Applying Heavy-Ion Storage Rings for Precision Studies at the Intersection of Atomic, Nuclear and Astrophysics

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For NuSTAR/ILIMA, SPARC and NUCAR Collaborations

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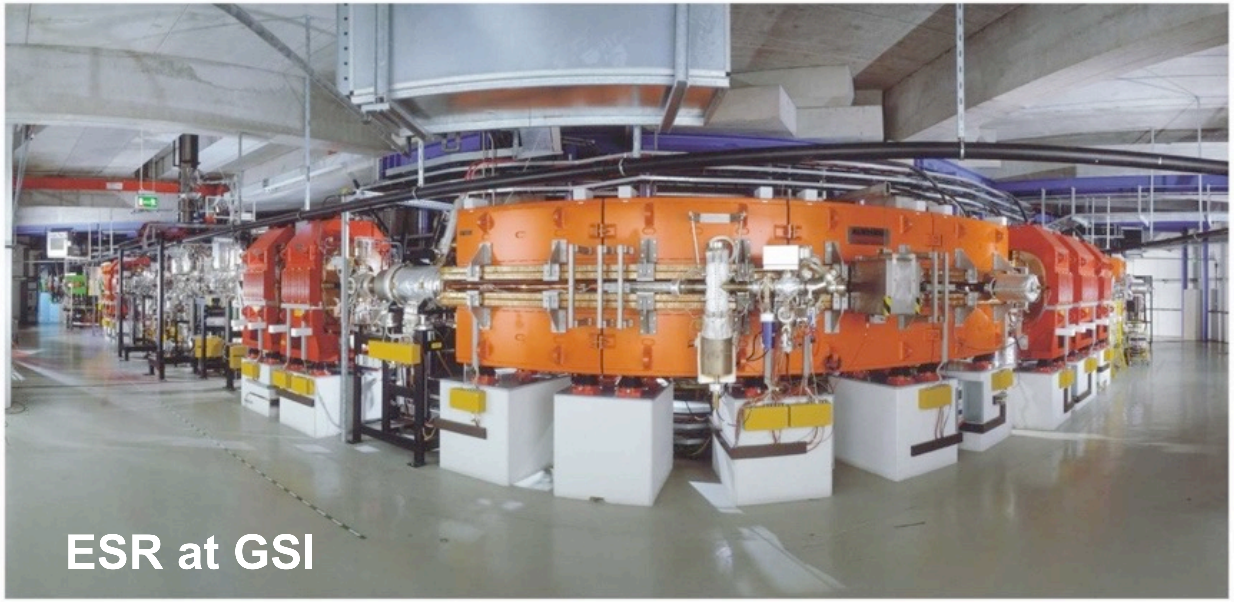
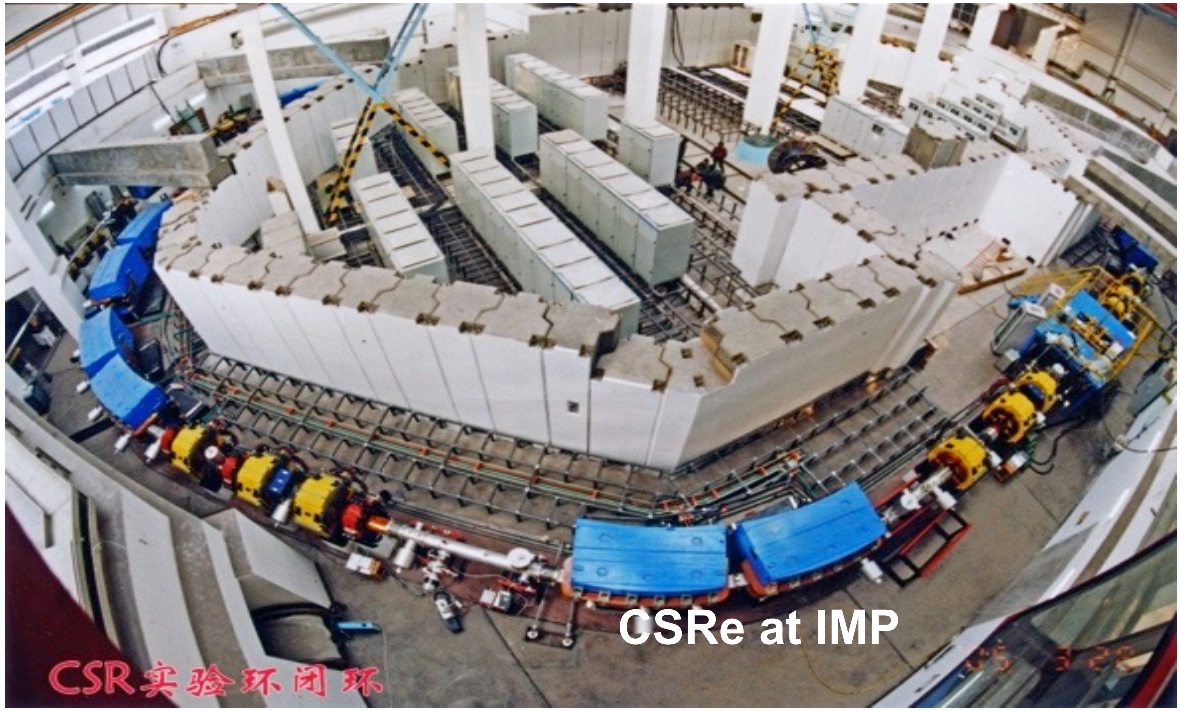
FAIR Phase-0 Research Program

Nuclear Physics at Storage Rings

Storage Rings stand for:

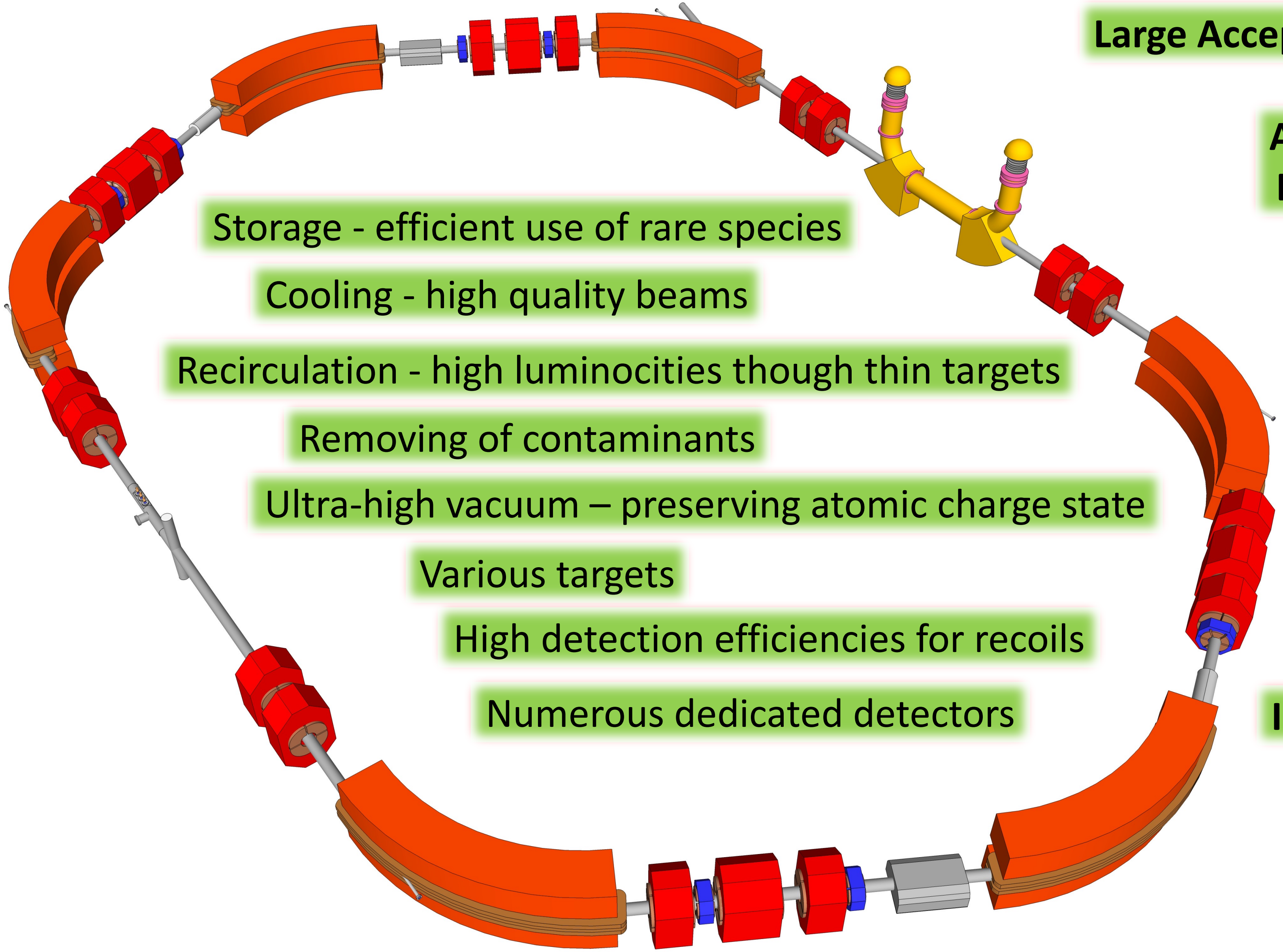
Single-particle sensitivity
High revolution frequencies
Broad-band measurements
High atomic charge states
High resolving power





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

Why storage rings? - Versatile Capabilities



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

Various targets

High detection efficiencies for recoils

Numerous dedicated detectors

Large Acceptance

Beam Accumulation

Acceleration/ Deceleration

Beam Cooling:
- Stochastic
- Electron
- (Laser)

UHV

Beam Bunching

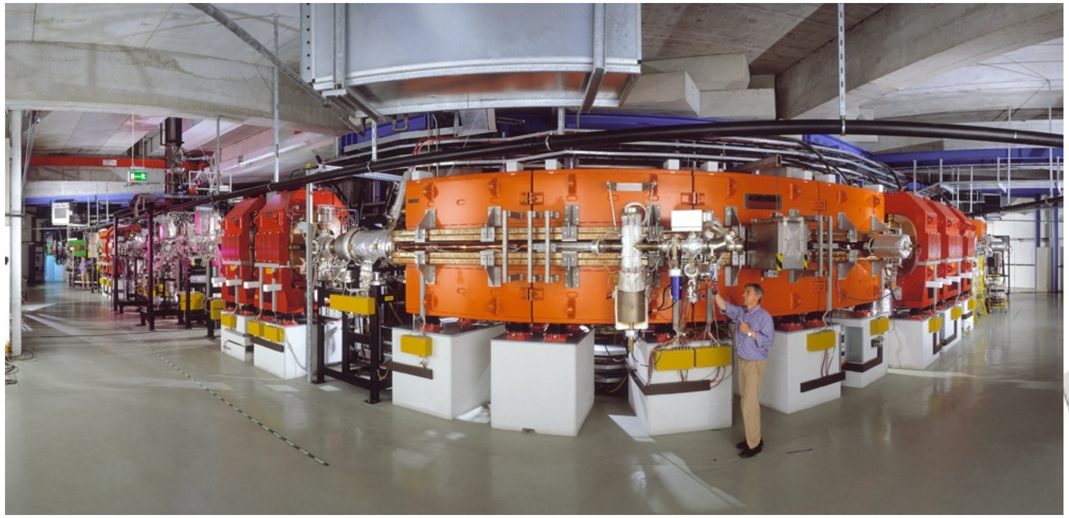
Detection:
- Electrons
- Photons
- Recoils

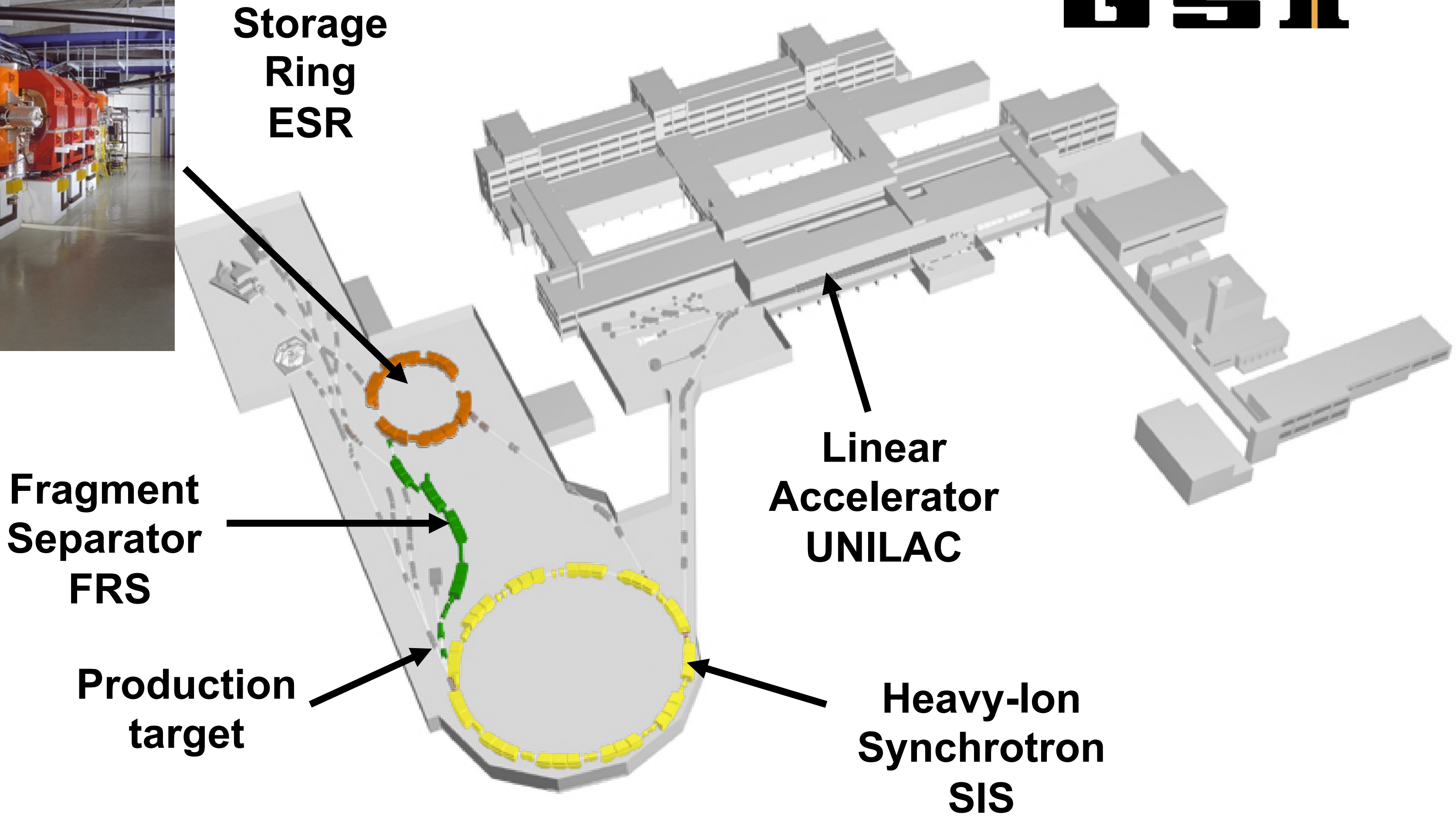
Various targets:
- Electrons
- Photons
- Atoms
- (Ions)
- (Neutrons)

Internal Gas-Jet Target

Non-destructive particle detection

Radioactive Ion Beam Facility at GSI





Experimental Storage Ring (ESR)

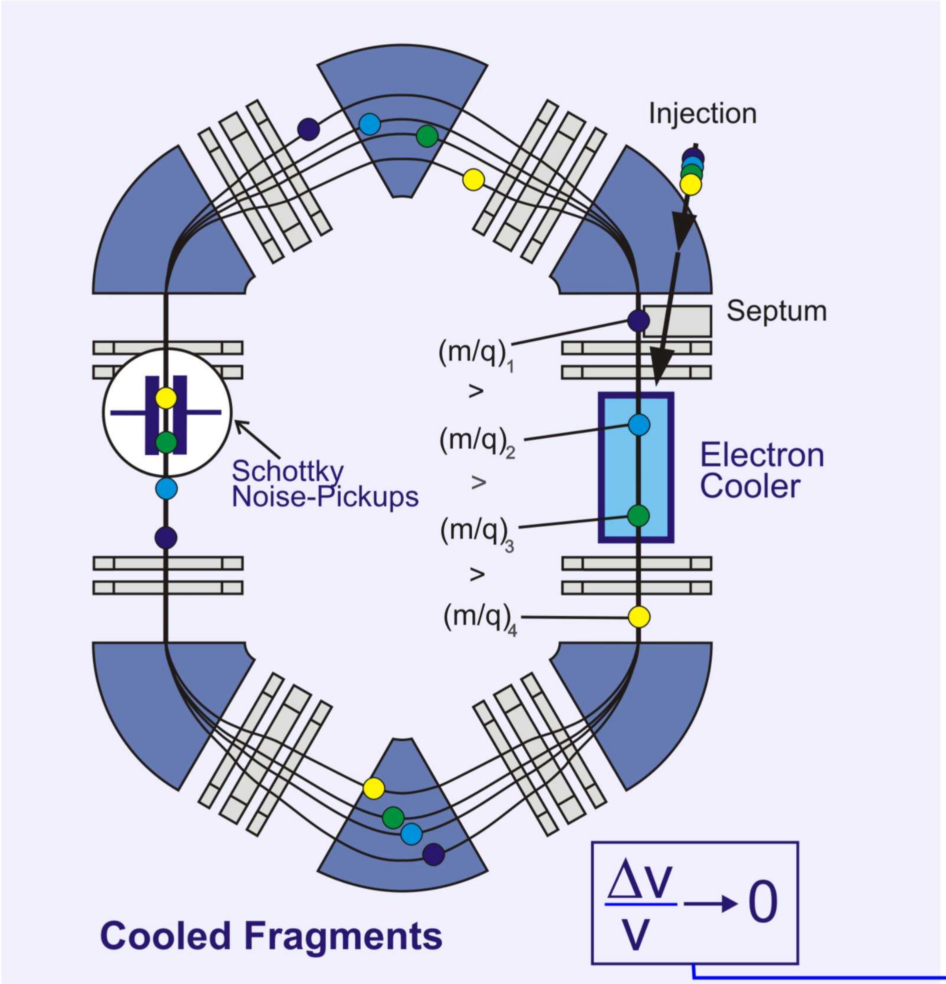
In operation since 1990
Circumference = 108.3 m
UH Vacuum = 10^{-10}—10^{-12} mbar
Electron, stochastic cooling
Energy range = 3 – 400 MeV/u
Slow and fast extraction

Schottky and Isochronous Storage RIng Mass Spectrometry

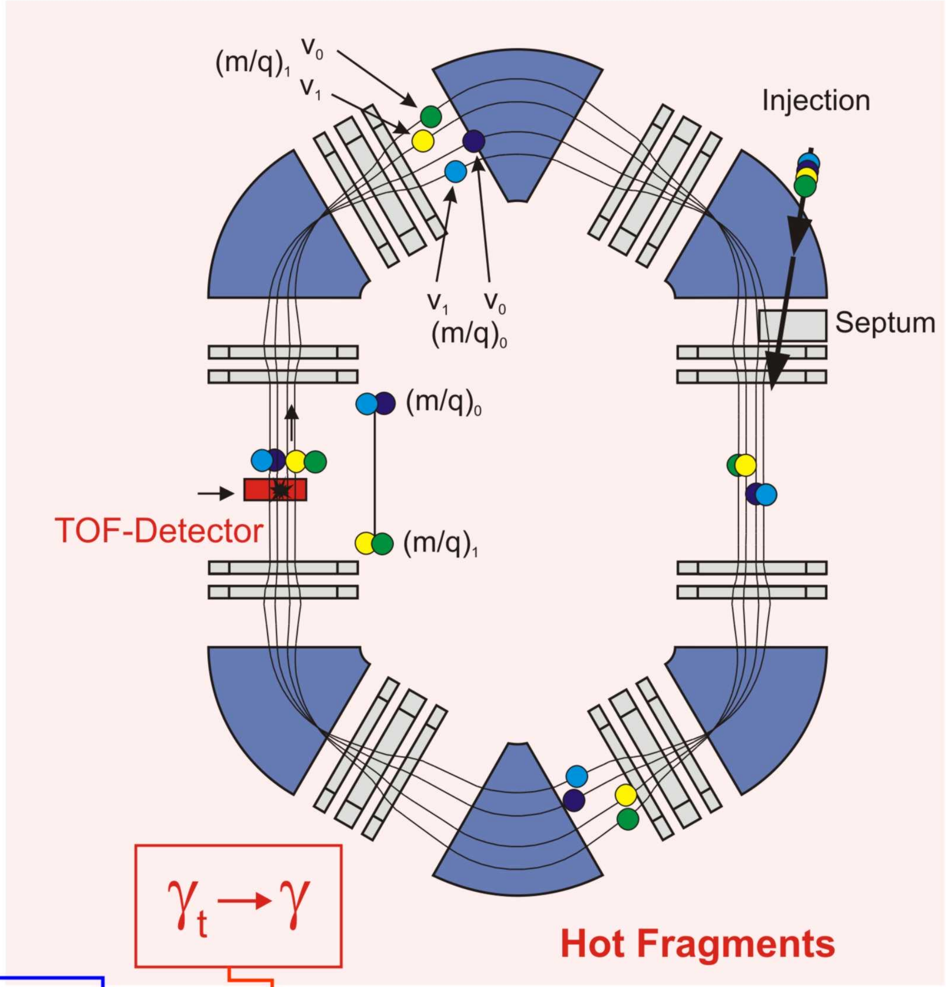
Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

SCHOTTKY MASS SPECTROMETRY



ISOCHRONOUS MASS SPECTROMETRY

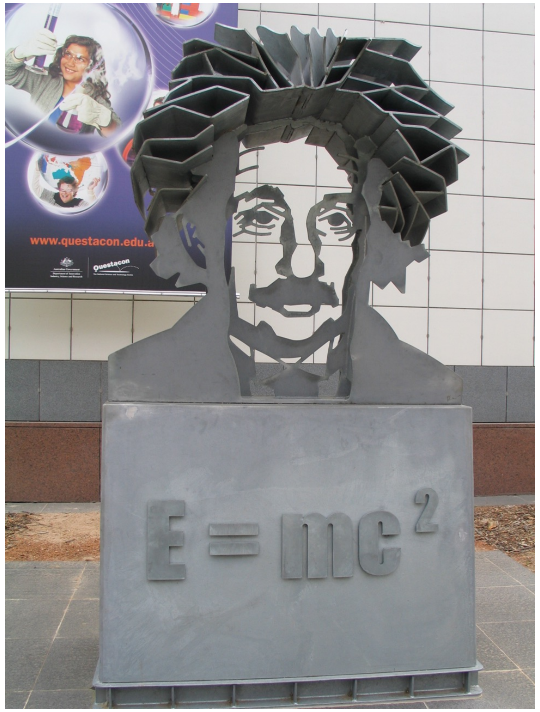


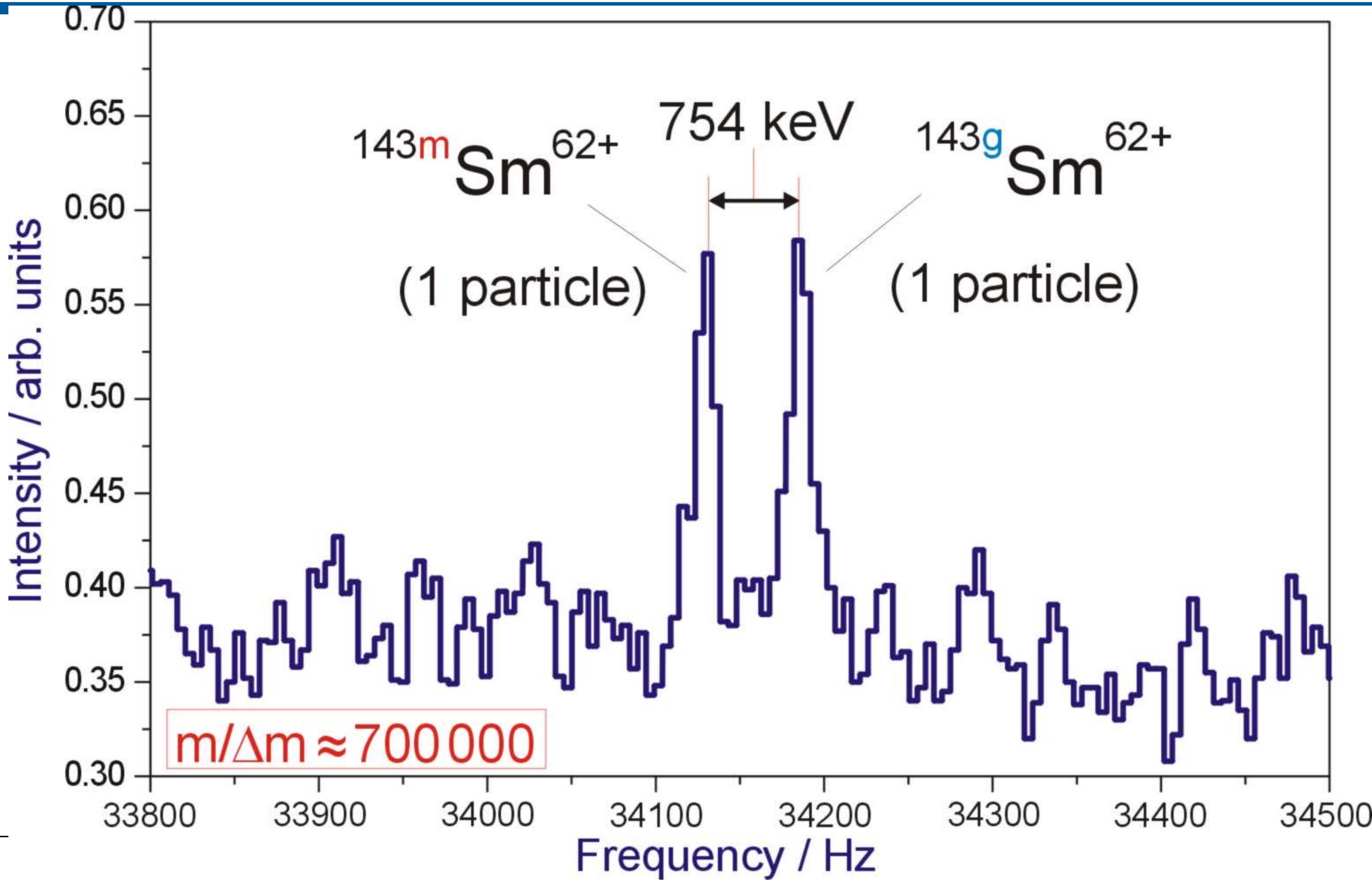
Destructive Detectors (foil-based Secondary electron detectors)

No cooling

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

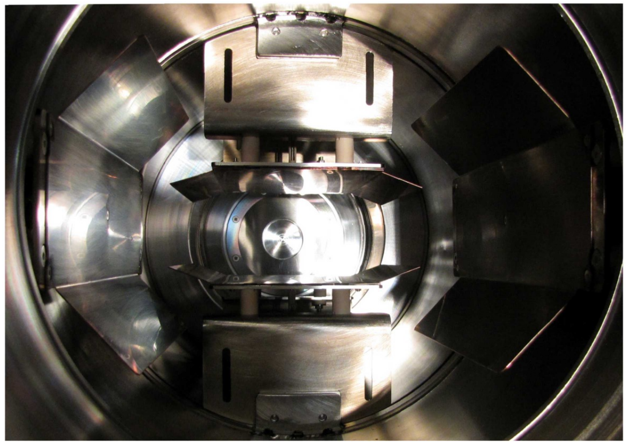
Frequency Spectrum



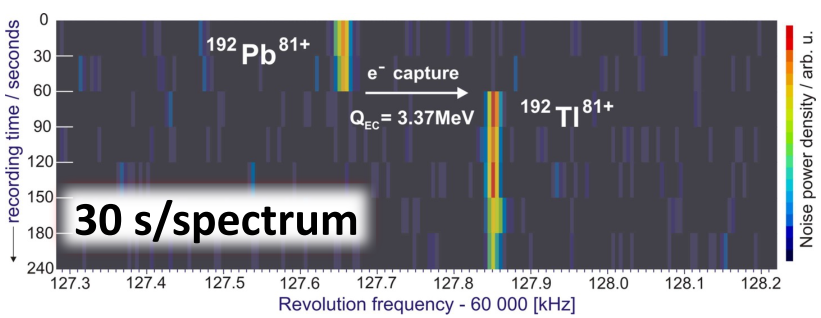


Non-Destructive Particle Detection

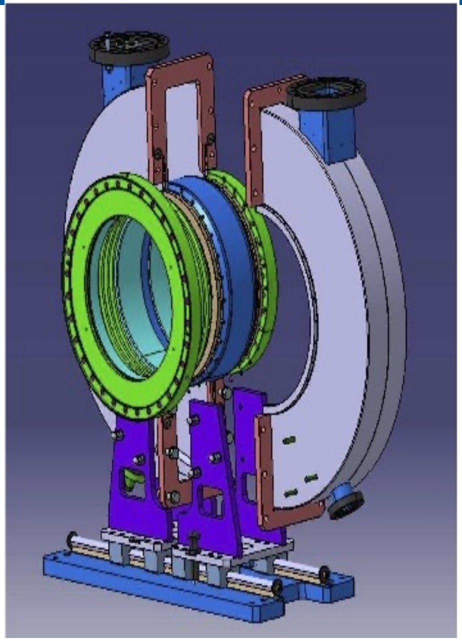
FAIR Phase-0 Research Program



1992

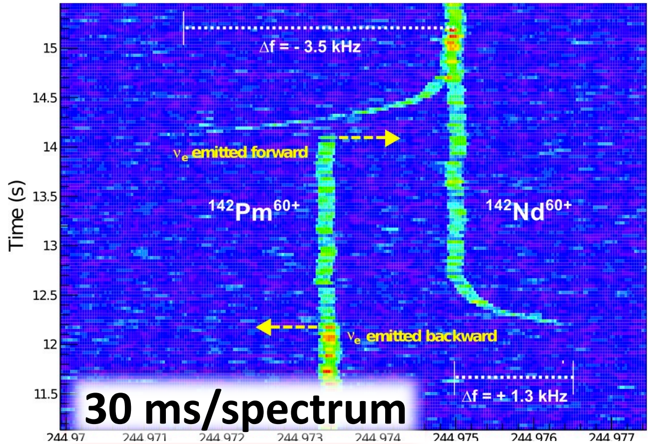


- Masses and lifetimes ($T_{1/2}$>5 s)

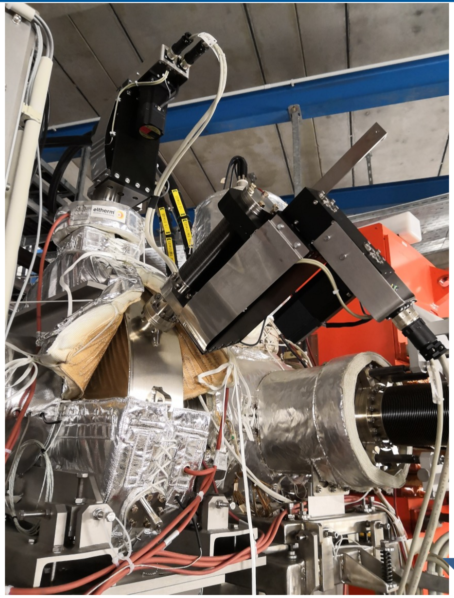


2011

F. Nolden et al., NIM A (2011)



- Longitudinal changes of momenta
- E-cooling process

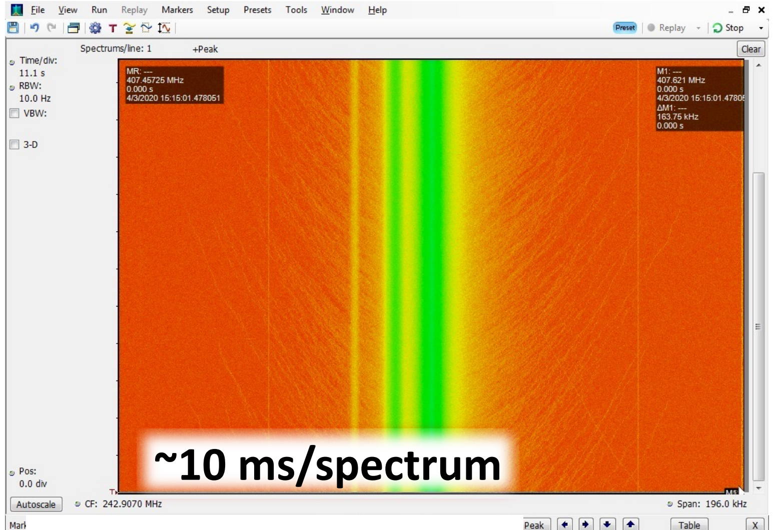


2020

erc

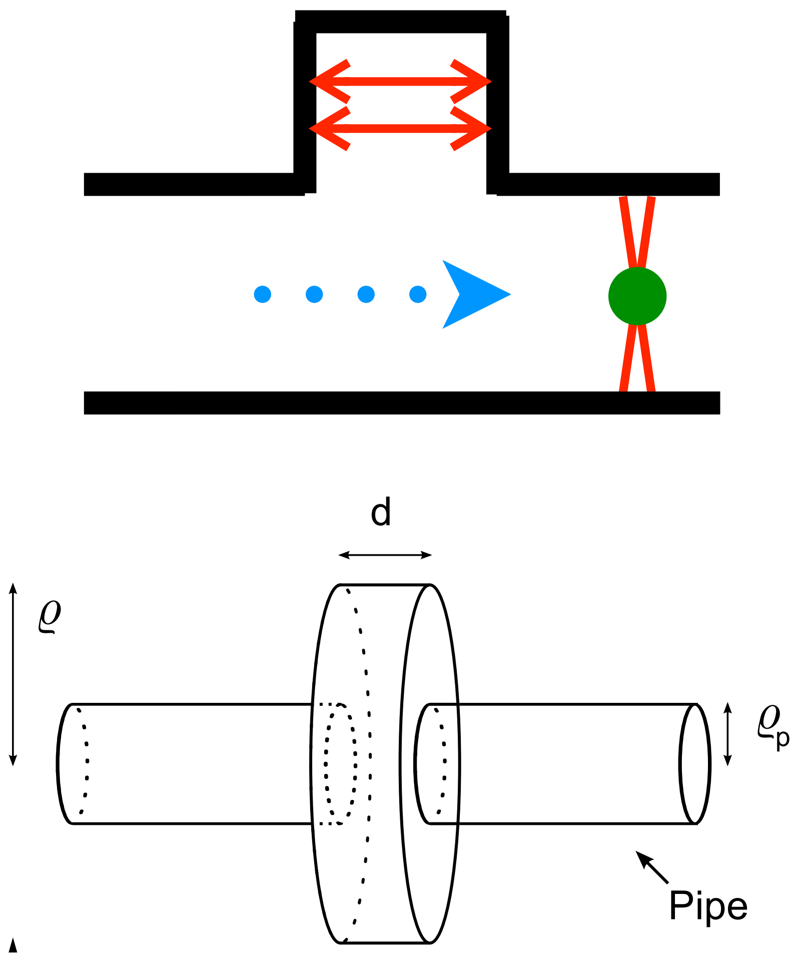
ASTRUm

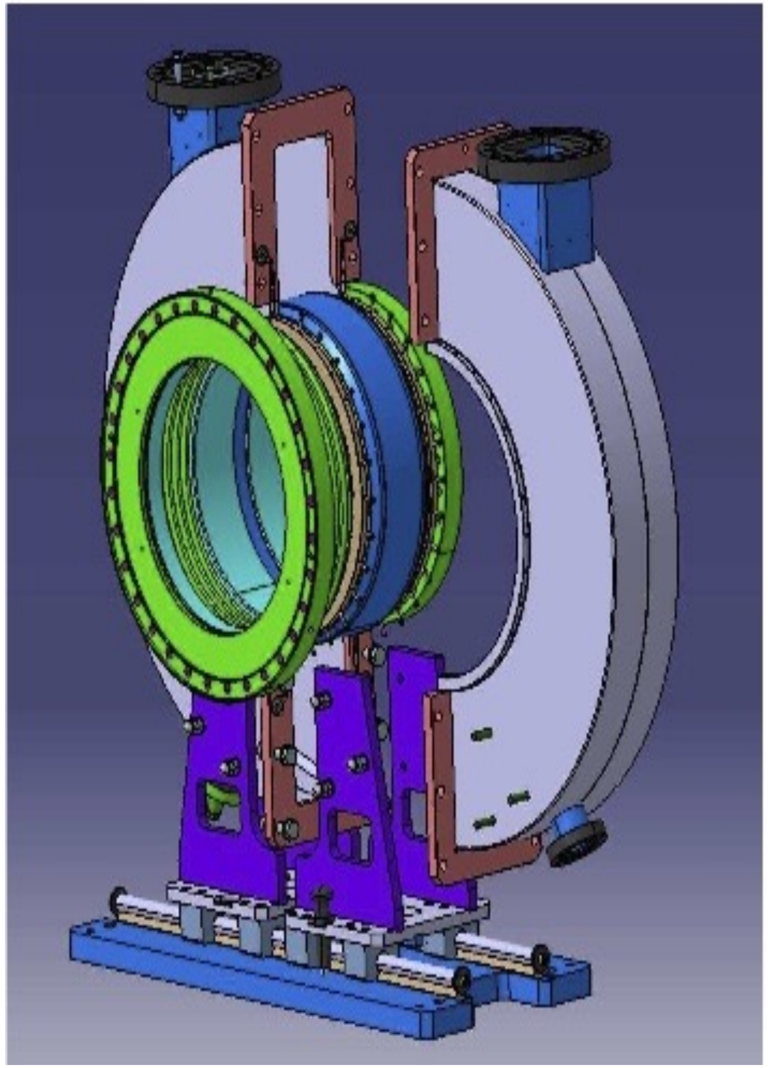
M. S. Sanjari et al., RSI 91 (2020) 083303

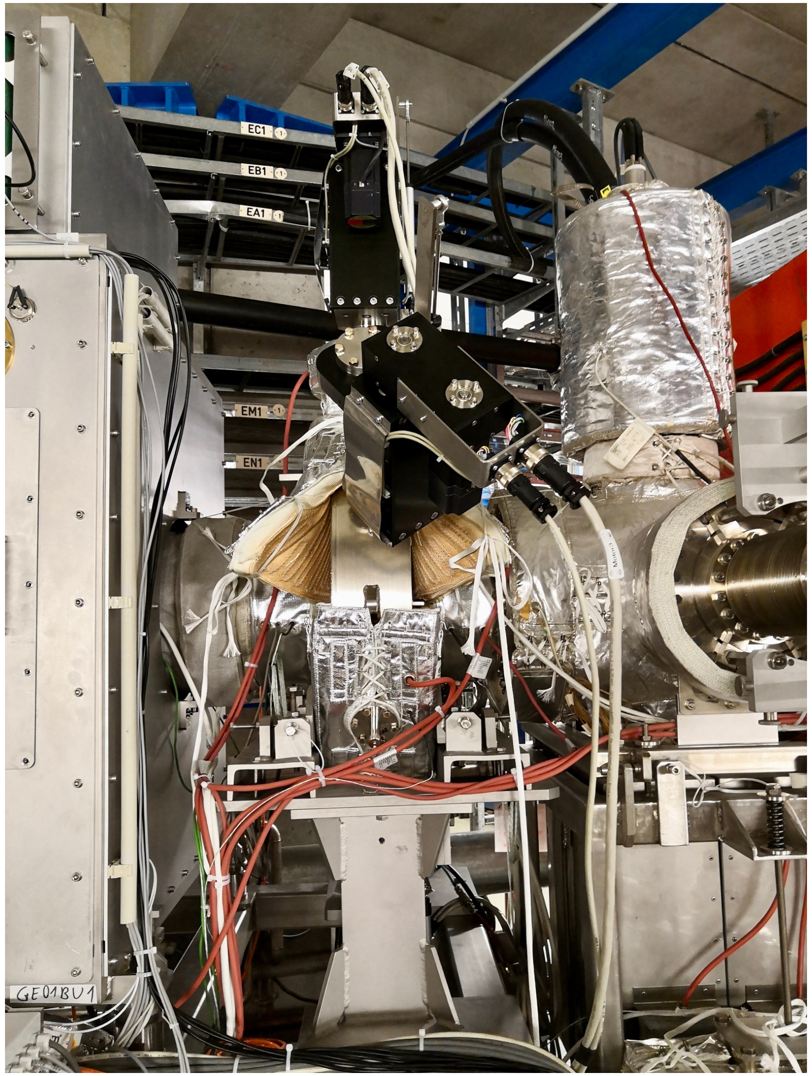


Intra-beam scattering

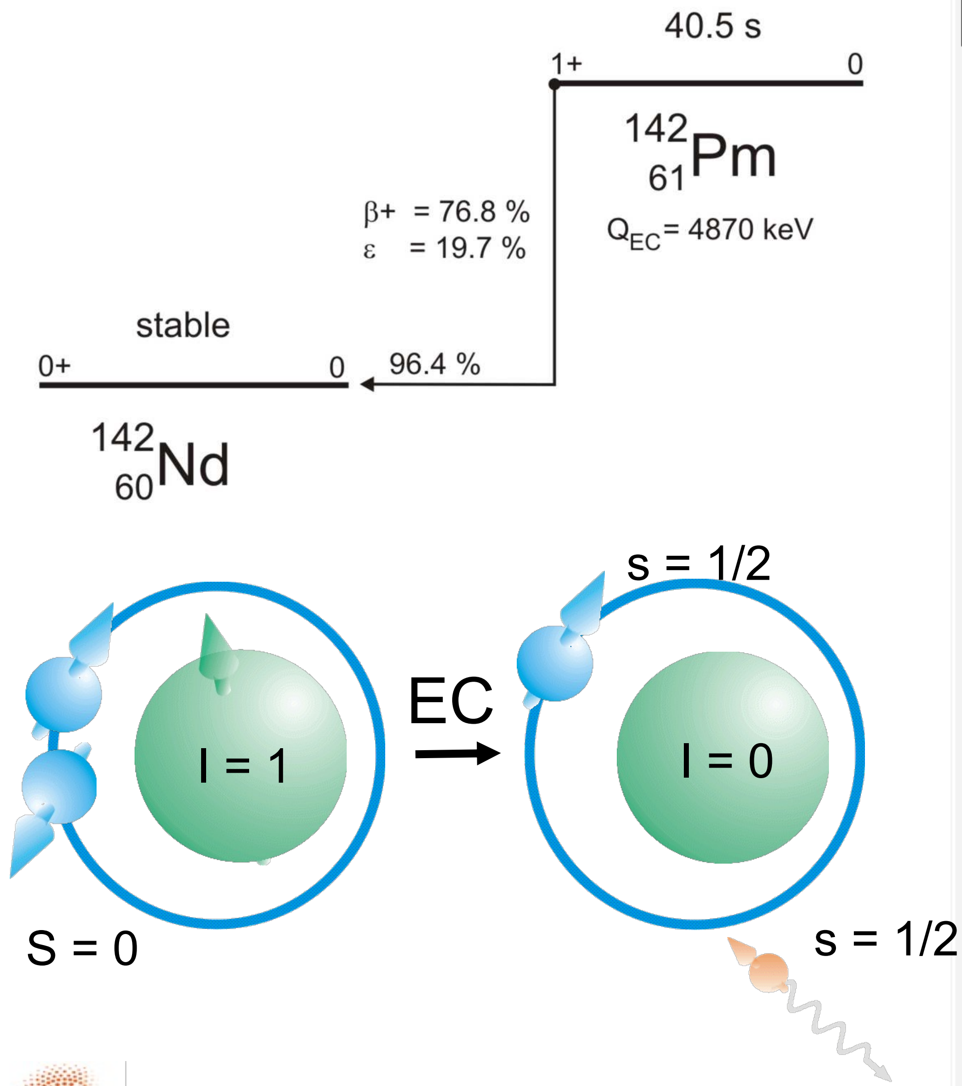
Non-Destructive Particle Detection

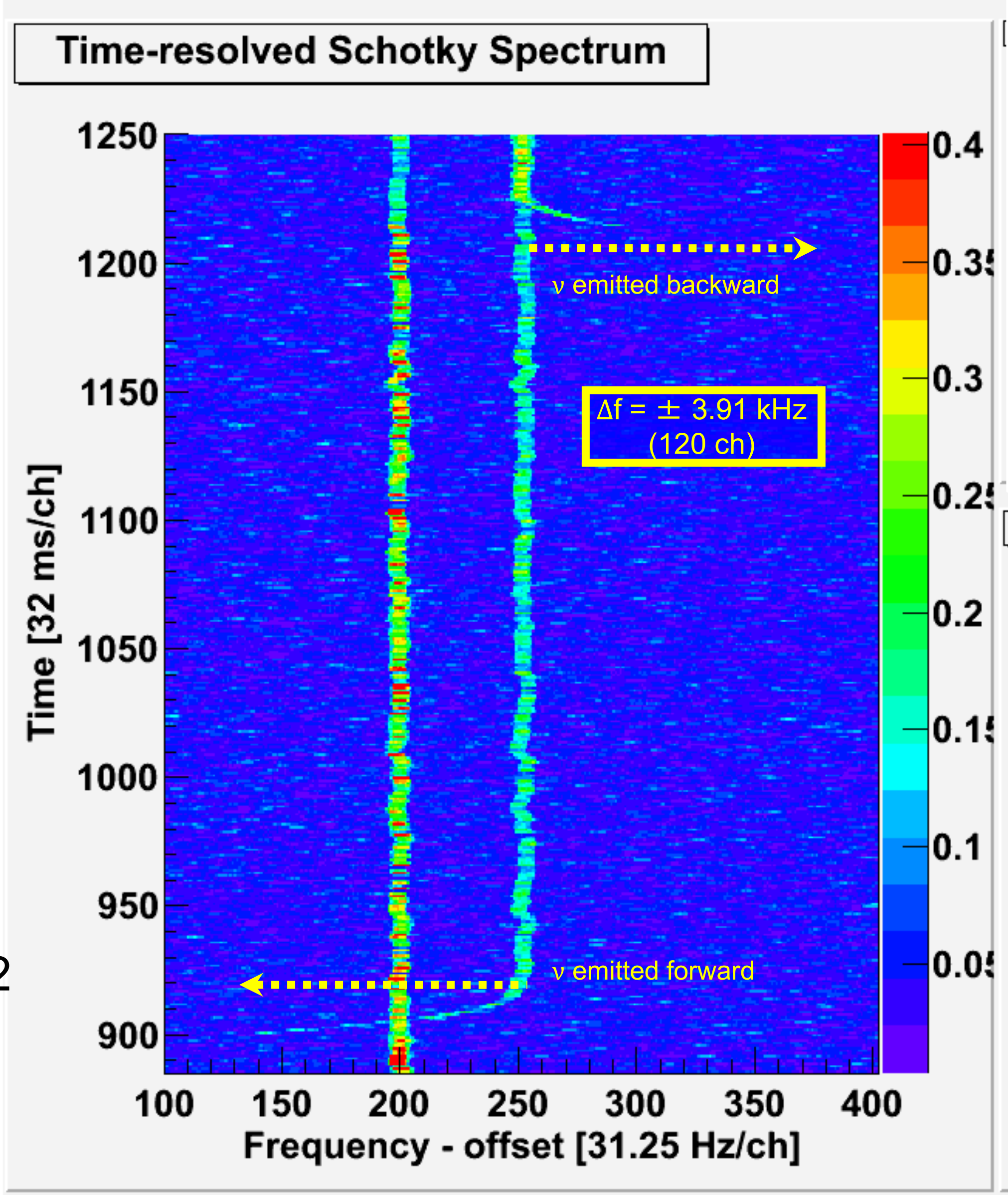


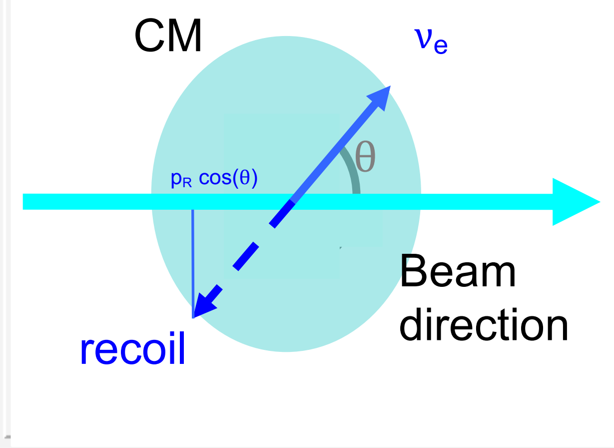


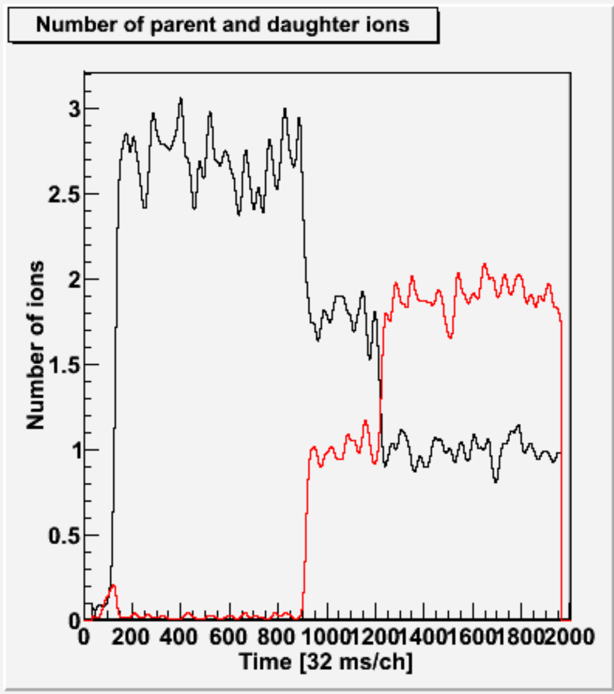


Three Parent He-Like ^{142}Pm Ions



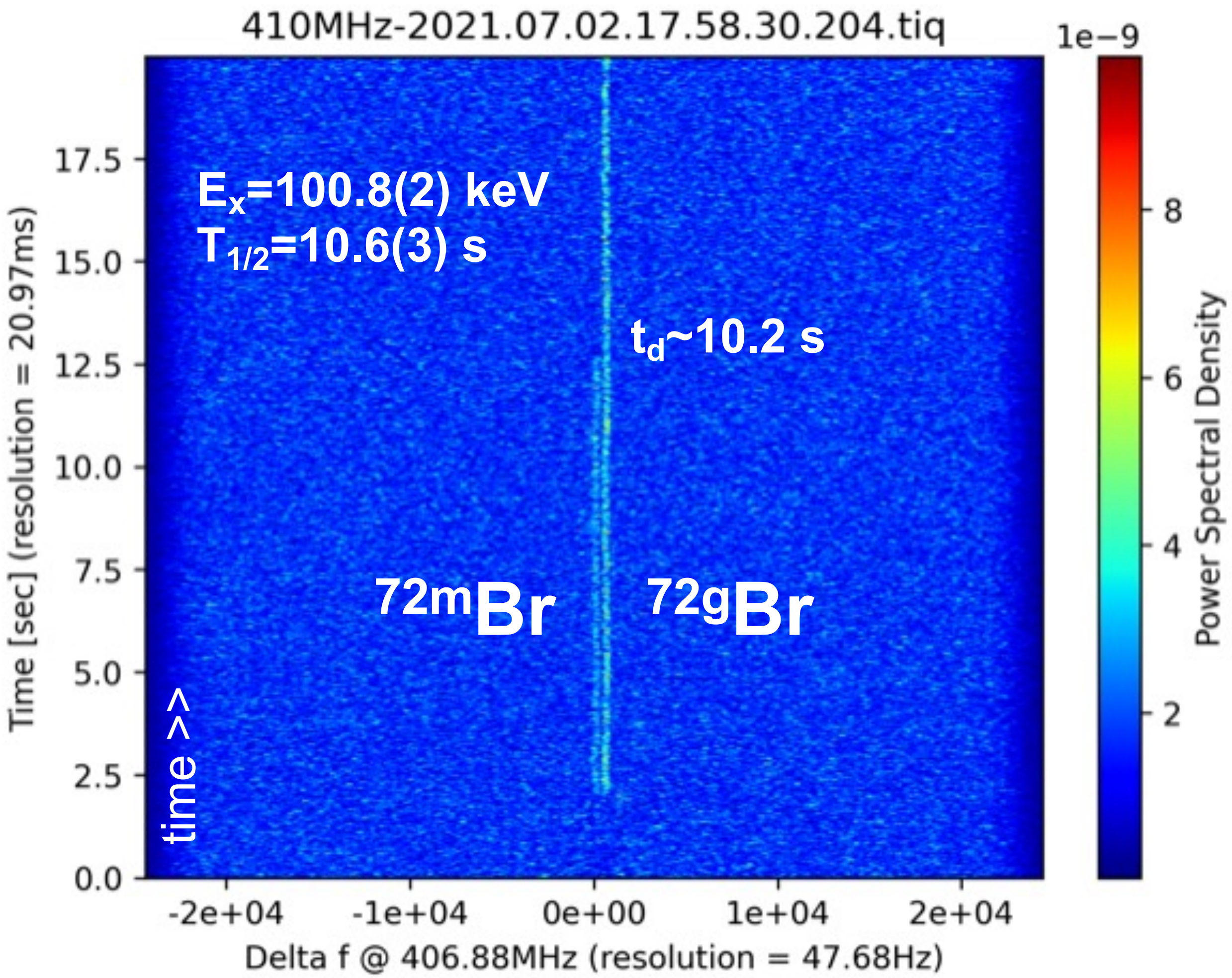






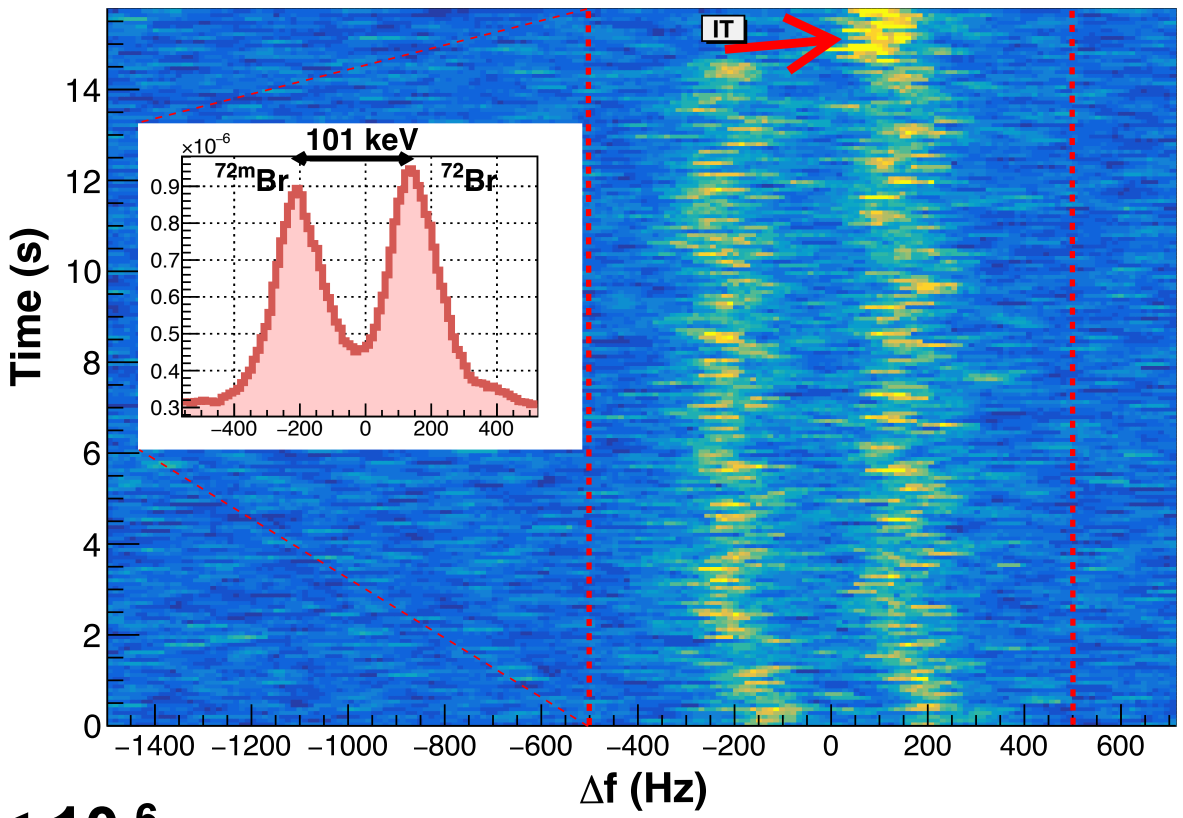
Courtesy: N. Winckler

Combined Isochronous+Schottky Mass Spectrometry



Schottky spectra of single events

Separation of the 101 keV isomer in ^{72}Br



→ $\Delta m/m < 10^{-6}$

Isochronous+Schottky Mass Spectrometry

Highly-charged ions

Mass Measurements

Exotic decay modes

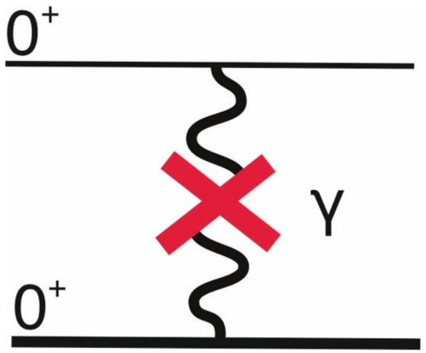
Half-life measurements

Nuclear two-photon decay and bound-state e^+- e^- pair conversion

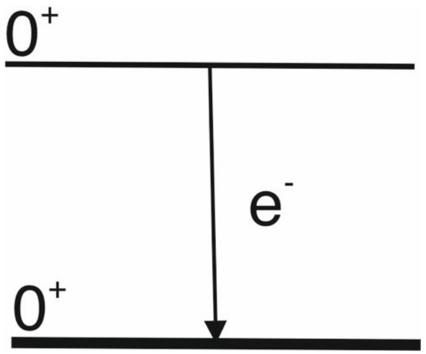
E143 Experiment

Spokesperson Wolfram Korten

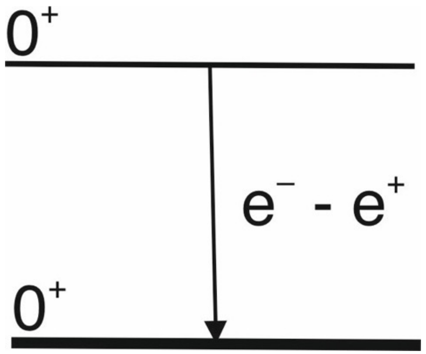
Nuclear two-photon or double-gamma decay



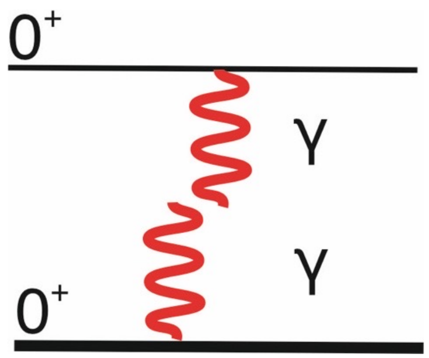
Single photon de-excitation is forbidden



conversion electron



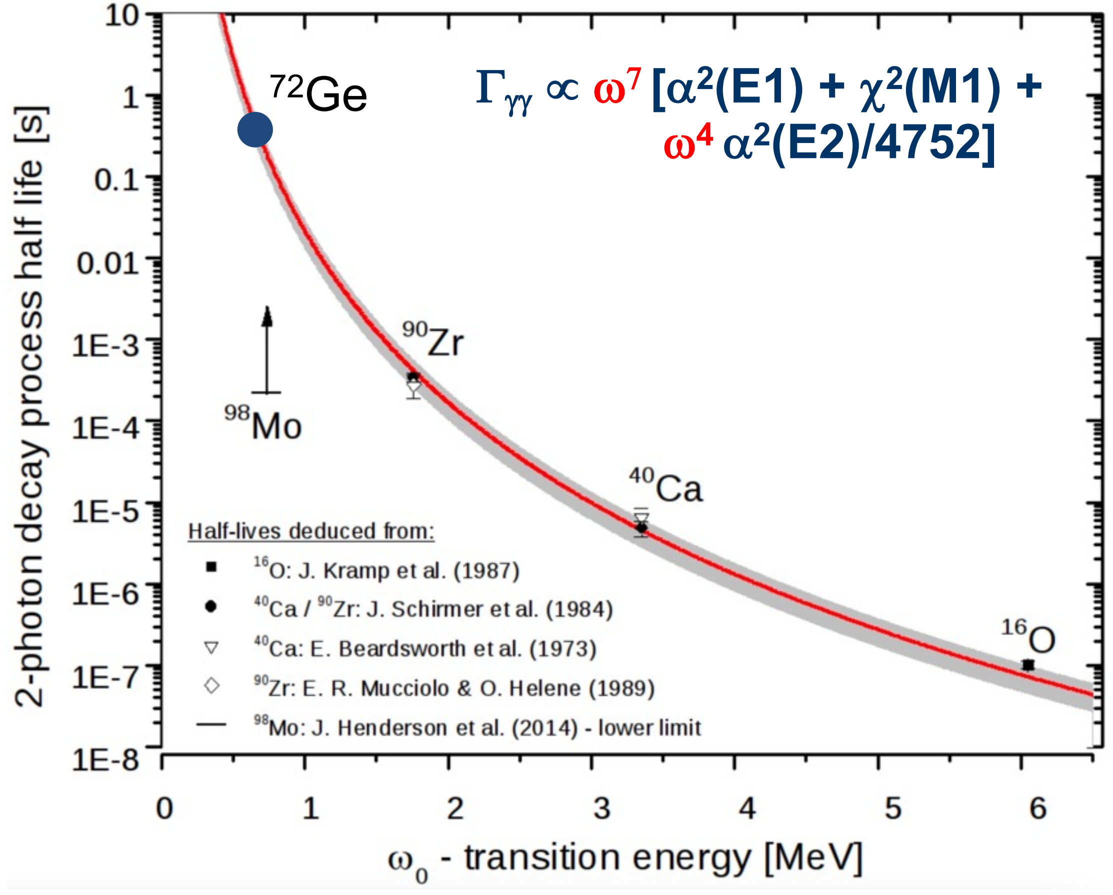
electron-positron pair
(E*> 1.022 MeV)

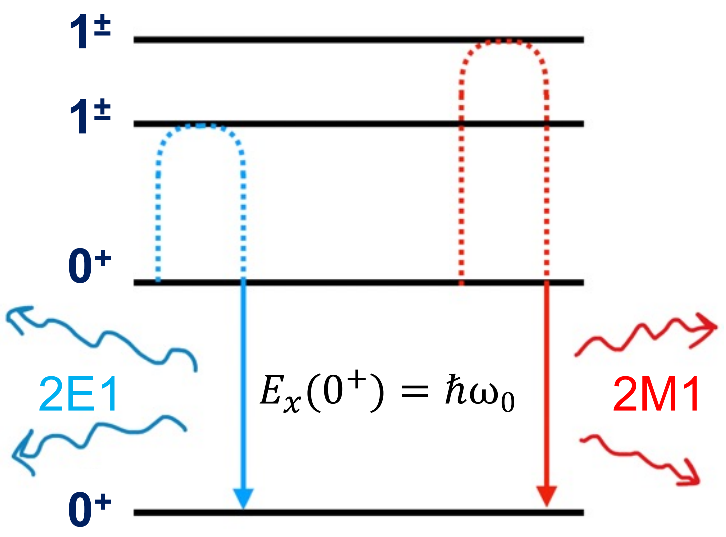


two-photon emission

First observation in 1985 with the HD-DA Crystal Ball (NaI array)

Comparison of Two-Photon Decay Half Lives





$$\Gamma_{\gamma\gamma} = \frac{\omega_0^7}{105\pi}\left(\alpha_{E1}^2 + \chi_{M1}^2 + \frac{\omega_0^4}{4752}\alpha_{E2}^2\right)$$

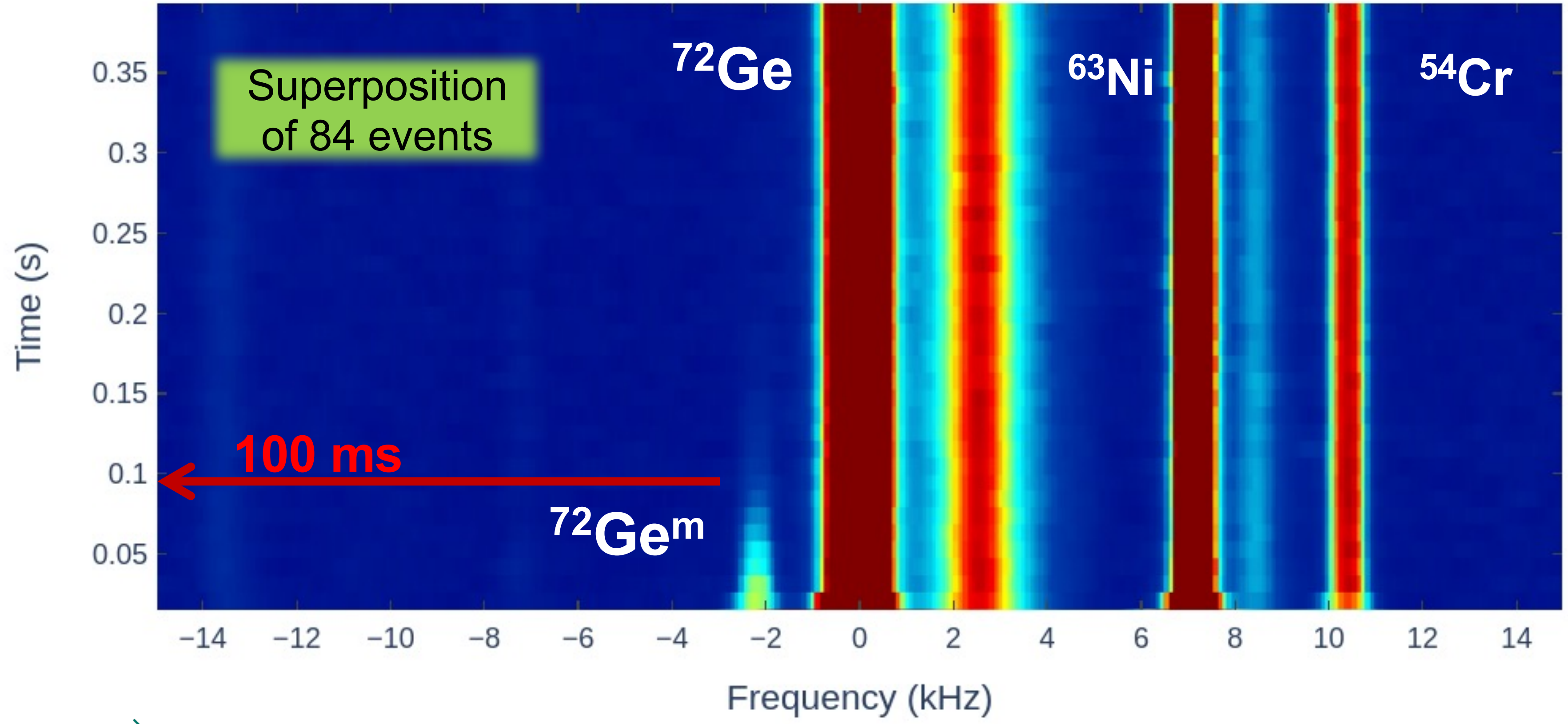
Electric dipole transition polarizability

Magnetic dipole transition susceptibility

Electric quadrupole transition polarizability

usually $\alpha_{E1} \gg \chi_{M1} \gg \alpha_{E2}$

Combined Isochronous+Schottky Mass Spectrometry



Joint PhD Position

CEA Saclay
GSI Darmstadt
MPIK Heidelberg

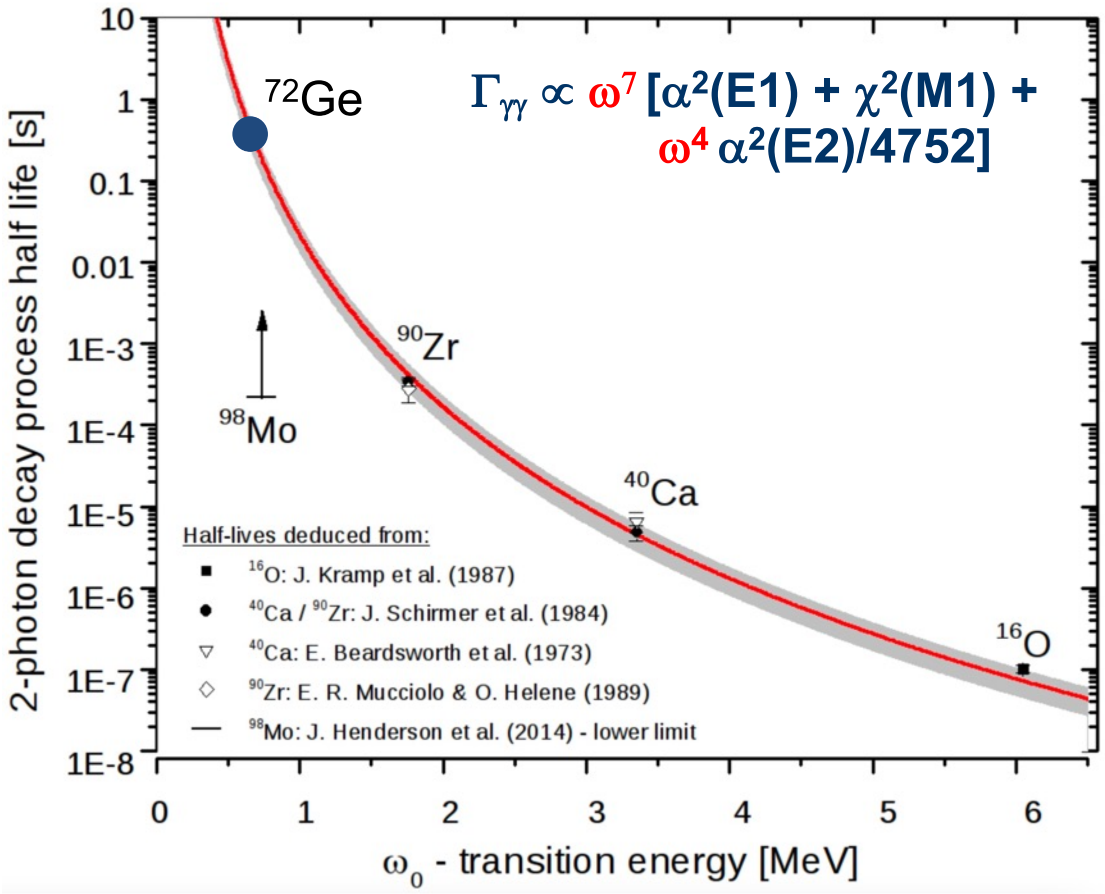
David
Freire Fernández

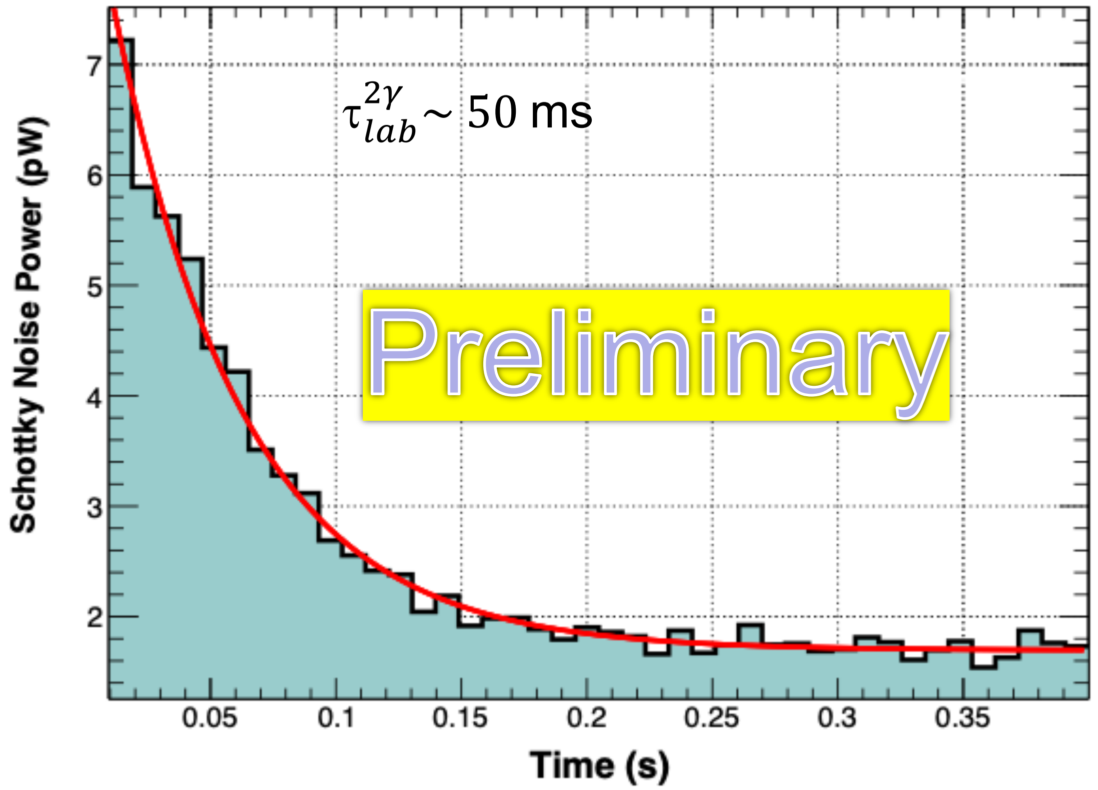
^{72}Ge^m: $0^+ \rightarrow 0^+$ (single γ emission forbidden)

New tool to search for 0^+ isomers in exotic nuclei
$0^+ \rightarrow 0^+$ decays as laboratory for BSM physics

Courtesy: D. Fernandes and W. Korten

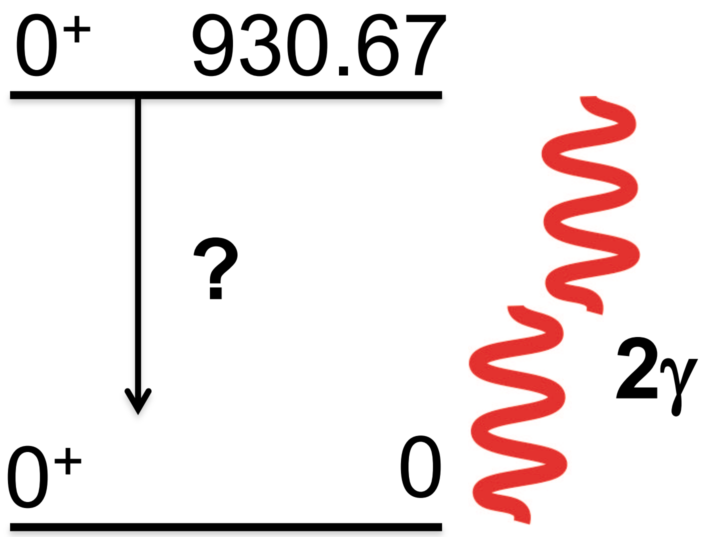
Comparison of Two-Photon Decay Half Lives





Two-photon decay in ^{72}Ge substantially faster than extrapolated from "magic" nuclei ^{16}O, ^{40}Ca, ^{90}Zr

Bound state electron-positron pair decay in ^{194}Pb



$^{196}Pb^{82+}$

B(K)=101.336 keV

E(0^+_2)=930.67 keV

1032 keV

Fritz Bosch
1940-2016

EPJ Web of Conferences **123**, 04003 (2016)
Heavy Ion Accelerator Symposium 2015

Ion Beam Facilities / Trapping & Storage

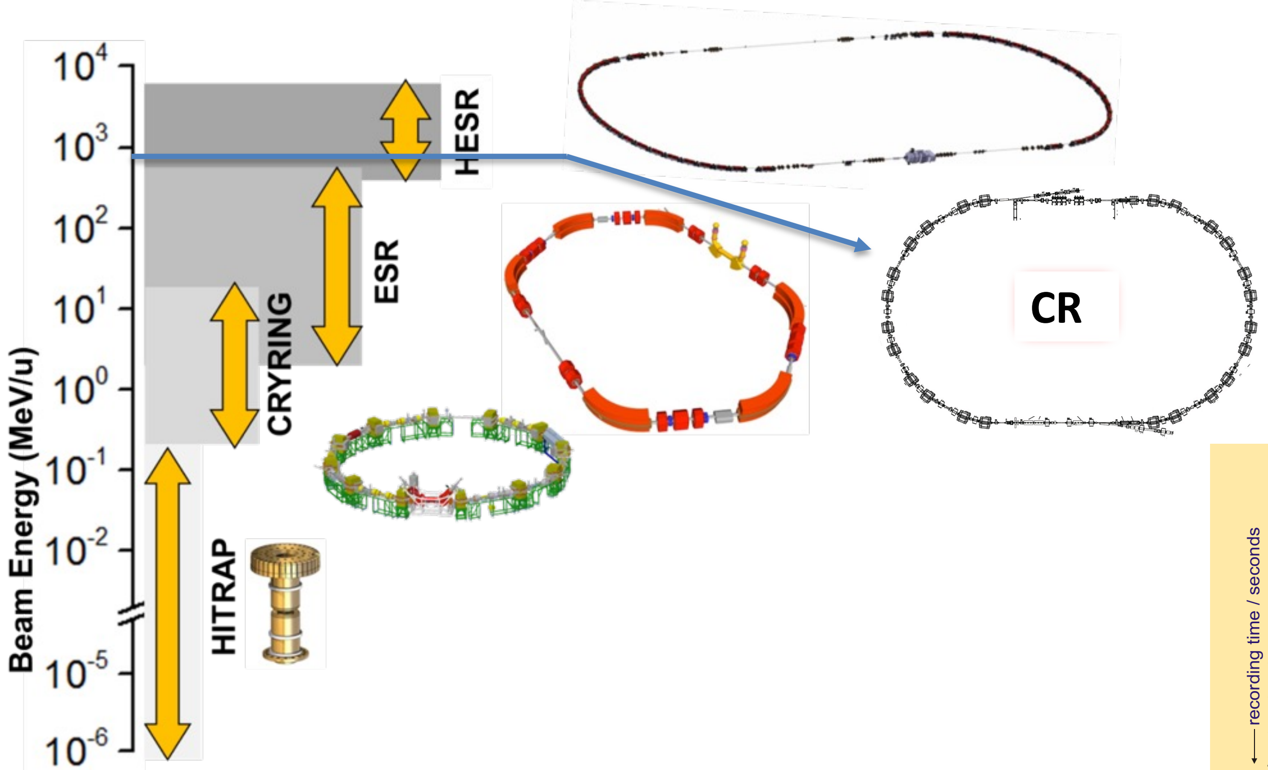
Worldwide Unique !

Stored and Cooled

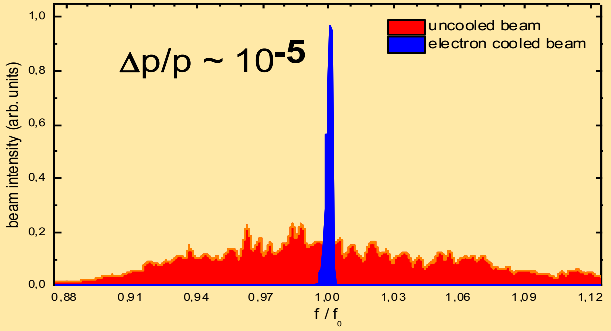
Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei

From Rest to Relativistic Energies (up to 4.9 GeV/u)

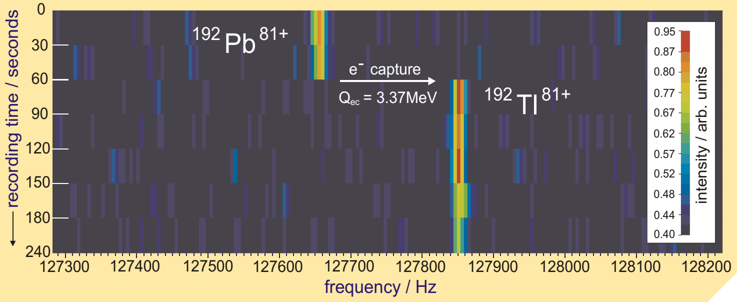
Control of atomic charge states
Photon, electron, atom, (ion) targets
Highest quality beam (cooling)
Variation of kinetic energies



Cooling: The Key for Precision



From Single Ions to Highest Intensities



FAIR Phase-0 Research Program

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

NucAR

sparc Stored Particles Atomic Physics Research Collaboration

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RIKEN

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GSI

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