Laser SpHERe

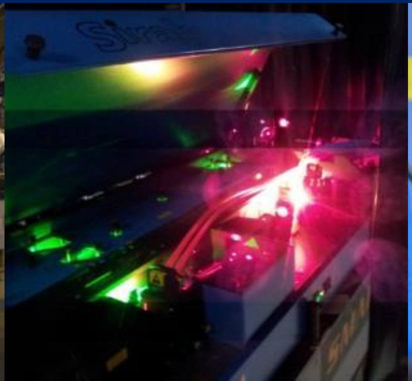
Laser Spectroscopy of Highly Charged Ions and Exotic Radioactive Nuclei

Libelle

Lithium like Bismuth Experiment with Laser Light at ESR

Johannes Ullmann
for the LIBELLE collaboration

Recent results from the hyperfine spectroscopy experiment at the ESR

Outline

I. Ground-state hyperfine structure

A QED-testing toolkit

II. Experimental setup at GSI

Collinear in-ring laser spectroscopy

III. Results of 2014 beamtime

Hydrogen- and lithium-like Bismuth

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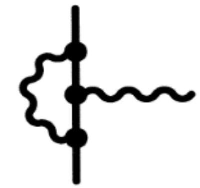
Testing QED

"Quantum Electrodynamics (QED) is the ***most precisely tested theory*** in physics…"

Fundamental QED Interactions:

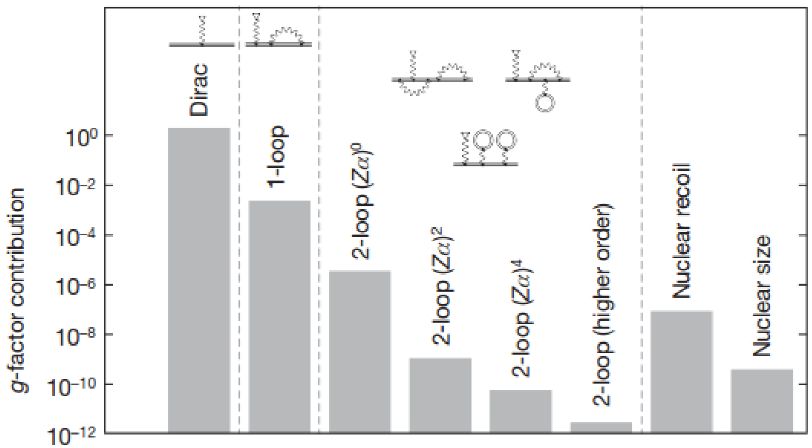
Self - Energy

Vacuum - Polarization



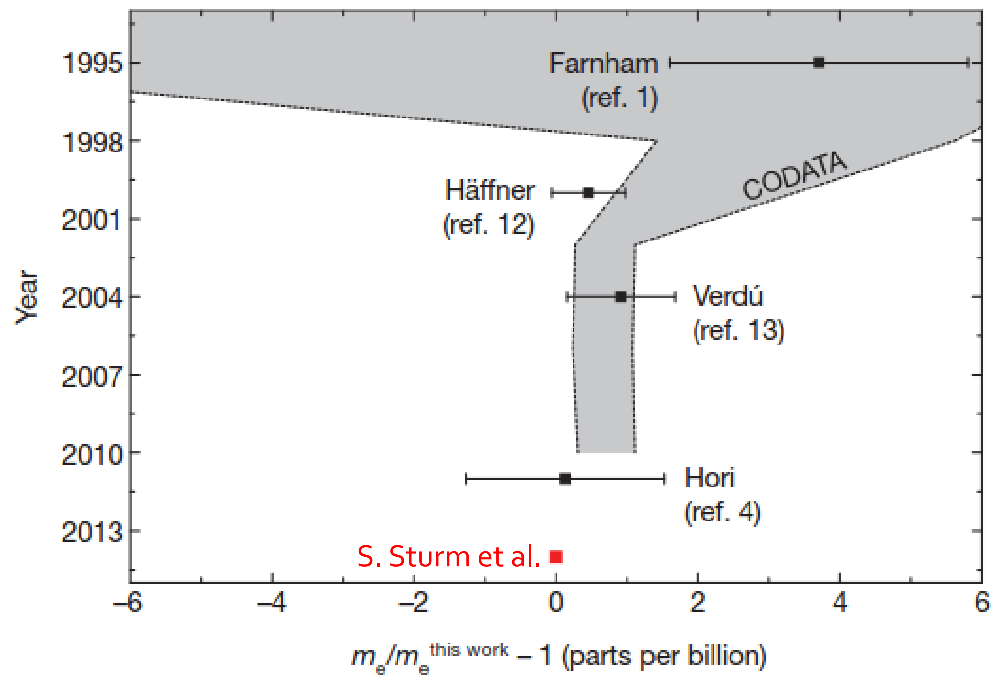
Vertex - Correction

<u>g-factor of the electron in H-like Carbon:</u>



$$m_e = \frac{g}{2}\frac{e}{q}\frac{\nu_{cyc}}{\nu_L} m_{ion} \equiv \frac{g}{2}\frac{e}{q}\frac{1}{\Gamma} m_{ion}$$

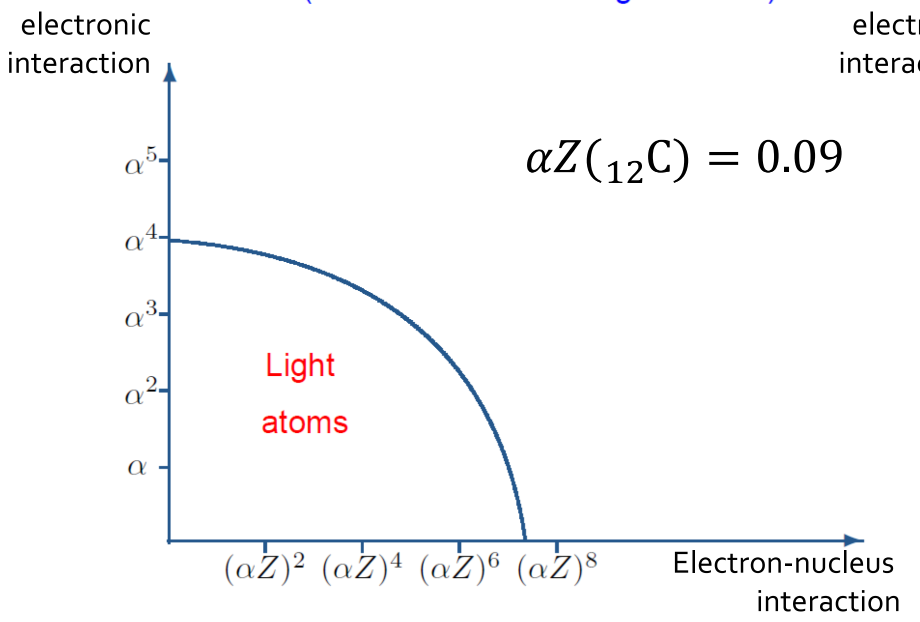
$$m_e = 0.000548579909067(14)(9)(2)$$



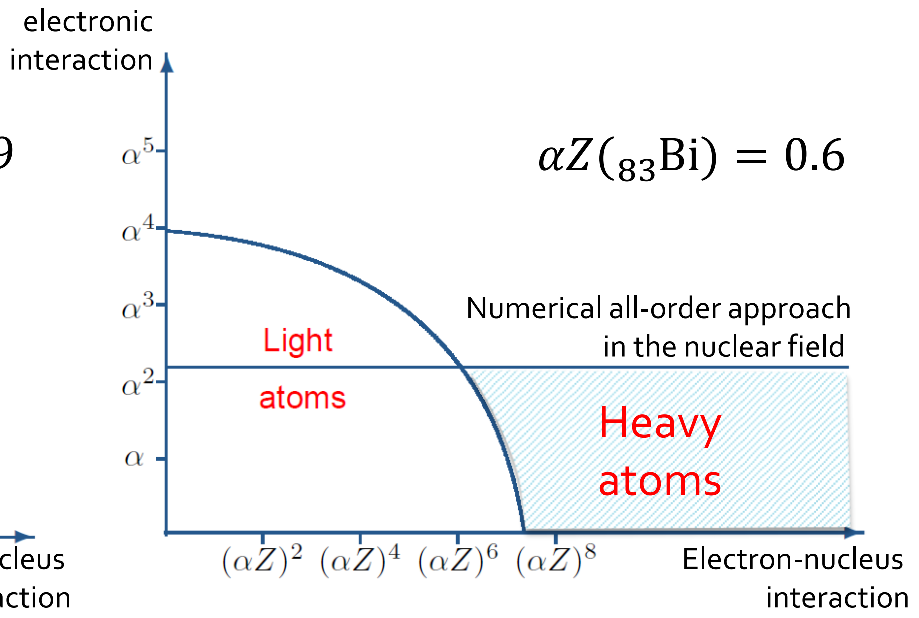
S. Sturm et al., Nature **506**, 467 (2014)

Weak field vs. strong field

Tests of QED to lowest orders in $\alpha \approx \frac{1}{137}$ and in $\alpha Z \ll 1$
(Z is the nuclear charge number)

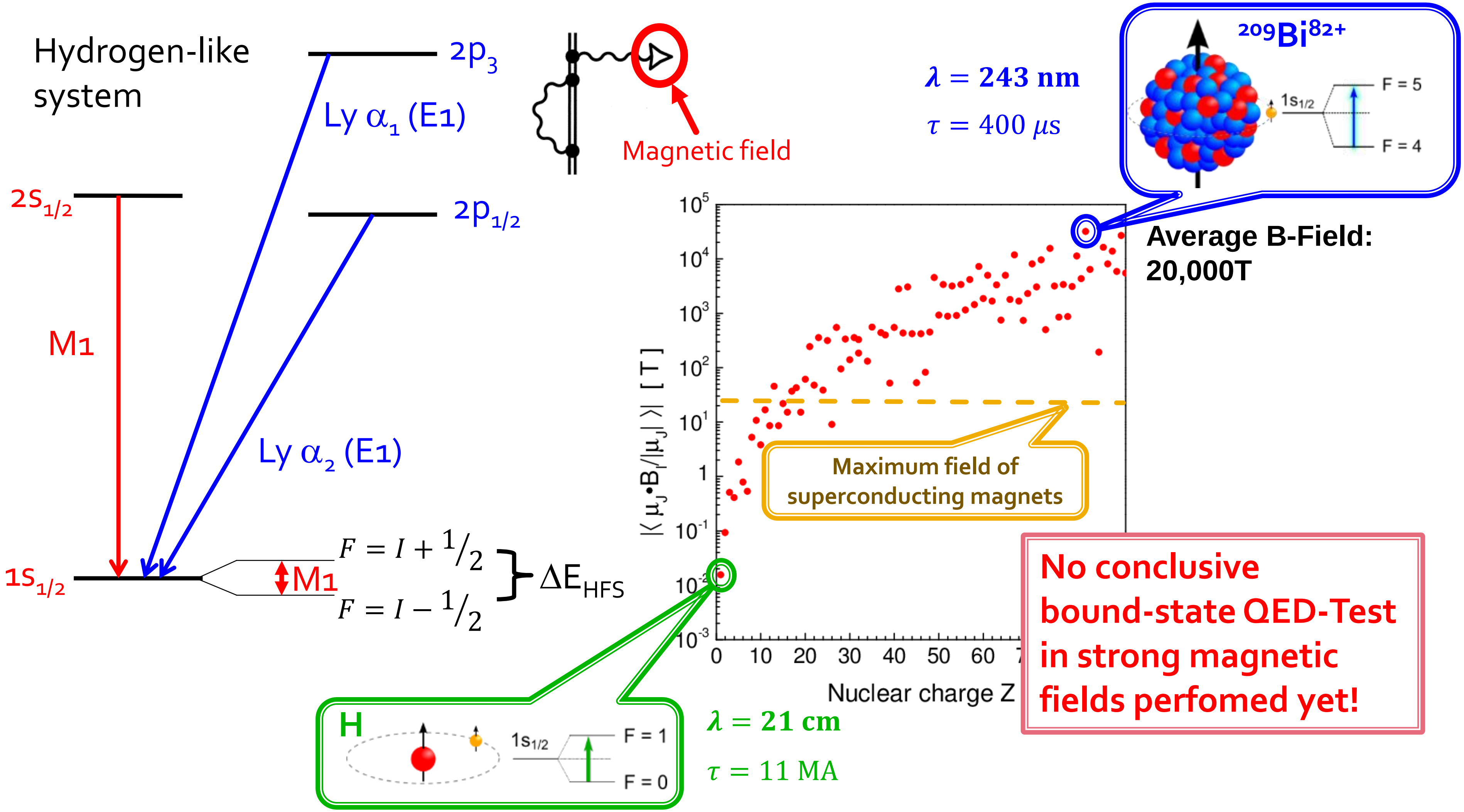


Tests of QED to lowest orders in α and to all orders in αZ



Courtesy of V. Shabaev

Probing the nuclear magnetic field

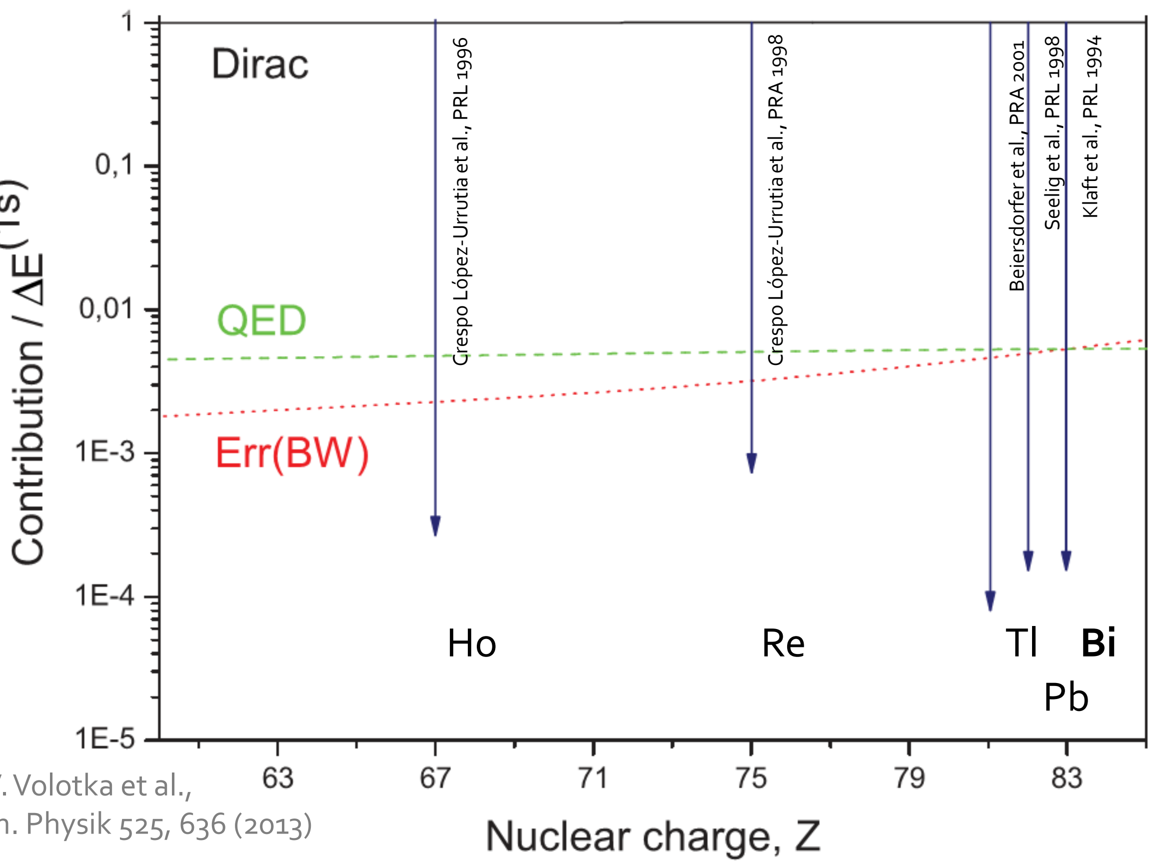


No conclusive bound-state QED-Test in strong magnetic fields perfomed yet!

Hyperfine splitting in hydrogen-like ions

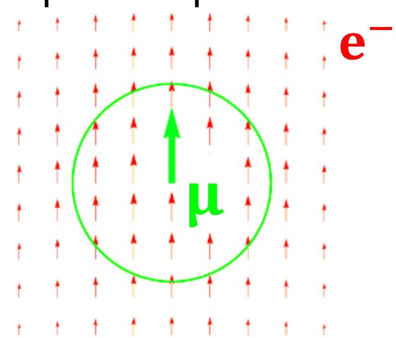
$$\Delta E_{HFS} = \underbrace{\frac{4}{3}\alpha(\alpha Z)^3 \frac{\mu}{\mu_N}\frac{m}{m_p}\frac{2I+1}{2I}mc^2 \times \left[A(\alpha Z)\cdot(1-\delta)\cdot\right.}_{\text{known}} (1-\varepsilon) + \left.\chi_{QED}\right]$$

BW: Bohr-Weisskopf-Effect: nuclear magnetization distribution

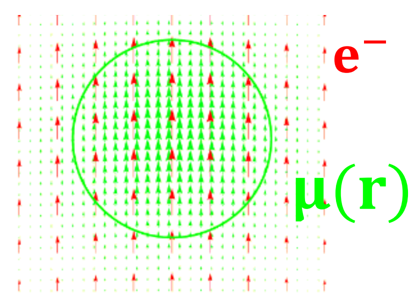


A.V. Volotka et al., Ann. Physik 525, 636 (2013)

point dipole



distributed dipole: Nuclear model sensitive!



Bohr, PR **77**, 94 (1950)

Testing QED in the HFS

$f(\alpha Z) = \frac{\varepsilon^{(2s)}}{\varepsilon^{(1s)}}$ $f_{\mathrm{int}}(\alpha Z) = \frac{\varepsilon^{(int)}}{\varepsilon^{(2s)}}$ ε – BW–correction

$$\xi = f(\alpha Z)\frac{\Delta E^{2s}_{\mathrm{Dirac}} - f_{\mathrm{int}}(\alpha Z)\Delta E_{\mathrm{int}}}{\Delta E^{1s}_{\mathrm{Dirac}}} = 0.16886, \qquad \text{for } Z = 83$$

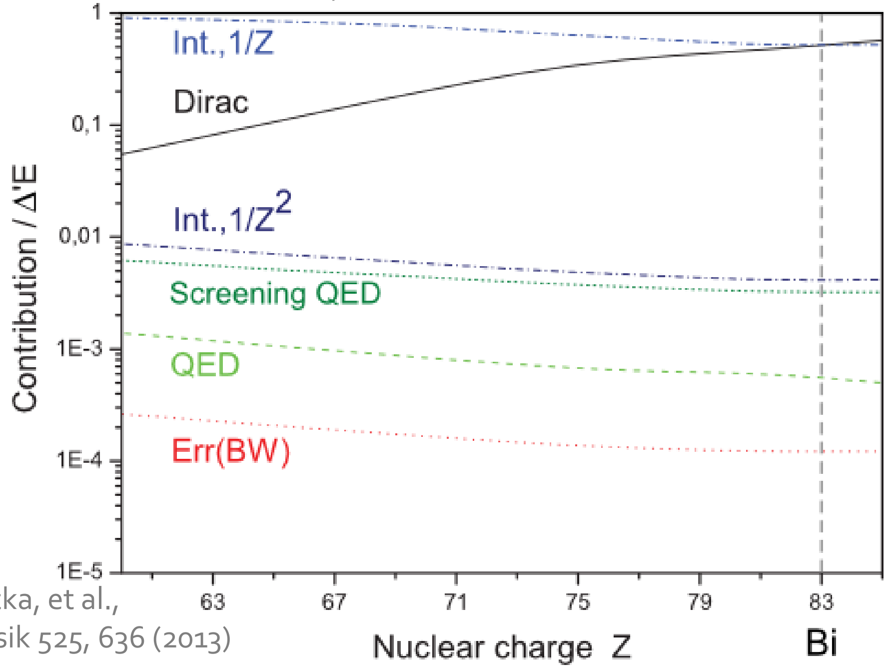
chosen to cancel Bohr-Weisskopf-effect

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

V.M. Shabaev et al., Phys. Rev. Lett. 86, 3959 (2001).

$\Delta' E$	= -61 .320(4) meV
QED	= 0.036 meV
Screened QED	= 0.193(2) meV
$QED_{total} / \Delta' E$	≈ 3×10^{-3}

O. Andreev et al., PRA 85, 022510 (2012)
A.Volotka et al., PRL 108, 073001 (2012)

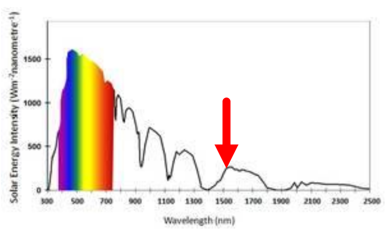


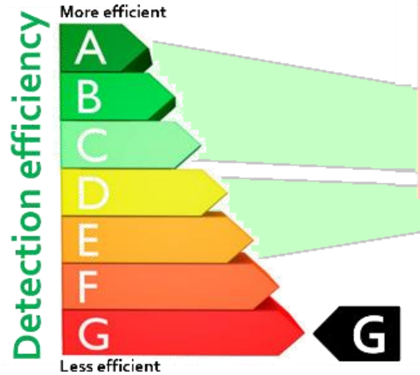
A.V. Volotka, et al., Ann. Physik 525, 636 (2013)

A 20 year old puzzle of finding the resonance

<u>Li-like Bi challenges:</u>

- $\lambda_0 \approx 1555$ nm (infrared)
- Low fluorescence rate
- Low detection efficiencies





1994
- Beamtime 1
- H-Like: ✓

1998
- Beamtime 2
- H-Like: ✓
- Li-like: ✗

10/2001
- Beamtime 3
- H-Like: ✓
- Li-like: ✗

03/2004
- Beamtime 4
- H-Like: ✓
- Li-like: ✗

08/2011
- Beamtime 5
- H-Like: ✓
- Li-like: ✓

03/2014
- Beamtime 6

Unforeseen systematics! ☹

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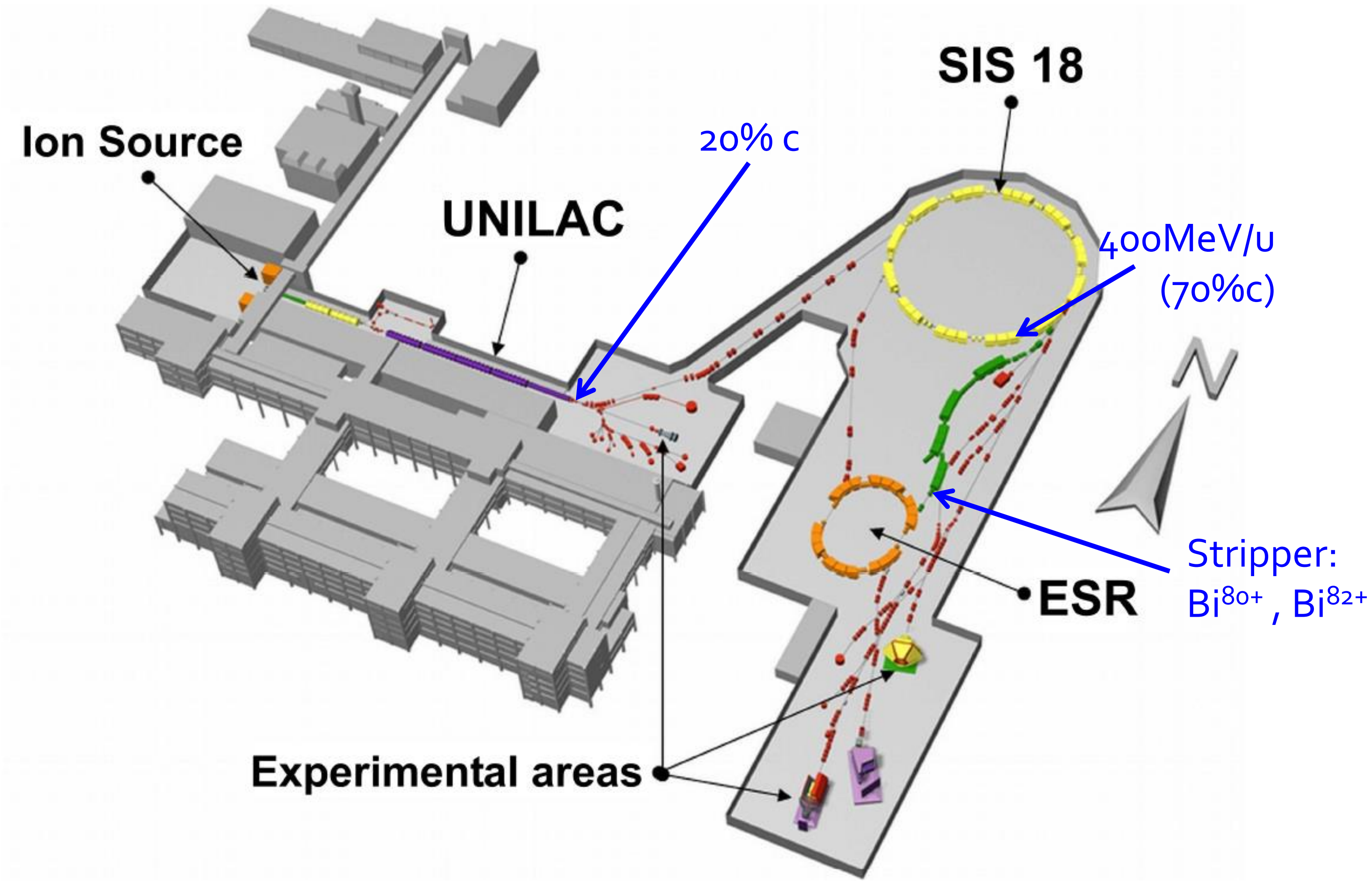
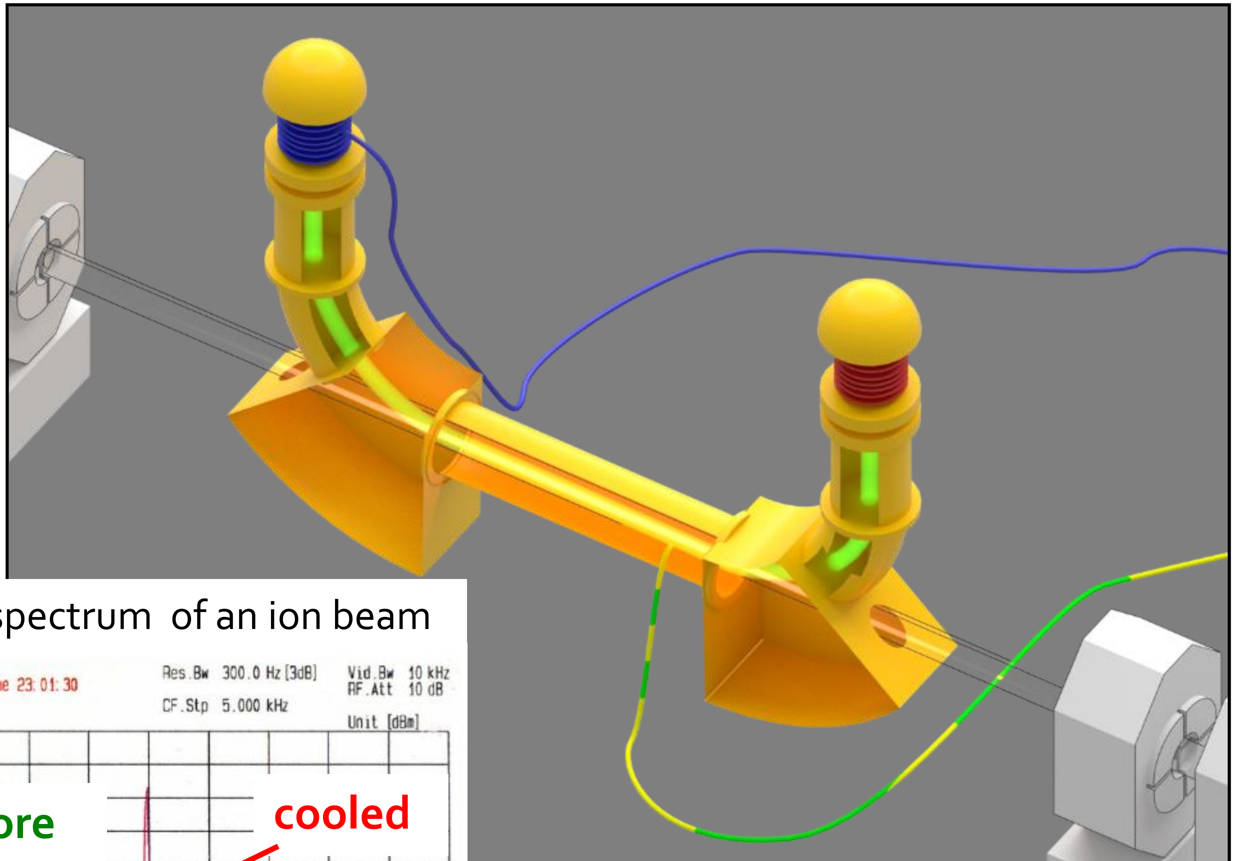
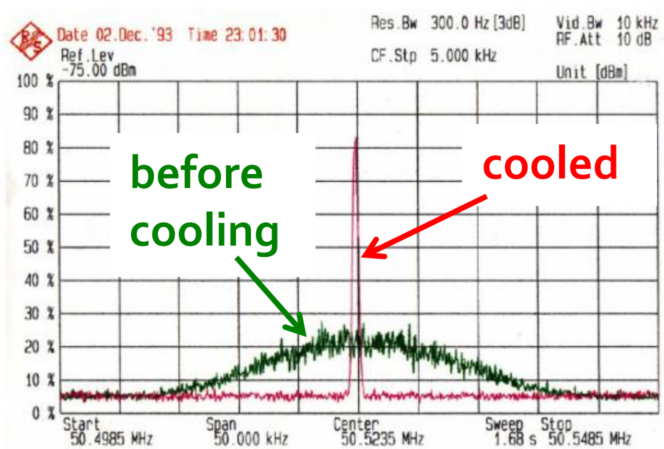
GSI Accelerator System



Ion Injection and Cooling

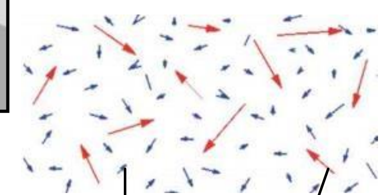


Schottky spectrum of an ion beam



Ion beam storage time	τ = 20 s… minutes
Momentum spread	$\Delta p/p \sim 8 \times 10^{-6}$
Typical Doppler width	$\Delta\nu \sim$ 1-50 GHz

Ions‘ rest frame



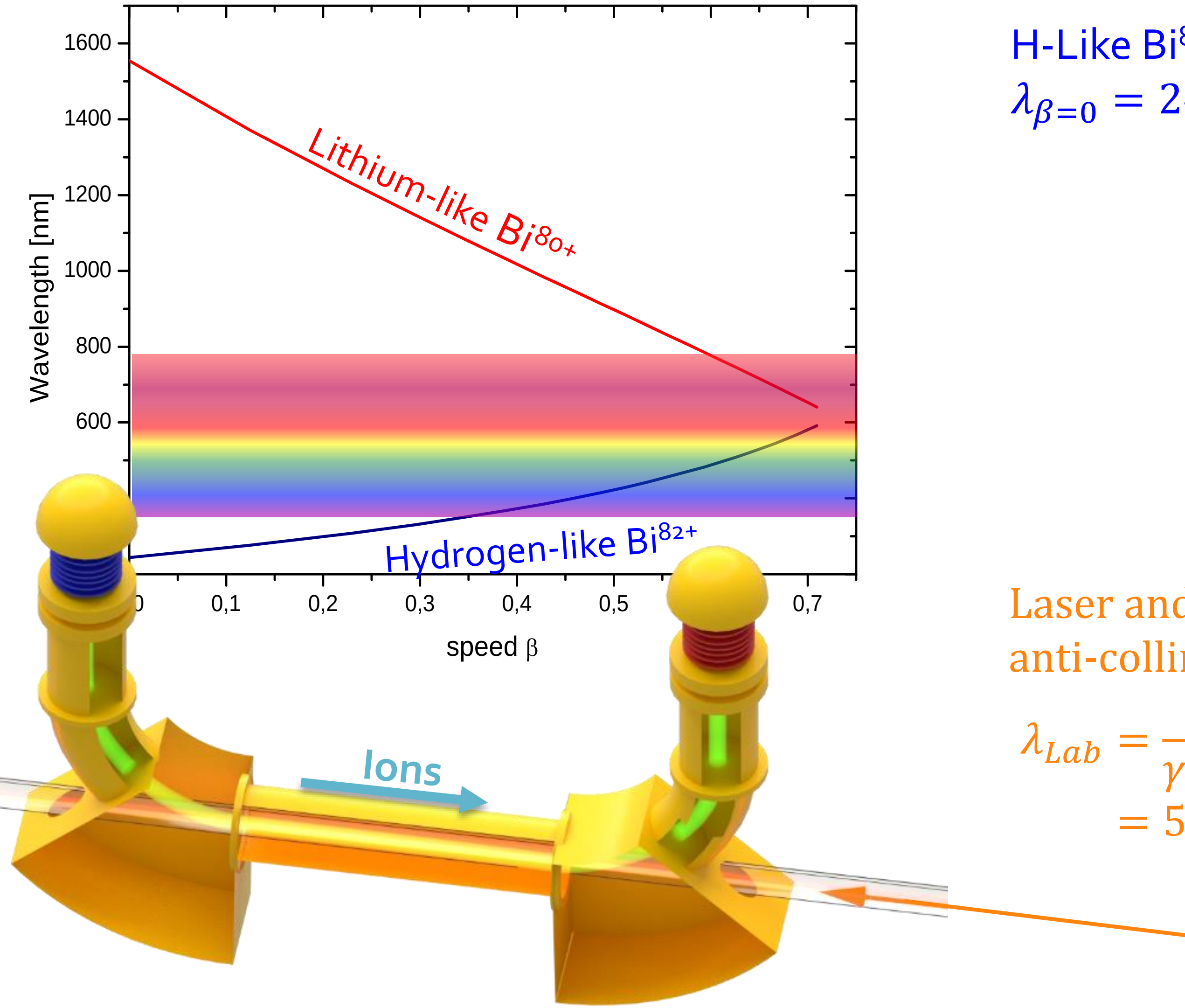
Laser Excitation

Li-like Bi^{80+}:

$$\lambda_{\beta=0} = 1555 \text{ nm}$$

H-Like Bi^{82+}:

$$\lambda_{\beta=0} = 244 \text{ nm}$$



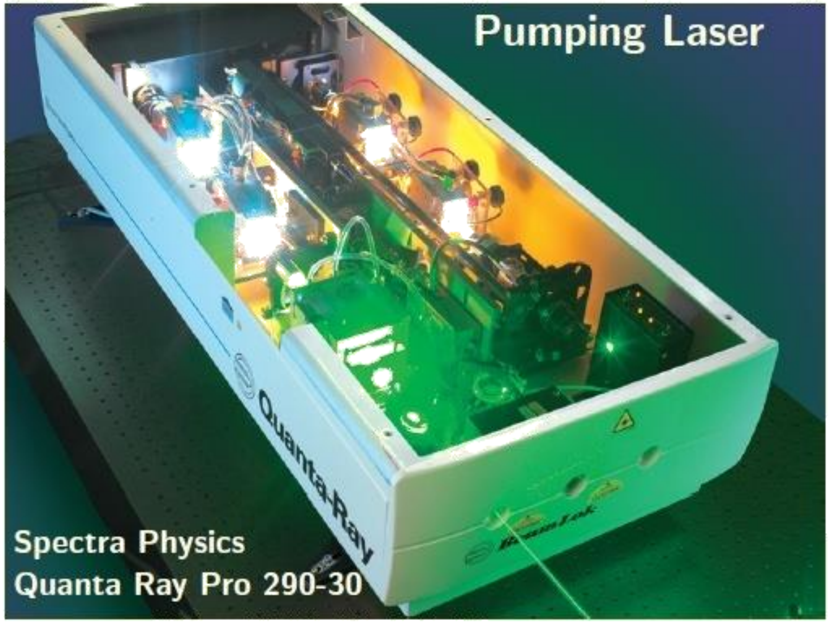
Laser and Ions collinear

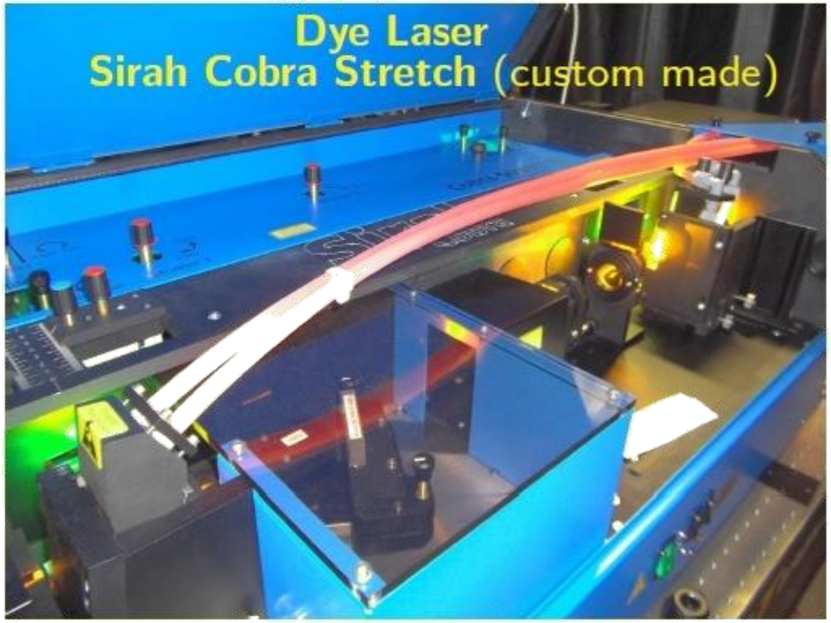
$$\lambda_{Lab} = \frac{\lambda_0}{\gamma(1+\beta)} = 640 \text{ nm}$$

Laser and Ions anti-collinear

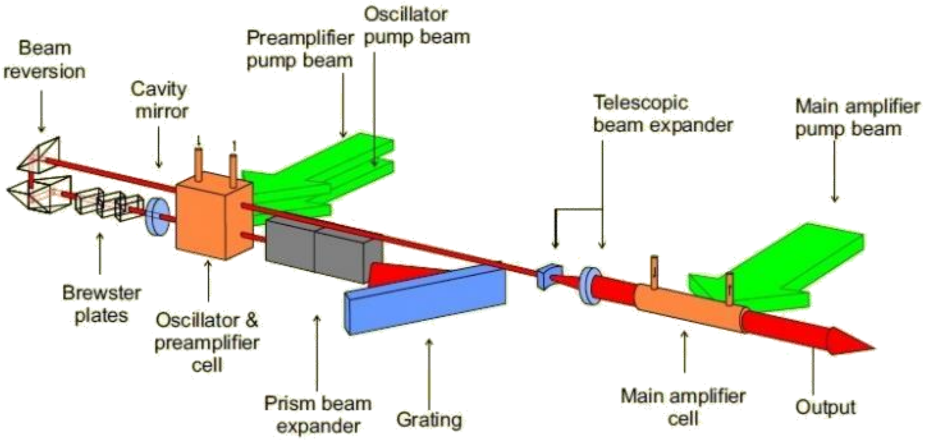
$$\lambda_{Lab} = \frac{\lambda_0}{\gamma(1-\beta)} = 590 \text{ nm}$$

Pulse Laser system

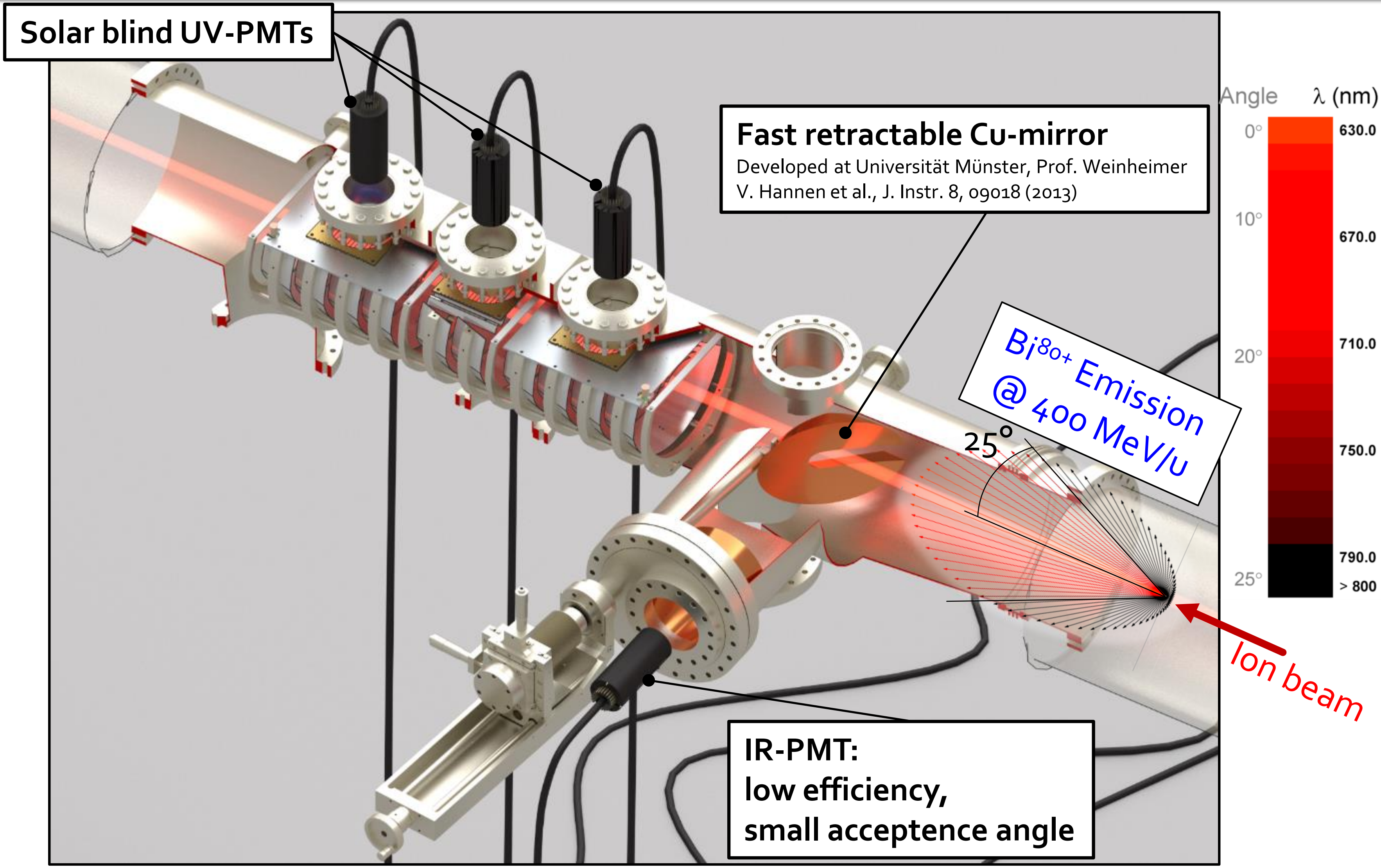




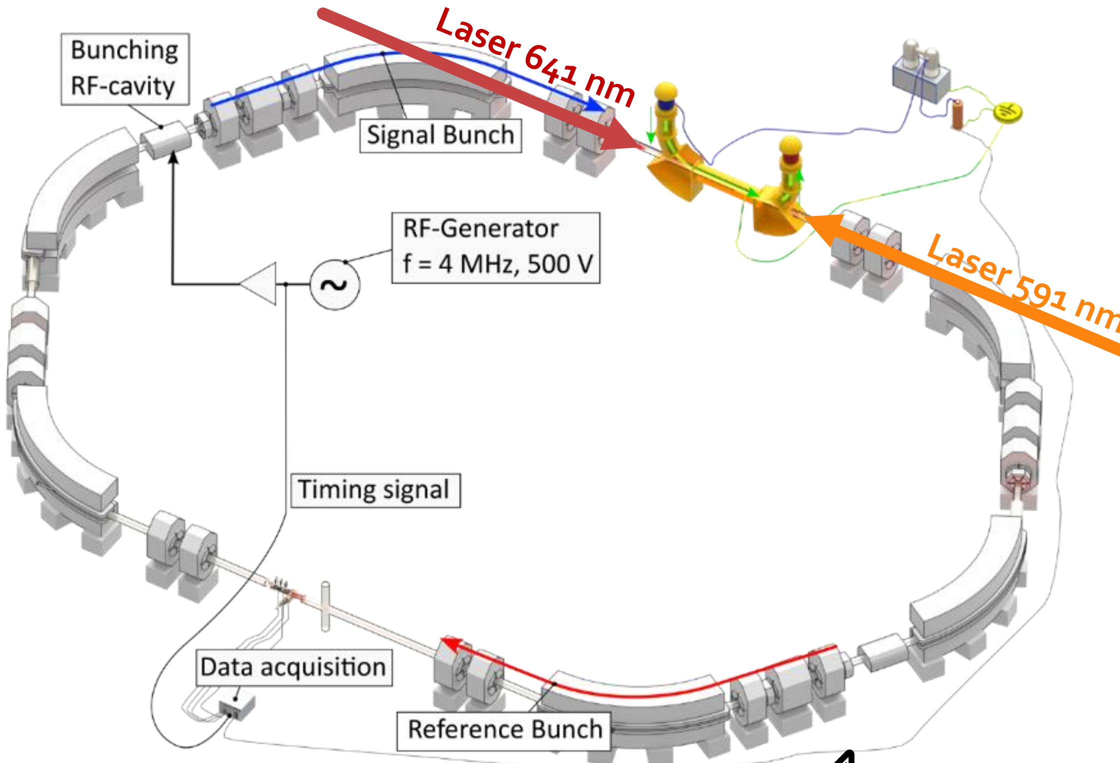
- E_{pulse} up to 600 mJ (pump laser @ 532nm)
- E_{pulse} up to 150 mJ (dye laser @ 590 / 640 nm)
- repetition rate 30 Hz
- pulse length 4-7 ns
- linewidth $\approx$2 GHz



Fluorescence Detection

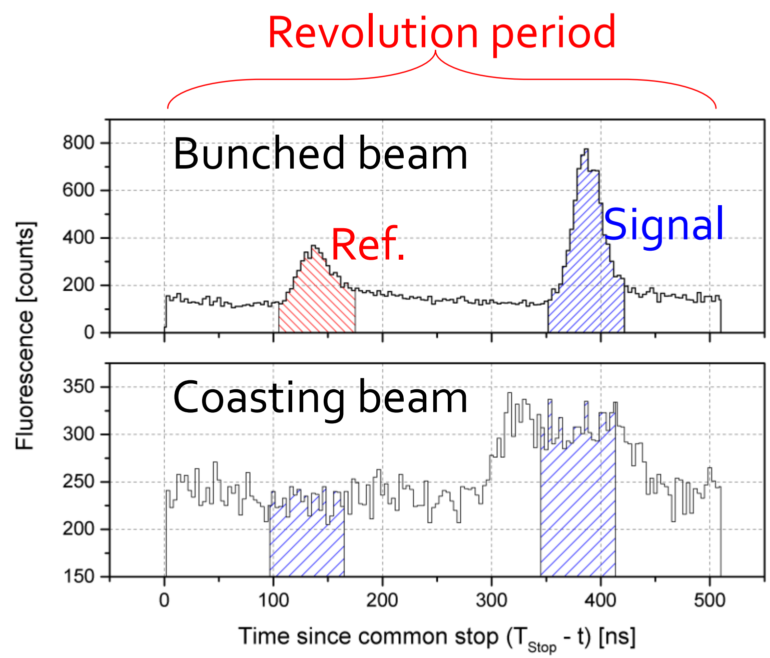


Ion Bunching and measurement principle

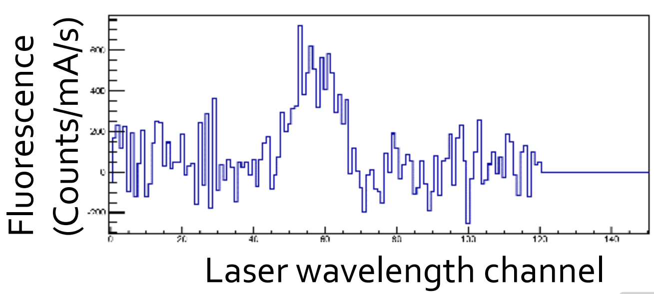


Bunching:
- Improved laser interaction
- Background reduction

Photon tagging:
- time information



$$\frac{\sum \text{Signal} - \sum \text{Ref}}{I_{\text{Ion}}\, \tau_{\text{live}}}$$



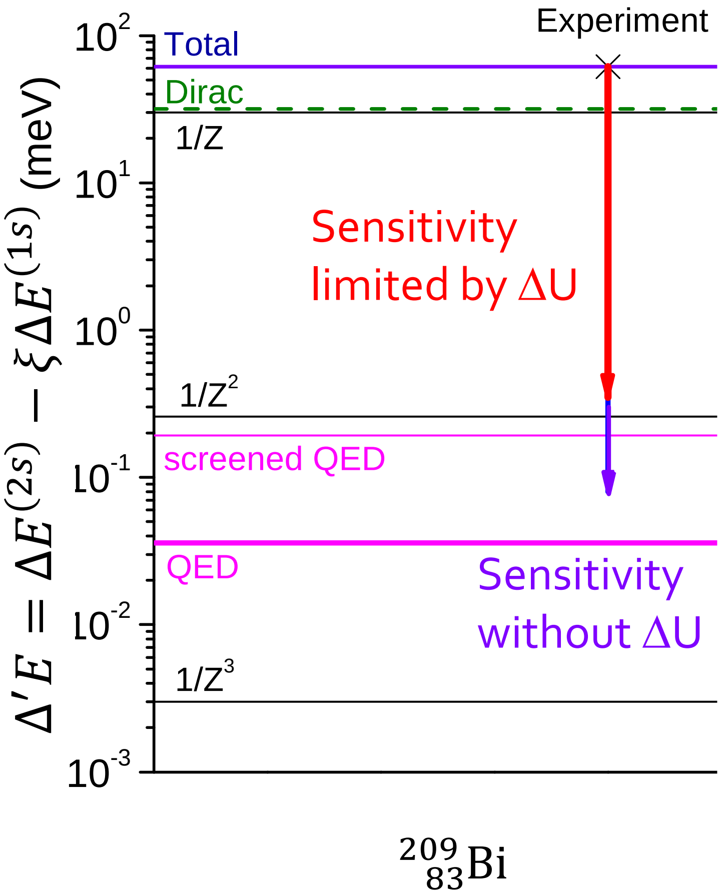
Transformation to rest frame

$$\lambda_0 = \lambda_{Labor} \cdot \gamma \cdot (1-\beta)$$

$$\beta(eU) = \sqrt{1-\gamma^{-2}} = \sqrt{1-\left(1+\frac{eU}{mc^2}\right)^{-2}}$$

laser wavelength measurement by wavemeter $\delta\lambda_{Labor}$

acceleration voltage δU



Results of 2011 beamtime

$\delta\lambda_{Labor} = 0.025\ nm$
$\delta U = 110\ V$

$$\frac{\delta\Delta E^{(1s)}}{\Delta E^{(1s)}} = \frac{\delta\Delta E^{(2s)}}{\Delta E^{(2s)}} = 2.7 \cdot 10^{-4}$$

Exp: $\frac{\delta\Delta' E}{\Delta' E} = 7 \cdot 10^{-3}$

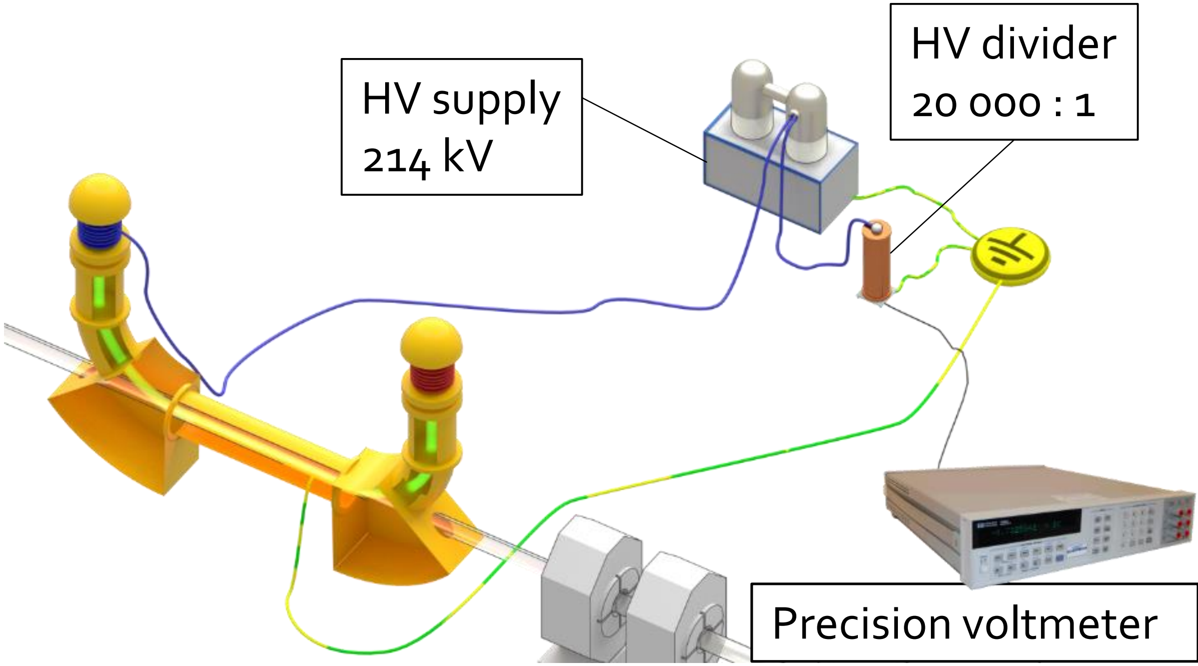
Theory: $\frac{\delta\Delta' E}{\Delta' E} = 1 \cdot 10^{-4}$

→ Repeat measurements and get voltage under control !

New Equipment at the ESR Electron Cooler

In-situ measurement with 200 kV High-Voltage Divider

Accuracy $\Delta U \approx 4\,\mathrm{V}$ (2011: $\Delta U = 110\,\mathrm{V}$)



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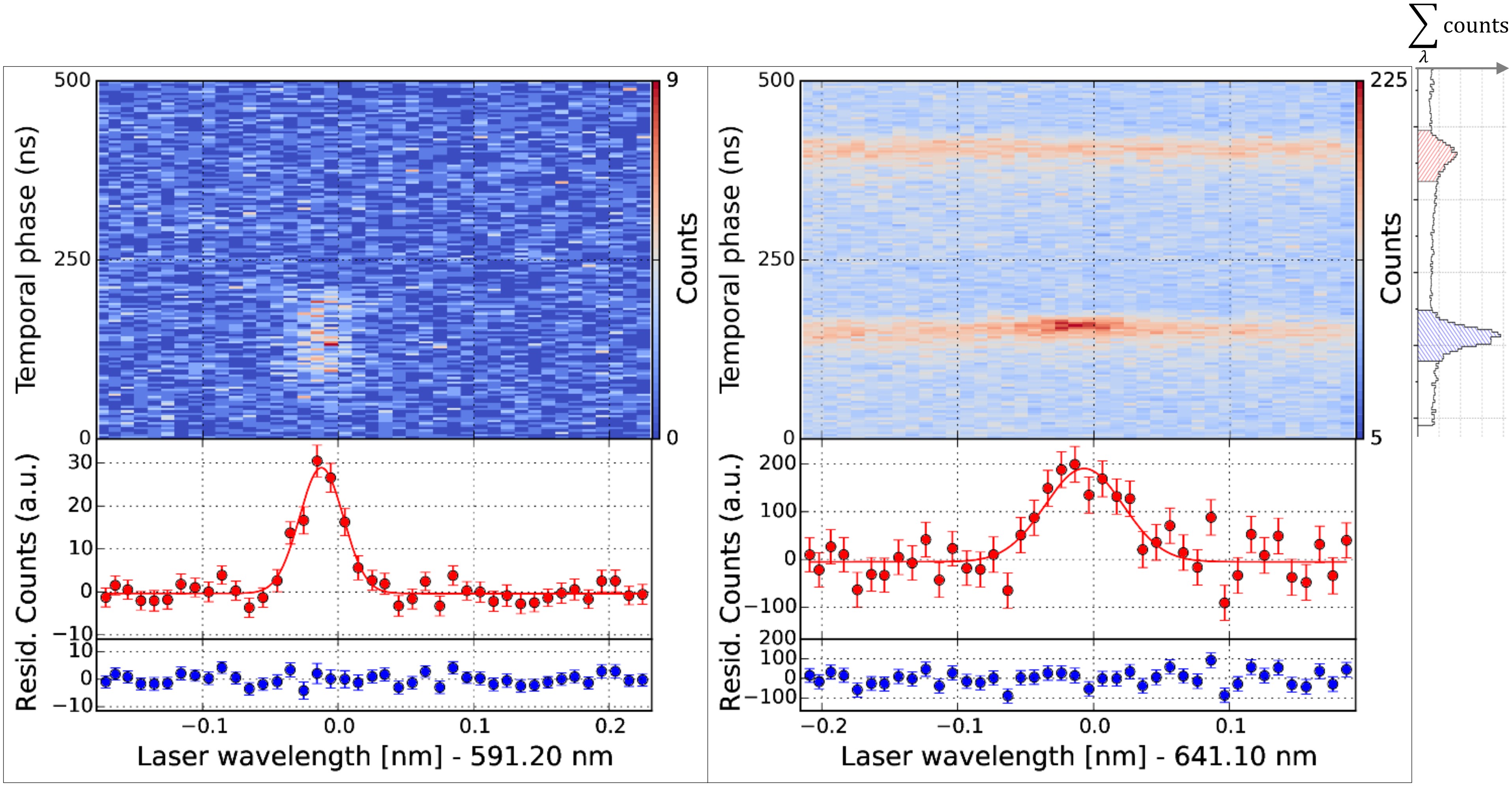
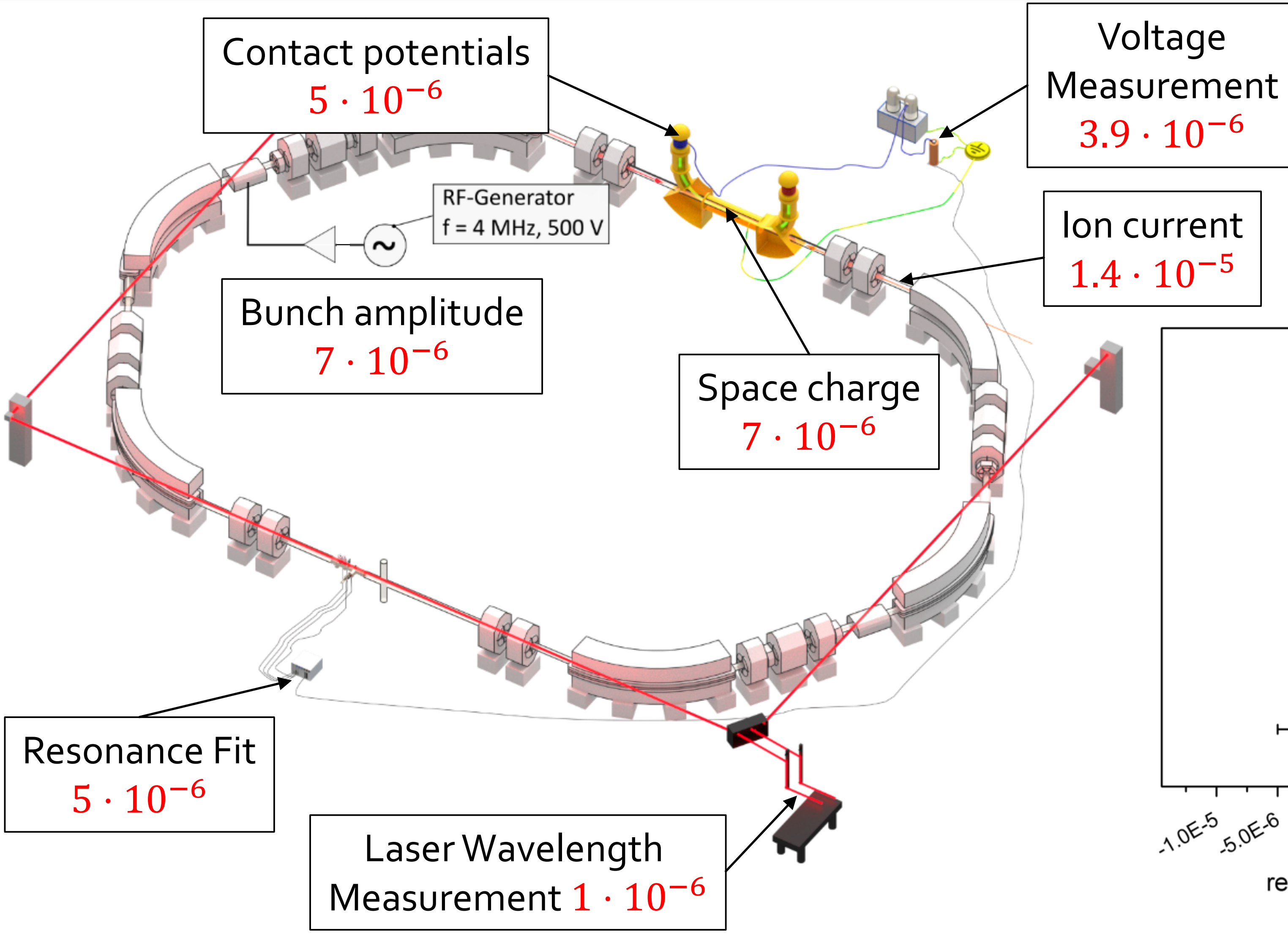
Resonances

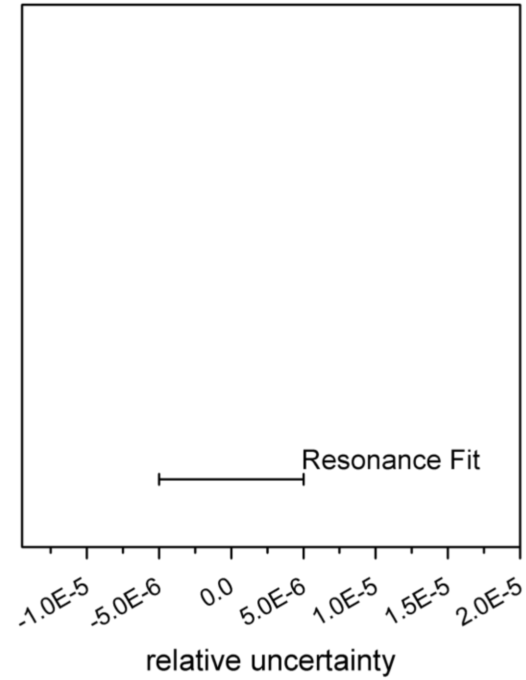


H-like Bi^{82+} coasting beam

Li-like Bi^{80+} bunched beam

Relative Uncertainty contributions





Electron-Beam Space Charge Contribution

Doppler correction

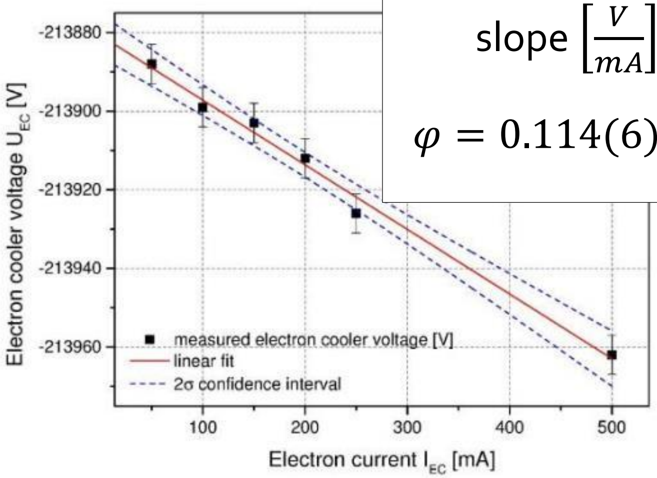
$$\lambda_0 = \lambda_{Labor}\,\gamma(1 \pm \beta)$$

$$\beta(U) = \sqrt{1 - \left(1 + \frac{eU}{mc^2}\right)^{-2}}$$

$$U = U_{e^-Cooler} - \Phi_{SpaceCharge}$$

$$\Phi_{SpaceCharge} = \varphi \frac{I_e}{\beta_e}$$

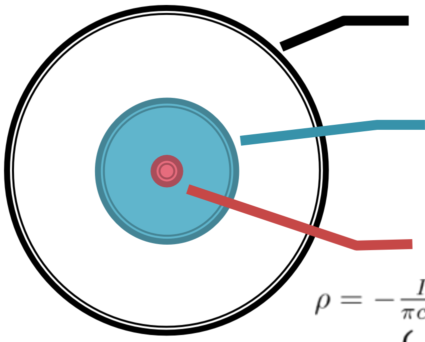
Experimental determination



$$\text{slope}\left[\frac{V}{mA}\right] \sim \varphi$$

$$\varphi = 0.114(6)\frac{I_e}{\beta_e}$$

Theoretical determination

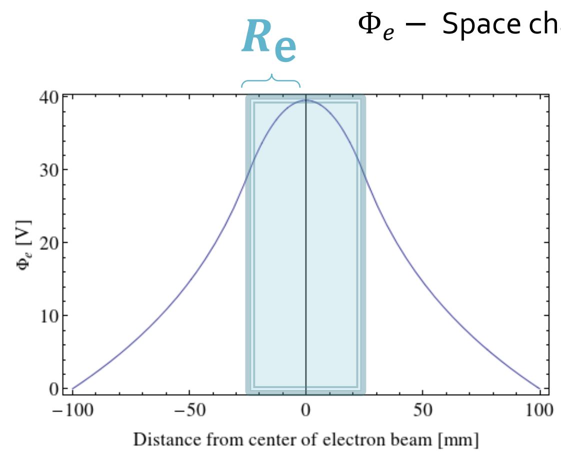


$$\rho = -\frac{I_{el}}{\pi c \beta_{el}}$$

$$\Phi_e = \begin{cases} \frac{\rho}{4\epsilon_0}\left(\frac{r^2}{R_e^2} - 2\ln\left(\frac{R_{Dr}}{R_e}\right) - 1\right), & 0 \le |r| \le R_e \\ -\frac{\rho}{2\epsilon_0}\ln\left(\frac{R_{Dr}}{r}\right), & |r| > R_e \end{cases}$$

Φ_e – Space charge potential, ρ – Charge density

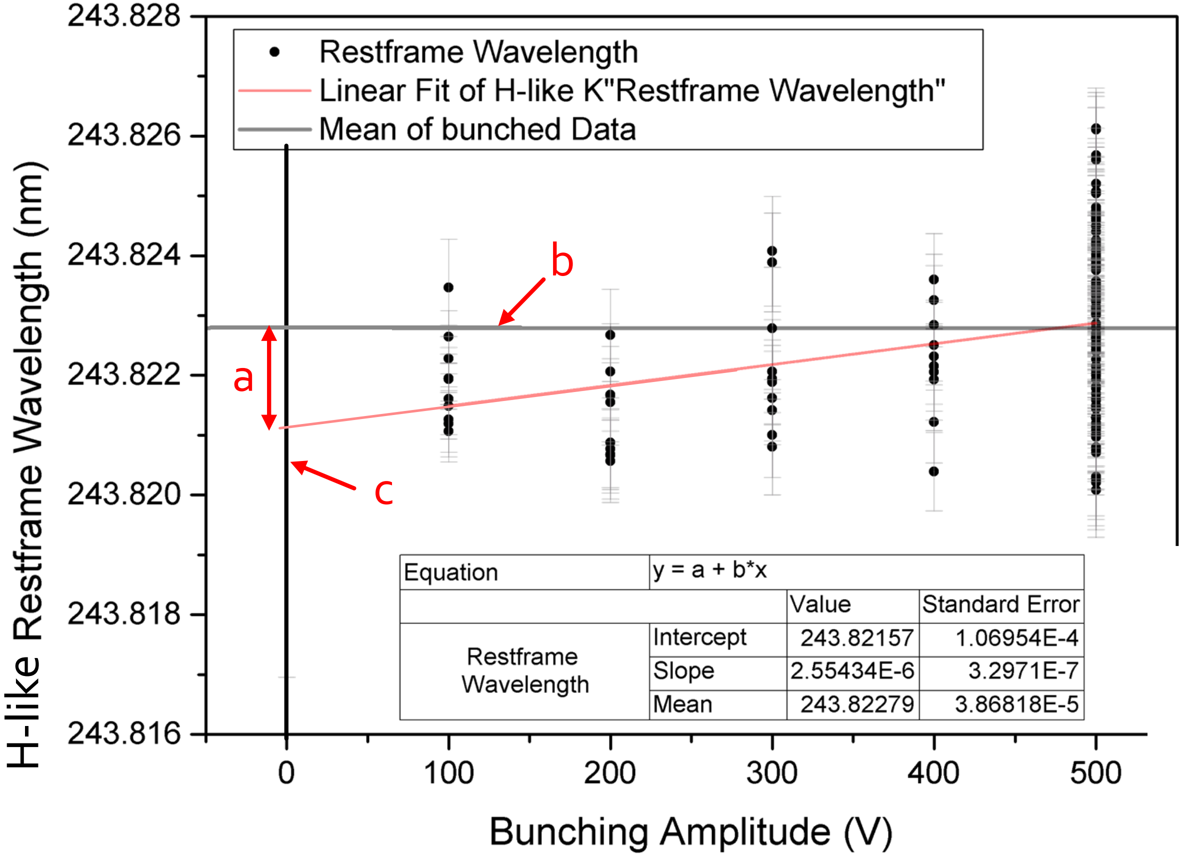
Winkler, Diss. 1996

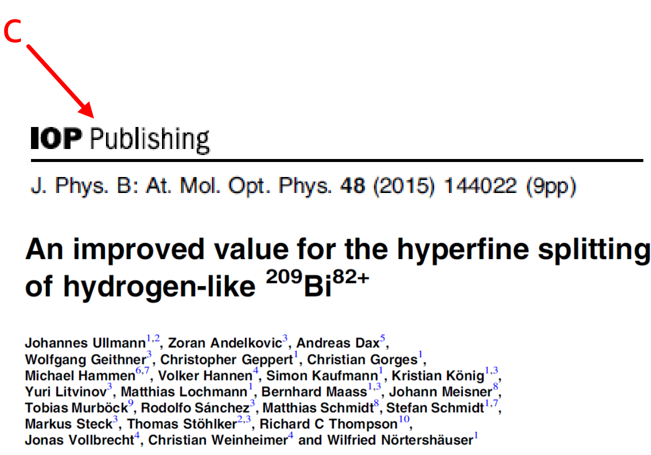


$I_e = 250$ mA
$R_{Dr} = 10$ mm
$R_e = 25.4$ mm
$\beta_e = 0.709$

$$\Phi_e = \varphi(r)\frac{I_e}{\beta_e} \approx 0.112\frac{I_e}{\beta_e}$$

Effect of bunching





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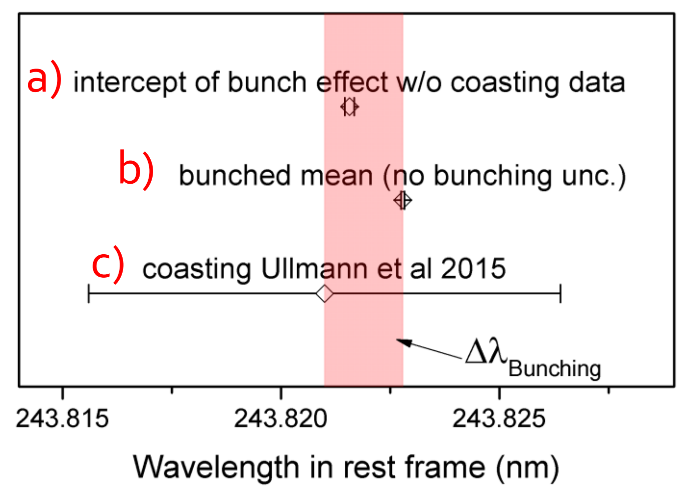
IOP Publishing

J. Phys. B: At. Mol. Opt. Phys. 48 (2015) 144022 (9pp)

An improved value for the hyperfine splitting of hydrogen-like $^{209}Bi^{82+}$

Johannes Ullmann[1,2], Zoran Andelkovic[3], Andreas Dax[5], Wolfgang Geithner[3], Christopher Geppert[1], Christian Gorges[1], Michael Hammen[6,7], Volker Hannen[4], Simon Kaufmann[1], Kristian König[1,3], Yuri Litvinov[3], Matthias Lochmann[1], Bernhard Maass[1,3], Johann Meisner[8], Tobias Murböck[9], Rodolfo Sánchez[3], Matthias Schmidt[8], Stefan Schmidt[1,7], Markus Steck[3], Thomas Stöhlker[2,3], Richard C Thompson[10], Jonas Vollbrecht[4], Christian Weinheimer[4] and Wilfried Nörtershäuser[1]

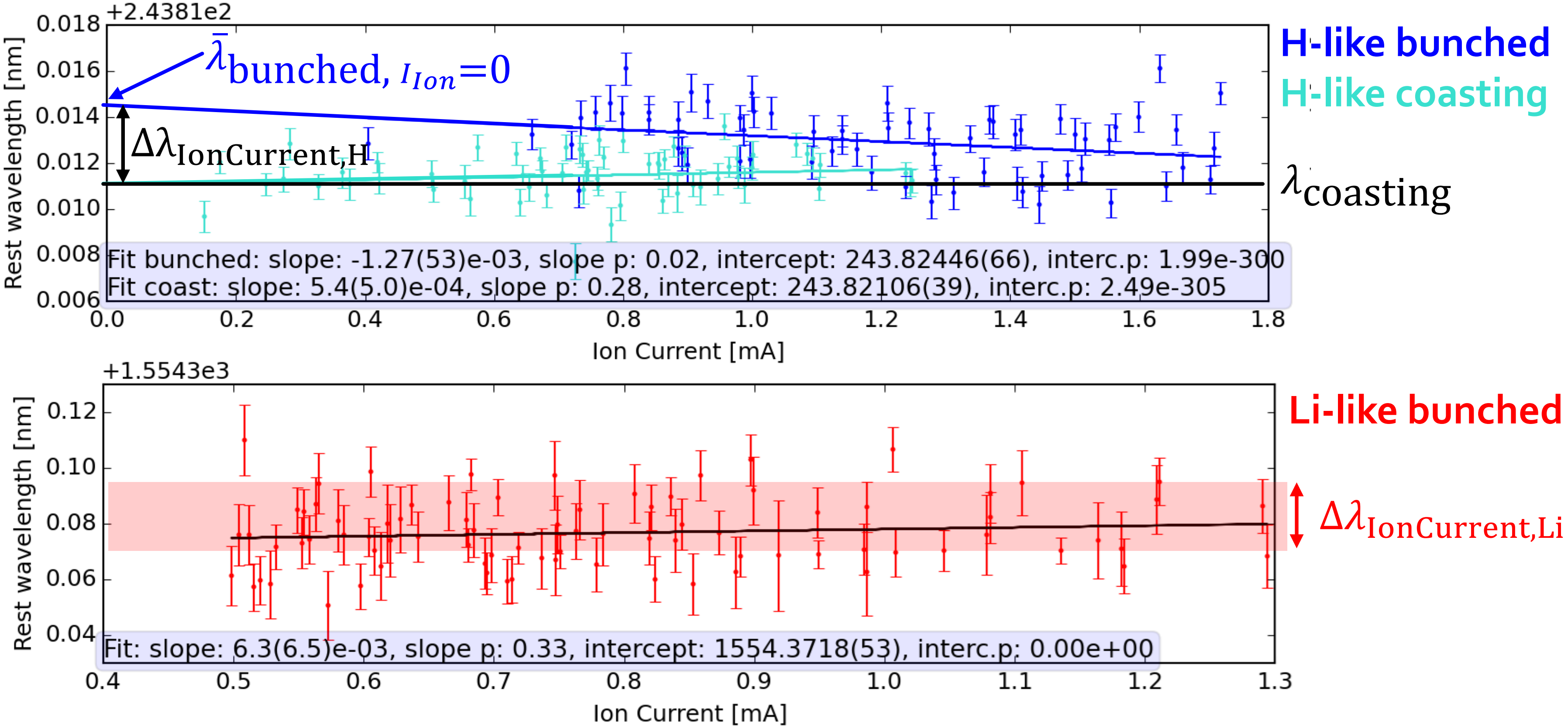


H-like: $\delta\lambda_{\text{Bunching,H}} = \bar{\lambda}_{\text{bunched}} - \lambda_{\text{coasting}} = 1.8$ pm

$$\rightarrow \frac{\delta\lambda}{\lambda} = 7.3 \cdot 10^{-6}$$

Li-like: $\delta\lambda_{\text{Bunching,Li}} = 11.4$ pm

Effect of ion current



H-like: $\delta\lambda_{\text{IonCurrent,H}} = \bar{\lambda}_{\text{bunched}, I_{Ion}=0} - \lambda_{\text{coasting}} = 3.5$ pm

relative uncertainty $\rightarrow \frac{\delta\lambda}{\lambda} = 1.42 \cdot 10^{-5}$

Li-like: same effect assumed $\rightarrow \delta\lambda_{\text{IonCurrent,Li}} = 22$ pm

Results

Conclusion and outlook

?

7 σ

preliminary

Bi-208?

Bi-207?

The beam time crew

The LIBELLE Collaboration …

Laser SpHERe

PTB

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

HELMHOLTZ GEMEINSCHAFT
Helmholtz Institut Jena
Helmholtz Institut Mainz

Imperial College London

Libelle

Lithium like **B**ismuth **E**xperiment with **L**aser **L**ight at **ESR**

GSI

Westfälische Wilhelms-Universität Münster

Z. Andelkovic, D. Anielski, B. Botermann, M. Bussmann, C. Brandau, A. Dax, N. Frömmgen, W. Geithner, **Ch. Geppert**, Ch. Gorges, M. Hammen, V. Hannen, K. König, S. Kaufmann, T. Kühl, Y. Litvinov, **M. Lochmann**, B. Maass, J. Meisner, T. Murböck, **W. Nörtershäuser**, **R. M. Sánchez**, St. Schmidt, M. Schmidt, M. Steck, Th. Stöhlker, R. C. Thompson, Ch. Trageser, **J. Ullmann**, **J. Vollbrecht**, A. Volotka, Ch. Weinheimer, W. Wen, E. Will, D. Winters

CERN

TECHNISCHE UNIVERSITÄT DARMSTADT

Institut für Kernphysik

Laser SpHERe

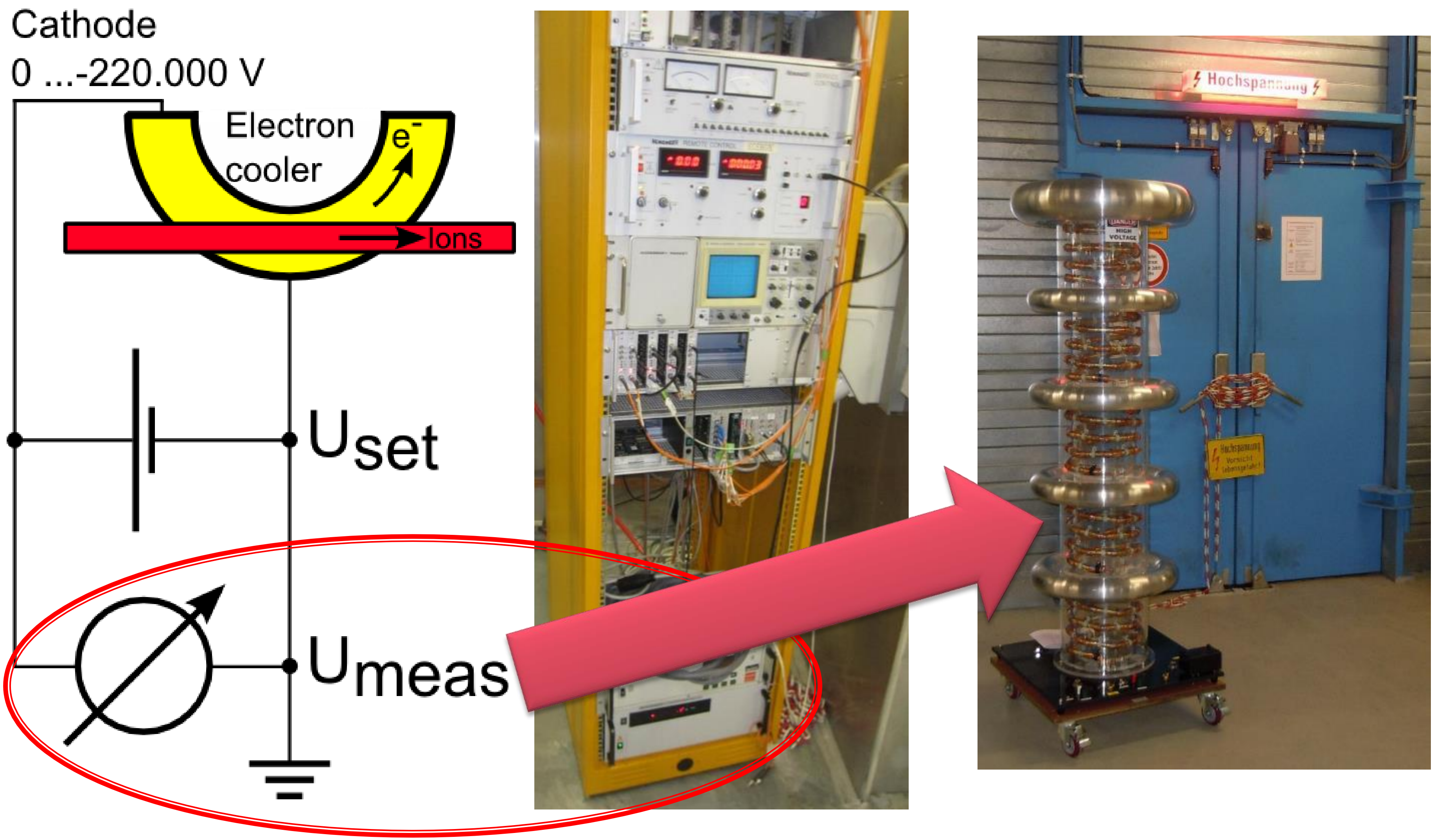
Laser Spectroscopy of **H**ighly Charged Ions and **E**xotic **R**adioactive Nucl**e**i

TECHNISCHE UNIVERSITÄT DRESDEN

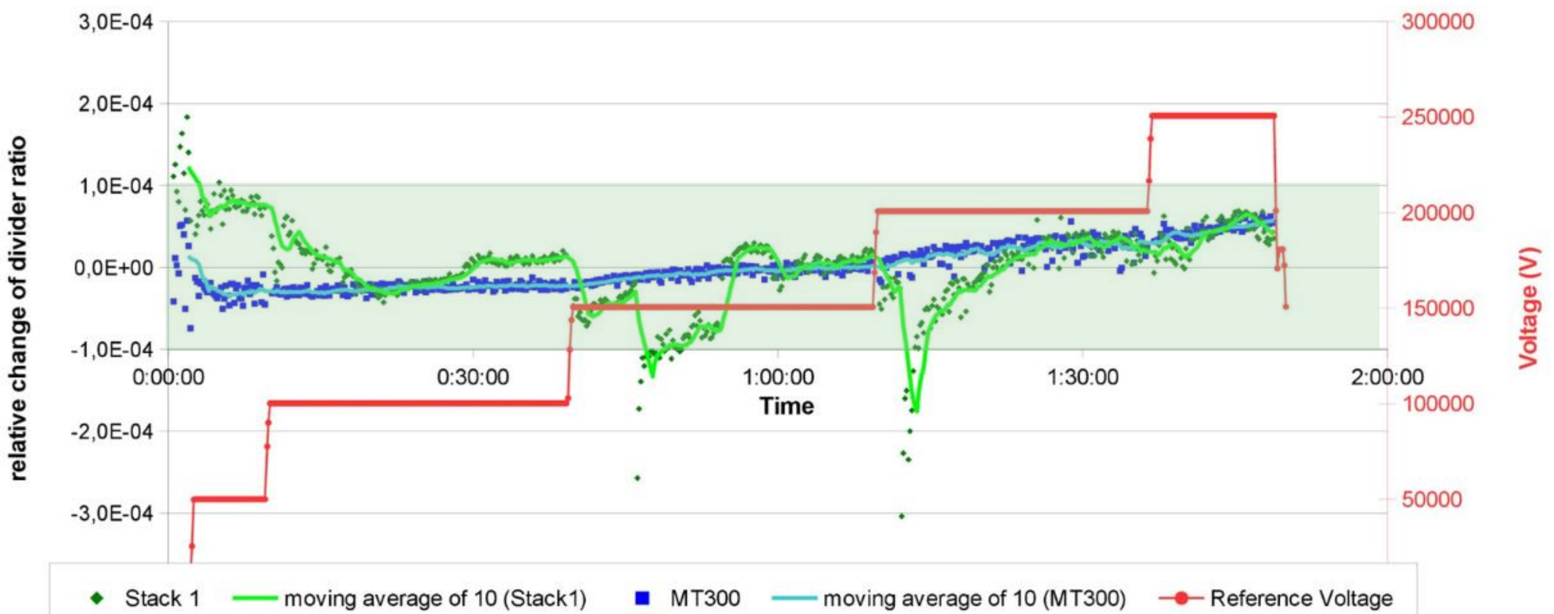
Support: HELMHOLTZ GEMEINSCHAFT

Bundesministerium für Bildung und Forschung

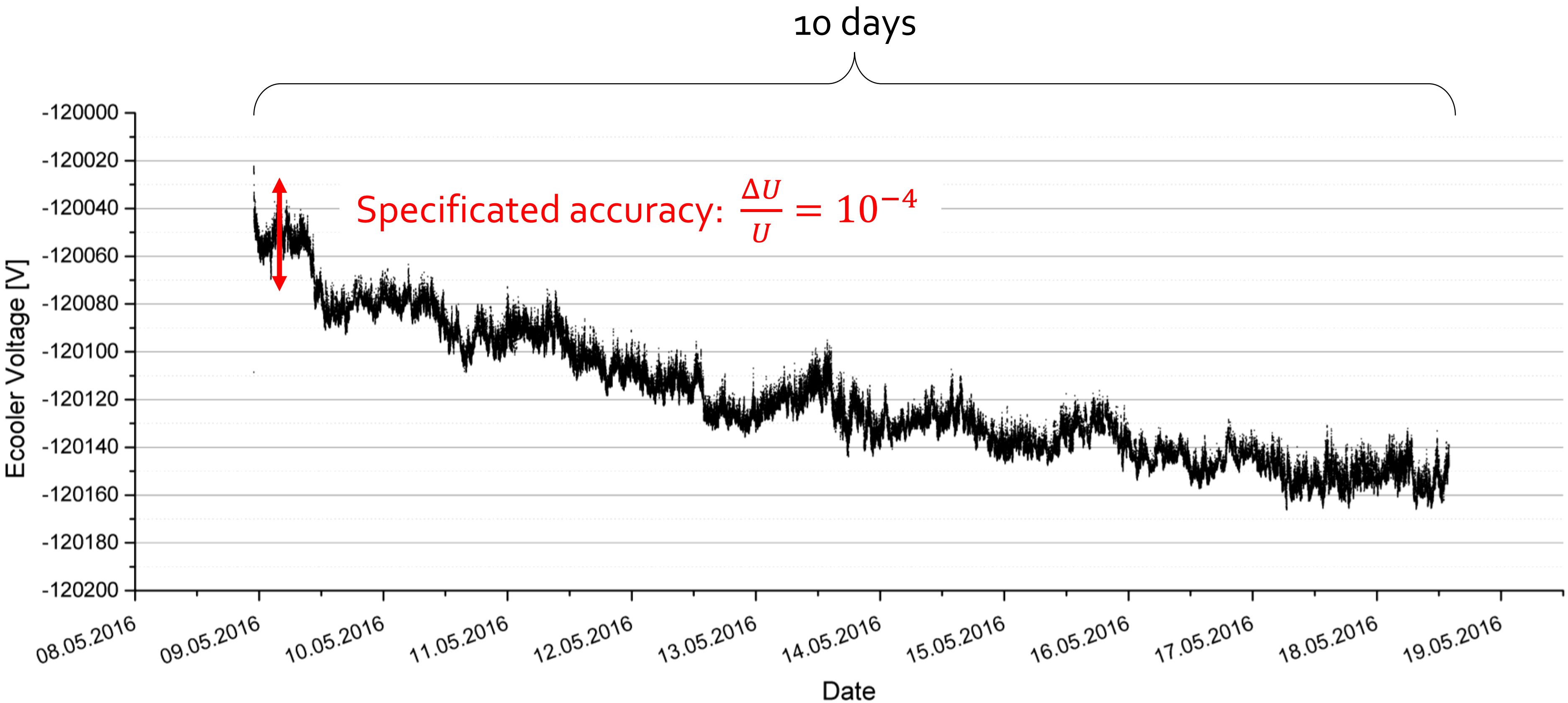
Calibration at 200 kV: insufficient!



Calibration December 2014 at PTB



Commissioning at Ecooler



Most probable cause: ageing of resistors

Motivation | Setup | Results | Aftermath




Thank you for listening!