The APPA Research Programm in HFHF

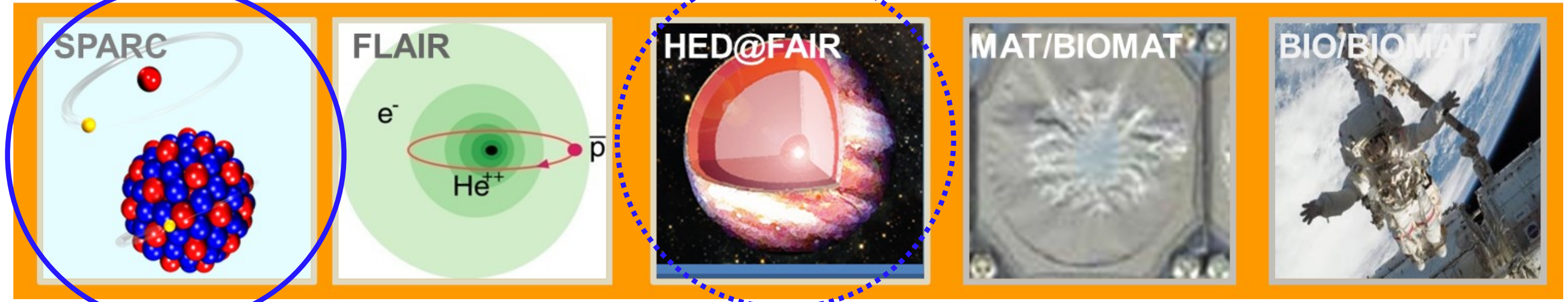
Plans and Recent Results

TECHNISCHE UNIVERSITÄT DARMSTADT

APPA @ HFHF Helmholtz Forschungsakademie Hessen für FAIR

LASER SpHERe
Fachbereich Physik | Institut für Kernphysik | Prof. W. Nörtershäuser

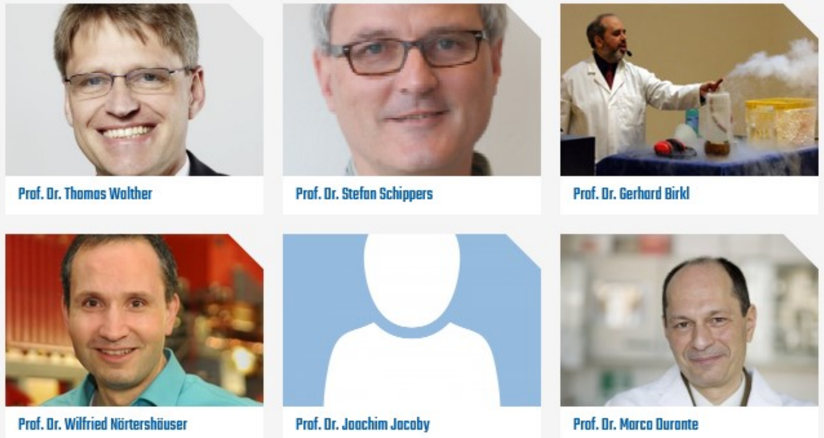
From Fundamental to Applied Research

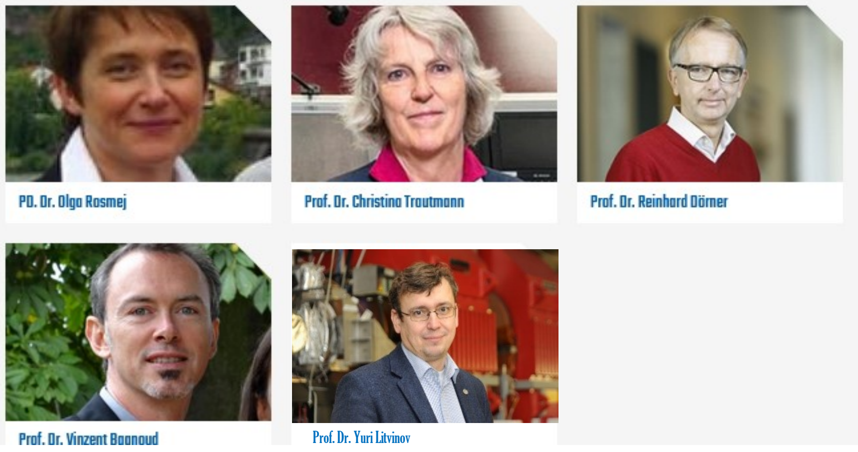


SPARC	HED@FAIR	BIOMAT
Atomic Physics 430 members from 26 countries	Plasma Physics 200 members from 11 countries	Biophysics and Materials Research 150 members from 20 countries

APPA White book: *APPA at FAIR: From fundamentals to applied research* NIM B **365**, 680-685 (2015)

HFHF APPA Members





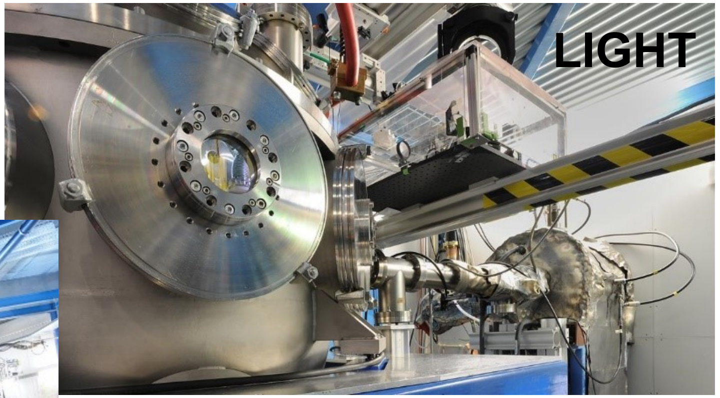
Periode 2021-2025:
Focus on precision spectroscopy and ion manipulation techniques.

Content of the Scientific Program (2021-2025)

Overarching Topics:

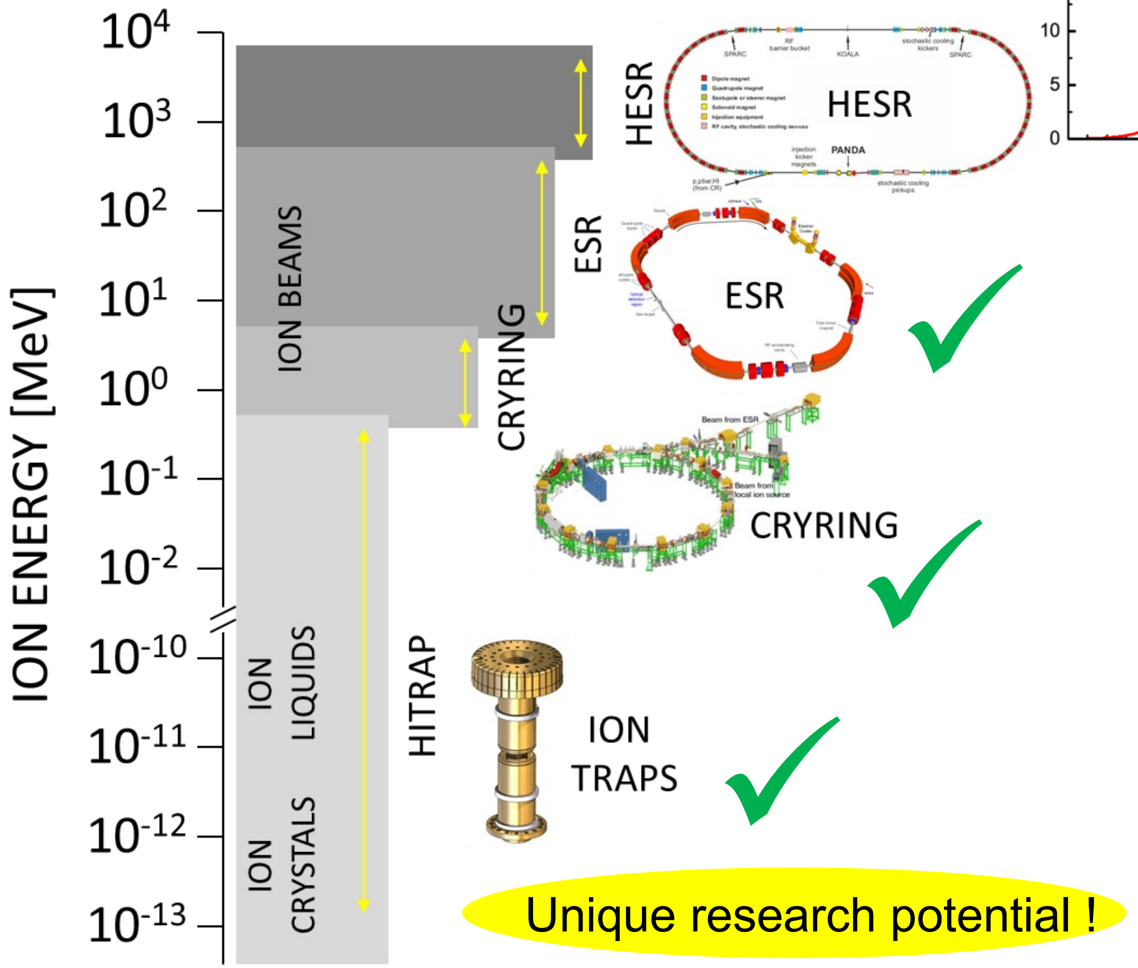
- Atomic processes in the strongest electromagnetic fields
- Precision spectroscopy of (multiply) excited atomic energy levels
- Experiments at the border between atomic and nuclear physics
- Ion Manipulation: Control of outer and inner degrees of freedom

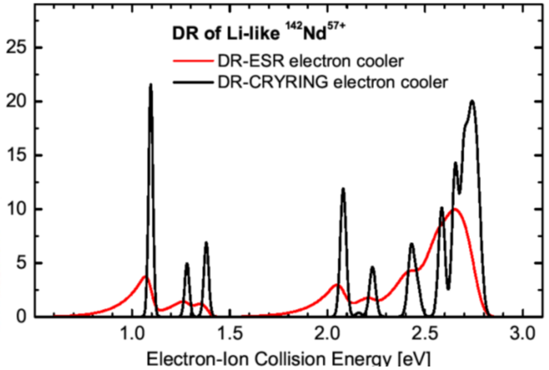
All projects are related to GPAC proposals that have received Grade A or A-.



The Working Program: Precision Physics and Ion Manipulation

From rest to relativistic energies
(up to 4.9 GeV/u)

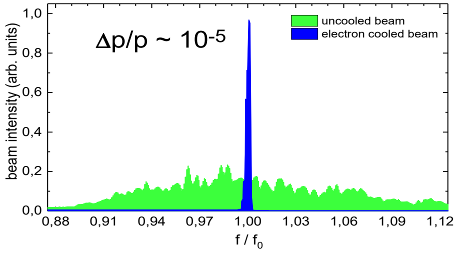


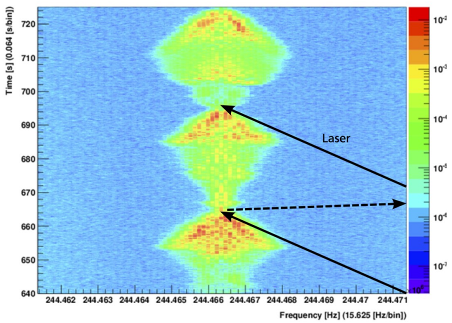


Topic A: Precision Experiments

DR and laser spectroscopy of Be-like ions
Laser spectroscopy of H/Li-like ions
Merging DR and Laser Spectroscopy
Laser excitation of a nuclear transition
Establish Reaction Microscope CRY-RIMS

Cooling: key for precision





Topic B: Ion Manipulation

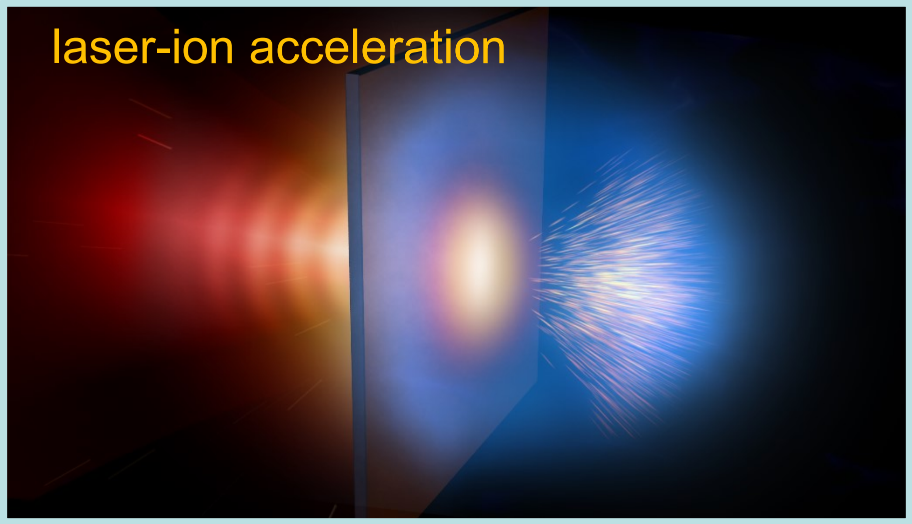
External DoF:
- Laser acceleration
- Laser and electron cooling

Internal DoF:
- Optical pumping and polarization

HFHF Research on Laser-Ion Acceleration

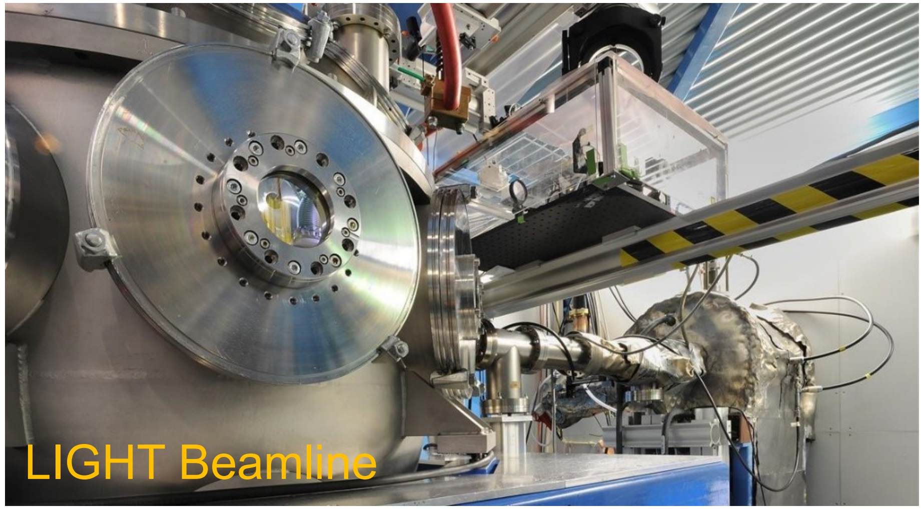
Many schemes have been proposed for accelerating light ions with lasers

Still, the scaling and even the single evidence of these remains experimentally challenging



We follow two lines of research:

- Understanding the underlying physics of laser-ion acceleration using time-resolved diagnostics
- Exploring application with the LIGHT beamline



LIGHT – Laser Ion Generation, Handling and Transport

PHELIX

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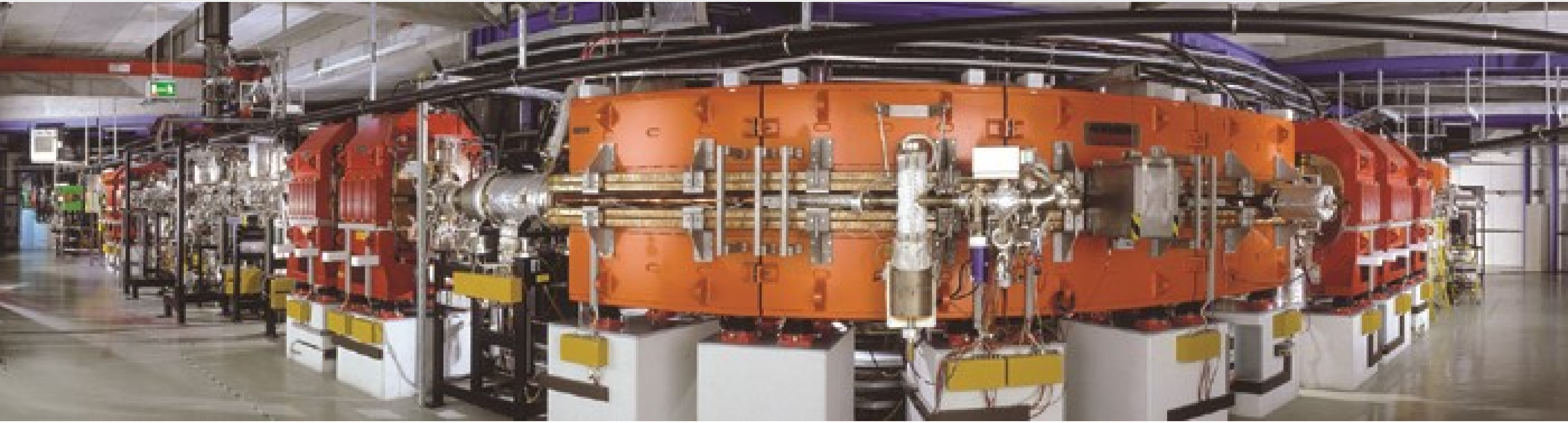
Activities at the ESR

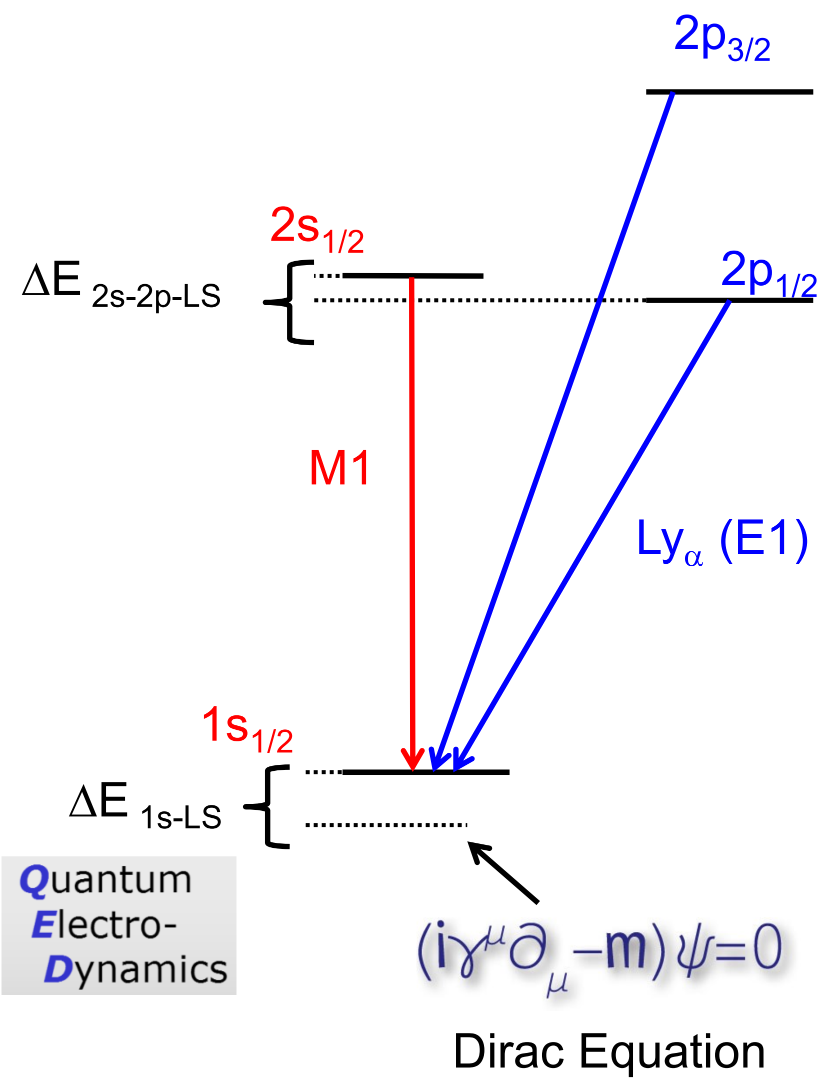


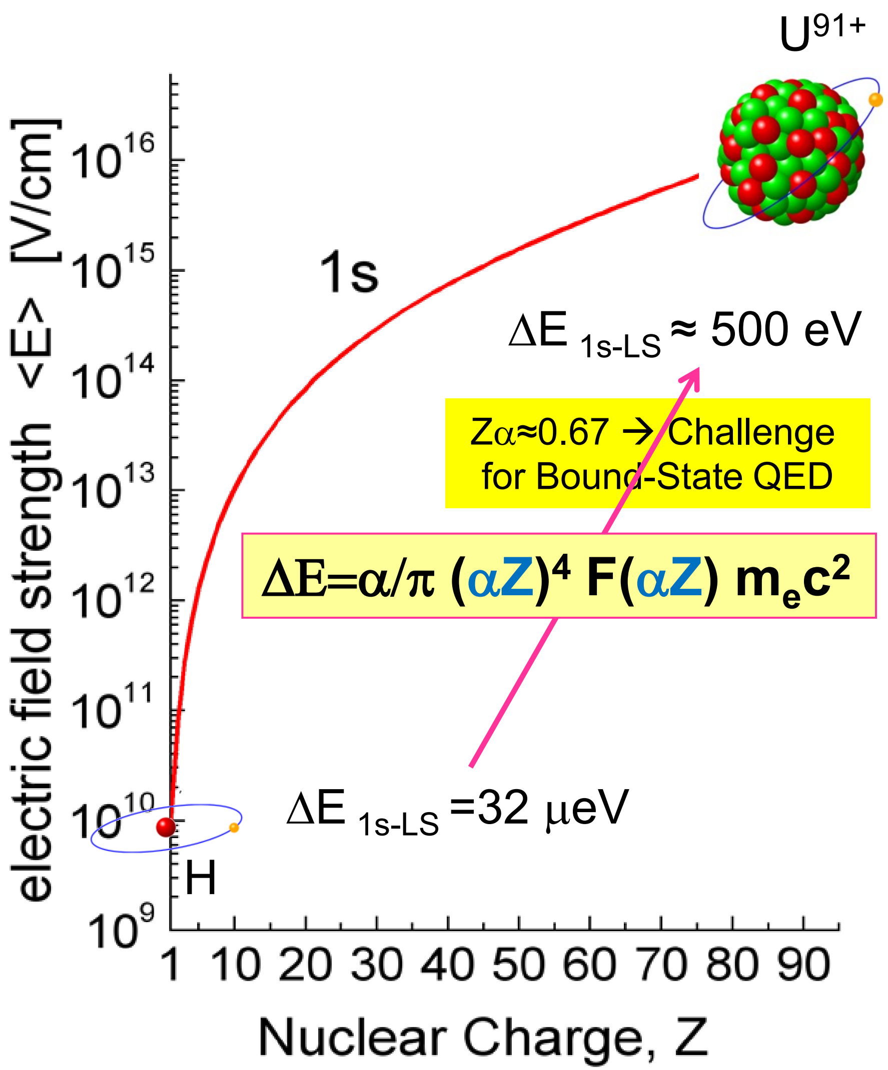
Dielectronic Recombination Assisted Laser Spectroscopy of $^{209}Bi^{80+}$
(W. Nörtershäuser, TU Darmstadt; Y. Litvinov, GSI; S. Schippers, Uni Gießen et al.)

Laser Spectroscopy of the Nuclear Transition in ^{229}Th
(C. Brandau, S. Schippers, Uni Gießen; W. Nörtershäuser, TU Darmstadt; Y. Litvinov, GSI et al.)

Laser Cooling of C^{3+}, Laser Spectroscopy of Be-like Kr^{32+}
(D. Winters, GSI; Th. Walther, TU Darmstadt; G. Birkl, TU Darmstadt et al.)

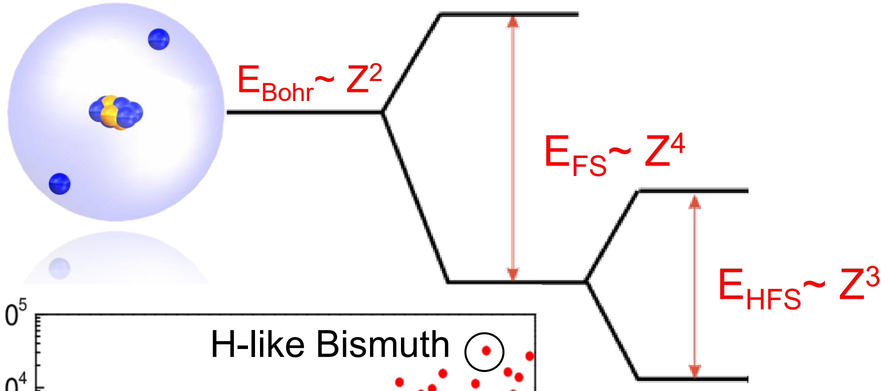
Highly Charged Heavy Ions

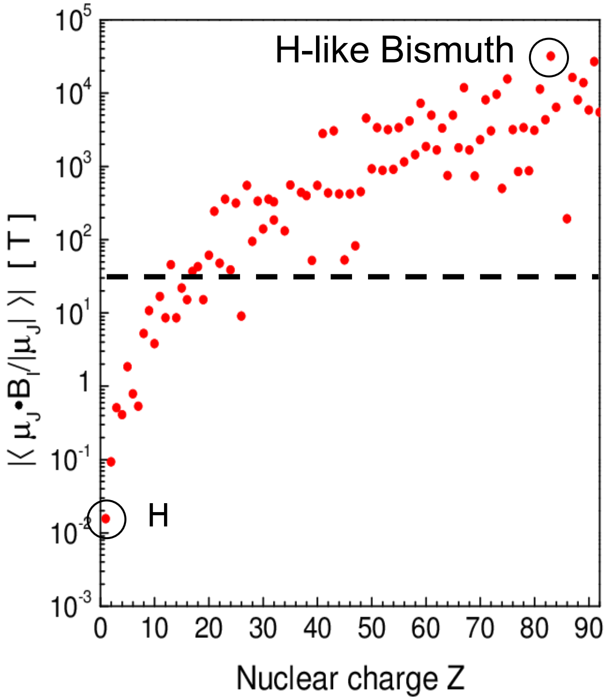




Test of BS-QED in Highly Charged Ions

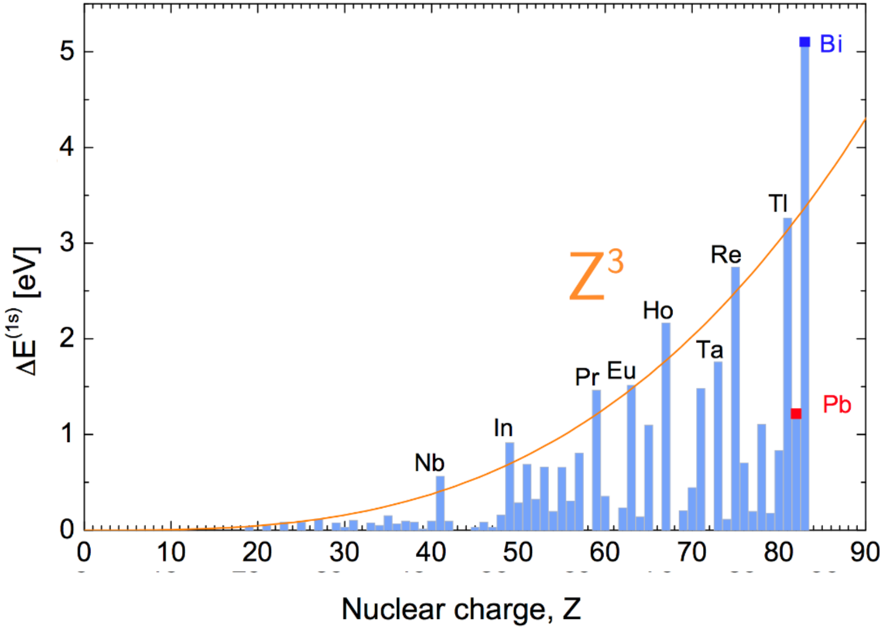
atomic structure:

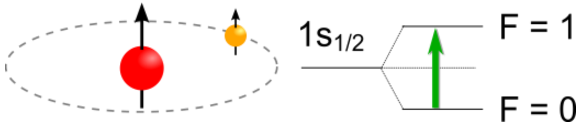


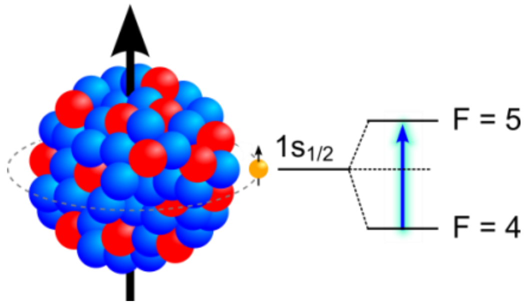


H: λ = 21 cm
τ = 11 MA

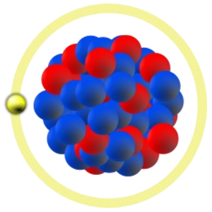
$^{209}Bi^{82+}$: λ = 244 nm
τ = 0.39 ms







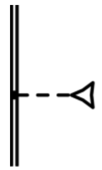
Test of BS-QED in the HFS of H-Like Heavy Ions



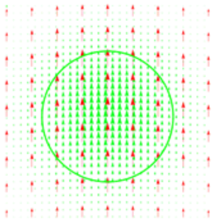
Bi^{82+}

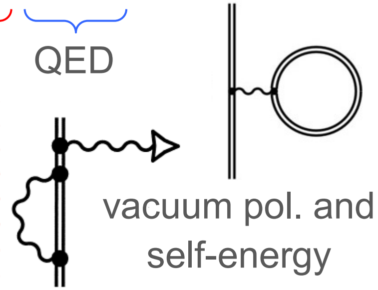
$$\Delta E^{(1s)} = \underbrace{\frac{4}{3}\alpha(\alpha Z)^3 \frac{\mu_I}{\mu_N}\frac{m}{m_p}\frac{2I+1}{2I} mc^2 \times (A(\alpha Z)^{1s}}_{\text{Dirac}} \underbrace{(1-\epsilon^{1s}_{\mathrm{BR}})(1-\epsilon^{1s}_{\mathrm{BW}})}_{\text{nuclear contributions}} + \underbrace{x^{1s}_{\mathrm{red}}}_{\text{QED}})$$

known (?)

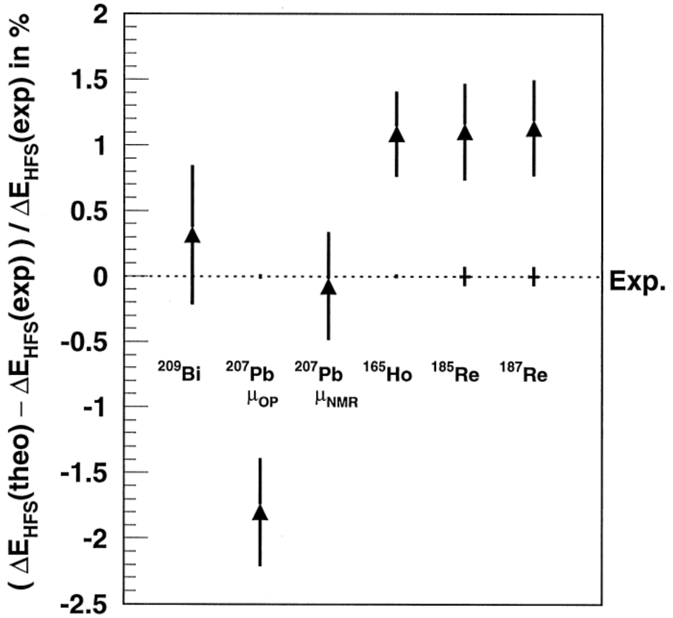


Bohr-Weisskopf effect
Breit-Rosenthal effect
nuclear polarization



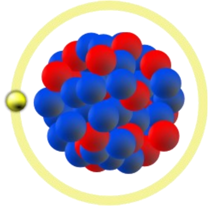


vacuum pol. and self-energy



T.Beier, Phys.Rep. **339**, 79 (2000)

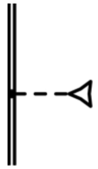
Theory: Trouble & Solution



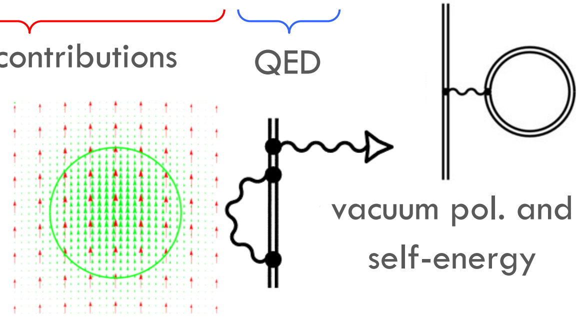
Bi^{82+}

$$\Delta E^{(1s)} = \underbrace{\frac{4}{3}\alpha(\alpha Z)^3 \frac{\mu_I}{\mu_N}\frac{m}{m_p}\frac{2I+1}{2I}mc^2 \times (A(\alpha Z)^{1s}}_{\text{Dirac}}\underbrace{(1-\epsilon_{BR}^{1s})(1-\epsilon_{BW}^{1s})}_{\text{nuclear contributions}} + \underbrace{x_{red}^{1s}}_{\text{QED}})$$

known (?)



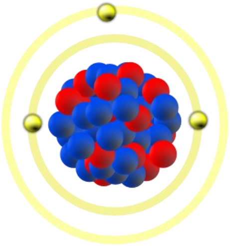
Bohr-Weisskopf effect
Breit-Rosenthal effect
nuclear polarization



vacuum pol. and self-energy

uncertainty Bohr-Weisskopf > QED contribution

Bi^{80+}



$$\Delta E^{(2s)} = \frac{1}{6}\alpha(\alpha Z)^3 \frac{\mu_I}{\mu_N}\frac{m}{m_p}\frac{2I+1}{2I}mc^2 \times (A(\alpha Z)^{2s}(1-\epsilon_{BR}^{2s})(1-\epsilon_{BW}^{2s}) + x_{red}^{2s} + B_Z + C_Z)$$

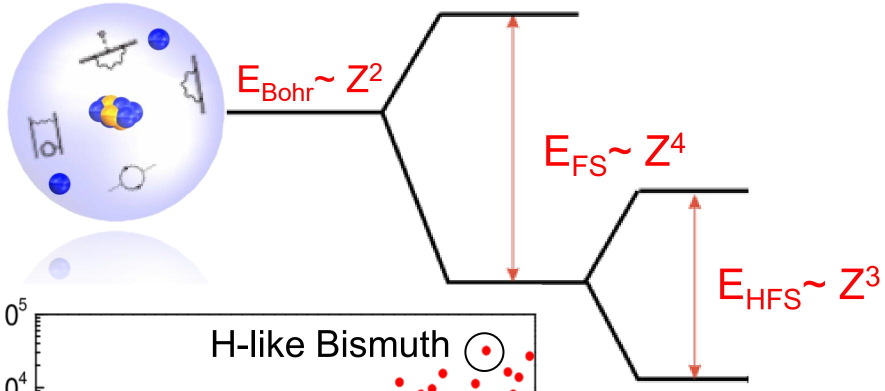
specific difference (V. M. Shabaev et al. PRL 86 (2001))

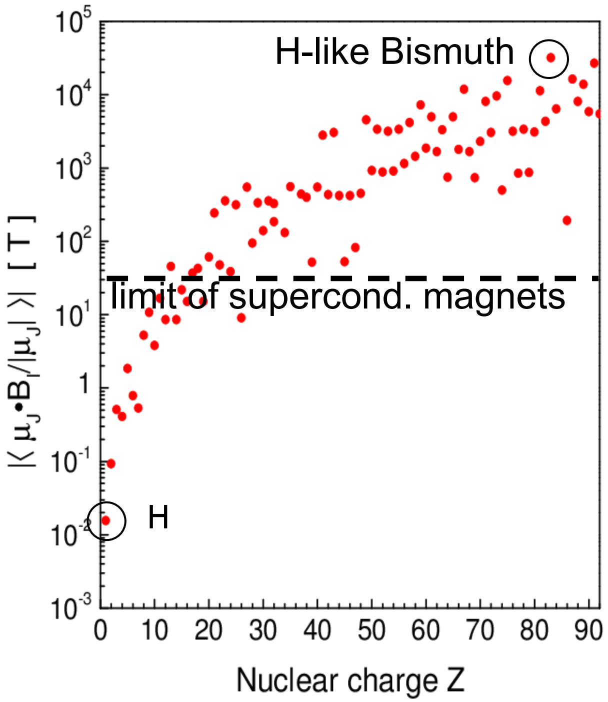
$$\boxed{\Delta' E = \Delta E^{(2s)} - \xi\, \Delta E^{(1s)}}$$

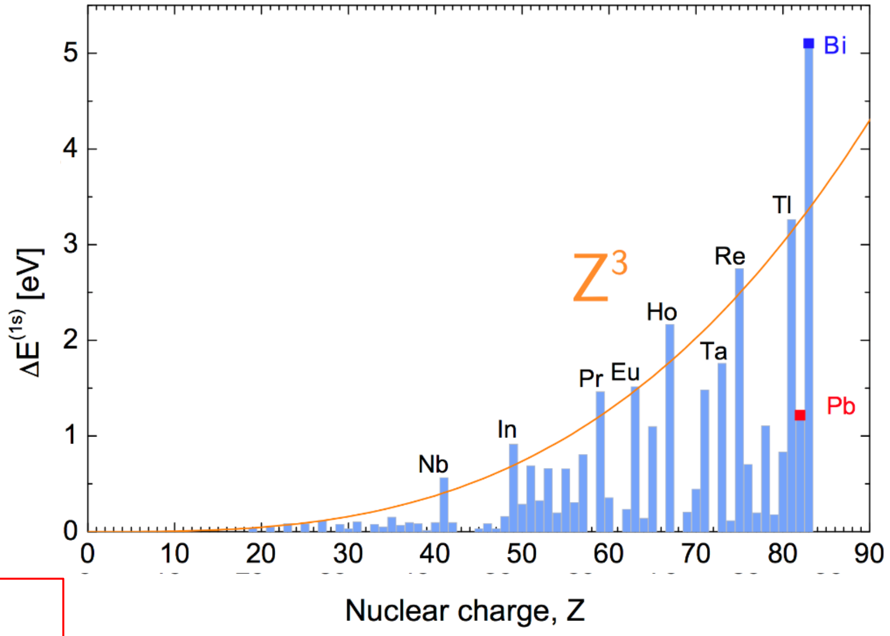
nuclear contributions removed

Test of BS-QED in Highly Charged Ions

Atomic structure:



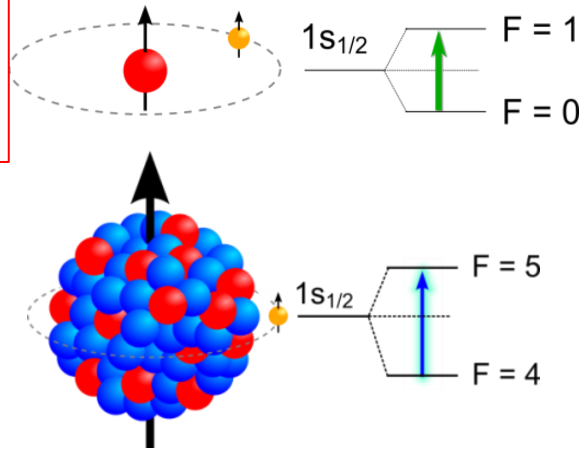




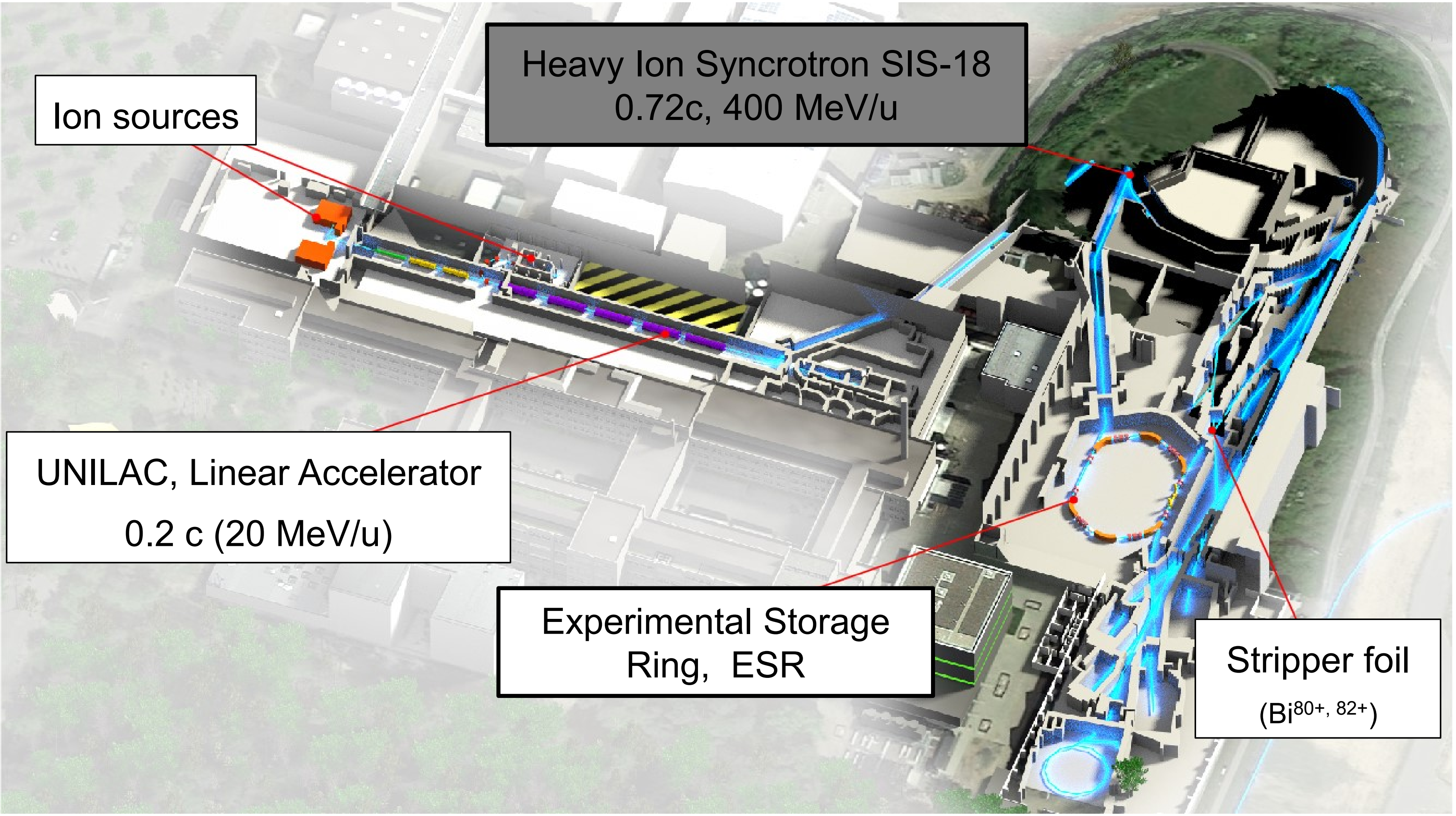
No conclusive test of bound-state QED in the strongest magnetic fields so far!

$^{209}Bi^{82+}$: λ = 244 nm
τ = 0.39 ms

$^{209}Bi^{80+}$: λ = 1555 nm
τ = 83.3 ms

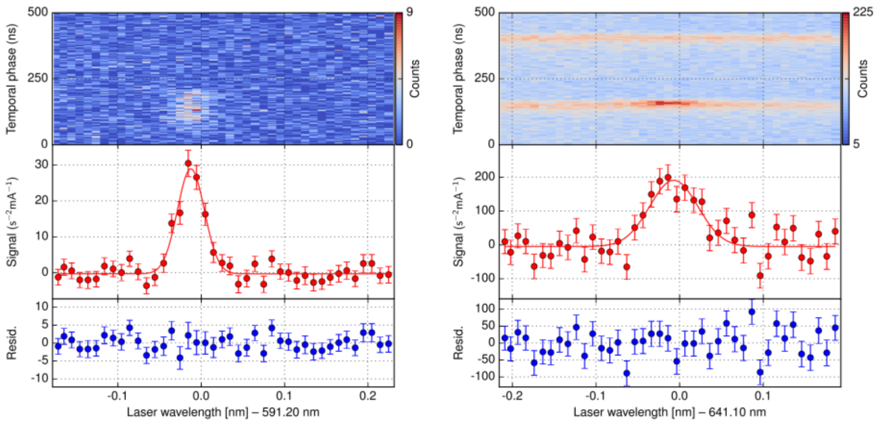


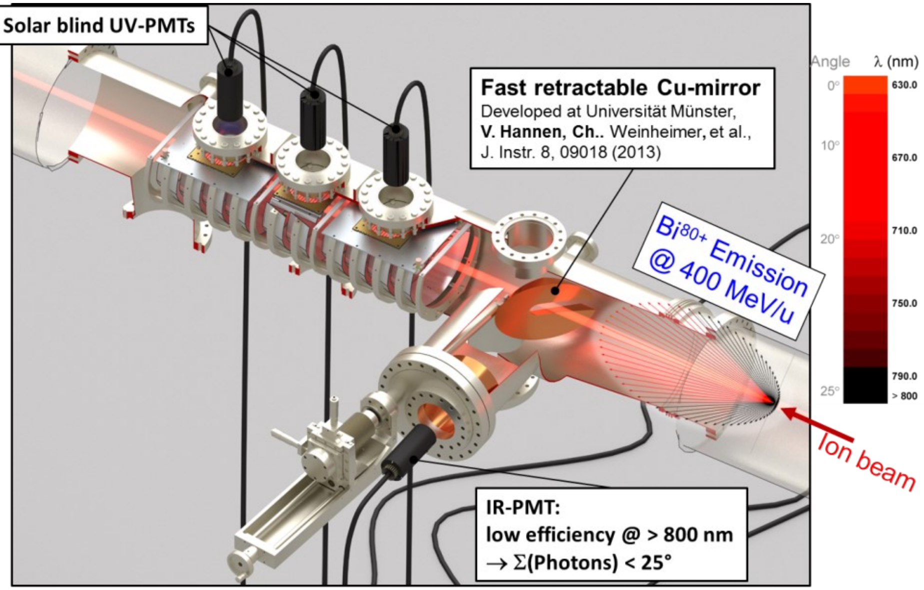
Production of $^{209}Bi^{80,82+}$

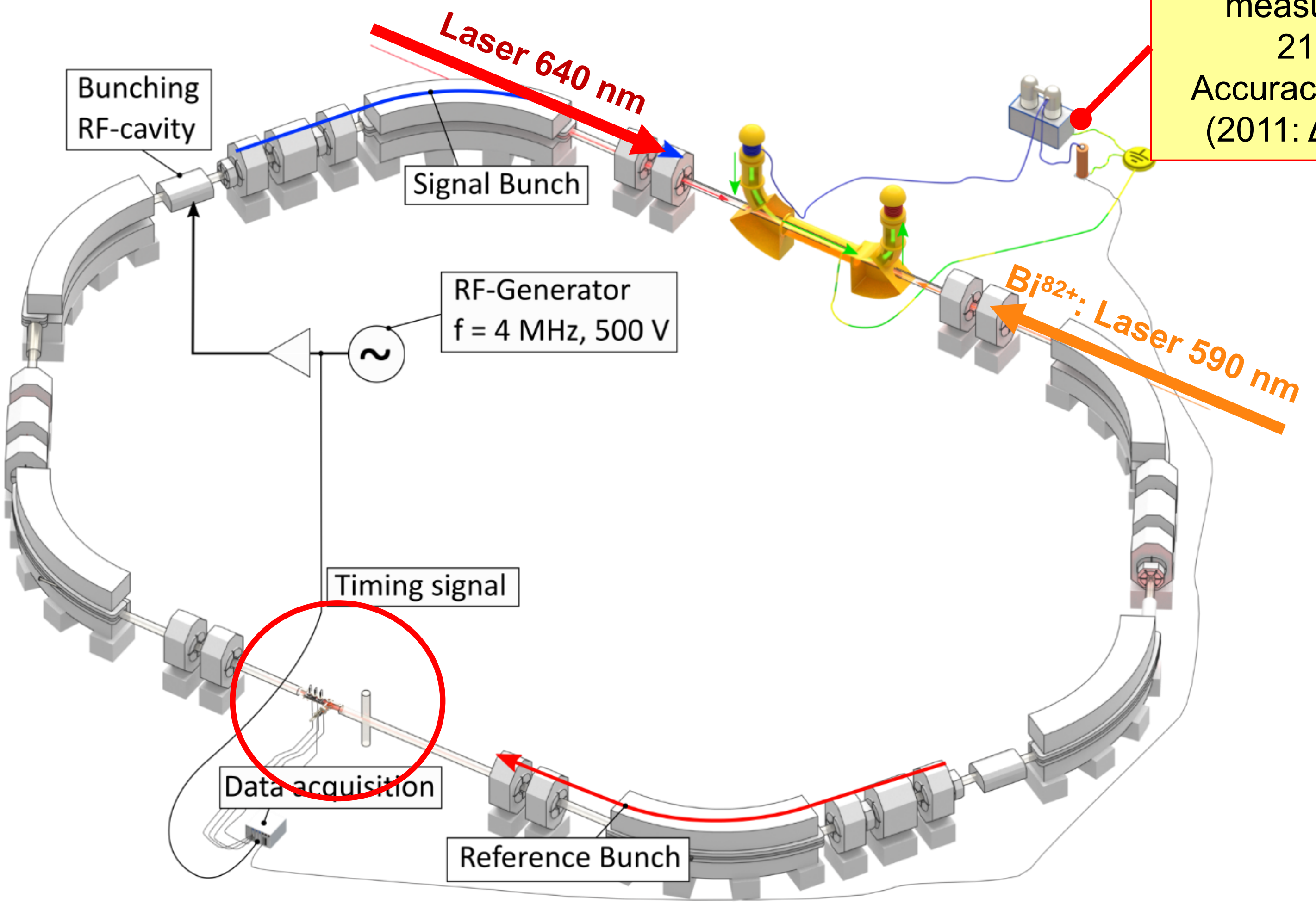


First High Accuracy Measurement of Δ‘E

$^{209}Bi^{82+}$ $^{209}Bi^{80+}$

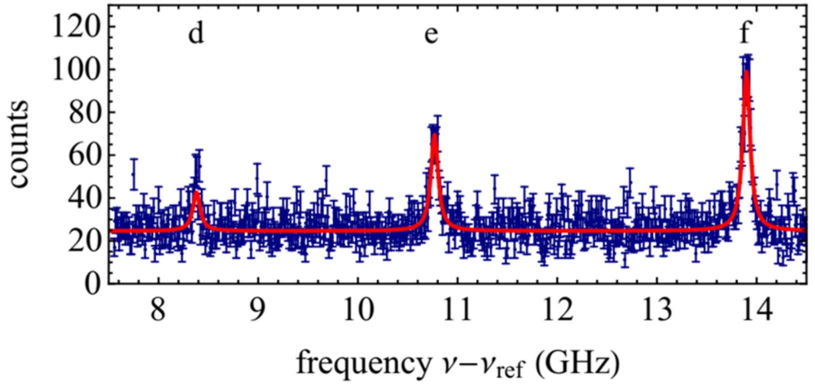






In-situ high-voltage measurement
214 kV
Accuracy: ΔU~ 4V
(2011: ΔU=110V)

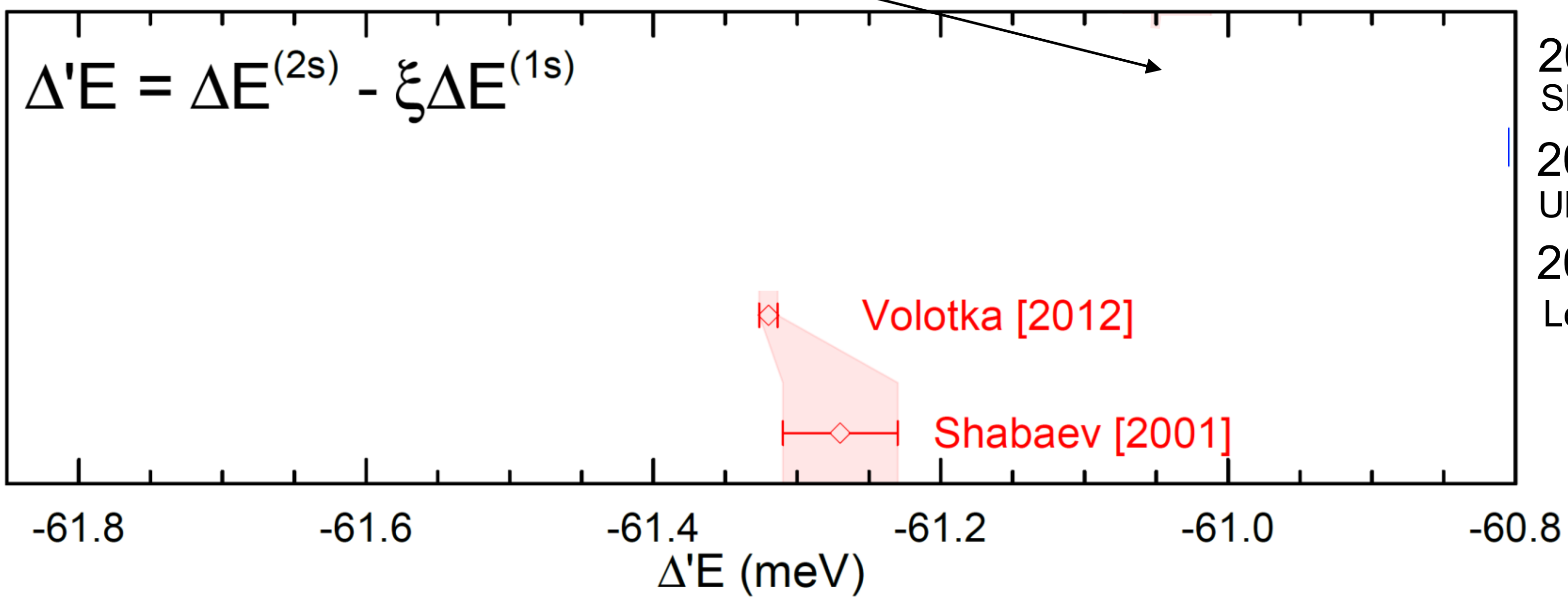
History of $\Delta' E$ Measurements



2018 determination of $\mu(^{208}Bi)$ @ ISOLDE
Schmidt et al., Phys. Lett. B **779**, 324 (2018)

2017 Suggestion: Test $\Delta' E$ on $^{208}Bi^{80+,82+}$
Required: magnetic moment of ^{208}Bi
higher sensitivity for laser spectroscopy

Theory limited by accuracy of $\mu(^{209}Bi)$ → HITRAP

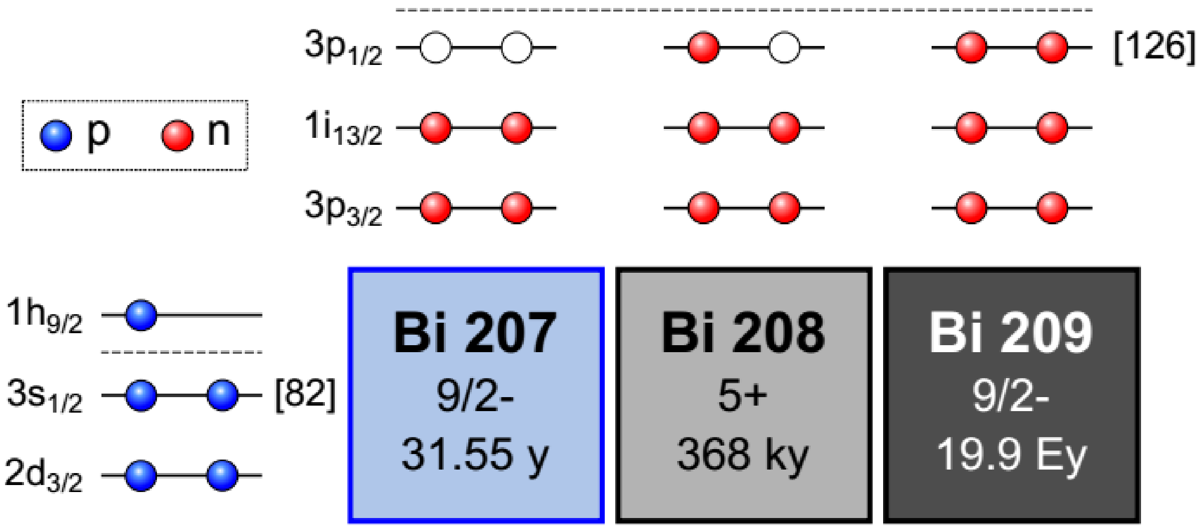


2018 new NMR measurement of $\mu(^{209}Bi)$
Skripnikov *et al*., Phys. Rev. Lett. **120**, 093001 (2018)

2014 Improved Measurement
Ullmann *et al*., Nature Comm. **8**, 15484 (2017)

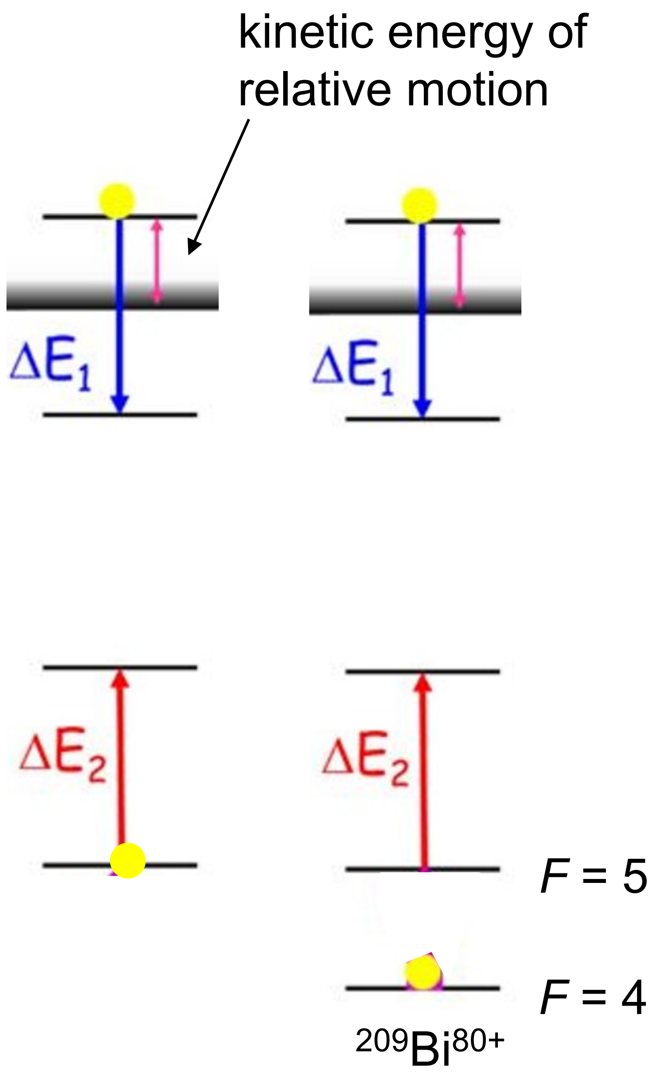
2011 First observation of the HFS in $^{209}Bi^{80+}$
Lochmann *et al*., Phys. Rev. A **90**, 030501 (2014)

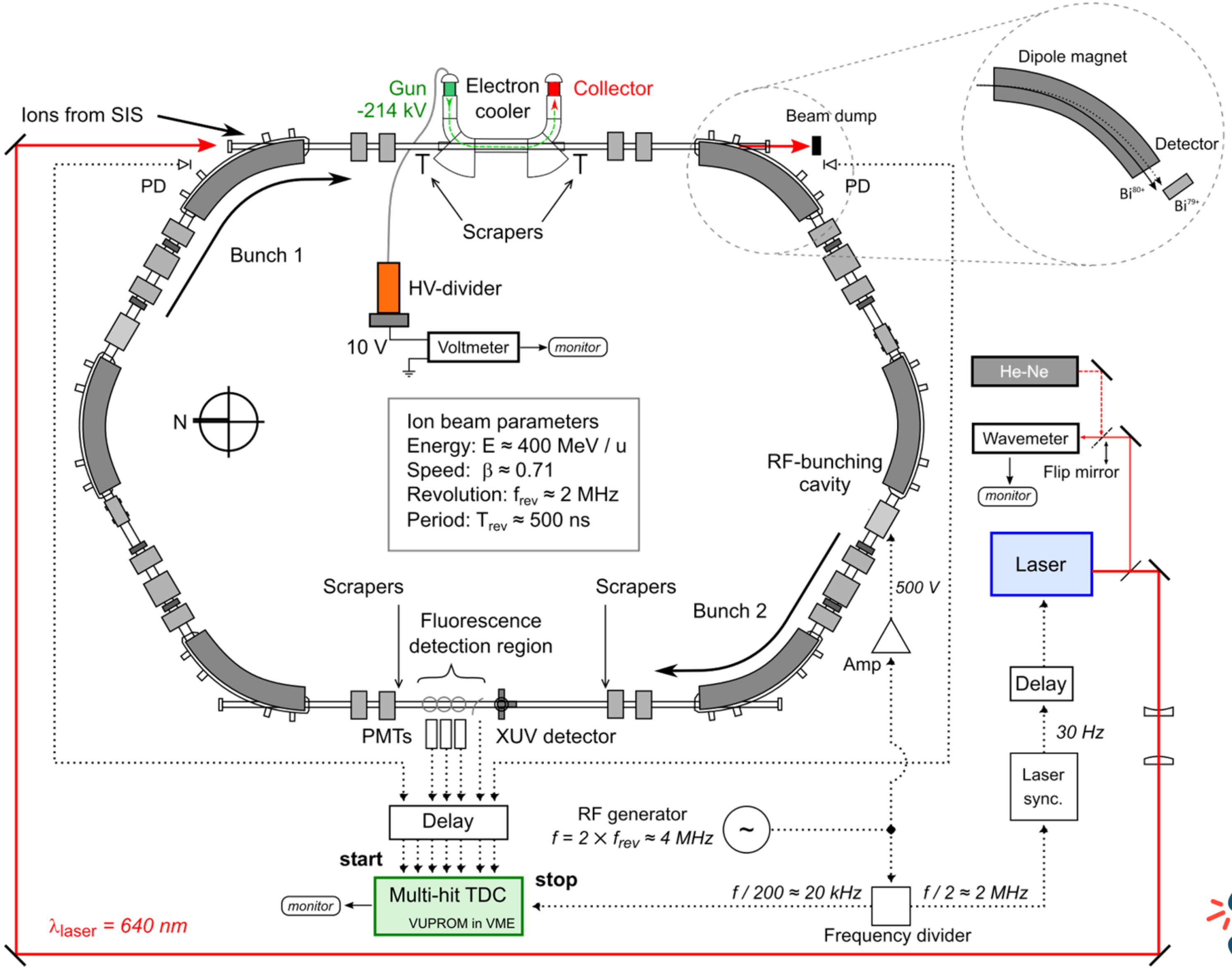
Bi Isotopes of Interest



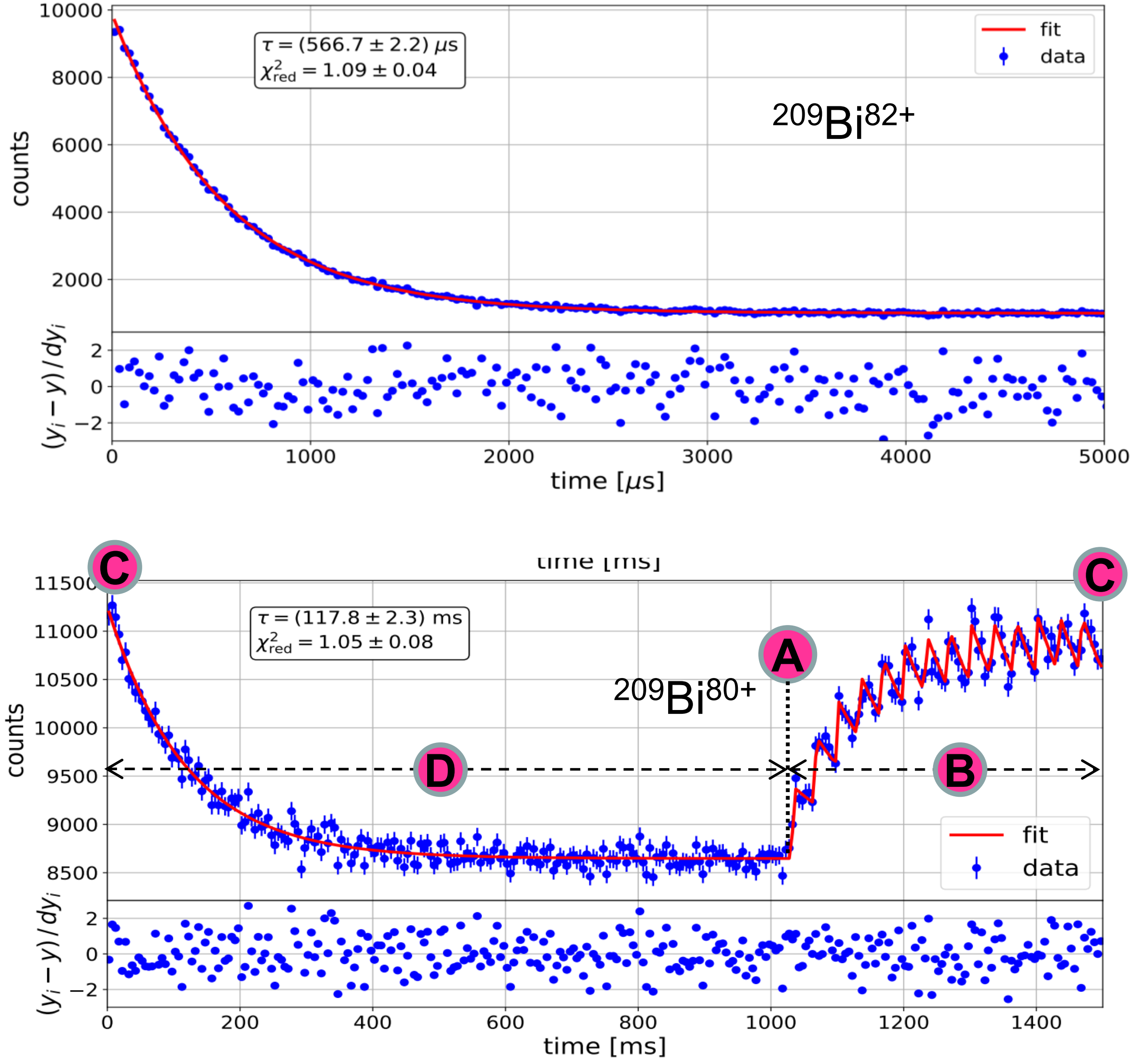
	Bi 207	Bi 208	Bi 209
$\Delta E^{(1s)}$ (eV)	5.085	5.661	5.08503(9)
$\lambda^{(1s)}$ (nm)	244	**219**	243.8221(44)
$\Delta E^{(2s)}$ (eV)	0.7976	0.8894	0.797645(14)
$\lambda^{(2s)}$ (nm)	1554	**1394**	1554.377(29)

DR-Assisted Laser Spectroscopy





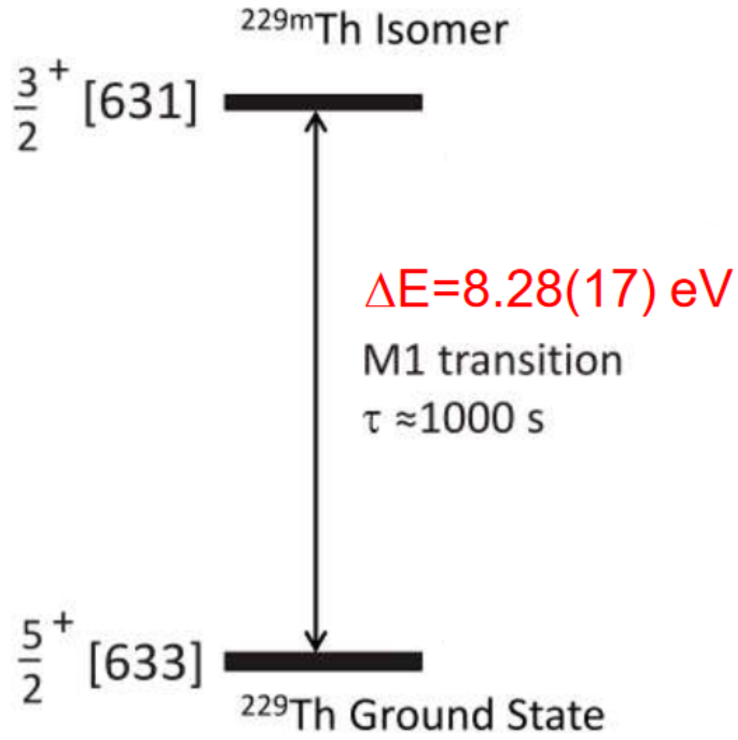
Lifetime Measurements of $^{209}Bi^{80+,82+}$



V. Hannen et al., J. Phys. B **52**, 085003 (2019)

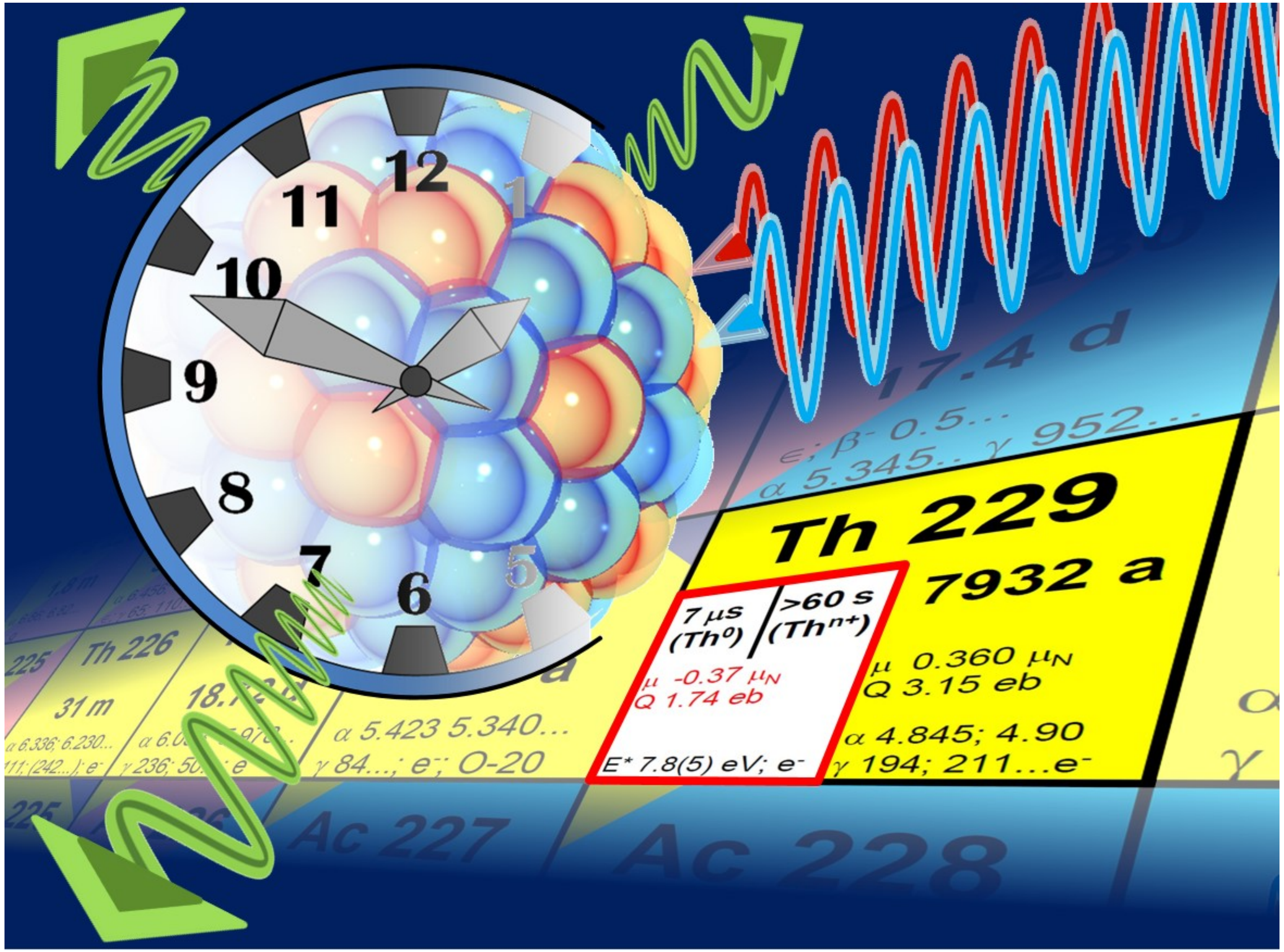
- **A** laser on, repetition rate 30 Hz
- **B** 15 laser pulses
- **C** laser blocked
- **D** undisturbed fluorescence decay observed

Spectroscopy of ^{229}Th: Motivation



Potential candidate for a nuclear clock

- ↑ Accuracy: less field-induced shifts than standard clocks
- ↑ Stability: Mößbauer solid-state nuclear clock could be operated with $>10^{10}$ particles
- Sensitivity to variation of fundamental constants

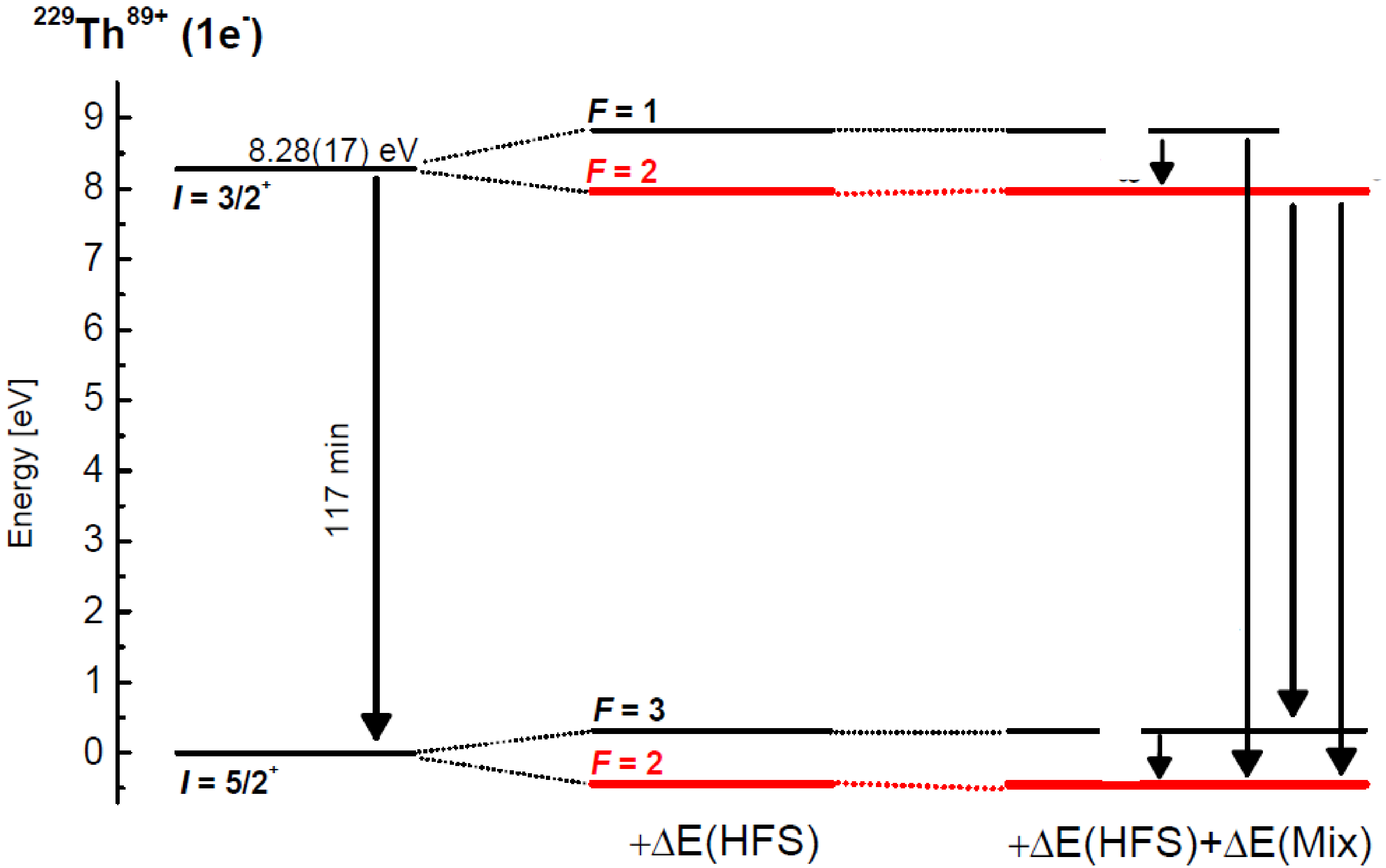


Spokesperson: C. Brandau, Uni Gießen

Laser Spectroscopy on ^{229}Th

Advantages of spectroscopy on Th^{89+}:

- Transition wavelength in the vacuum UV (~140 nm) is Doppler-shifted into the UV region (~300 nm)
- Lifetime of the nuclear transition gets quenched by hyperfine induced mixing between the ground state and the isomeric state
  $\rightarrow$ transition strength comparable to $^{209}Bi^{80+}$

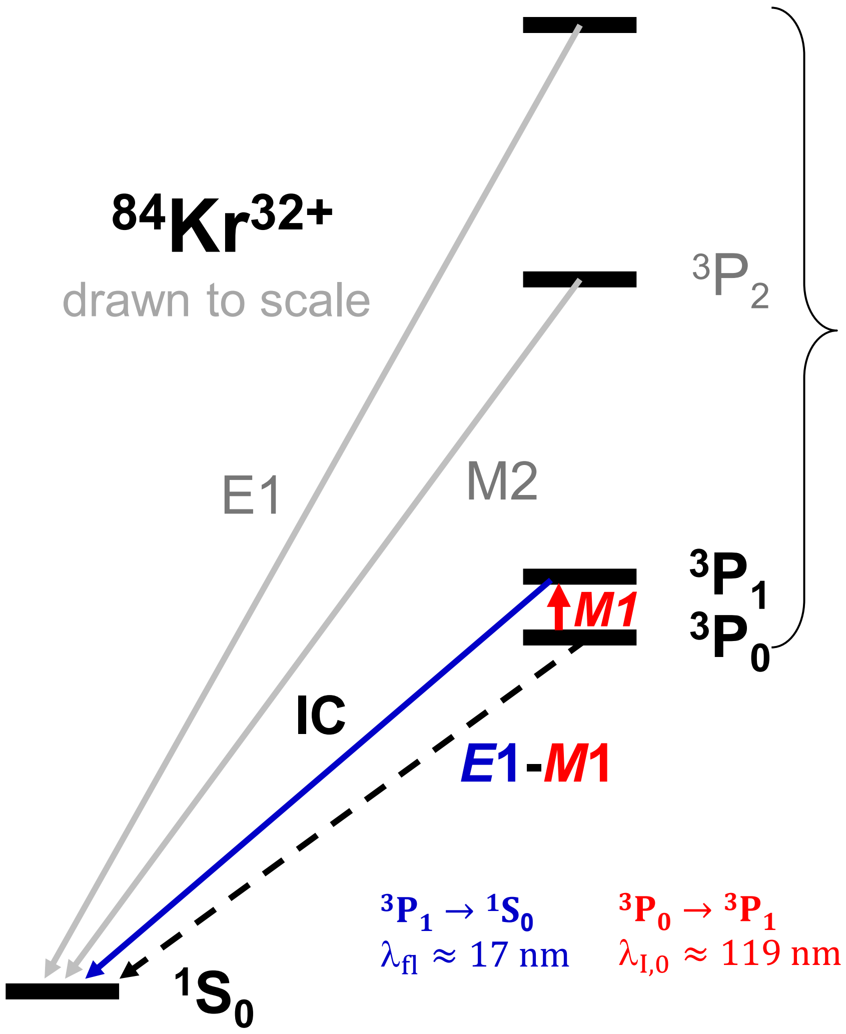


Challenges:

- small number of ions
- emission boosted into XUV
- large wavelength search range

Brandau, Schippers, Nörtershäuser, et al.

E135 Laser Spectroscopy of Be-like Krypton



2s2p states

M1-Transition:
- Electron-Electron correlation
- Basically free of QED perturbations

IC = intercombination line, E1 with ΔS=1

Safronova (1996)
Edlén (1983)
Cheng (2008)
Indelicato (2017)

2s2p	$^1P_1$	170.399	eV	
				44.758
2s2p	$^3P_2$	125.641	eV	
				52.666
2s2p	$^3P_1$	72.975	eV	
				10.356
2s2p	$^3P_0$	62.619	eV	

$^1P_1$: 170.454 eV (Cheng), 170.662 eV (Edlén)

$^3P_2$: 125.656 eV (Cheng), 125.628 eV (Edlén)

$^3P_0$: 62.521 eV (Edlén), 62.623 eV (Cheng)

$^3P_1$: 72.883 eV (Edlén), 72.987 eV (Cheng)

10.356: 10.362 eV (Edlén), 10.364 eV (Cheng), **10.420 eV** (Indelicato) — **1% effect !**

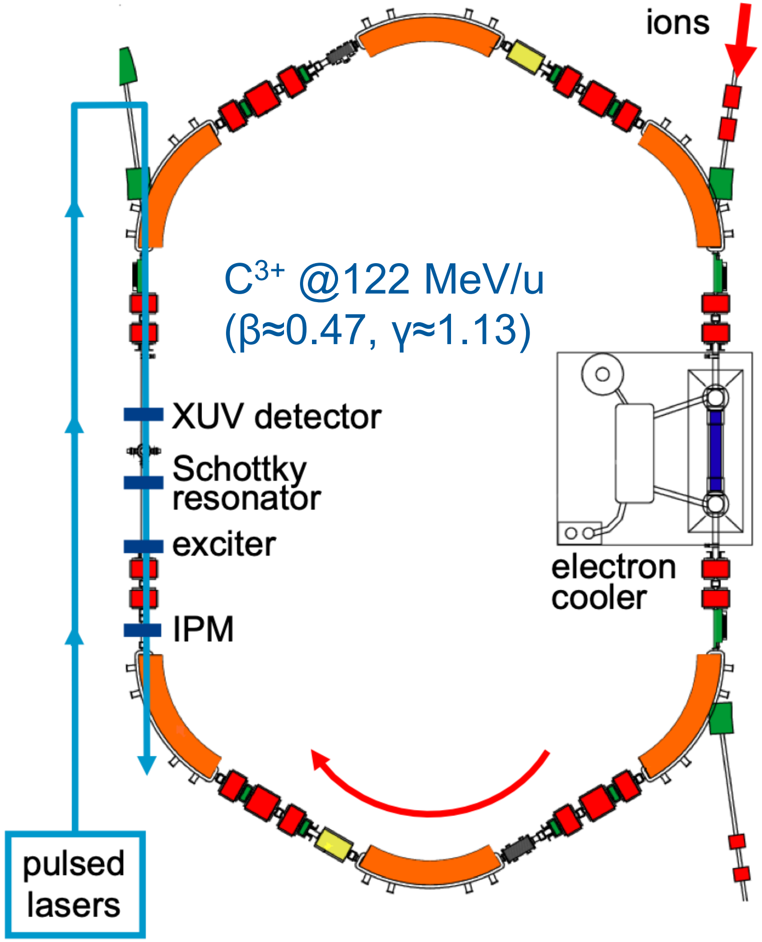
→ electron correlations included

excitations up to 5g level considered and extrapolated to infinity

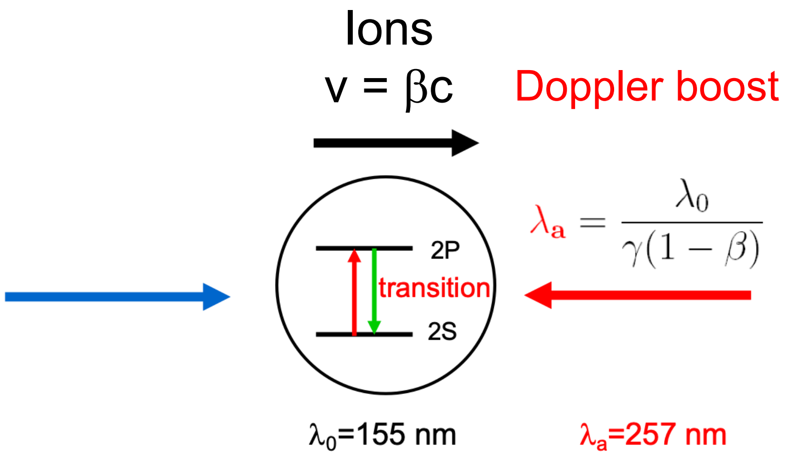
→ ~0.1 eV range can be covered by ESR cooler and laser systems

Laser Cooling of C^{3+} at the ESR

Blueprint and test bed:
Laser Cooling of C^{3+} at ESR



Principle of laser cooling (bunched ion beam)

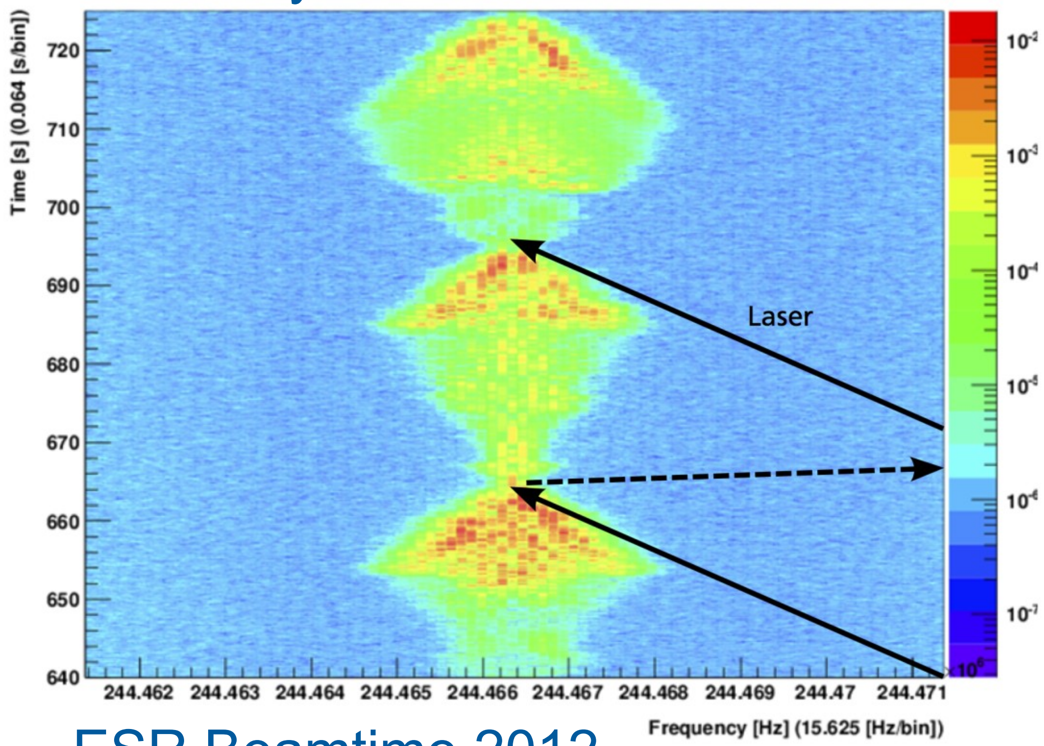


Counteracting force from rf-bucket

Force by radiation pressure (laser)

Phase-space Cooling of Relativistic Ion Beams (ESR & SIS100)

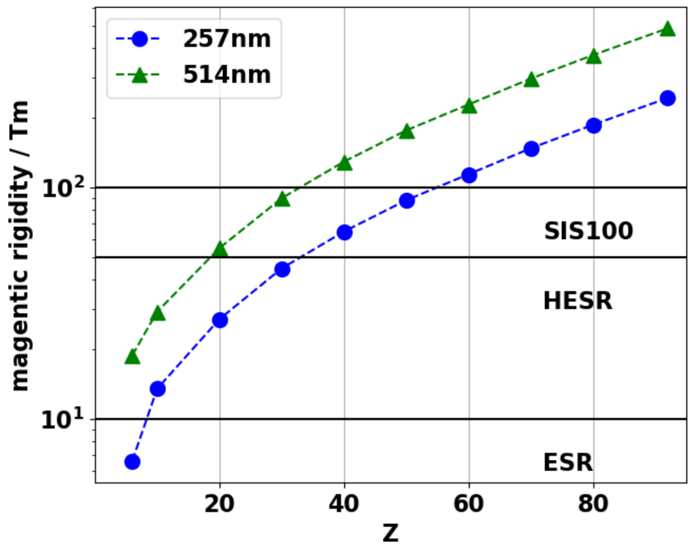
Status:
- **Successful laser cooling using cw laser (sharp δ–like frequency spike)**
- **=>Electron pre-cooling required**
- Bunched beam
- Limited by IBS



ESR Beamtime 2012

At SIS100 laser cooling is the only way for phase-space cooling

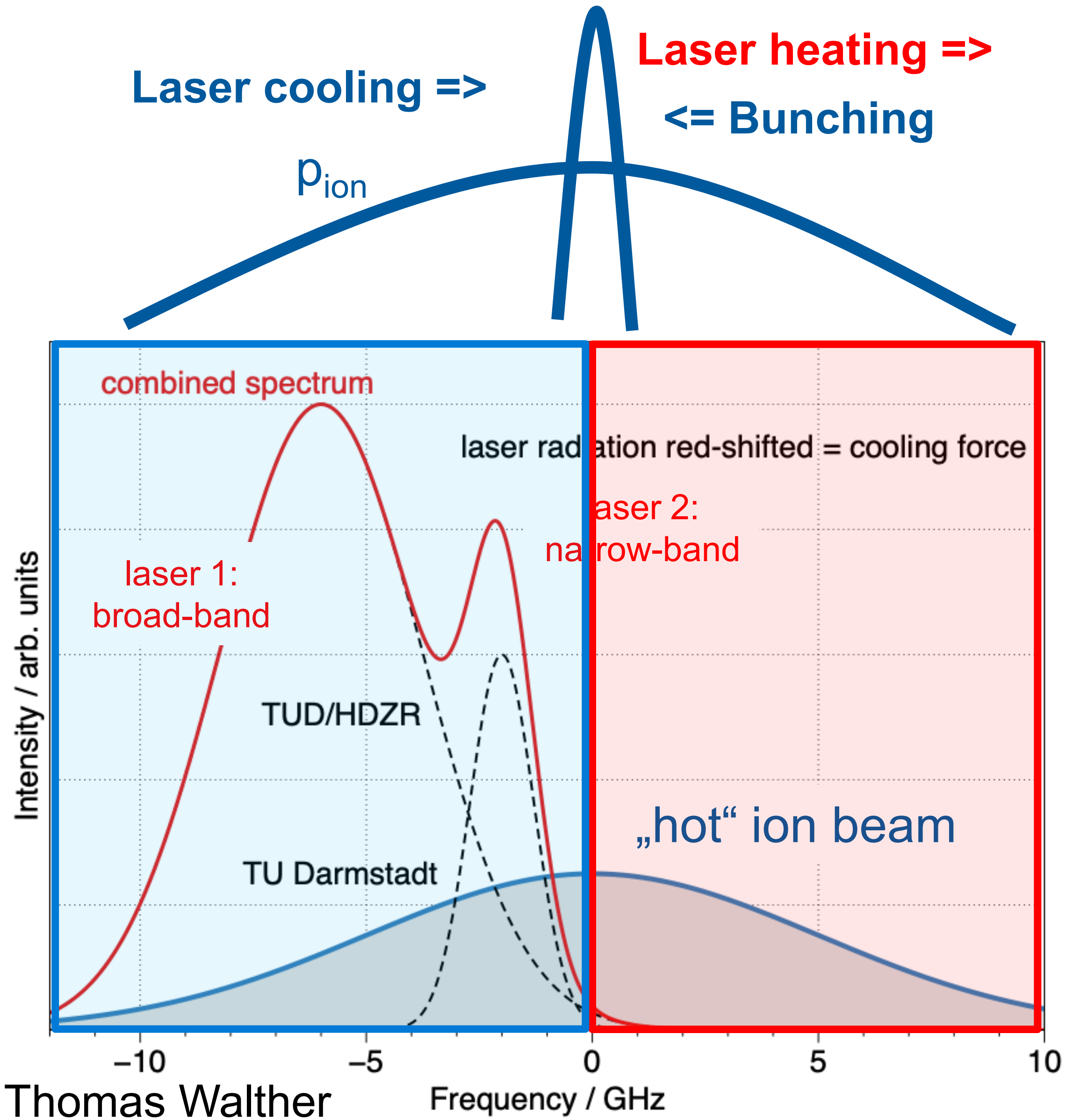
e.g. 2s→ 2p in Li-like ions



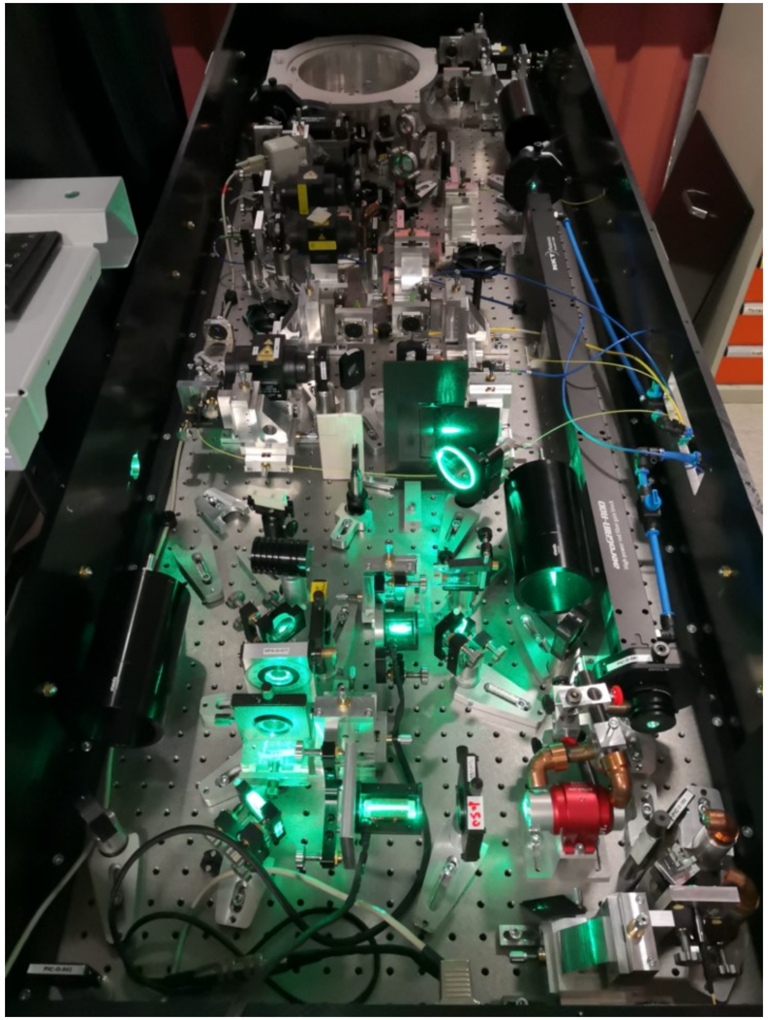
Laser Cooling @ SIS100
- High brilliance ion beams
- **High resolution spectroscopy**
- Beam diagnostics (fluorescence)

Laser Cooling of C^{3+} at the ESR + SIS100

- **Cooling of „hot“ ion beam ($\delta p/p \approx 10^{-3}$) w/o electron pre-cooling**
- Stronger cooling force counteracts IBS
- laser cooling using **two synchronized** pulsed, high rep. rate, FT limited **UV laser systems**
- **Combined laser:**
  Laser 1: broad-band (“catches” all ions)
  Laser 2: narrow-band (cools to min. $\delta p/p$)



CW and Pulsed Laser Systems for FAIR



D. Kiefer et al., Opt. Lett. **16** (2020) 4488

Tunable Pulsed

UV Laser Sources

High rep rate. up to 10 MHz

FT limited pulses

Adjustable bandwidth

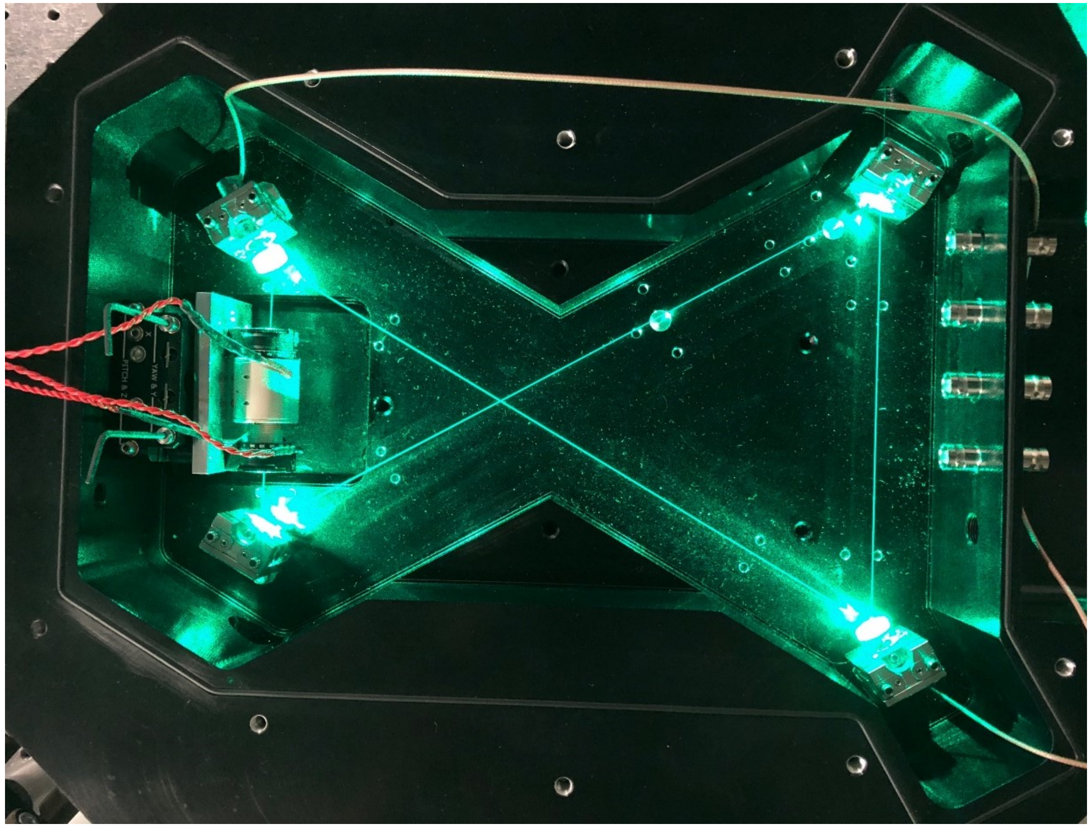
Pulse duration 47 - 740 ps

Tunable cw All-Solid state UV Laser Source

Narrow linewidth

> 600 mW @ 257 nm

D. Kiefer et al., Laser Phys. Lett. **16** (2019) 075403



Projects at CRYRING@ ESR

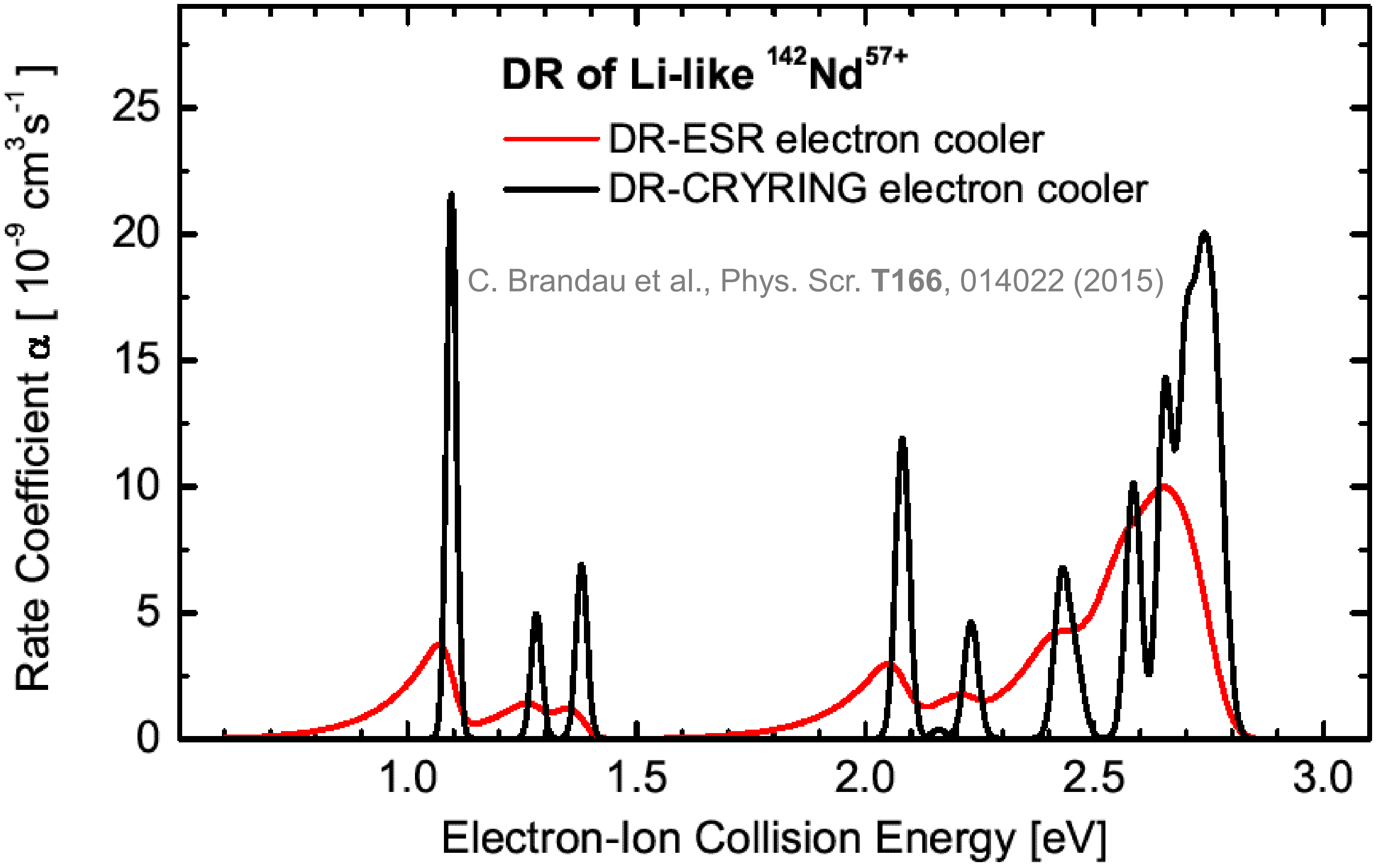
Precision collision-spectroscopy of highly charged ions in the CRYRING@ESR electron cooler
(S. Schippers, Uni Gießen)

Reaction Microscope
(R. Dörner, Uni Frankfurt)

Optical Pumping in a Storage Ring
(R. Sanchez, GSI; W. Nörtershäuser, TU Darmstadt; Y. Litvinov, GSI)

Precision Collision-Spectroscopy at CRYRING@ESR

DR provides:
- precise **level and ionization energies**, e.g. for tests of QED)
- access to **hyperfine structure** and **charge radii**



Local Team:

Prof. Stefan Schippers (JLU)

Dr. Carsten Brandau (BMBF)

Sebastian Fuchs, MSc (HFHF)

E131: Precision collision spectroscopy of Be-like ions at the CRYRING@ESR electron cooler (rated A)
Beamtime: March 2021

DR at CRYRING@ESR: Status

cooler control
& DAQ
JLU Gießen

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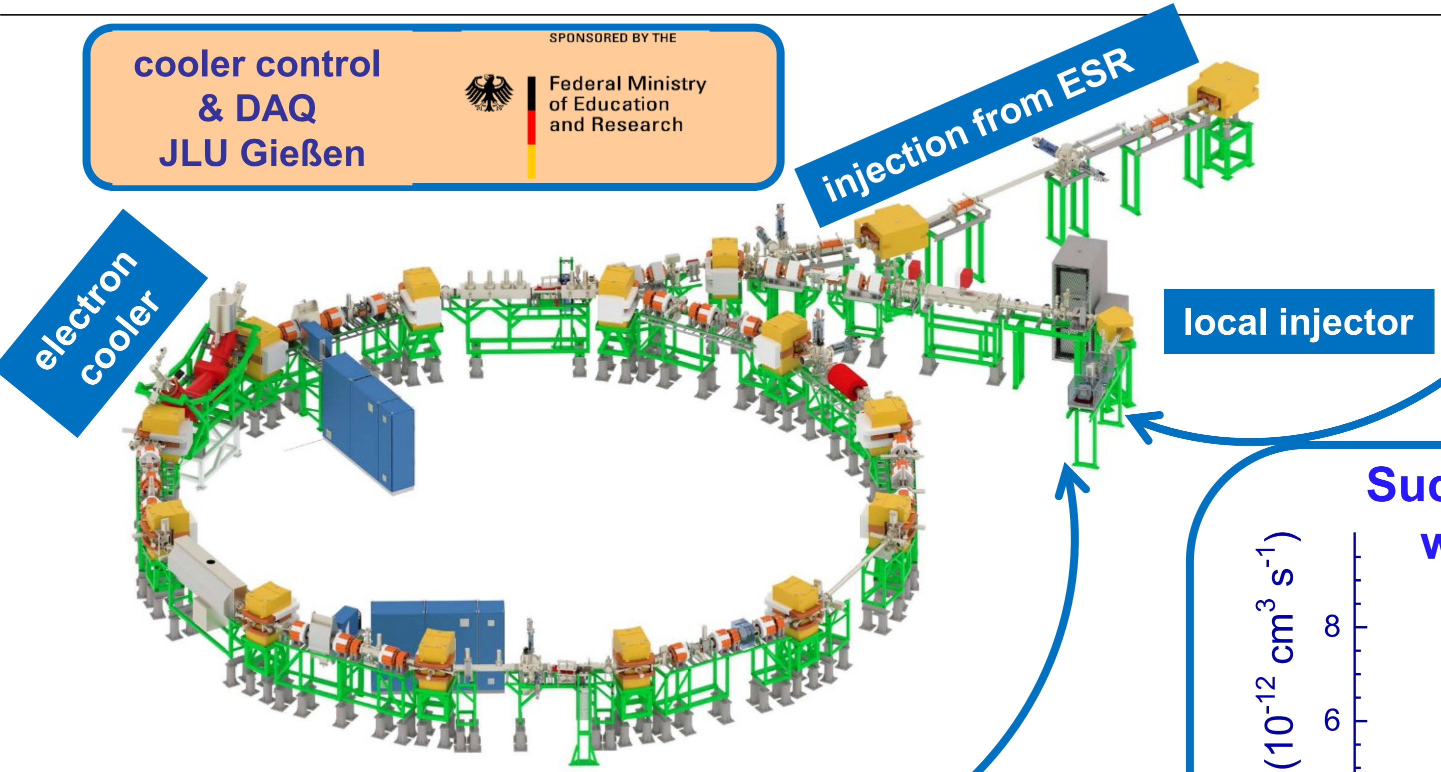
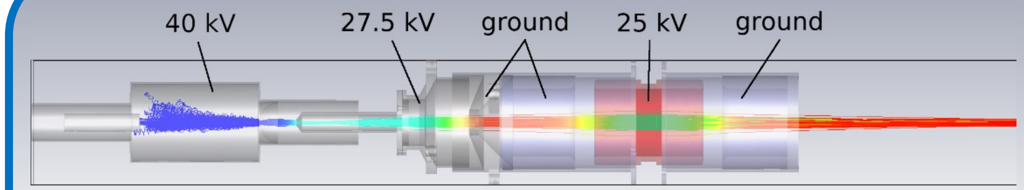
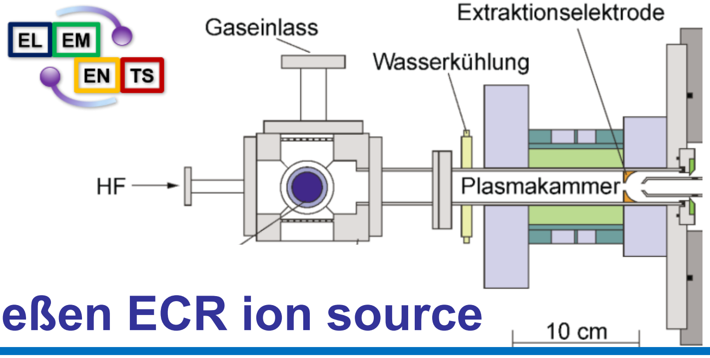


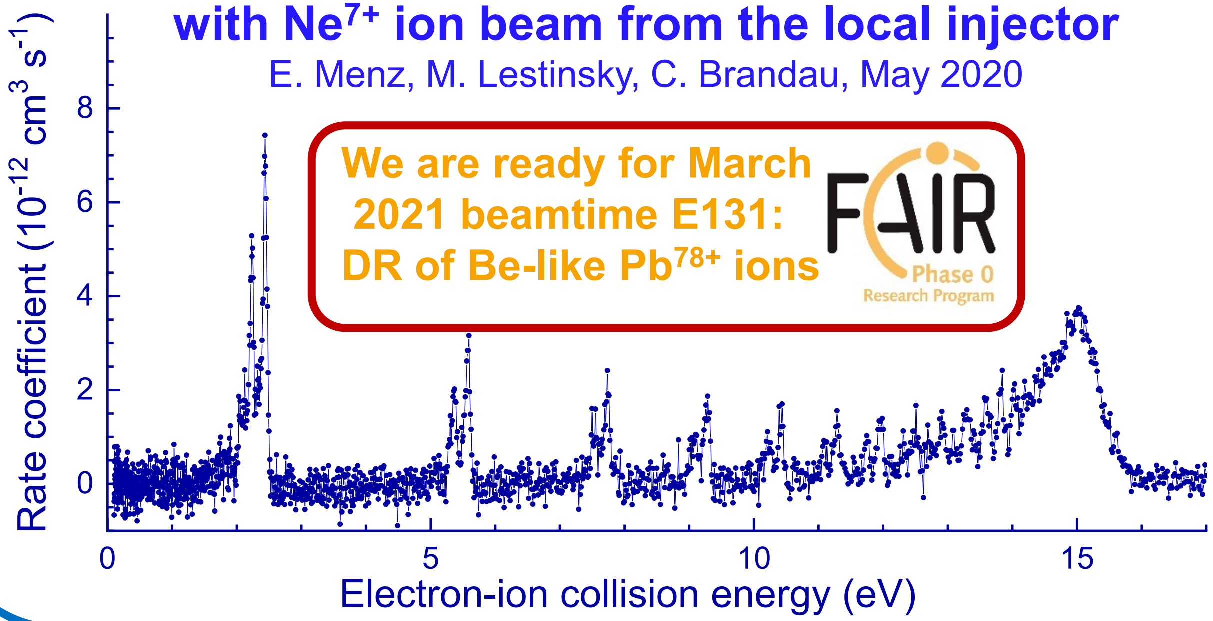


matching of ECR source to local injector
P. Willamowski, MSc Thesis, JLU Gießen (2020)
together with S. Fuchs & A. Borovik



Gießen ECR ion source

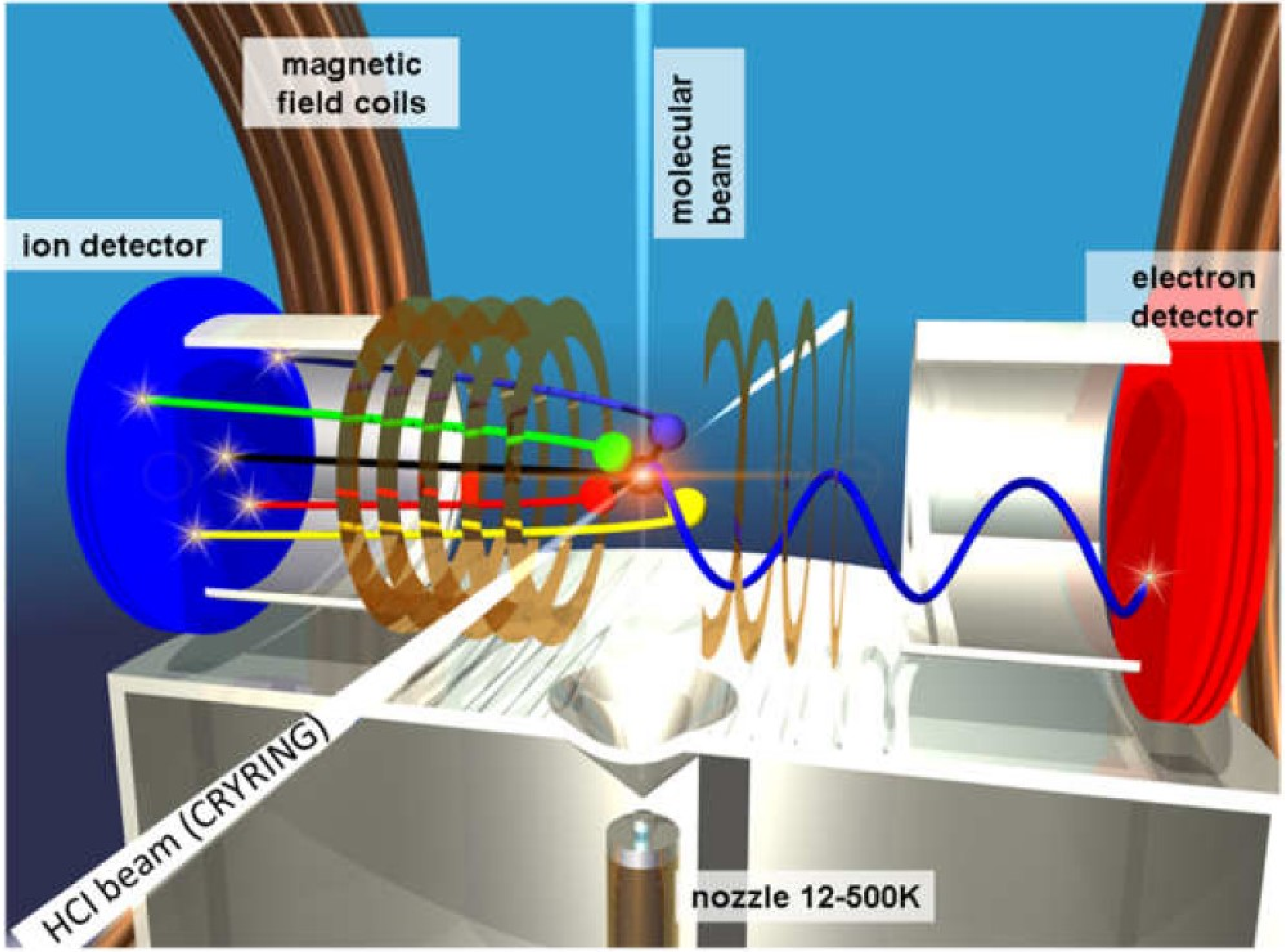
Successful comissioning of the DR setup with with Ne^{7+} ion beam from the local injector
E. Menz, M. Lestinsky, C. Brandau, May 2020



We are ready for March 2021 beamtime E131: DR of Be-like Pb^{78+} ions

FAIR Phase 0 Research Program

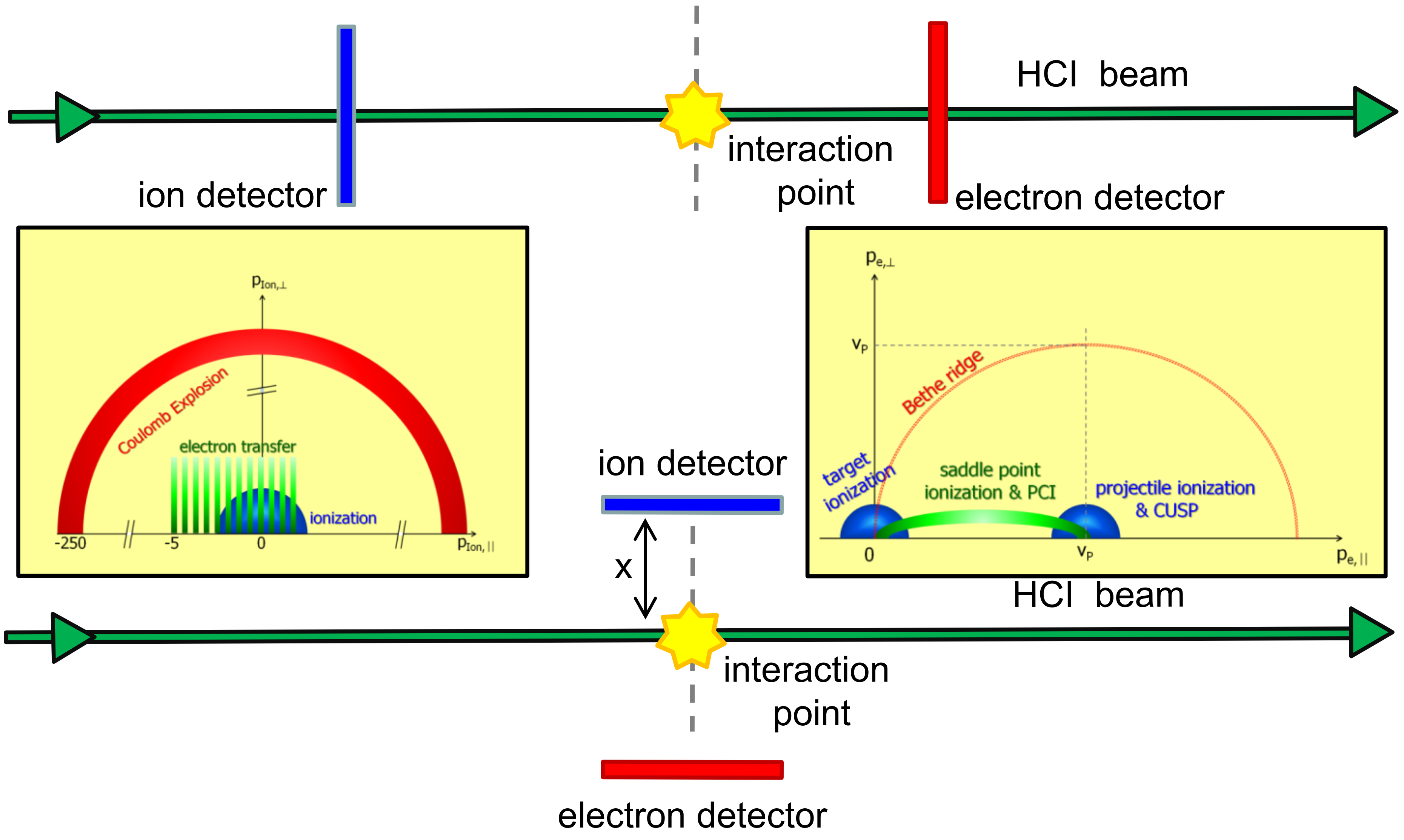
CRY-RIMS: A COLTRIMS Reaction Microscope at CRYRING@ESR



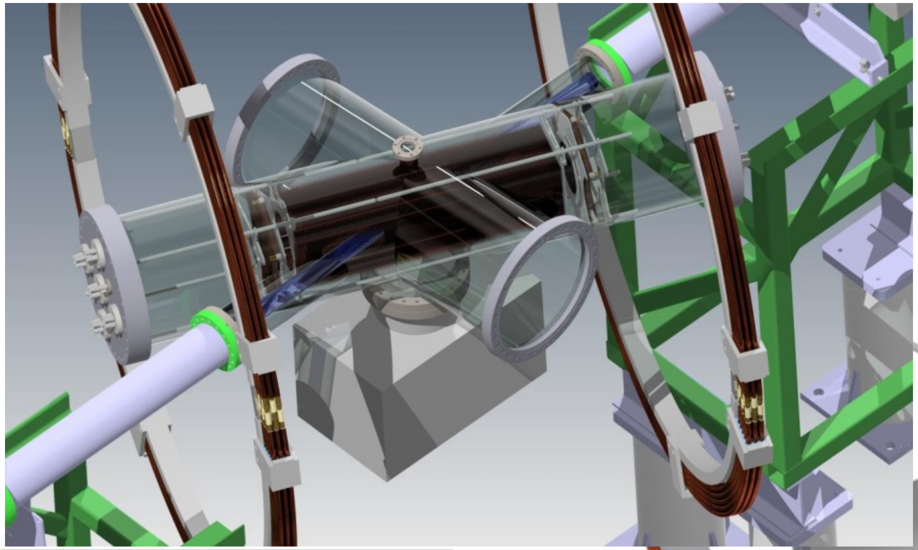
First physics cases:

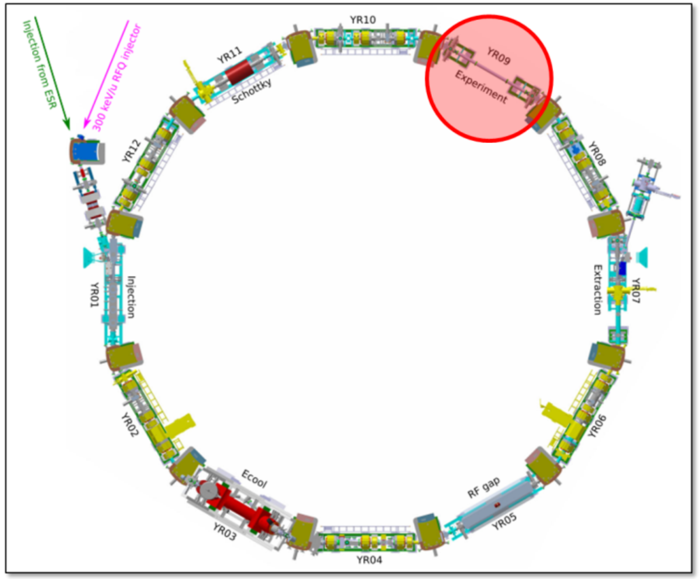
- Projectile double electron-loss of helium like ions
- Comparison of ionizing collisions of stored ions with He and H_2 gas $\Rightarrow$ role of projectile coherence.

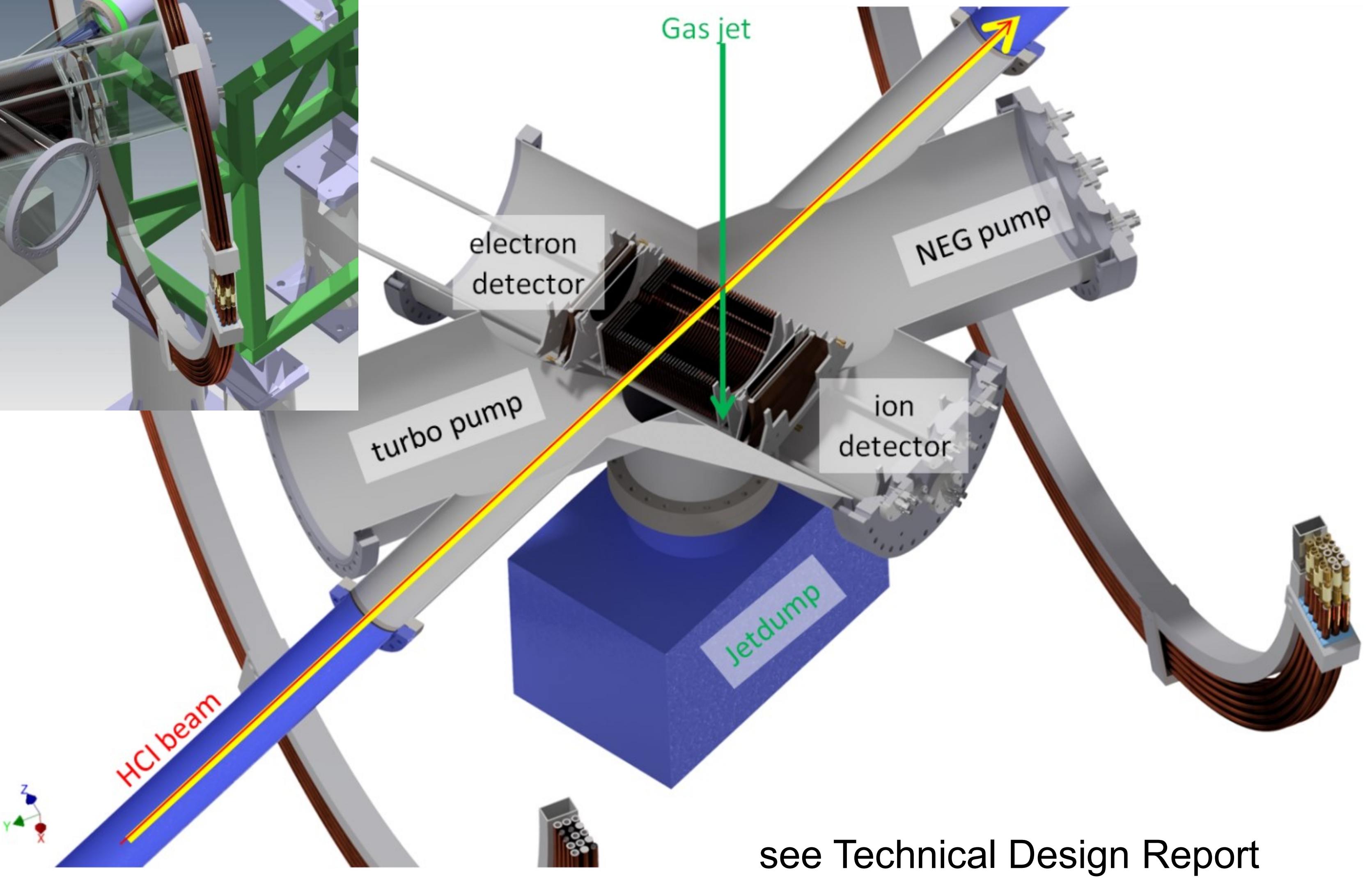
A Reaction Microscope (REMI) for CRYRING@ESR



CRY-RIMS: Location & Design (0th Version)







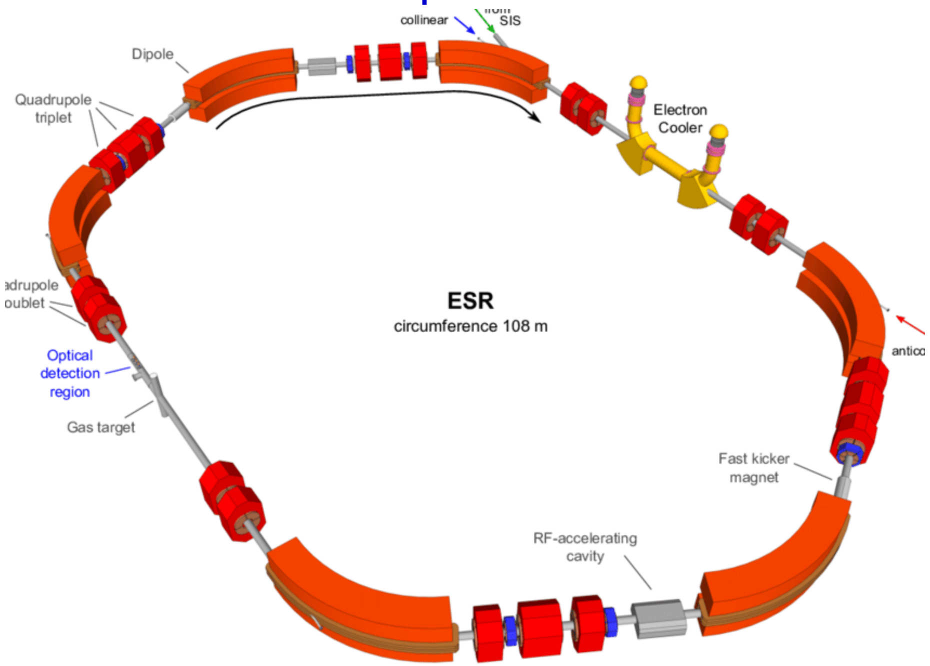
see Technical Design Report

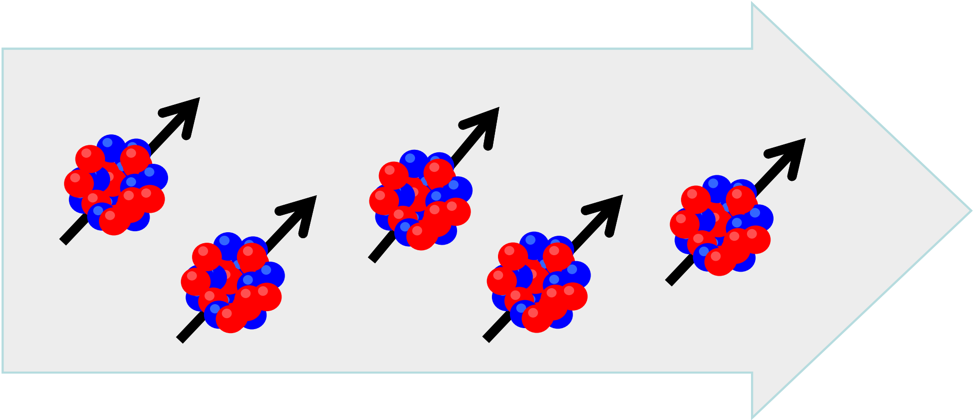
Spin-Polarized Ions in Storage Rings

During the last decade, considerable interest has been paid to experiments with spin-polarized ions at storage rings.

There are three questions to be solved:

- Production of polarized ion beams
- Detection of the polarization
- Preservation of the polarization

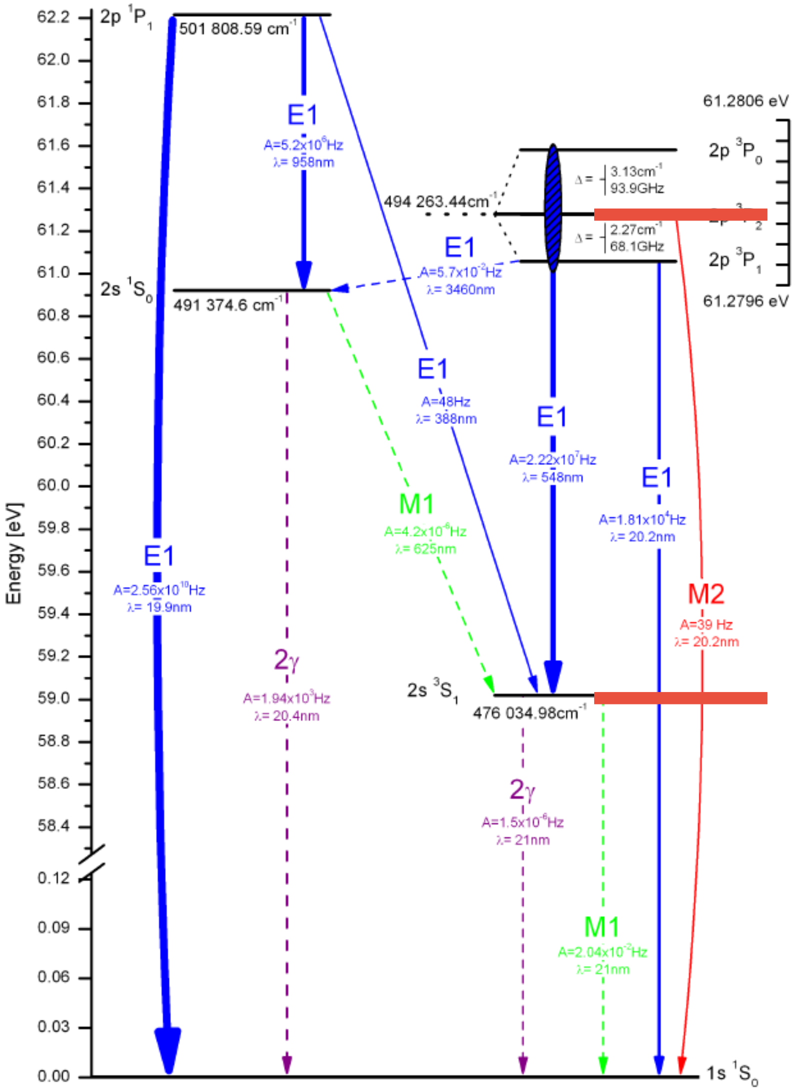


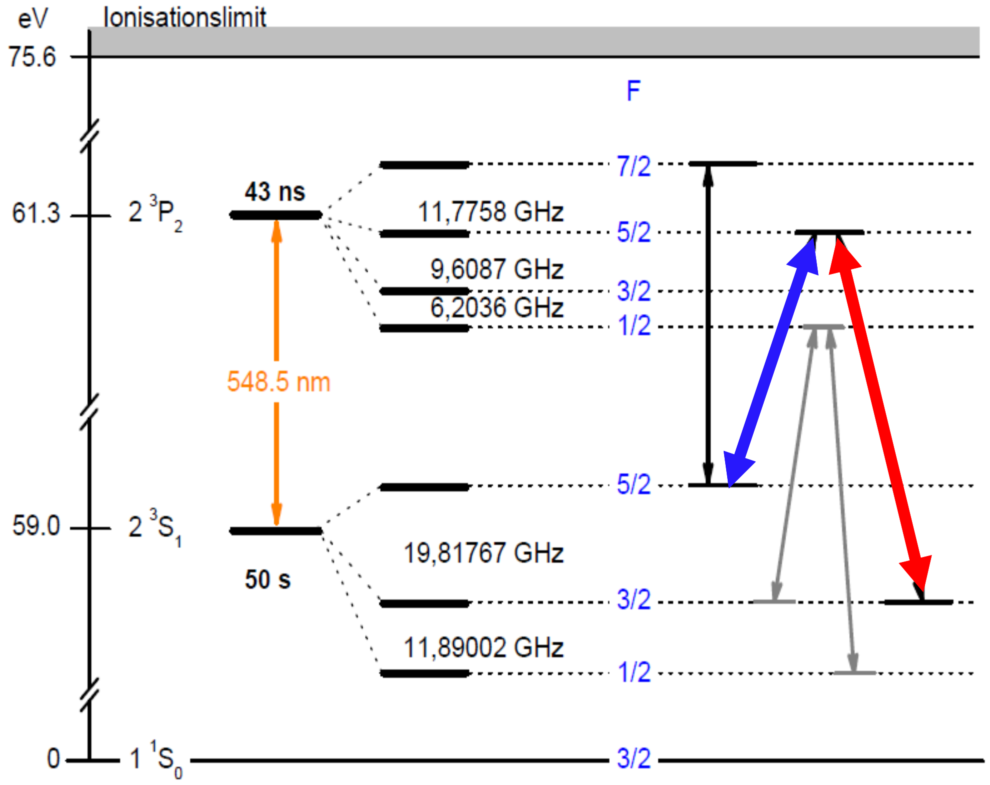


$$\lambda_I = \frac{1}{I}\sum_{M_I} n_{M_I} M_I$$

Degree of nuclear polarization is statistical characteristics!

$^7Li^+$ Ions: Hyperfine Structure



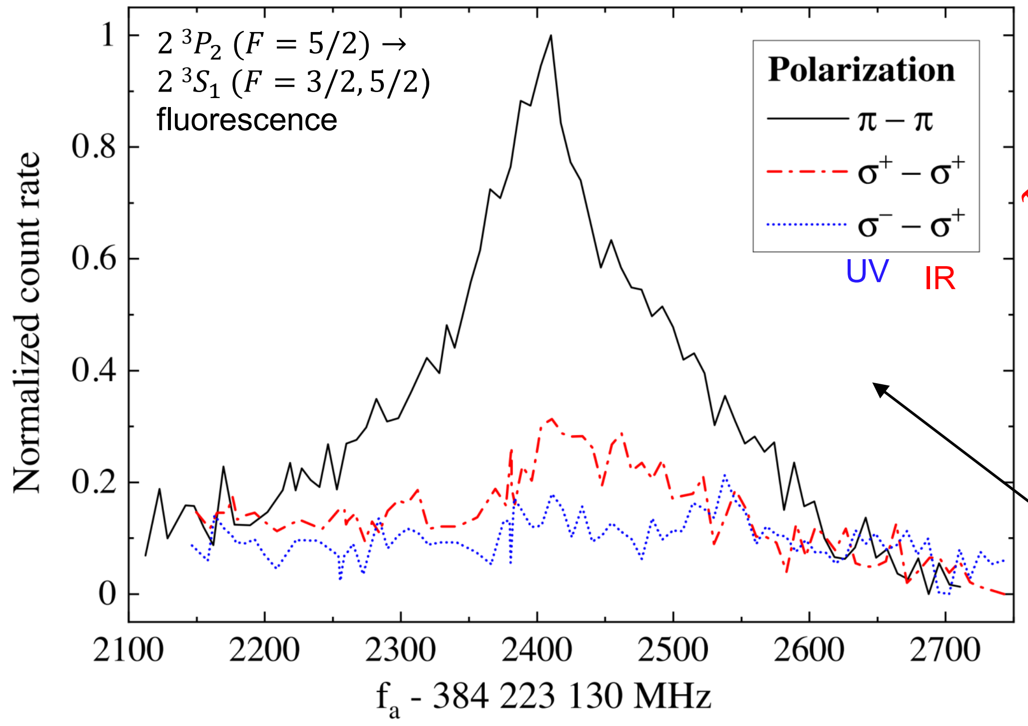


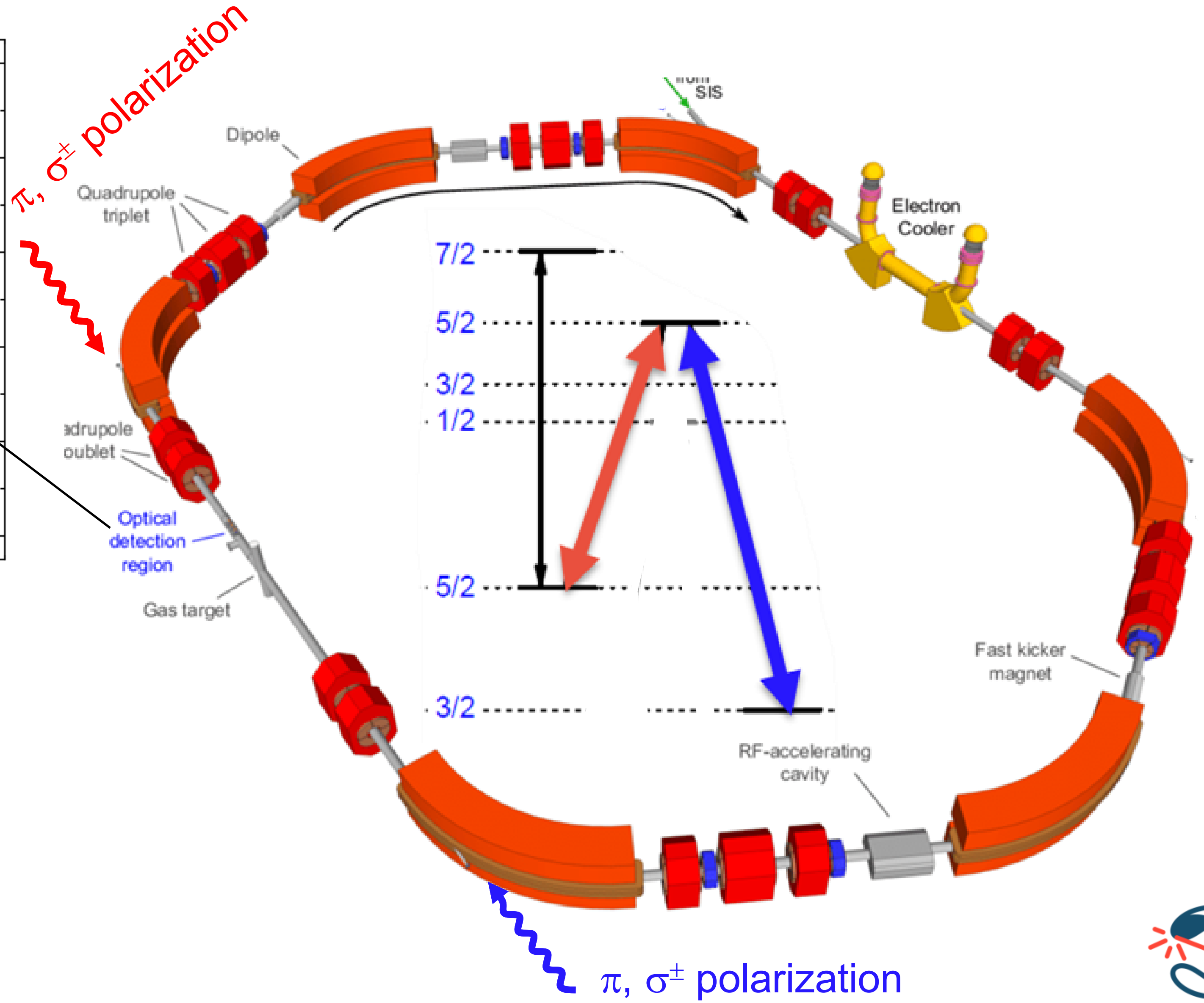
Recently, optical pumping of $^7Li^+$ ions (nuclear spin $I = 3/2$) has been performed at the ESR storage ring at the GSI facility in Darmstadt.

We used two lasers to induce Λ-transition:

$$2^3S_1: F = 5/2 \leftrightarrow 23P_2: F = 5/2 \leftrightarrow 2^3S_1: F = 3/2$$

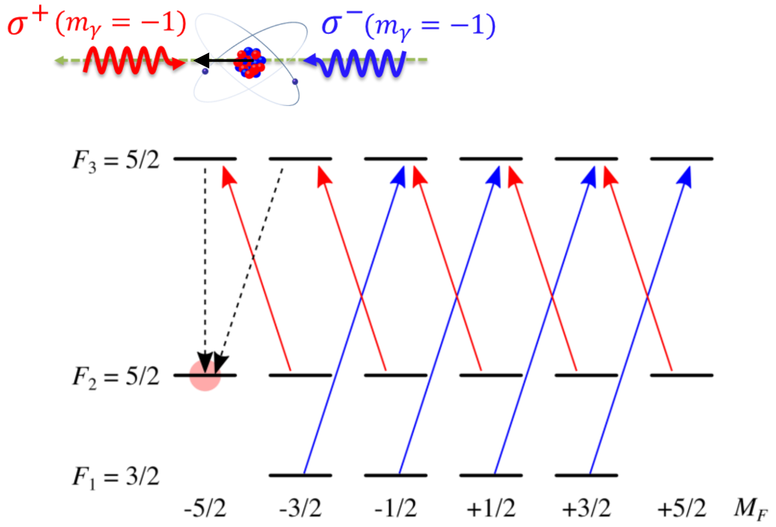
$^7Li^+$ Spectroscopy at the ESR: Setup and Result

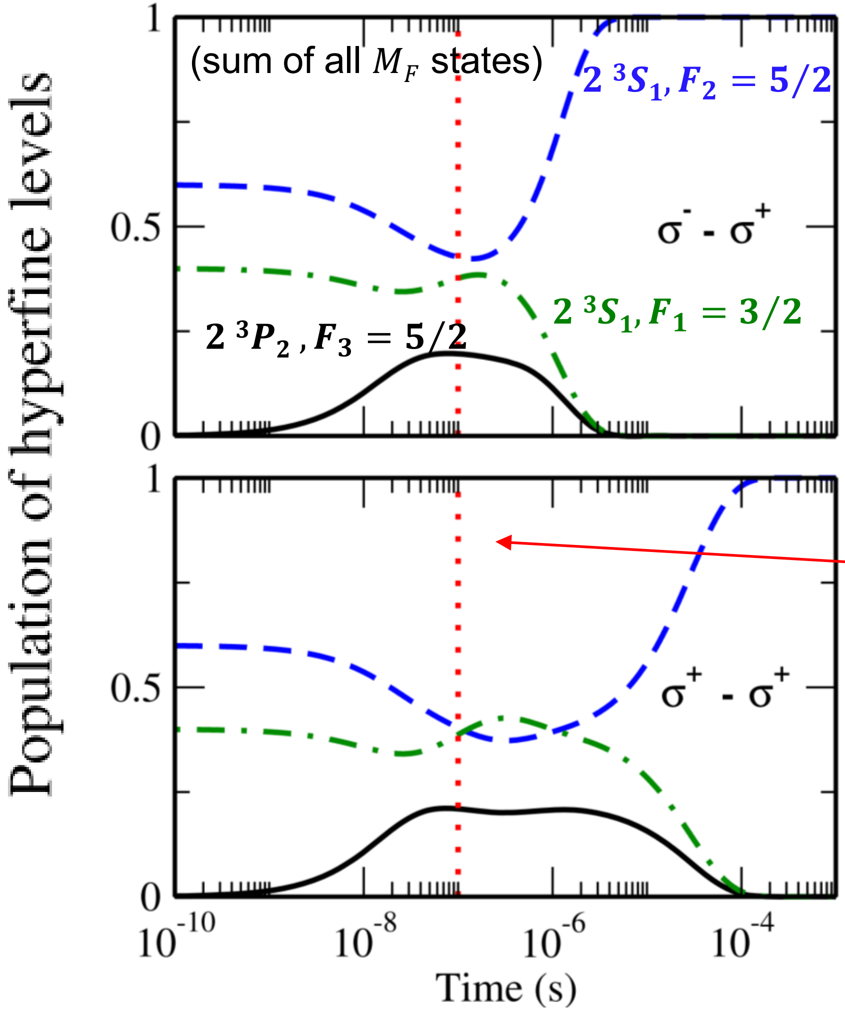


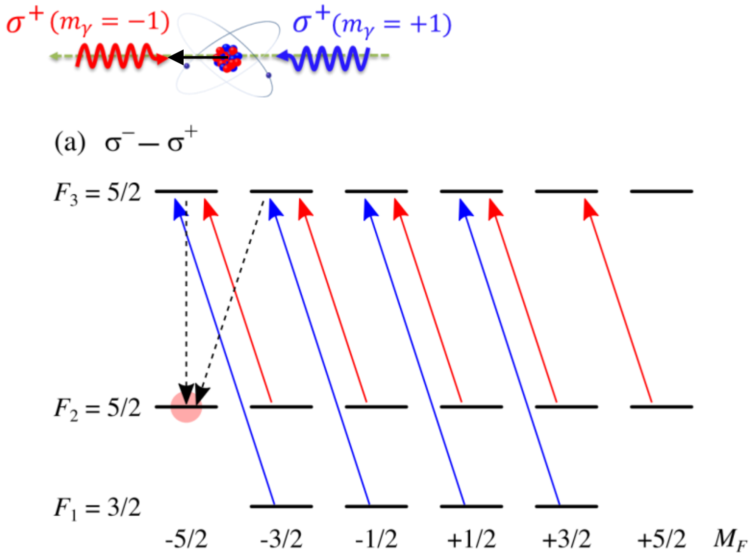


- Clear signal for linear polarization
- Weak signal for circular case $\sigma^+\ \sigma^+$
- No signal for circular case $\sigma^-\ \sigma^+$

Dark-State Population and Fluorescence Signal







Indicated is the level population for continuous excitation und the initial condition

$$N_{F_1 M_{F_1}}(0) \equiv N_{2^3S_1:F_1=3/2\,M_{F_1}}(0) = 1/10$$

$$N_{F_2 M_{F_2}}(0) \equiv N_{2^3S_1:F_2=5/2\,M_{F_2}}(0) = 1/10$$

$$N_{F_3 M_{F_3}}(0) \equiv N_{2^3P_2:F_2=5/2\,M_{F_3}}(0) = 0\,,$$

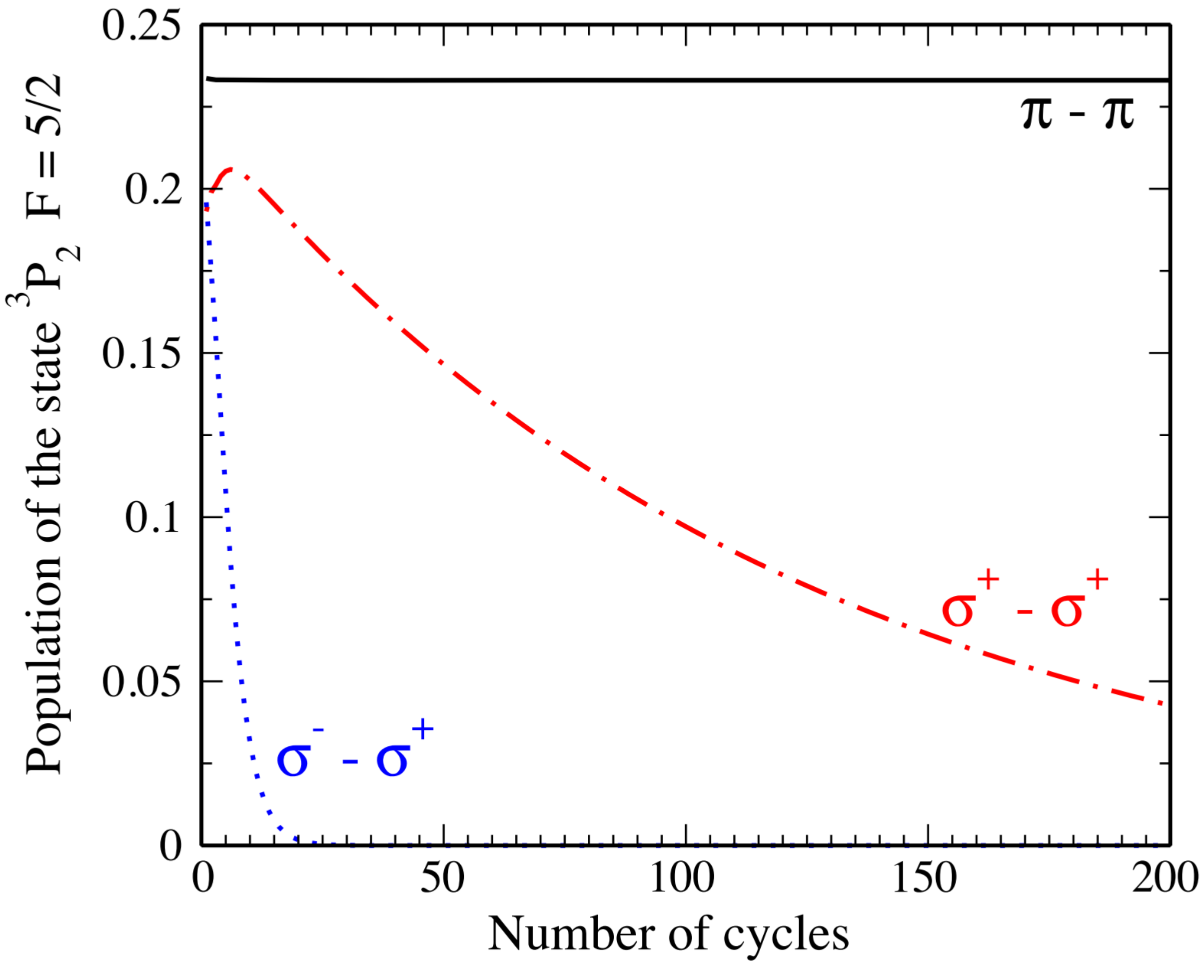
→ unpolarized beam !

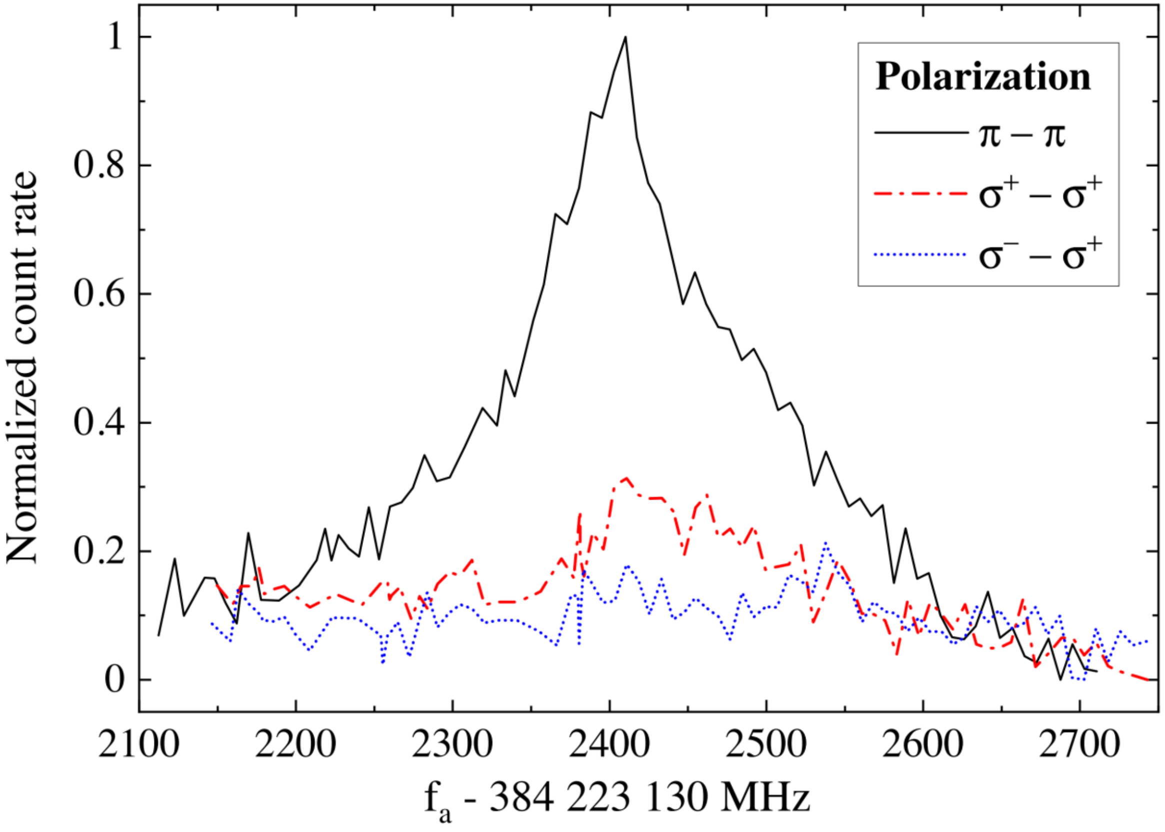
Red dotted line indicates time-of-flight to fluorescence detection region

In both cases, a full fluorescence signal should be obsevable at the detector, but this is not what we observed experimentally

Possible Explanation

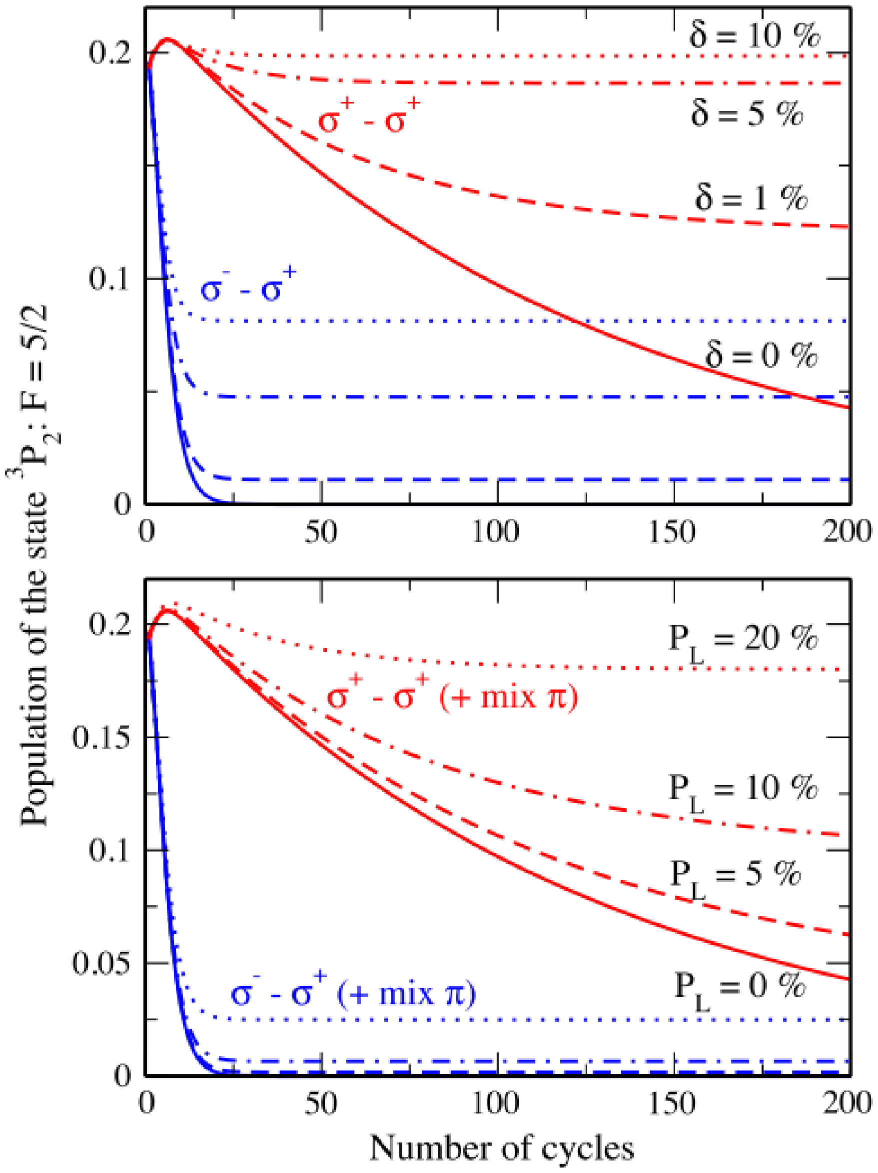
Fluoresence at the detector position with **conserved sub-state population** after each round-trip





much **better agreement** with experiment!
Consequently, the ion beam should be **polarized**!

Effects of Depolarization and Impure Laser Polarization



Influence of **depolarization**

δ: redistribution of M_F state population per round trip

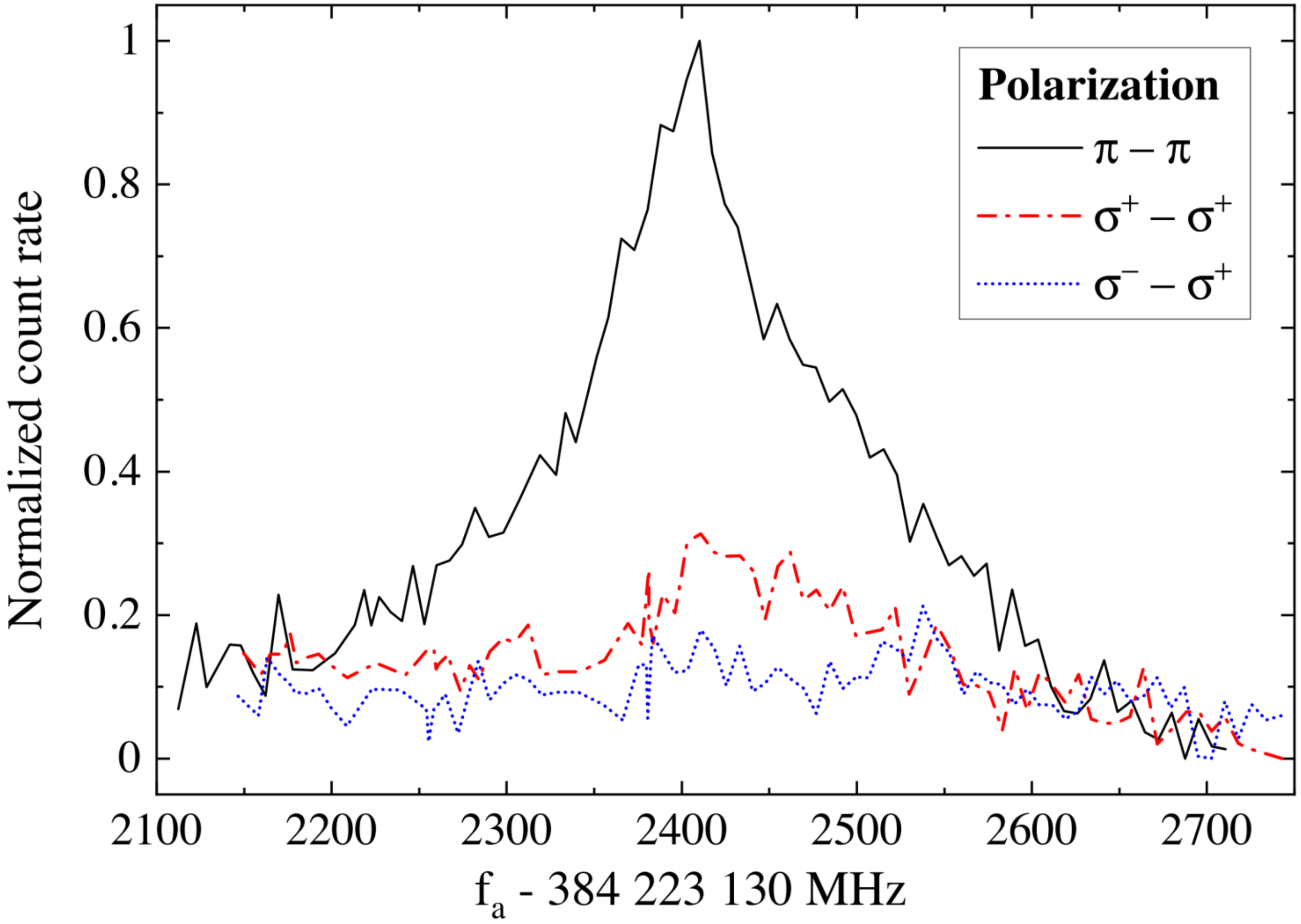
The case $\sigma^- - \sigma^+$ is more robust to a "reshuffling" of the population. In contrast, even a small depolarization for the $\sigma^+ - \sigma^+$ case leads to a remarkable enhancement of the population of the excited state.

Influence of **impure laser polarization**

P_L: Amount of linearly polarized light admixture

Again, the case $\sigma^- - \sigma^+$ is more robust to small contributions of π-light, since both circularly-polarized parts pump the population quickly back to the dark state.

Conclusion



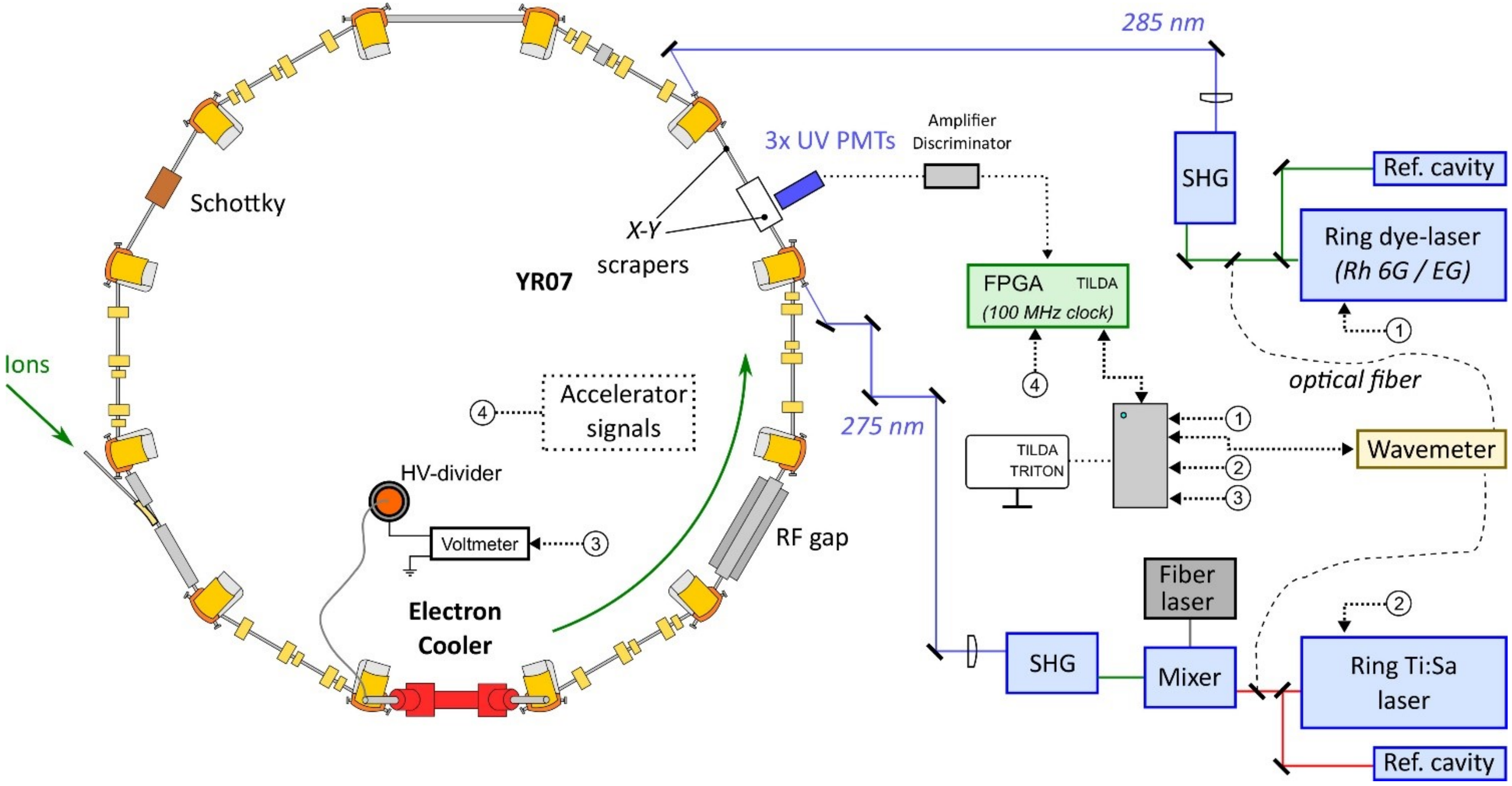
Signal disappearance can be conclusively explained by optical polarization of the ion beam, including the weak reminiscence of the signal in the $\sigma^+ - \sigma^+$ case.

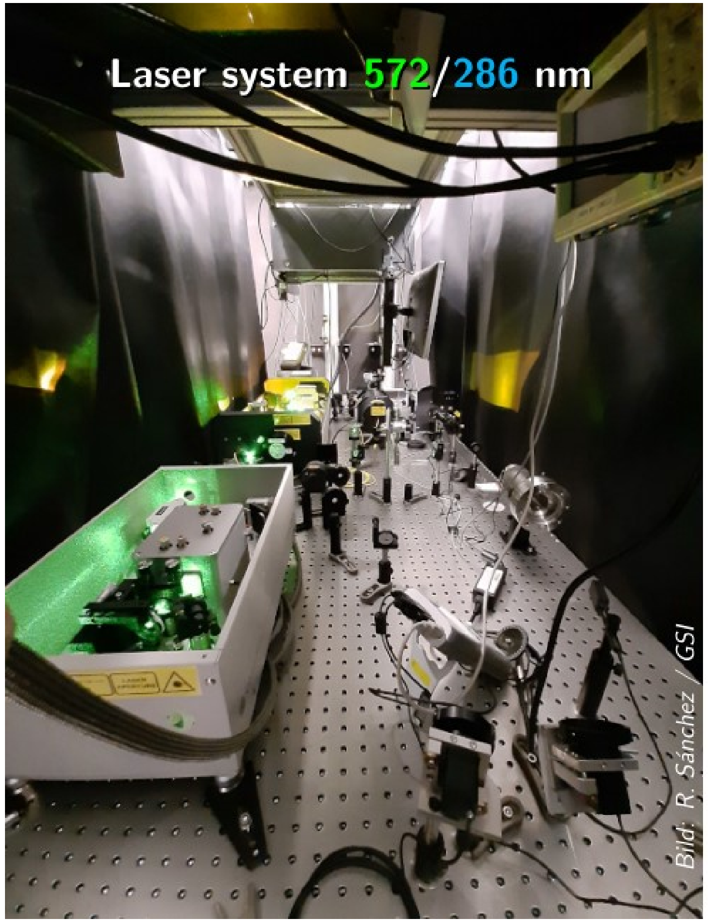
But our model is very naïve! We neglected dynamics of polarized ions in the bending magnets! Further studies are needed!

→ CRYRING@ESR

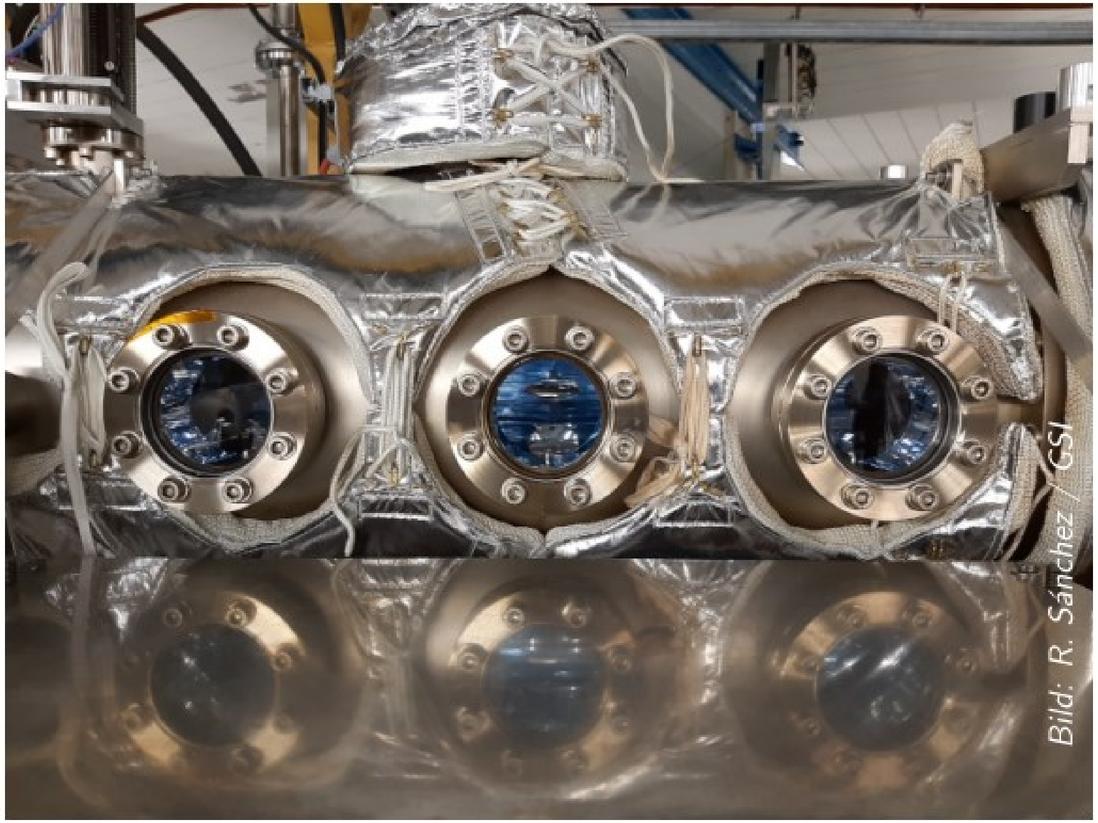
For detailled analysis, see
W. Nörtershäuser, A. Surzhykov, R. Sànchez et al.. Phys. Rev. Acc. Beams **24**, 024701 (2021).

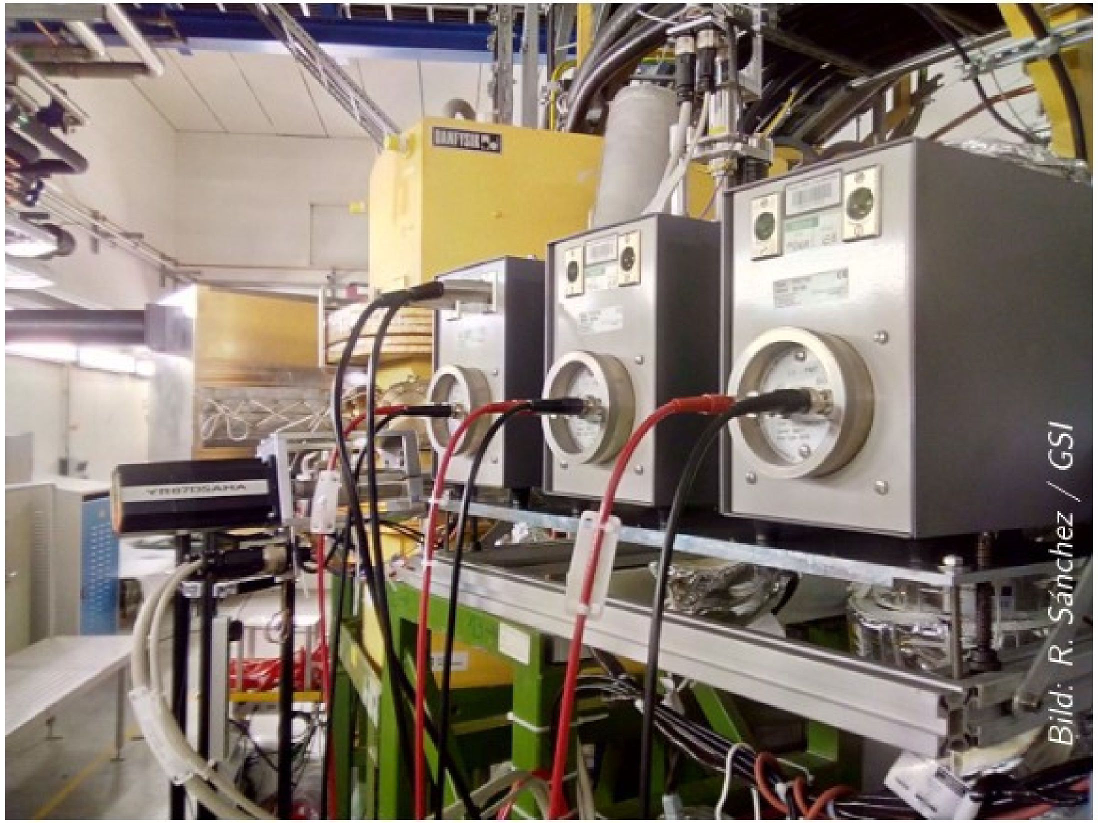
Laser Spectroscopy Setup at CRYRING@ESR





Fluorescence Detection Region at CRYRING@ESR

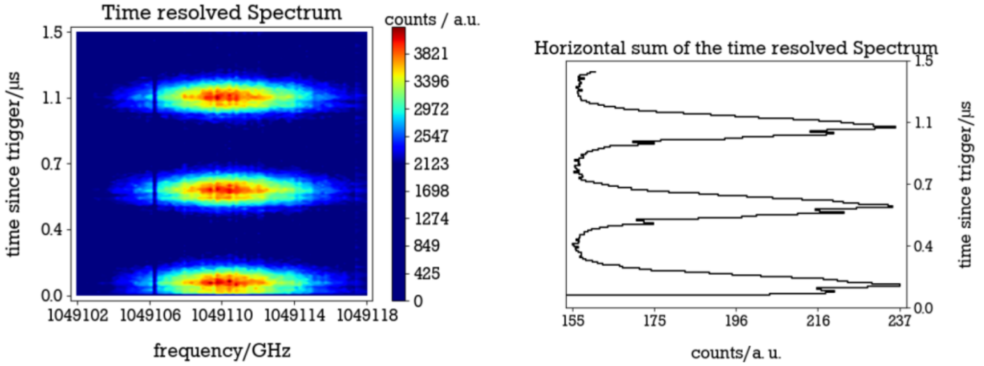




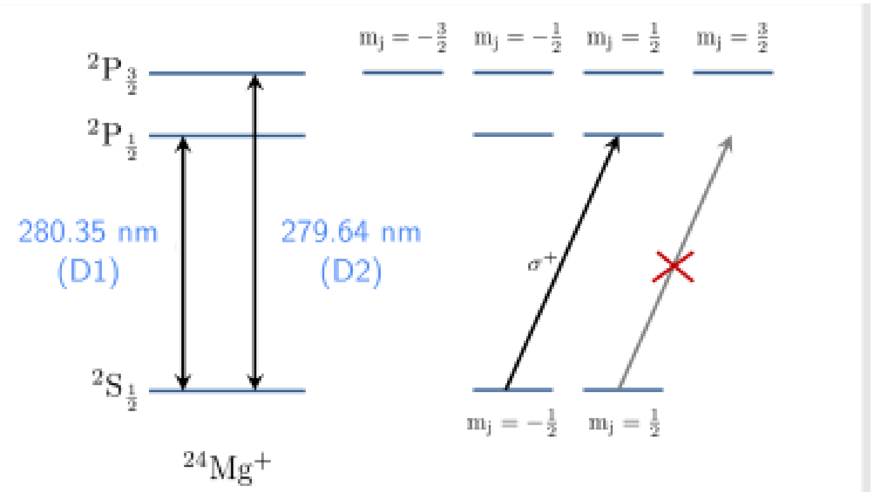
- Multipurpose fluorescence detector system (200-800 nm) installed at CRYRING.
- Designed and built at AG Weinheimer (Institut für Kernphysik, WW-U Münster) by Axel Buß, Volker Hannen *et al.*

Preparatory Work

Optical detection and new DAQ serve as beam diagnostics

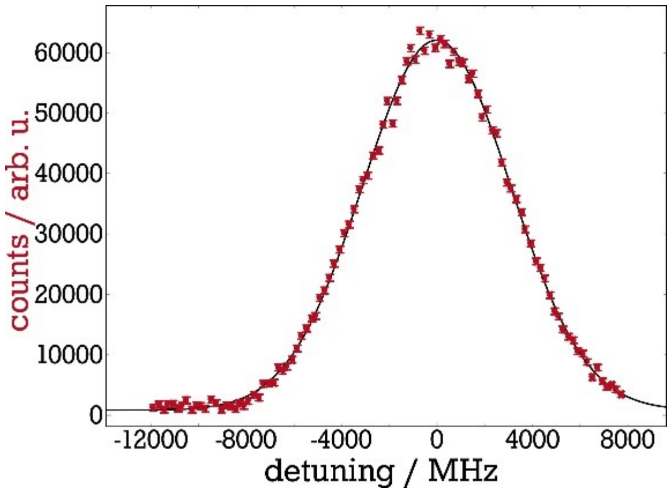


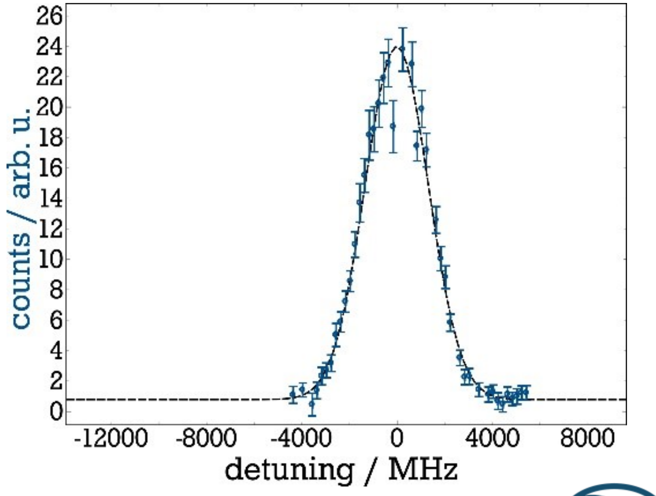
Optical pumping in $^{24}Mg^{+}$



Resonance

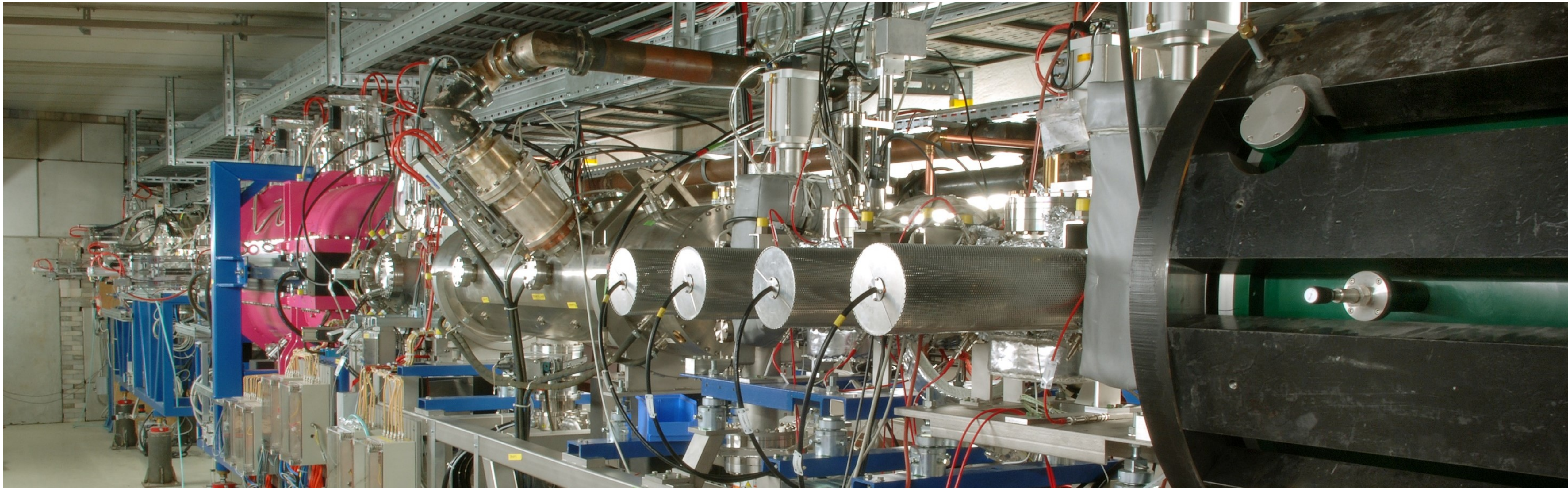
Commissioning of the optical detection region





Electron cooling *OFF* *ON*

HITRAP

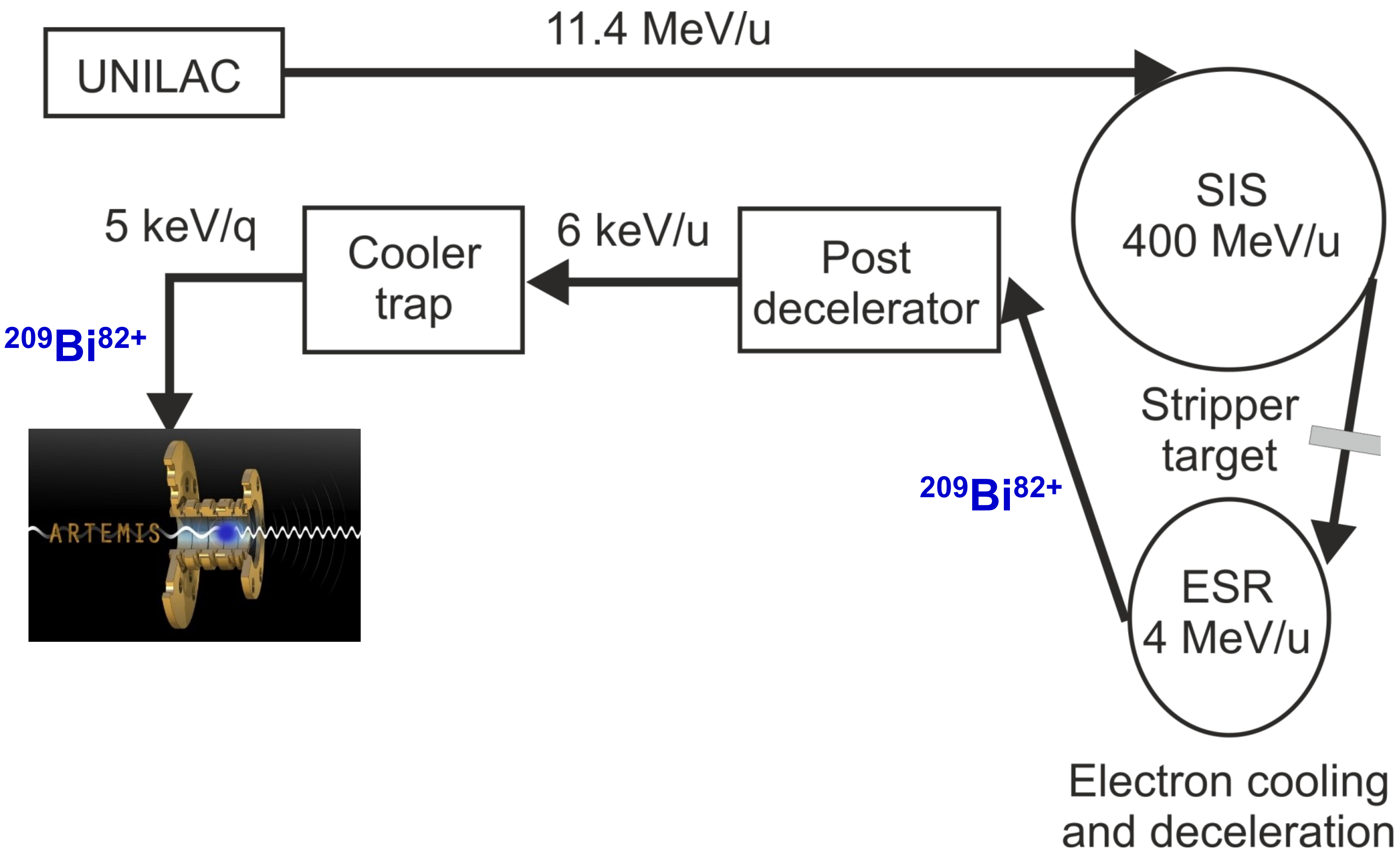


Cooling of trapped highly charged ions at HITRAP
(W. Nörtershäuser, TU Darmstadt; Frank Herfurth, Zoran Andelkovich, et al., GSI)

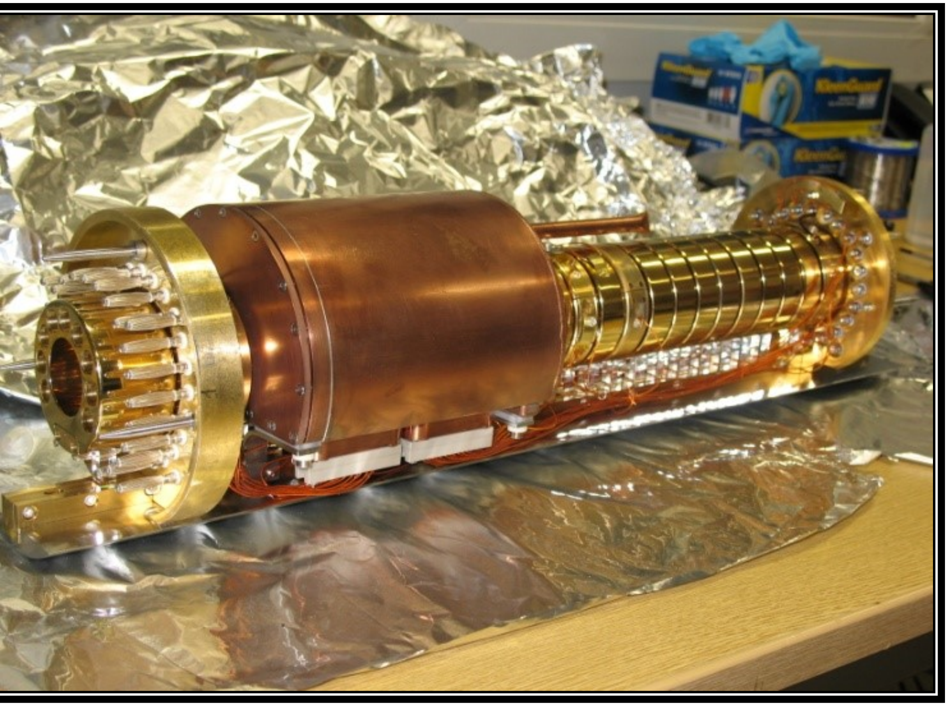
Laser Spectroscopy of $^{209}Bi^{80+,82+}$ at HITRAP
(G. Birkl, W. Nörtershäuser, TU Darmstadt)

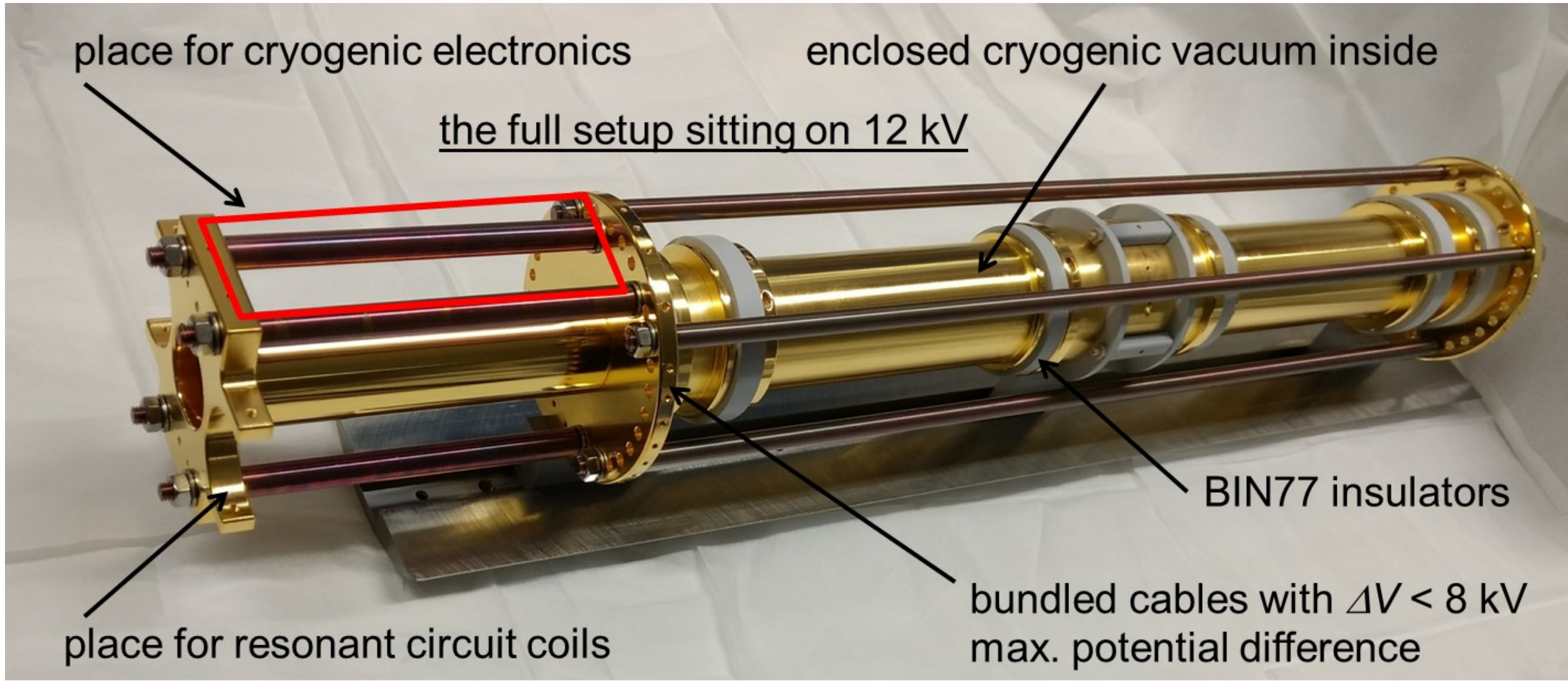
HITRAP

First target system: hydrogen-like bismuth $^{209}Bi^{82+}$

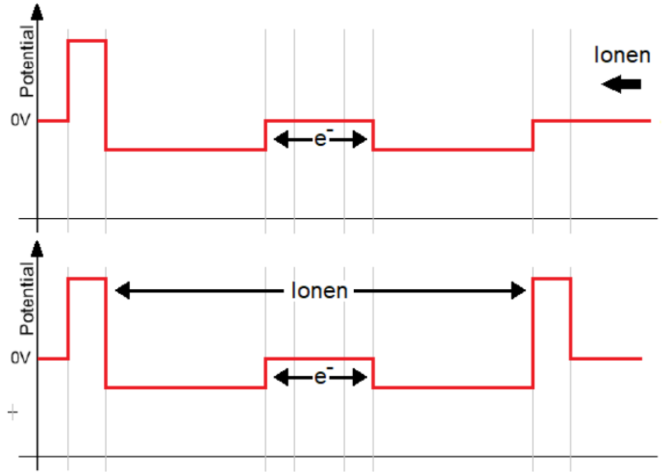


HITRAP - Cooler Trap

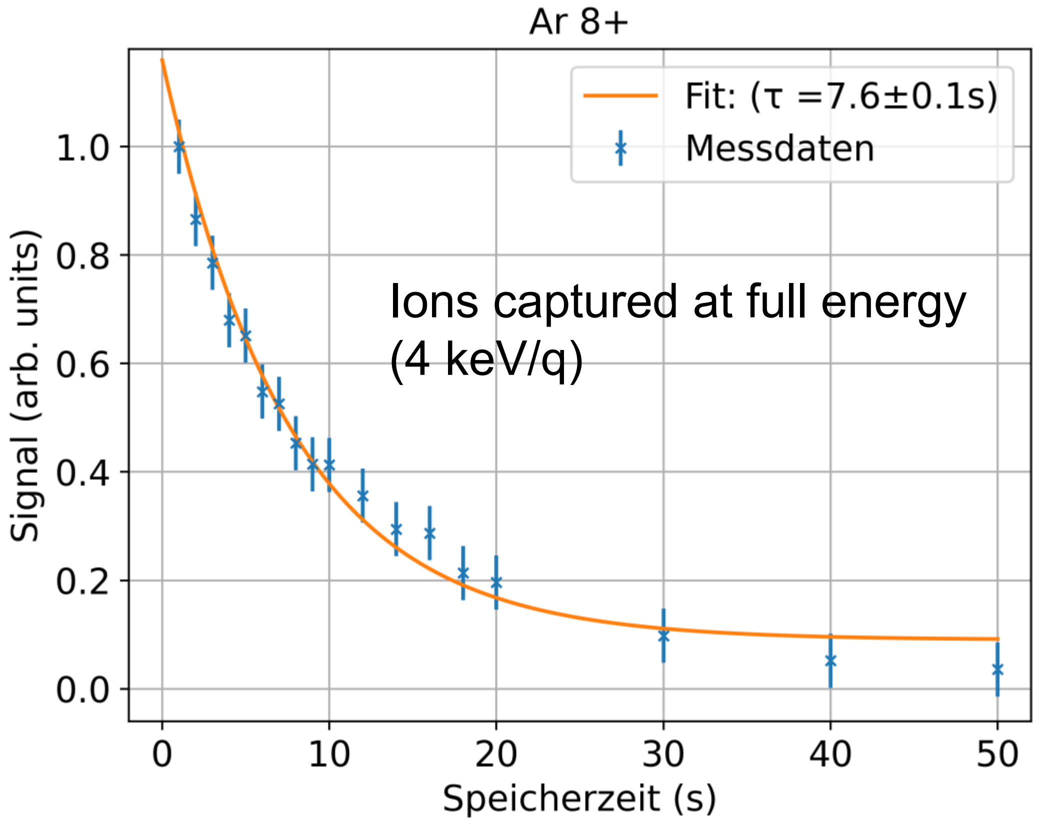


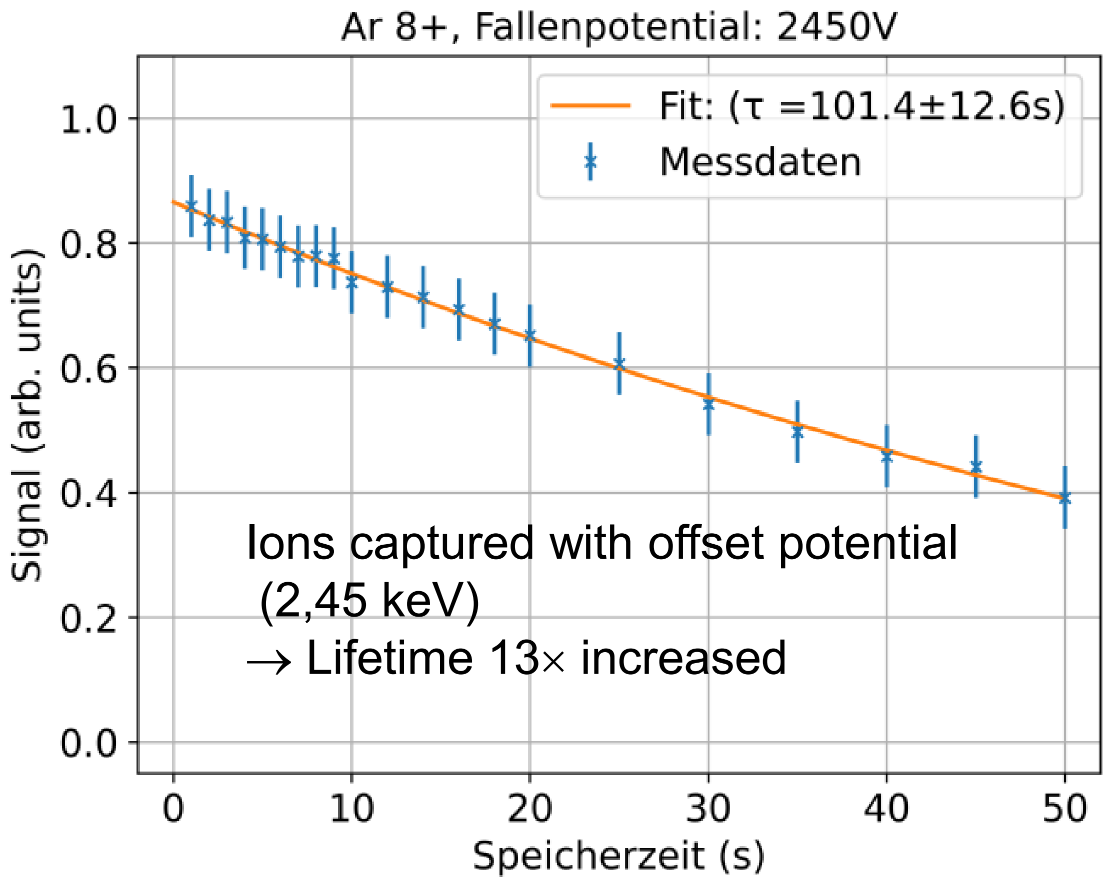


	original trap	new trap
No. of electrodes	21	7
No. of connection	52	12
Connection system	wires in ceramic tubes	bundled cables
Potential differences	up to 18 kV	up to 8 kV
Insulator material	Sapphire	BIN77



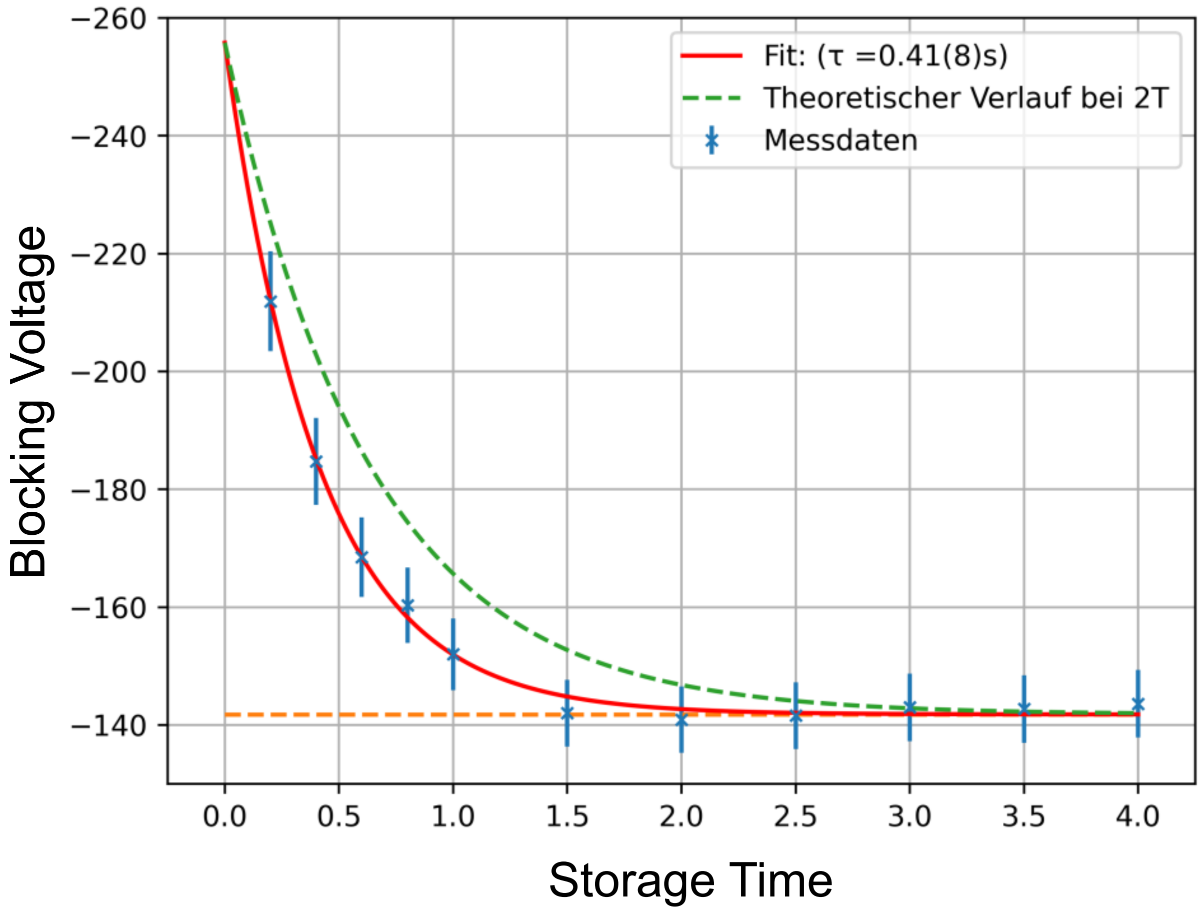
Recently Achieved





Storage Time of Ar^{8+} ions of >100 s

Synchrotron Radiation Cooling of Electrons



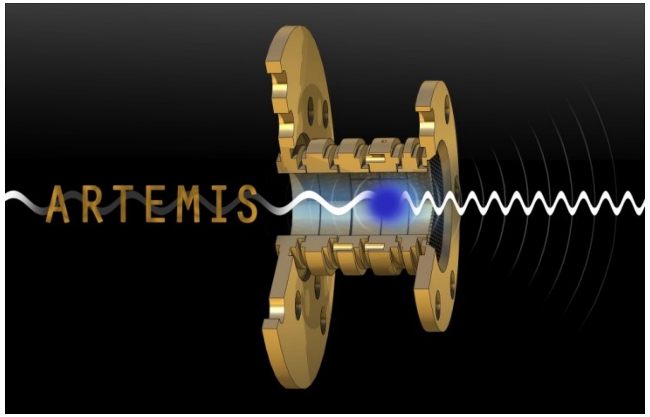
Summary of recent achievements:

- New trap in operation
- Electrons stored and self-cooling demonstrated
- Ions stored for sufficiently long times

- Simultaneous storage of electrons and ions achieved
- Cooling not yet observed

Double-resonance spectroscopy of highly charged ions

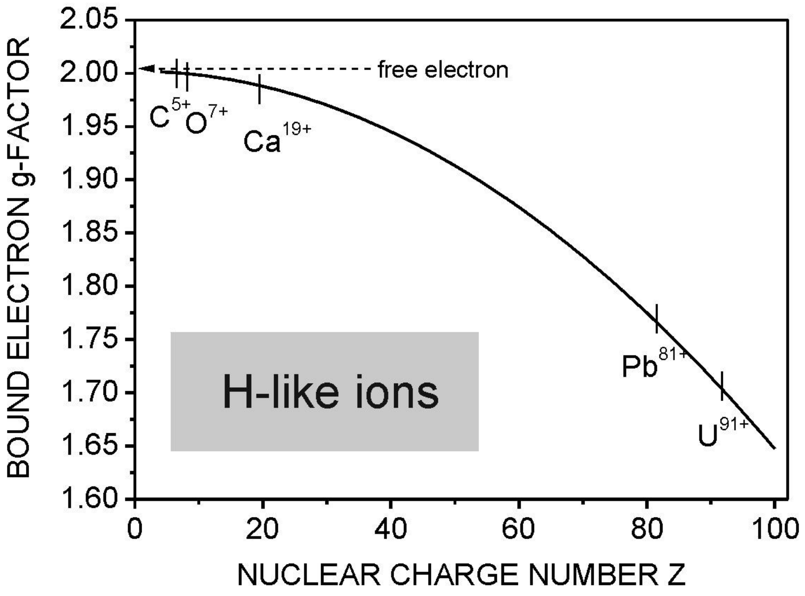
Goal: magnetic moments (g-factors) of bound electron

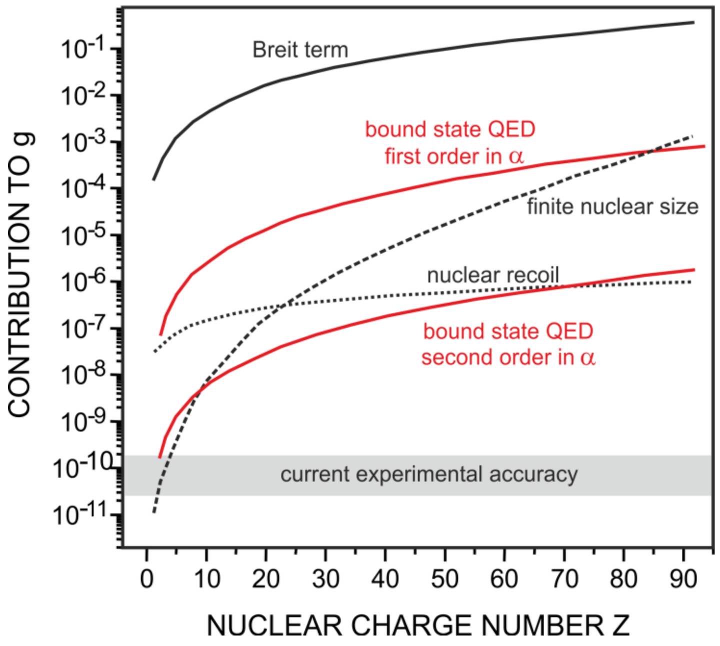


RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG

GSI

TECHNISCHE UNIVERSITÄT DARMSTADT



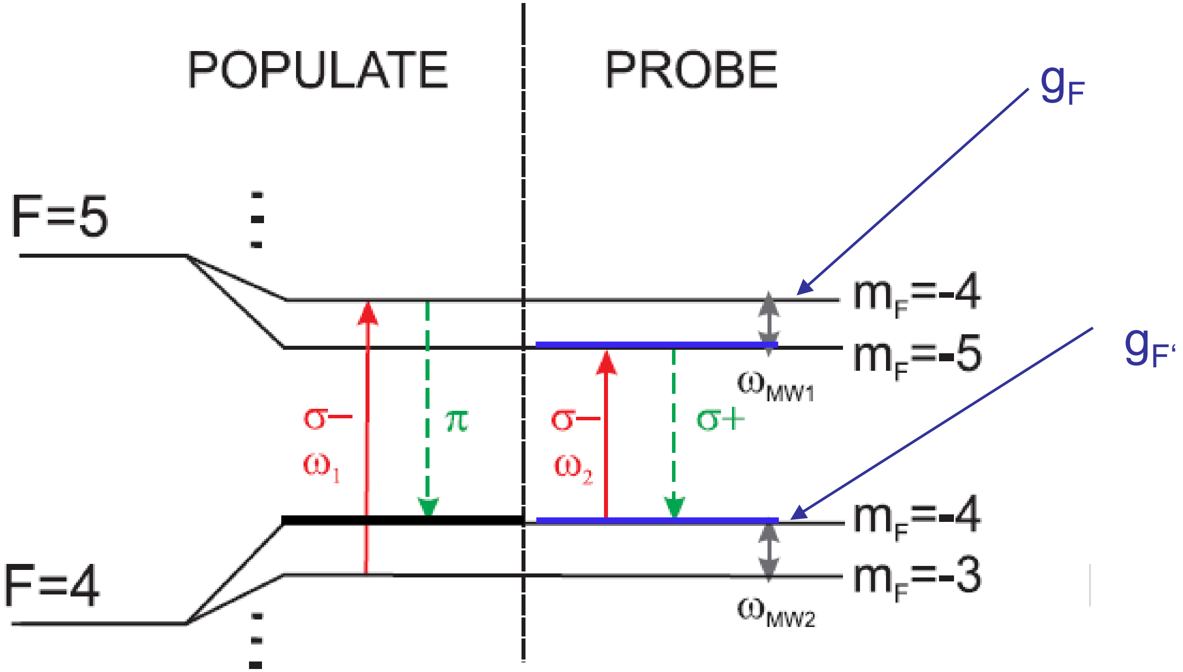


Apart from relativity, significant contributions to *g* come from QED and the nucleus

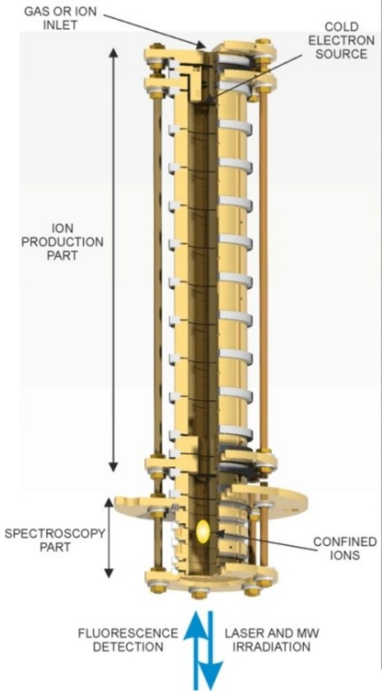
Test of QED in strong fields, higher-order Zeeman effects,
Nuclear information in absence of shielding,...

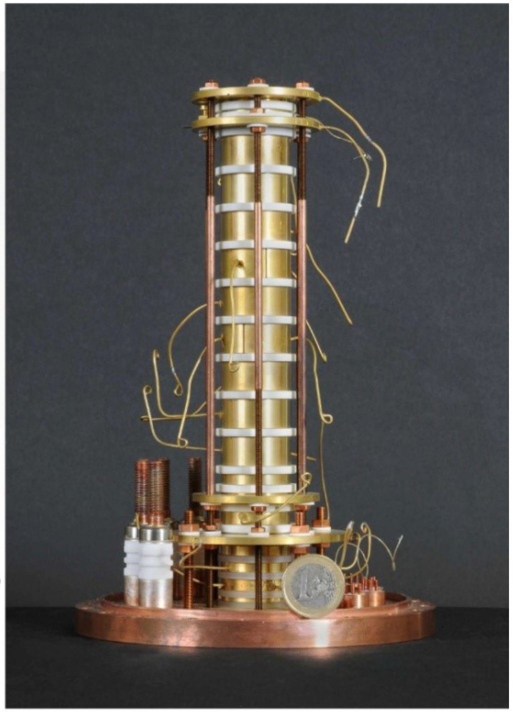
Novel technique for high-precision spectroscopy:

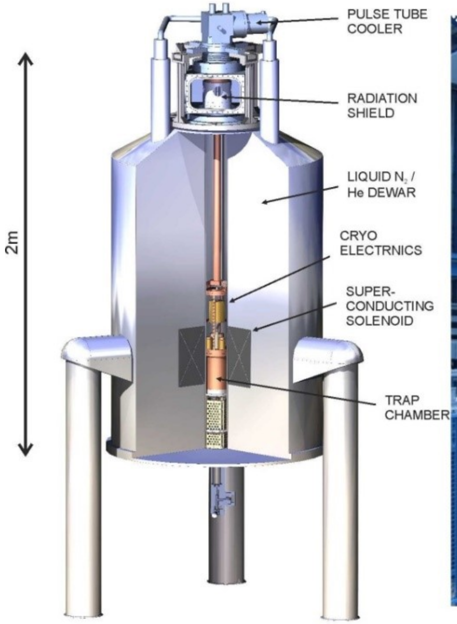
Laser-microwave double-resonance spectroscopy for bound-electron g-factor measurements in hydrogen-like argon Ar^{13+} and bismuth $^{209}Bi^{82+}$

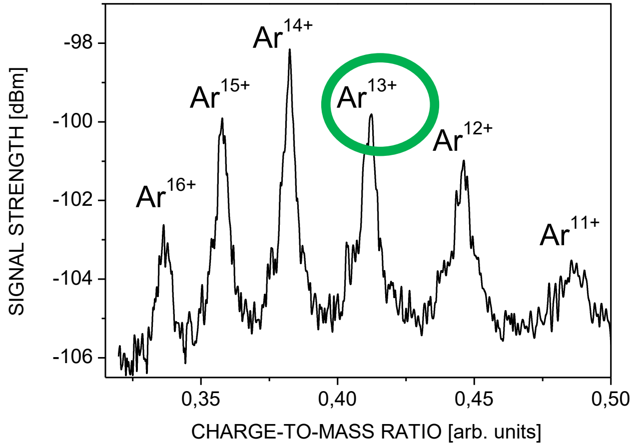


ARTEMIS @ HITRAP









Current Work: Ar^{13+}

in-trap ion production

storage time: weeks

pressure ~ 10^{-16} mbar

Thanks

to
the **LaserSpHERe Group**
especially
Max Horst
Phillip Imgram
Jörg Krämer
Konstantin Mohr
Simon Rausch

<u>HFHF</u>
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Gerhard Birkl
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Stefan Schippers,
Thomas Walther

<u>GSI</u>
Zoran Andelkovic
Carsten Brandau (JLUG)
Frank Herfurth
Yuri Litvinov
Rodolfo Sanchez
Markus Steck
Thomas Stöhlker
Danyal Winters

<u>Theory on Optical Pumping</u>
Andrey Surzhykov

<u>WWU Münster</u>
Axel Buß
Volker Hannen,
Christian Weinheimer

Bundesministerium für Bildung und Forschung

HIC for FAIR Helmholtz International Center

HESSEN Hessisches Ministerium für Wissenschaft und Kunst

DFG Deutsche Forschungsgemeinschaft

SFB 1245

HFHF Helmholtz Forschungsakademie Hessen für FAIR

+ all other collaborators on the various projects