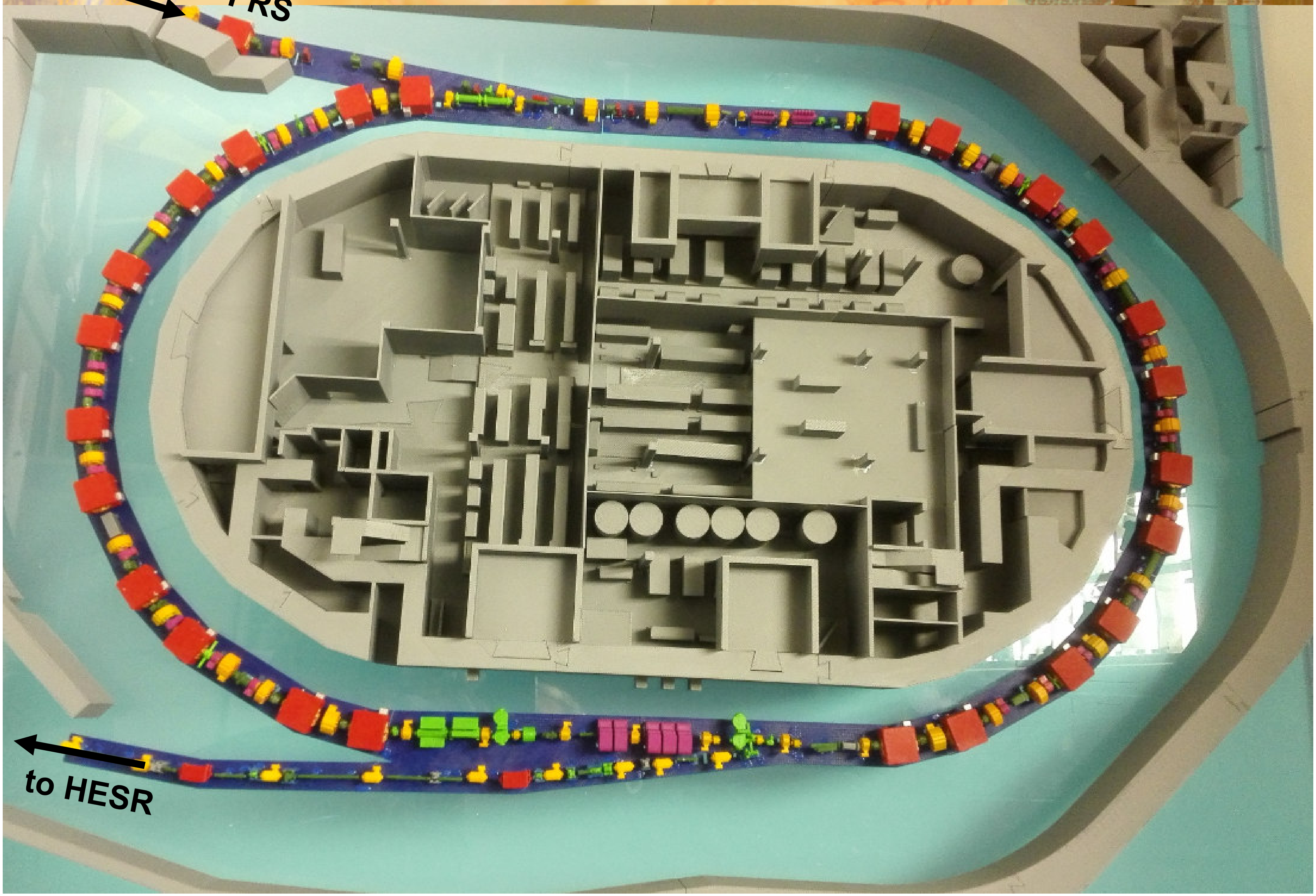
ILIMA Status and Experiments

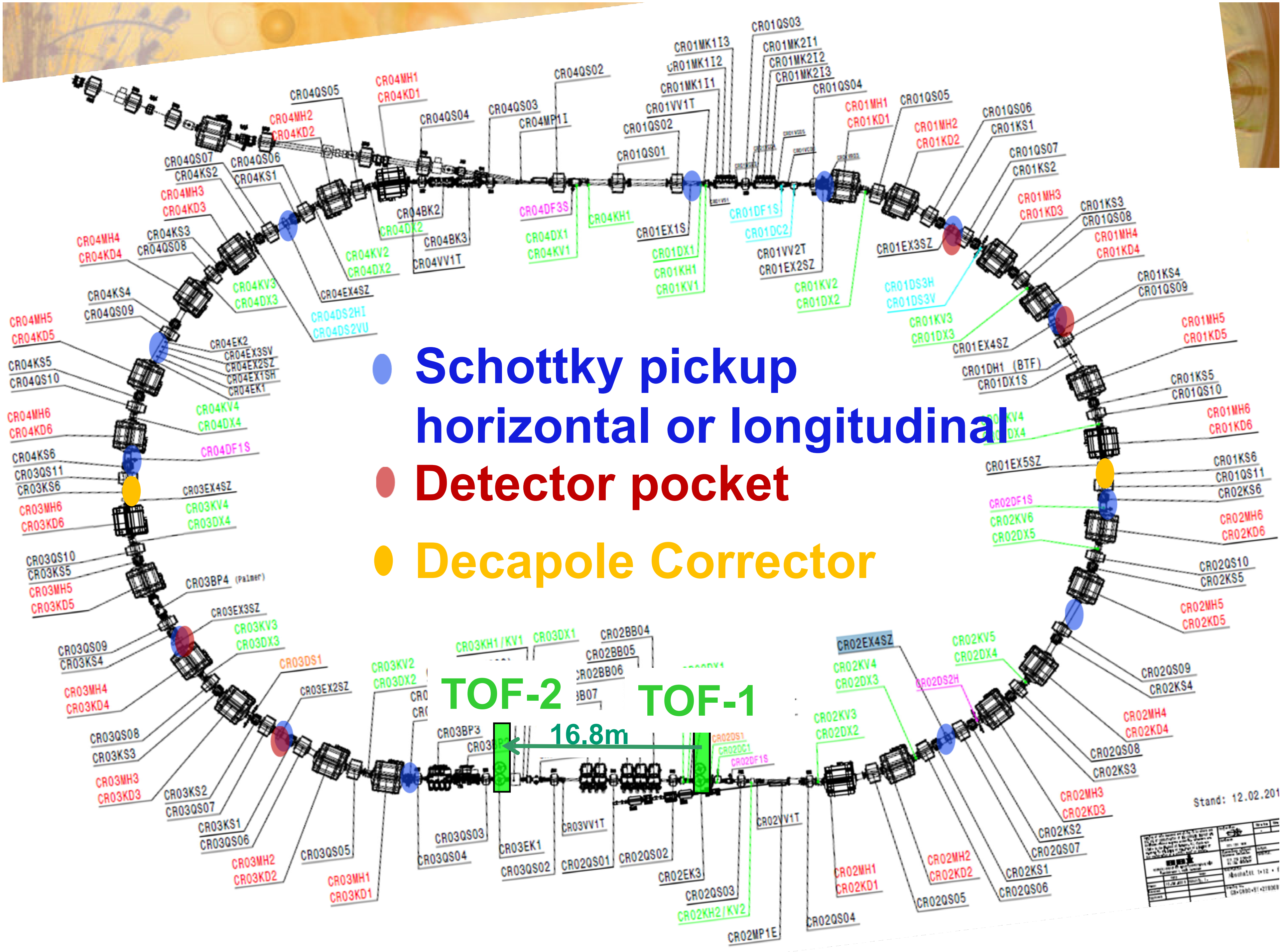
Helmut Weick, GSI, for the ILIMA collaboration
NUSTAR Week GSI, 30th Sept. 2020

- **ILIMA plans and status**
- **Experiments this year (^{205}Tl)**
- **New Experiments (double gamma decay)**

ILIMA

Collector Ring



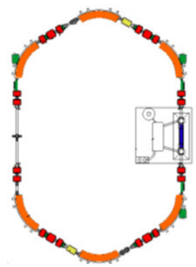

Schottky pickup
horizontal or longitudinal
Detector pocket
Decapole Corrector
TOF-2
TOF-1
16.8m
Stand: 12.02.201

ToF Detector Comparison

ESR

L = 108.36 m
Bρ = 8-10 Tm
γ_t = 1.4
Δp/p = ±0.2 %
ε_x = 7 mm mrad

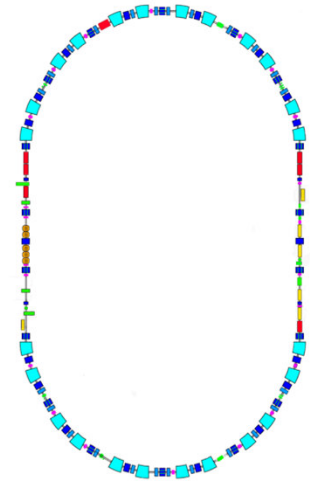
TOF detector (1x)



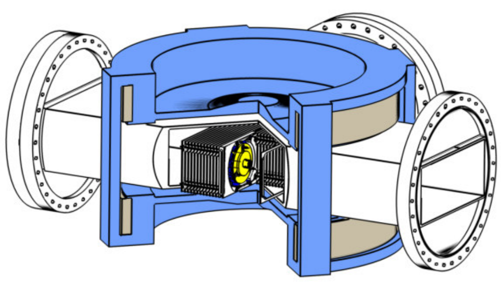
CR

L = 221.45 m
Bρ = 13 Tm
γ_t = 1.68
Δp/p = ±0.5 %
ε_x = 100 mm mrad

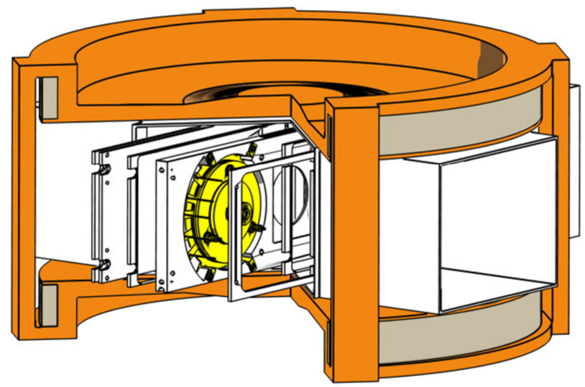
TOF detector (2x)



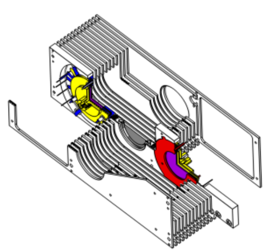
x 1000



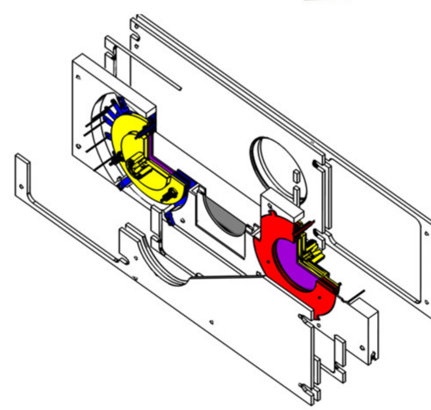
B-field homogeneity radius 100 mm



B-field homogeneity radius 200 mm



Foil diameter 40 mm
Efficiency ≈ 38%
Timing accuracy ≈ 45 ps



Foil diameter 80 mm
Efficiency ≈ 98%
Timing accuracy ≈ 37 ps

$$\sigma = \sqrt{\sigma^2(\mathrm{Transport}) + \sigma^2(\mathrm{MCP}) + \sigma^2(\mathrm{ETD})}$$

N. Kuzminchuk-Feuerstein

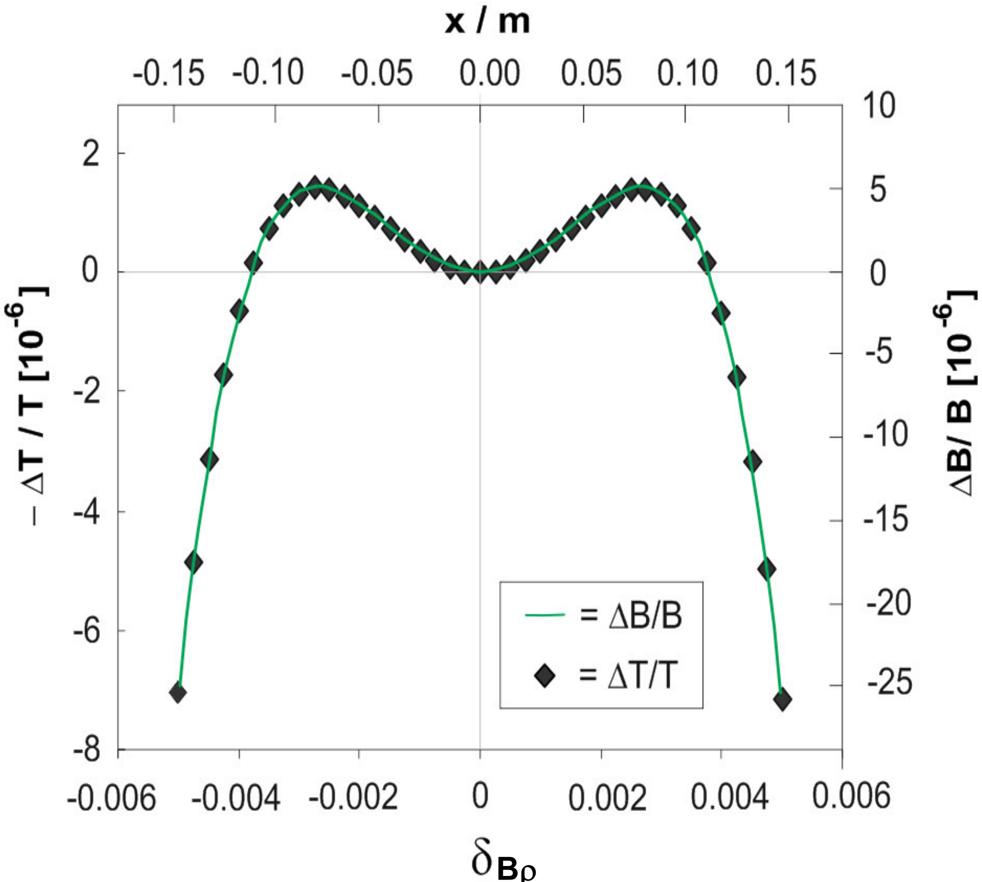
Decapole Corrector

Dipole homogeneity cannot be on $\Delta B/B = 10^{-6}$ level, rather 10^{-4}.

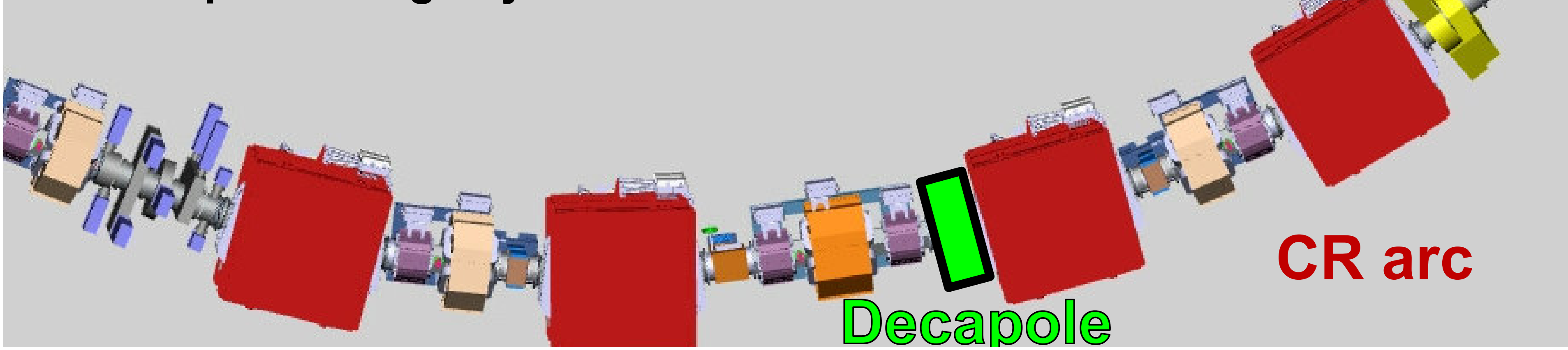
$\Delta T/T$ over a full turn can reach this level with correctors.

Model with Taylor expansion: quadrupole tune or energy change, sextupole, octupole and decapole.

With full correction



→ Conceptual design by BINP Novosibirsk



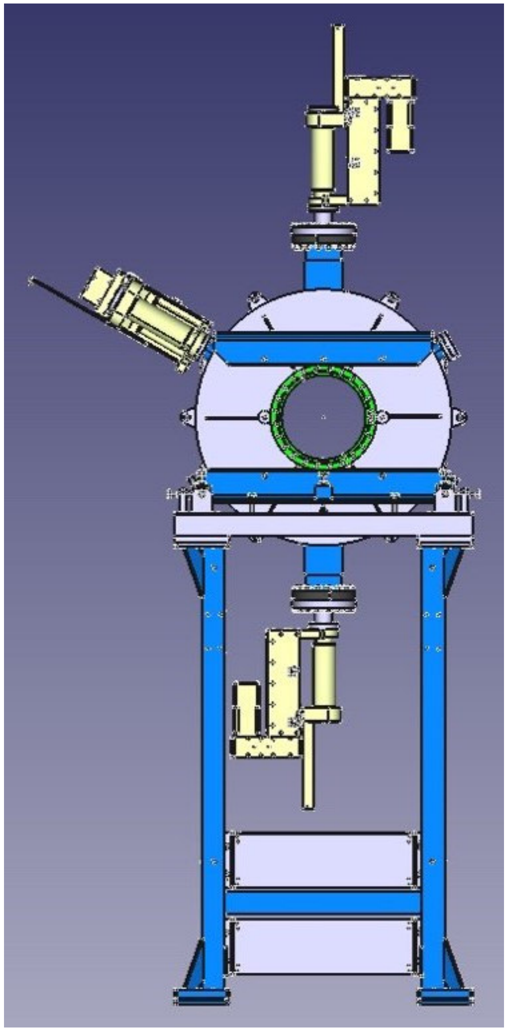
Schottky Development

- Symmetric design
- Made of 100% stainless steel
  - Vacuum friendly
  - Easy construction
  - No movable parts in the support

- No ceramic gap
  (hence no reliance on ceramic spec)

- Variable sensitivity (Q value)
  - “follow” the beam during cooling
  - Dynamic loading

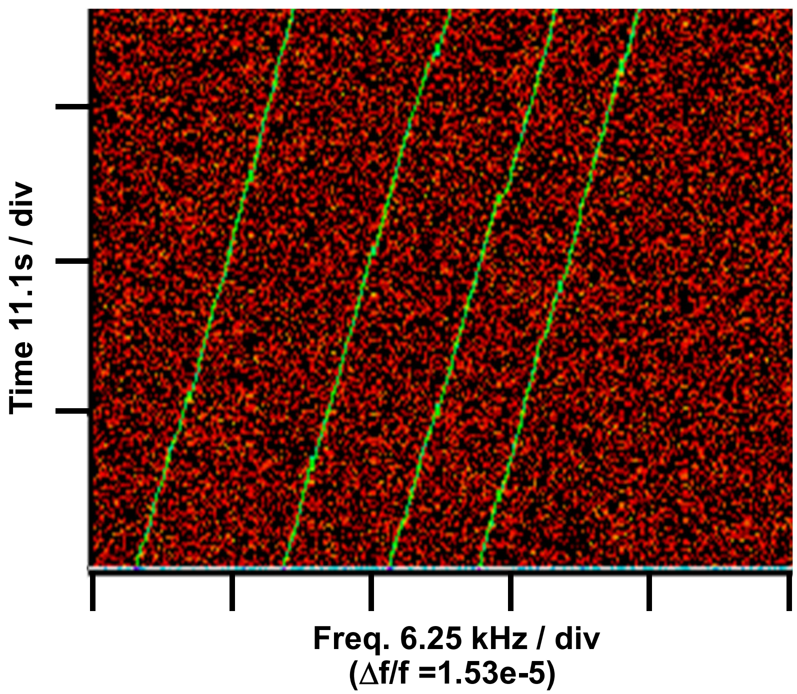
- Variable Frequency (ca. 4 MHz at 410 MHz)



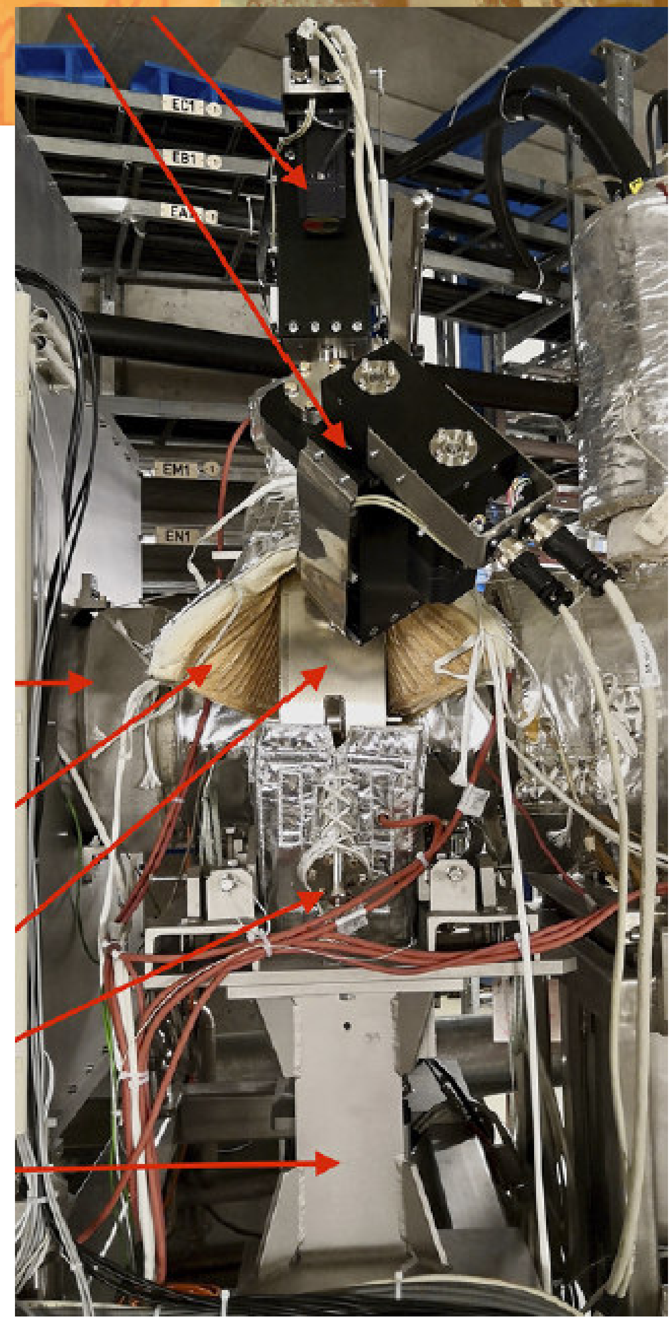
New Prototype Schottky Pick-up

Installed in ESR arc, first test in Nov 2019
resonance at 407.7 MHz (h=240)

$^{205}Tl^{81+}$ at 400 MeV/u in March 2020
single ions moved by electron cooler

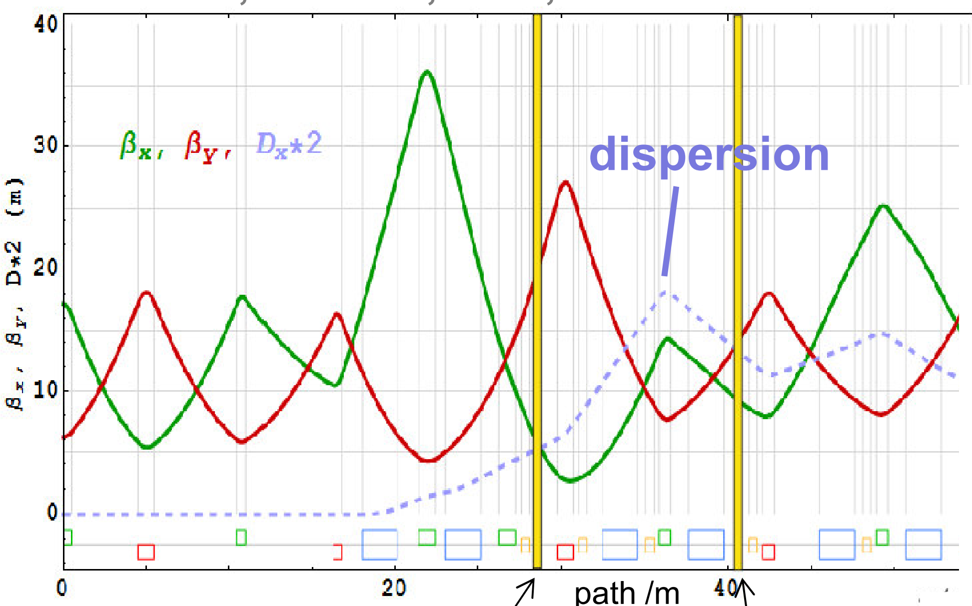


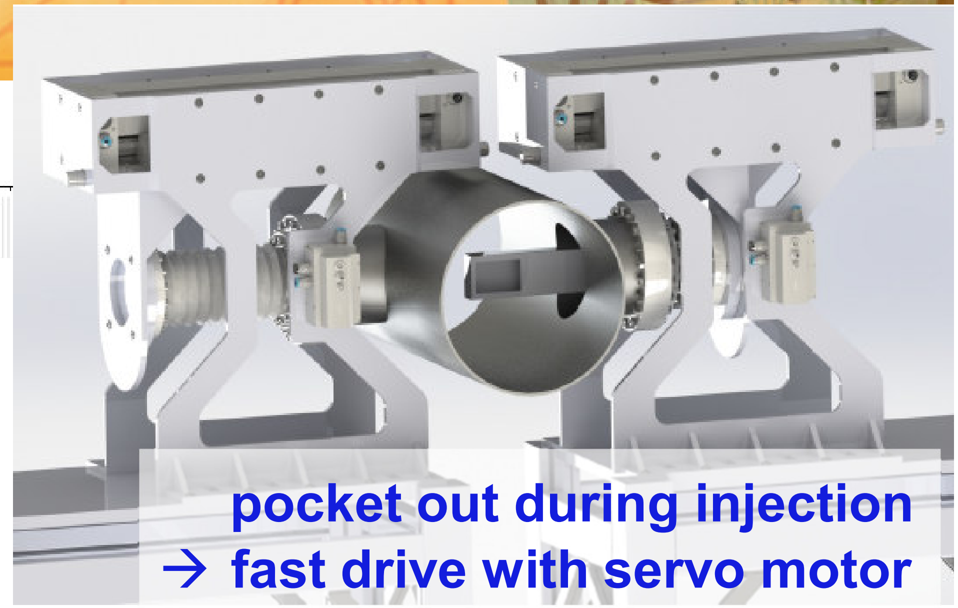
S. Sanjari et al., Rev. Sci. Instrum. **91**, 083303 (2020).



Heavy-Ion ΔE-E Telescope

CR TDR, Annex 1, 2016, RIB mode



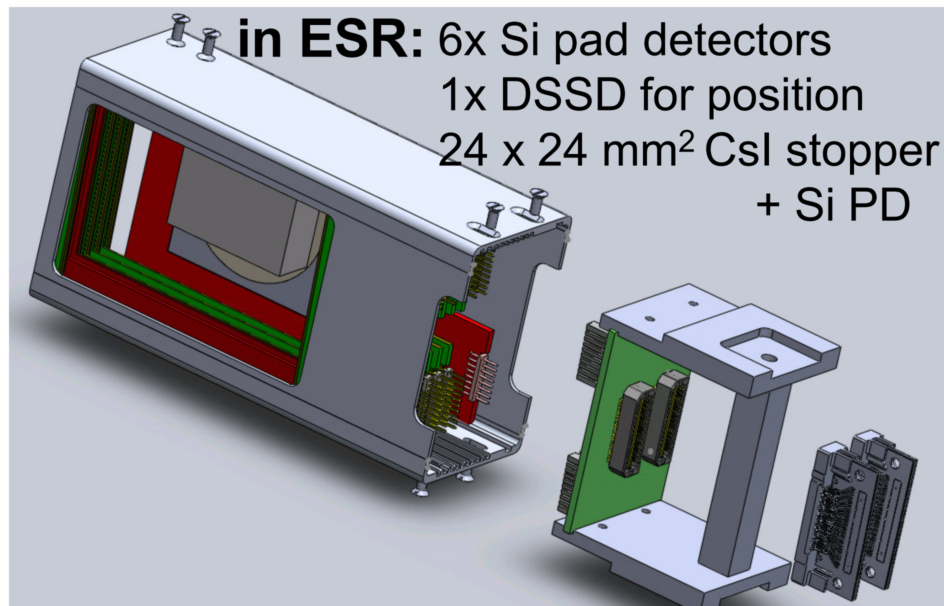


Detect daughter after β-n decay

for Z=50, m=132
x = -72 mm

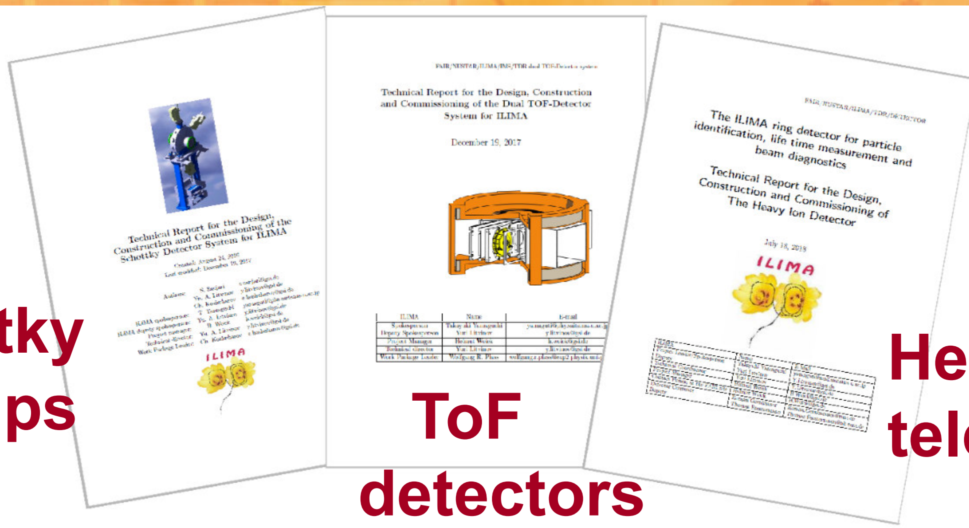
for Z=82, m=126
x = -130 mm

cooled beam (ε_x = 1 mm mrad)
➔ dx = 2.2 – 3.2 mm



M.A. Najafi *et al.*, NIM A **836** (2016).

From TDR to Construction



- All three TDRs approved by ECE
- In-kind funding by Germany (GSI), telescopes from Canada (TRIUMF), smaller fraction for ToF missing, limited number of Schottky pick-ups, German funding 740 k€ in 2005 prices.
- Detailed specifications approved for ToF + Schottky
- In-kind contract signed for ToF (May 2020) -> tender process
- Decapole corrector magnets shall be part of CR by BINP Novosibirsk
- Installation in CR Jan. 2023? → no, later ☹

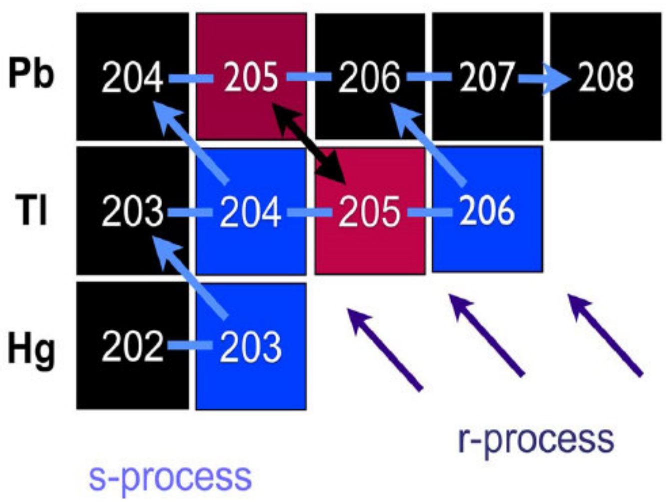
Experiments in phase 0

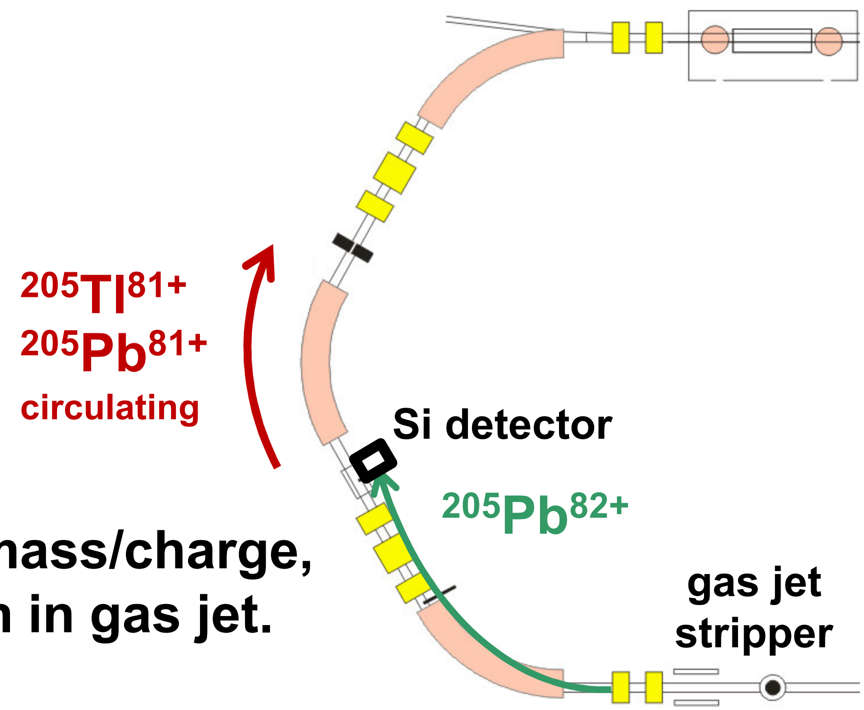
FAIR
Phase 0
Research Program

Lifetime of ^{205}Tl for bound-state β-decay

1. Calibrate neutrino capture cross section in Tl for solar neutrino flux
2. Influence on cosmic clock for s-process ^{205}Pb ($T_{1/2}$=1.7x10^7 y)

^{205}Pb EC Q-value so small that for highly ionised ions bound-state β-decay is possible (Q=+31 keV, $T_{1/2}$ ~100d ?).

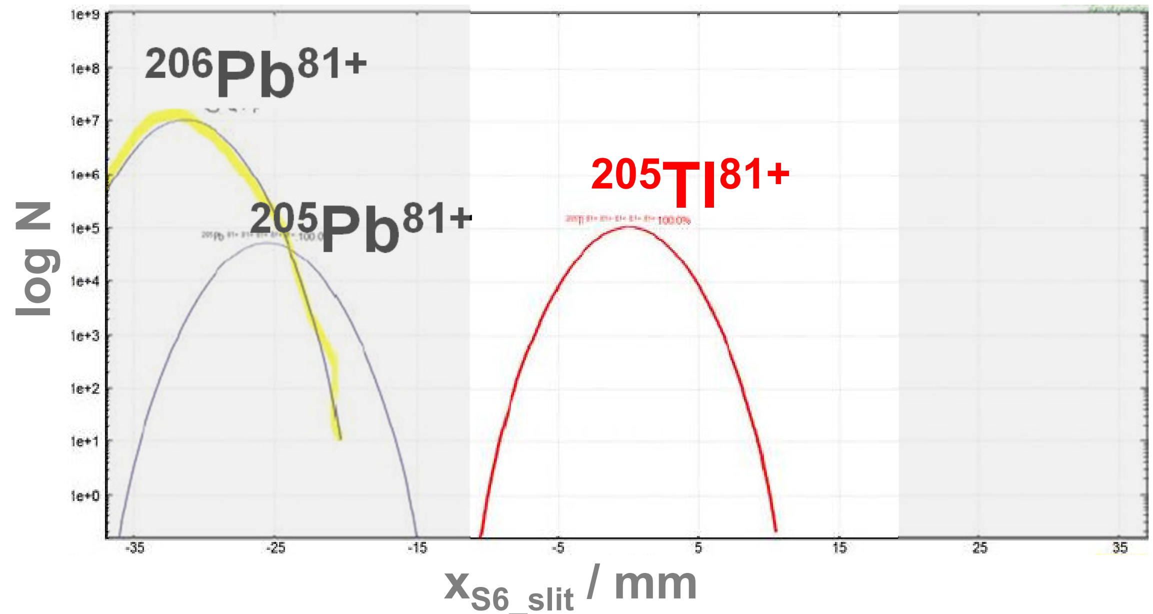


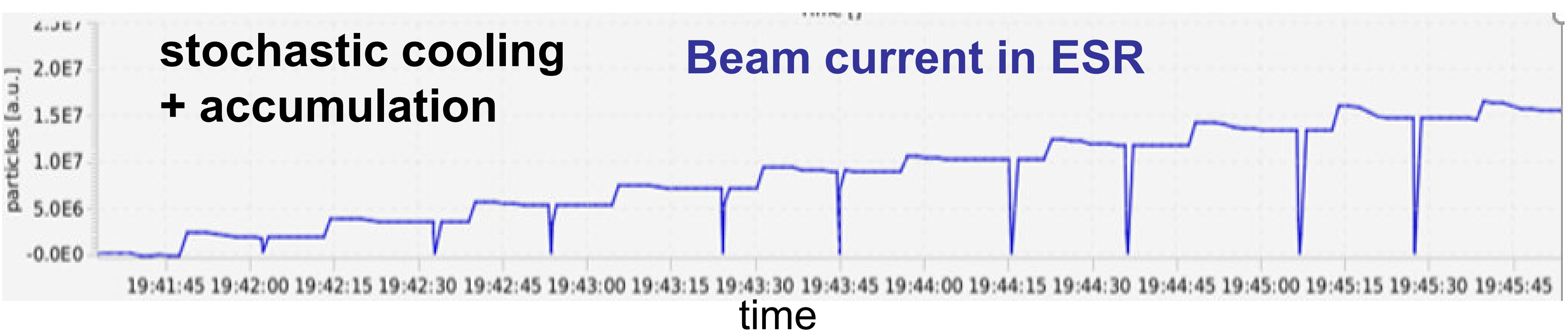


Intense beam needed, no separation in mass/charge, but detectable after stripping off electron in gas jet.

^{205}Tl Separation + Accumulation

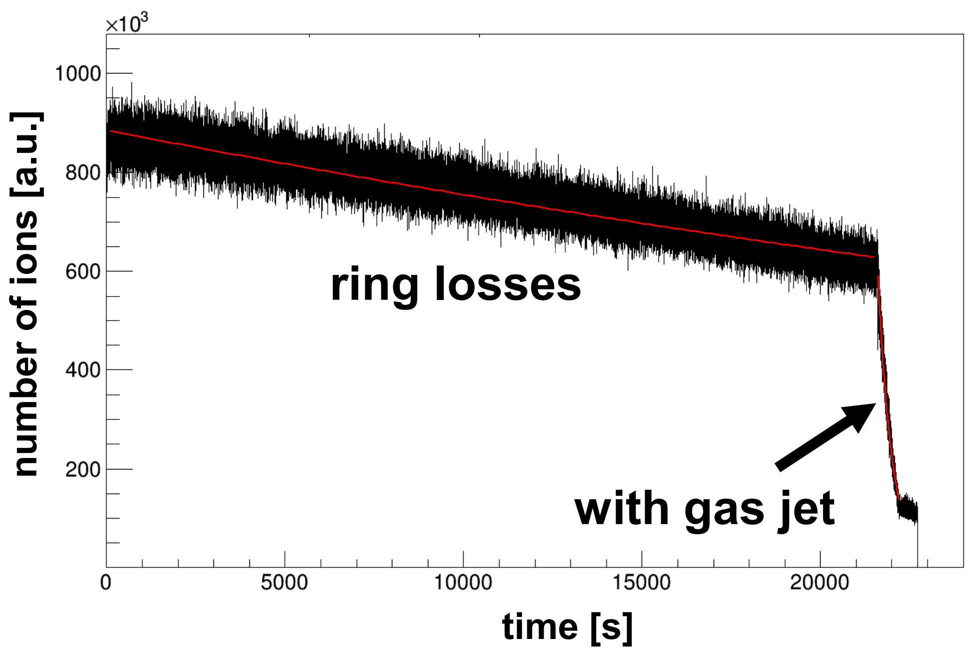
LISE^{++} simulaton looks nice and optics was verified, but peaks are wider due to charge-exchange straggling in degrader (Δx ×2).

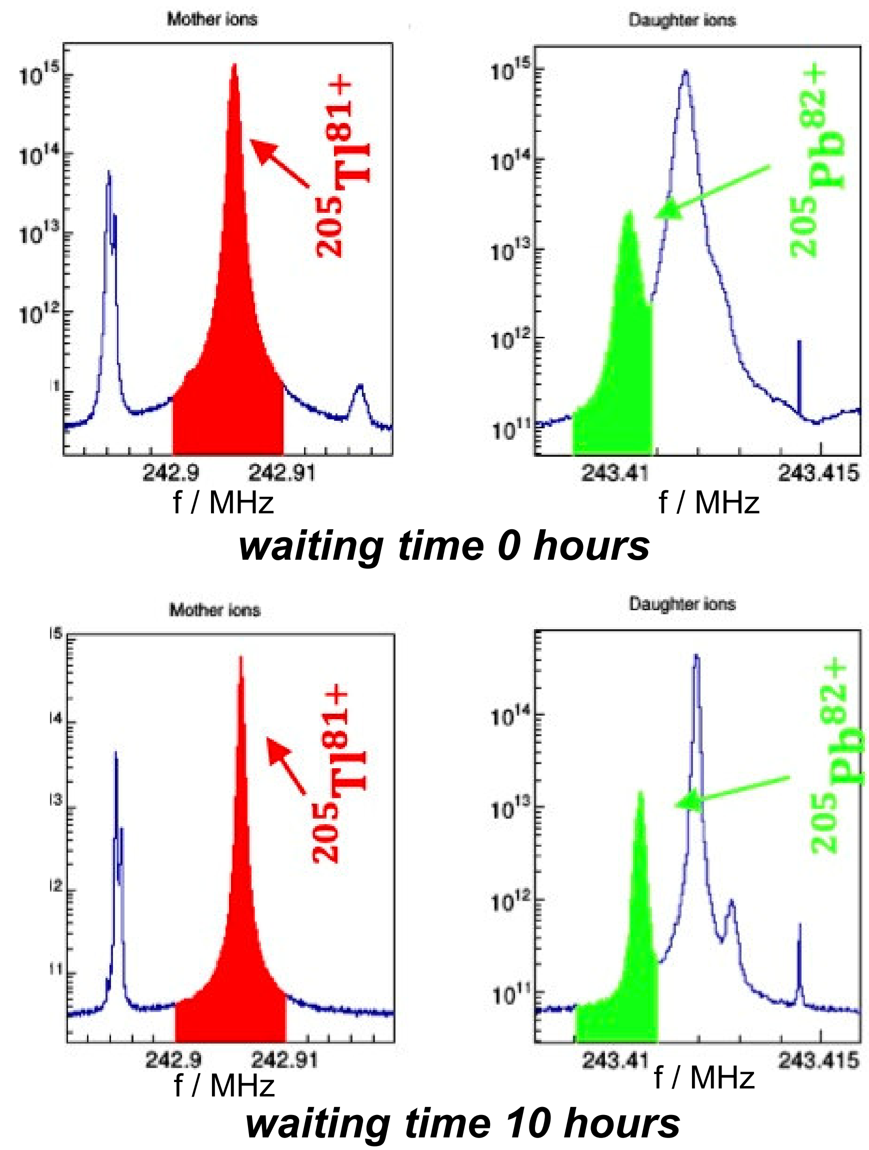




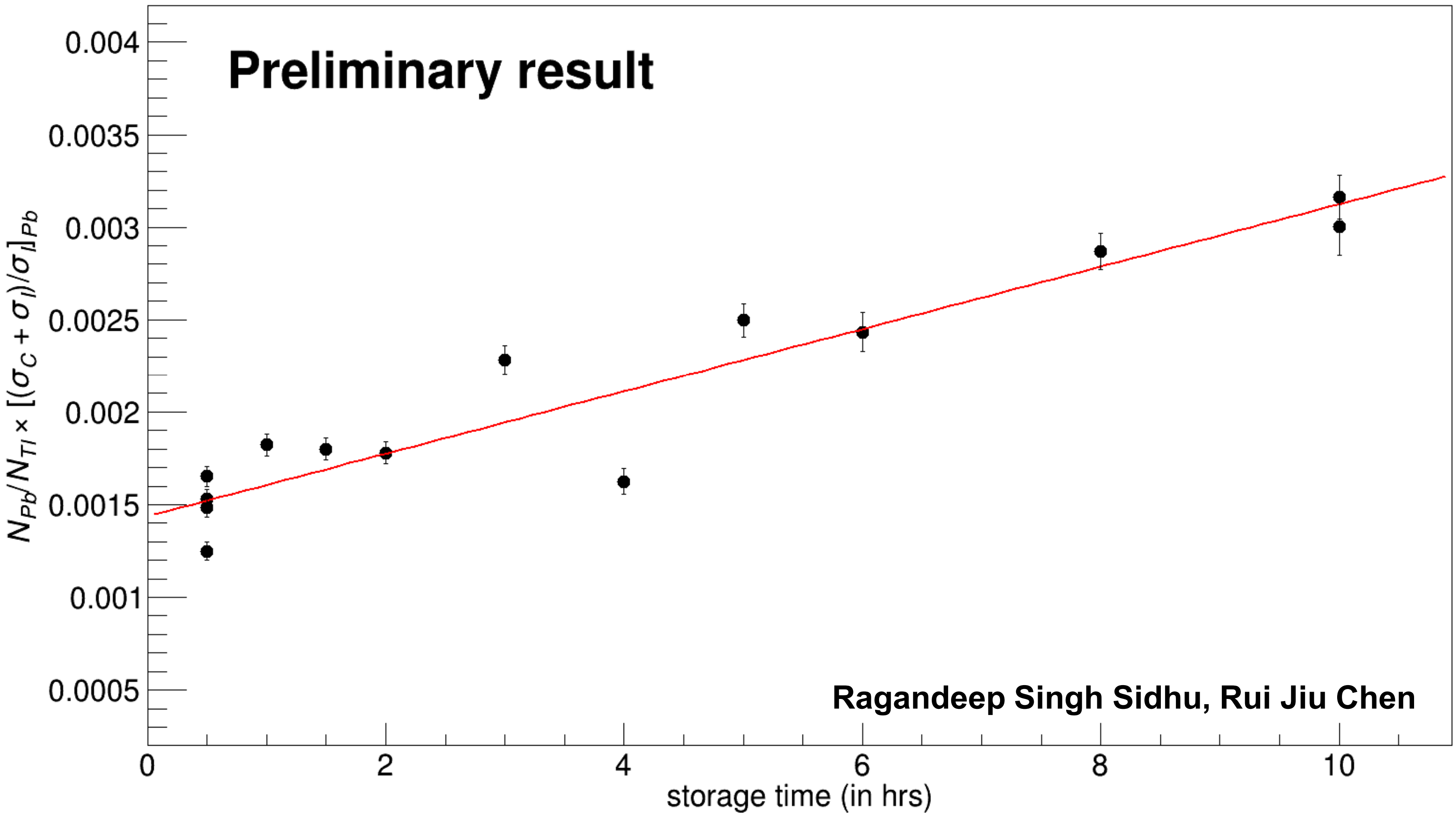
Measurement

- Accumulate up to 10^6 ions
- wait for many hours
- switch on gas jet
- look at vanishing intensity
- cross check on particle detector



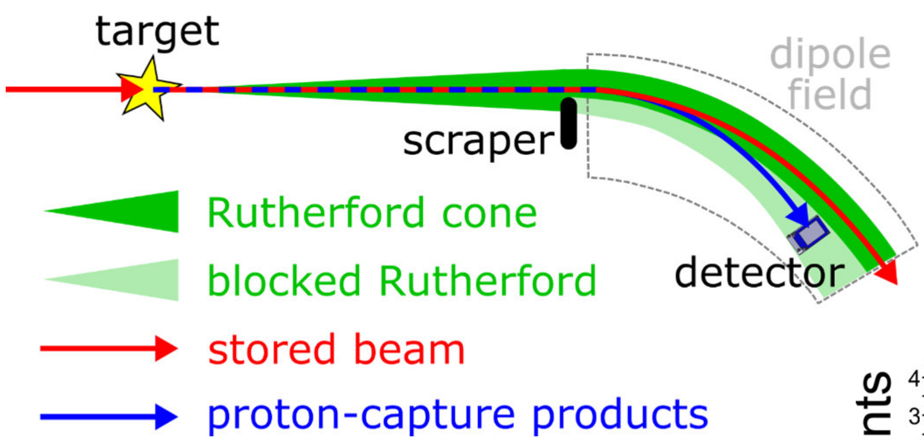


Bound State β-decay Lifetime

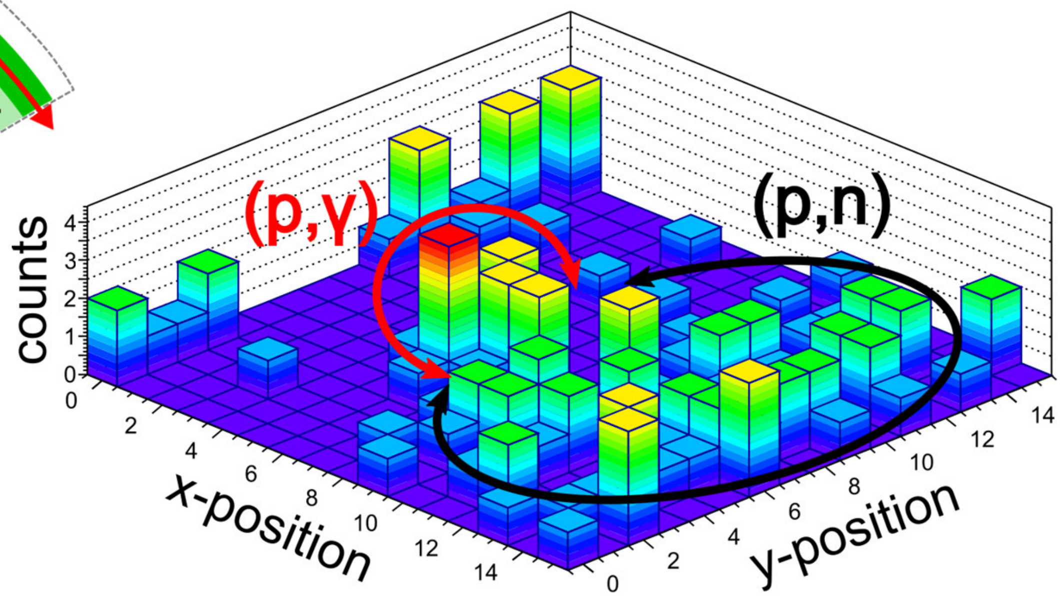


Proton-induced reaction rates on radioactive isotopes for the astrophysical p process

- **Proton capture in inverse kinematics to investigate radioactive isotopes in rings**
- **Feasibility demonstrated, could not reach low energy**
- **Unexpectedly long setup time**



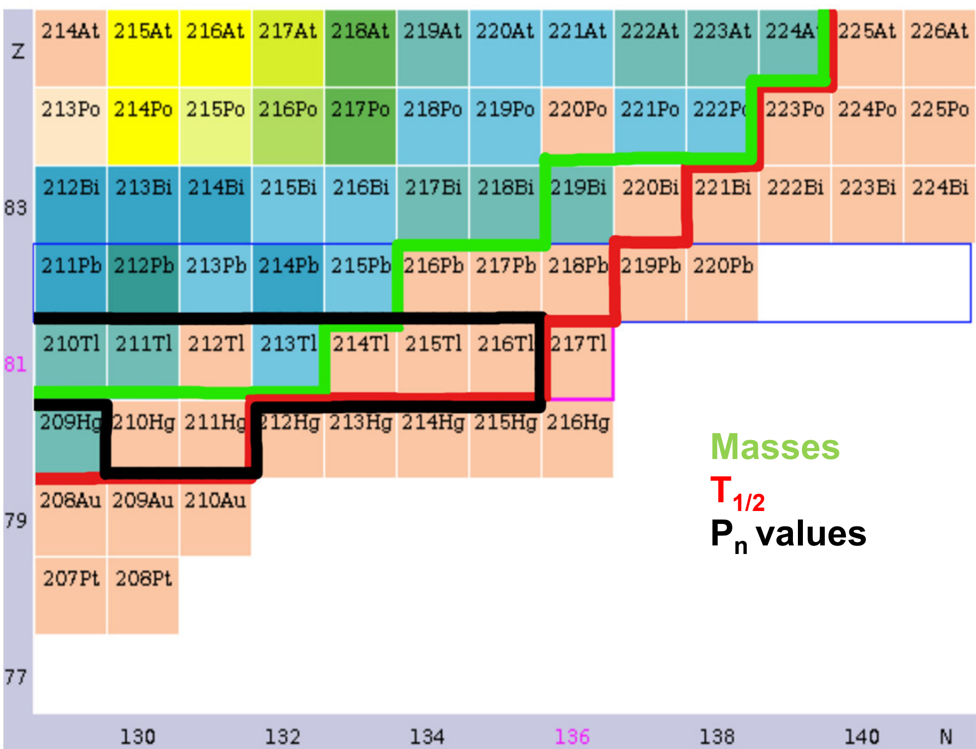
^{118}Te ($T_{1/2}$ = 6 d)
Beam time: 3 shifts



β-Delayed Neutron Emission Probabilities

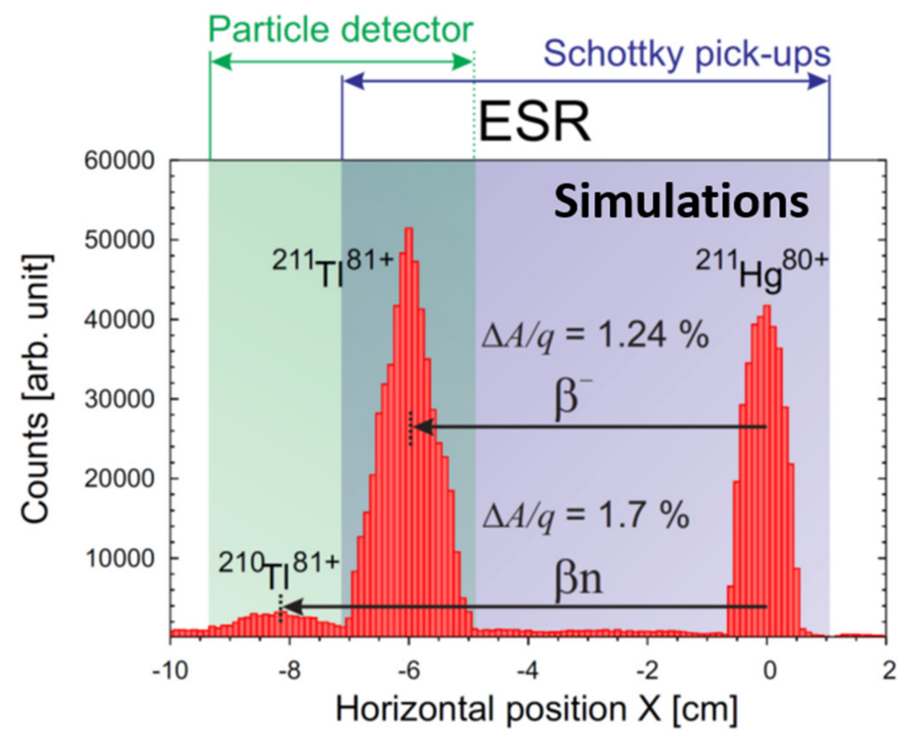
proposal C.J. Griffin, I. Dillmann, et al.

TRIUMF



Problem: very rare ions and low transmission into ESR

After β-decay ions hit detector, at different position with β-n, take ratio of peaks.



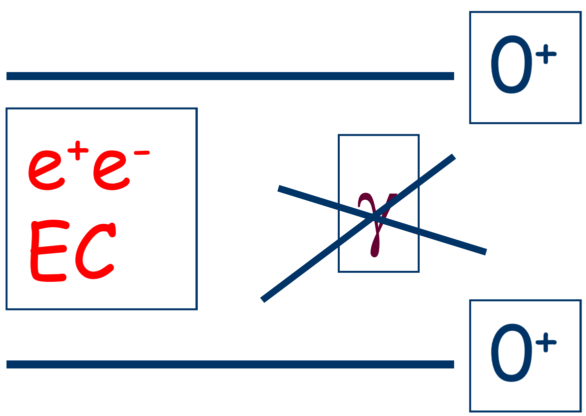
A. Evdokimov *et al.*, Proceedings of Science (PoS) SISSA **146** (2013) 115

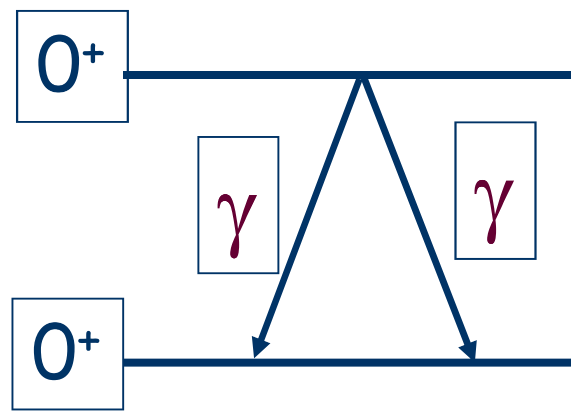
Nuclear Two-Photon or double-gamma decay

Rare decay mode whereby two gamma rays are simultaneously emitted

- Second order quantum mechanical process proceeds through virtual excitation of higher-lying intermediate states
- Observable only when first order decays are hindered
  ex. $0^+ \rightarrow 0^+$ E0 decay : single γ-ray emission is forbidden

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





- **$E_x(0^+) < 2\, m_e c^2$ → no e^+e^- decay**
- **fully stripped ions → no EC decay**

$$E_{\gamma 1} + E_{\gamma 2} = \omega = E_x(0^+)$$

$$\Gamma_{\gamma\gamma} \propto \omega^7 \left[\alpha^2(E1) + \chi^2(M1) + \omega^4 \alpha^2(E1)/4752\right]$$

Two-Photon decay experiments in stable nuclei

Isotope	E_x (0_2) [MeV]	$T_{1/2}$ [ns]	Decay modes	$\Gamma_{\gamma\gamma}/\Gamma_{tot}$	$\Gamma_{\gamma\gamma}/E_x^7$ [s^{-1}/MeV^{-7}]
^{16}O	6.05	0.067	e^+e^-, e^-, 2γ	$6.6\ 10^{-4}$	33.4
^{40}Ca	3.35	2.1	e^+e^-, e^-, 2γ	$4.5\ 10^{-4}$	31.5
^{90}Zr	1.76	62	e^+e^-, e^-, 2γ	$1.8\ 10^{-4}$	38.6

Very constant "reduced" 2γ decay strength ($\Gamma_{\gamma\gamma}/E_x^7$) : *average 34.5*

Isotope	E_x (0_2) [MeV]	$T_{1/2}$ [ns]	Decay modes	$\Gamma_{\gamma\gamma}/\Gamma_{tot}$	$\tau_{\gamma\gamma}$/s
^{72}Ge	0.691	444	e^-, (2γ)	➔ $1.7\ 10^{-7}$	*~0.4*
^{98}Mo	0.735	22	e^-, (2γ)	➔ $1.3\ 10^{-7}$	*~0.25*
(^{98}Zr)	0.854	64	e^-, (2γ)	➔ $1.1\ 10^{-6}$	*~0.1*

Low-energy 0^+ states not accessible in direct spectroscopy :

$$\Gamma_{\gamma\gamma}/\Gamma_{tot} \sim 10^{-6} - 10^{-7}$$

Long-lived isomeric states with lifetimes of several hundred ms in bare nuclei

SIS + (FRS) + ESR Setup

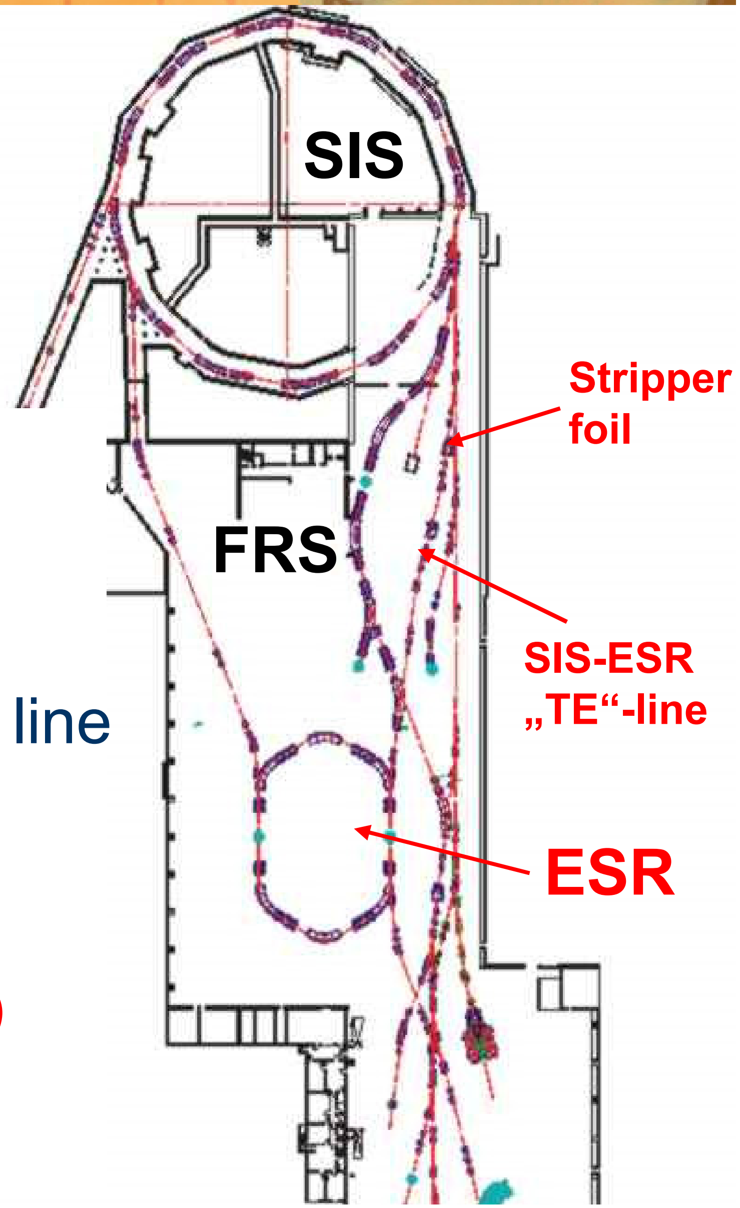
- FRS is needed for Z separation, see ^{205}Tl (spectrometer + degrader)
- FRS was used for Bρ cutting in IMS.
- For simple cases also straight beamline can be used, when FRS is busy.
- Schottky pickups can tolerate higher background when at different frequency.

^{78}Kr (460 MeV/u), ~10^9/spill

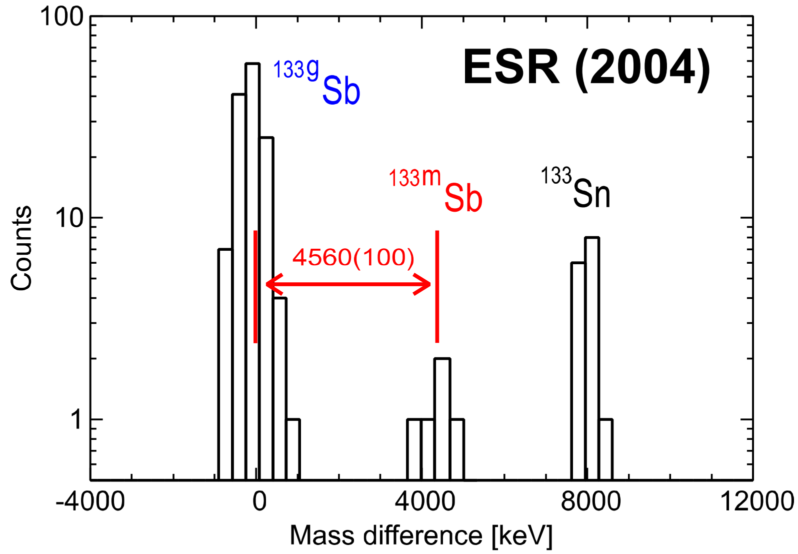
➢ Fragmentation in the SIS-ESR beam line in a Be "stripper" foil (~2 g/cm^2)

✚ **high cross section for ^{72}Ge (~10mb)**
large acceptance & transmission

➔ **~20 ions per spill in the isomer (500 total)**

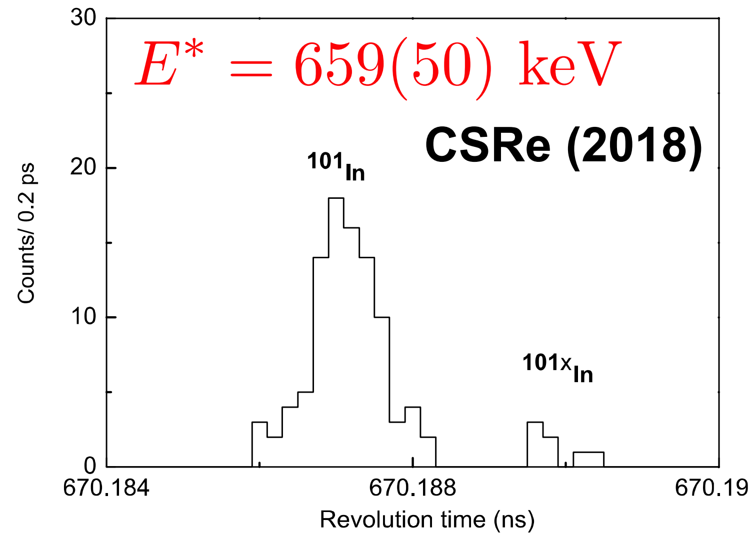


Mass Resolution



B. H. Sun et al., Phys. Lett. B688 (2010) 294

$$\frac{m}{\Delta m} \approx 200'000$$



X. Xu et al., Phys. Rev. C100 (2019) 051303(R)

$$\frac{m}{\Delta m} \approx 320'000$$

Required Mass Resolving Power for A=72, E*=691 keV

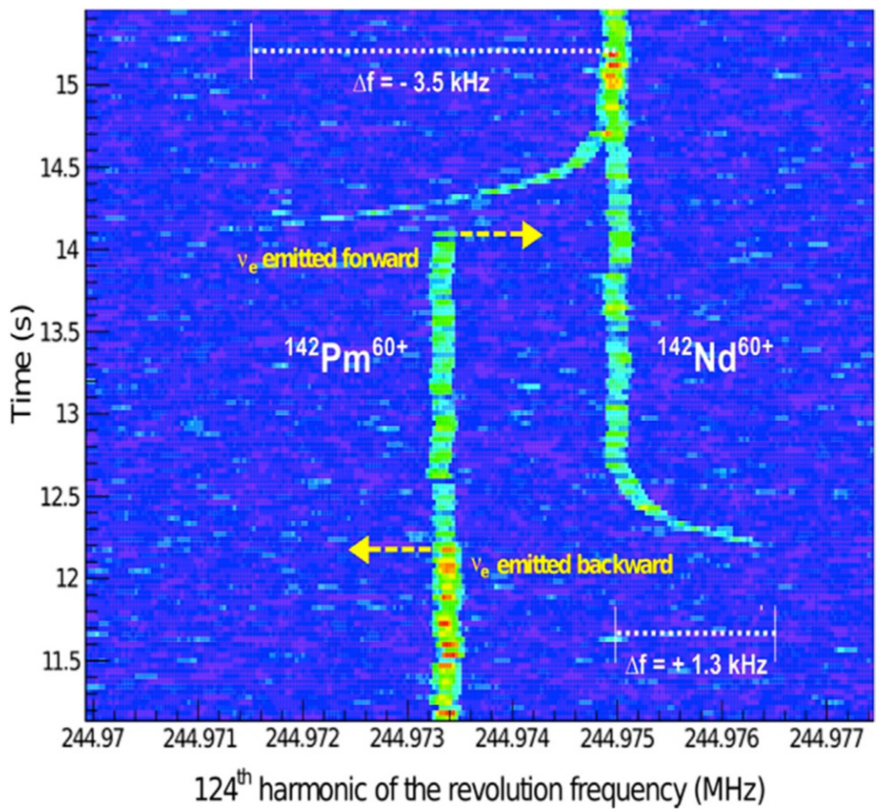
$$\frac{A}{E^*} = 97'100$$

^{72}Ge will be well separated with Schottky detector

Lifetime will be determined by the disappearance of the isomer peak

Time-Resolved Schottky

P. Kienle et al., PLB 726 (2013) 638



Few ion injection with resonant Schottky pick-up

$^{142}\mathrm{Pm} \rightarrow ^{142}\mathrm{Nd}$ EC decay $Q \sim 4870$ keV

$\Delta f \approx 1.6 \text{ kHz } (h = 124)$

Isochronous mass spectroscopy

$^{72}\mathrm{Ge}^{*} \rightarrow ^{72}\mathrm{Ge}$ $E_x = 691$ keV

$\Delta f \approx 1.2 \text{ kHz } (f \approx 245 \text{ MHz},\ h = 124)$

$$\alpha_p = \frac{1}{\gamma_t^2},\ \gamma_t = 1.41$$

In case of resolution problems use single ion traces, one Ge ion per injection, observe jump in frequency for decay.

Summary

Construction of detectors is in progress.
all three systems Schottky, ToF, Heavy-ion telescopes,
will be functional at day 1, when is CR ?

After 30 years ^{205}Tl experiment was finally done.

3 proposals at last G-PAC

- **“Search for the nuclear two-photon decay in fully-stripped ions”**
  find 0+ states, Schottky mass spectrometry in isochronous mode.
  Simple case, challenge only for ring optics. ranked A

- **Isomers and masses in n-rich Hf region**

- **Measurement of β-delayed n-emission branching ratios**
  needs more transmission into ESR, very good for CR.