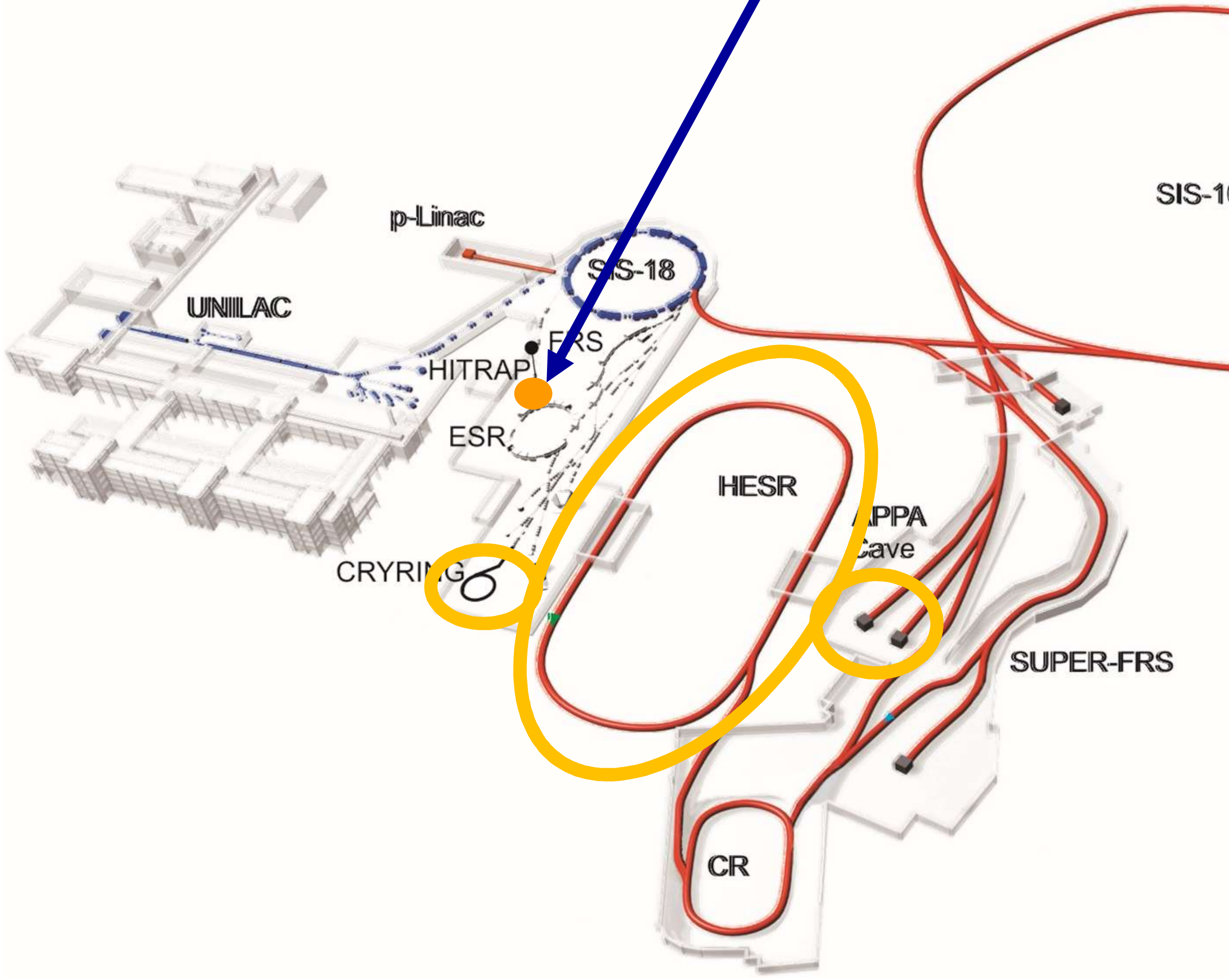
HITRAP Experiments

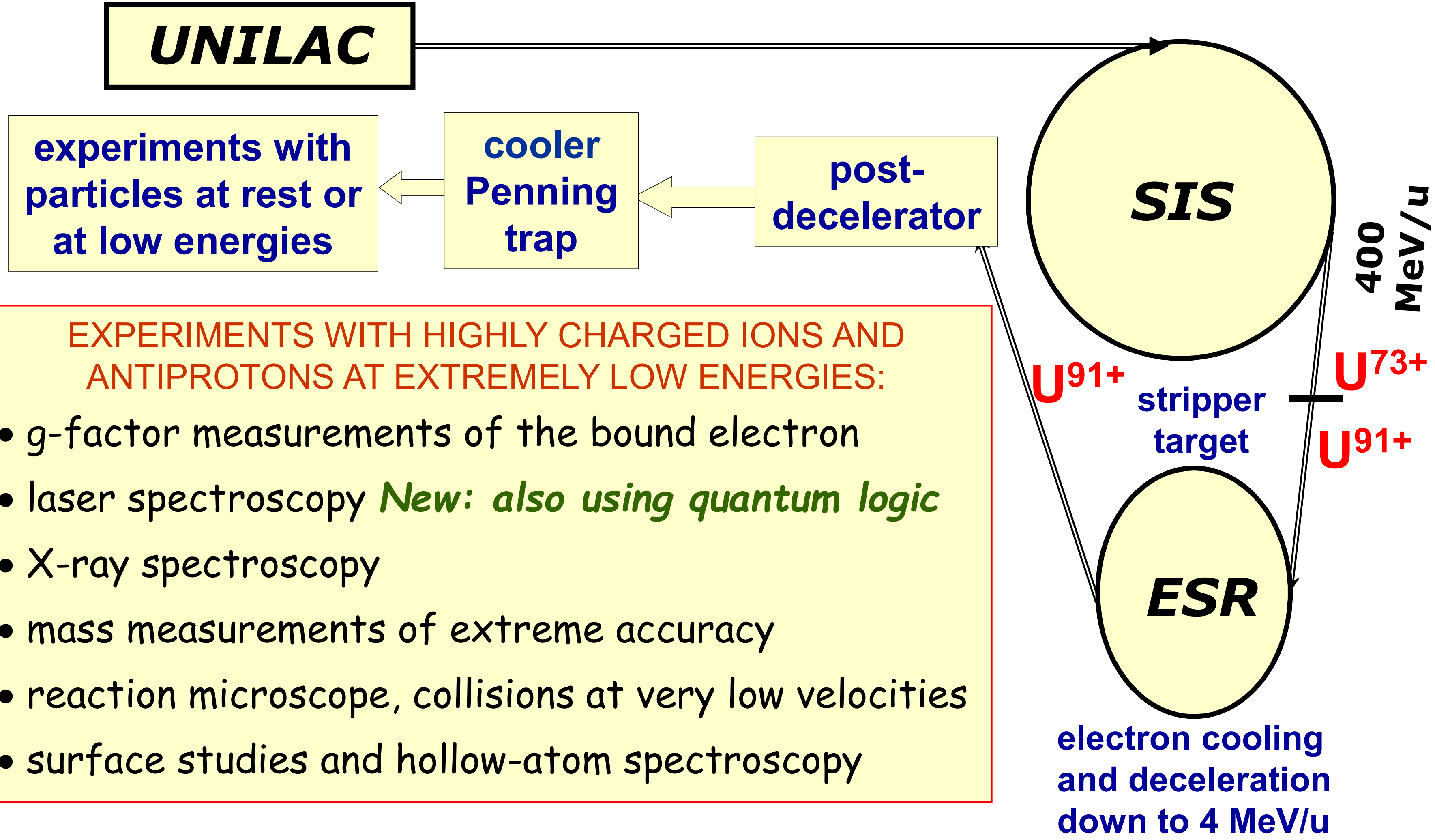


FACILITIES
SIS100
HESR
APPA-Cave
ESR
CRYRING
HITRAP

Wolfgang Quint
GSI Darmstadt and Univ. Heidelberg

HITRAP at the Experimental Storage Ring ESR

FAIR Phase 0 Research Program

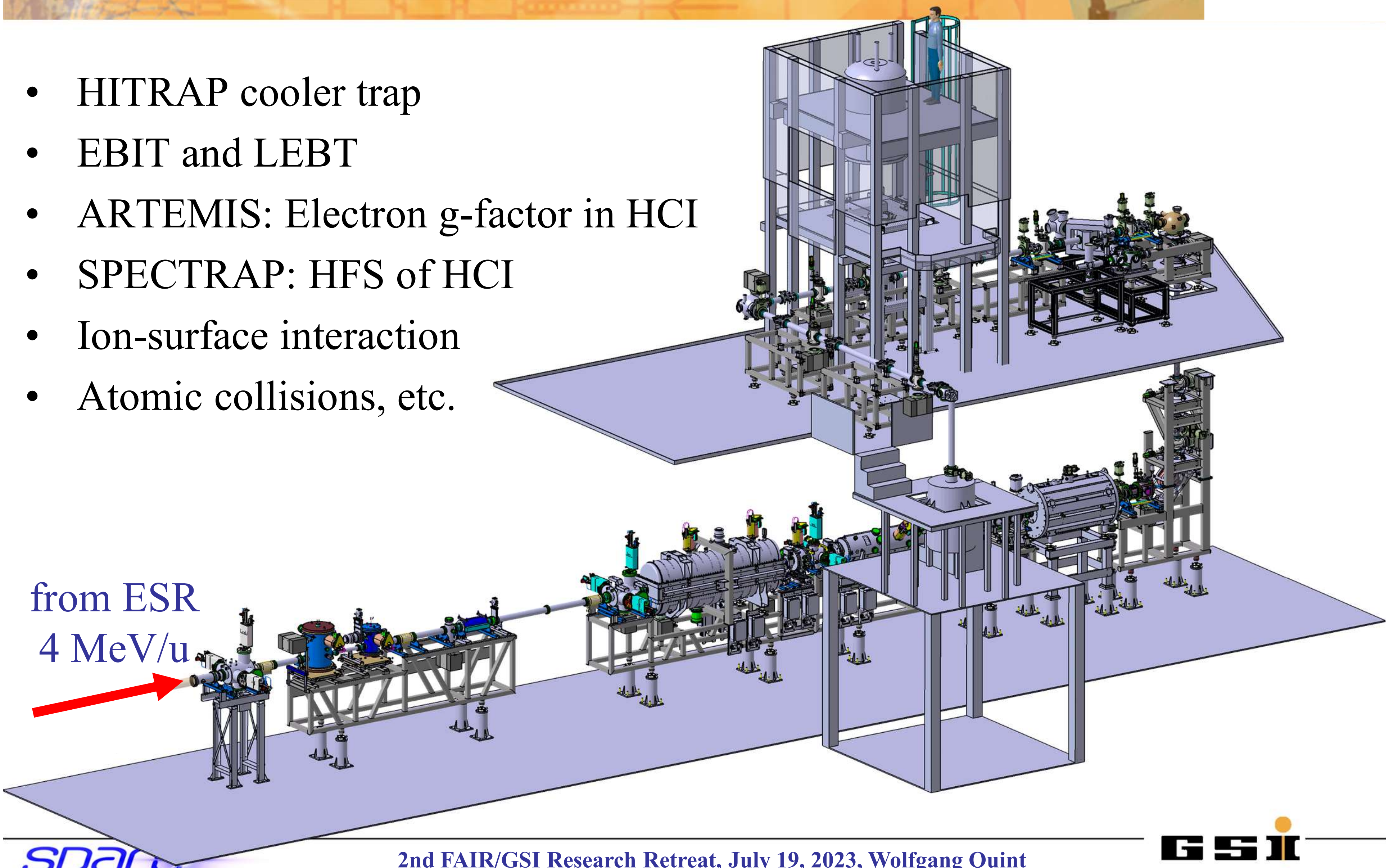


EXPERIMENTS WITH HIGHLY CHARGED IONS AND ANTIPROTONS AT EXTREMELY LOW ENERGIES:

- g-factor measurements of the bound electron
- laser spectroscopy *New: also using quantum logic*
- X-ray spectroscopy
- mass measurements of extreme accuracy
- reaction microscope, collisions at very low velocities
- surface studies and hollow-atom spectroscopy

HITRAP facility and experimental area

- HITRAP cooler trap
- EBIT and LEBT
- ARTEMIS: Electron g-factor in HCI
- SPECTRAP: HFS of HCI
- Ion-surface interaction
- Atomic collisions, etc.



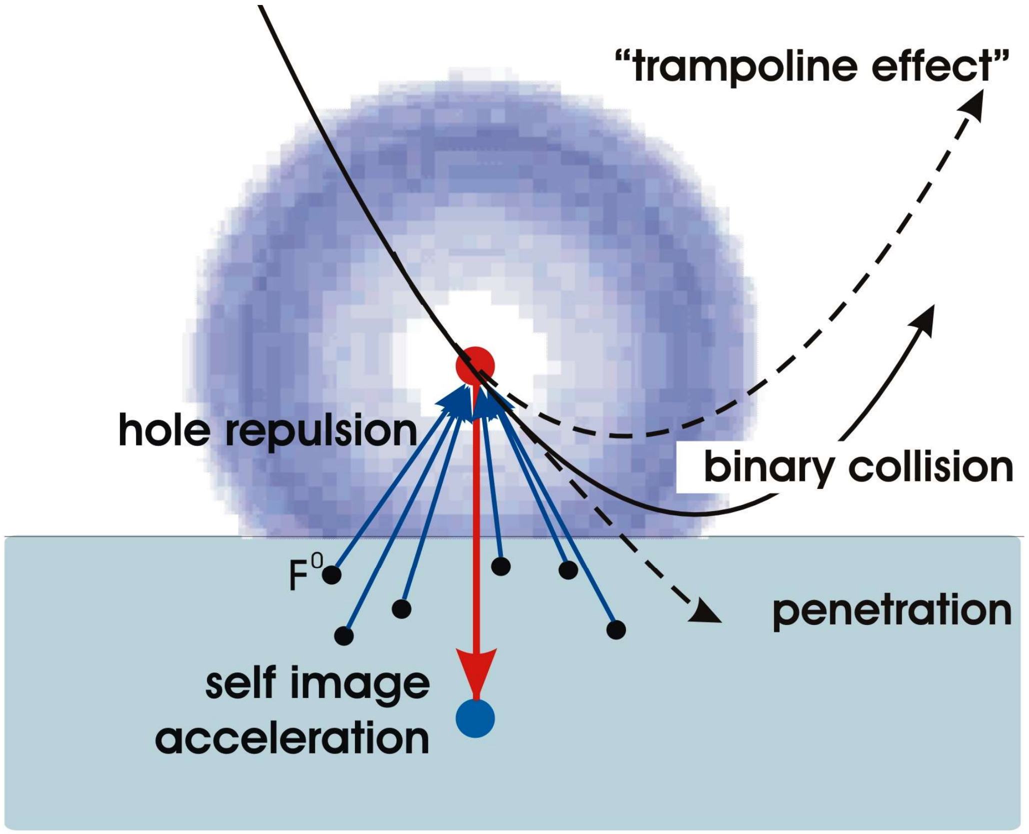
HITRAP: Experimental platform

- Sufficient space for several experimental setups

HCI-surface interaction with slow highly charged ions up to U^{92+}

Questions to be addressed:

- hollow atom spectroscopy
- high-spin states via electron capture from magnetized surfaces
- electron dynamics at surfaces and thin films
- trampoline effect existent above a critical charge state?
- surface lithography by means of HCI impact?

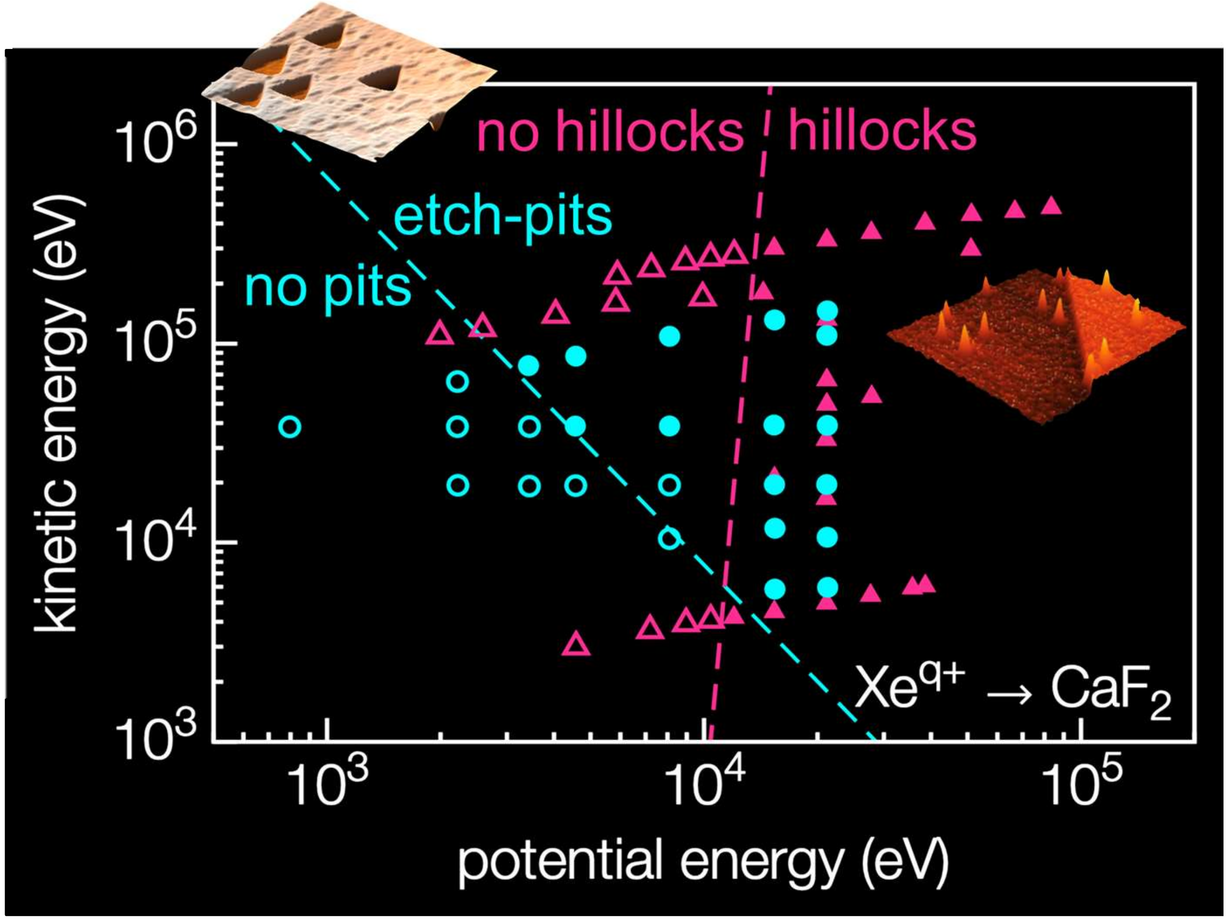


Beamtime approved by GPAC in 2023 with ranking A
A. Niggas, R. Wilhelm, F. Aumayr, TU Vienna

Nanostructuring of monolayer graphene using slow HCI
A. Niggas et al., G-22-00057

Observation of etch-pits and hillocks with Xe^{q+} ions on CaF_2

- **Nanostructure formation**
- **Etch-pits and hillocks**
- **Thresholds for kinetic and potential energies**
- **Terra incognita for larger potential energies**
- **HITRAP:** **E_{pot} > 1 MeV for U^{92+}**

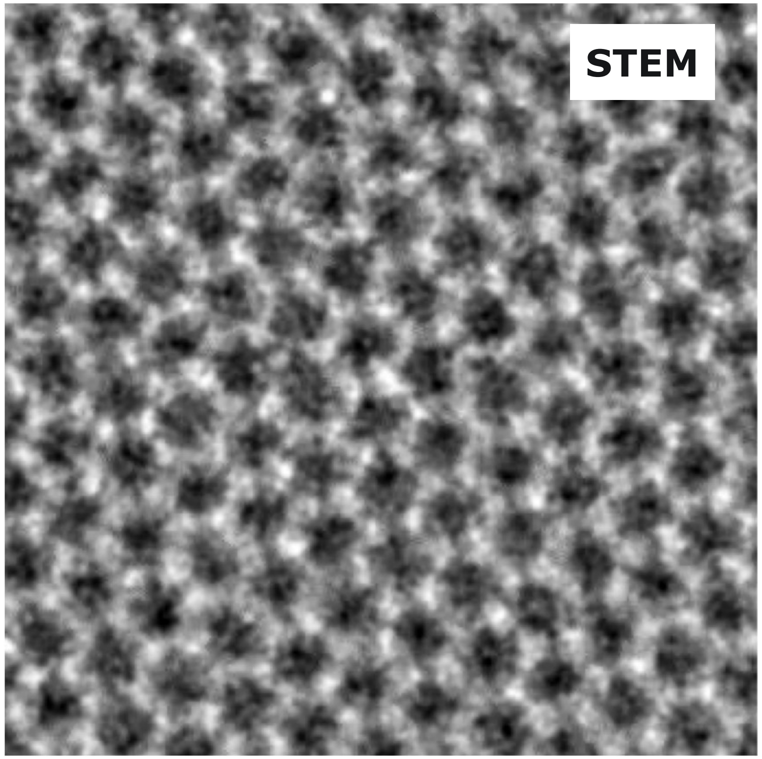


A.S. El-Said et al., Phys. Rev. Lett. 109, 117602 (2012)

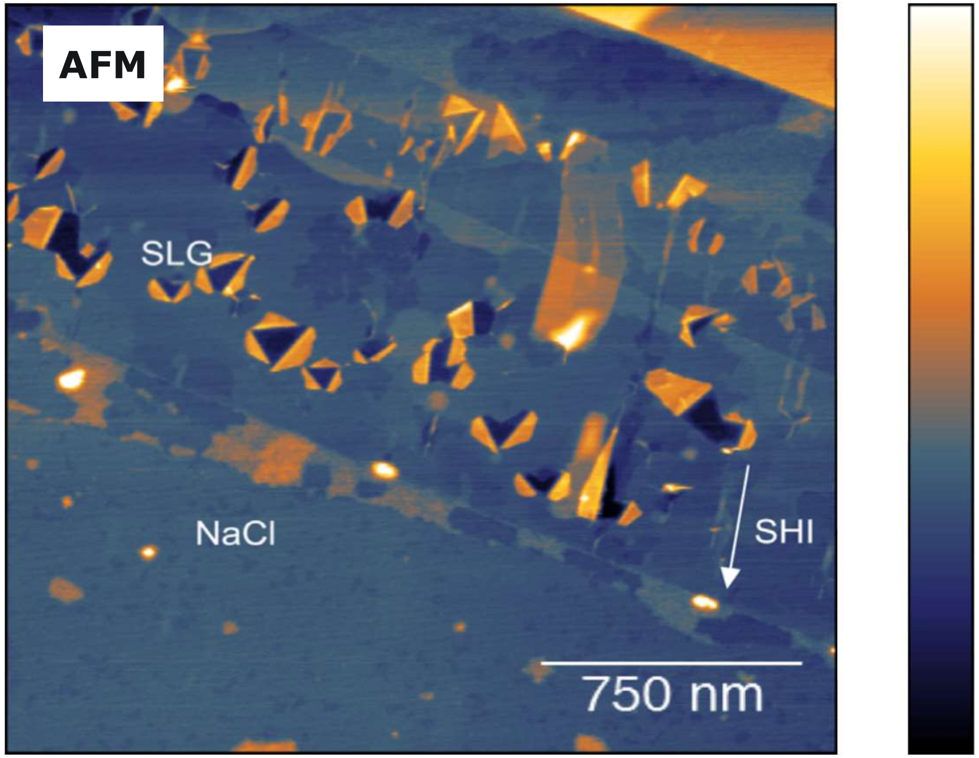
Nanostructuring of monolayer graphene using slow HCI
A. Niggas et al., G-22-00057

Comparison: Slow and swift HCI on graphene

Slow HCI on single-layer graphene (SLG): no induced nanostructures



Swift HCI (SHI) on single-layer graphene (SLG): induced foldings



- **1 week (21 shifts) of HITRAP beam time:**
- **6 keV/u U^{92+} → graphene, CaF_2 (4x10^8 ions/cm^2 each)**
- **Samples will then be transferred in protected atmosphere to Vienna for STEM/AFM analysis**

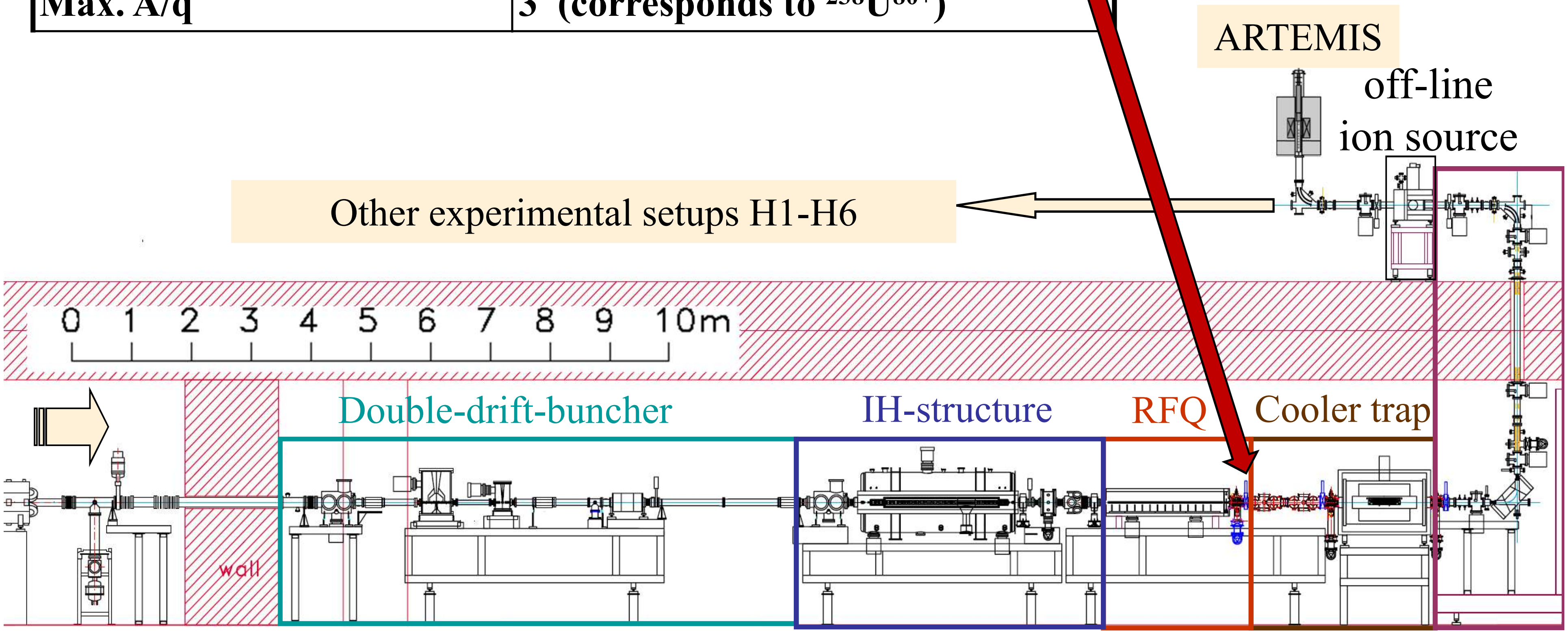
E. Gruber et al., Nat. Commun 7, 13948 (2016), O. Ochedowski et al., NIMB 314, 18 (2013)

Nanostructuring of monolayer graphene using slow HCI
A. Niggas et al., G-22-00057

FAIR Phase 0 Research Program

HITRAP facility at ESR

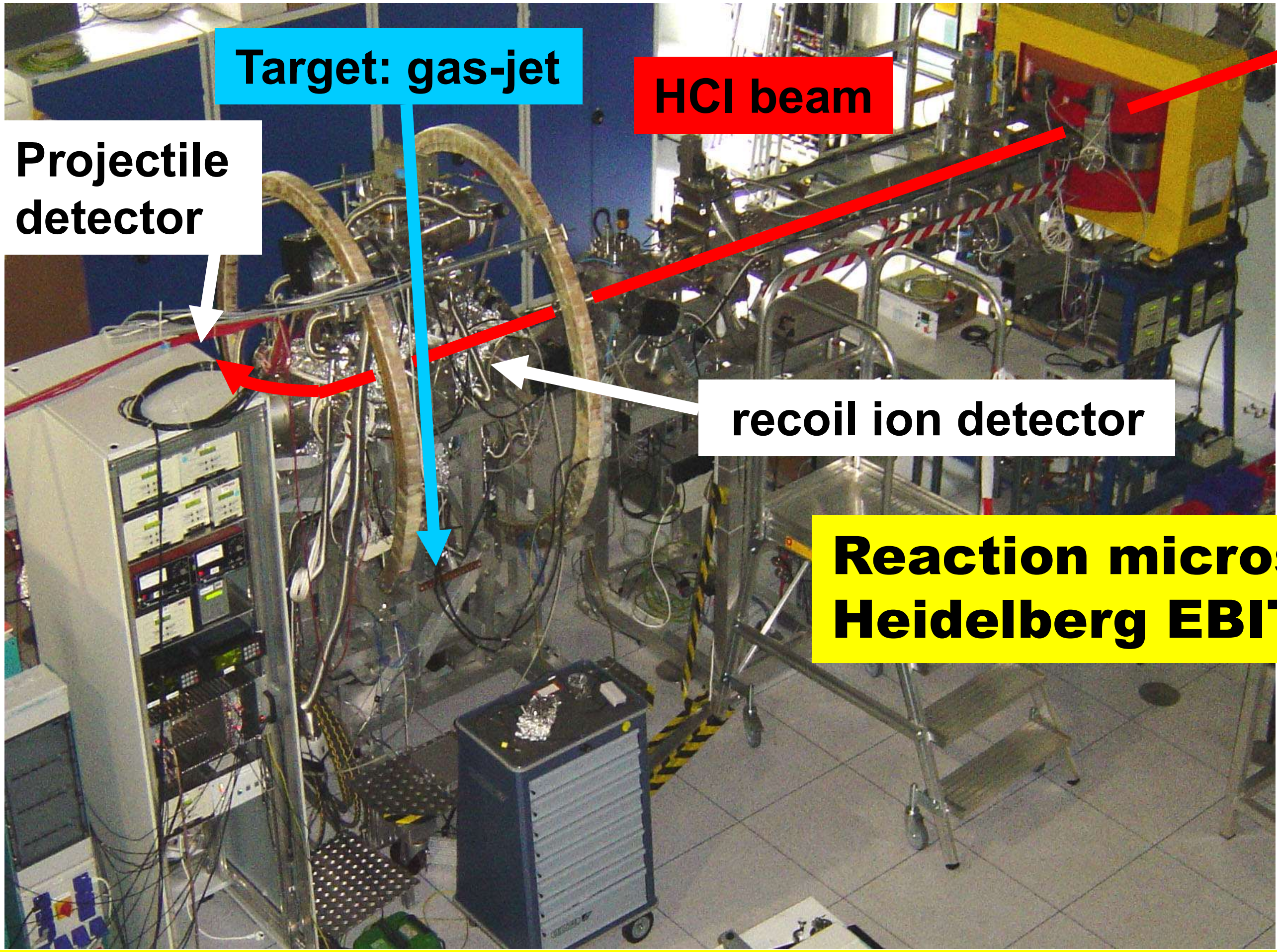
Linac operation frequency	108.408 MHz
IH-deceleration	4 MeV/u → 0.5 MeV/u
RFQ-deceleration	0.5 MeV/u → 6 keV/u
Max. A/q	3 (corresponds to $^{238}U^{80+}$)



HCI from ESR 4 MeV/u → 0.5 MeV/u → 6 keV/u

Precision spectroscopy of excited states of slow HCI by electron capture experiments in a reaction microscope

MAX-PLANCK-GESELLSCHAFT



EBIT

Extraction of HCI (e.g. Ne^{10+}, Ar^{18+}, Kr^{34+}, U^{64+}, Xe^{54+})

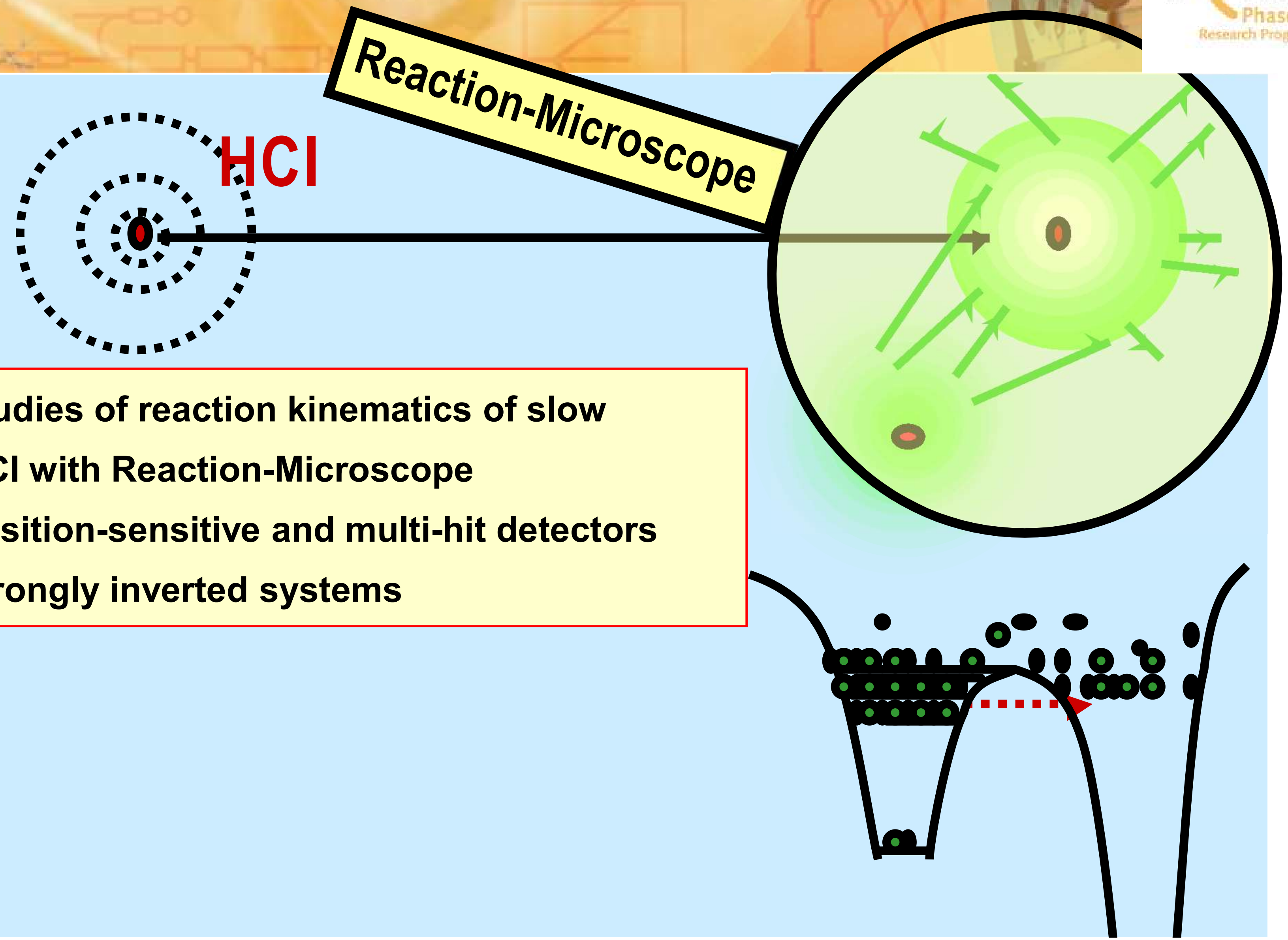
Reaction microscope at the Heidelberg EBIT

R. Moshammer,
MPIK Heidelberg

M. Schöffler, R. Dörner,
Goethe-Universität,
Frankfurt

Coincidence experiments of electron capture with the reaction microscope

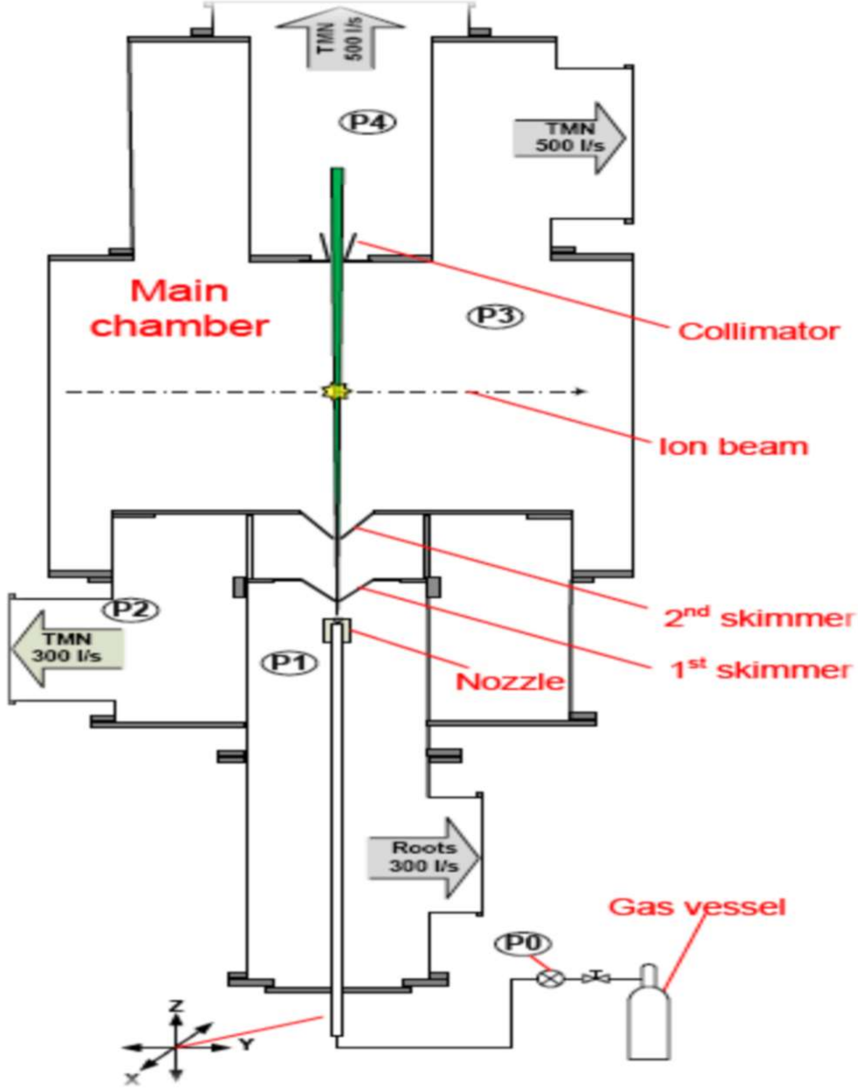
Collision Studies with Slow Highly Charged Ions up to U^{92+}

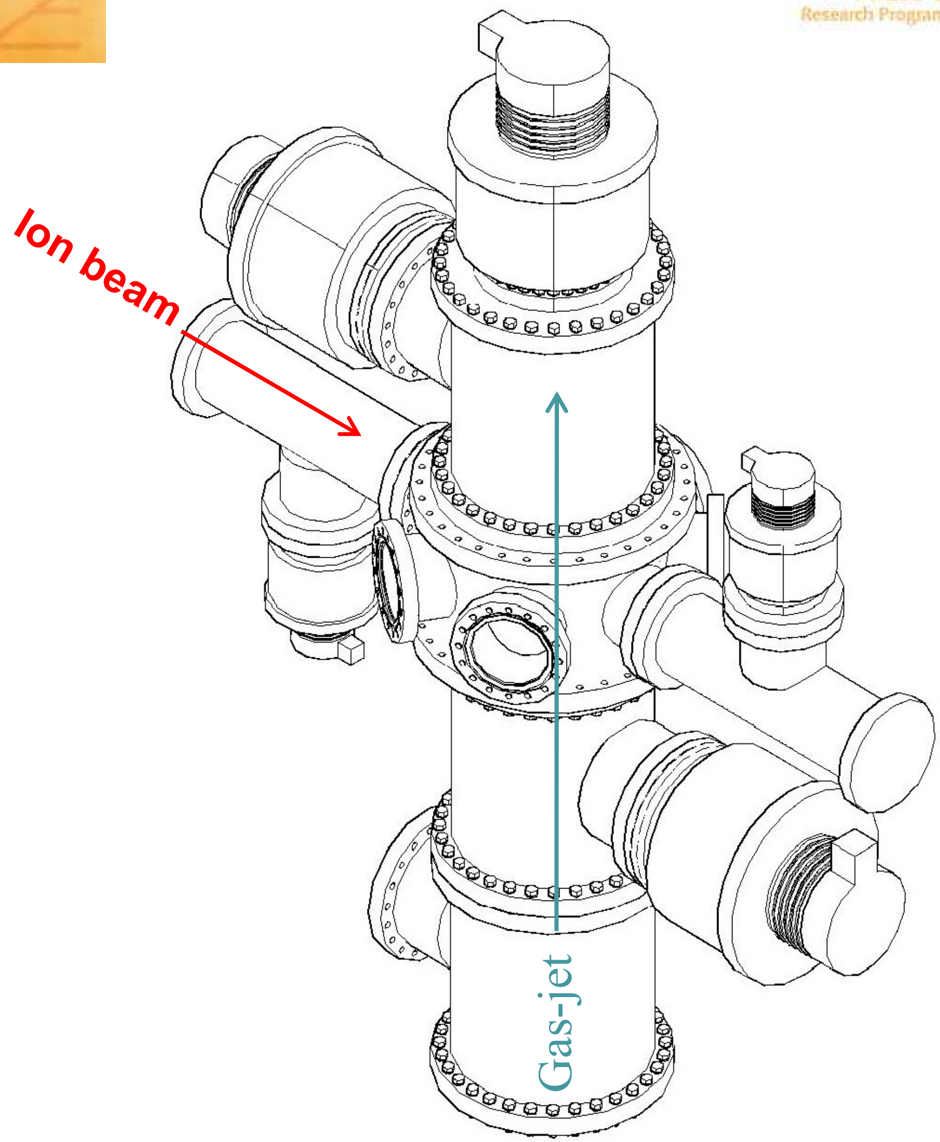


- Studies of reaction kinematics of slow HCI with Reaction-Microscope
- Position-sensitive and multi-hit detectors
- Strongly inverted systems

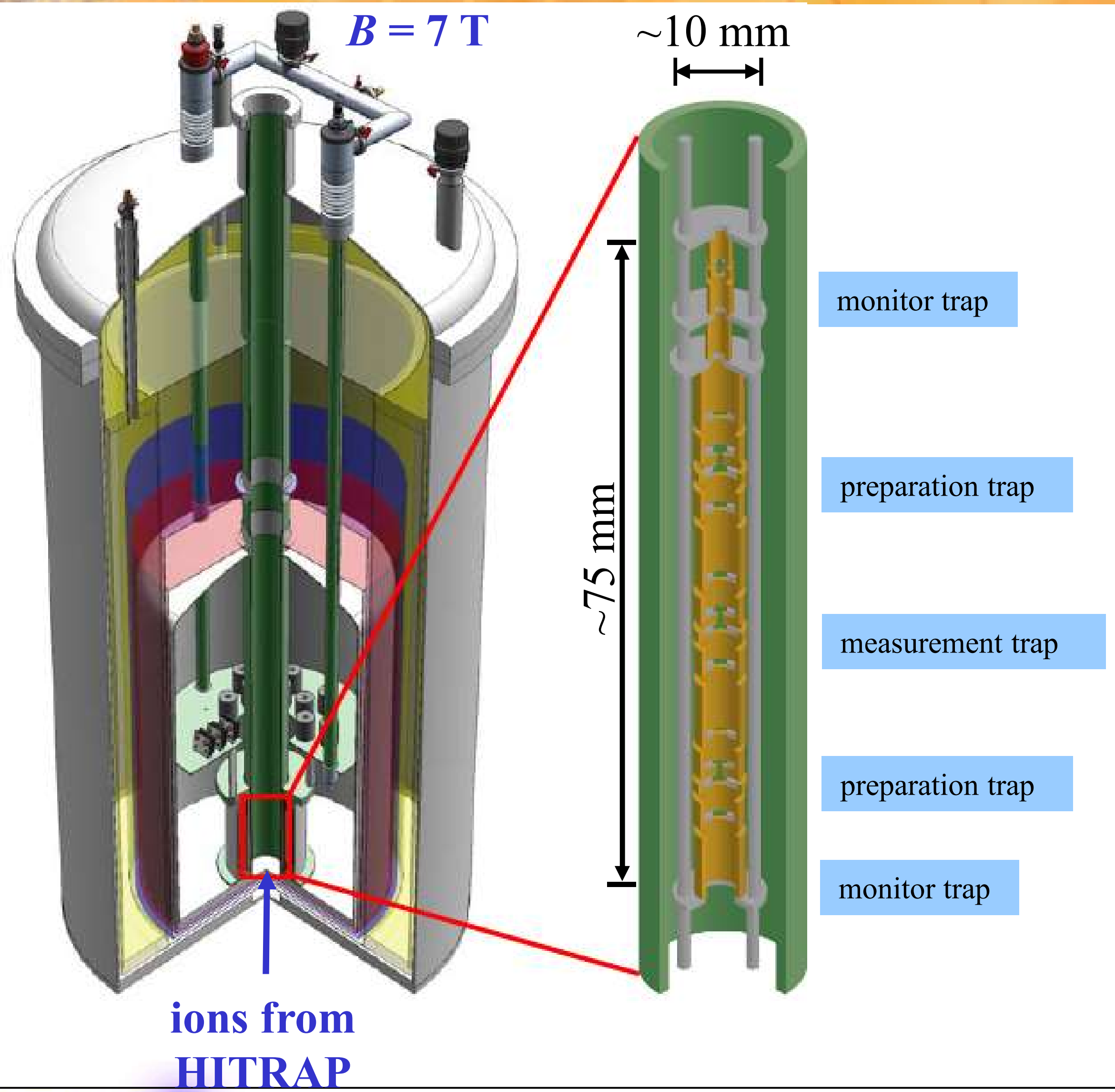
HITRAP gas-jet target

K. Stiebing, Univ. Frankfurt
A. Warczak, Univ. Krakow
V. Varentsov, FAIR





Precision ion trap experiments: High-accuracy mass measurements



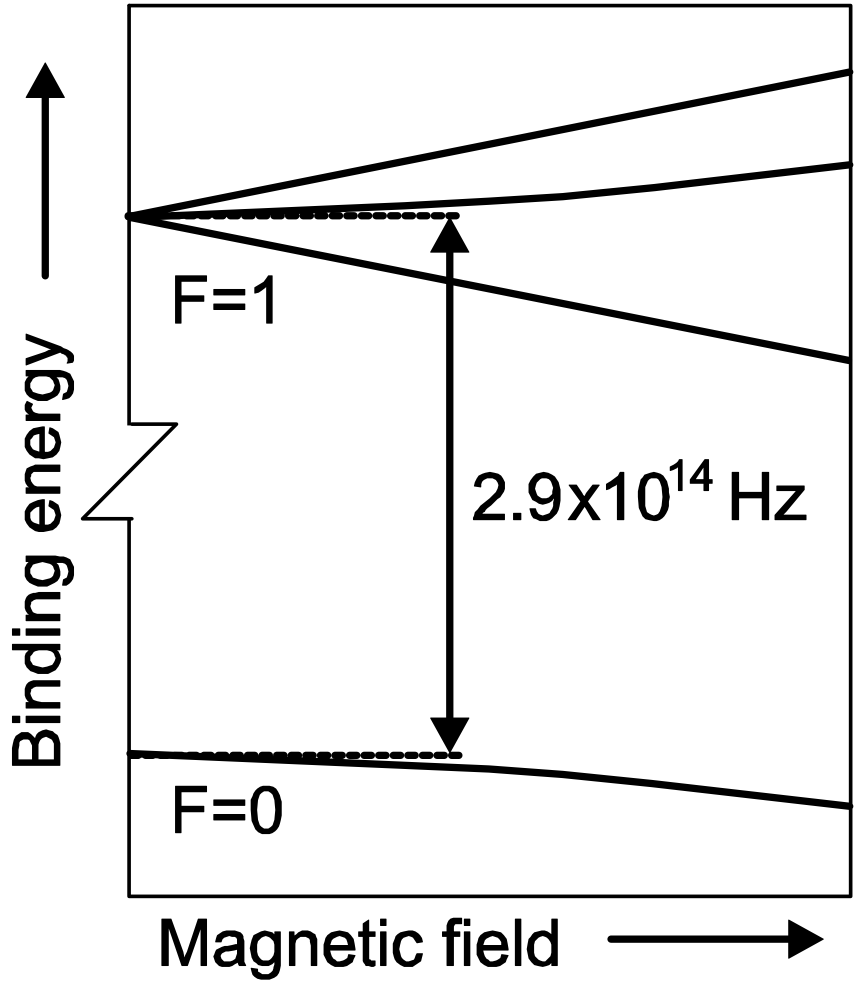
- measurement of cyclotron frequency in different charge states
- determination of atomic and nuclear binding energies

$\delta m/m < 1 \cdot 10^{-11} \rightarrow$
$\delta mc^2 \approx 2$ eV $\rightarrow$
'weighing' of Lamb shift

SPARC PhD Prize 2019
F. Heiße
Proton Mass

Collaborator:
MPIK HD, Klaus Blaum

SPECTRAP: Laser spectroscopy of hyperfine splitting in highly charged ions



- Example: H-like lead $^{207}Pb^{81+}$
- HFS wavelengths move into visible for Z>70
- very small Doppler width at T = 4 K
- relative wavelength accuracy ≤ 10^{-7}

Physics goals:

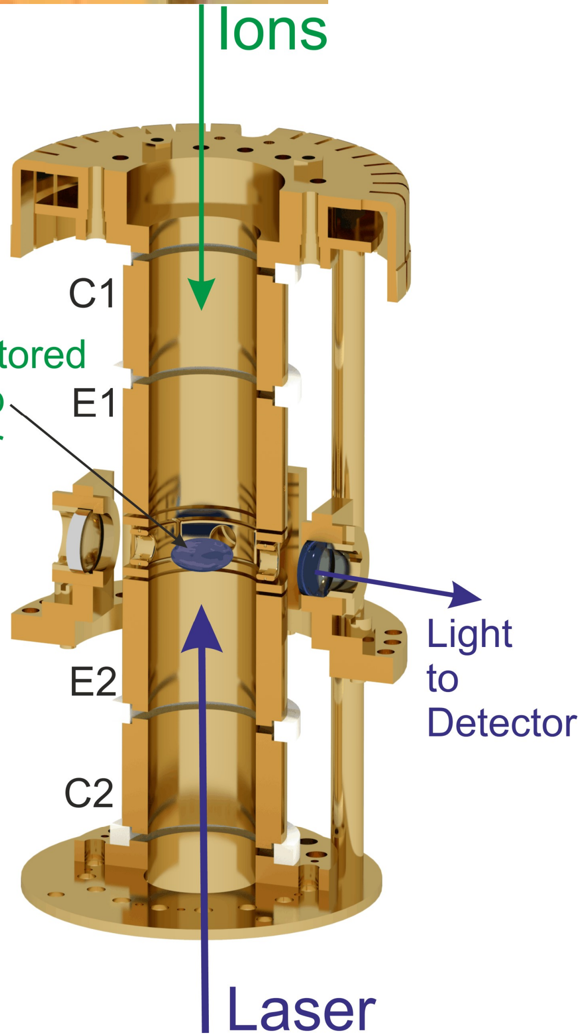
- test of QED in strong fields
- nuclear structure studies

G-22-00130: approved beamtime with ranking A^- for SPECTRAP and ARTEMIS

SPECTRAP setup and Penning trap

Top flange
('Ions in')

cryocooler



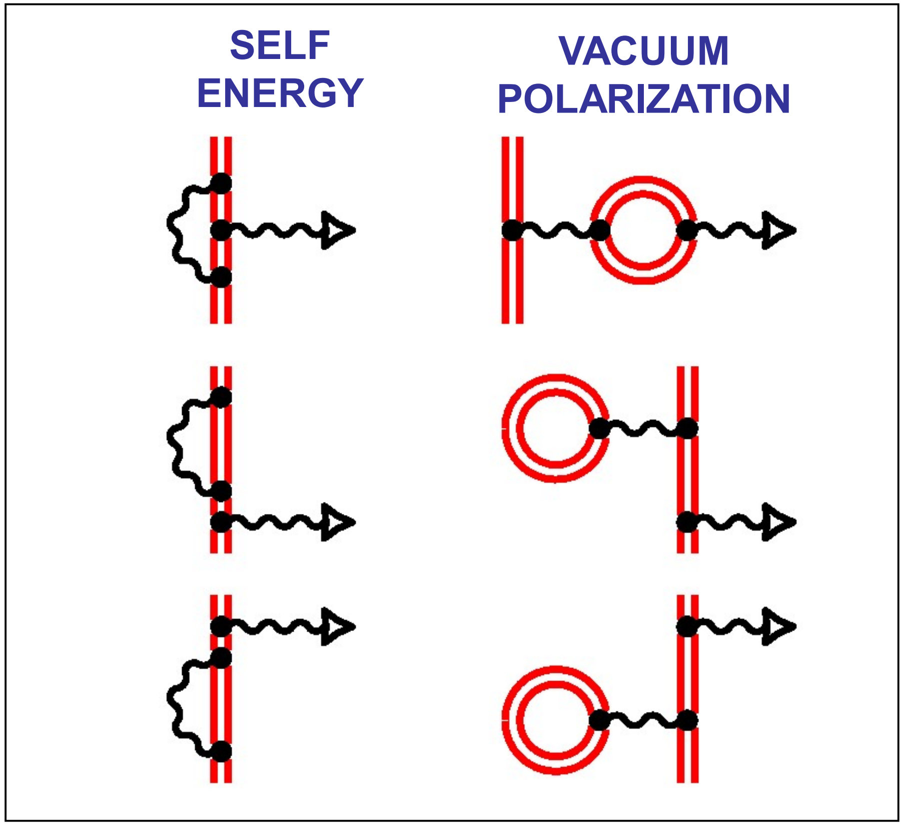
W. Nörtershäuser, D. Zisis, Z. Andjelkovic, A. Solders, R. Thompson, G. Birkl, M. Vogel, V. Hannen, C. Weinheimer

ARTEMIS: Bound-electron g-factor Feynman graphs 1st order in α/π

$$g_{bound}/g_{free} \approx 1 - (Z\alpha)^2/3 + \alpha(Z\alpha)^2/4\pi + \ldots.$$

Dirac theory

bound-state QED



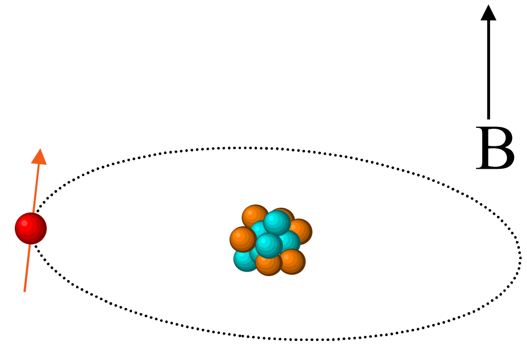
Ref.:
T. Beier, Physics Reports 339, 79 (2000)

ARTEMIS: g-Factor of the bound electron in a hydrogen-like ion (e.g. $^{208}Pb^{81+}$, $^{209}Bi^{82+}$, $^{238}U^{91+}$)

FAIR Phase 0 Research Program

Larmor precession frequency of the bound electron:

$$\omega_L^{\,e} = \frac{g_J}{2}\frac{e}{m_e}B$$



Ion cyclotron frequency:

$$\omega_c^{\,ion} = \frac{Q}{M_{ion}}B$$

$$g_J = 2\cdot\frac{\omega_L^{\,e}}{\omega_c^{\,ion}}\cdot\frac{m_e}{M_{ion}}\cdot\frac{Q^{ion}}{e}$$

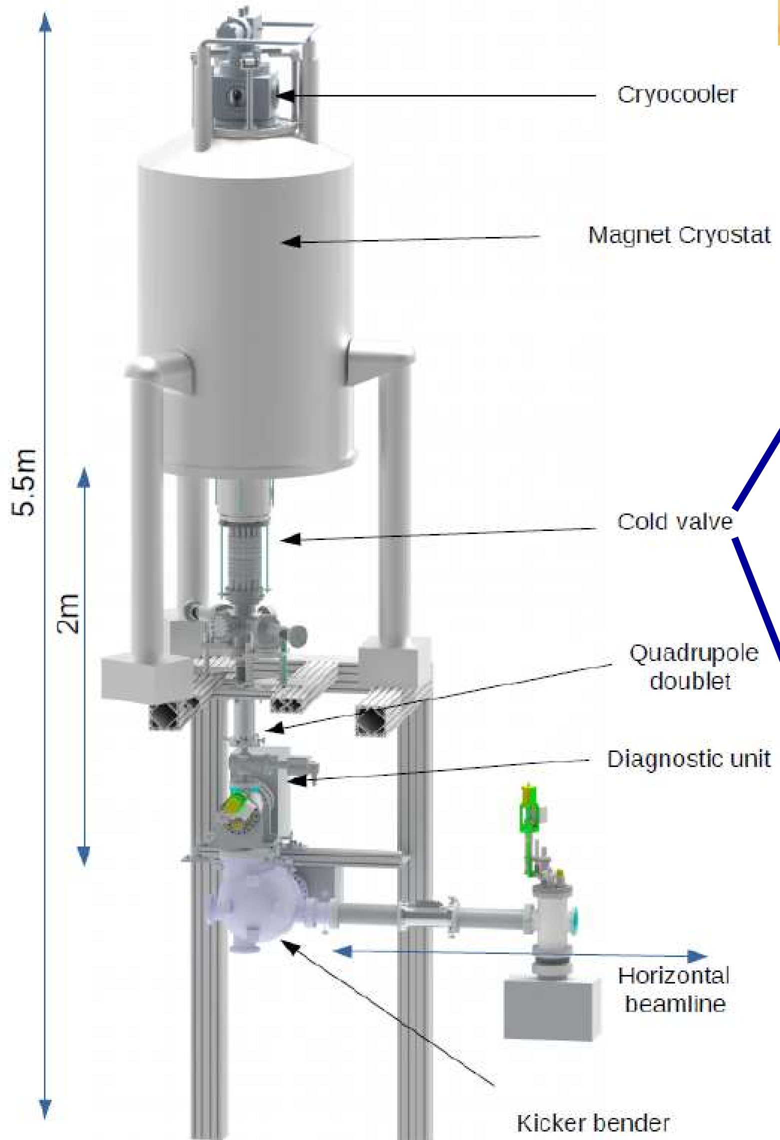
→ 'experimental g-factor'
→ comparison with theory

our measurement

external input parameter

ARTEMIS at HITRAP facility

ARTEMIS at HITRAP facility: connected to LEBT by cryovalve



Test setup with cryovalve

A. Krishnan, B. Reich, G. Birkl, P. Baus, J. Klimes, K. Kanika, K. Anjum, M. Vogel

Summary and discussion

- HITRAP is a unique facility for highly charged ions up to uranium U^{92+} at very low energies.
- HITRAP-workshop 2022 in Eisenach with 60 participants
- Strong support by GSI accelerator department and external groups required and appreciated.
- Beamtime scheduled for 2024

⇓

New collaborators are welcome to join!

Acknowledgements

TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

UPPSALA UNIVERSITET

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

WWU MÜNSTER

Helmholtz-Institut Jena
Friedrich-Schiller-Universität Jena

Stockholm University

Bundesministerium für Bildung und Forschung

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

TU WIEN

HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz

Deutsche Forschungsgemeinschaft DFG

Imperial College London

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

Thank you for your attention!