Laser Spectroscopy on Bunched Radioactive Ion Beams

Jon Billowes

University of Manchester

THE UNIVERSITY of MANCHESTER

Balkan School on Nuclear Physics, Bodrum 2004

Lecture 1.

1.1 Nuclear moments

1.2 Hyperfine interaction in free atoms

1.3 Lasers and laser spectroscopy

1.4 Collinear-beams laser spectroscopy

Lecture 2.

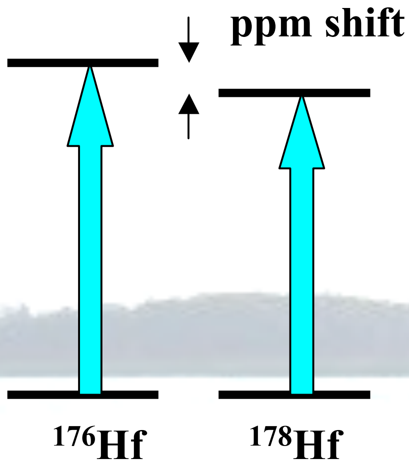
2.1 Ion beam cooling and bunching

2.2 Experiments with bunched beams

2.3 Laser ionization techniques

Summary of Isotope Shift and Hyperfine Structure

Isotope shift of atomic transition



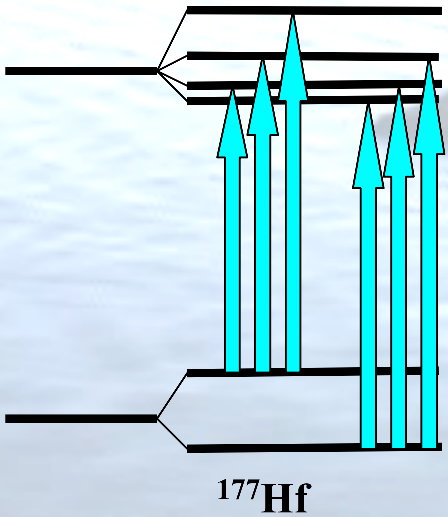
Analysis yields the change in nuclear mean square charge radius

↓

Nuclear size, static and dynamic deformations

Hyperfine structure of atomic transition

(Isotope shift found using centroids of hyperfine multiplet)

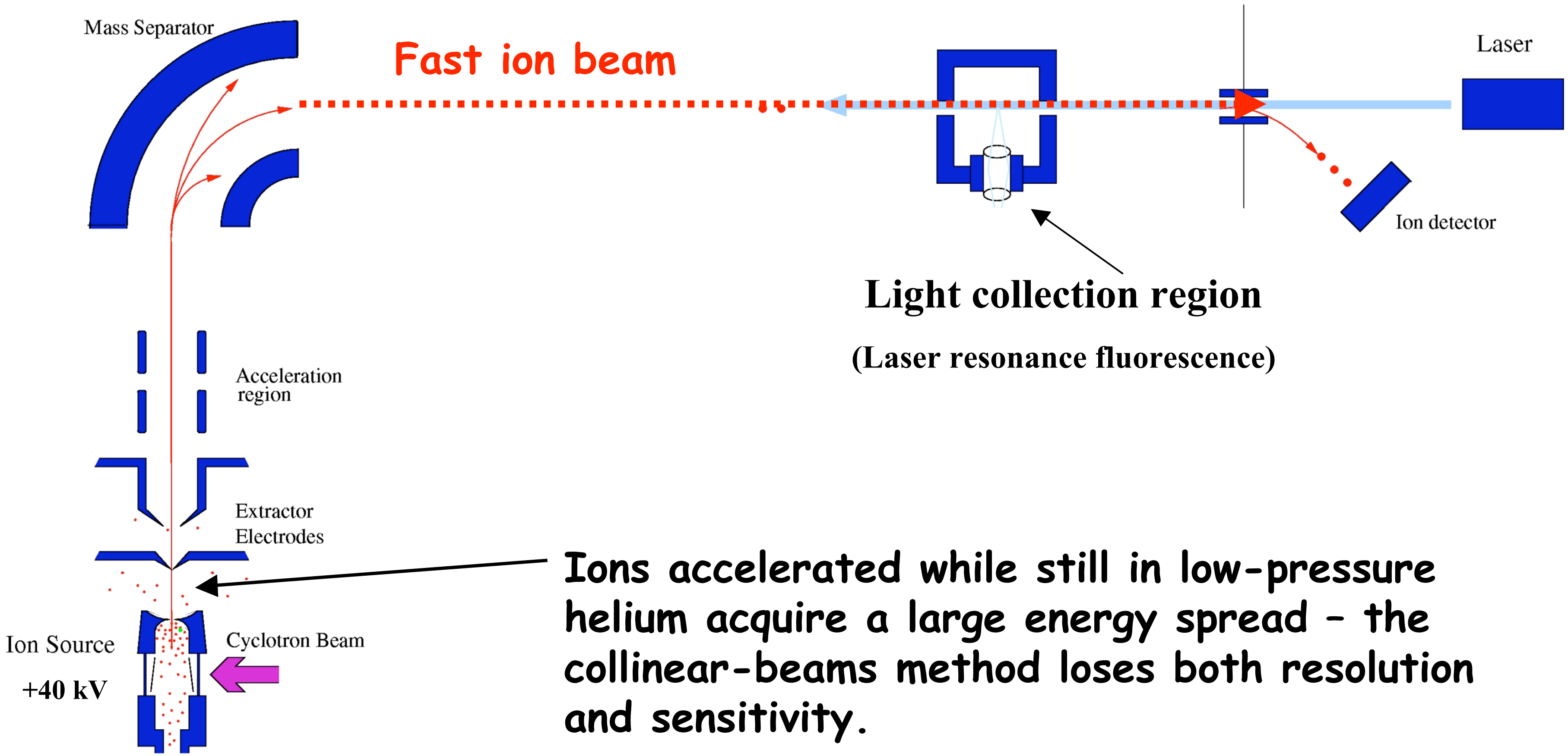


Nuclear spin I

Magnetic moment μ

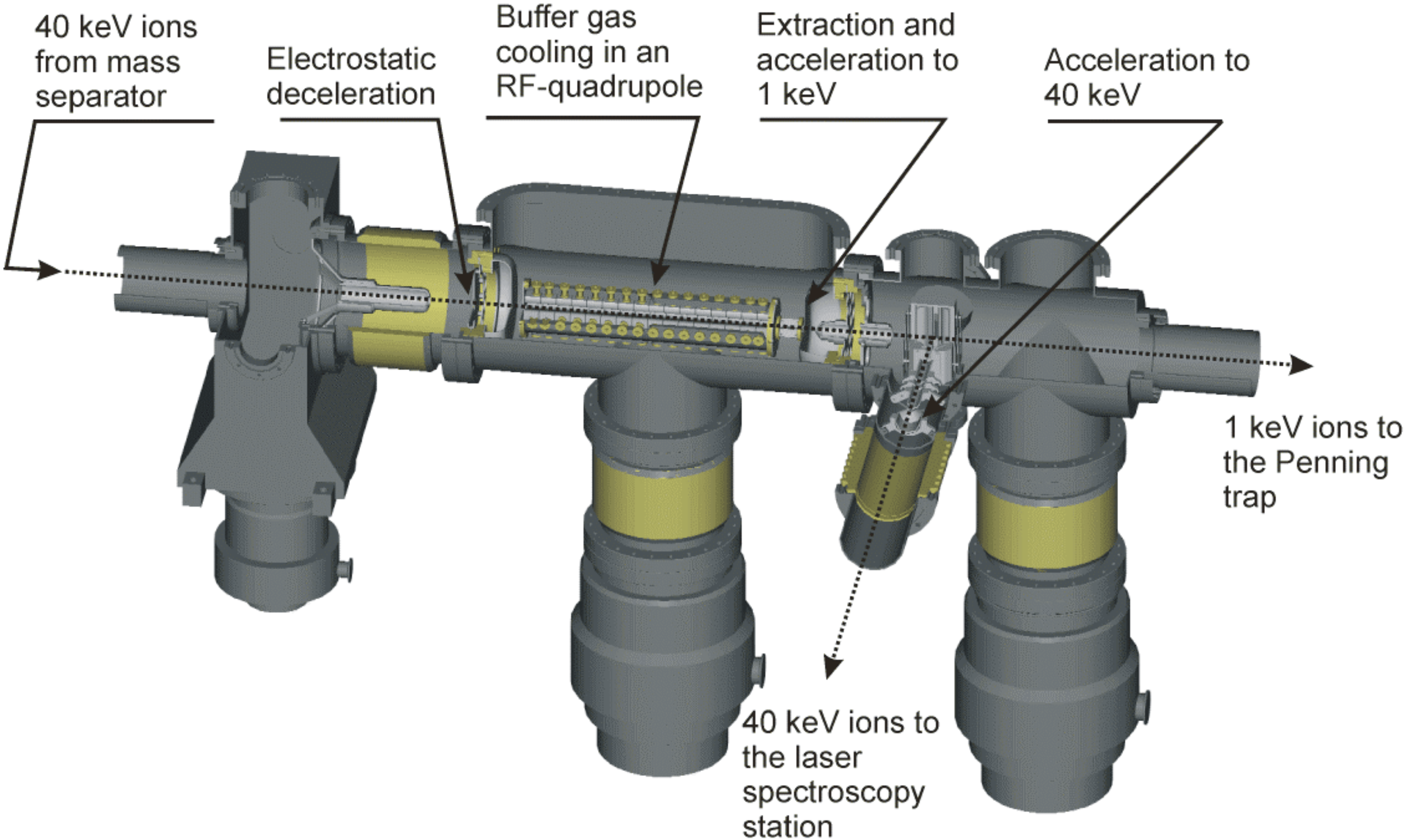
Quadrupole moment Q_s

2.1 Ion beam cooling and bunching



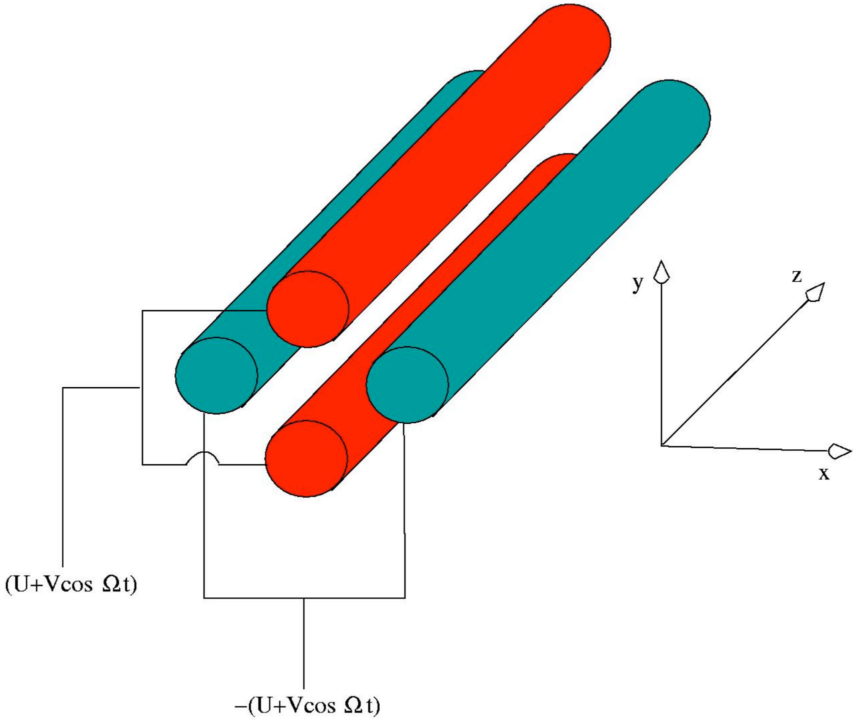
Ions accelerated while still in low-pressure helium acquire a large energy spread – the collinear-beams method loses both resolution and sensitivity.

Solution: an ion beam "cooler"



The JYFL cooler/buncher

Principle of RFQ trap



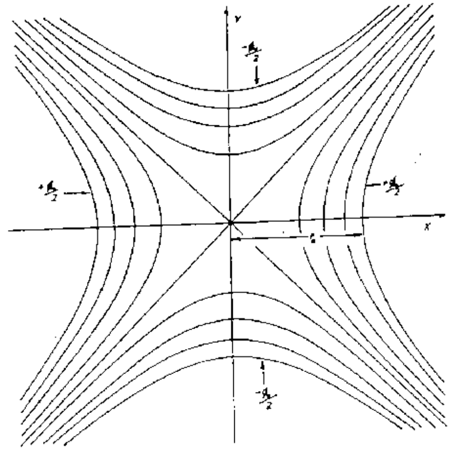


Fig. 1: Quadrupole field.

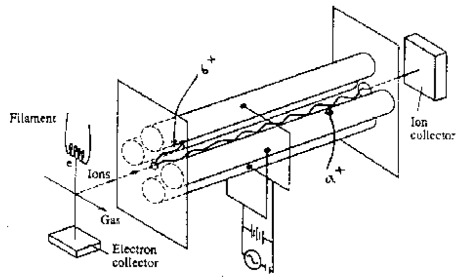
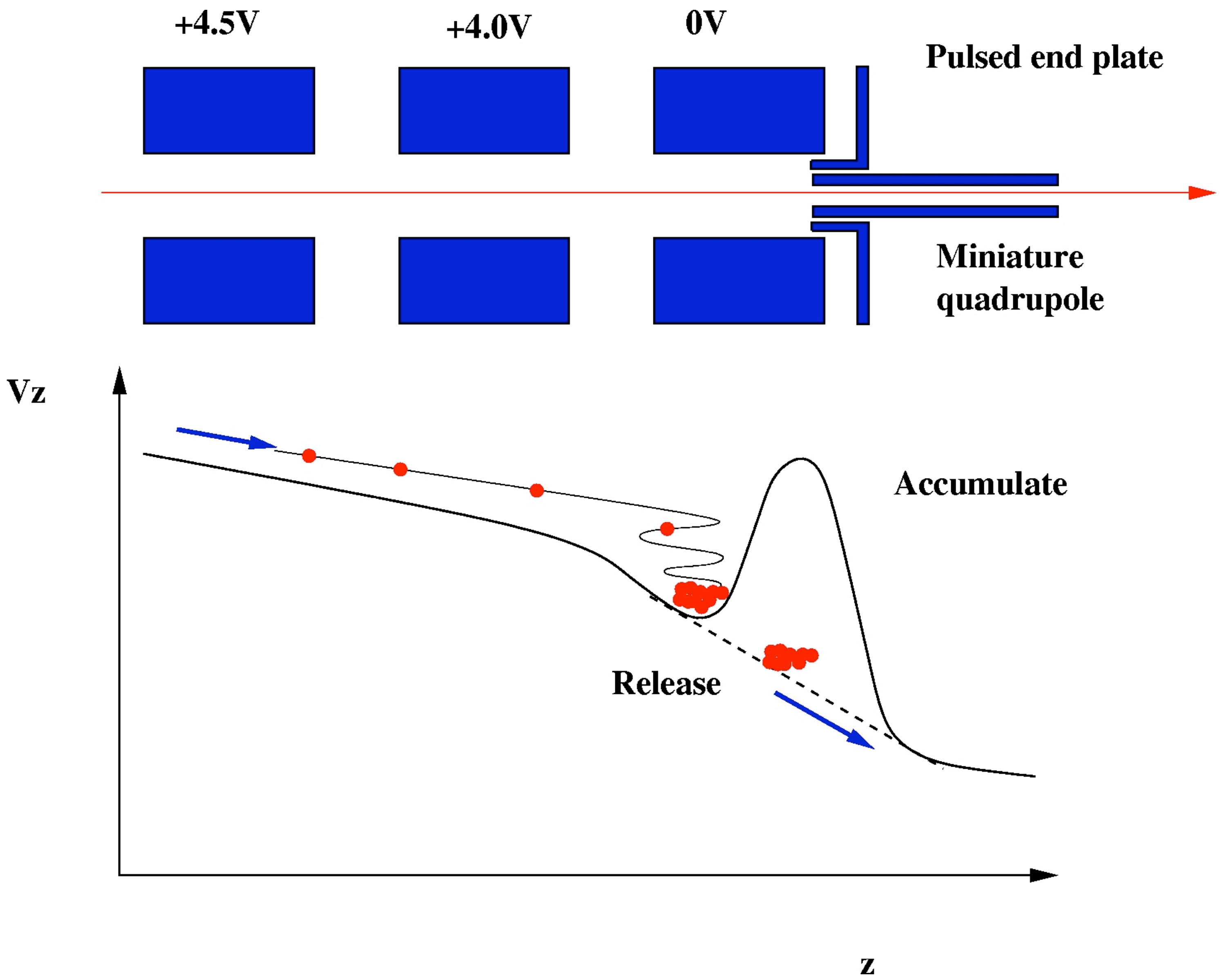


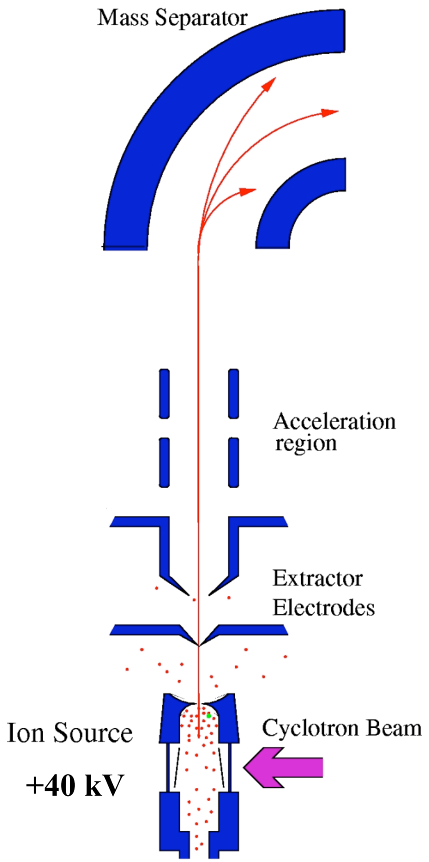
Fig. 2: Schematic of a quadrupole mass spectrometer

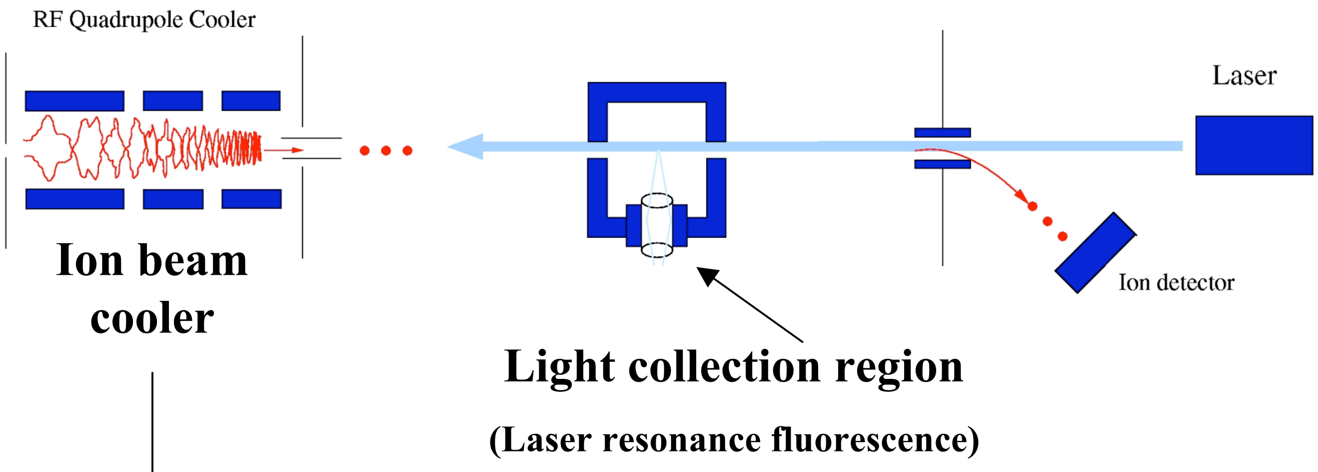
Time-averaged force towards central axis

Damping of motion provided by low-pressure helium gas at room temperature

Bunching ions in the RFQ cooler

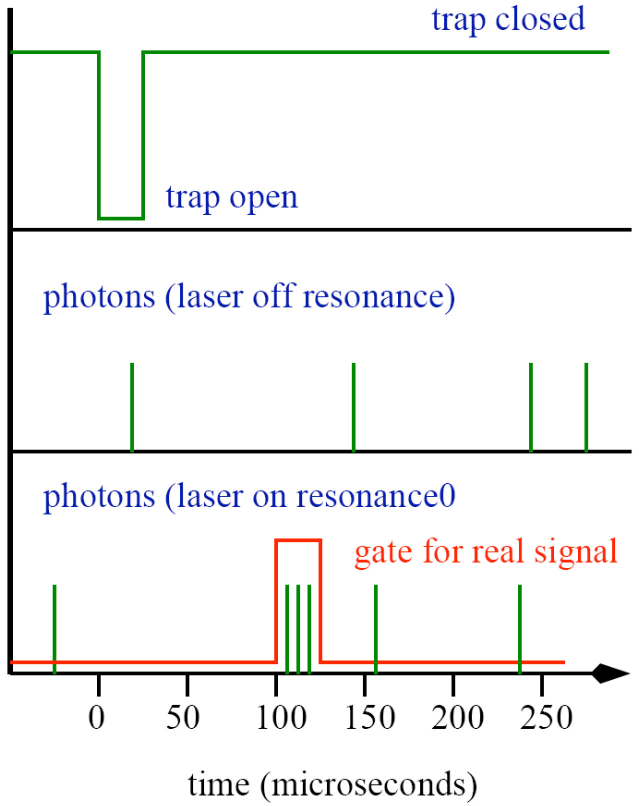


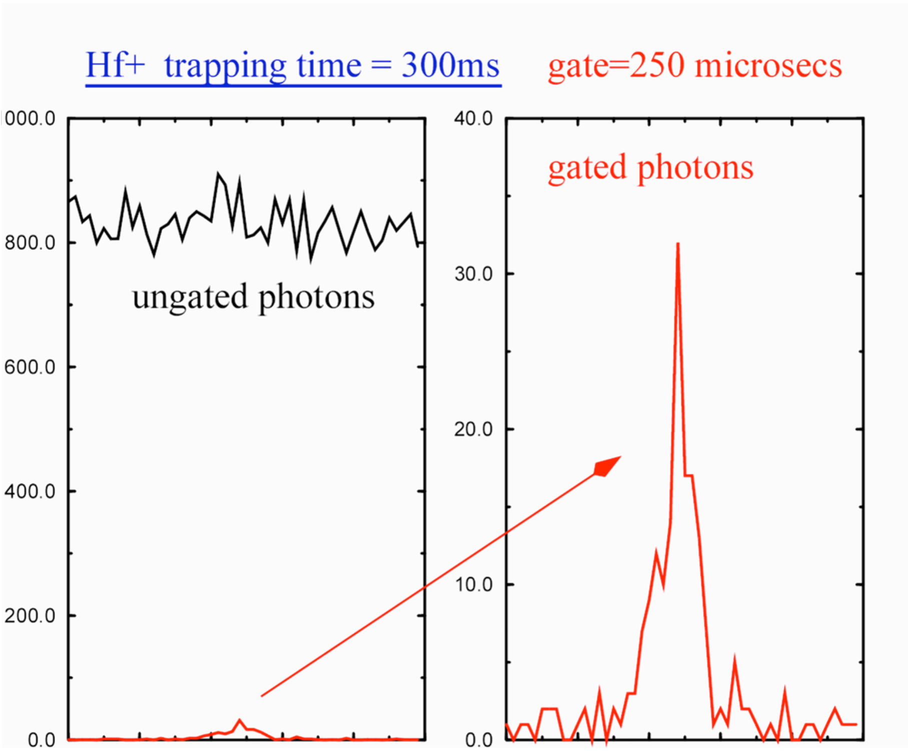




- **Reduces energy-spread of ion beam**
- **Improves emittance of ion beam**
- **Trap and accumulates ions – typically for 300 ms**
- **Releases ions in a 15 μs bunch**

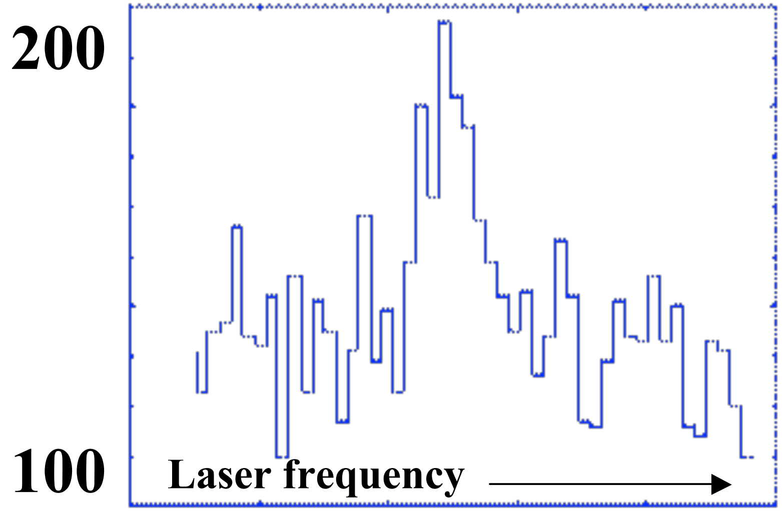
Background reduction by signal gating





Sensitivity gains using the RFQ ion-cooler

BEFORE

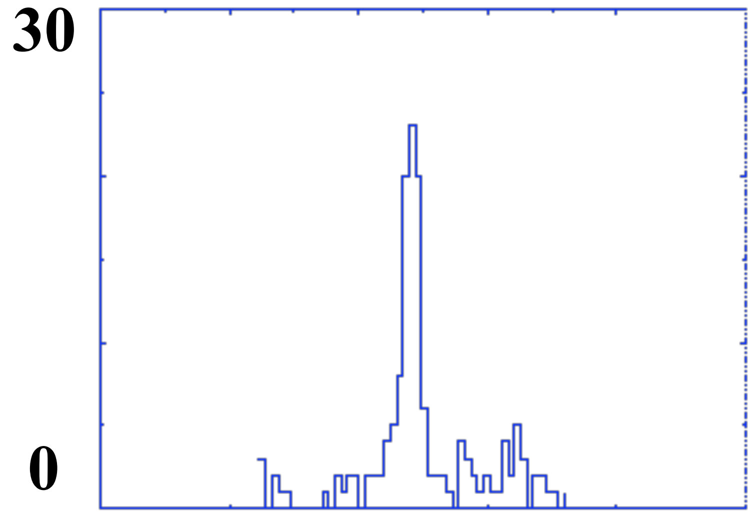


8000 ions/sec

5.3 hours

Photons from laser-excitation of radioactive ^{88}Zr

AFTER



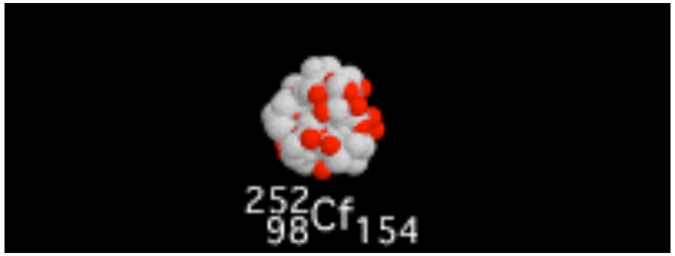
2000 ions/sec

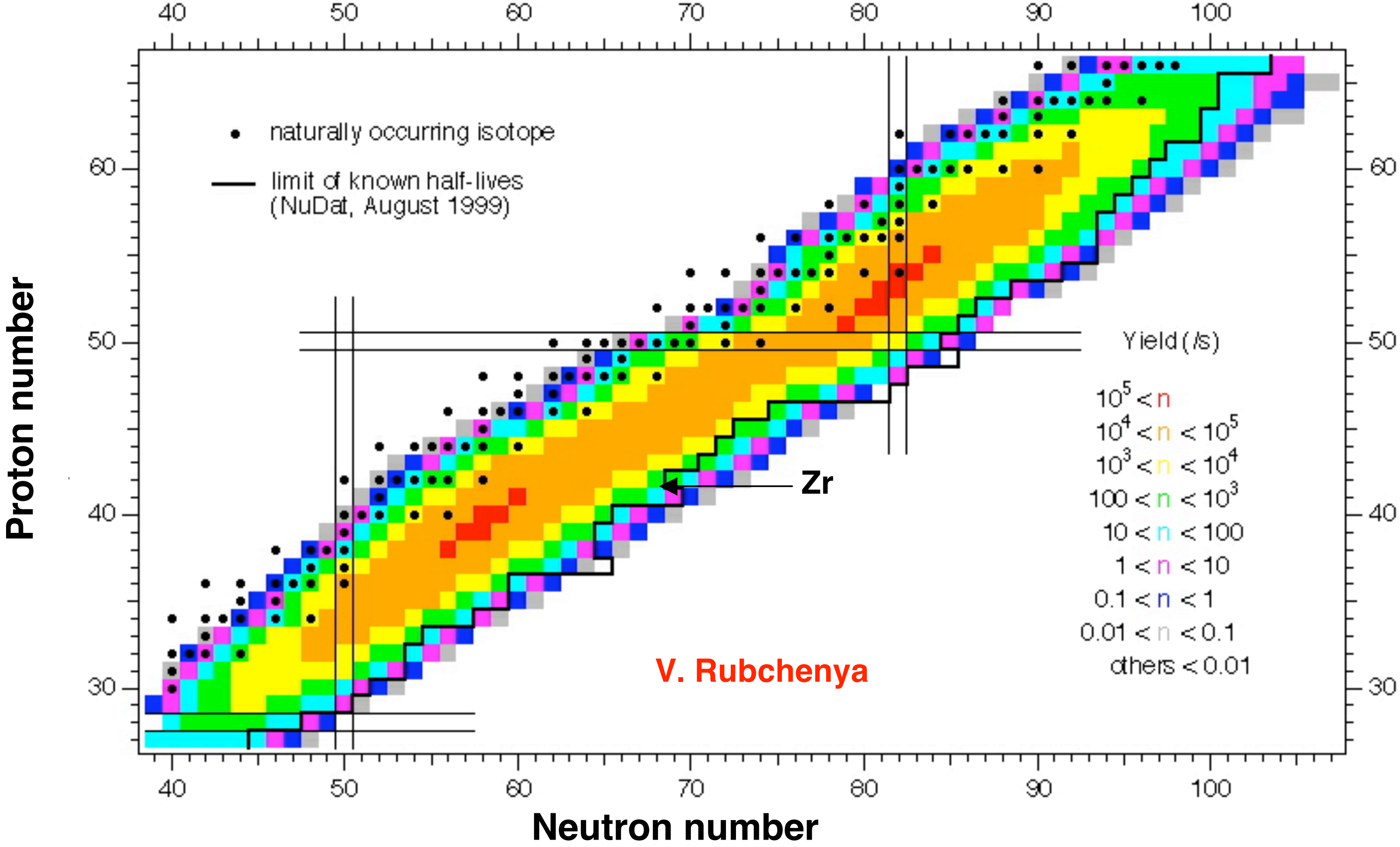
48 minutes

2.2 Experiments with bunched beams

1. Zr isotopes – shape changes near N=50 shell
2. Ce isotopes – shape transition at N=60
3. Neutron-deficient Ti – proton skins?
4. High spin isomers – effect of pairing reduction?

Fission fragment spectroscopy





Fission product yields at IGISOL (25 MeV p + ^{238}U)

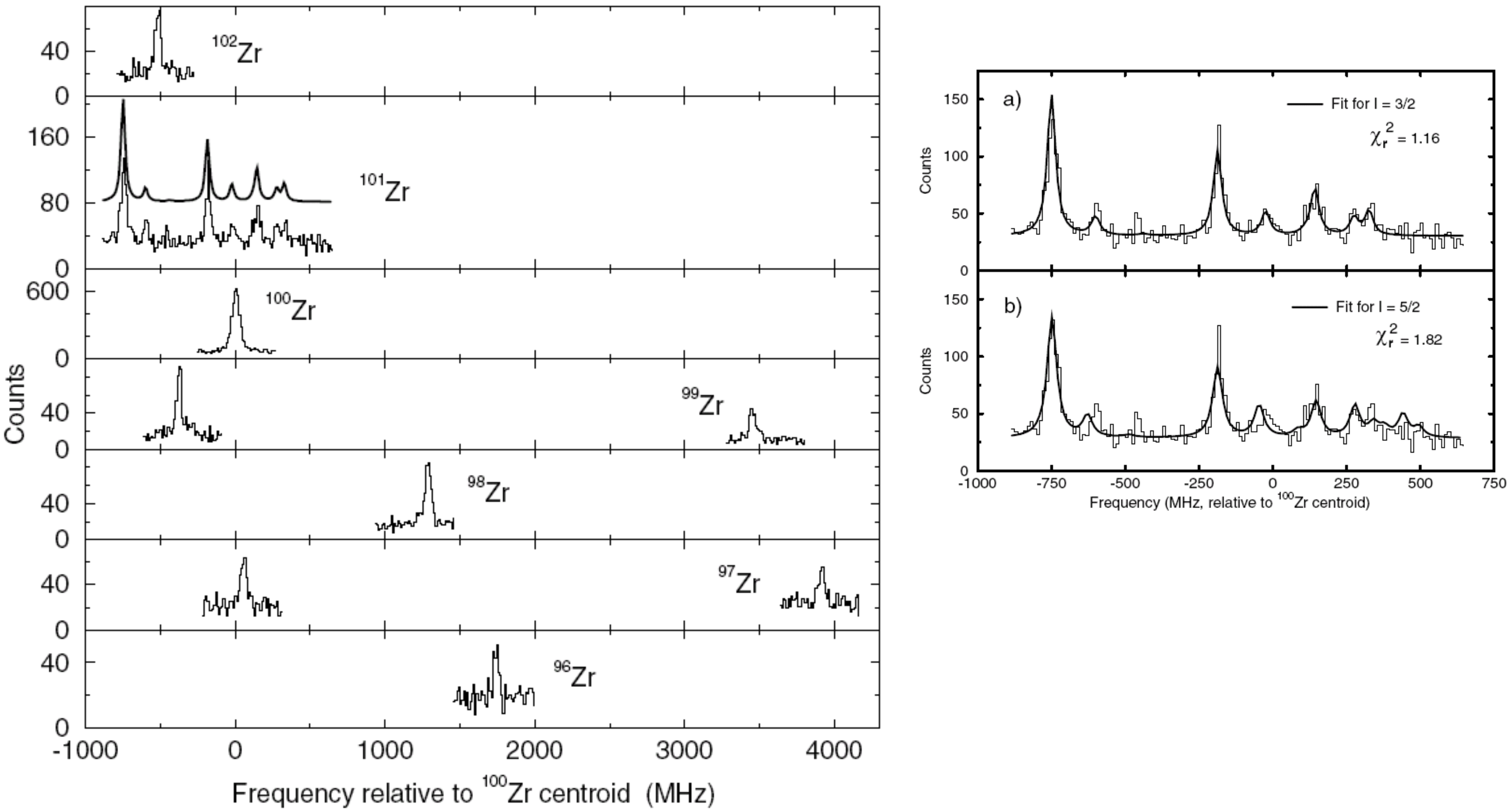
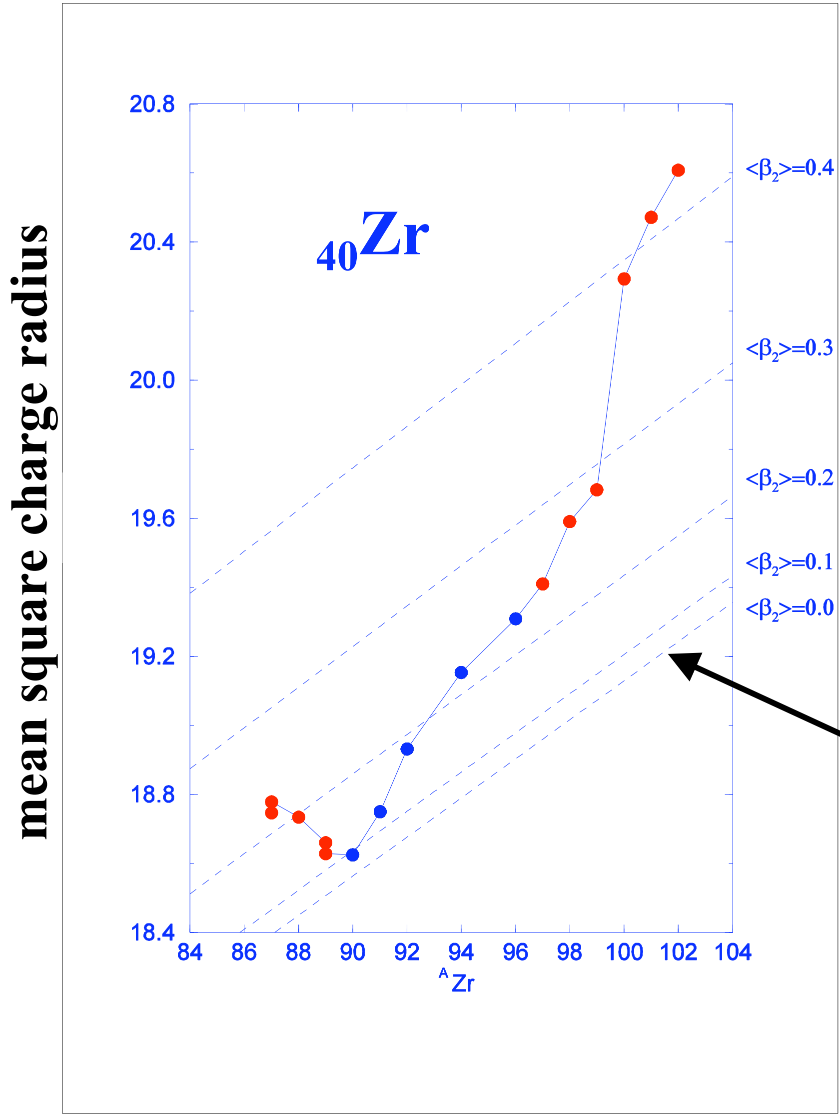


Figure 3. Spectra obtained for the neutron-rich isotopes of zirconium. The fit to ^{101}Zr is shown above the data.

Charge radii of Zr isotopes



Deformed nucleus

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

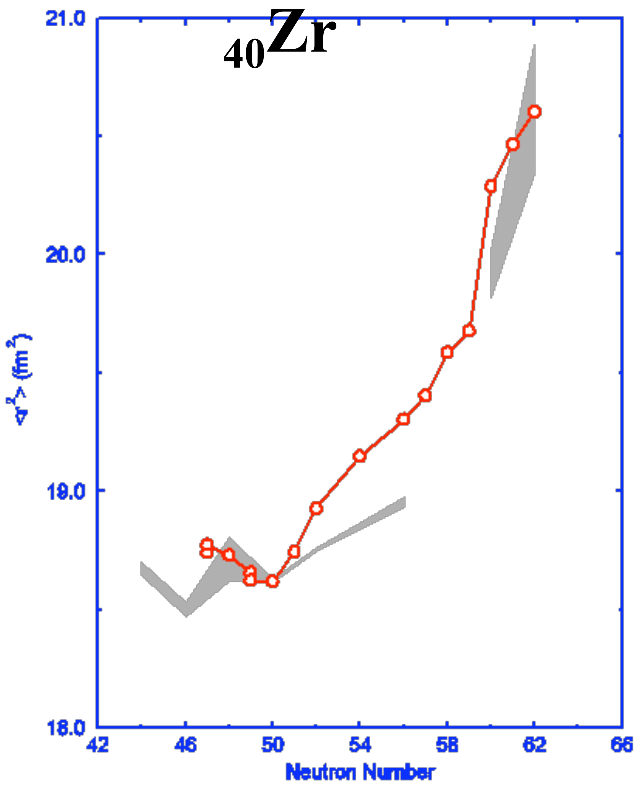
Spherical nucleus

Spherical droplet model

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

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

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

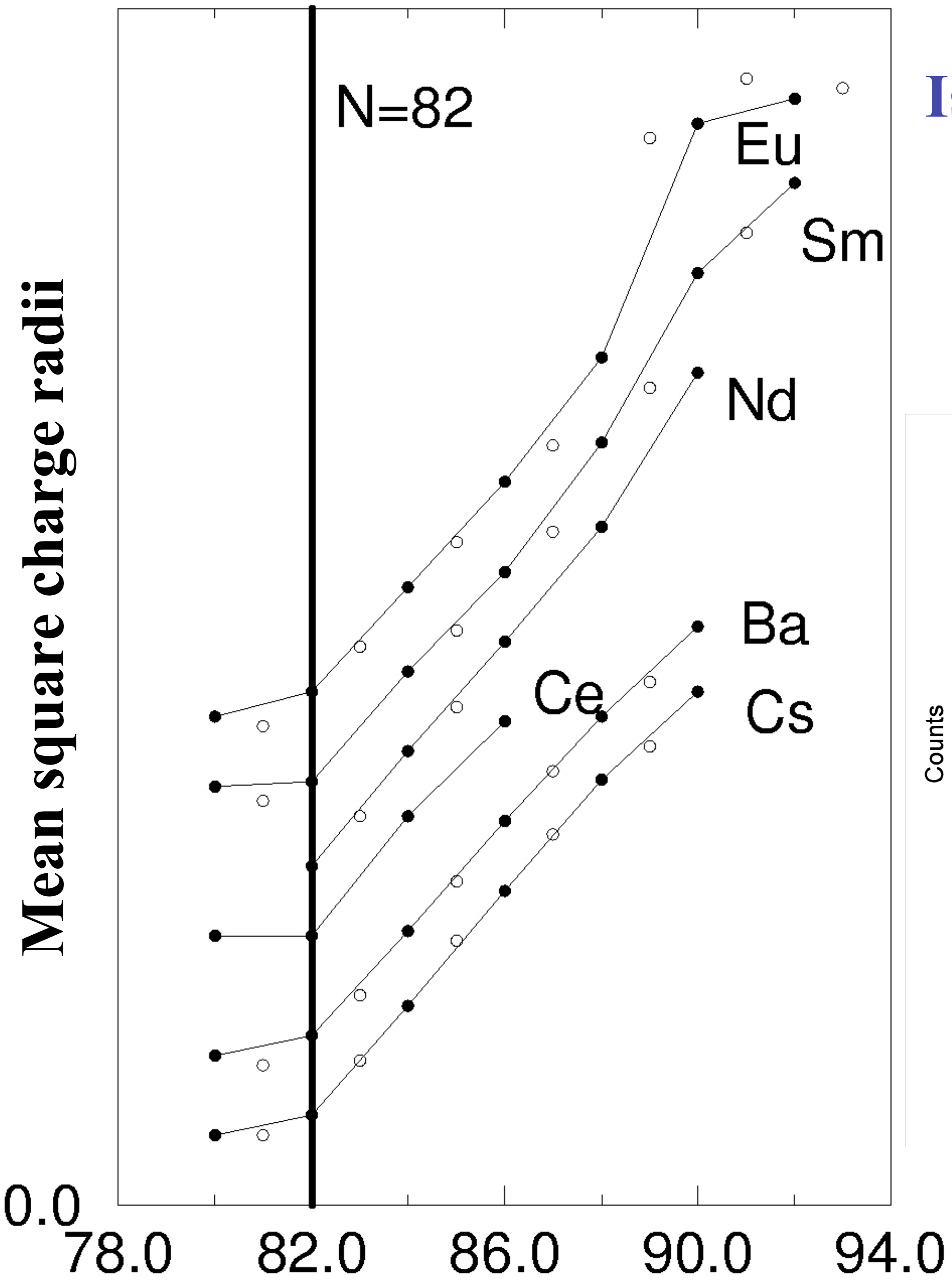


$$\langle \beta_\lambda^2 \rangle = \left(\frac{4\pi}{3ZeR_0^\lambda} \right) \sum_f B(E\lambda; J_{gs} \to J_f)$$

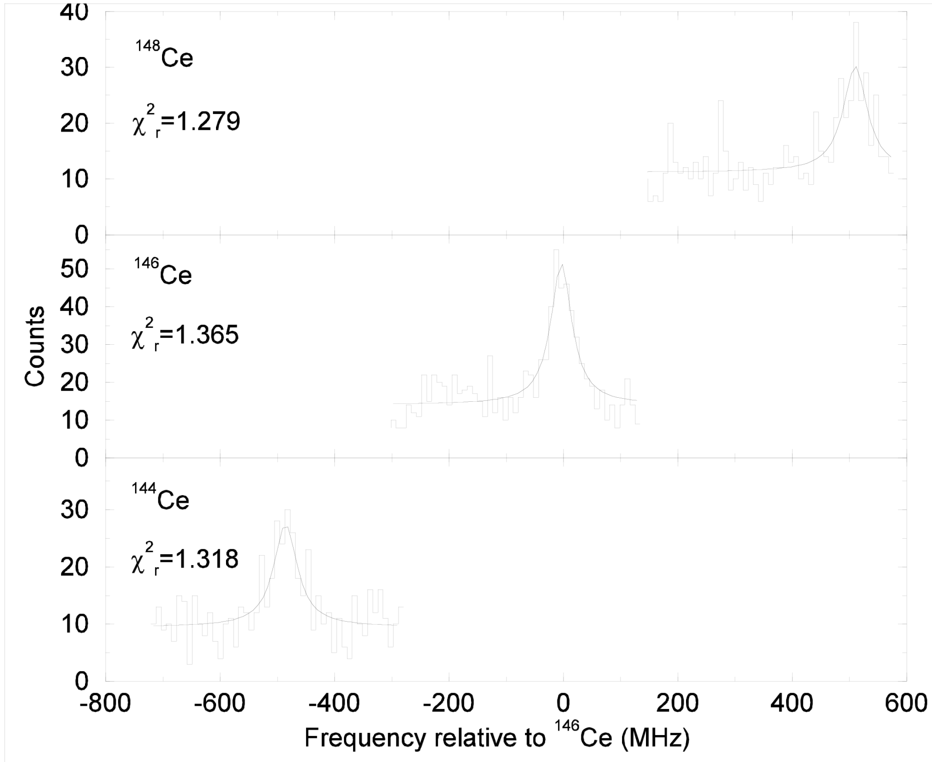
Shaded areas: only B(E2) to the first 2^+ state used.

Should also include higher states and B(E3) strenghts.

Isotope shifts of neutron-rich Ce

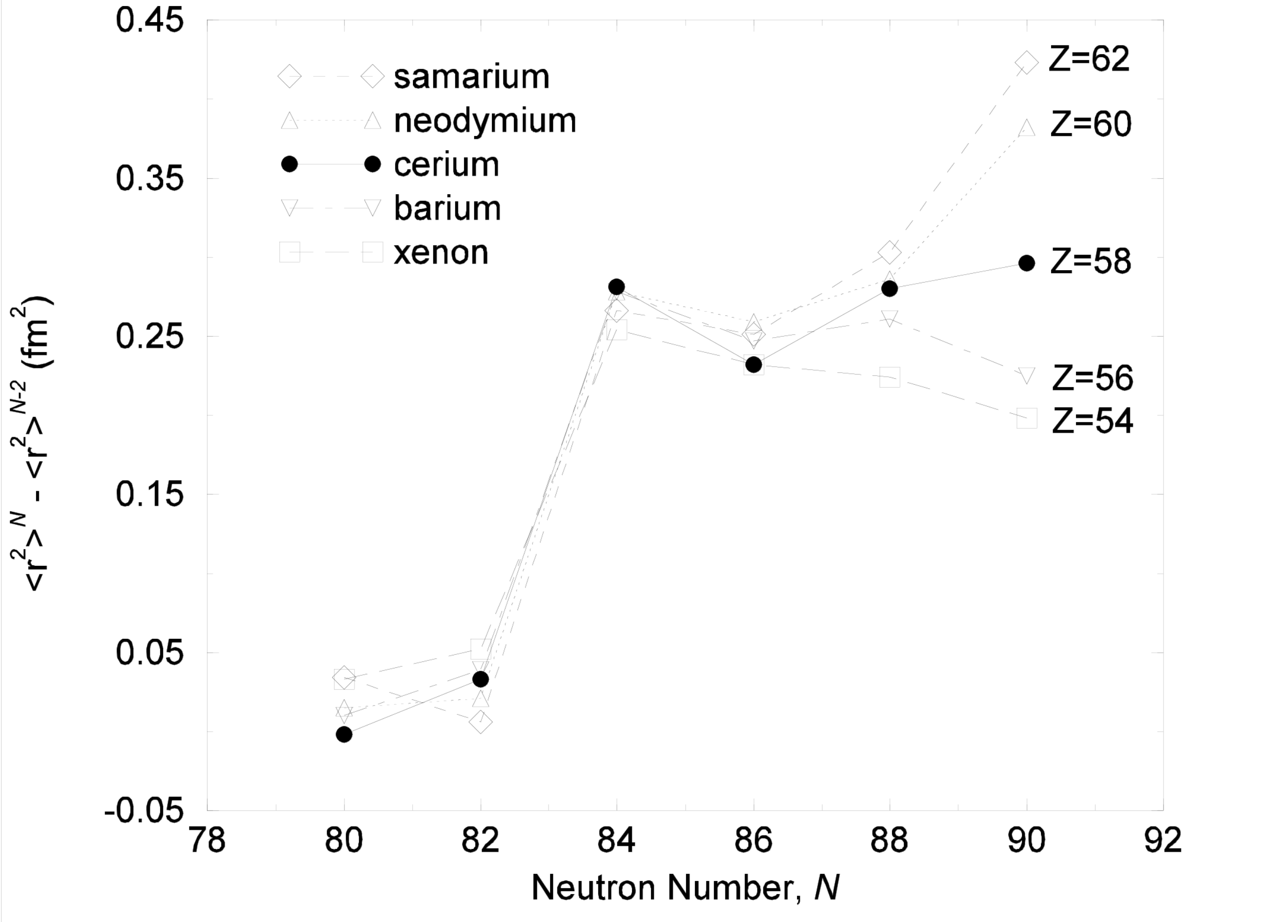


331 nm (Ce^{+})

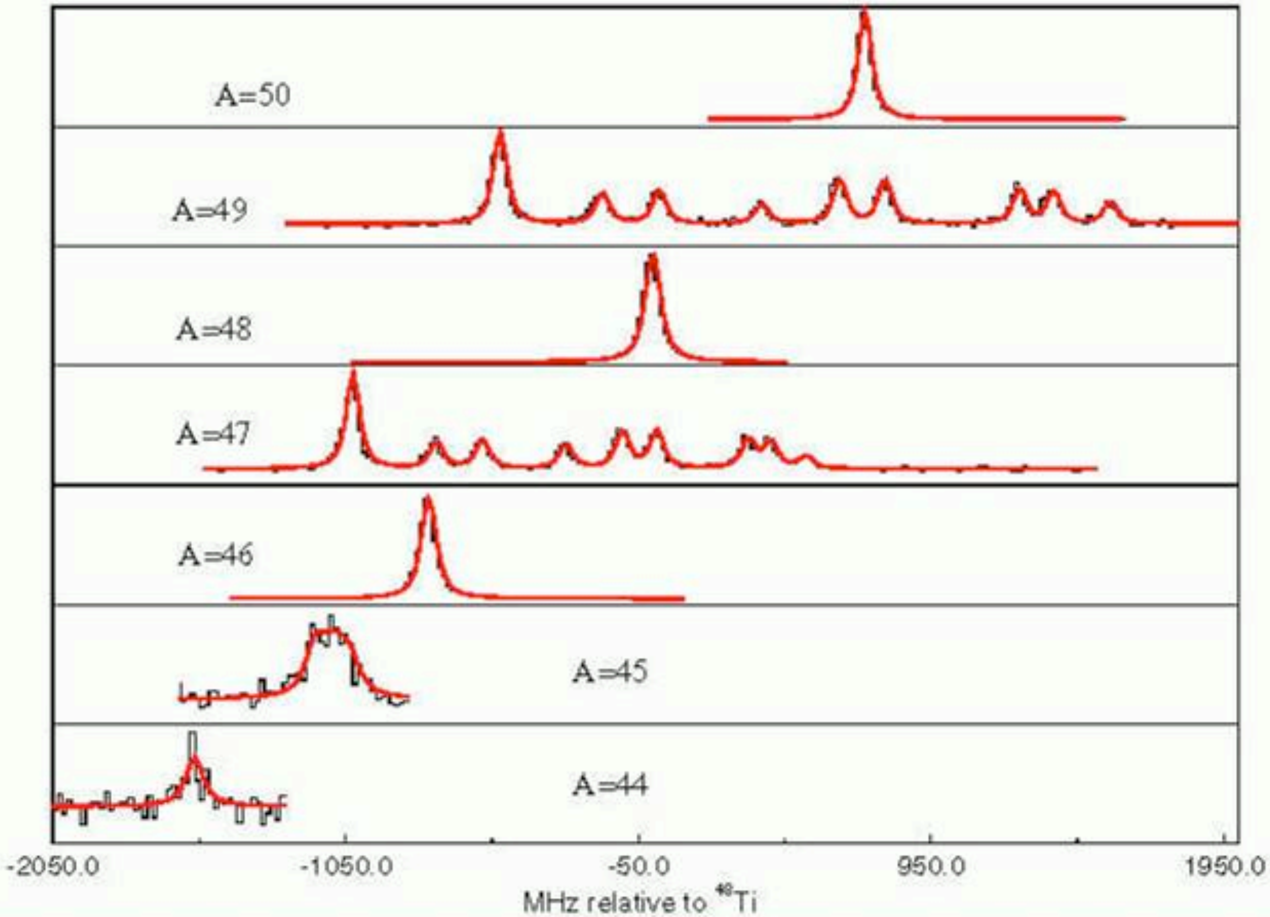


Brix-Kopfermann plot

(differential changes in mean square charge radii)



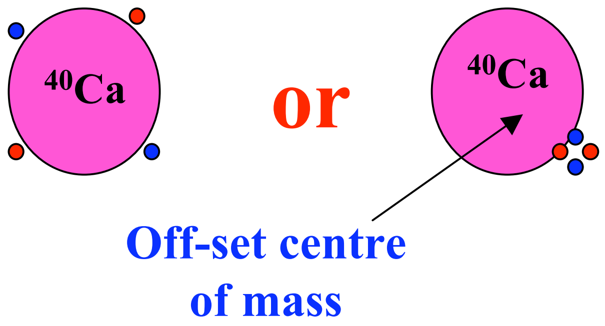
325nm transition in Ti II



Light Ti isotopes

Produced by $^{45}Sc\ (p, xn)\ ^{46-x}Ti$

Is ^{44}Ti an α-cluster nucleus?

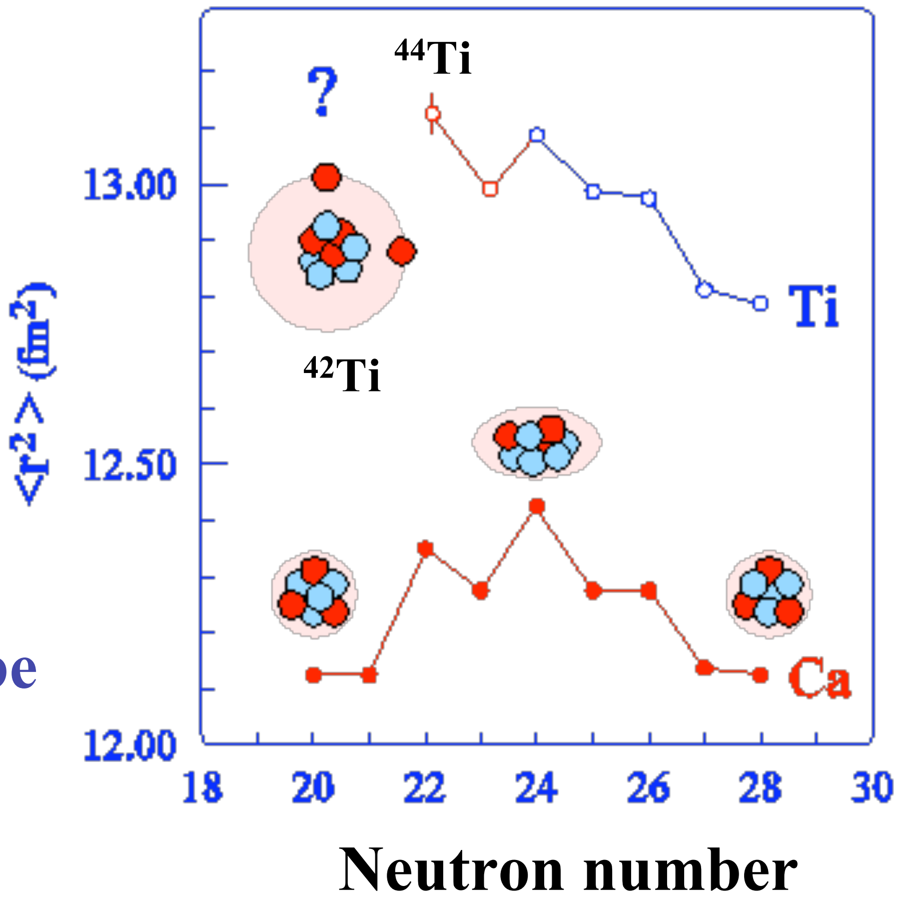


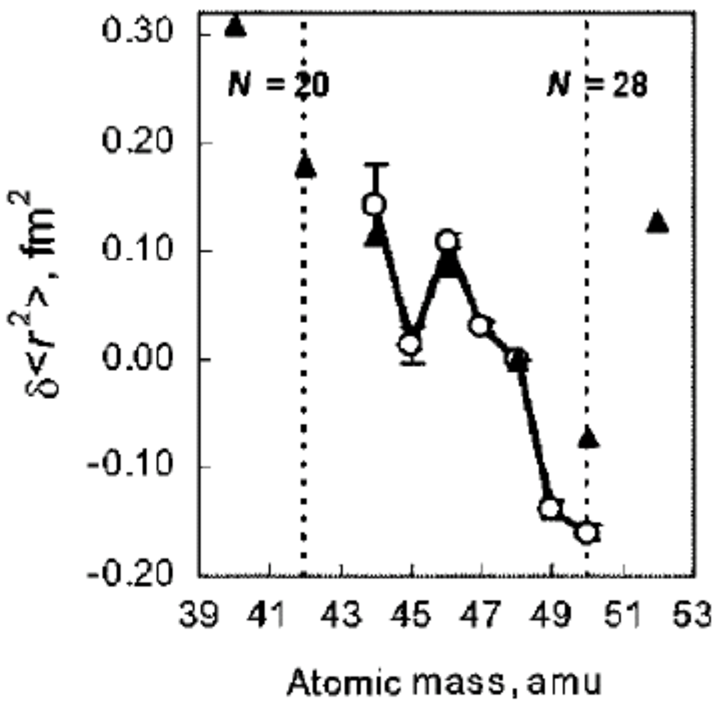
In fact: almost no difference in predicted rms radius!

Does ^{42}Ti have a proton skin?

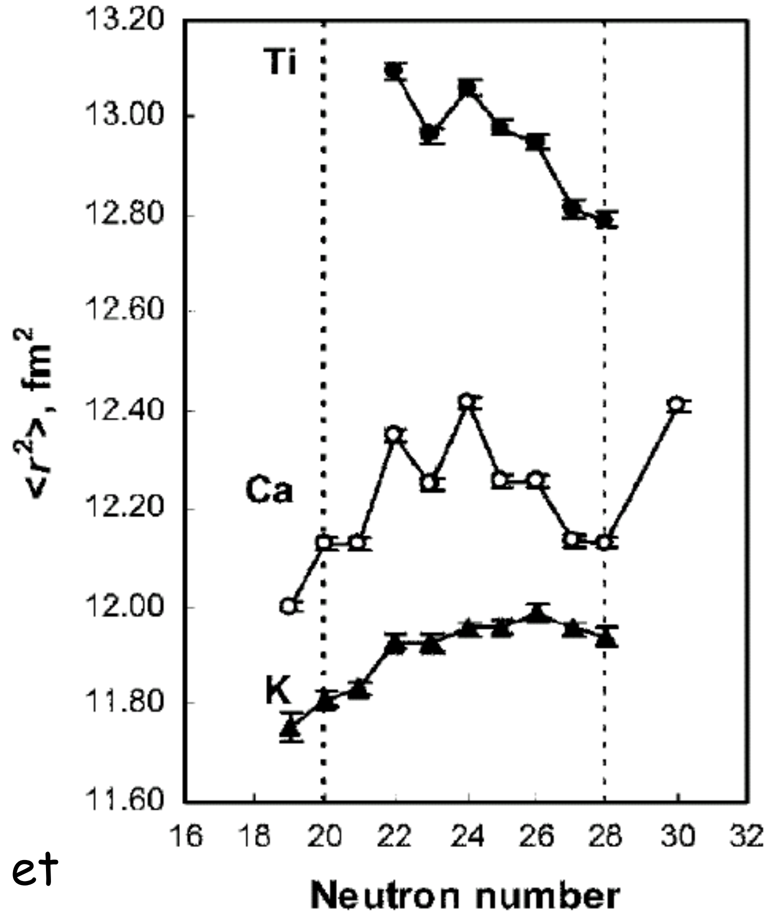
(the laser measurement would be very sensitive to this)

$T_{1/2} = 200$ ms





▲ Comparison with RMF (G. A. Lalazissis et al., Nucl. Phys. A628 (1998) 221



Comparison with neighbouring chains

The K=8 isomers in ^{130}Ba and ^{176}Yb

Structure of ^{178}Hf 16^+ (31 year) isomer

$$\left[\nu\ 7/2\ [514]\ \ \nu\ 9/2\ [624]\ \right]_{(8^-)}\ \left[\pi\ 7/2\ [404]\ \ \pi\ 9/2\ [514]\ \right]_{(8^-)}$$

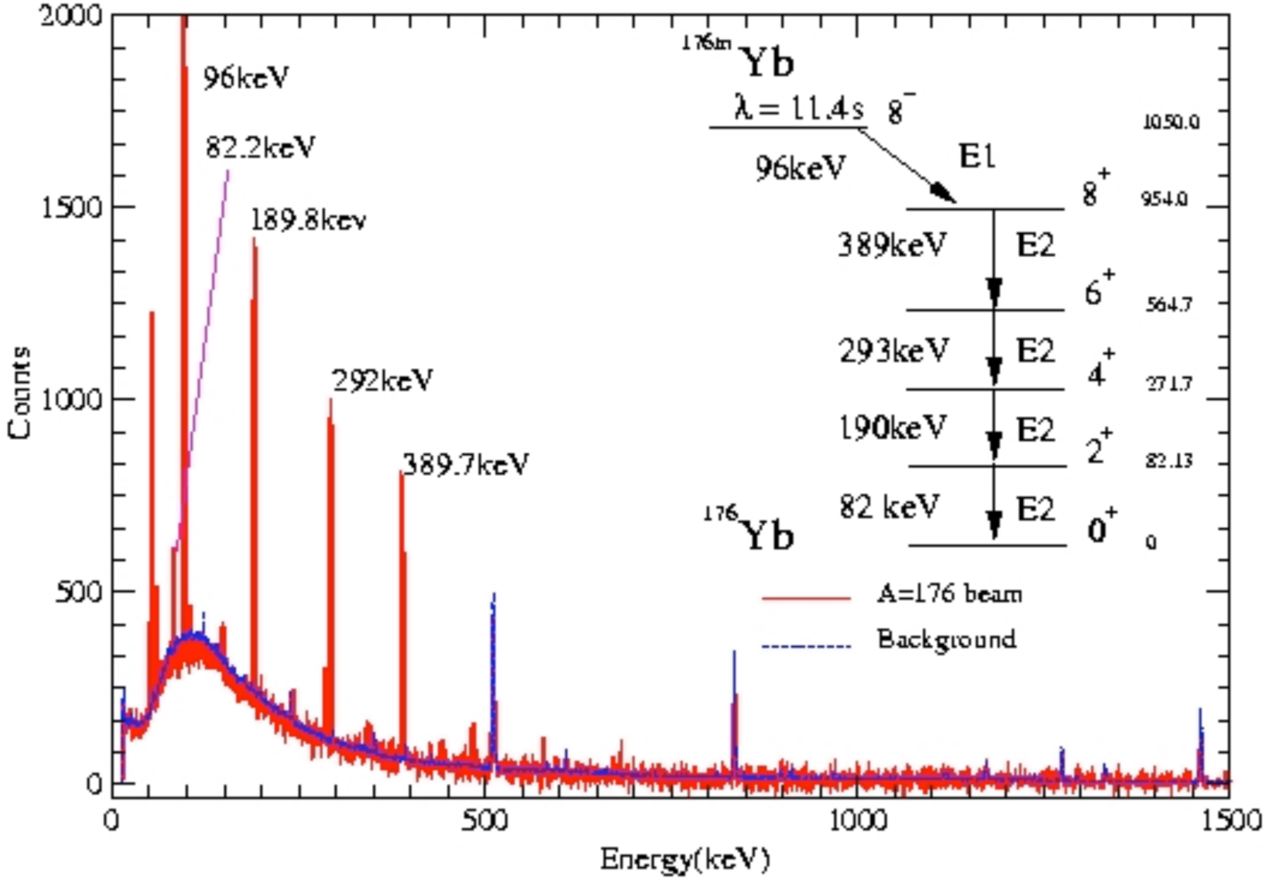
$$(\nu\ h_{9/2})(\nu\ i_{13/2})\quad (\pi\ g_{7/2})(\pi\ h_{11/2})$$

Structure of 2-neutron 8^- state in ^{176}Yb

Intrinsic quadrupole moment and mean square radii for N=106 isomers

Nucleus	State	Q_0 barns	$\langle r^2\rangle^{isomer} - \langle r^2\rangle^{g.s.}$ fm^2	
^{178}Hf	0^+ g.s.	6.961(43)		
	16^+ (4qp)	7.2(1)	–0.076(12)	Boos *et al* (1994)
^{177}Lu	$7/2^+$ g.s.	7.26(6)		
	$23/2^-$(3qp)	7.33(6)	–0.035(4)	Georg *et al* (1998)

The ^{176}Yb K=8 isomer

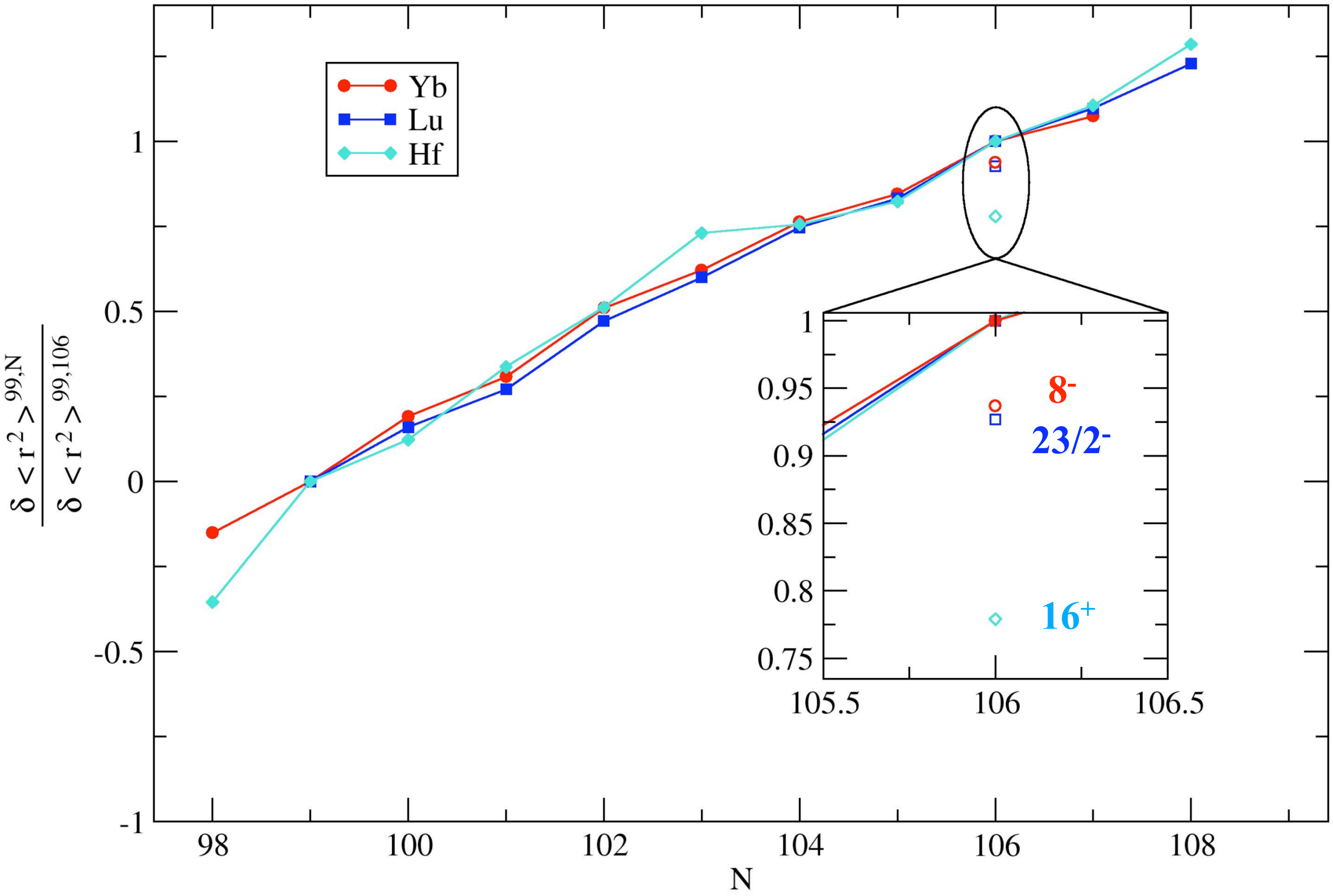


Production: (d,pn) at 13 MeV, 5.5 μA

Flux: 200 isomers/sec (total flux at A=176: 8,400 ions/sec)

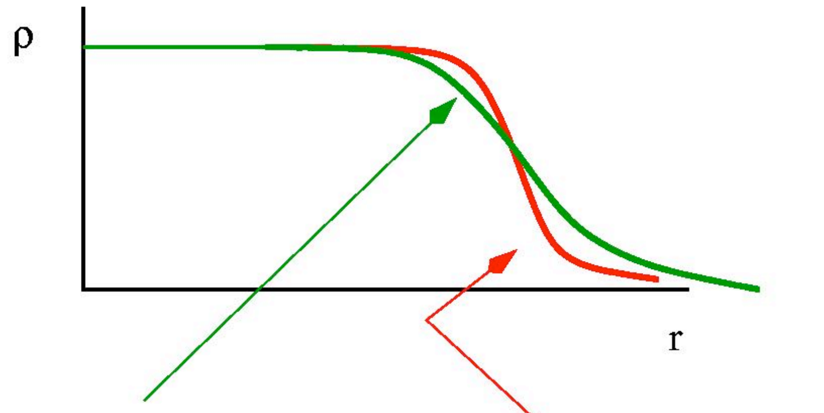
Experimental Deformation Parameters for Neighbouring Yb Isotopes

Nucleus	State	Q_0 barns	β_2
^{175}Yb	$7/2^-$ g.s.	7.52(11)	0.286(4)
^{176}Yb	0^+ g.s.	7.40(5)	0.280(2)
^{176}Yb	8^- (2qp)	7.54(11)	0.285(4)
^{177}Yb	$9/2^+$ g.s.	7.37(11)	0.278(4)



Yb
Lu
Hf
8-
23/2-
16+
105.5
106
106.5
1
0.95
0.9
0.85
0.8
0.75
98
100
102
104
106
108
N
1
0.5
0
-0.5
-1
$\frac{\delta <r^2>^{99,N}}{\delta <r^2>^{99,106}}$

Diffuseness of nuclear surface the 16^+ isomer in 178–Hf



Ground state	High–K isomer

Ground state	High–K isomer
pairing correlations	deformation alignment of 4 quasiparticles
↓	↓
wavefunction widely spread involving all levels near Fermi level.	blocking effect reduces pairing correlations
	↓
$\Psi = \|\phi\rangle + \sum \beta \,\|\, 2p - 2h \rangle$	less diffuse surface

	neutrons	protons		rms radius
9/2+	______	______	9/2–	6.008 fm
λ	....	....		
7/2–	______	______	7/2+	5.381 fm

Calculation by Bordeaux Group (Quentin, Pillet, Libert)

Without pairing effects,
Isomer shift = +0.092 fm^2

Including pairing
Isomer shift = -0.086 fm^2

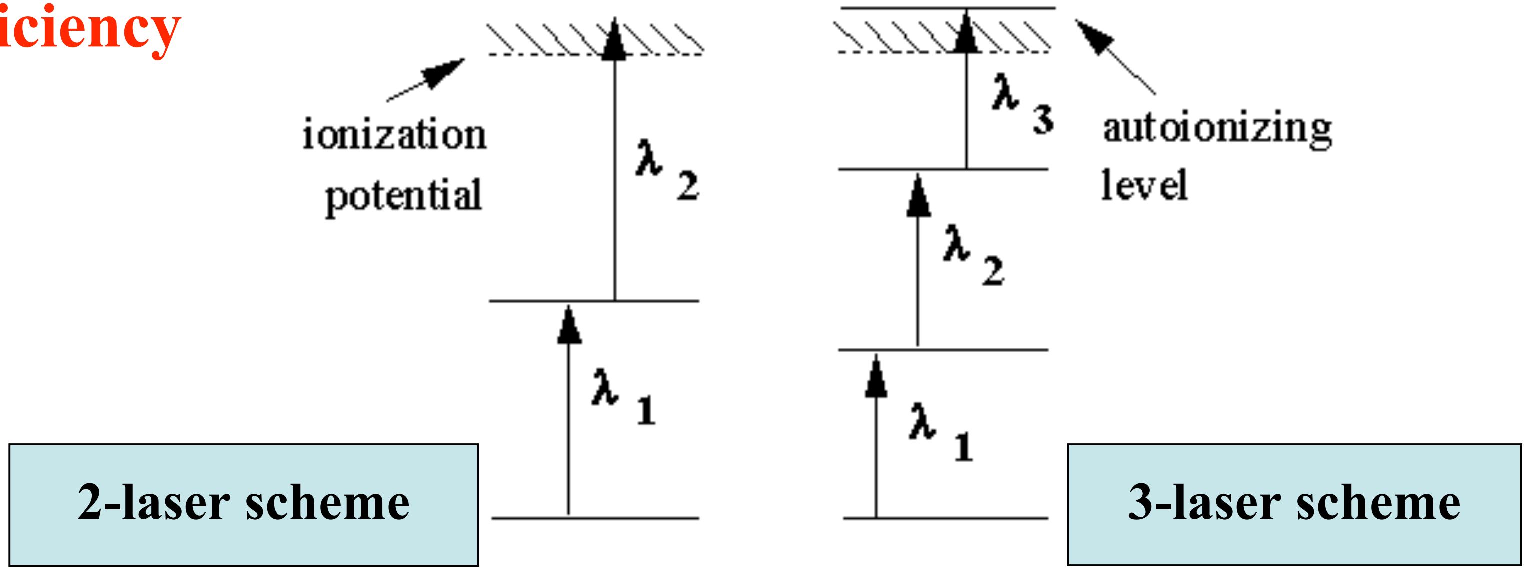
(Experiment: -0.076(12) fm^2)

Explaining ^{178}Hf (16^{+}) isomer shift

- Similar features now found in 4 isomers: smaller radius than ground state, but not due to reduction in deformation.
- Effect greatest for 4qp state.
- Effect for 2qp isomer is about twice the normal odd-even staggering (a 1qp effect?).

New development: Laser ion source FURIOS (using laser resonance ionization)

Powerful pulsed lasers can be tuned to ionize neutral atoms of a selected element with high efficiency

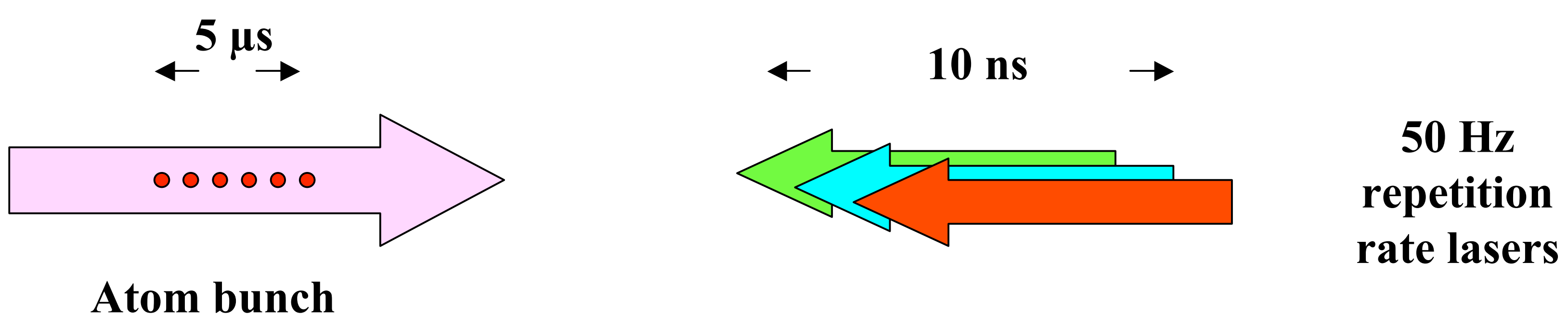


Applications:

Laser ion sources – beams selected by mass *and* atomic number

Ultra-high sensitivity laser spectroscopy – collinear beams RIS

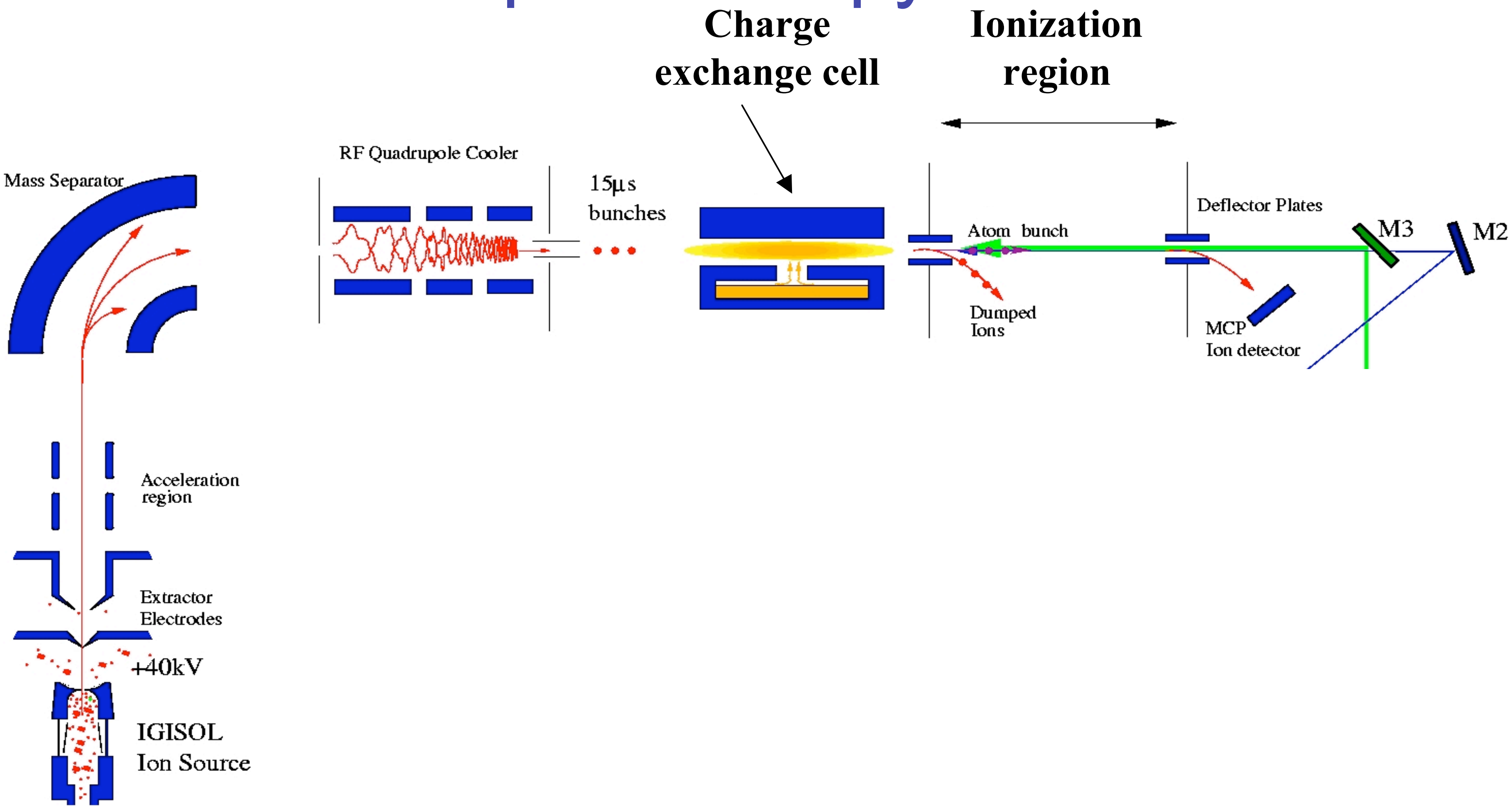
The CRIS method



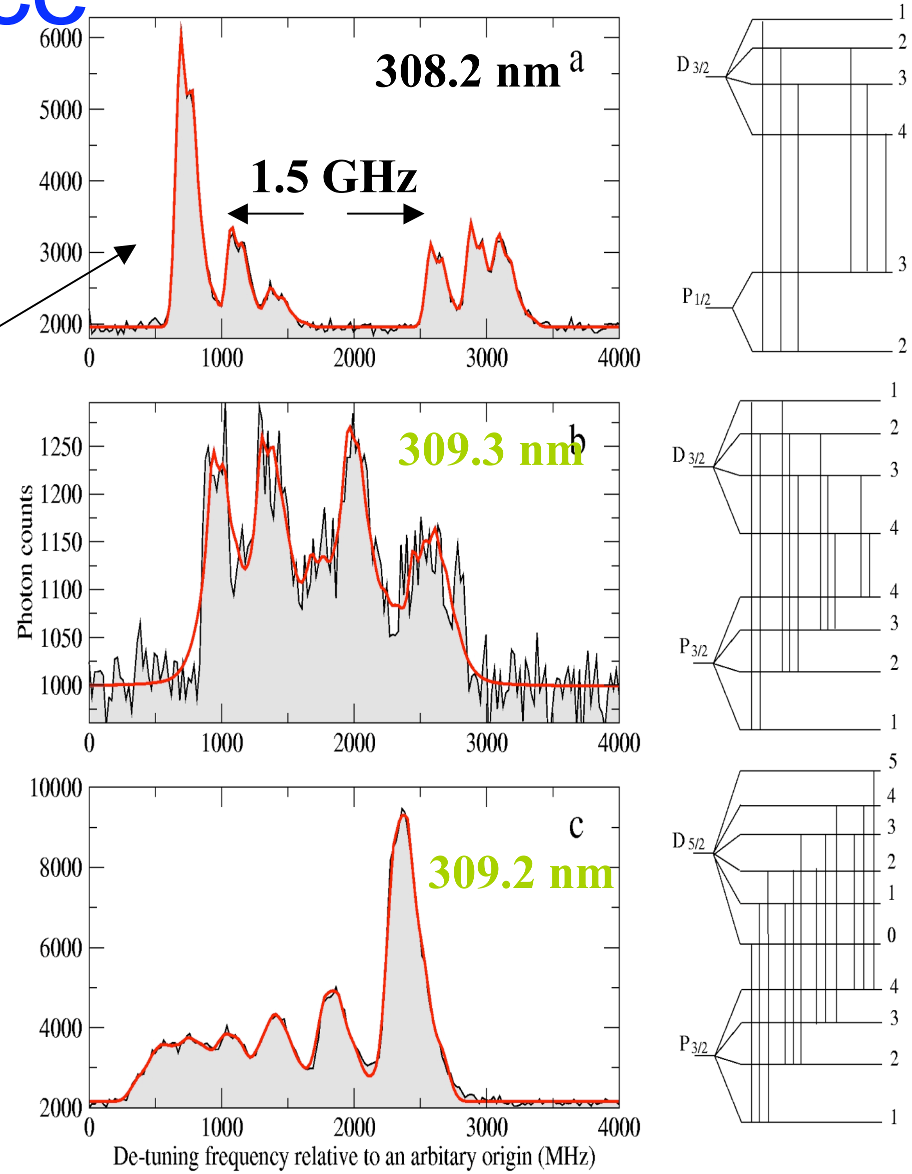
50 Hz delivery rate, synchronized with laser pulse

- All atoms from the ion source have a chance to be ionized
- Resonance located by ion counting (not photon counting)
- Doppler-broadening free

Collinear resonance ionization spectroscopy



Laser fluorescence spectra – ^{27}Al

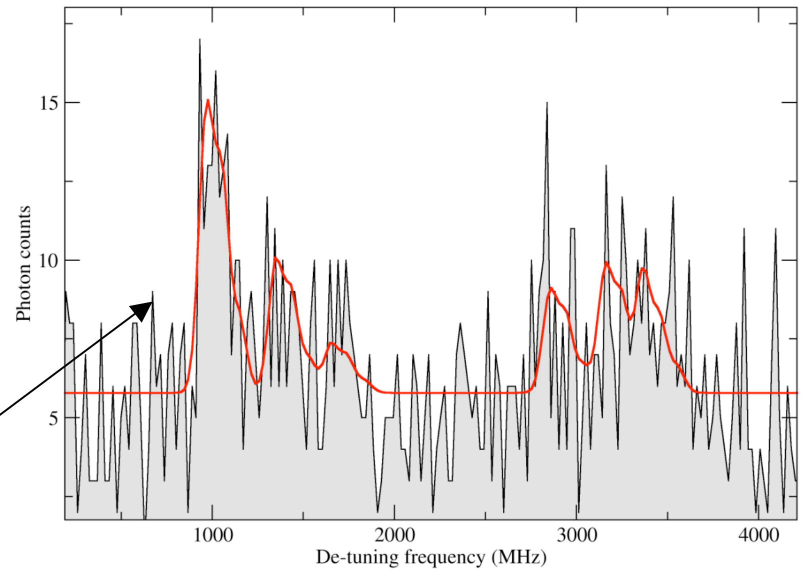


Detection efficiency:

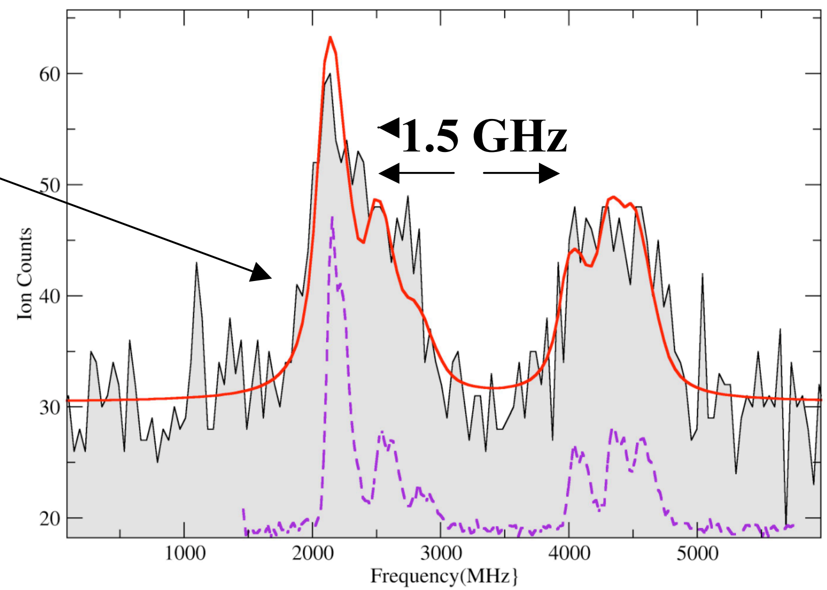
1 photon detected per 50,000 atoms in beam

Comparison with low-flux bunched beams

Photon counting (12 minutes)



Ion counting (4 minutes)

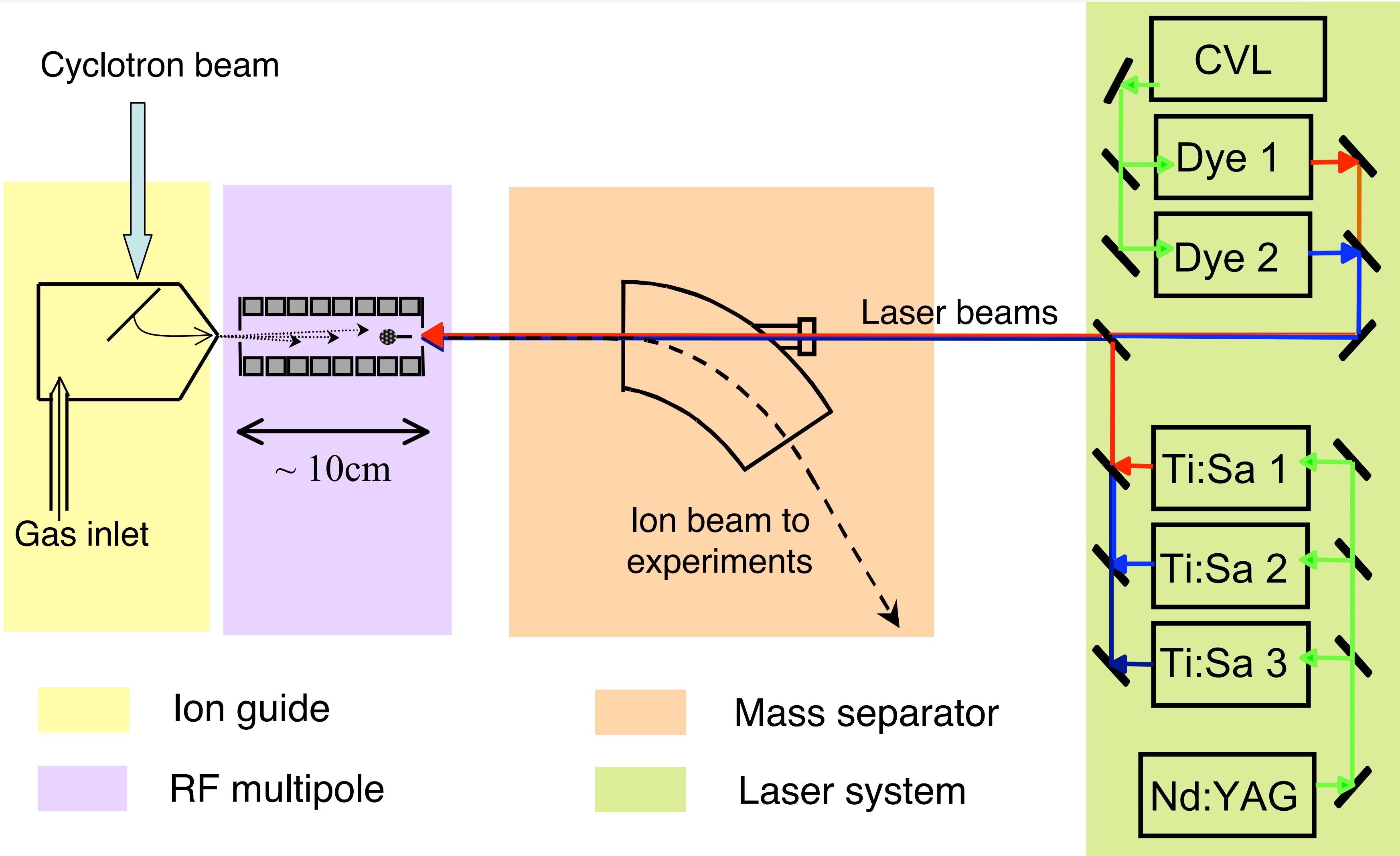


Sensitivity:

1 resonance ion per 30 atoms within 1 μs time window

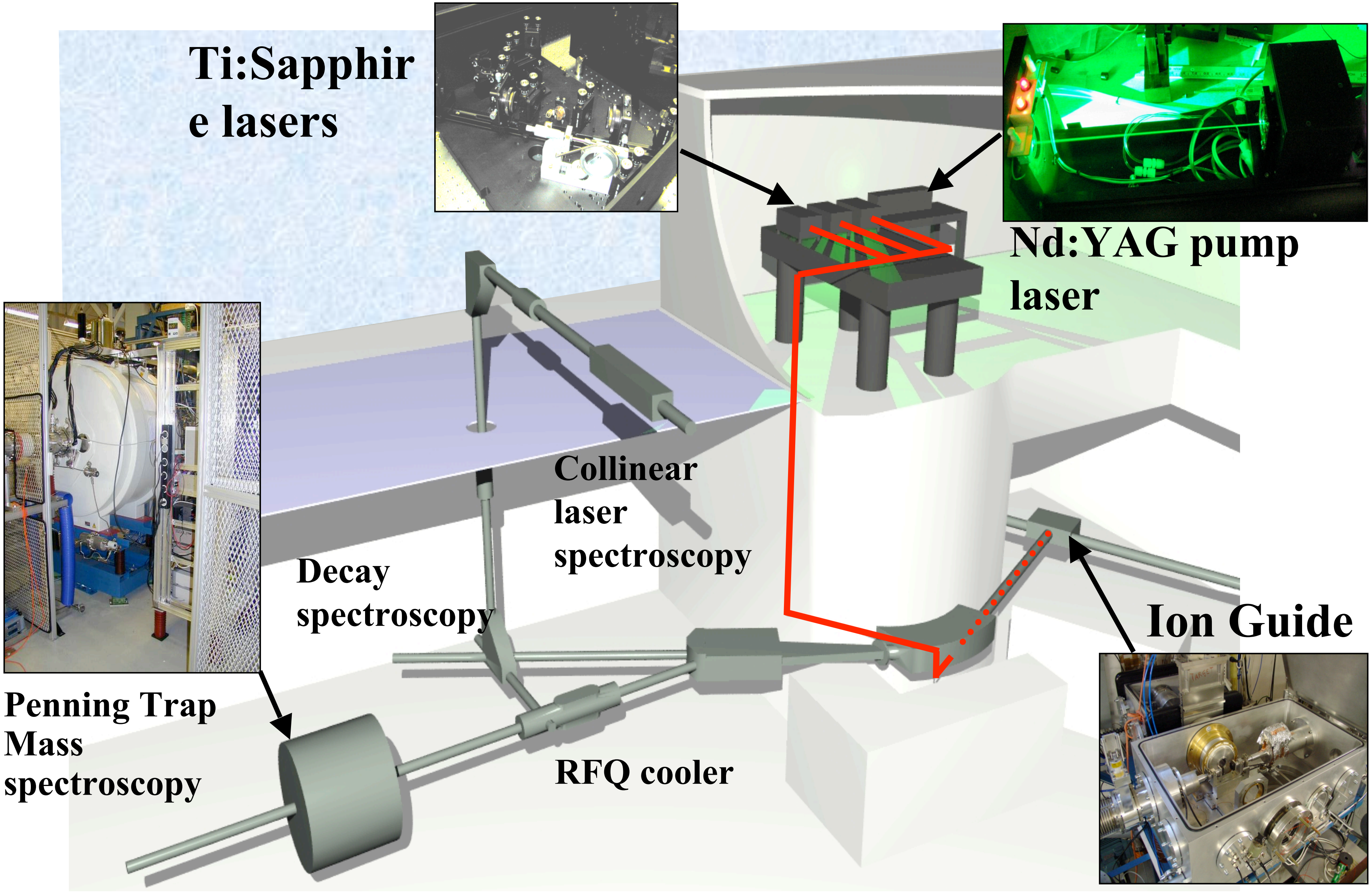
(compared with 1 photon per 50,000 atoms)

Laser transportation and atom beam overlap



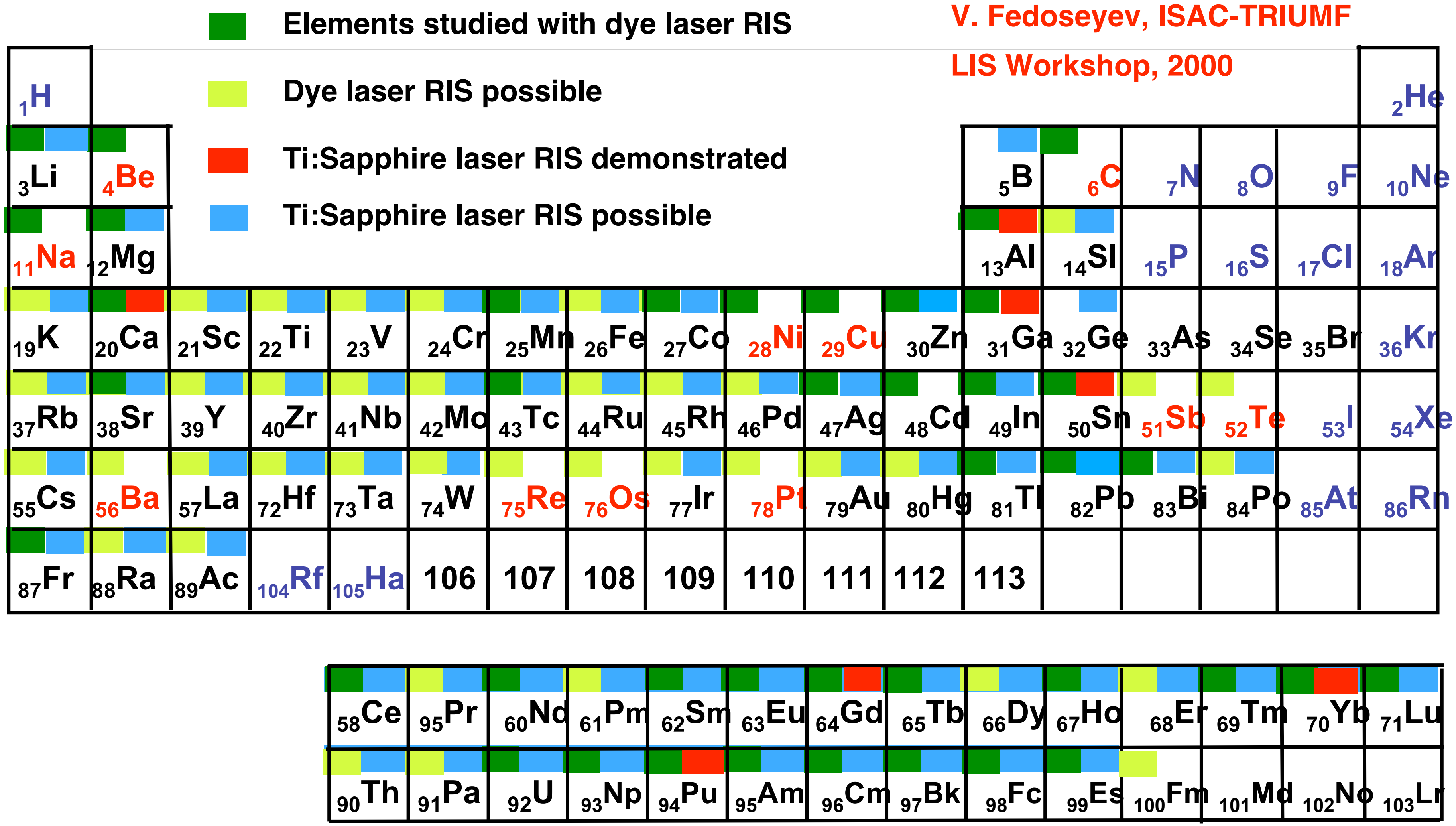
FURIOS

(Fast Universal Resonant laser IOn Source)



Accessibility of elements using lasers

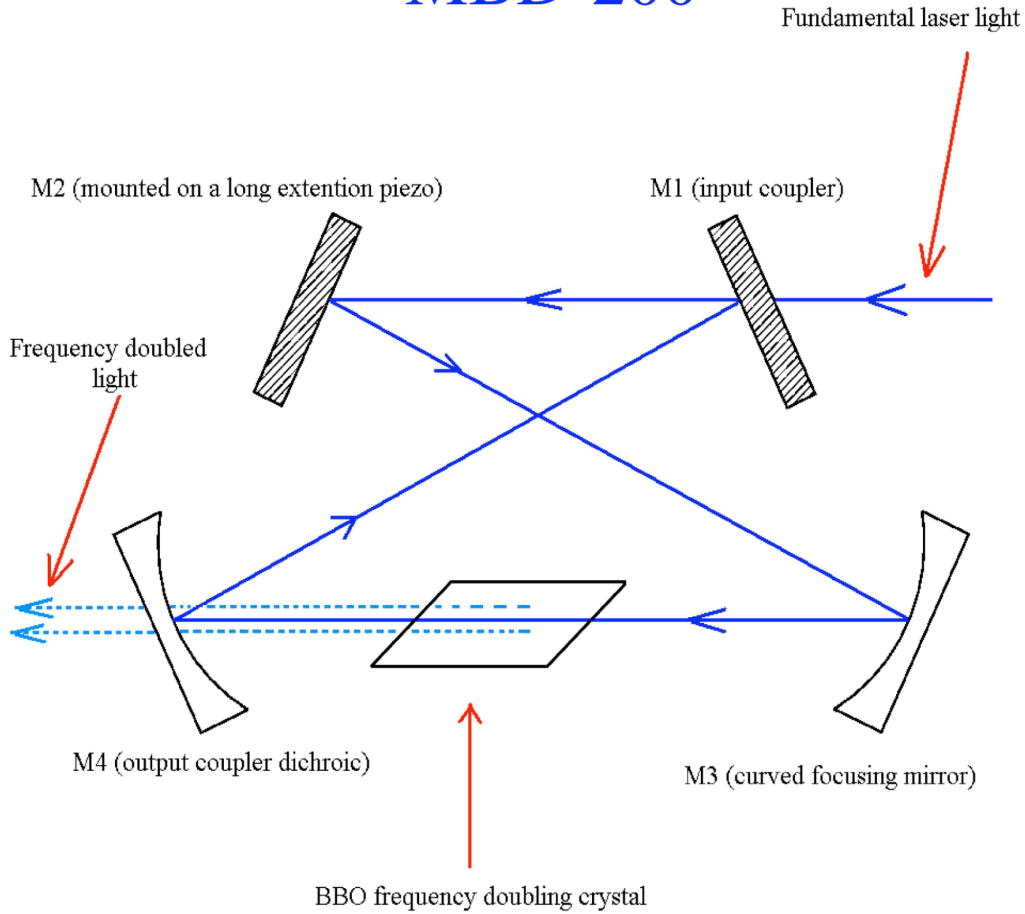
V. Fedoseyev, ISAC-TRIUMF
LIS Workshop, 2000

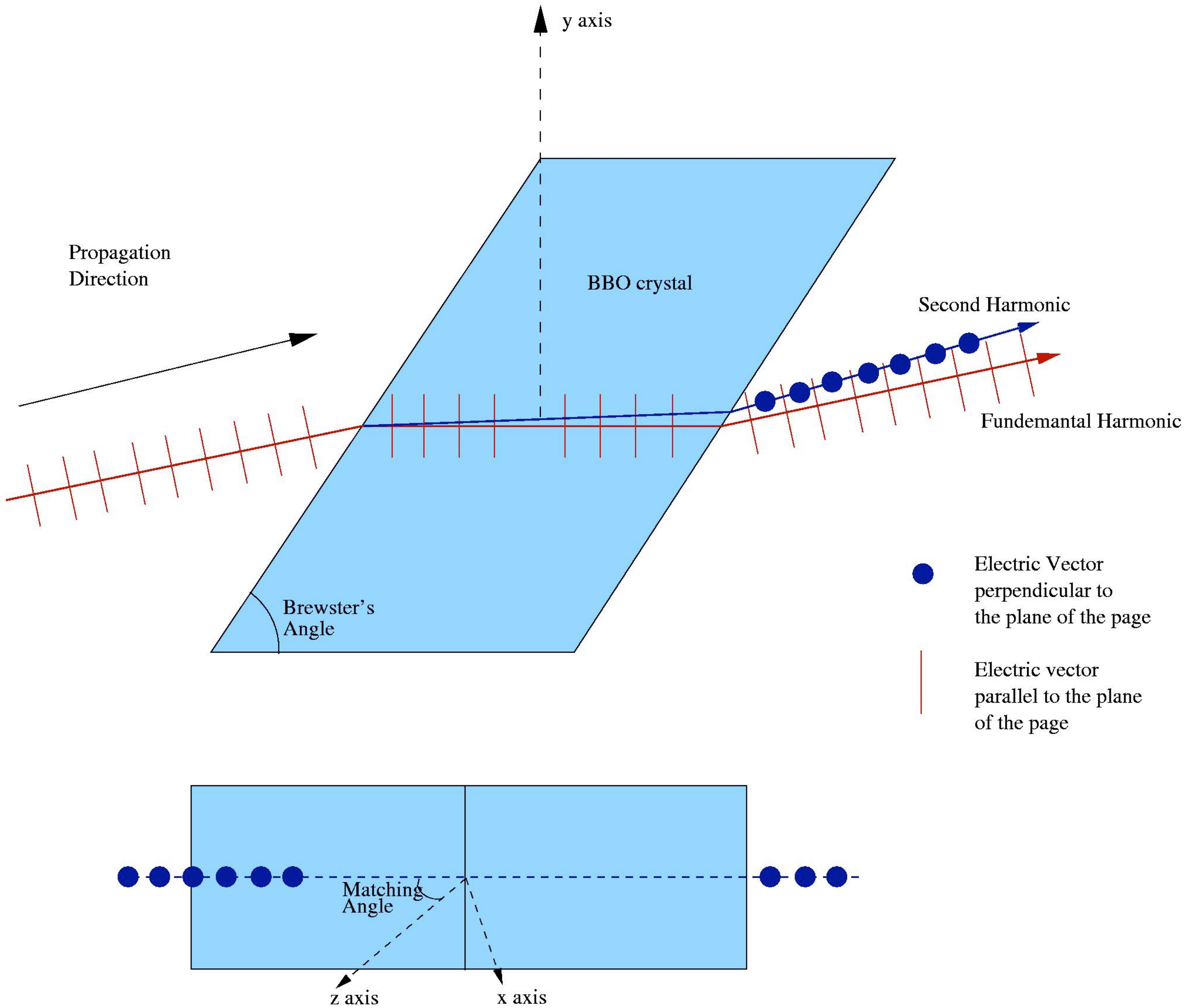


NIPNET meeting, Saariselka, April 2004

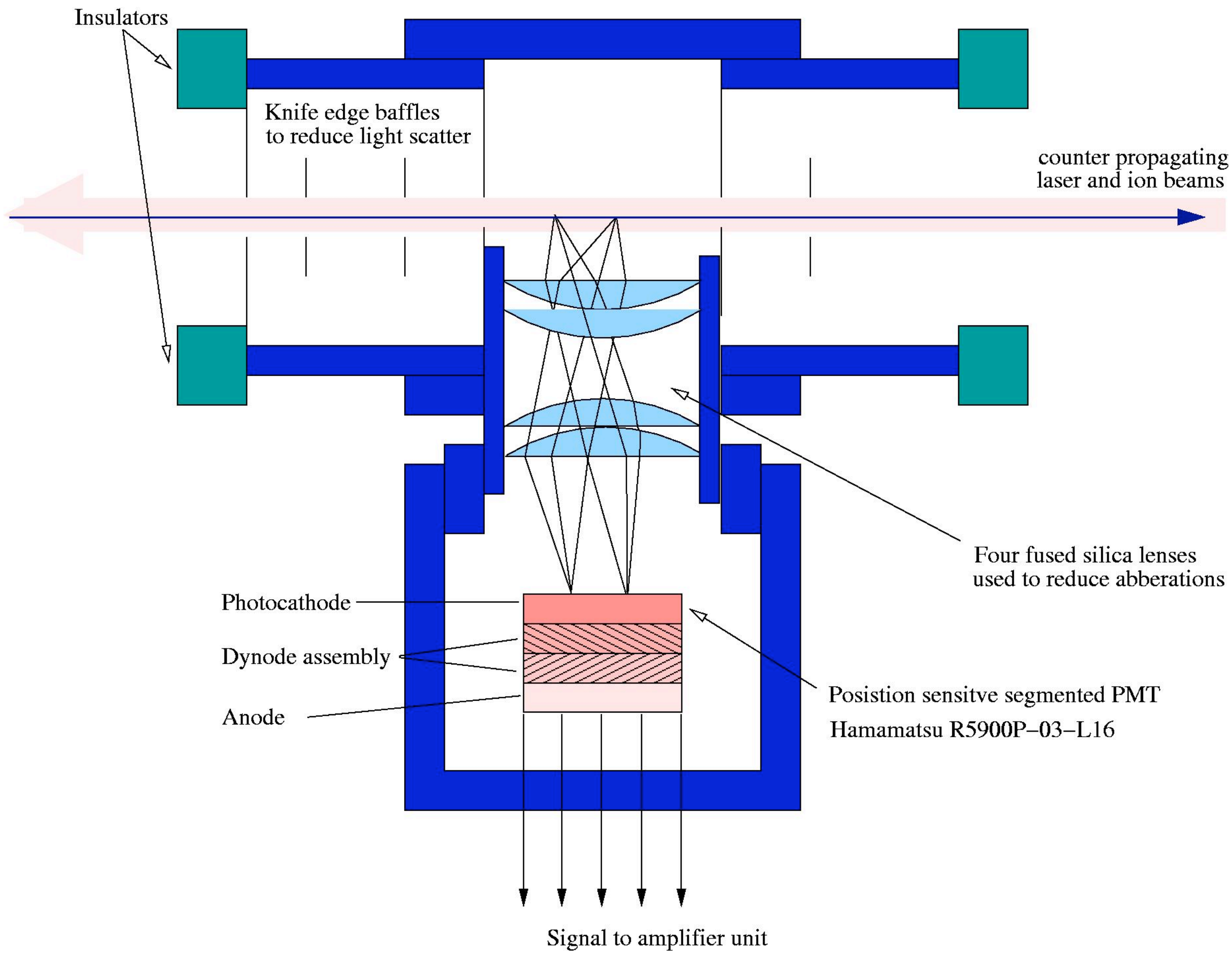
End of Lecture 2

Simplified schematic of MBD-200





y axis
Propagation
Direction
BBO crystal
Second Harmonic
Fundemantal Harmonic
Brewster's
Angle
Electric Vector
perpendicular to
the plane of the page
Electric vector
parallel to the plane
of the page
Matching
Angle
z axis
x axis


Insulators
Knife edge baffles
to reduce light scatter
counter propagating
laser and ion beams
Four fused silica lenses
used to reduce abberations
Photocathode
Dynode assembly
Anode
Posistion sensitve segmented PMT
Hamamatsu R5900P−03−L16
Signal to amplifier unit