Nuclear Astrophysics at Low-Energy Storage Rings

Yury A. Litvinov

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

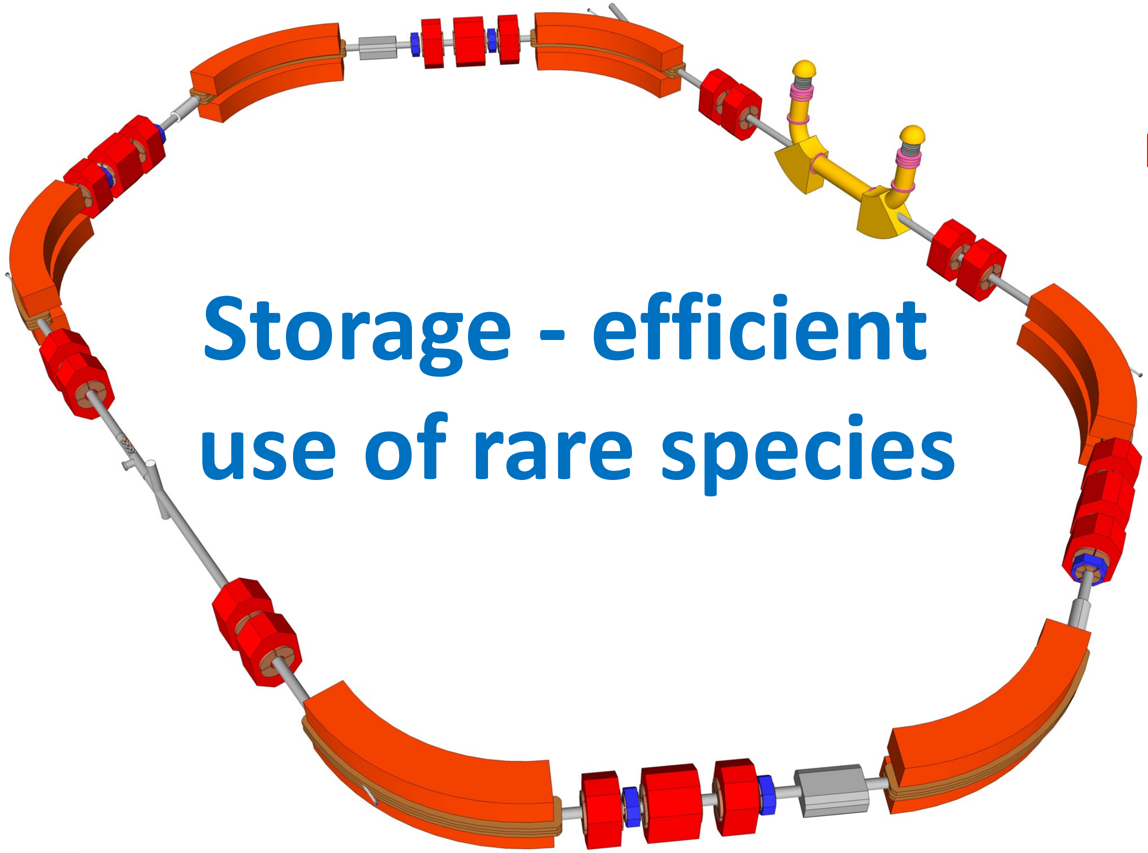
GSI

HALO-40
2025
INTERNATIONAL SYMPOSIUM COMMEMORATING THE 40TH ANNIVERSARY OF THE HALO NUCLEI

International Symposium Commemorating the 40th Anniversary of the Halo Nuclei
12-18 October 2025,
Capital Hotel, Beijing, China

Heavy-Ion Storage Rings - Versatile Instruments

Dedicated beam preparation and manipulation techniques



Storage - efficient use of rare species

A huge trap – more than 100 m circumference, aperture size – 25 cm

Nuclear reaction inevitably leads to large momentum spread of the secondary beam

Beam cooling - high quality beams

Isochronous mode – high mass resolution

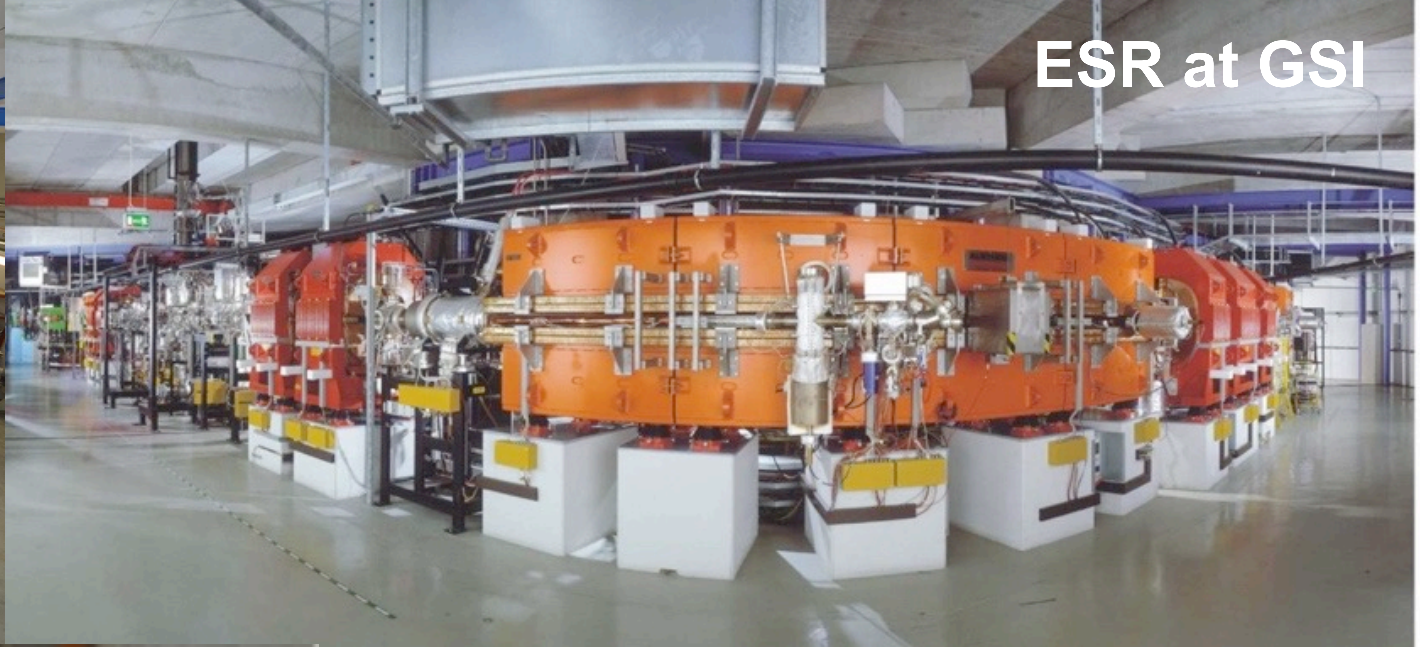
Small production rates of secondary beams

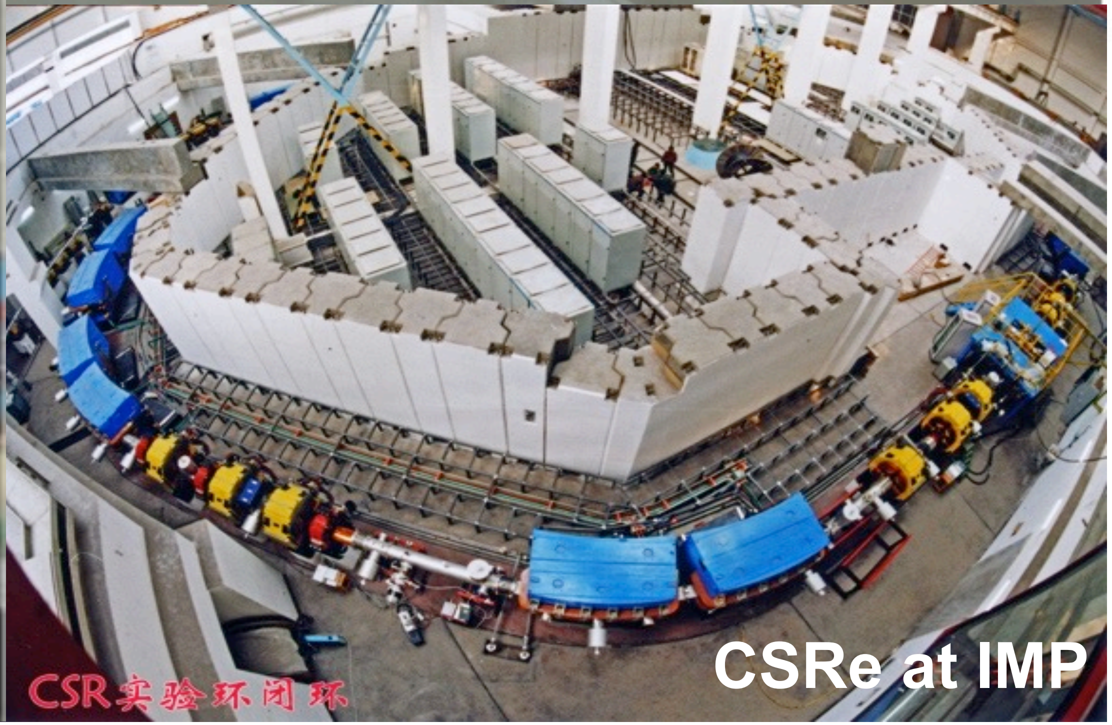
Accumulation techniques

Single-particle sensitivity detection

Short-lived species

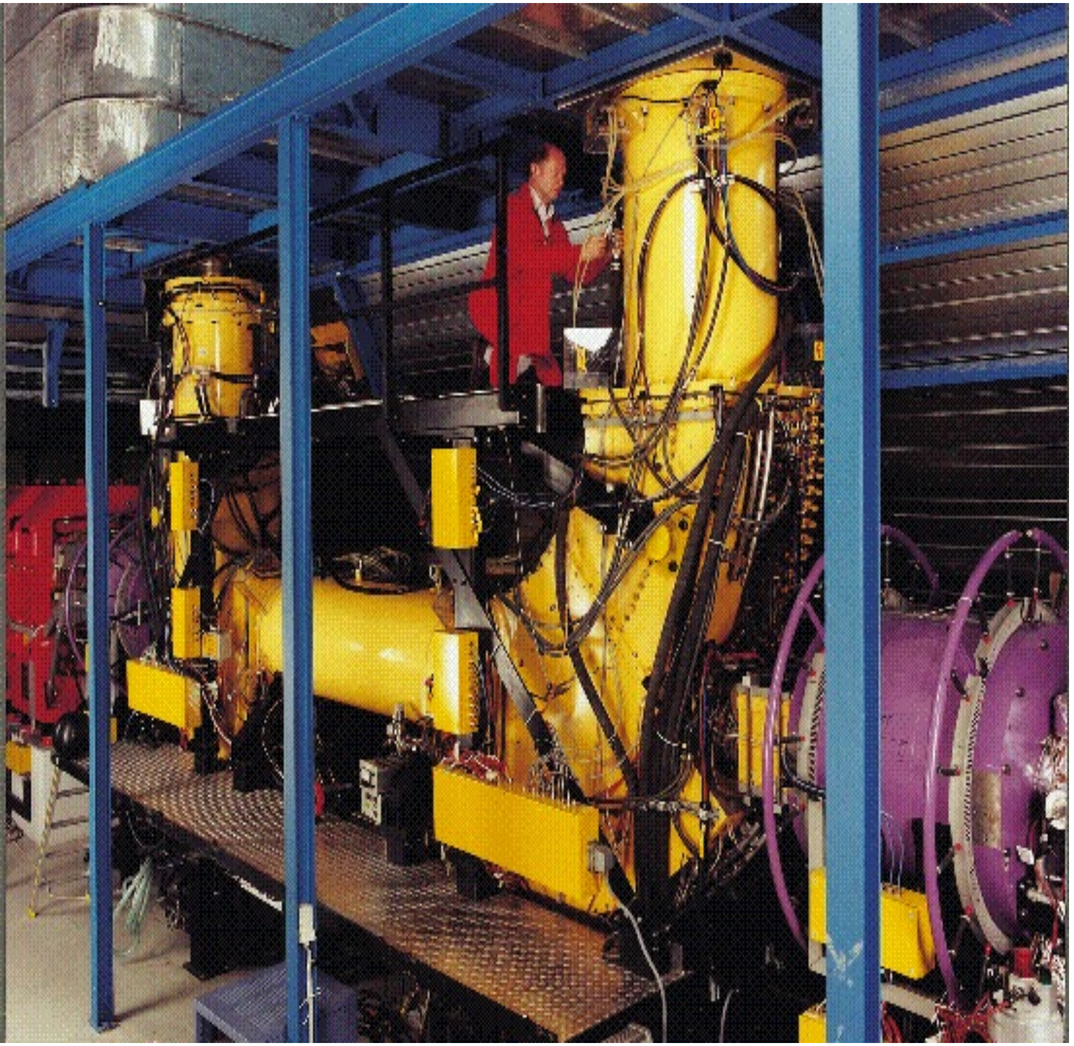
Instantaneous detection



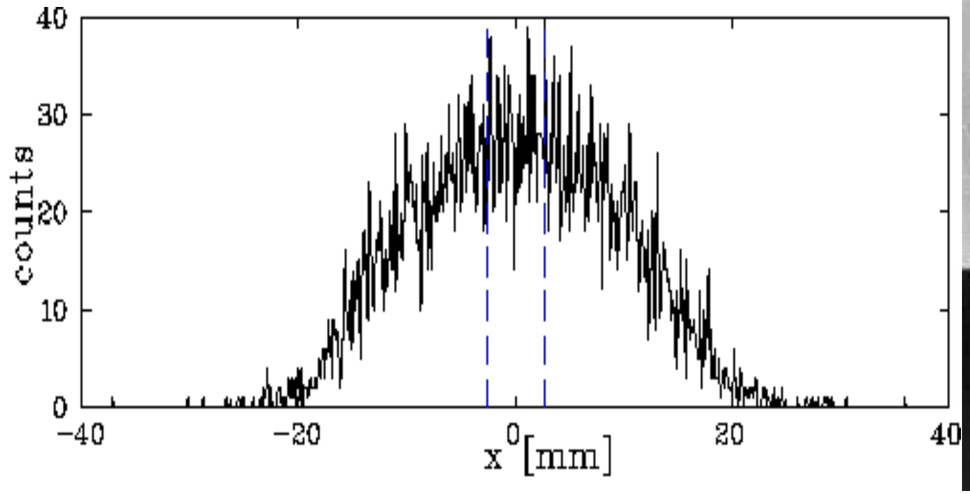


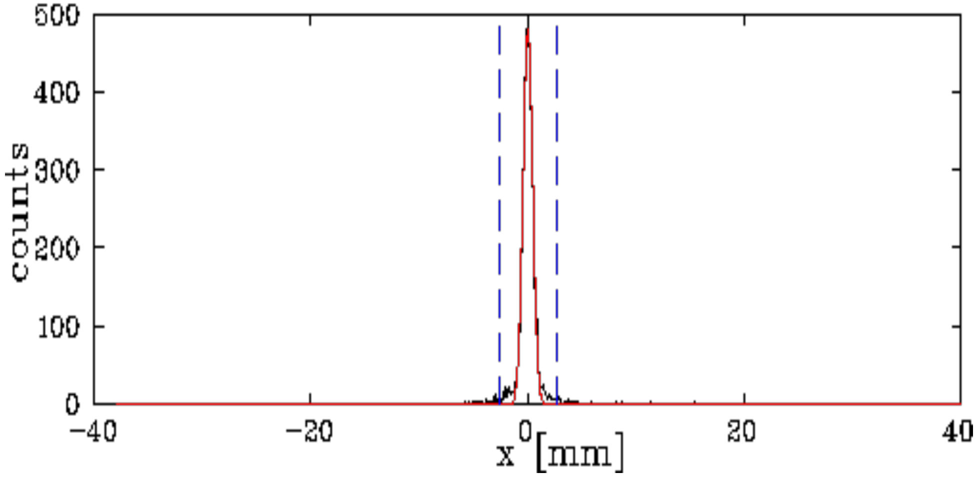
Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

Electron Cooling of Secondary Beams

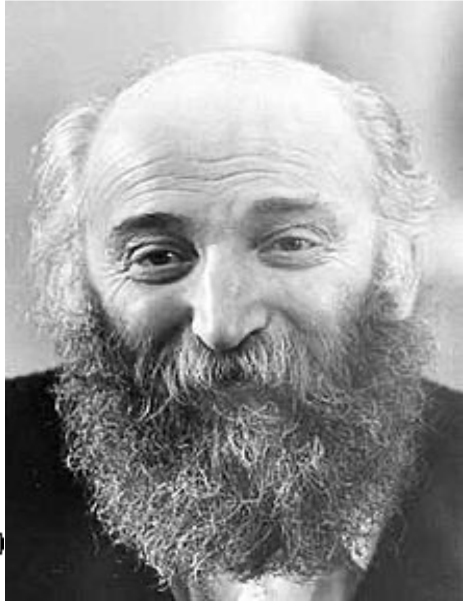


Exchange of momenta





$$\frac{\Delta v}{v} \approx 1 \cdot 10^{-7}$$



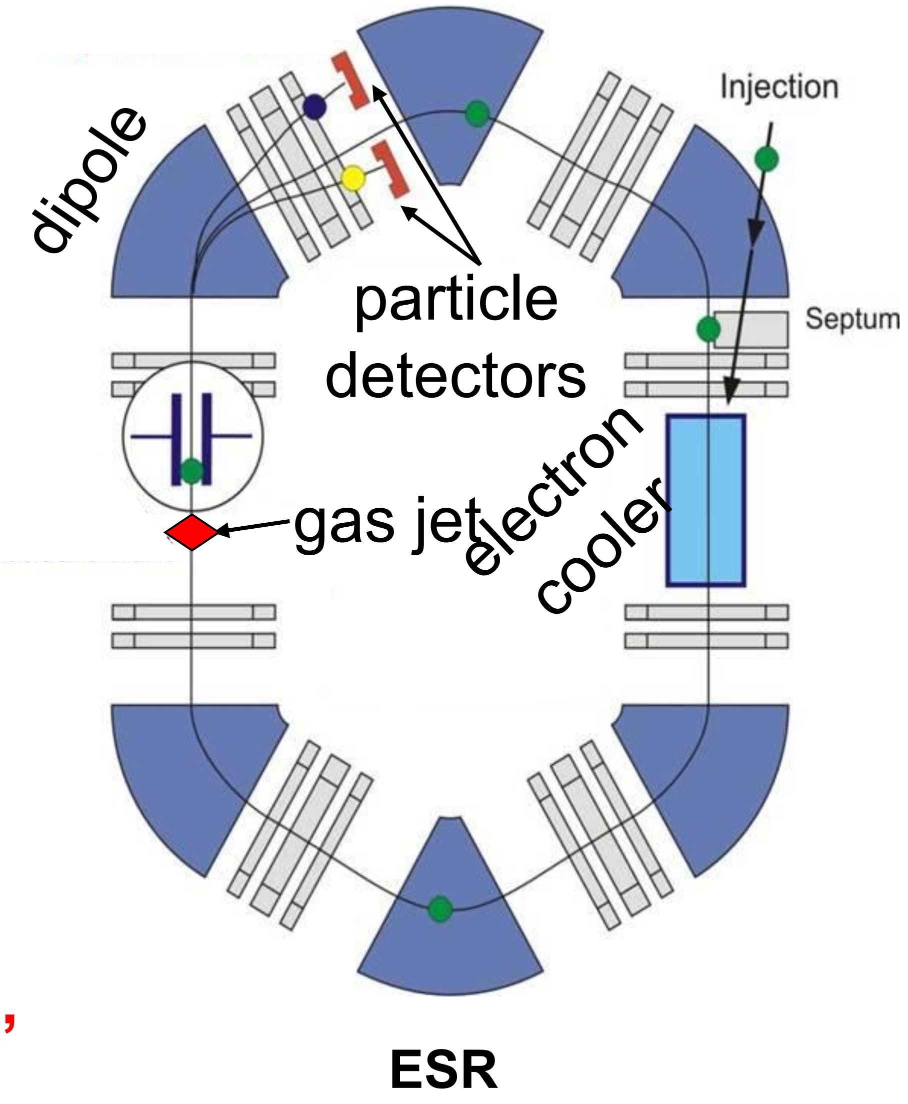
Gersh I. Budker
1918 - 1977

Markus Steck 2025^{+}

Proton-Capture Reactions in the ESR

refill ring periodically

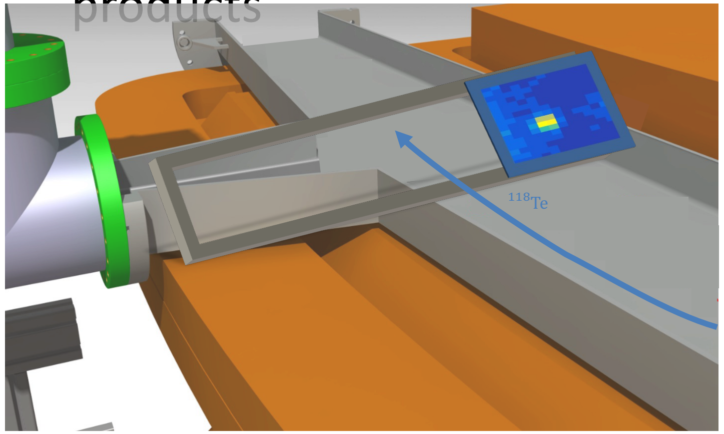
- injection of ions @ >100 MeV/u
  - ✓ **fully stripped ions**
- deceleration & cooling of the beam
  - ✓ **E = 3 - 10 MeV/u**
- activate internal **hydrogen target**
  - ✓ proton & electron capture reactions
  - ✓ separated by dipole
  - ✓ particle detectors on…
    - … inner tracks for (p,γ) products
    - … outer tracks for e^- capture products
- beam life time (residual gas + target interaction)
  - ➢ intensity goes down

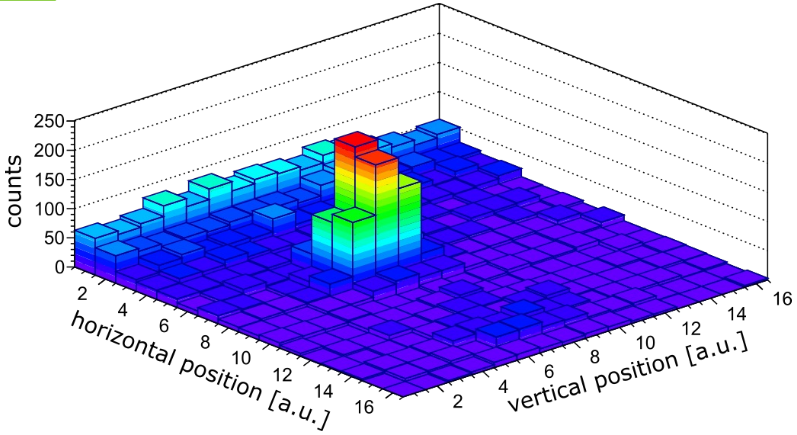


Jan Glorius: "A recycling recoil separator"

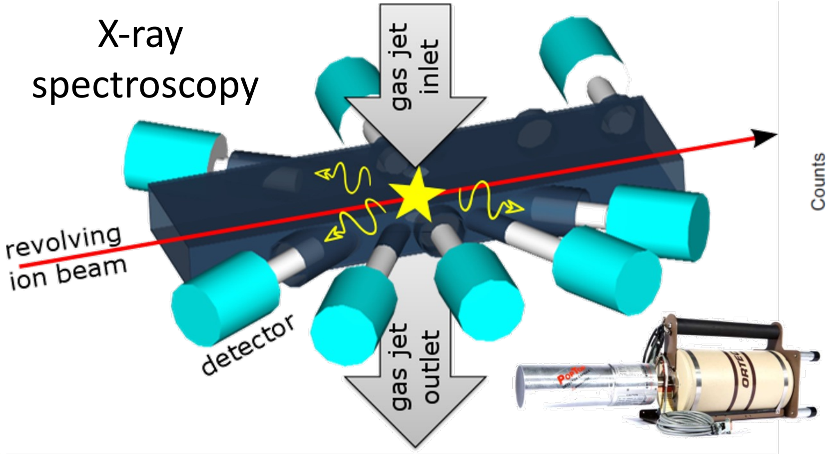
Proton-Induced Reactions in the Experimental Storage Ring

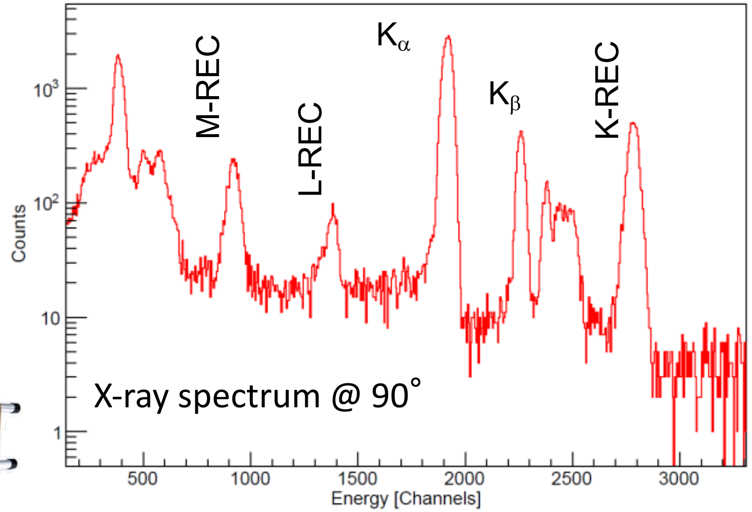
(p,g) and (p,n) reaction products

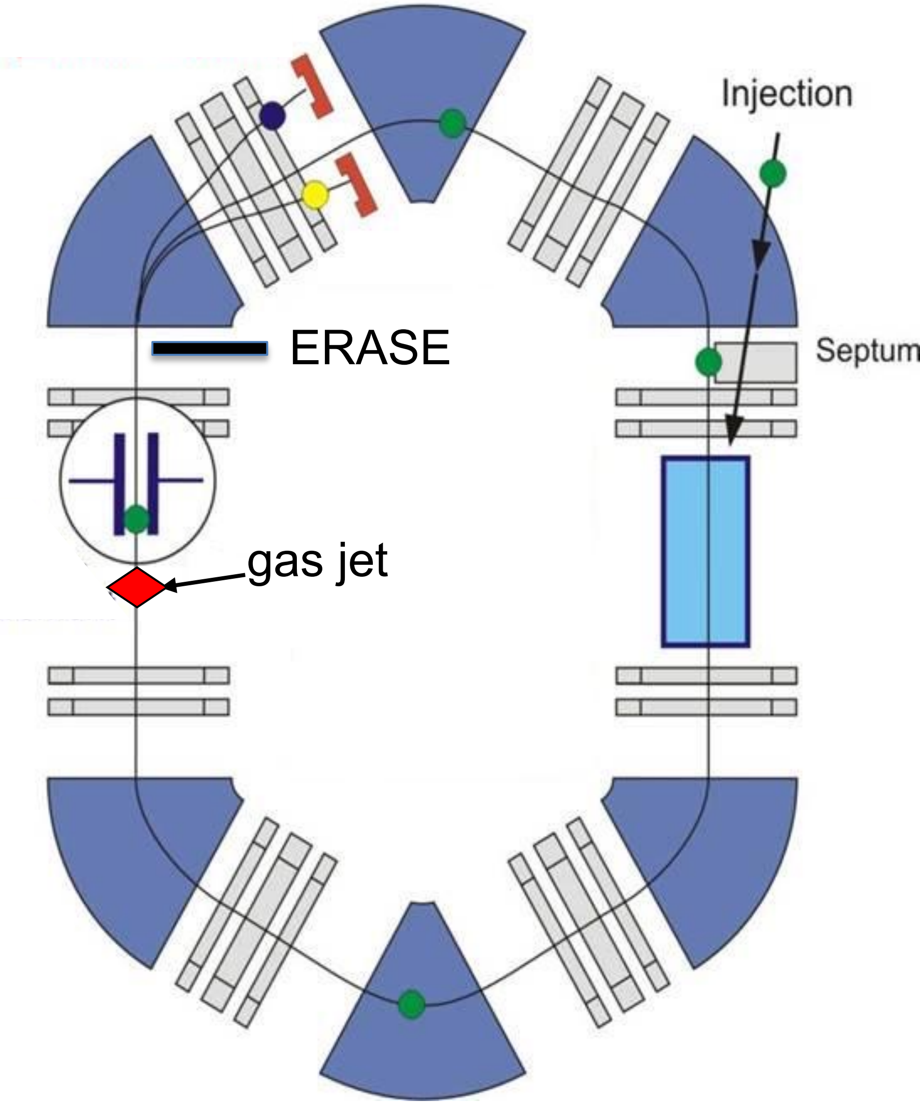




radiative e$^-$ capture rate [REC]

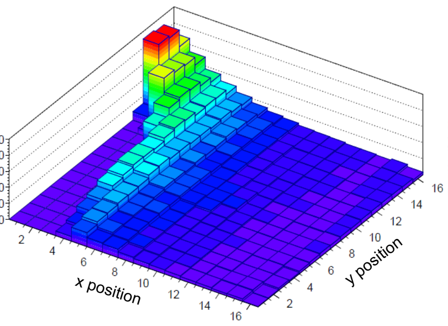




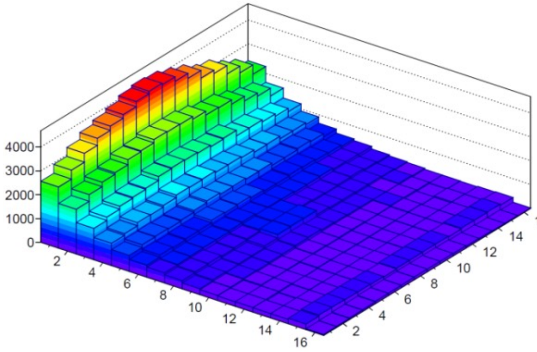


^{124}Xe(p,g) - Results

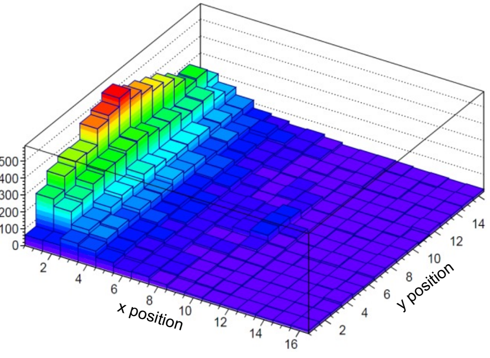
5.5 MeV/u



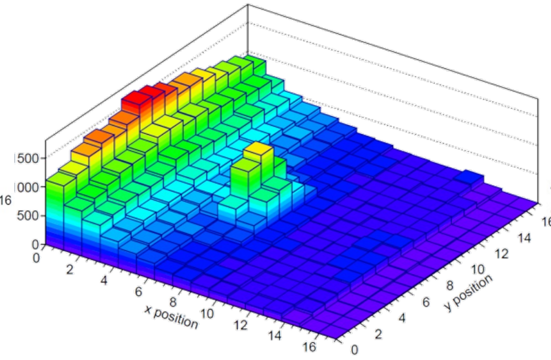
6 MeV/u



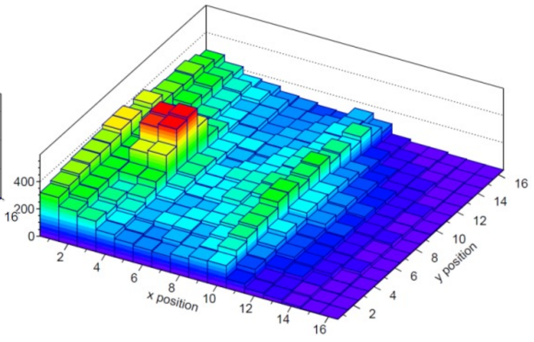
6.7 MeV/u

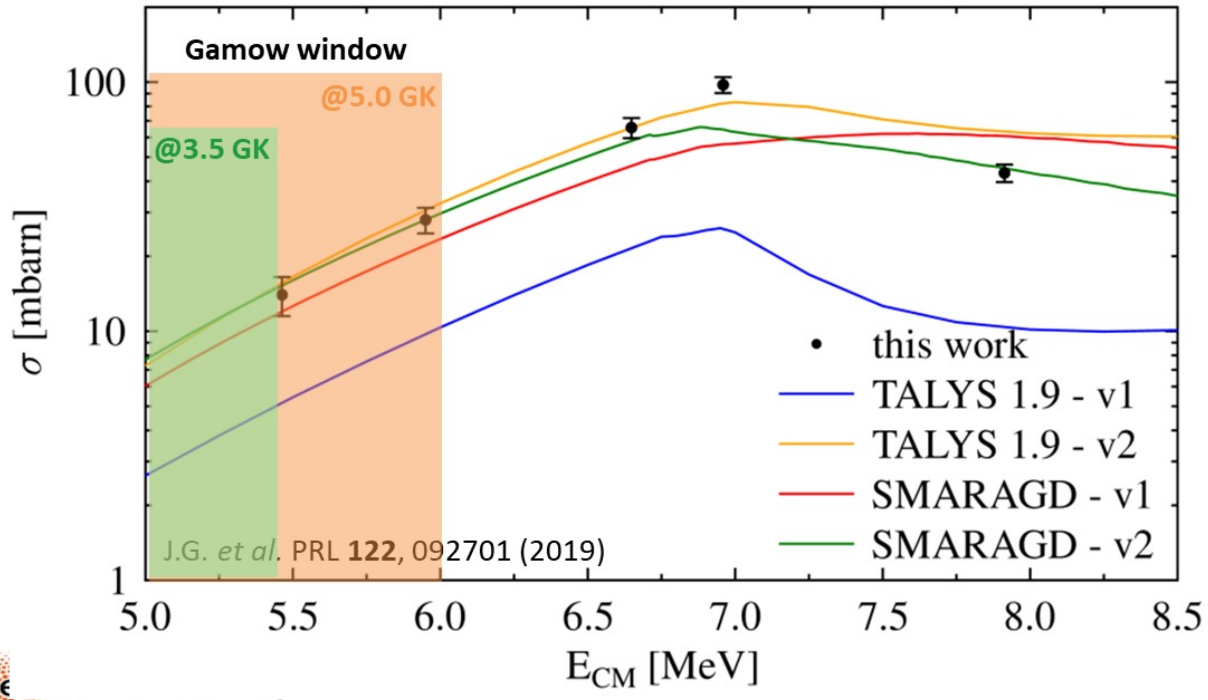


7 MeV/u



8 MeV/u



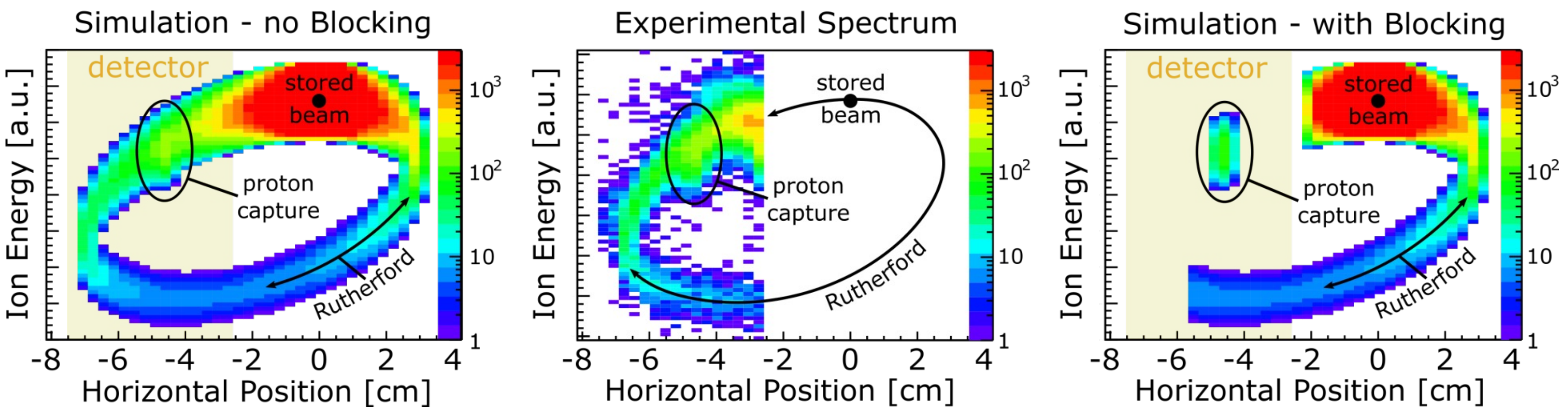


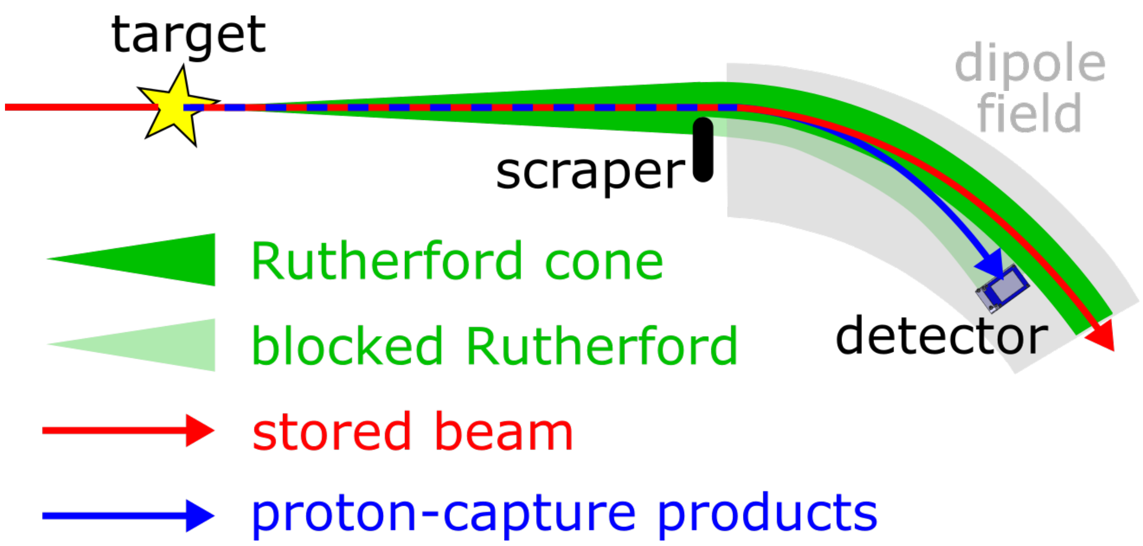
PHYSICAL REVIEW LETTERS **122,** 092701 (2019)

Approaching the Gamow Window with Stored Ions: Direct Measurement of $^{124}\mathrm{Xe}(p,\gamma)$ in the ESR Storage Ring

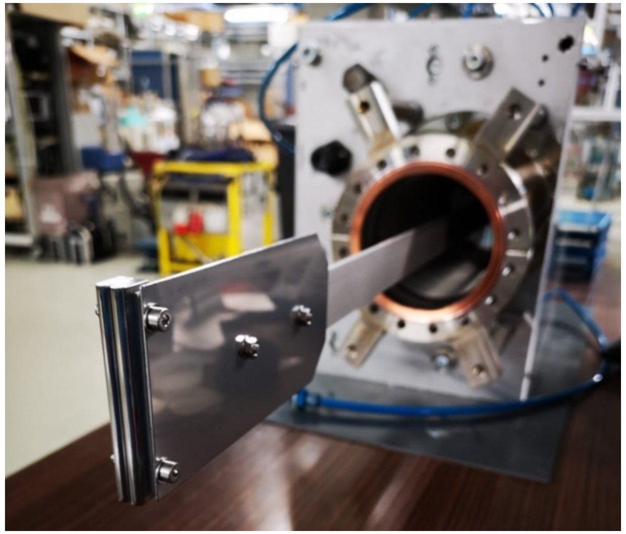
J. Glorius,[1,*] C. Langer,[2] Z. Slavkovská,[2] L. Bott,[2] C. Brandau,[1,3] B. Brückner,[2] K. Blaum,[4] X. Chen,[5] S. Dababneh,[6] T. Davinson,[7] P. Erbacher,[2] S. Fiebiger,[2] T. Gaßner,[1] K. Göbel,[2] M. Groothuis,[2] A. Gumberidze,[1] G. Gyürky,[8] M. Heil,[1] R. Hess,[1] R. Hensch,[2] P. Hillmann,[2] P.-M. Hillenbrand,[1] O. Hinrichs,[2] B. Jurado,[9] T. Kausch,[2] A. Khodaparast,[1,2] T. Kisselbach,[2] N. Klapper,[2] C. Kozhuharov,[1] D. Kurtulgil,[2] G. Lane,[10] C. Lederer-Woods,[7] M. Lestinsky,[1] S. Litvinov,[1] Yu. A. Litvinov,[1] B. Löher,[11,1] F. Nolden,[1] N. Petridis,[1] U. Popp,[1] T. Rauscher,[12,13] M. Reed,[10] R. Reifarth,[2] M. S. Sanjari,[1] D. Savran,[1] H. Simon,[1] U. Spillmann,[1] M. Steck,[1] T. Stöhlker,[1,14] J. Stumm,[2] A. Surzhykov,[15,16] T. Szücs,[8] T. T. Nguyen,[2] A. Taremi Zadeh,[2] B. Thomas,[2] S. Yu. Torilov,[17] H. Törnqvist,[1,11] M. Träger,[1] C. Trageser,[1,3] S. Trotsenko,[1] L. Varga,[1] M. Volknandt,[2] H. Weick,[1] M. Weigand,[2] C. Wolf,[2] P. J. Woods,[7] and Y. M. Xing[5,1]

Towards background free measurement





work of Laszlo Varga



Proton-Induced Reactions in the Experimental Storage Ring

ERASE vs no-ERASE: ^{124}Xe(p,x)

nearly background-free measurement

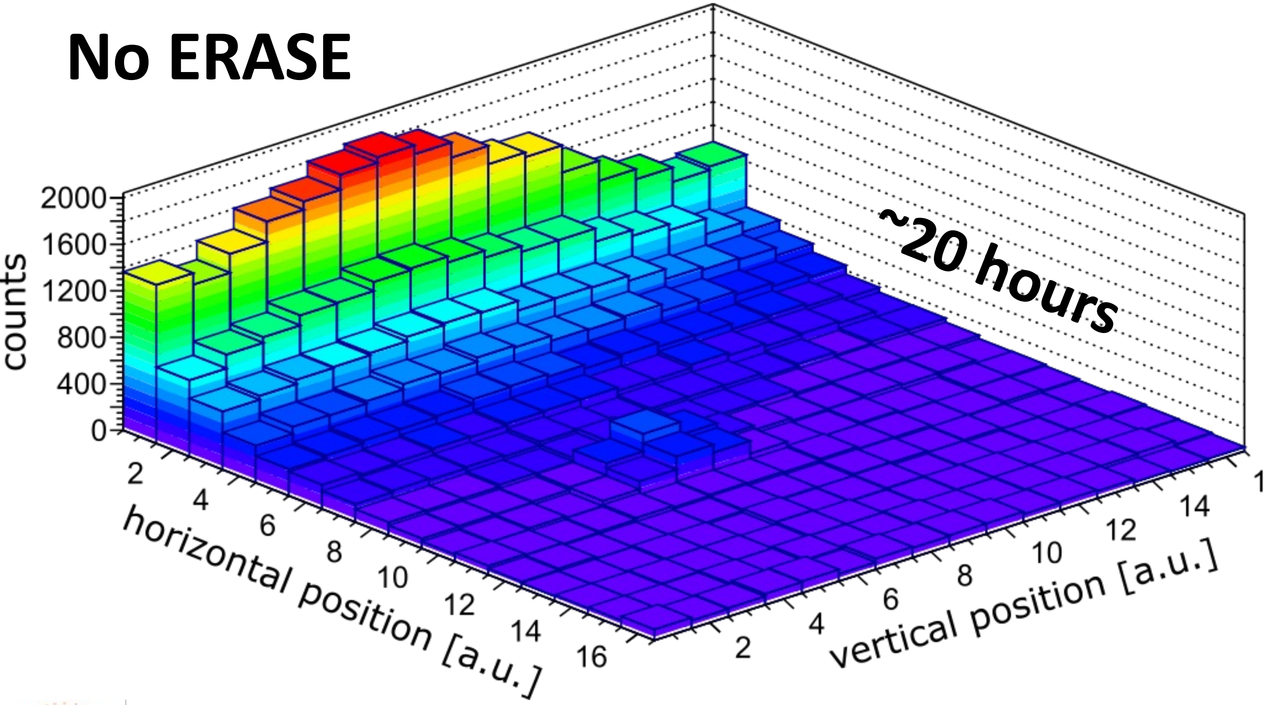
maximized experimental sensitivity

(p,n) reaction channel measured simultaneously

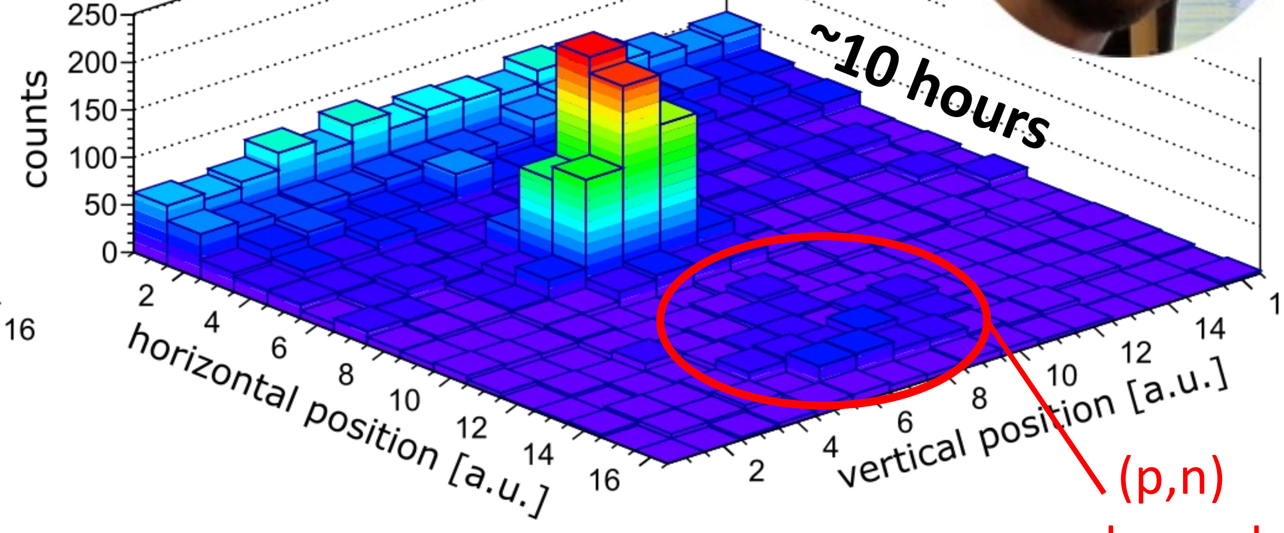
^{124}Xe(p,γ)

- 10^7 bare ions stored
- cooled and decelerated to 7 MeV/u

No ERASE



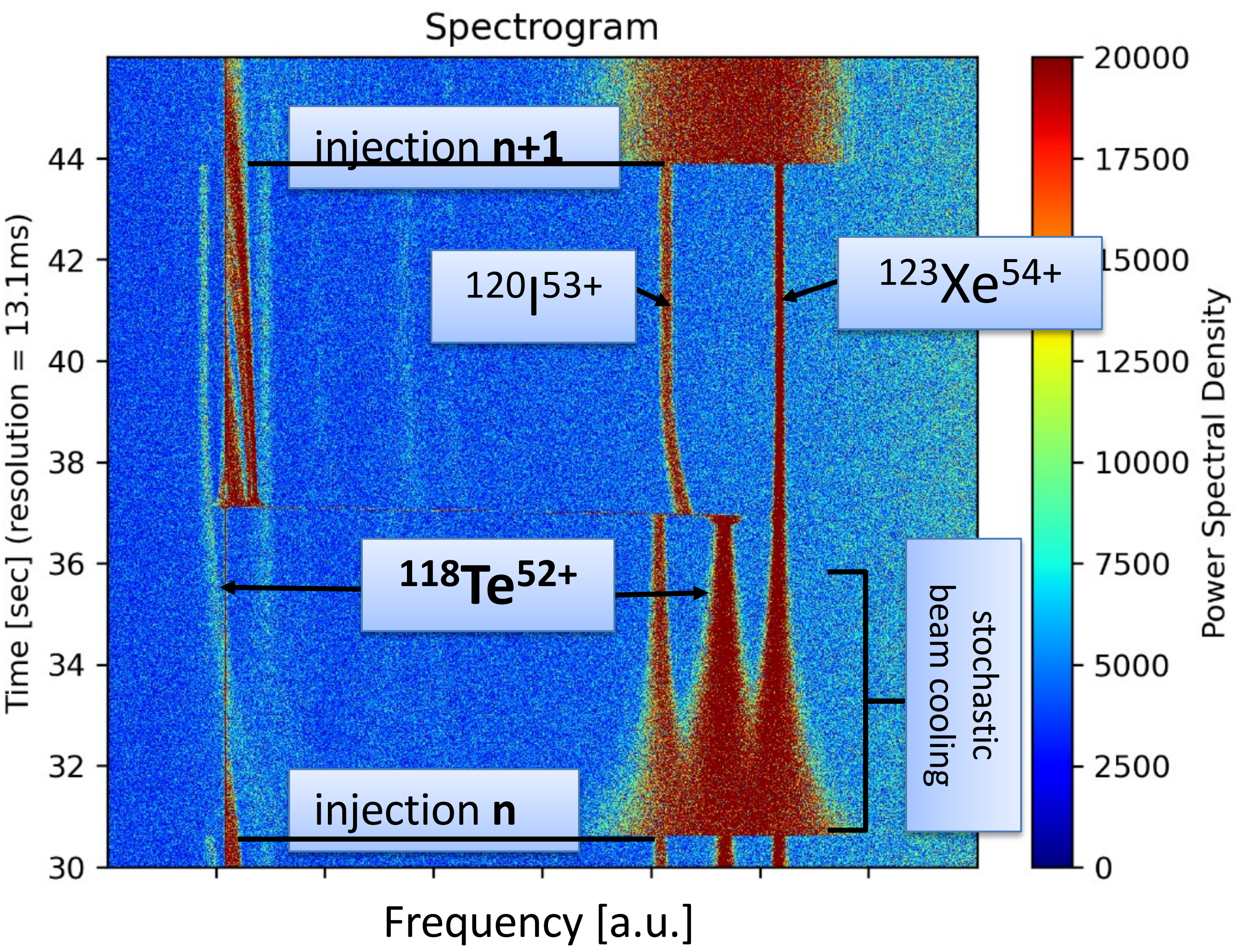
ERASE

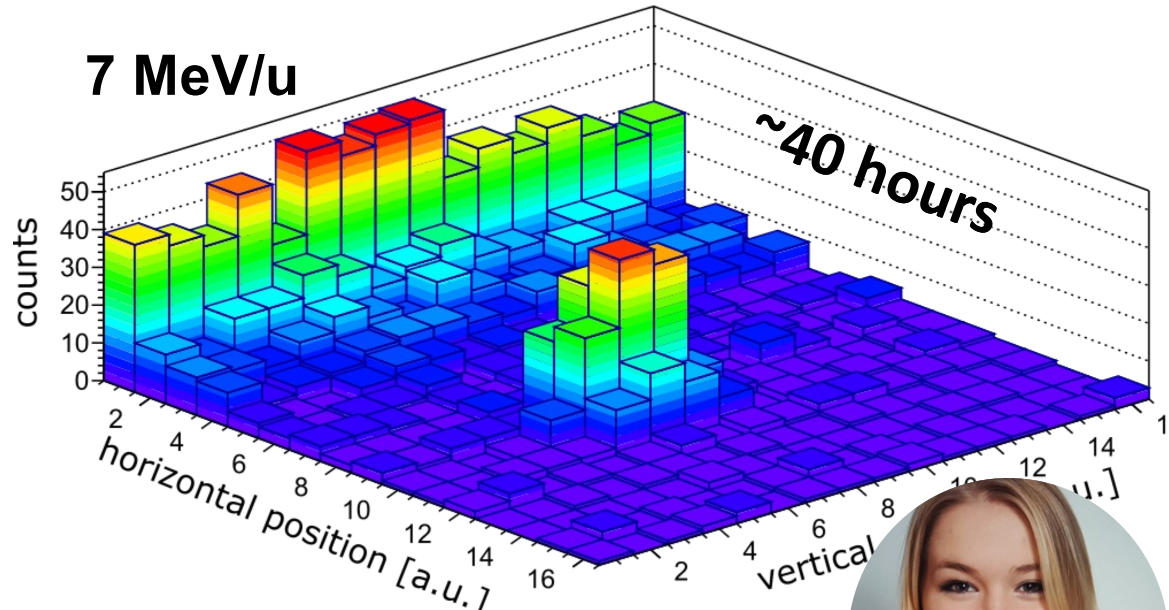


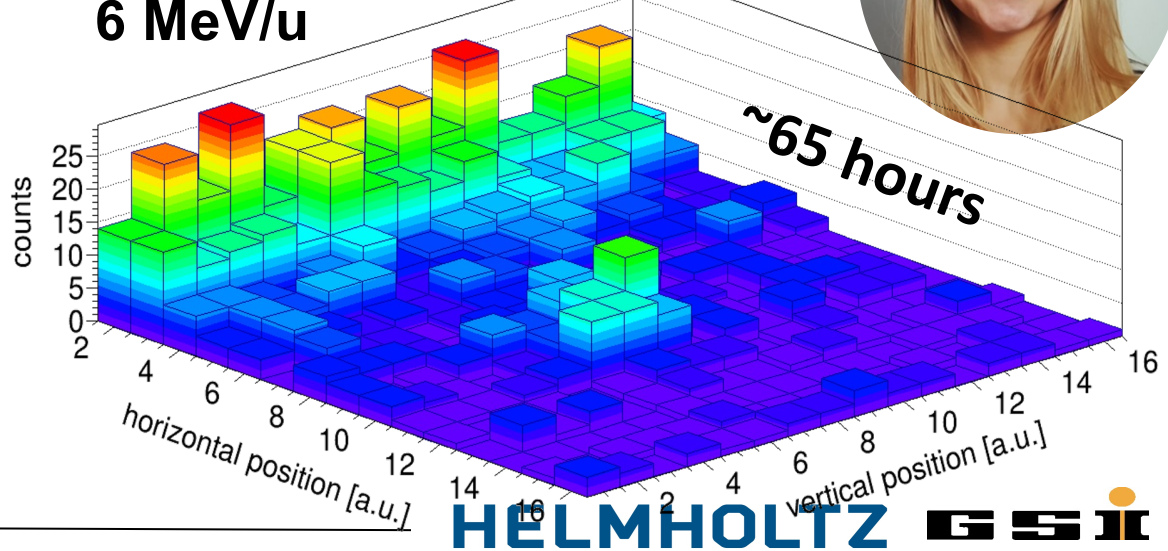
L. Vargo et al., Phys. Rev. Lett. 134, 082701 (2025)

Proton-Induced Reactions in the Experimental Storage Ring

First study on radioactive ion beam





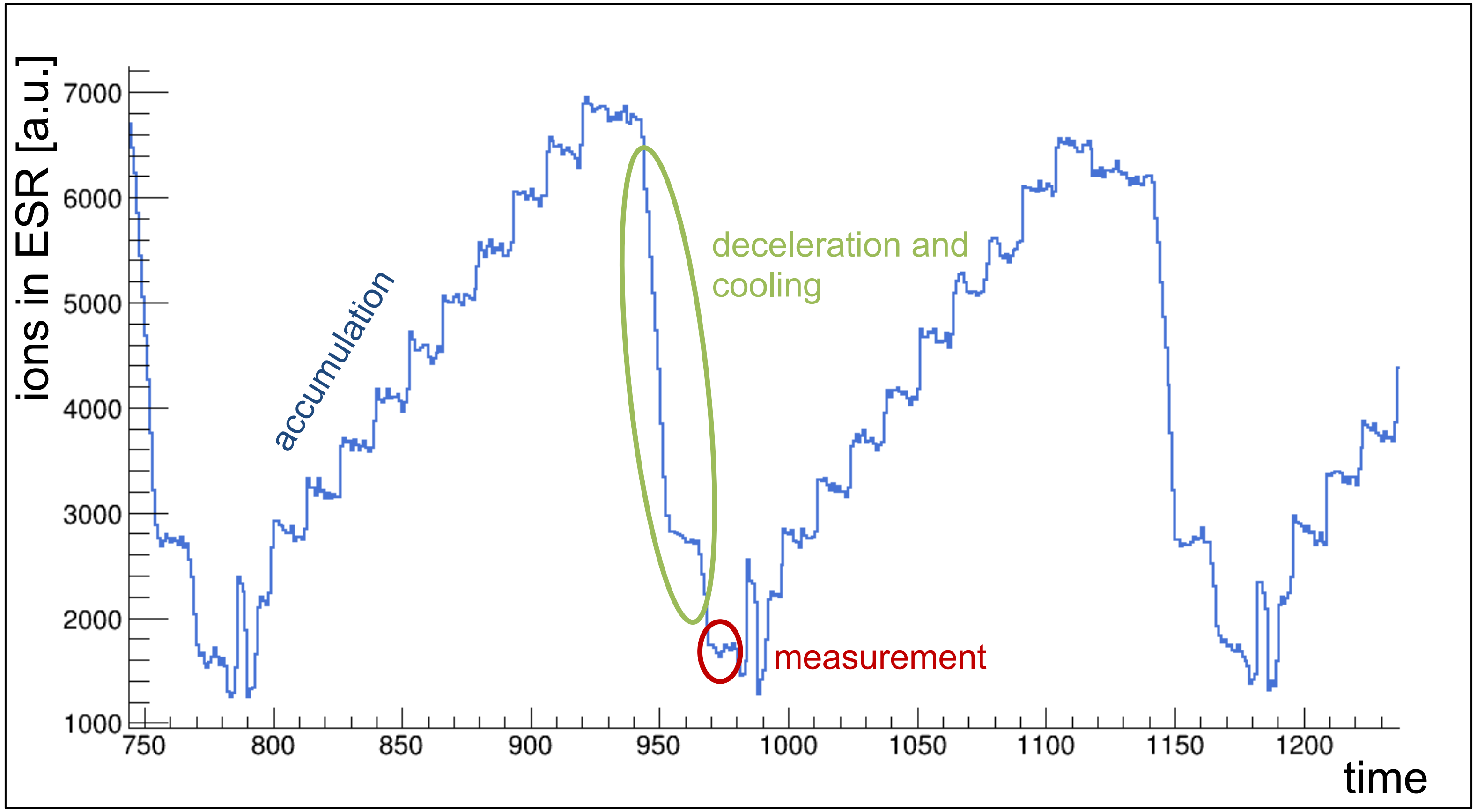


erc ASTRUm

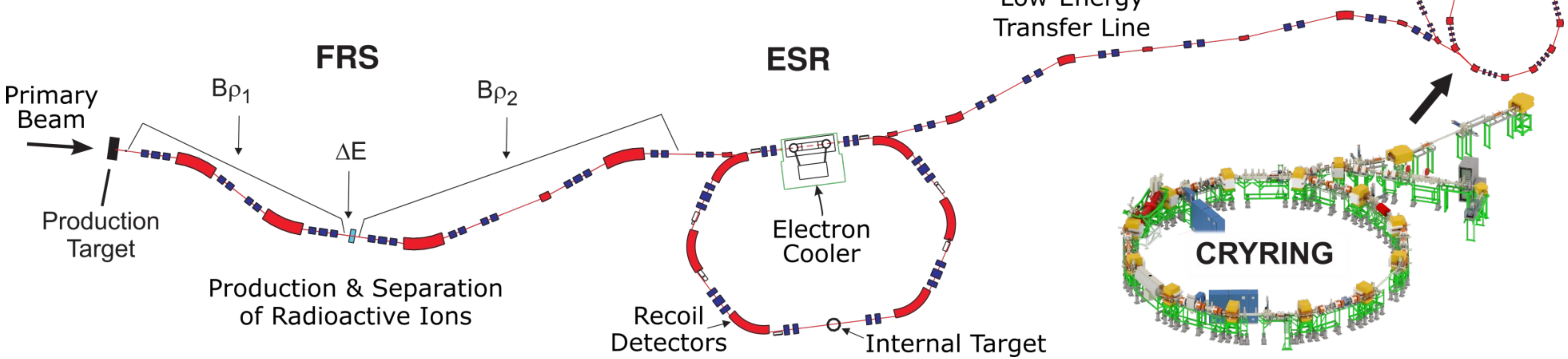
S. Dellmann et al., Phys. Rev. Lett. 134, 142701 (2025)

HELMHOLTZ GSI

Proton capture on radioactive ^{118}Te



The CRYRING@ESR facility

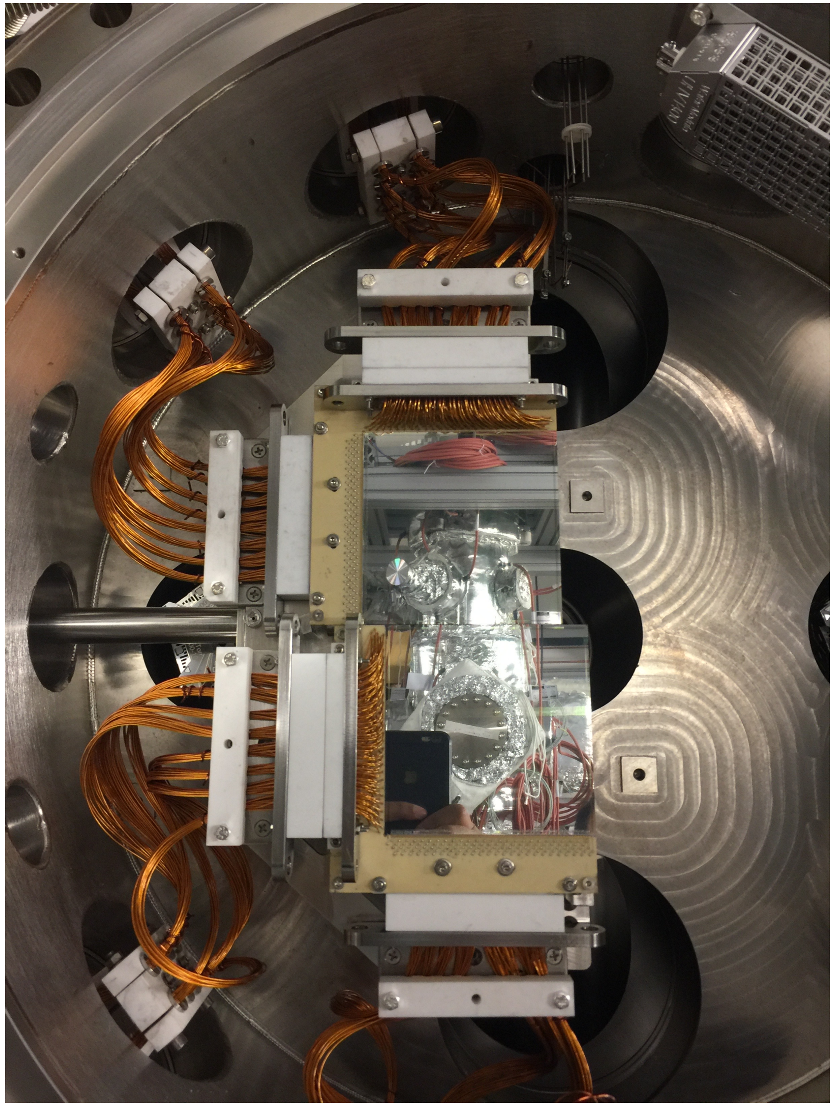


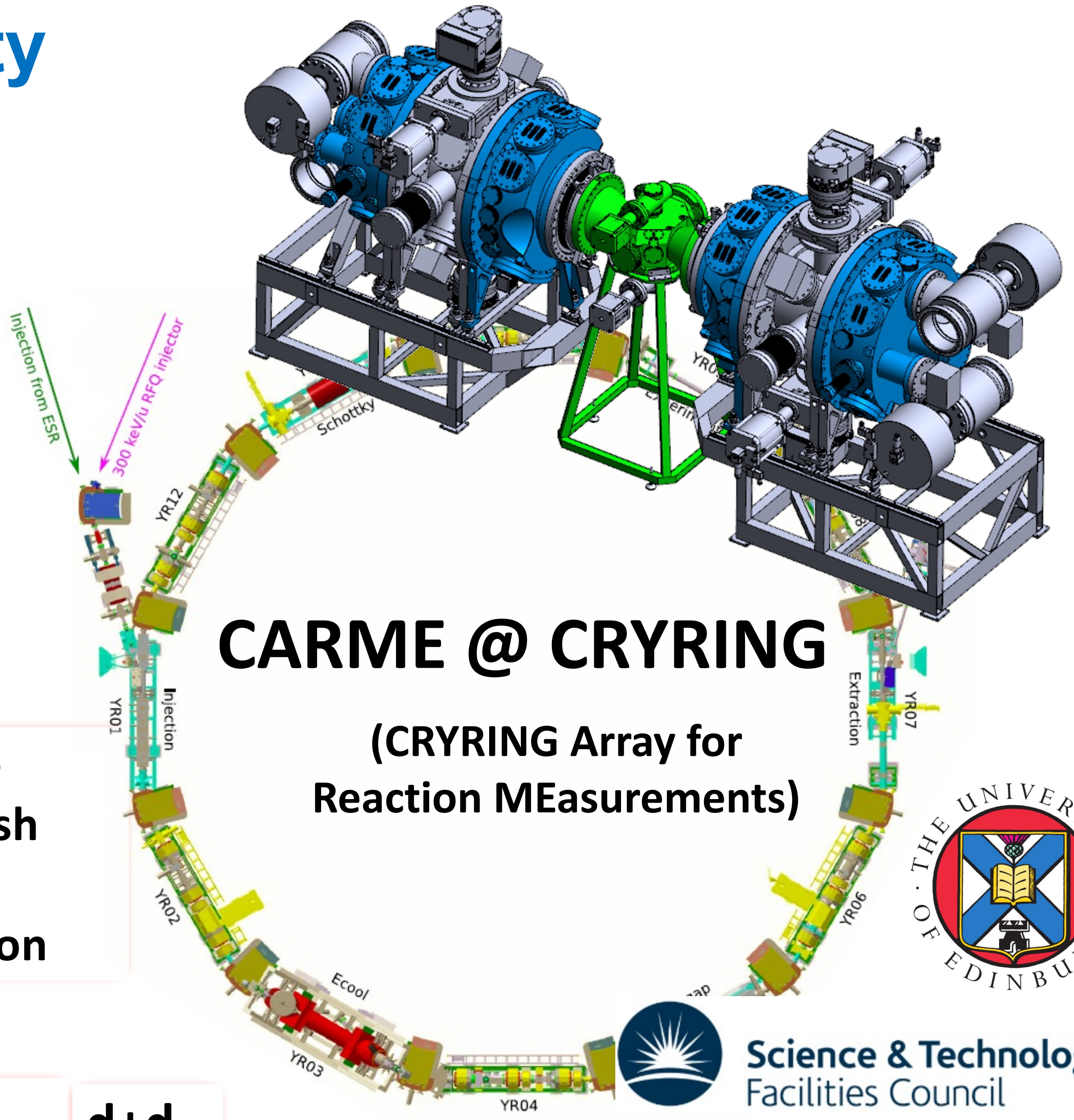
CRYRING
(transported from Stockholm University)

Start of operation (local source) – 2019
Start of operation (beams from ESR) – 2020
Circumference = 54.15 m
XH Vacuum = 10^{-11}—10^{-12} mbar
Electron cooling
Energy range = ~0.1 – 15 MeV/u
Slow and fast extraction

M. Lestinsky, GSI, Darmstadt

The CRYRING@ESR facility





CARME @ CRYRING

(CRYRING Array for Reaction MEasurements)

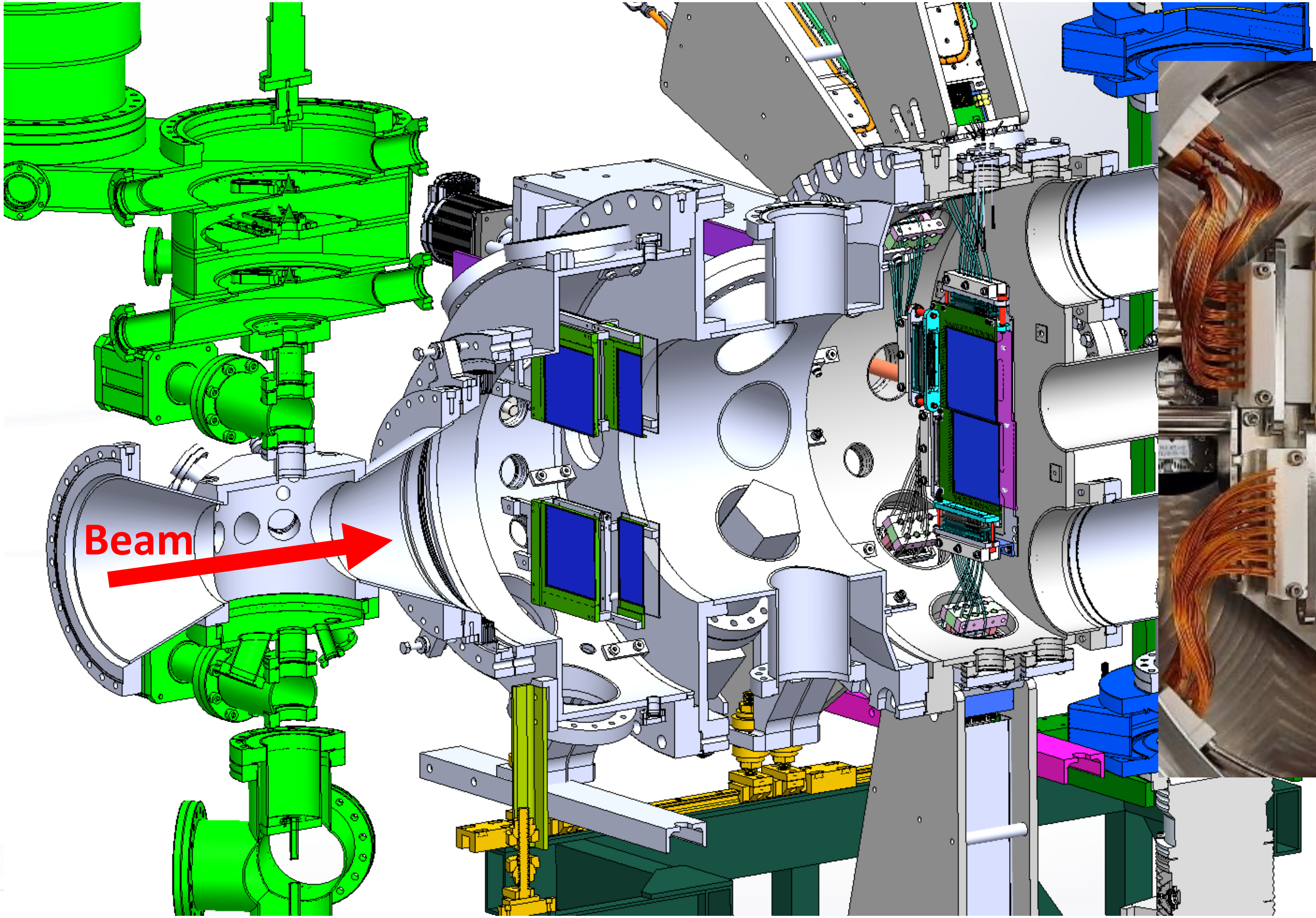
Carlo Bruno
Jordan Marsh
Phil Woods
Tom Davinson

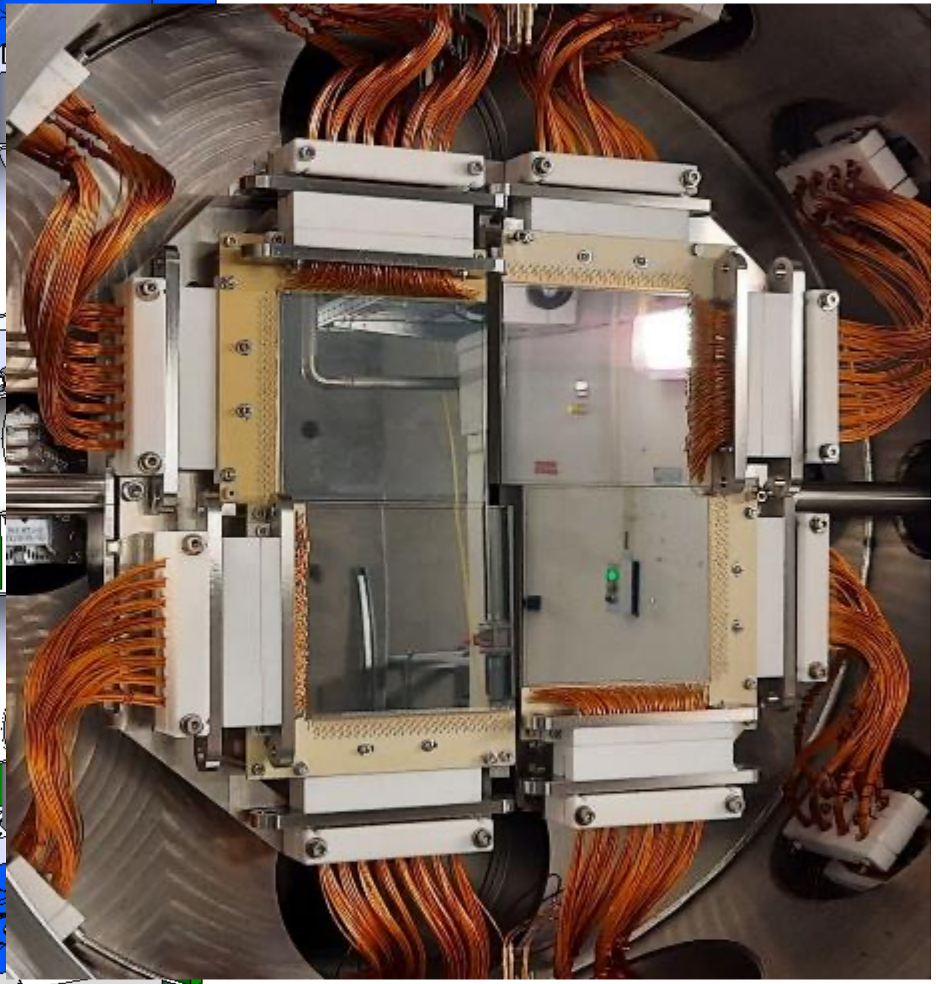
^{7}Li+p

d+d

CARME array

Courtesy of Jordan Marsh and Carlo Bruno

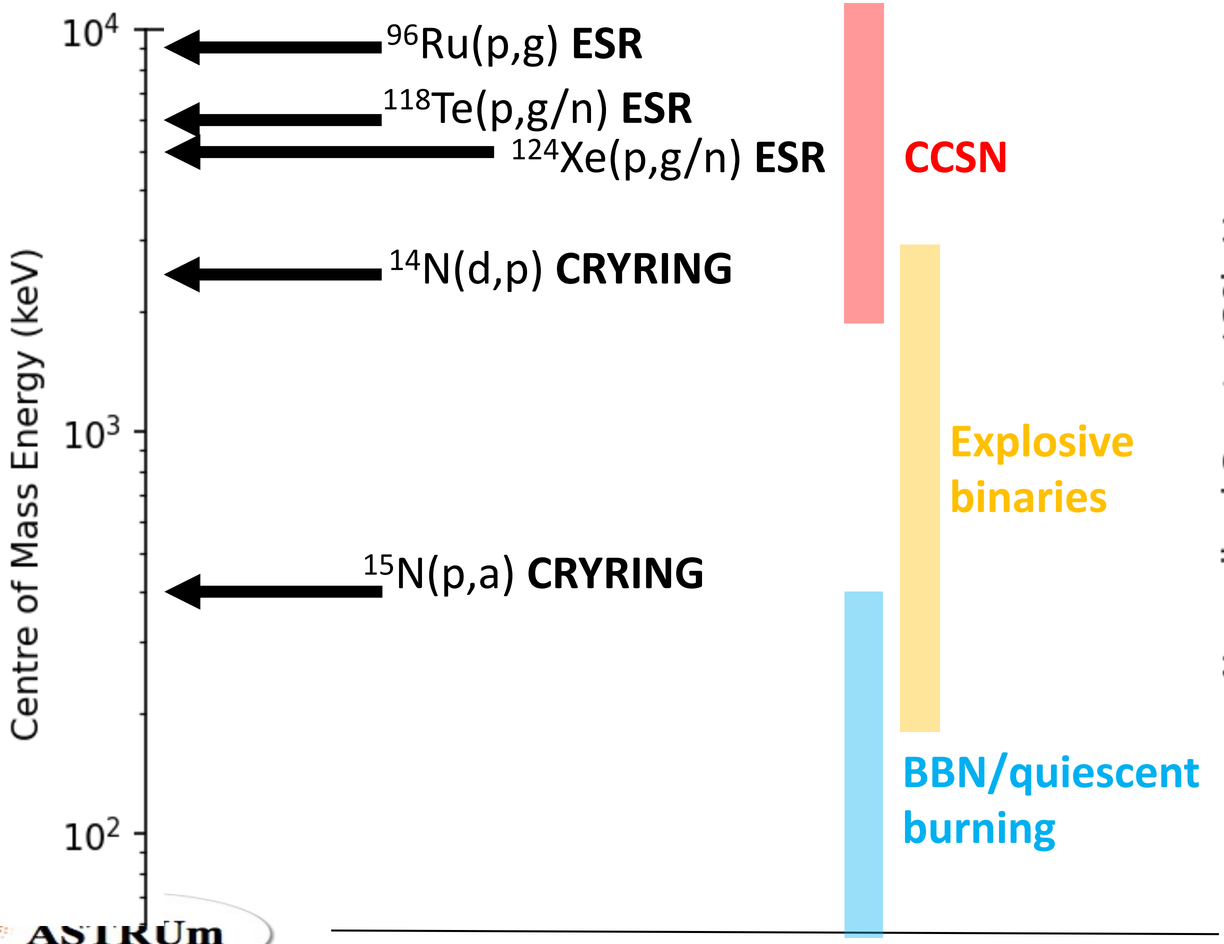


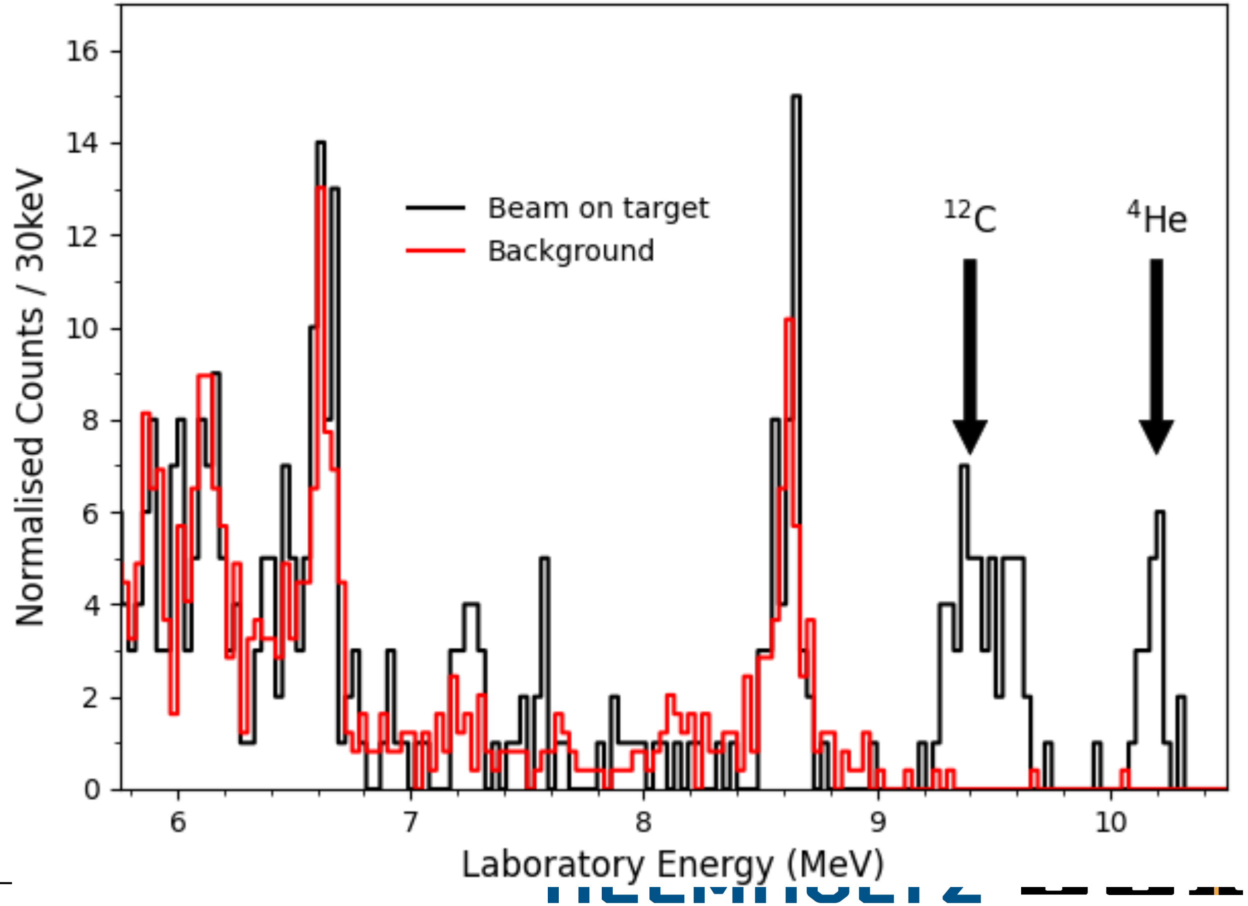


.MHOLTZ GSI

2024 measurement – ^{15}N+p

- We took data at 1.125, 1.06 and 0.426 MeV/A
- 15N(p,a)12C reaction was observed at 0.426 MeV/A
- This is the lowest energy a nuclear reaction has ever been measured on a storage ring





Courtesy of Jordan Marsh and Carlo Bruno

Status and Perspectives

- **two successful stable beam experiments @ ESR**
  - ^{96}Ru(p,γ) & ^{124}Xe(p,γ) & ^{124}Xe(p,n)
  - development of an in-vacuum detection and ERASE systems
  - arrival inside the **Gamow window**

- **First radioactive beam study @ ESR**
  - ^{118}Te(p,γ) measured at 6 and 7 MeV/u

- **future prospects**
  - ^{91}Nb(p,γ) or ^{109}In(p,γ) are key reations in the γ process
  - ^{59}Cu(p,γ) is a key reaction in the *rp* process
  - Expansion to (α,γ), (α,p), (α,n) in heavier systems for the γ process
  - CRYRING gives access to the full Gamow Window

Unfortunately, NO astrophysics experiments with radioactive beams approved by the GSI General PAC

Technical Meeting on Neutron-induced Reactions on Short-lived Nuclei

IAEA

International Atomic Energy Agency

25-29 August 2025
International Atomic Energy Agency
United Nations Headquarters Vienna, Austria

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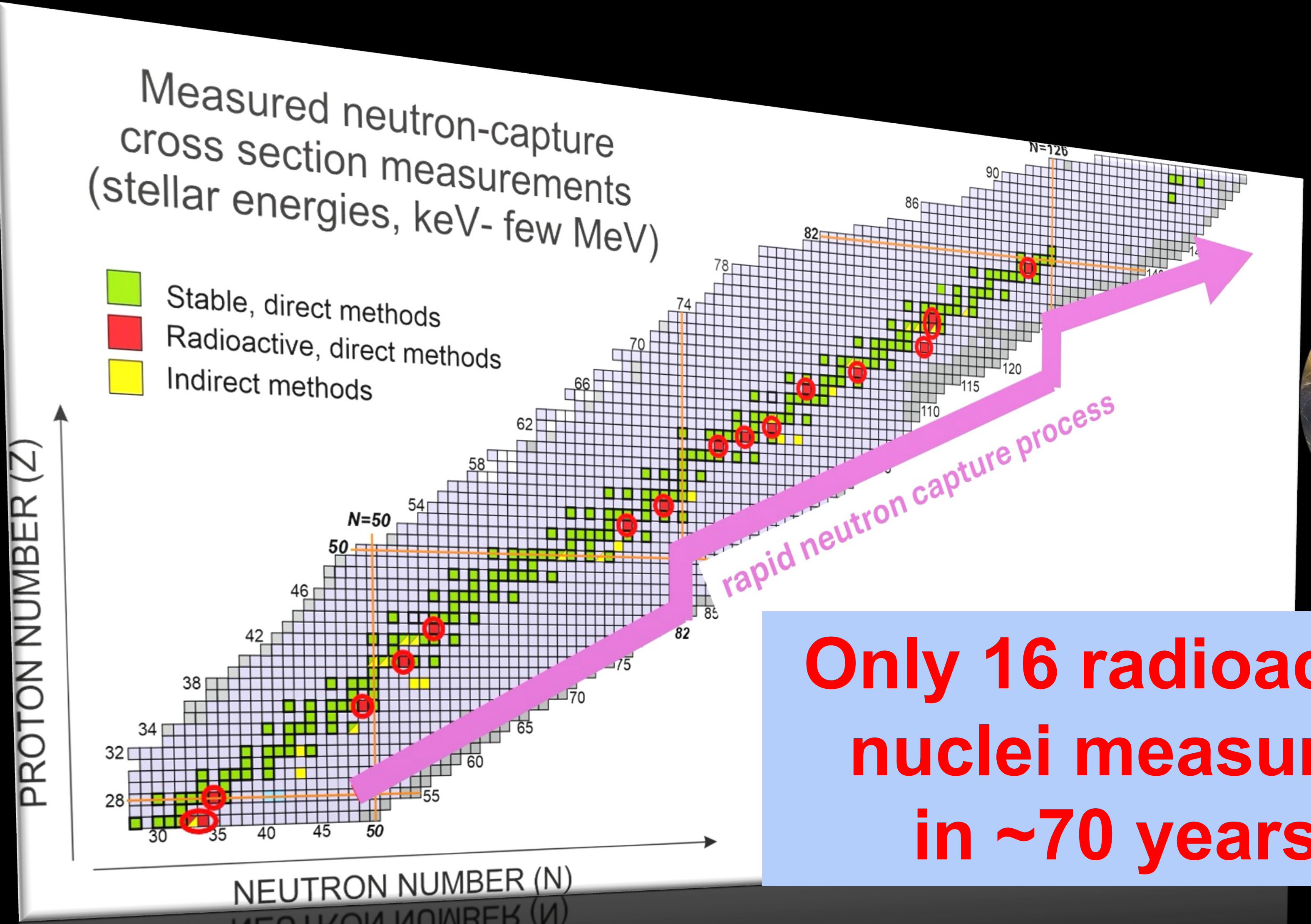
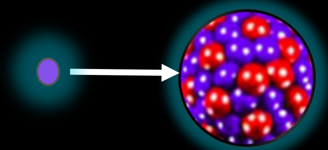
Status Quo



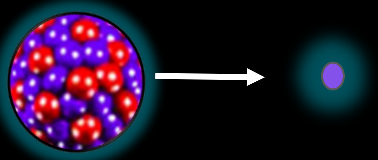
Only 16 radioactive nuclei measured in ~70 years!



Nuclear data are key to understand the production in stellar events

We are lacking data for neutron capture reactions on radioactive nuclei!

Turning “Impossible” into “Possible”?



Unlock access to neutron reaction rates of short-lived nuclei with pivotal interest in astrophysics

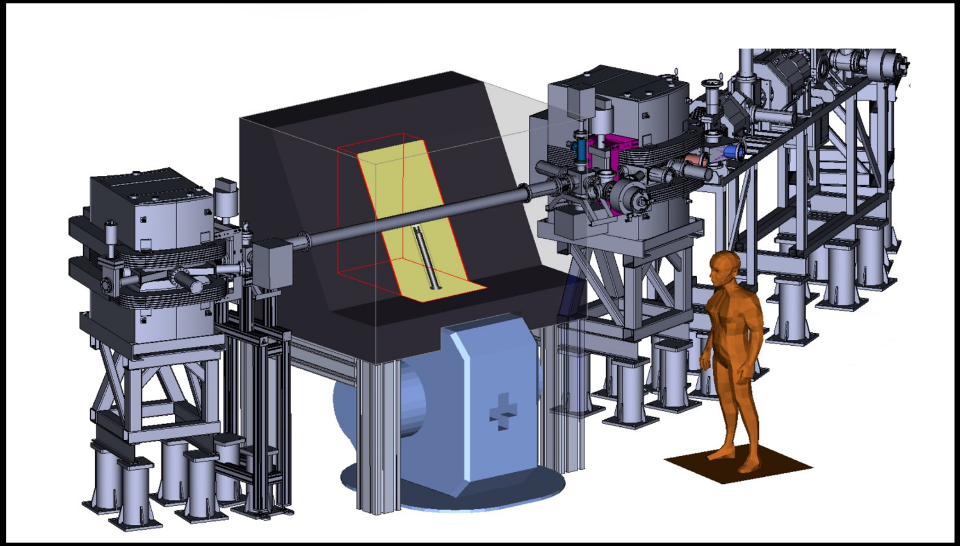
→ Only marginal gains are possible with conventional methods!

→ Theoretical models may deviate by orders of magnitude

→ Previous proposals require huge investments without guaranteed success

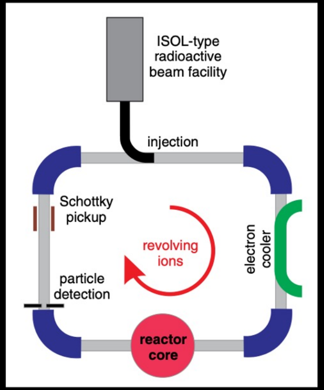
→ **High-current super-compact cyclotrons, scalable and cost-effective**

Tarifeño et al. arXiv:2508.15465v1

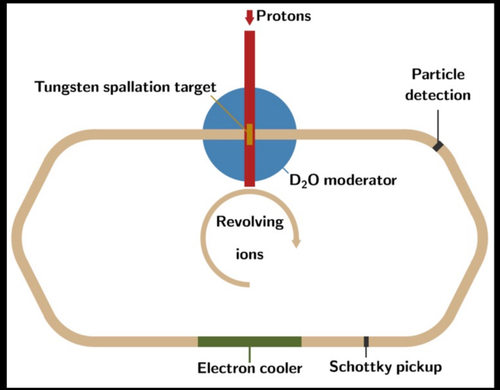


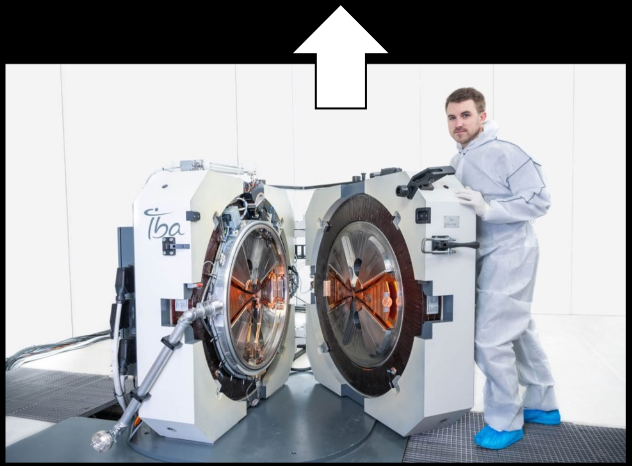
The NSTAR team, Phys. Rev. Acc. Beams (2025) (submitted)

Nuclear reactor



Spallation n-source

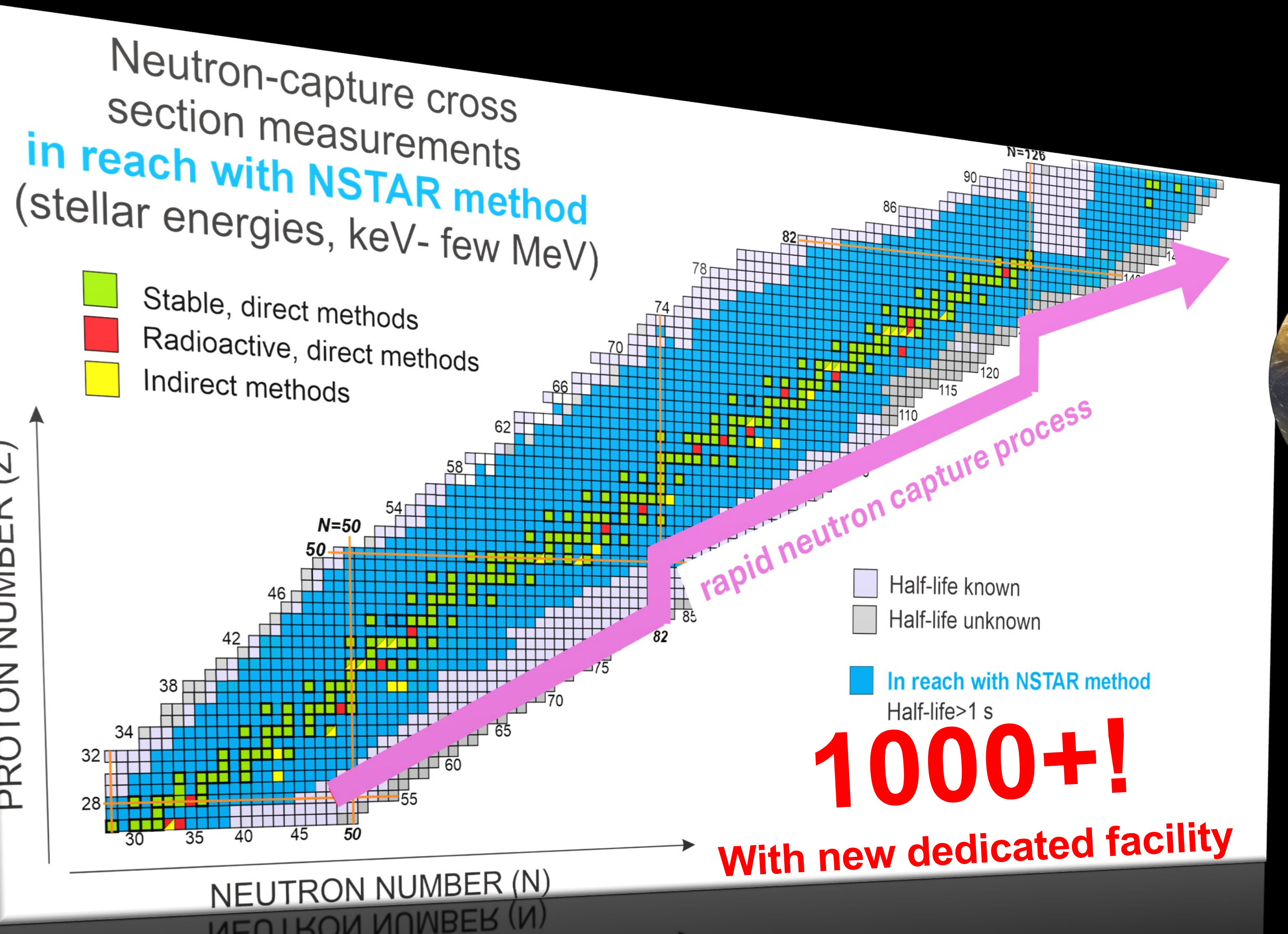




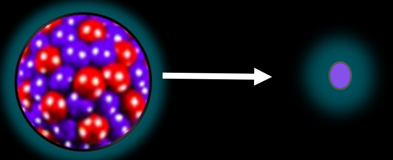
(Image source: IBA Ion Beam Applications)

R.Reifarth & **Y. Litvinov,** Phys. Rev. ST Acc. Beams, 20 (2017) 044701
R.Reifarth et al., Phys. Rev. Acc. Beams, 17 (2014) 014701

The potential



NSTAR concept!



From 16 → 1000+ neutron capture reactions on radioactive nuclei!

Why storage rings? - Versatile Capabilities

Masses and lifetimes of exotic nuclei

ERC CG ASTRUm

Nuclear Excitation by (target) Electron Capture

Nuclear Excitation by (free) Electron Capture

Hyperfine Quenching in few-electron ^{229}Th

ERC AG HIThor

Decays of highly charged ions (^{205}Tl, ^{111}Sn)

Transfer reactions

Long-lived isomeric states

Di-electronic recombination on exotic nuclei

Astrophysical reactions for BBN and
Novae, rp-, nup-, and p-processes

ERC SG ELDAR

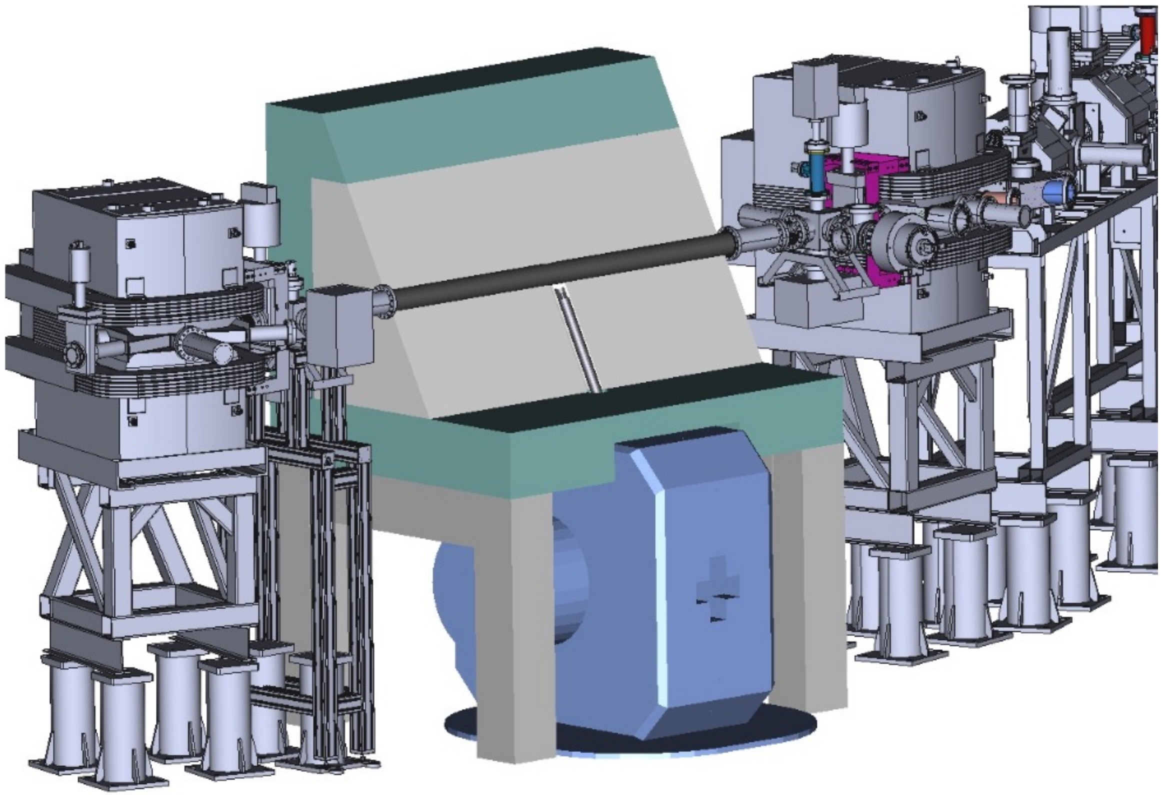
Surrogate reaction studies

ERC AG NECTAR

Giant resonances

Electron-Ion scattering (future)

Neutron-induced reactions (future)



Courtesy: Ariel Tarifeno Saldivia

Free-neutron target at CRYRING
C. Domingo-Pardo et al. NSTARS-Project

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

TRIUMF

Many thanks to our collaborators from all over the world !!!

NucAR

sparc
Stored Particles Atomic Physics Research Collaboration

NUSTAR

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