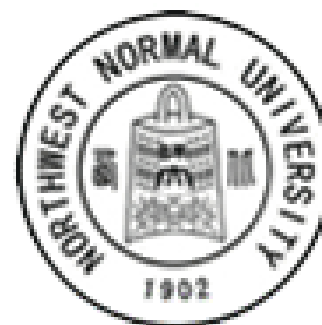
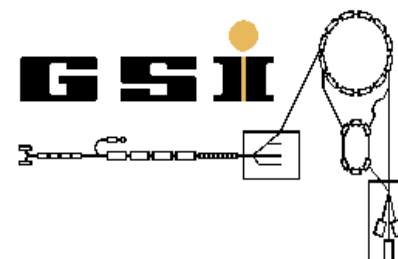


RIB Physics with Heavy-Ion Storage Rings

Yuri A. Litvinov



16th International Conference on
Electromagnetic Isotope Separators and Techniques Related to their Applications
Matsue, Japan, 2-7 December 2012

Physics at Storage Rings

Single-particle sensitivity

High atomic charge states

Long storage times

Broad-band measurements

High resolving power

Very short lifetimes

Direct mass measurements of exotic nuclei

Radioactive decay of highly-charged ions

Charge radii measurements [DR, scattering]

Experiments with polarized beams

Experiments with isomeric beams [DR, reactions]

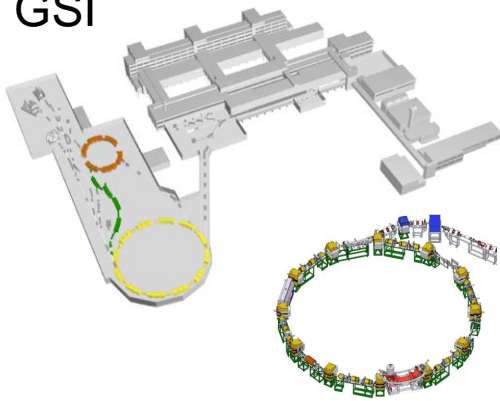
Nuclear magnetic moments [DR]

Astrophysical reactions [(p,g), (a,g) ...]

In-ring nuclear reactions

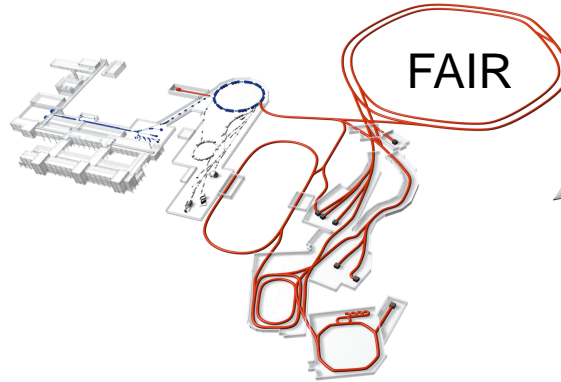
Physics at Storage Rings

GSI

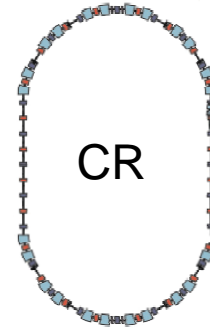


CRYRING

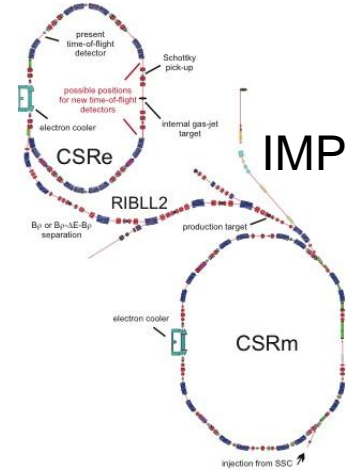
→ T. Nilsson



FAIR

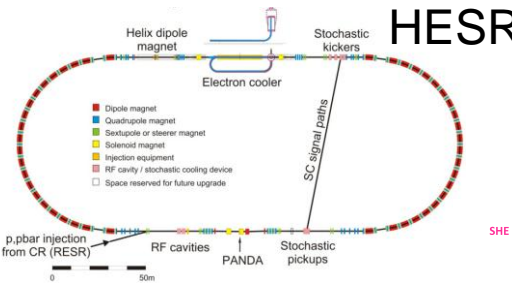


CR



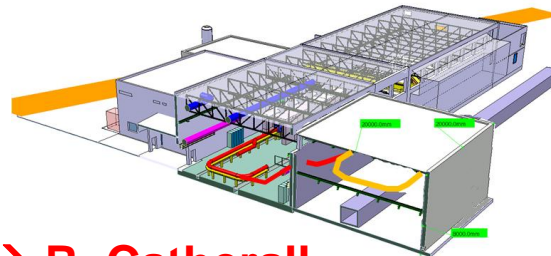
IMP

→ R.C. Lu

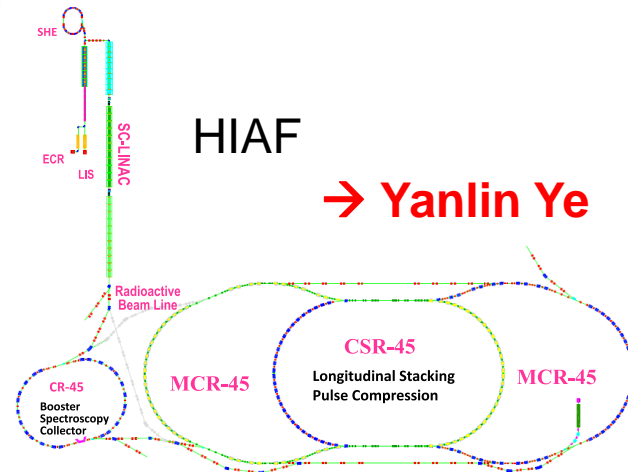


HESR

TSR@ISOLDE

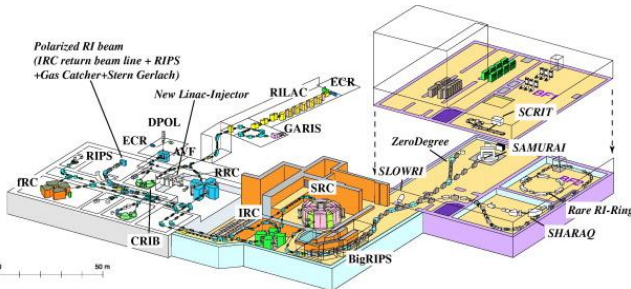


→ R. Catherall



HIAF

→ Yanlin Ye



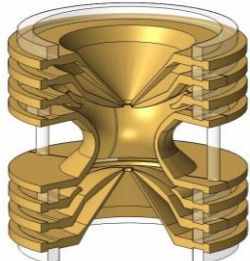
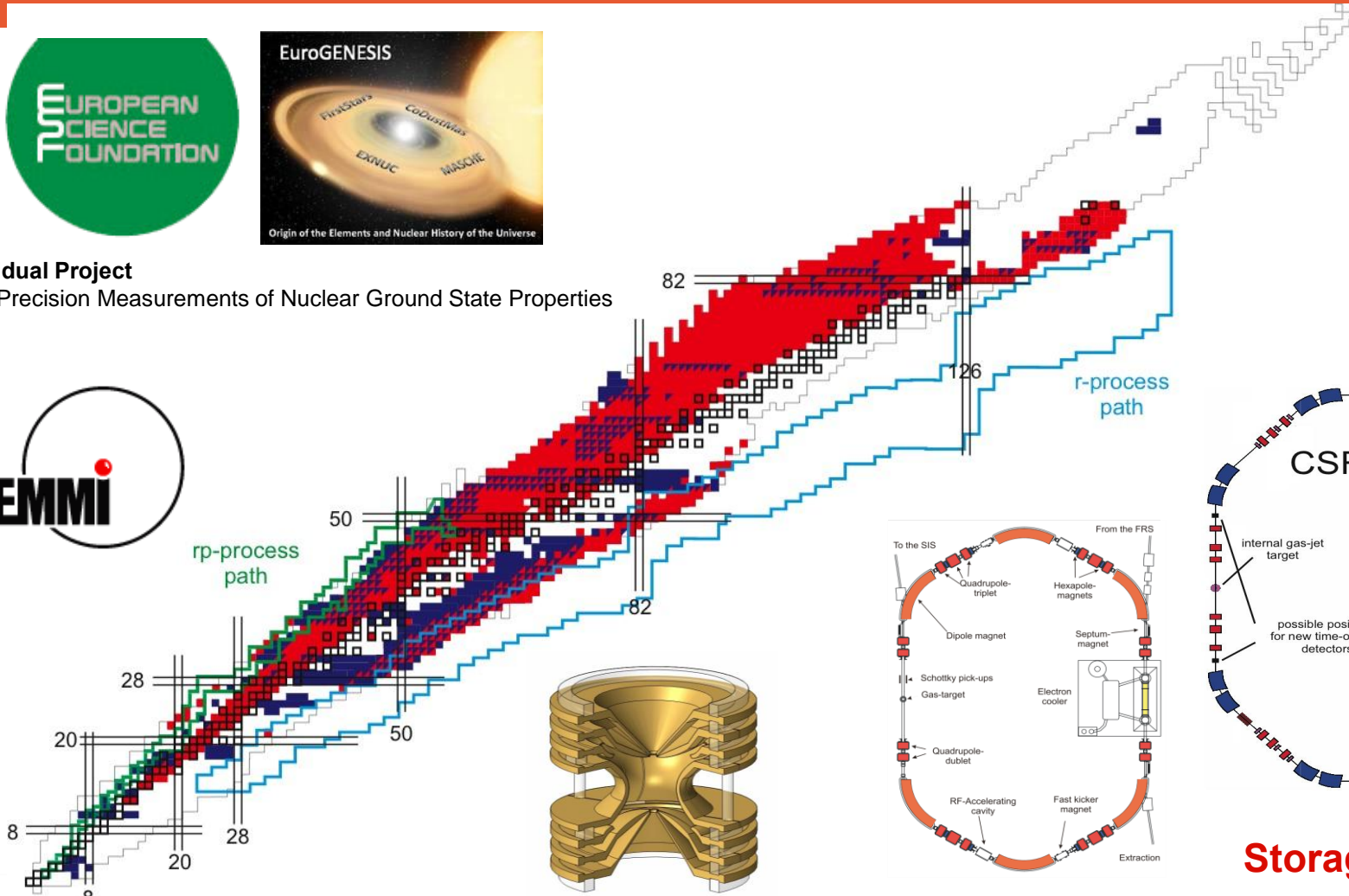
RI-RING

→ Y. Yamaguchi

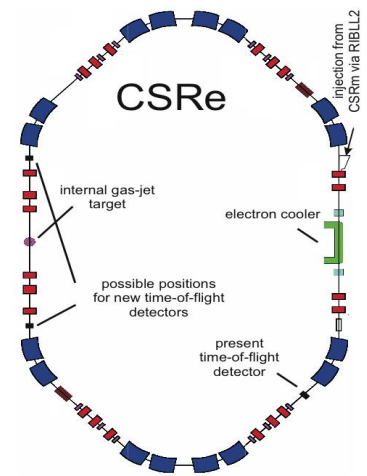
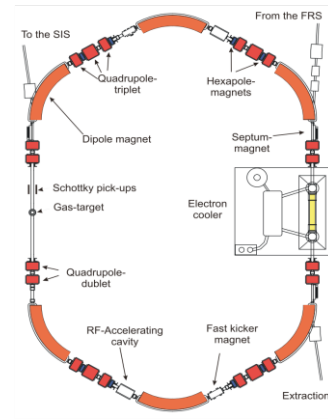
Direct Mass Measurements on the Chart of the Nuclides



Individual Project
High-Precision Measurements of Nuclear Ground State Properties



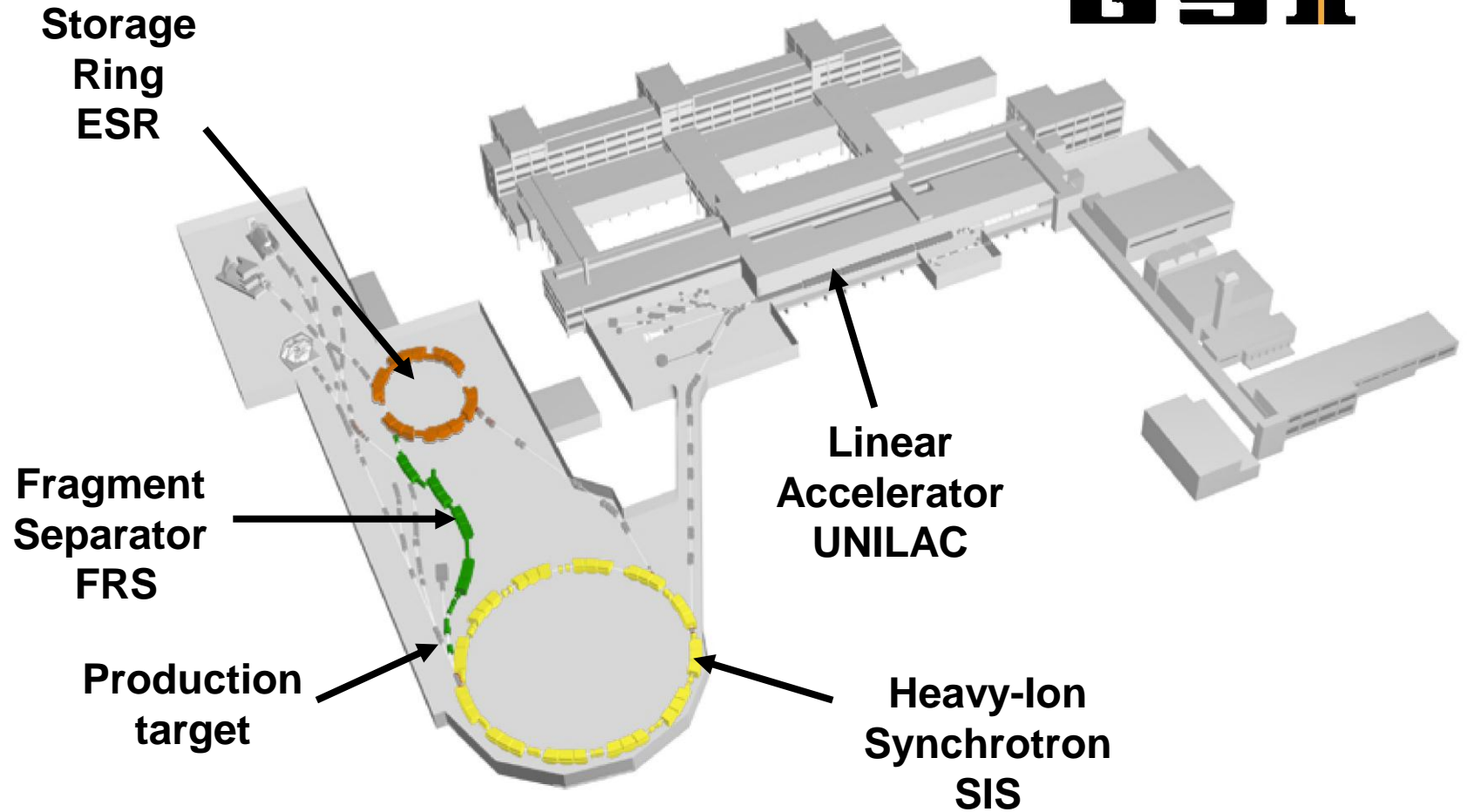
Penning Traps



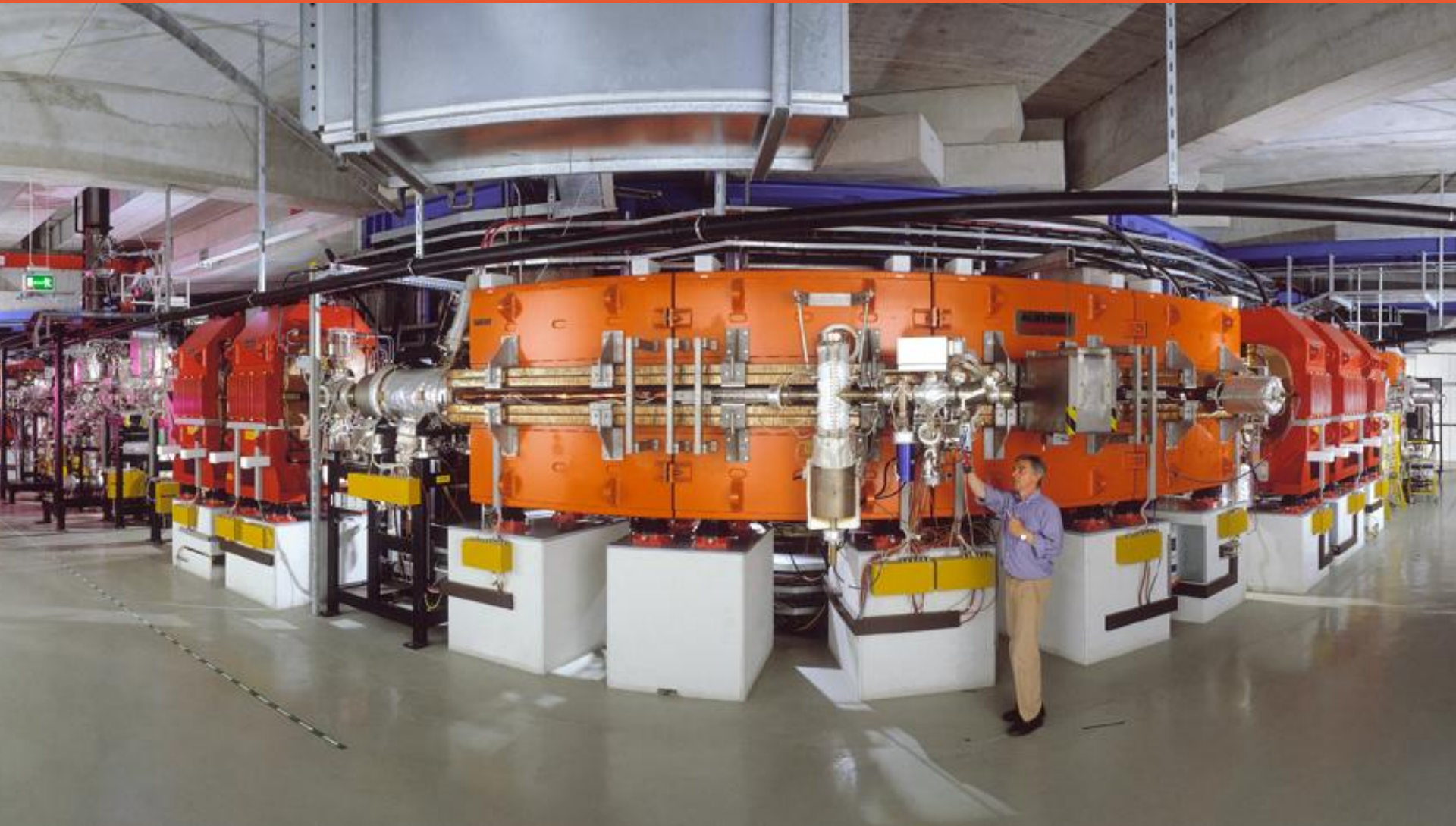
Storage Rings

TRAPS → S. Kreim, S.Nagy, M. Block, A. Kwiatkowski, D. Rodriguez, V. Kolhinen M. Redshaw
MR-TOF → S. Kreim, P. Schury, T. Dickel, J. Aoki

Secondary Beams of Short-Lived Nuclei



Experimental Storage Ring ESR

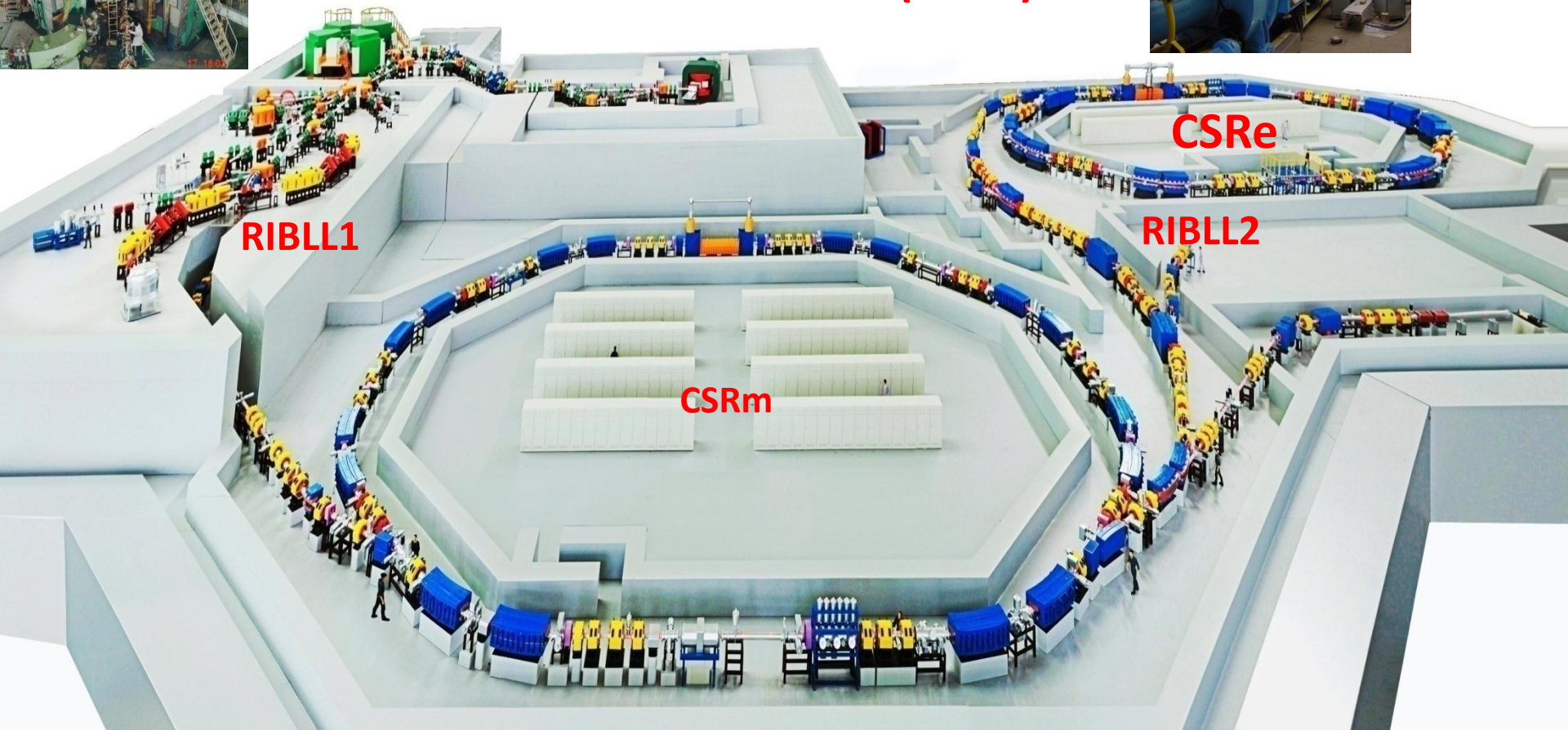


Heavy Ion Research Facility in Lanzhou (HIRFL)



SSC(K=450)

SFC (K=69)



RIBLL1

CSRe

RIBLL2

CSRm

Experimental Cooler Storage Ring CSRe

$$\frac{\Delta f}{f} = \frac{1}{\gamma_t^2} \frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v} \cdot \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)$$

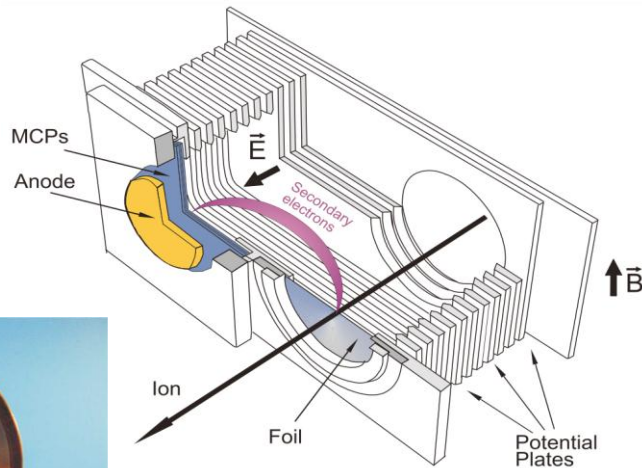
CSR实验环闭环

Isochronous Mass Spectrometry

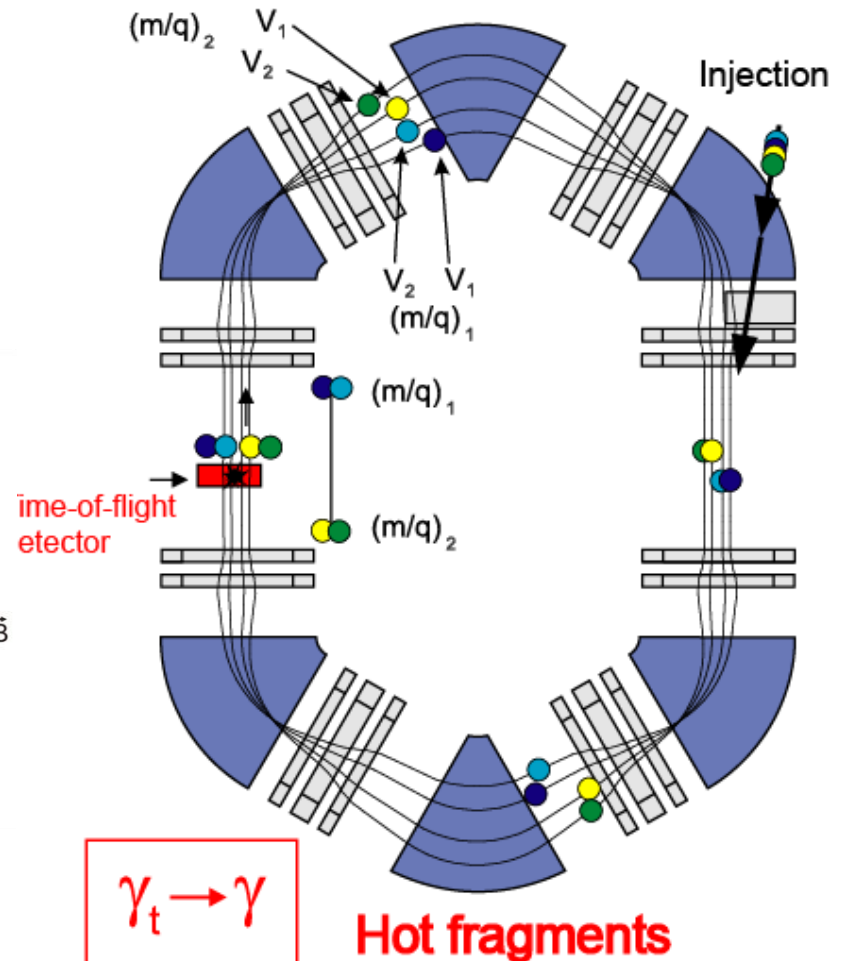
H. Wollnik et al., GSI Proposal, 1985

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2} \frac{\Delta(m/q)}{m/q} + \frac{\Delta V}{V} \left(1 - \frac{\gamma^2}{\gamma_t^2} \right)$$

$$\gamma_t \rightarrow \gamma$$



Isochronous-Mass-Spectrometry



Mass Measurements of ^{78}Kr Projectile Fragments

New masses of ^{63}Ge , ^{65}As , ^{67}Se , and ^{71}Kr

NUCLEAR ASTROPHYSICS

Star bursts pinned down

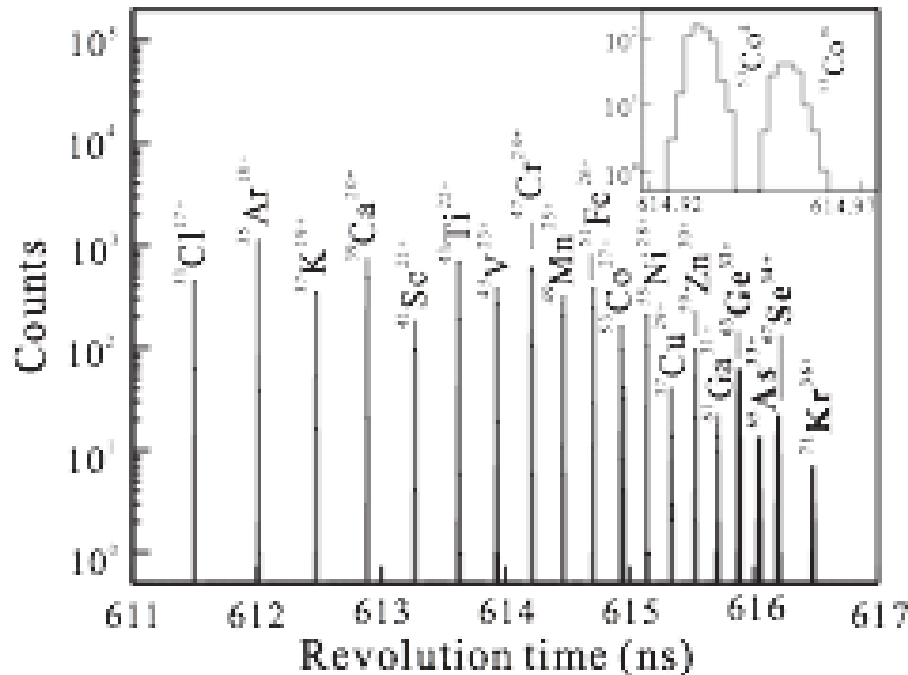
One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As , at a new ion storage ring.

NATURE PHYSICS | VOL 7 | APRIL 2011 | www.nature.com/naturephysics

BRENNPUNKT

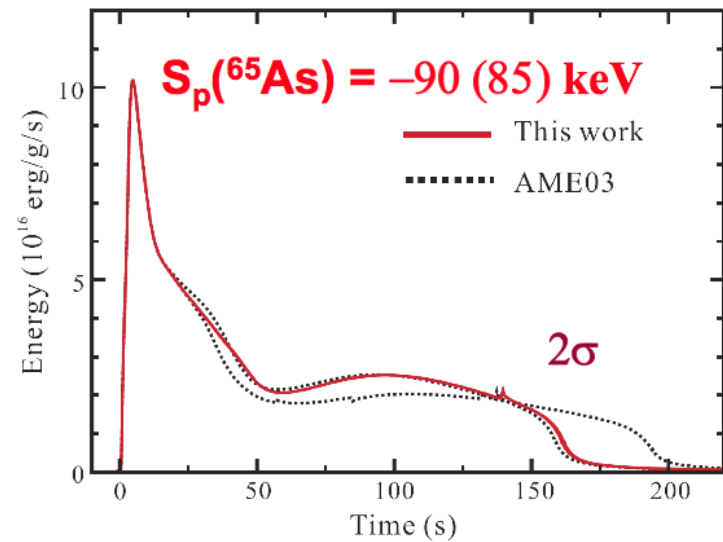
Kein Halten am Wartepunkt

Hochpräzise Massenmessungen erklären die Kernreaktionen bei Ausbrüchen von Röntgenstrahlung.
Physik Journal 10 (2011) Nr. 6



Rate of ^{71}Kr was just 2 ions/day

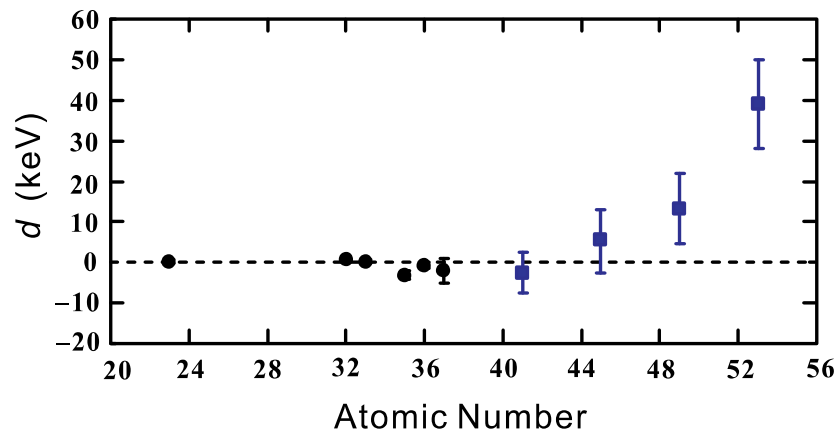
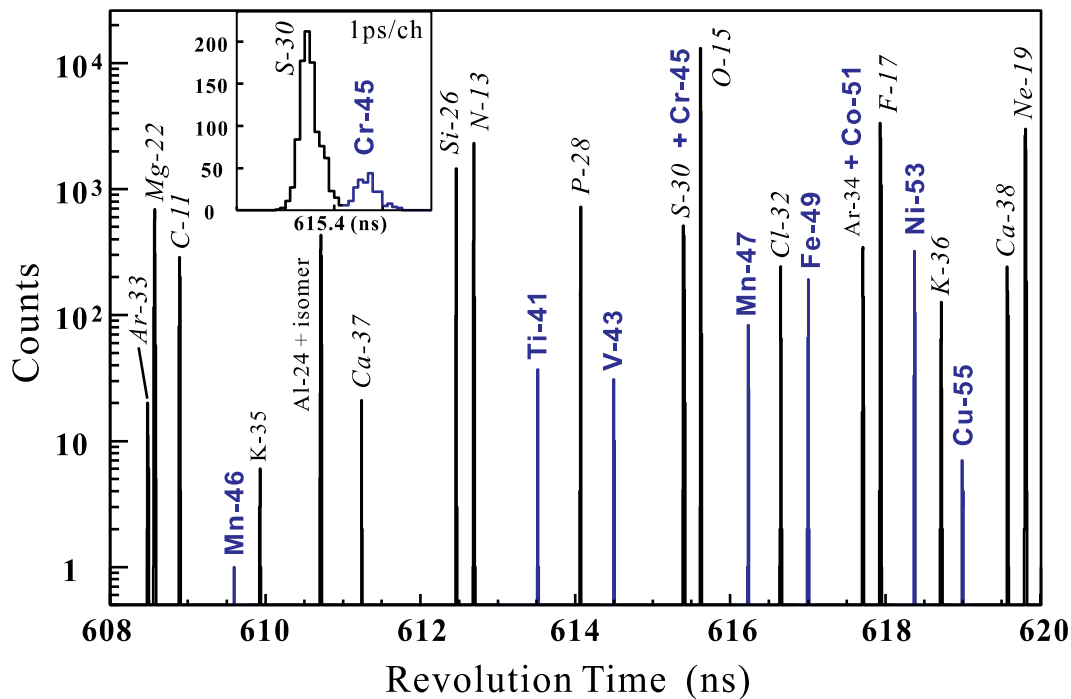
80-90% of the reaction flow passes through ^{64}Ge via proton capture reactions
Light curve shape of Type I x-ray burst



X.L. Tu, et al., Phys. Rev. Lett. 106 (2011) 112501

Mass Measurements of ^{58}Ni Projectile Fragments

New masses of ^{43}V , ^{45}Cr , ^{47}Mn , ^{49}Fe , ^{51}Co , ^{53}Ni , and ^{55}Cu



Isobaric Multiplet Mass Equation

$$ME(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2 \quad dT_z^3 ?$$

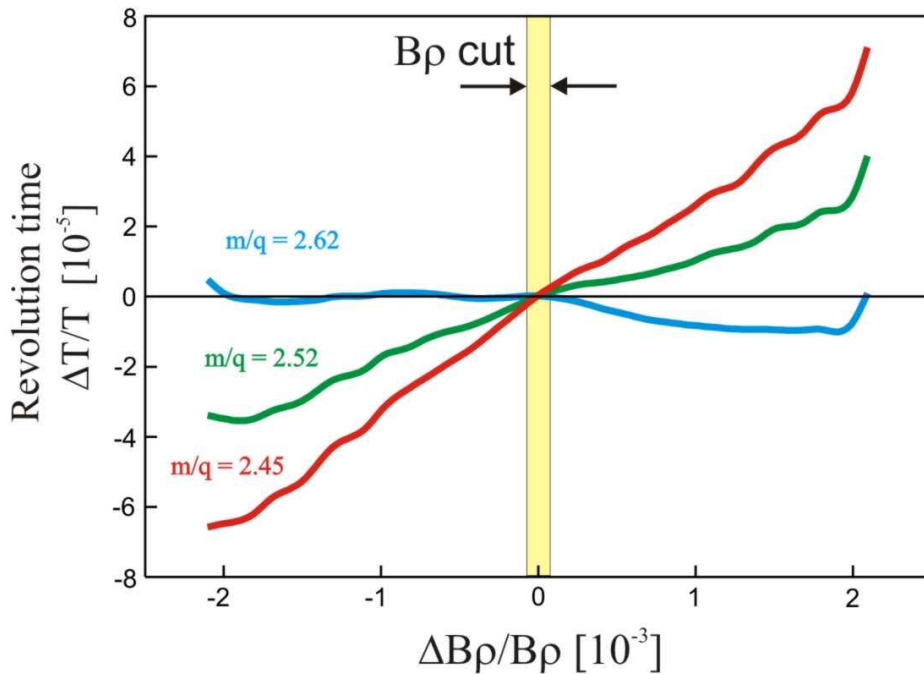
Y.H. Zhang et al., Phys. Rev. Lett. 109 (2012) 102501

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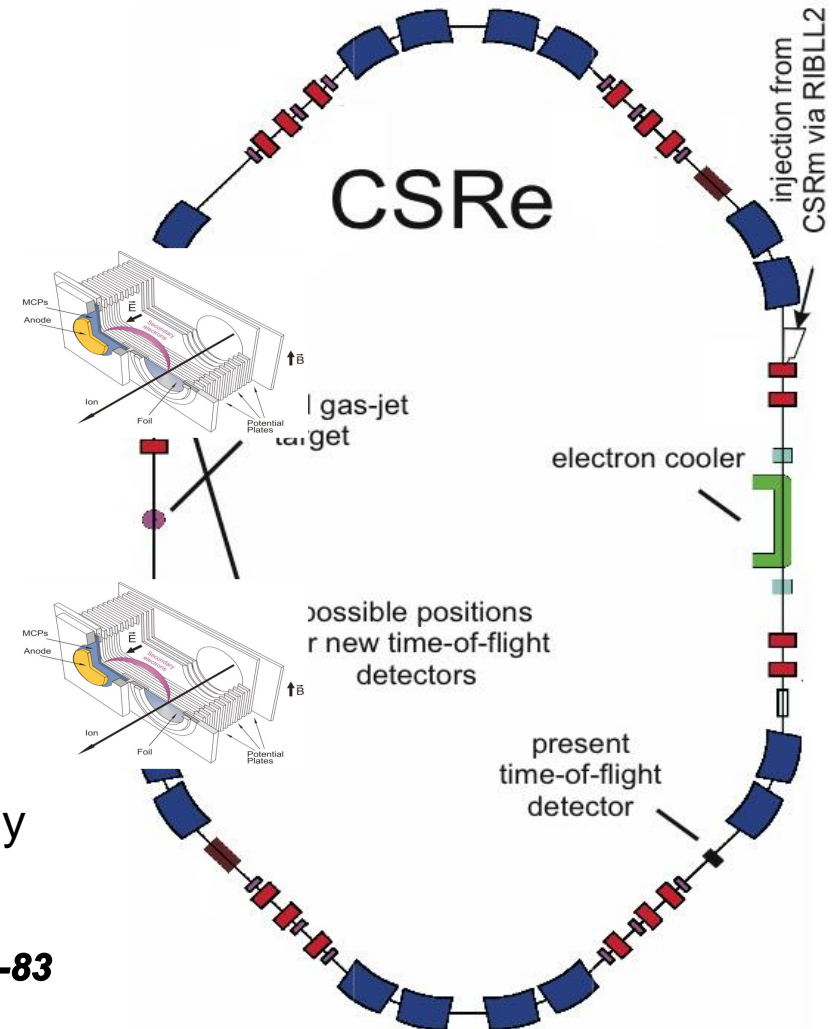
Future Improvements

Magnetic rigidity $B\rho = \frac{m}{q}v\gamma$



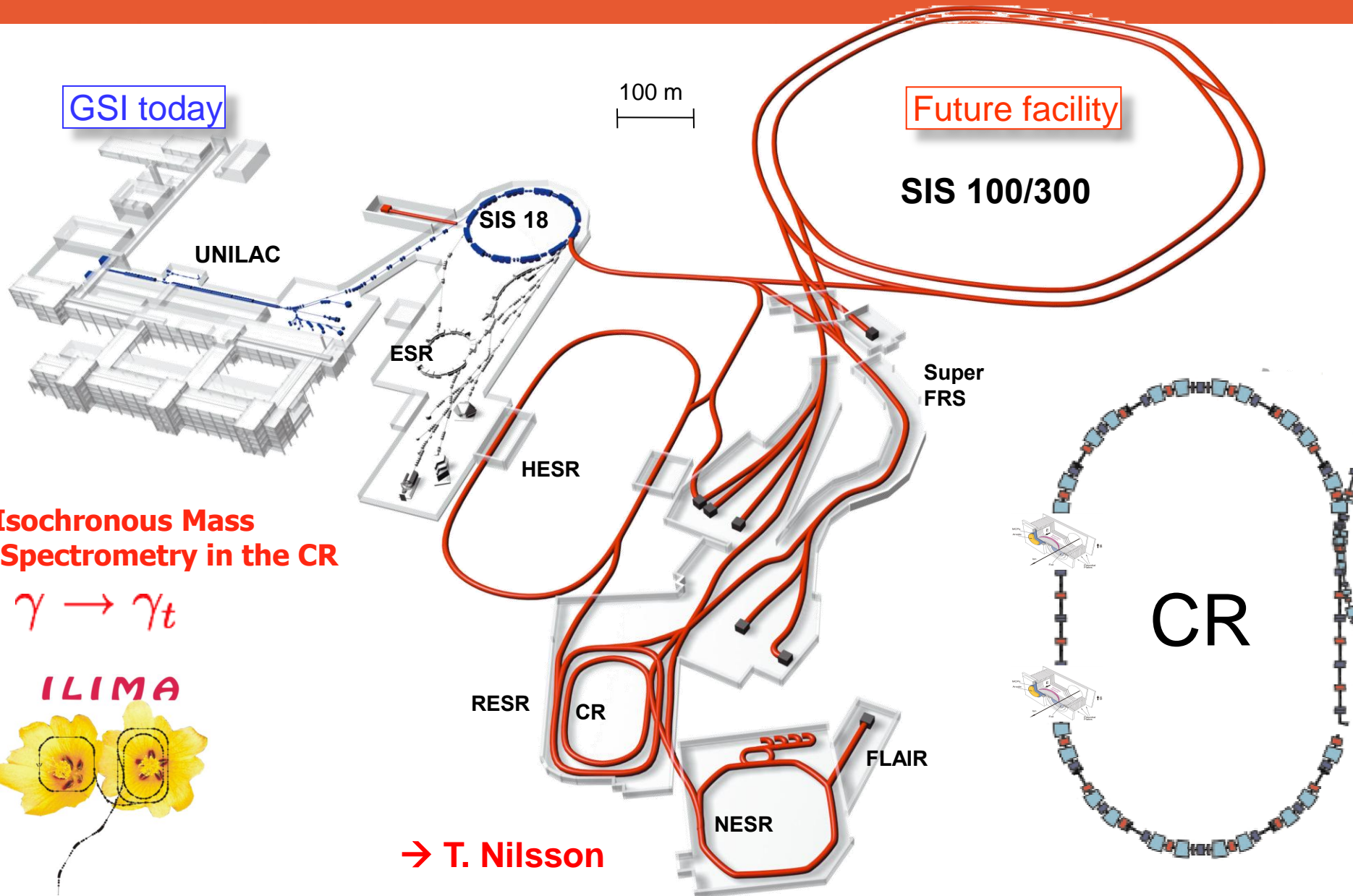
Good isochronous conditions are fulfilled only in a small range

H. Geissel and Yu. Litvinov, J. Phys. G31 (2005) S1779--83



Yu. Litvinov and H.S. Xu, Nucl. Phys. News. 21:2 (2011) 13--7

FAIR - Facility for Antiproton and Ion Research



Isochronous Mass Spectrometry in the CR

$$\gamma \rightarrow \gamma_t$$

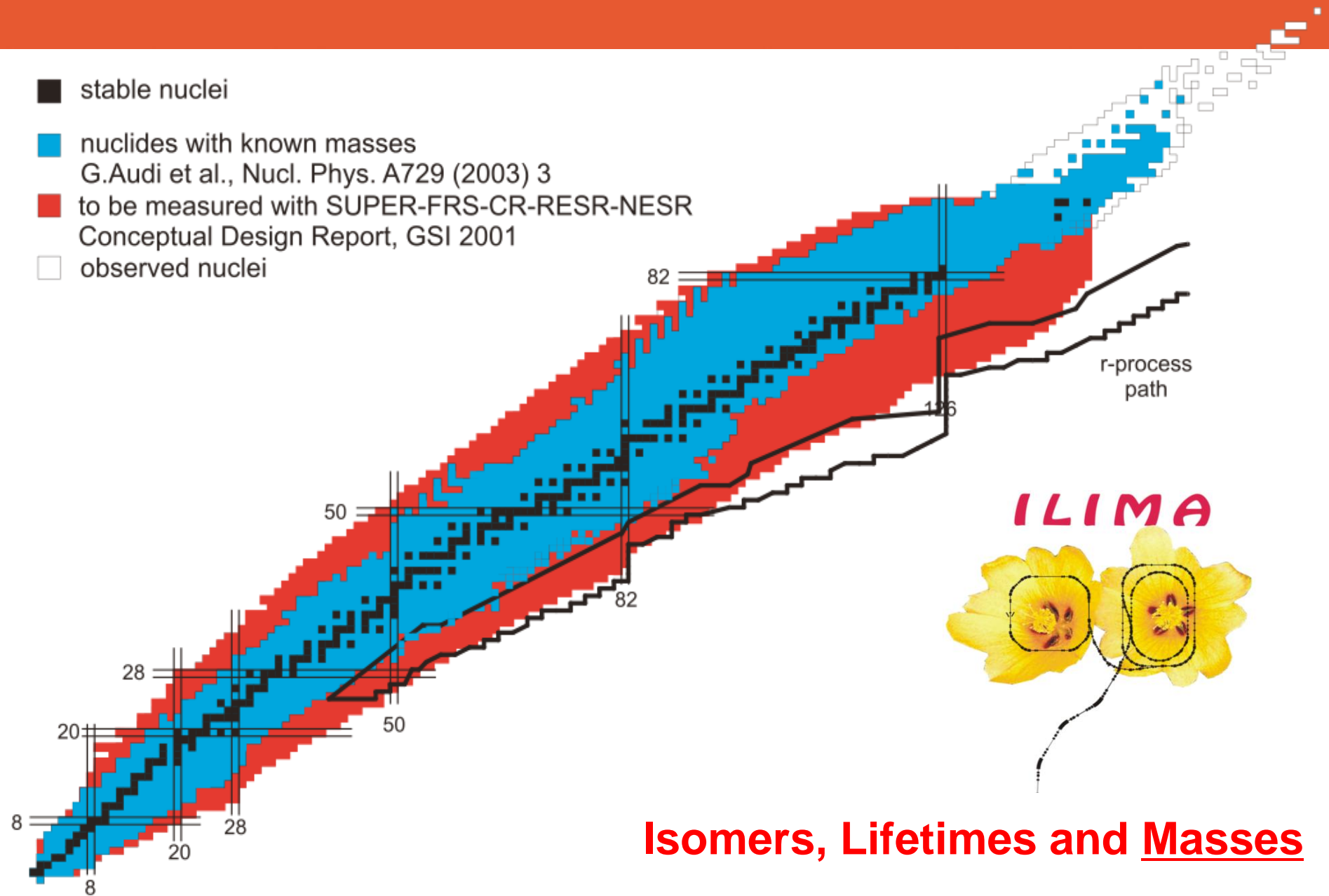
ILIMA



→ T. Nilsson

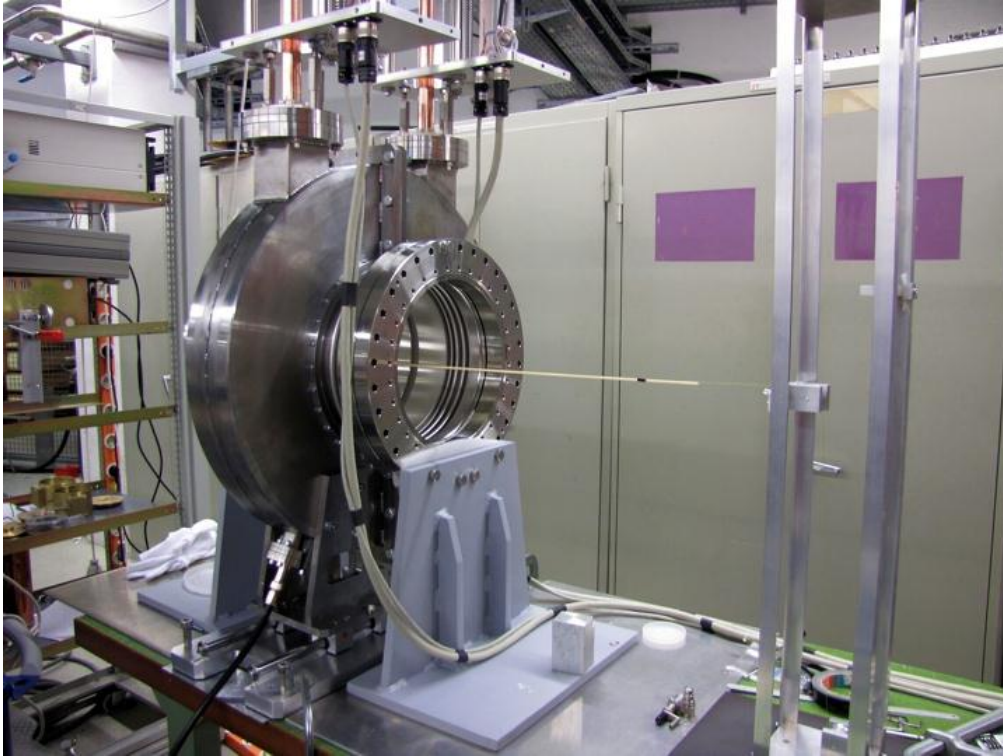
ILIMA: Masses and Halflives

- stable nuclei
- nuclides with known masses
G.Audi et al., Nucl. Phys. A729 (2003) 3
- to be measured with SUPER-FRS-CR-RESR-NESR
Conceptual Design Report, GSI 2001
- observed nuclei

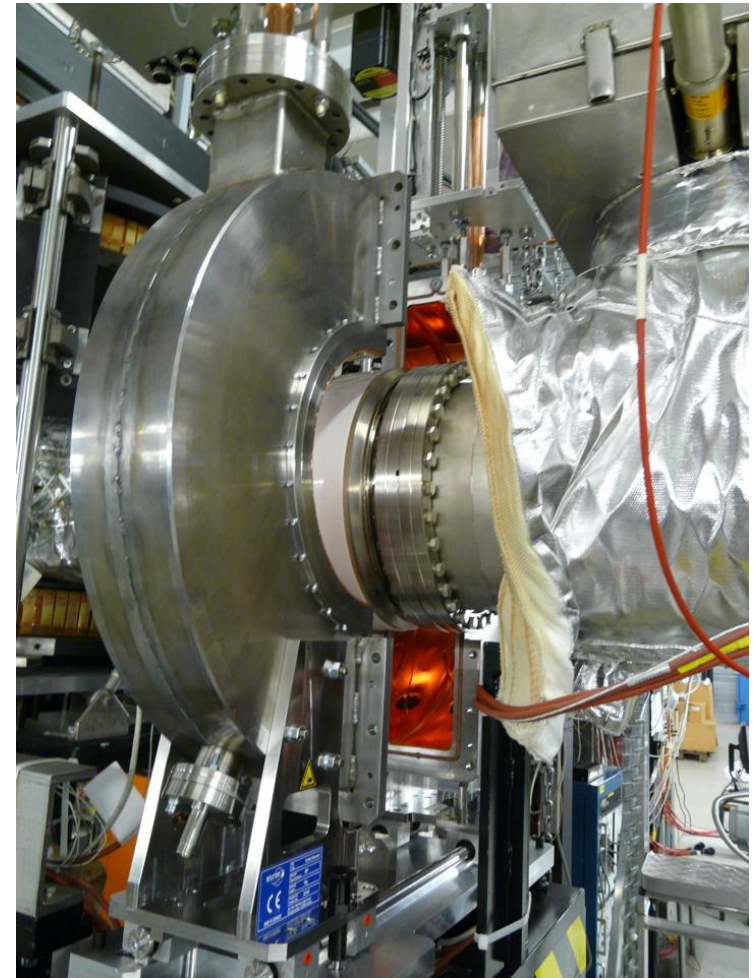


Isomers, Lifetimes and Masses

New Resonant Schottky Cavity



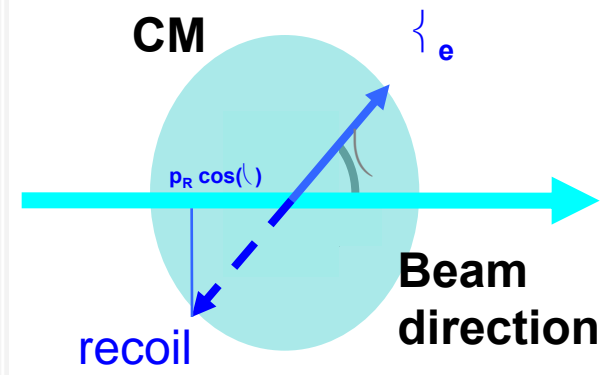
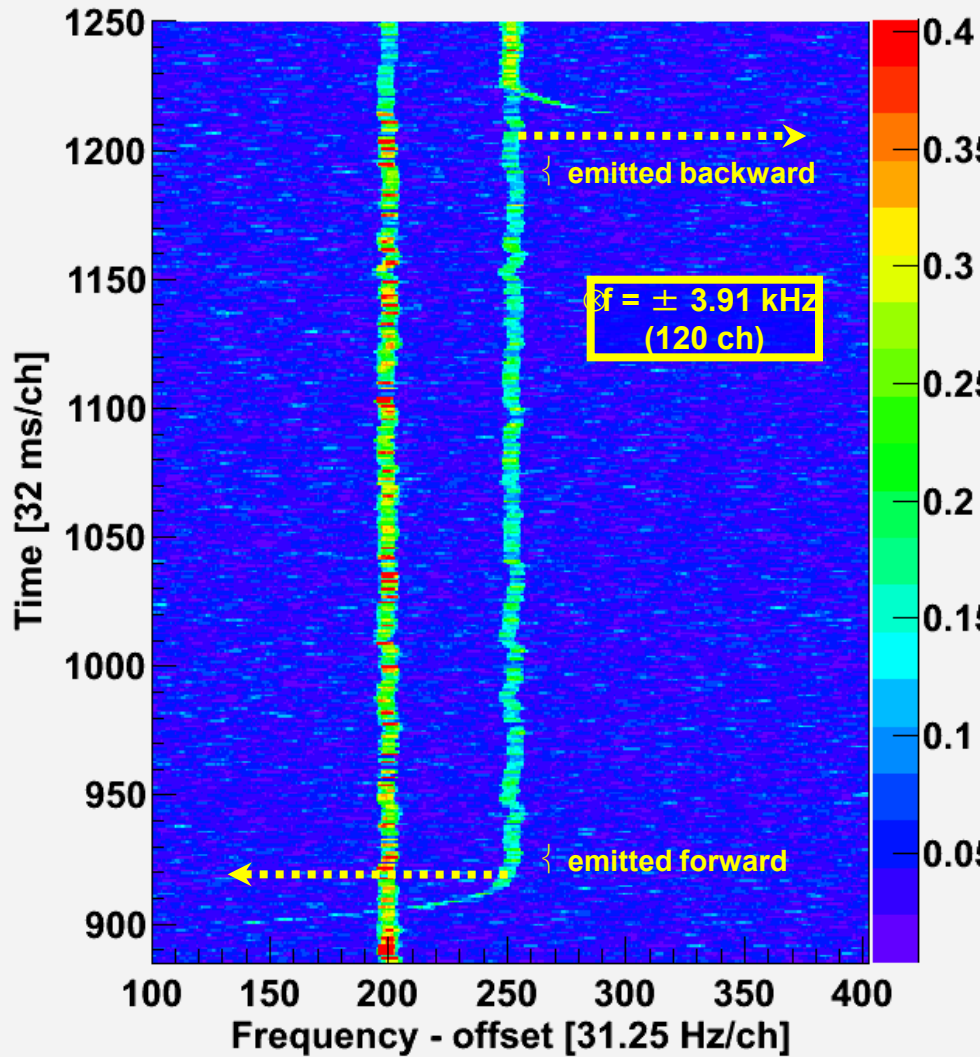
The signal-to-noise ratio is improved by a factor of about 100



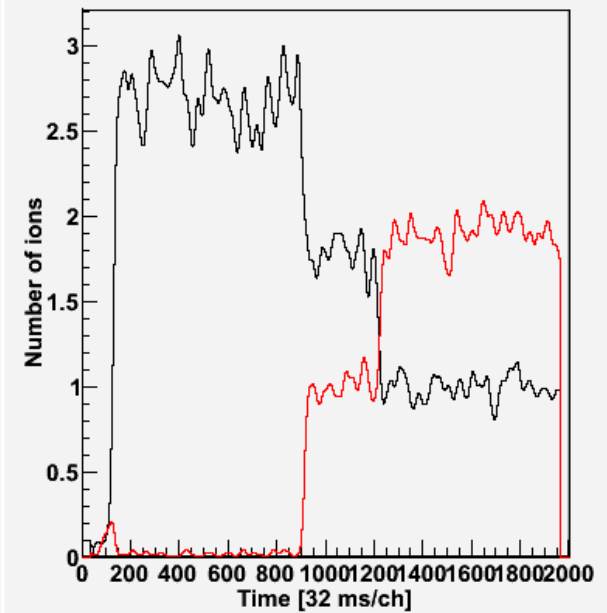
F. Nolden et al., Nucl. Instr. Meth. A659 (2011) 69--77

Three Parent He-Like ^{142}Pm Ions

Time-resolved Schotky Spectrum



Number of parent and daughter ions

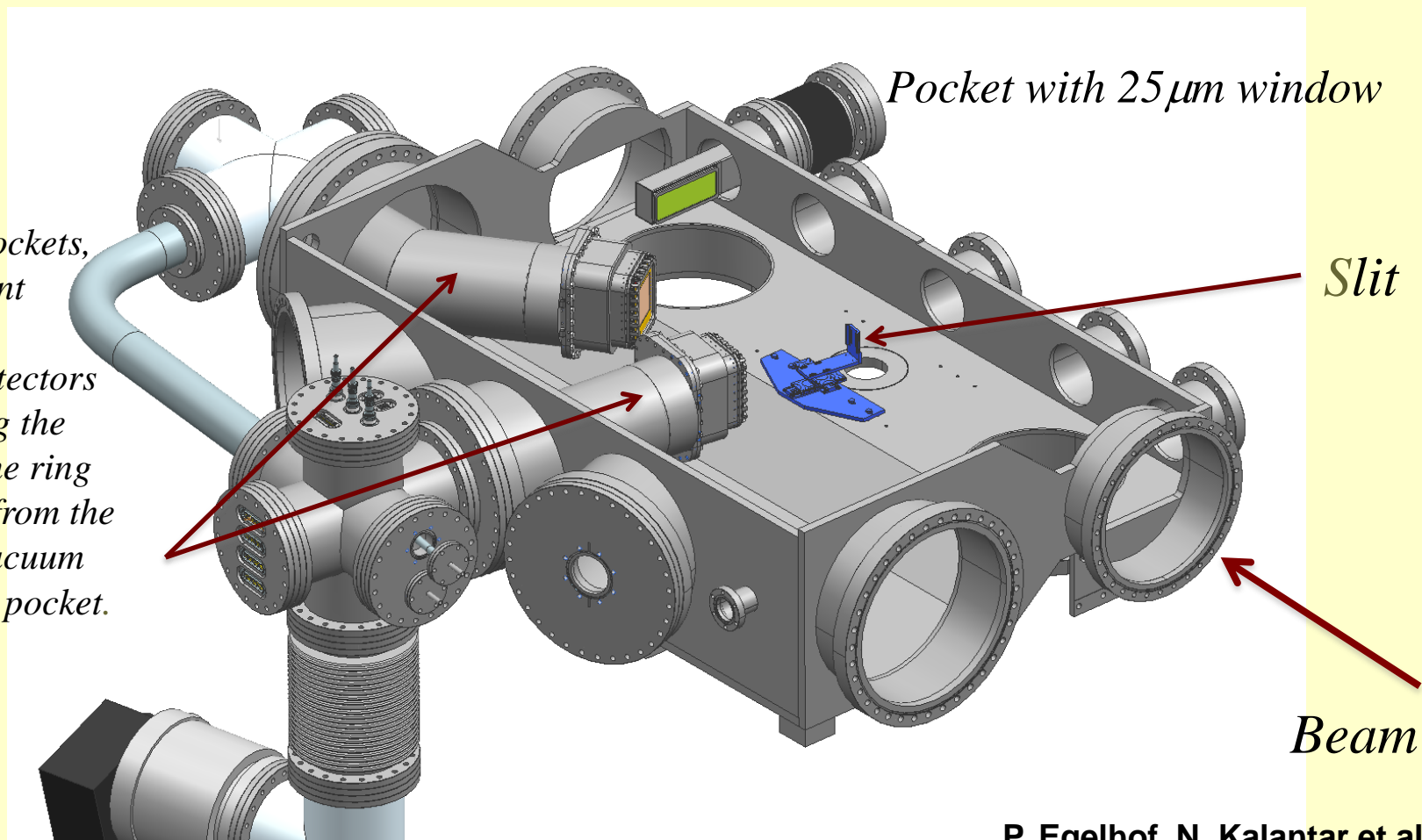


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E105: EXL @ ESR



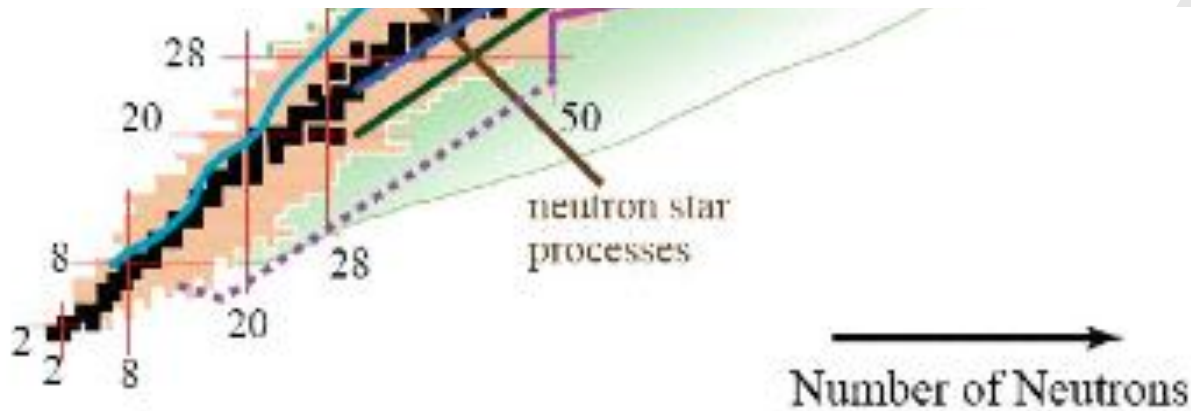
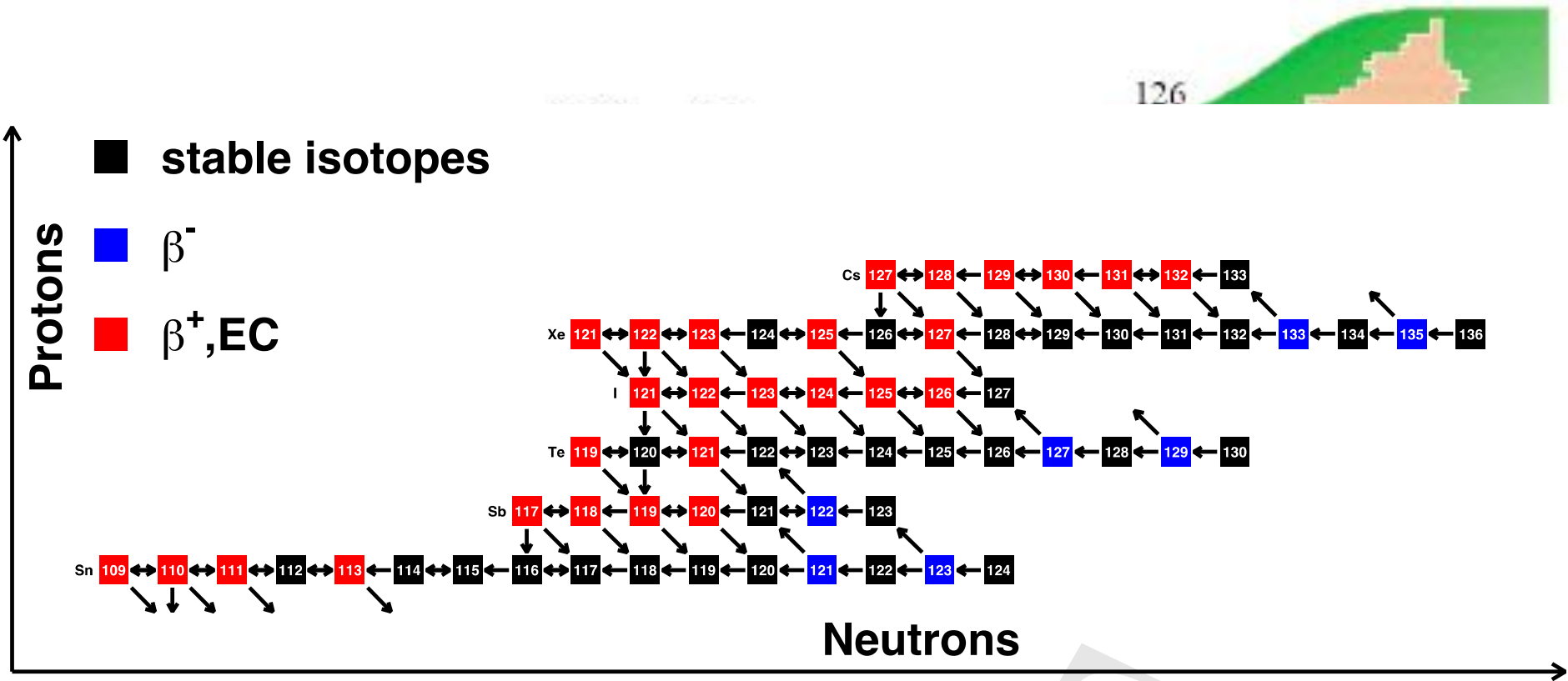
Experimental setup for E105 at ESR



P. Egelhof, N. Kalantar et al.

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Capture reactions for astrophysics



ESR: $^{96}\text{Ru}(p, \text{c})^{97}\text{Rh}$ at 10 MeV/u

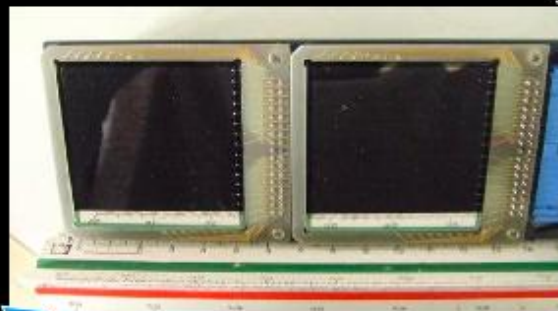
Main Reactions:

$^{96}\text{Ru}(p, g)^{97}\text{Rh}$

$^{96}\text{Ru}(p, n)^{96}\text{Rh}$

$^{96}\text{Ru}(p, a)^{93}\text{Tc}$

$^{96}\text{Ru}^{44+} \rightarrow ^{96}\text{Ru}^{43+}$



DSSSD:

Strips: 16*16

Strip width: 3mm

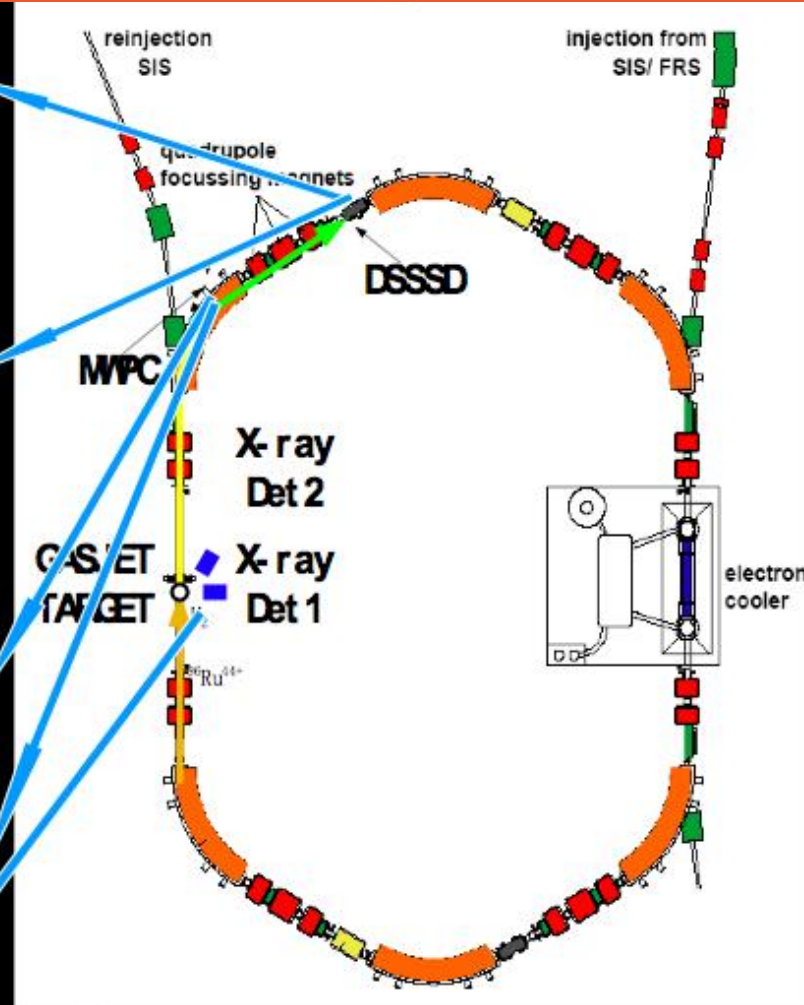


MWPC:

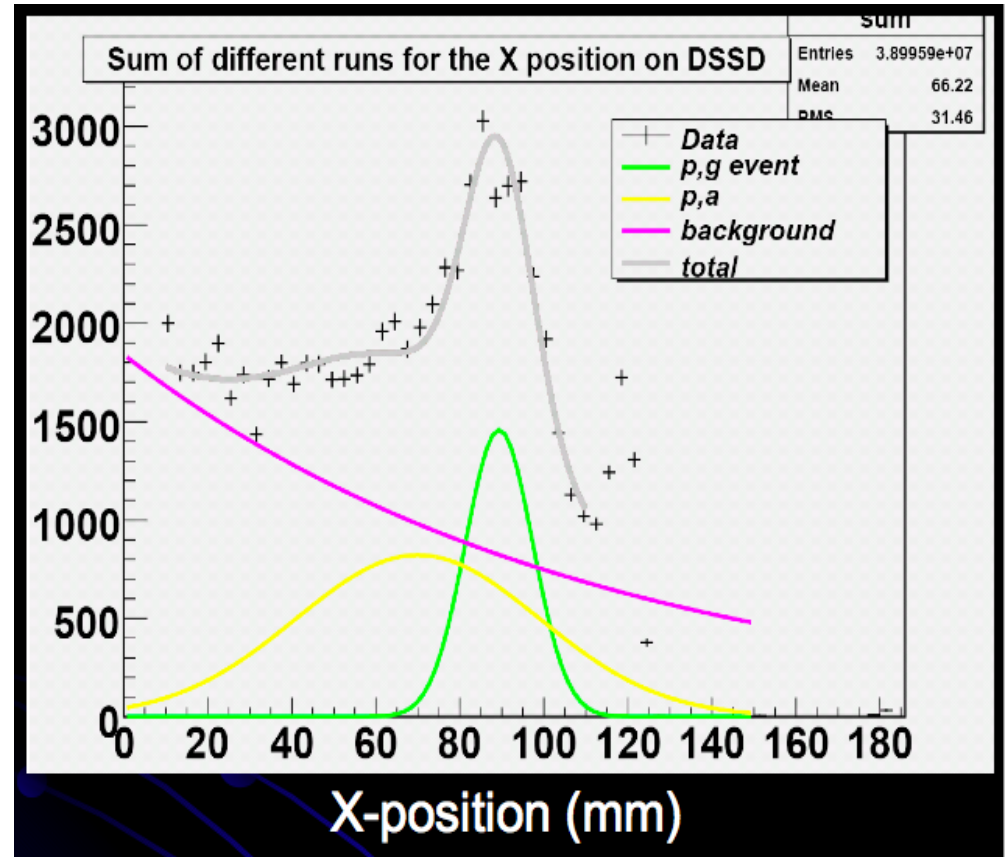
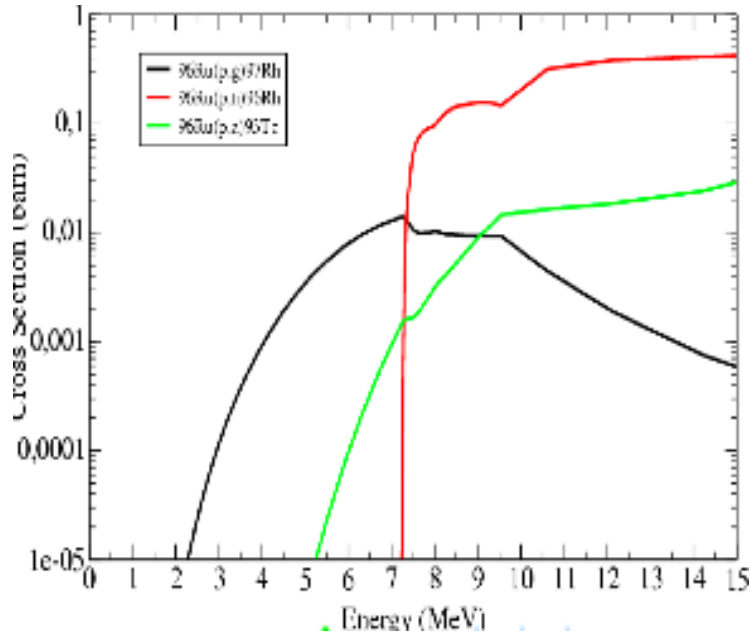
Active area: $\sim 120 \times 20 \text{mm}^2$

X-Ray detector:

GLP Series Planar Germanium, good energy resolution in the 3~300keV range



ESR: $^{96}\text{Ru}(p,\gamma)^{97}\text{Rh}$ at 10 MeV/u



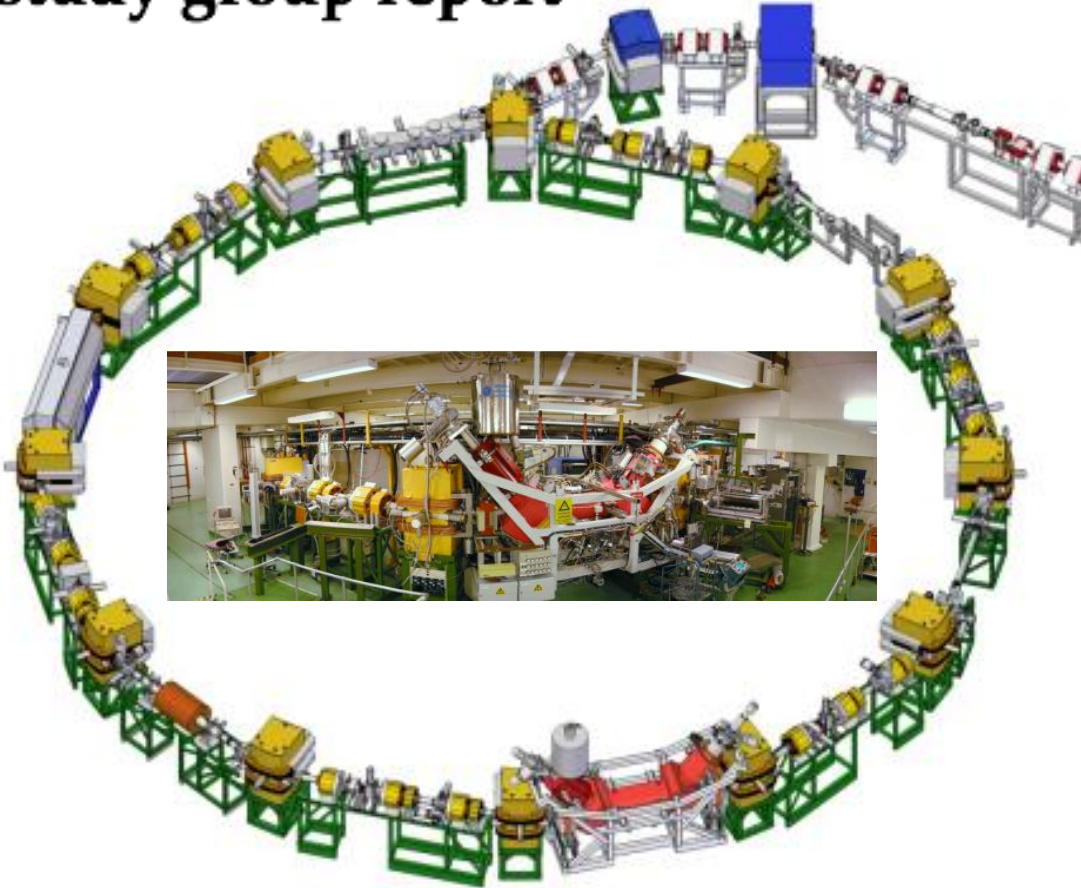
- Measurements directly in the Gamow window of the p-process
- Applicable to radioactive beams
- Clean experimental conditions

$$\sigma_{(p,\gamma)} = 3.6(5) \cdot 10^{-3} b$$

Q. Zhong et al., *J. Phys. Conf. Series* 202 (2010) 012011
 R. Reifarh et al., *GSI Experimental Proposal*

CRYRING@ESR

CRYRING@ESR: A study group report



Study Group

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Angela Bräuning-Demian
Hakan Danared
Wolfgang Enders
Mats Engström
Bernhard Franzke
Anders Källberg
Oliver Kester
Michael Lestinsky
Yuri Litvinov
Markus Steck
Thomas Stöhlker

CRYRING@ESR: Highly-Charged Ions at Low Energies

- **Spectroscopy for tests of QED**

- High-precision x-ray spectroscopy
 - 1s-Lamb-Shift
 - Two-Electron-QED
- Recoil ion momentum spectroscopy
 - Highly-excited states
- Laser spectroscopy
- Recombination spectroscopy with high resolution

- **Atomic collisions**

- Sub-femtosecond correlated dynamics
- Unexplored regime: strong perturbation Q/v

- **Nuclear Physics at low-energies**

- exotic nuclear decay modes
- astrophysical reactions
- Transfer reactions at Coulomb barrier

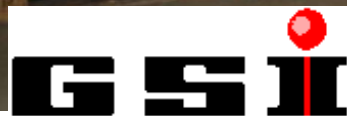
Features@Cryring

- Low-energy and electron cooled beams
- Electron cooling with adiabatic expansion
- High-luminosity for in-ring experiments
- Very fast deceleration 7 T/s
- Internal jet and electron target
- Slow extraction

CRYRING@ESR



November 2012



B. Aurand,[?] V. Bagnoud,¹ H. Beyer,¹ S. Bishop,^a C. J. Bostock,² C. Brandau,^{b,c}
A. Bräuning-Demian,¹ I. Bray,² T. Davinson,^d P. Egelhof,¹ M. Engström,ⁿ C. Enss,^s
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J. Goullon,^f R. Grisenti,¹ A. Gumberidze,^{b,c} S. Hagmann,¹ M. Heil,¹ A. Heinz,^e R. Hubele,^f
P. Indelicato,^t A. Källberg,ⁿ C. Kozhuharov,¹ T. Kühl,¹ M. Lestinsky,¹ D. Liesen,¹
Yu. A. Litvinov,^{1,f} R. Martin,^j R. Moshhammer,^f A. Müller,^g S. Namba,³ P. Neumeyer,^b
T. Nilsson,^e G. Paulus,^{i,j} R. Reifarh,^{1,h} R. Reuschl,^{b,c} S. Schippers,^g H. Schmidt,ⁿ R. Schuch,ⁿ
M. Schulz,^{p,h} V. Shabaev,[?] A. Simonsson,ⁿ J. Sjöholm,ⁿ Ö. Skeppstedt,ⁿ K. Sonnabend,^h
U. Spillmann,¹ K. Stiebing,^h Th. Stöhlker,^{1,i,j} A. Surzhykov,^q E. Träbert,^k M. Trassinelli,^u
S. Trotsenko,^j I. Uschmann,^{i,j} P. M. Walker,^{l,m} G. Weber,^{1,j} D. F. A. Winters,¹ P. J. Woods,^d
H. Y. Zhao,[?] *et al.*

This text is an an early editing stage and is not authorized by the
respective coauthors!

Editors:

M. Lestinsky et al.

Atomic Physics Division
GSI Helmholtzzentrum für Schwerionenforschung
D-64291 Darmstadt

October 23, 2012

\$Revision: 1.9 \$ \$Date: 2012-08-09 12:52:22 \$

Presently:

**63 Scientists from
24 Institutions in
10 Countries**

More contributions are expected

New contributions are welcome



- Half-life measurements of ^7Be in different atomic charge states
- Capture reactions for astrophysical p-process
- Nuclear structure through transfer reactions
- Long-lived isomeric states
- Atomic effects on nuclear half-lives
- Nuclear effects on atomic decay rates
- Di-electronic recombination on exotic nuclei
- Neutrino physics; Tests for the neutrino beam project
- Purification of secondary beams from contaminants
-

TDR positively evaluated by

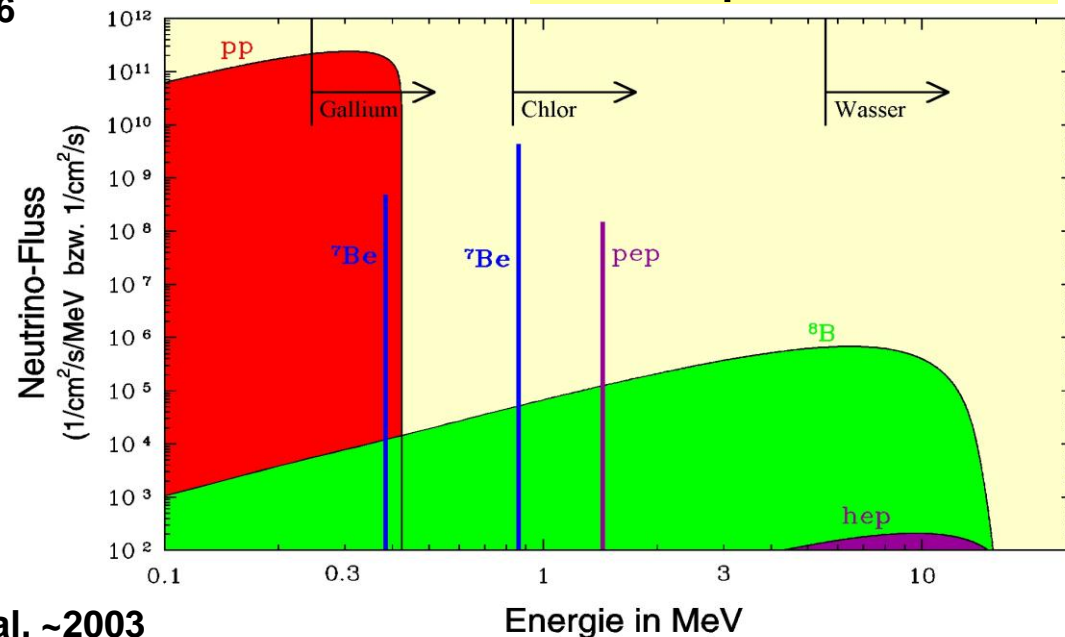
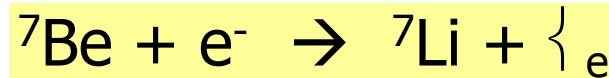
→ R. Catherall

The fate of ${}^7\text{Be}$ in the Sun

J.N. Bahcall, Phys. Rev. C 128 (1962) 1297
 I. Iben, K. Kalata, J. Schwartz, ApJ 150 (1967) 1001
 J.N. bahcall, C.P. Moeller, ApJ 155 (1969) 511
 C.W. Johnson, E. Kolbe, S.E. Koonin,
 K. Langanke, ApJ 392 (1992) 320
 A.V. Gruzinov, J.N. Bahcall, ApJ 490 (1997) 437
 A.V. Gruzinov, J.N. Bahcall, ApJ 504 (1998) 996
 and many others

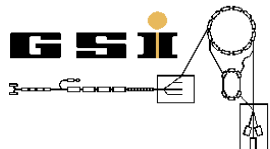
$T_{1/2} ({}^7\text{Be}^{0+}) \sim 53.22$ days
 $T_{1/2} ({}^7\text{Be}^{4+}) \sim \text{infinity}$
 $T_{1/2} ({}^7\text{Be}^{3+}) \sim 106$ days
 $T_{1/2} ({}^7\text{Be}^{2+}) \sim 53$ days
 $T_{1/2} ({}^7\text{Be}^{1+}) \sim 53$ days

About 20% of ${}^7\text{Be}$ EC decay rate in the Sun are due to bound electrons

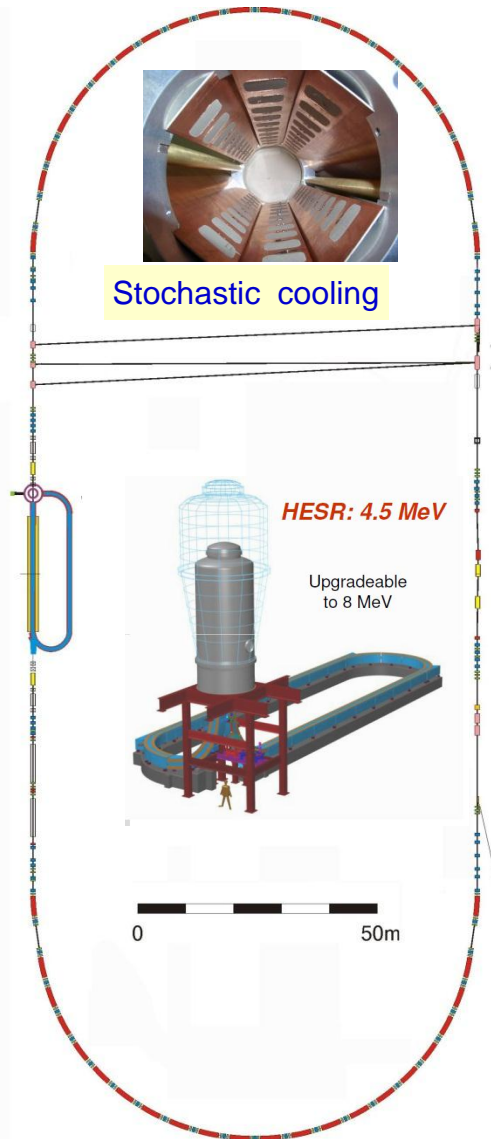


C. Rolfs et al., suggestion for an ESR proposal, ~2003
 C. Rolfs, W. Rodney, Cauldrons in the Cosmos, 1988

**TSR@ISOLDE will be the best
 place to perform such
 experiments!**



The High Energy Storage Ring HESR



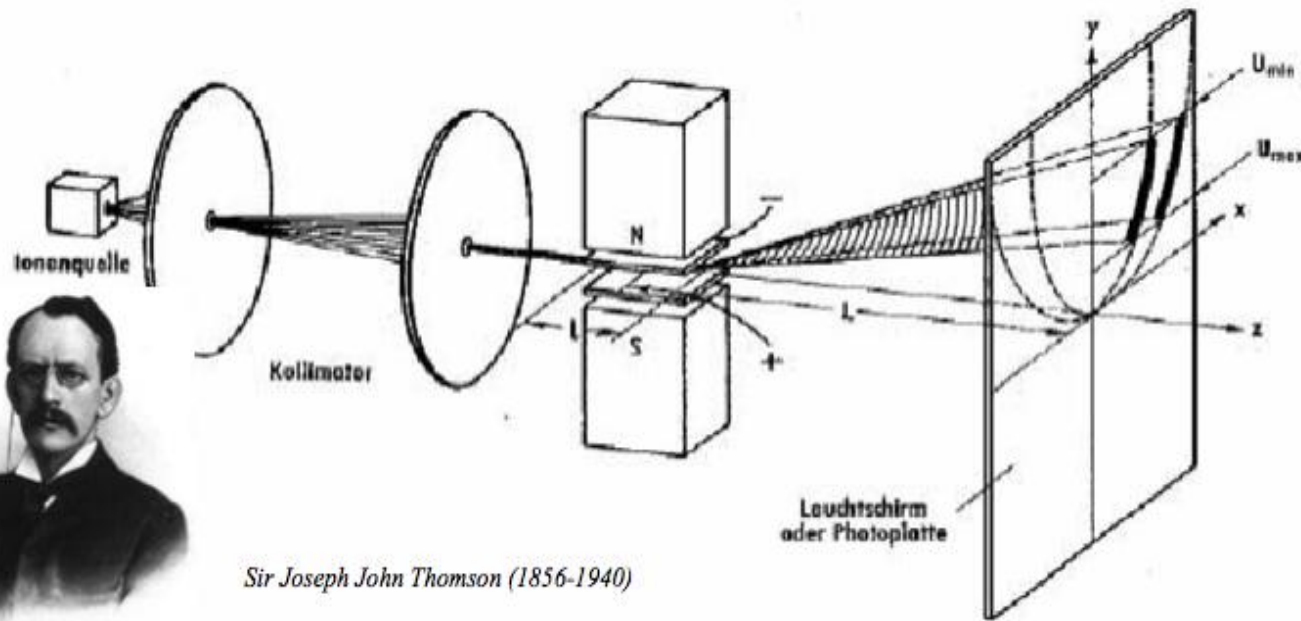
SPARC Experiments at the HESR: A Feasibility Study

sparc
Small Particle Accelerator Research Collaboration

Thomas Stöhlker^{1,2,3}, Reinhold Schuch⁴, Siegbert Hagemann^{1,5}, Yuri A. Litvinov^{1,2}
for the SPARC Collaboration⁷
Christina Dimopoulou¹, Alexei Dolinskii¹, & Markus Steck¹

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1913 - J. Thompson, Discovery of Isotopes (Nobel prize 1906)



- **Special Issue of Int. J. Mass Spectr. “Birth of Mass Spectrometry”**
- **DPG Symposium “100 Years of Mass Spectrometry”, Hanover, 2013**
- **513. WE-Heraeus Seminar: “Astrophysics with Ion-Storage Rings”, January 2013**
- **530. WE-Heraeus Seminar on “Nuclear Masses and Nucleosynthesis”, April 2013**
- **New Atomic Mass Evaluation (AME2012) is to appear in 2013 December 2012**

Many-many thanks to all my colleagues from all over the world !!!

