Exploring Nuclear Astrophysics with Heavy-Ion Storage Rings

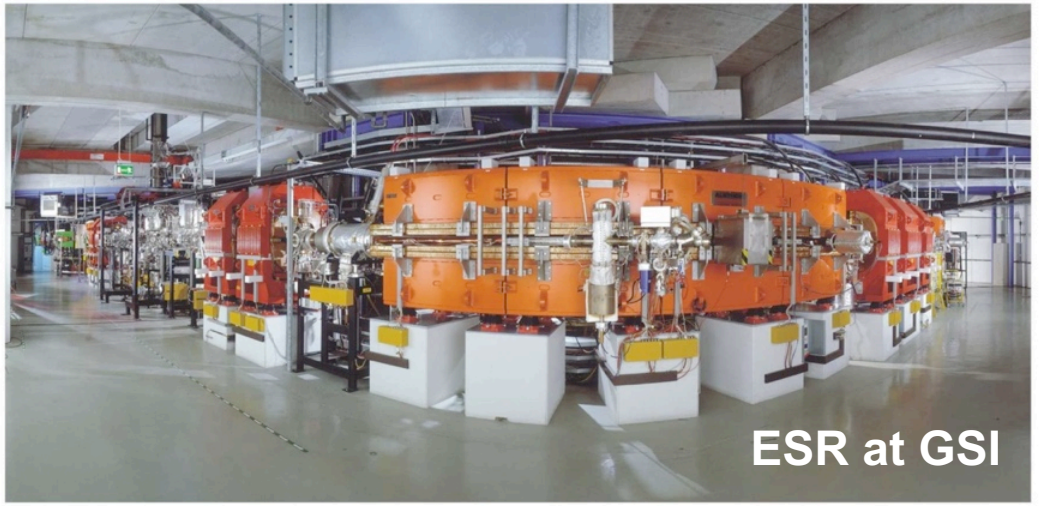
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Yuri A. Litvinov

GSI

African Nuclear Physics Conference
Kruger National Park, South Africa, 1-5 July 2019

Physics at Storage Rings



Storage rings stay for:

Single-particle sensitivity

Broad-band measurements

High atomic charge states

High resolving power

Physics with Storage Rings

Nuclear Physics

Nuclear structure through transfer reactions

Long-lived isomeric states

Atomic effects on nuclear half-lives

Half-life measurements of ^{7}Be

Nuclear effects on atomic decay rates

Exotic decay modes (NEEC/NEET, unbound states, …)

Di-electronic recombination on exotic nuclei

Purification of secondary beams from contaminants

Nuclear magnetic moments

Neutron–induced reactions

Capture reactions for p-process

….

Atomic Physics

Precision x-ray spectroscopy

Super-Critical fields

Electron-Ion collisions

Atomic lifetimes

Nuclear effects on atomic decay rates

Photoionization

Di-electronic recombination on exotic nuclei

Electron spectroscopy / electron scattering

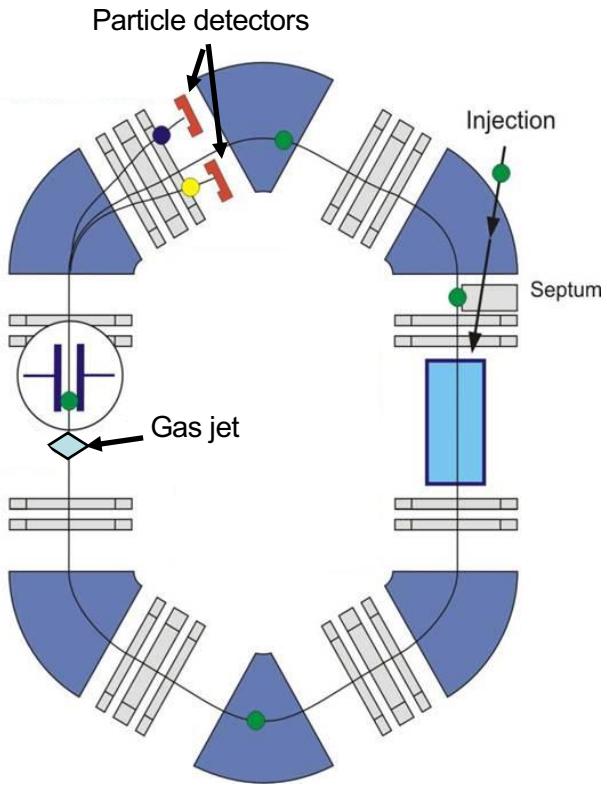
Atom/Molecule fragmentation

Ion-molecule interactions

Laser induced recombination

.....

Nuclear reaction studies in a storage ring



ESR

High revolution frequency

→ **high luminosity even with thin targets**

Detection of ions via in-ring particle detectors

→ **low background, high efficiency**

Well-known charge-exchange rates

→ **in-situ luminosity monitor**

Ultra-thin windowless gas targets

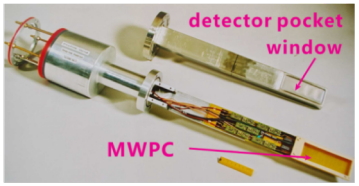
→ **excellent resolution**

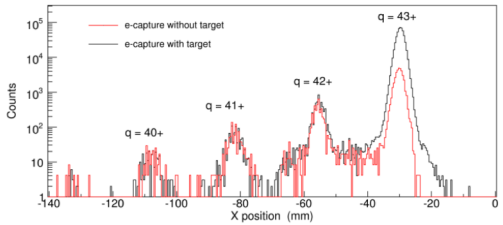
Applicable to radioactive nuclei

Normalization of Nuclear Cross Sections

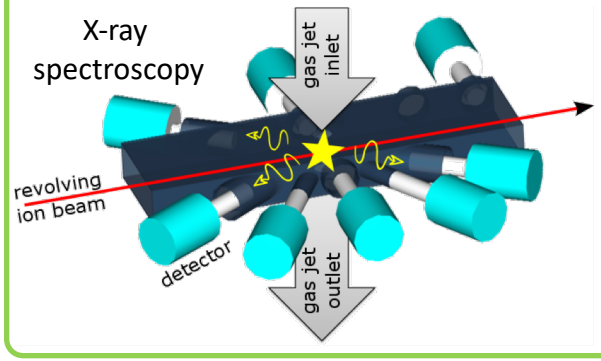
total e⁻ capture rate [NRC + REC]

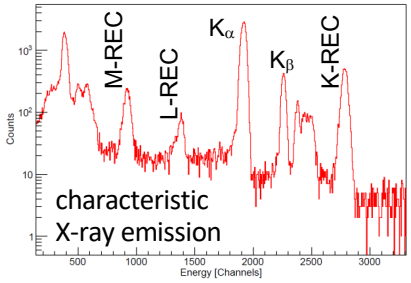
measured by particle detection

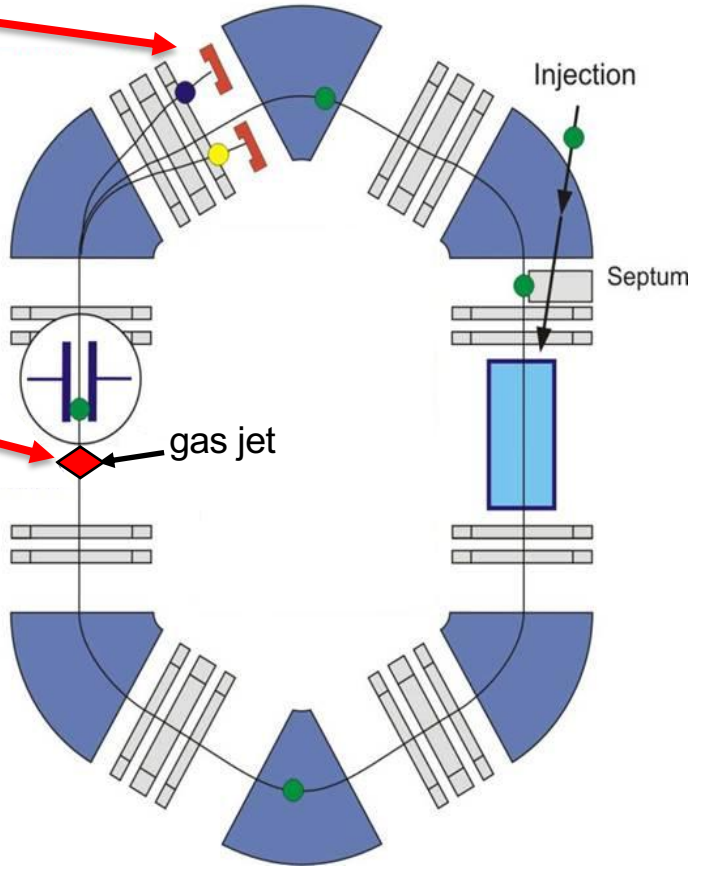




radiative e⁻ capture rate [REC]





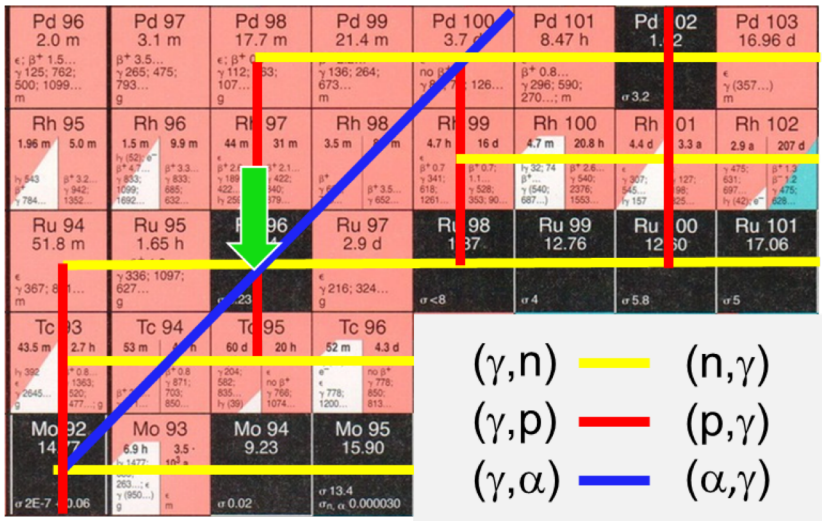


Courtesy Jan Glorius

The Proof-Of-Concept $^{96}Ru(p,\gamma)^{97}Rh$ (2008)

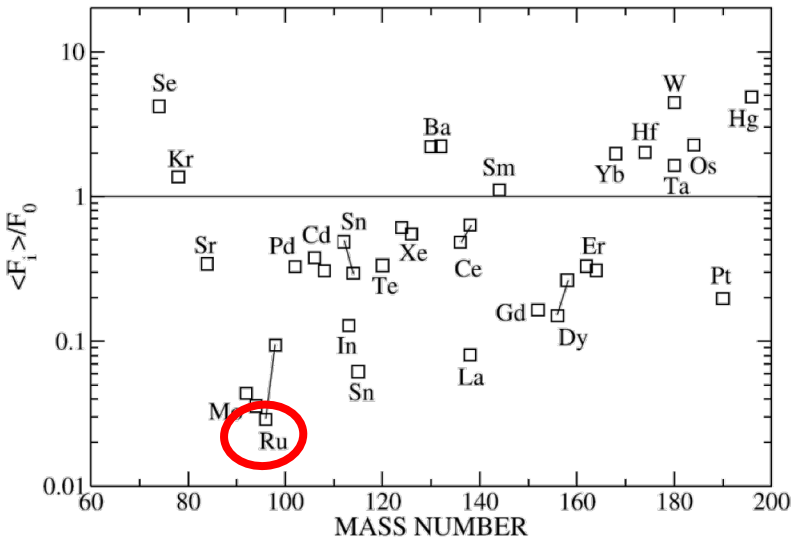
- ^{96}Ru is a *p* nucleus
- it is largely underproduced by models
- proton-capture is important to understand production/destruction in star

➢ perfect stable beam for a proof-of-concept experiment



Simplified γ process network around ^{96}Ru

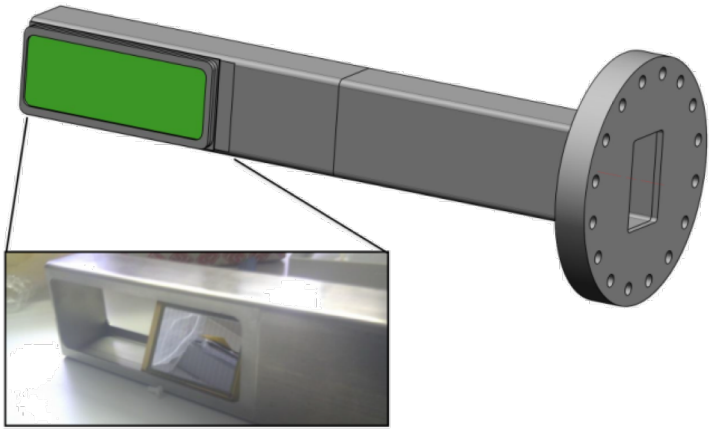
p nuclei production yield from simulation

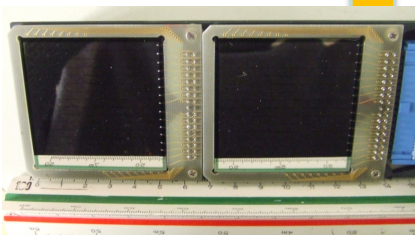


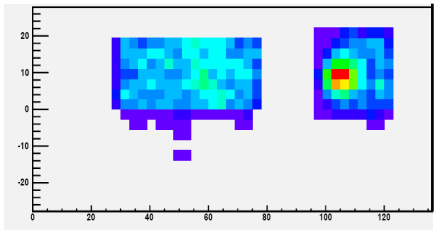
Rapp et al. ApJ 653 (2006) 474

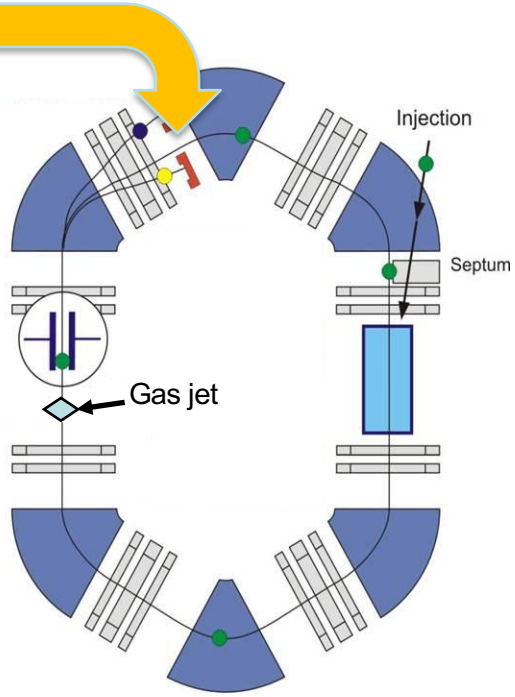
^{96}Ru(p,g)^{97}Rh Experiment at the ESR

double sided silicon strip detectors
(16 x 16 strips)
(energy and position resolution)
inside vacuum pocket







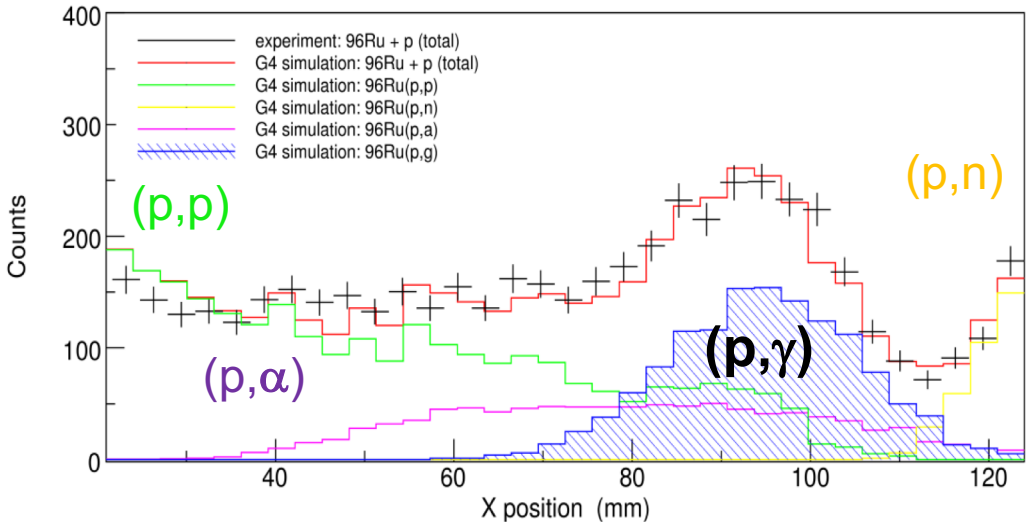


ESR

B. Mei et al, PRC 92 (2015) 35803

The Proof-Of-Concept ^{96}Ru(p,γ)^{97}Rh (2008)

silicon detector data



- (p,γ) superimposed by other channels
- Geant4 simulation of each channel
  - ➢ disentangle different contributions
- clean extraction of (p,γ) signal

PHYSICAL REVIEW C **92**, 035803 (2015)

First measurement of the ^{96}Ru$(p,\gamma)^{97}$Rh cross section for the p process with a storage ring

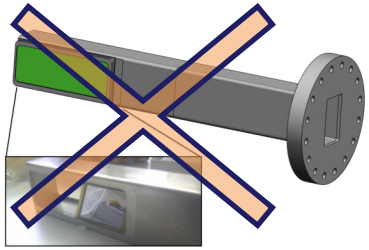
Bo Mei,[1,2] Thomas Aumann,[3] Shawn Bishop,[4] Klaus Blaum,[5] Konstanze Boretzky,[1] Fritz Bosch,[1] Carsten Brandau,[1] Harald Bräuning,[1] Thomas Davinson,[6] Iris Dillmann,[1] Christina Dimopoulou,[1] Olga Ershova,[2] Zsolt Fülöp,[7] Hans Geissel,[1] Jan Glorius,[2] György Gyürky,[7] Michael Heil,[1] Franz Käppeler,[8] Aleksandra Kelic-Heil,[1] Christophor Kozhuharov,[1] Christoph Langer,[9] Tudi Le Bleis,[4] Yuri Litvinov,[1] Gavin Lotay,[6] Justyna Marganiec,[1] Gottfried Münzenberg,[1] Fritz Nolden,[1] Nikolaos Petridis,[1] Ralf Plag,[1,2] Ulrich Popp,[1] Ganna Rastrepina,[2] René Reifarth,[2,*] Björn Riese,[1] Catherine Rigollet,[10] Christoph Scheidenberger,[1] Haik Simon,[1] Kerstin Sonnabend,[2] Markus Steck,[1] Thomas Stöhlker,[1,11] Tamás Szücs,[7] Klaus Sümmerer,[1] Günter Weber,[1,11] Helmut Weick,[1] Danyal Winters,[1] Natalya Winters,[1] Philip Woods,[6] and Qiping Zhong[1]

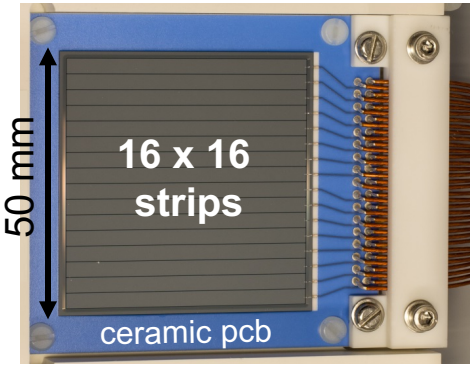
Courtesy Jan Glorius

New in-vacuum particle detectors

How to reach the down into the Gamow window?

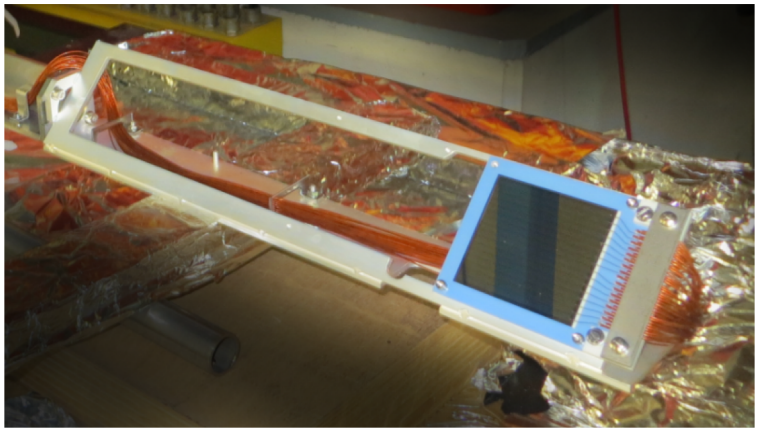
getting rid of detector pockets





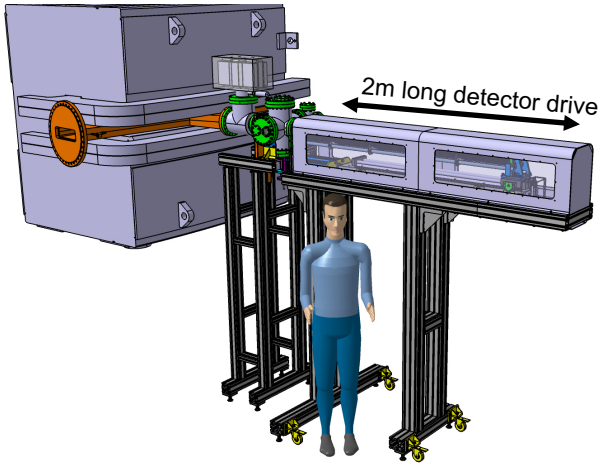
- **Double Sided Silicon Strip Detector (DSSSD)**
  - ✓ **x & y segmentation**
  - ✓ **500 μm thickness (ions are stopped)**
  - ✓ **ultra thin dead layer of 0.3 μm**

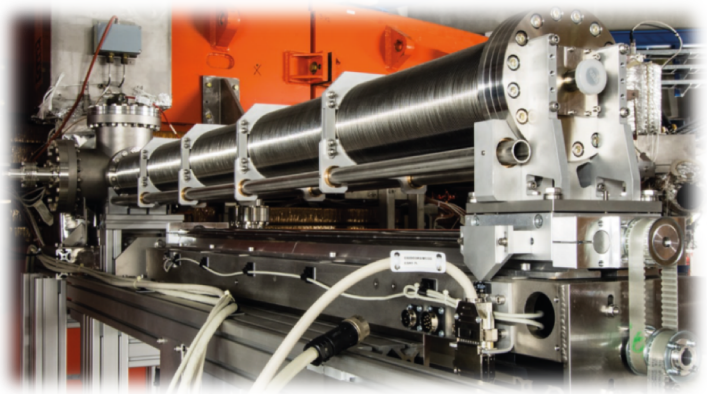
- **compatible to UHV conditions**
  - ✓ **low outgassing rate**
  - ✓ **bakeable at T > 125°C**

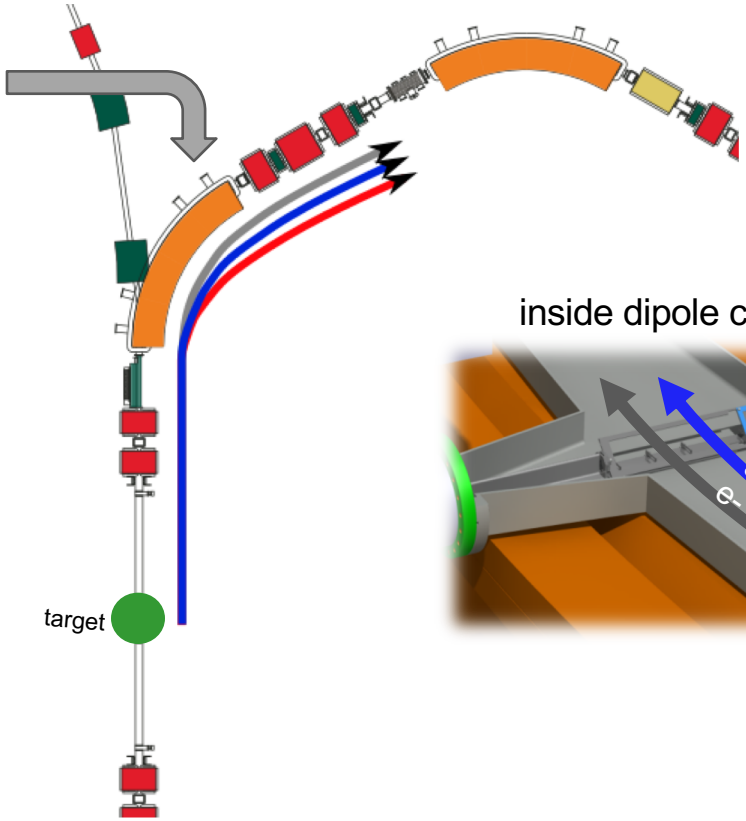


Courtesy Jan Glorius

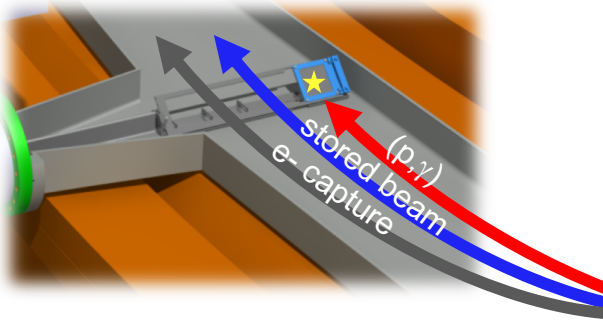
The new setup @ ESR







inside dipole chamber



Courtesy Jan Glorius

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Federal Ministry of Education and Research
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
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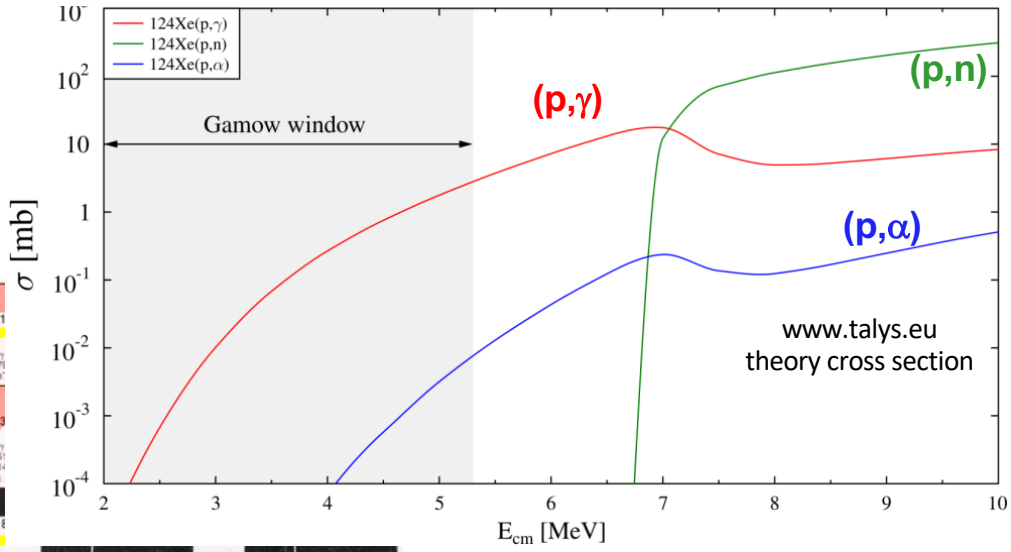
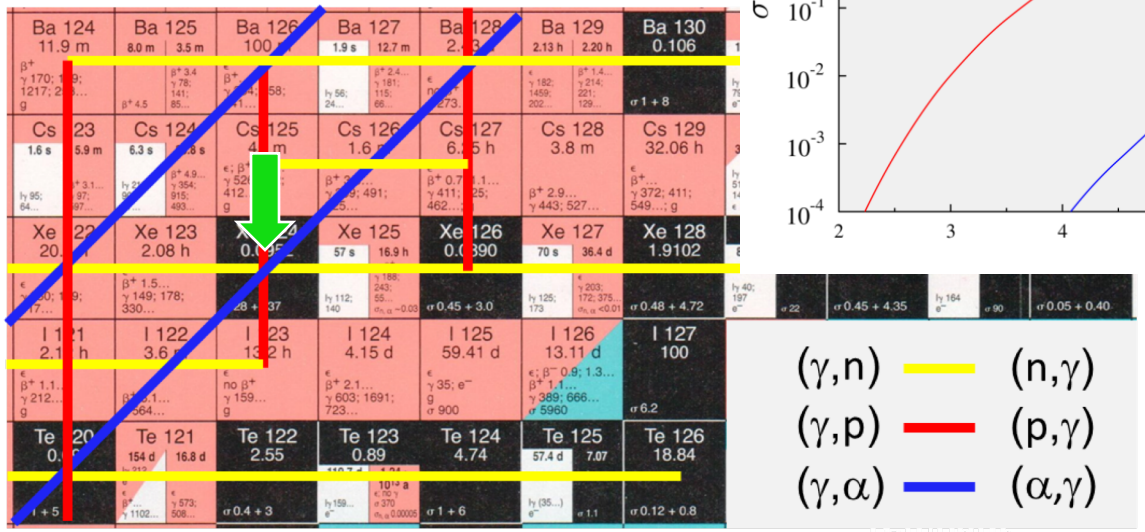
ESR Test Beam Time 2016 $^{124}Xe(p,\gamma)^{125}Cs$

- **test experiment for new setup:**
  - **^{124}Xe: technically simple, stable beam, high intensity**
  - **10-100 mbarn cross section expected for proton capture @ 7 MeV/u**

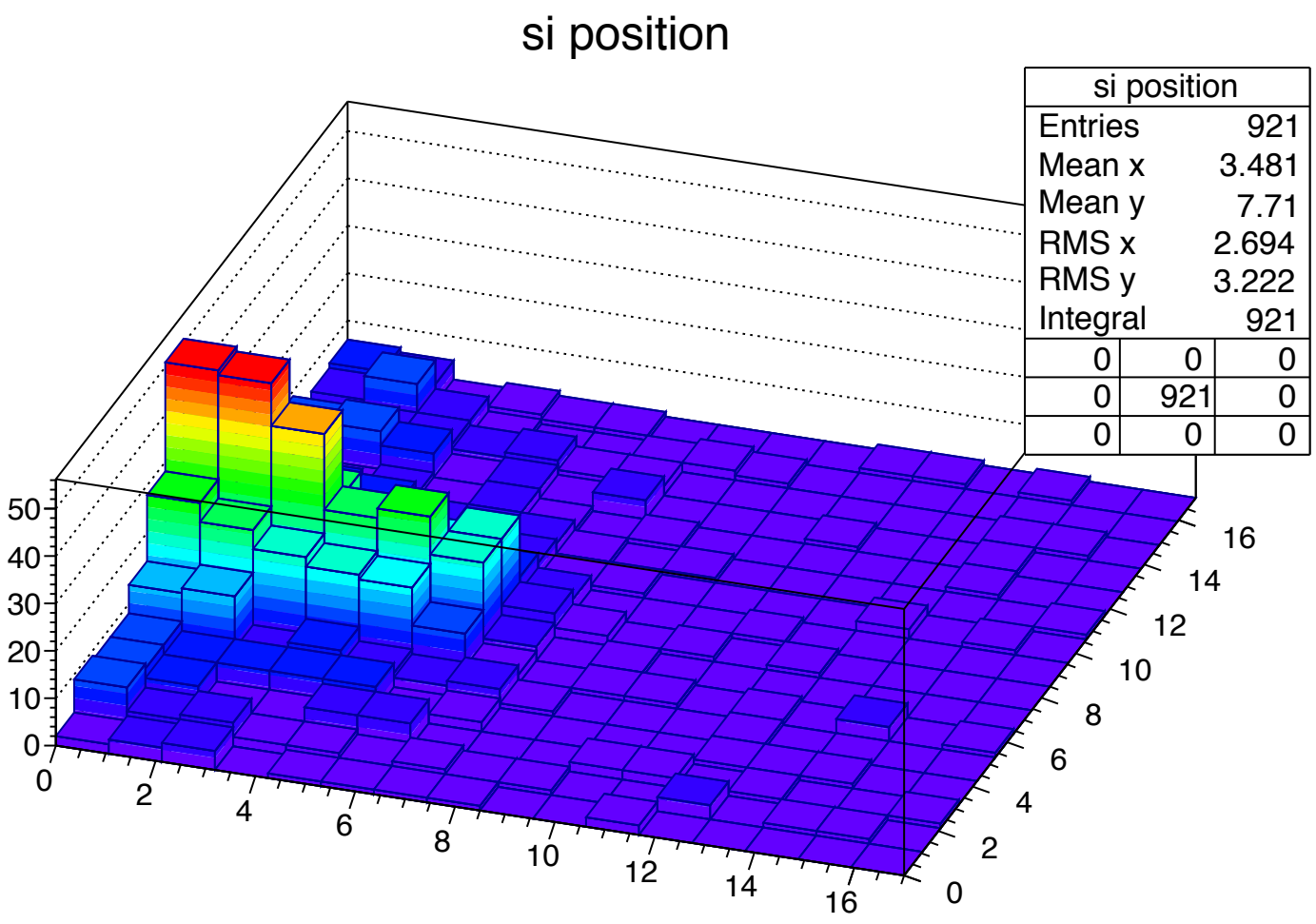
- **science case ^{124}Xe:**
  - ✓ ***p* nucleus**
  - ✓ **reaction is important in production/destruction**



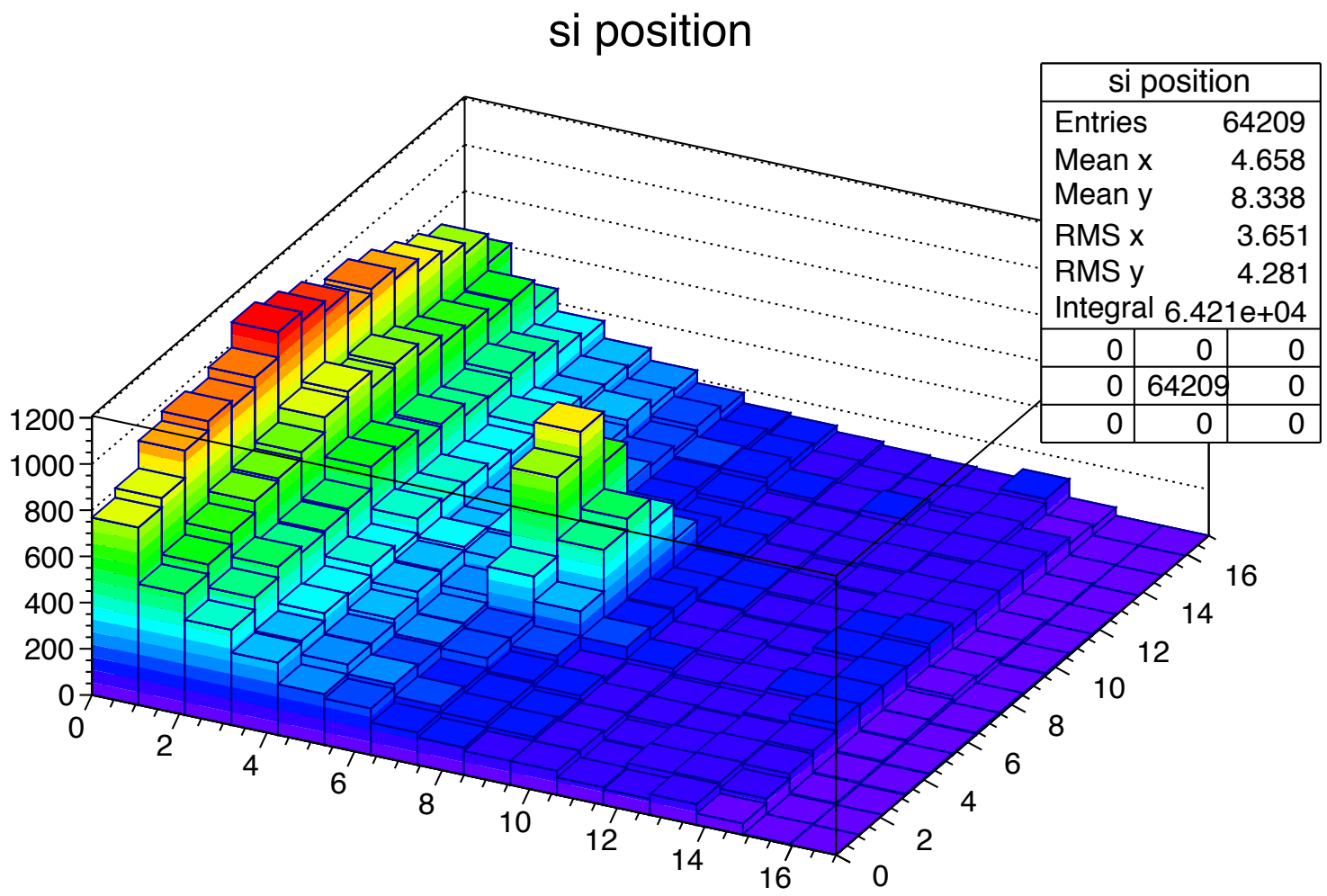


Courtesy Jan Glorius

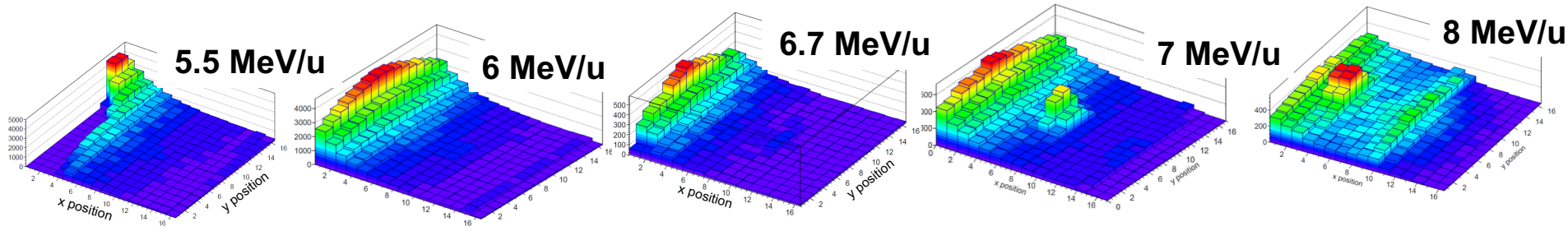
^{124}Xe(p,g)^{125}Cs Experiment at the ESR

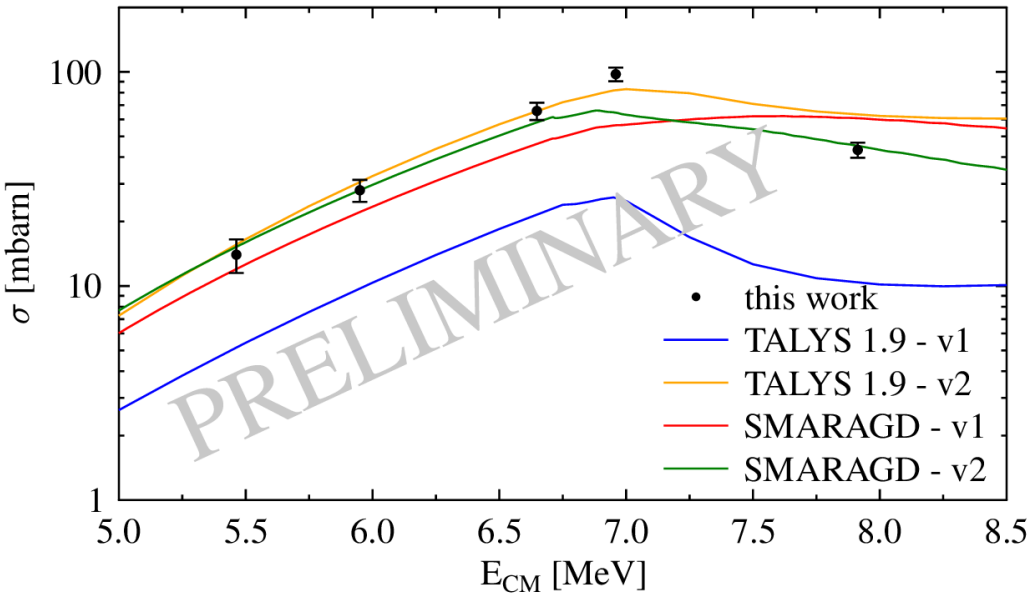


^{124}Xe(p,g)^{125}Cs Experiment at the ESR



^{124}Xe(p,γ) - Results





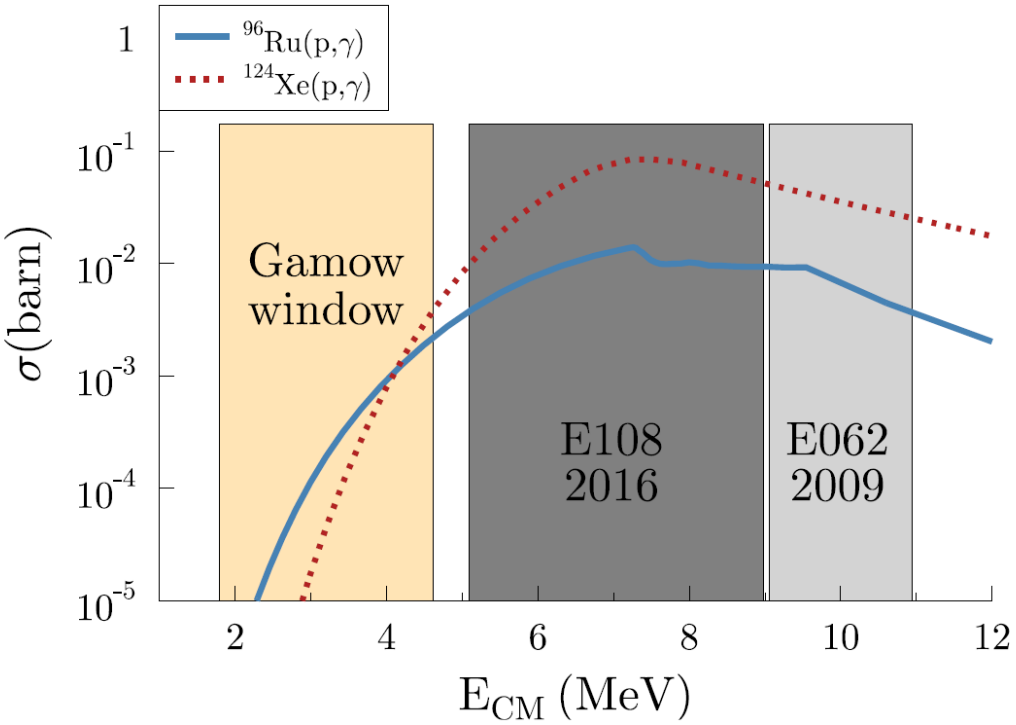
PHYSICAL REVIEW LETTERS **122,** 092701 (2019)

Approaching the Gamow Window with Stored Ions: Direct Measurement of ^{124}Xe(p,γ) in the ESR Storage Ri

J. Glorius,[1,*] C. Langer,[2] Z. Slavkovská,[2] L. Bott,[2] C. Brandau,[1,3] B. Brückner,[2] K. Blaum,[4] T. Davinson,[7] P. Erbacher,[2] S. Fiebiger,[2] T. Gaßner,[1] K. Göbel,[2] M. Groothuis,[2] A. Gumberidz R. Hess,[1] R. Hensch,[2] P. Hillmann,[2] P.-M. Hillenbrand,[1] O. Hinrichs,[2] B. Jurado,[9] T. Kaus T. Kisselbach,[2] N. Klapper,[2] C. Kozhuharov,[1] D. Kurtulgil,[2] G. Lane,[10] C. Lederer-Woods,[7] M 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 D. Savran,[1] H. Simon,[1] U. Spillmann,[1] M. Steck,[1] T. Stöhlker,[1,14] J. Stumm,[2] A. Surzhykov,[15,16] A. Taremi Zadeh,[2] B. Thomas,[2] S. Yu. Torilov,[17] H. Törnqvist,[1,11] M. Träger,[1] C. Trageser,[1,3] M. Volknandt,[2] H. Weick,[1] M. Weigand,[2] C. Wolf,[2] P. J. Woods,[7] and Y. M.

Courtesy Jan Glorius

Future measurements

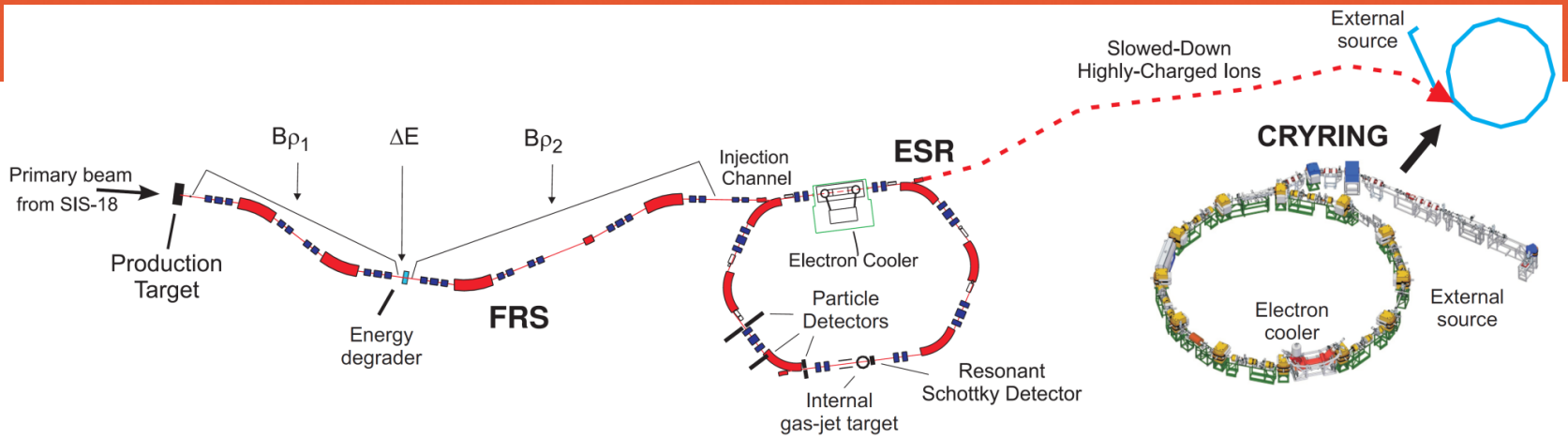


E127 R. Reifarth et al.

NucAR

*Regarding the proposal "Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process" (Proposal E127), the G-PAC recommends this proposal with **highest priority (A)** and that **15 shifts of main beam time** be allocated for this measurement.*

The CRYRING facility



- **CRYRING is a dedicated low-energy storage ring**
  - **all GSI beams available between ~100 keV/u and ~15 MeV/u**
  - **longer beam lifetimes for highly charged ions at low energies**

- **first commissioning phase is finished**

- **CRYRING is the ideal machine for**
- **astrophysical reaction studies**

Courtesy Jan Glorius

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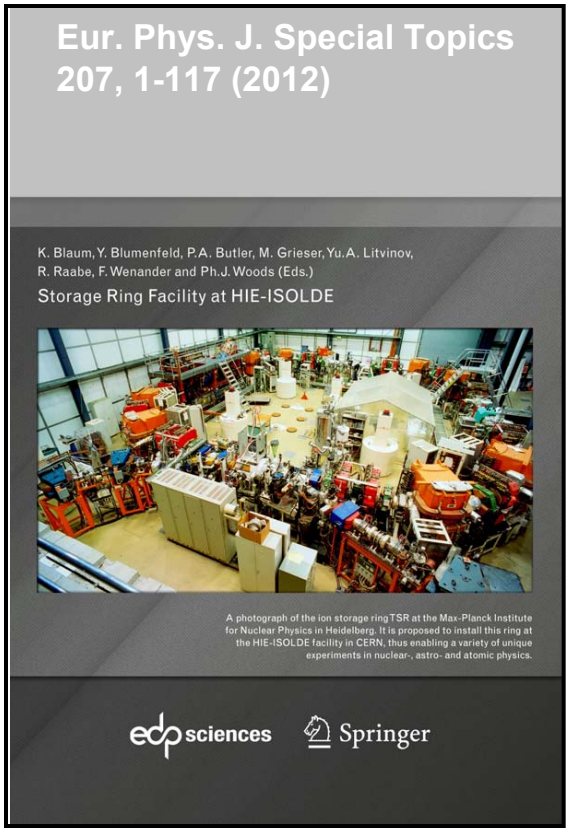
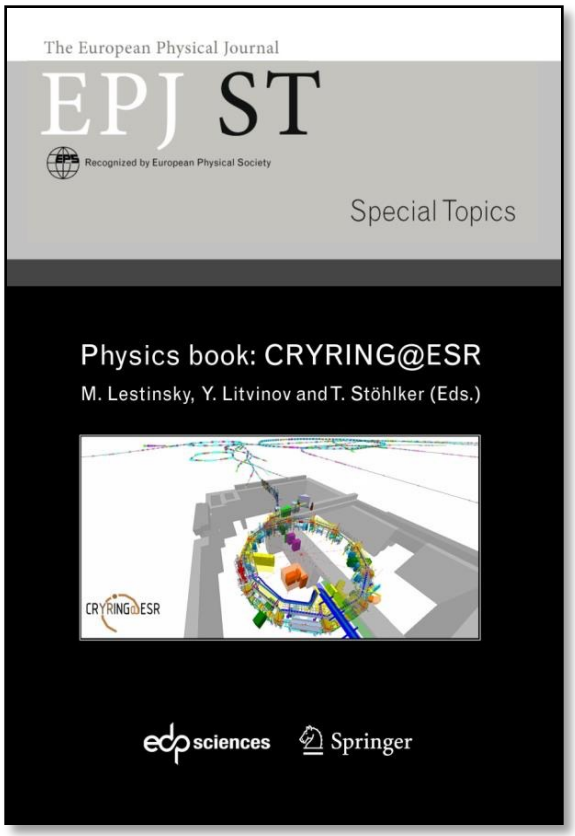
Two basis publications



Techinical Design Report:
TSR@ISOLDE
(2012)



Physics book:
CRYRING@ESR
(2016)

Thank you!

the NucAR collaboration

GSI

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IMP 中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences

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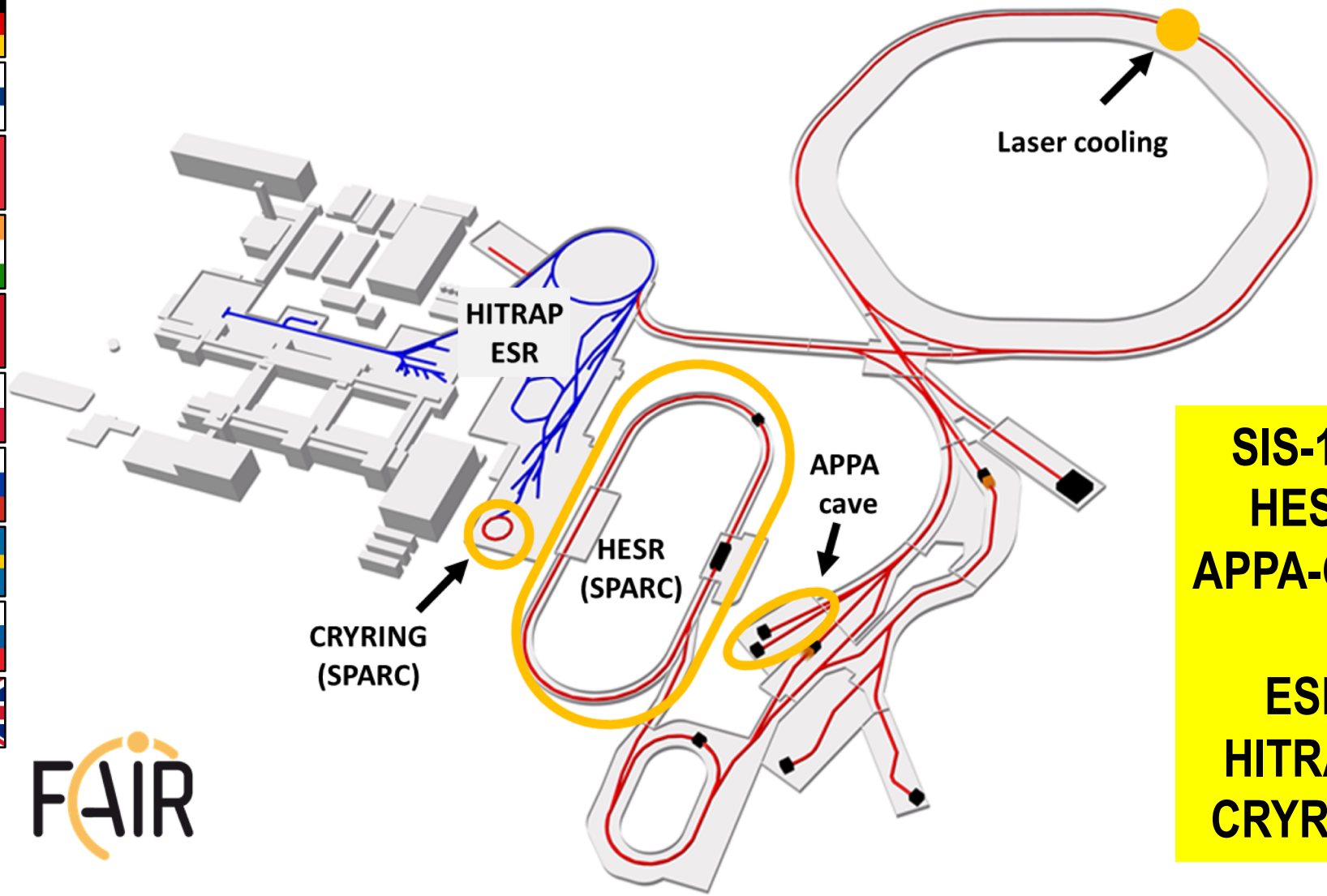
Established by the European Commission

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Bundesministerium für Bildung und Forschung

FAIR: SPARC/APPA Facilities



SIS-100
HESR
APPA-Cave

ESR
HITRAP
CRYRING