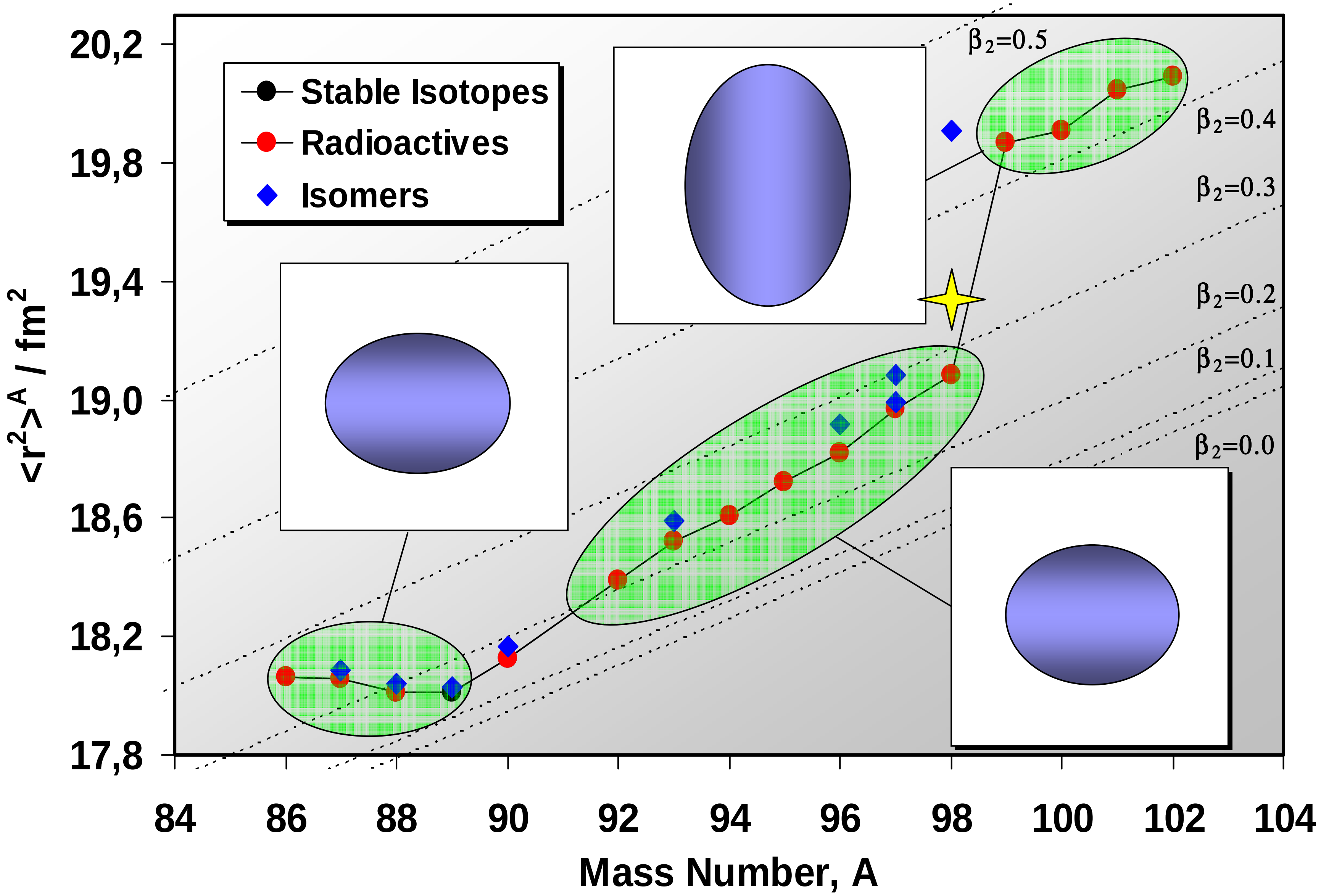
$_{39}$Y isotopes and isomers



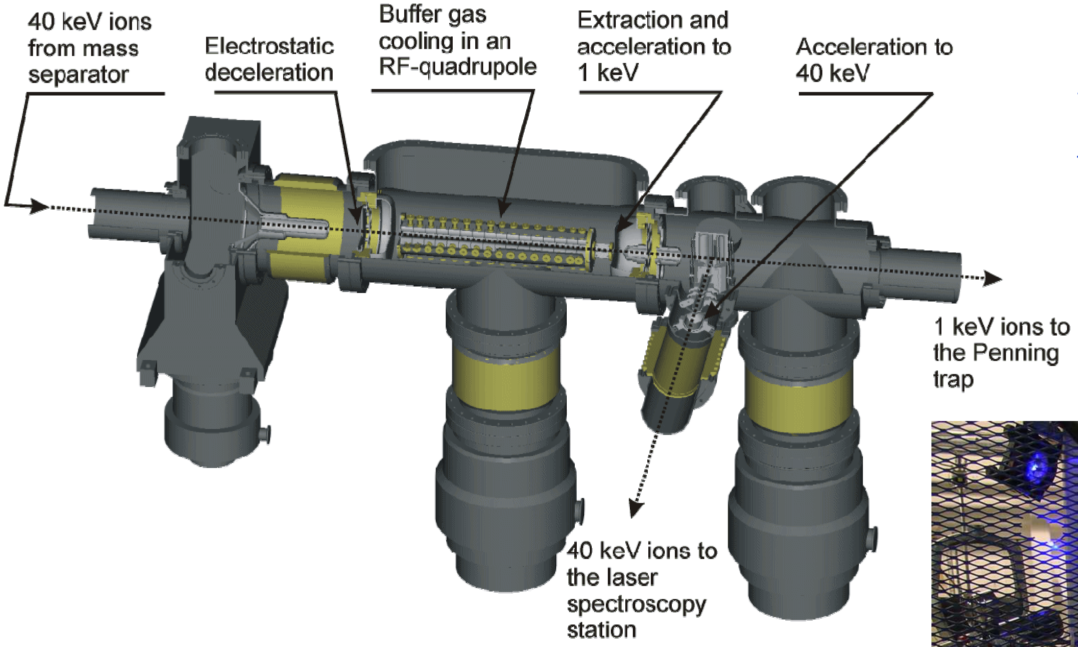


- Shape change at N=59
- 98m is well deformed

Yttrium charge radii

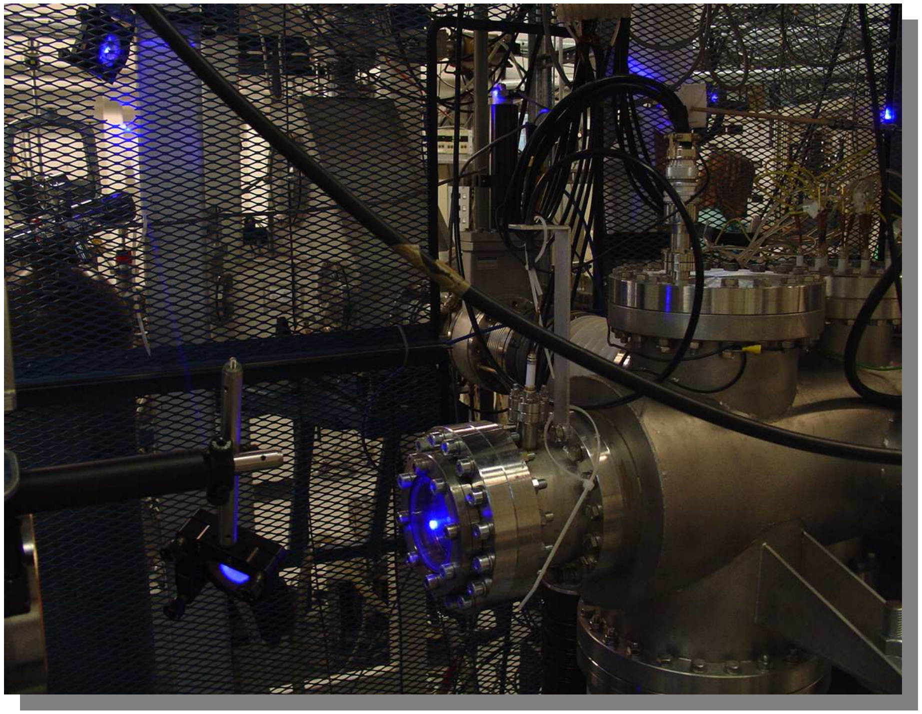


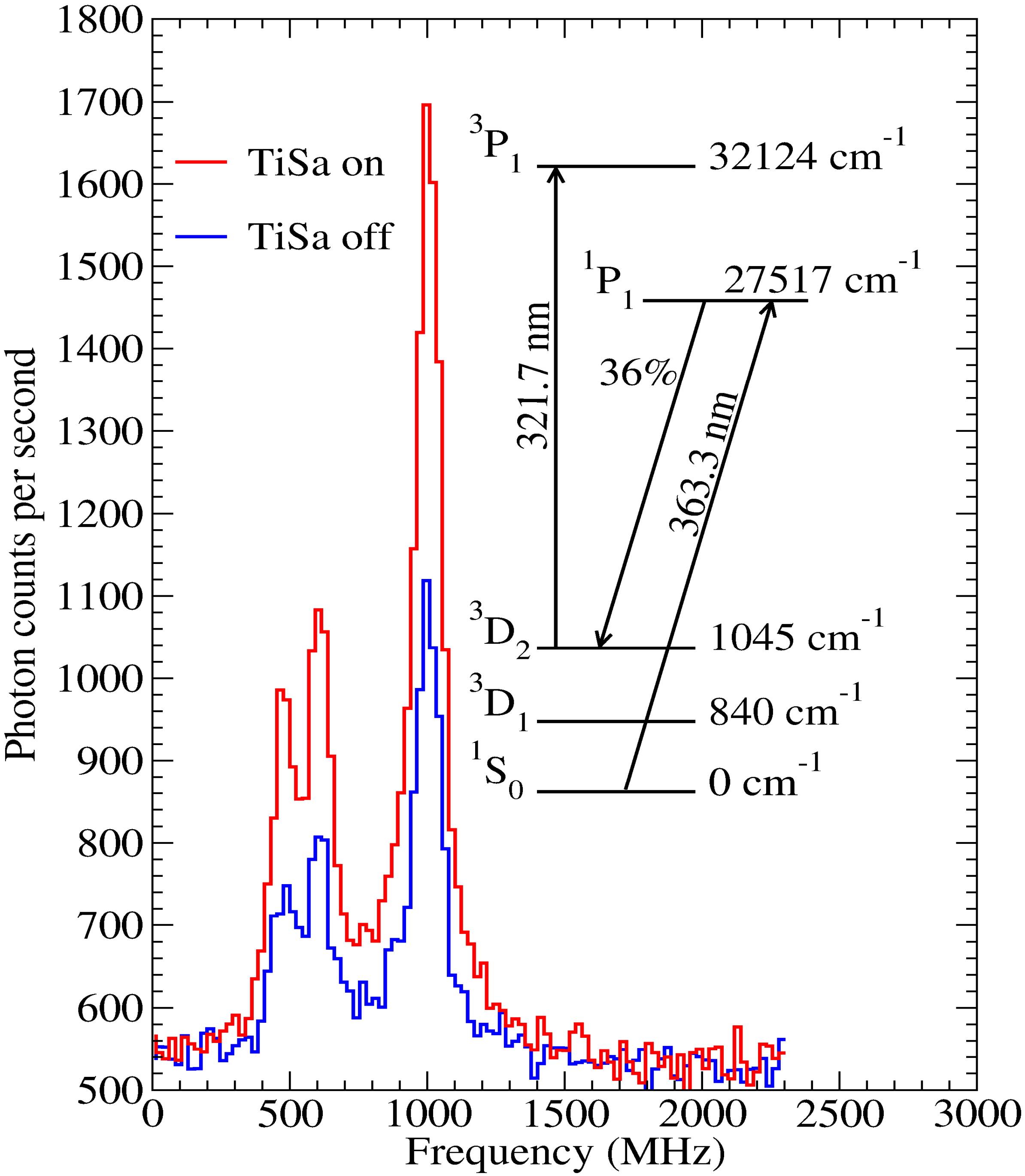
Optical manipulation in the RF cooler-buncher



In some isotopes of yttrium the nuclear spin is uncertain. We can manipulate the atomic state to provide a better starting point for collinear work

This is done by "optically pumping" the yttrium in the RF cooler – a new technique!



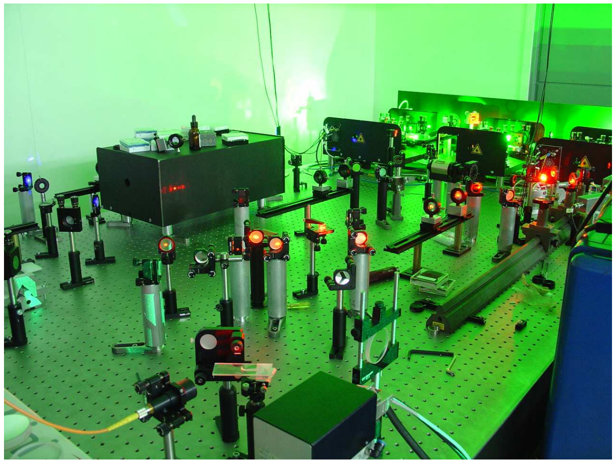


363.3nm pumping (40% transfer)

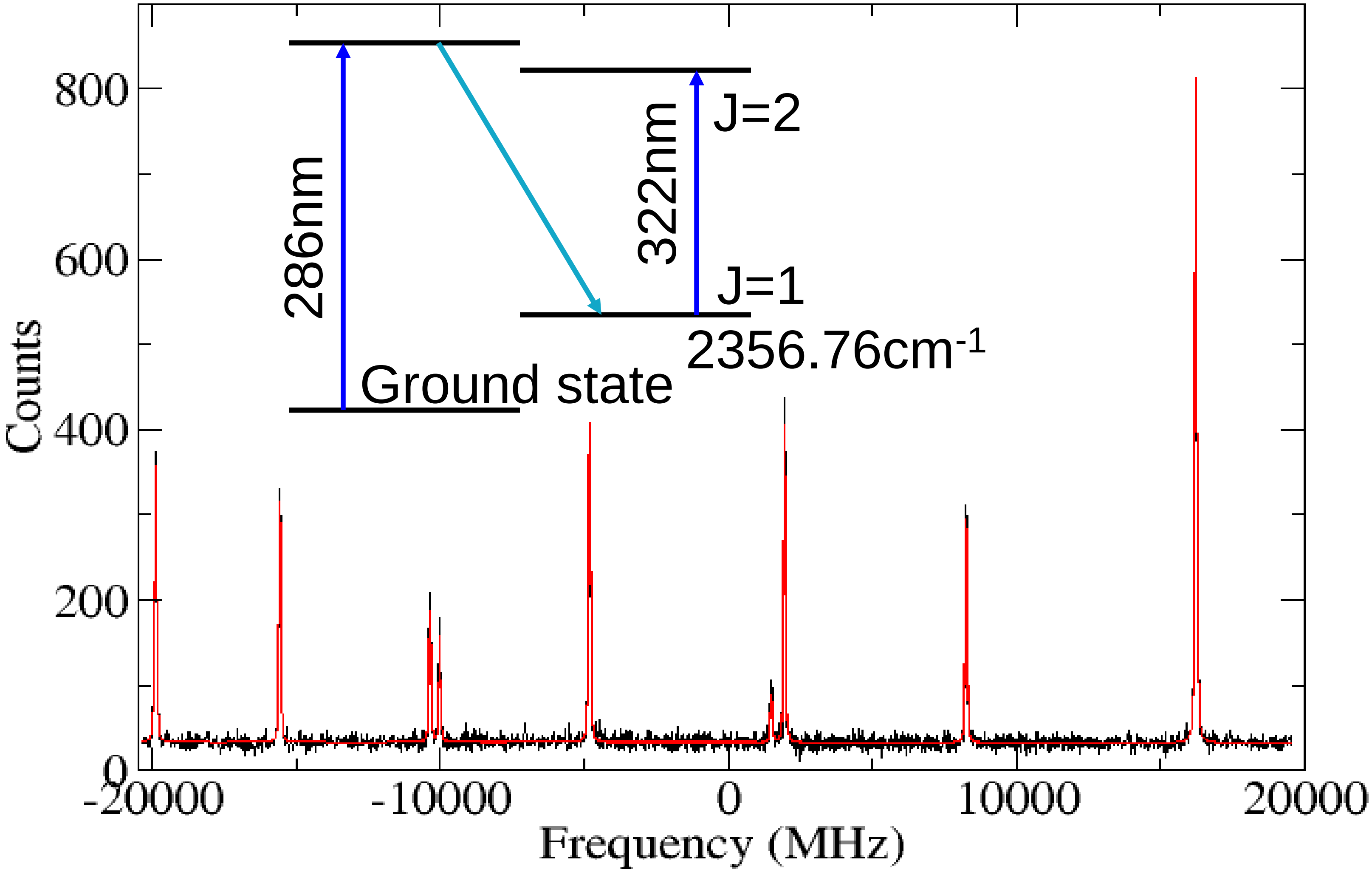
1pA of ^{89}Y continuous beam

Indifference to bunching

Use broadband pulsed lasers with high repetition rates (10 kHz)

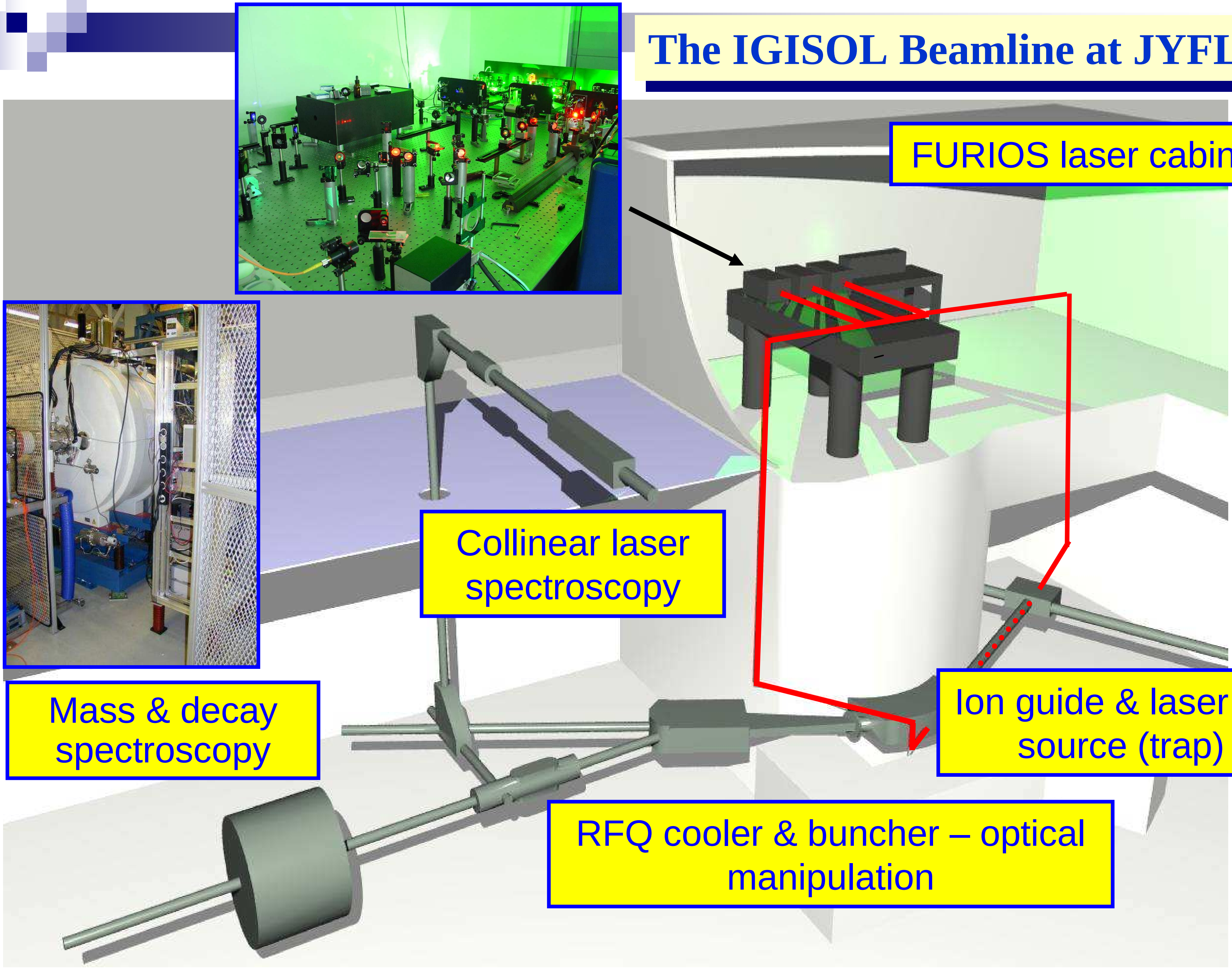


Laser spectroscopy of niobium



50% increase due to pumping ➔ 1 photon per 2700 ions

The IGISOL Beamline at JYFL



FURIOS laser cabin

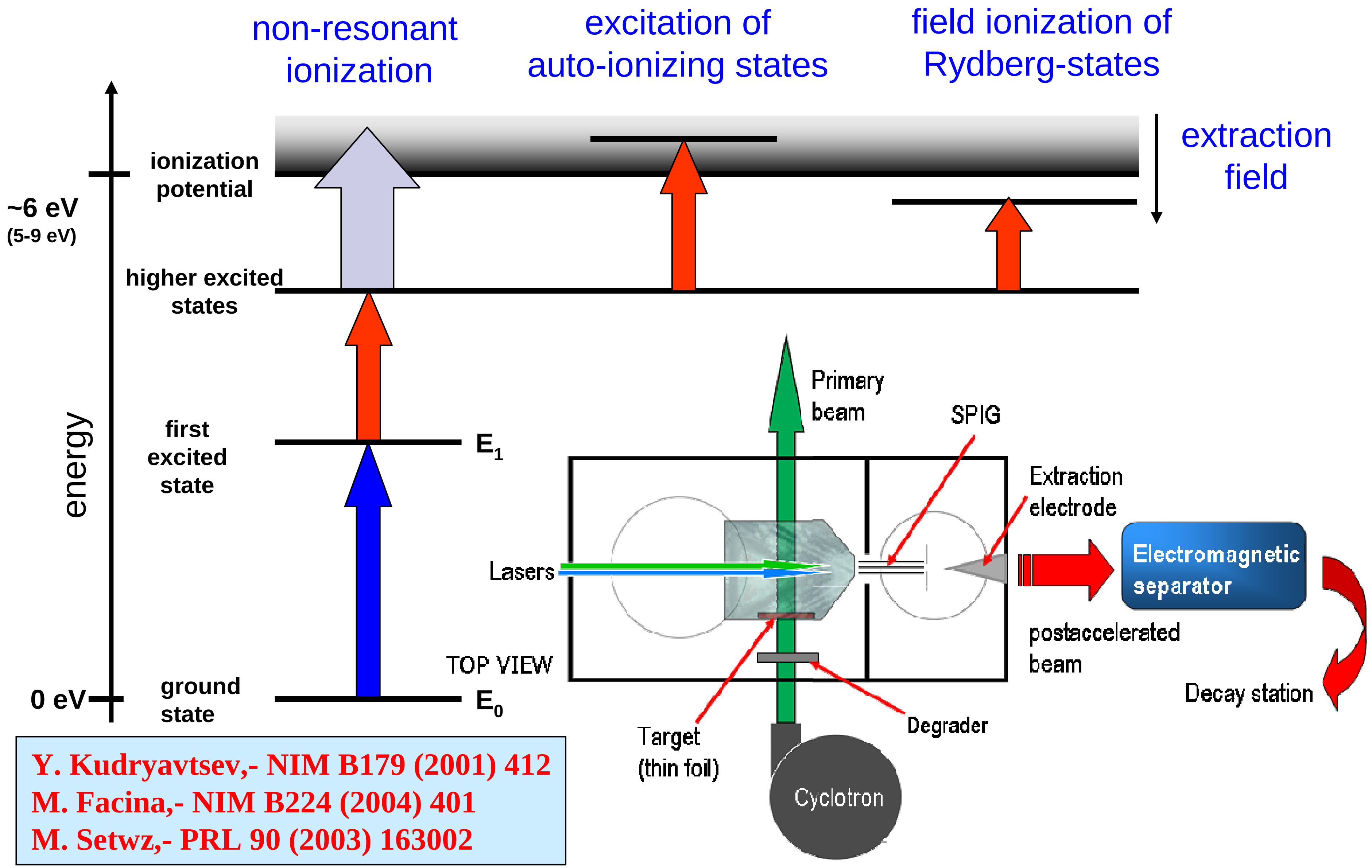
Collinear laser spectroscopy

Mass & decay spectroscopy

Ion guide & laser ion source (trap)

RFQ cooler & buncher – optical manipulation

Principles of Resonance Ionization



non-resonant ionization

excitation of auto-ionizing states

field ionization of Rydberg-states

extraction field

energy

~6 eV

(5-9 eV)

0 eV

ionization potential

higher excited states

first excited state

ground state

E_1

E_0

TOP VIEW

Lasers

Primary beam

SPIG

Extraction electrode

Electromagnetic separator

postaccelerated beam

Decay station

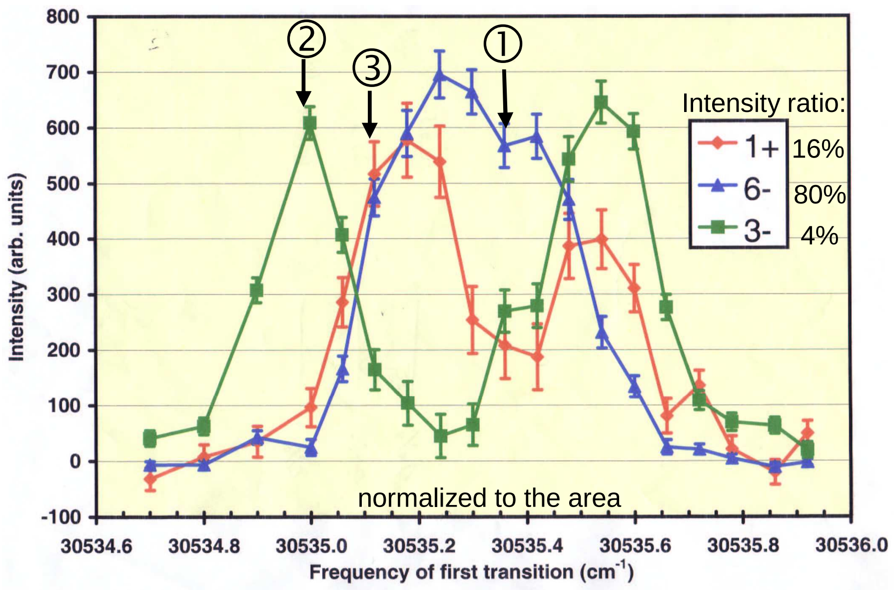
Target (thin foil)

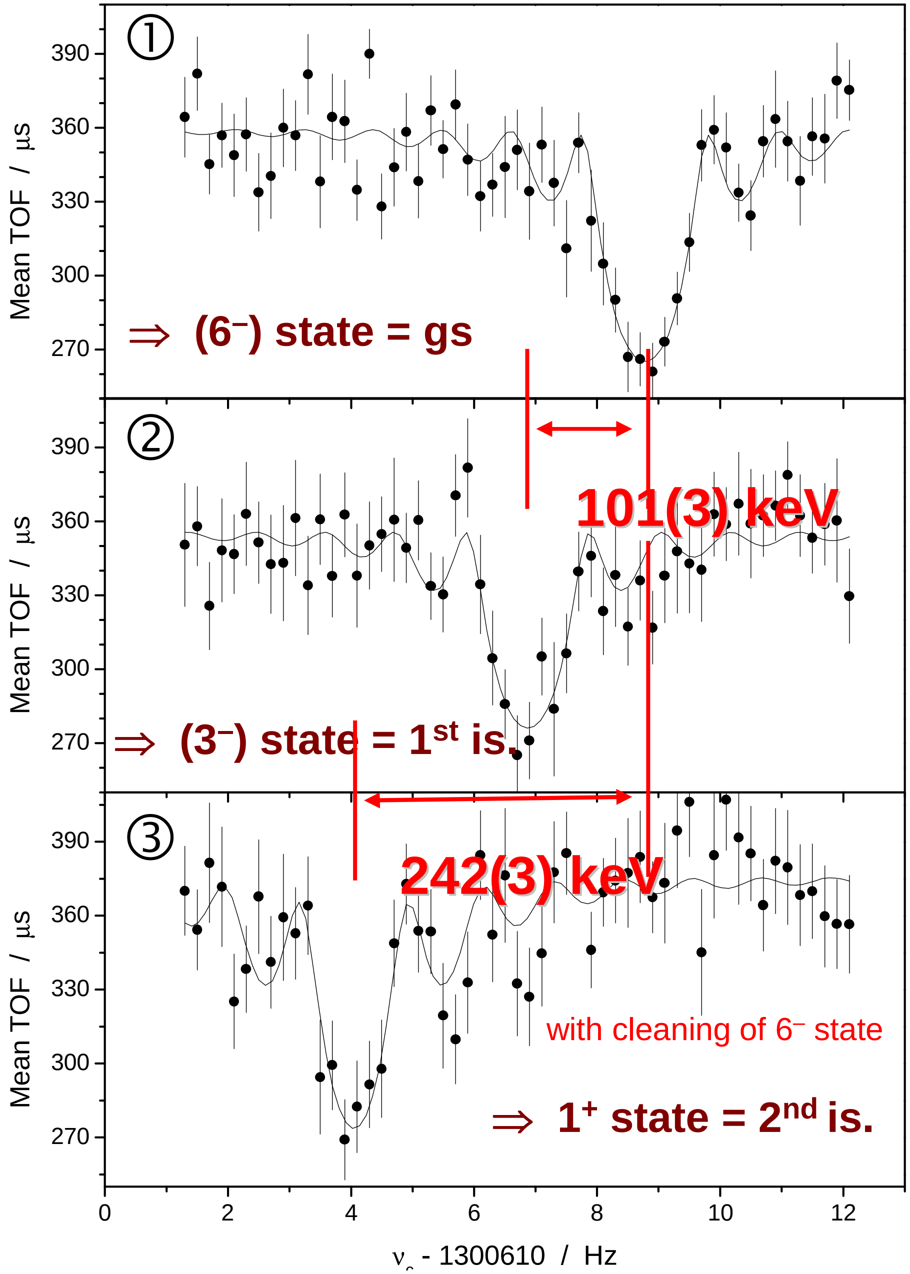
Degrader

Cyclotron

Y. Kudryavtsev,- NIM B179 (2001) 412
M. Facina,- NIM B224 (2004) 401
M. Setwz,- PRL 90 (2003) 163002

Example on RILIS: Triple Isomerism in ^{70}Cu (RILIS & ISOLTRAP)





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

Unambiguous state assignment!

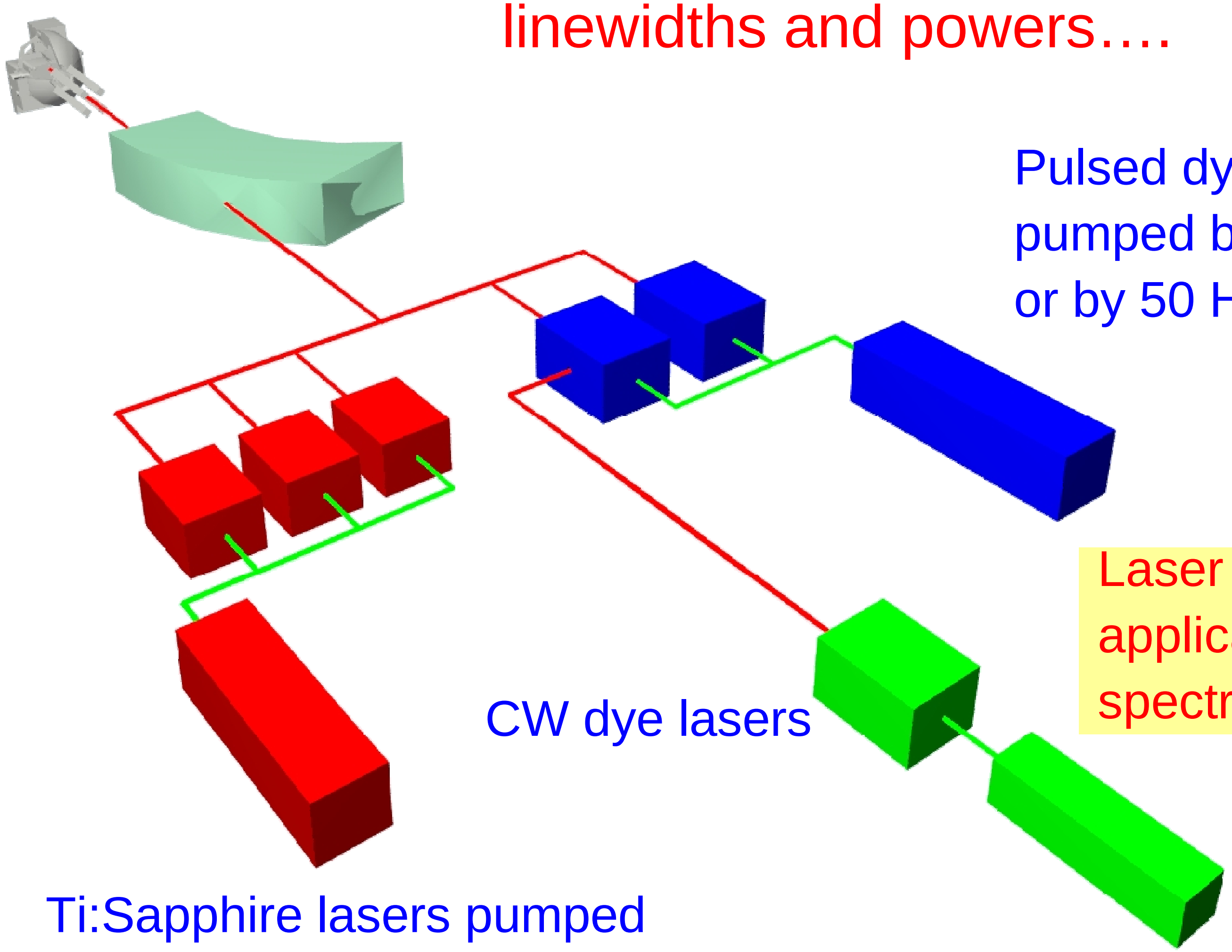
ME of ground state is 240 keV higher than literature value!

$R \approx 1\cdot10^7, \delta m/m \approx 4\cdot10^{-8}$

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

Fast Universal Resonant laser IOn Source

Full spectral coverage at a range of repetition rates, linewidths and powers….



Pulsed dye lasers,
pumped by CVL (12 kHz)
or by 50 Hz Nd:YAG

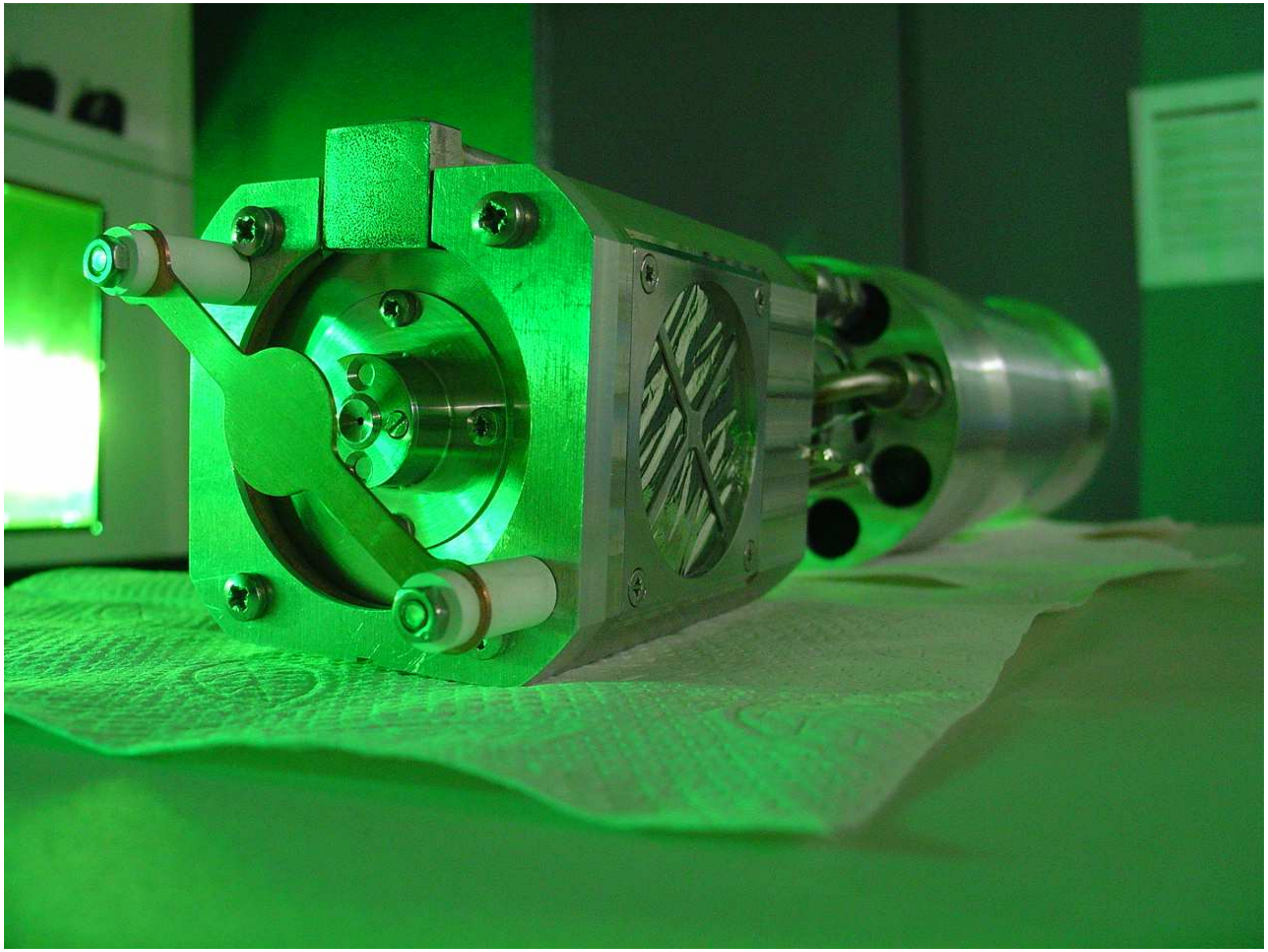
Laser development for applications of in-source spectroscopy

CW dye lasers

Ti:Sapphire lasers pumped
by Nd:YAG (12 kHz)

I.D. Moore, J. Phys. G 31 (2005) S1499

A laser ion guide for heavy-ion fusion evaporation reactions



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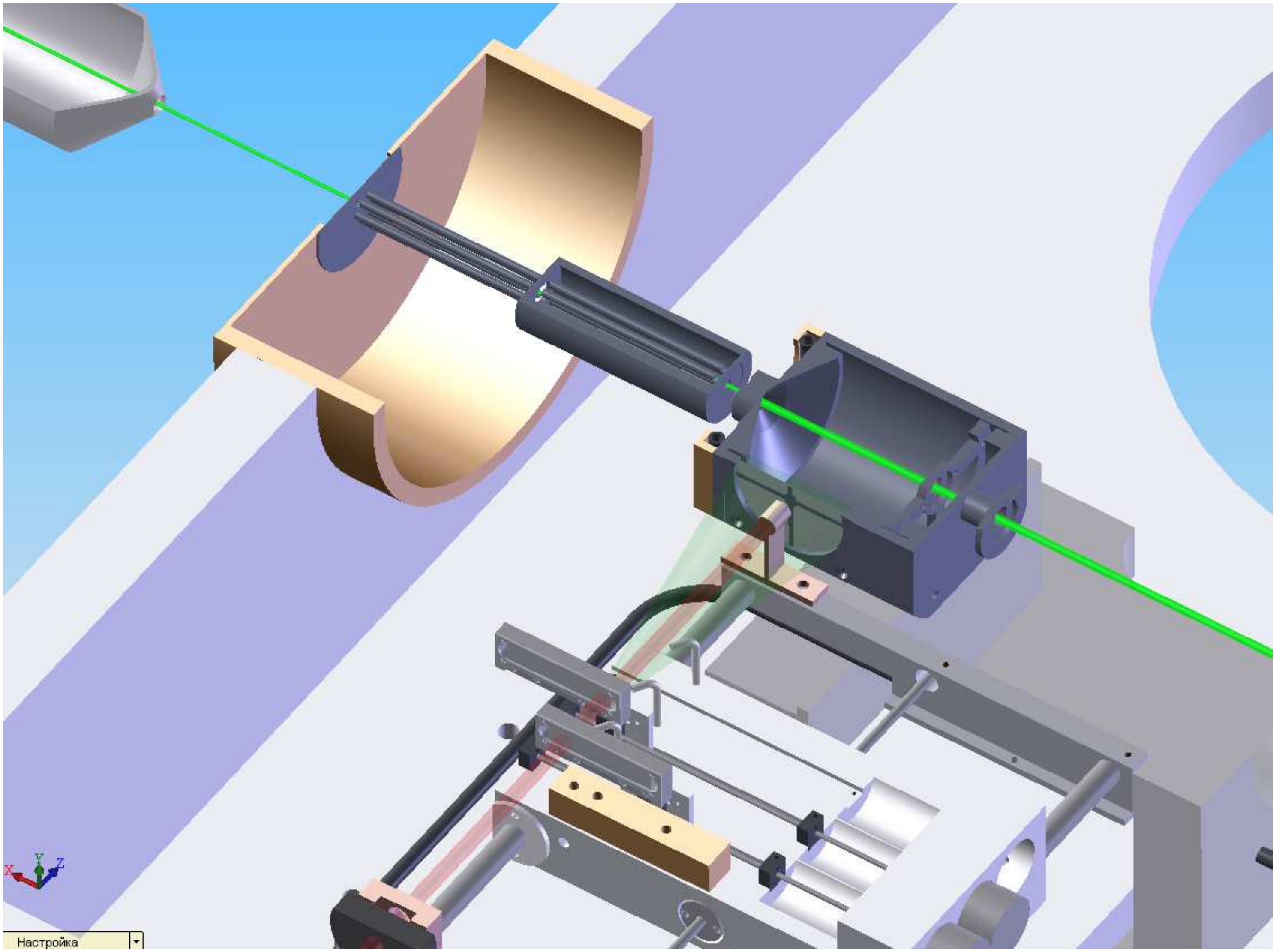
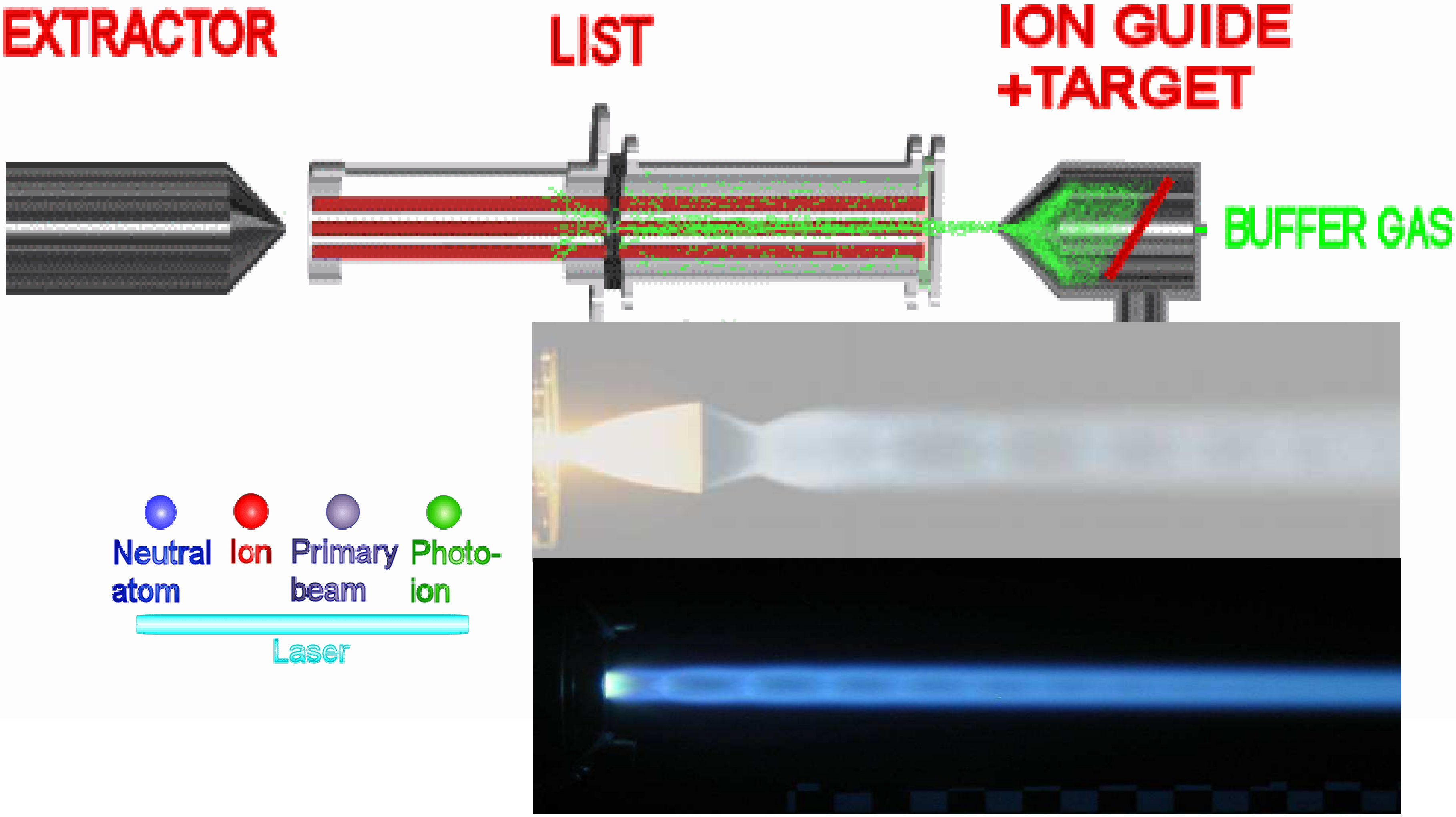
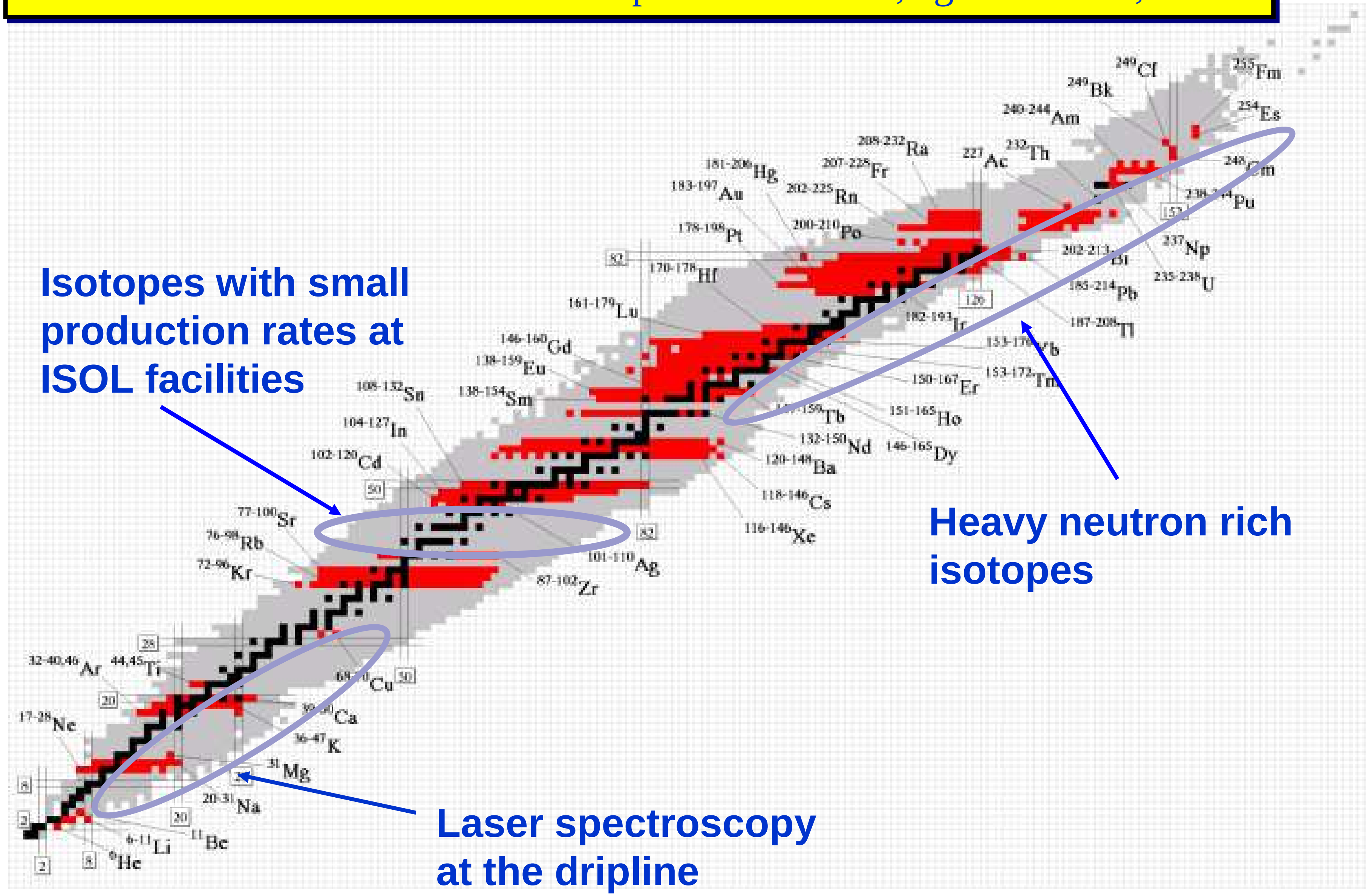


Laser ion source trap technique at IGISOL

I.D. Moore et al., AIP Conference Proceedings Series, 831 (2006) 511.



Next generation on-line facilities, SLOWRI at RIKEN and LASPEC at GSI.
Much of the work can still be done at present facilities, eg at IGISOL, JYFL.



Isotopes with small production rates at ISOL facilities

Heavy neutron rich isotopes

Laser spectroscopy at the dripline