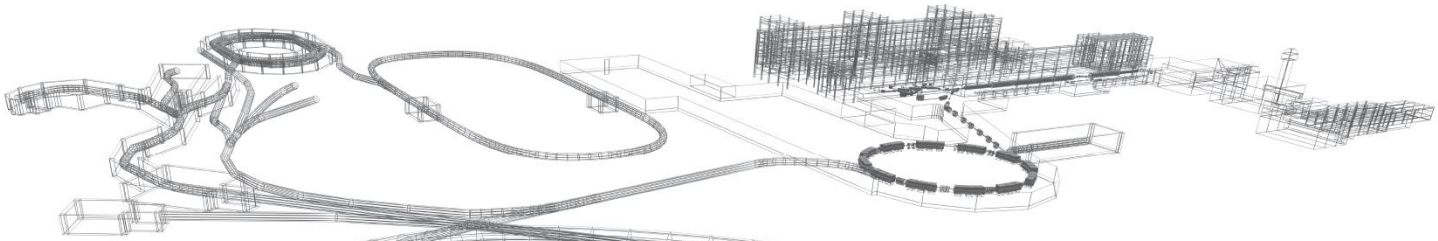


Slow, exotic, Ions at GSI/FAIR

Deceleration and Storage of heavy, highly charged ions

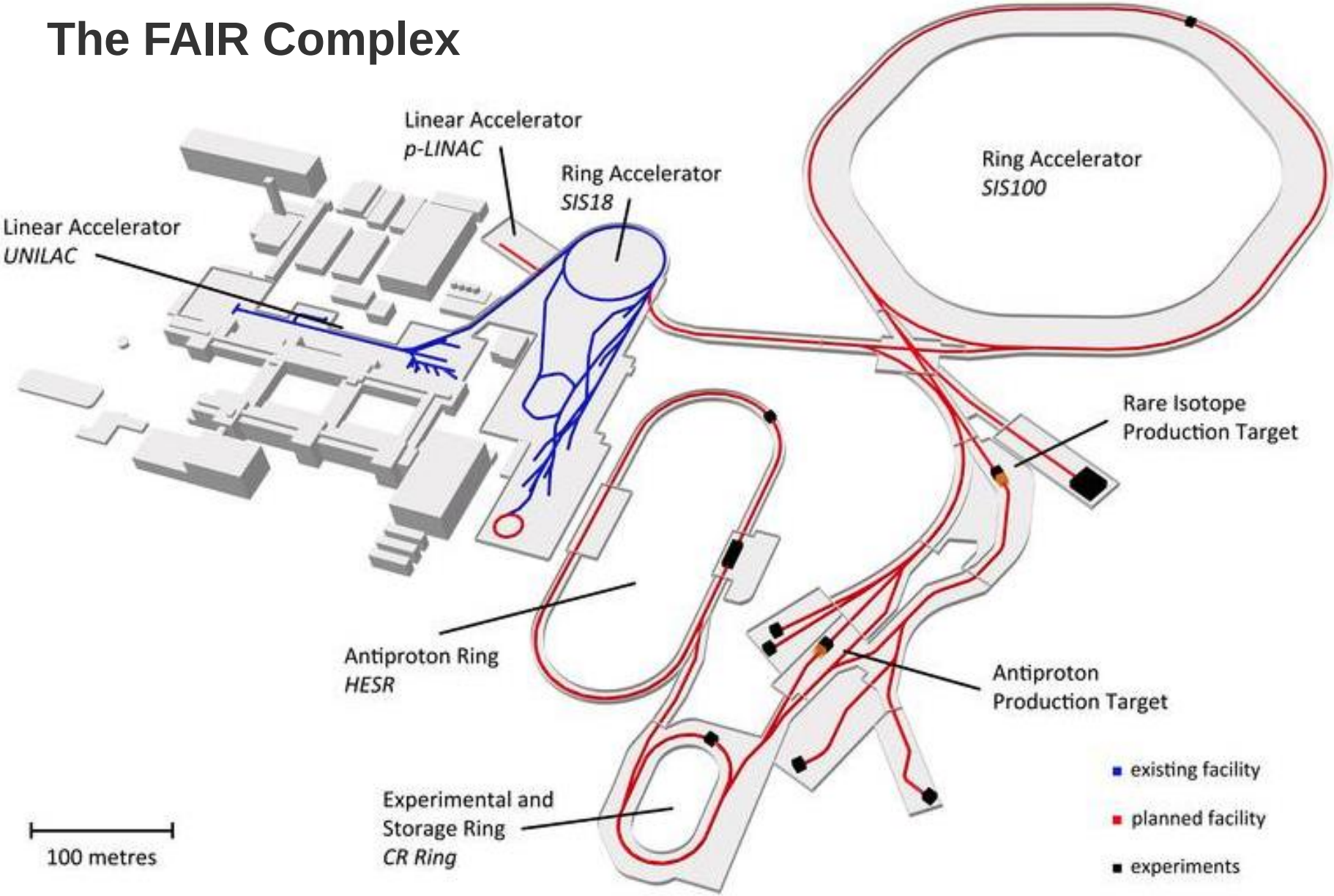
CRYRING@ESR

Commissioning and Performance

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, ...

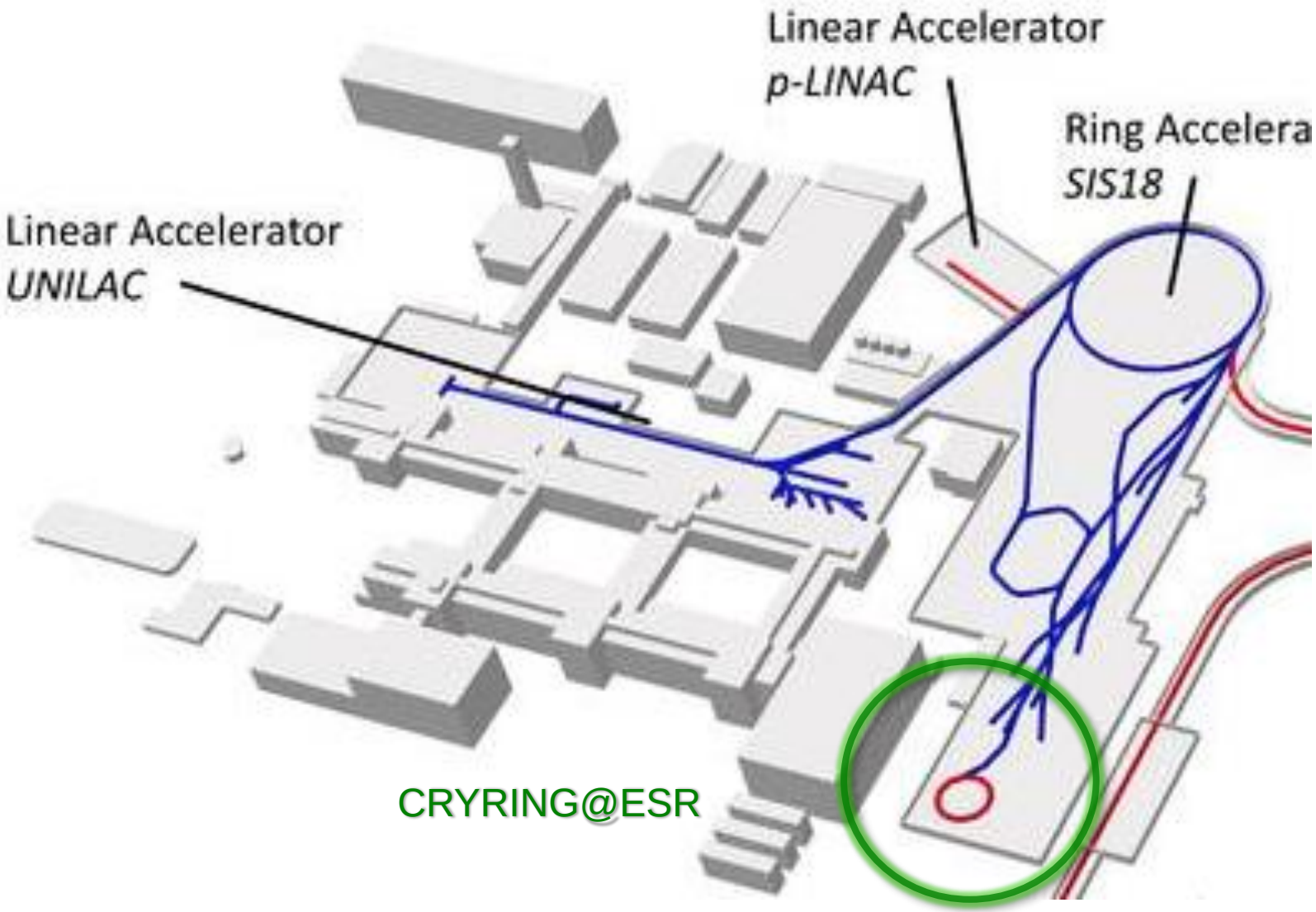
Stockholm University, KVI Groningen, HI Jena, Krakow University

The FAIR Complex

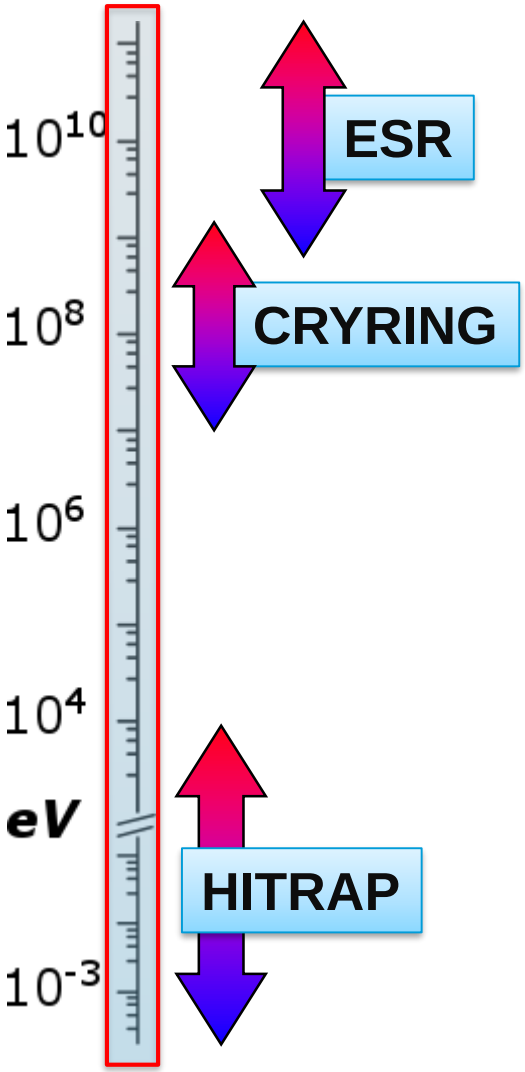


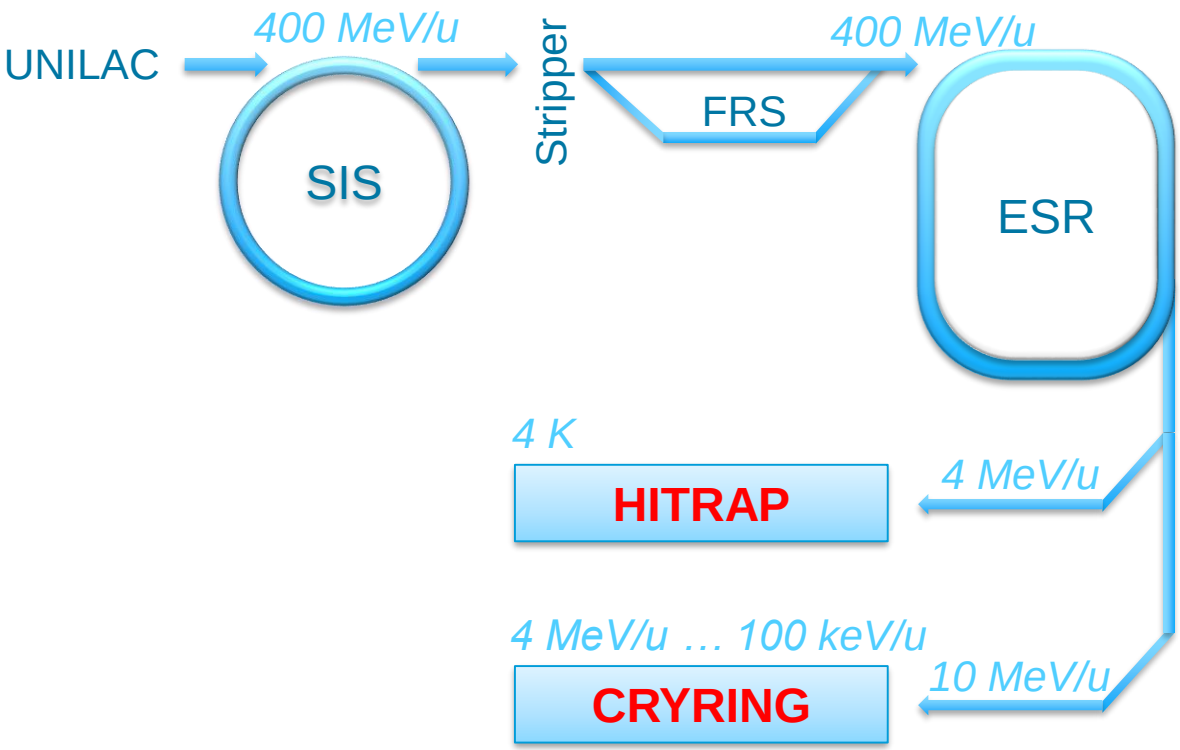
Status of FAIR construction

FAIR Phase 0

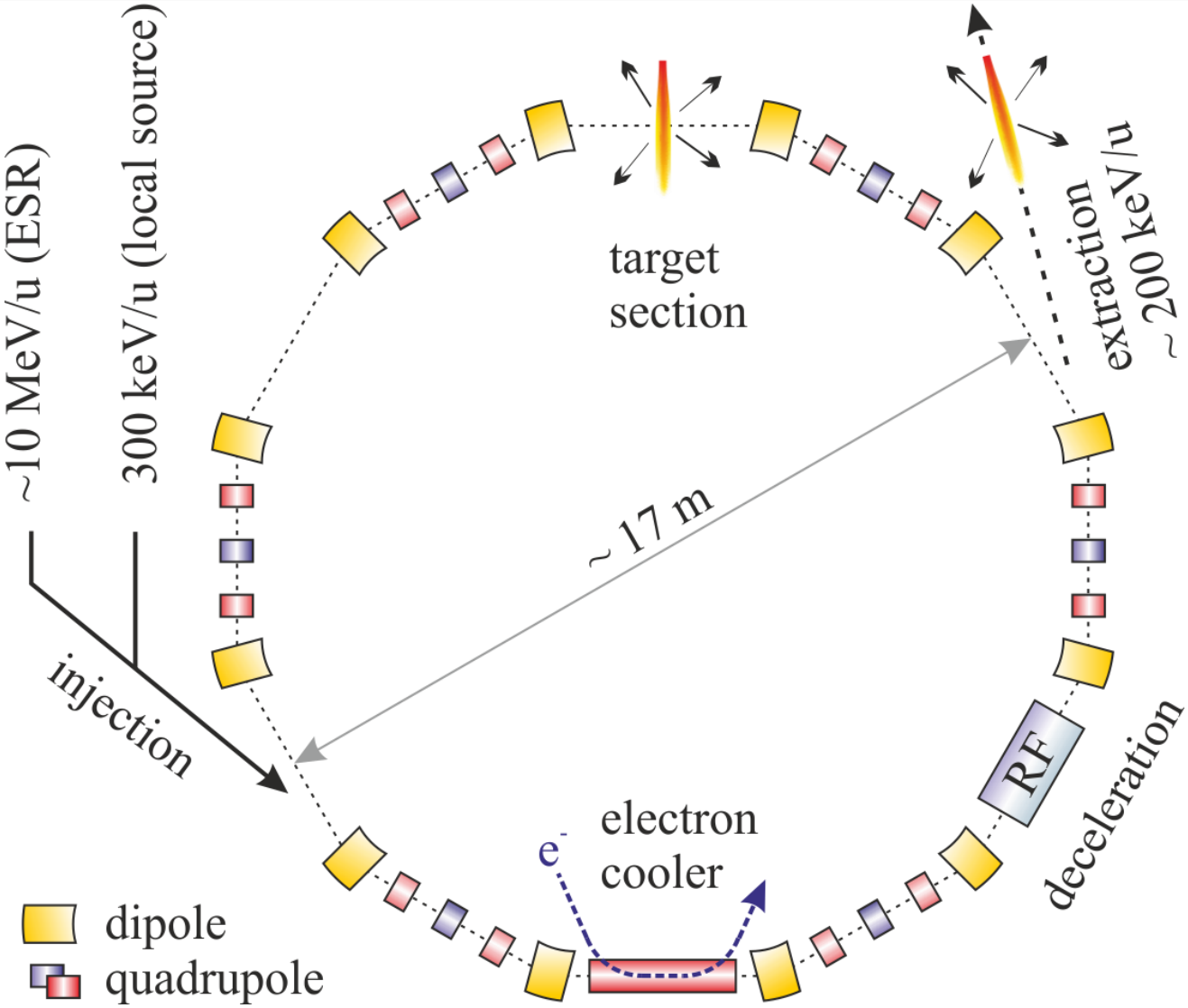

Linear Accelerator
p-LINAC
Ring Accelera
SIS18
Linear Accelerator
UNILAC
CRYRING@ESR

Highly Charged Ion Storage at GSI ("low energy")





CRYRING@ESR


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

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.)

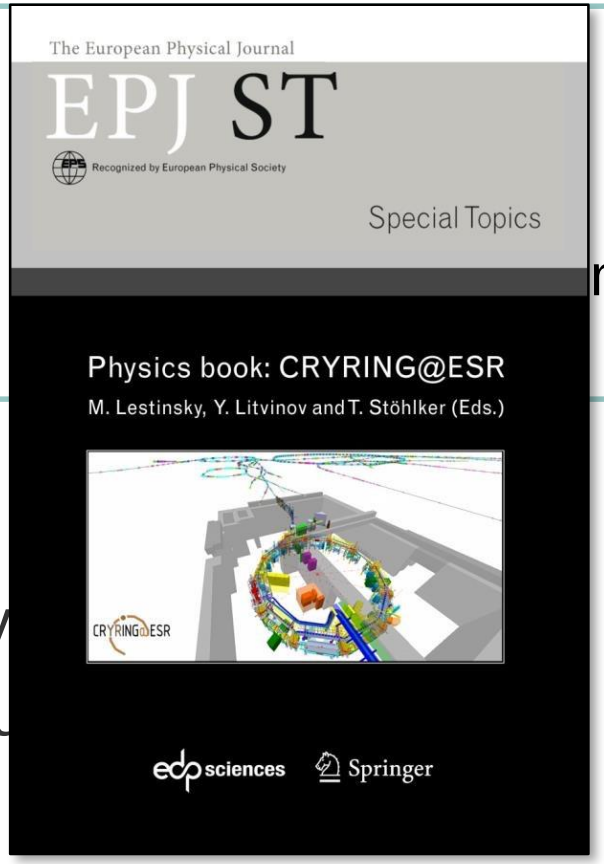
- Successful operated from 1992 to 2010
- Dismantled and shipped to FAIR/GSI in 2012/13

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

CRYRING@ESR

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

<u>with real beam</u> (standalone operation du

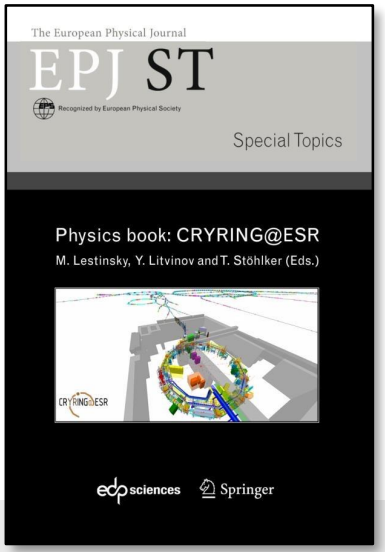


- **Scientific Opportunities**
- Heavy, highly-charged ions available at GSI (up to U^{92+}, fragmentation products) at low energy 100 keV/u .. 10 MeV/u – bridge the energy gap between the ESR (> 4 MeV/u) and HITRAP (<10 keV/u)

Scientific Opportunities – FAIR Phase 0

- Atomic and molecular structure, slow collision dynamics, elementary processes
- Nuclear structure, astrophysically relevant rates in the Gamov window of p-process, *(p,γ)*, nuclear collisions at the Coulomb barrier
- Intersections of atomic and nuclear physics (nuclear magnetic moments, isotope shifts and charge radii, NEEC, nuclear Polarization ...)
- HCI and surfaces/bulk material

} already using the present GSI accelerator chain ~2018++



- 3 PAC proposals granted
- 17 Letters of intent

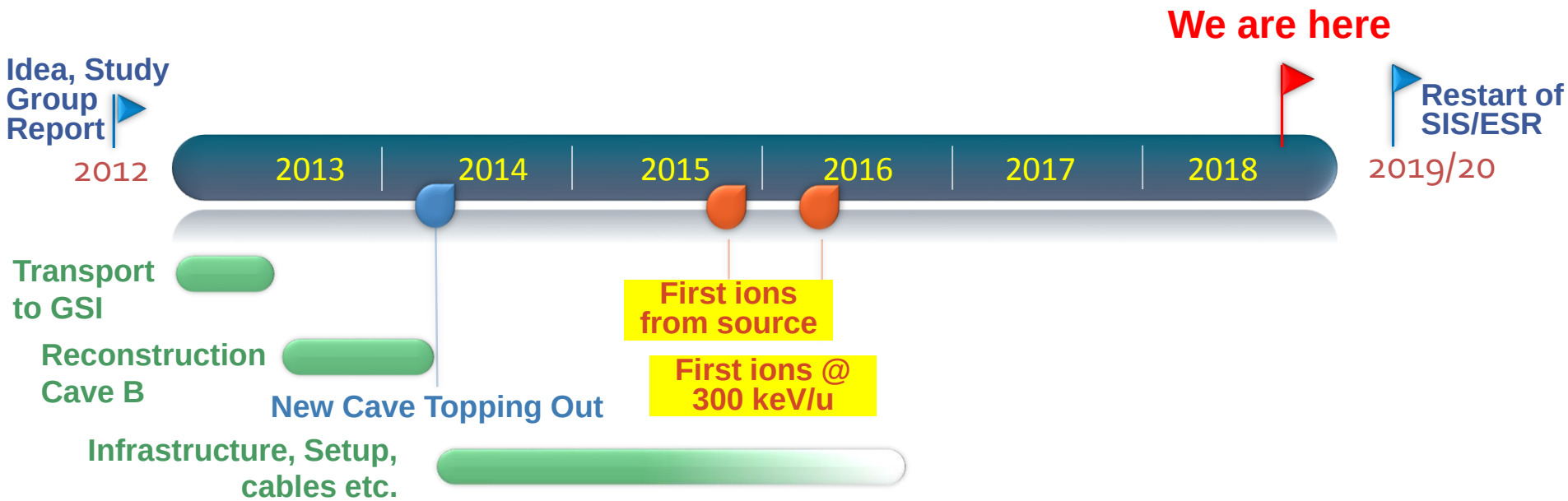
Timeline CRYRING@ESR

New, FAIR controls, first integration of … databases, machine model, user interface, timing, ...

2012-2013

Karte: © OpenStreetMap

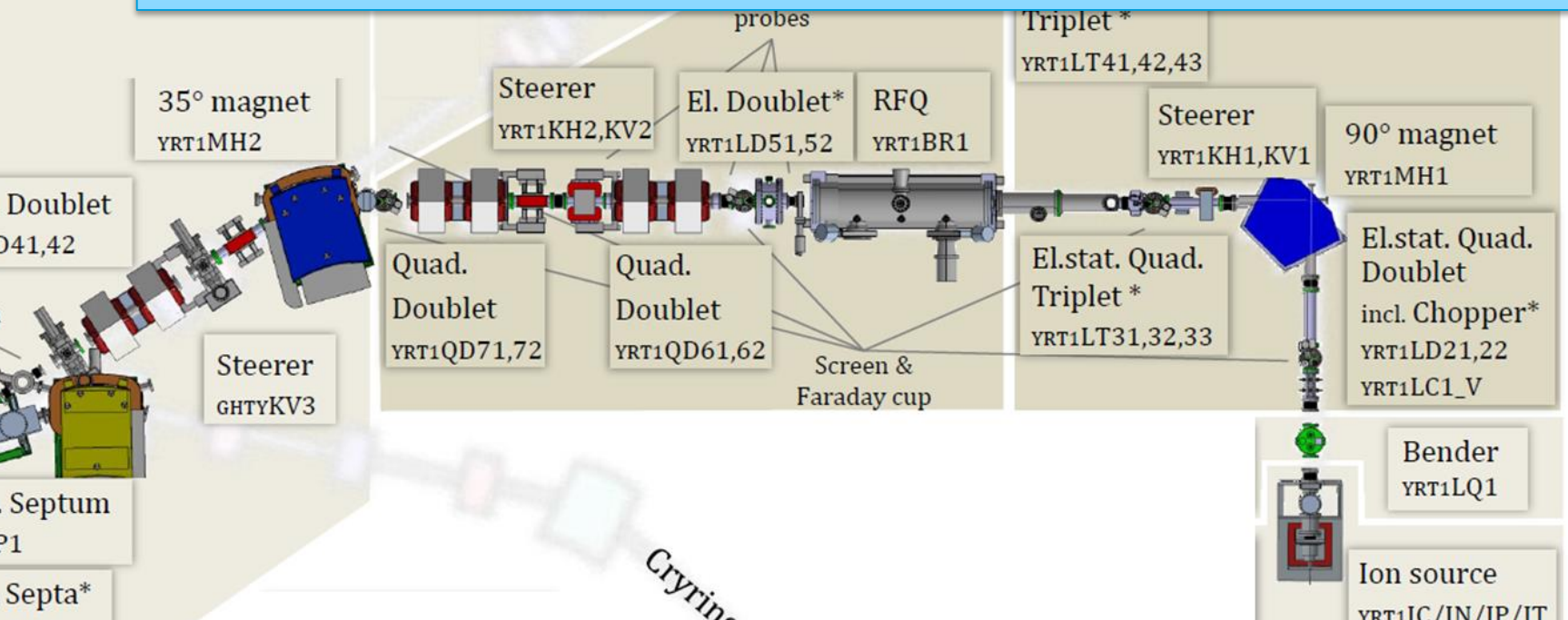
Timeline CRYRING@ESR



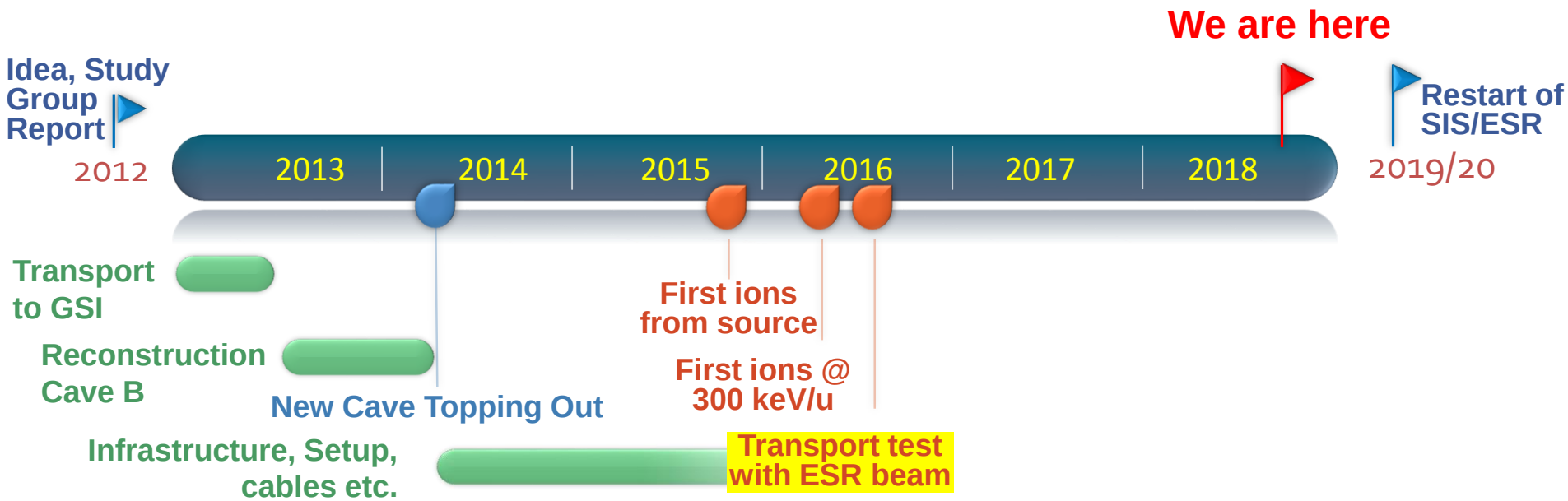
New, FAIR controls, first integration of … databases, machine model, user interface, timing, ...

Local Ion Source

- Typical ions so far – H_2, D_2, Ar, **Mg**
- Typical intensities of beam for injection – 40 μA for gases, 4 μA for Mg, 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



Timeline CRYRING@ESR



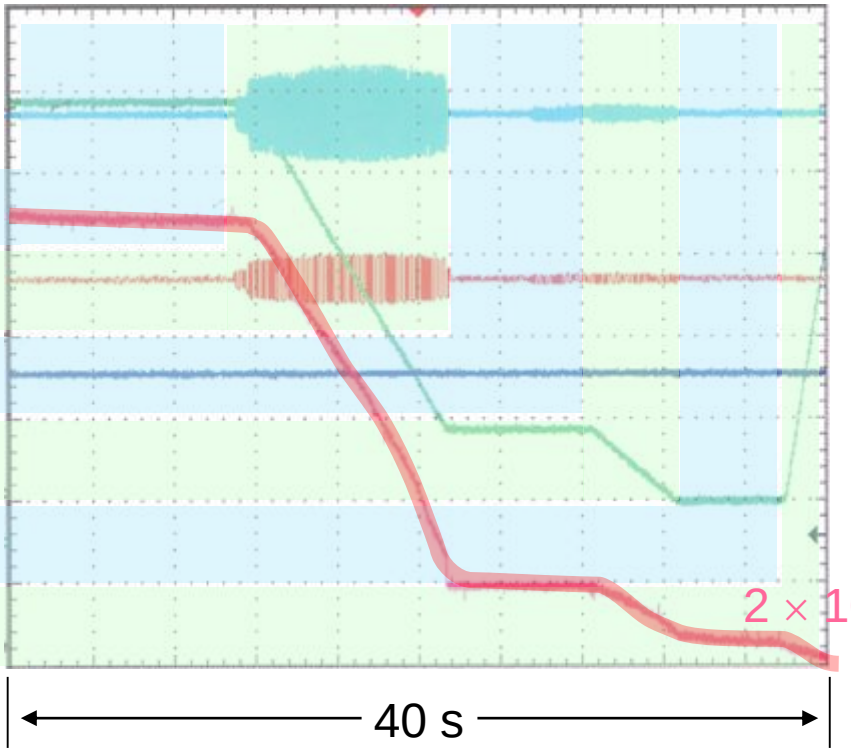
New, FAIR controls, first integration of … databases, machine model, user interface, timing, ...

ESR – From 400 to 4 MeV/u

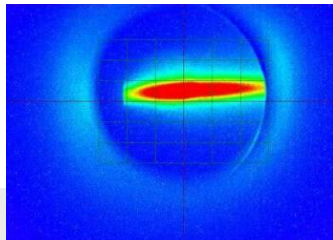
ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

Ni^{28+} 400 → 30 → 4 MeV/u

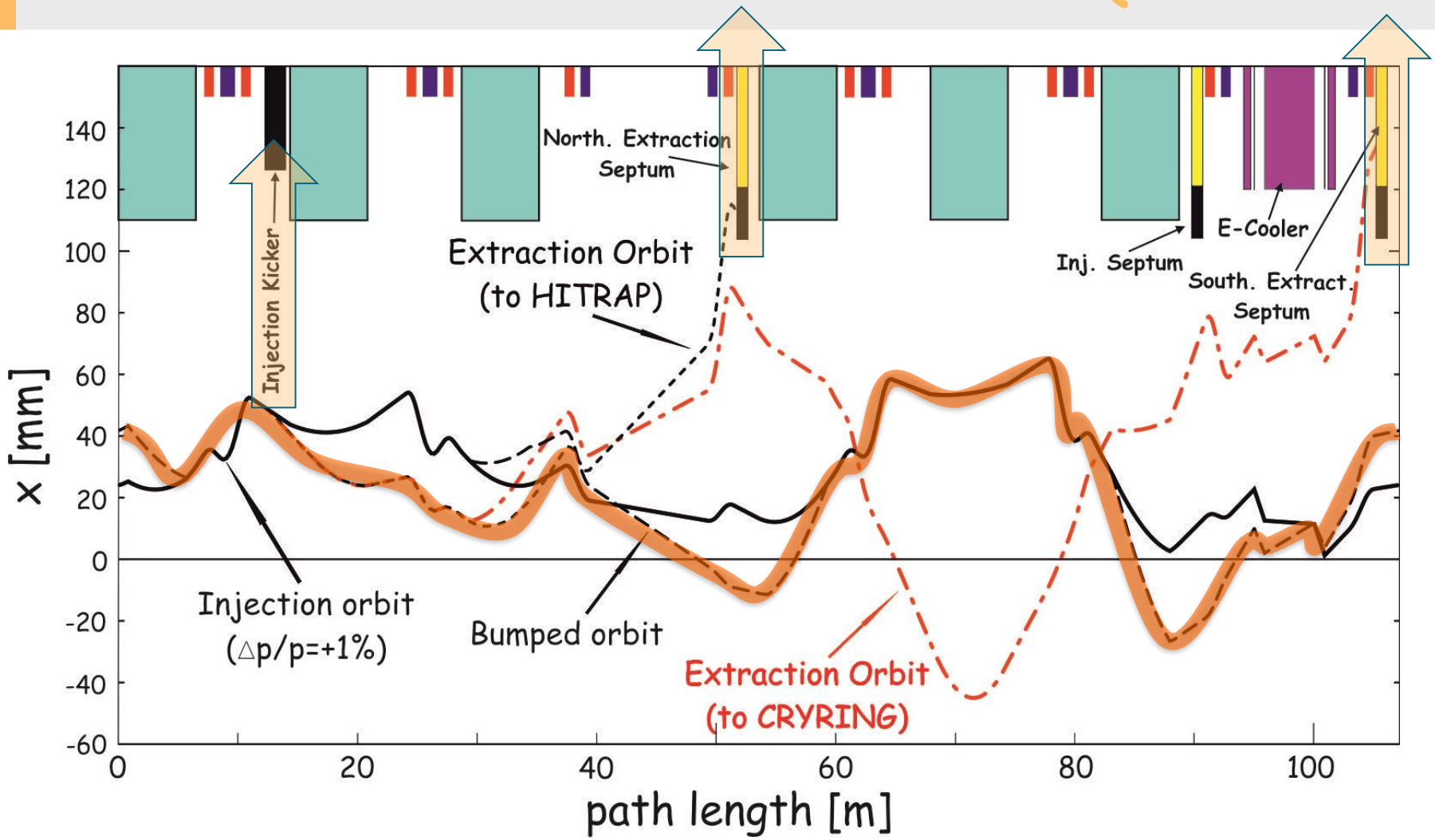
time (s)	**ESR cycle during recent experiment**
5..20	injection, **stoch. cooling**
3..10	deceleration 400 – 30 MeV/u
2..6	e^- cooling, rebunching
2..5	deceleration 30 – 4 MeV/u
2..5	e^- cooling, ejection
3	reset magnets



M. Steck et al.



Fast Extraction from ESR to CRYRING



S. Litvinov et al.

Decelerate, Extract, Transfer

ESR —> **CRYRING@ESR**

> 60%

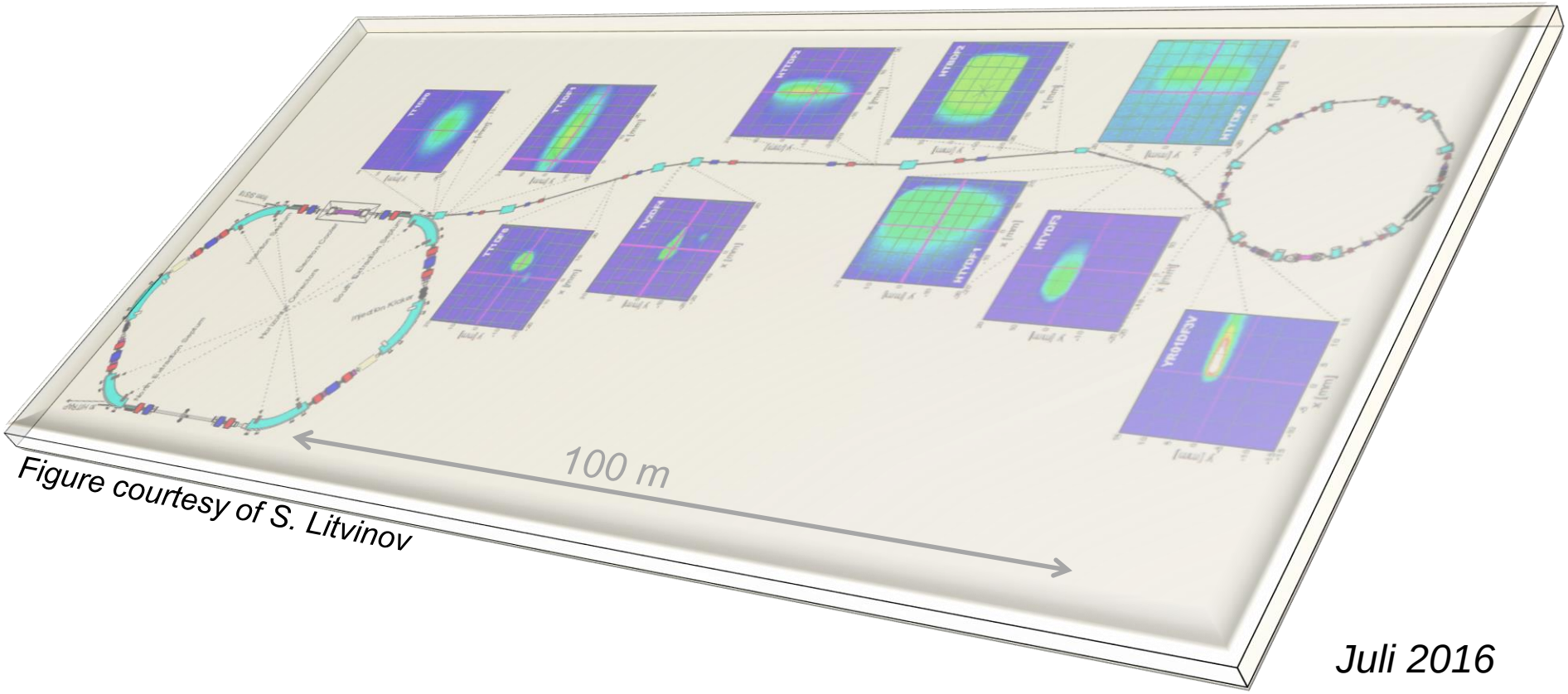
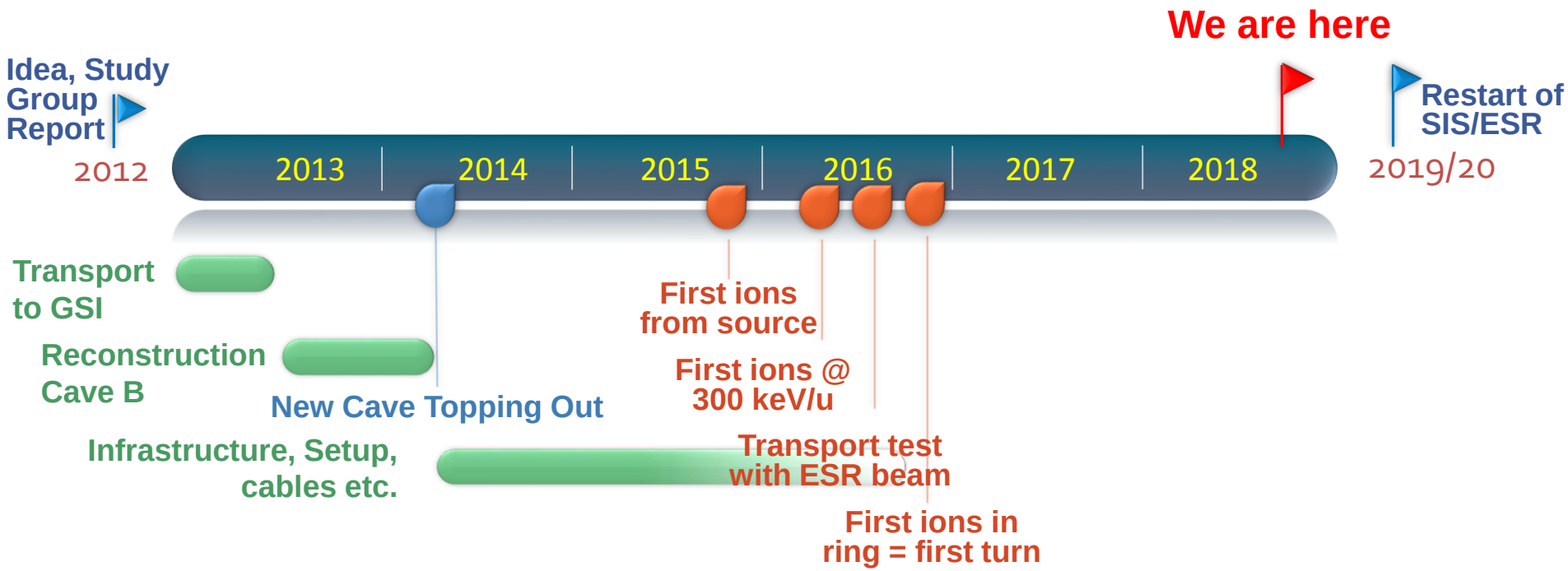


Figure courtesy of S. Litvinov

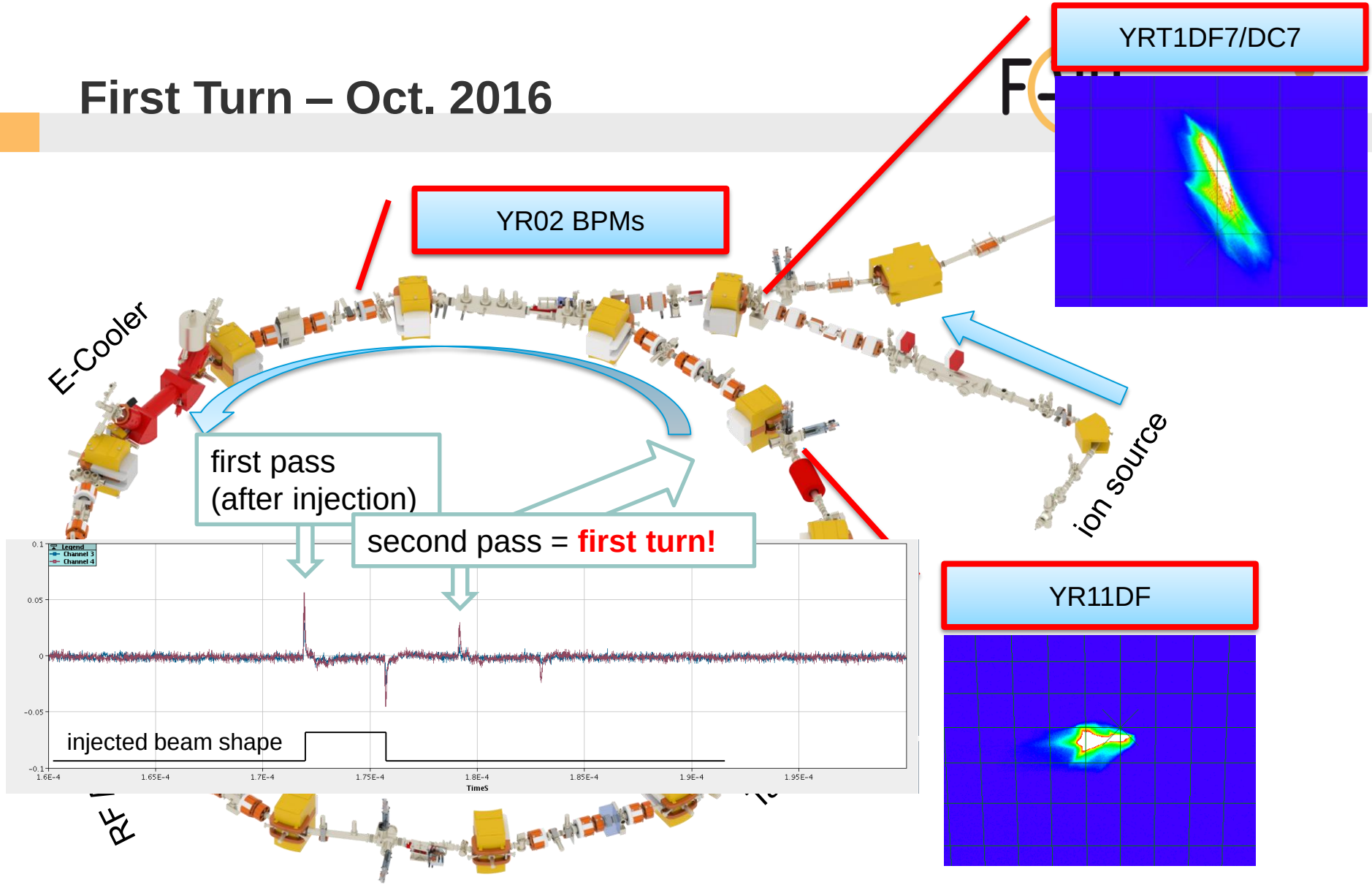
Juli 2016

Timeline CRYRING@ESR



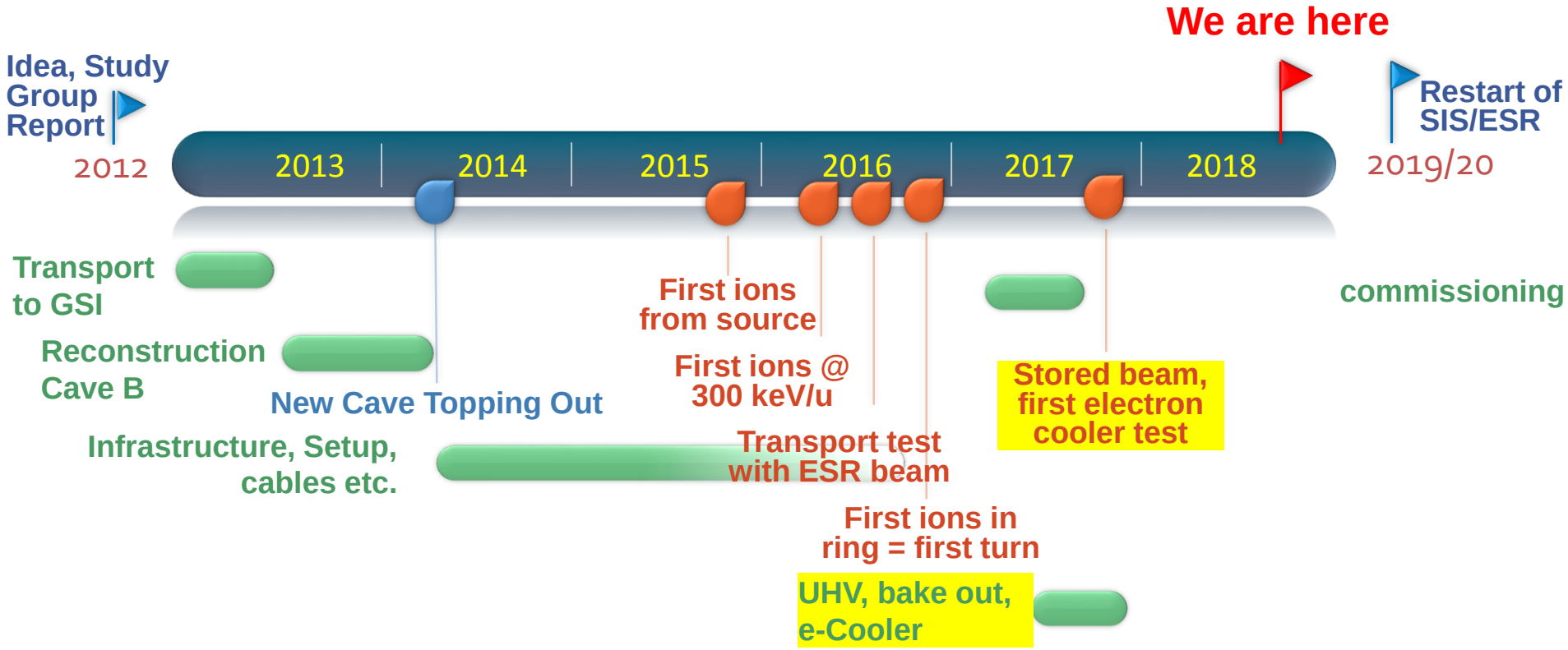
New, FAIR controls, first integration of … databases, machine model, user interface, timing, ...

First Turn – Oct. 2016



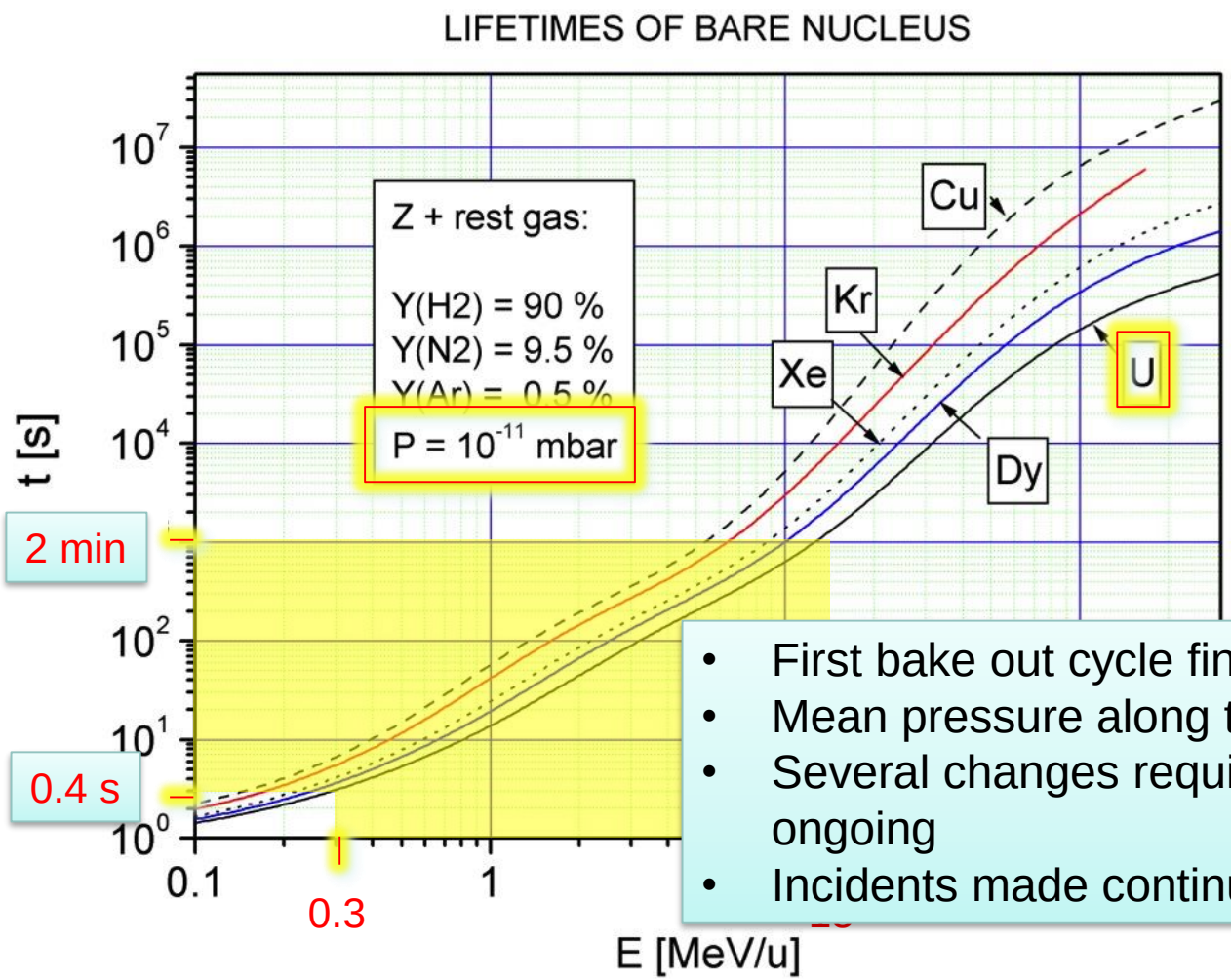
Successful testbed for FAIR type control system stack

Timeline CRYRING@ESR

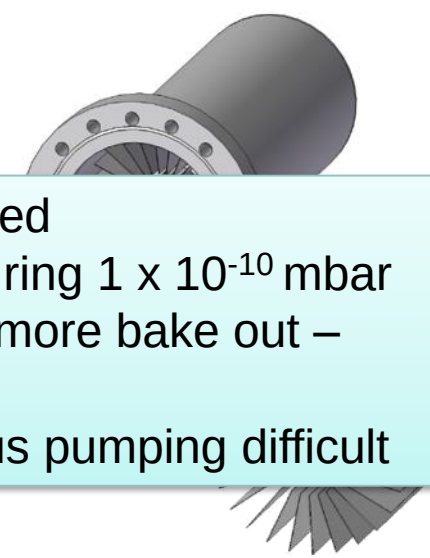


New, FAIR controls, first integration of … databases, machine model, user interface, timing, ...

Ultra High Vacuum & Beam Life Time

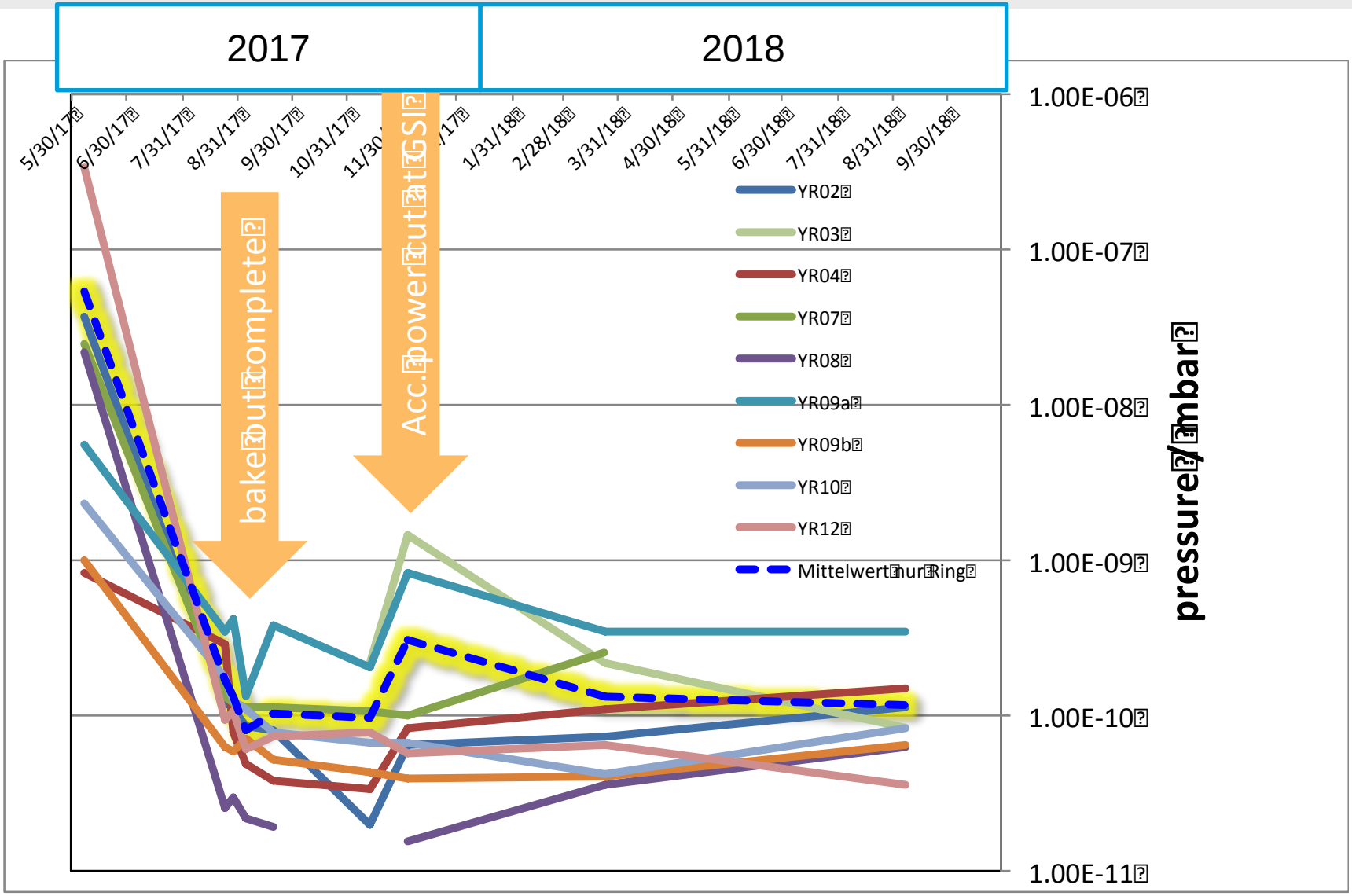


- Ion pumps
  ~ 10
- Cryopumps
- NEG pumps
  ~ 100

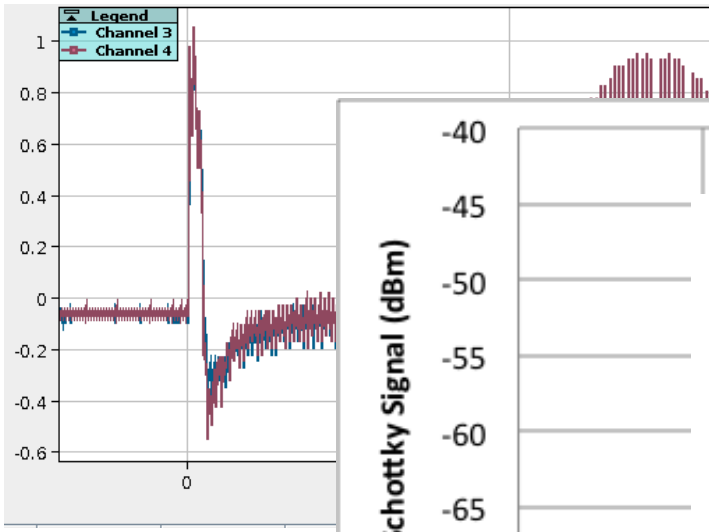


- First bake out cycle finished
- Mean pressure along the ring 1 x 10^{-10} mbar
- Several changes require more bake out – ongoing
- Incidents made continuous pumping difficult

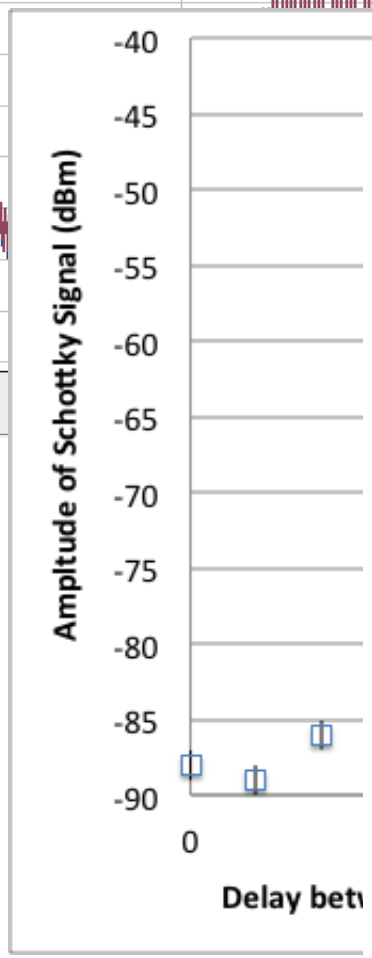
Vacuum Conditions



Some results of Commissioning

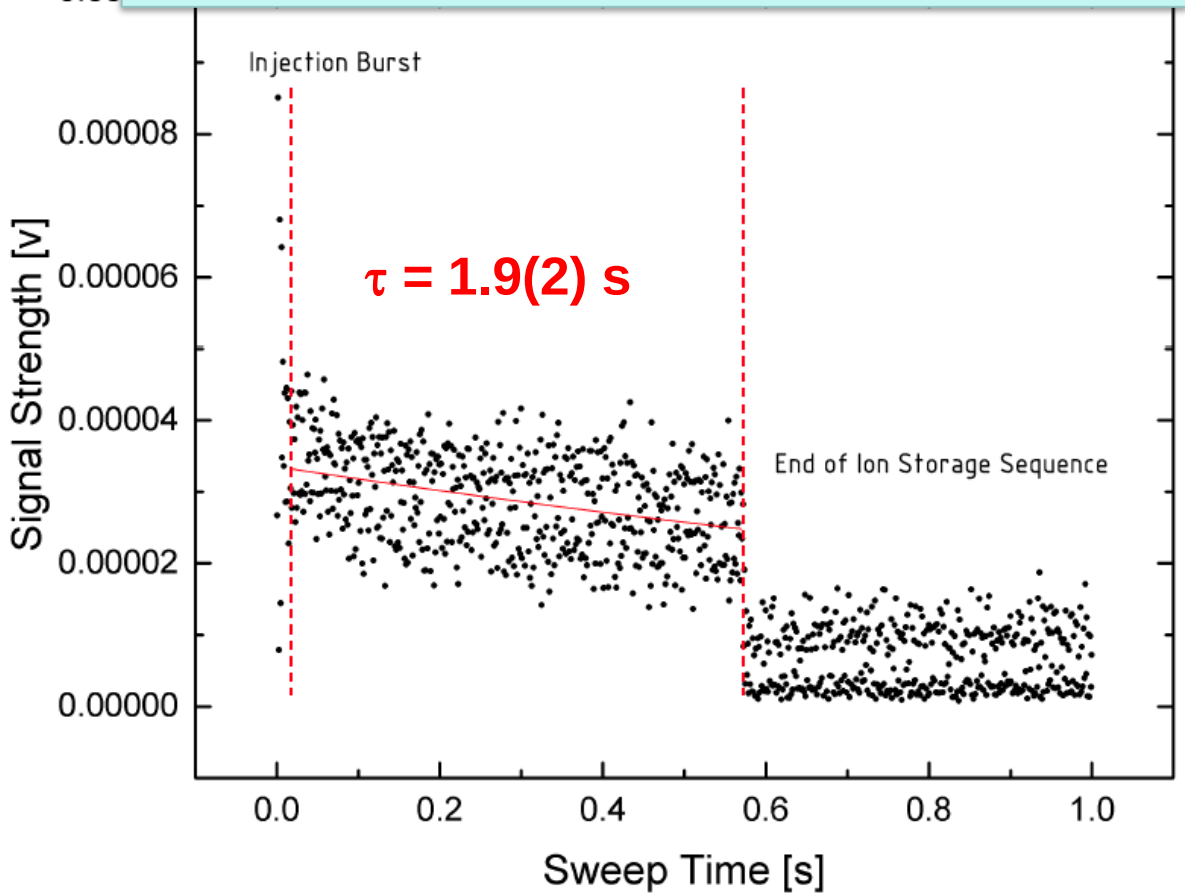


Many turns and RF bunching



Multi turn injection (still improving)

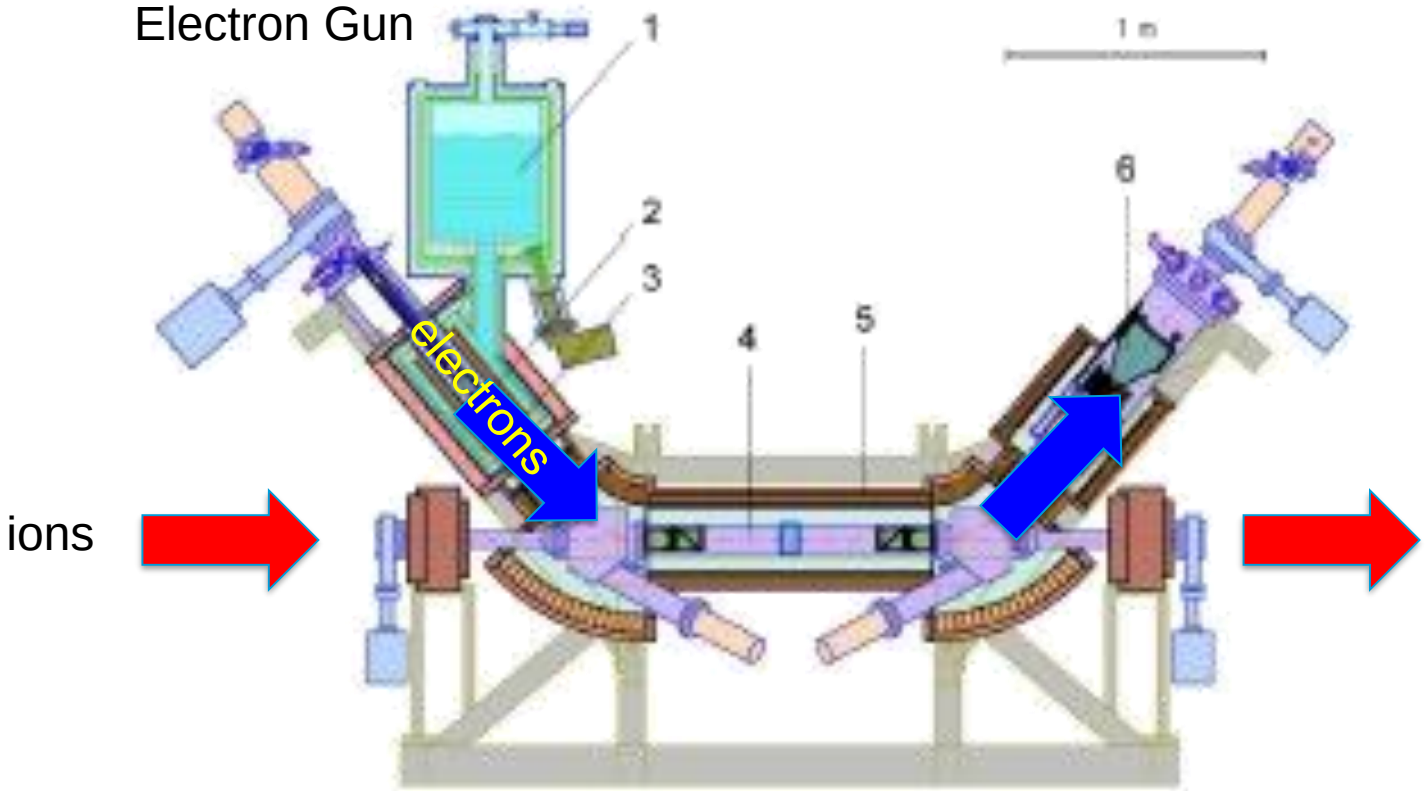
Stored Beam Lifetime Measurement in Schottky



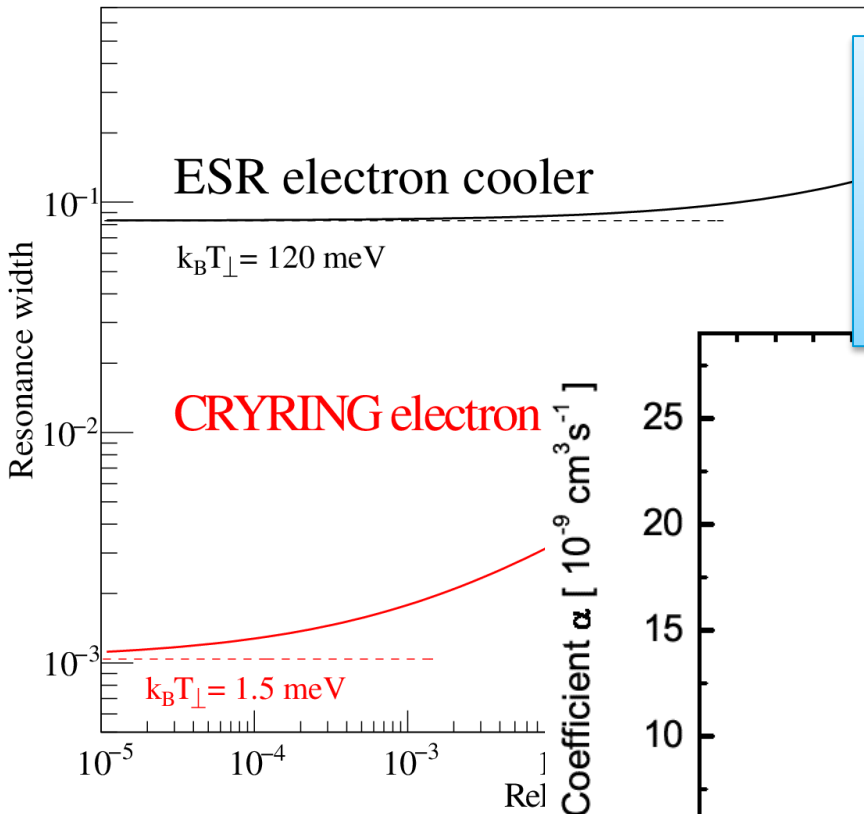
Okt. 2017

Electron Cooler

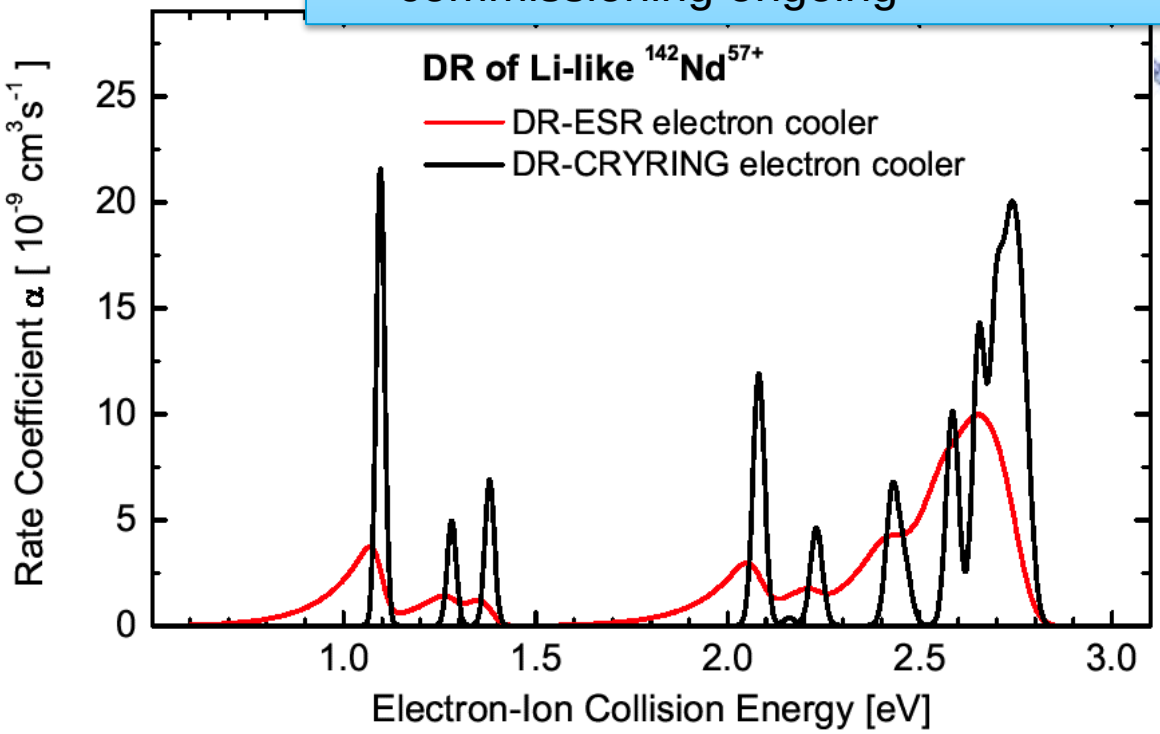
Superconducting magnet for Electron Gun



Electron Cooling ESR - CRYRING

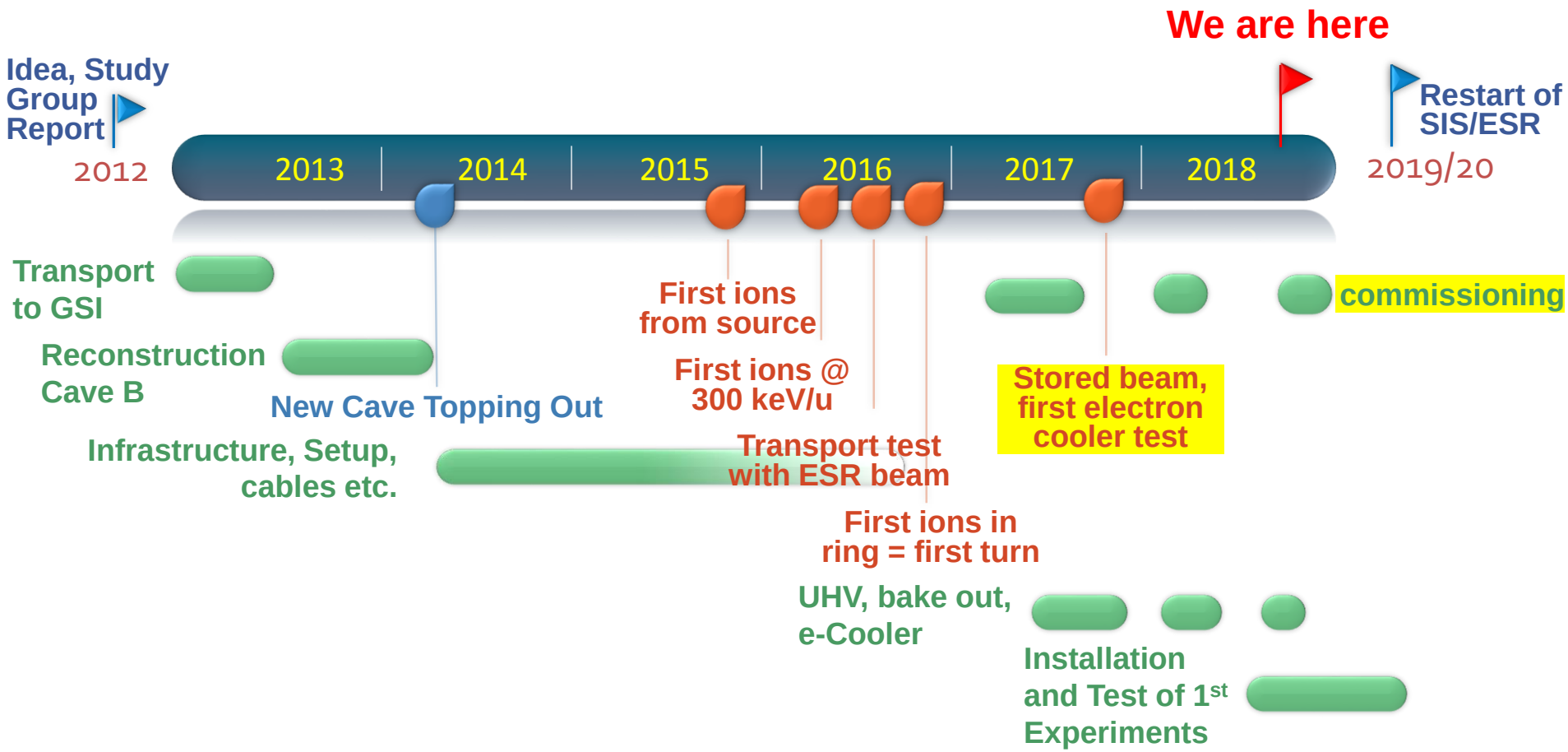


- cathode replaced
- superconducting magnet tested
- bake out done
- *Set backs: Water leak, LHe filling issues*
- commissioning ongoing



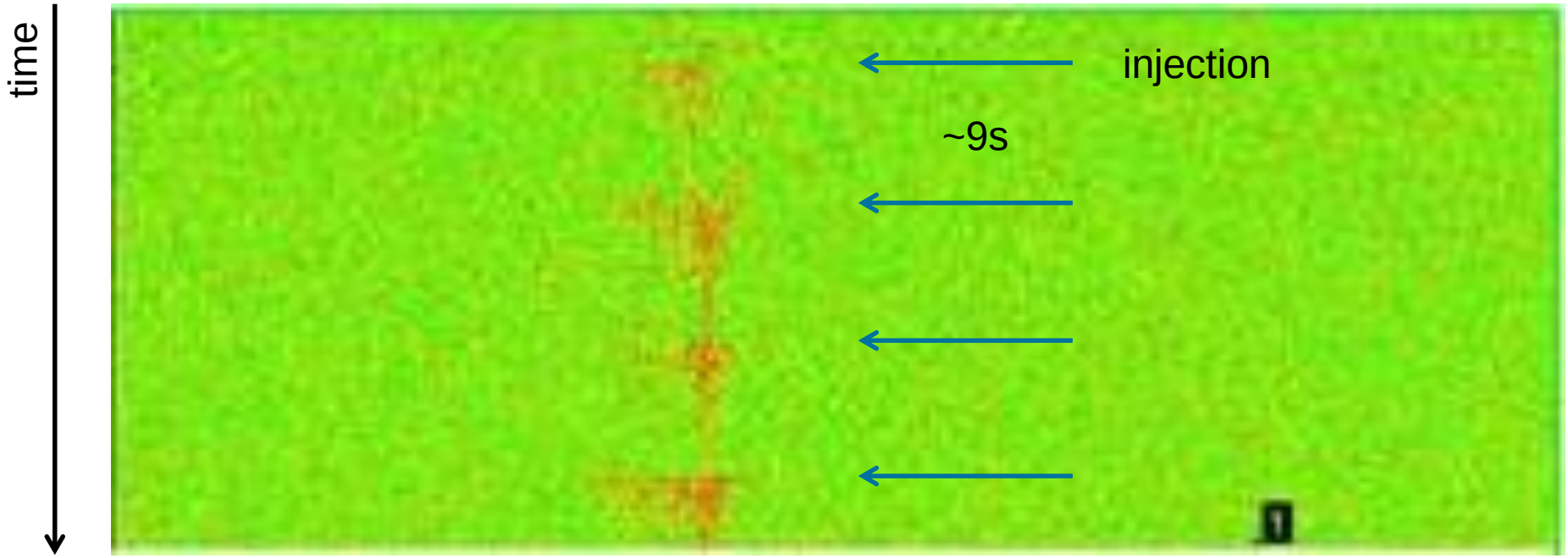
C. Brandau priv. comm.

Timeline CRYRING@ESR



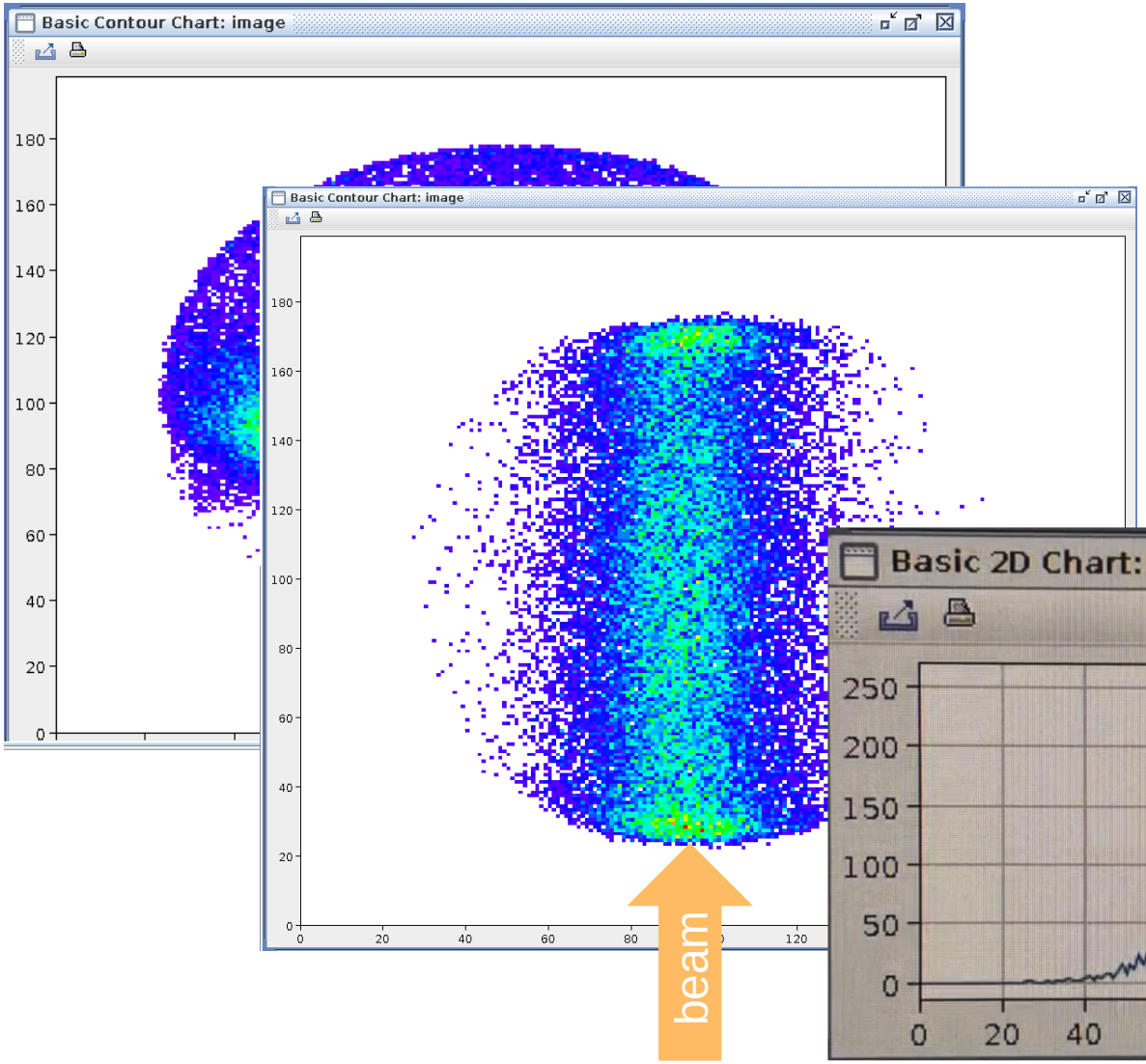
New, FAIR controls, first integration of … databases, machine model, user interface, timing, ...

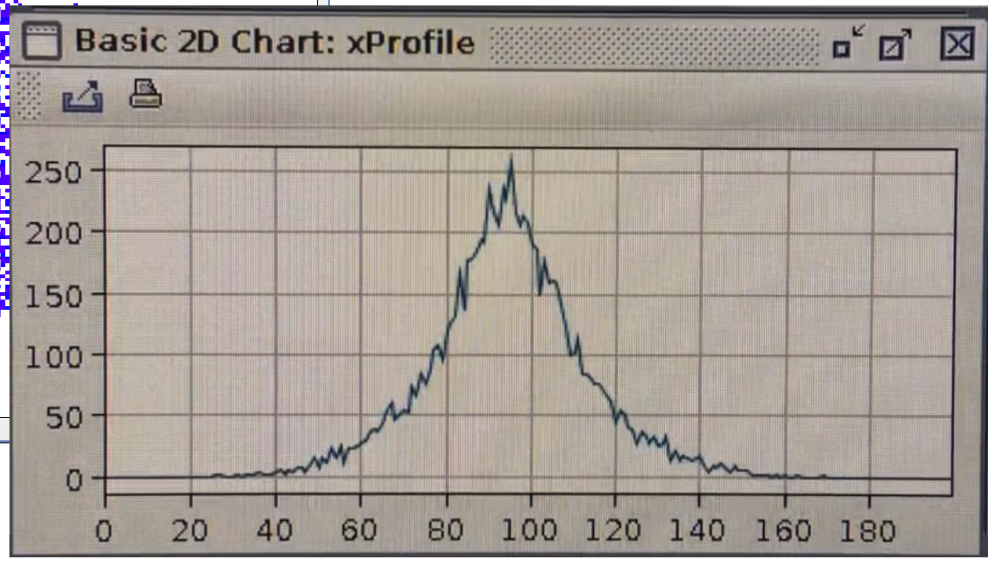
Cooling in CRYRING@ESR

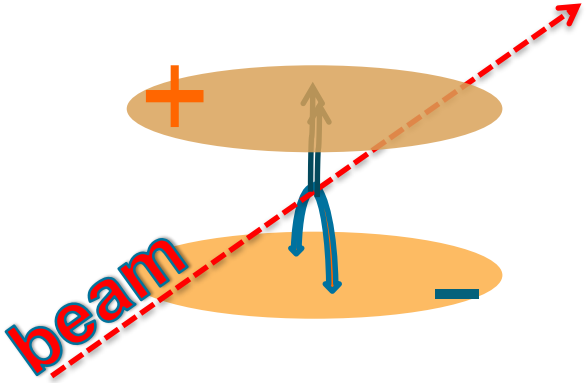


22nd of November, 2017

Ionization Profile Monitor

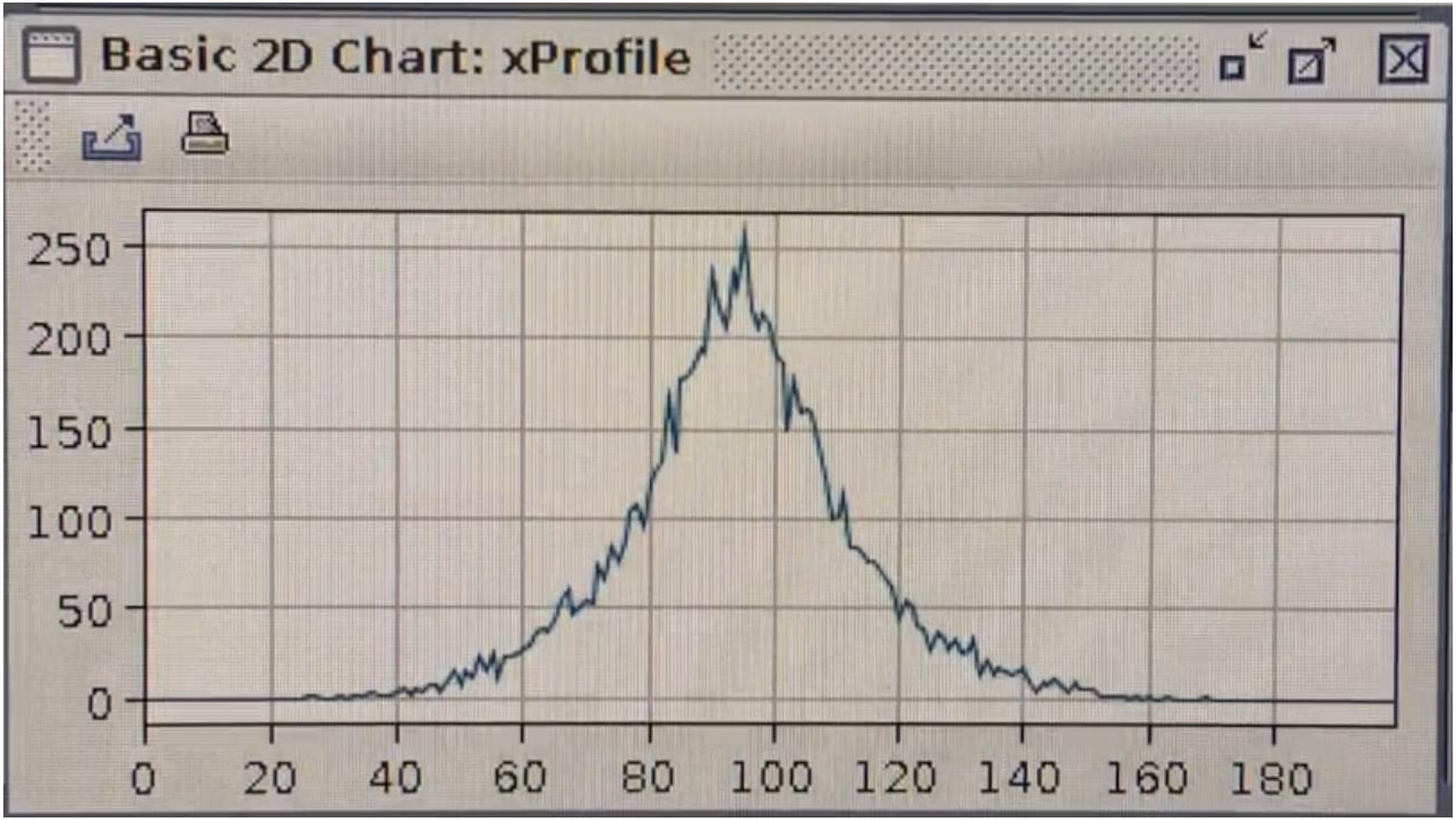






Cooling in CRYRING@ESR

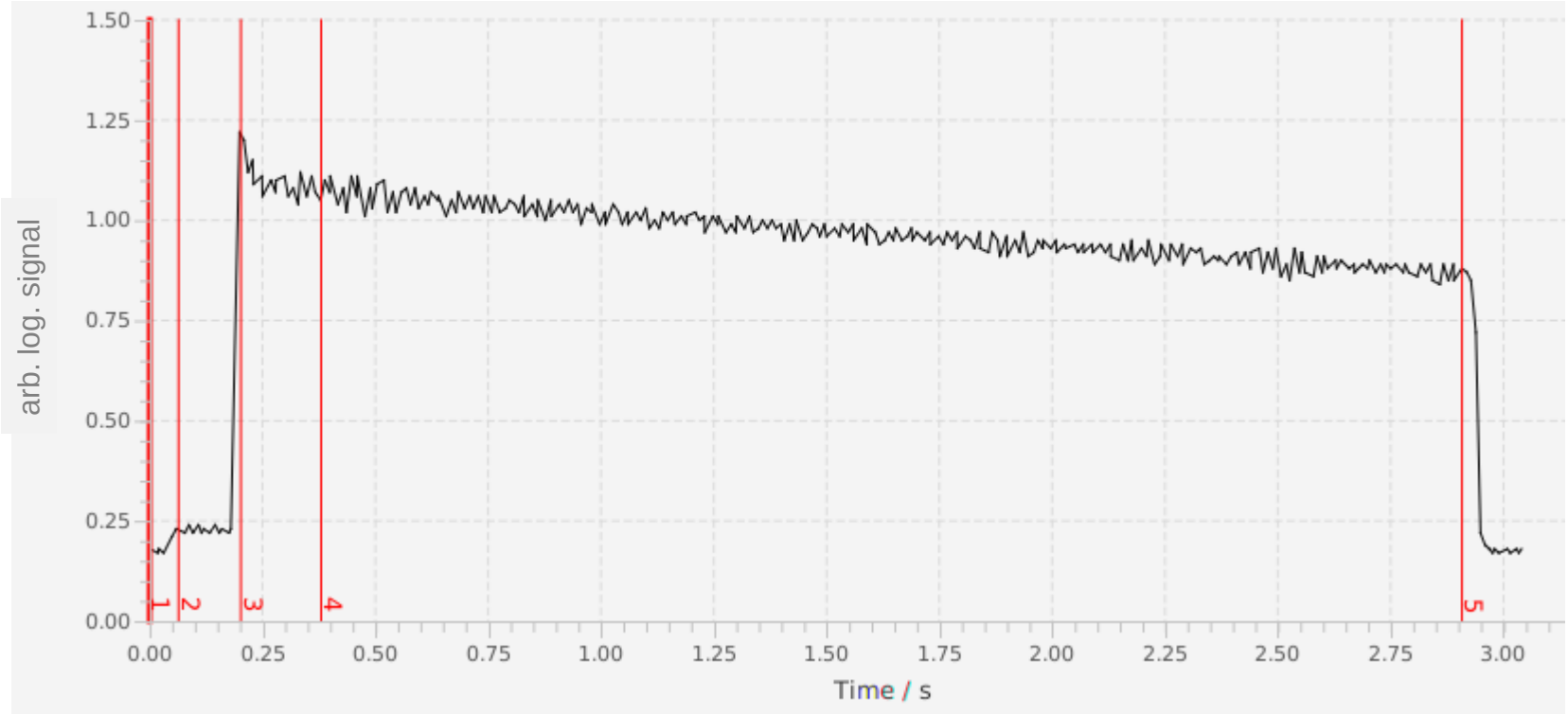
Vertical beam profile recorded on the **I**onization **P**rofile **M**onitor



22nd of November, 2017

Injection and Storage of Mg^+

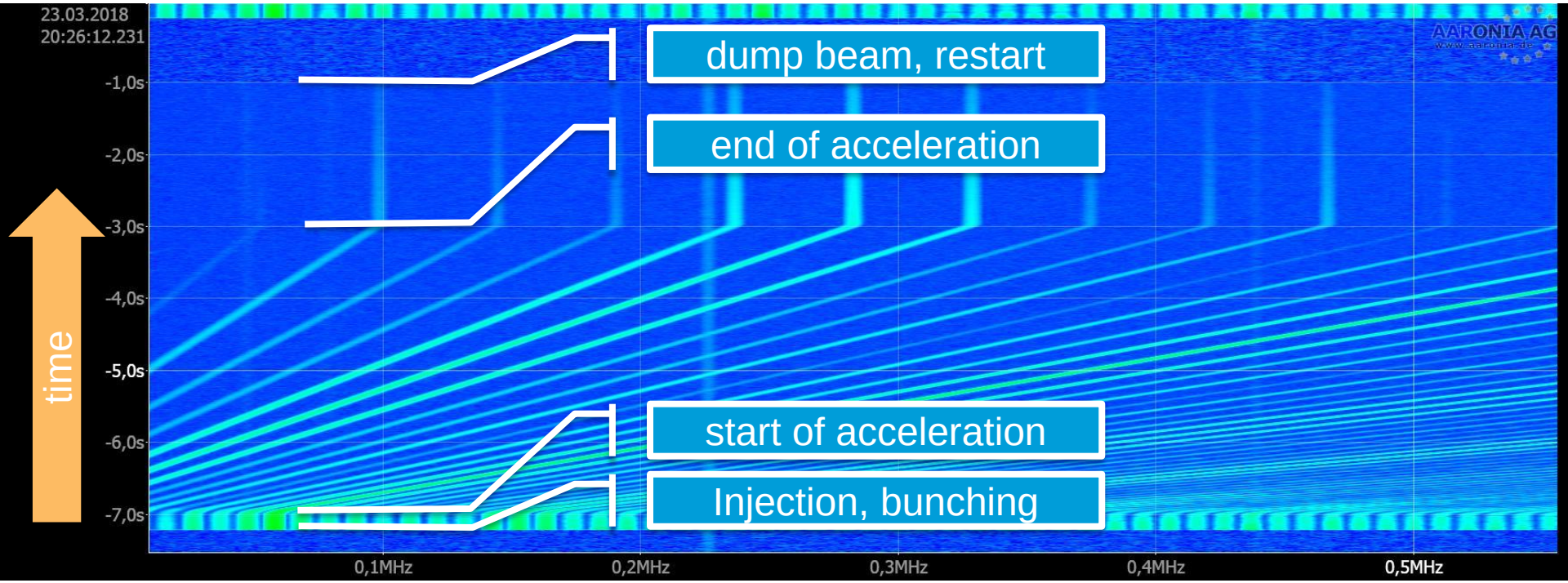
- Lifetime at injection energy (40 keV)



- τ ~ 10 seconds = sufficient for laser experiments!

Acceleration of Mg^+

- Mg^+ from injection energy (2 keV/u - Bρ 0.14) to (32 keV/u, Bρ 0.62)



CRYRING@ESR Status Summary

- Both ion paths towards CRYRING@ESR are operating, from ESR and from the local injector.
- Assembly and alignment of the ring is complete.
- System is fully baked (p ≤ 1e-10 mbar ↓).
- Ion beam storage accomplished (H^{2+} at 300 keV/u, ~10^8 particles, ~5 s lifetime).
- ECOOL showed first signs of ion beam cooling.
- Installations for first experiments will be ready end of 2018
- Multiturn injection: n = 3...4.
- Beam acceleration achieved (0.3 → 24 MeV for H_2^+)

- Beam from ESR ~ 2018-19 (depending on GSI/FAIR)

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

Thank You

Photo: J. Hosan/GSI Helmholtzzentrum für Schwerionenforschung GmbH