Development of a detector setup to determine the 2s – hyperfine transition of $^{209}Bi^{80+}$ at the Experimental Storage Ring at GSI

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Outline

- Motivation for physics of highly charched Ions
- Hyper fine structure
- Laser spectrocopy ESR
- Monte-Carlo-Simulation
- “Old” mirror system
- Parabolic mirror system

The status of QED in the low field regime

„Quantum electrodynamics (QED) is the most precise theory in physics“

- g-factor of the free electron
- Lamb-Shift
- HFS of hydrogen
- …

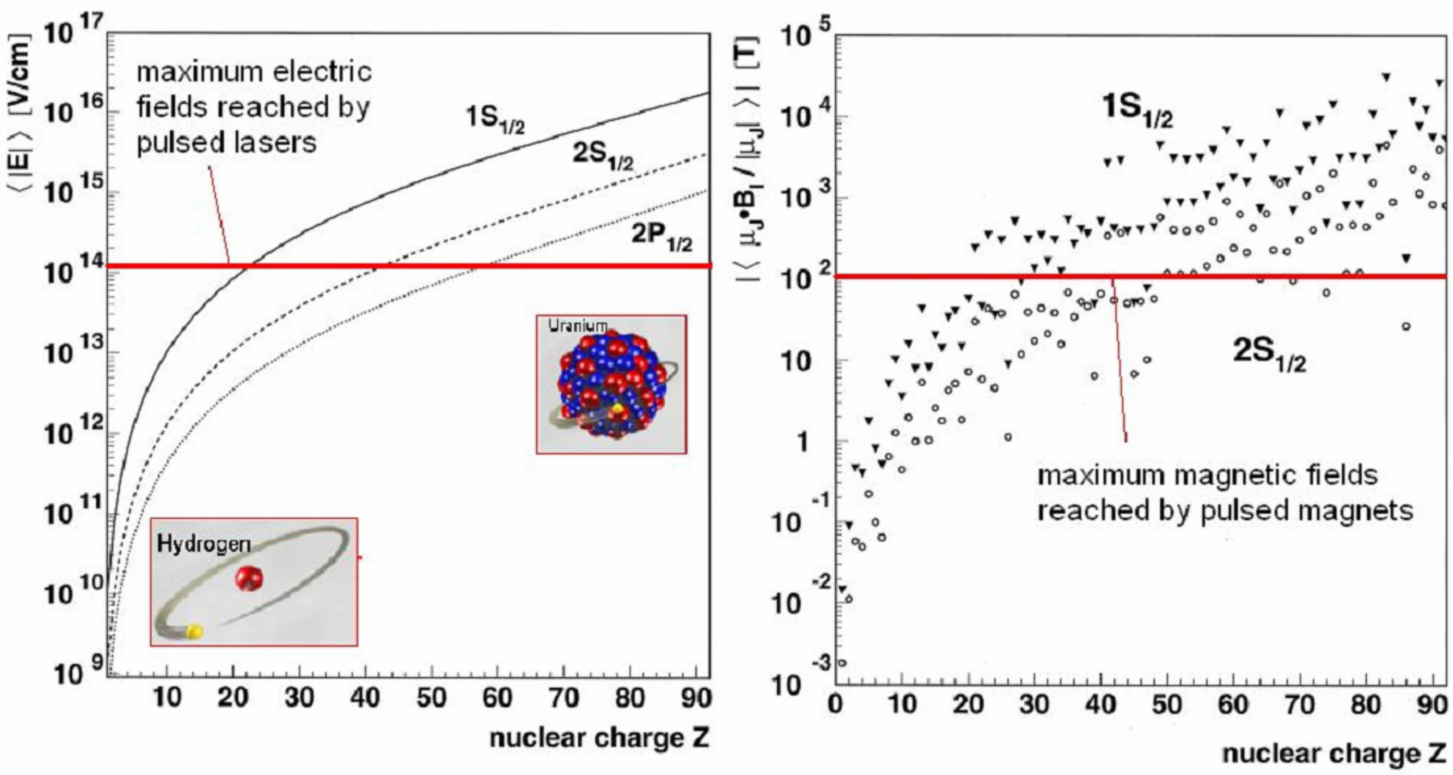
Example: g-factor of the free electron $\vec{\mu}_s = g_s \mu_B \frac{\vec{s}}{\hbar}$

g/2 = 1. 001 159 652 180 85 (76) Experiment [1]

g/2 = 1. 001 159 652 180 86 (10)(26)(848) Theory [2]

[1] Kinoshita et al., PRD 73(1), 013003-27 (2006)
[2] Odom et al., PRL 97, 030801 (2006)

Extremes at Highly Charged Heavy Ions



- Extremely high electromagnetic fields near the nucleus
- $Z\alpha \approx 10^{-2}$ ⟶ $Z\alpha \approx 1$ ⟶ non-pertubative calculations

⟶ Test of QED in heavy H-like Ions

Hyperfine structure

$$\Delta E'_{\mathrm{HFS}} = \alpha g_I \frac{m_e}{m_p} \frac{F(F+1) - I(I+1) - j(j+1)}{2j(j+1)} m_e c^2 \frac{(Z\alpha)^3}{n^3(2l+1)}$$

H	H-like →	$^{207}Pb^{81+}$	$^{209}Bi^{82+}$
$\lambda = 21$ cm	$\sim \Delta E^{-1} \sim Z^{-3}$ →	$\lambda = 1020$ nm	$\lambda = 244$ nm
$\tau = 1.1 \cdot 10^7$ a	$\sim \Delta E^{-3} \sim Z^{-9}$ →	$\tau = 52$ ms	$\tau = 0.4$ ms

Full description including rel. effects, nuclear structure and QED contributions

$$\Delta E_{\mathrm{HFS}} = \Delta E'_{\mathrm{HFS}} \cdot \mathcal{M} \left(A(Z\alpha)(1-\delta)(1-\epsilon) + \frac{\alpha}{\pi} \Delta\epsilon_{QED} \right)$$

Finite mass of nucleus	Relativistic Effects	Breit-Rosenthal-Effect	Bohr-Weisskopf-Effect	QED-Contribution

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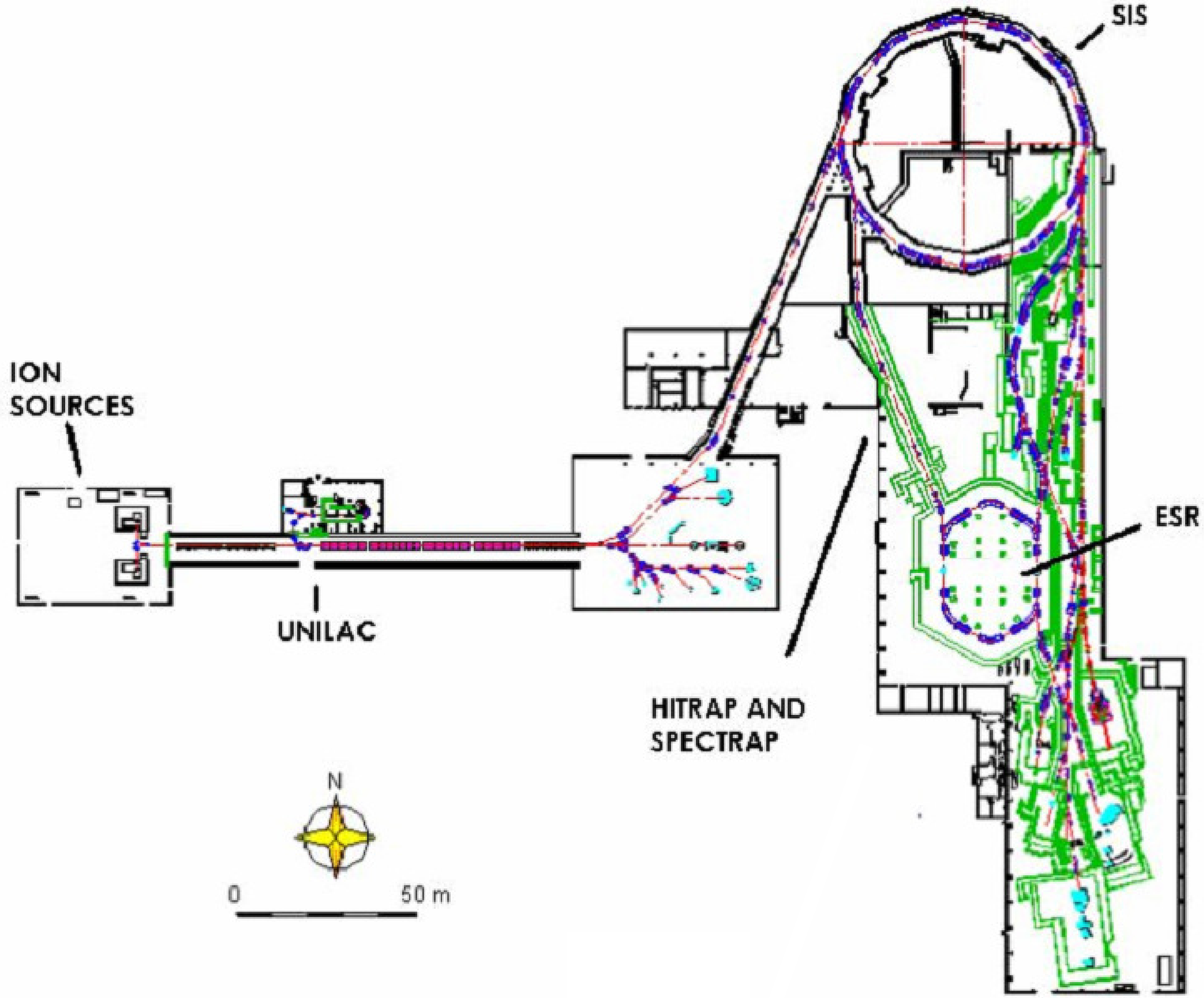
The Accelerator Facility at GSI

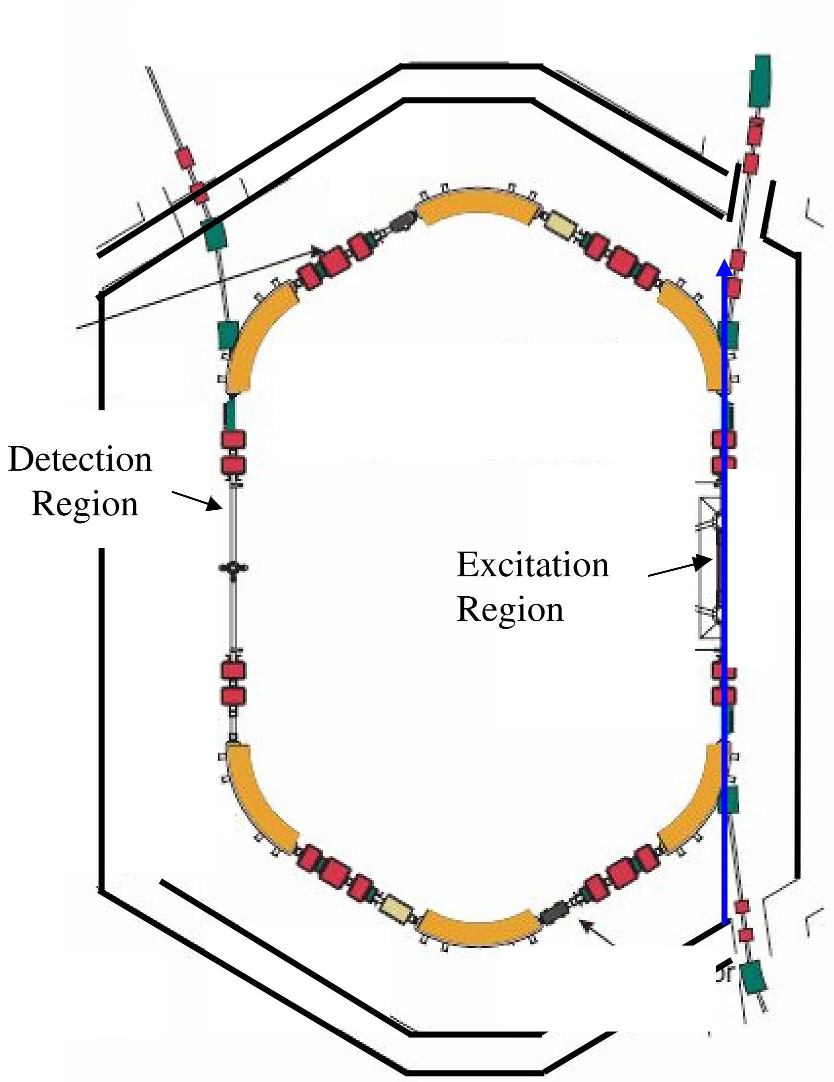


Li-like Bi:

400 MeV/u

$\beta = 0.71$

Doppler-Assisted Laser Spectroscopy @ ESR



- Relativistic Doppler effect

$$\lambda_{\downarrow\uparrow} = \lambda' \gamma (1 - \beta)$$

$^{209}Bi^{80+}$: $\lambda_0 = 1555$ nm
$\beta = 0.71$ (400 MeV/u)
$\lambda_{Lab} = 640$ nm

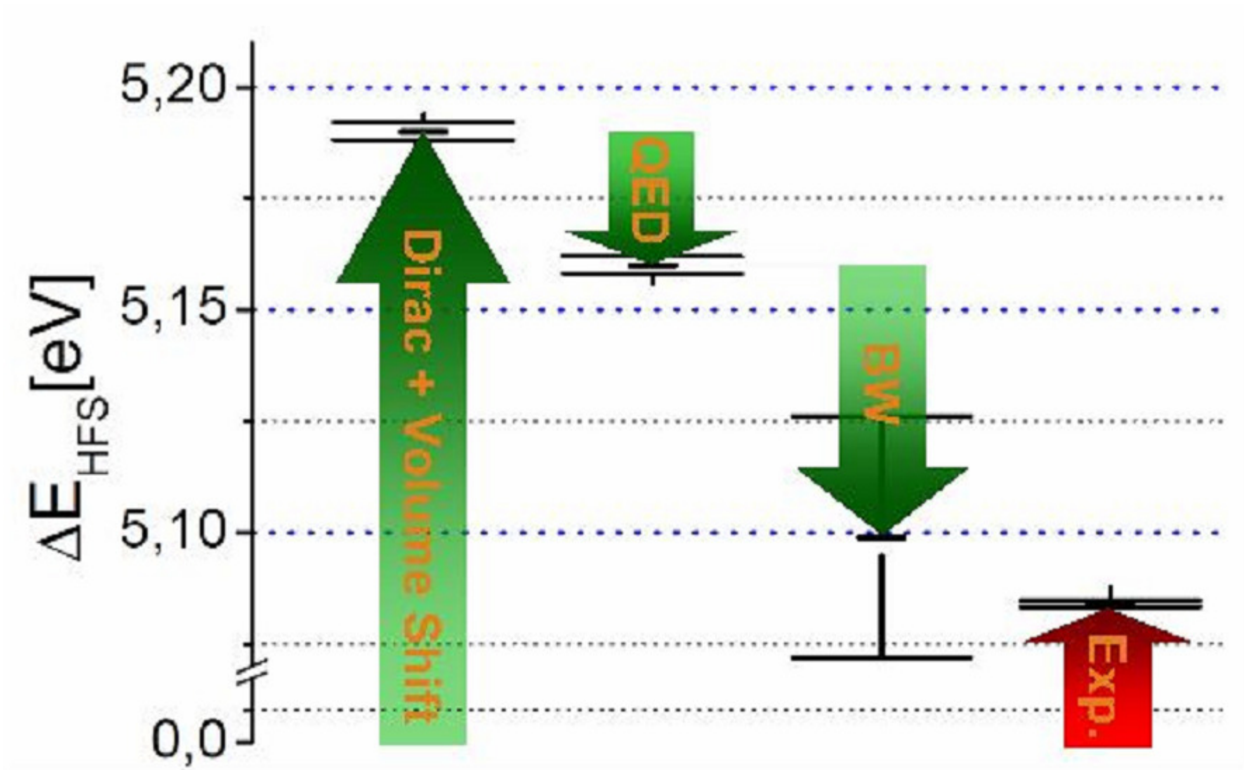
- Change wavelength of laser

  ⟶ E_{HFS}

- Reduced Background:
  - Signal- und Reference-bunch
  - Small window for DAQ

Results for H-like HCI

$^{207}Pb^{81+}$	λ=1019.7 (2) nm	ΔE_{HFS}=1.2159 (2) eV	[1]
$^{209}Bi^{82+}$	λ=243.87 (4) nm	ΔE_{HFS}=5.0841 (4) eV	[2]



Experimental uncertainties are very small!

Theoretical uncertainties of BW-Effect are very high!

Test of QED not possible!

[1] Seelig, Dissertation Uni Mainz (1999)
[2] Klaft et al., PRL 73, 2425-2427 (1994)

Disentangling QED and nuclear structure

$\mathrm{HFS}_{\text{H-like}}$ $$\Delta E^{(1s)} = \Delta E^{(1s)}_{Dirac}(1 - \epsilon^{(1s)}) + E^{(1s)}_{QED}$$

$\mathrm{HFS}_{\text{Li-like}}$ $$\Delta E^{(2s)} = \Delta E^{(2s)}_{Dirac}(1 - \epsilon^{(2s)}) + \Delta E_{int}(1 - \epsilon^{(int)}) + \Delta E^{(2s)}_{QED} + \Delta E_{int-QED}$$

The specific difference

$$\Delta E' = \Delta E^{(2s)} - \xi \Delta E^{(1s)}$$ with

$$\xi = f(\alpha Z)\frac{\Delta E^{(2s)}_{Dirac} + f_{int}(\alpha Z)\Delta E_{int}}{\Delta E^{(1s)}_{Dirac}} \qquad \frac{\epsilon^{(2s)}}{\epsilon^{(1s)}} \equiv f(\alpha Z) \qquad \frac{\epsilon^{(int)}}{\epsilon^{(2s)}} \equiv f_{int}(\alpha Z)$$

is independent of the BW-effect and can be calculated to rather high accuracy!

$\Delta E' = \Delta E'_{\text{non-QED}} + \Delta E'_{\text{QED}} = (61.25 \pm 0.04)$ meV

Solution: Measurement of HFS of H- and Li-like Ion of the same Isotope!

Shabeav et al., PRL 86, 3959 (2001)

Test of QED with ^{209}Bi

Isotope		Wavelength [nm]	Life time [ms]
$^{207}Pb^{81+}$	(H-like)	1020	52
$^{209}Bi^{82+}$	(H-like)	244	0.4
$^{209}Bi^{80+}$	(Li-like)	≈ 1555	82

2x without success ⟶ Monte-Carlo Simulation

$HFS_{Li\text{-}Bi}$ between 1500 nm and 1590 nm

Measurement time

Measurement time is the relevant value to decide if signal rate is to low or not

$$\Delta x = \sqrt{X + Y}$$

$$\Delta x \approx \sqrt{2 \cdot X}$$

$$S \cdot t \geq n \cdot \sqrt{2 \cdot (U_{ESR} + D) \cdot t}$$

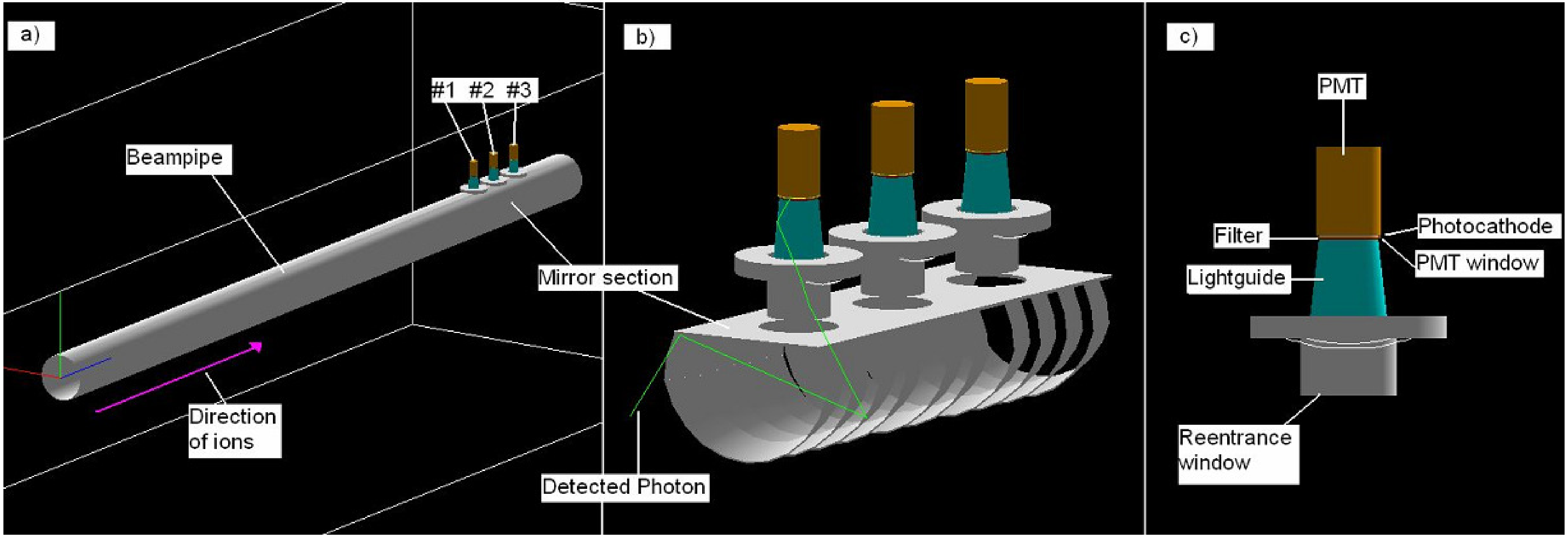
$$\Longleftrightarrow t = \frac{2 \cdot n^2 \cdot (U_{ESR} + D)}{S^2}$$

n = 3

Seven days beam time

⟶ at most 10 s to 12 s measurement time per wavelength

Monte-Carlo-Simulation



Check with measurement of HFS of H-like Pb:

Measured: S = (416 ± 1) cps

Simulated: S = (423 ± 4) cps

Signal rate of Li-like bismuth at mirror section

S = (14 ± 1) cps (Simulation)

U = (772 ± 2) cps (2003 measured)

$\mathbf{t_{n=3} = (71 \pm 1)\ s}$

$\mathbf{t_{n=2} = (31 \pm 1)\ s}$ Probably the reason, why Signal has not been found

Optimizations:

- Different detectors
- Larger window (∅60 mm ⟶ ∅70 mm)
- Lightguide

No significant change

⟶ **Development of a new detector setup!**

Relativistic photon sources

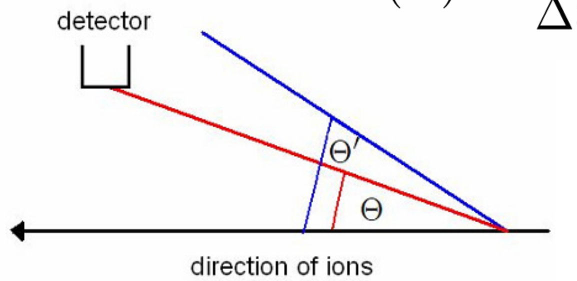
Rel. Doppler effect:

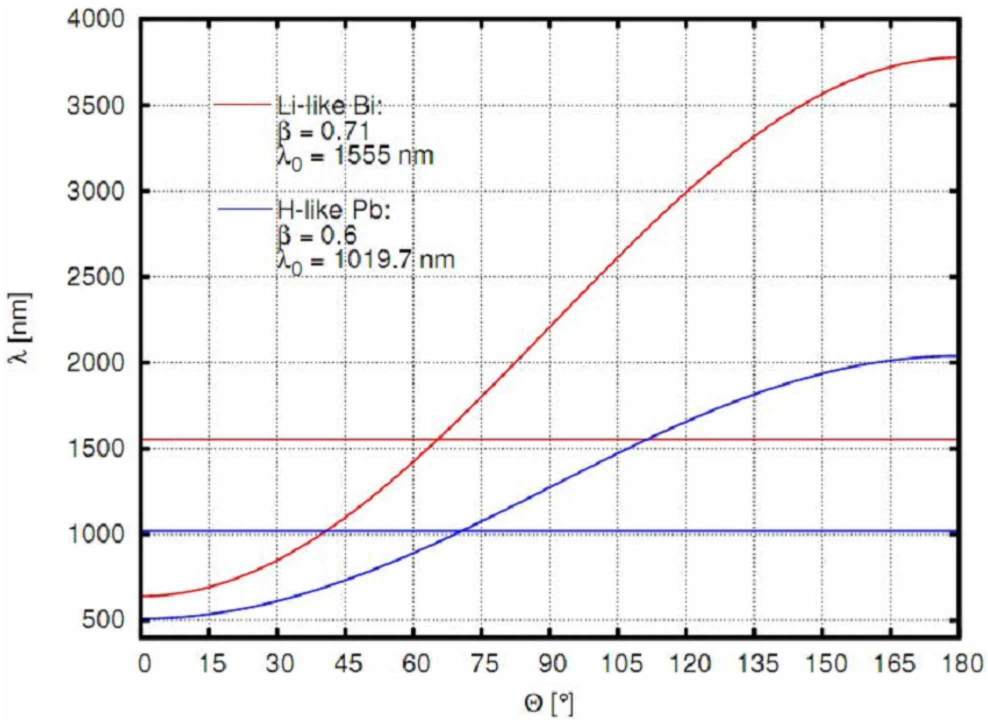
$$\lambda = \lambda' \cdot \gamma(1 - \beta\cos(\Theta))$$

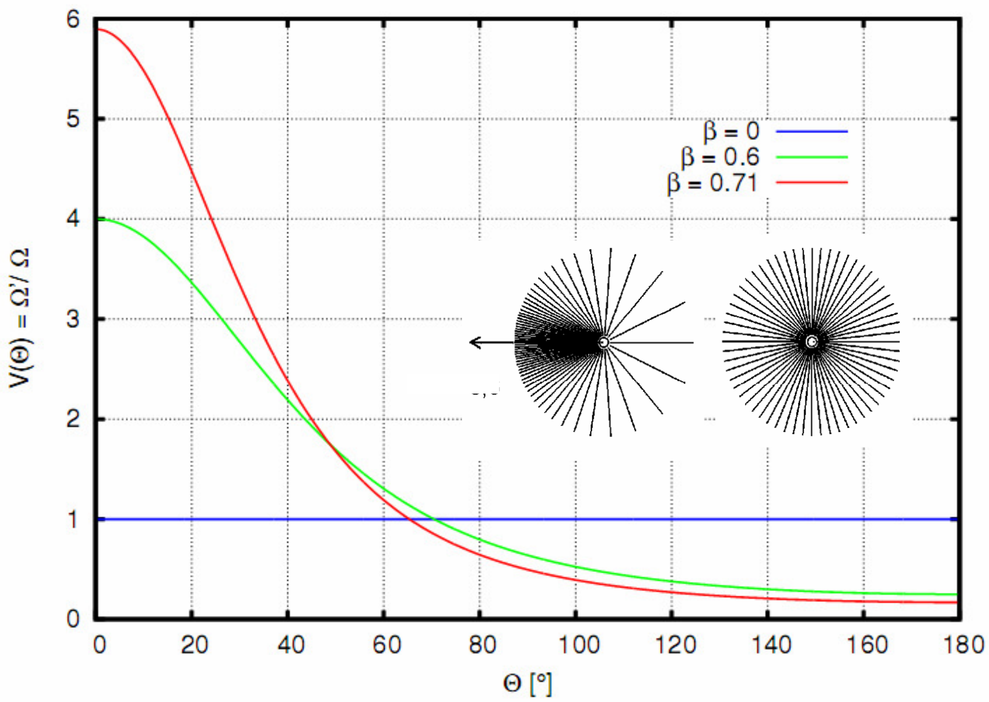
($25° \triangleq$ 800 nm)

Rel. Boost:

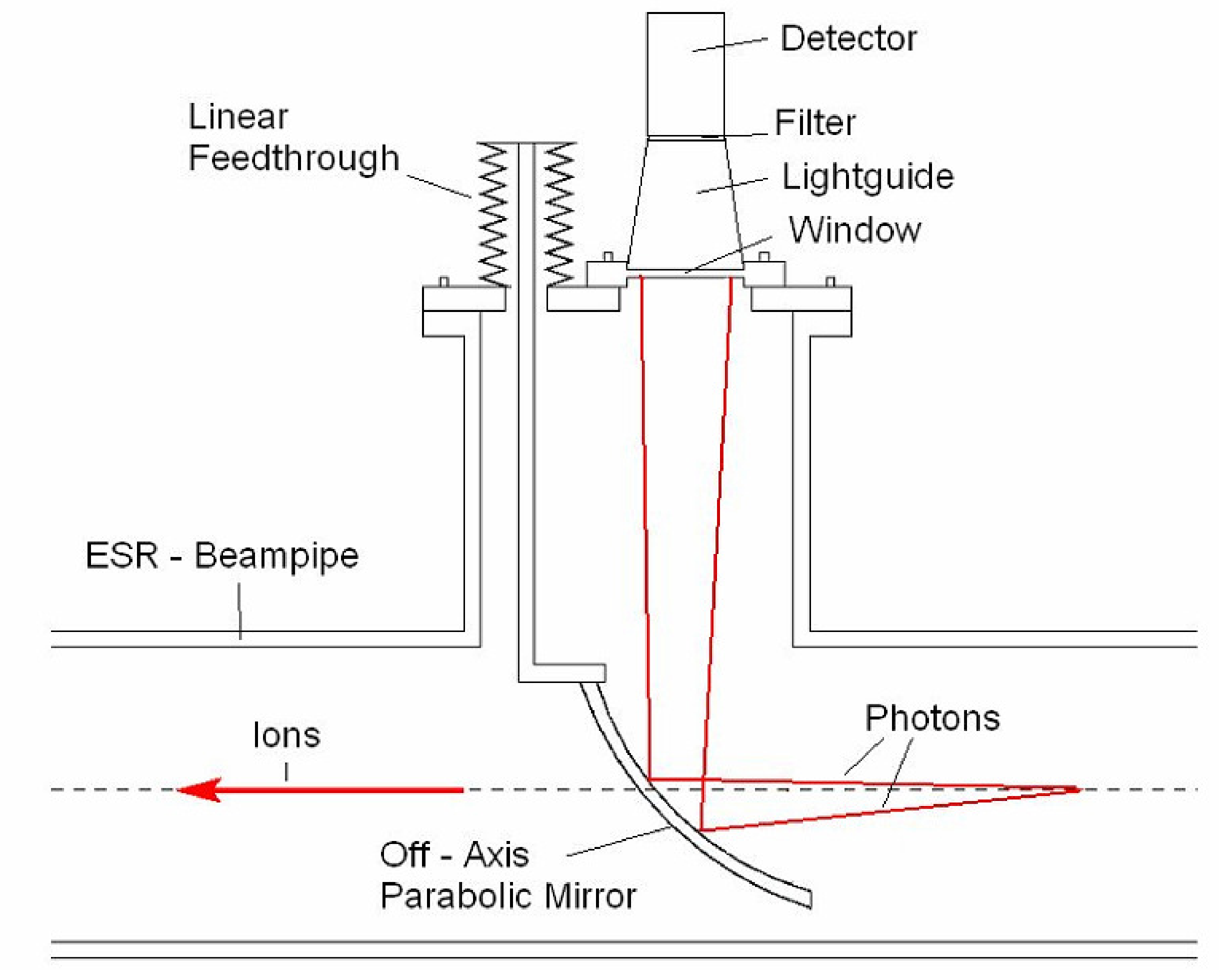
$$V(\Theta) = \frac{\Delta\Omega'}{\Delta\Omega} = \frac{\sin\Theta' d\Theta'}{\sin\Theta d\Theta} = \frac{1-\beta^2}{(1-\beta\cos(\Theta))^2}$$







Parabolic mirror system

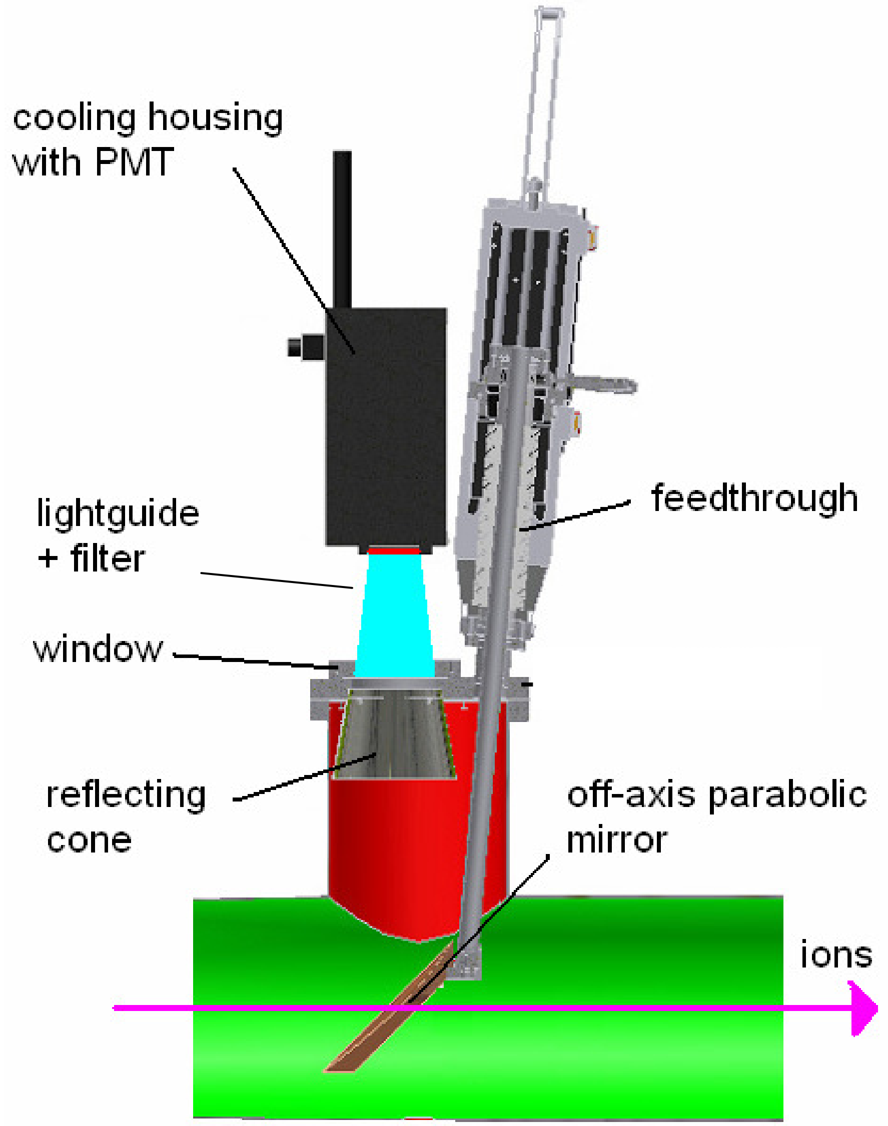


Mirror as seen by ions

Moveable off-axis-parabolic mirror ± 100 mm ↕

Optimization of parabolic mirror system

1. 1-flange-option vs. 2-flange-option
2. Reentrance window vs. “cone”
3. Shape of mirror
4. Detector
5. Size of window
6. Lightguide
7. “Extreme” wavelength



Results parabolic mirror system

Parabolic mirror:

S = (60 ± 1) cps

U = (427 ± 9) cps   t = (**2.1** ± 0.1) s

Old mirror:

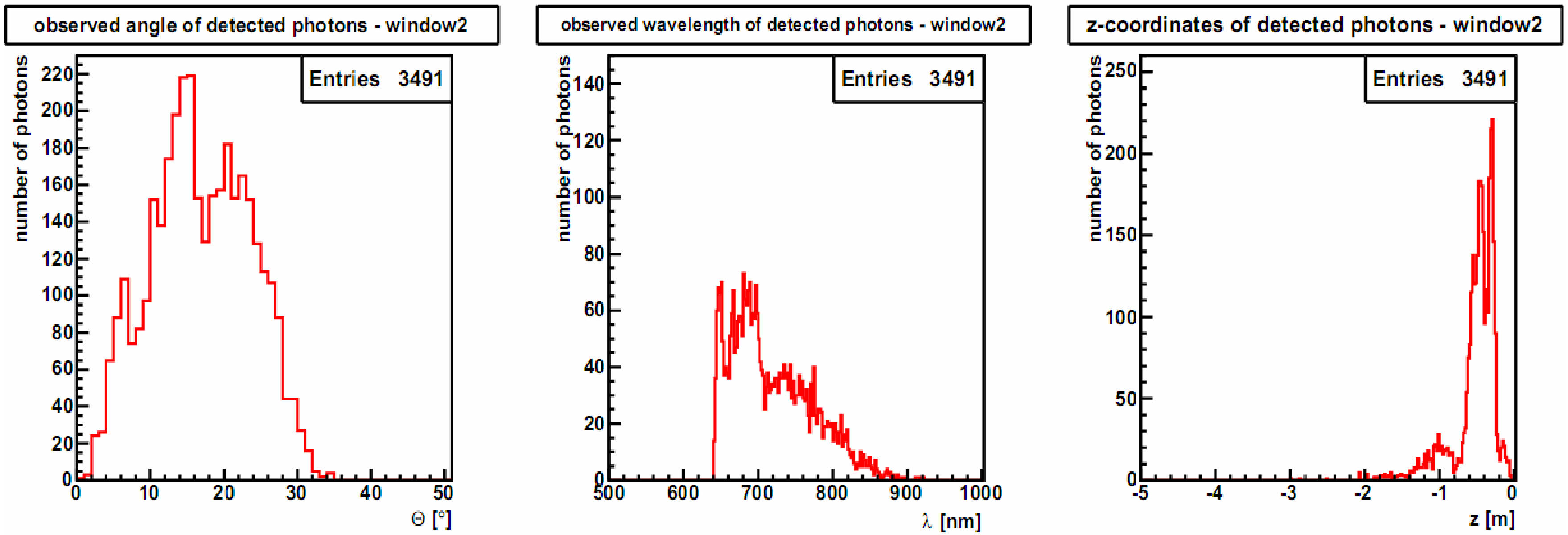
S = (14 ± 1) cps

U = (772 ± 1) cps   t = (**70.5** ± 1) s

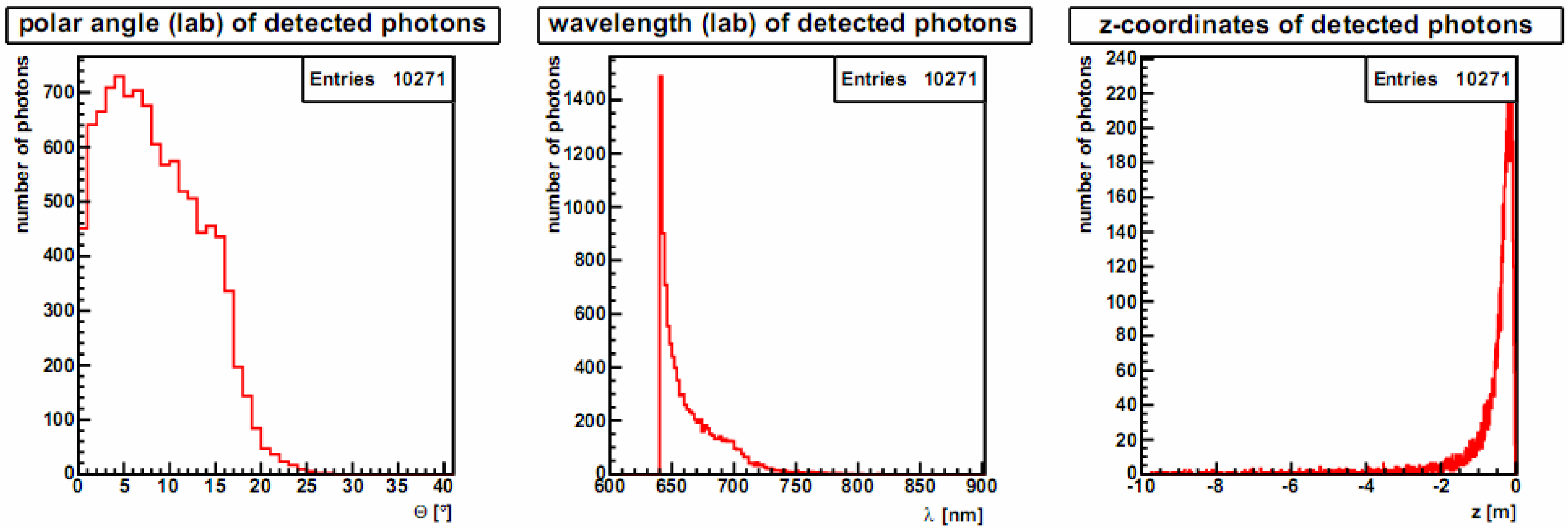
t < 10 s!!!

33 times better!

Detected photons

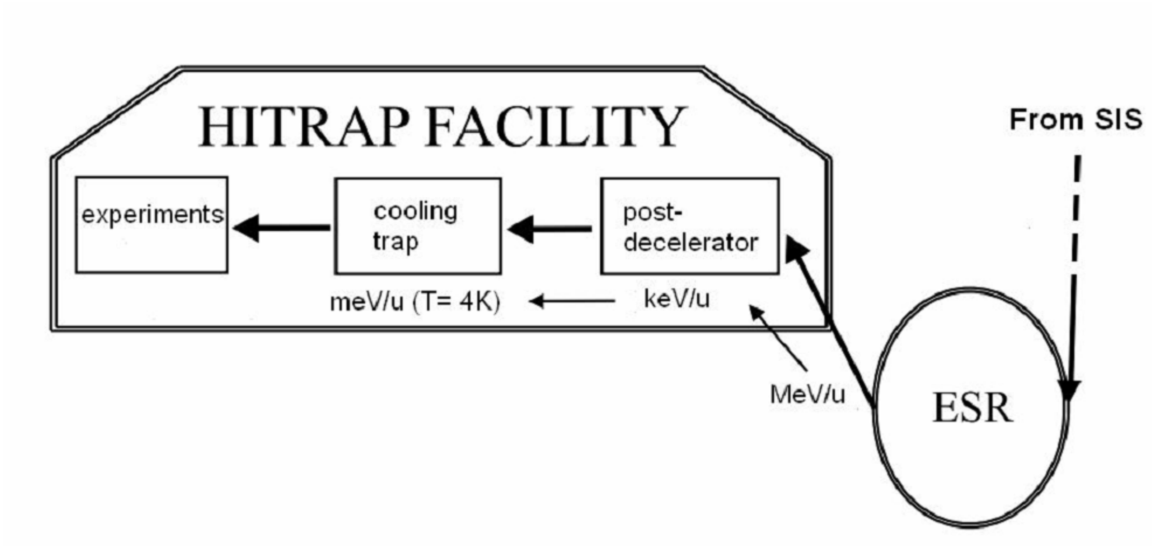


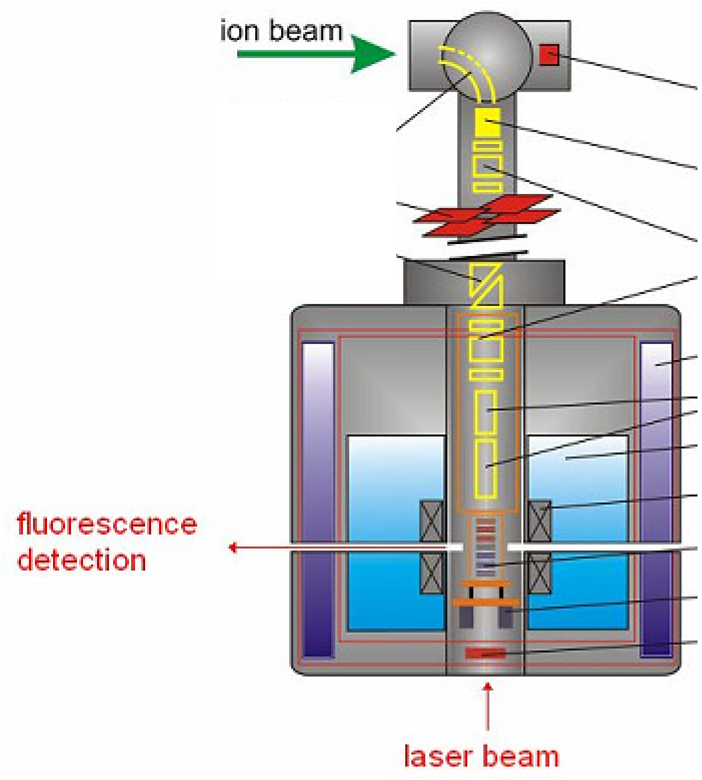
Mirror section



Parabolic mirror

Spectrap



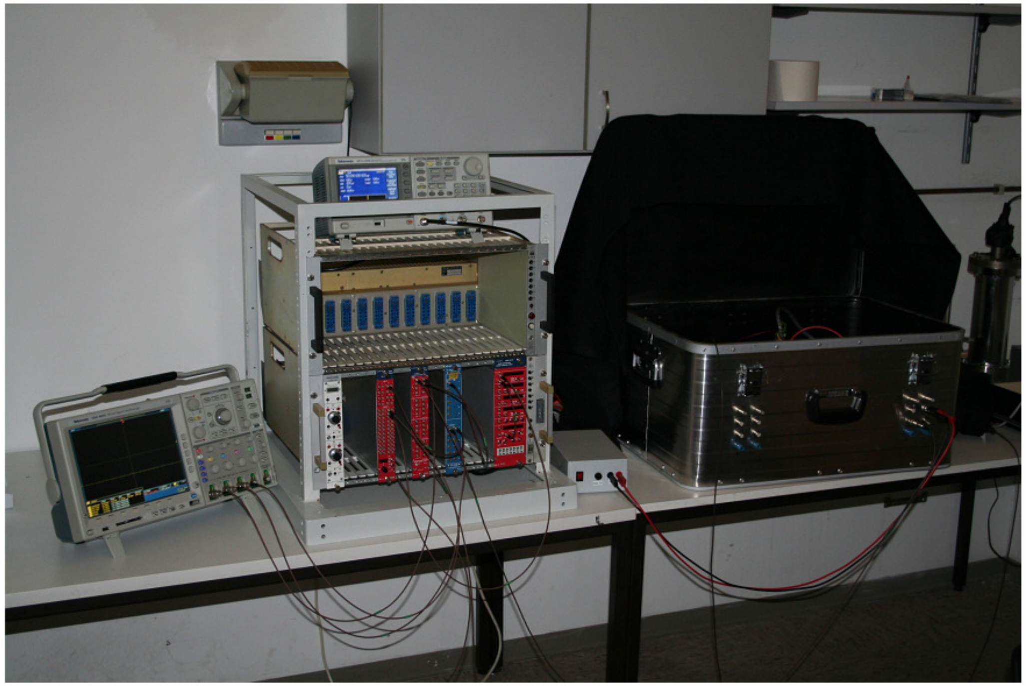


ESR: $\Delta\lambda / \lambda = 10^{-4}$

Spectrap: $\Delta\lambda / \lambda = 10^{-7}$ ⟶ Test of QED of a few per cent

Determination of HFS at ESR is required before measuring with Spectrap!

Detectors



Setup in photographic laboratory

Characterization of PMT and CPM

- Single Photon Plateaus
- Sensitivity in B-field
- Jitter
- Dark counting rate (cooled)
- Test at ESR
- Detection of single photons
- Determination of QE

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Summary

- Testing QED with laser spectroscopy at highly charged ions
- HFS of $^{209}Bi^{82+}$ determind, $^{209}Bi^{80+}$ under investigation
- Old mirror system not appropriate
- Development of new detector setup with off-axis parabolic mirror

- parabolic mirror successfully tested at ESR
- Development of new laser system and new DAQ at GSI
- Measurement spring 2011