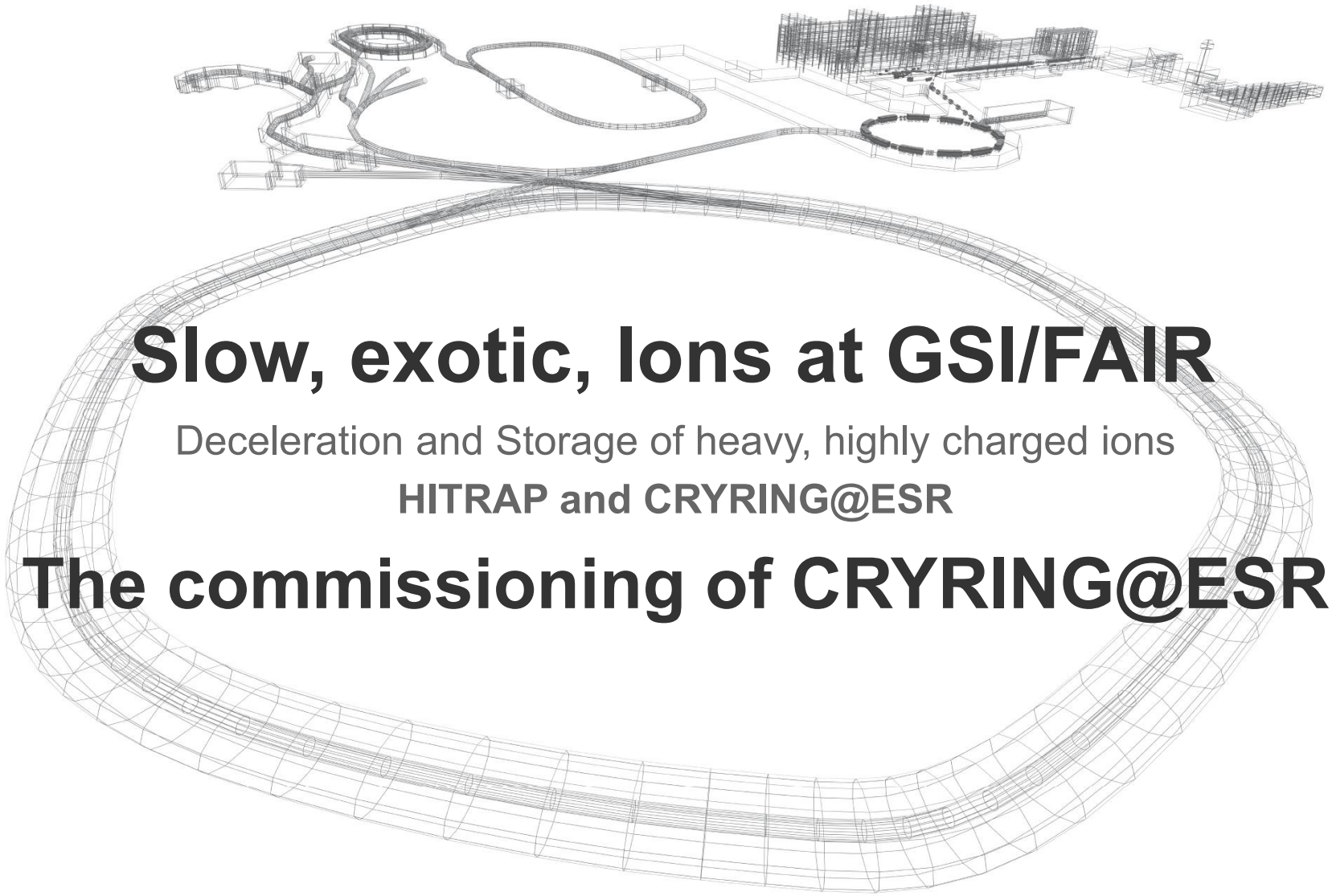


Slow, exotic, Ions at GSI/FAIR

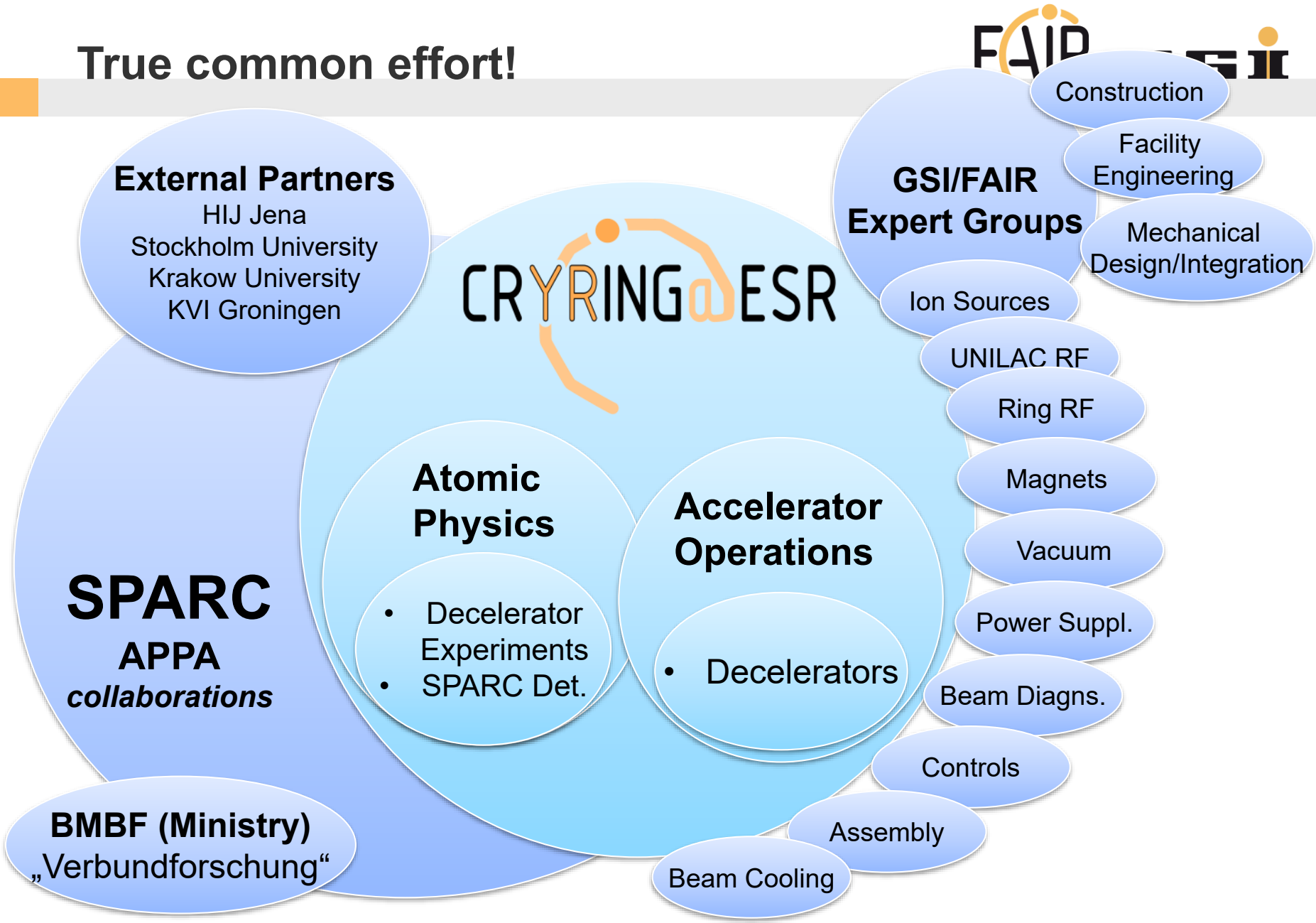
Deceleration and Storage of heavy, highly charged ions

HITRAP and CRYRING@ESR

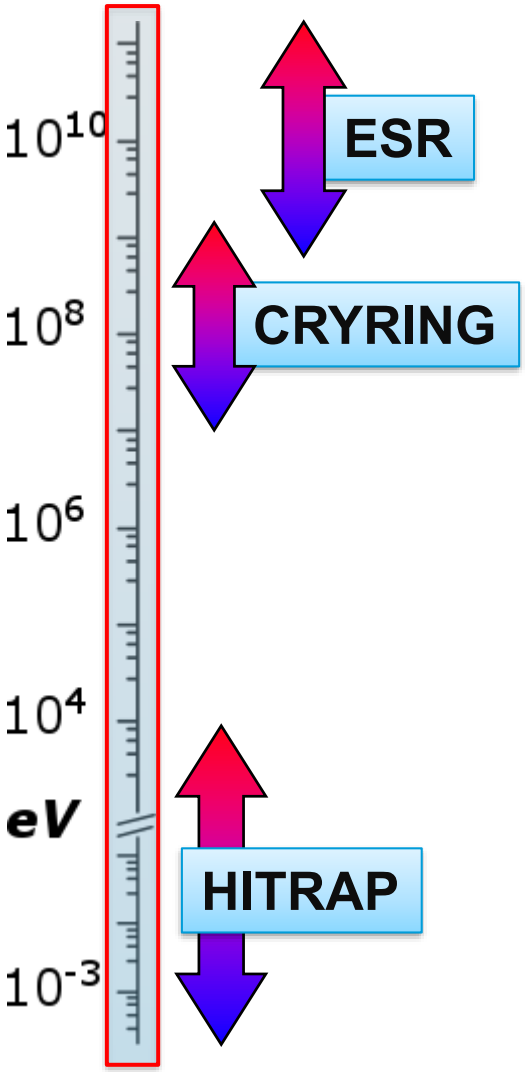
The commissioning of CRYRING@ESR

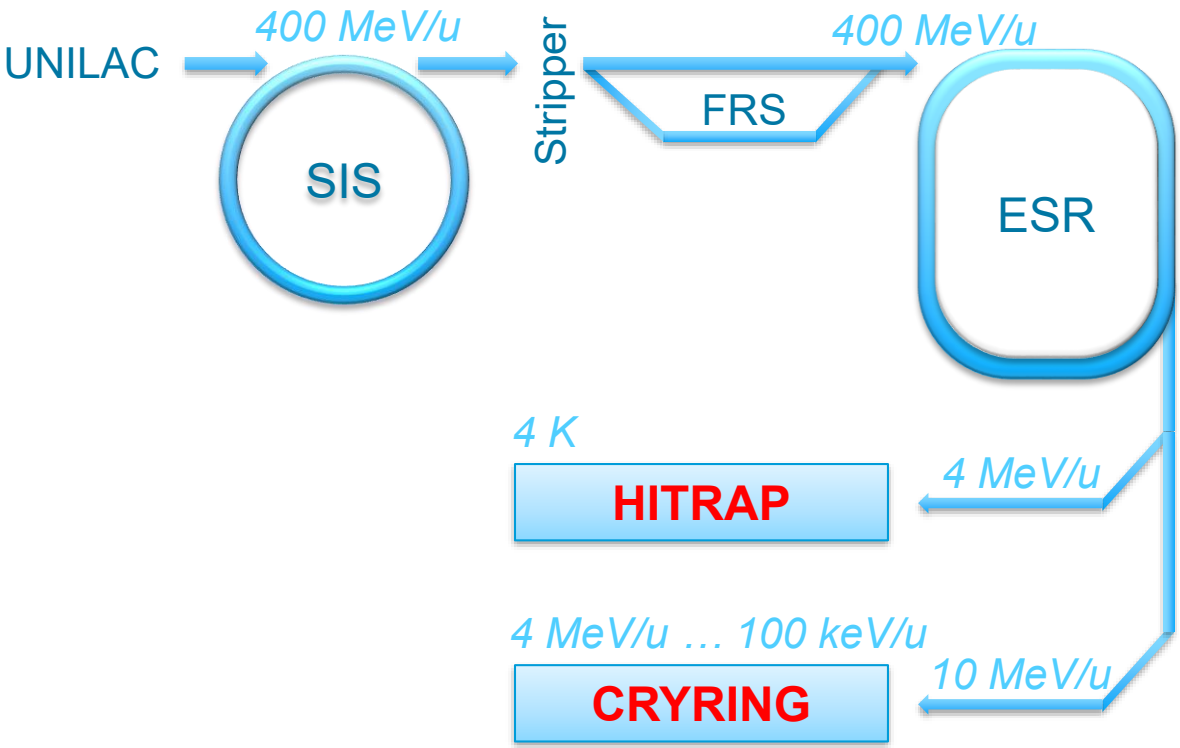
Frank Herfurth for the HITRAP and CRYRING@ESR teams

True common effort!



Ion Storage at GSI ("low energy")





Atomic Properties, Other fields

- Precision tests of modern theory in strong fields
  - Electron binding energies
    - Lamb shift (QED test)
  - g-factor of bound electrons
    - QED test, m_e, α
- Collision spectroscopy with electrons, atoms, and molecules
- Atomic processes, reaction dynamics, and lifetimes
- Surface modifications using HCI
- Hollow atoms and trampoline effect

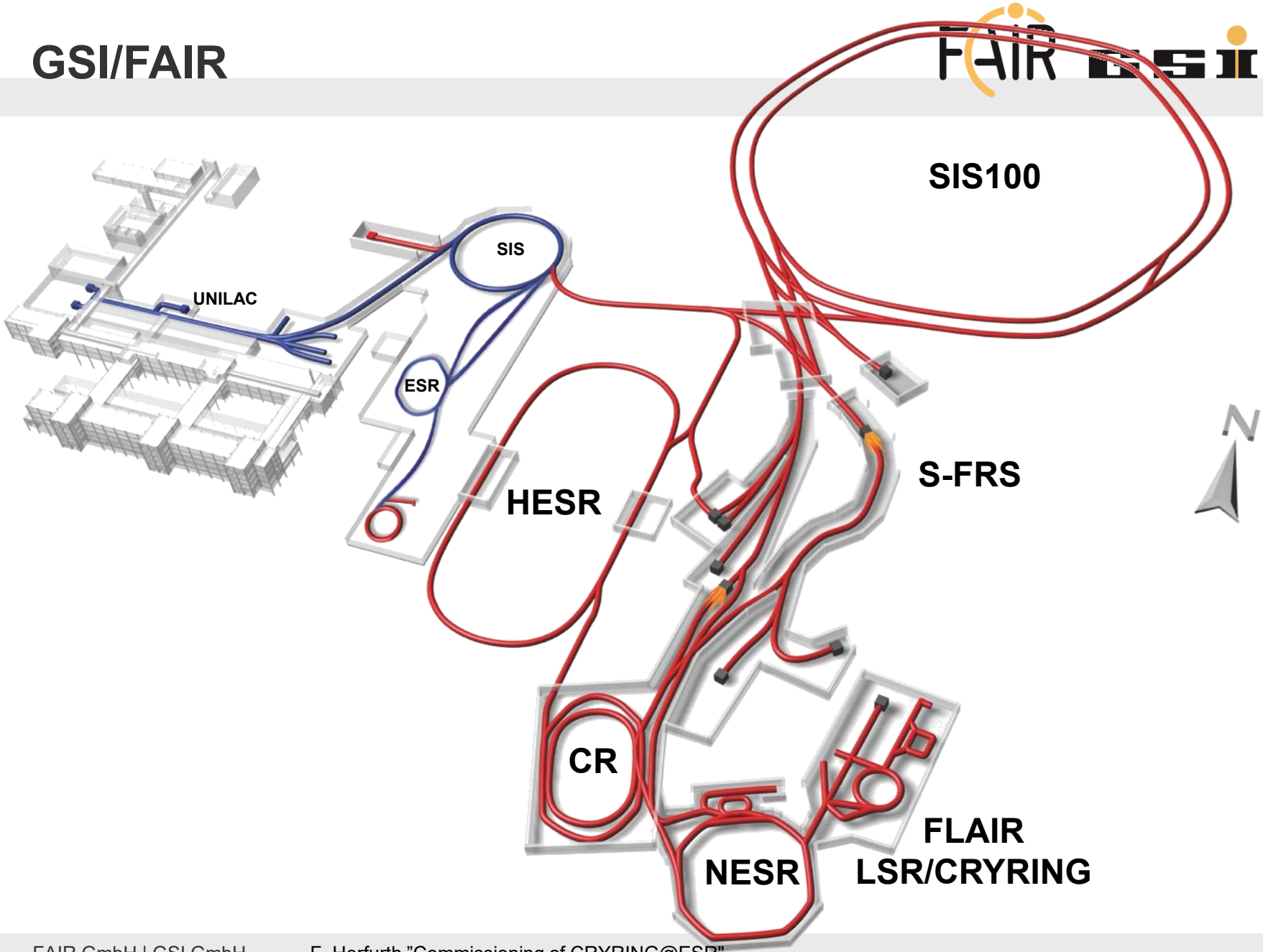
We need to control
– location
– observation time
– energy

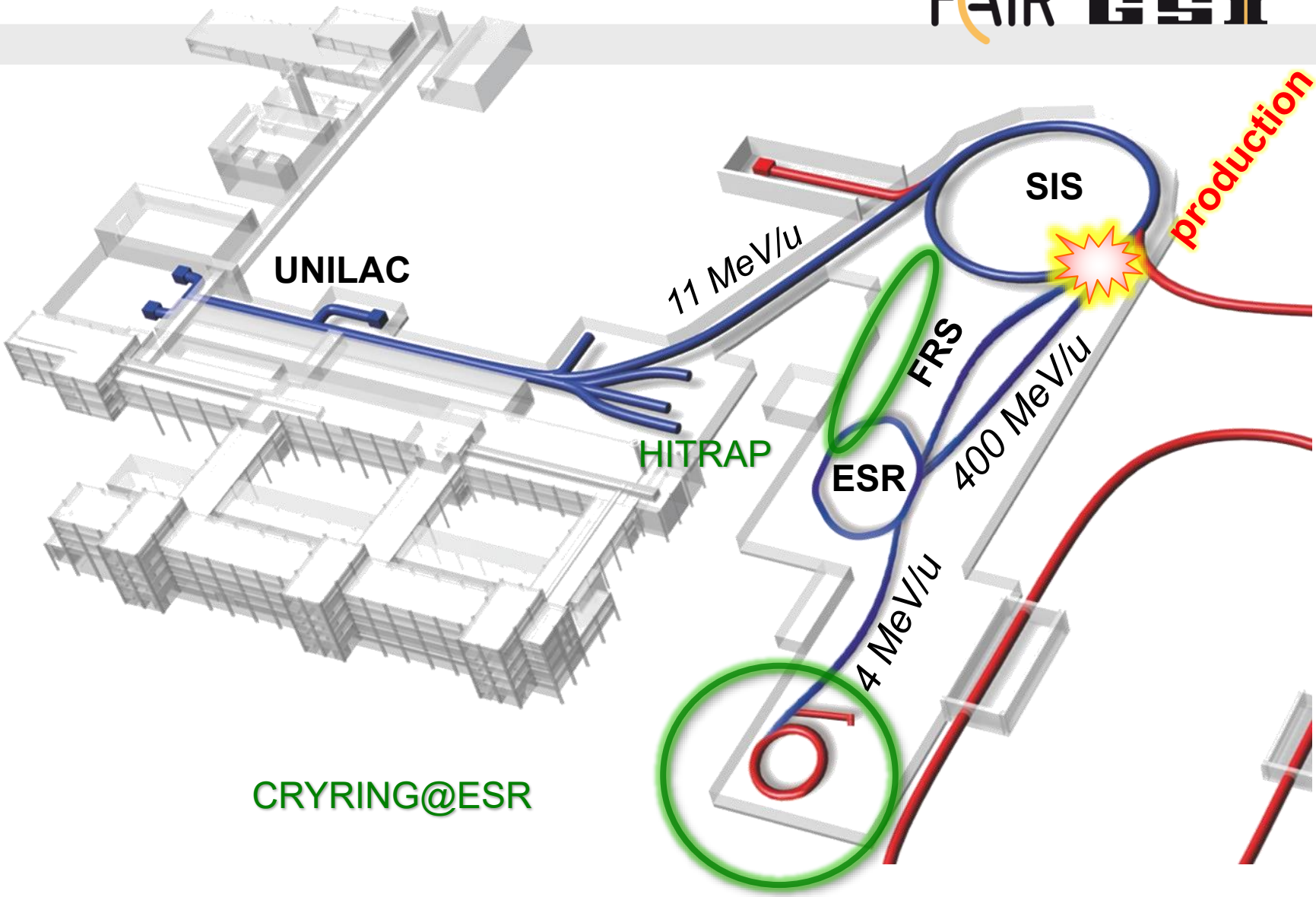
Nuclear Properties

- Atomic Mass
- Nuclear Lifetime
- Nuclear Charge Radius
- Reaction cross sections and channels
- Exotic nuclear decay modes

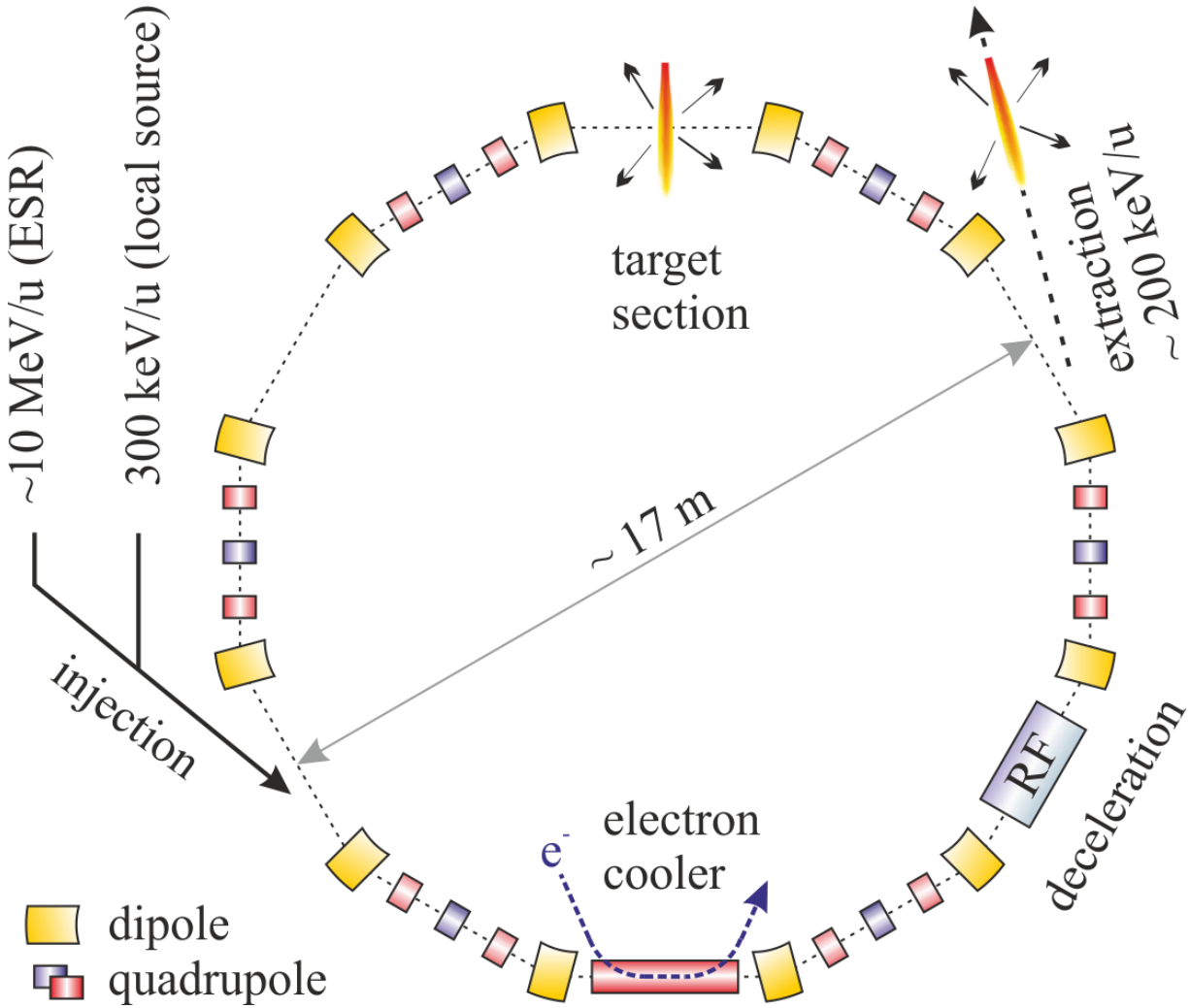
We need to control
– location
– observation time
– energy

GSI/FAIR




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

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

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^+, $N_2O_2^+$, $CH_3OCOH_2^+$, $D_7O_3^+$, $N_3D_{10}^+$, $C_4D_6^+$, $S^{18}O_2^+$, ArN_2^+,
$H_9O_4^+$, $CD_3COHNHCH_3^+$, $CD_3CONHDCH_3^+$, $C_6D_6^+$, $PO^{37}Cl^+$, $H_{11}O_5^+$, $C_2S_2H_6^+$,
$C_2S_2H_7^+$, $H_{13}O_6^+$, $PO^{35}Cl_2^+$

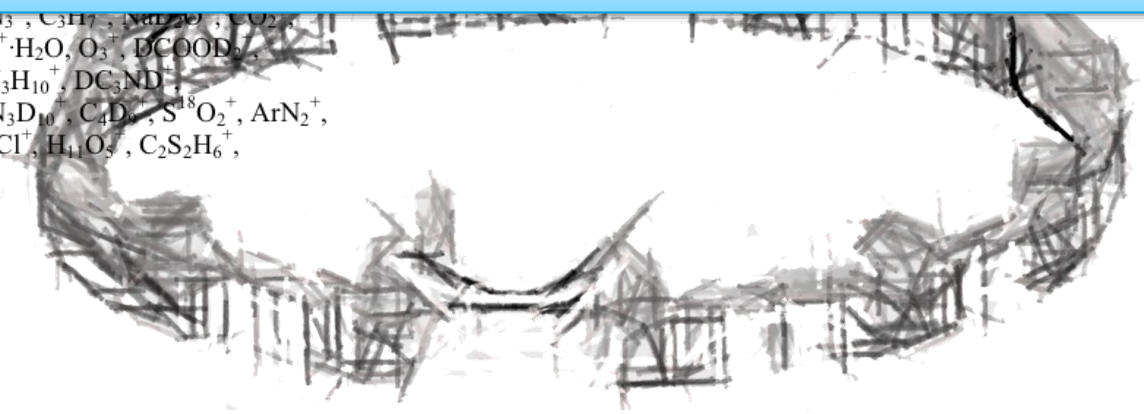
Negative atomic ions:
H^-, Li^-, F^-, Si^-, S^-, Cl^-, Se^-, Te^-

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



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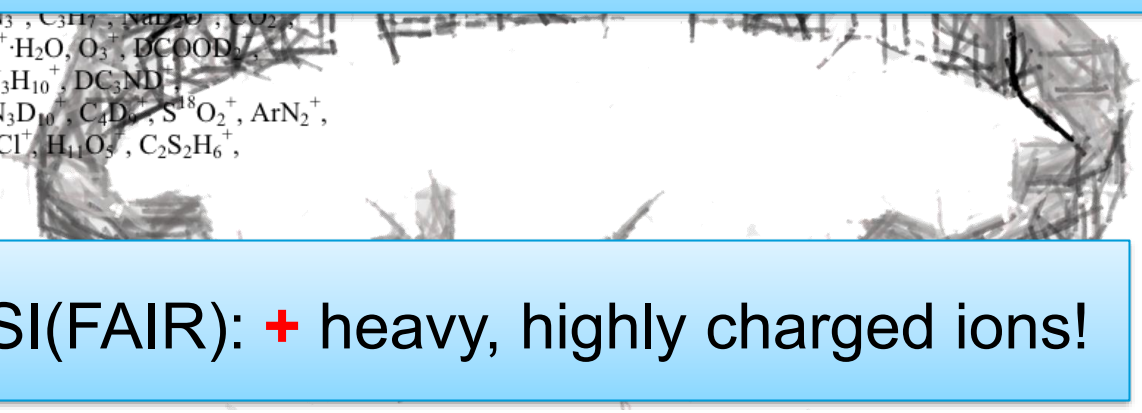


GSI(FAIR): + heavy, highly charged ions!

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 control system
- Training of operators on FAIR control system

with real beam (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)

Documents

- Max. rigidity 1.44 Tm
  - 15 MeV/u U^{92+}
  - 96 MeV/u protons

FACILITY FOR ANTIPROTON AND ION RESEARCH

SPARC Collaboration

Technical Design Report:

Experimental Instrumentation
of CRYRING@ESR

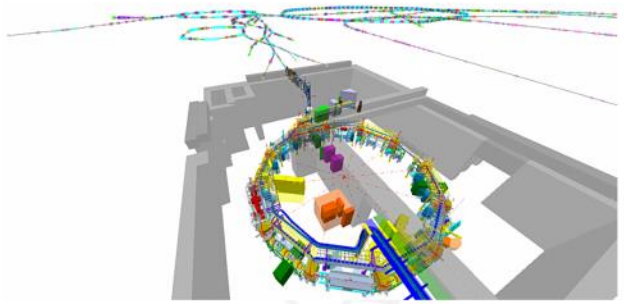
Z. Andelkovic,[1] C. Brandau,[1,2] M. Dumchev,[3] A. Ehresmann,[4] W. Geithner,[1] A. Georgiadis,[3]
V. Hannen,[5] M. Lestinsky,[1*] Y. Litvinov,[1] W. Nörtershäuser,[6] R. Reifarth,[7] Ph. Reiss,[4]
O. Rest,[5] R. Sánchez,[1] S. Schippers,[2] T. Stöhlker,[1,8,9] C. Weinheimer,[5] and D. Winzen[5]

on behalf of the SPARC Collaboration

[1] GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt
[2] Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Gießen, D-35392 Gießen
[3] Leuphana Universität Lüneburg, D-21335 Lüneburg
[4] Institut für Physik, Universität Kassel, D-34132 Kassel
[5] Institut für Kernphysik, Universität Münster, D-48149 Münster
[6] Institut für Kernphysik, Universität Darmstadt, D-64289 Darmstadt
[7] Institut für Angewandte Physik, Goethe-Universität Frankfurt, D-60438 Frankfurt am Main
[8] Helmholtz-Institut Jena, D-07743 Jena
[9] Friedrich-Schiller-Universität Jena, D-07743 Jena
[*] Contact person for this TDR

Accepted
SPARC TDR

Physics book:
CRYRING@ESR



Editors:

M. Lestinsky, Y. Litvinov, Th. Stöhlker
m.lestinsky@gsi.de

Atomic Physics Division
GSI Helmholtzzentrum für Schwerionenforschung
D-64291 Darmstadt

April 13, 2016

CRYRING@ESR

$Revision: 1.47 $ $Date: 2016/04/11 14:51:45 $

EPJ-ST 225 (2016) 797

Contact: Michael Lestinsky

Technical Design Report items being realized already

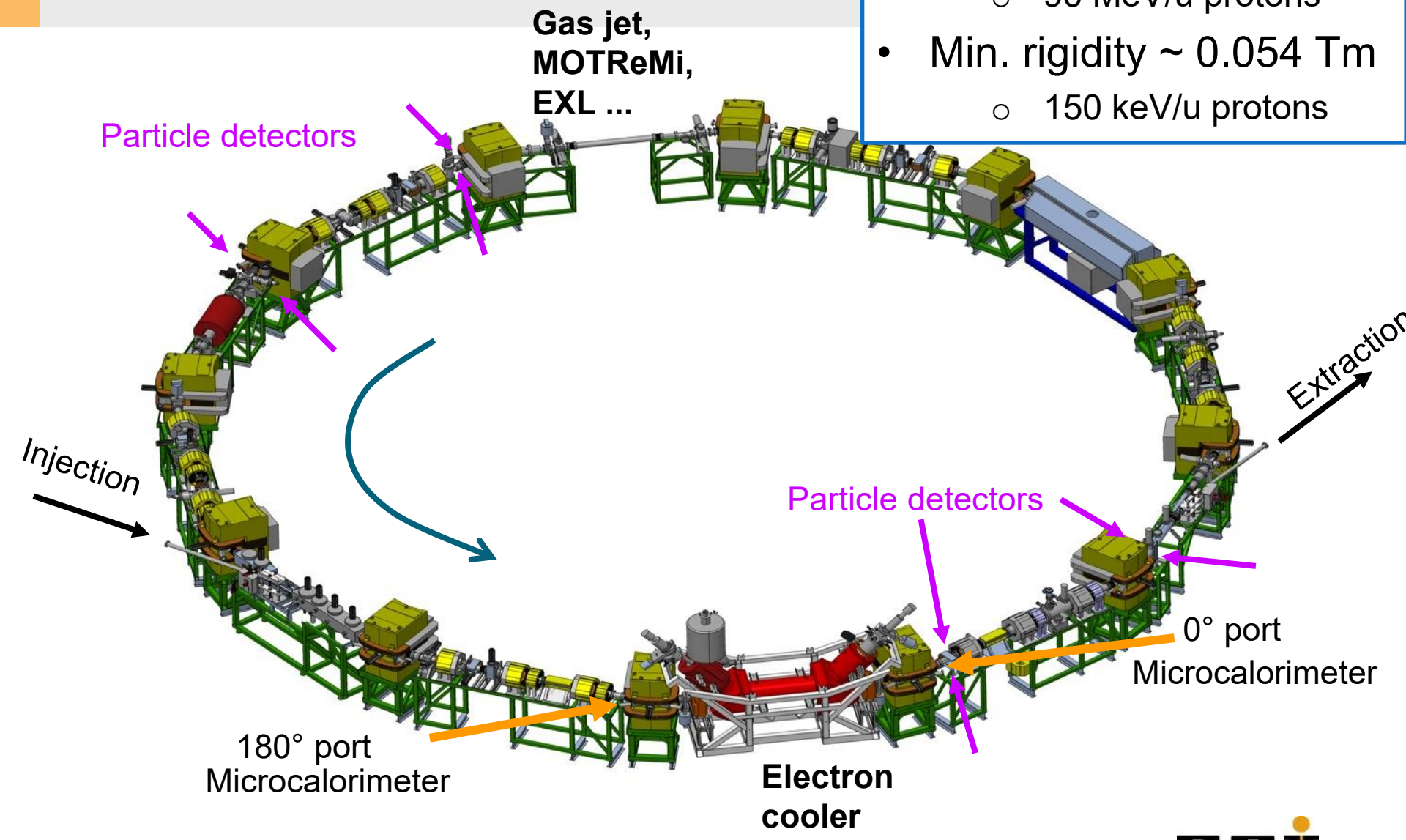
- ECOOL
  - HV-amplifier and DAQ electronics (→ Schippers/Gießen)
  - precision HV-divider (→ Weinheimer/Münster)
- Probes
  - laser lab (→ Nörtershäuser/Darmstadt)
  - transverse electron target (→ Schippers/Gießen and Kester/Frankfurt)
- Detectors
  - particle detector mount mounts (→ Reifarth/Frankfurt)
  - Seya-Namioka VUV-VIS spectrometer (→ Ehresmann/Kassel)
  - MWPC/MTPC counters for Xrays (→ Georgiadis/Lüneburg)

- Related TDRs: maXs, SimX, gasjet target (TBD)

http://appa-rd.fair-center.eu

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



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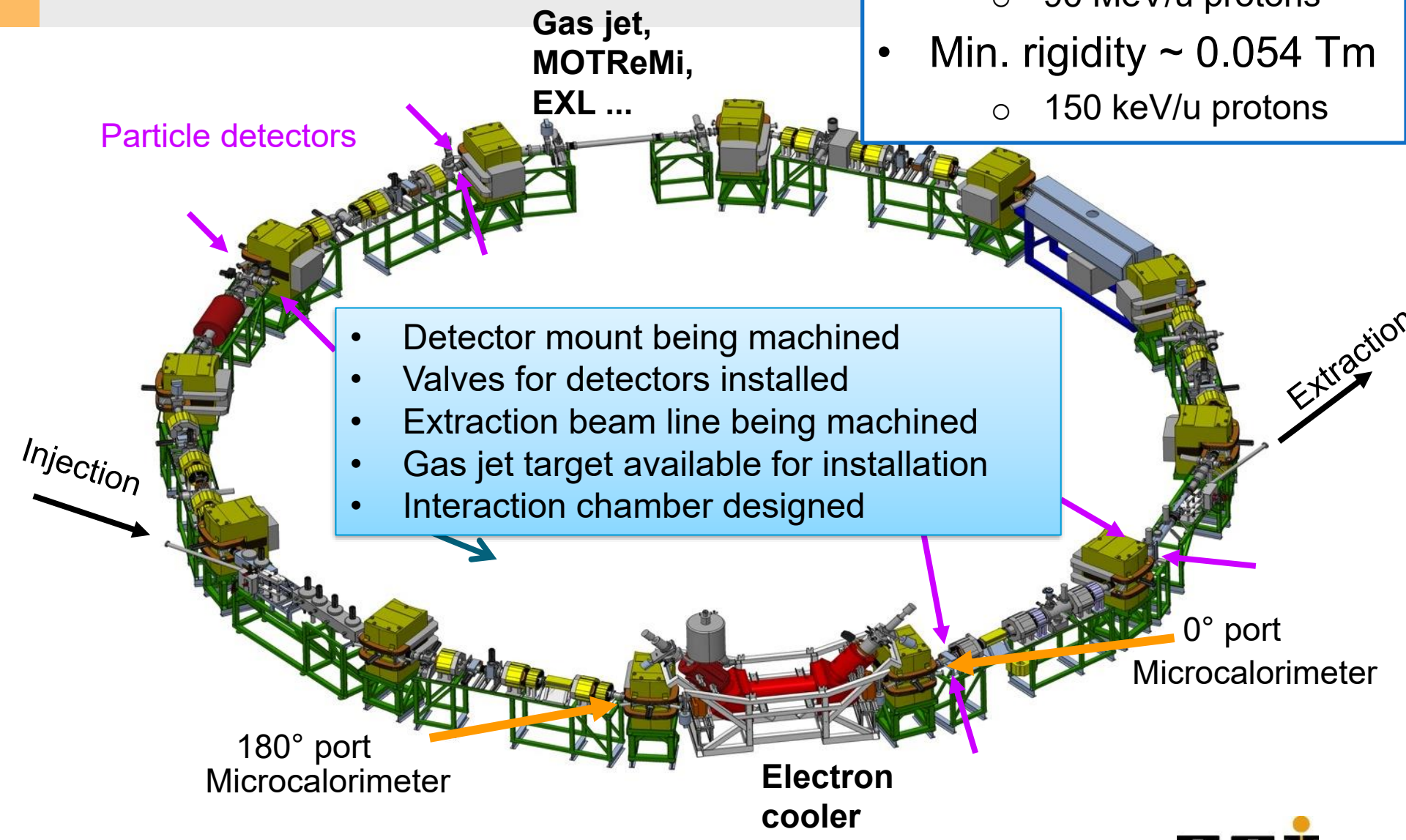
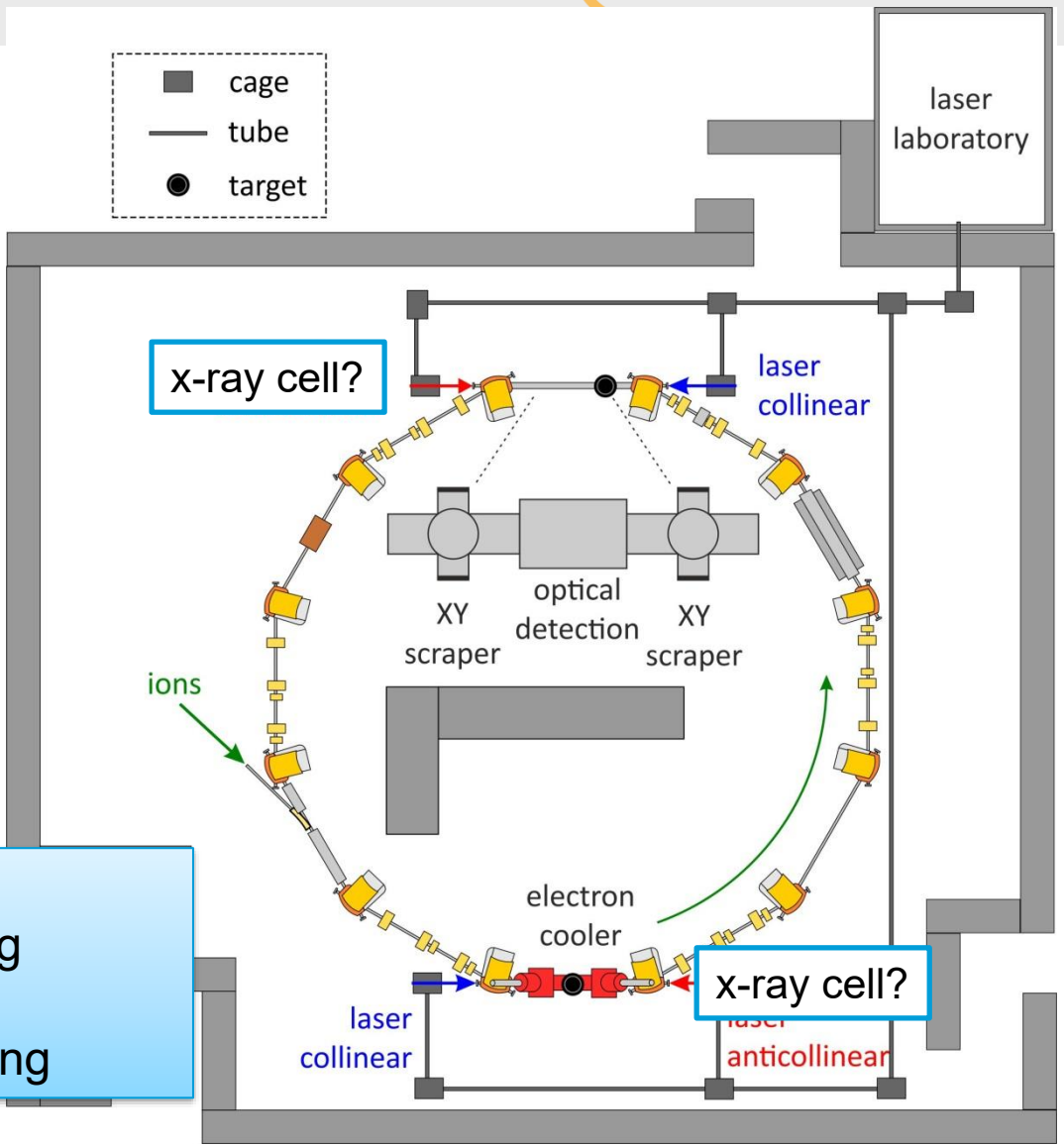


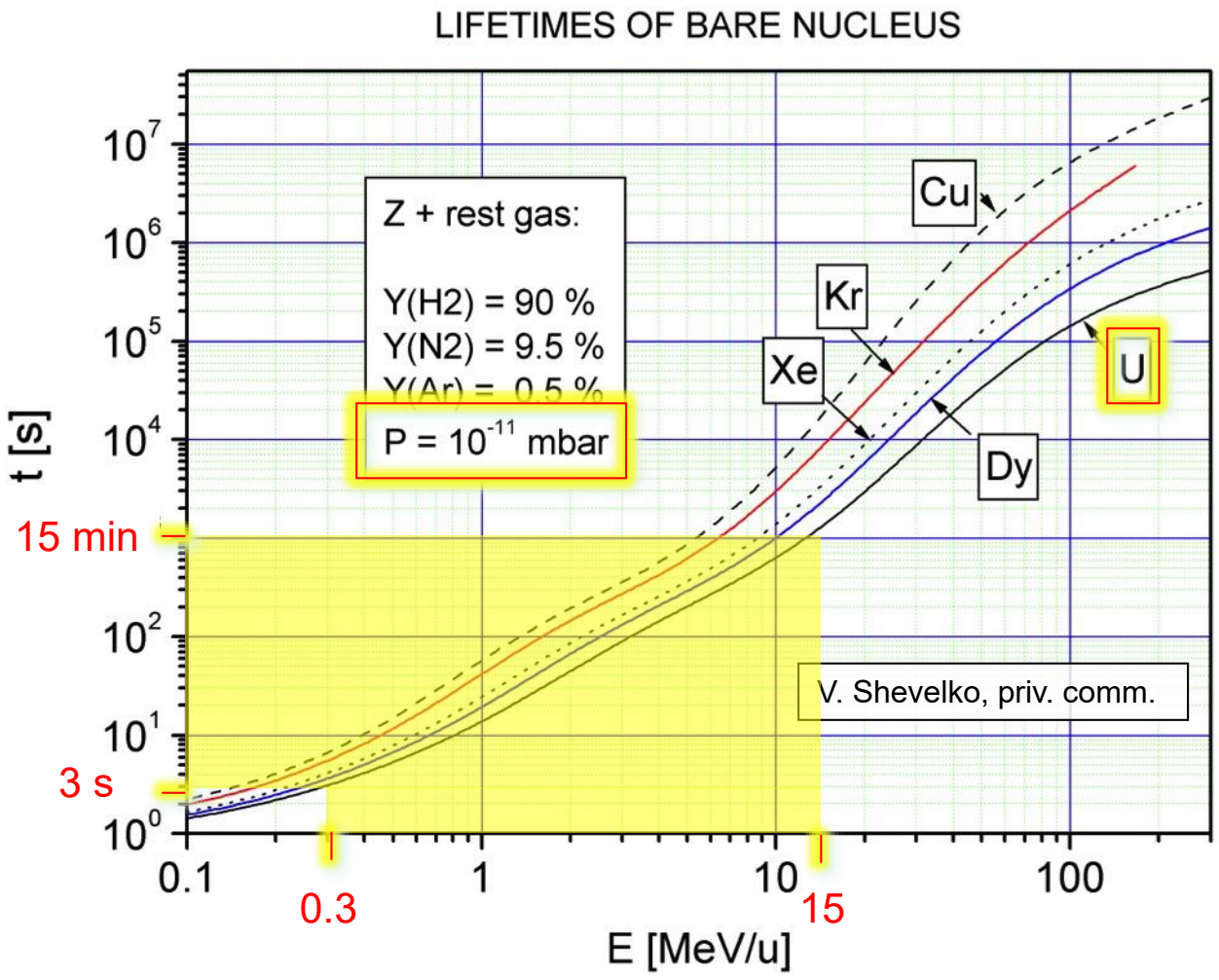
Laser Experiments - CRYRING@ESR

- 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

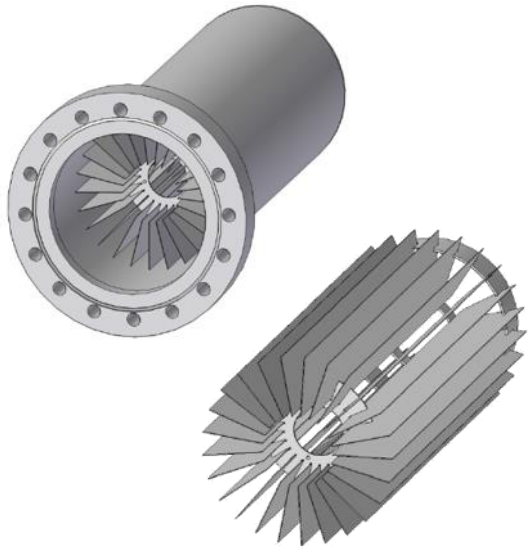


- Laser lab infrastructure ready
- Design of laser beam line ongoing
- Detection chamber in production
- Development of ion source ongoing

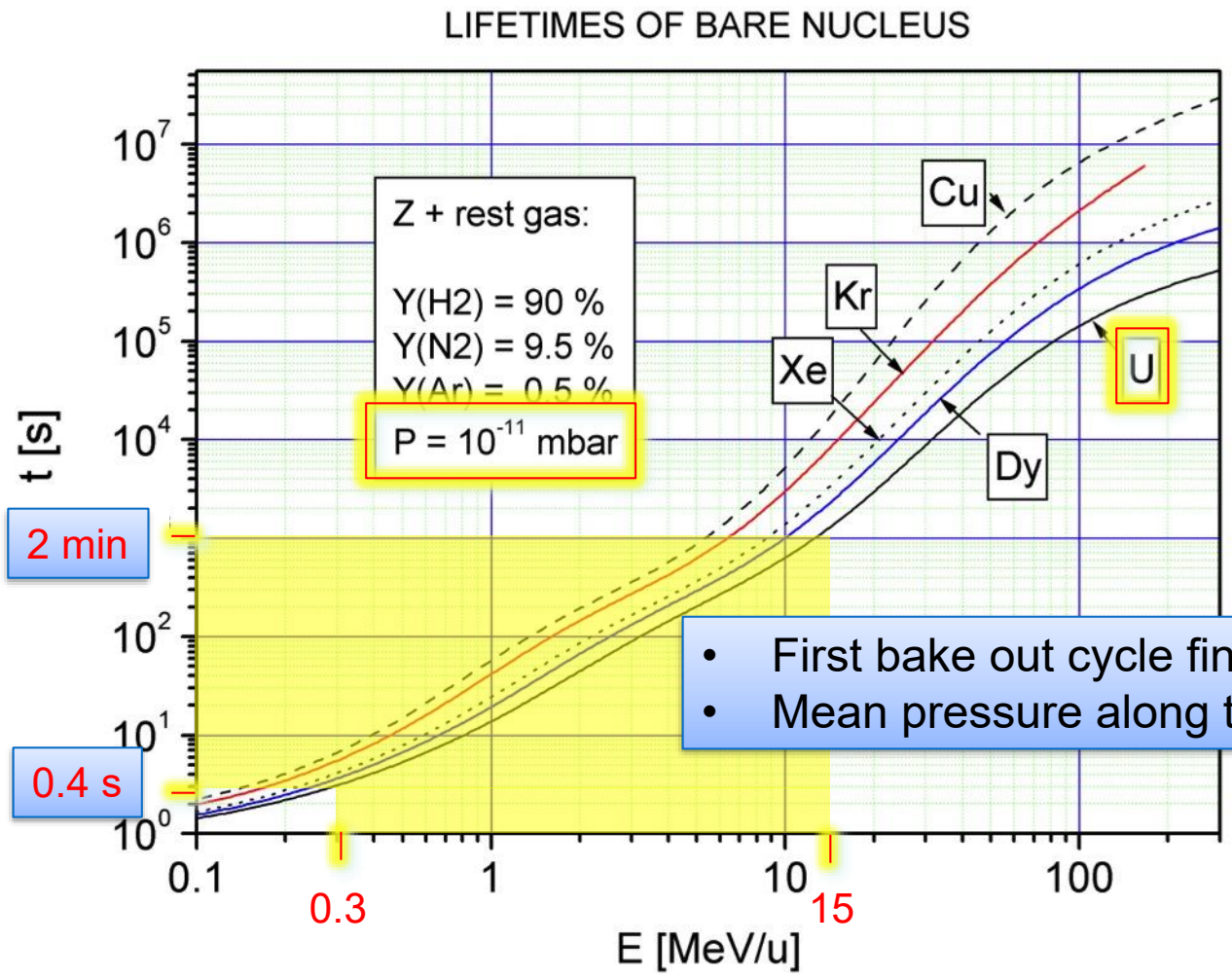
Ultra High Vacuum & Beam Life Time



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



Ultra High Vacuum & Beam Life Time



- Ion pumps
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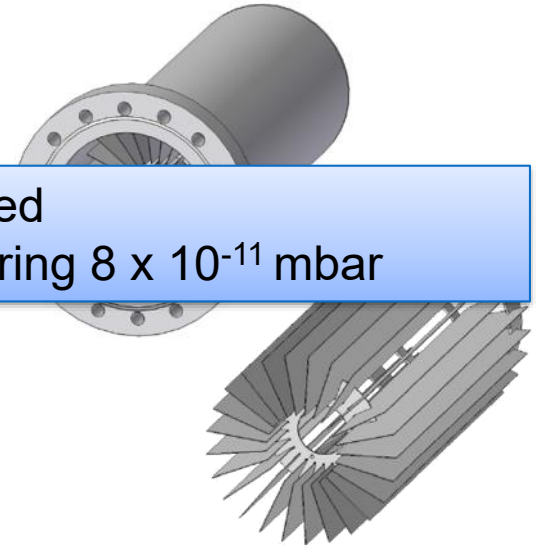
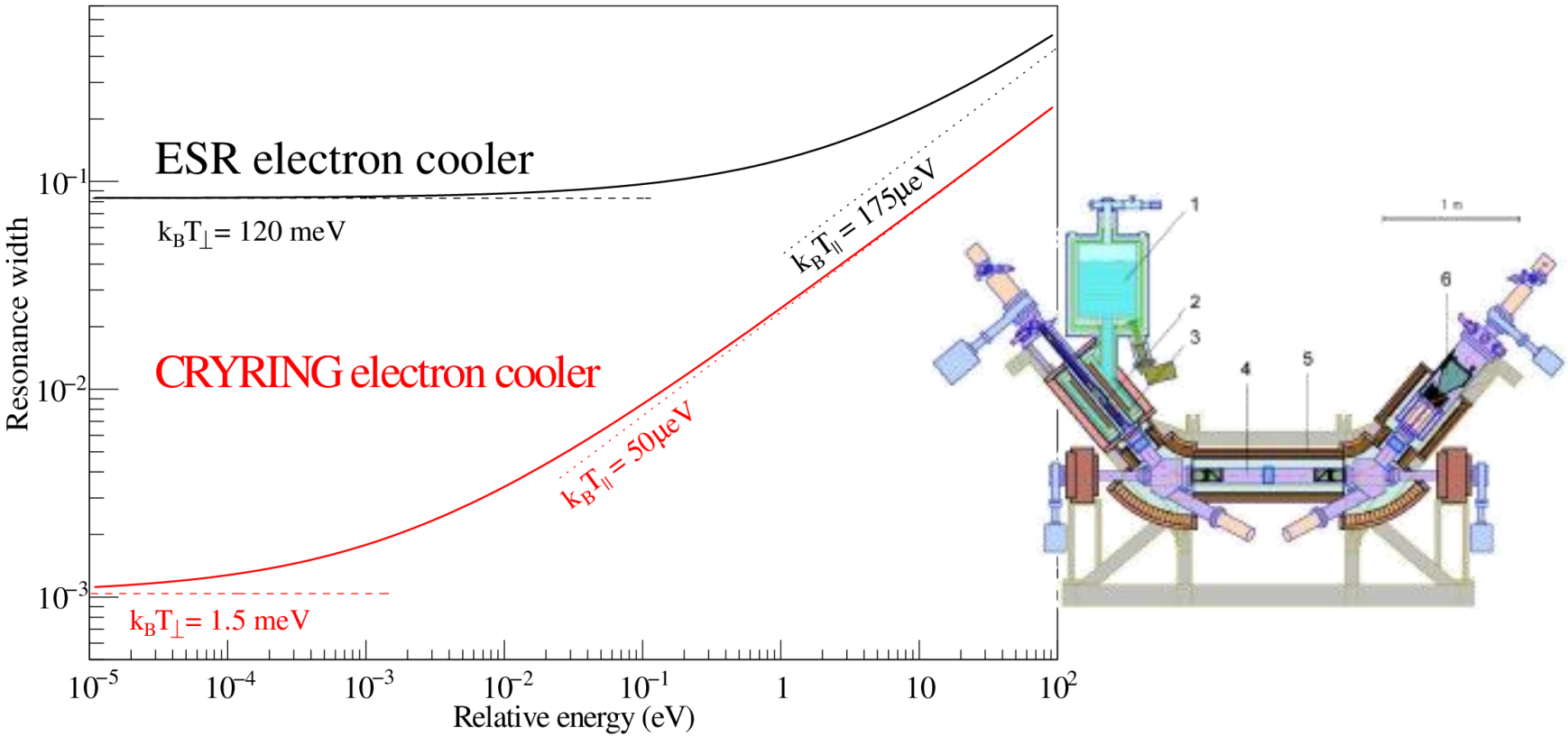


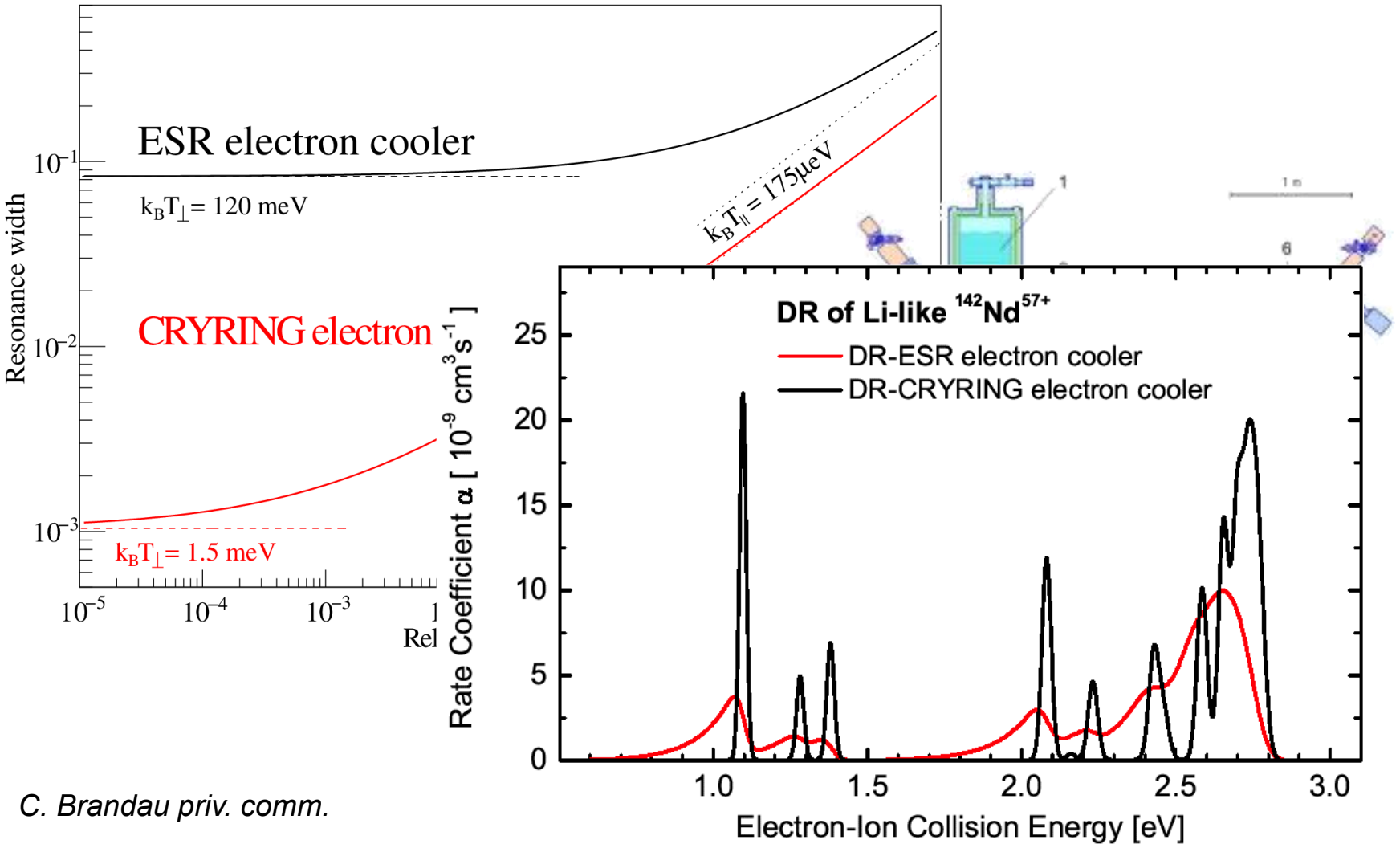
- First bake out cycle finished
- Mean pressure along the ring 8 x 10^{-11} mbar

Electron Cooling ESR - CRYRING



C. Brandau priv. comm.

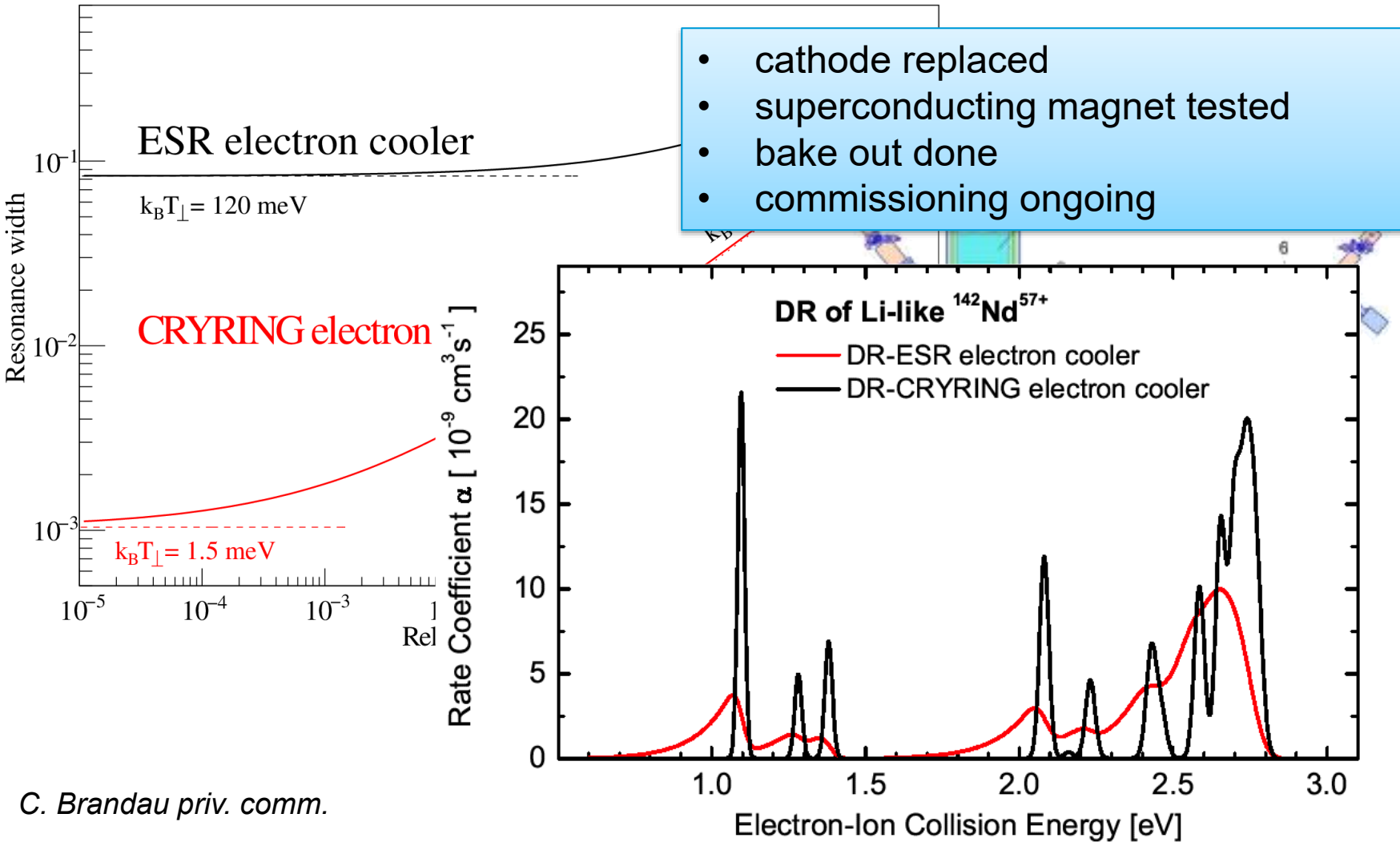
Electron Cooling ESR - CRYRING



C. Brandau priv. comm.

Electron Cooling ESR - CRYRING

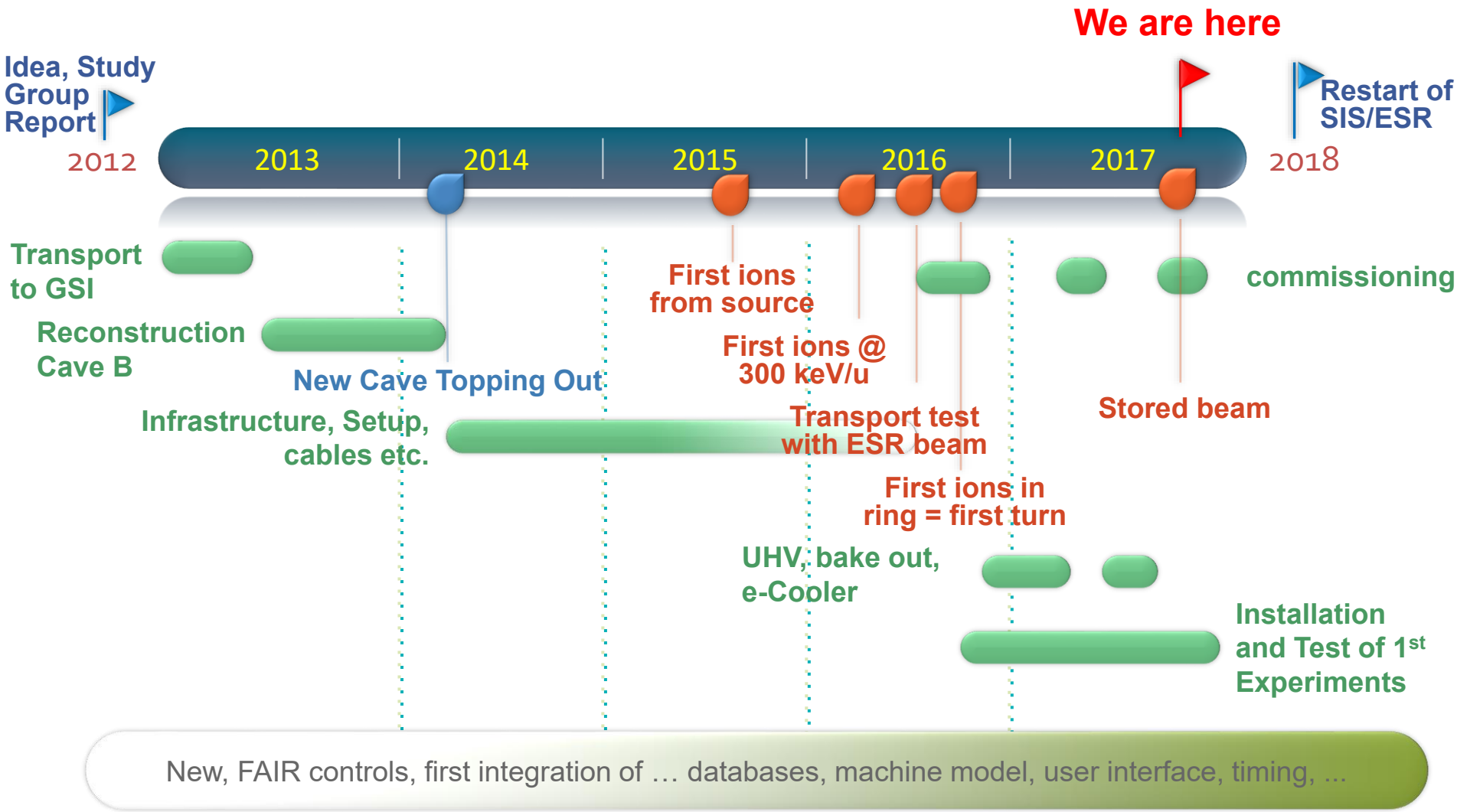
- cathode replaced
- superconducting magnet tested
- bake out done
- commissioning ongoing



C. Brandau priv. comm.

CRYRING@ESR in new Cave

Timeline CRYRING@ESR

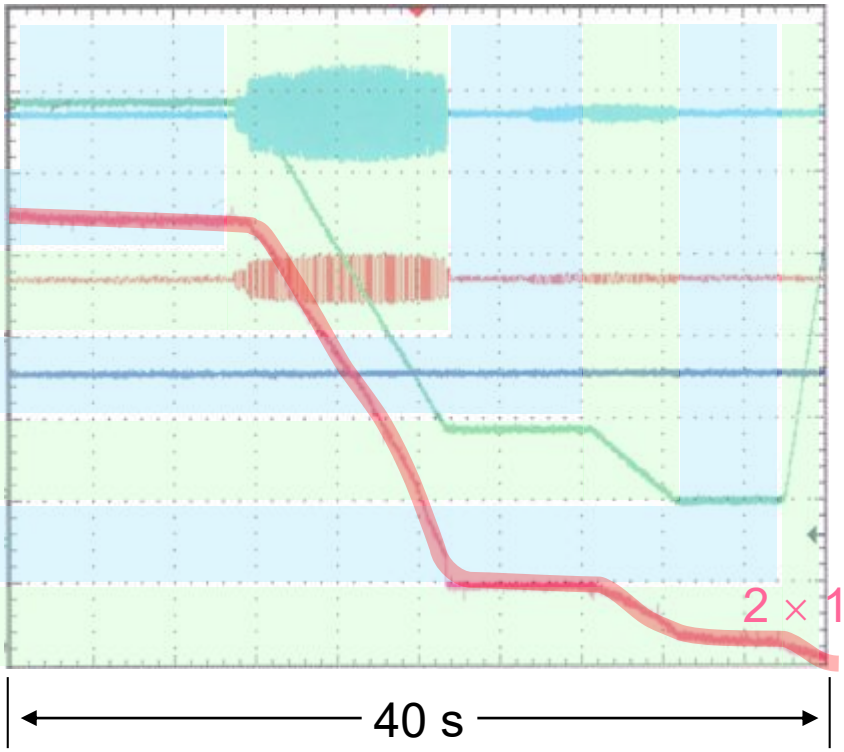


ESR – From 400 to 4 MeV/u

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

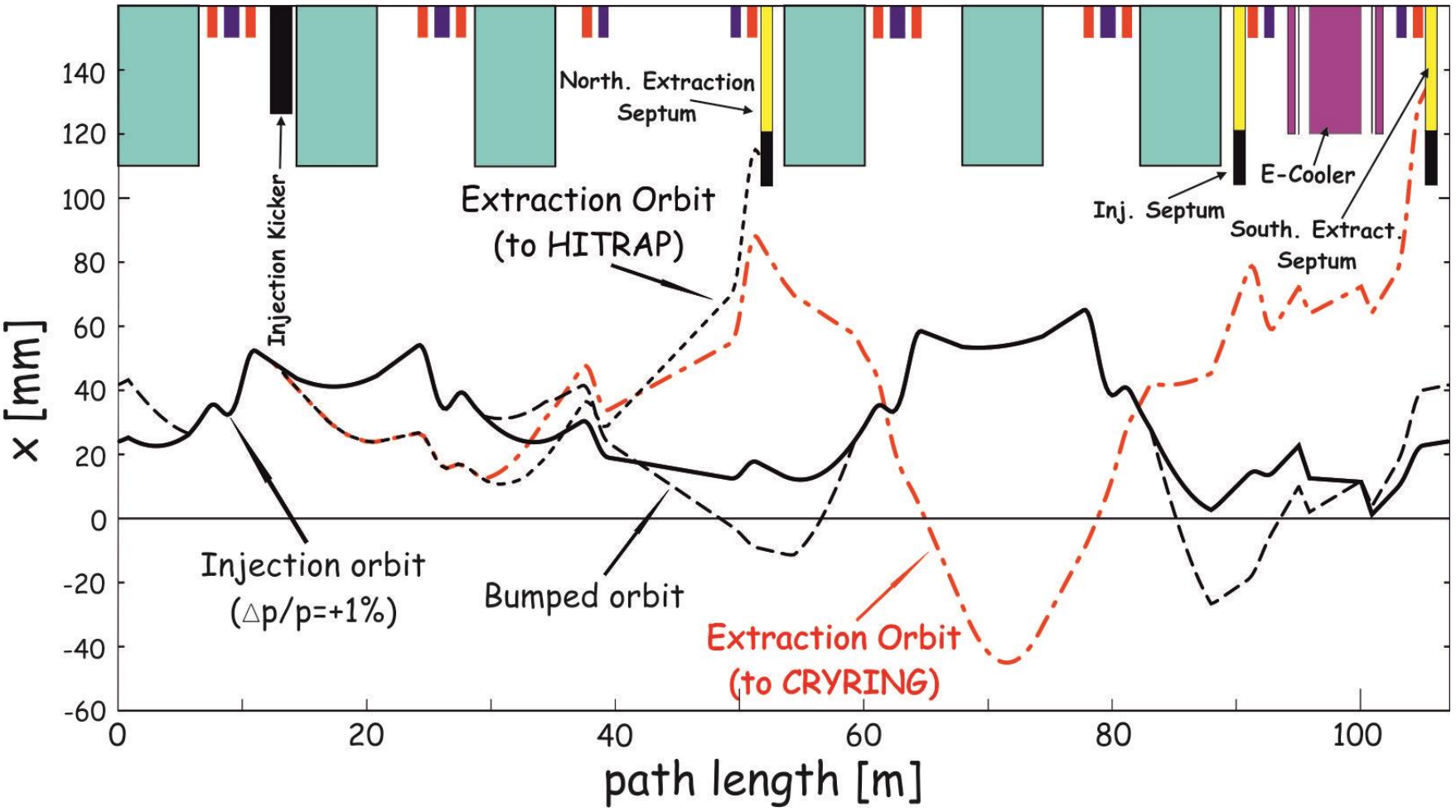
Ni^{28+} 400 → 30 → 4 MeV/u

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



1100 μA → 180 μA → 25 μA

Fast Extraction from ESR to CRYRING



S. Litvinov et al.

Decelerate, Extract, Transfer

> 60%

ESR → **CRYRING@ESR**

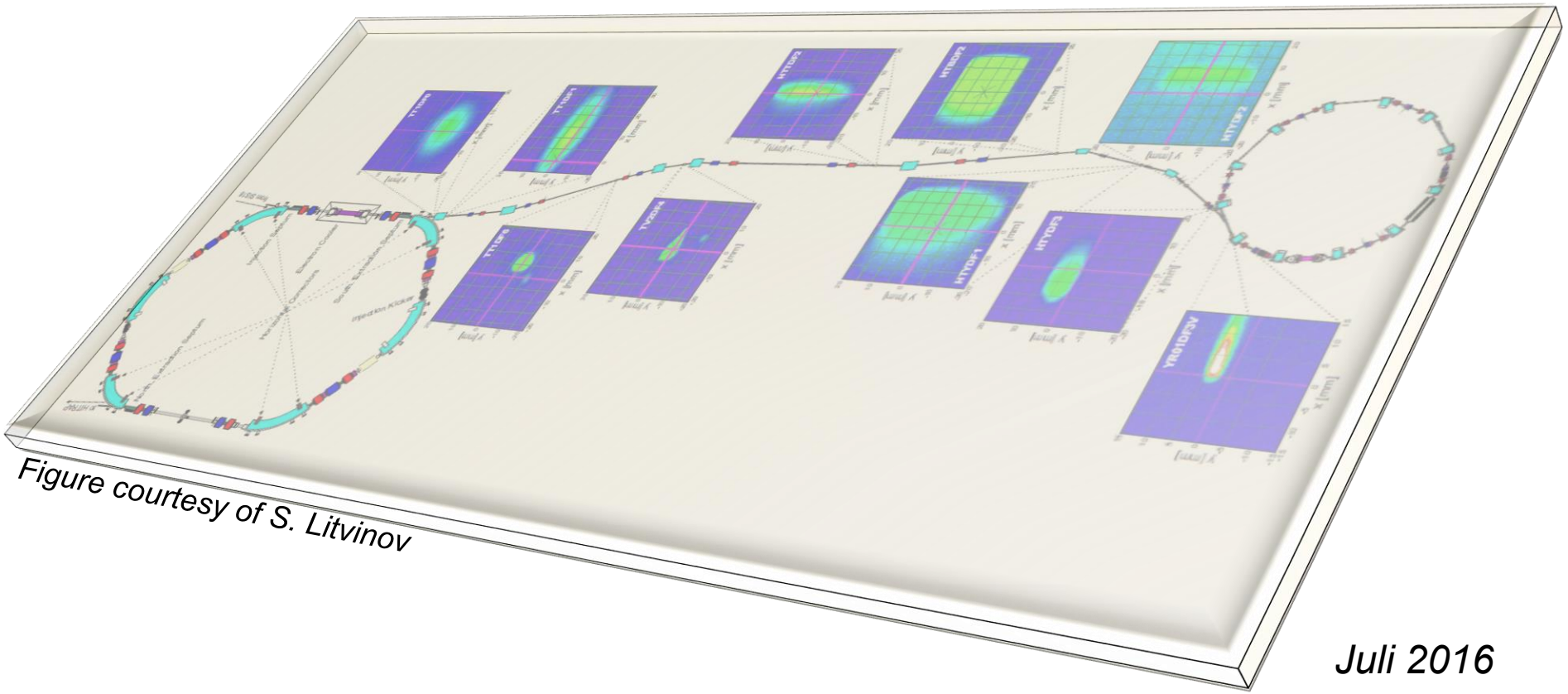


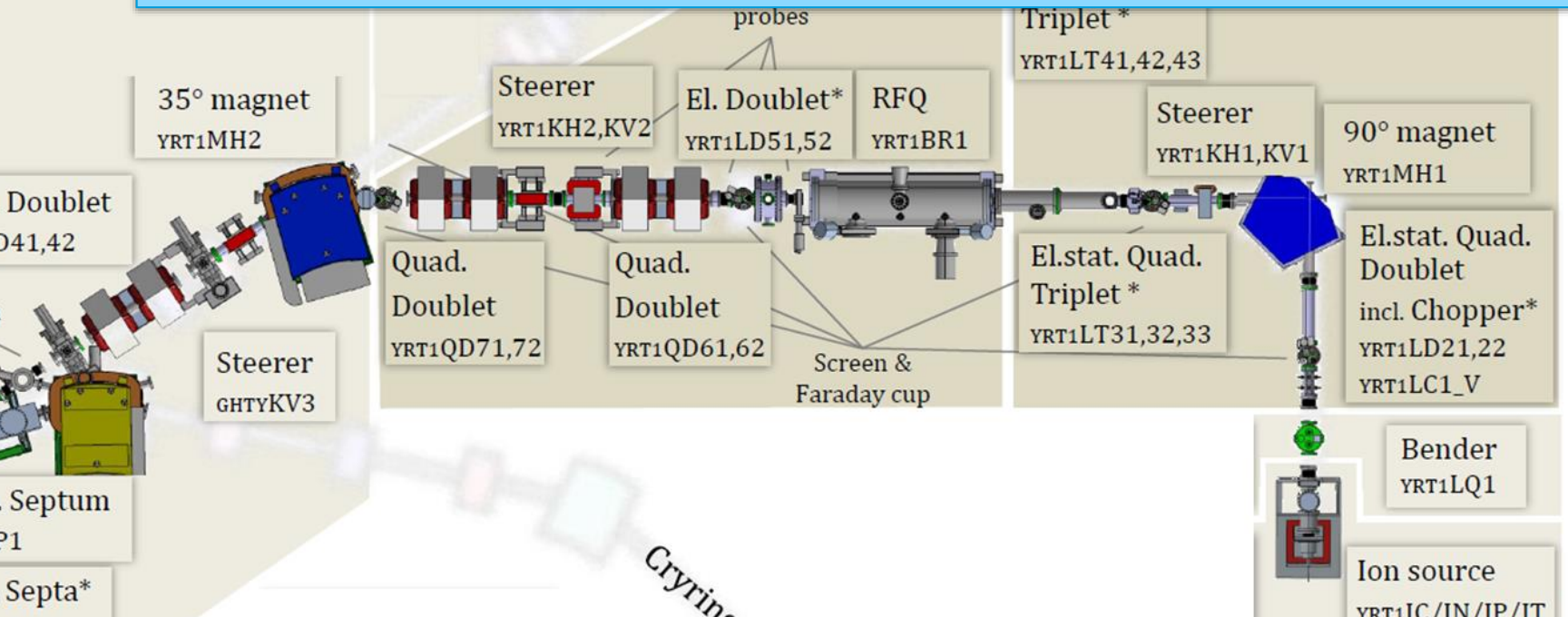
Figure courtesy of S. Litvinov

Juli 2016

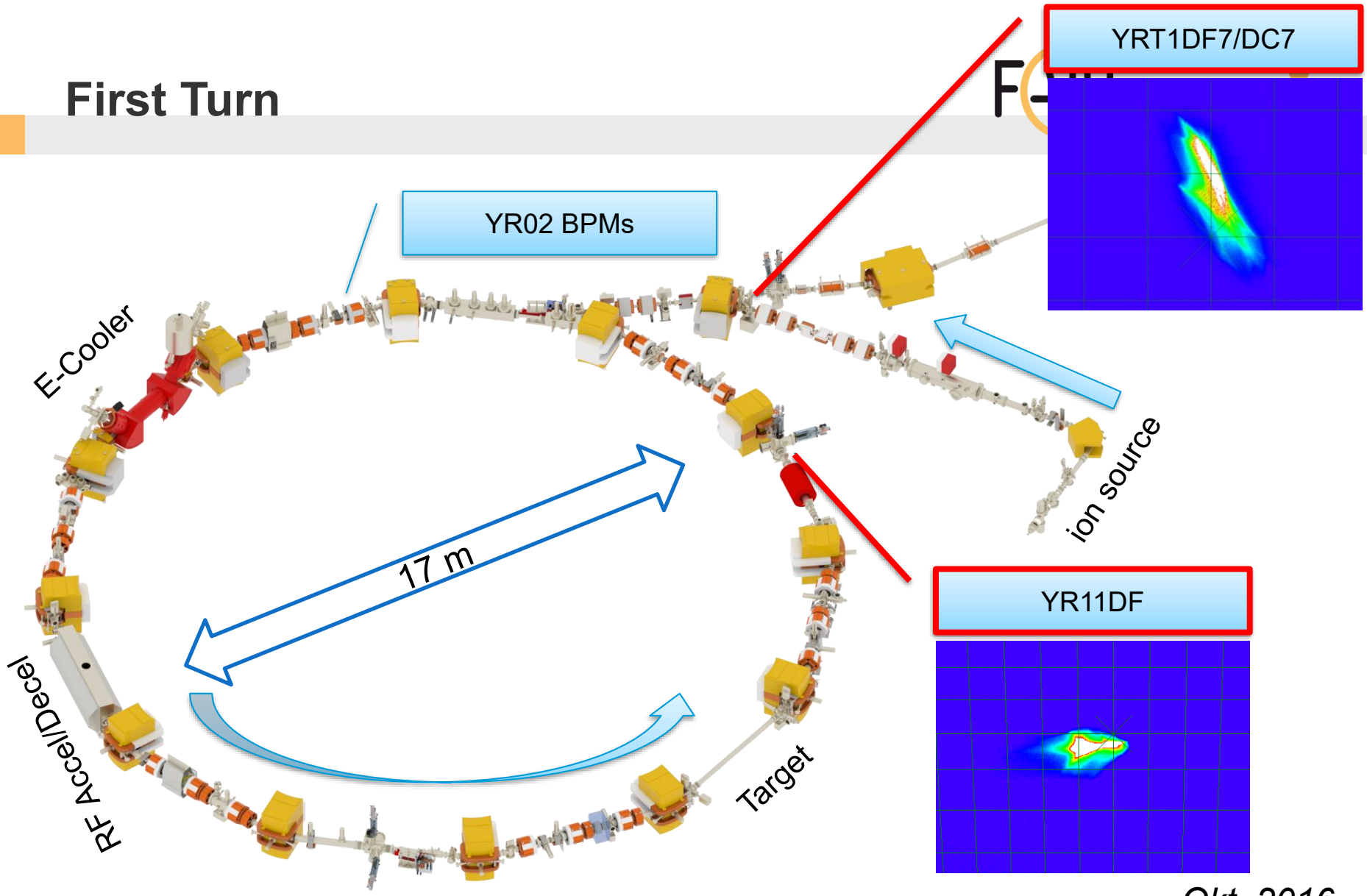
2015, M. Lestinsky (GSI)

Local Ion Source

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



First Turn

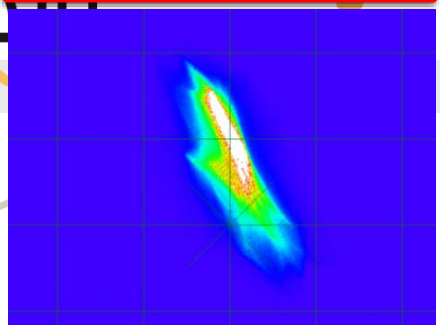


Okt. 2016

Successful testbed for FAIR type control system stack

First Turn

YRT1DF7/DC7



YR02 BPMs

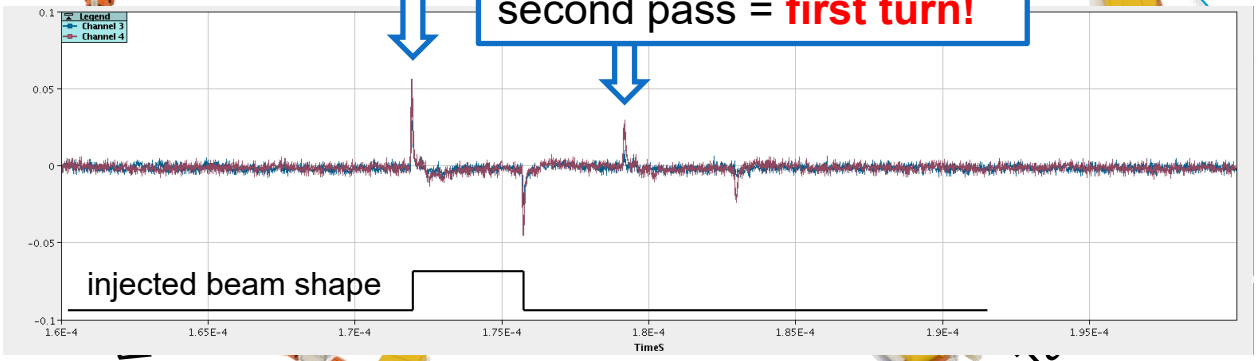
E-Cooler

first pass
(after injection)

second pass = **first turn!**

ion source

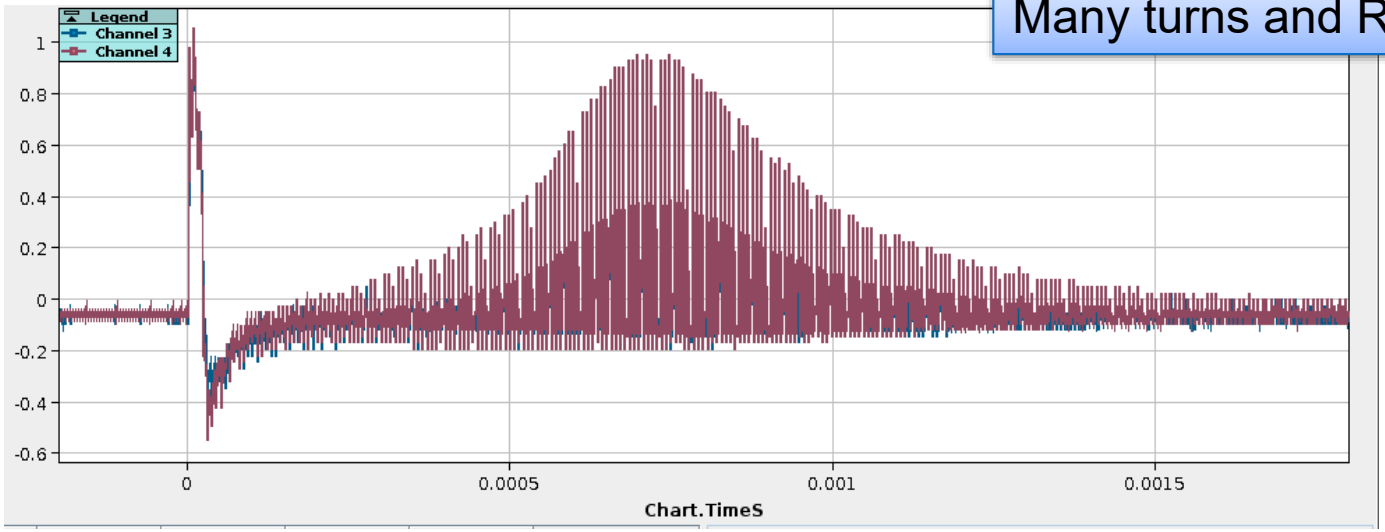
YR11DF



Okt. 2016

Successful testbed for FAIR type control system stack

Status of Commissioning

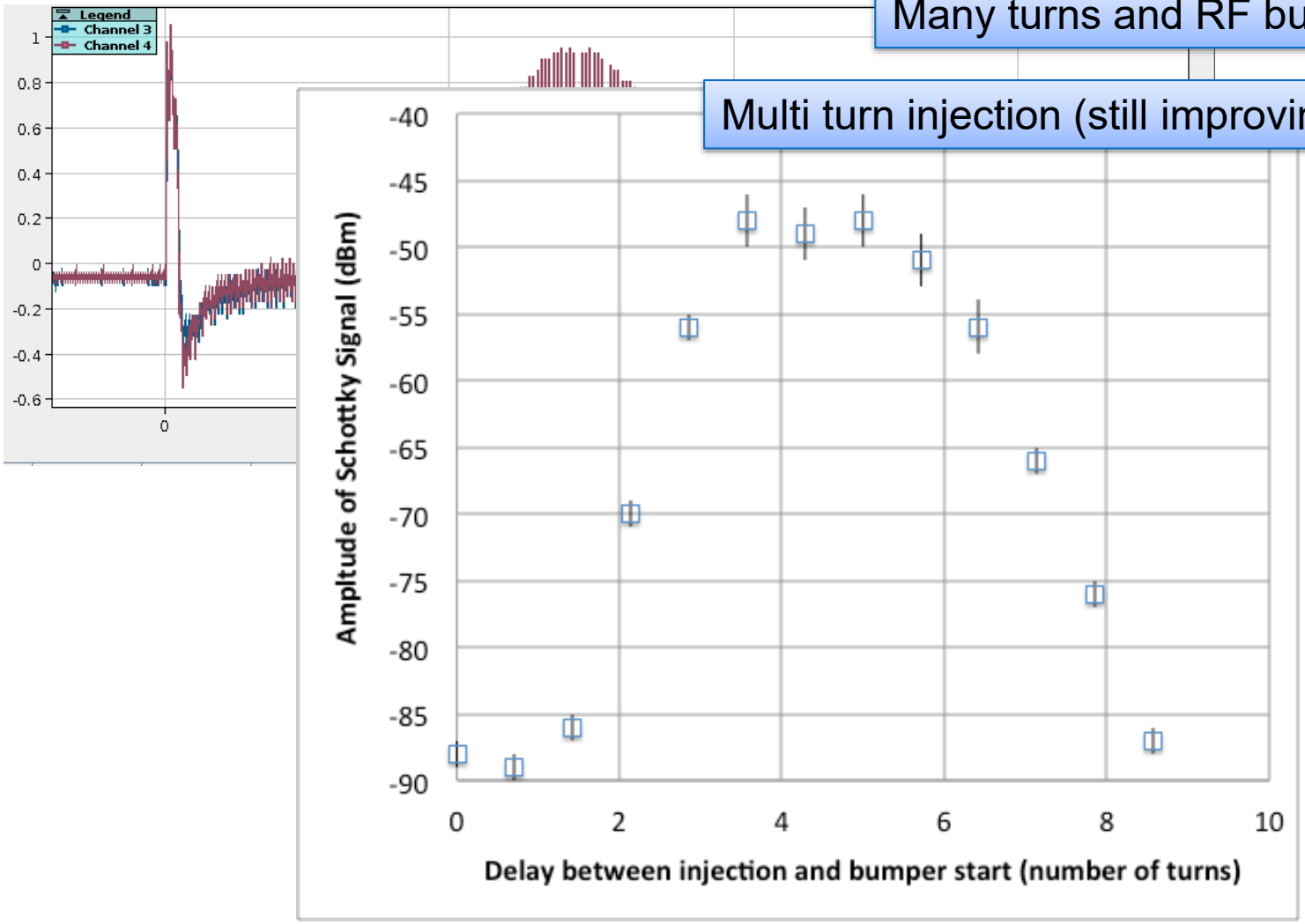


Many turns and RF bunching

Status of Commissioning

Many turns and RF bunching

Multi turn injection (still improving)

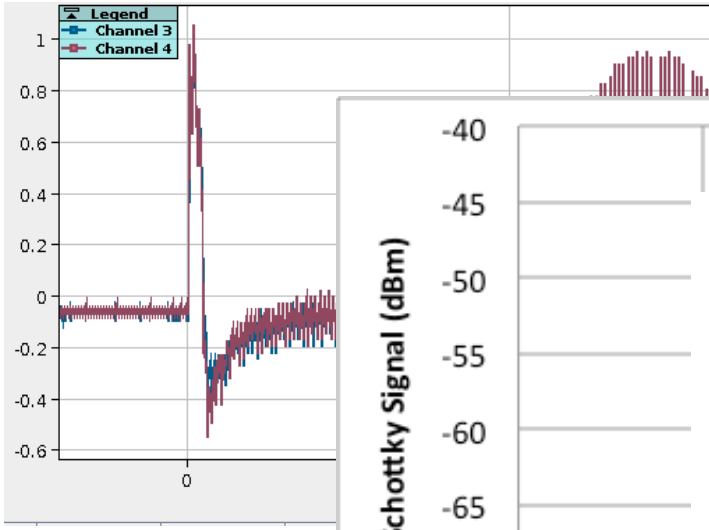


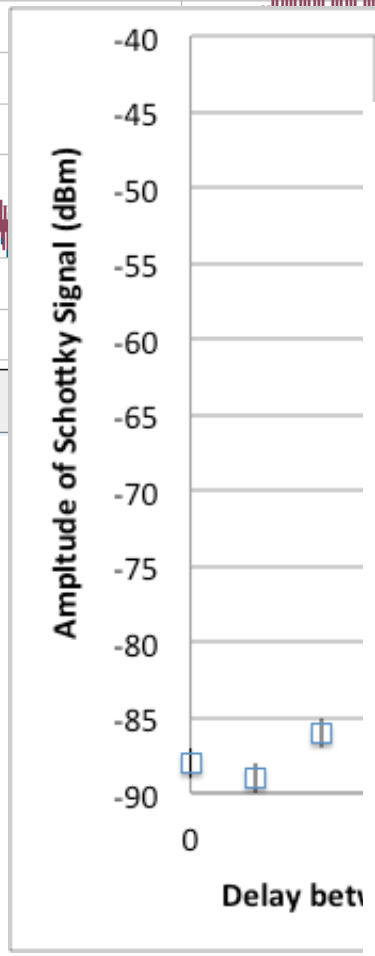
Status of Commissioning

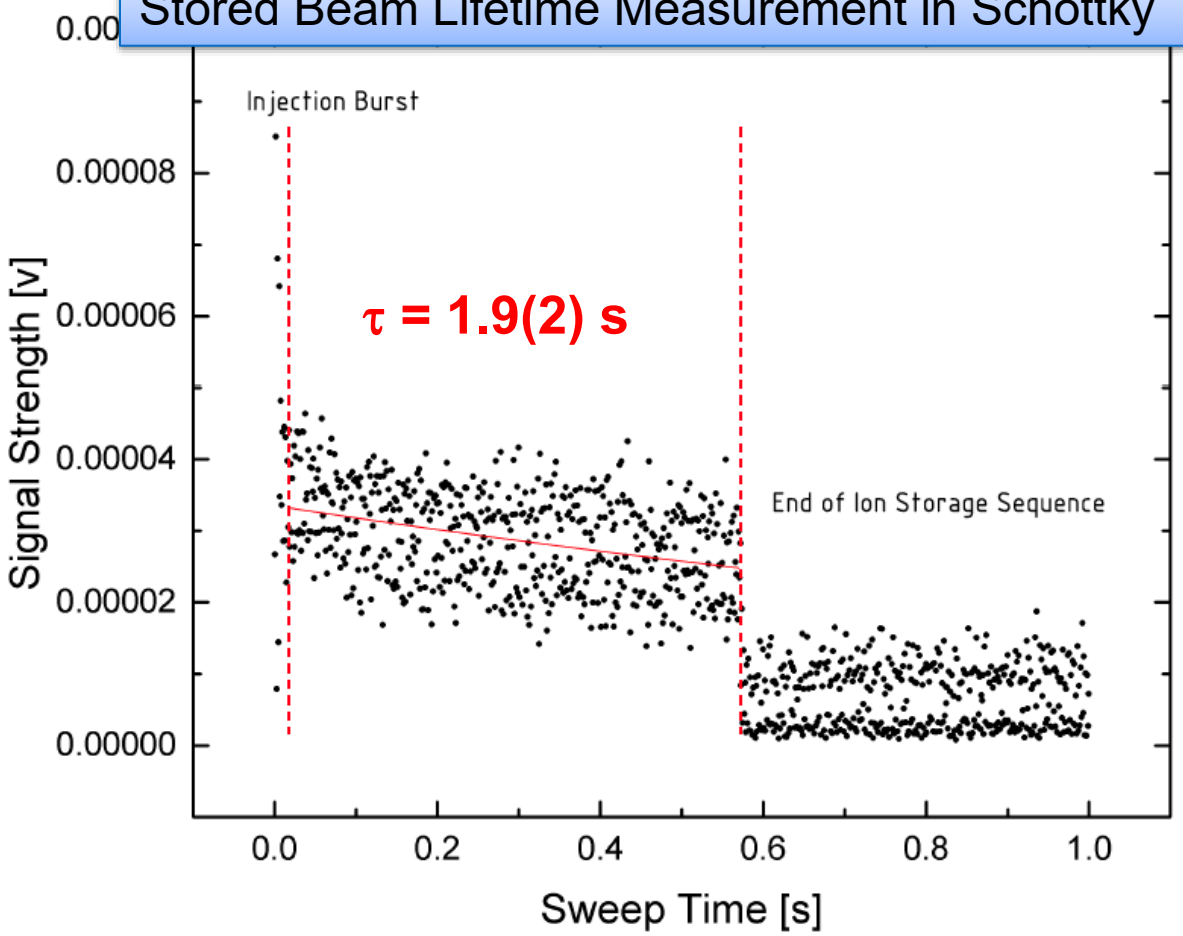
Many turns and RF bunching

Multi turn injection (still improving)

Stored Beam Lifetime Measurement in Schottky

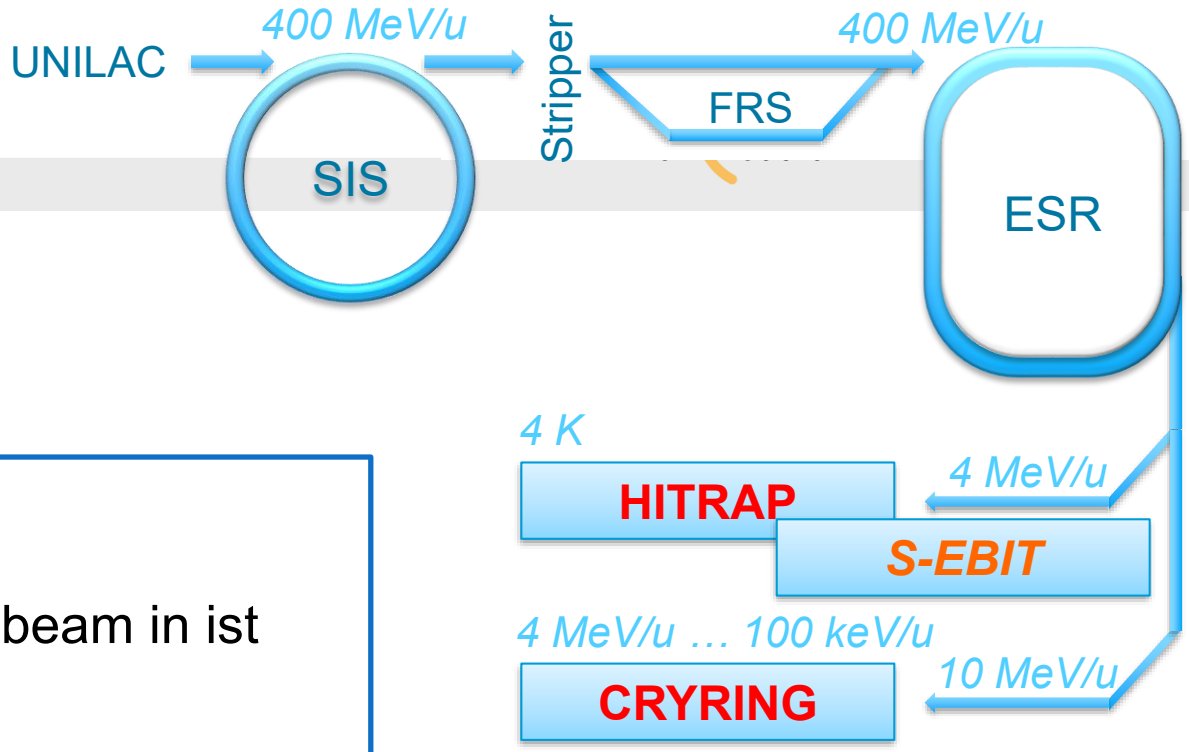




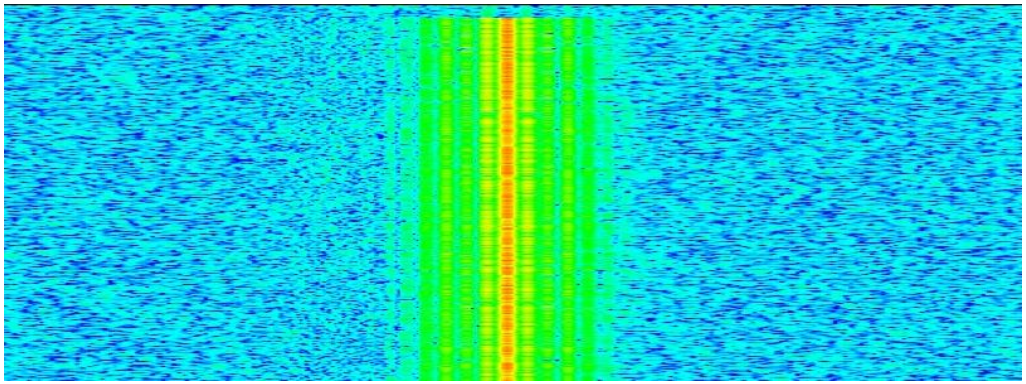


Status of Commissioning

Summary



- **CRYRING@ESR**
  Achieved stored beam in ist new location



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