Towards a Nuclear Charge Radius Determination of the One-Neutron Halo Nucleus ^{11}Be

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BeTINa Collaboration

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Outline

- Isotope shift method
- Collinear laser spectroscopy
- Experimental setup
- Beamtime
- Preliminary results

Isotope Shift

$$\Delta\nu_{IS} = \Delta\nu_{MS} + \Delta\nu_{FS} \rightarrow \underbrace{\frac{2\pi Z}{3}\Delta|\psi(0)|^2}_{\text{field shift coefficient C}}\delta\langle r^2\rangle$$

$\approx$10 GHz $\approx$5 MHz

field shift coefficient C

$\Delta\nu_{IS}$ - experiment

$\Delta\nu_{MS}$ - theory, up to 3-electron system $\Rightarrow$ Be^+

Li: C = 1.566 MHz/fm^2

Yan and Drake, PRA 61, 022504 (2000)

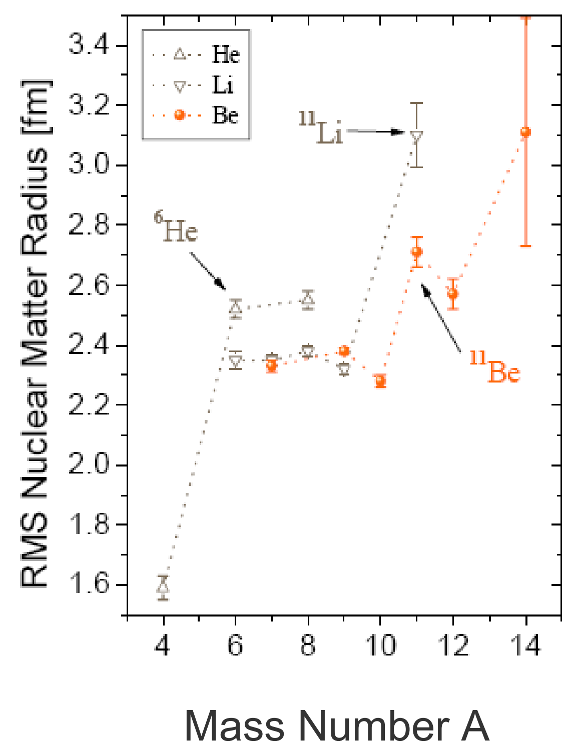
Be^+: C = 16,912 MHz/fm^2

Yan, Nörtershäuser, Drake, PRL 100, 243002 (2008)

Beryllium Properties

Isotope	I	μ_I/μ_N	Lifetime	$<r_c^2>^{1/2}$/ fm
^{7}Be	3/2	1.398 (15)	53.1 d	
^{9}Be	3/2	1.7749(2)	Stable	2.519(12)[(1)] 2.390(170)[(2)]
^{10}Be	0	0	1.5×10^6 a	
^{11}Be	1/2	1.6814(13)	13.8 s	
^{12}Be	0	0	23.6 ms	
^{14}Be	0	0	4.35 ms	

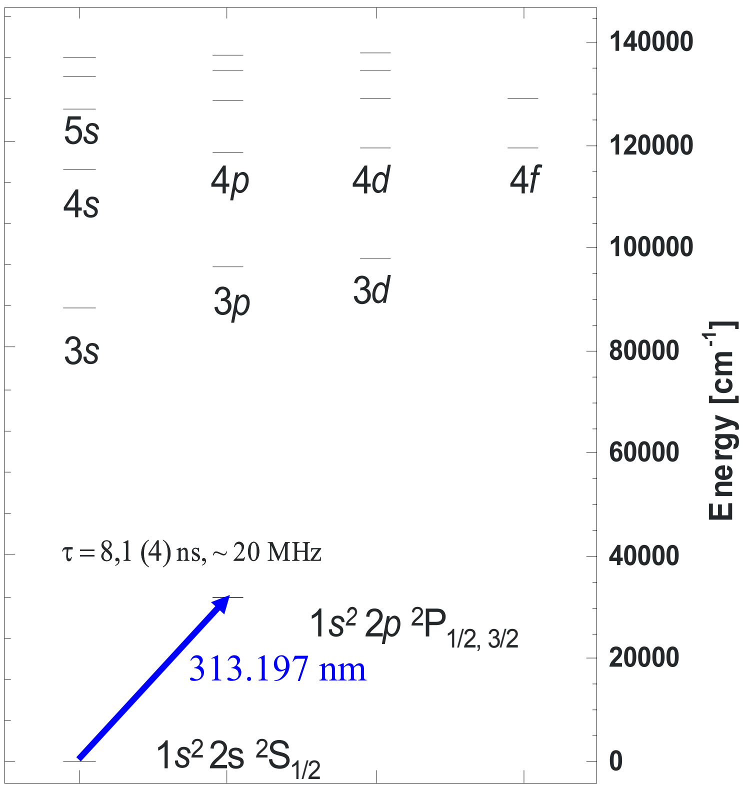
Interaction Cross Section

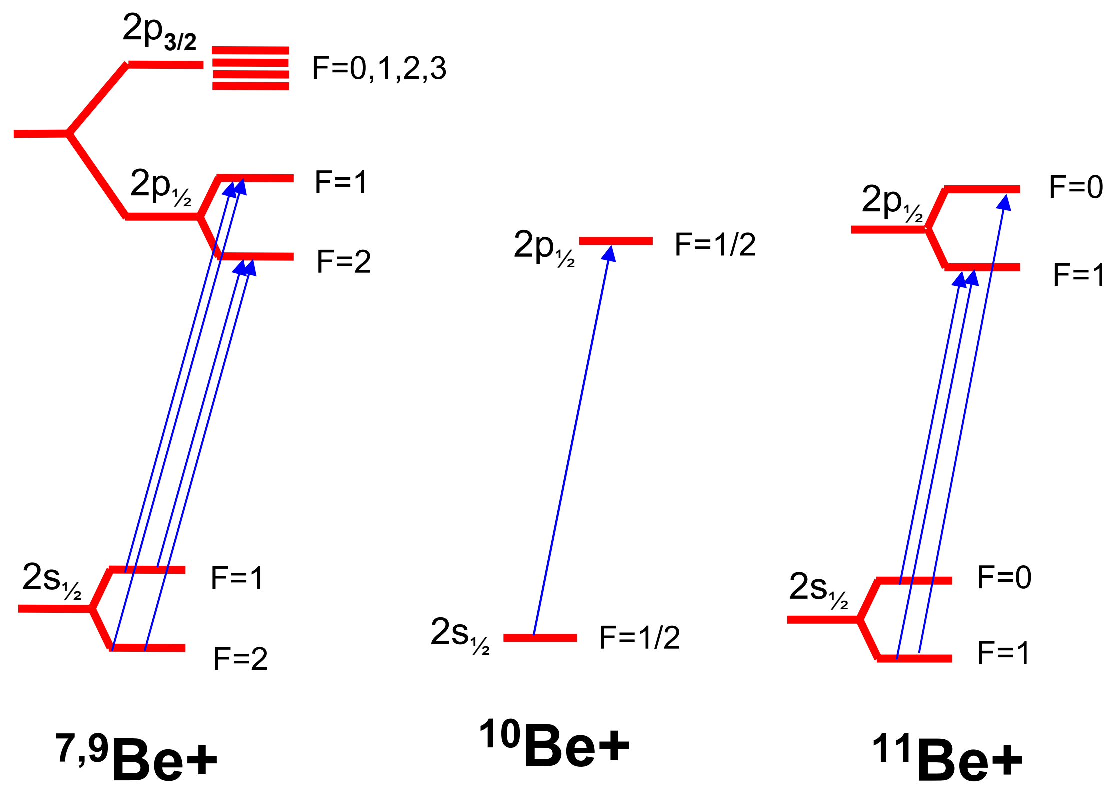


(1) J. A. Jansen, *et.al.* Nuclear Physics **A188**(1972)
(2) L. A. Schaller, *et.al.* Nuclear Physics **A343**(1980)

I. Tanihata *et. al.* PRL **55**, 2676 (1985)
I. Tanihata *et. al.* PL B **206**, 592 (1988)

Energy Level Scheme





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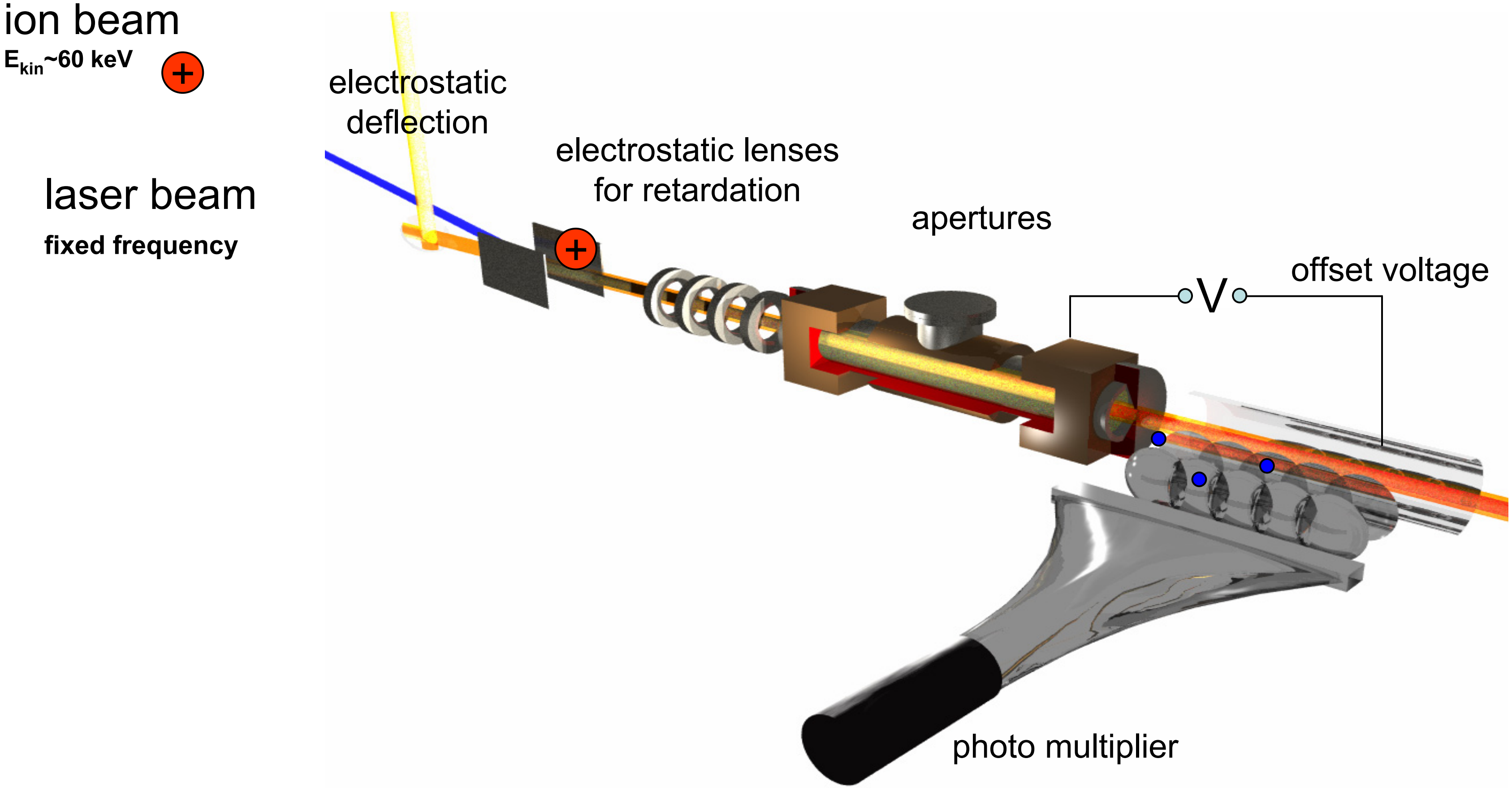
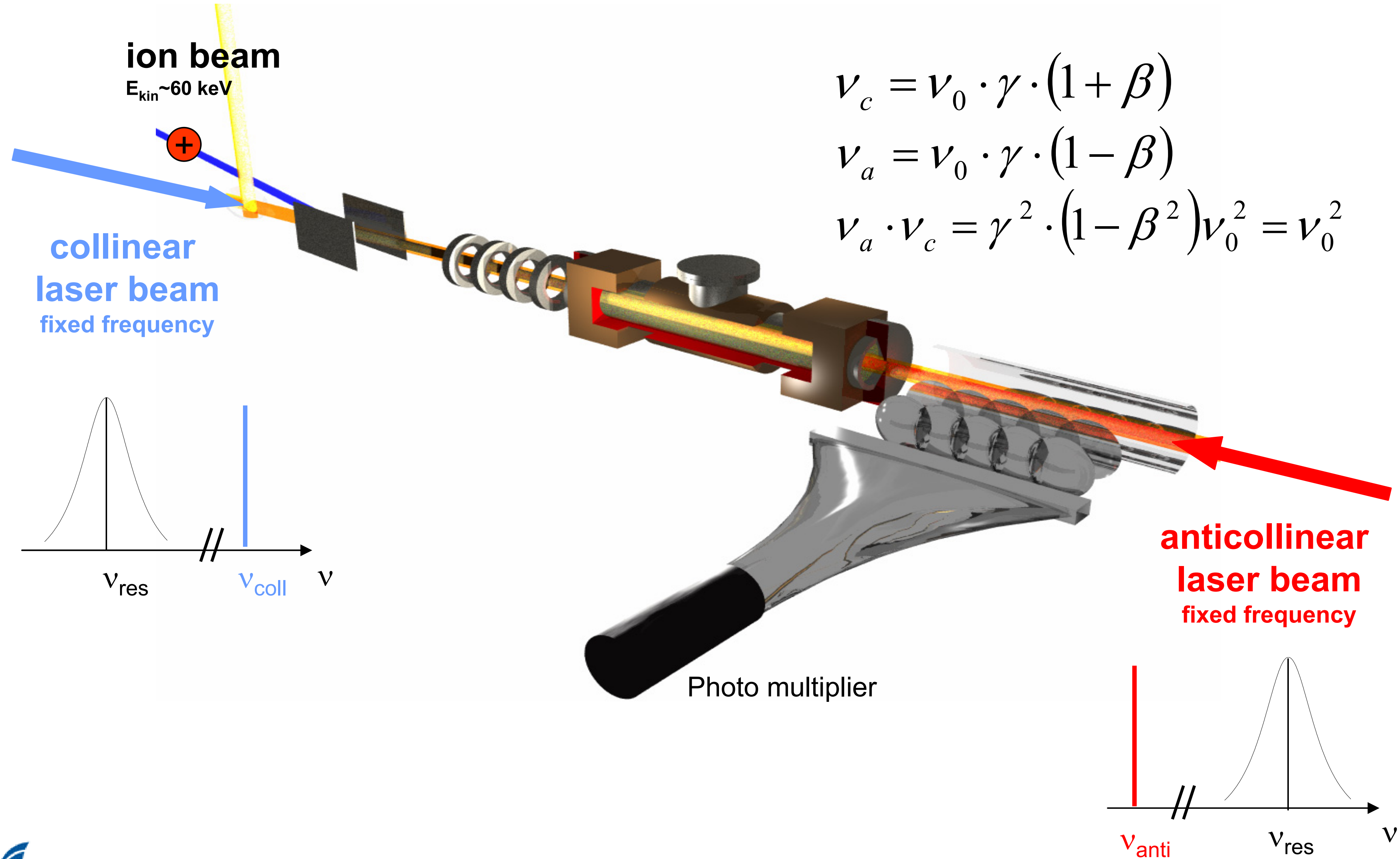
Experimental Setup at COLLAPS

- (Be) scaling factor 30MHz/ Volt
- precision of HV divider at ISOLDE is 10^{-4}



Experimental Setup at COLLAPS

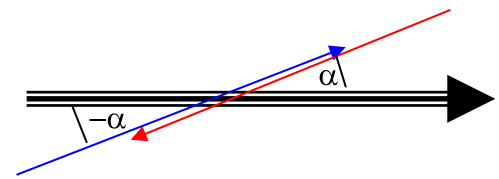
$$\nu_c = \nu_0 \cdot \gamma \cdot (1+\beta)$$
$$\nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$$
$$\nu_a \cdot \nu_c = \gamma^2 \cdot (1-\beta^2)\nu_0^2 = \nu_0^2$$



Reachable Accuracy

Absolute frequency determination

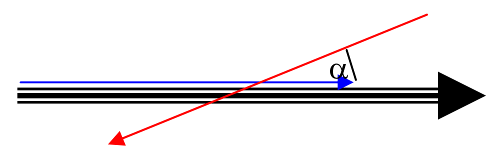
Line center accuracy	1 MHz
1 mrad Laser – Ion Beam Angle	0.005 MHz
1 mrad Misalignment of laser beams	0.750 MHz
Clock-related comb uncertainty	< 0.400 MHz
Total Uncertainty	**~ 2 MHz**



ion-laser beam misalignment

IS determination (differential effects)

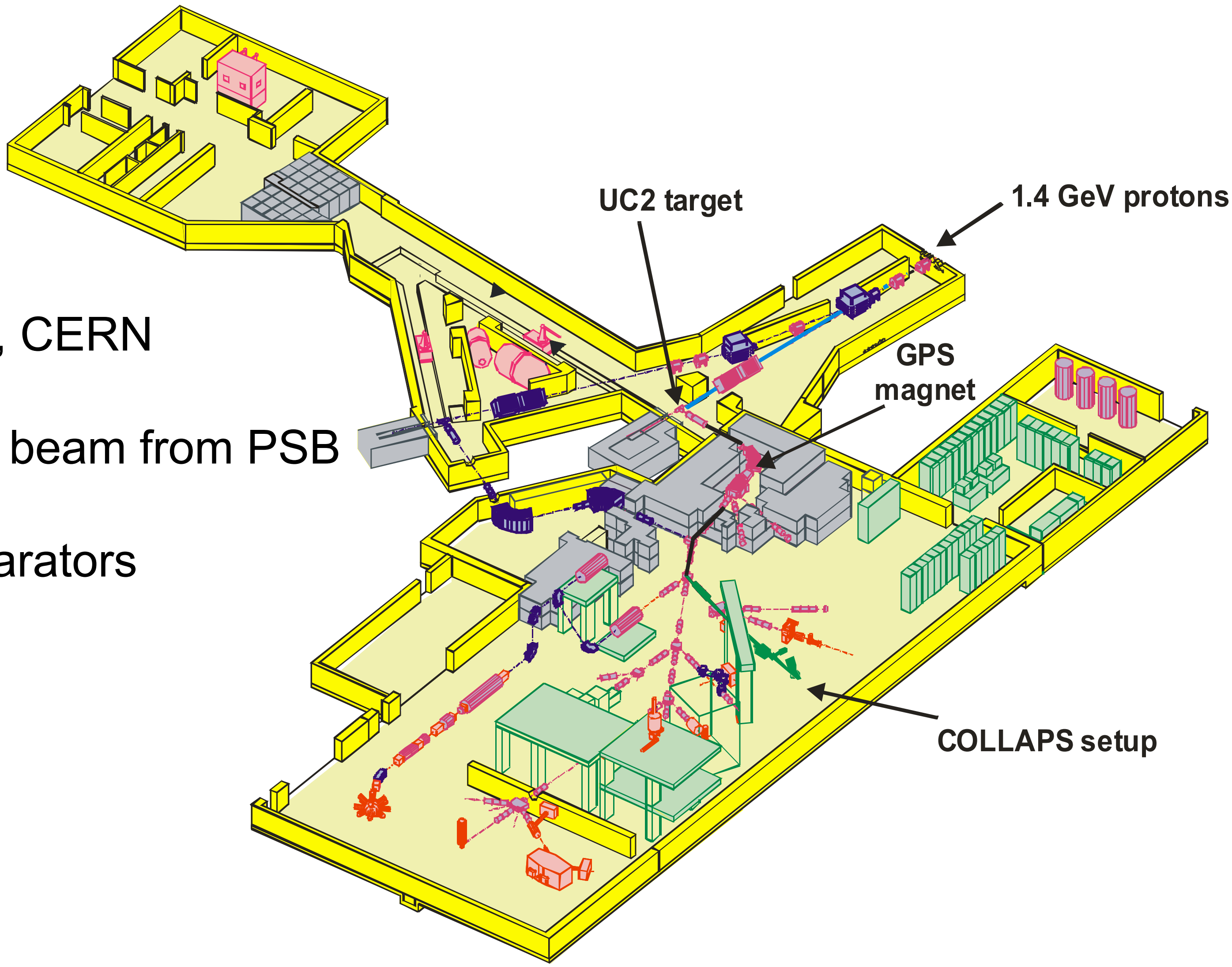
Line center accuracy	1 MHz
1 mrad Laser – Ion Beam Angle	0.005 MHz
1 mrad Misalignment of laser beams	0.075 MHz
Total Uncertainty	**~ 1 MHz**



laser-laser beam misalignment

Beryllium Ion Production

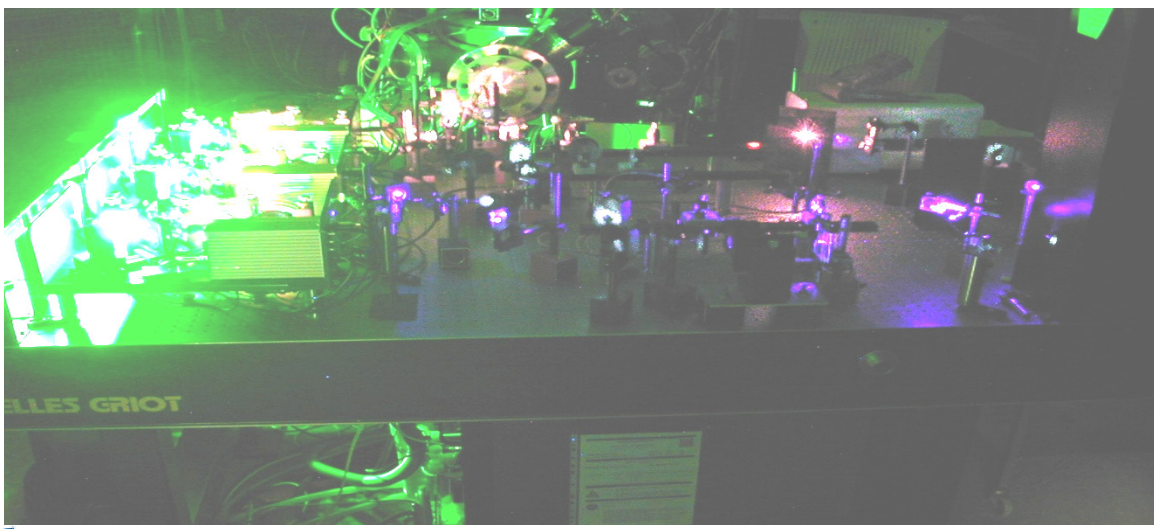
- ISOLDE facility, CERN
- 1.4 GeV proton beam from PSB
- GPS mass separators

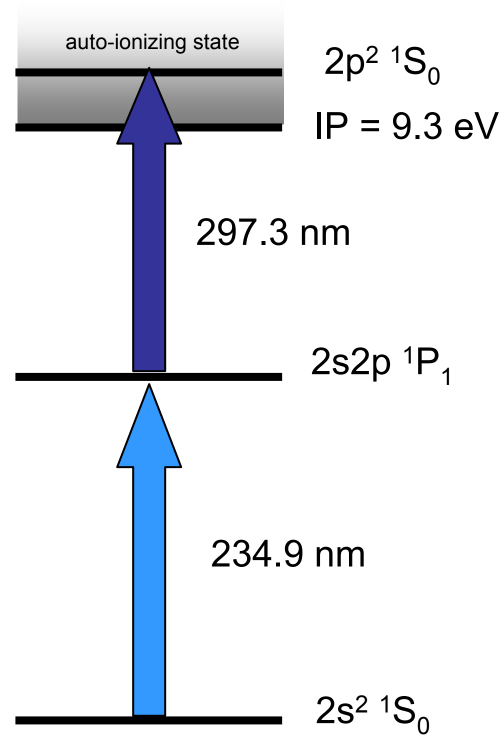


Beryllium Ion Production

- RILIS (ISOLDE laser ion source)

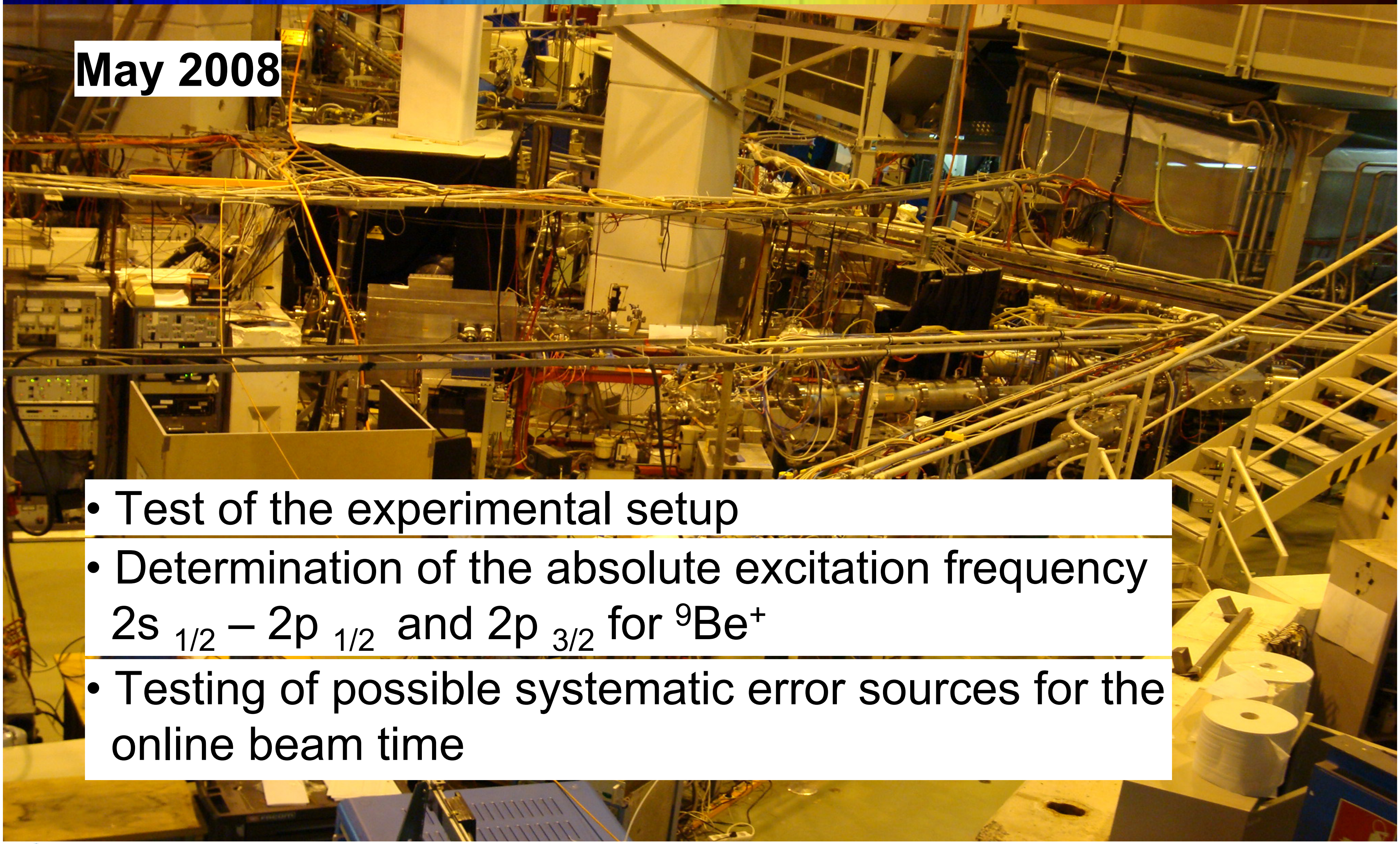
Element	A number	Half life	Yield (ions/μC)
Be	7	53.12 d	1.4E+10
Be	10	1.51E+6 a	6.0E+09
Be	11	13.8 s	7.0E+06
Be	12	23.6 ms	1.5E+03
Be	14	4.35 ms	4.0E+00





Efficiency: ~ 7 %

Offline Beamtime

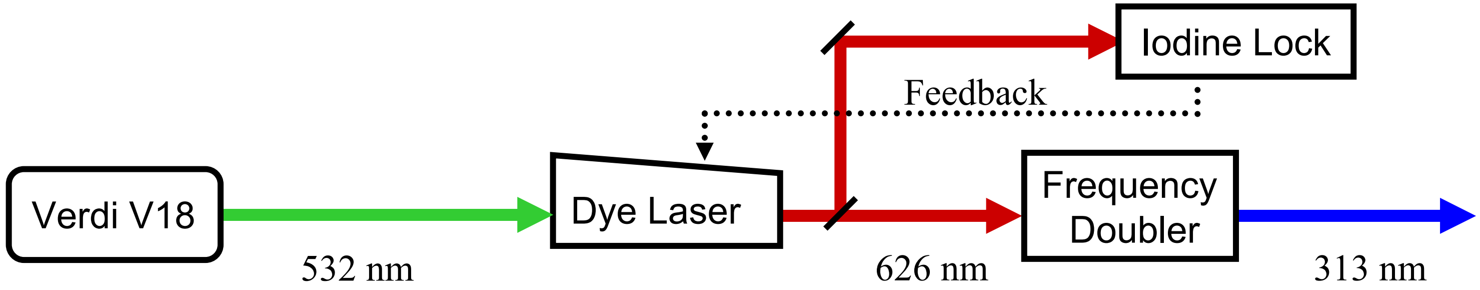


May 2008

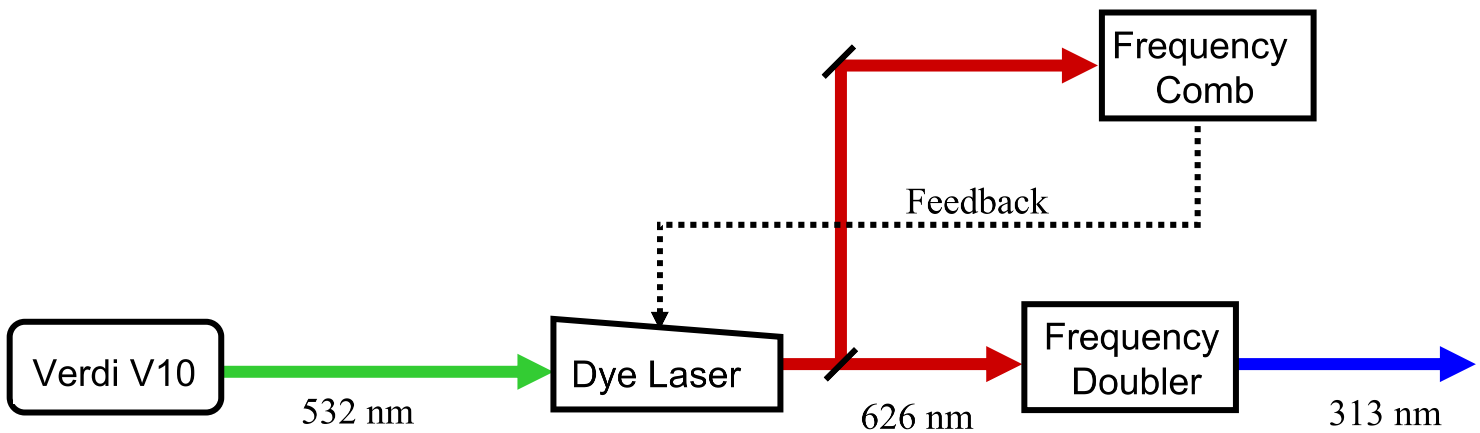
- Test of the experimental setup
- Determination of the absolute excitation frequency $2s_{1/2} - 2p_{1/2}$ and $2p_{3/2}$ for $^{9}Be^{+}$
- Testing of possible systematic error sources for the online beam time

Laser System

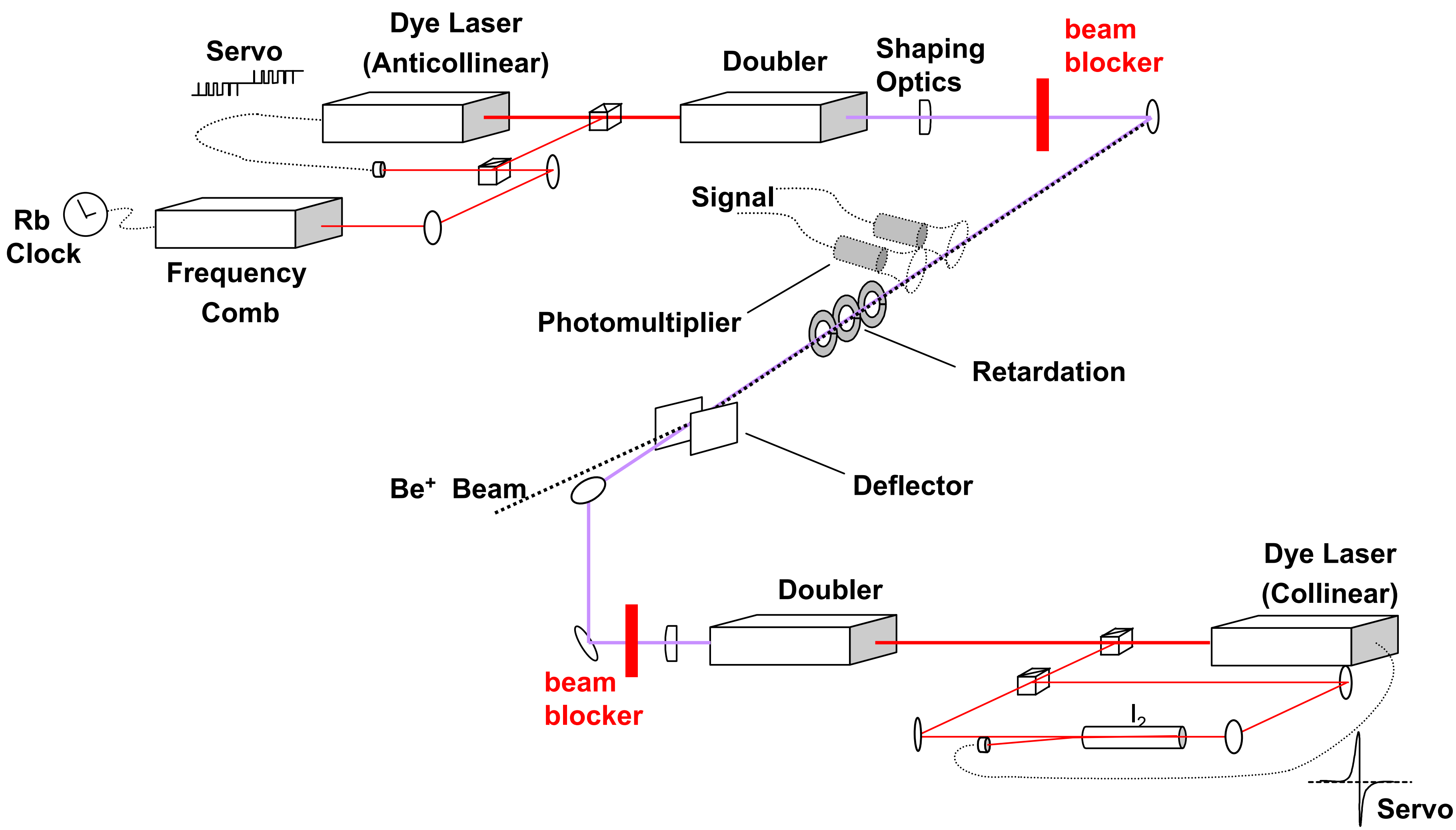
Collinear laser beam

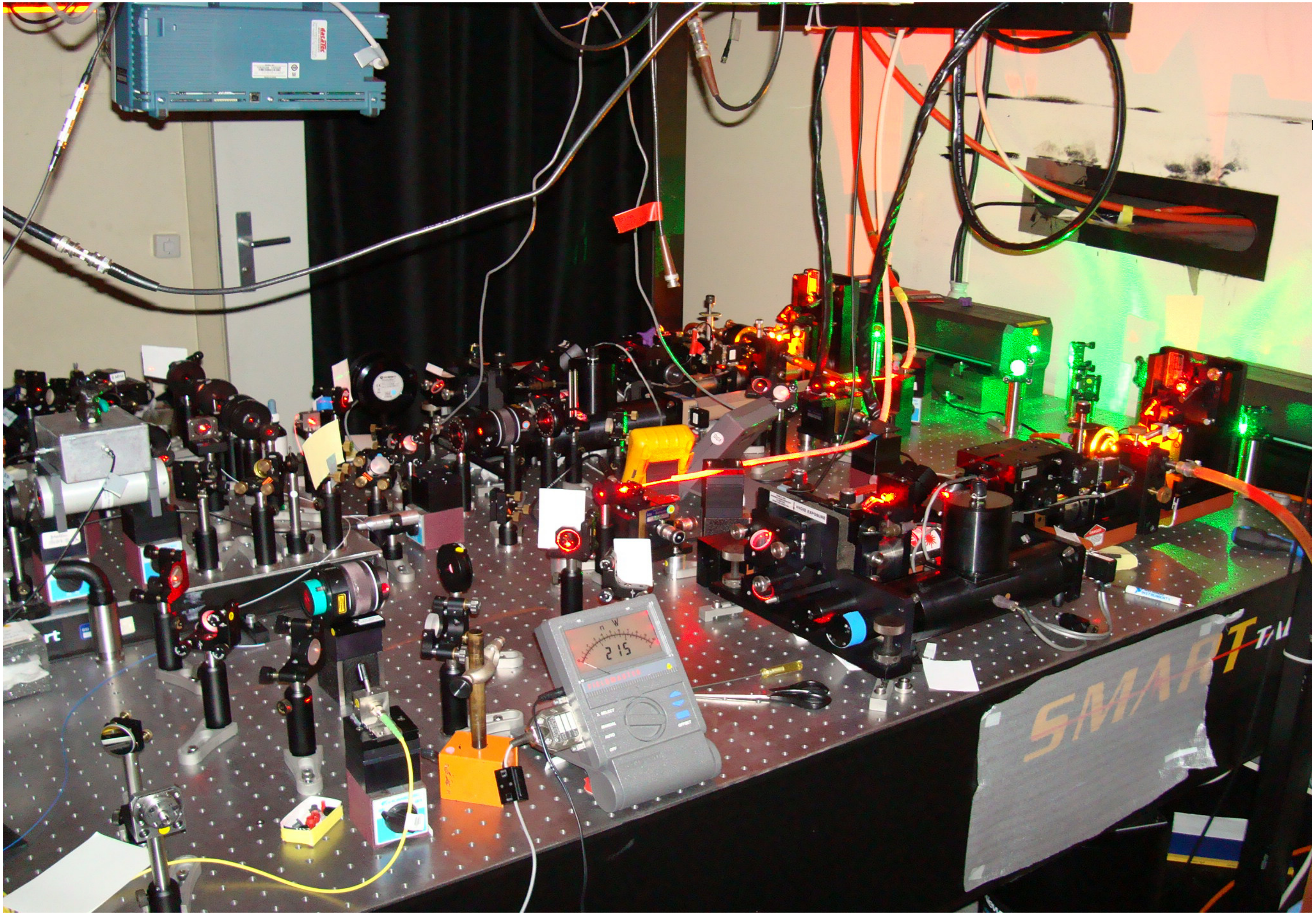


Anticollinear laser beam

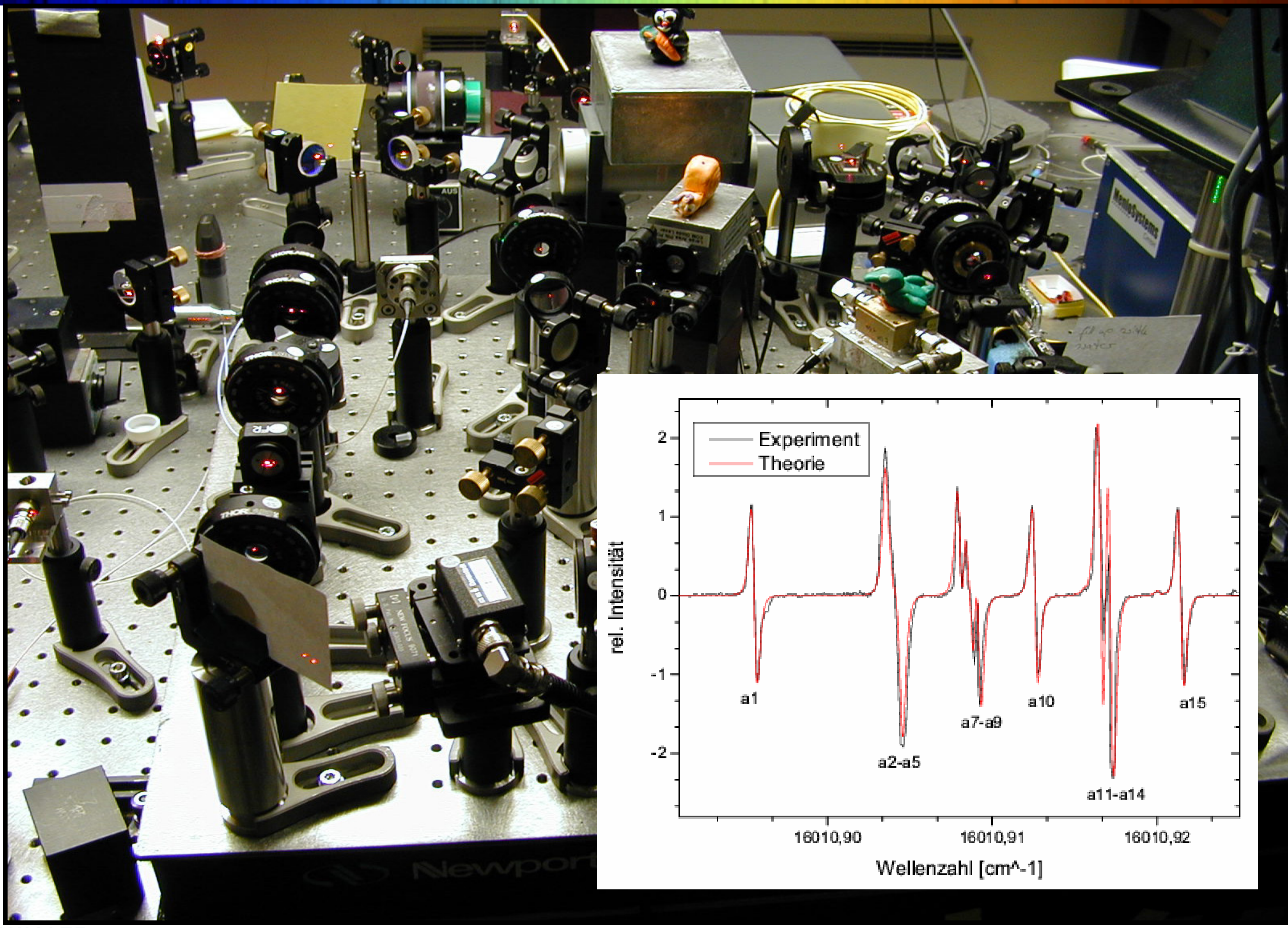


BeTINa Setup

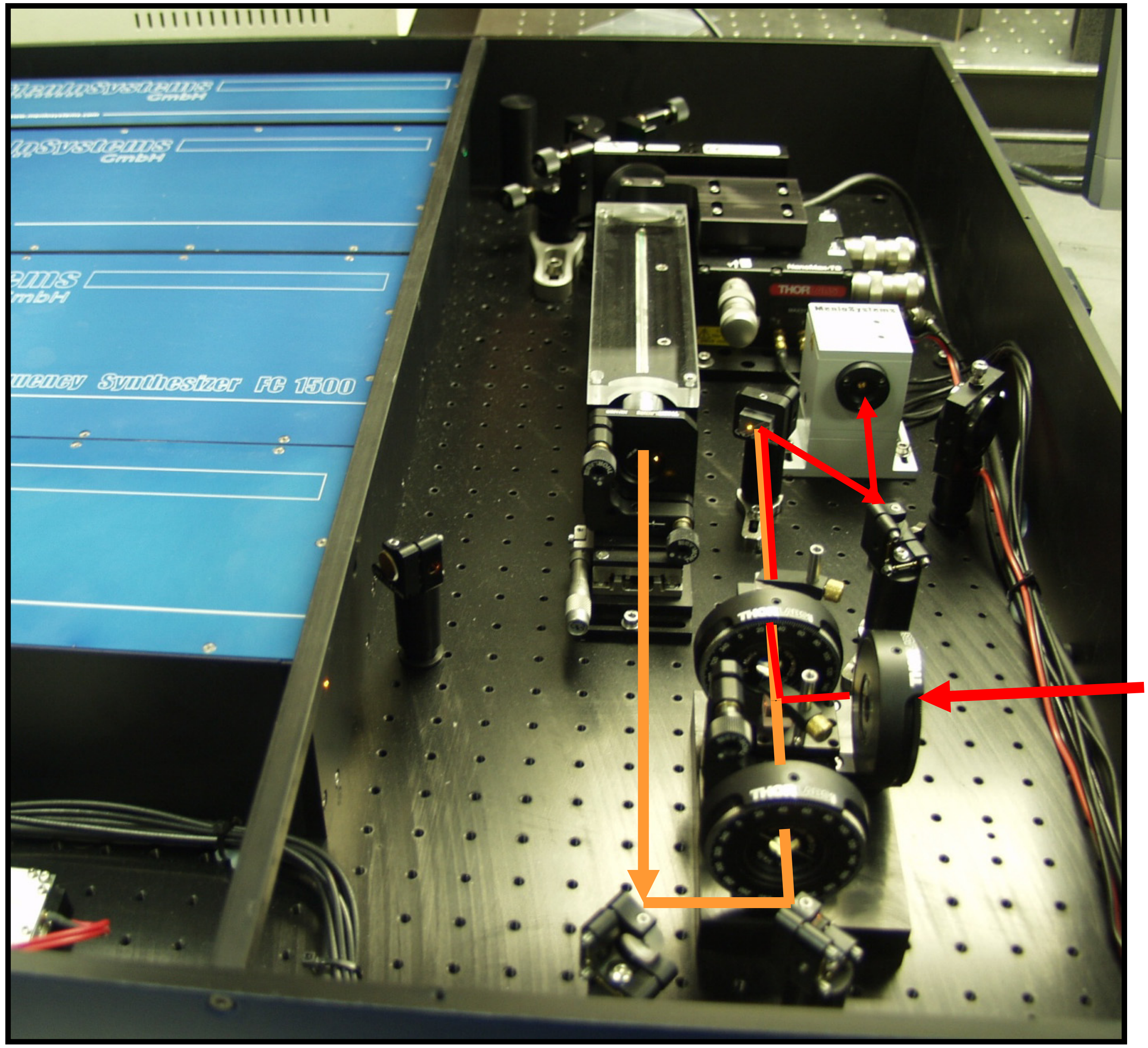



SMART

Iodine Lock


Experiment
Theorie
rel. Intensität
2
1
0
-1
-2
a1
a2-a5
a7-a9
a10
a11-a14
a15
16010,90
16010,91
16010,92
Wellenzahl [cm^-1]

Frequency Comb Lock



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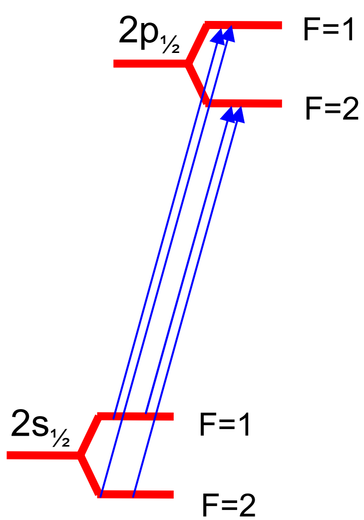
GSI

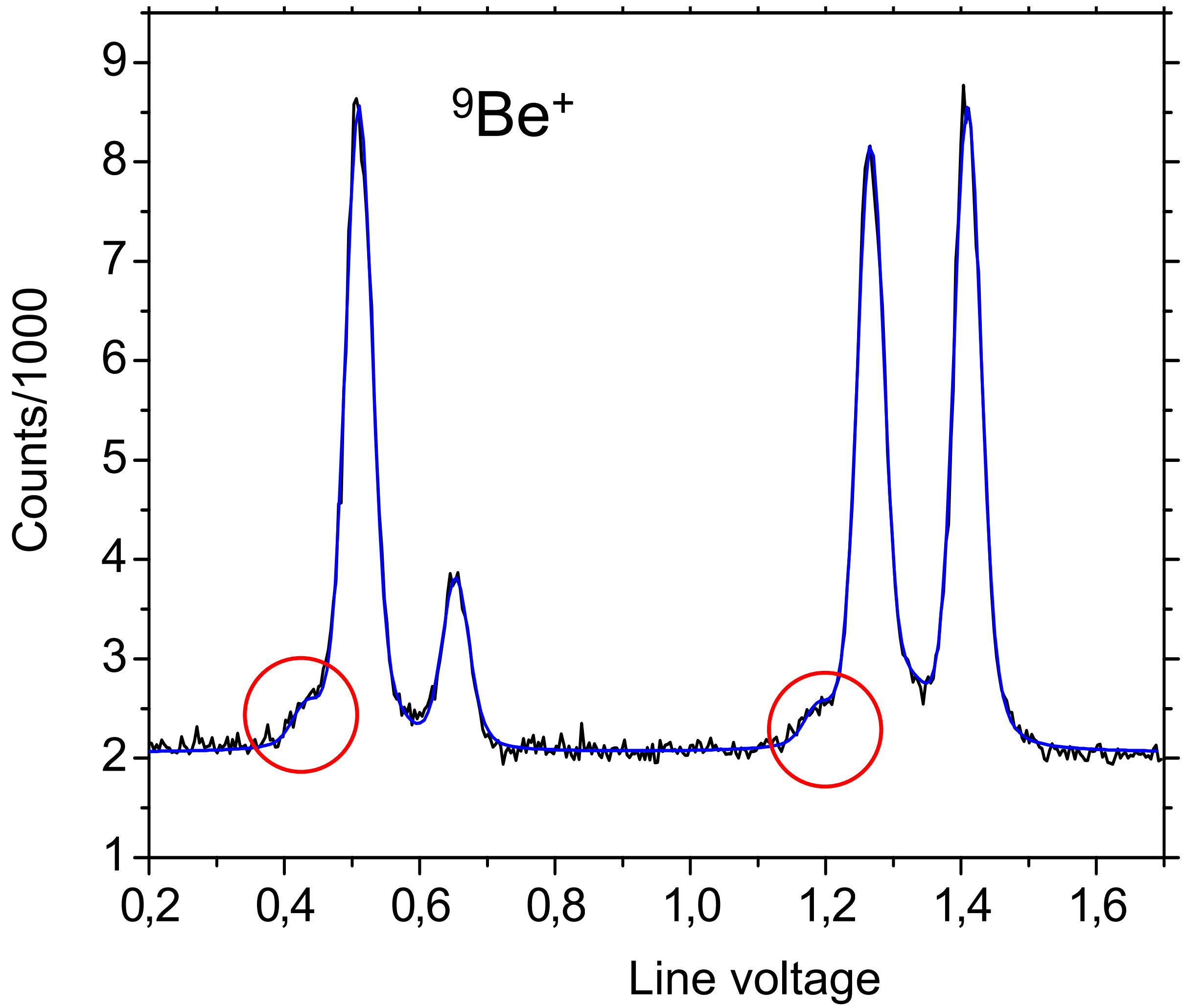
Results

Beryllium Spectra

- Voigt profile



- Side peak position ≈ 4 Volts (inelastic interaction)



Voltage Corrections

• expected high voltage was compared to the HV read out

• difference at 60 kV: ≈ 40 V

• discrepancy confirmed using precision HV divider (KATRIN), < 1ppm

• Prof. Weinheimer (Münster)

Systematic Error Estimation

intentionally …

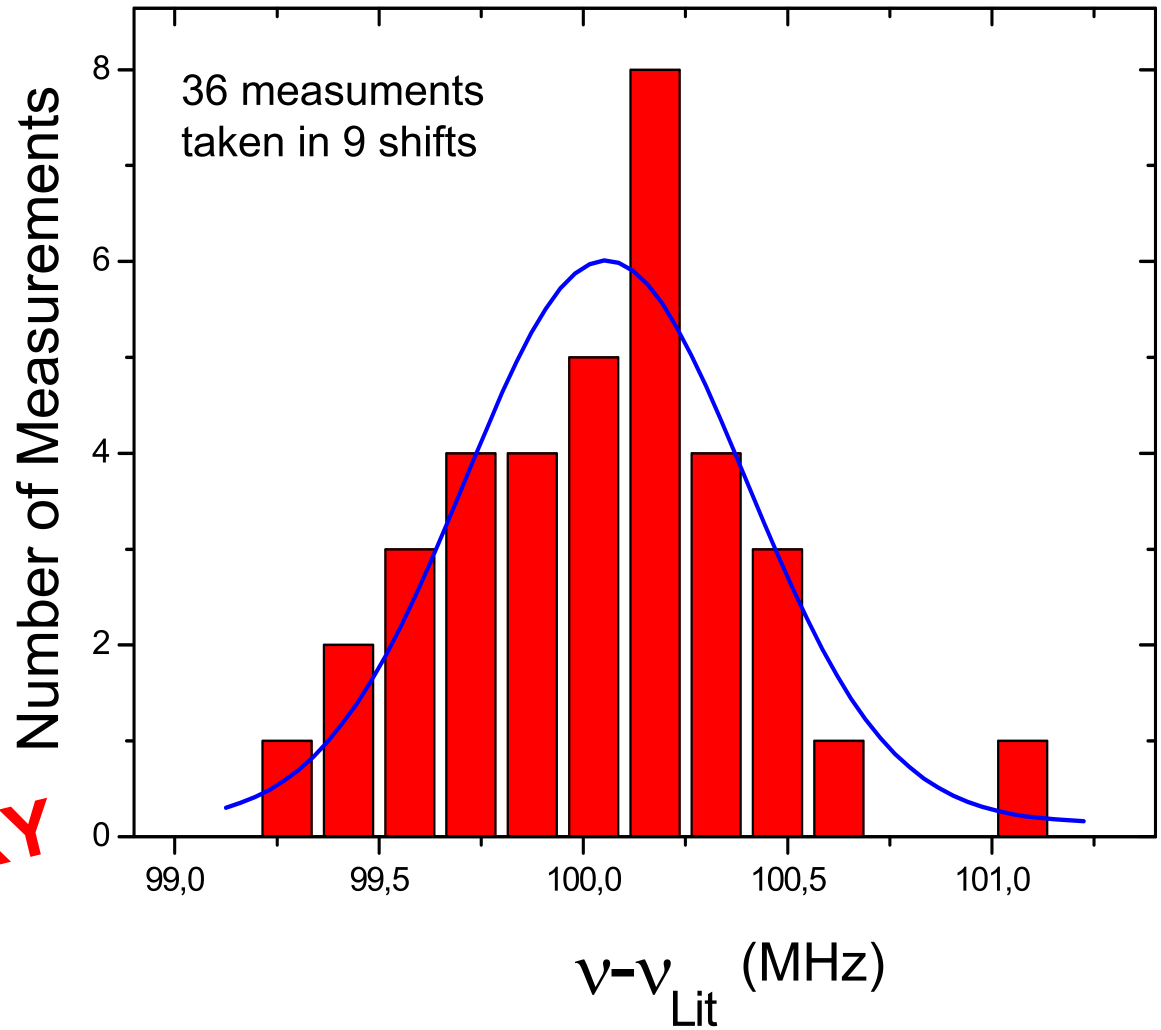
- laser beam misalignment
- focus of the laser beam
- ion beam misalignment
- focus of the ion beam
- different iodine lines

... included

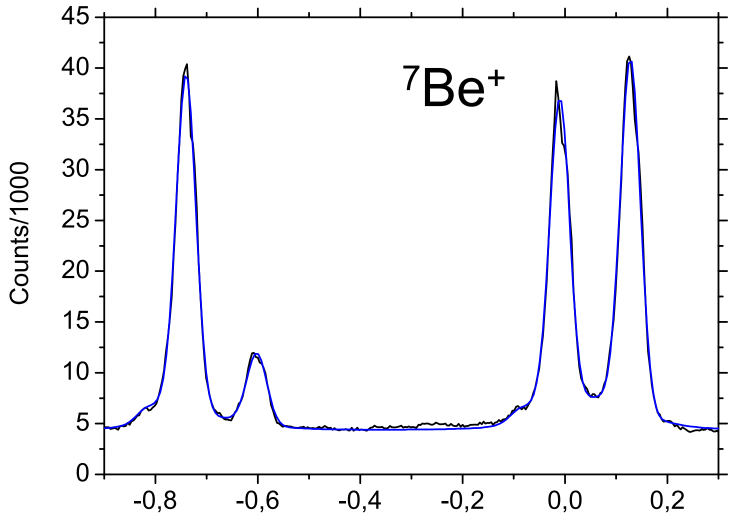
$^9Be^+$ ($2s_{1/2}$ → $2p_{1/2}$)

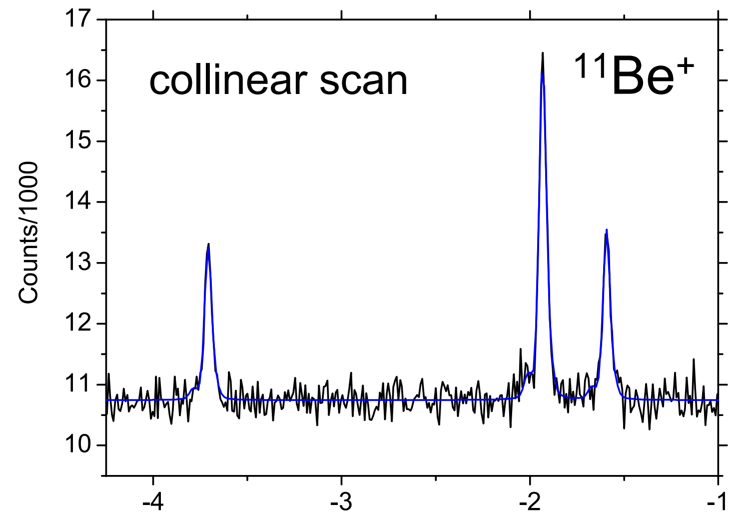
<u>957,199,752(2) MHz</u>

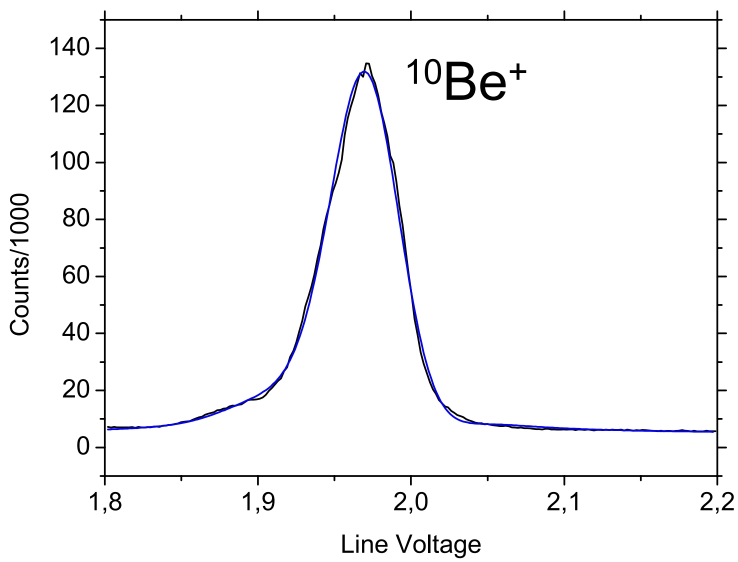
PRELIMINARY

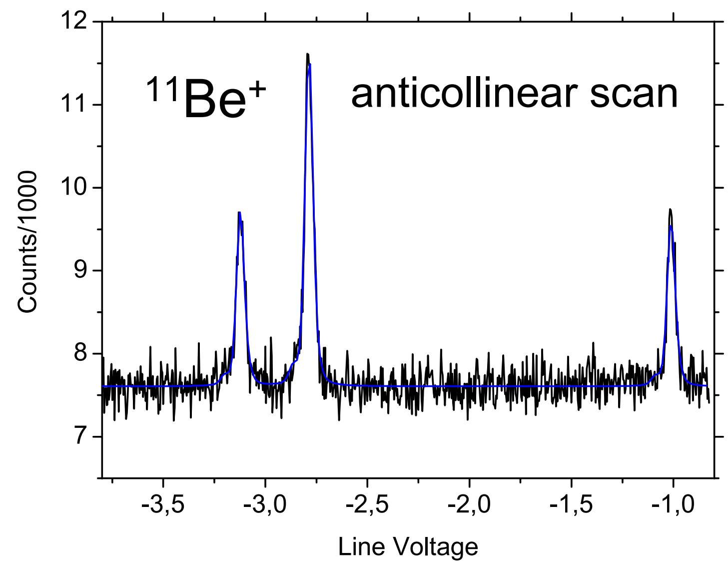


Beryllium Spectra – Online Beamtime!









Preliminary Results

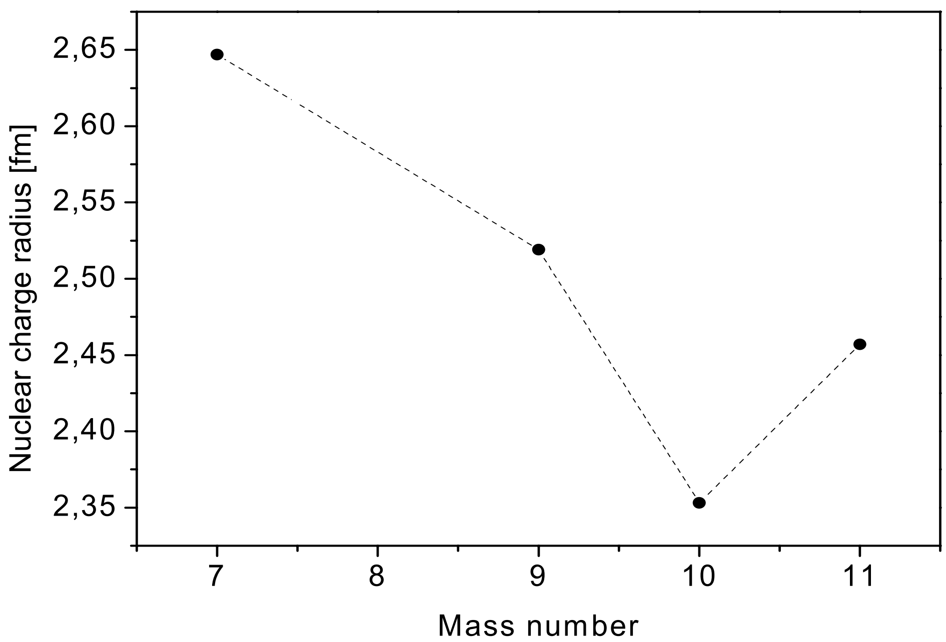
isotope	absolute transition frequency (GHz)	isotope shift ($\Delta\nu_{IS}$ MHz)	mass shift ($\Delta\nu_{MS}$ MHz)	field shift ($\Delta\nu_{FS}$ MHz)	$(\Delta\nu_{FS})/C^*$	nuclear charge radius (fm) [r]
Be-7	957150.5372 (20)	-49214.5	-49225.8	11.2	0.7	2.647
Be-9	957199.7518 (20)					2.519
Be-10	957217.0486 (20)	17296.8	17310.4	-13.7	-0.8	2.353
Be-11	957231.3065 (20)	31554.8	31560.0	-5.2	-0.3	2.457

*C = 16,912 MHz/fm^2

Z.-C. Yan, *et.al.* PRL **100** (2008)

[r] ^{9}Be, 2.519(12) electron scattering method

J. A. Jansen, *et.al.* Nuclear Physics **A188**(1972)



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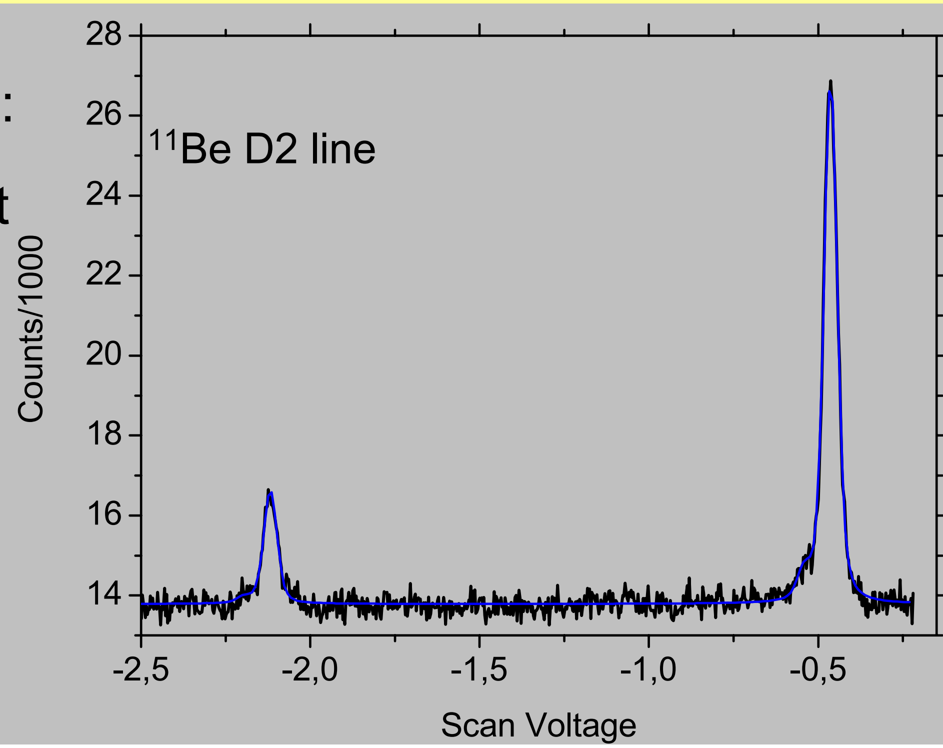
Summary and Outlook

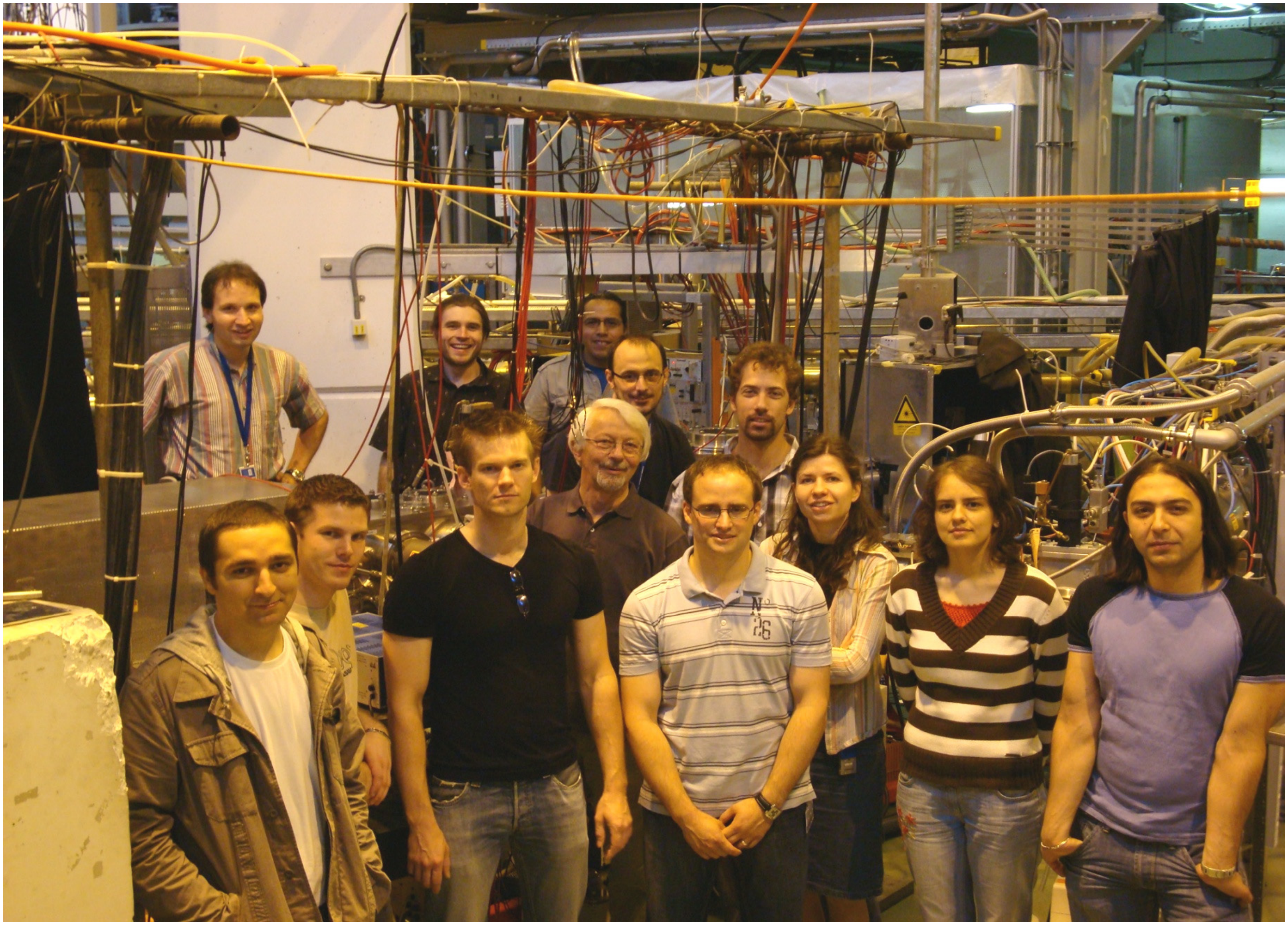
D1 ($2s_{1/2} \rightarrow 2p_{1/2}$) and D2 ($2s_{1/2} \rightarrow 2p_{3/2}$) absolute transition frequencies of $^{7,9,10,11}Be^{+}$ isotopes were measured

Measurement of the D2 line will provide:

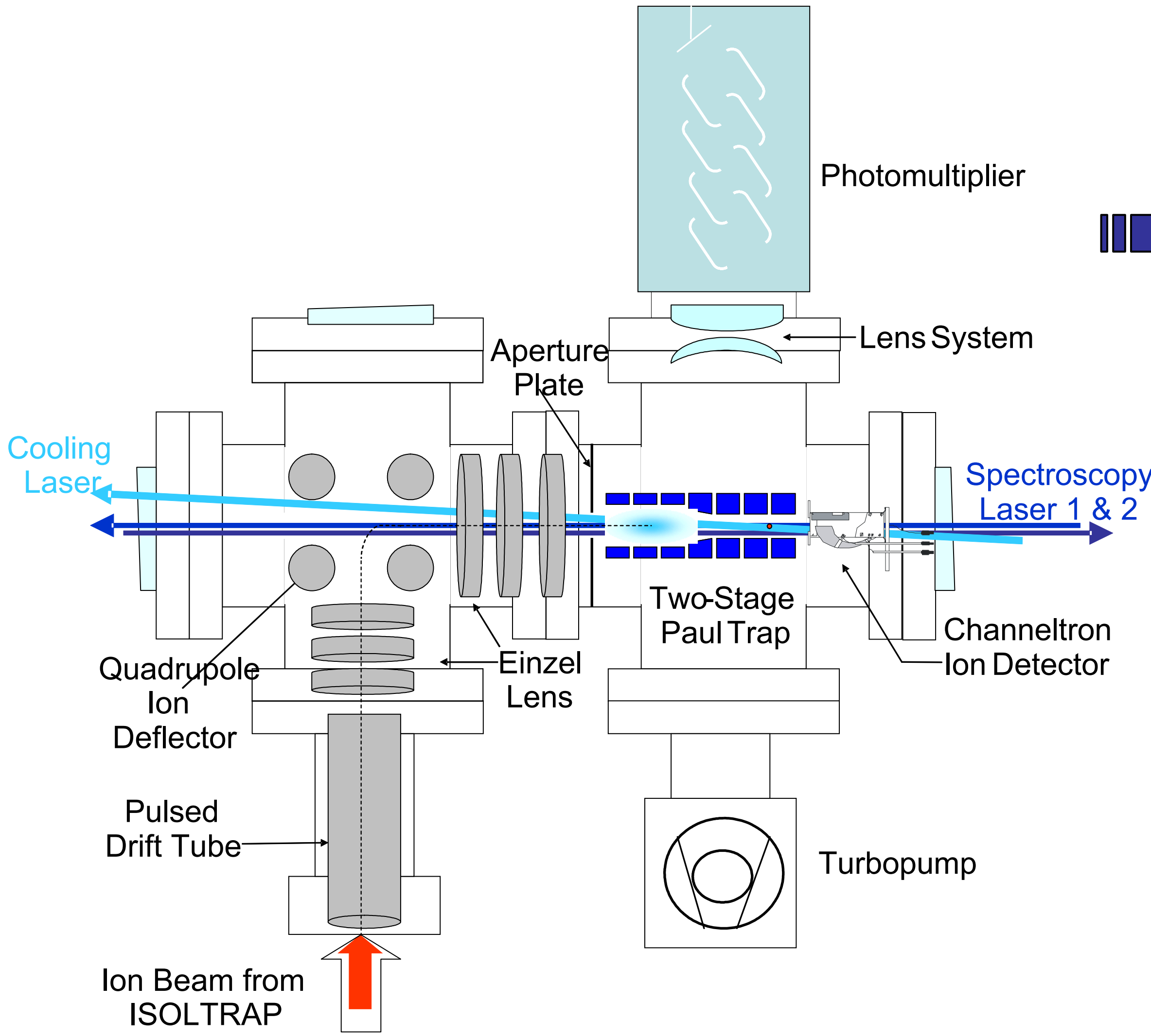
- Independent check of the Isotope Shift
- Splitting Isotope Shift (difference in Isotope Shift between the lines)



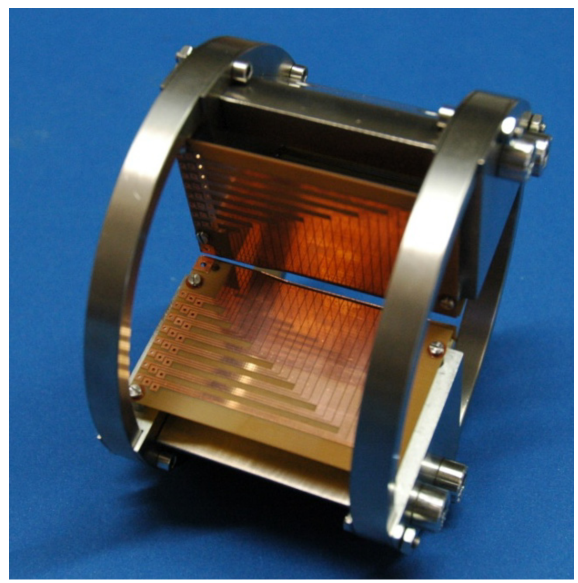
Beamtime Crew

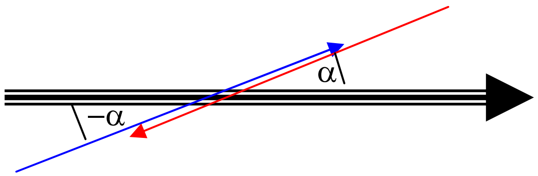


Initial plan



collinear
laser spectroscopy





$$\nu_a = \nu_0 \gamma (1 - \beta \cos\alpha)$$
$$\nu_p = \nu_0 \gamma (1 + \beta \cos\alpha)$$

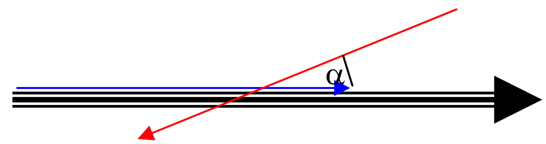
$$\nu_a \cdot \nu_p = \nu_0^{\,2} \gamma^2 (1 - \beta^2 \cos^2 \alpha)$$

$$\nu_0 = \sqrt{\frac{\nu_a \nu_p}{\gamma^2 (1 - \beta^2 \cos^2 \alpha)}}$$

U = 42.2 kV
β = 0.00317
γ-1 = 5E-6
α = 1mrad

$$\Delta\nu_p = -1.1519 MHz$$
$$\Delta\nu_a = 1.1519 MHz$$

$$\Delta\nu_0 = 5 kHz$$



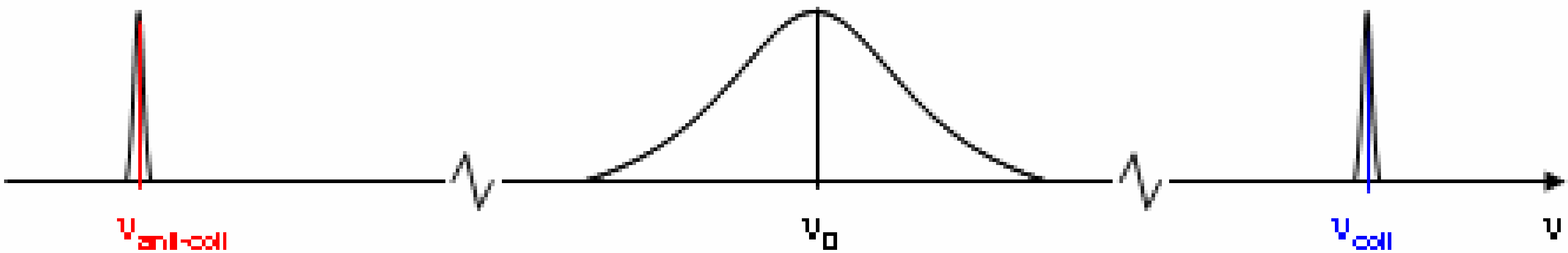
$$\nu_a = \nu_0 \gamma (1 - \beta \cos\alpha)$$
$$\nu_p = \nu_0 \gamma (1 + \beta)$$

U = 42.2 kV
β = 0.00317
γ-1 = 5E-6
α = 1mrad

$$\Delta\nu_p = 0 MHz$$
$$\Delta\nu_a = 1.1519 MHz$$

$$\Delta\nu_0 = 0.762 MHz$$

The Principle of Collinear Laser Spectroscopy



$\nu_a = \nu_0 \cdot \gamma \cdot (1 - \beta)$

$\nu_p = \nu_0 \cdot \gamma \cdot (1 + \beta)$

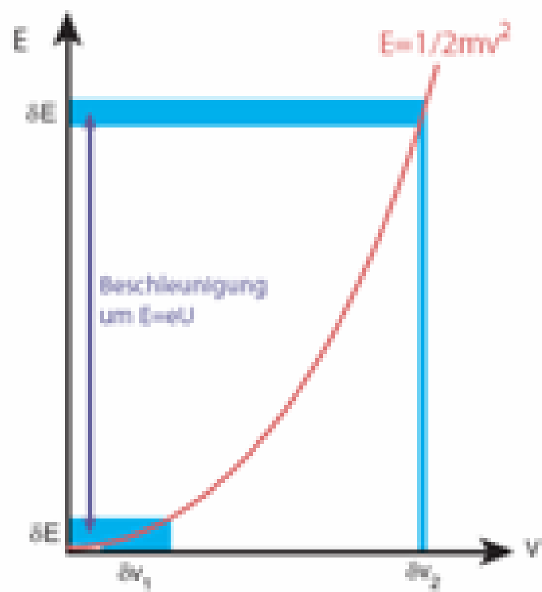
$\delta E = 1\ \mathrm{eV}$

typ. Accelaration Voltage

$U \approx 10\text{-}60\ \mathrm{kV}$

$\delta\nu \approx 10\ \mathrm{MHz}$

natural linewidth

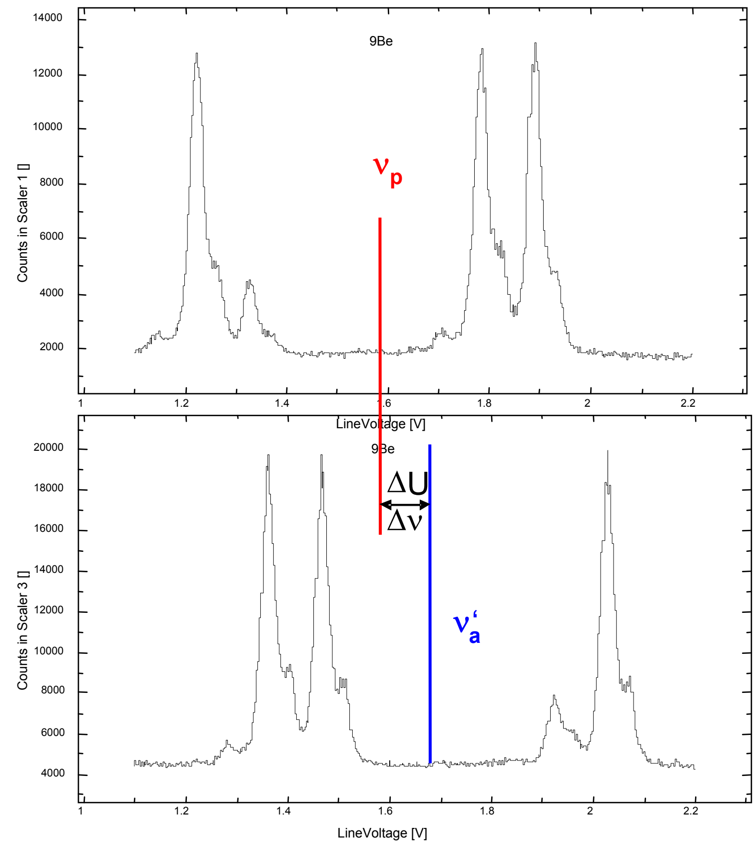


$$\gamma = 1 + \frac{eU}{m_0 c^2}$$

$$\beta = \sqrt{1 - \frac{m_0^2 c^4}{\left(m_0 c^2 + eU\right)^2}}$$

$$\beta \approx \sqrt{\frac{2eU}{m_0 c^2}}$$

1. Calculate the difference between the center of gravity in collinear and anti-collinear spectra
2. One can only extract the absolute transition frequency, when the center of gravity is measured at the same β.
3. This can be artificially attained, by shifting the frequency of one laser by the frequency difference which has been calculated before.



$\nu_a = \nu'_a - \Delta\nu$

$\nu_0^2 = (\nu_a \times \nu_p)$

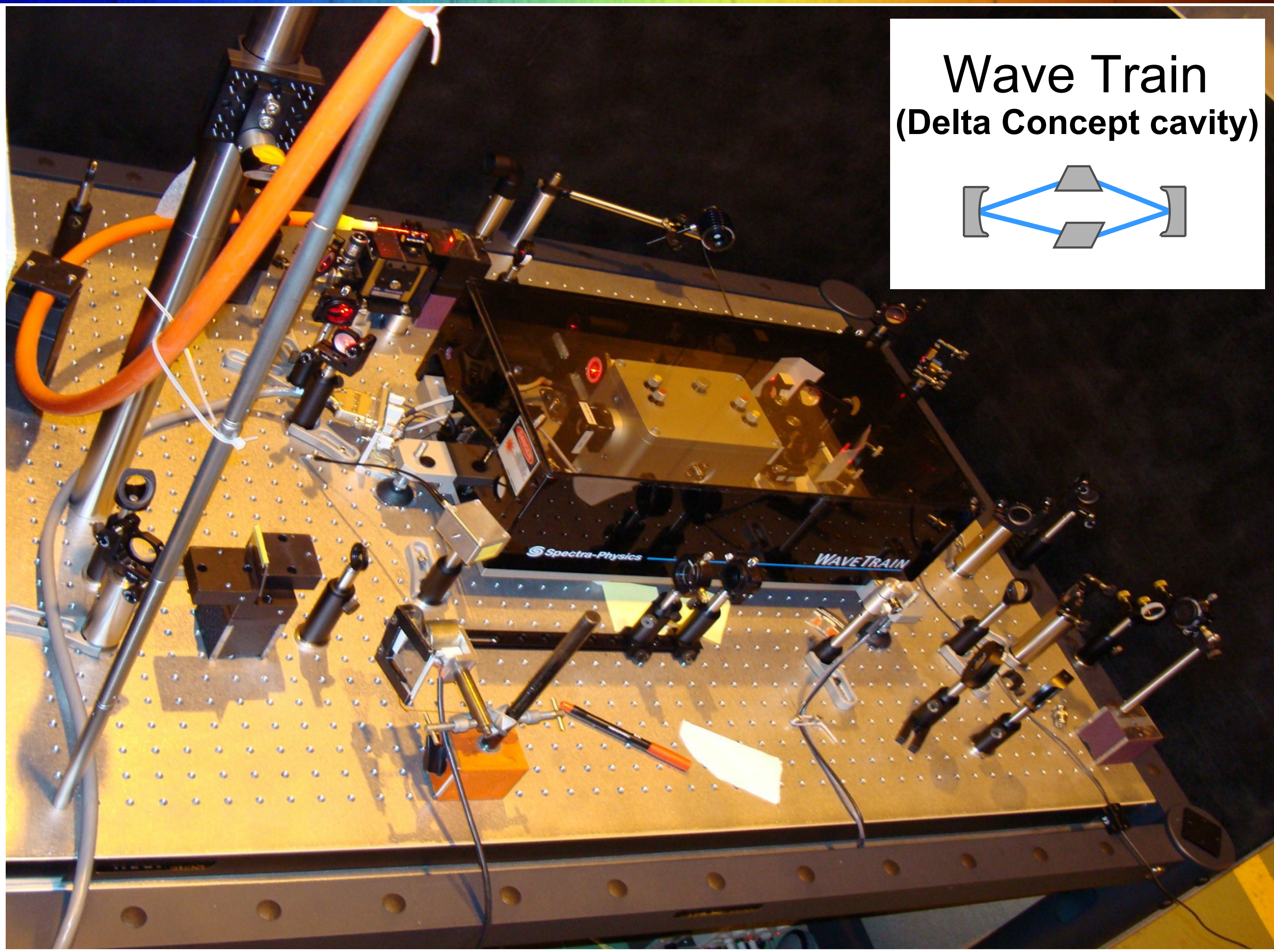
$\Delta U/U = 10^{-4}$

⇩

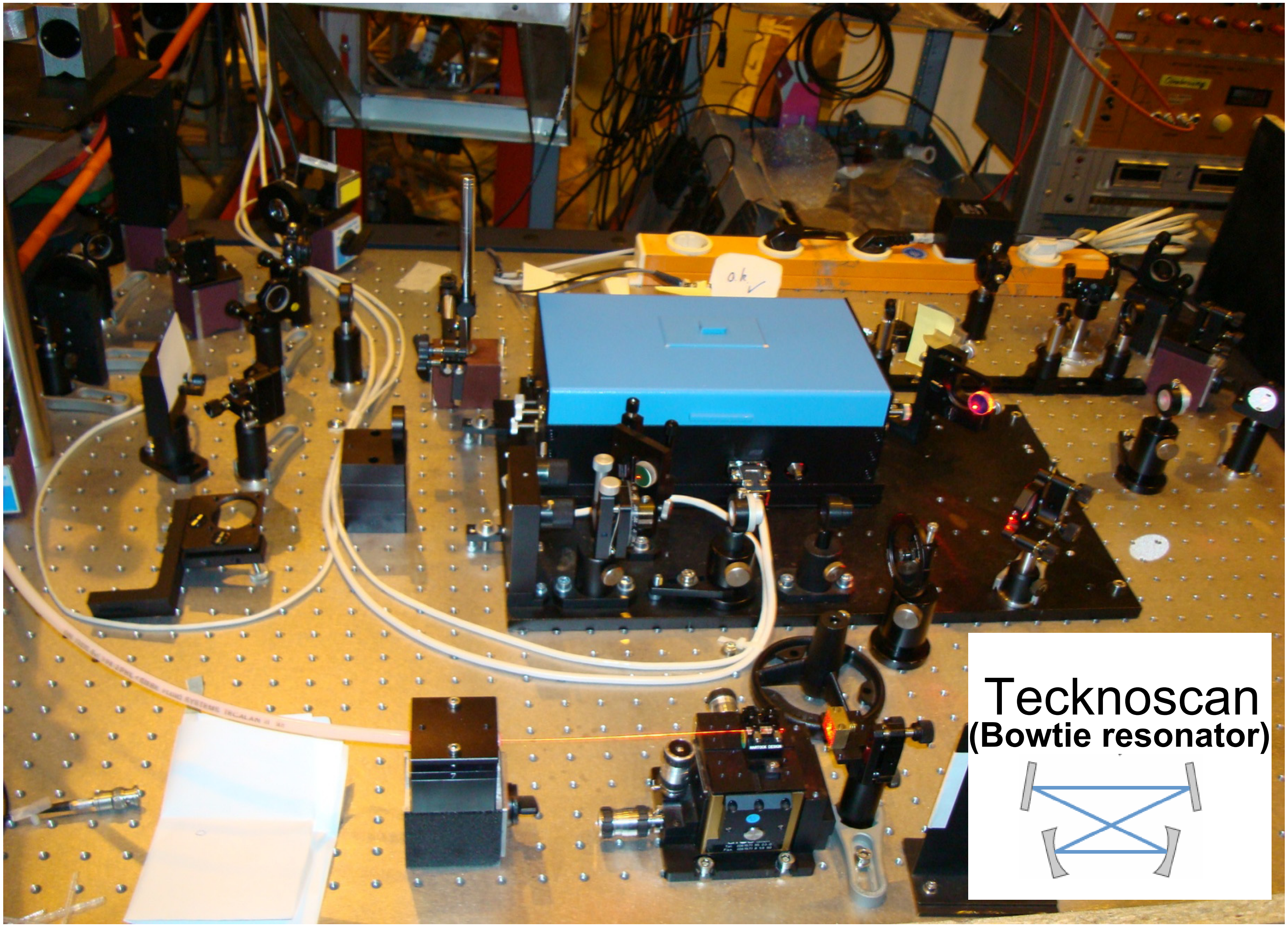
(^{9}Be – ^{11}Be) Δν ≈ 10 MHz

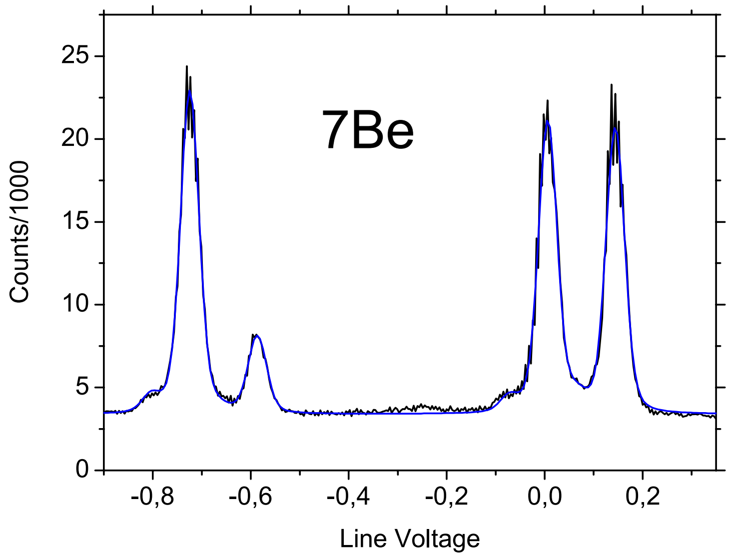
$$\nu_0 = \sqrt{(\nu_{collinear} - \delta\nu) \cdot \nu_{anti-collinear}}$$

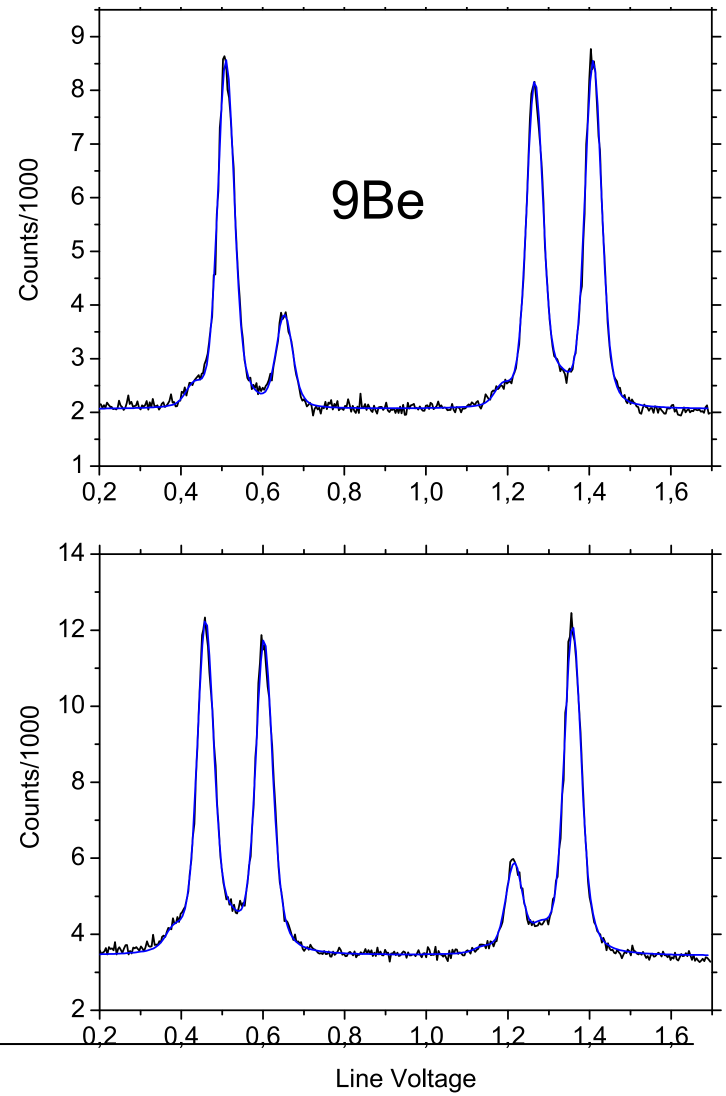
Frequency Doubling



Frequency Doubling







error estimation

Chi^2/DoF = 1.02892
R^2 = 0.85029

y0	**0.14407**	**0.57925**
xc	**100.05455**	**0.04185**
w	**0.69168**	**0.12529**
A	**5.08526**	**1.17877**

Measurement of Ground State Properties of Nuclei

Aim: determination of......

- nuclear g-factor and magnetic dipole moment (g_I and μ_I)
- electric quadrupole moment (Q)
- charge radius ($\langle r^2 \rangle$)
- spin, parity (I_p)

by measurement of.....

$$\Delta E_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I\cdot J}$$

$$\text{where } K = F(F+1) - I(I+1) - J(J+1)$$

$$A = \frac{\mu_I H_e(0)}{I\cdot J} \qquad B = eQV_{zz}(0)$$

$$\delta\nu^{A,A'} = (K_{NMS} + K_{SMS}) \times \frac{A'-A}{A'A} + F\times\delta\langle r^2\rangle^{A,A'}$$

$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2}Q\cdot V_{zz}$$

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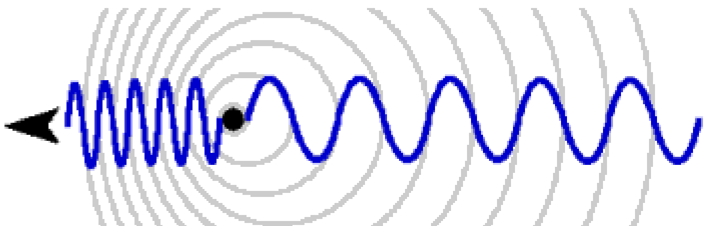
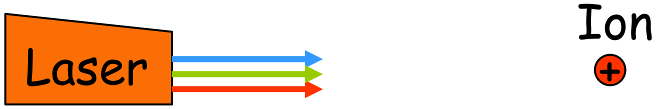
Basics on Doppler Spectroscopy

1. Doppler tuning

$$f' = f(1 + \frac{v}{c}).$$

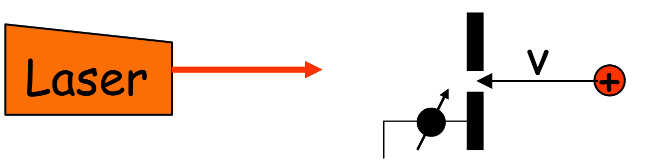
$$f' = f(1 - \frac{v}{c})$$





tuning wavelength

fixed (thermal)



fixed wavelength

tuning (accerlating)

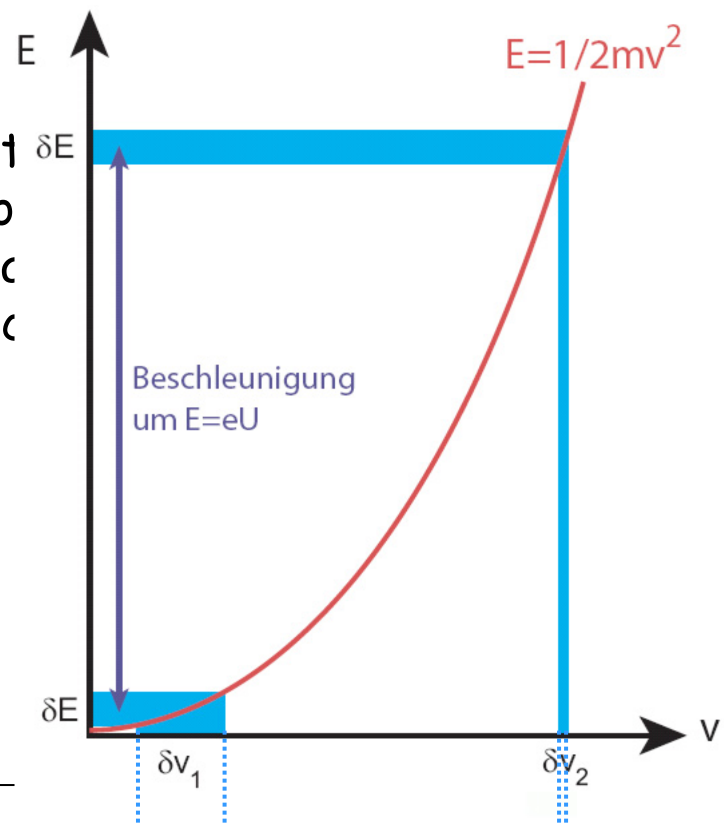
2. Doppler compression

$$\delta E = \delta(\tfrac{1}{2} m v^2) = m v \delta v = const$$

$$\Rightarrow \delta v = \sqrt{\frac{k^2 T^2}{2Uem}}$$

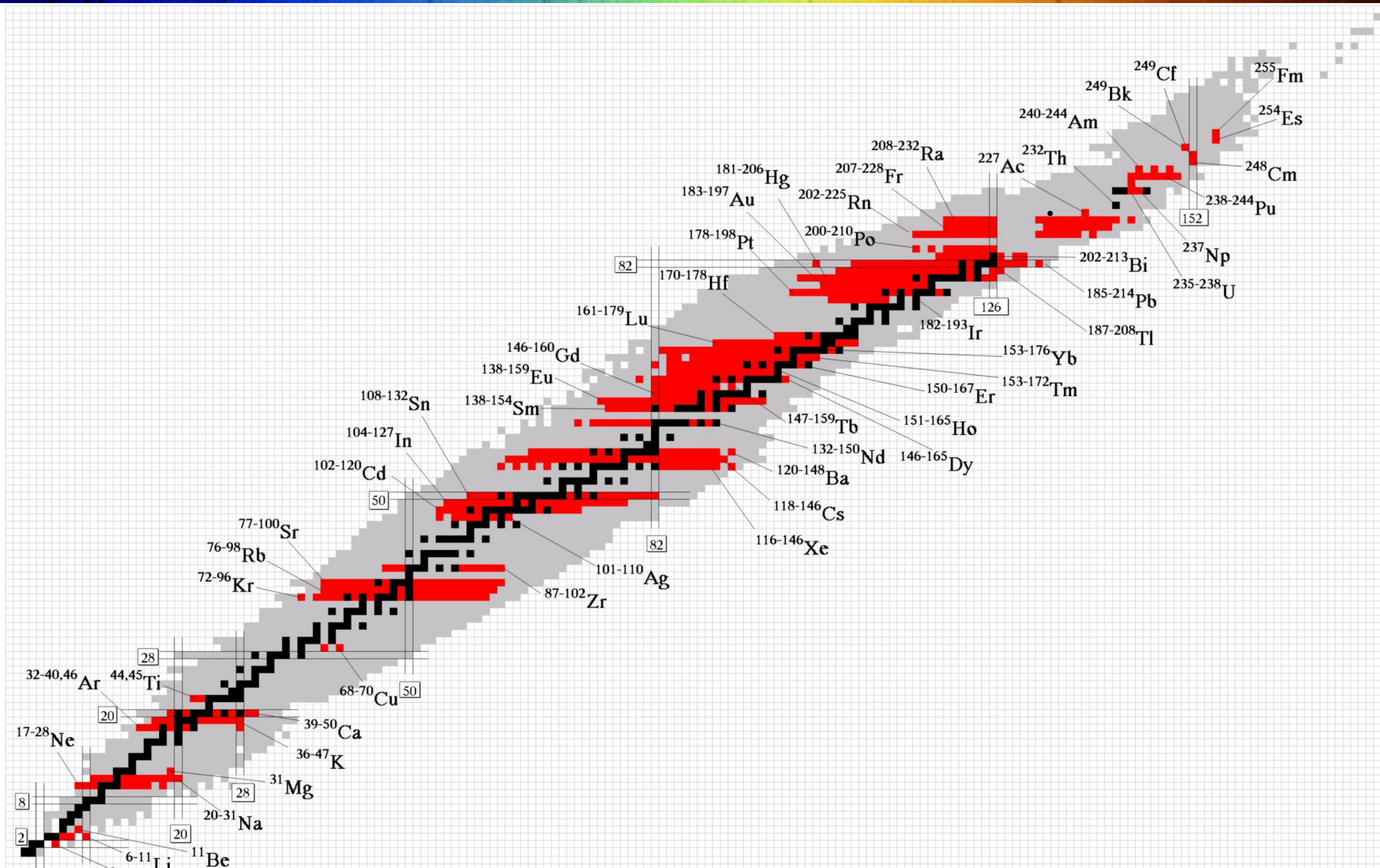
at
io
cc
ac

he



Laser Spectroscopy Method

Laser SpHERe



H.-J. Kluge and W. Nörtershäuser, Spectrochim. Acta B, 58 (2003).