New opportunities for in-ring experiments using ISOLDE beams

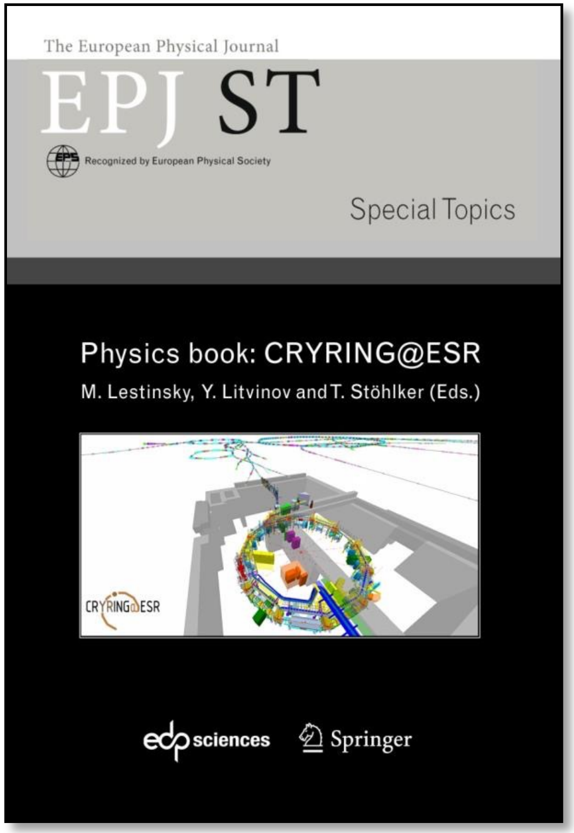
Yuri A. Litvinov

First ISOLDE-EPIC Workshop

3-4 December 2019, CERN, Switzerland

Why storage rings?

- Storage - efficient use of rare species
- Cooling - high quality beams
- Recirculation - high luminocities though thin targets
- Removing of contaminants
- Ultra-high vacuum – preserving atomic charge state
- Laser-ion interaction
- Various gaseous internal targets, electrons, (neutrons)
- High detection efficiencies for recoils



Physics book: CRYRING@ESR (2016)

Physics Case For a Low-Energy Storage Ring

1. Nuclear Physics

- Capture reactions for astrophysical p-process
- Nuclear structure through transfer reactions
- Long-lived isomeric states
- Atomic effects on nuclear half-lives

  Half-life measurements of ^{7}Be in different atomic charge states
- 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
- ….

Physics Case For a Low-Energy Storage Ring

2. 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
- .....

Just a few examples of physics cases

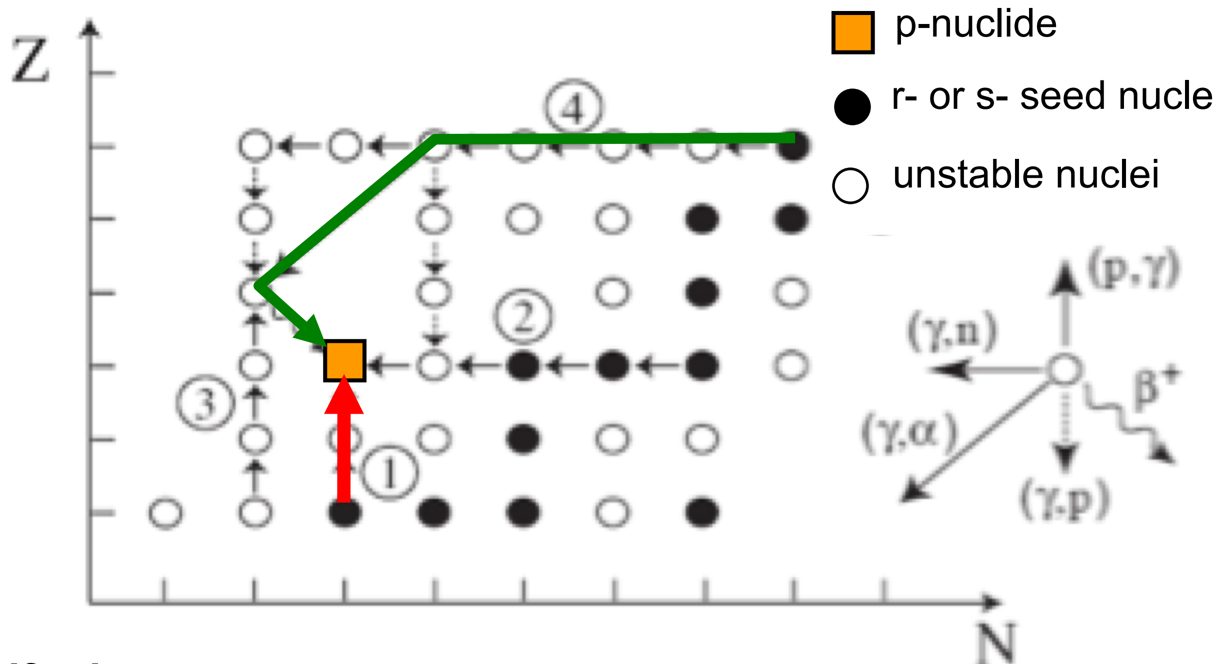
Astrophysics motivation: the p-process

35 stable neutron-deficient isotopes between ^{74}Se and ^{196}Hg

Dominating reactions: (p,γ) for light nuclei;
(γ,n), (γ,p), (γ,α) and β^+ decays for heavier nuclei

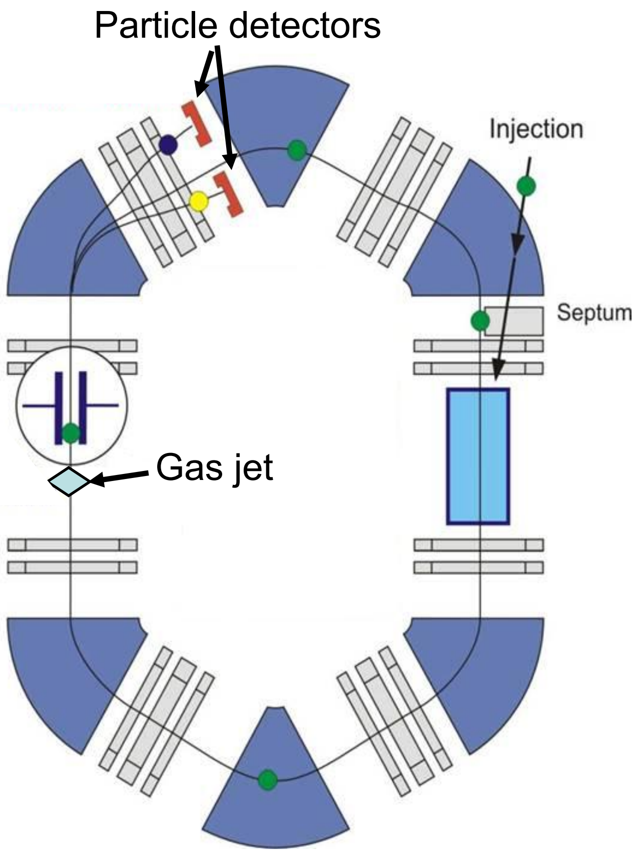
Temperatures of 2-3 × 10^9 K during time scales of a few seconds are required (type II supernovae explosions)

Network calculations
more than 2000 nuclei
(mostly unstable)
more than 20000 reactions



Courtesy Rene Reifarth

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

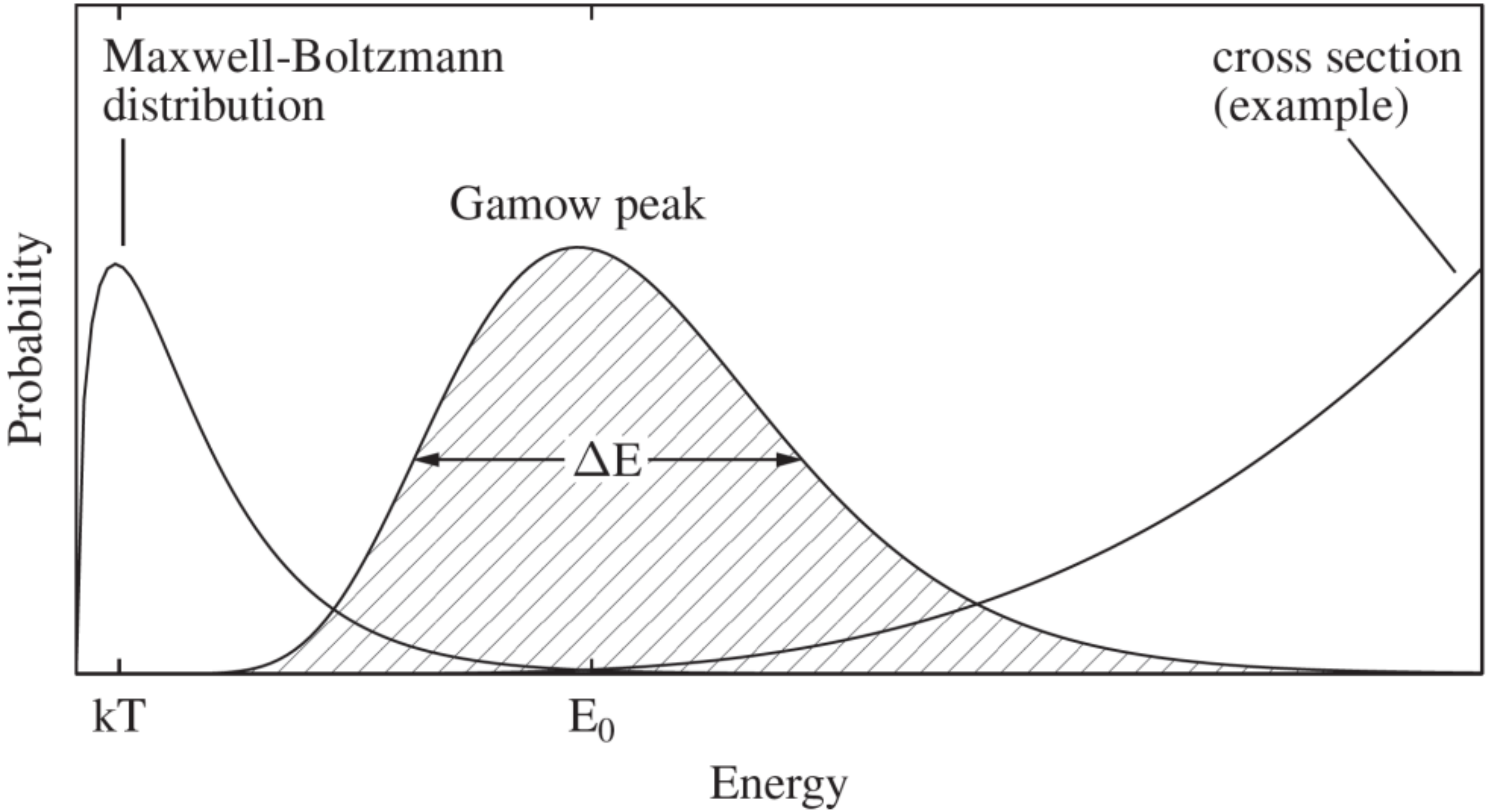
→ in-situ luminosity monitor

Ultra-thin windowless gas targets

→ excellent resolution

Applicable to radioactive nuclei

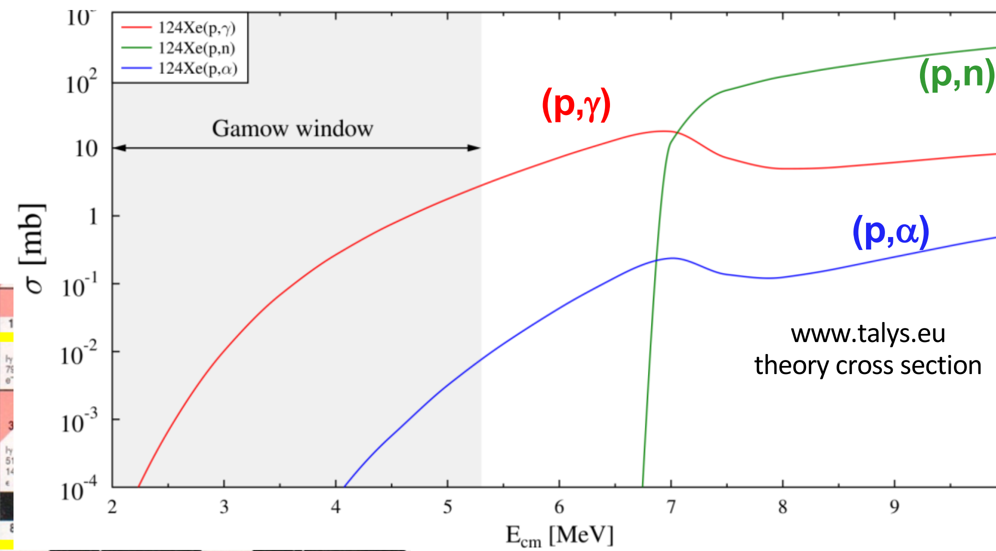
Astrophysical Gamow Window

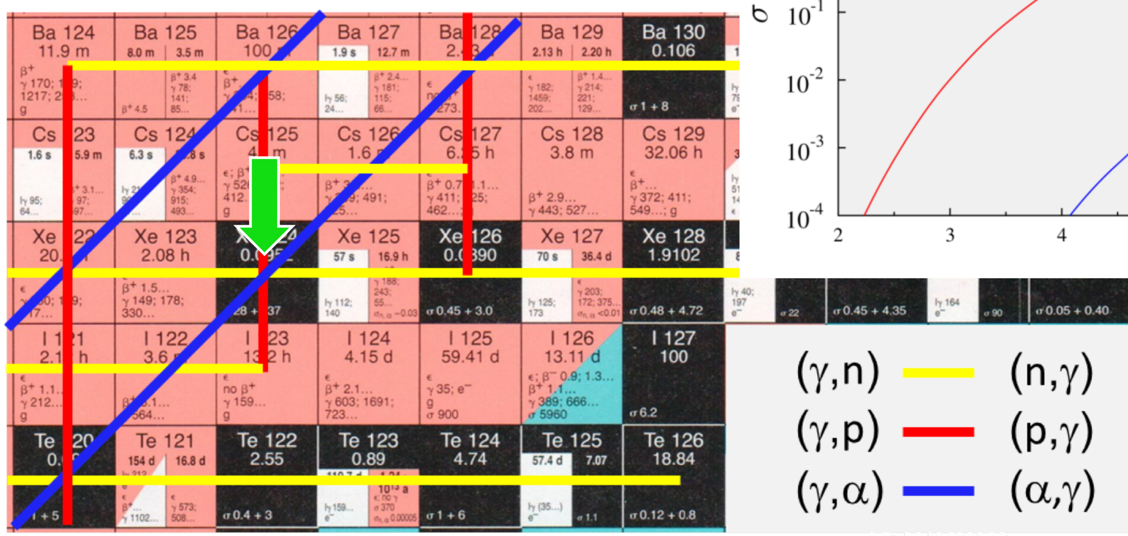


ESR Test Beam Time 2016 ^{124}Xe(p,γ)^{125}Cs

- **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**



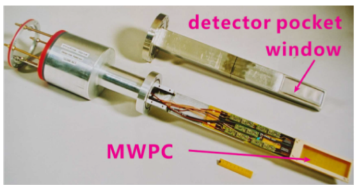


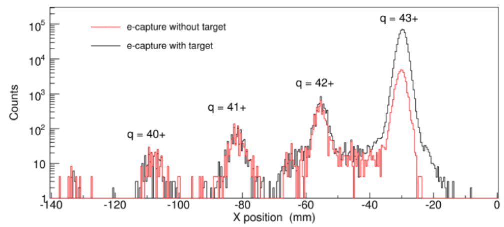
Courtesy Jan Glorius

Normalization of Nuclear Cross Sections

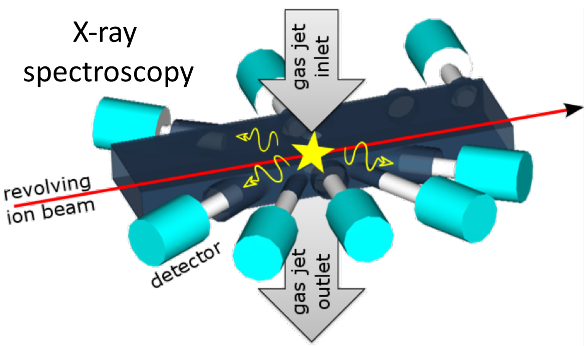
total e^- capture rate [NRC + REC]

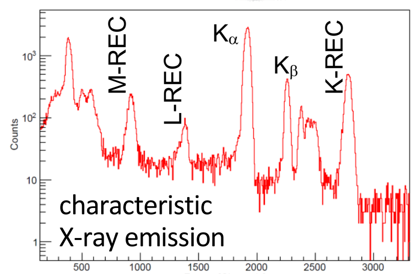
measured by particle detection

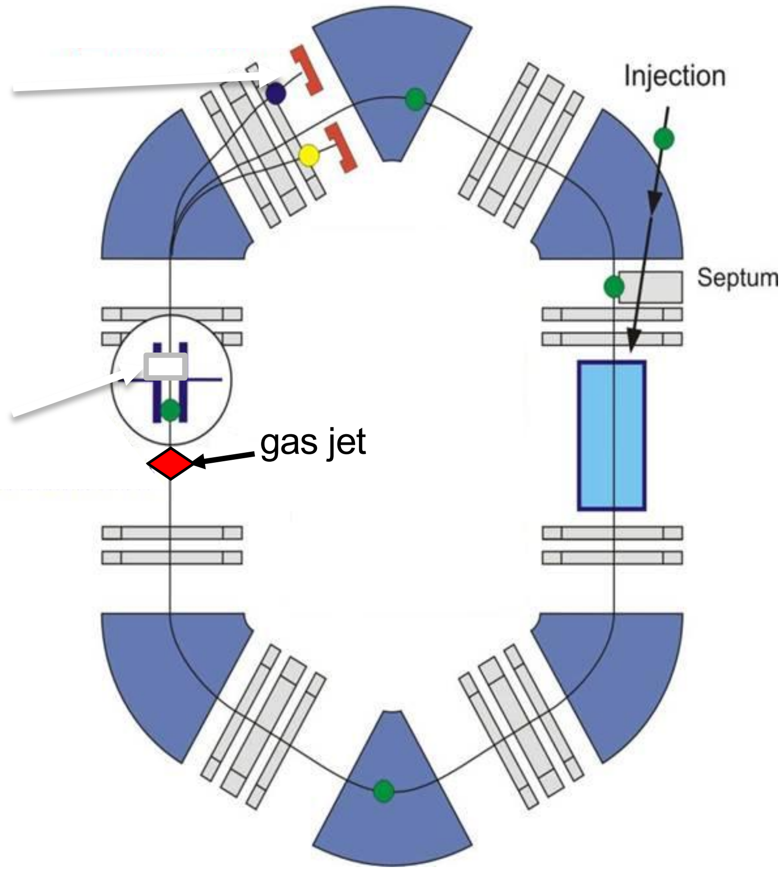




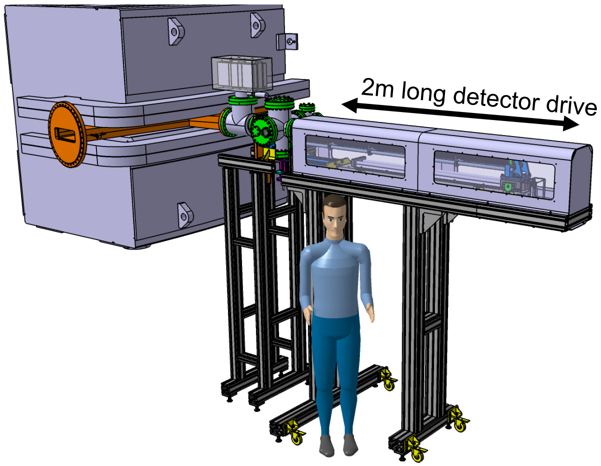
radiative e^- capture rate [REC]

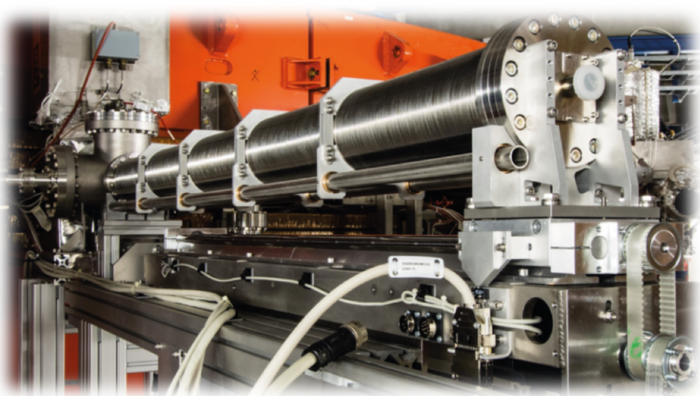


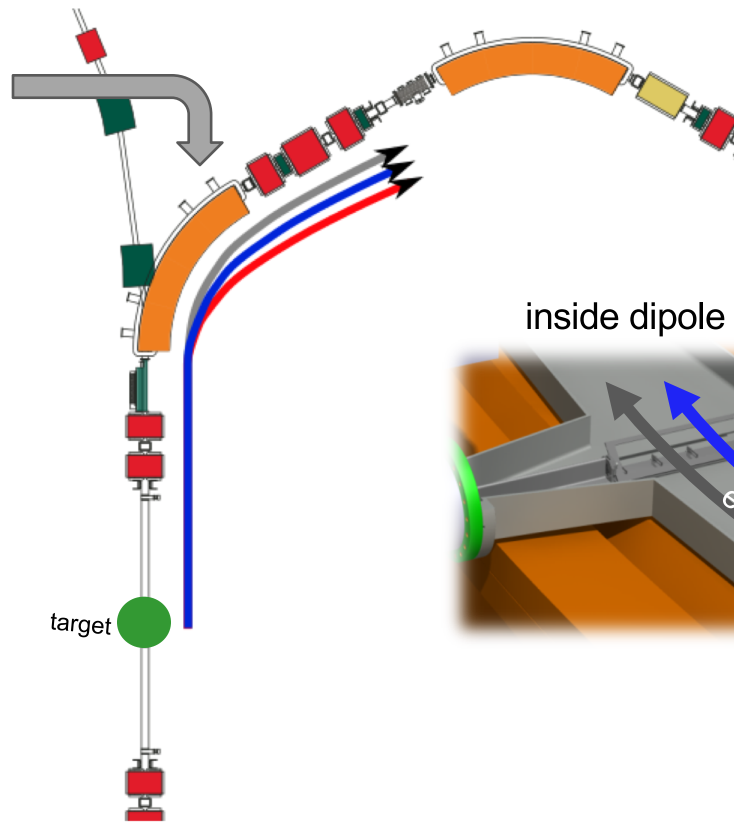




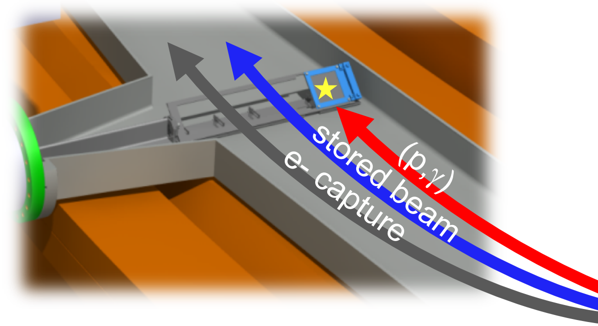
The new setup @ ESR







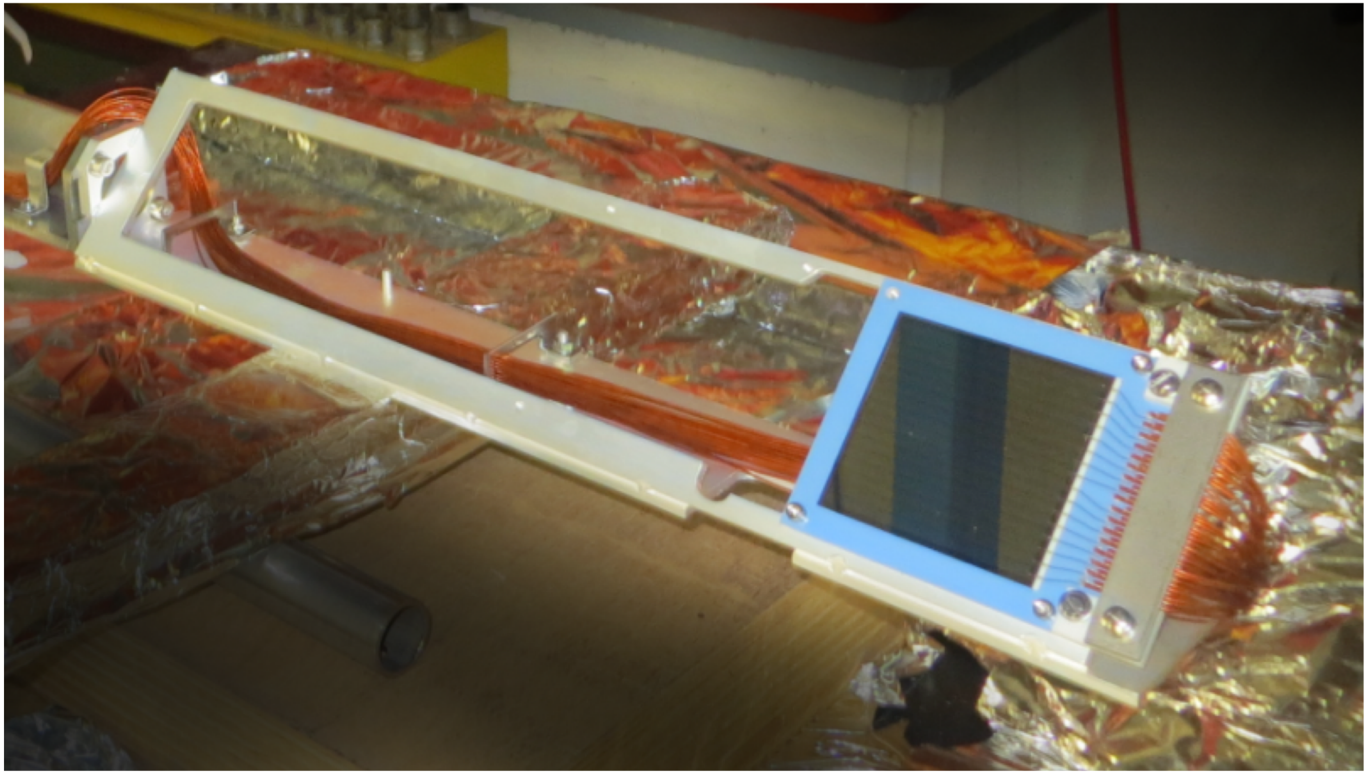
inside dipole chamber



Courtesy Jan Glorius

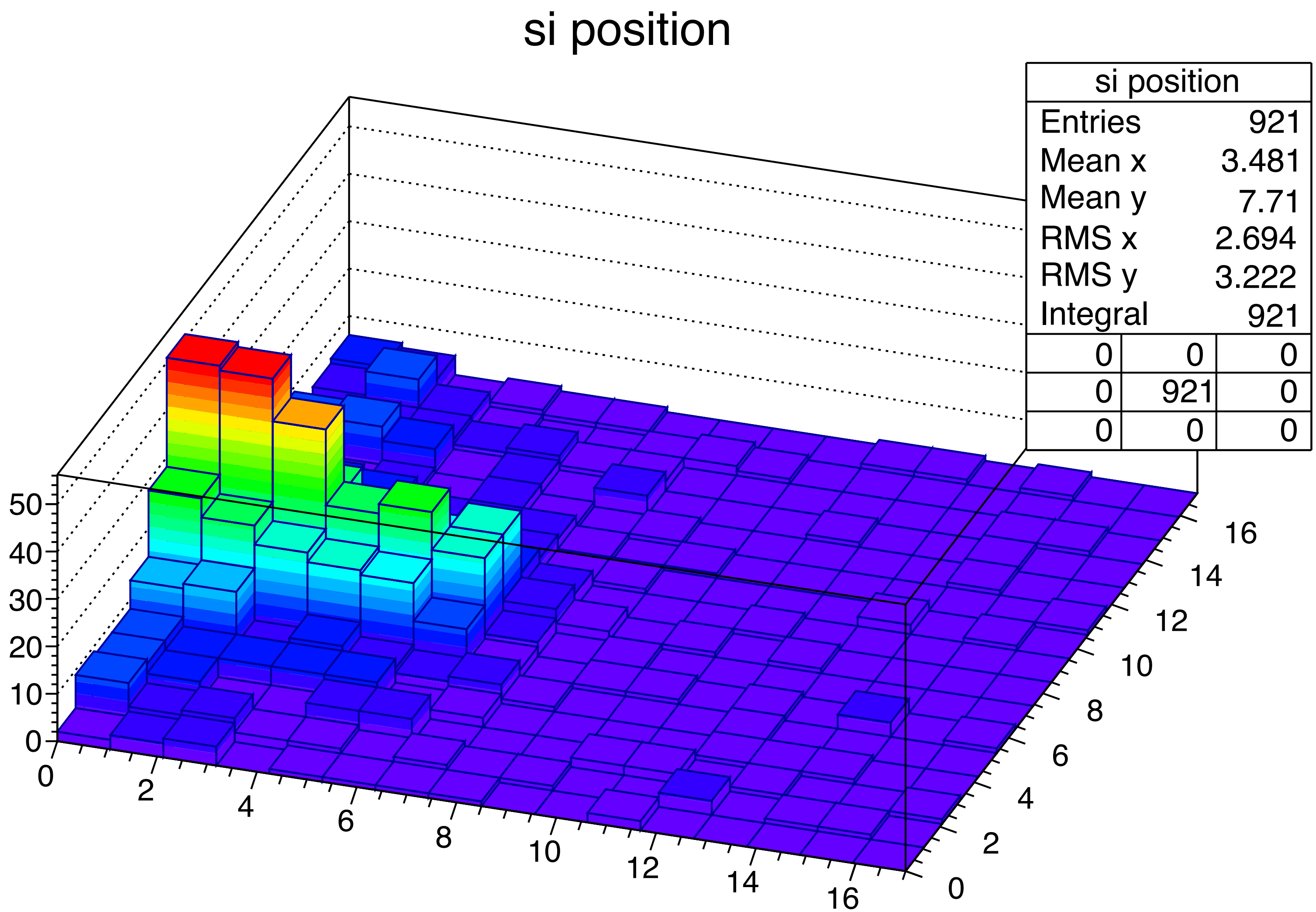
New in-vacuum particle detectors

- Double Sided Si 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

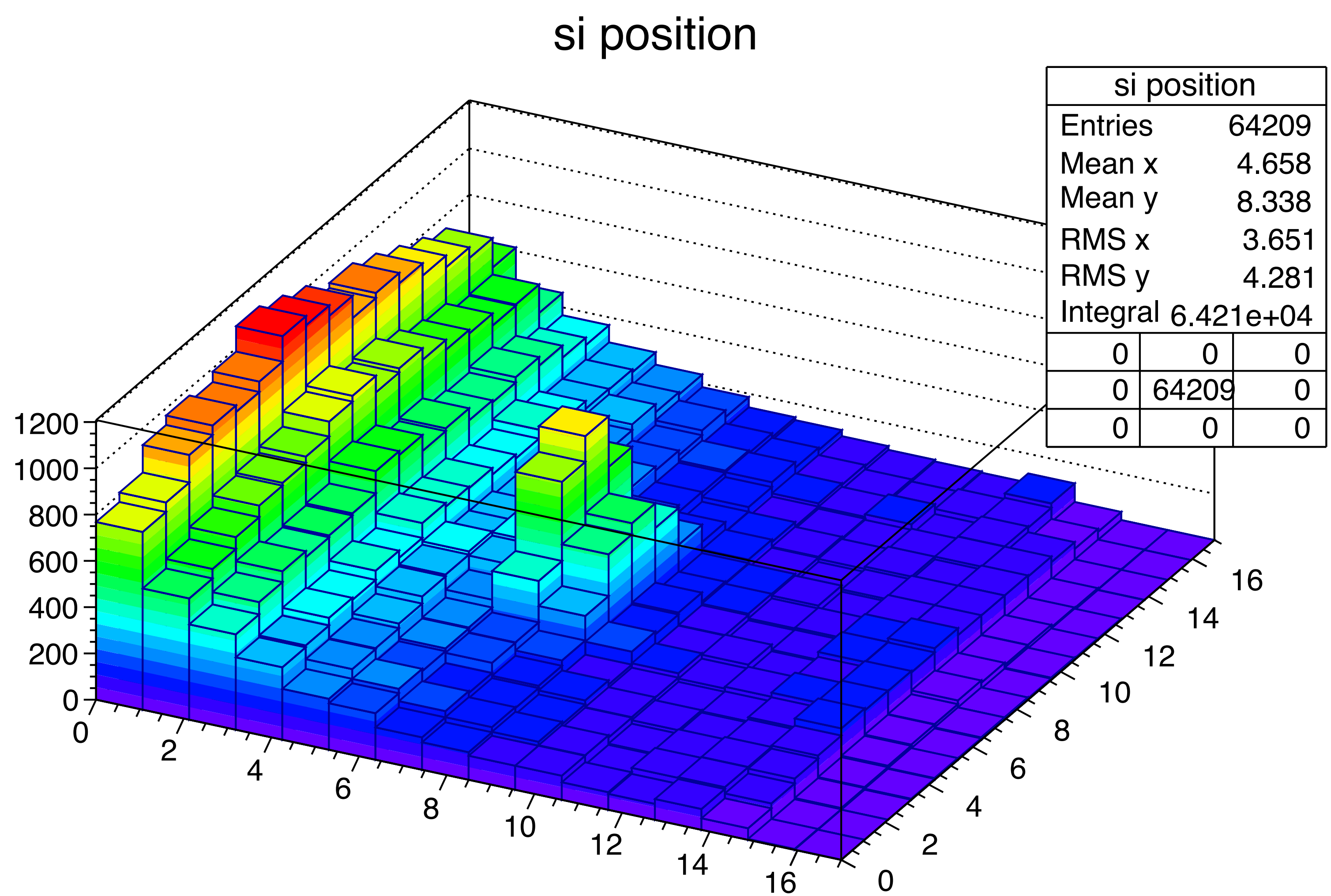


Courtesy Jan Glorius

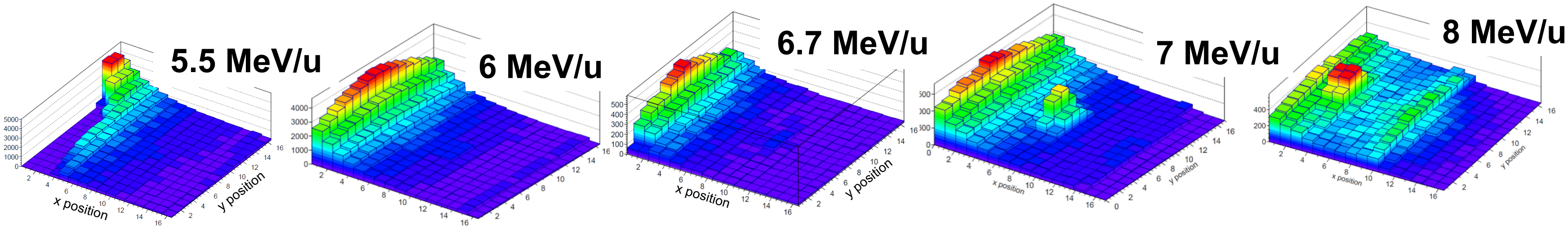
$^{124}Xe(p,g)^{125}Cs$ Experiment at the ESR

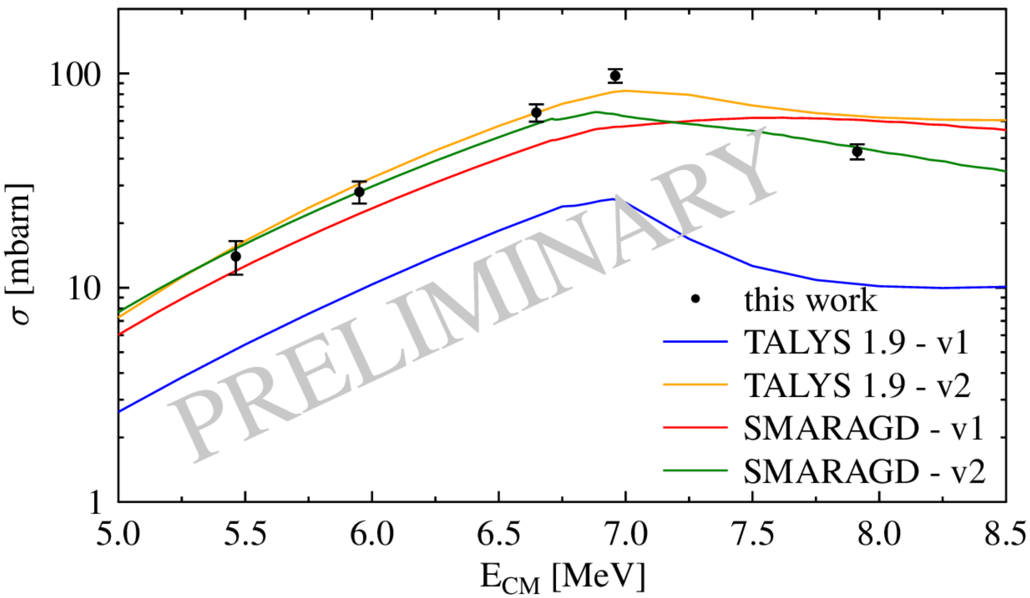


$^{124}Xe(p,g)^{125}Cs$ Experiment at the ESR



$^{124}Xe(p,\gamma)$ - Results





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

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

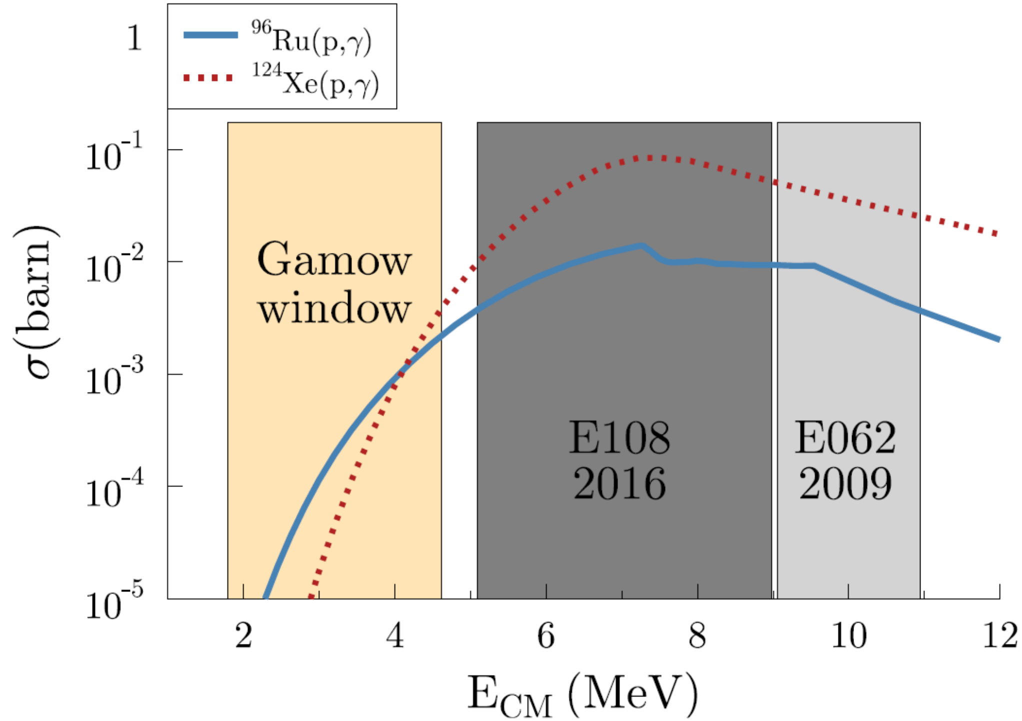
J. Glorius,[1,*] C. Langer,[2] Z. Slavkovská,[2] L. Bott,[2] C. Brandau,[1,3] B. Brückner,[2] K. Blaum,[4]
T. Davinson,[7] P. Erbacher,[2] S. Fiebiger,[2] T. Gaßner,[1] K. Göbel,[2] M. Groothuis,[2] A. Gumberidz
R. Hess,[1] R. Hensch,[2] P. Hillmann,[2] P.-M. Hillenbrand,[1] O. Hinrichs,[2] B. Jurado,[9] 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.

erc ASTRUm

Courtesy Jan Glorius

HELMHOLTZ GSI

Future measurements

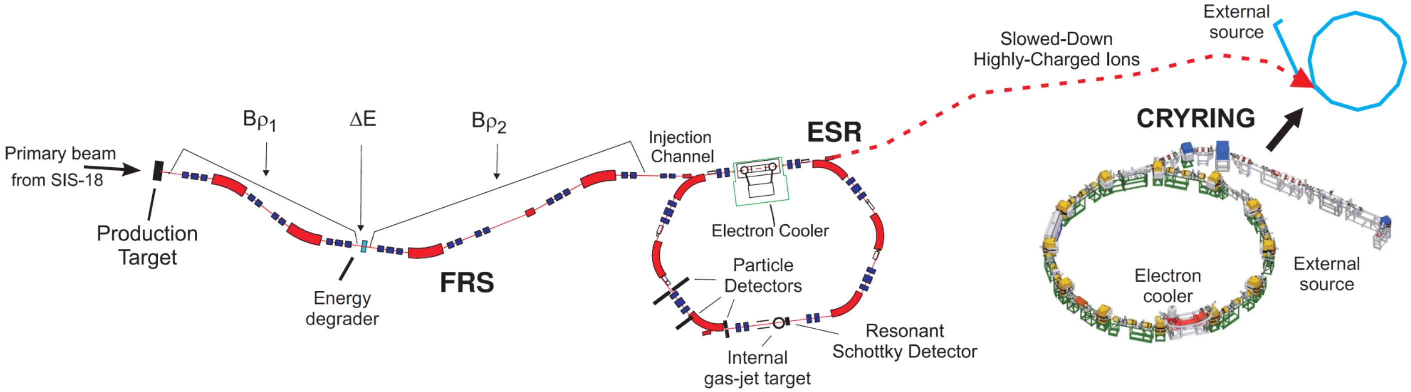


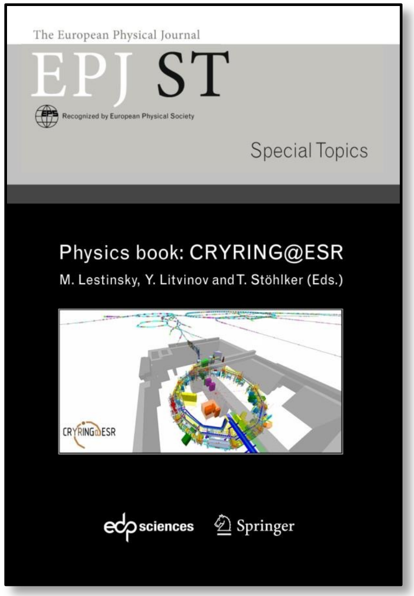
E127 R. Reifarth et al.

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

CRYRING@ESR

ESR: beam energies > 4.0 MeV/u reaction rates measurements in the Gamow window of the **p-process**

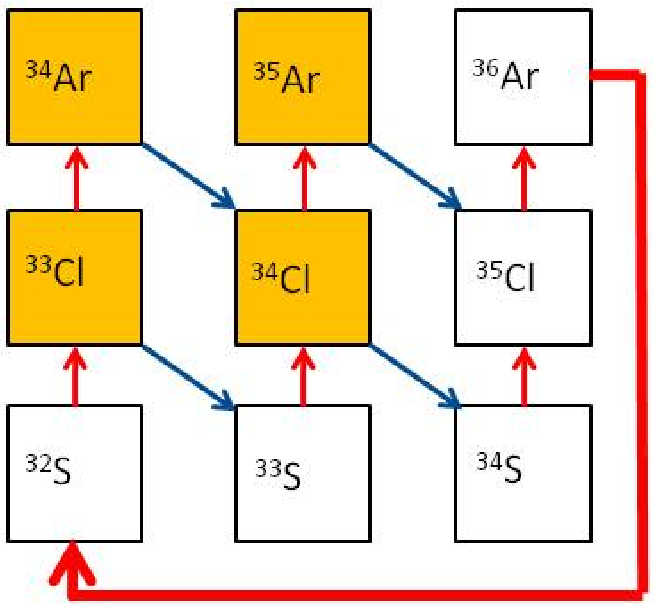
→

Cryring+ESR: beam energies 0.1-1.0 MeV/u reaction rates measurements in the Gamow window of the **rp-process**

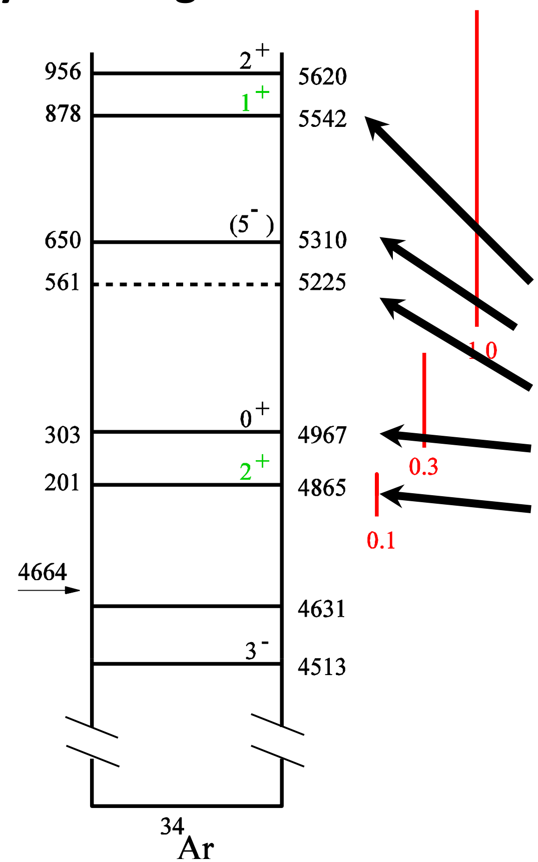
Example: ^{33}Cl(p,γ)^{34}Ar by-pass of ^{34m}Cl γ-ray emitting isomer

Novae physics

Production of ^{34m,g}Cl



S. Bishop et al.



resonance strengths

assuming 10^6 stored ^{33}Cl we can expect:

1200 count/hr

1 count/s

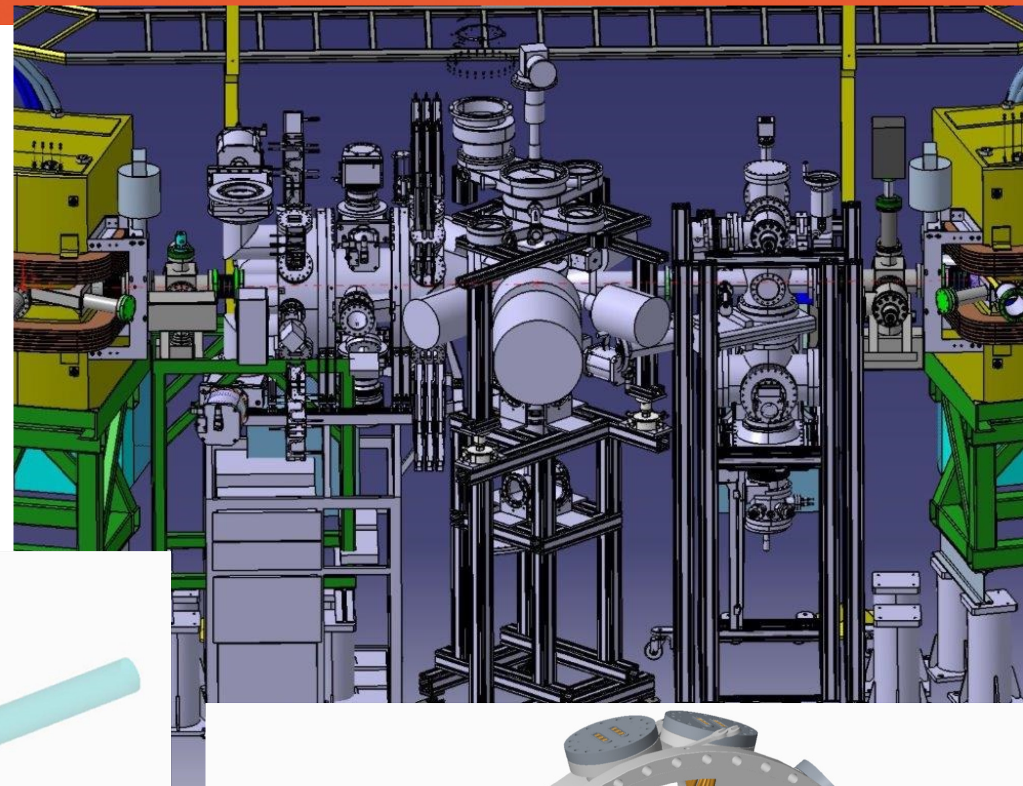
2 counts/s

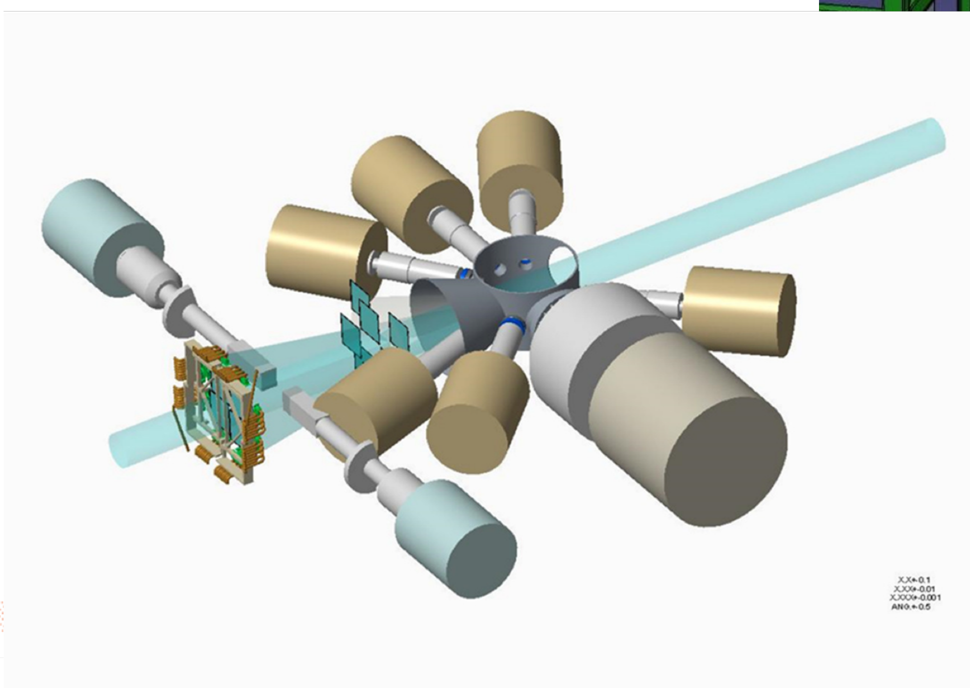
10 counts/day

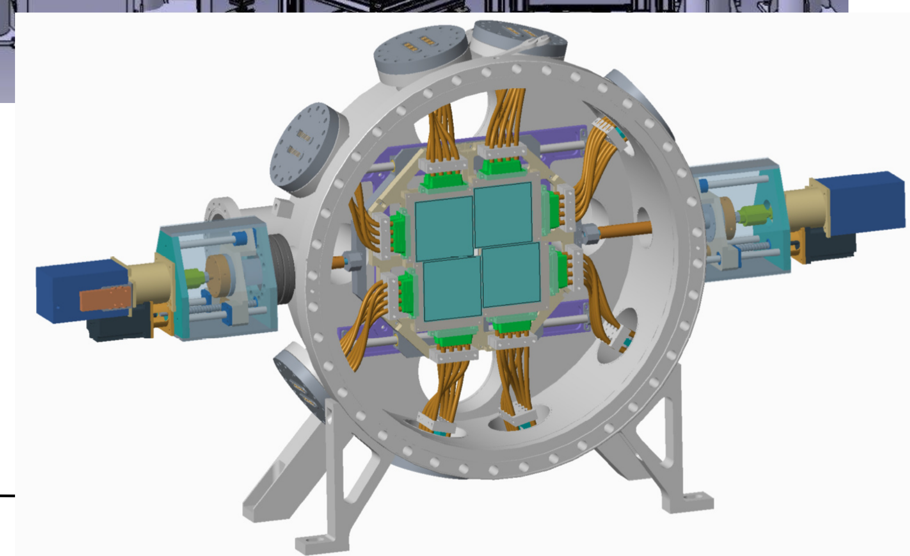
1 count/s

CARME@CRYRING

C. Bruno, T. Davinson,
P. Woods, C. Lederer-Woods et al.







Nuclear astrophysical reaction studies using the CRYRING reaction chamber system

Proposal S461

C.G. Bruno†, P.J. Woods, T. Davinson, R. Garg, O. Hall, D. Kahl, C. Lederer-Woods, A.S. Murphy
School of Physics and Astronomy, University of Edinburgh, EH9 3FD Edinburgh, UK
†Spokesperson

Yu. Litvinov, C. Brandau, J. Glorius, A. Gumberidze, M. Lestinsky, S. Litvinov, C. Nociforo, F. Nolden, N. Petridis, U. Popp, M.S. Sanjari, M. Steck, T.Stoehlker, H. Weick
GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

C. Langer, R. Reifarth, Z. Slavkovská
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J. José
Dept. de Fisica, Universitat Politècnica de Catalunya (UPC), E-08019 Barcelona, Spain

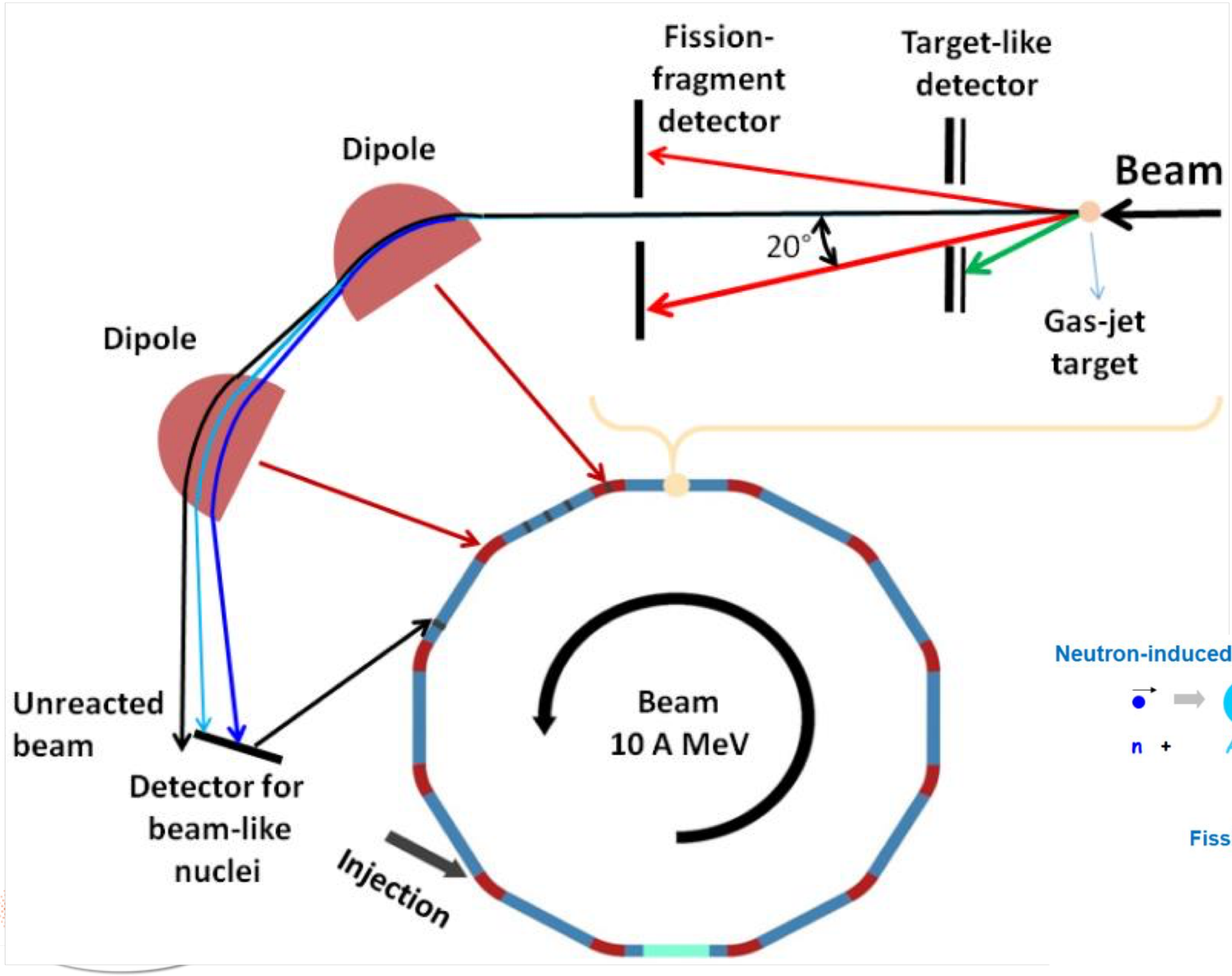
H. Schatz
National Superconducting Cyclotron Laboratory, East Lansing MI 48864, USA

B. Jurado
CENBG, Bordeaux, France

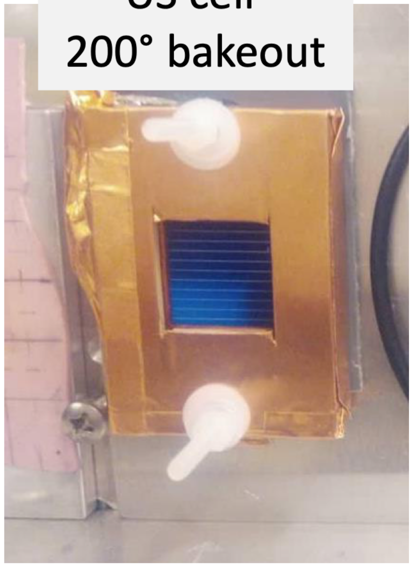
NucAR: Nuclear Astrophysics at Rings – exp-astro.de/nucar/

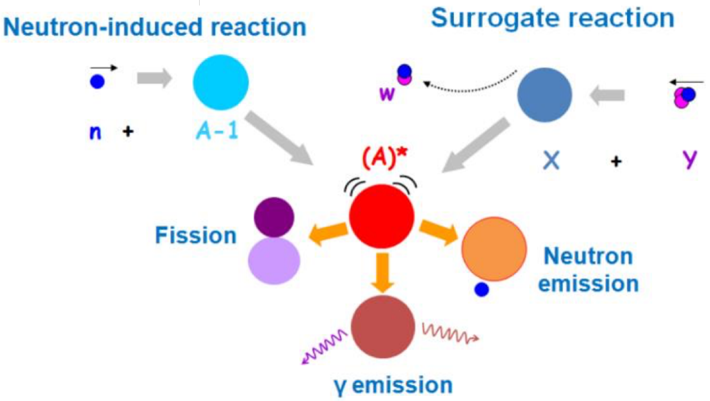
Neutron-induced reactions via surrogate method

A. Henriques, B, Jurado, M. Grieser, et al.



Det3: 2x2cm²
US cell
200° bakeout



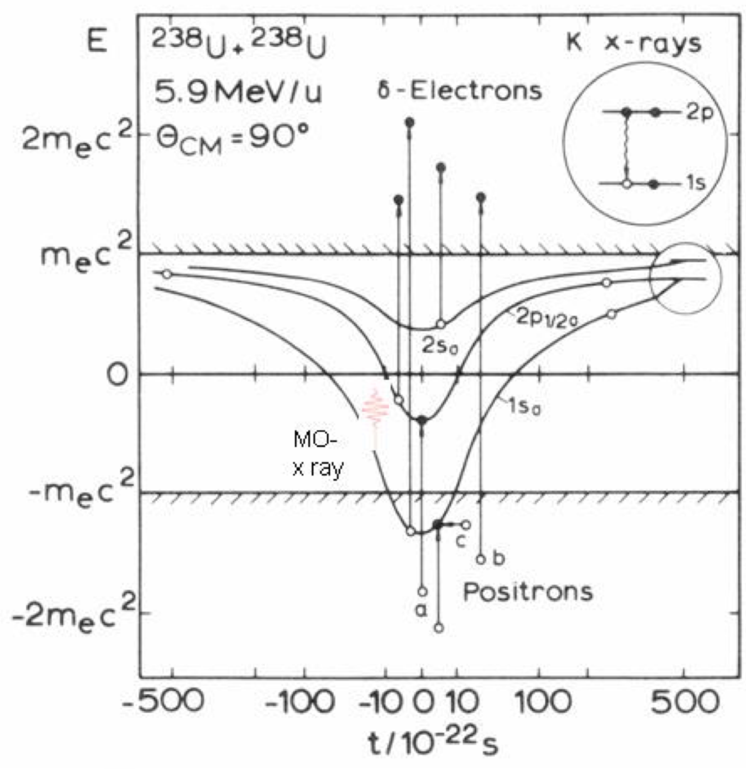


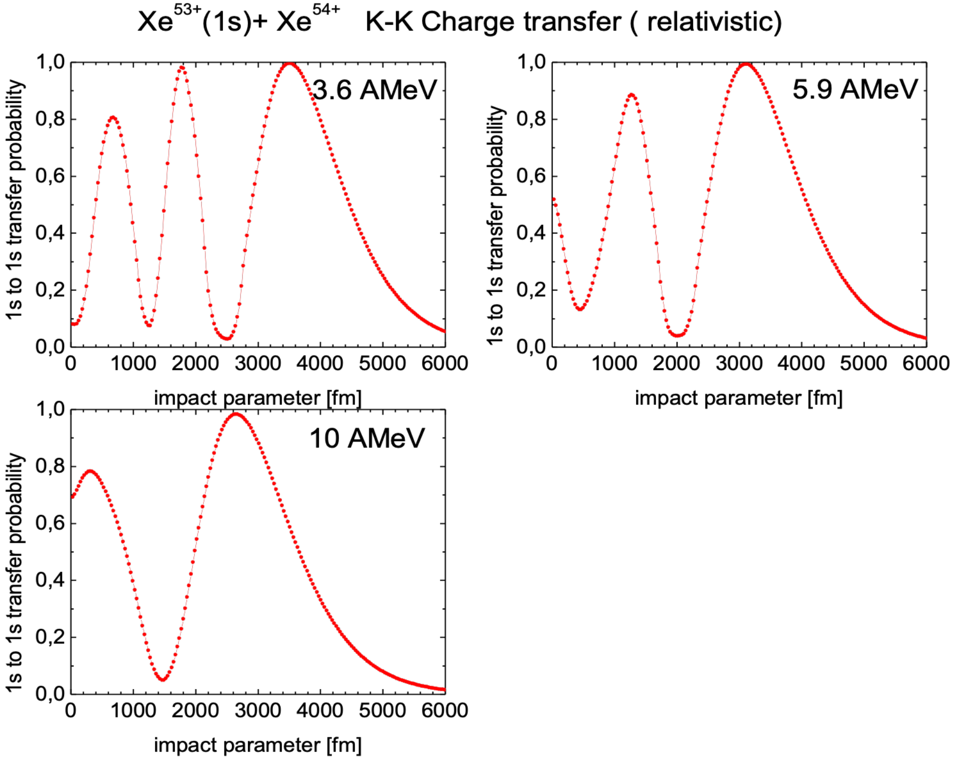
Proposal for an experiment to be conducted at ESR

Electron Emission following 1s Adiabatic Ionization and Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions

Updated from previously accepted proposal E102

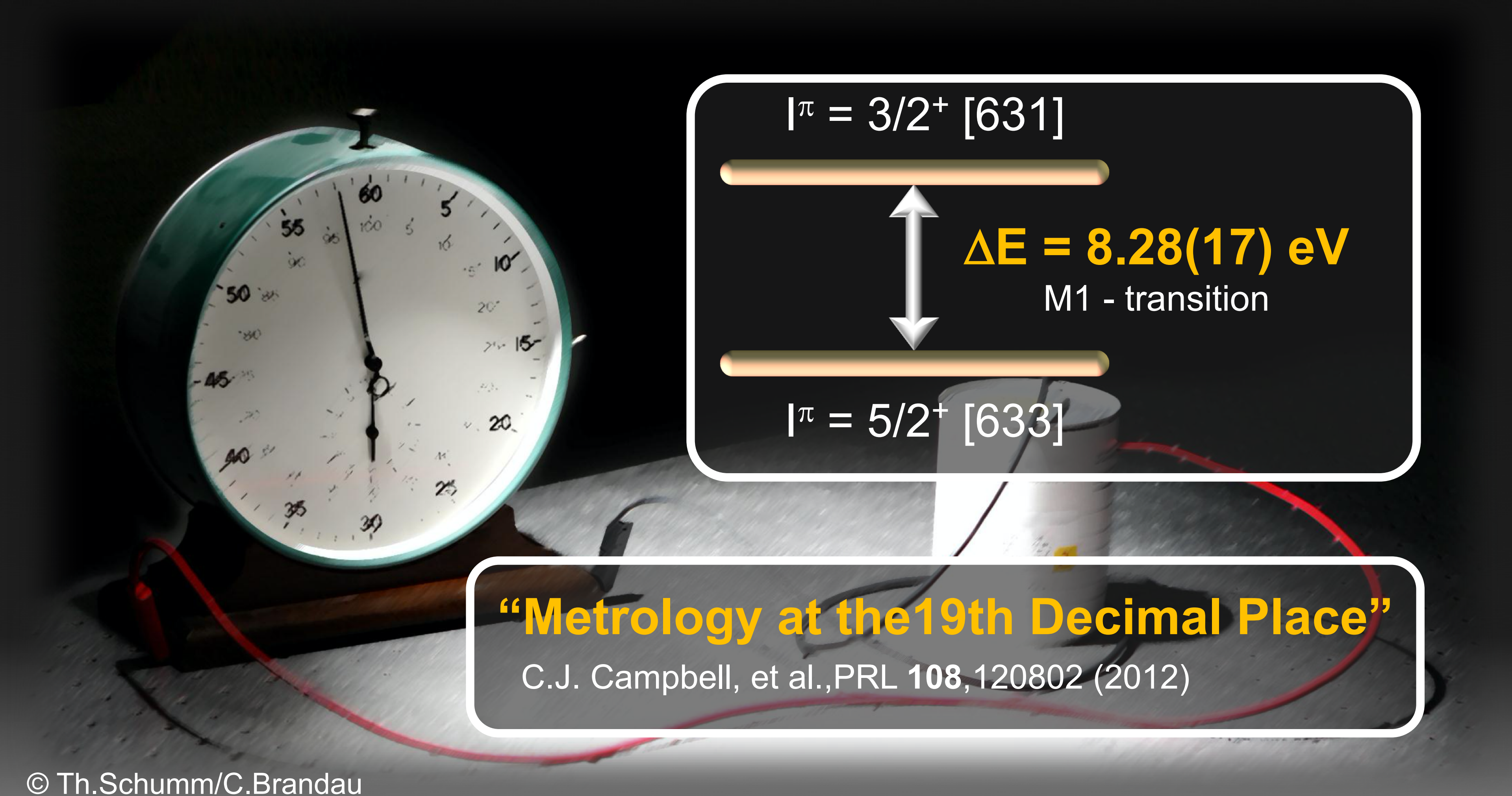
S. Hagmann[1], P.-M. Hillenbrand[1,2], Yu. Litvinov[1], U. Spillmann[1], V. Shabayev[3], I. Tupitsyn[3], E. de Filippo[4], M. Schöffler[5], L. Schmidt[5], Ch. Kozhuharov[1], M. Benis[6], A. Gumberidze[1,7], M. Lestinski[1], N. Petridis[1], H. Rothard[8], Th. Stöhlker[1,9,10]





$^{229(m)}$Th: A Unique Candidate for a Nuclear Optical Frequency Standard

Concept: E. Peik and C. Tamm, Europhys. Lett. **61**, 181 (2003)



$I^{\pi} = 3/2^{+}$ [631]

ΔE = 8.28(17) eV

M1 - transition

$I^{\pi} = 5/2^{+}$ [633]

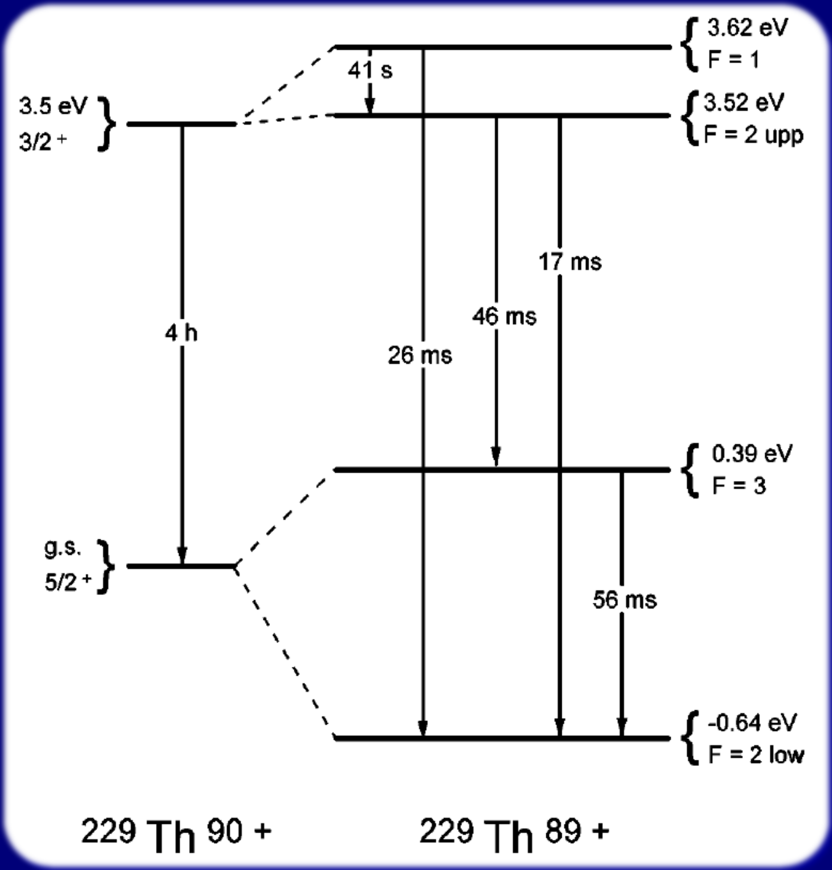
“Metrology at the19th Decimal Place”

C.J. Campbell, et al.,PRL **108**,120802 (2012)

E123

Effect of Atomic Electrons: ^{229m}Th („Nuclear Level Quenching“)

Bare: H-like (1 electron):



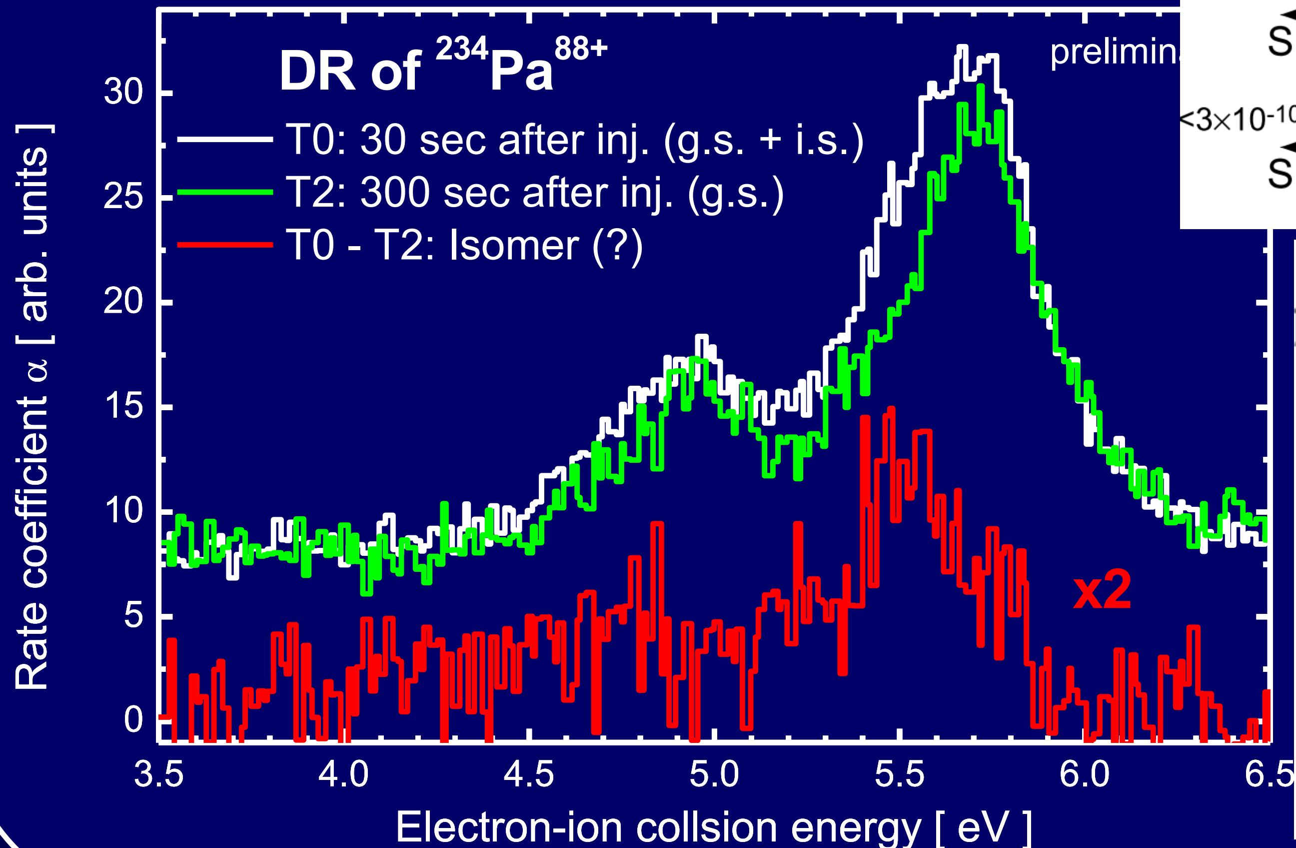
Nuclear spin mixing due to HF interaction of bound electrons:

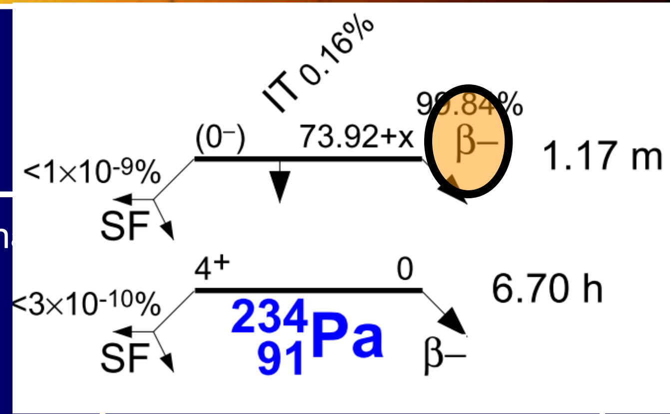
Slow: 0, 2e-, 4e-
(e-spin paired, no HFS)

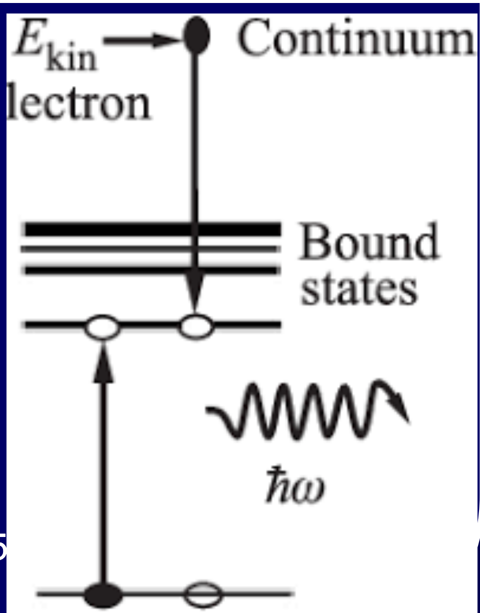
Fast: 1e-, 3e-,… (HFS)
(„nuclear level quenching“)

Wycech & Zylicz, Ac.Phys.Pol. **24**(1993)637
F.F. Karpeshin, et al., PRC **57**(1998)3085
K. Pachucki, et al., PRC **64**(2001)064301

DR of 0⁻- Isomers in $^{234}Pa^{88+}$





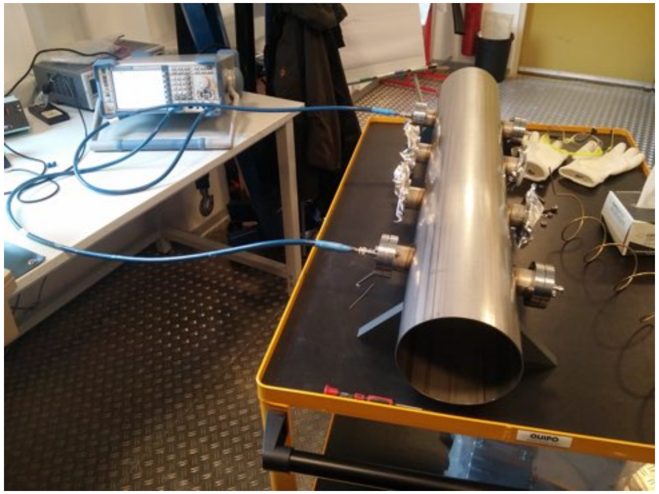


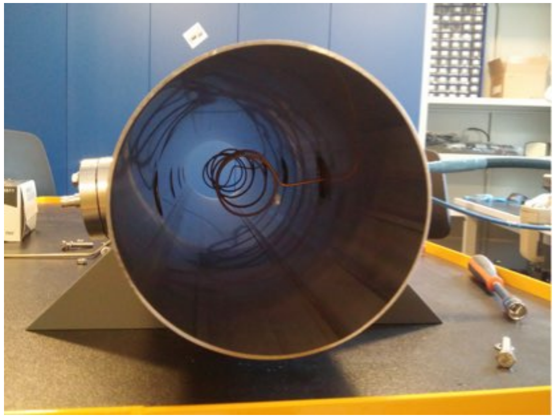
C. Brandau et al., in preparation

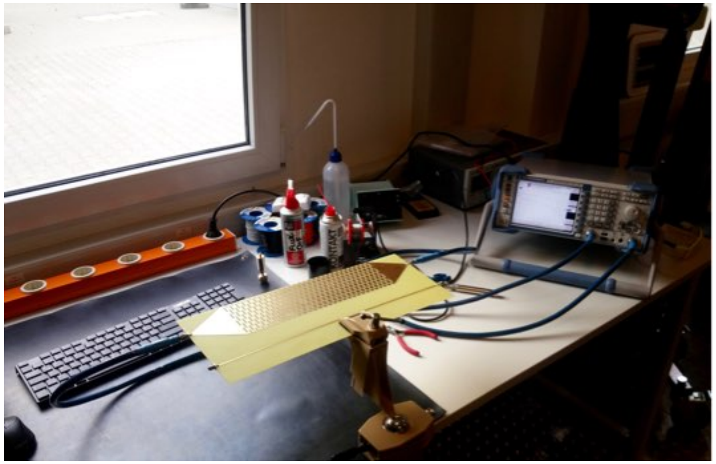
Courtesy to Carsten Brandau 21/09/2017

Some prototypes

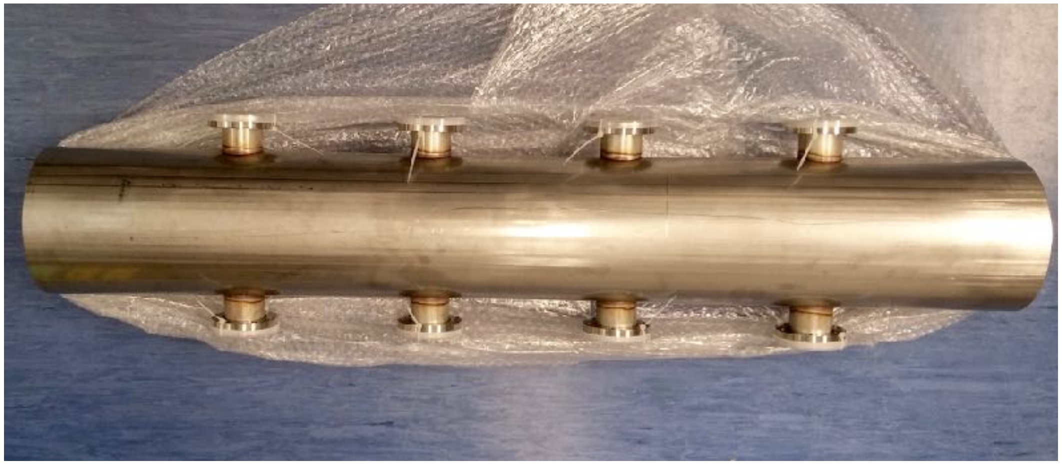
- Different topologies are known in the literature
- Even used in accelerator physics (e.g. Faltin-Pickup)
- Currently studying and optimizing
  - Planar
  - Spiral

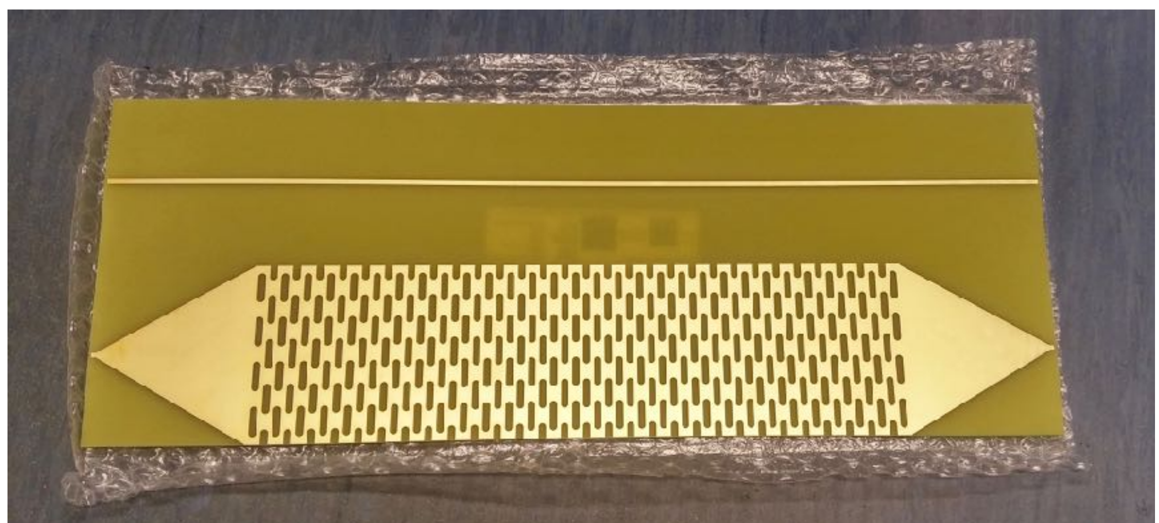






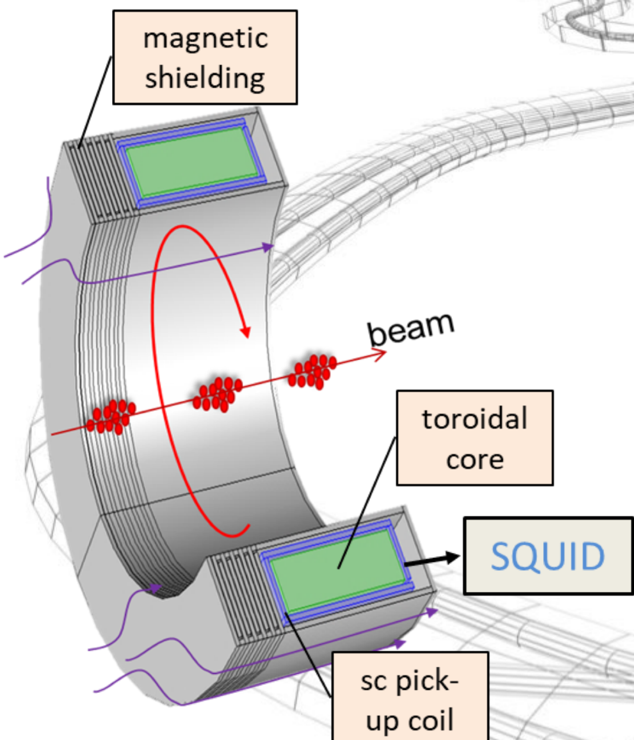
Bench top models



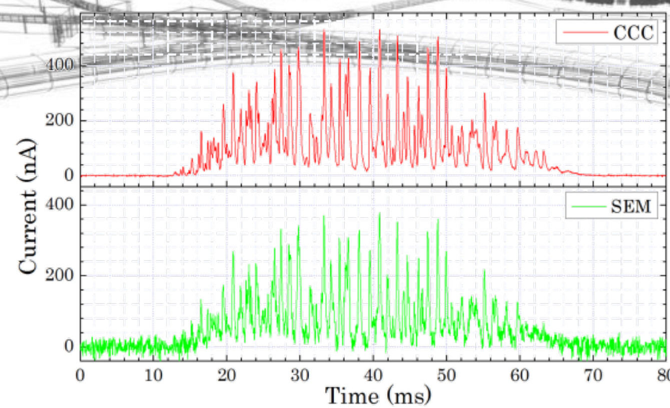


Development of Cryogenic Current Comparators (CCC) for nA Beams: Absolute Measurements

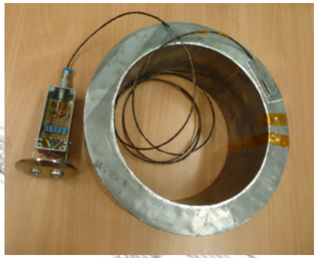
CCC Principle

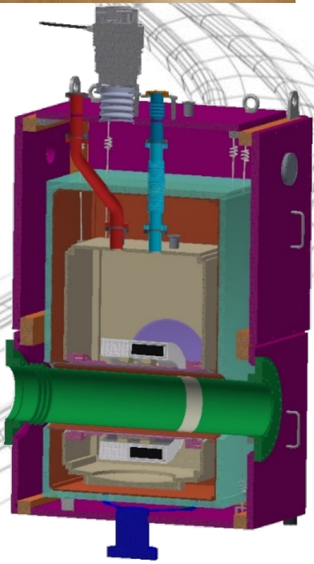


Spill Analysis with nA Resolution at SIS18



Advanced CCC Design for FAIR





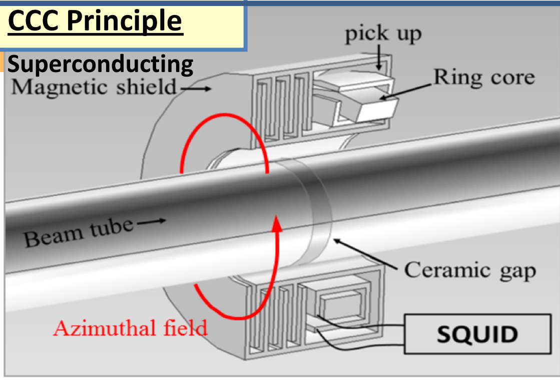
Investigation of new Shielding Geometries → Test at CRYRING

M. Schwickert, Th. Sieber et al., GSI
V. Tympel et al., HI Jena and FSU Jena

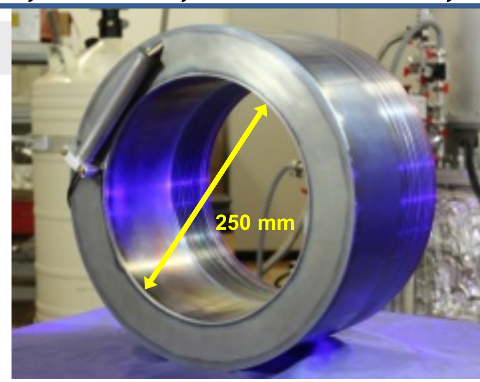
Cryogenic Current Comparator (CCC) for nA Beam Measurements

GSI Darmstadt, HI Jena, TU Darmstadt, FSU and IPHT Jena

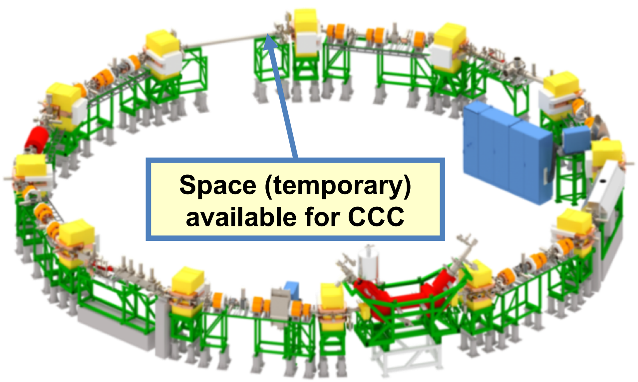
CCC Principle



Superconducting shield/pickup -> detection of beam azimuthal field with SQUID sensor

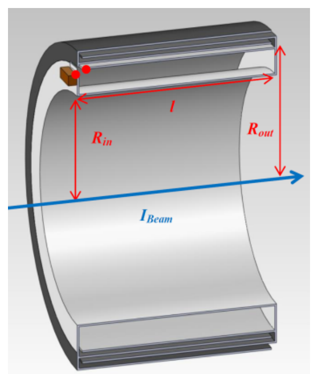


CCC-XD Nb detector and shield for 150 mm beam tubes. Tested and ready for operation



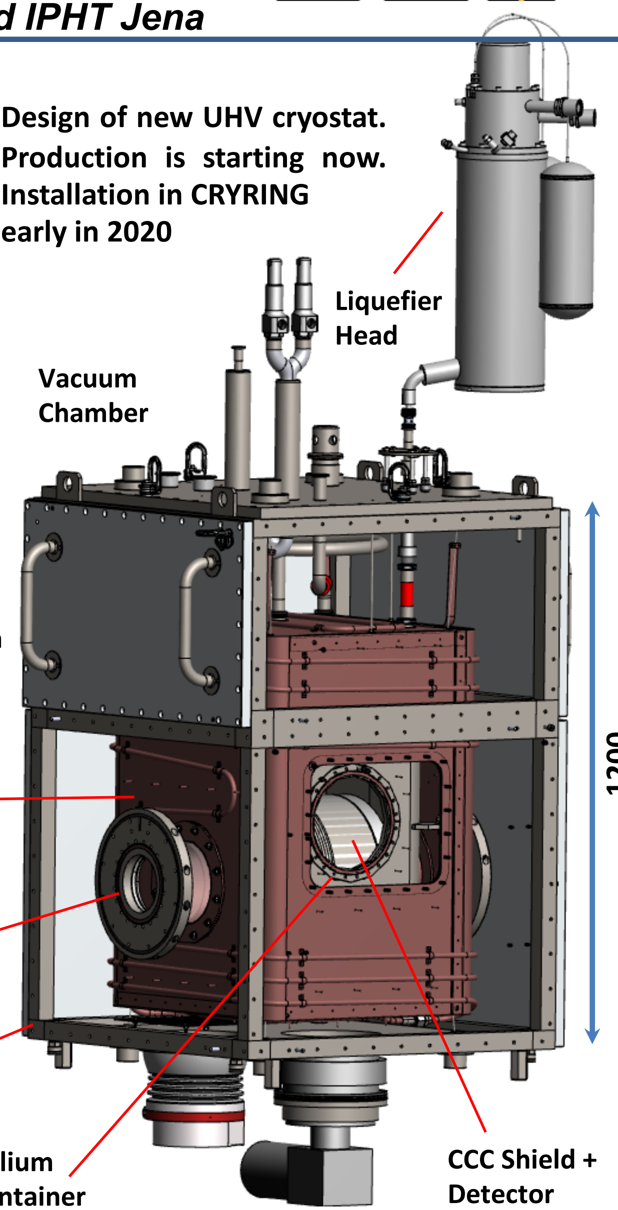
CCC in CRYRING (2019/2020):

- → tool for commissioning
- → support for exp. program
- → test bench for further development



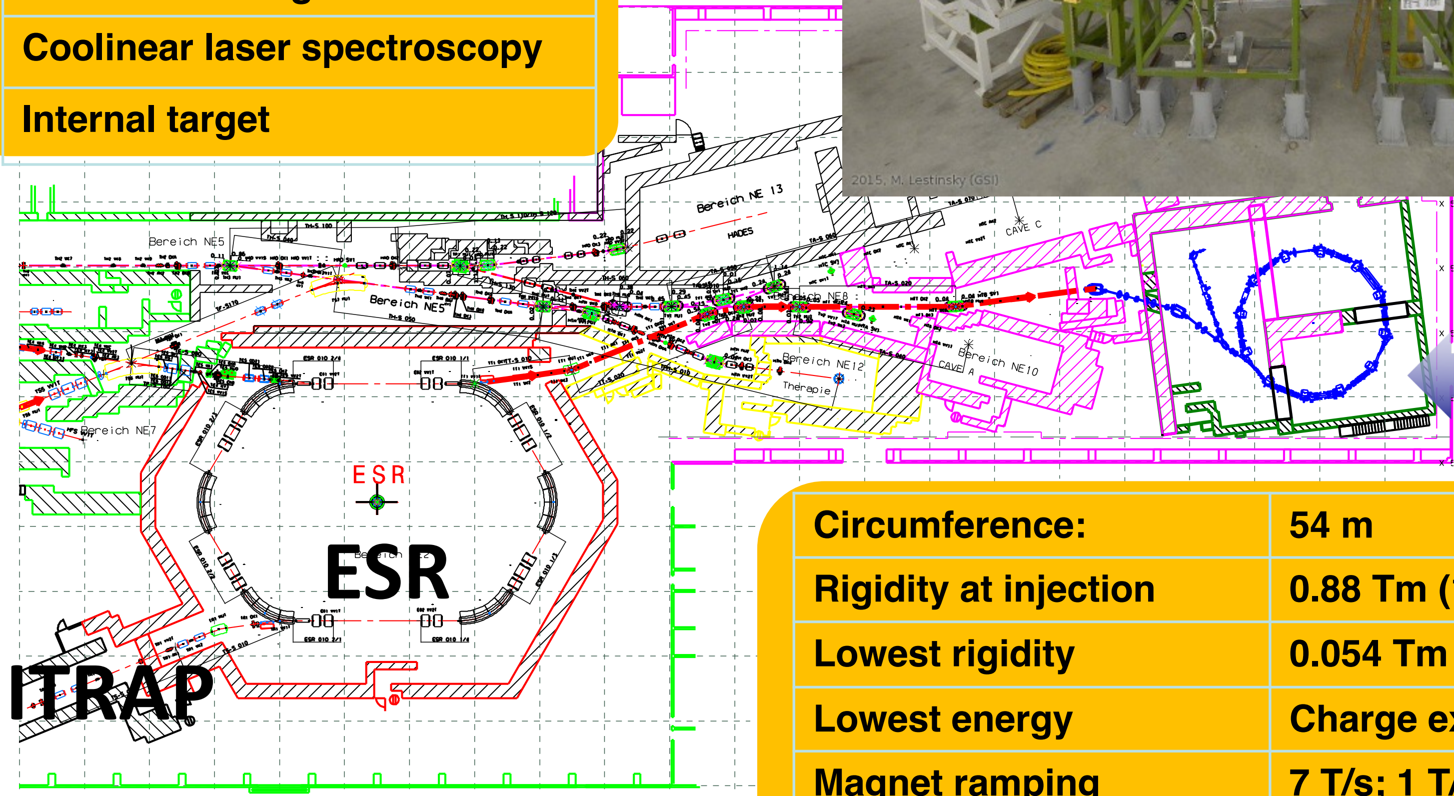
Coreless CCC with axial meander Pb shield (IPHT Jena). Significant cost reduc-tion --> tests in CRYRING

Design of new UHV cryostat. Production is starting now. Installation in CRYRING early in 2020

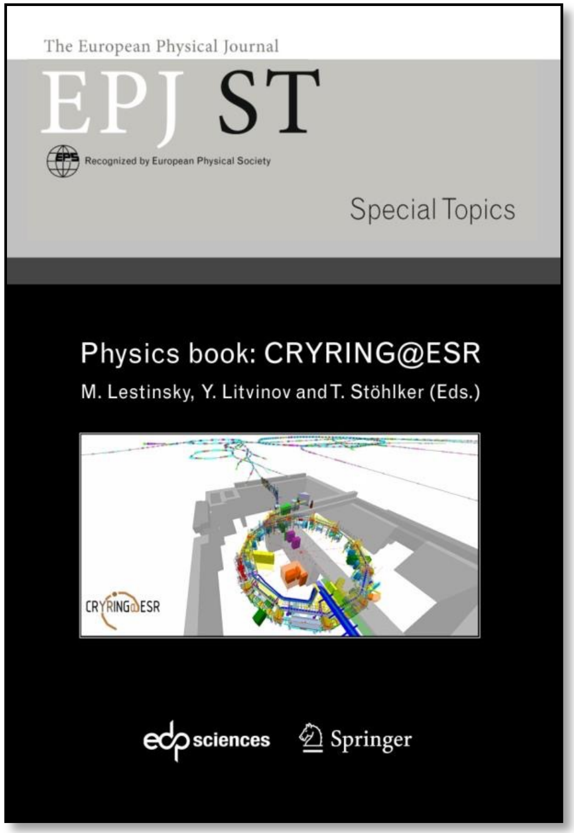


CRYRING@ESR

- Electron cooling
- Coolinear laser spectroscopy
- Internal target

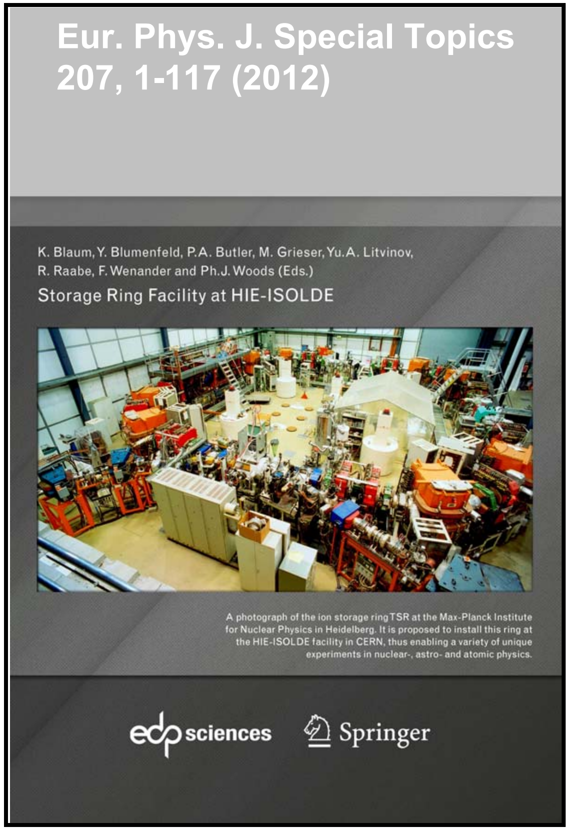


Circumference:	54 m
Rigidity at injection	0.88 Tm (1.44 Tm)
Lowest rigidity	0.054 Tm
Lowest energy	Charge exchange limited
Magnet ramping	7 T/s; 1 T/s
Slow extraction	

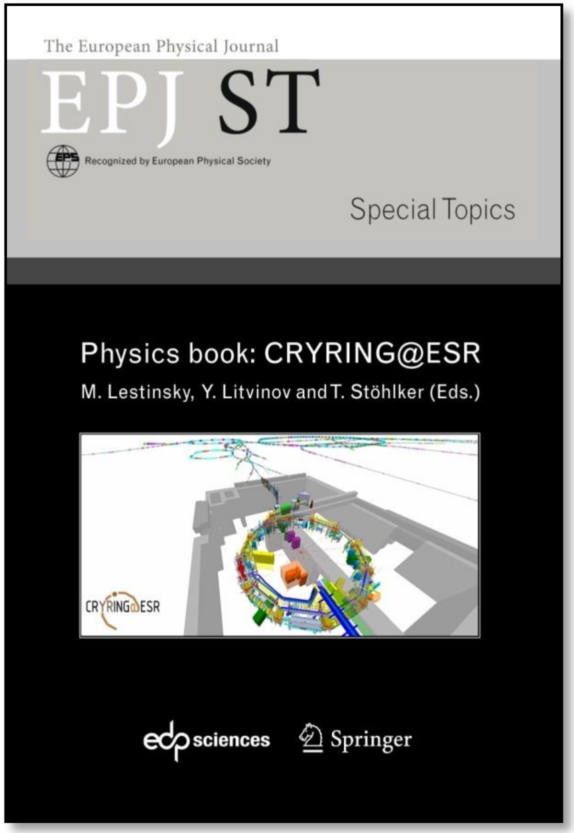


Physics book: CRYRING@ESR (2016)

Two basis publications



Techinical Design Report:
TSR@ISOLDE
(2012)



Physics book:
CRYRING@ESR
(2016)

Physics Case For a Low-Energy Storage Ring

TSR@ISOLDE Workshop at the
Max-Planck-Institute for Nuclear Physics
28.-29.10.2010

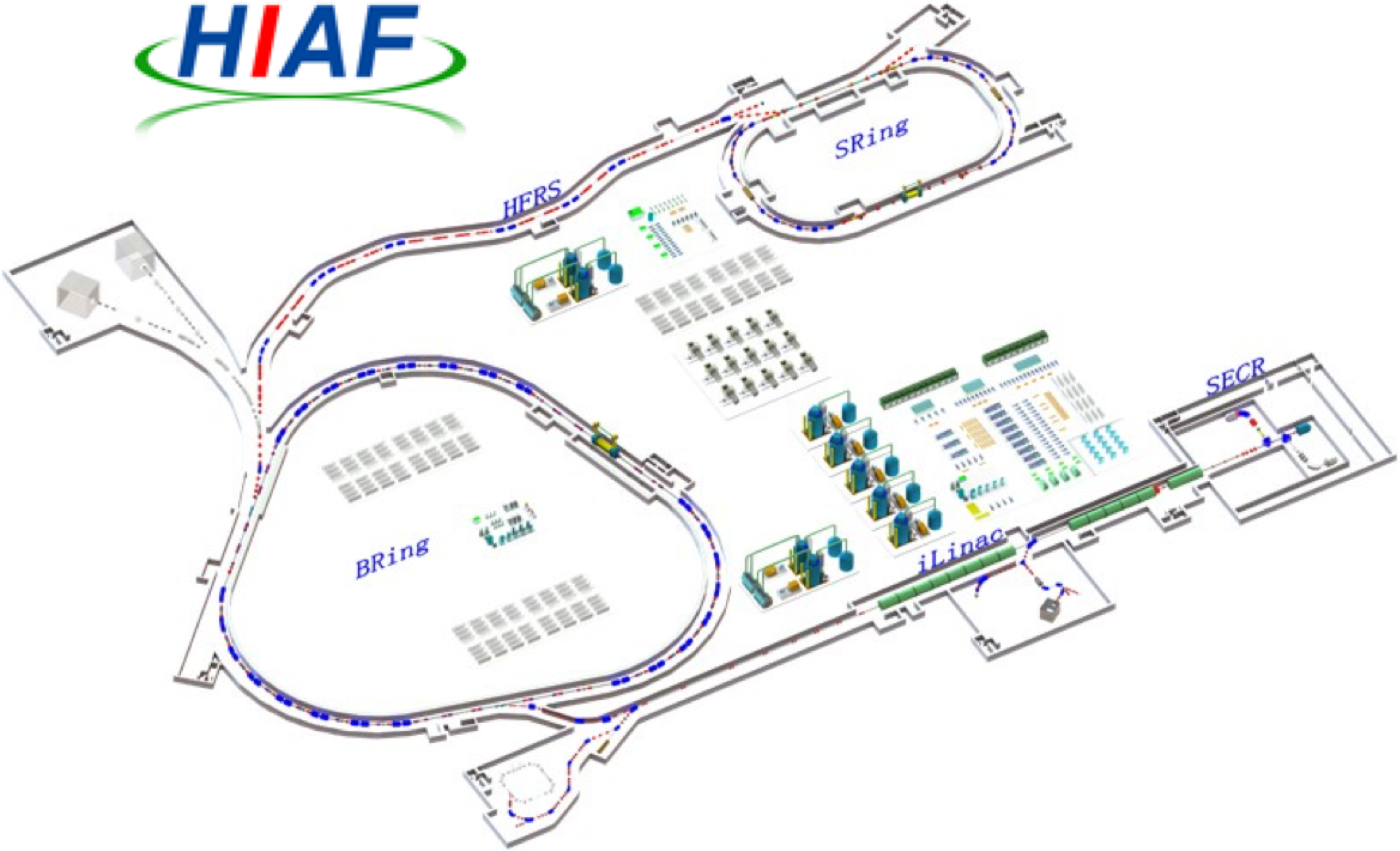
about 50 participants
from 15 institutions
from 7 countries

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

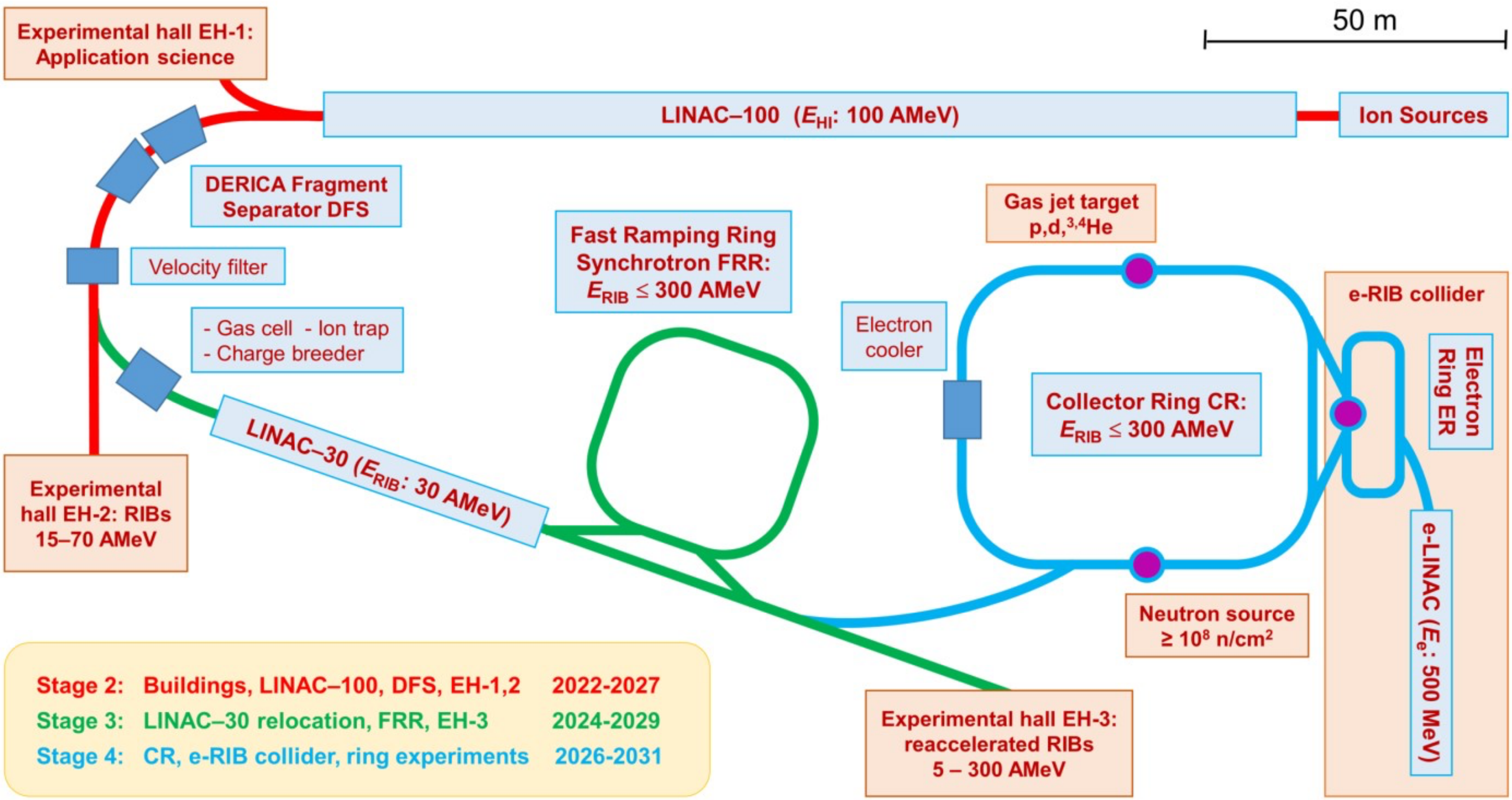
Storage ring facility at HIE-ISOLDE

evaluated at INTC meeting on 2nd February 2011

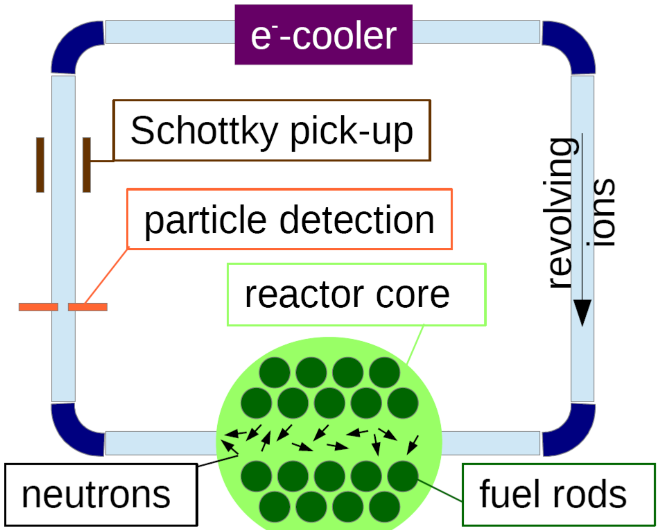
High Intensity Heavy-ion Accelerator Facility

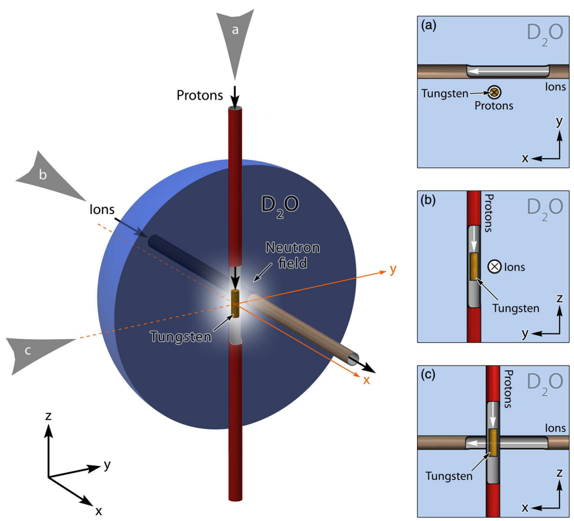


DERICA Project @ JINR, Dubna



Neutron captures in inverse kinematics





Workshop on Opportunities with a Neutron Target Facility

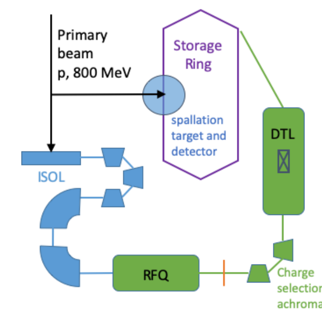
Neutron-induced reactions play a key role in understanding such diverse scientific fields as nuclear astrophysics, stockpile stewardship, reactor performance, and nuclear forensics. For many of these endeavors, reactions on short-lived nuclei offer key insights into the physical environment. Neutron reactions on short-lived nuclei have presented particular challenges, however, as both beam and target are unstable.

In a revolutionary development, a first concept has been proposed for performing neutron induced reactions using thermalized neutrons from a spallation target with short-lived charged particles in a storage ring. One possible driver for the spallation target and an ISOL-based rare isotope beam factory is the proton accelerator at the Los Alamos Neutron Science Center.

In this two-day workshop, we will discuss technical concepts for the spallation source, the ISOL source, and the storage ring as well as potential applications for stockpile stewardship, nuclear forensics, and basic science. Finally, we will open the discussion to possible applications of post-accelerated ISOL beams prior to ring injection.

Location Information

Dates: 19-20 August 2019
Location: Santa Fe, NM, USA
Venue: El Dorado Hotel, Historic Santa Fe Plaza
Organizing Committee: A. Couture, S. M. Mosby, D. Gorelov, N. Moody, N. Roelofs



Los Alamos NATIONAL LABORATORY EST. 1943

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

Reifarth & Litvinov , Phys. Rev ST Accelerator and Beams, 17 (2014) 014701
Reifarth et al., Phys. Rev ST Accelerator and Beams, 20 (2017) 044701

Thank you!

the NucAR collaboration

GSI

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

THE UNIVERSITY OF EDINBURGH

CENBG

AARHUS UNIVERSITY

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

CHALMERS UNIVERSITY OF TECHNOLOGY

Saitama University 埼玉大学

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