Slow, exotic, Ions at GSI/FAIR

Deceleration and Storage of heavy, highly charged ions

HITRAP and CRYRING@ESR

Frank Herfurth for the HITRAP and CRYRING@ESR teams

CRYRING@ESR
Project Structure – True common effort!

External Partners
HIJ Jena
Stockholm University
Krakow University
KVI Groningen

GSI/FAIR Expert Groups
- Construction
- Facility Engineering
- Mechanical Design/Integration
- Ion Sources
- UNILAC RF
- Ring RF
- Magnets
- Vacuum
- Power Suppl.
- Beam Diagns.
- Controls
- Assembly
- Beam Cooling

CRYRING@ESR

Atomic Physics
- Decelerator Experiments
- SPARC Det.

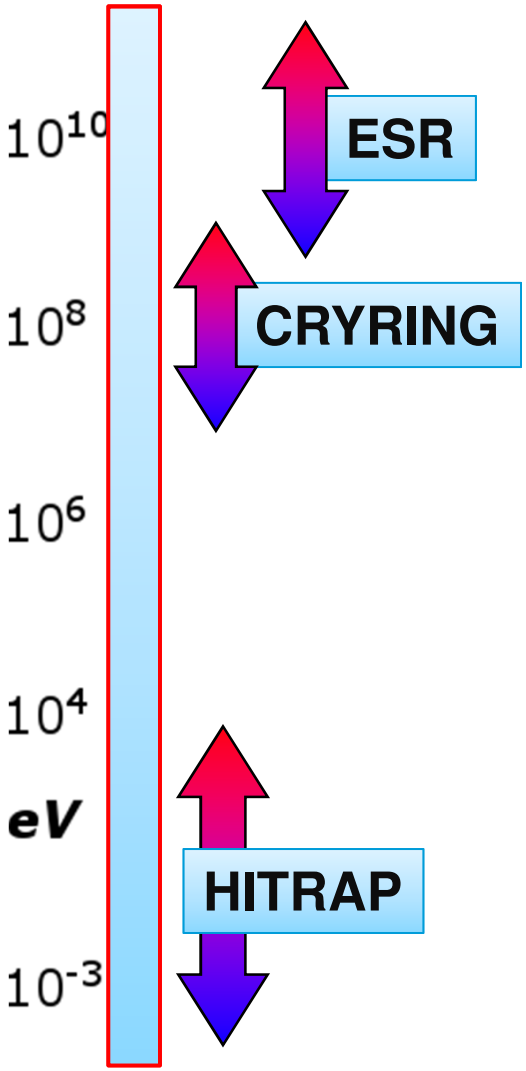
Accelerator Operations
- Decelerators

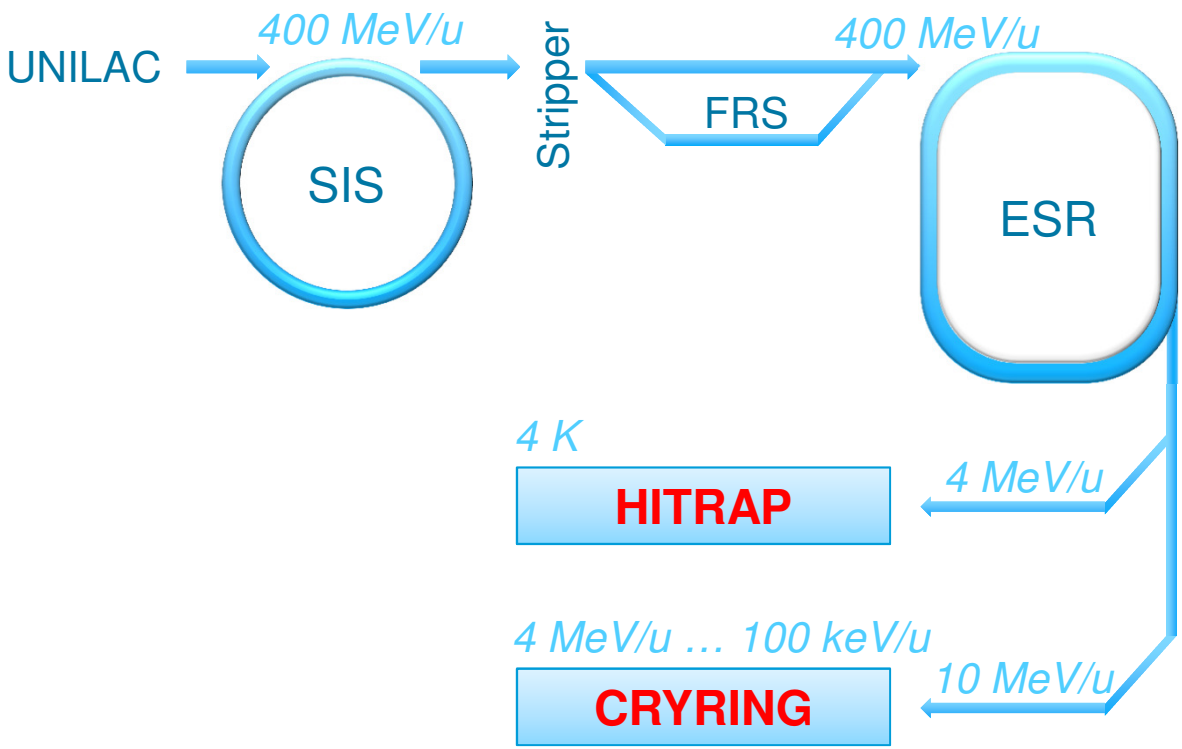
SPARC
APPA
collaborations

BMBF (Ministry)
„Verbundforschung“

HITRAP is very similar

Ion Storage at GSI ("low energy")





WHY?

Highly **C**harged **I**ons

HCI

Elements

Isotopes

+ Matter

Charge radii

FS, HFS

g-factor

e--binding

BW effect

+ surface

α, m_e

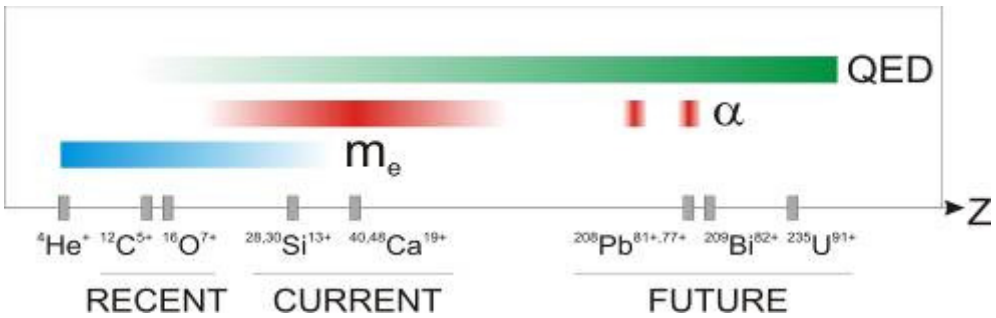
Lamb-shift

Structures

QED test

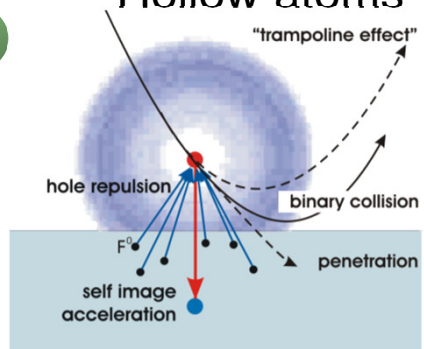
+ atoms

Hollow atoms



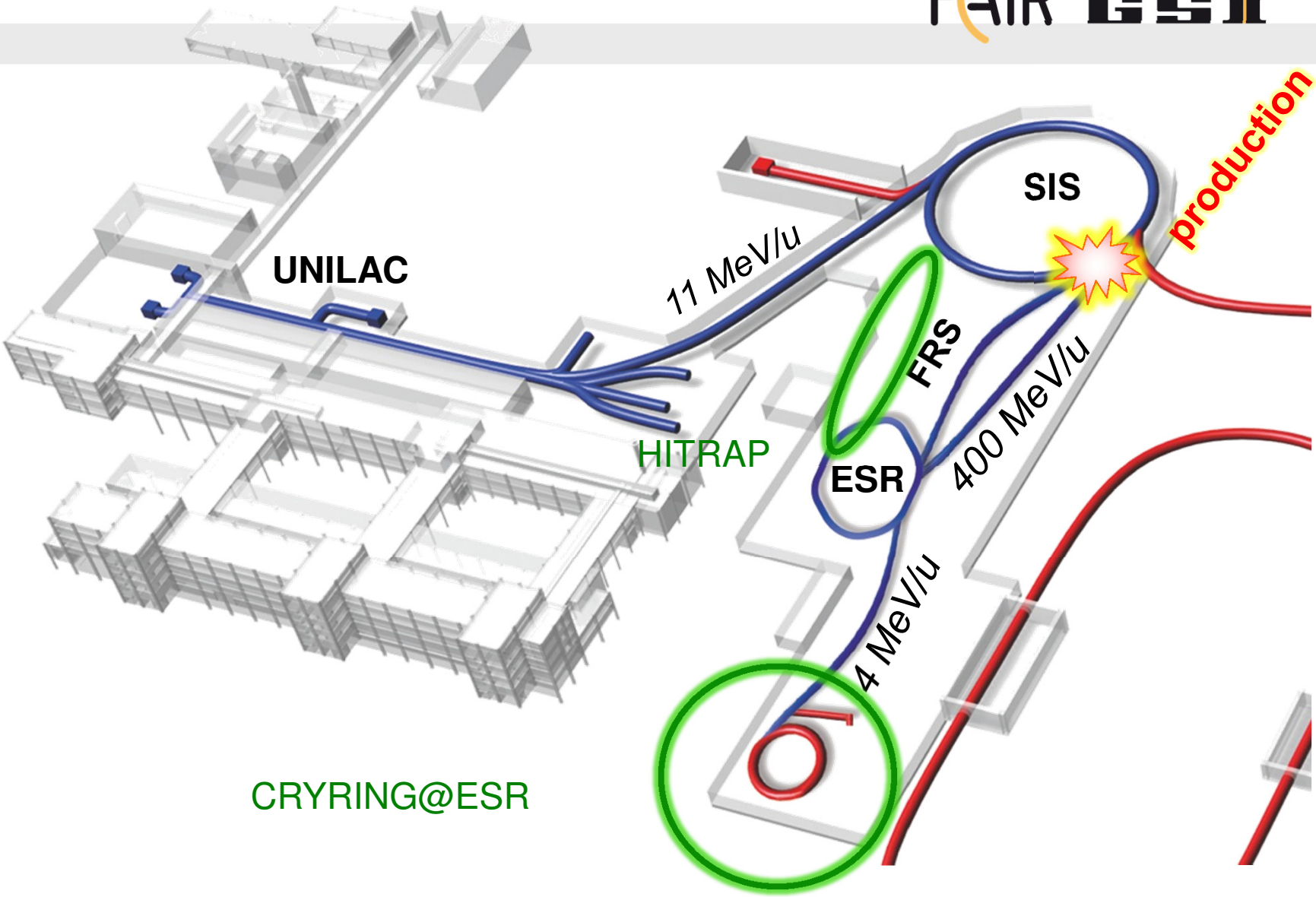
Charge exchange

Collision dynamics



We need to control

Location – Observation Time – Energy

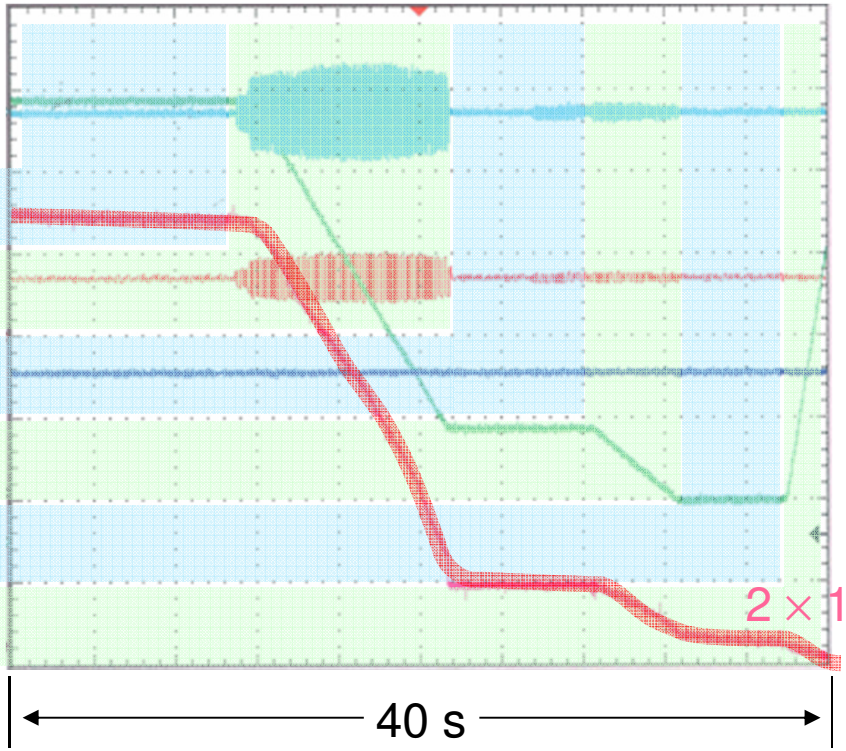

UNILAC
11 MeV/u
SIS
production
FRS
400 MeV/u
HITRAP
ESR
4 MeV/u
CRYRING@ESR

ESR – From 400 to 4 MeV/u

ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

Ni^{28+} 400 → 30 → 4 MeV/u

time (s)	**ESR cycle during recent experiment**
5..20	injection, **stoch. cooling**
3..10	deceleration 400 – 30 MeV/u
2..6	e^- cooling, rebunching
2..5	deceleration 30 – 4 MeV/u
2..5	e^- cooling, ejection
3	reset magnets



signal:

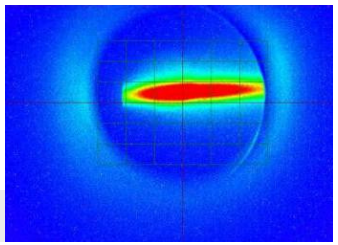
RF amplitude

magn.dipole field

2×10^7 ion current

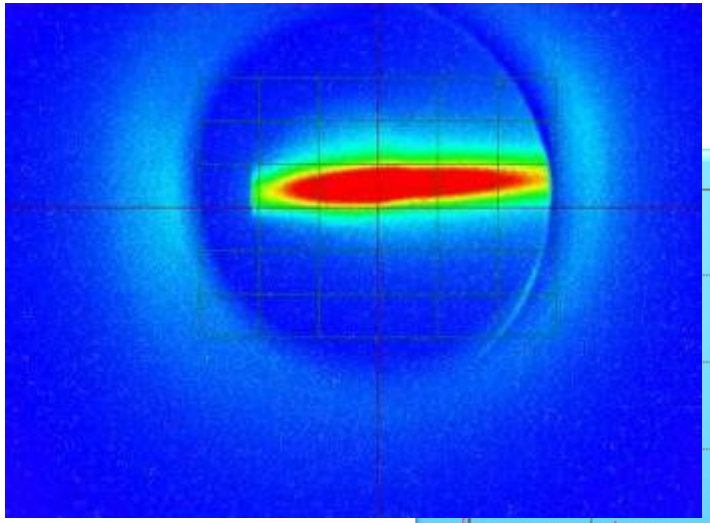
M. Steck et al.

1100 µA → 180 µA → 25 µA

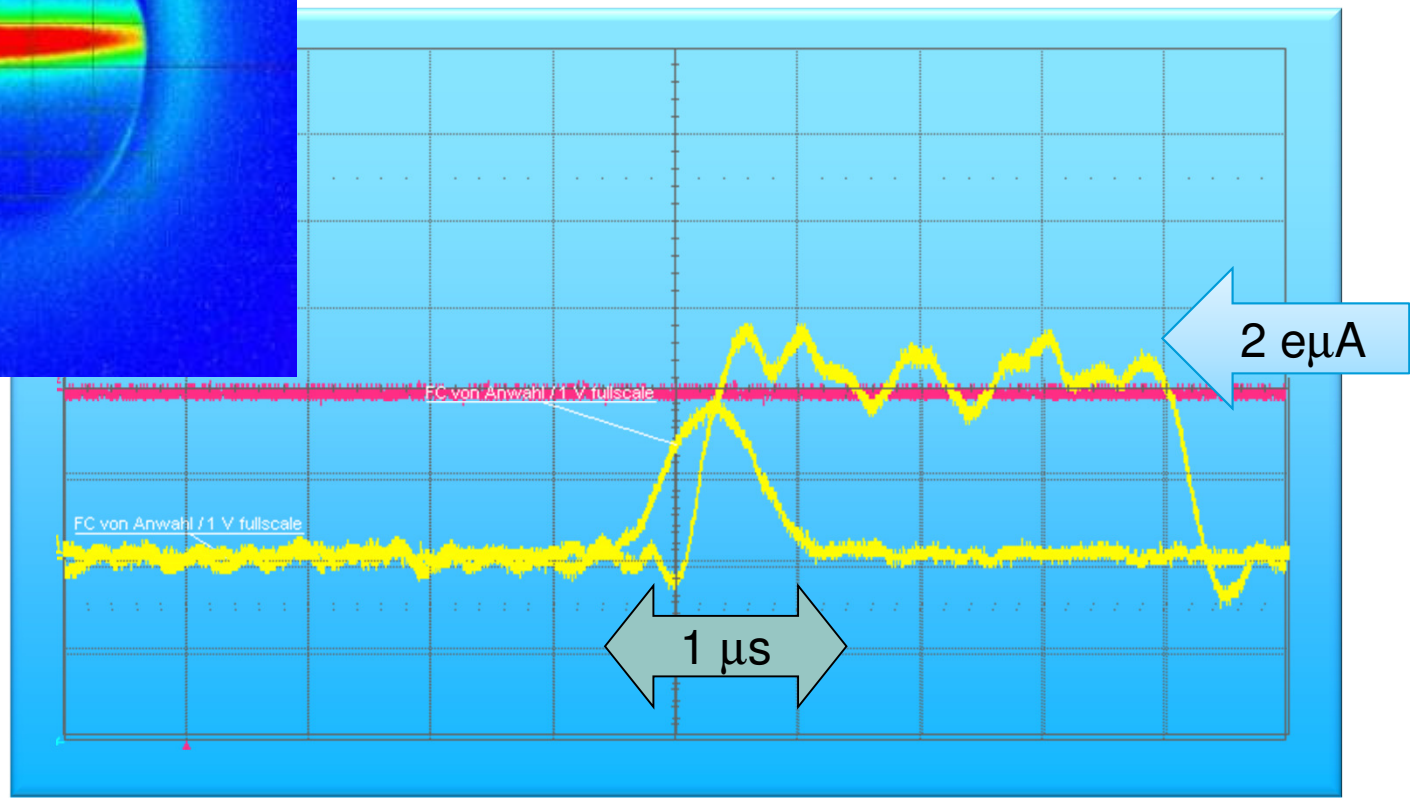


4 MeV/u ions from ESR

First fluorescent Screen towards HITRAP



10^6 $^{136}Xe^{50+}$ extracted from ESR



Faraday Cup signal in the HITRAP beam line

Decelerate, Extract, Transfer

ESR —— > 60% ——→ **CRYRING@ESR**

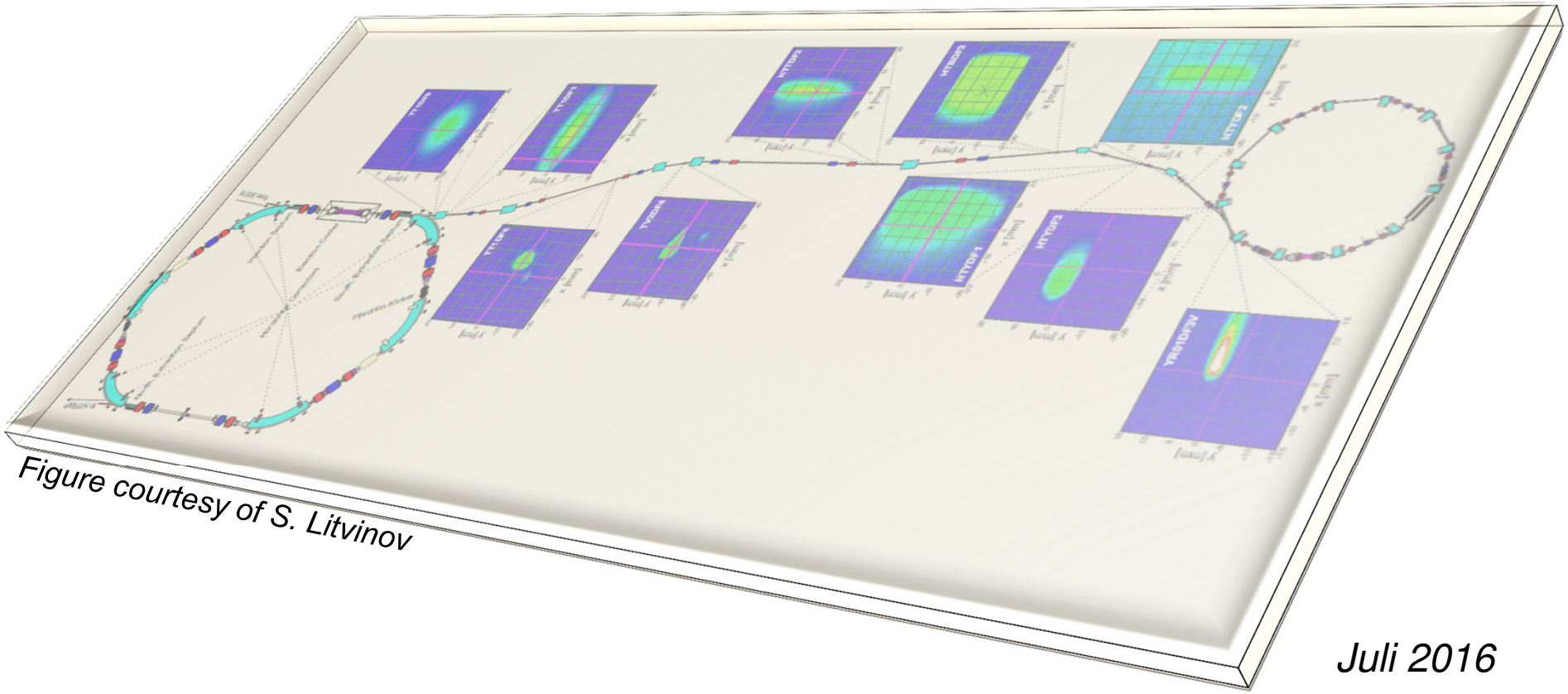
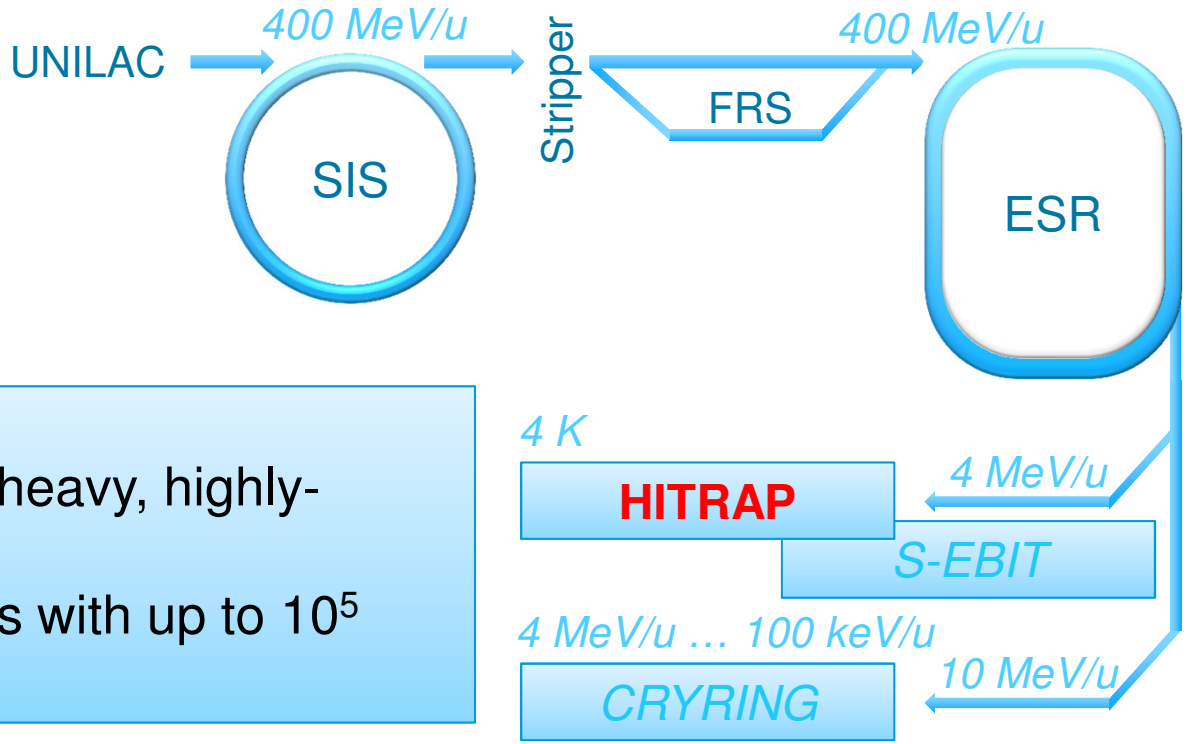


Figure courtesy of S. Litvinov

Juli 2016

Slow, Heavy, Highly Charged Ions @ GSI/FAIR



HITRAP

- A linear decelerator for heavy, highly-charged ions
- A facility for experiments with up to 10^5 ions like U^{91+} or Bi^{82+}

HITRAP

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

400 MeV/u — ESR — *4 MeV/u* — Buncher — *500 keV/u* — IH — RFQ — *6 keV/u* — Trap — Experiments

10 … 60 s

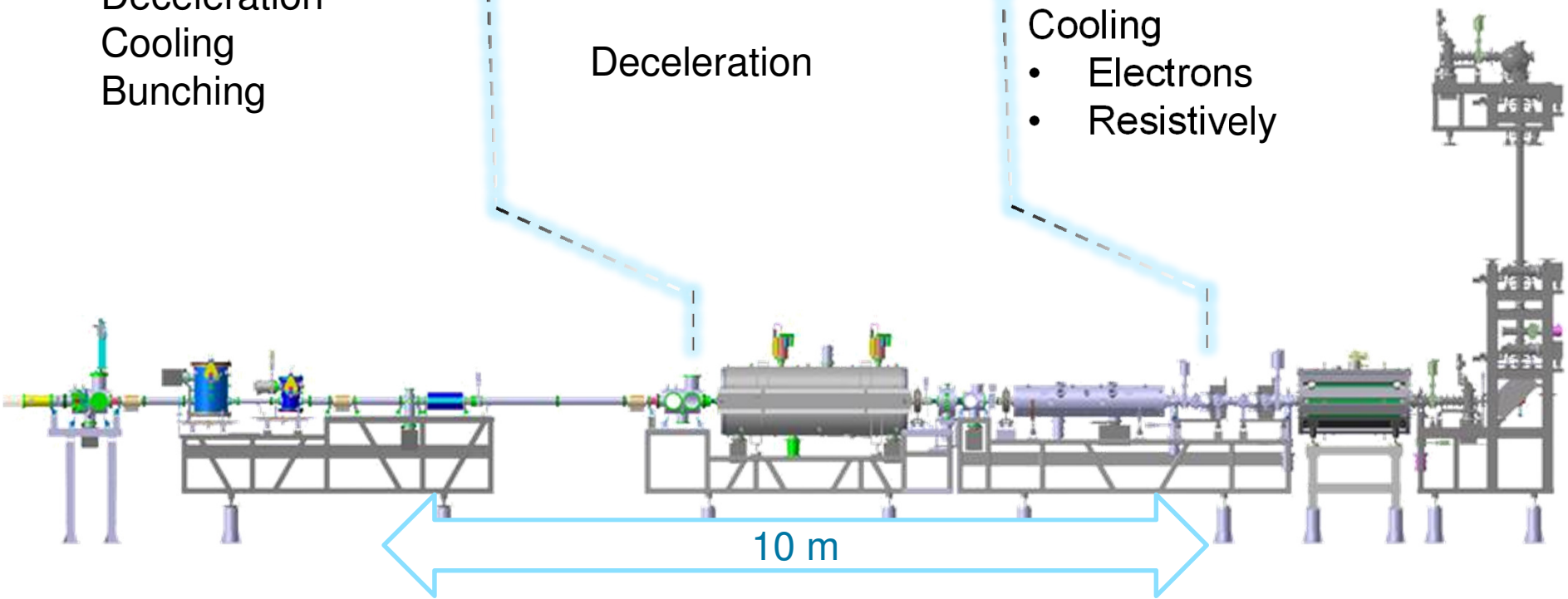
Deceleration
Cooling
Bunching

few µs

Deceleration

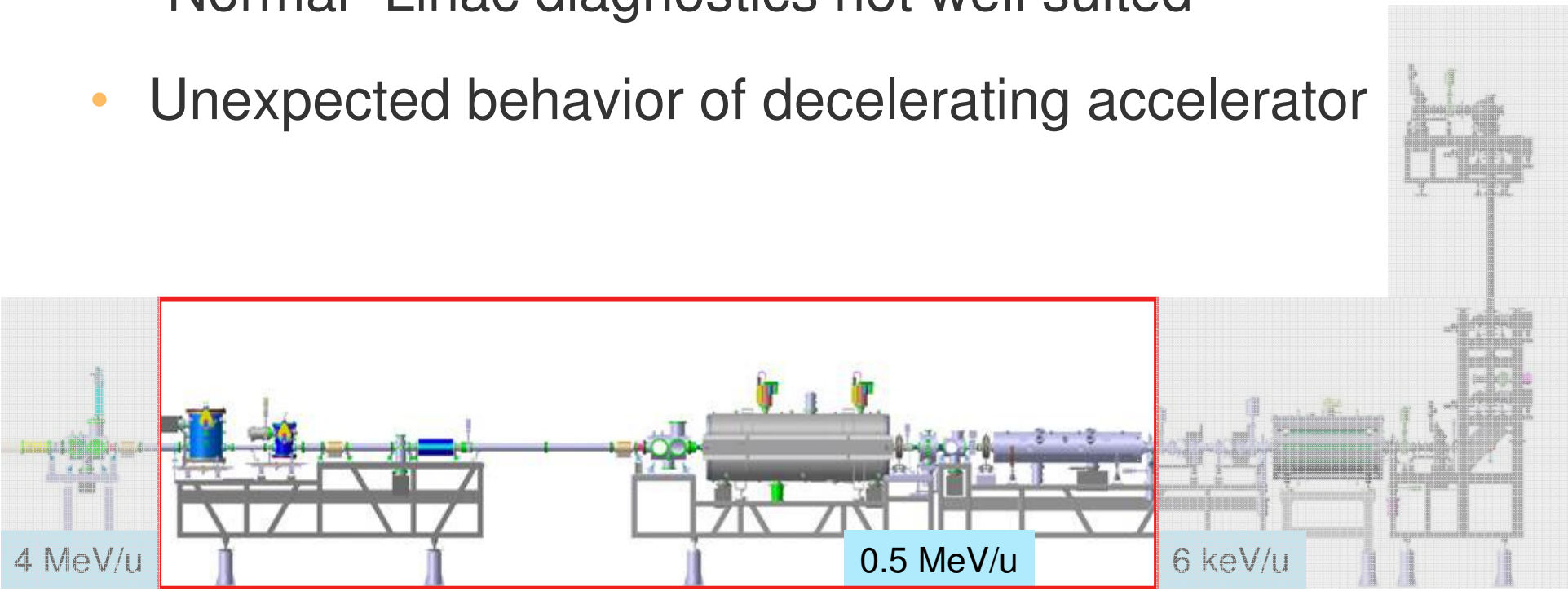
~ 10 s

Capture
Cooling
- Electrons
- Resistively



Challenges

- Never done before!
- 1 ion pulse with only 10^6 ions every 30 to 60 seconds
- “Normal” Linac diagnostics not well suited
- Unexpected behavior of decelerating accelerator



HITRAP Timeline

Start of Budget

Restart of SIS/ESR

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

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

2004 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | ... | 2017

IH Retuning

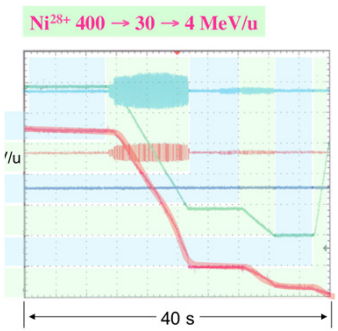
First ions @ 500 keV/u

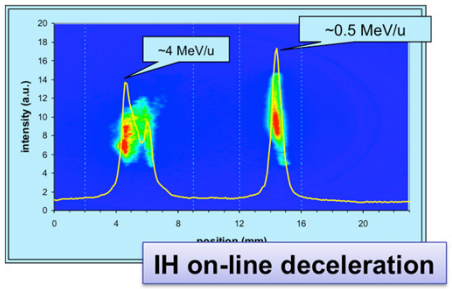
RFQ installed, beam transmitted

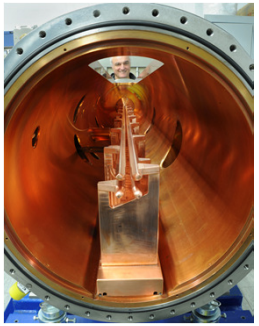
RFQ Reconstruction

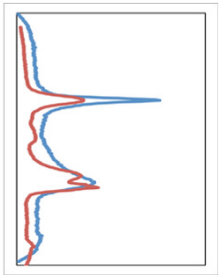
RFQ Offline Tests at MPI-K Heidelberg

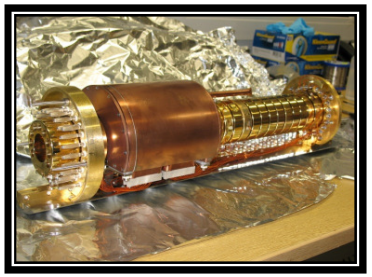
First ions @ 6 keV/u



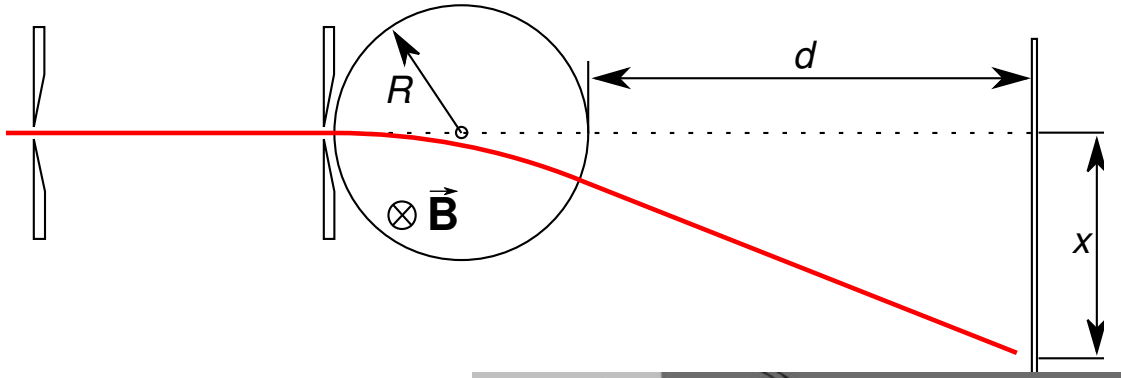


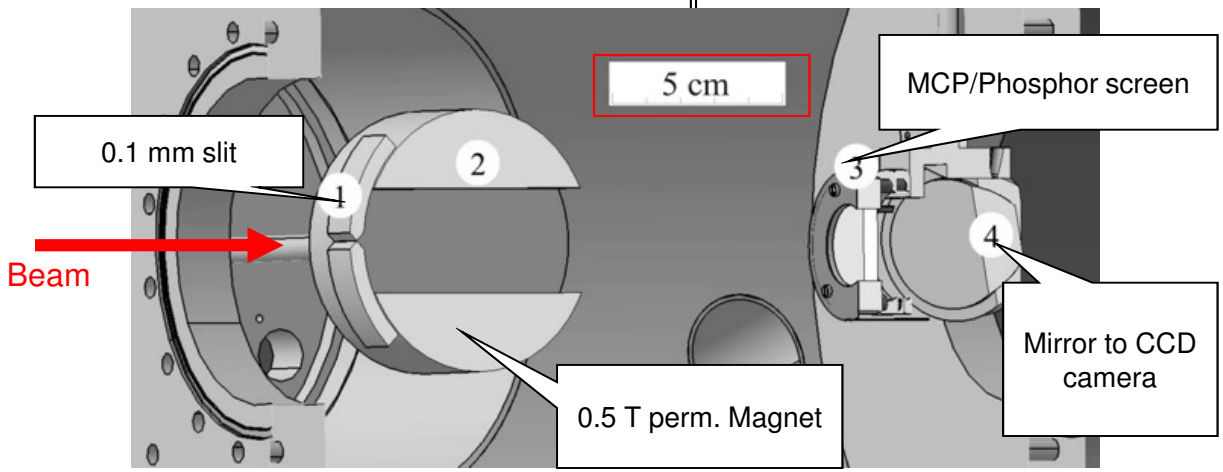




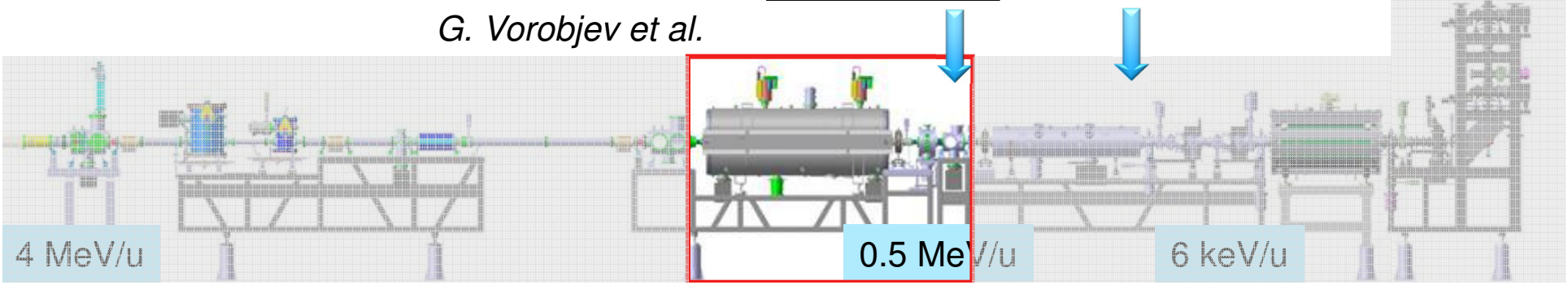


One Shot Energy Analyzer

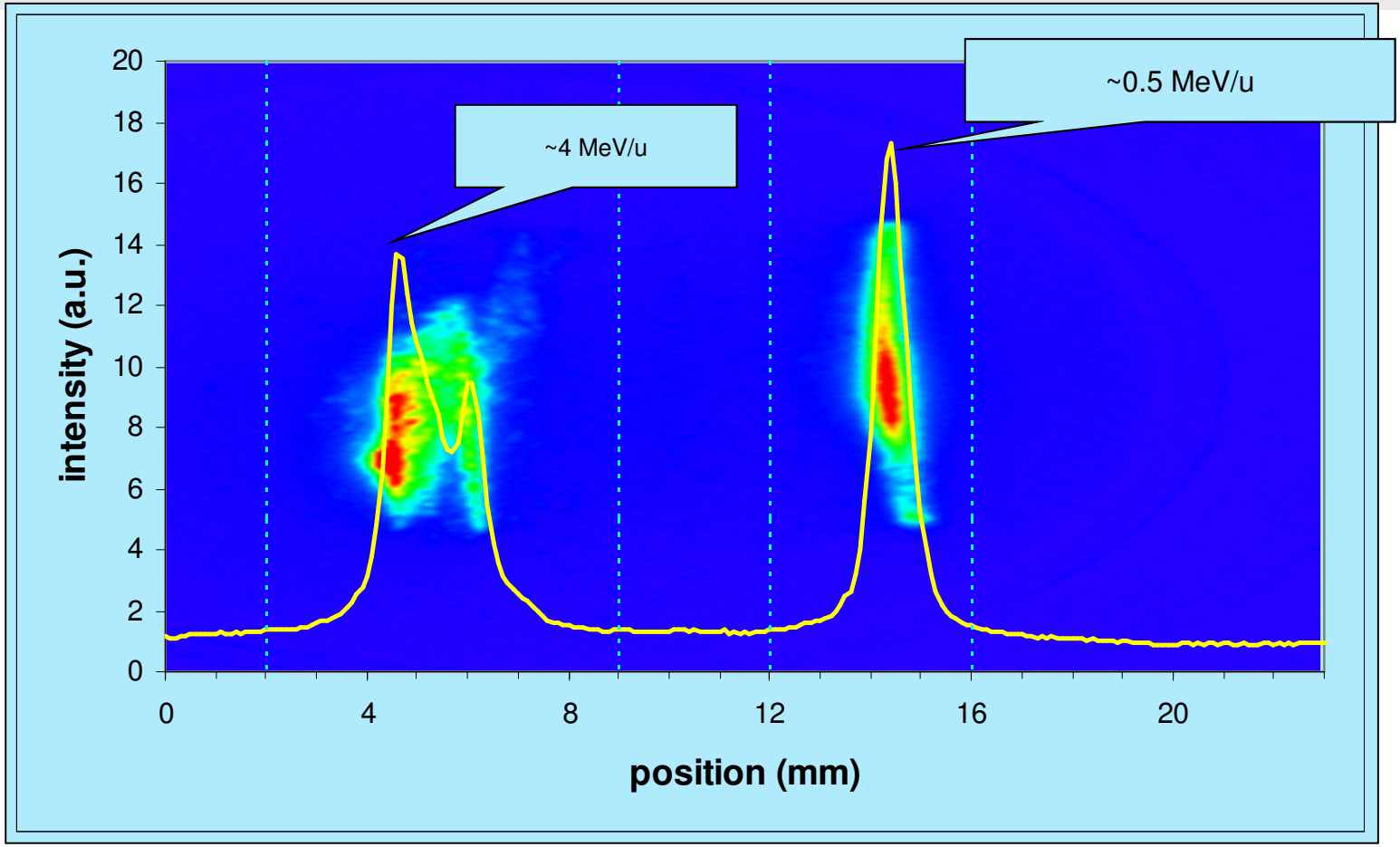




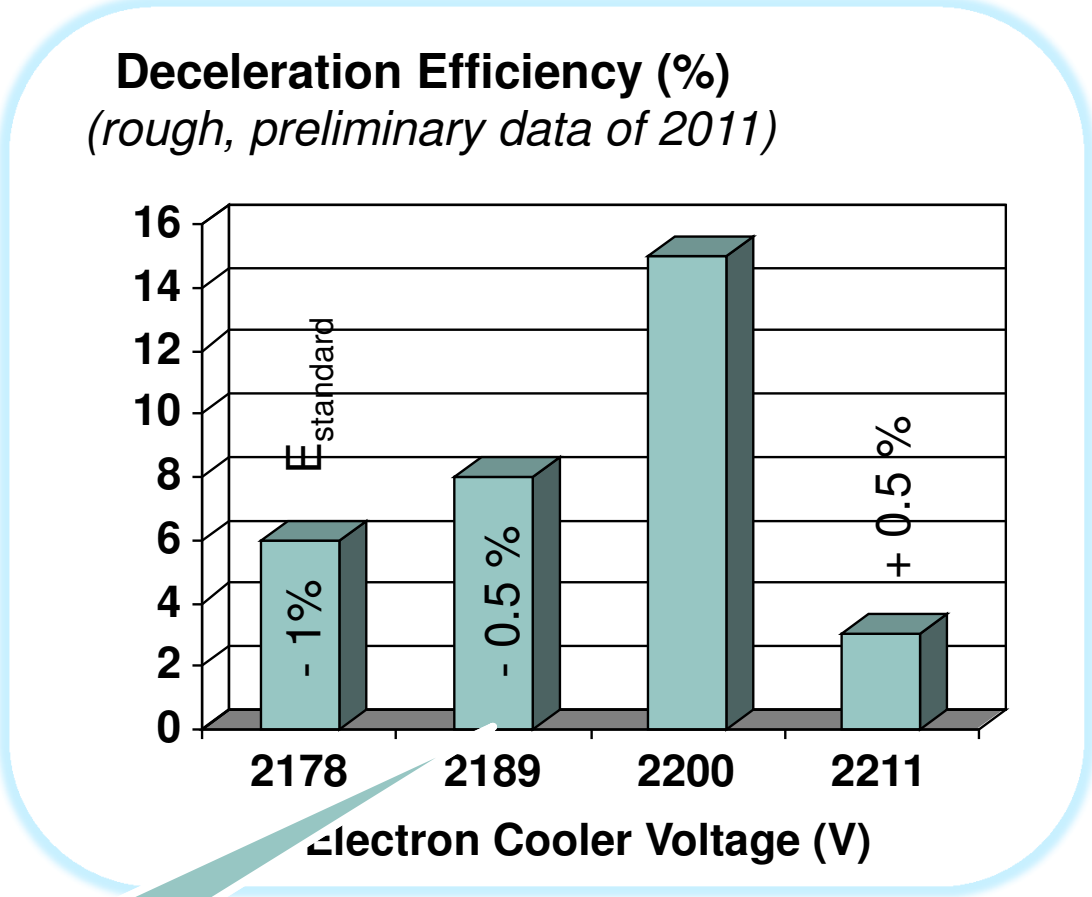
G. Vorobjev et al.



Decelerated Ions after the IH

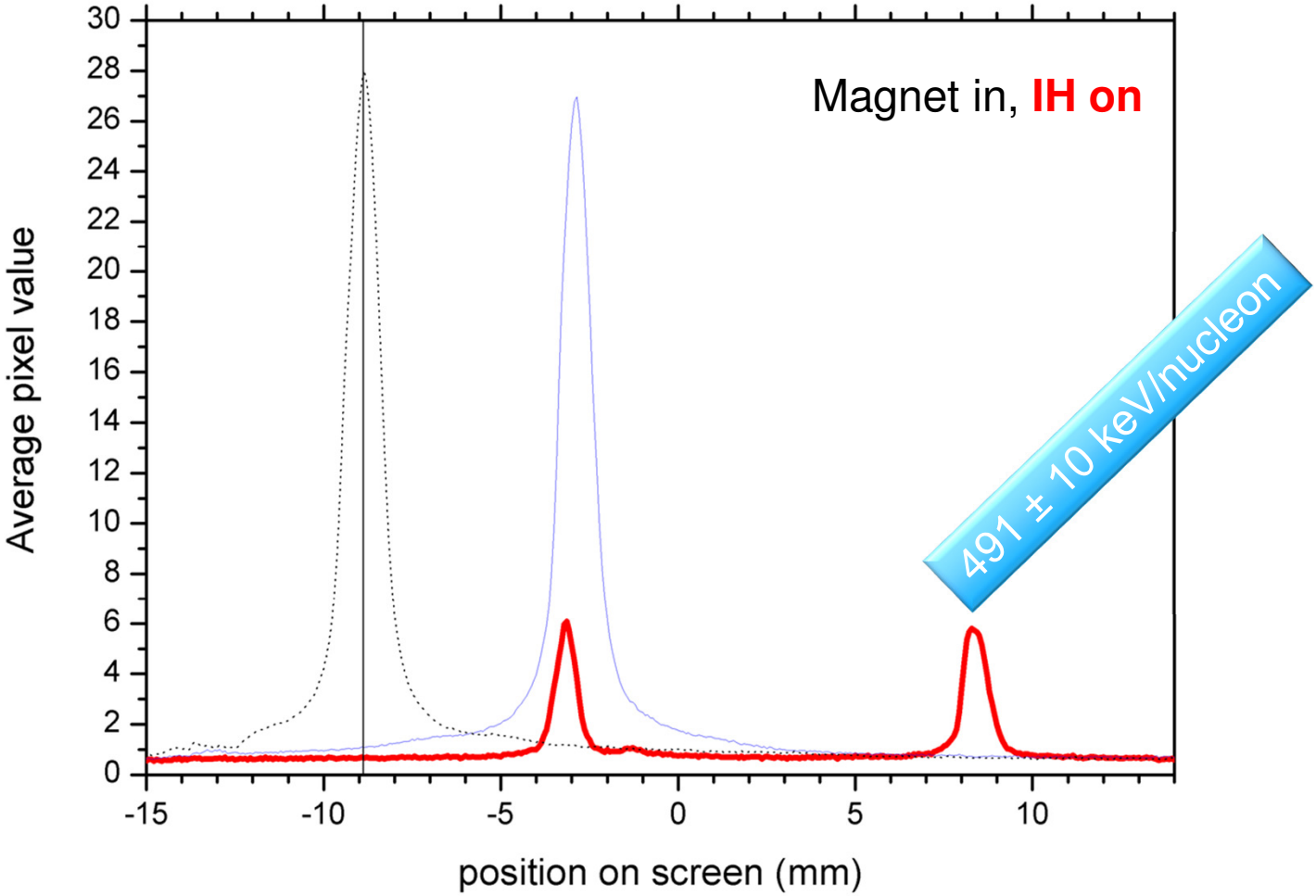


Input Energy Acceptance of IH



4024 keV/nucleon

IH Output Energy



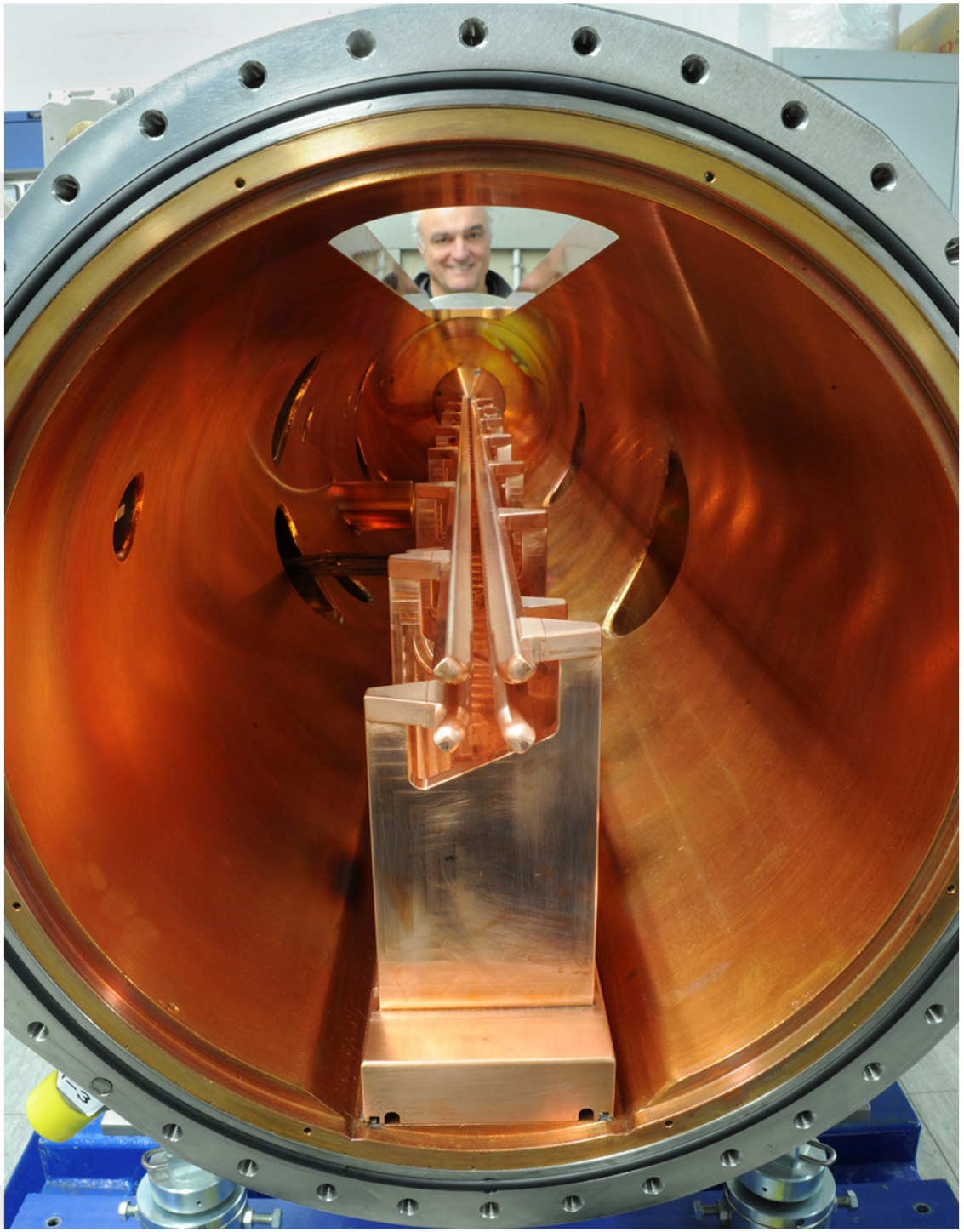
Measured during on-line commissioning in spring 2012

The RFQ

- RFQ Test off-line at MPI-K Heidelberg
  - Energy mismatch

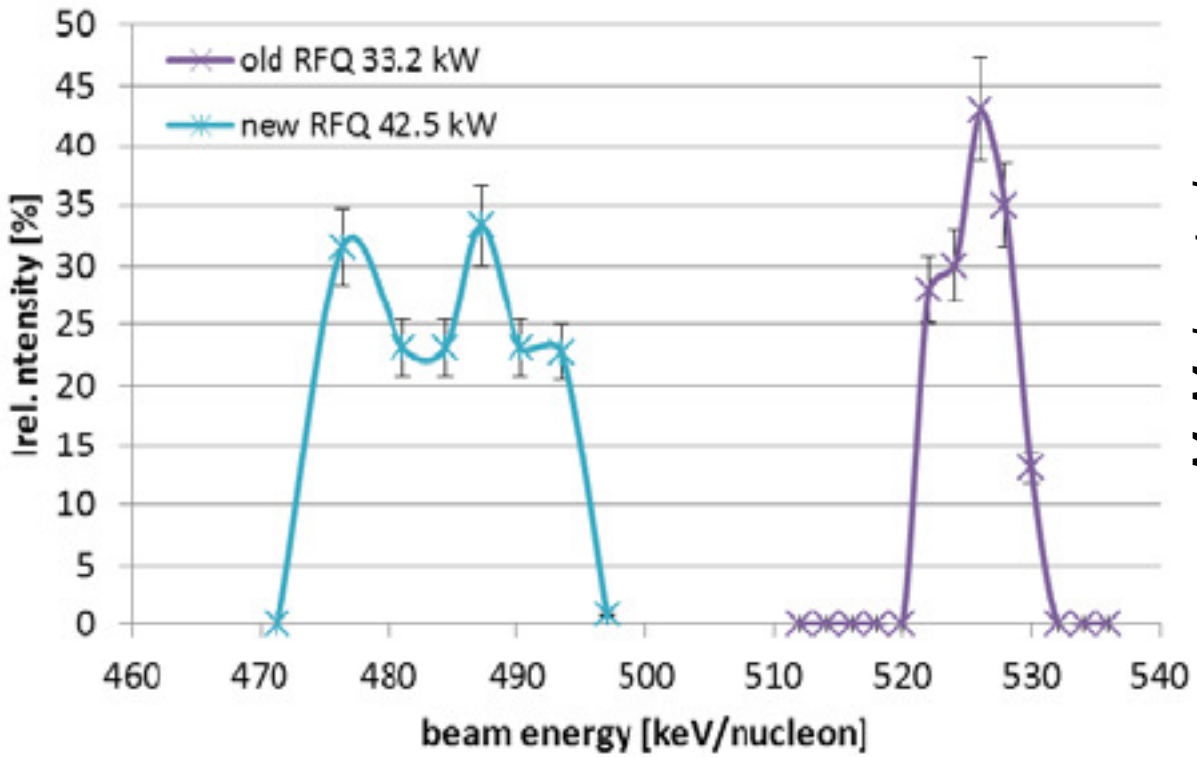
Need new RFQ!

- New Electrodes calculated (*S. Yaramyshev*)/machined (*GSI workshop*)
  - Wider energy acceptance
  - Completely new alignment concept

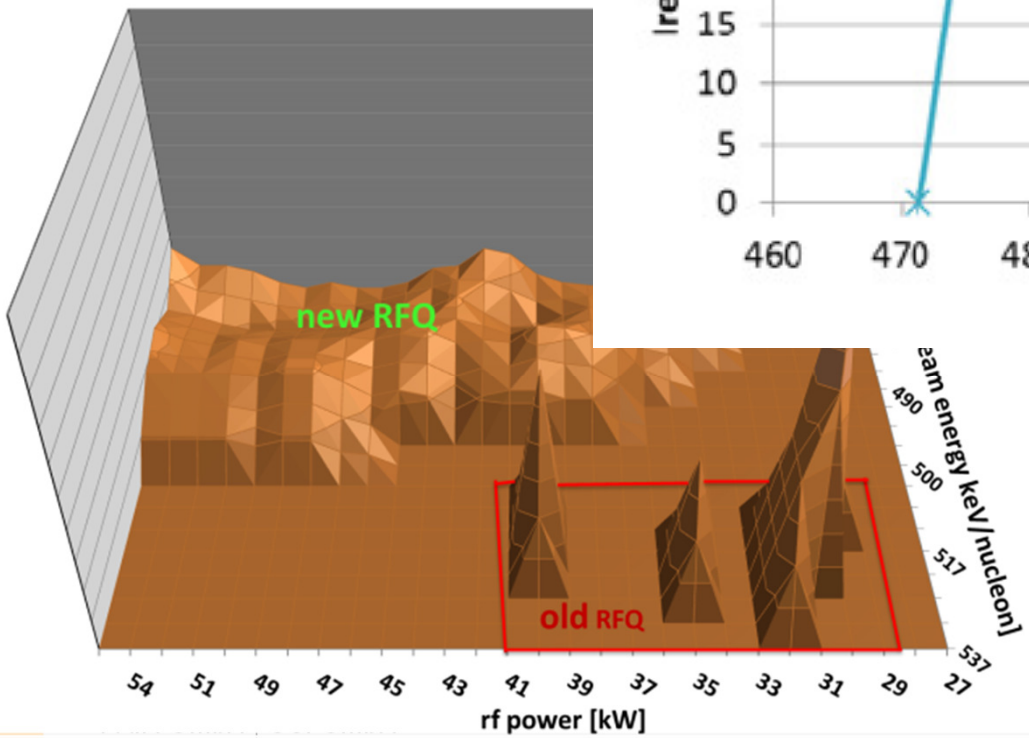


Results for new RFQ Electrodes

December 2012
(at MPI-K in Heidelberg)

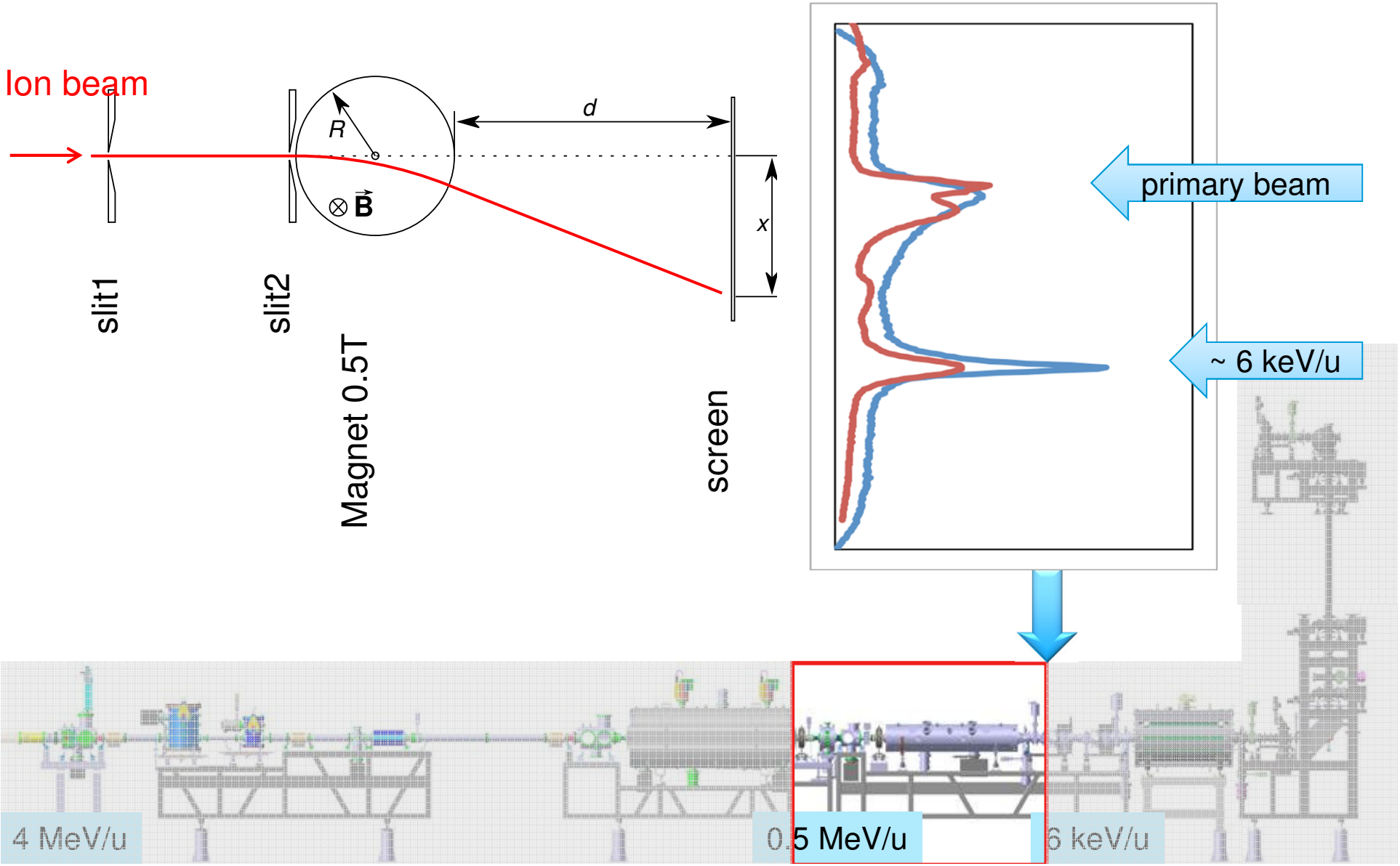


M. Maier et al.



- Energy acceptance increased
- More robust operation

Deceleration from 4 MeV/u to 6 keV/u



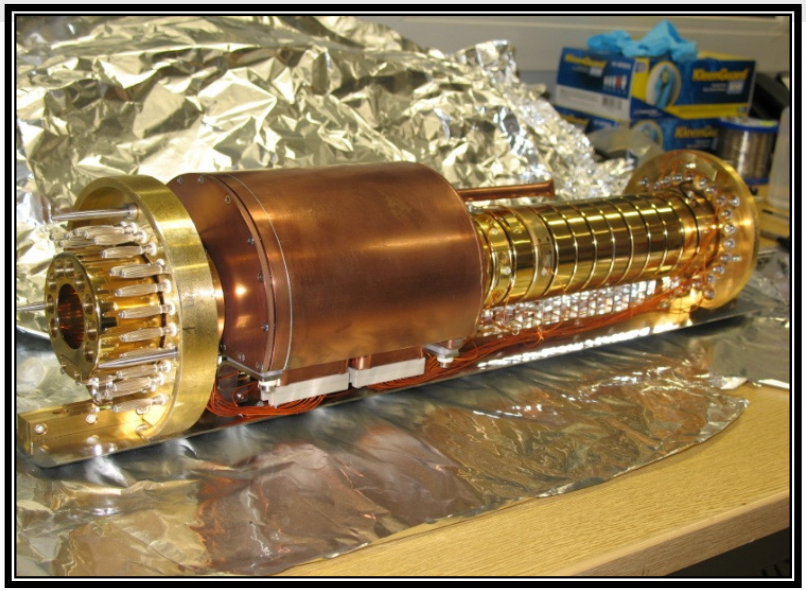
The HITRAP Cooling Penning Trap - Challenges

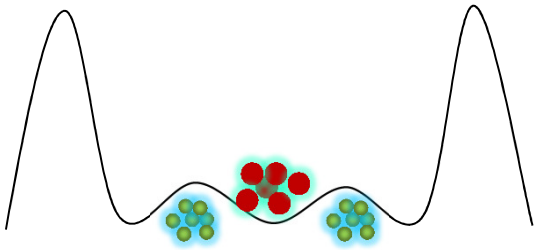
UHV 10^{-13} mbar

20 kV

4 K

6 T





electron & resistive cooling down to 4K

ion start E~15 keV/q

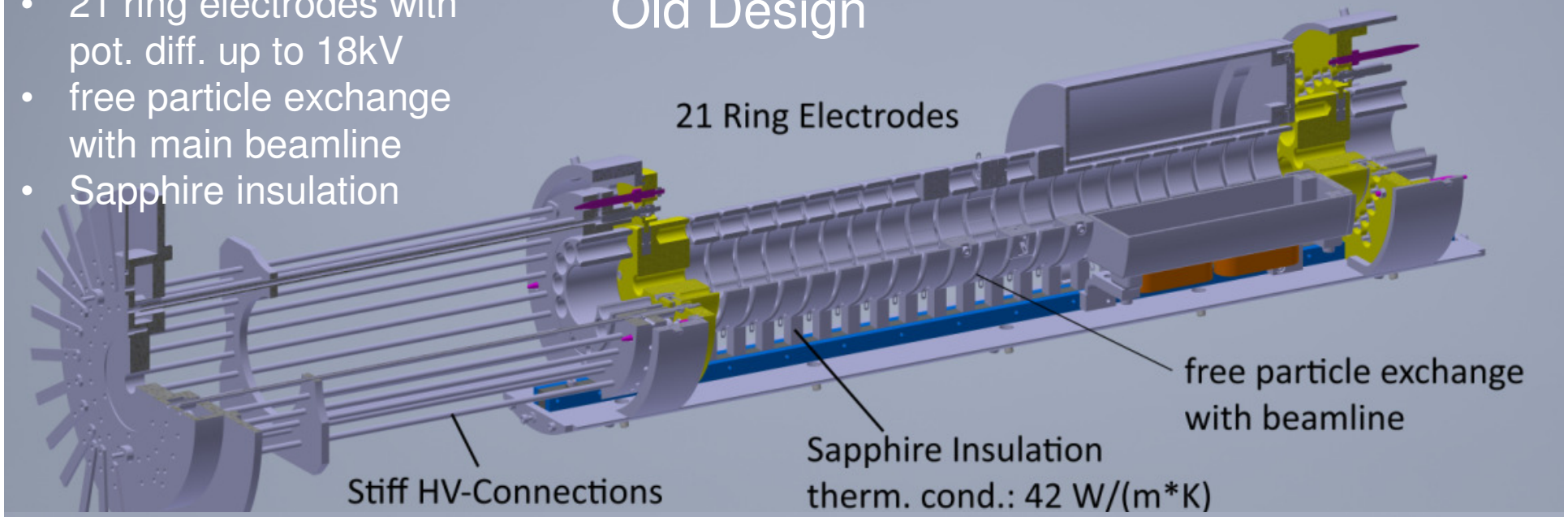
ion final E~1 meV

up to 10^5 U^{+92} ions

tens of seconds storage time

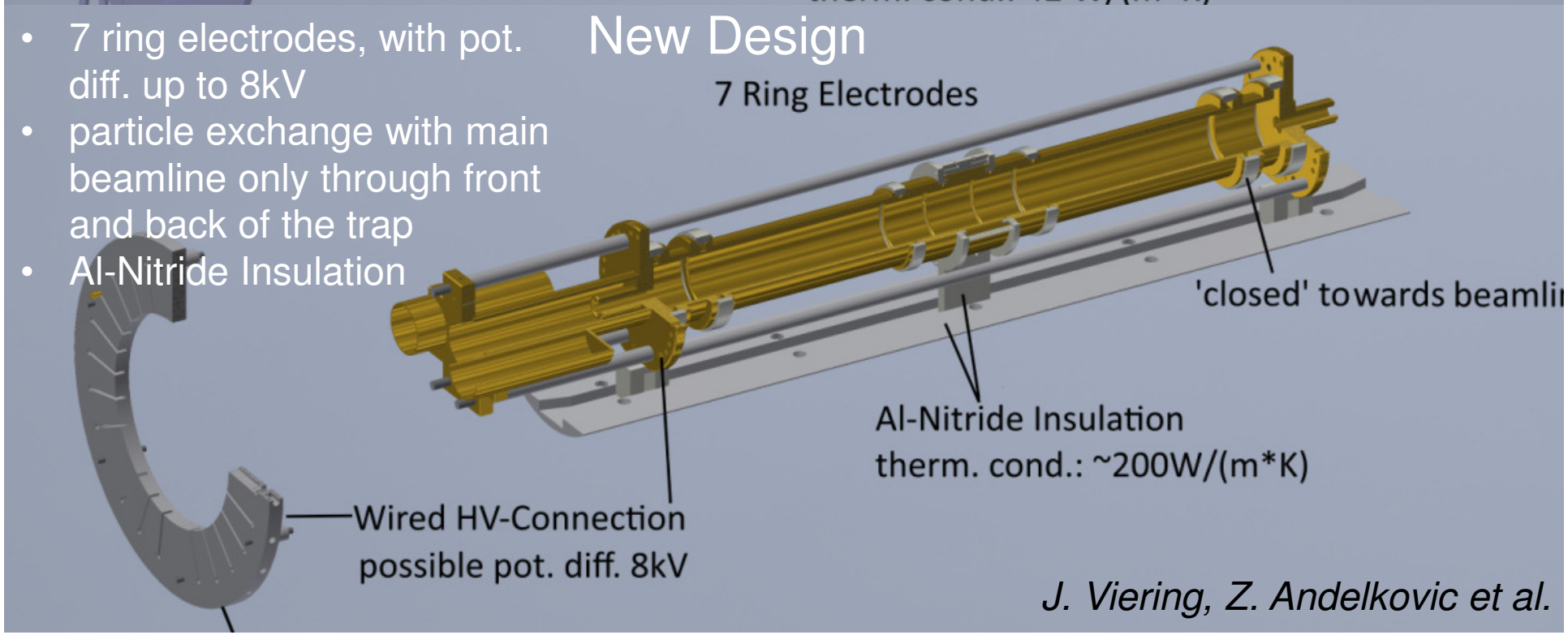
Old Design

- 21 ring electrodes with pot. diff. up to 18kV
- free particle exchange with main beamline
- Sapphire insulation



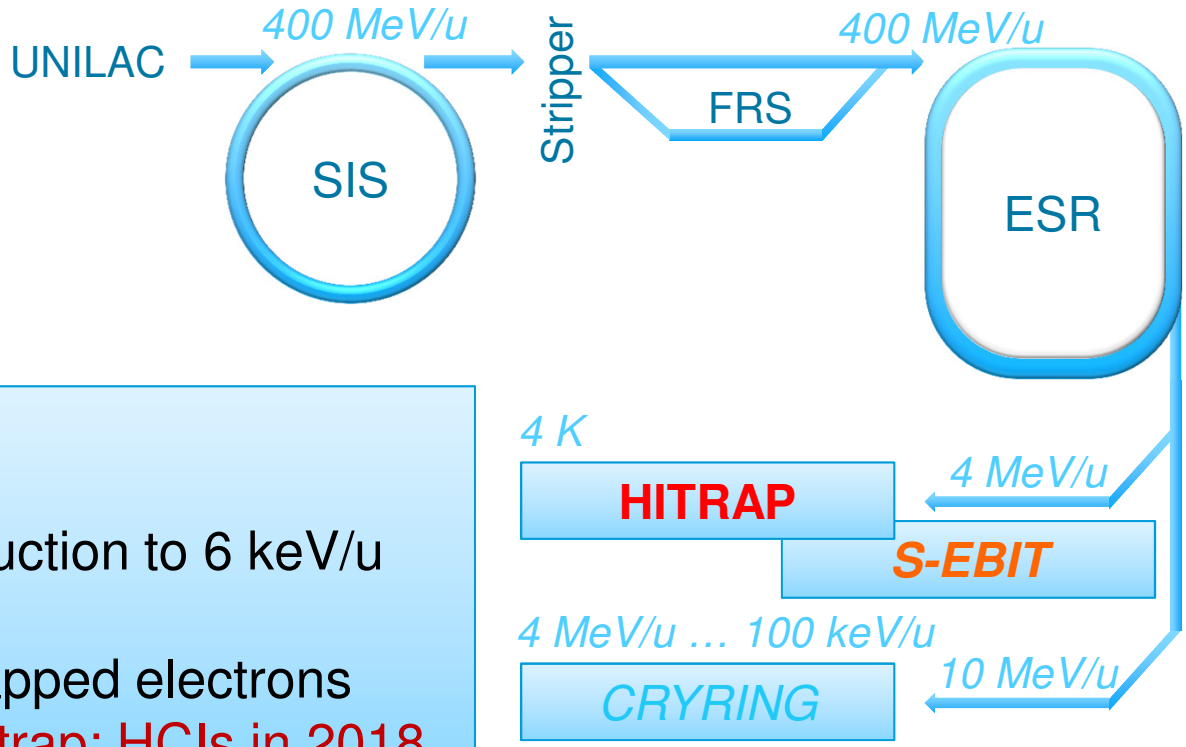
New Design

- 7 ring electrodes, with pot. diff. up to 8kV
- particle exchange with main beamline only through front and back of the trap
- Al-Nitride Insulation



J. Viering, Z. Andelkovic et al.

Slow, Heavy, Highly Charged Ions @ GSI/FAIR

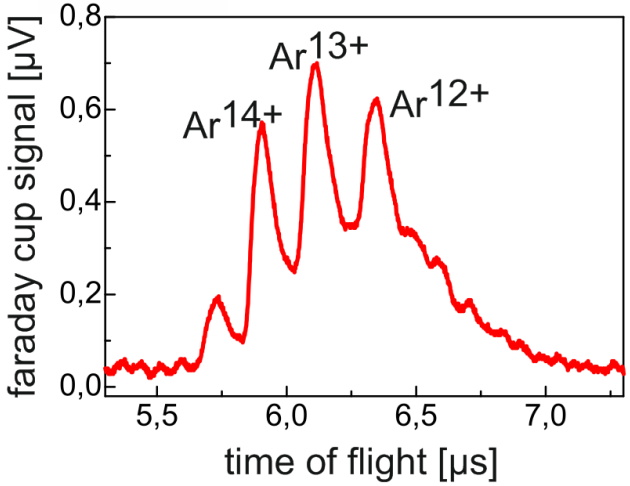


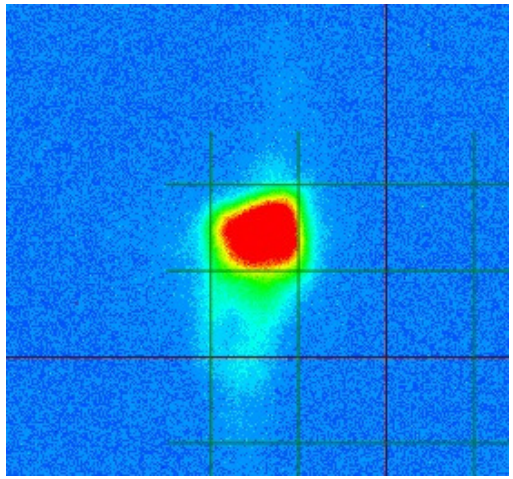
HITRAP Facility Status

- Deceleration from production to 6 keV/u achieved
- Trapped ions offline, trapped electrons
- Next step: New, robust trap; HCIs in 2018

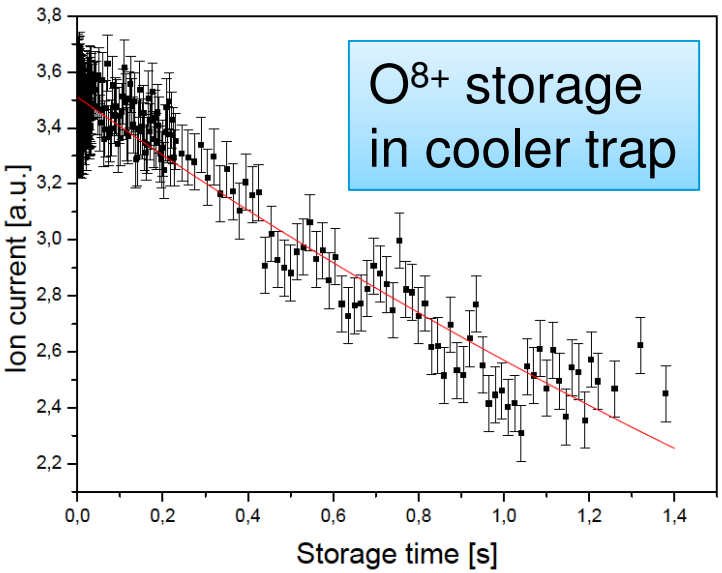
An EBIT to produce light HCI

Charge breeding





beam after 10 m

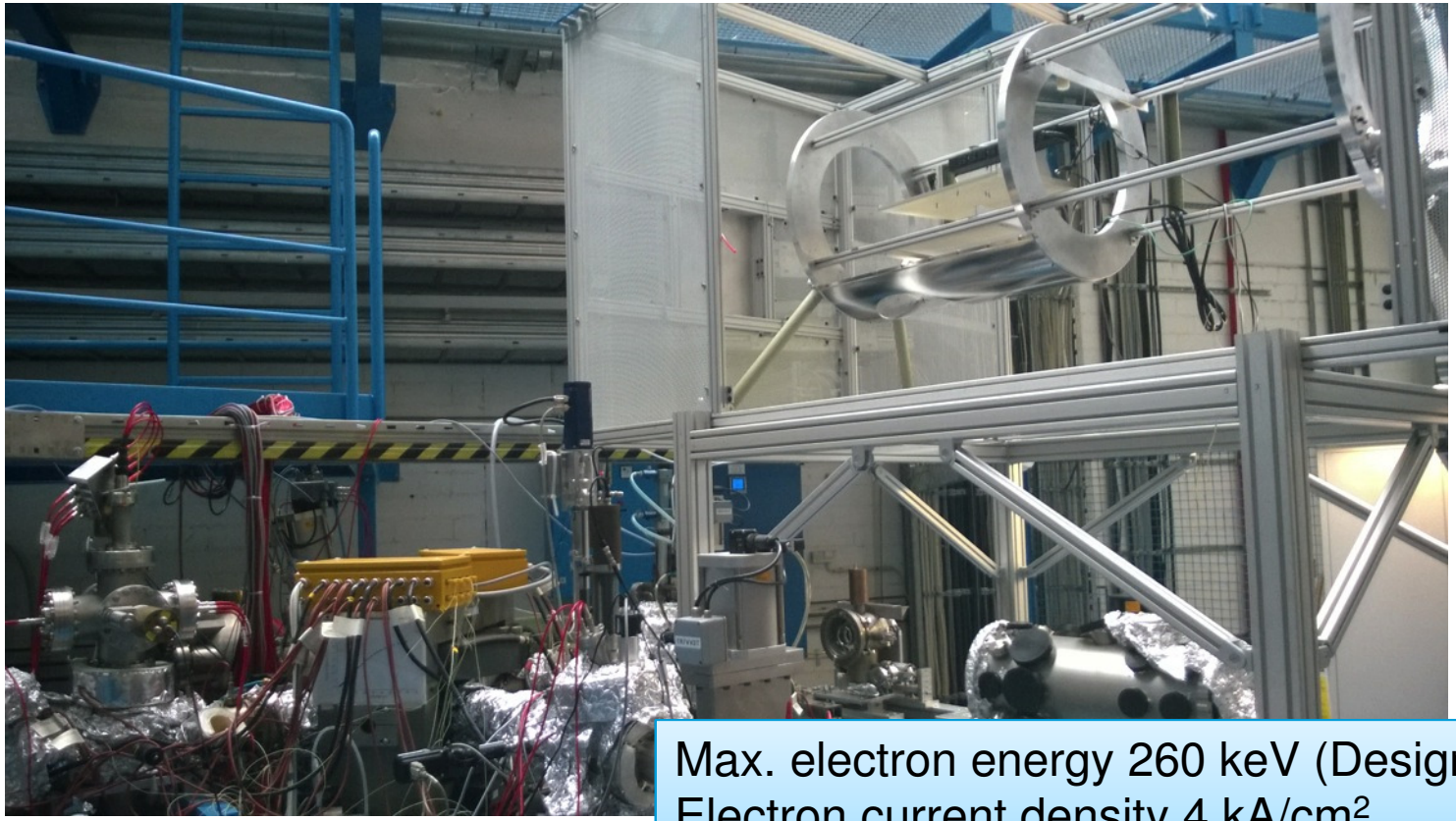


Characteristics of the HITRAP exp. LEB	
beam energy	2-10 keV/q
beam size	~ 5 mm
transport efficiency	up to 95%
charge states	up to ~ 44+
ion species (DREEBIT)	Ar, Xe, Kr, O, C, K, Ca, ...

Preparing for S-EBIT

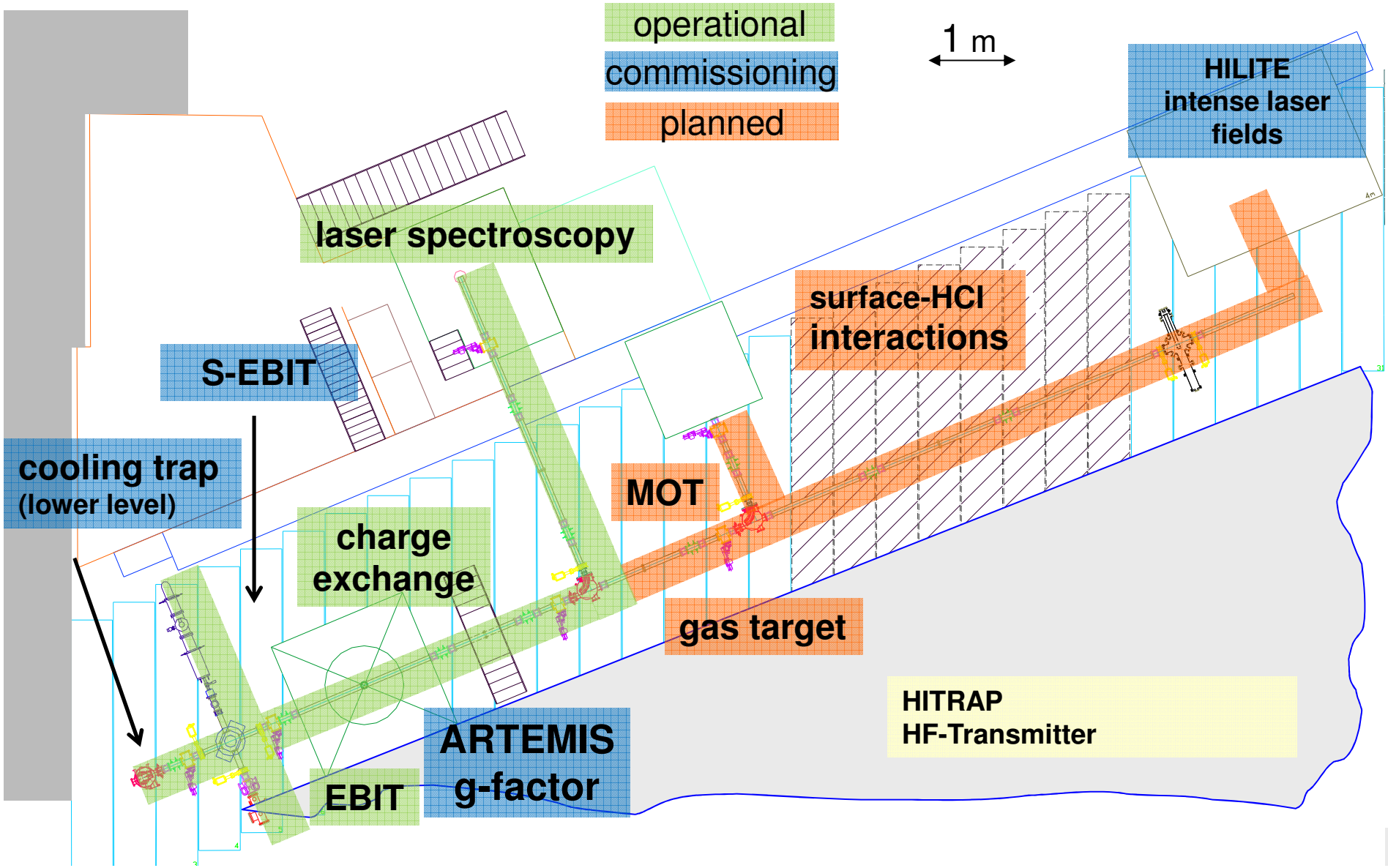
S. Trotsenko

Loan from Helmholtzinstitute Jena (HIJ), Originally from Stockholm Univ. (R. Schuch et al.)

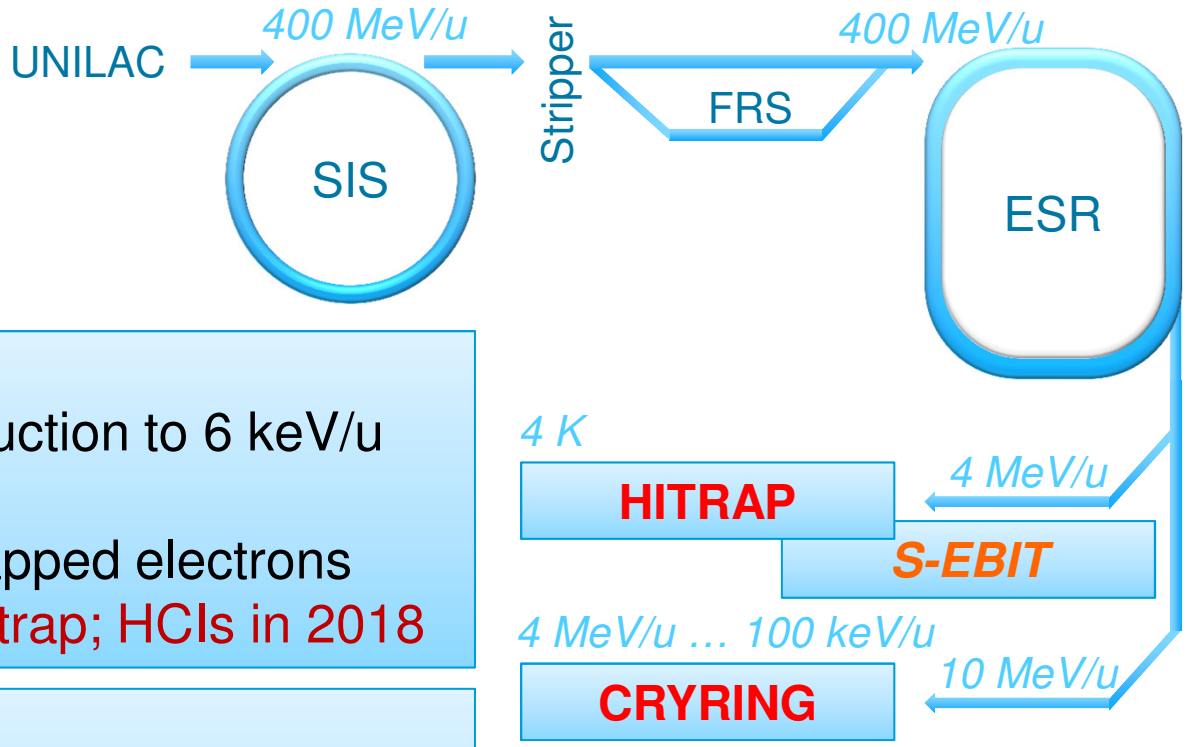


Max. electron energy 260 keV (Design Goal)
Electron current density 4 kA/cm^2
Ion capacity – 10^8 charges

HITRAP Experimental Area



Slow, Heavy, Highly Charged Ions @ GSI/FAIR



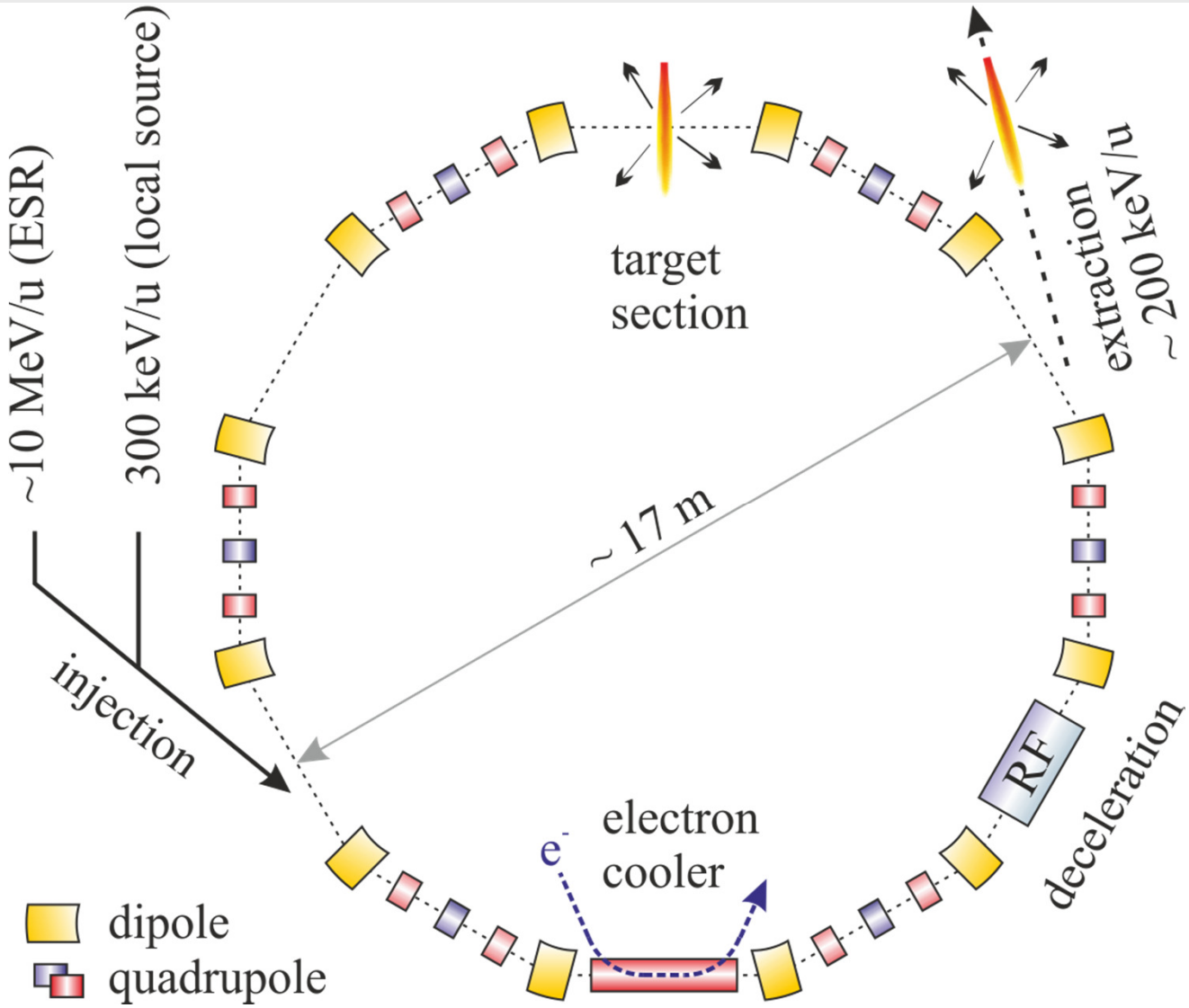
HITRAP

- Deceleration from production to 6 keV/u achieved
- Trapped ions offline, trapped electrons
- Next step: New, robust trap; HCIs in 2018

CRYRING@ESR

- Low energy storage ring in Stockholm
- In-Kind contribution to FAIR
- Modernized and Reinstalled at ESR (GSI/FAIR)

CRYRING@ESR


~10 MeV/u (ESR)
300 keV/u (local source)
injection
target
section
~ 17 m
extraction
~ 200 keV/u
RF
deceleration
electron
cooler
e-
dipole
quadrupole

CRYRING@ESR

- Max. rigidity 1.44 Tm
  - 15 MeV/u U^{92+}
  - 96 MeV/u protons
- Min. rigidity ~ 0.054 Tm
  - 150 keV/u protons

- **FAIR Research & Development**
- Detectors and diagnostic systems
- FAIR type control system
- Training of operators on FAIR type system
- FAIR type safety and radiation monitoring/access system

<u>with real beam</u> (standalone operation during commissioning)

- **Scientific Opportunities**
- Heavy, highly-charged ions as 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 in Stockholm (MSL)

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

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

Positive molecular ions:
H_2^+, HD^+, H_3^+, D_2^+, H_2D^+, ^{3}He
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^+, $N_2O_2^+$, $CH_3OCOH_2^+$, $D_7O_3^+$, $N_3D_{10}^+$, $C_4D_6^+$, $S^{18}O_2^+$, 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^-

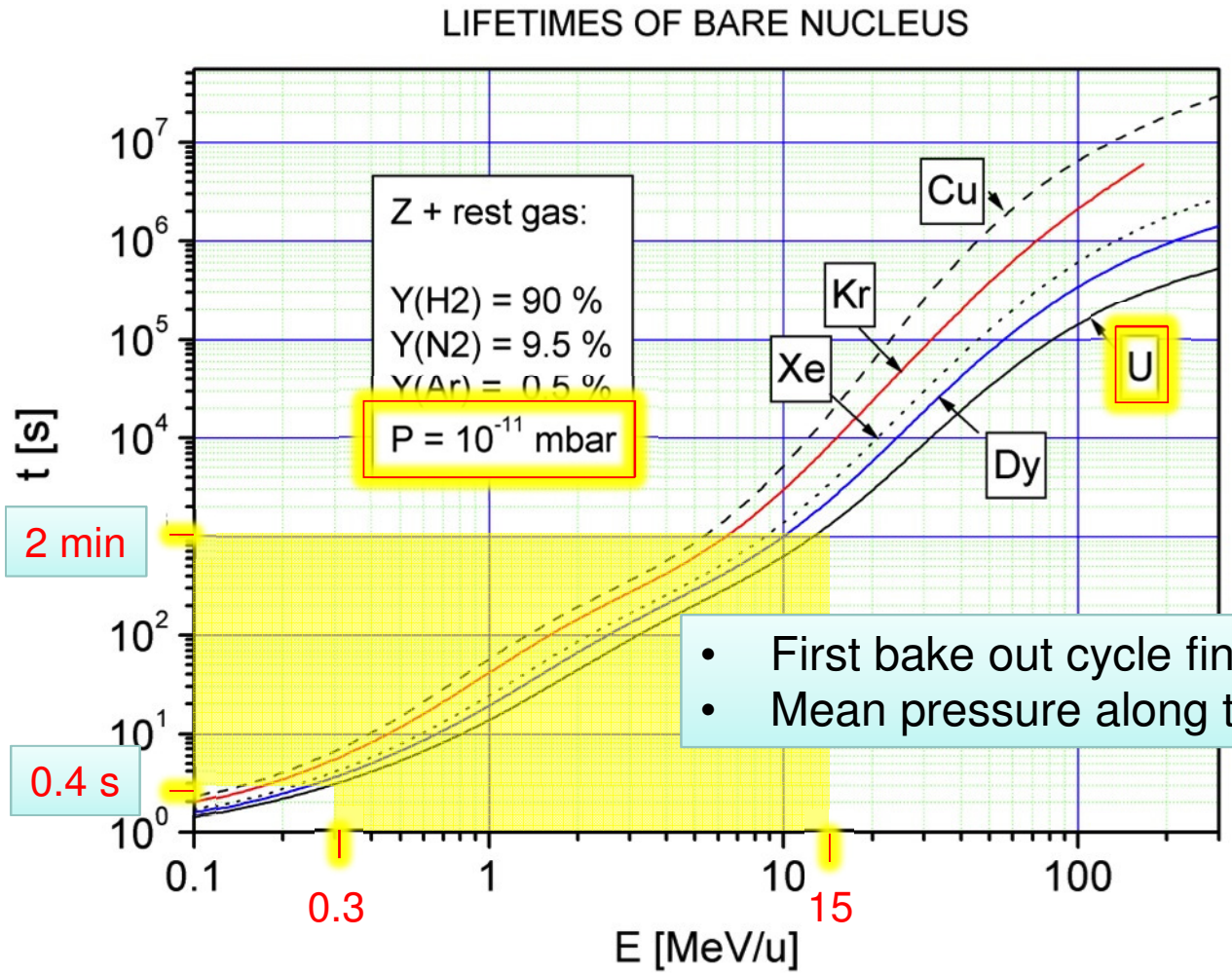
~200 different ion species

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

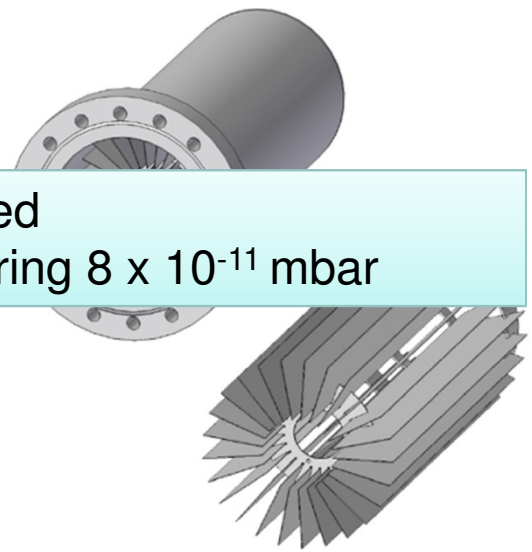
- Successful operated from 1992 to 2010
- Dismantled and shipped to FAIR/GSI in 2012/13

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

Ultra High Vacuum & Beam Life Time



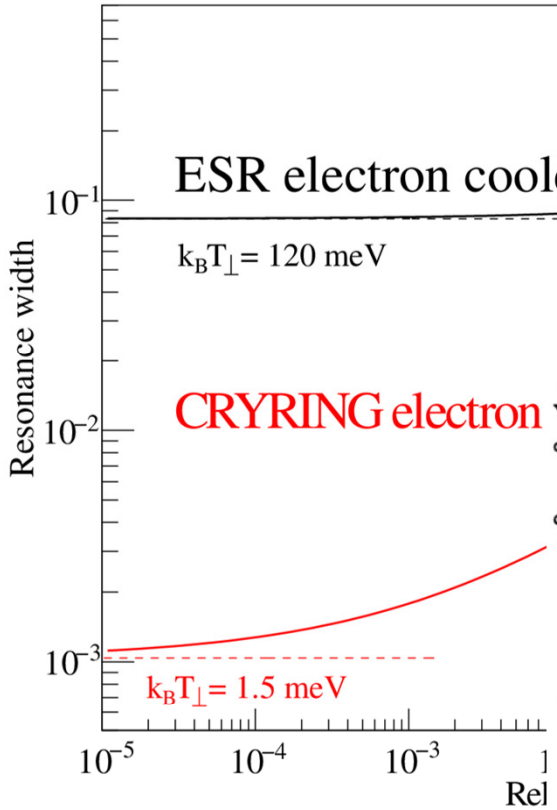
- Ion pumps
  ~ 10
- Cryopumps
- NEG pumps
  ~ 100

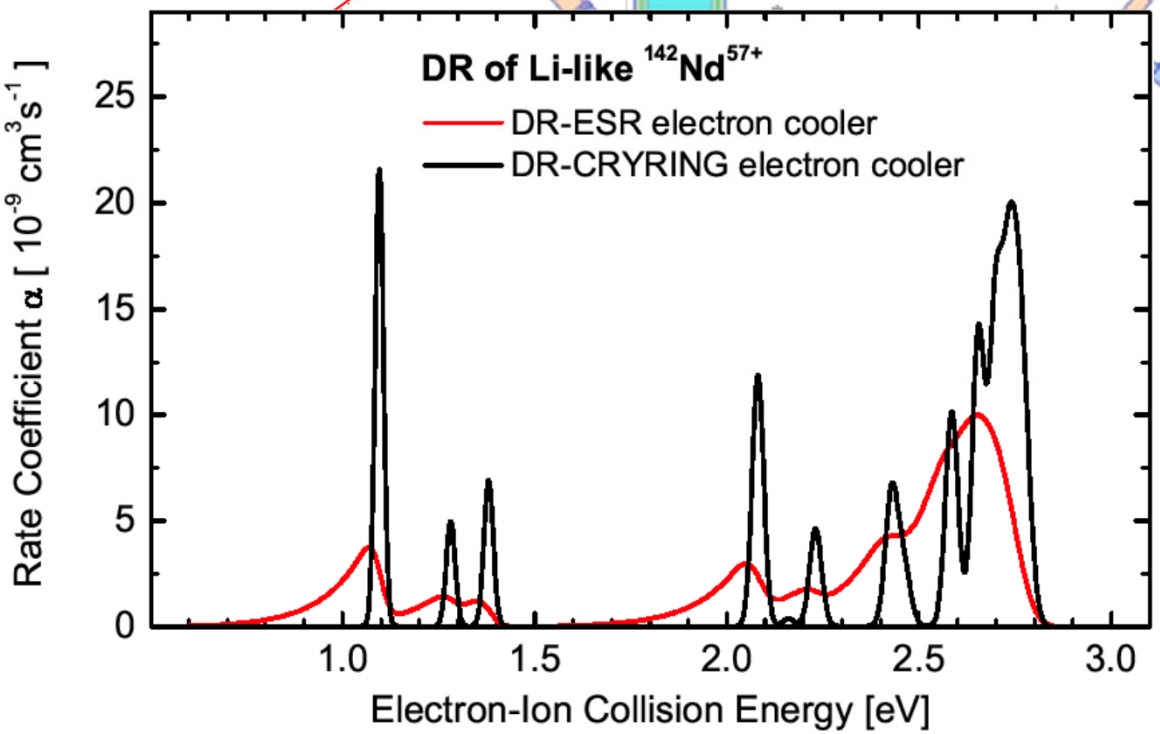


- First bake out cycle finished
- Mean pressure along the ring 8 x 10^{-11} mbar

Electron Cooling ESR - CRYRING

- cathode replaced
- superconducting magnet tested
- bake out done
- commissioning ongoing

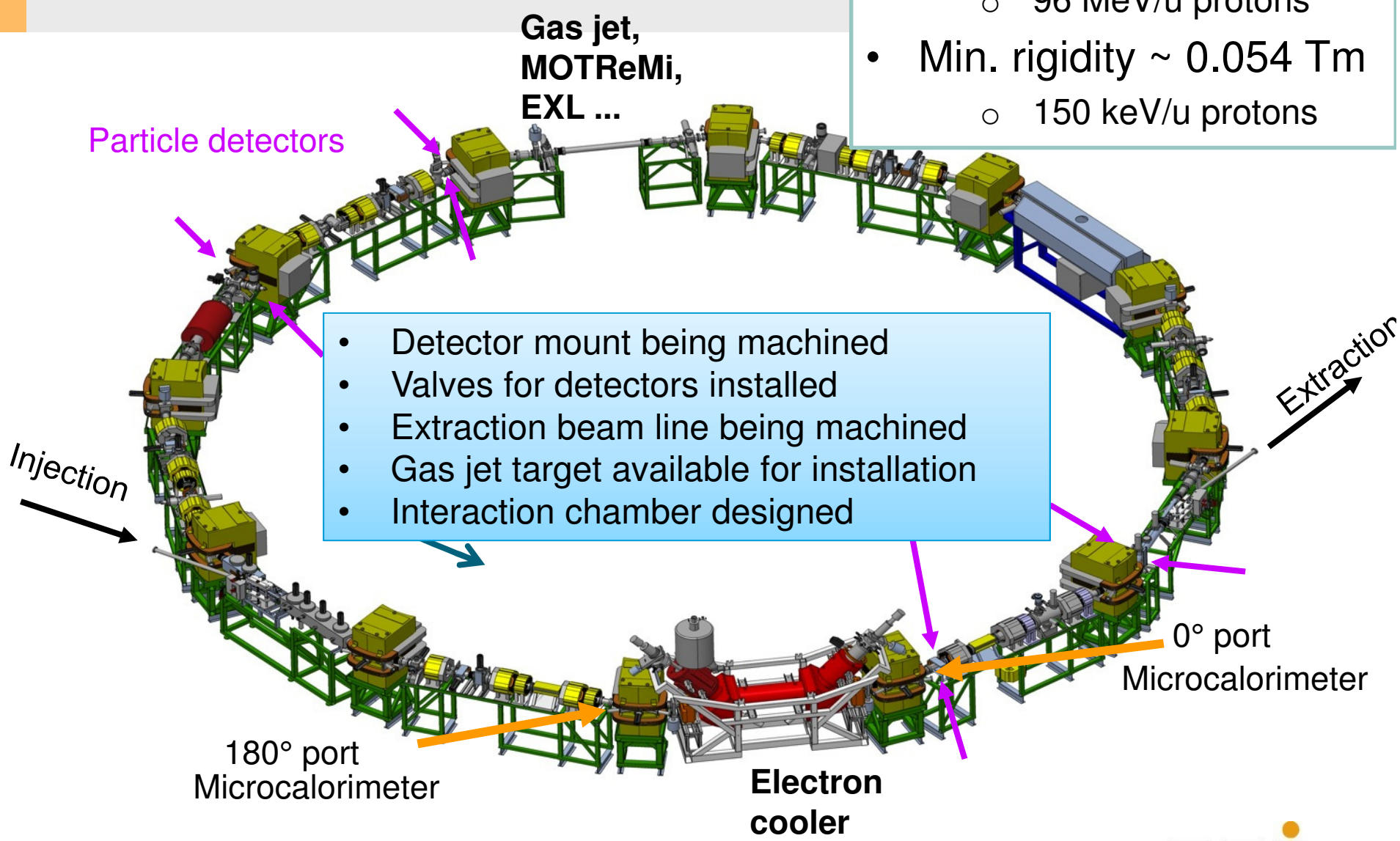




C. Brandau priv. comm.

Experiment Equipment

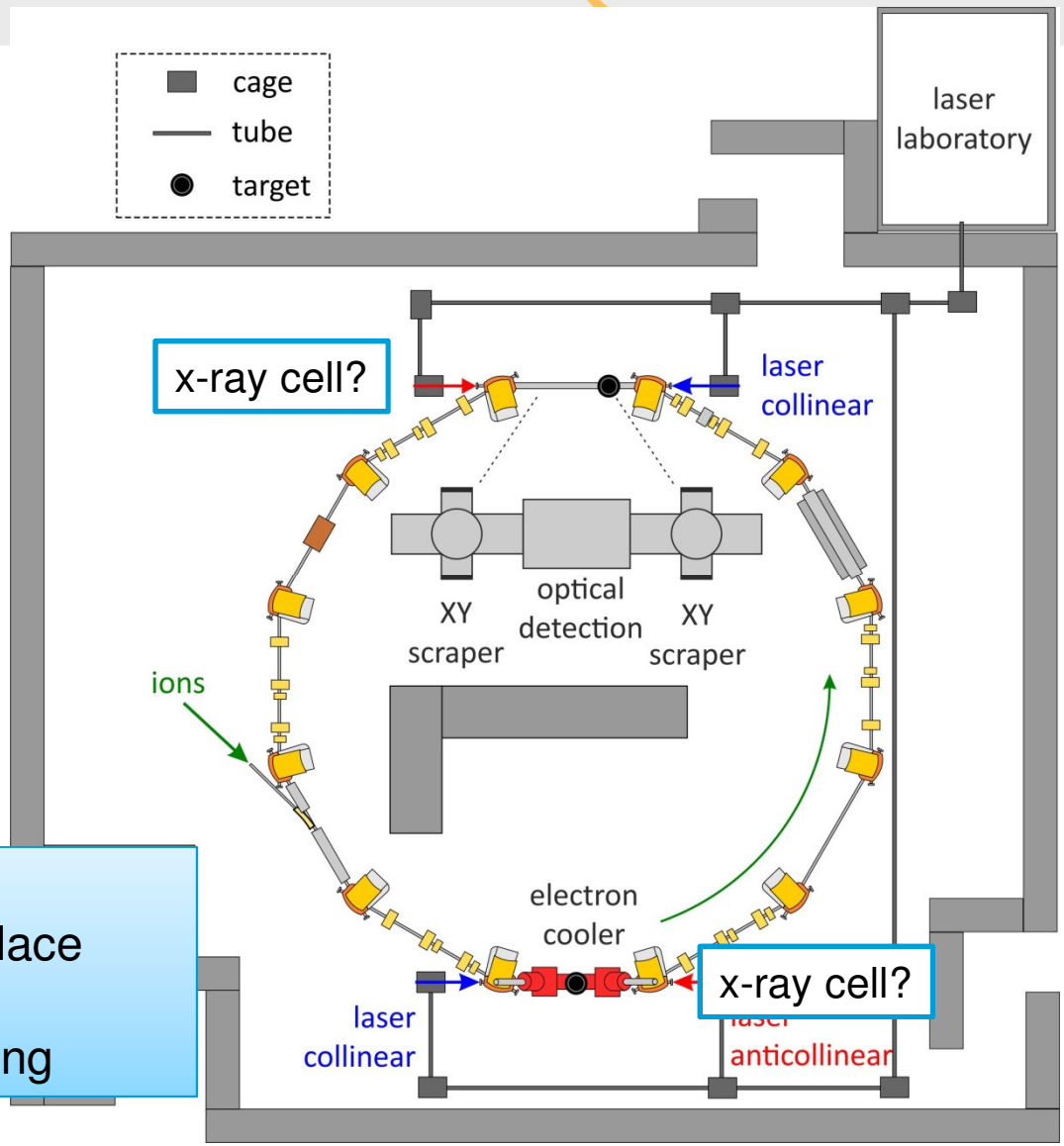
- Max. rigidity 1.44 Tm
  - 15 MeV/u U^{92+}
  - 96 MeV/u protons
- Min. rigidity ~ 0.054 Tm
  - 150 keV/u protons



- Detector mount being machined
- Valves for detectors installed
- Extraction beam line being machined
- Gas jet target available for installation
- Interaction chamber designed

Laser Experiments - CRYRING@ESR

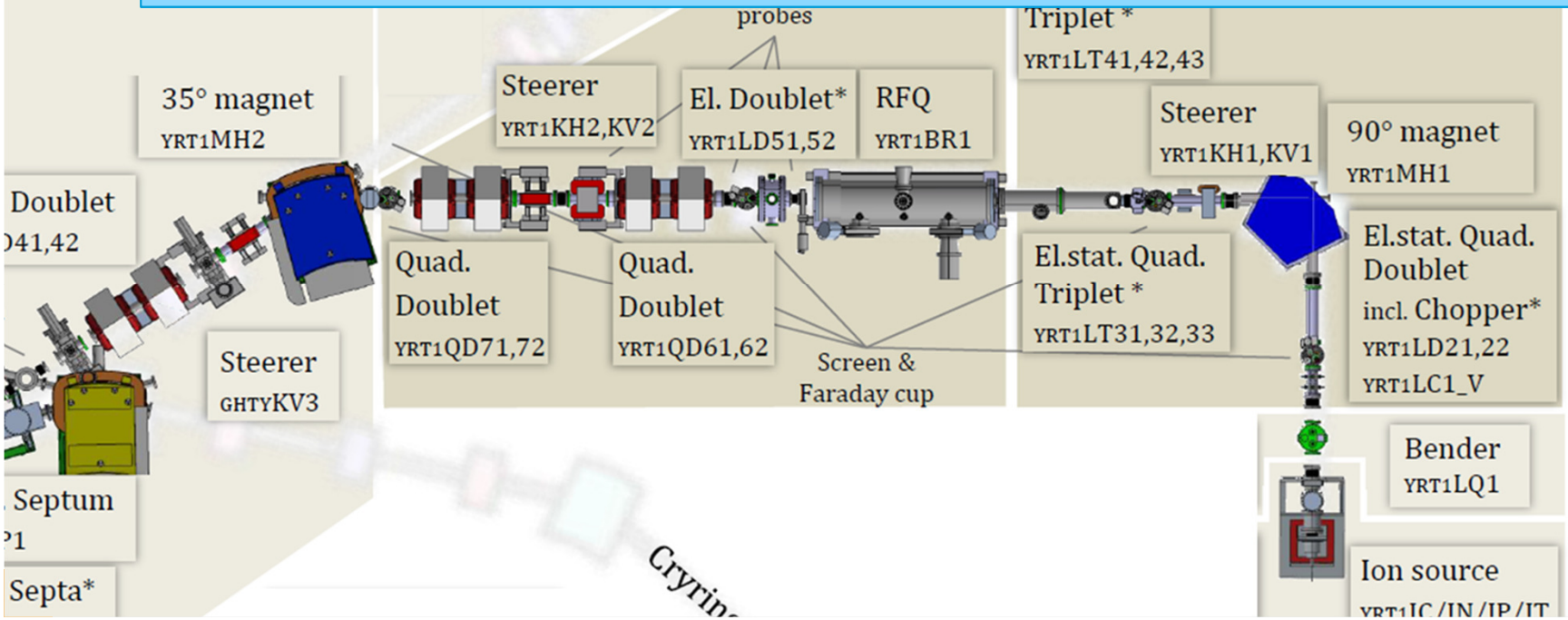
- Dielectronic recombination assisted laser spectroscopy
- Preparation of polarized ion beams in a storage ring
- …
- Start with
  - $^{24,25}Mg^{+}$
  - $^{9}Be^{+}$
  - …
  - H and Li like Pr, Pb, and Bi



- Laser lab infrastructure ready
- First parts of laser beam line in place
- Detection chamber in production
- Development of ion source ongoing

Local Ion Source

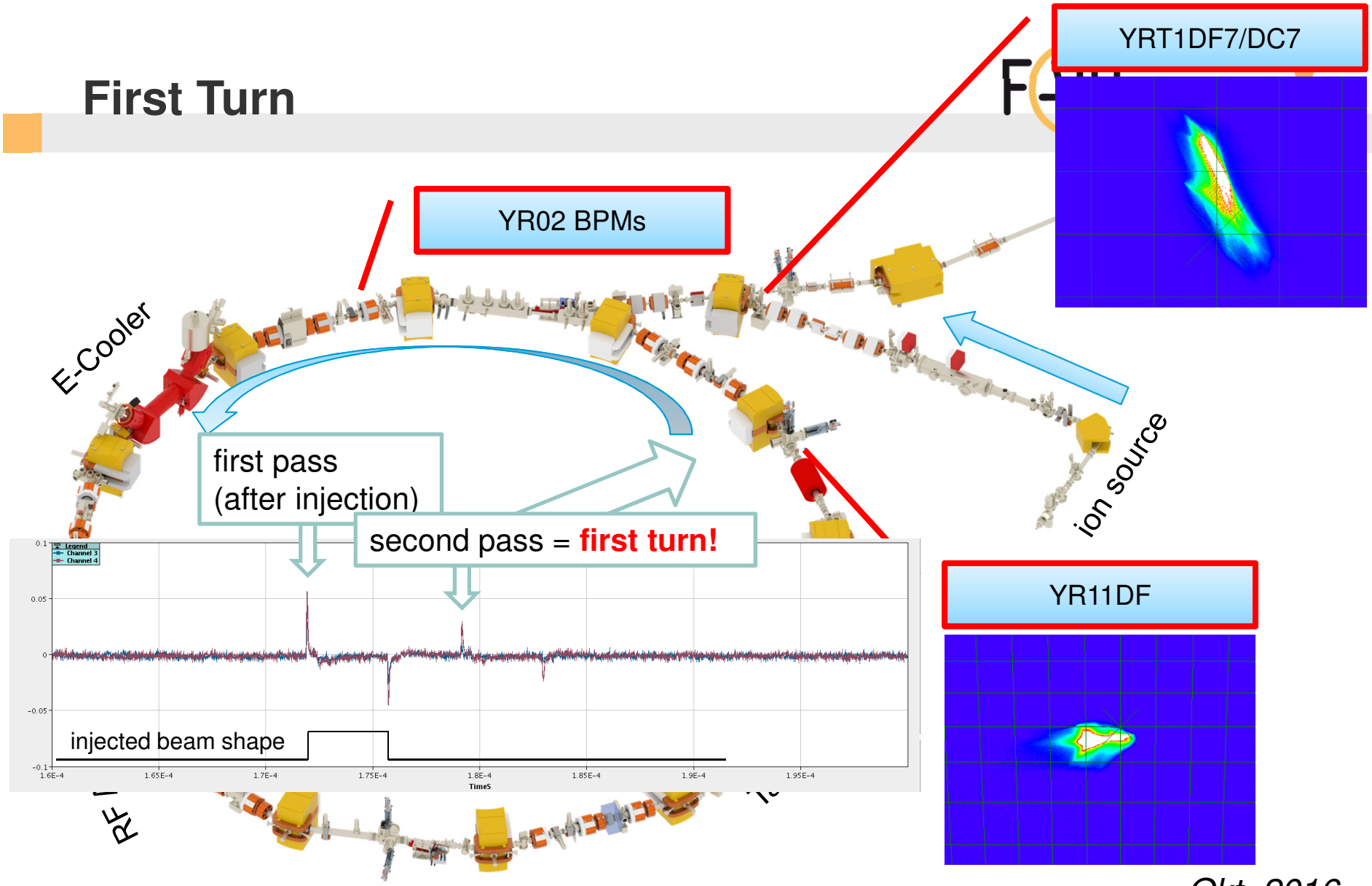
- Typical gases so far – H_2, D_2, Ar
- Typical intensities of beam for injection – 40 µA, has been improved from the initial 1 µA
- Uninterrupted operation time – improved from a few days to weeks
- Second and third version built for fast change over and development work
- Other source types (e.g. EBIT) and upgrade of RF Power discussed or already scheduled



Flight along the ions Path

Credits for piloting the drone to Andreas Bonin

First Turn



Okt. 2016

Successful testbed for FAIR type control system stack

Decelerate, Extract, Transfer

ESR —— > 60% ——→ **CRYRING@ESR**

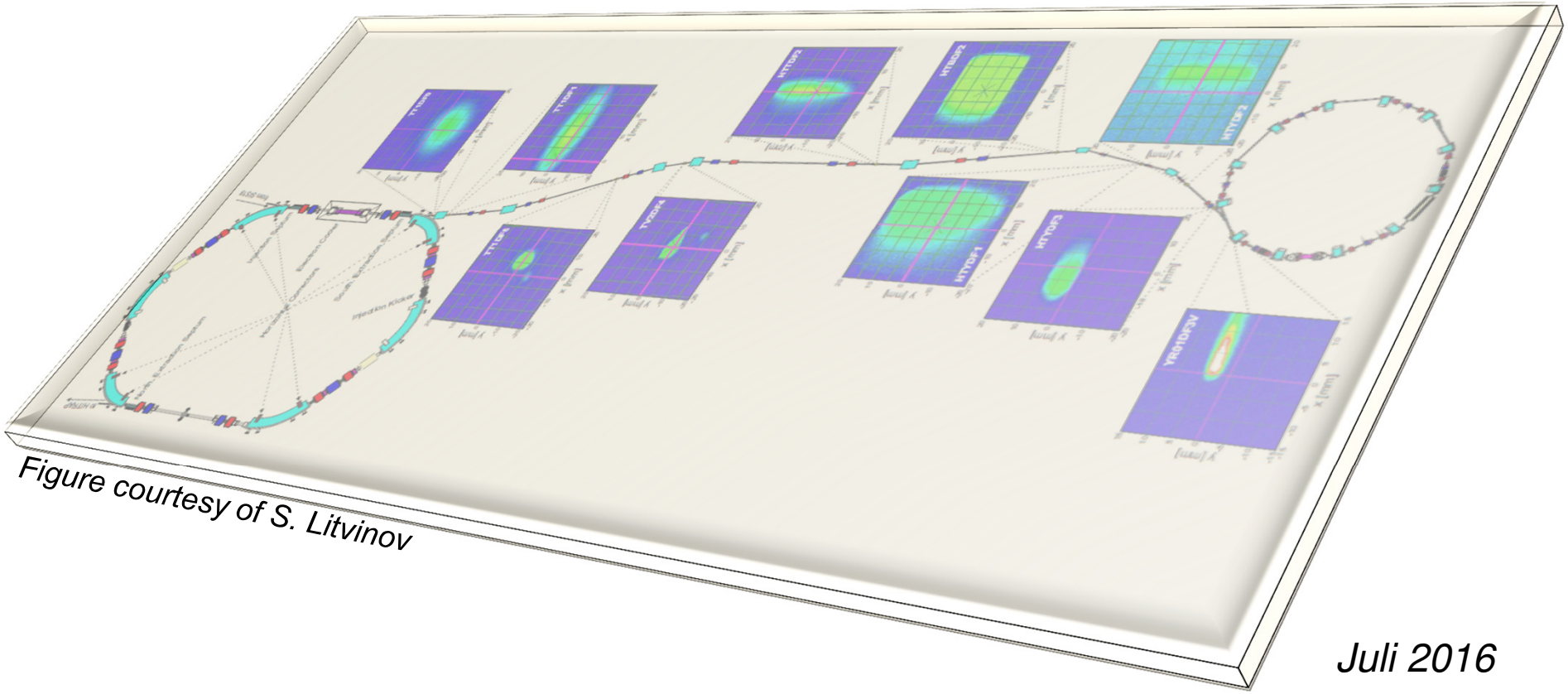
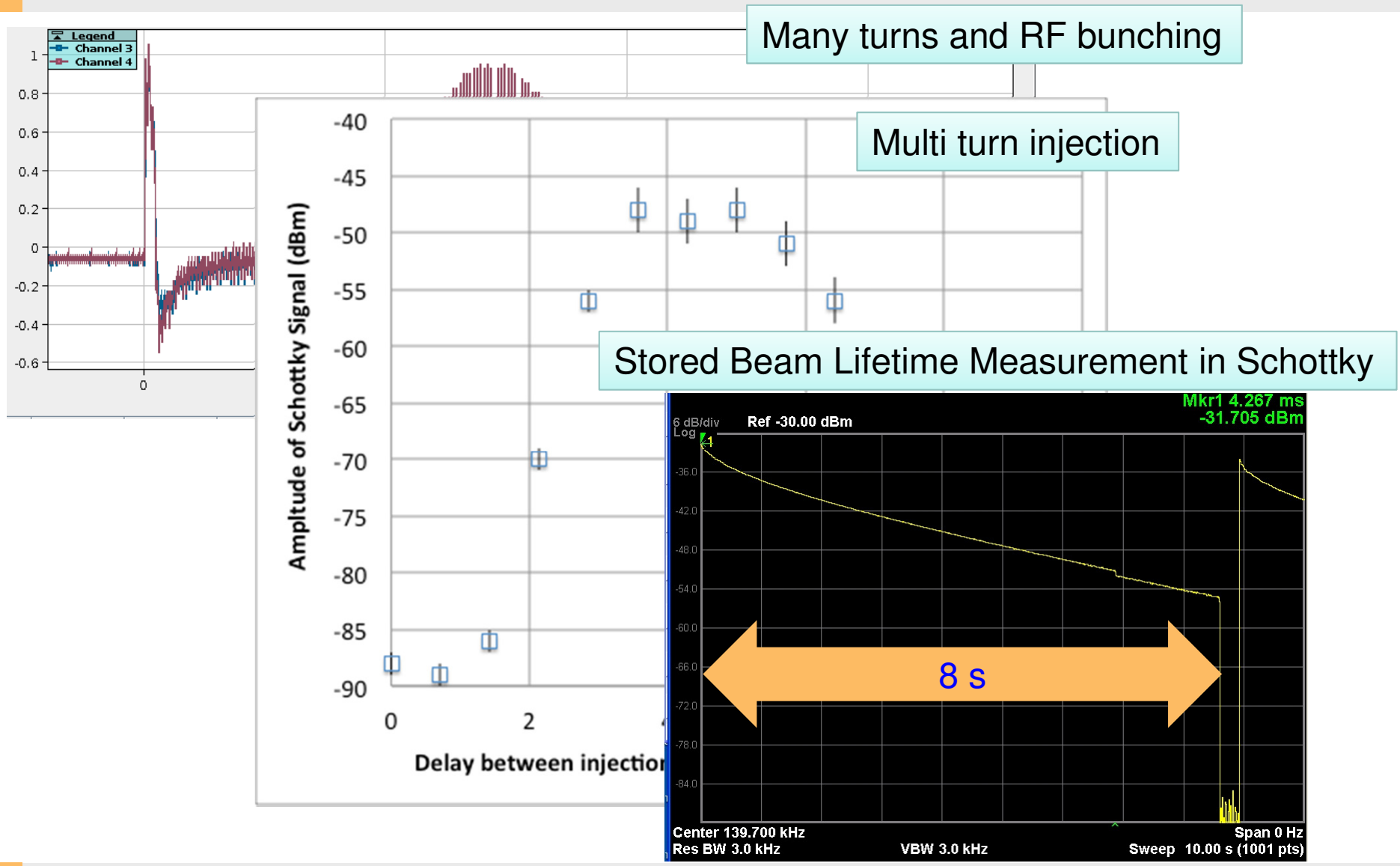


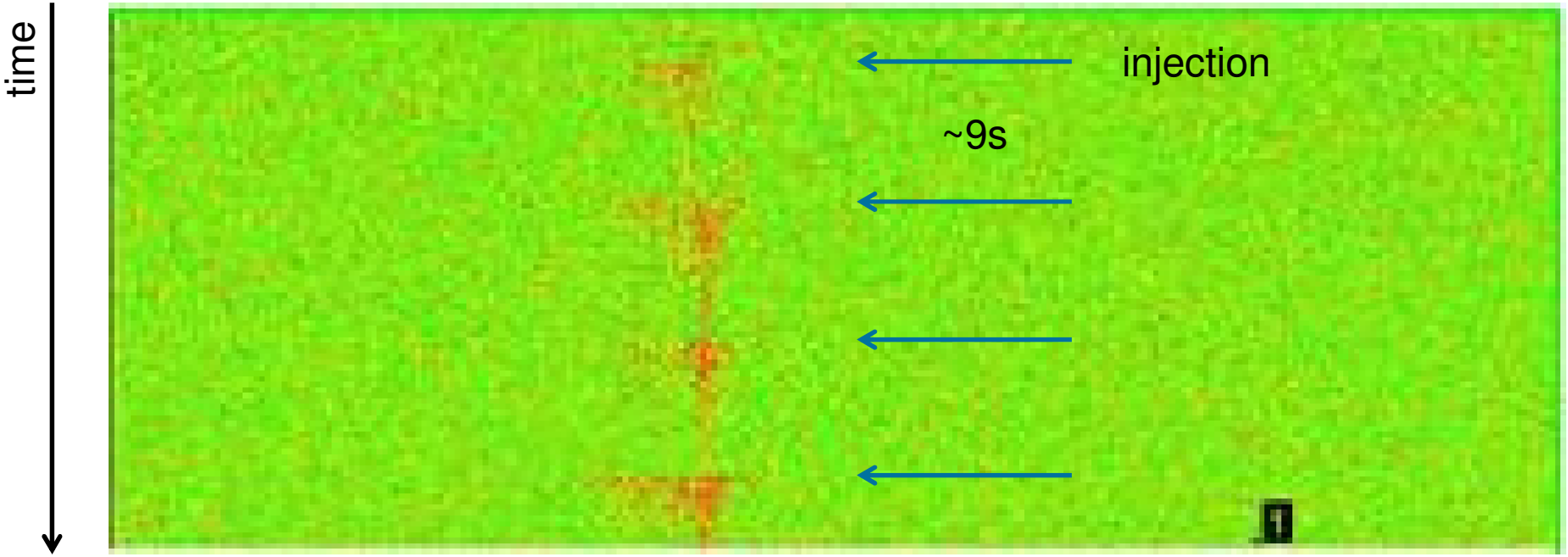
Figure courtesy of S. Litvinov

Juli 2016

Status of Commissioning

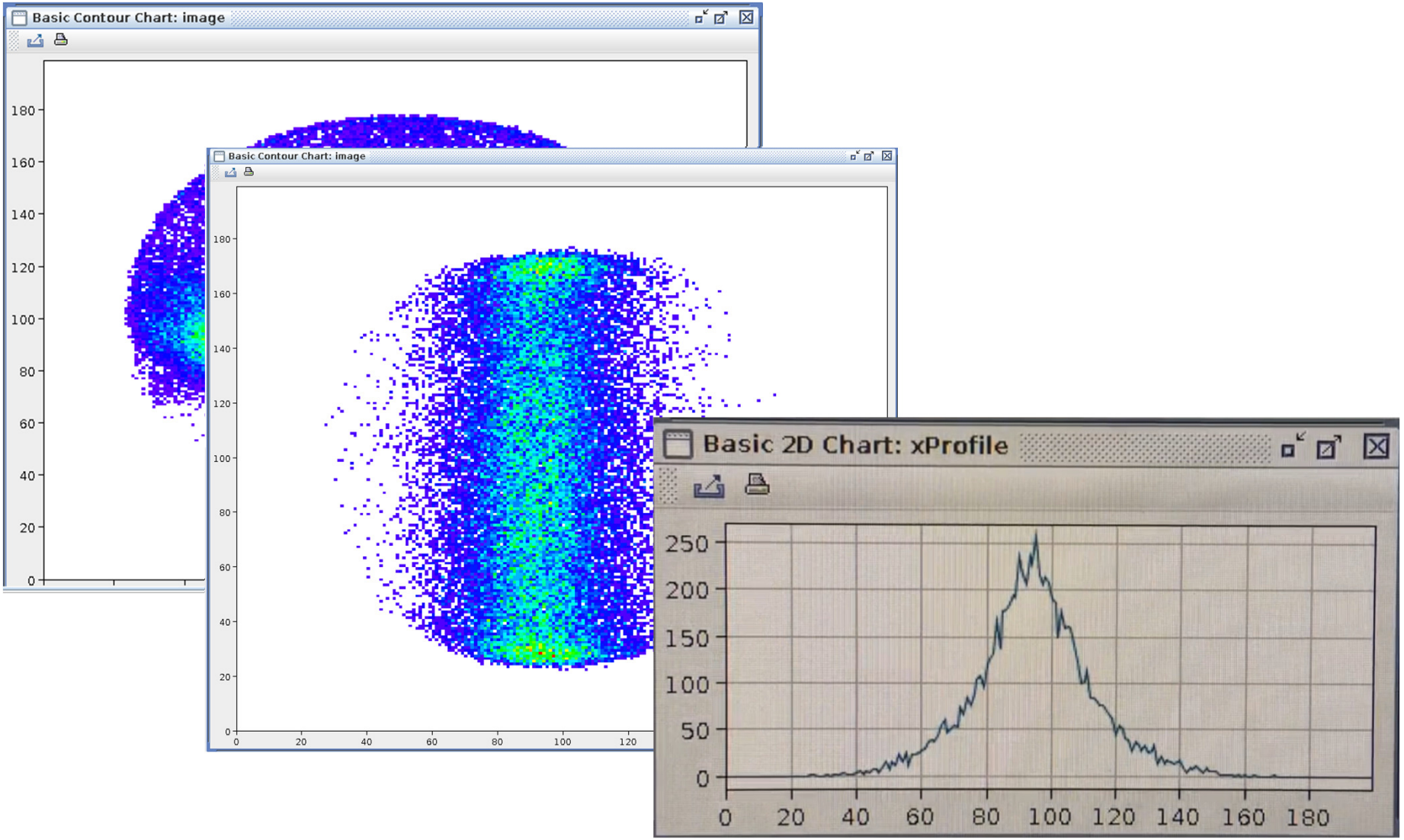


Cooling in CRYRING@ESR



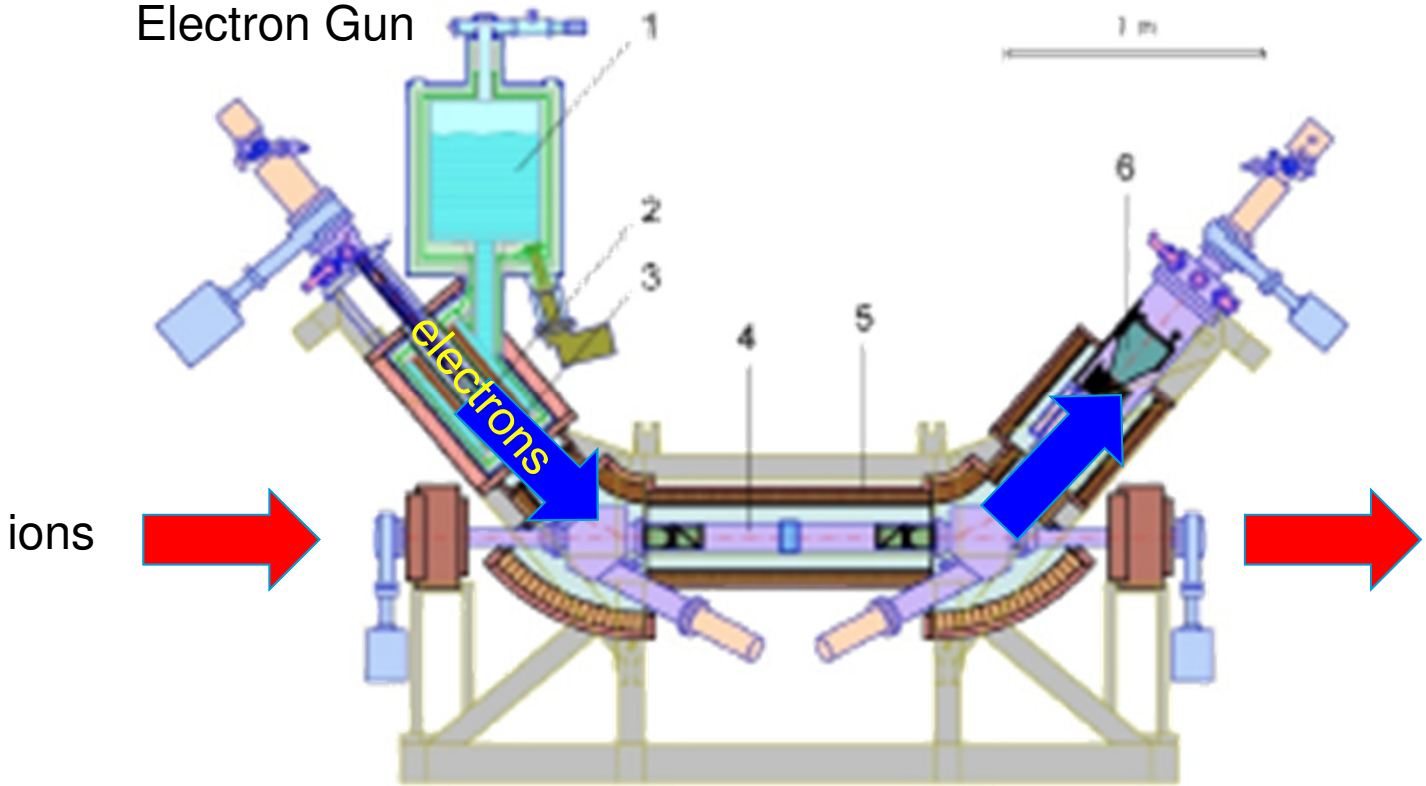
22nd of November, 2017

Ionization Profile Monitor



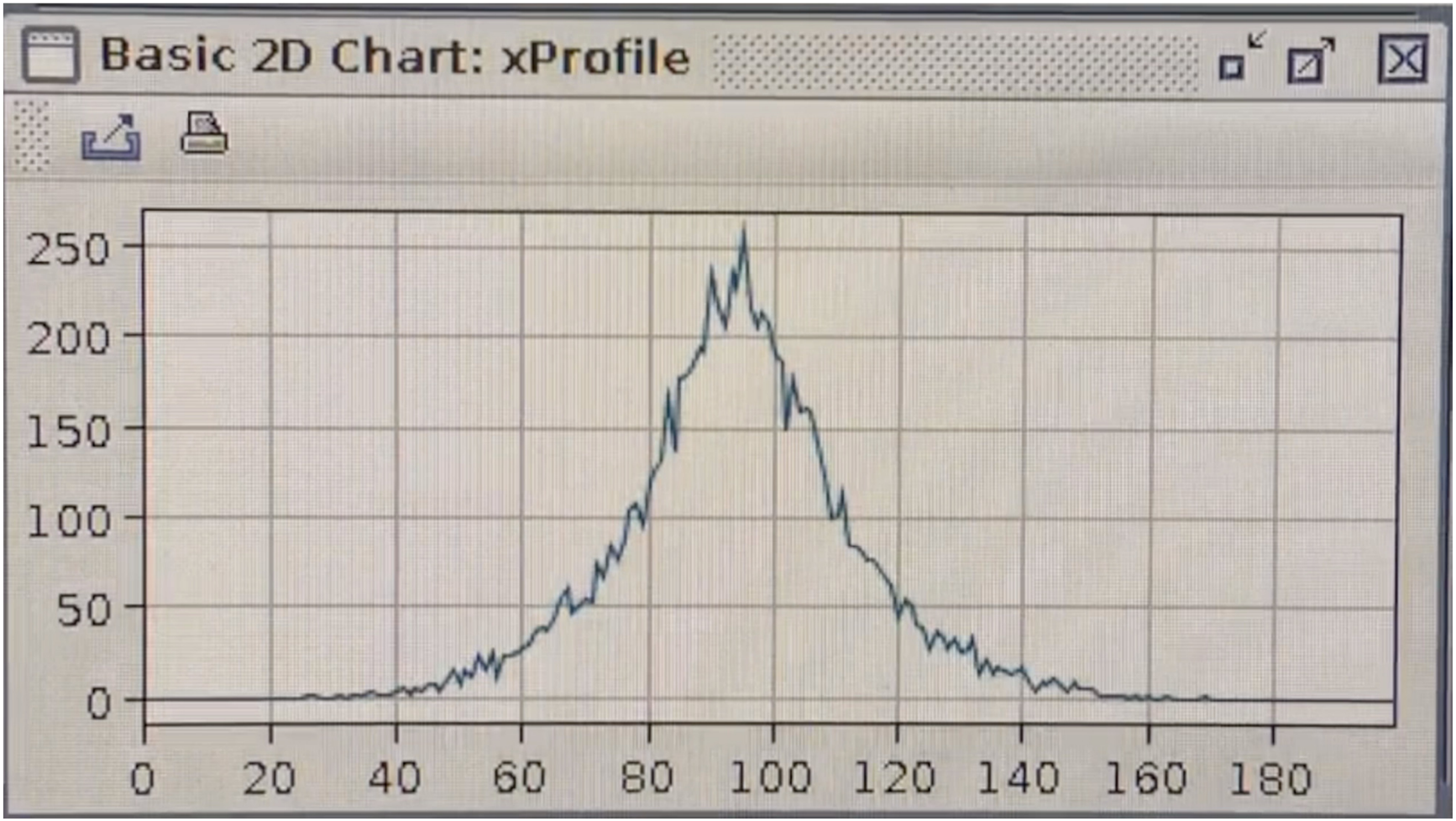
Electron Cooler

Superconducting magnet for
Electron Gun



Cooling in CRYRING@ESR

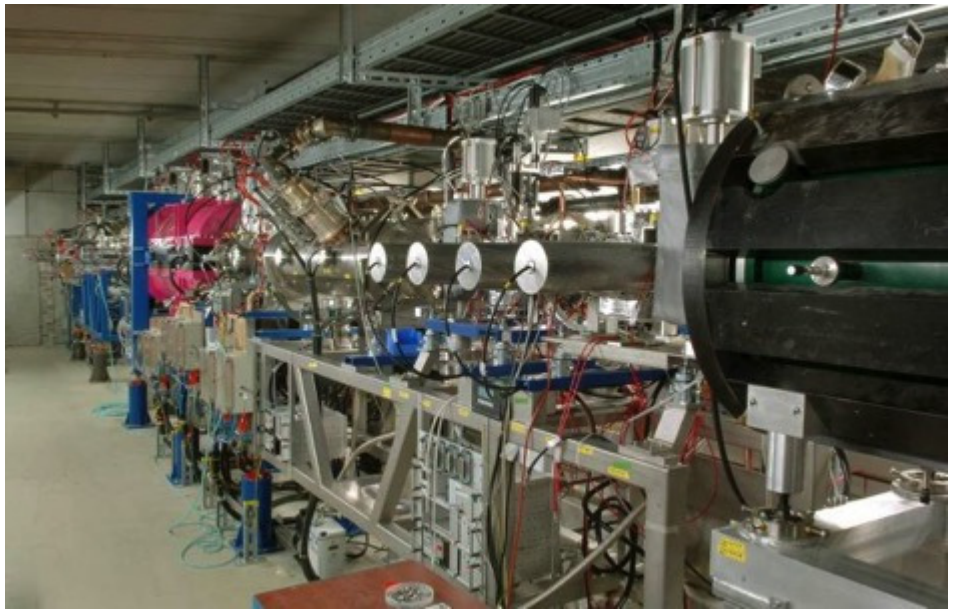
Vertical beam profile recorded on the **I**onization **P**rofile **M**onitor



22nd of November, 2017

The HITRAP decelerator facility

- g-factor of bound electron in HCI
- Precise hyperfine structure splitting in heavy, highly charged ions (Bi, …)



Z. Andelkovic, W. Barth, D. Beck, T. Beier, M. Block, A. Bräuning-Demian, H. Brand, K. Brantjes, E. Bodewits, G. Clemente, L. Dahl, C. Dimopoulou, S. Eliseev, S. Fedotova, P. Forck, F. Herfurth, R. Hoekstra, M. Kaiser, O. Kester, H.-J. Kluge, S. Koszudowski, N. Kotovskiy, C. Kozhuharov, C. Krantz, S. Litvinov, M. Maier, F. Nolden, W. Nörtershäuser, F. Peldzinski, J. Pfister, W. Quint, U. Ratzinger, A. Sauer, A. Schempp, M. Shaaban, A. Sokolov, M. Steck, J. Steinmann, K. Stiebing, Th. Stöhlker, W. Vinzenz, M. Vogel, H. Vormann, G. Vorobjev, D. Winters, A. Wolf, ..

Univ. Frankfurt, Univ. Mainz, MPI-K Heidelberg, KVI Groningen

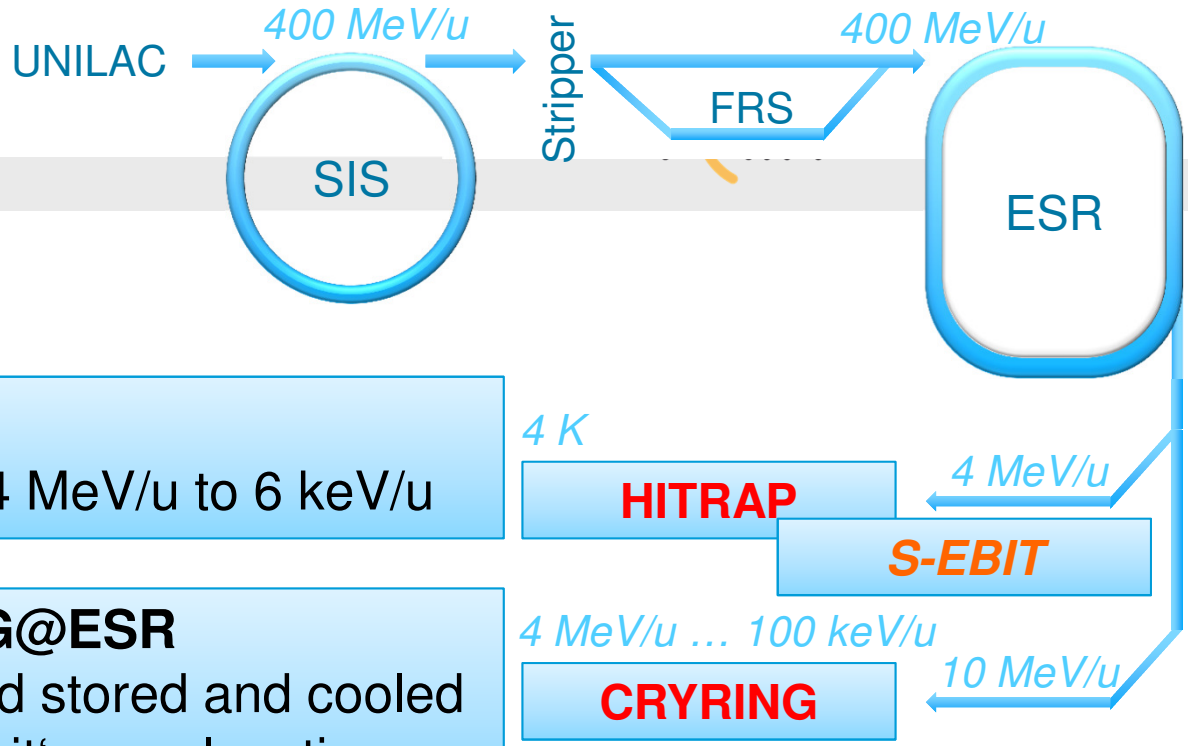
CRYRING@ESR

- Most precise Lamb shift in HCI
- Nuclear reaction cross sections in Gamov Window

Z. Andelkovic, N. Bauer, A. Bräuning-Demian, R. Bär, H. Danared, C. Dimopoulou, O. Dolinskyy, W. Enders, M. Engström, S. Fedotova, B. Franzke, M. Frey, W. Geithner, O. Gorda, F. Herfurth, L. Heyl, P. Hülsmann, A. Källberg, Th. Köhler, N. Kotovskiy, M. Lestinsky, S. Litvinov, Y. Litvinov, J. Mohr, I. Pschorn, A. Reiter, G. Riefert, J. Roßbach, A. Simonsson, T. Sieber, J. Sjöholm, M. Steck, Th. Stöhlker, G. Vorobjev, N. Winckler, ...

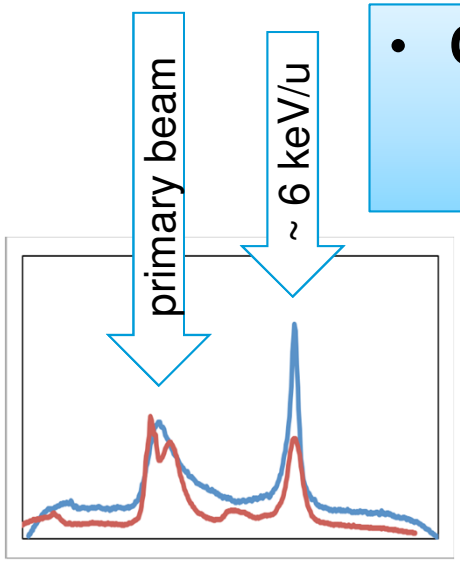
Stockholm University, KVI Groningen, HI Jena, Krakow University

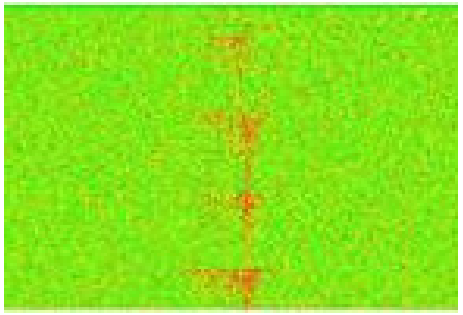
Summary



- **HITRAP**
  Achieved deceleration 4 MeV/u to 6 keV/u

- **CRYRING@ESR**
  Achieved stored and cooled beam in it's new location





Rare, heavy, highly-charged Ions stored at very low energy is the key to precision measurements testing the limits of our knowledge.

We will be ready for physics with decelerated ions for upcoming beam period 2018/19