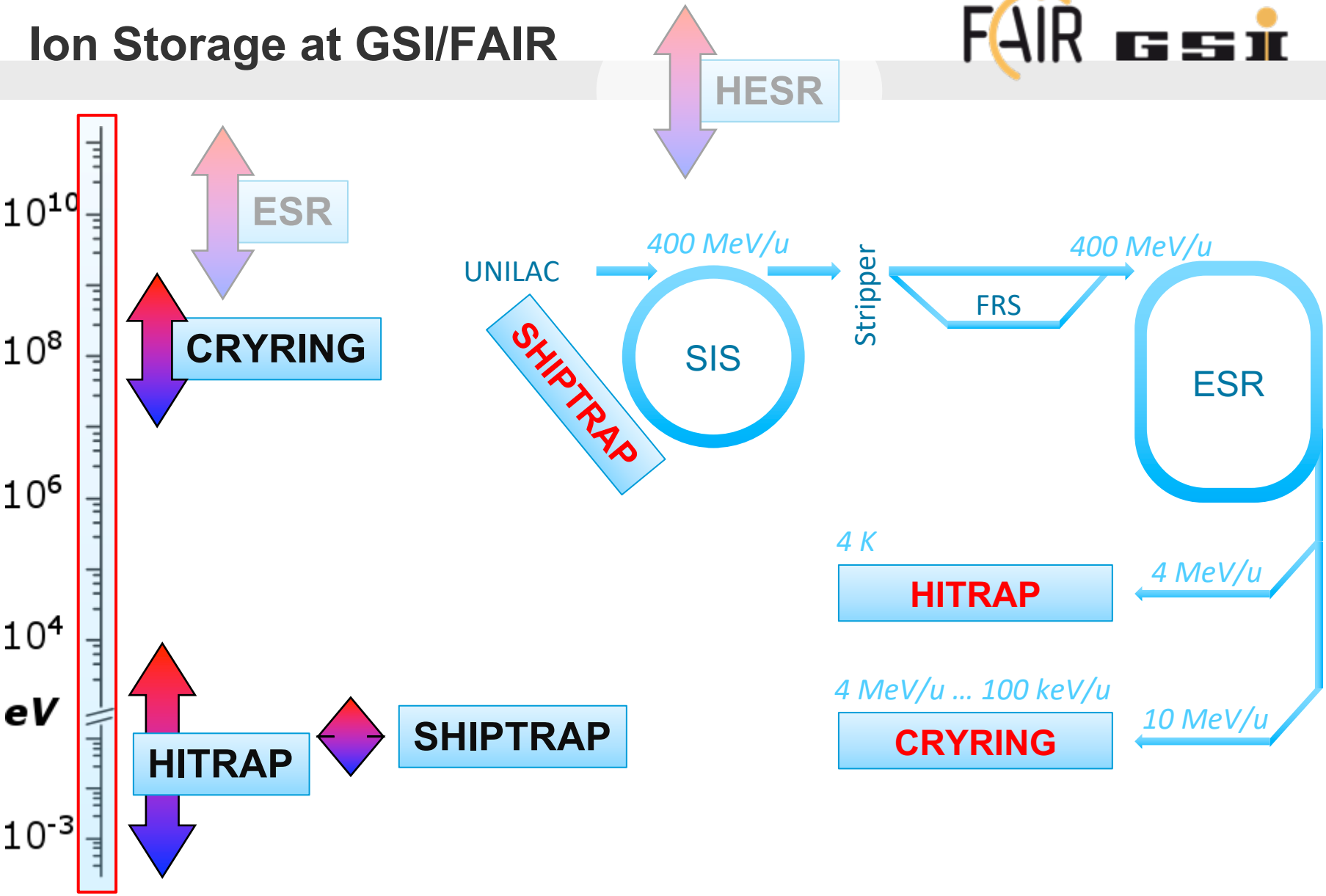
"Storage of low energy heavy ions at FAIR"

Deceleration and Storage of heavy, highly charged ions

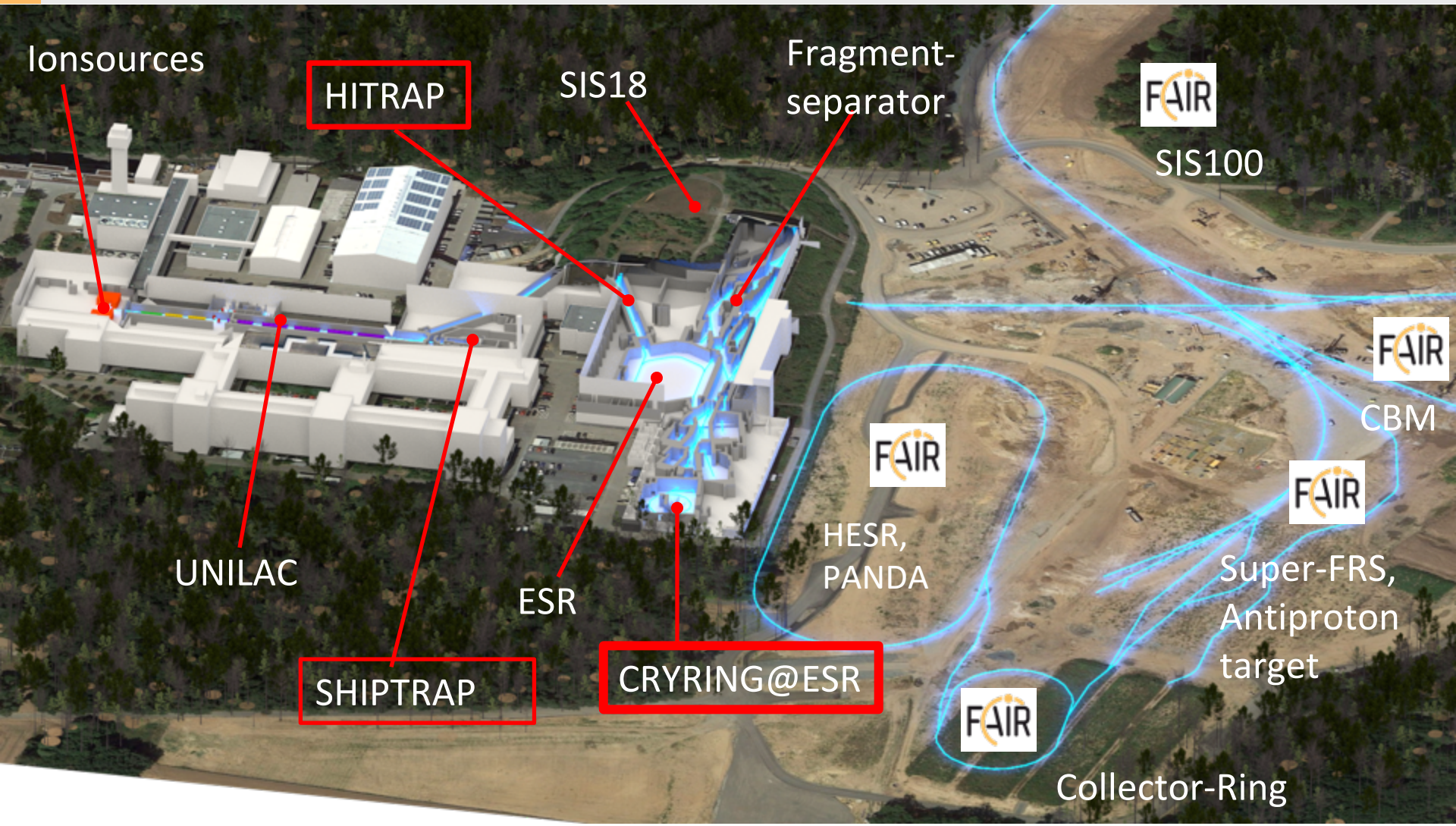
CRYRING@ESR and HITRAP

Frank Herfurth

Ion Storage at GSI/FAIR



The GSI/FAIR Site



CRYRING in Stockholm (MSL)

Singly charged positive atomic ions:
H^+, D^+, $^3He^+$, $^4He^+$, $^7Li^+$, $^9Be^+$, $^{11}B^+$, $^{12}C^+$, $^{14}N^+$, $^{16}O^+$, $^{40}Ar^+$, $^{40}Ca^+$, $^{45}Sc^+$, $^{48}Ti^+$, $^{56}Fe^+$, $^{83}Kr^+$, $^{84}Kr^+$, $^{86}Kr^+$, $^{88}Sr^+$, $^{129}Xe^+$, $^{131}Xe^+$, $^{132}Xe^+$, $^{138}Ba^+$, $^{139}La^+$, $^{142}Nd^+$, $^{151}Eu^+$, $^{197}Au^+$, $^{208}Pb^+$

Multiply charged atomic ions:
$^4He^{2+}$, $^{11}B^{2+}$, $^{12}C^{2+}$, $^{12}C^{3+}$, $^{12}C^{4+}$, $^{12}C^{6+}$, $^{14}N^{2+}$, $^{14}N^{3+}$, $^{14}N^{4+}$, $^{14}N^{7+}$, $^{16}O^{2+}$, $^{16}O^{3+}$, $^{16}O^{4+}$, $^{16}O^{5+}$, $^{16}O^{8+}$, $^{19}F^{6+}$, $^{19}F^{9+}$, $^{20}Ne^{2+}$, $^{20}Ne^{5+}$, $^{20}Ne^{6+}$, $^{20}Ne^{7+}$, $^{20}Ne^{10+}$, $^{28}Si^{3+}$, $^{28}Si^{11+}$, $^{28}Si^{14+}$, $^{32}S^{5+}$, $^{36}Ar^{9+}$, $^{36}Ar^{10+}$, $^{36}Ar^{12+}$, $^{36}Ar^{13+}$, $^{40}Ar^{7+}$, $^{40}Ar^{9+}$, $^{40}Ar^{11+}$, $^{40}Ar^{13+}$, $^{40}Ar^{15+}$, $^{48}Ti^{11+}$, $^{58}Ni^{17+}$, $^{58}Ni^{18+}$, $^{84}Kr^{33+}$, $^{126}Xe^{36+}$, $^{129}Xe^{36+}$, $^{129}Xe^{37+}$, $^{136}Xe^{39+}$, $^{136}Xe^{44+}$, $^{207}Pb^{53+}$, $^{208}Pb^{53+}$, $^{208}Pb^{54+}$, $^{208}Pb^{55+}$

Positive molecular ions:
H_2^+, HD^+, H_3^+, D_2^+, H_2D^+, ^3He
NH_2^+, OH^+, CH_5^+, NH_4^+, H_2O^+
$C_2H_2^+$, HCN^+, $C_2H_3^+$, $HCNH^+$,
NO^+, $D^{13}CO^+$, CH_3O^+, CF^+, O_2
$N_2H_7^+$, $D_2{}^{32}S^+$, $CD_3OH_2^+$, CD_3
$D_3{}^{34}S^+$, $C_3H_4^+$, $D_2{}^{37}Cl^+$, $D_5O_2^+$, CH_3CNH^+, $C_3D_3^+$, $N_2D_7^+$, N_3^+, $C_3H_7^+$, NaD_2O^+, CO_2
HCS^+, $C_2H_5O^+$, DN_2O^+, $C_2H_5OH^+$, CO_2D^+, CD_3CDO^+, $NO^+{\cdot}H_2O$, O_3^+, $DCOOD_2^+$,
$CD_3OCD_2^+$, $C_3D_7^+$, CF_2^+, $NO^+{\cdot}D_2O$, DC_3N^+, $CD_3OCD_3^+$, $N_3H_{10}^+$, DC_3ND^+,
$CD_3ODCD_3^+$, $H_7O_3^+$, COS^+, $N_2O_2^+$, $CH_3OCOH_2^+$, $D_7O_3^+$, $N_3D_{10}^+$, $C_4D_9^+$, $S^{18}O_2^+$, ArN_2^+,
$H_9O_4^+$, $CD_3COHNHCH_3^+$, $CD_3CONHDCH_3^+$, $C_6D_6^+$, $PO^{37}Cl^+$, $H_{11}O_5^+$, $C_2S_2H_6^+$,
$C_2S_2H_7^+$, $H_{13}O_6^+$, $PO^{35}Cl_2^+$

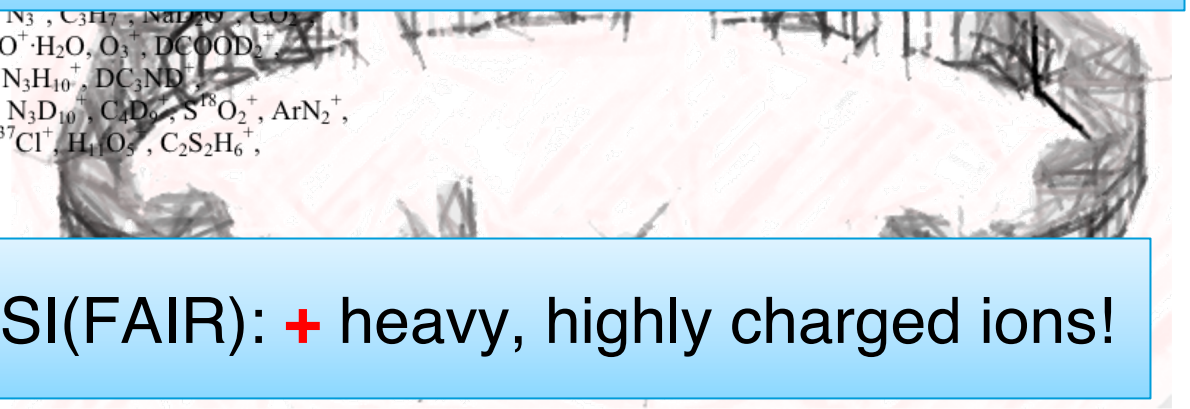
Negative atomic ions:
H^-, Li^-, F^-, Si^-, S^-, Cl^-, Se^-, Te^-

Negative molecular ions:
CN^-, C_4^-, Si_2^- Cl_2^-

~200 different ion species

singly charged (pos. & neg.)
multiply charged
molecular (pos. & neg.)

- Successful operated from 1992 to 2010
- Dismantled and shipped to FAIR/GSI in 2012/13

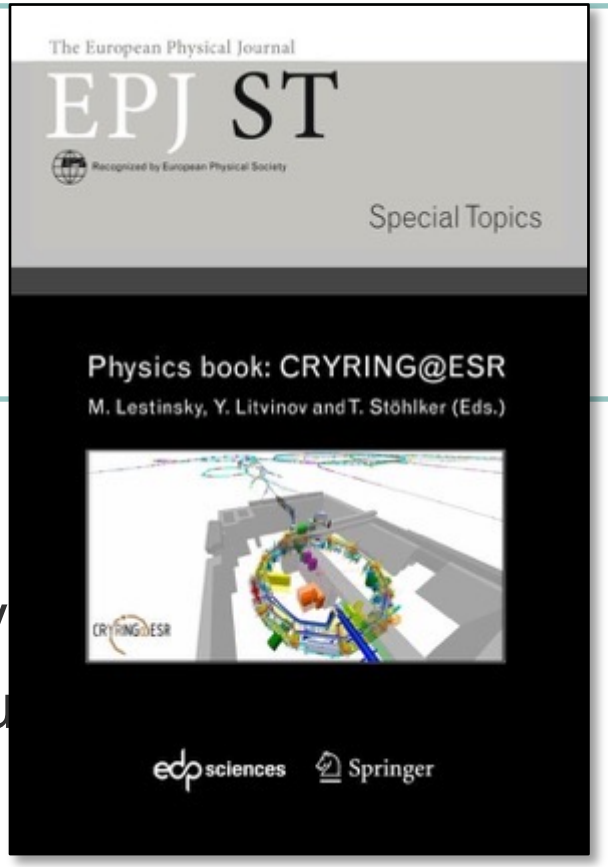


GSI(FAIR): + heavy, highly charged ions!

CRYRING@ESR

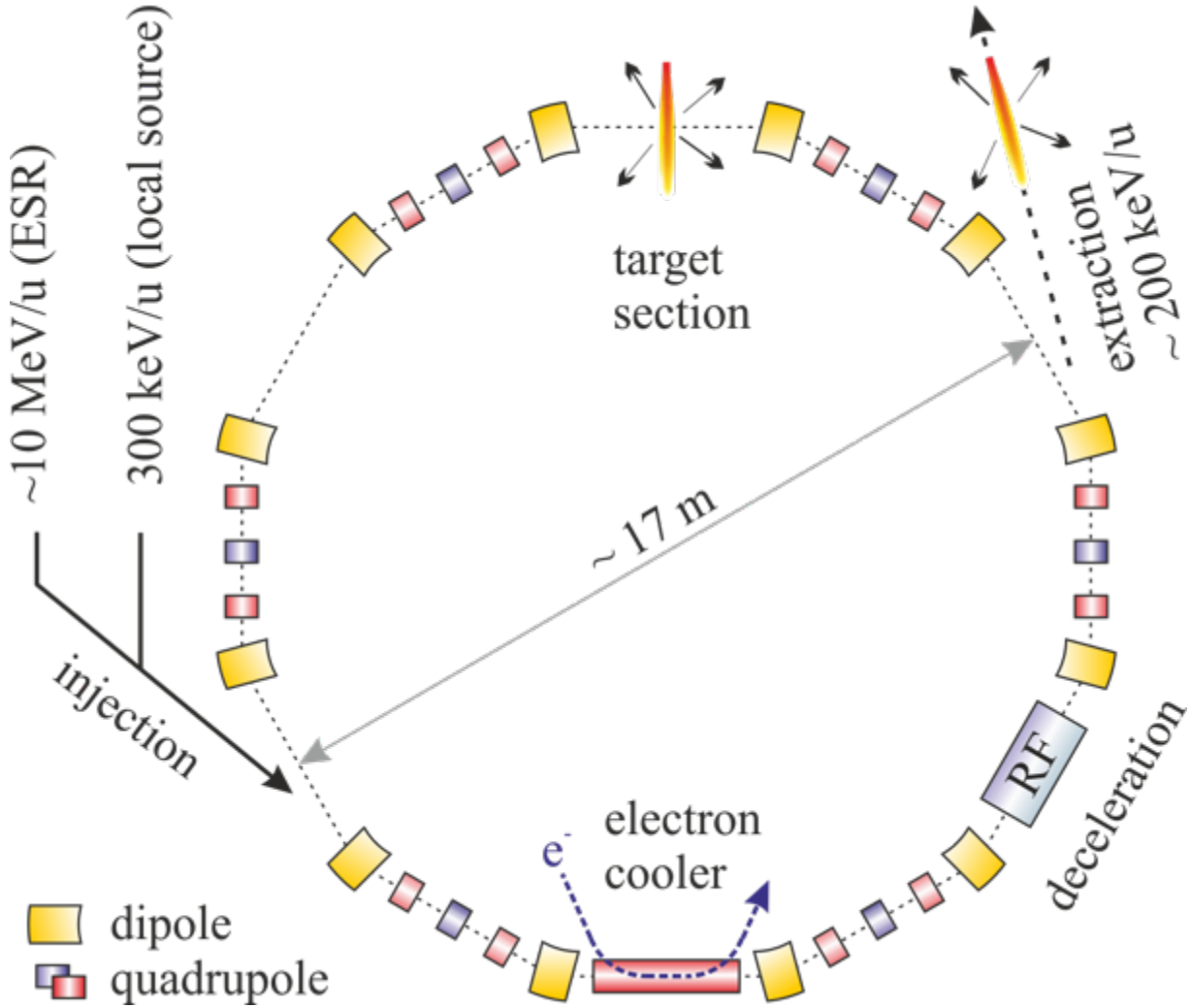
- **FAIR Research & Development**
- Detectors and diagnostic systems
- FAIR type control system
- Training of operators on FAIR type sy

with real beam (standalone operation du



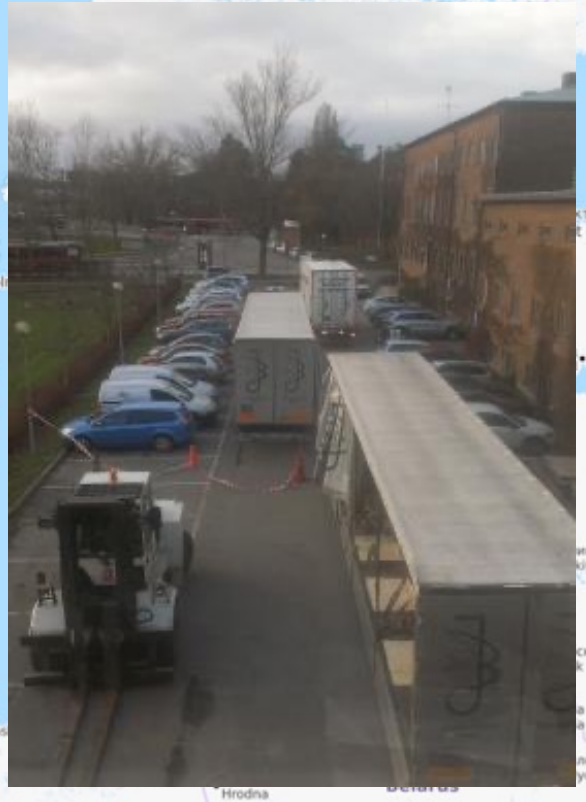
- **Scientific Opportunities**
- Heavy, highly-charged ions available at GSI (up to U^{92+}, fragmentation products) at low energy 100 keV/u .. 10 MeV/u – bridge the energy gap between the ESR (> 4 MeV/u) and HITRAP (<10 keV/u)

CRYRING@ESR



- Max. rigidity 1.44 Tm
  - 15 MeV/u U^{92+}
  - 96 MeV/u protons
- Min. rigidity ~ 0.054 Tm
  - Actual limit given by beam life time
- UHV … 10^{-11} mbar

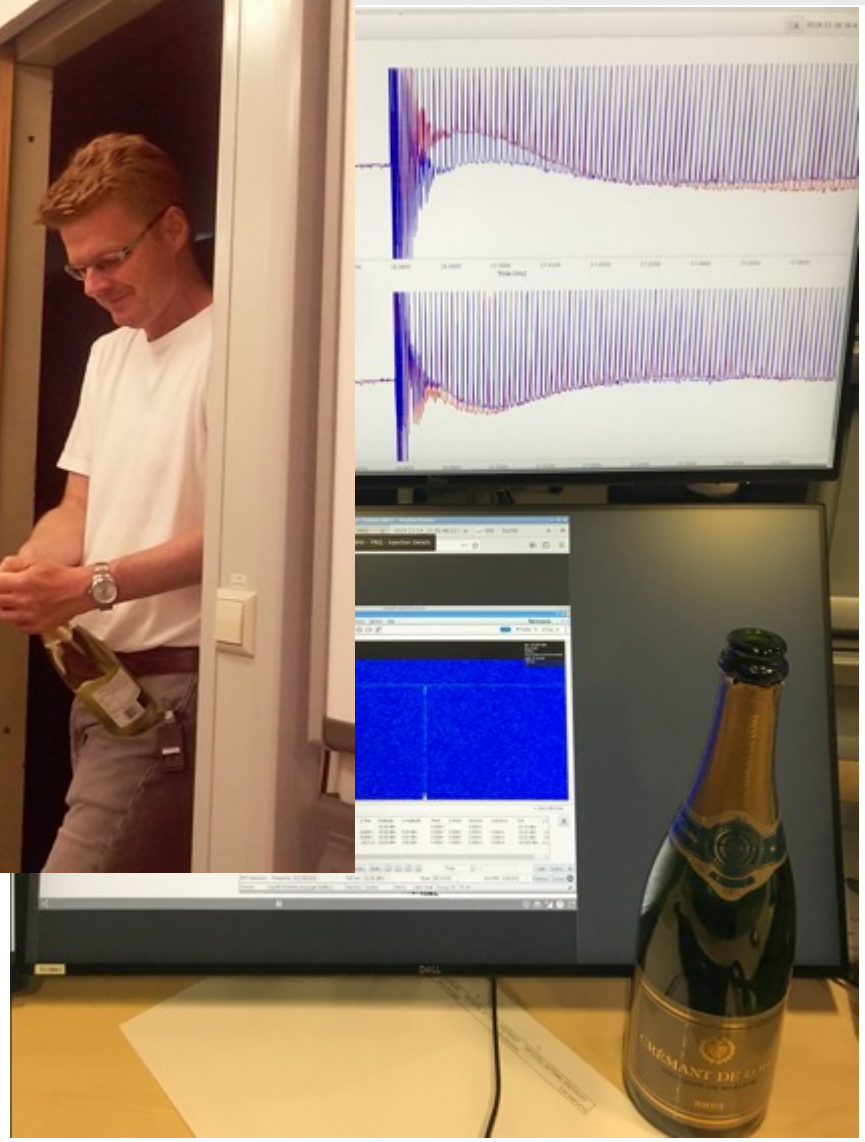
2012-2013



12 truck tours

Karte: © OpenStreetMap

some years later ..



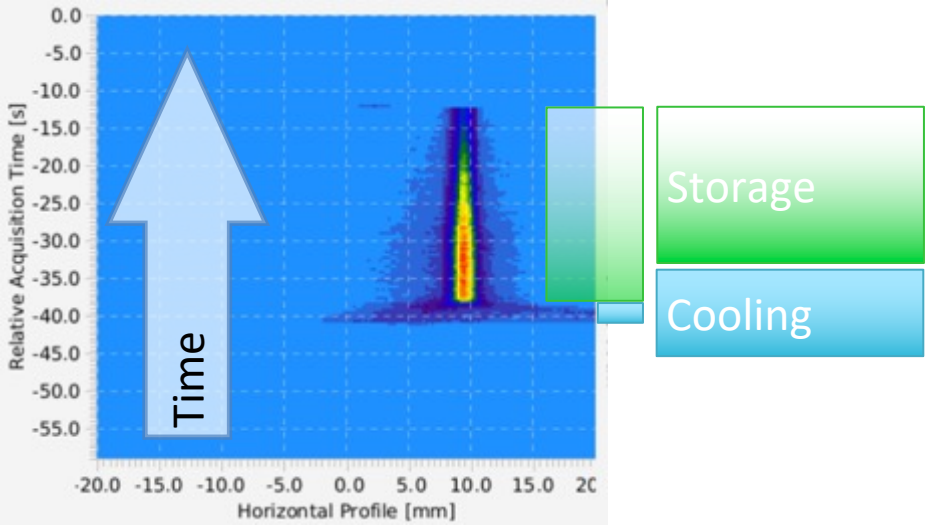
CRYRING

some years later ..

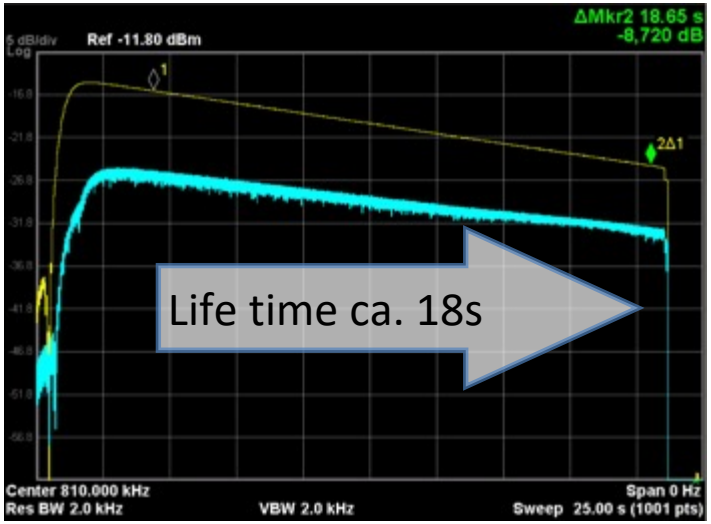
… arrived at ESR

Beamtime Q1/2 2020

- Captured, Stored and Cooled Pb^{78+} and Pb^{82+} (bare)
  - 6 x 10^6 particles extracted from ESR at 10 MeV/nucleon
  - 3 x 10^5 particles available for experiments in CRYRING@ESR after cooling
  - Ion beam deceleration to 4 MeV/nucleon has been successfully tested
- Lifetimes measured for different energies and ions
  - Pb^{82+} lives between 10 and 20 seconds @10MeV/u

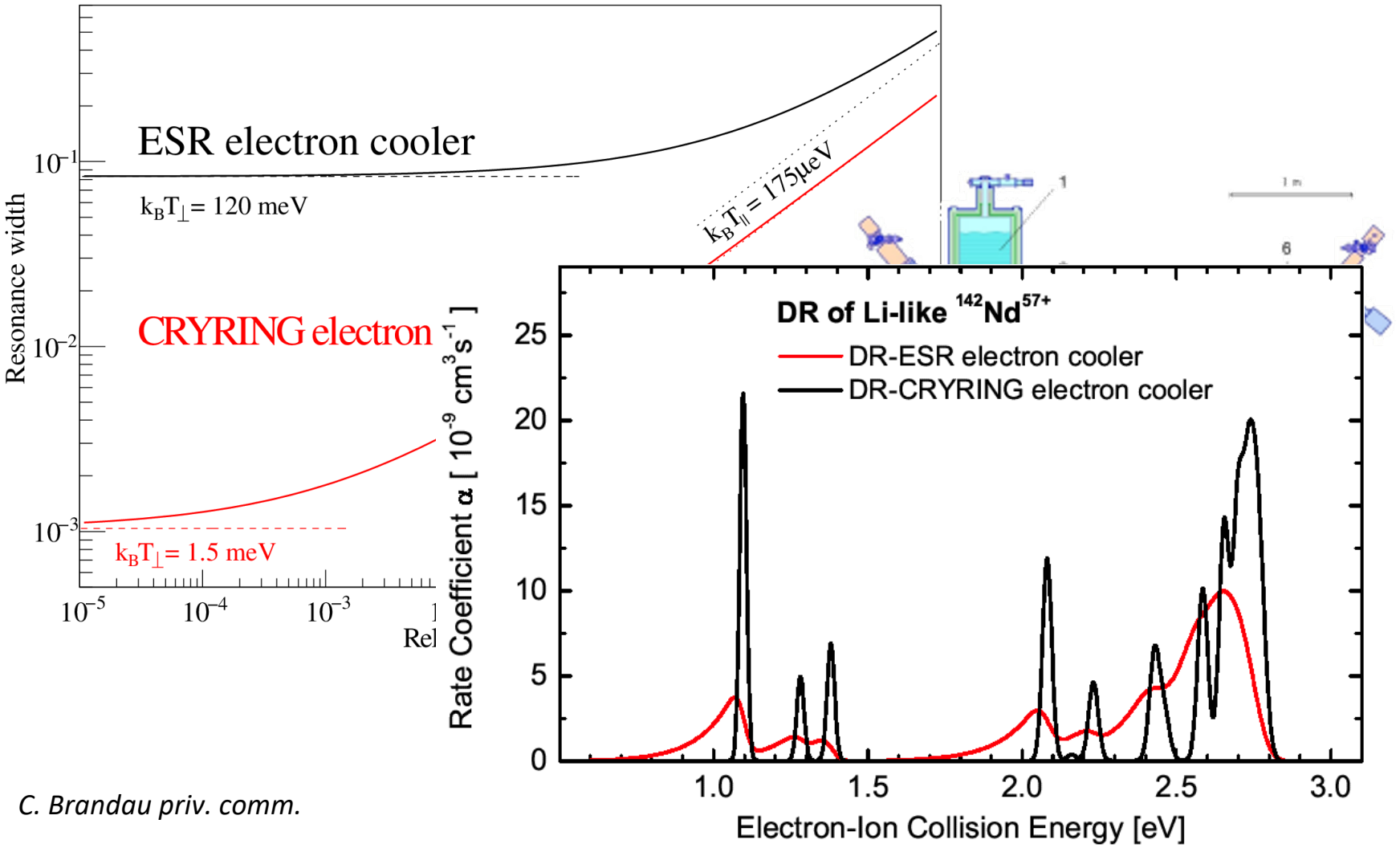


Horizontal beam profile over time



Lifetime, i.e. time for a signal drop of 8 dB

Electron Cooling ESR - CRYRING

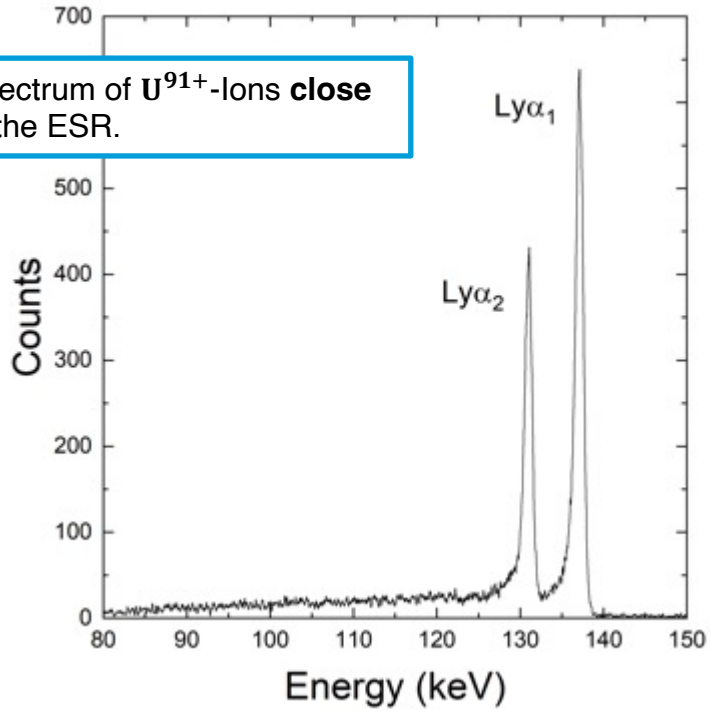


C. Brandau priv. comm.

Electron Cooling ESR – CRYRING@ESR

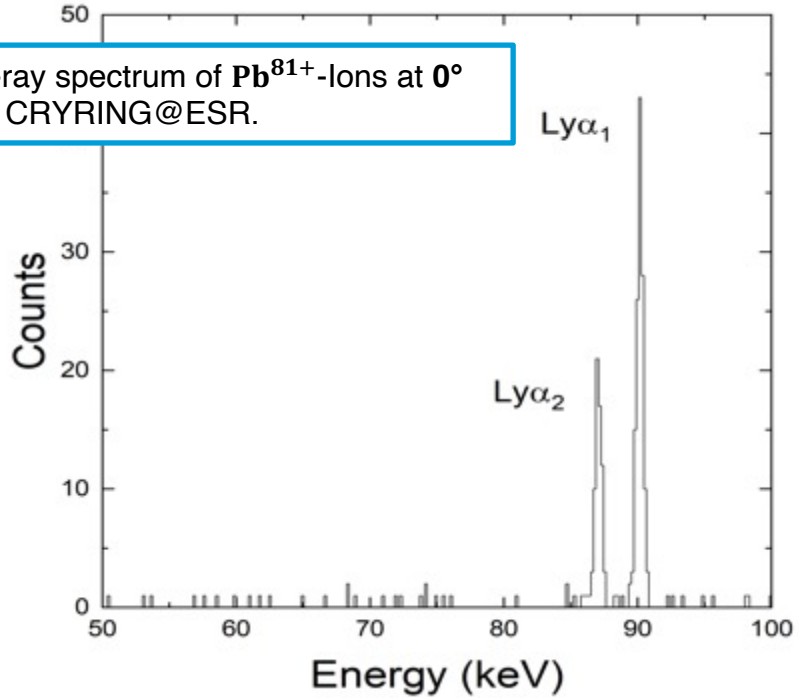
$$U^{92+} + e^- \rightarrow U^{91+} + \hbar\omega$$

X-ray spectrum of U^{91+}-Ions **close to 0°** at the ESR.



$$Pb^{82+} + e^- \rightarrow Pb^{81+} + \hbar\omega$$

X-ray spectrum of Pb^{81+}-Ions at **0°** at CRYRING@ESR.

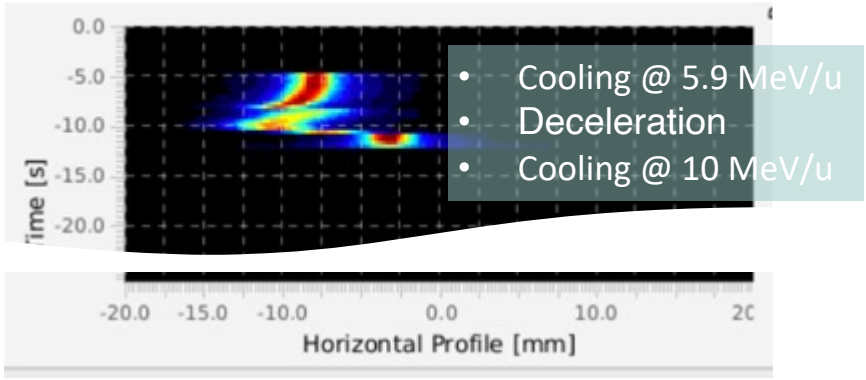


comparison plot: M. Lestinsky; Publication: B. Zhu et al., submitted to PRA, arXiv:2201.06977v1

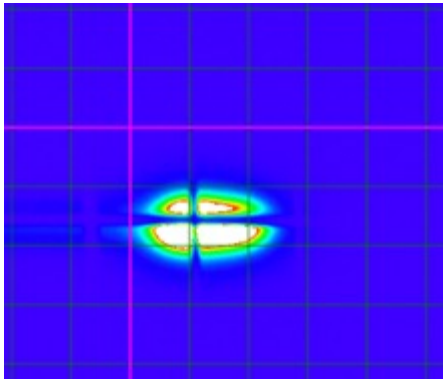
Fast Extraction, Deceleration, CCC

$^{107}Ag^{47+}$ ions
injected, cooled, decelerated, cooled, extracted

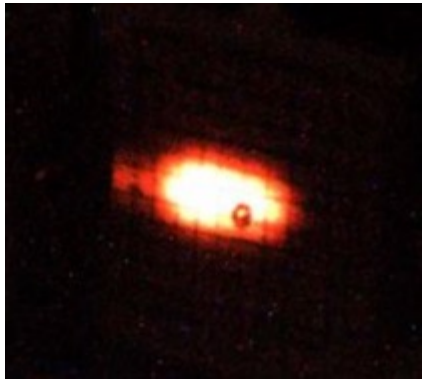
horiz. beam profile of stored beam



Extraction Beam Line



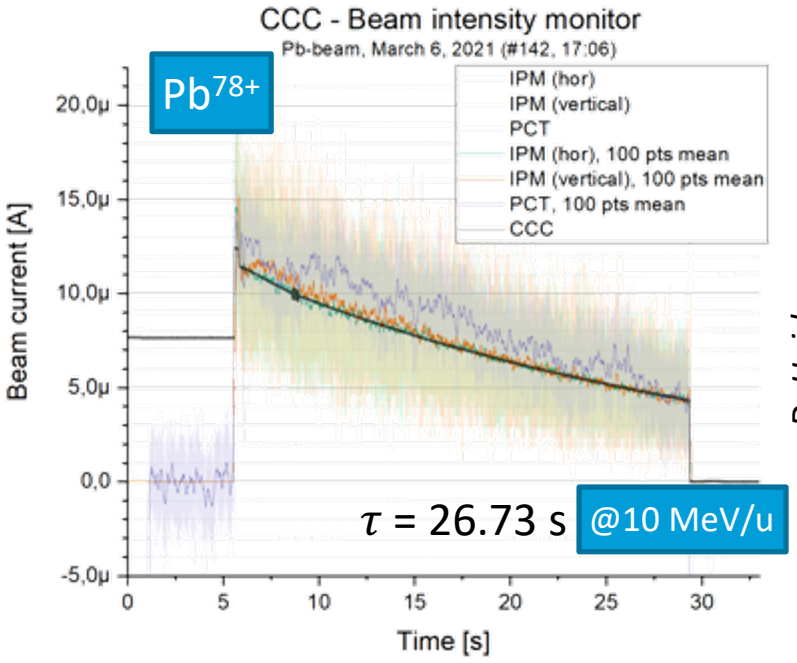
Experiment Detector



L. Breuer et. al

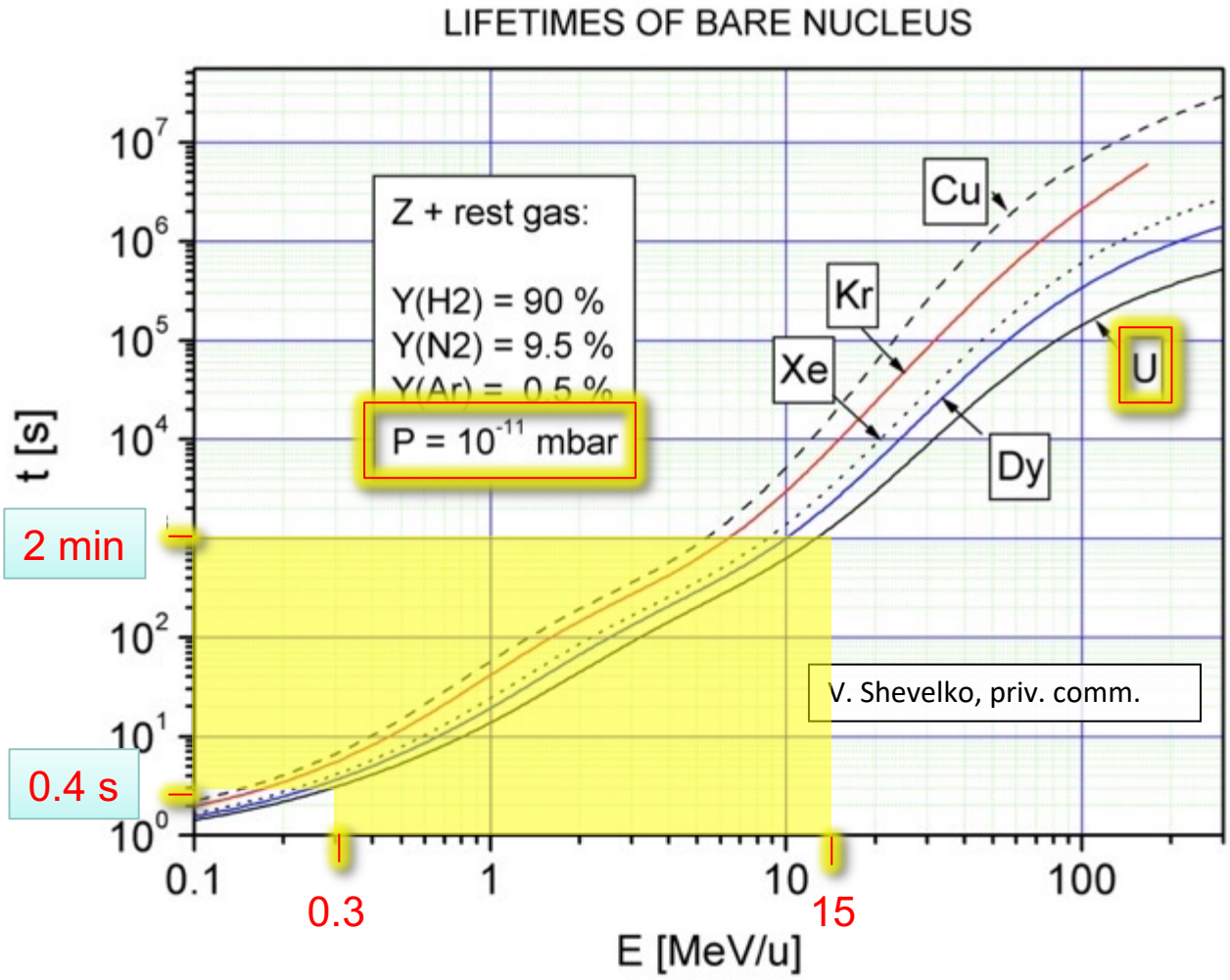
about $4 \cdot 10^6$ ions reach the target

Cryogenic Current Comparator
installed, tested



D. Haider

Ultra High Vacuum & Beam Life Time

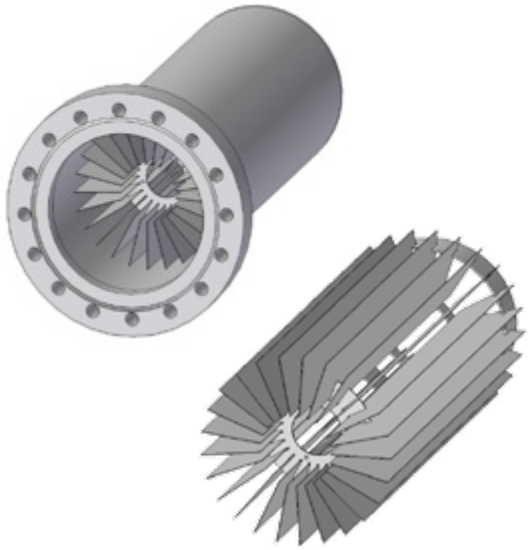


- Ion pumps

~ 10

- Cryopumps
- NEG pumps

~ 100



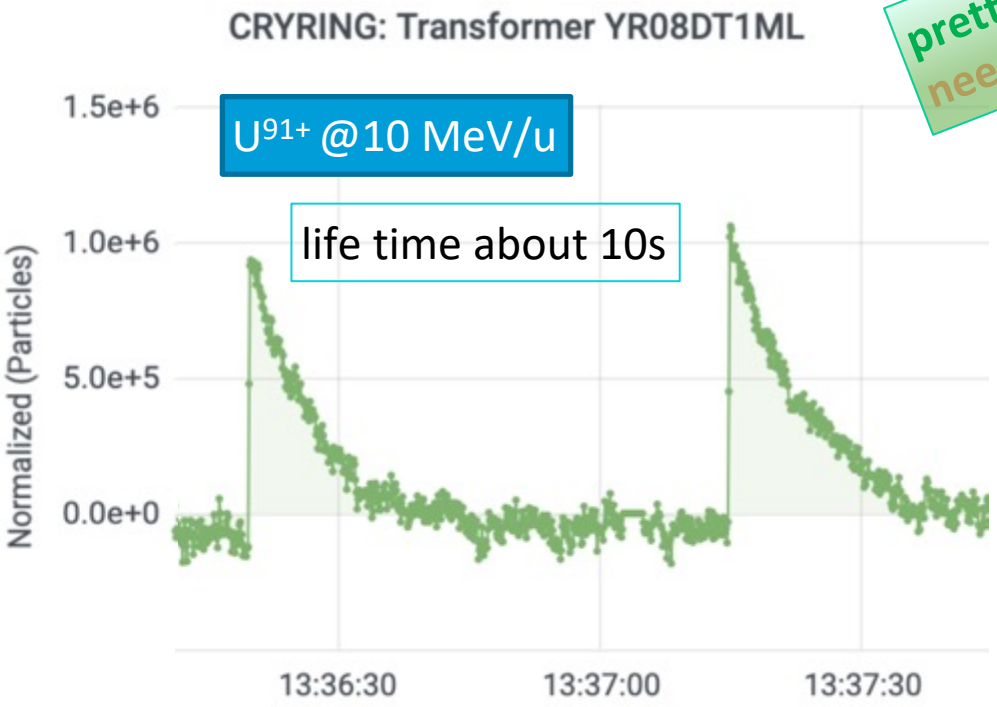
CRYRING@ESR

Vacuum Conditions

Main effort in 2020 went into sections 05 – 08:

- addition of new ion getter pumps
- NEG coating of some easily accessible parts

pretty good for first experiments
needs improvements for later experiments



Electron Current	Measured lifetime/s	Beamcalc lifetimes/s	@10 MeV/u
12 mA	24	33	Pb^{78+}
22 mA	8	28	Pb^{78+}
12 mA	19	28	Pb^{82+}
22 mA	12	23	Pb^{82+}
			@ 7MeV/u
12	12	18	Pb^{78+}
			@4 MeV/u
0 mA	5	7.5	Pb78+

calculations (M. Lestinsky et al.):
http://web-docs.gsi.de/~lestinsk/beamcalc

Experiments at the CRYRING@ESR facility

General-Program Advisory Committee accepted: (A and A-)

E129	J. Rothhardt	IAP Jena	Photoionization of C+ ions at CRYRING
E131	S. Schippers	U Giessen	Precision collision spectroscopy of Be-like ions at the CRYRING@ESR electron cooler
E138	G. Weber	U Jena	The Ground-State Lamb Shift in the Heaviest Hydrogen-like Ion (U91+): High Resolution X-ray Spectroscopy at the CRYRING electron cooler
E140	M. Lestinsky	GSI	Absolute rate coefficients from dielectronic recombination for astrophysically important ion species
E148	R. Sanchez	GSI	A Test of Optical Pumping at CRYRING
E149	C. Brandau	U Giessen	Commissioning and First Storage Ring Experiments of the CRYRING Transverse Electron Target
E151	O. Forstner	U Jena	Measurement of the astrophysical relevant alpha-capture reaction rate 44Ti(α,p)47V
E153	W. Biela	U Krakow	Multielectron recombination processes in He-like oxygen at the CRYRING@ESR electron cooler
E154	S. Bernitt	HI Jena	High-Resolution Spectroscopy of Charge Exchange Between Highly Charged Ions and Molecular Hydrogen for Laboratory X-ray Astrophysics at CRYRING
E155	E. Lamour	INSP Paris	Letter of Intent: Fast Ion – Slow Ion Collisions @ CRYRING
S461	C. Bruno	U Edinburgh	Nuclear astrophysical reaction studies using the CRYRING reaction chamber system (CARME)
Smat_Breuer_Commissioning	L. Breuer	U Duisburg-Essen	Commissioning of the MAT target station at CRYRING
Smat_Umat_Velthaus	V. Velhaus	GSI	Ion-induced desorption at room temperature for different surface treatments and beam parameters

G-PAC proposals for 2021 and 2022

12 proposals total ~400 shifts

4 proposals with ESR beam ~120 shifts

1 LOI for 2023ff

contact: D. Severin, M. Lestinsky

Overview

A/q < 3 (U^{92+} ...)
10^5 ions/pulse @ keV/q ... meV/q (Δ < 0.3 meV)

400 MeV/u

4 MeV/u *500 keV/u* *6 keV/u*

ESR | Buncher | IH | RFQ | Trap

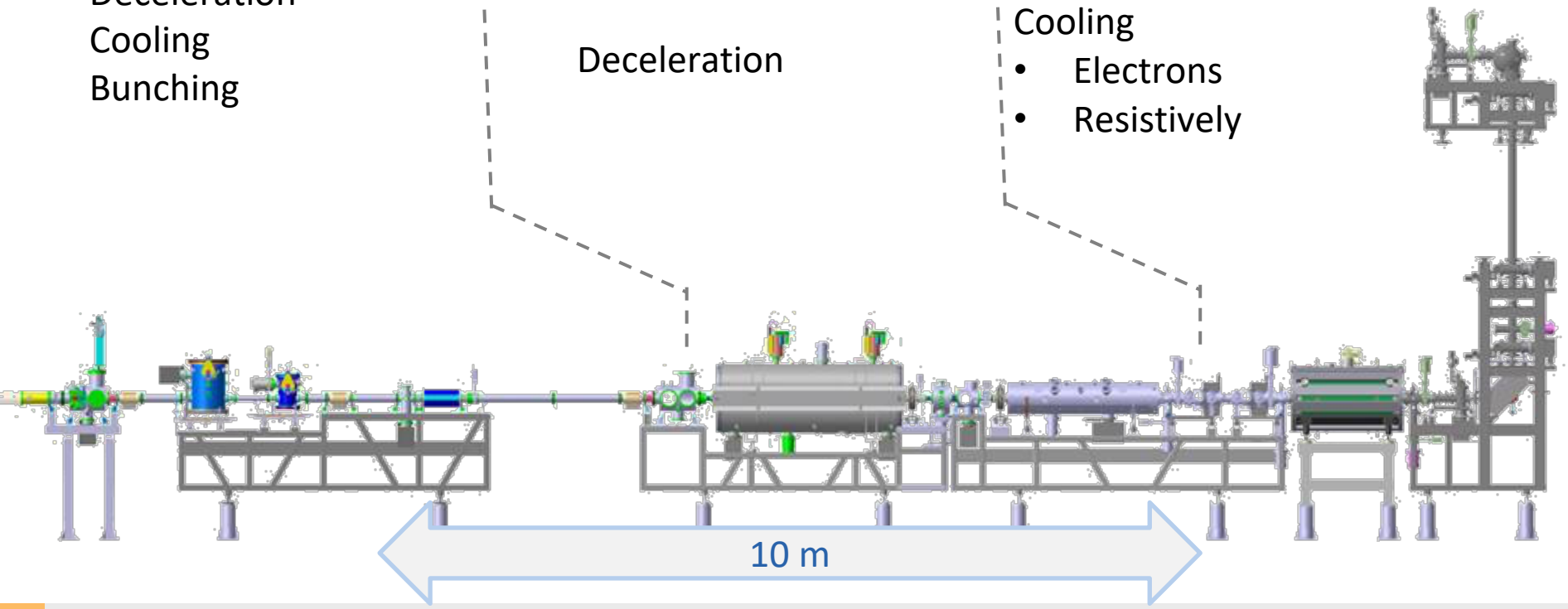
- Experiments
- Ion sources

10 ... 60 s *few µs* *~ 10 s*

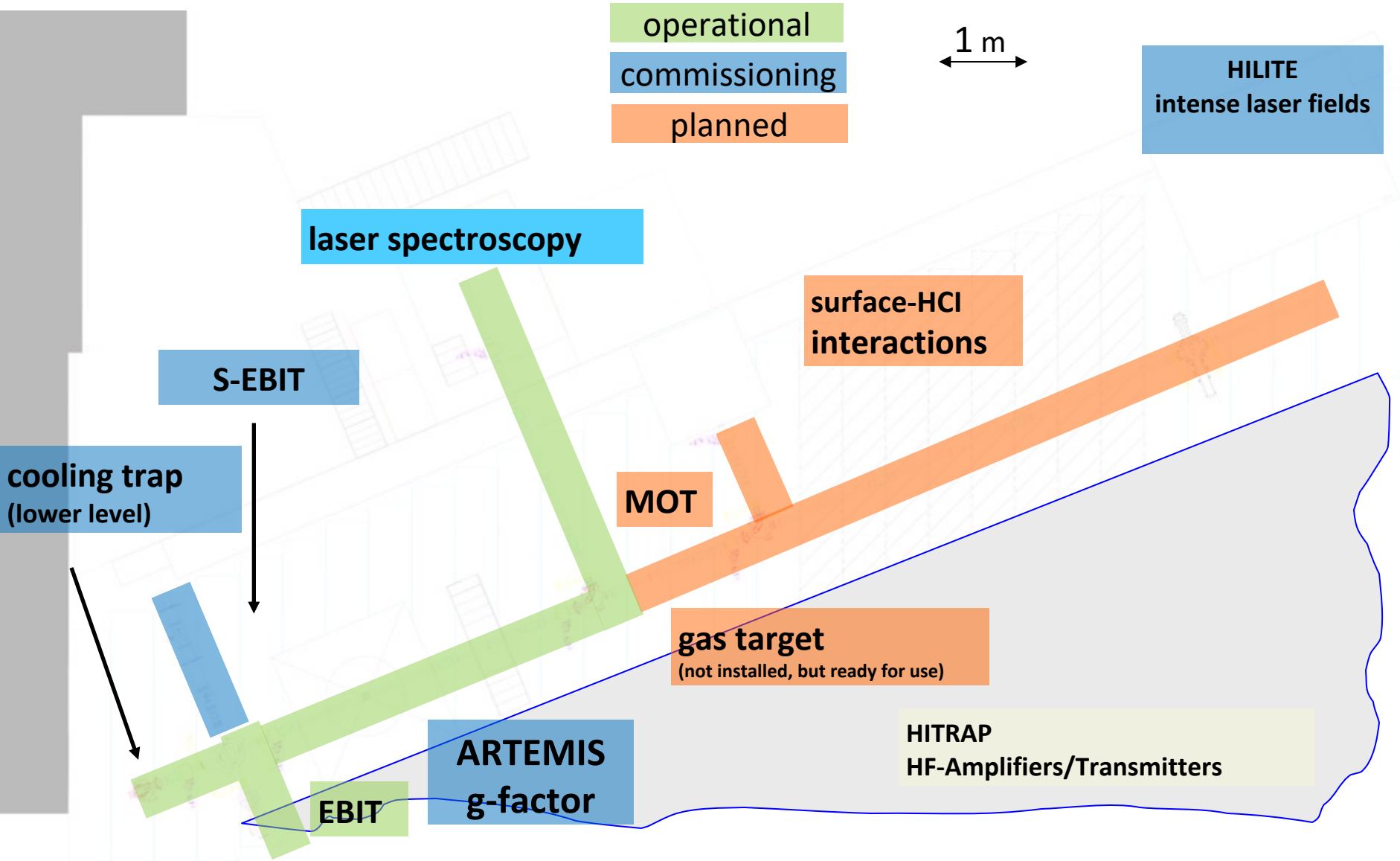
Deceleration
Cooling
Bunching

Deceleration

Capture
Cooling
- Electrons
- Resistively



Experimental Area



Timeline

Start of Budget

Integrated Intensity equivalent to only 1 hour @ 50 Hz I_{peak} = 2 eμA

Restart of SIS/ESR

16 On-Line Tests (between 3 and 7 days each, 1..2 shots per minute)

2004 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | … | ~~2018~~ ~~2020~~ 2022

IH Retuning

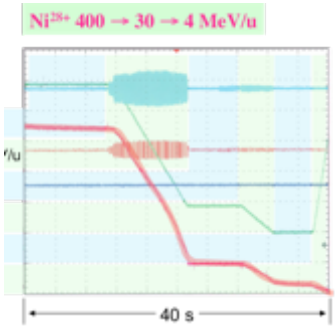
First ions @ 500 keV/u

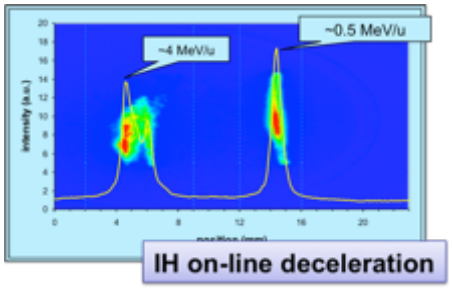
RFQ installed, beam transmitted

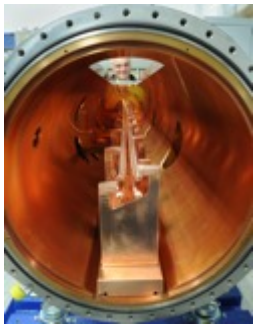
RFQ Reconstruction

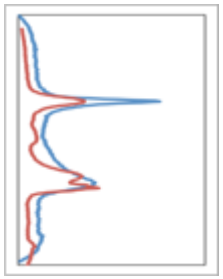
RFQ Offline Tests at MPI-K Heidelberg

First ions @ 6 keV/u

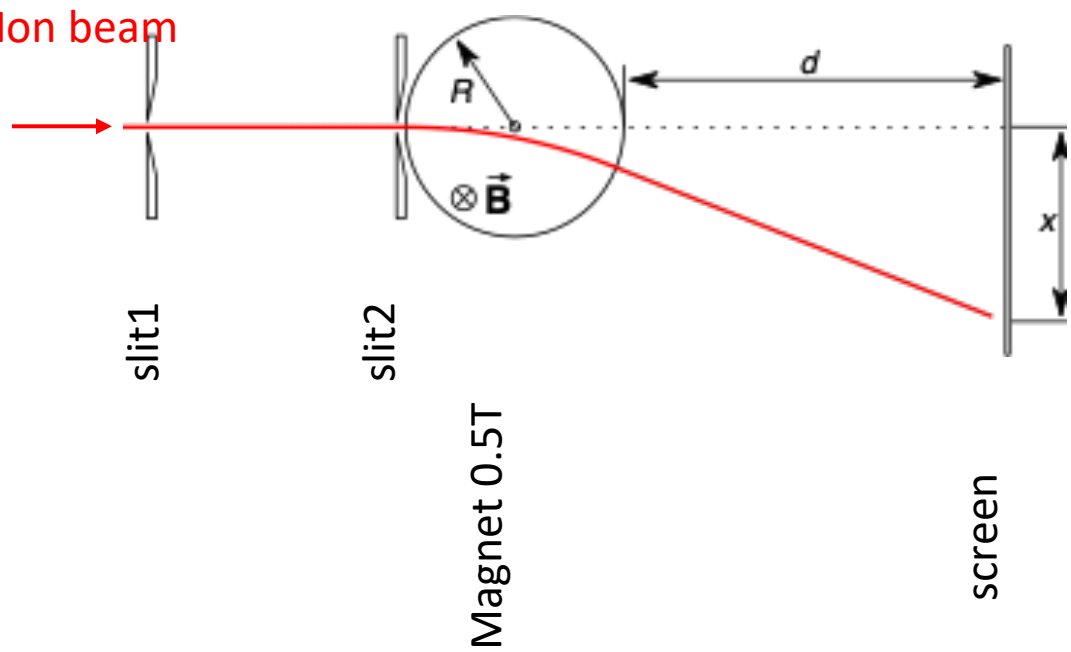


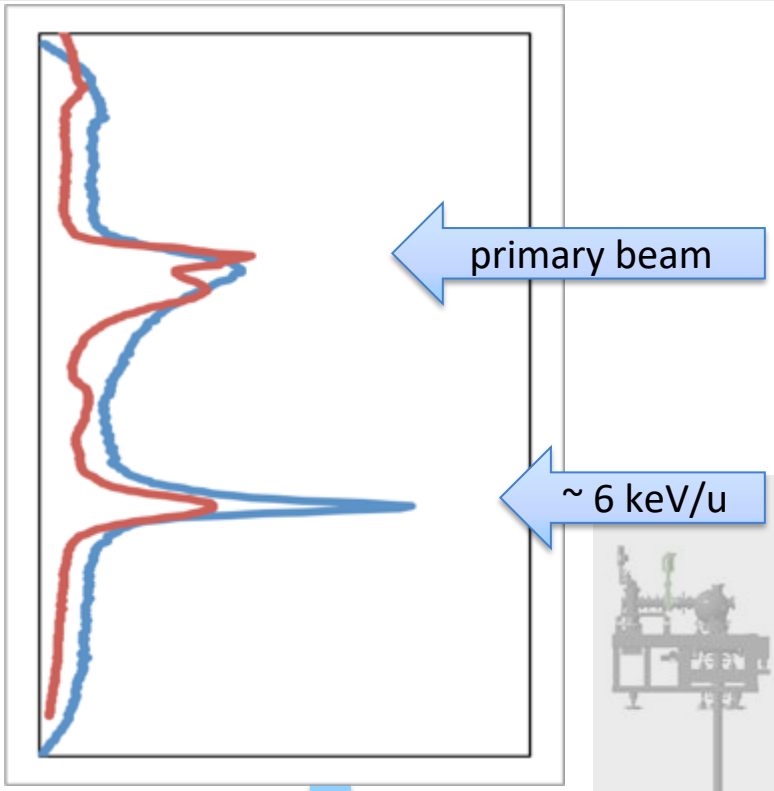


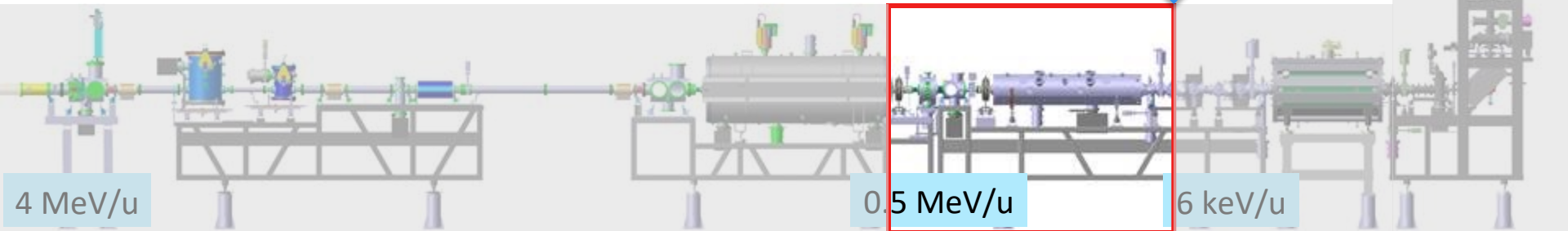




Deceleration from 4 MeV/u to 6 keV/u

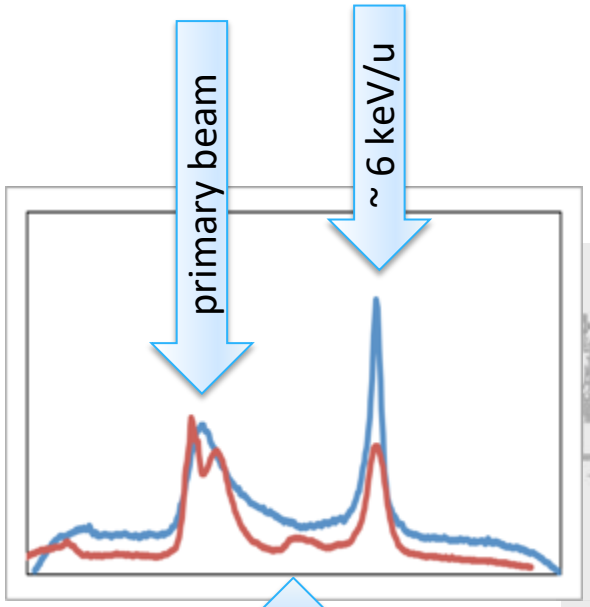


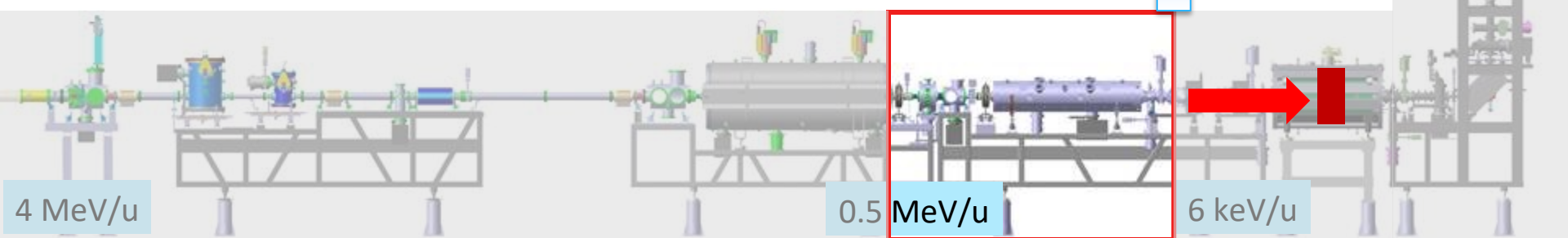




Status of commissioning

- deceleration from 4 MeV to 6 keV/nucleon demonstrated
- Test ion source operational - also for light, but highly charged ions (EBIT)
- transport from trap to experiments routinely achieved
- final step still to be commissioned
  - capture and cooling of HCI –





CRYRING@ESR and HITRAP

Storage of low energy heavy ions at

- **CRYRING@ESR served experiments with very few failures and will serve them in 2022 too.**
- Challenges:
  - Beam intensity expected vs. delivered
  - Vacuum conditions
  - ECooler small defects need large intervention

- **HITRAP will continue commissioning in 2022**
- Challenges:
  - reestablish deceleration from 4 MeV/u to 6 keV/u
  - capture and cool HCI in cooling Penning trap