CRYRING @ ESR

heavy, highly-charged Ions stored at low Energy

- Why?
- Details of Installation
- Some Physics Aspects
- Schedule

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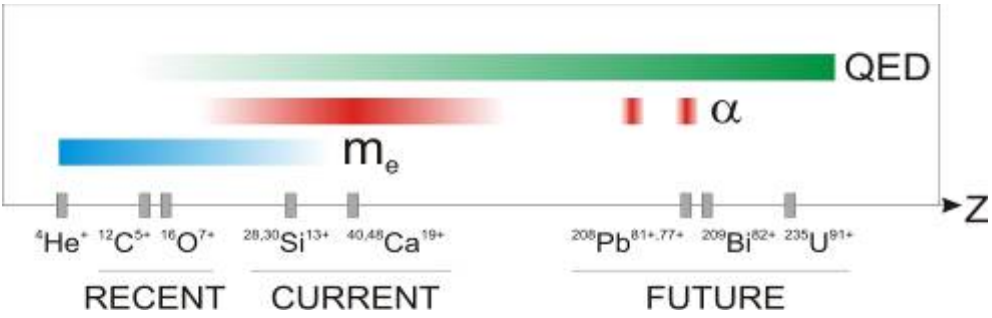
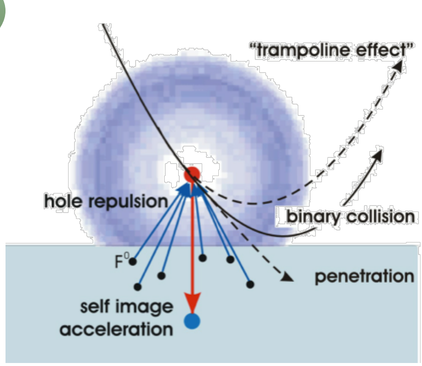
[6]Helmholtz-Institut Jena, Germany
[7]IOQ, Friedrich-Schiller-Universität Jena, Germany

WHY?

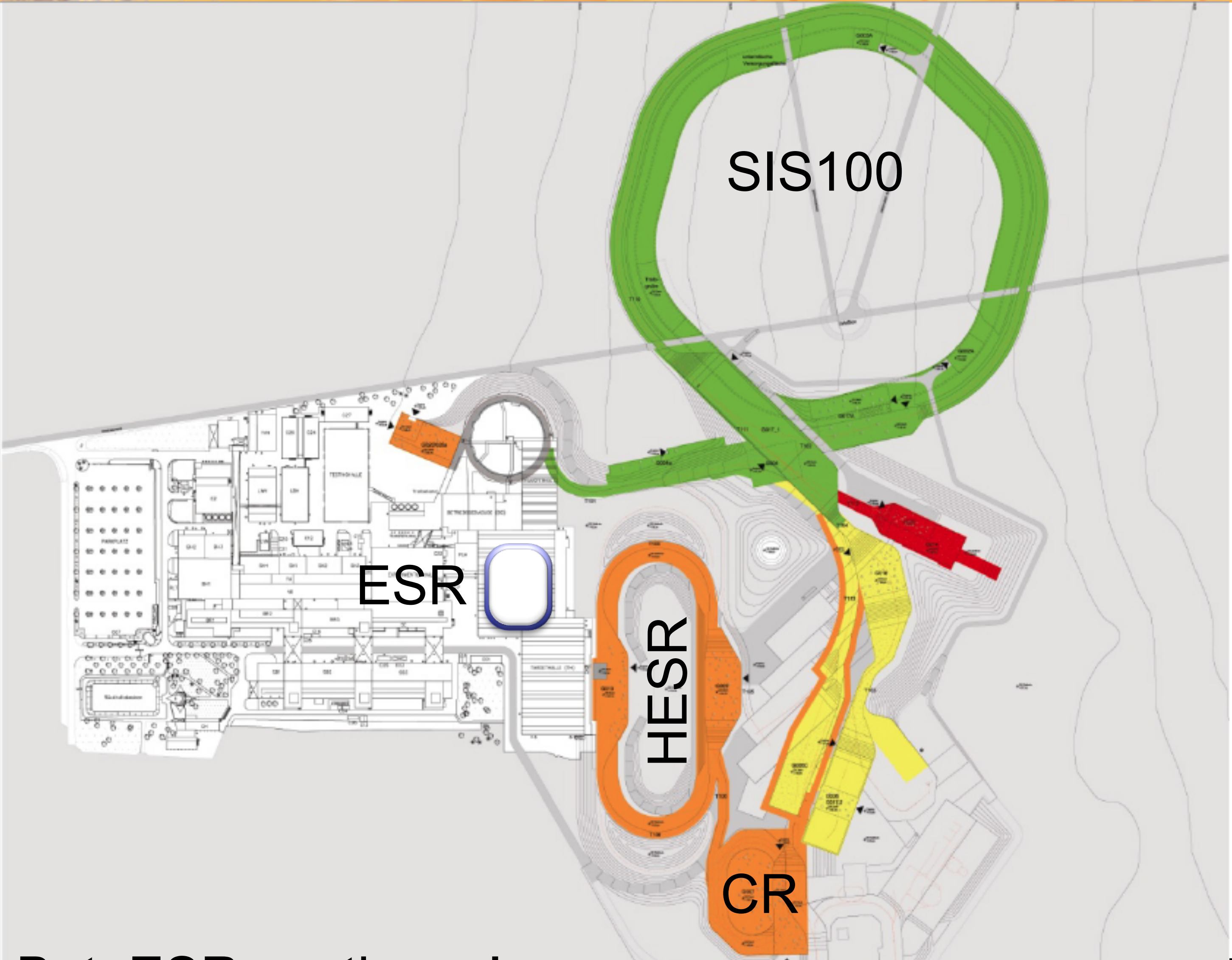
HCI — **H**ighly **C**harged **I**ons

- **Elements**
  - **g-factor**
    - α, m_e
  - **e⁻-binding**
    - QED test
    - Lamb-shift
- **Isotopes**
  - Charge radii
  - **FS, HFS**
    - BW effect
- **+ Matter**
  - **+ surface**
    - Structures
    - Hollow atoms
  - **+ atoms**
    - Charge exchange
    - Collision dynamics





The "Green Paper" – Stepwise to FAIR



Module 0
SIS 100

Module 1
Exp. Areas CBM/ HADES, APPA

Module 2
Super-FRS

Module 3
Antiprotons for PANDA (CR, HESR)

Upgrade

But: ESR continues!

CRYRING @ ESR

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

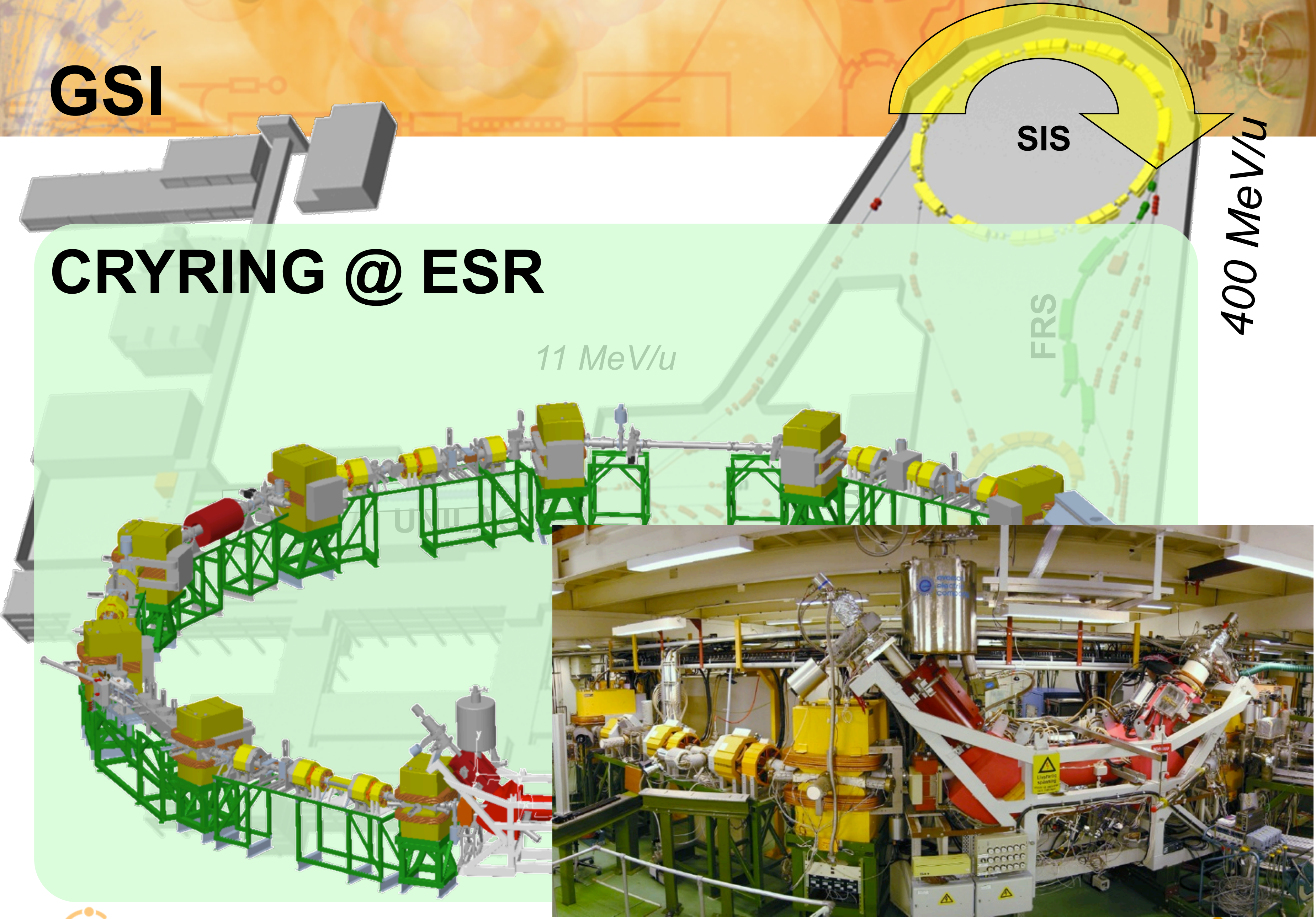
All this with real beam!

Scientific Oportunities

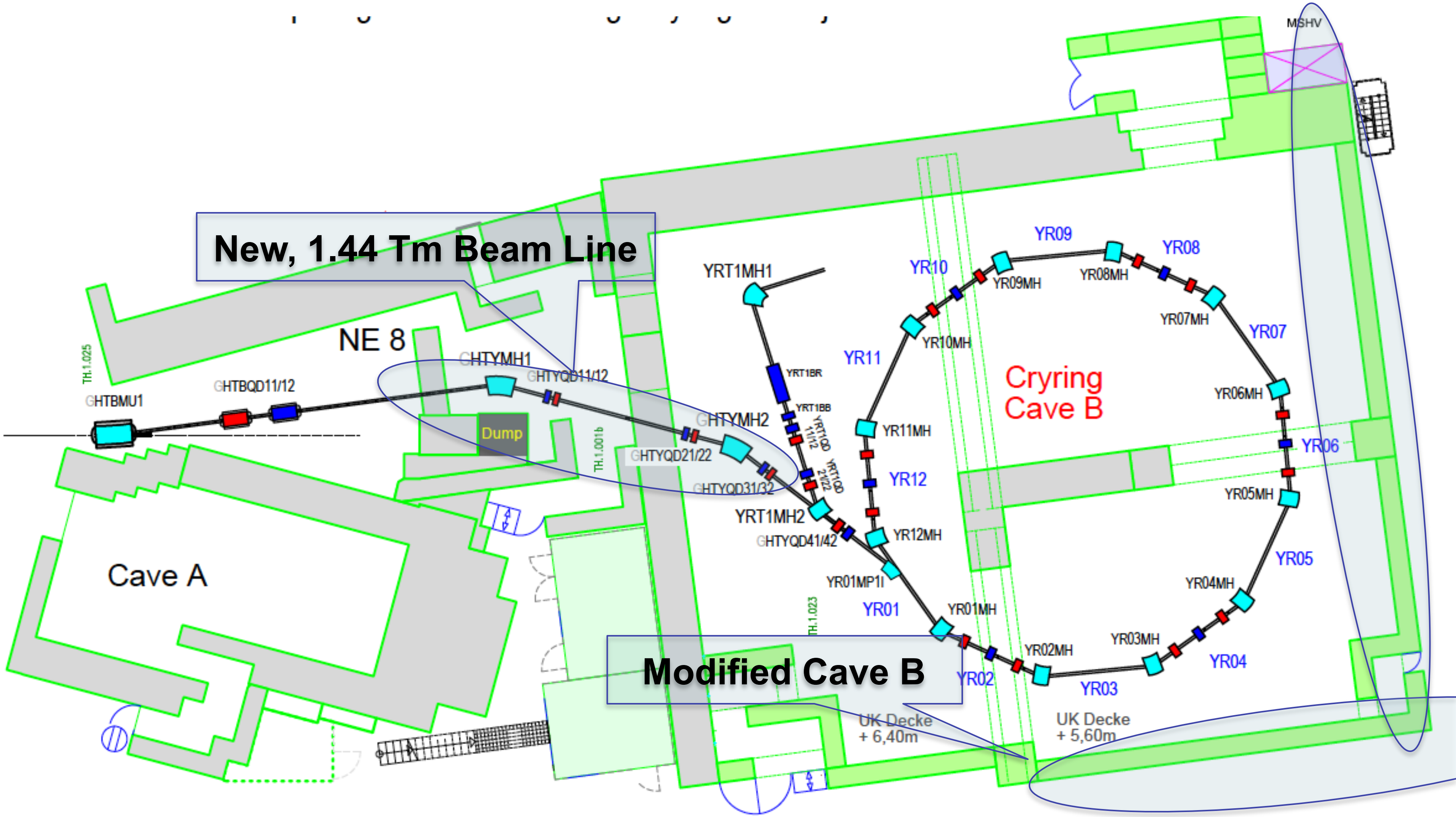
- Heavy, highly-charged ions as available at GSI (up to U^{92+}) at low energy ~ 100 keV/u .. 10 MeV/u – bridge the energy gap between the ESR (> 4 MeV/u) and HITRAP (<10 keV/u)

GSI

CRYRING @ ESR

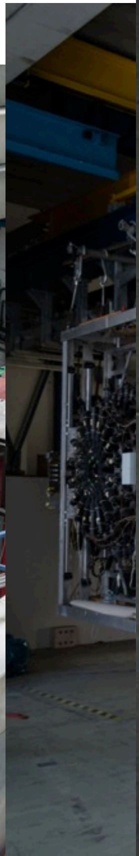


CRYRING @ ESR in “Cave B”



Status of Cave Preparation

- FOPI Magnet moved out and detector is being uninstalled
- Final clean up ongoing
- Concrete movements started, hole to NE8 has been drilled

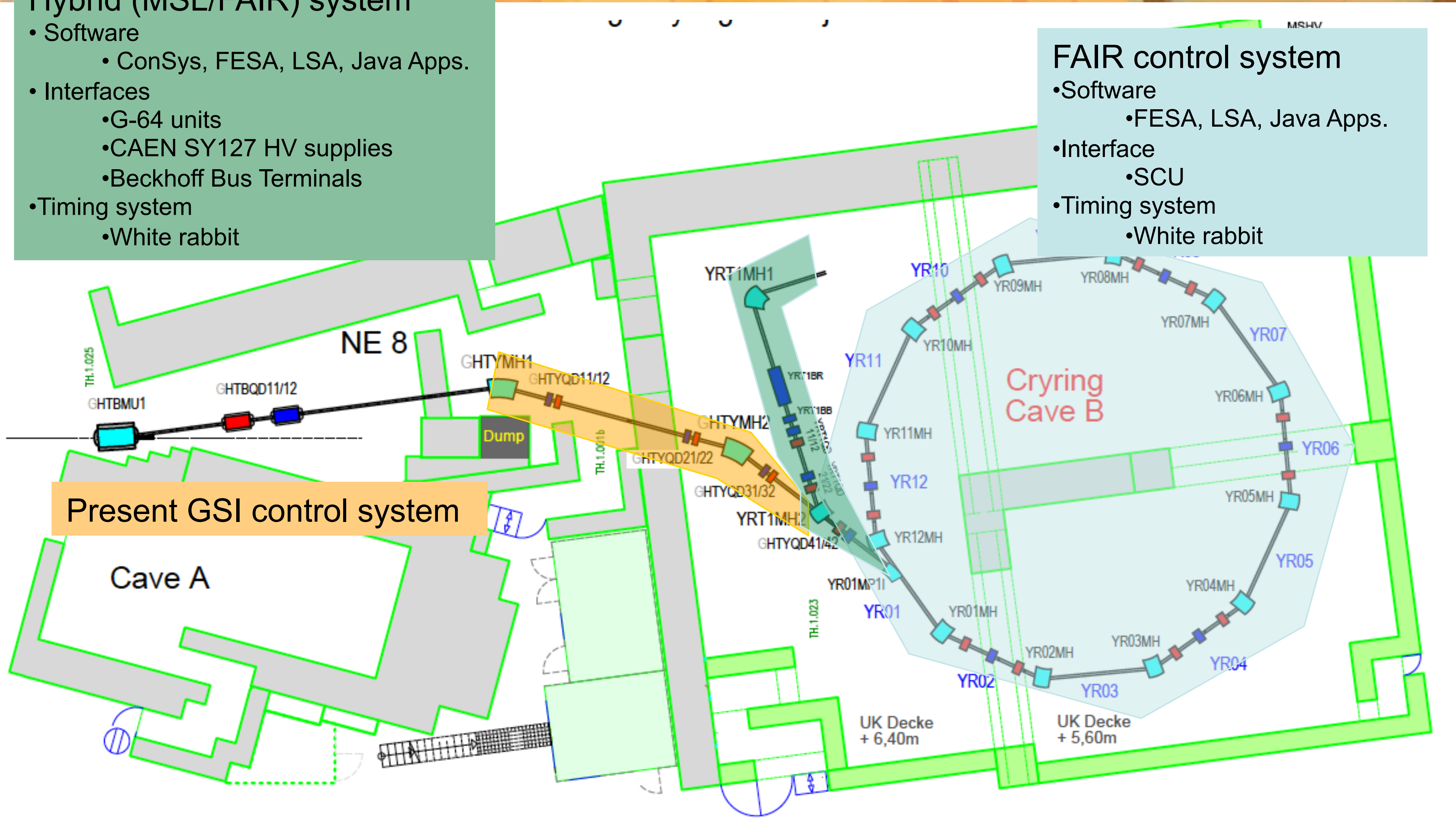


CRYRING @ ESR Control System

Hybrid (MSL/FAIR) system
- Software
    - ConSys, FESA, LSA, Java Apps.
- Interfaces
    - G-64 units
    - CAEN SY127 HV supplies
    - Beckhoff Bus Terminals
- Timing system
    - White rabbit

FAIR control system
- Software
    - FESA, LSA, Java Apps.
- Interface
    - SCU
- Timing system
    - White rabbit

Present GSI control system

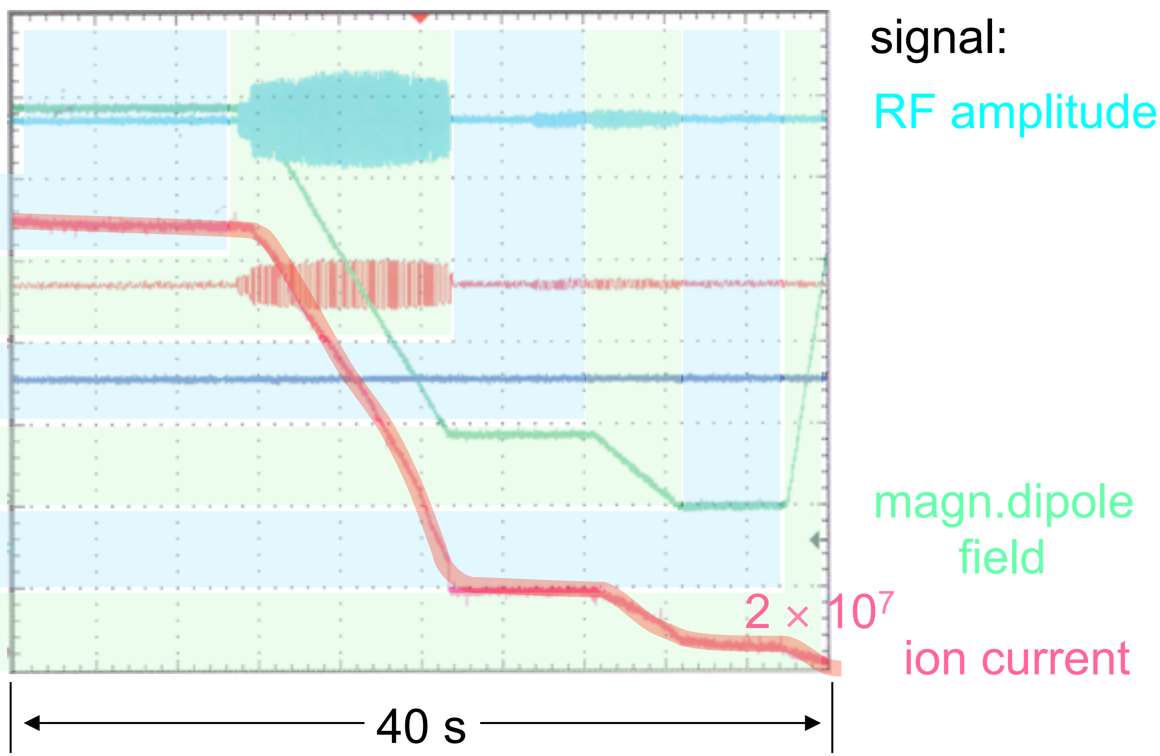


ESR – From 400 to 4 MeV/u

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

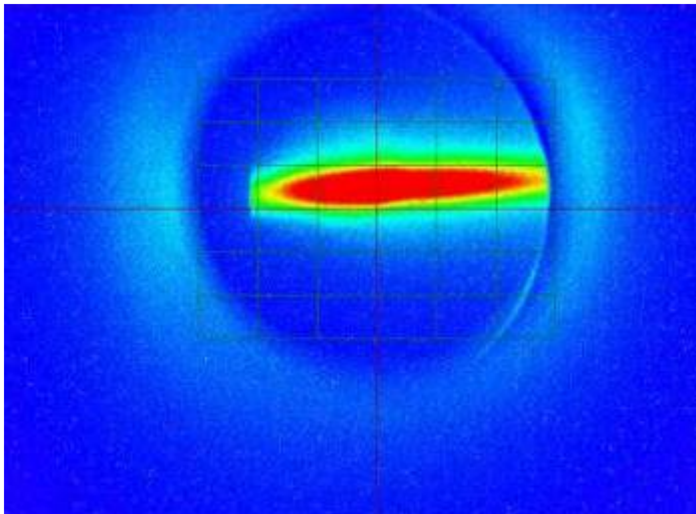
Ni^{28+} 400 → 30 → 4 MeV/u

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

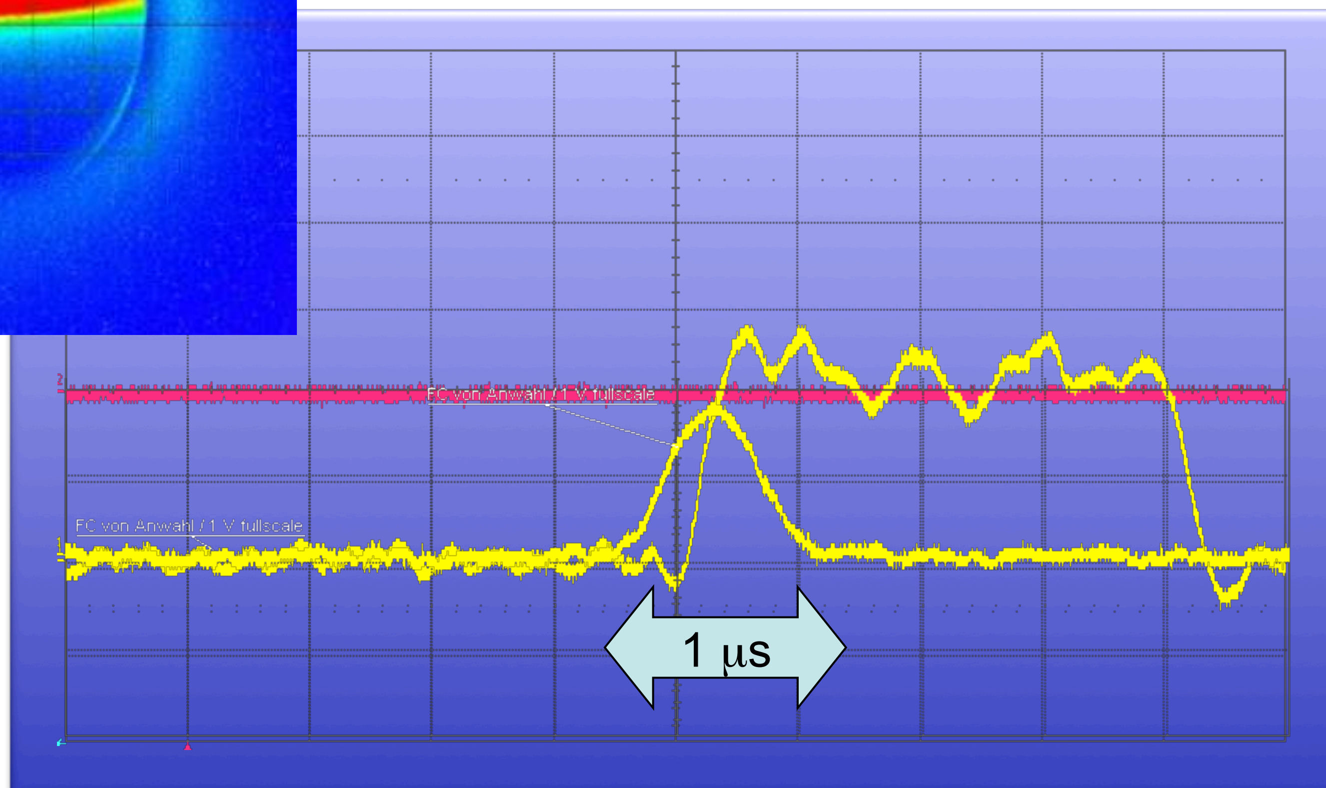


1100 μA → 180 μA → 25 μA

4 MeV/u ions from ESR

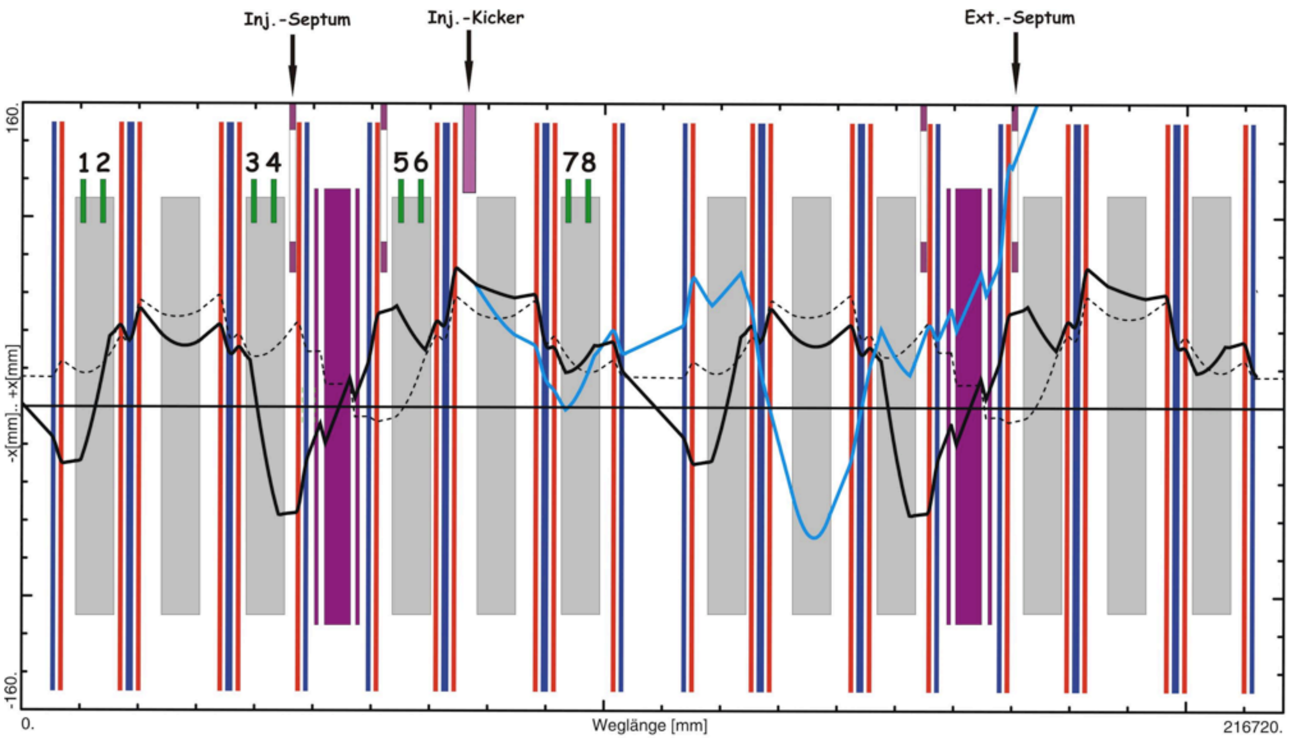


2×10^{7} $^{136}Xe^{50+}$ extracted from ESR



Modification of ESR for CRYRING

- Additional Kicker
  but in the mean time …



Injection orbit (Δp/p = 1%) - - - - - - - -

Bumped Orbit ———

Extraction Orbit (kicker -3.5 mrad) ———

1. E01KX1 = 7 mrad
2. E01KX2 = -14 mrad
3. E01KX5 = -18 mrad
4. E01KX6 = 9.5 mrad
5. E02KX1 = -8 mrad
6. E02KX2 = 10.5 mrad
7. E02KX5 = 6.4 mrad
8. E02KX6 = -5.7 mrad

S. Litvinov

Modification of ESR for CRYRING

- Additional Kicker
  in the mean time … creative use of existing kicker

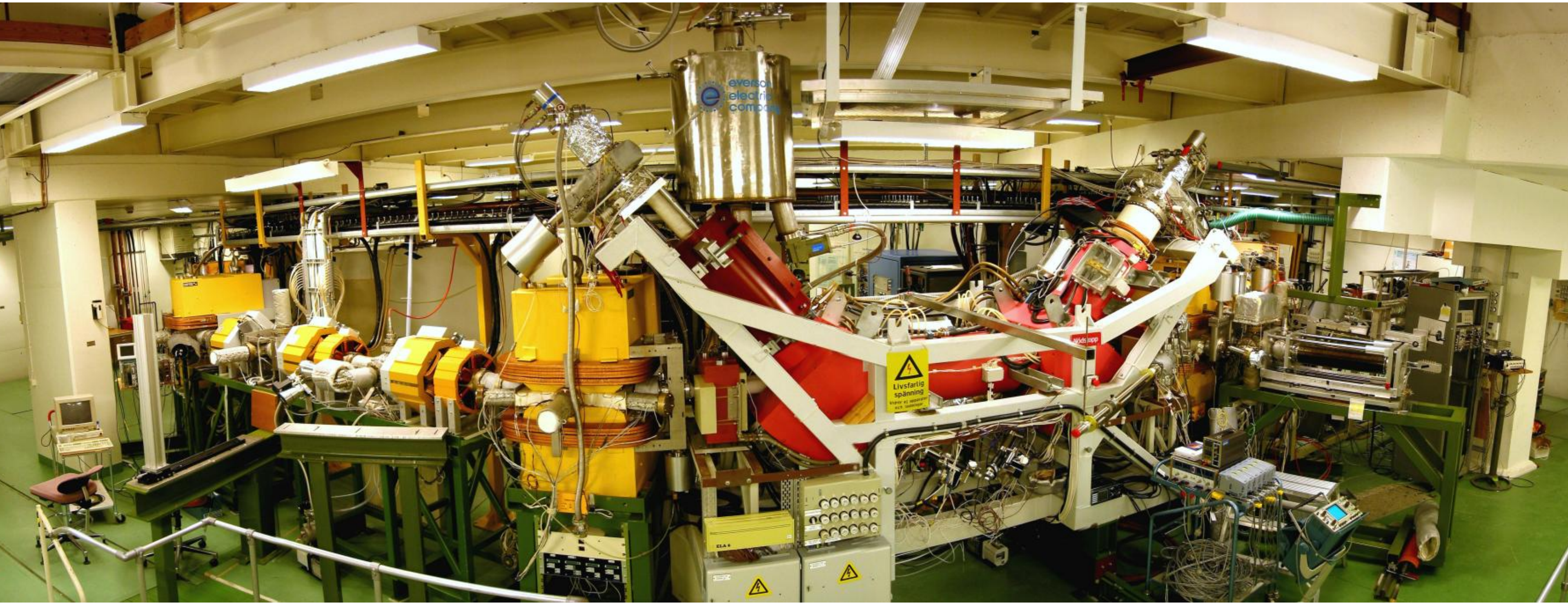
- Beam line upgrade (ESR – Cave B)
  added steering, dipoles; additional diagnostics

- Synchronization ESR/CRYRING Kickers/RF
  got easier by increasing the diameter of CRYRING to ESR/2

Towards a reduced cycle time

- Requires faster cooling and more flexible control system

CRYRING in Stockholm



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

CRYRING History

1985	CRYRING funded by K. and A. Wallenberg foundation
1991	First beam (deuterons)
1992-2010	CRYRING at MSL in Stockholm produces ~400 papers, 43 dissertations, 39 licentiate theses
2006	FAIR Technical report on APPA, SPARC, and FLAIR: CRYRING proposed as LSR
2009	Modularized Start Version (MSV) of FAIR: NESR, FLAIR...
Nov. 2011	Proposal for an early installation of CRYRING@ESR to GSI Science Council
Jun. 2012	"CRYRING@ESR: A study group report" submitted

Ions handled with CRYRING

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^+, $^3HeH^+$, $^3HeD^+$, $^4HeH^+$, D_3^+, He_2^+, LiH_2^+, D_5^+, BH_2^+, CH_2^+, NH_2^+, OH^+, CH_5^+, NH_4^+, H_2O^+, H_3O^+, HF^+, ND_3H^+, CD_5^+, ND_4^+, D_3O^+, C_2H^+, CN^+, $C_2H_2^+$, HCN^+, $C_2H_3^+$, $HCNH^+$, $C_2H_4^+$, CO^+, N_2^+, N_2^{2+}, $^{13}CO^+$, N_2H^+, $C_2H_5^+$, $H^{13}CO^+$, NO^+, $D^{13}CO^+$, CH_3O^+, CF^+, O_2^+, $CH_3NH_3^+$, CH_3OH^+, $CH_3OH_2^+$, H_2S^+, CD_3O^+, PD_2^+, $N_2H_7^+$, $D_2{}^{32}S^+$, $CD_3OH_2^+$, CD_3OD^+, $H_5O_2^+$, $D_2{}^{34}S^+$, $D_3{}^{32}S^+$, $CD_3OD_2^+$, $^{13}CD_3OD_2^+$, $D_3{}^{34}S^+$, $C_3H_4^+$, $D_2{}^{37}Cl^+$, $D_5O_2^+$, 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^-

Range of energies per nucleon: 38 eV/u – 92 MeV/u

Range of total energies: 5 keV – 1.4 GeV

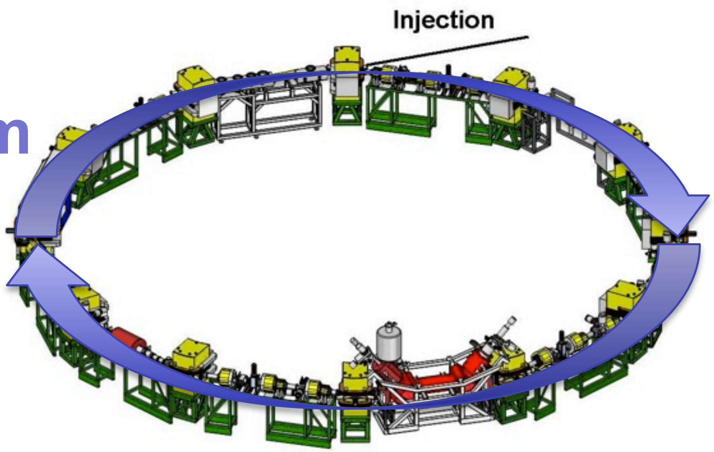
~200 different ion species

CRYRING Parameters

54 m = ESR/2

⇧

52 m



- Max. rigidity 1.44 Tm
  - 15 MeV/u U^{92+}
  - 96 MeV/u protons
- Min. rigidity ~ 0.054 Tm
  - 150 keV/u protons
- Ramping speed 1 T/s; 7 T/s

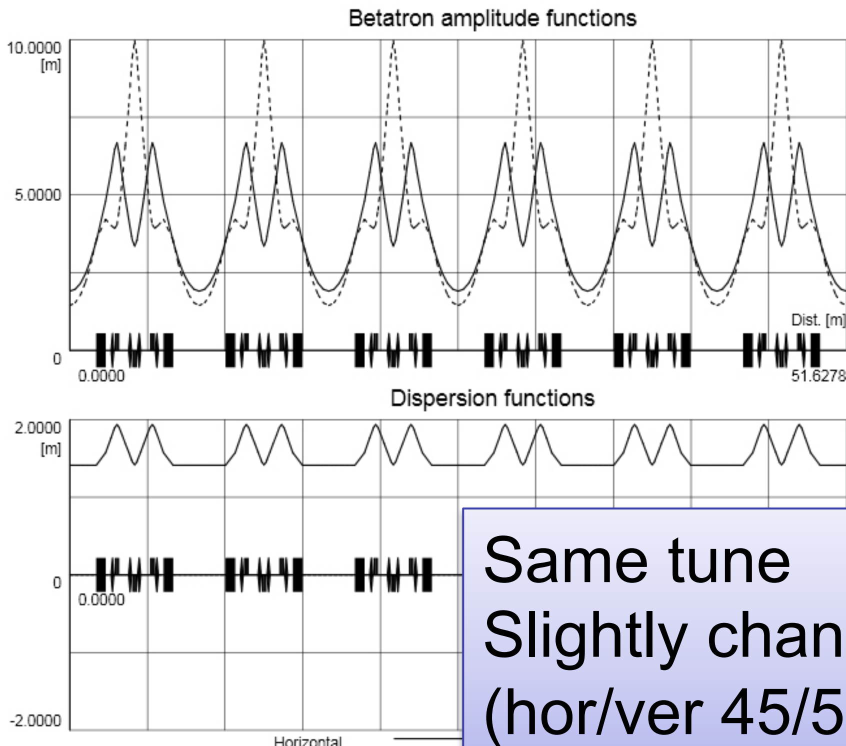
CRYRING Parameters

54 m = ESR/2

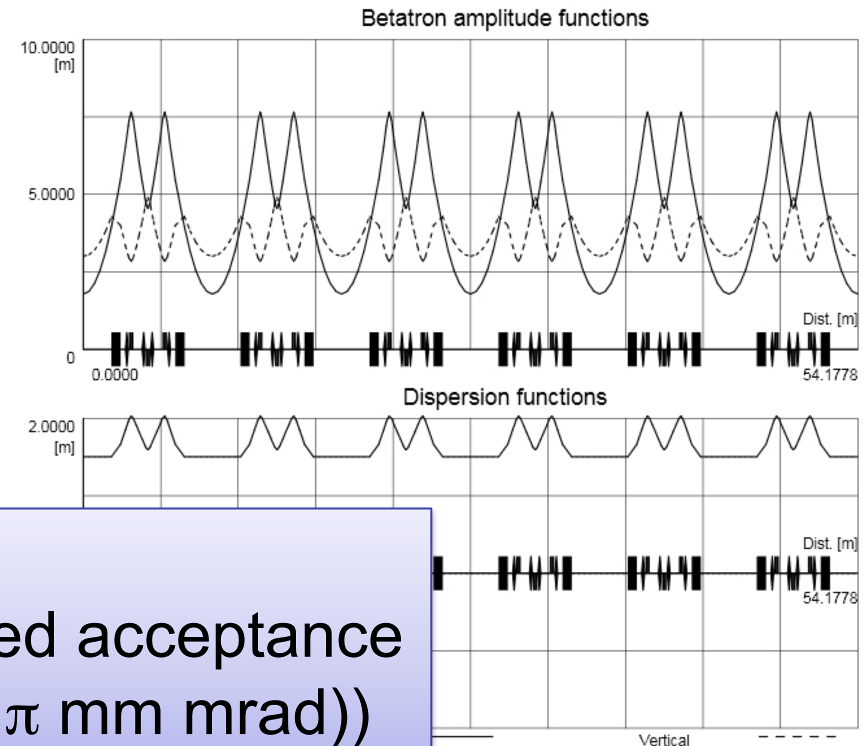
52 m

- Max. rigidity 1.44 Tm
- Min. rigidity ~ 0.054 Tm
- Ramping speed 1 T/s; 7 T/s

Original CRYRING C=51.62 m



New circumference C=54.18 m

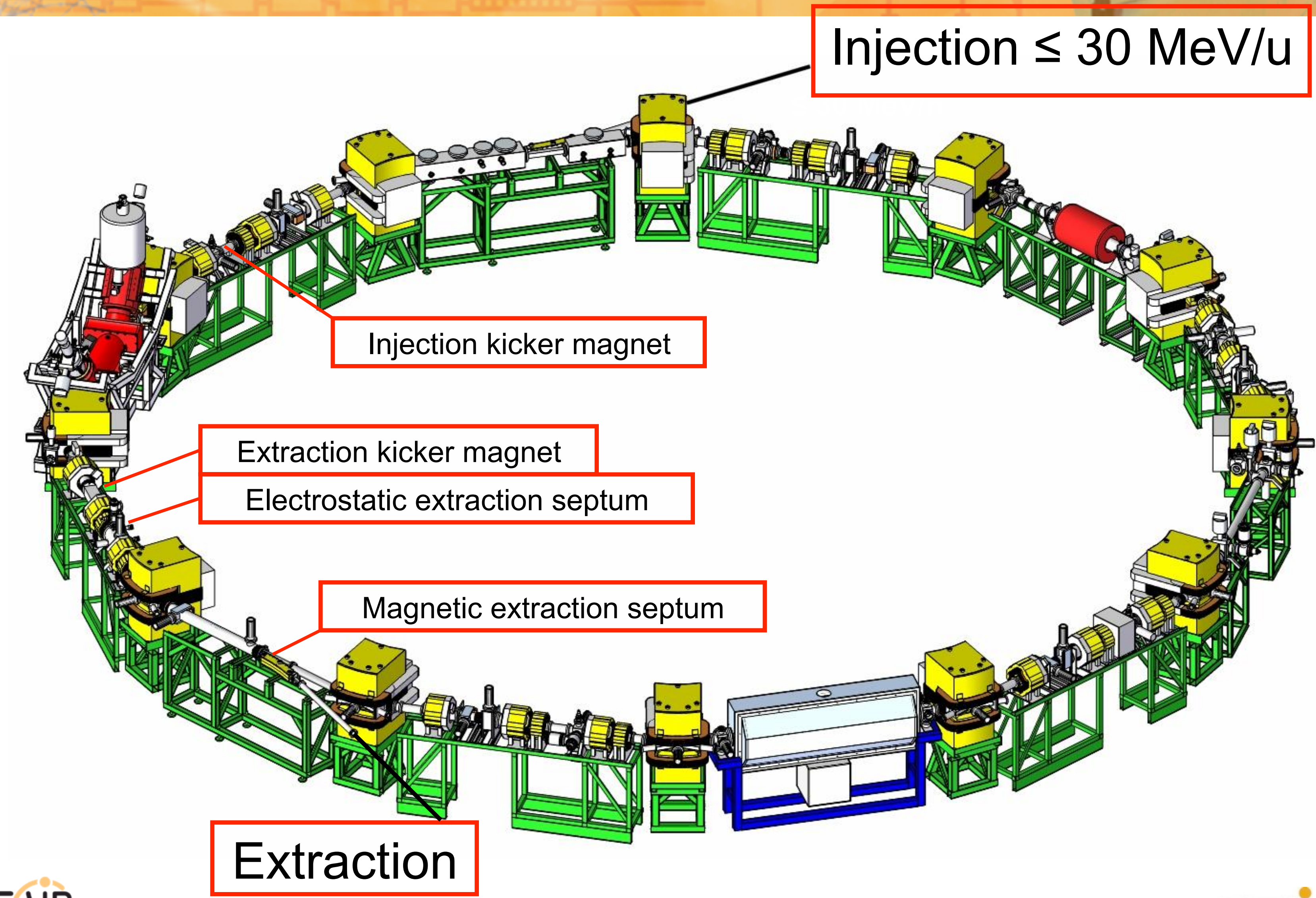


Same tune

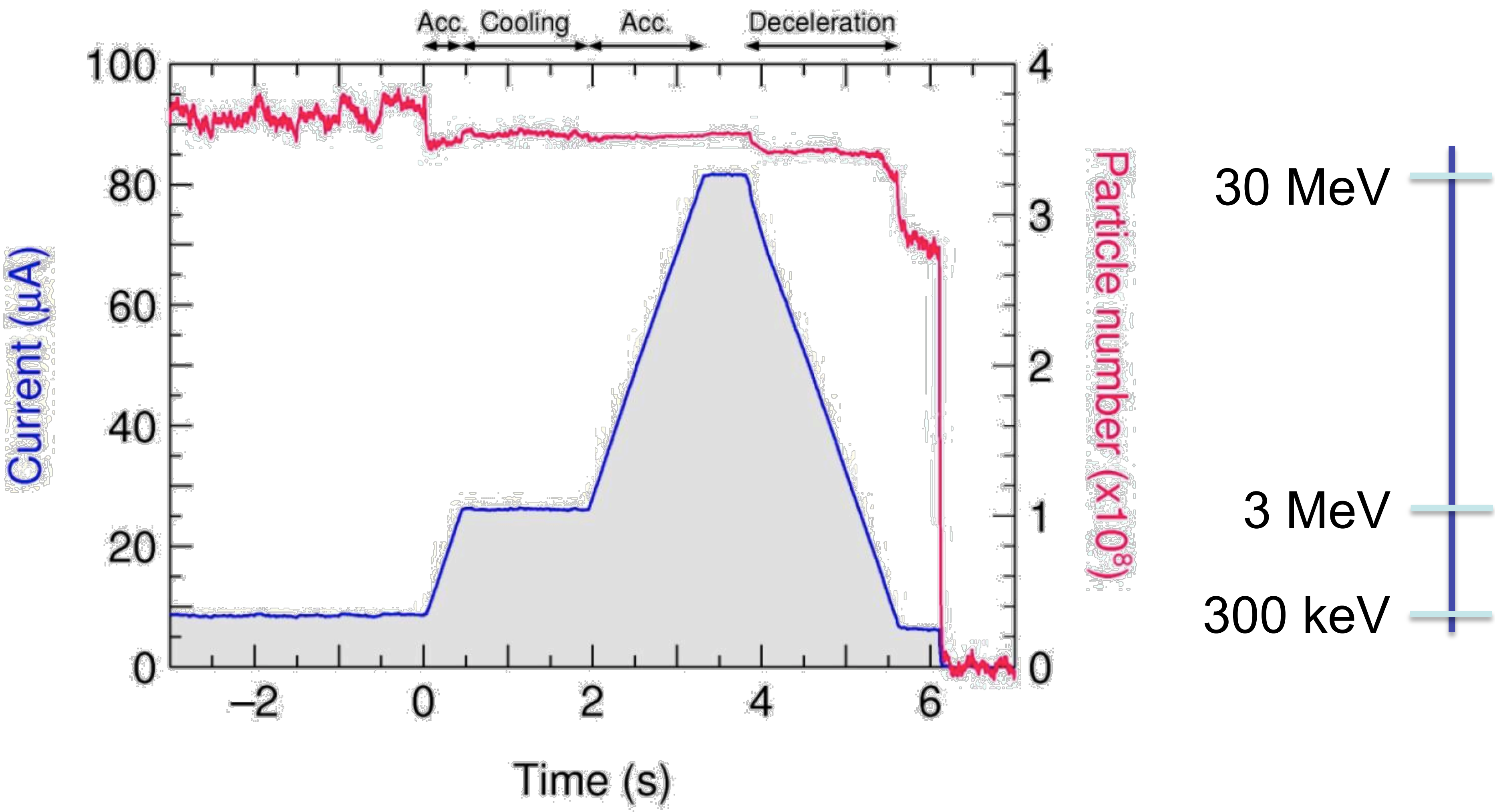
Slightly changed acceptance

(hor/ver 45/55 π mm mrad))

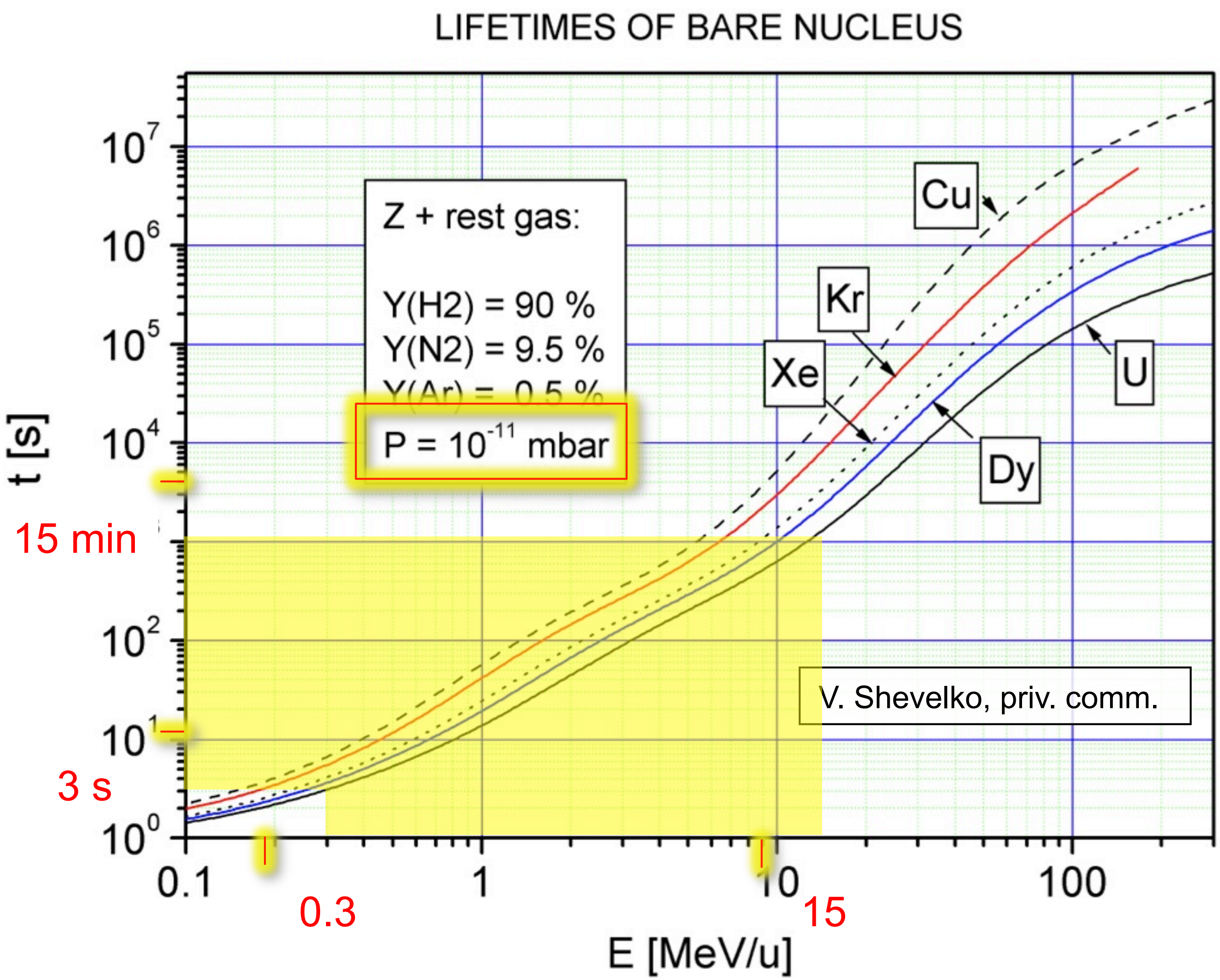
CRYRING modifications toward FAIR/GSI



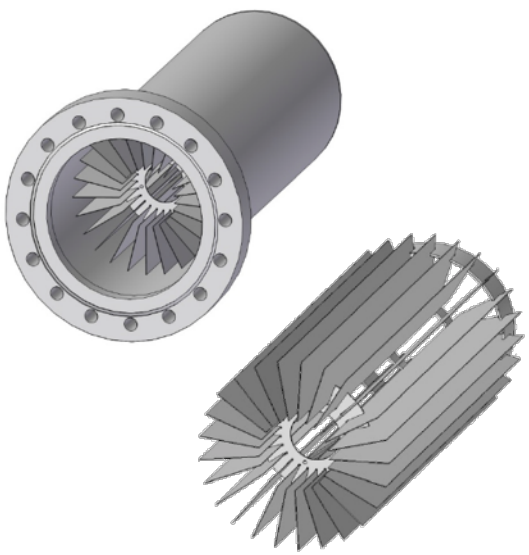
Deceleration in CRYRING



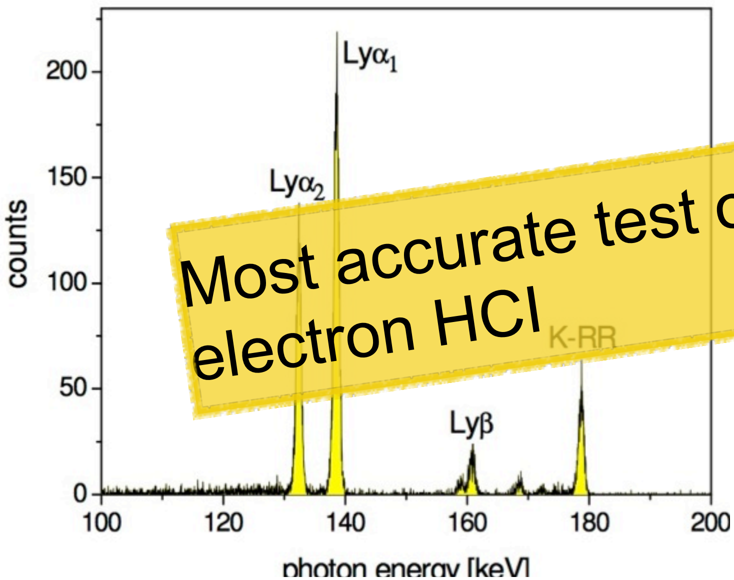
Vacuum & Beam Life Time

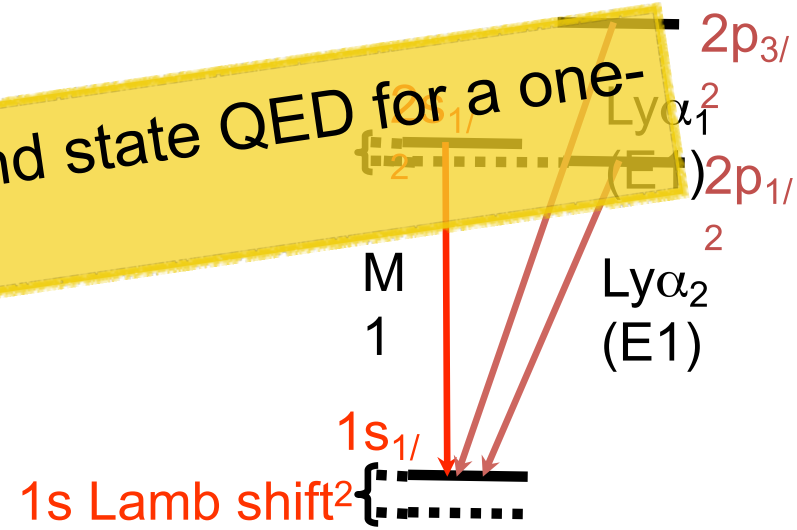


- Ion pumps
  ~ 10
- Cryopumps
- NEG pumps
  ~ 100



1s Lambshift in H-like Uranium





Most accurate test of bound state QED for a one-electron HCI

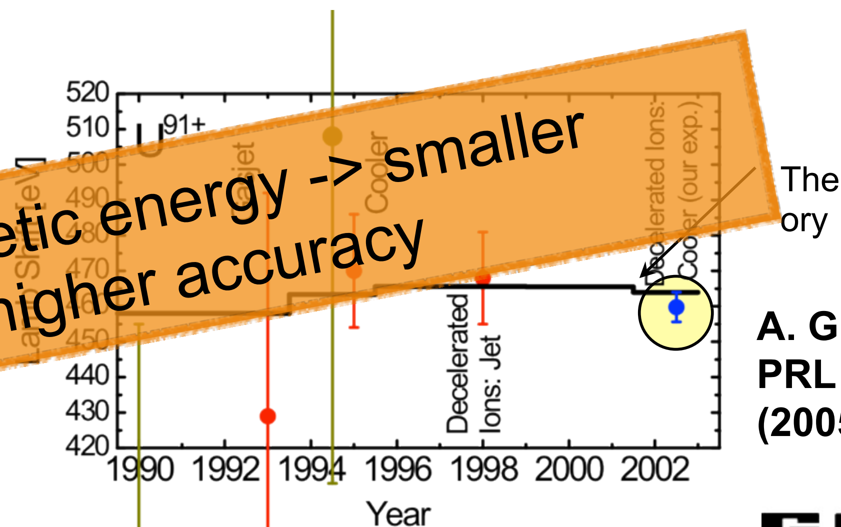
1s-Lamb Shift:

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV

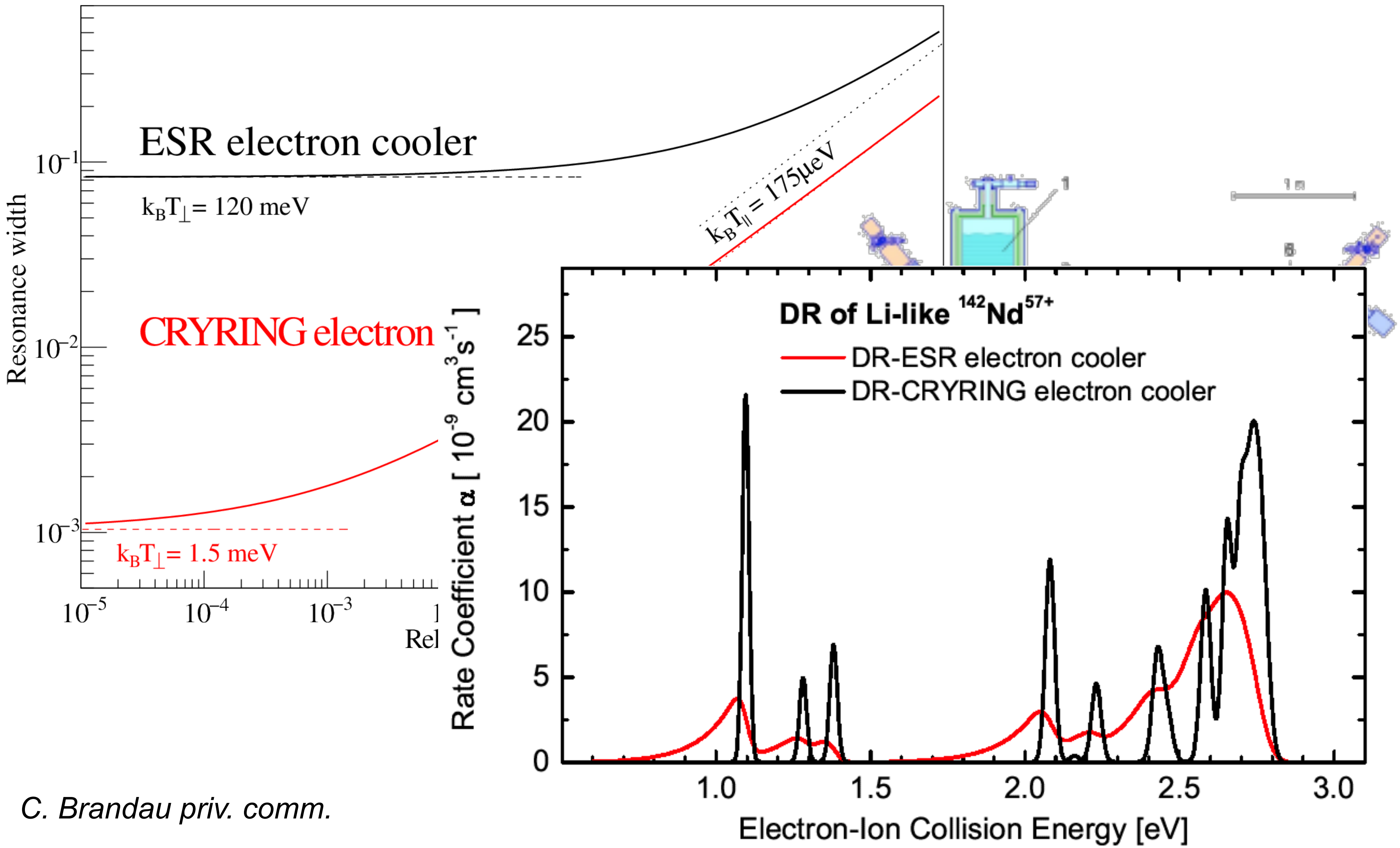
At CRYRING: lower kinetic energy -> smaller doppler broadening -> higher accuracy

Research Highlights
Nature **435**, 858-859
(16 **June 2005**)



A. Gumberidze PRL 94, 223001 (2005)

Electron Cooling ESR - CRYRING



C. Brandau priv. comm.

(p,γ) Reaction Rates

T. Davinson, M. Heil, Yu.A. Litvinov, R. Reifarth, K. Sonnabend, P.J. Woods

Nucleosynthesis of proton-rich nuclei beyond iron
Only few experimental data for relevant energy range (Gamow window) in *p*-process

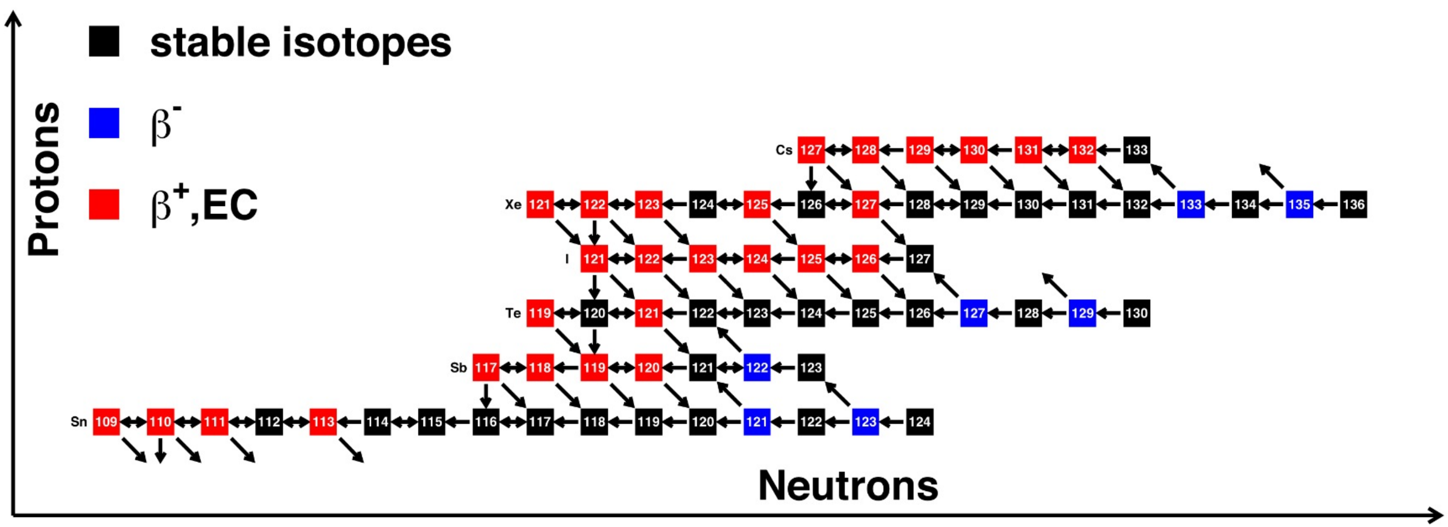


Figure 4.1. Reaction network during the *p*-process nucleosynthesis between Sn and Cs for $T_9 = 2.4$. The *p*-process network is dominated by (γ,n) reactions. Other reactions are shown, if they are dominating. See (Arnould and Goriely, 2003) for more details.

Experimental Equipment to be installed

- **Schottky beam diagnostics**
- **Electron cooler / electron-ion merged beam experiments**
- Atomic targets (**gas target**, MOTReMi)
- Transverse electron targets
- Particle, X-Ray photon, recoil ion detectors
- Cryogenic current comparator
- Slow extraction beam line


Physics book
CRYRING@ESR

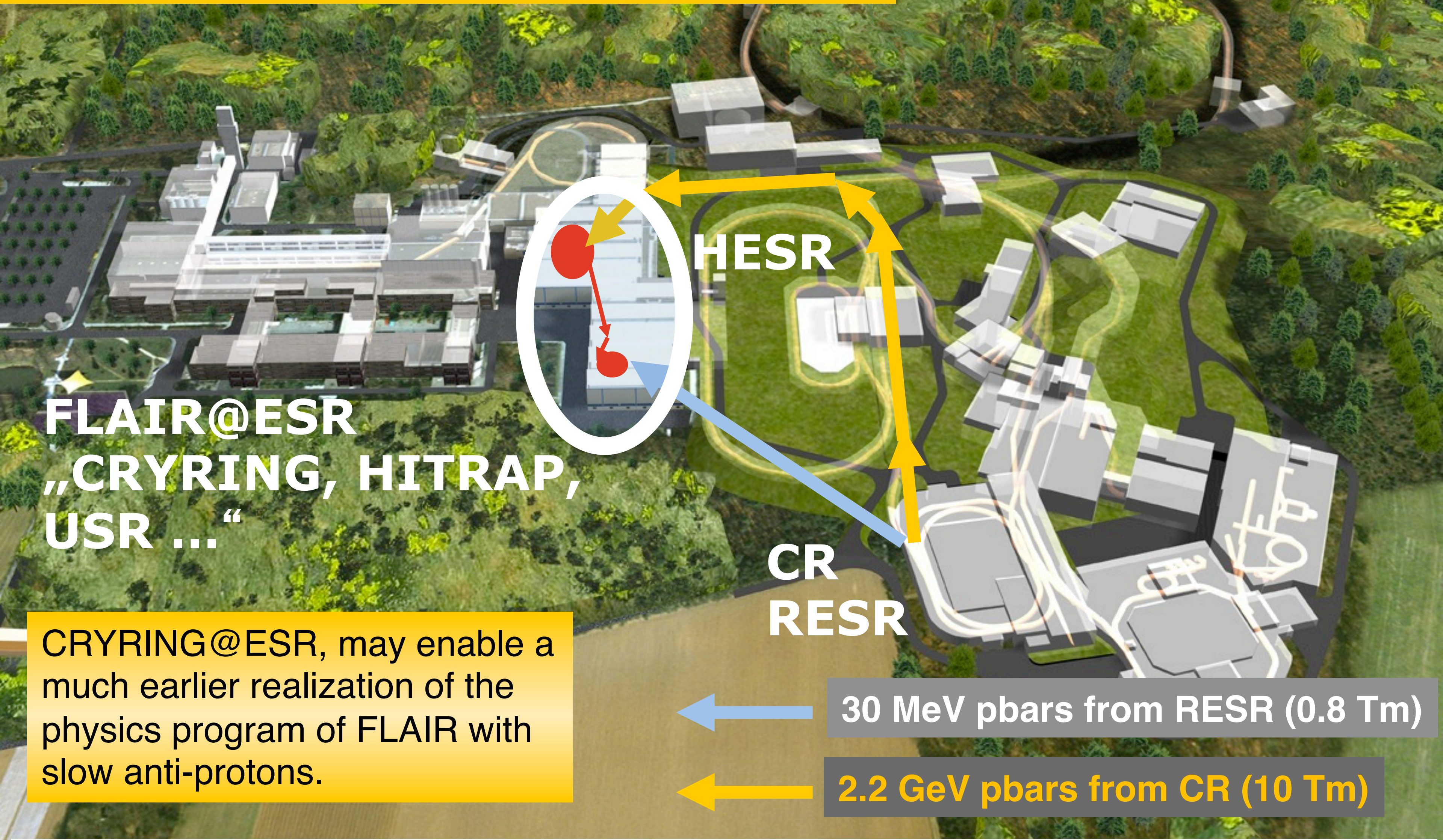
in preparation

Documents related to CRYRING @ GSI and FAIR

- LSR (Low Energy Storage Ring) – TDR (2011)
- “CRYRING@ESR - A study group report” (2012)
- “CRYRING@ESR - The physics book” (in preparation)

Modularized Start Version of FAIR and beyond

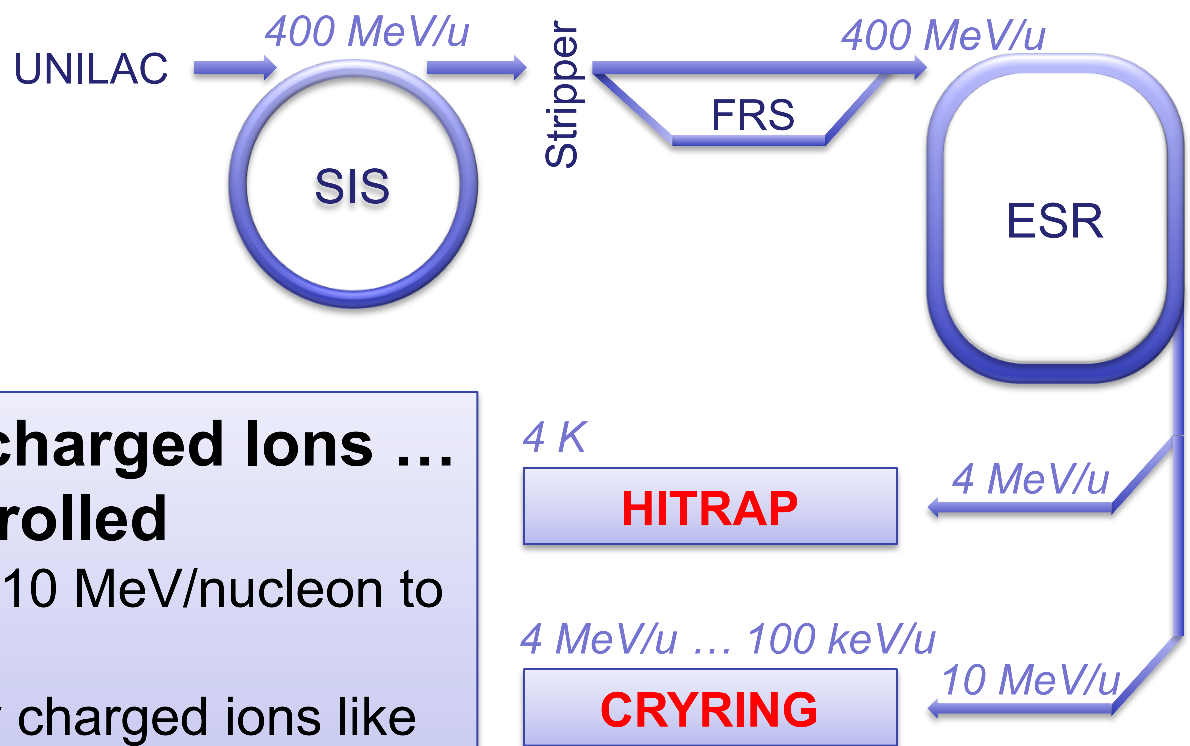
FLAIR
Facility for Low-energy Antiproton and Ion Research



CRYRING@ESR, may enable a much earlier realization of the physics program of FLAIR with slow anti-protons.

CN DE ES FI FR GB GR IN IT PL RO RU SE

Slow, Heavy, Highly Charged Ions @ GSI/FAIR



Slow, heavy, highly charged Ions … stored and well controlled

- Energy range between 10 MeV/nucleon to sub eV/Ion
- 10^5 to 10^7 heavy, highly charged ions like U^{91+}
- Low energy antiprotons in the future