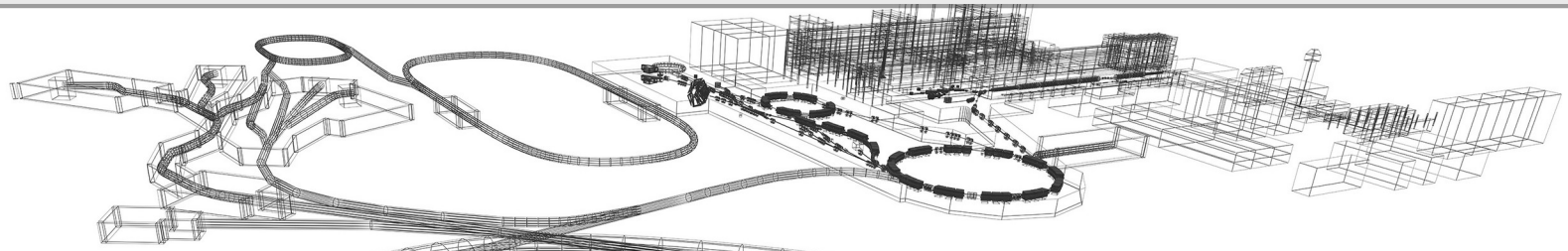


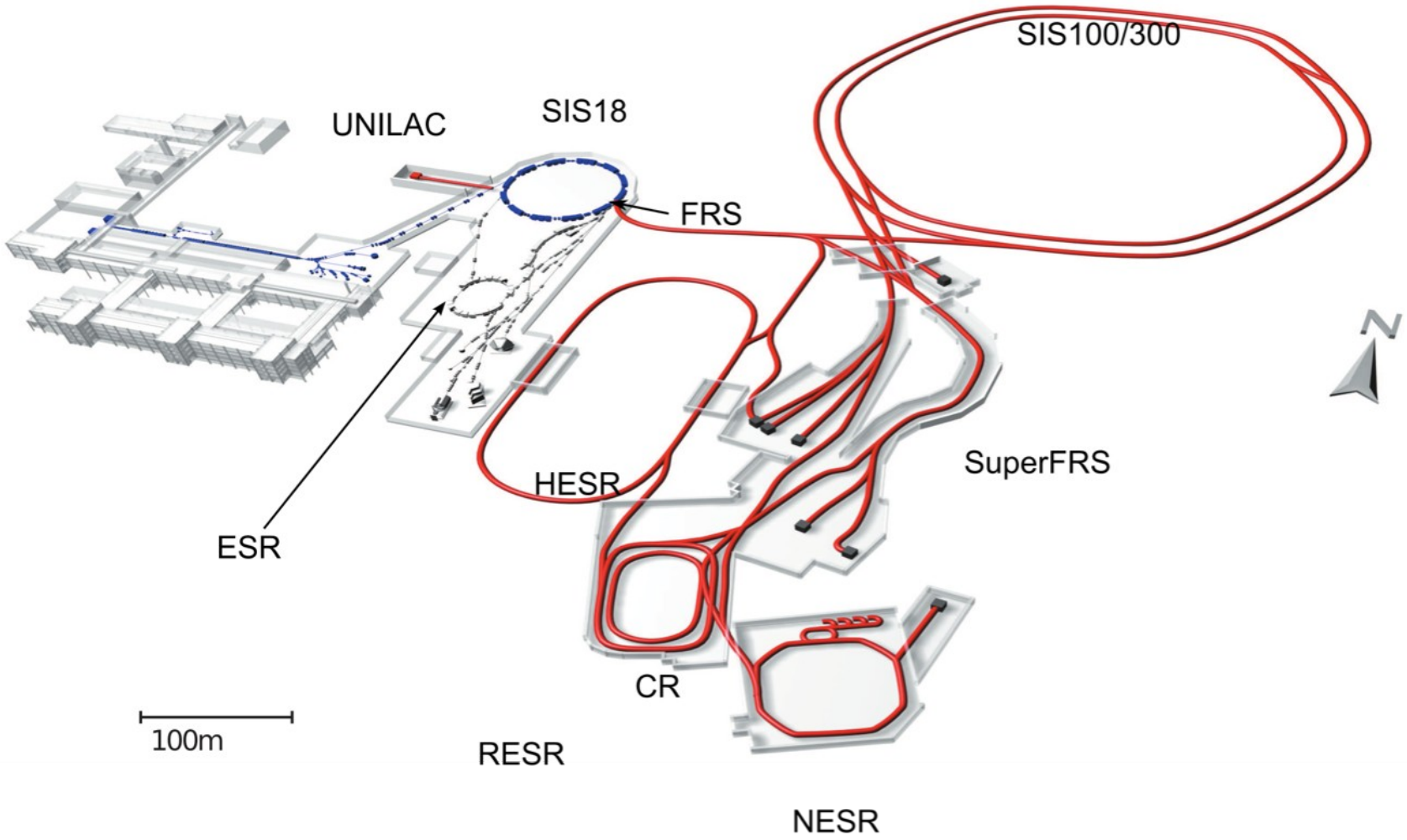
Non destructive lifetime measurement of isomeric states in heavy ion storage rings

Shahab Sanjari
GSI Darmstadt

17th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG 2024)
Chengdu 2024-SEP-10

GSI and FAIR

- Located in Darmstadt (Germany)


SIS100/300
UNILAC
SIS18
FRS
N
HESR
SuperFRS
ESR
CR
100m
RESR
NESR

Storage ring mass and lifetime spectrometry

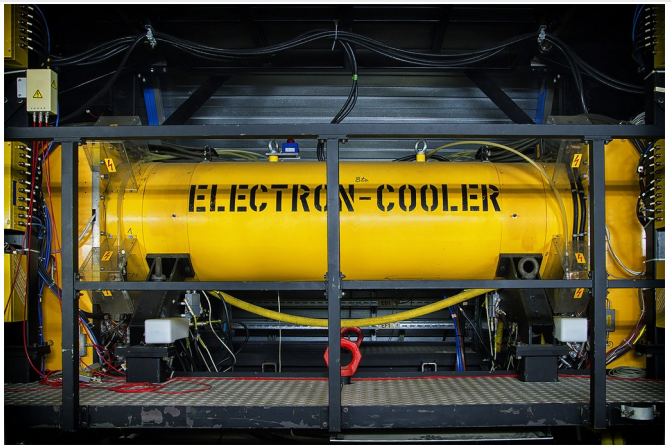
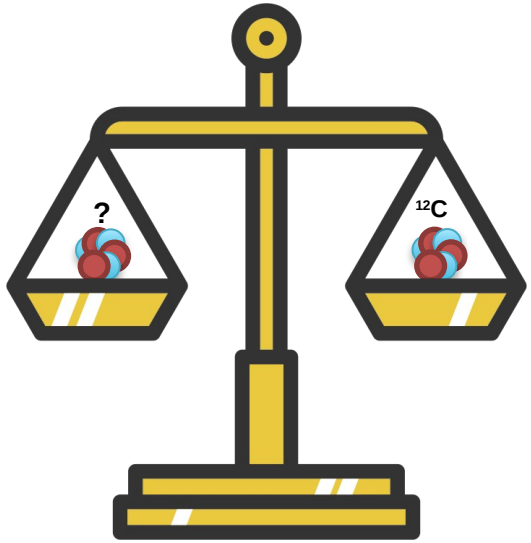
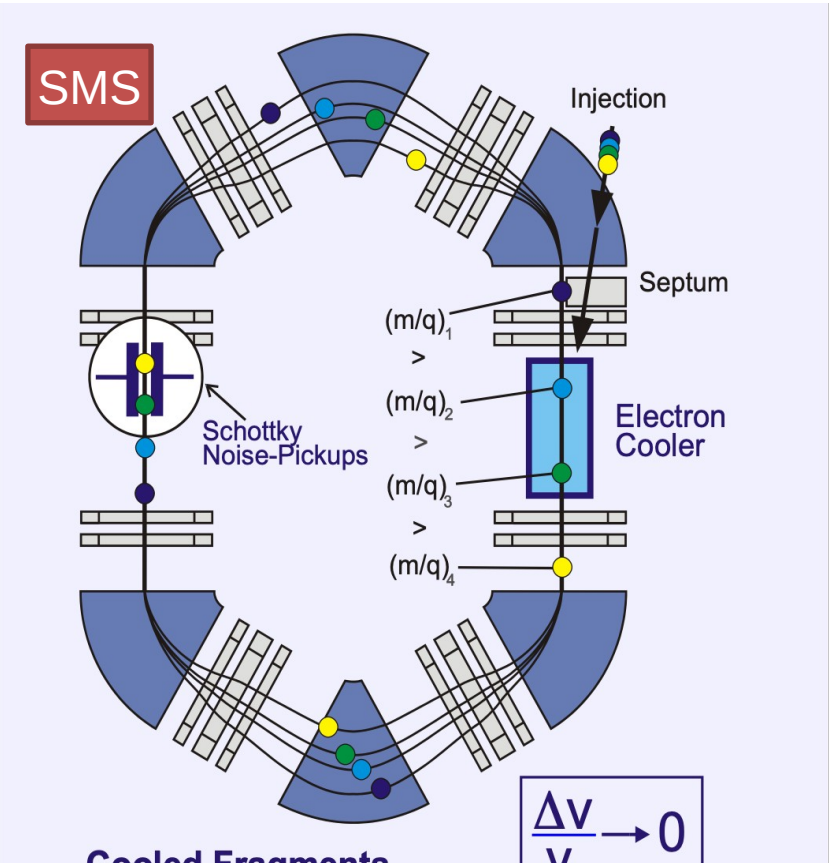
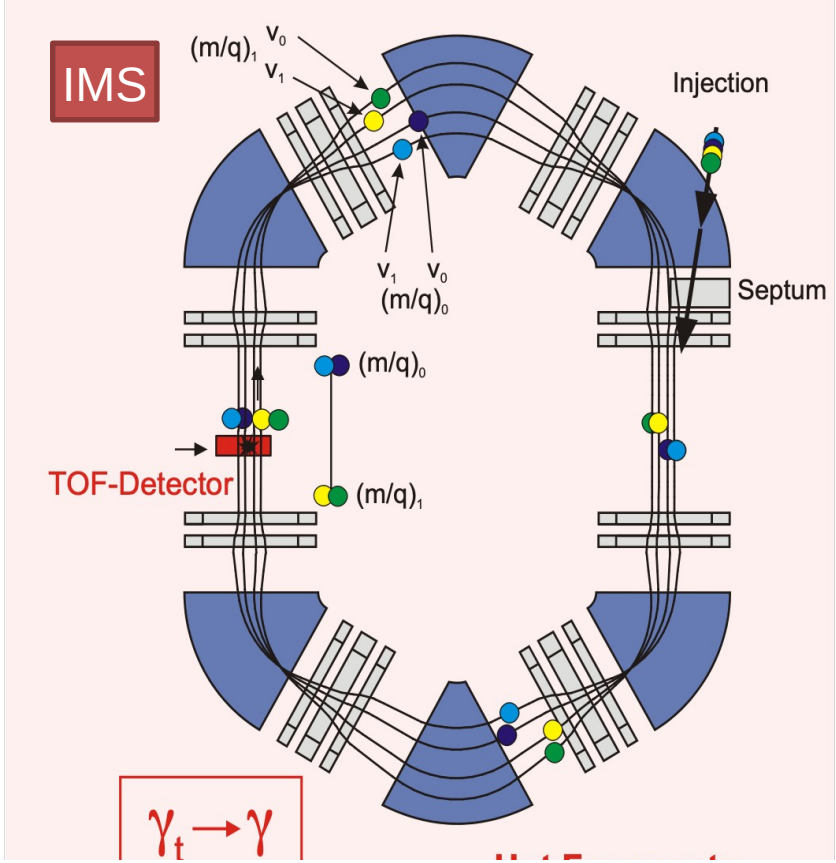


Image: GSI Darmstadt

- Storage Ring Standard Mode **(SMS)**:
  - Using Schottky detectors and E-Cooler
  - Simultaneous lifetime measurement possible
  - Time scales ~ order of s
- Storage Ring Isochronous Mode **(IMS)**:
  - Using ToF detectors
  - MS of very short lived nuclei (~ us)
  - No lifetime measurement possible
- Combined Schottky+Isochronous Mass and Lifetime Spectrometry (**S+IMS)**
  - Simultaneous lifetime measurement possible
  - new method developed in ESR since 2021



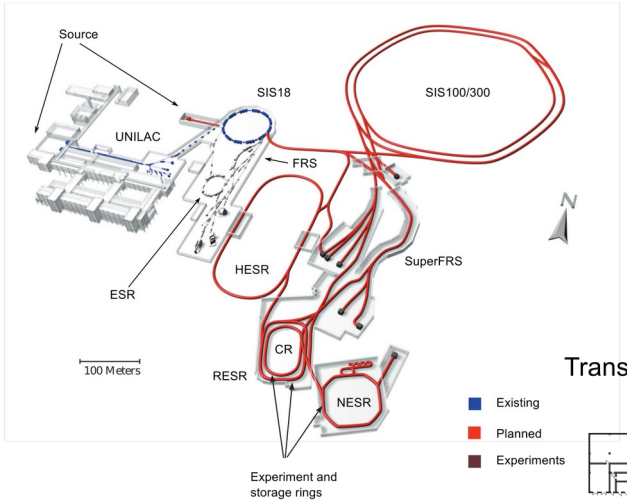


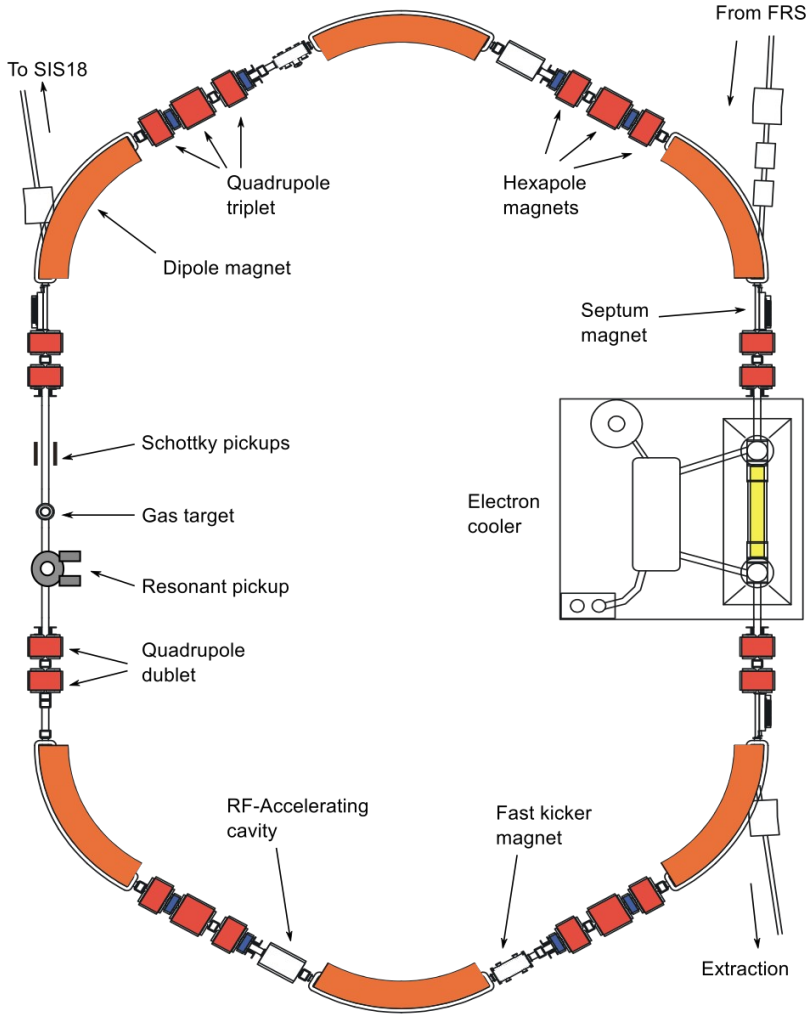


Images courtesy: Yu. A. Litvinov

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

Schottky detectors @ GSI

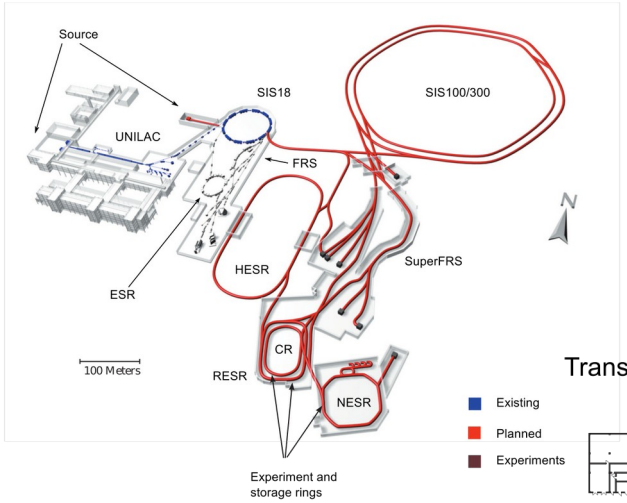


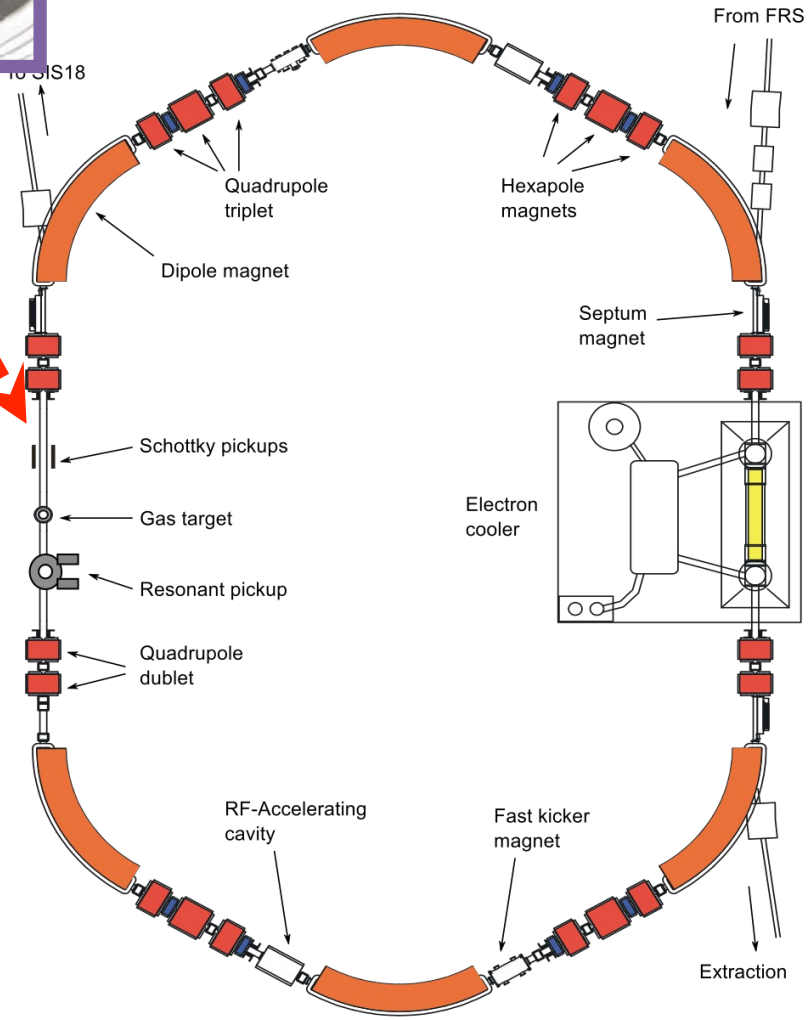


Schottky detectors

B. Schlitt, PhD Thesis 1997

60 MHz

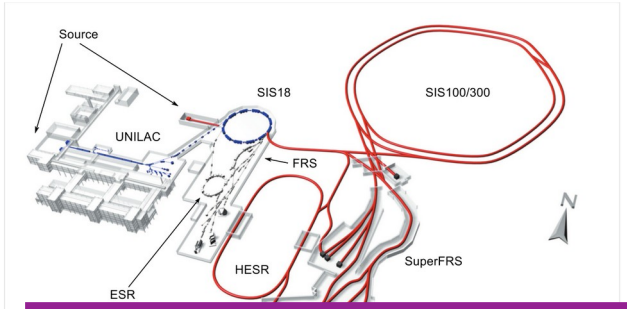


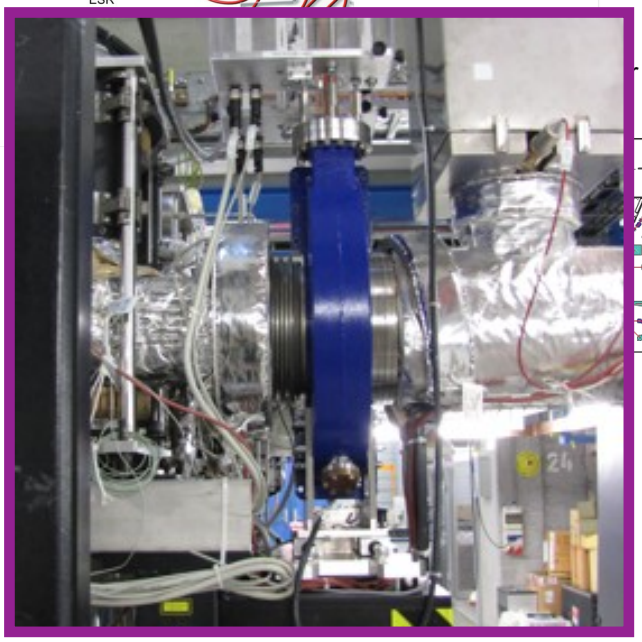


Schottky detectors

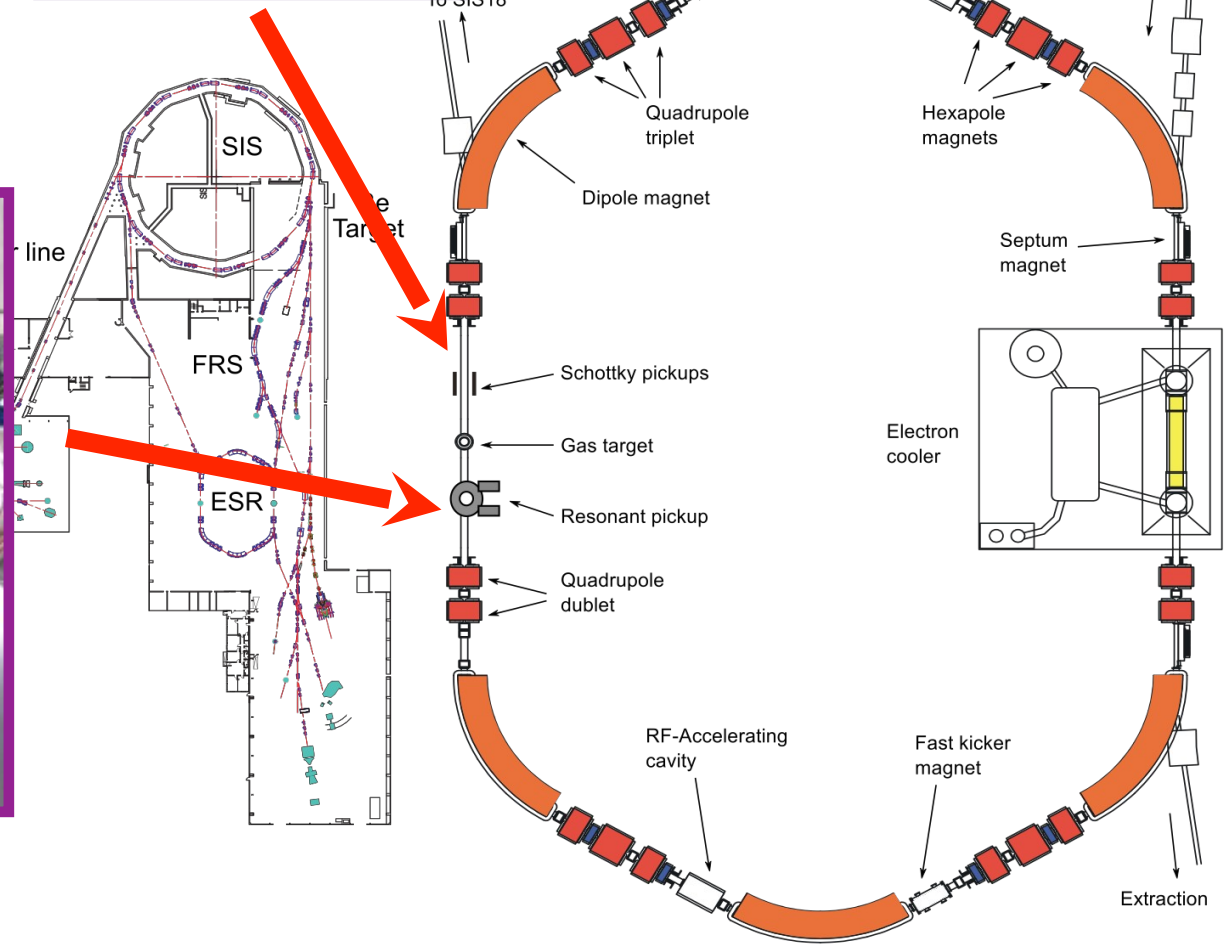
B. Schlitt, PhD Thesis 1997

60 MHz





245 MHz



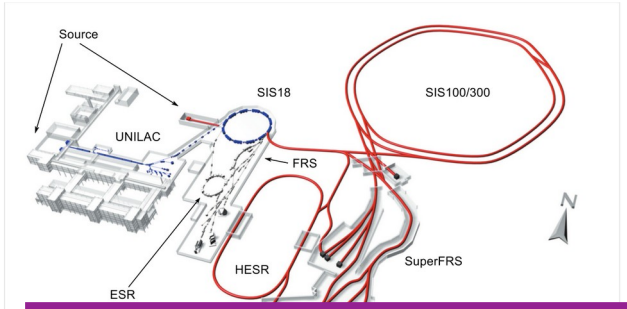
Sanjari et. al. Phys. Scr. 014088 (2013)

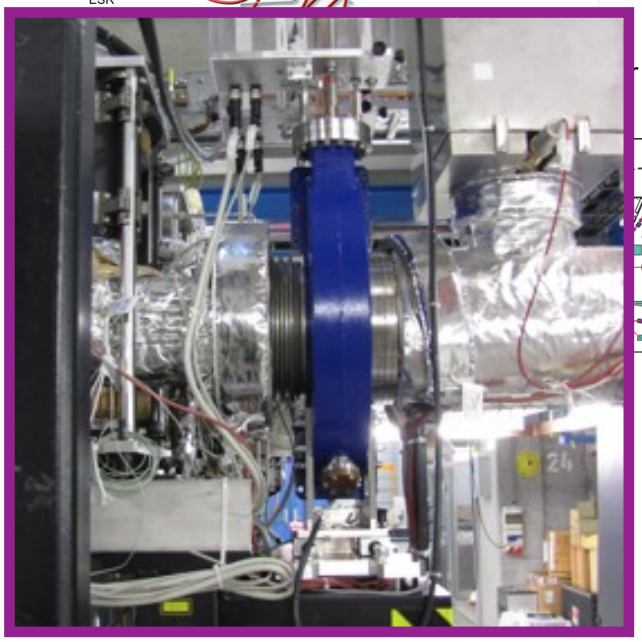
Nolden et. al. NIM-A 659-1 (2011)

Schottky detectors

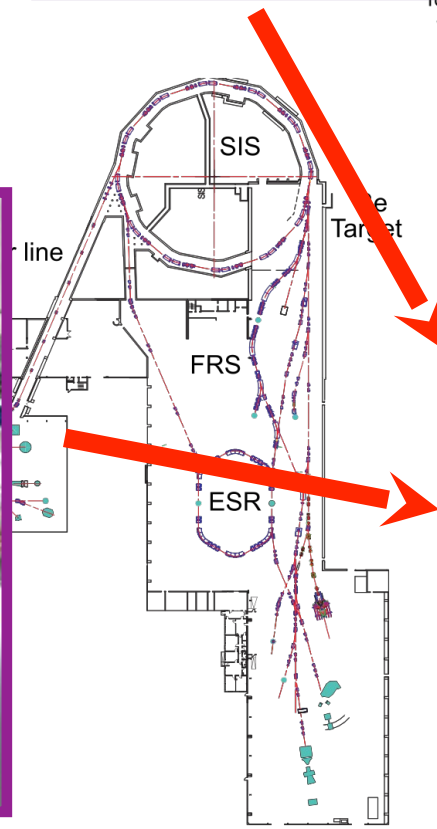
B. Schlitt, PhD Thesis 1997

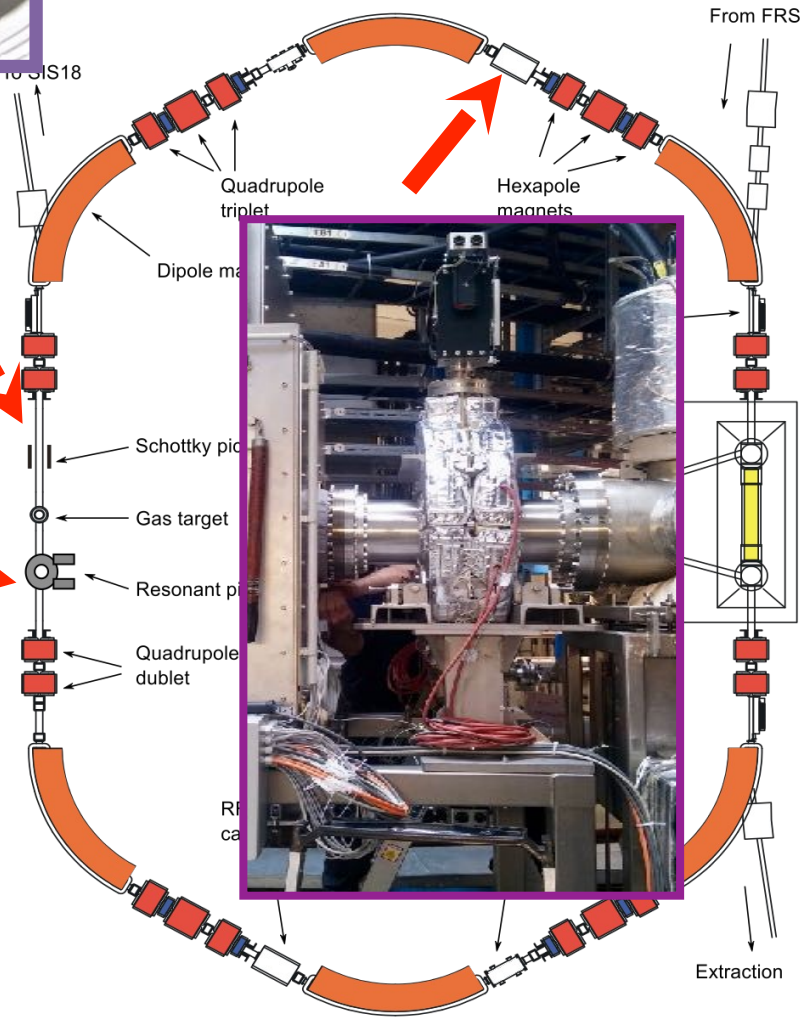
60 MHz





245 MHz





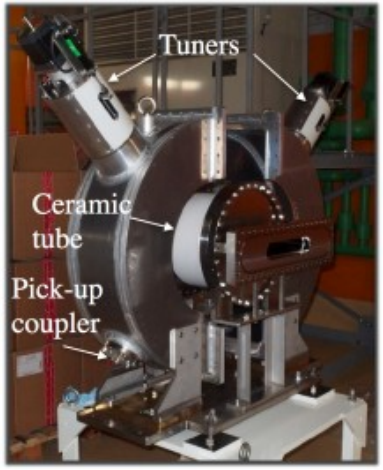
Sanjari et. al. Phys. Scr. 014088 (2013)

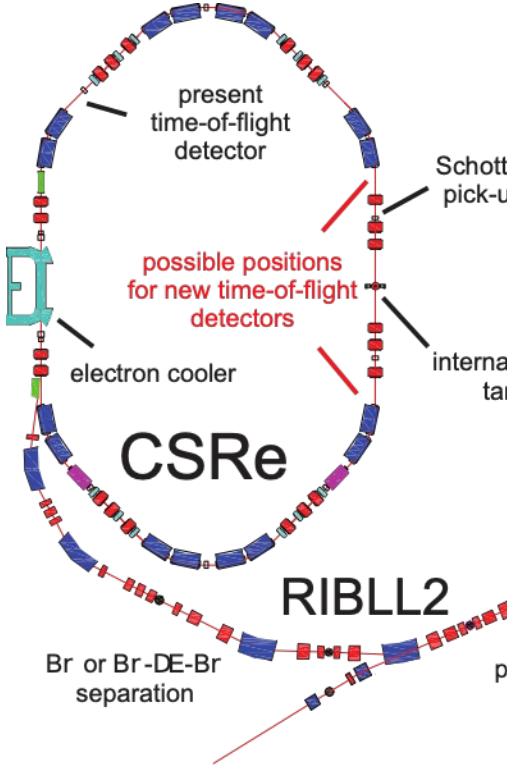
Nolden et. al. NIM-A 659-1 (2011)

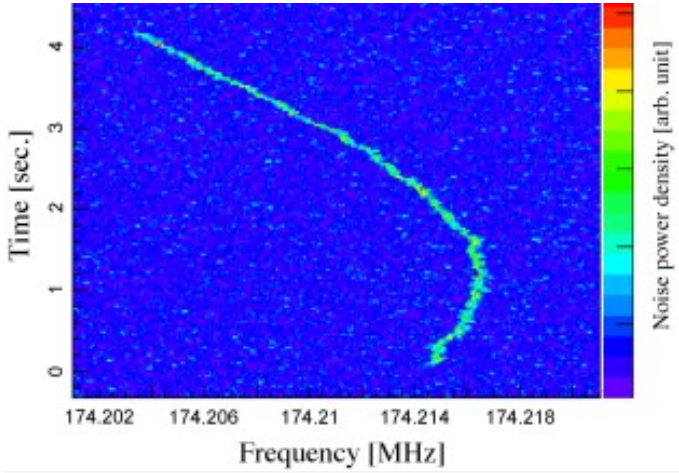
Sanjari et. al. Rev. Sci. Inst. 91(8), pp. 083303 (2020)

410 MHz

- Resonant Schottky detectors at CSRe IMP-Lanzhou and R3 RIKEN



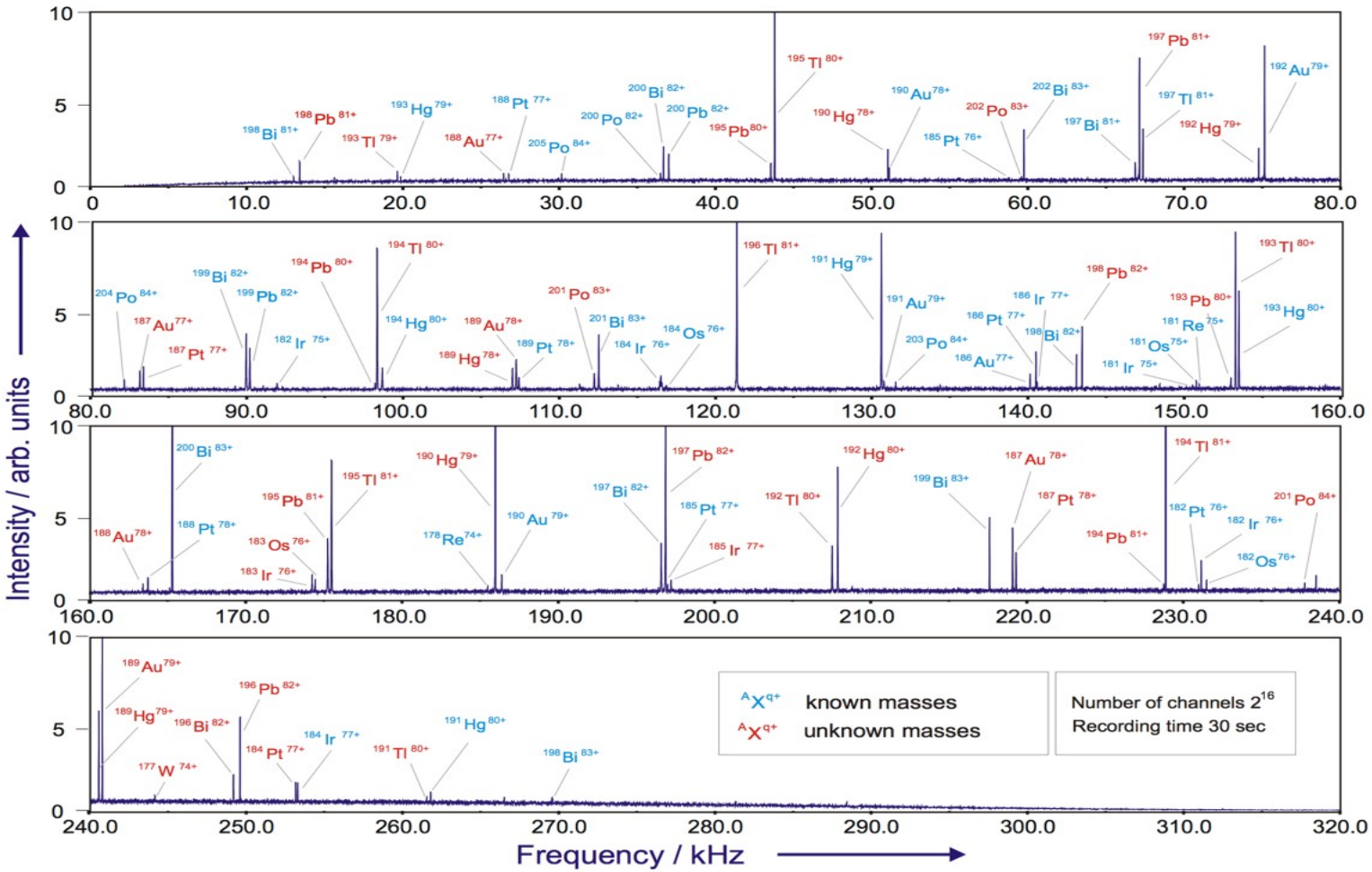




Wu J. et. al. NIM-B 317 (2013)

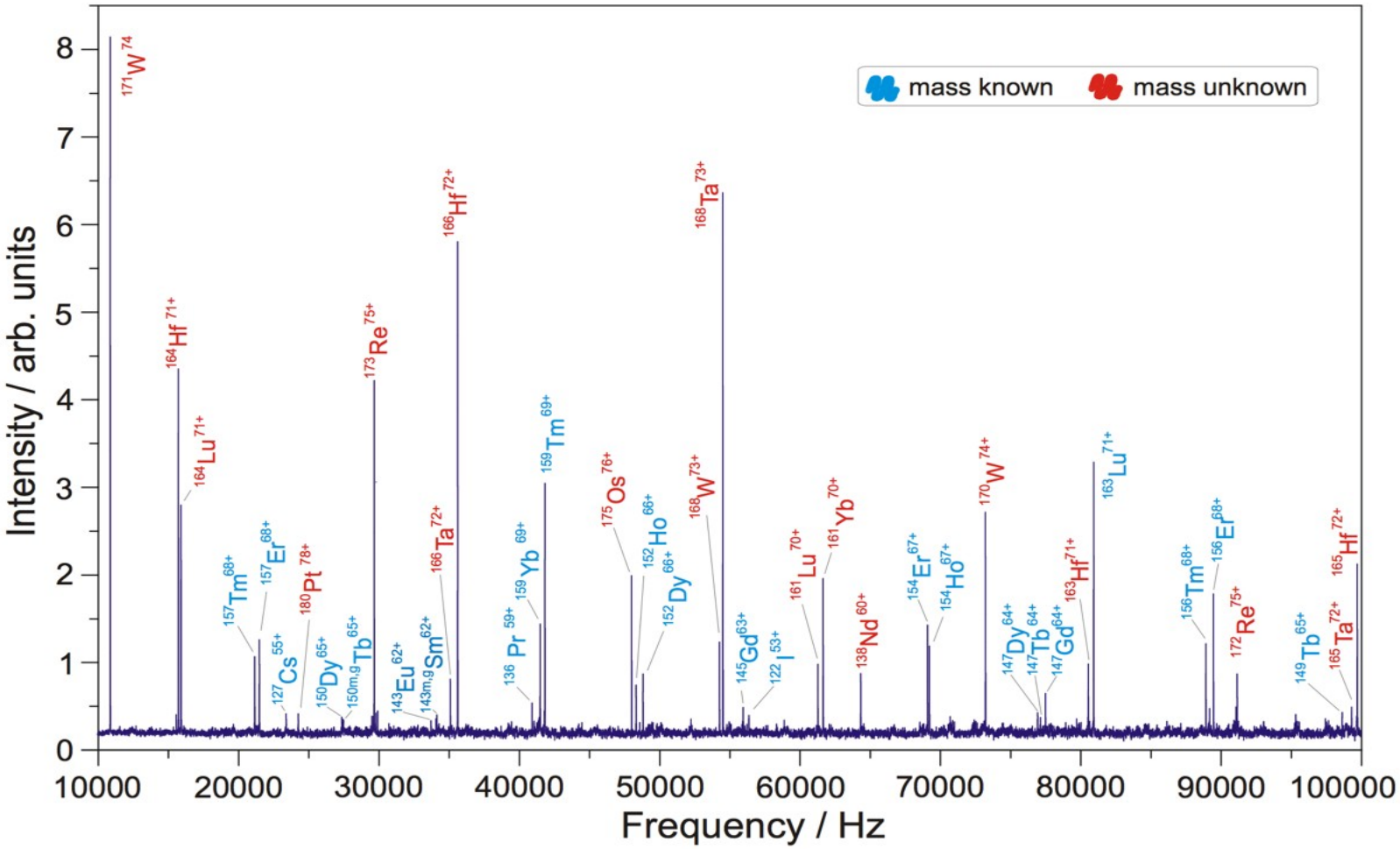
Suzaki et. al. Phys. Scr. T166 (2015)
Yamaguchi et. al. Proc. COOL 2015 (2016)

SMS mass measurement example



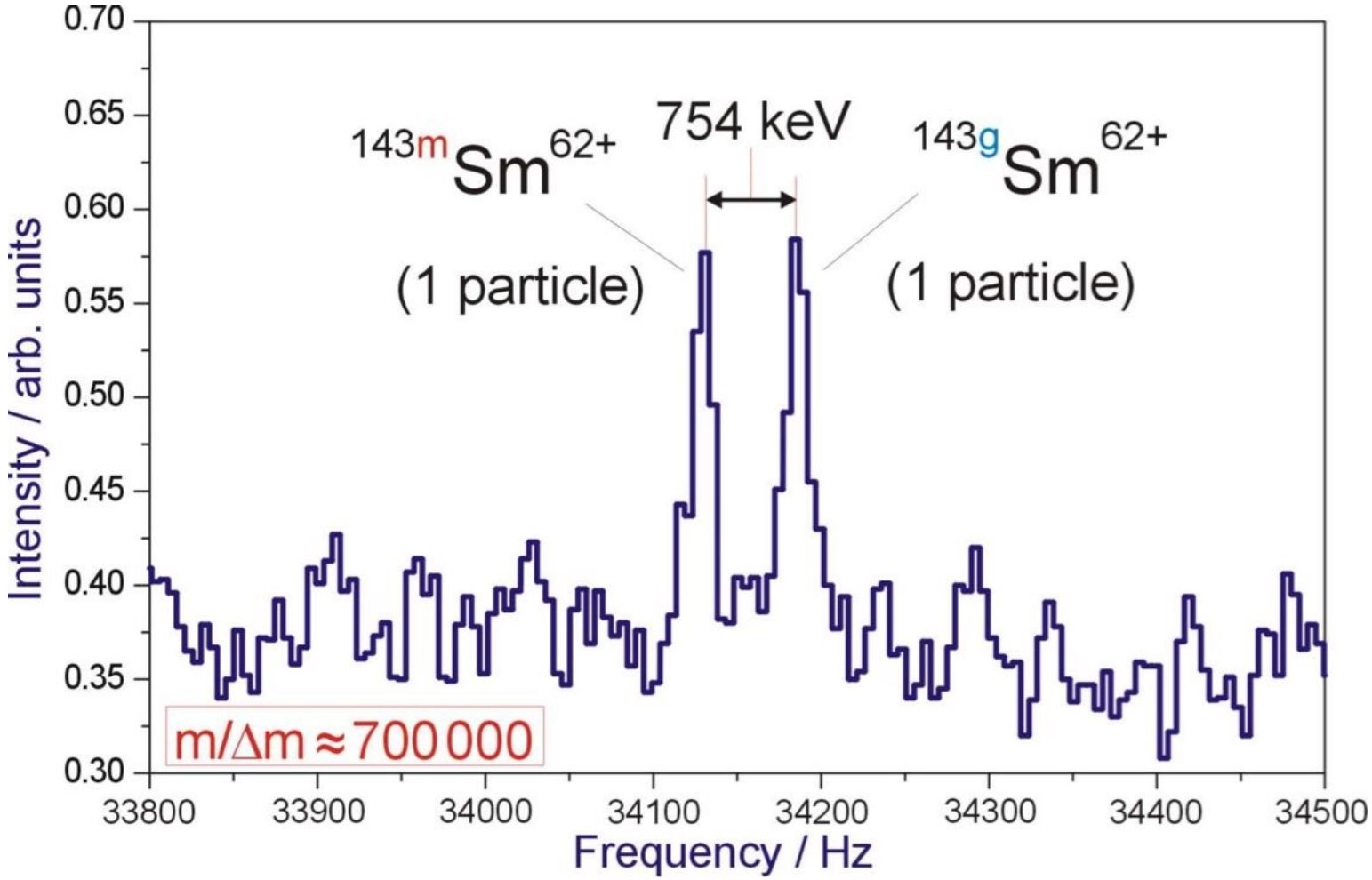
Bosch F., Litvinov Yu. A. Int. J. Mass Spec. V349-350, (2013)

SMS mass measurement example



Bosch F., Litvinov Yu. A. Int. J. Mass Spec. V349-350, (2013)

SMS mass measurement example

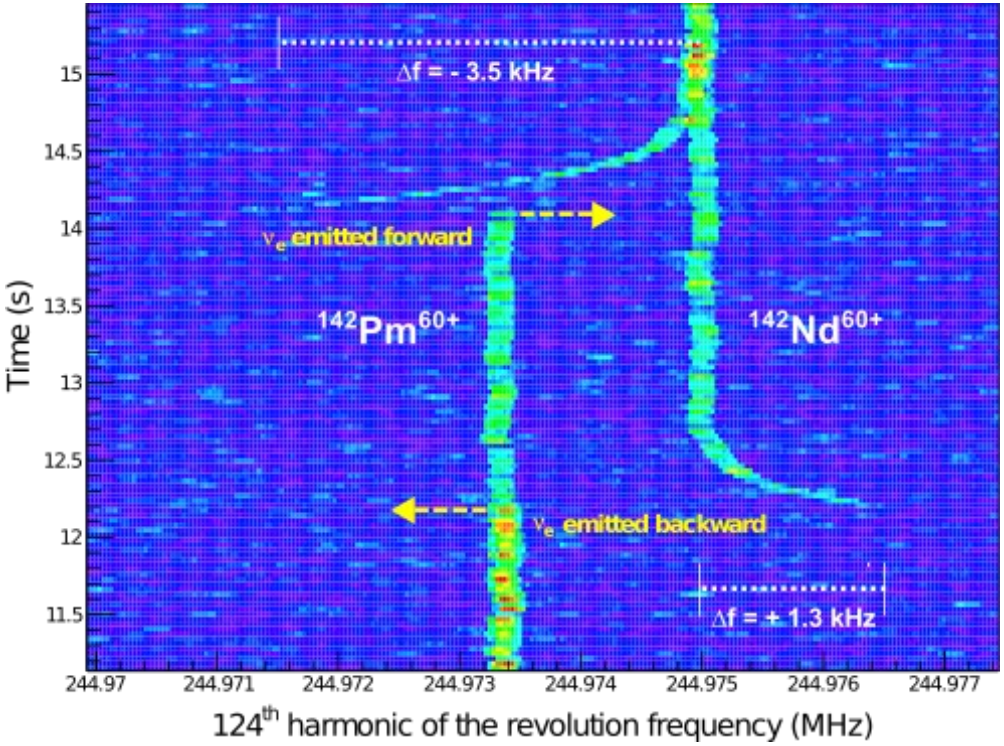


Bosch F., Litvinov Yu. A. Int. J. Mass Spec. V349-350, (2013)

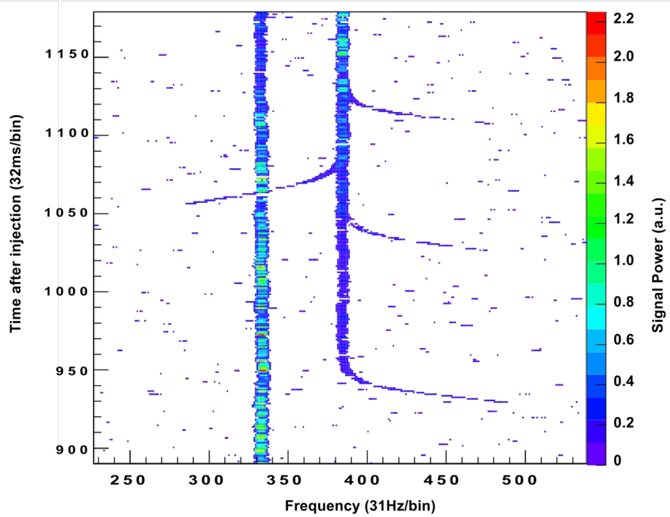
SMS lifetime measurement example

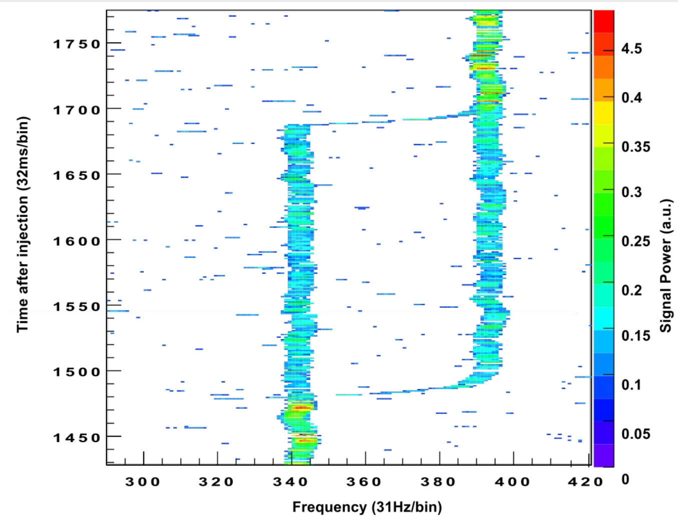
- Single ion 2 body decay study
  - approx. same m/q ratio

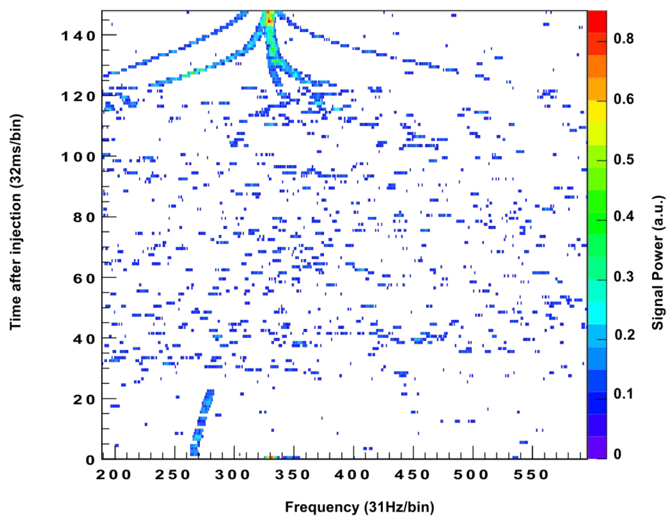
$$^{142}_{61}\mathrm{Pm}^{60+} \longrightarrow {}^{142}_{60}\mathrm{Nd}^{60+} + \nu_e$$

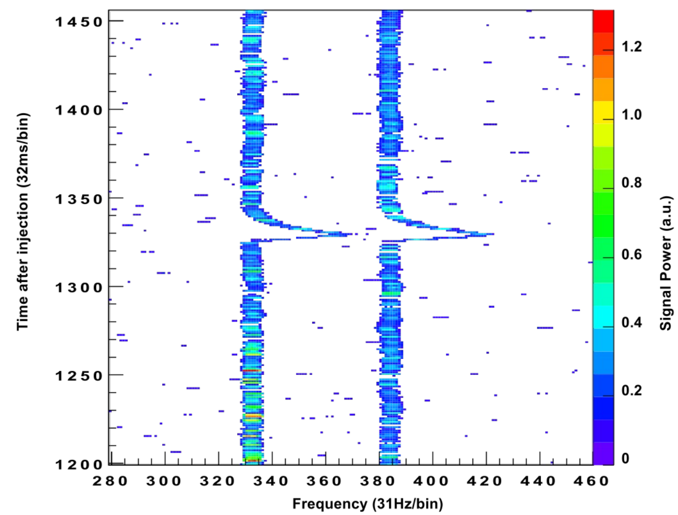


Kienle, Bosch et. al., Phys. Lett. B 726 (2013) 4–5, p.638

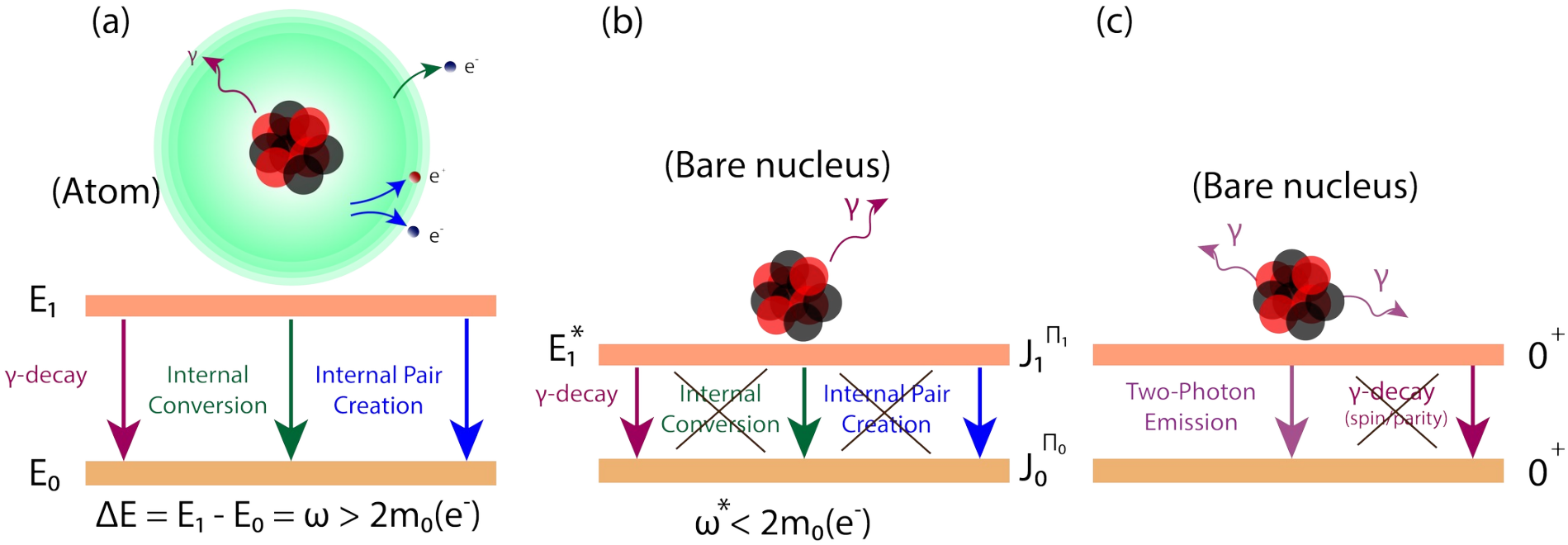

Time after injection (32ms/bin)
900 950 1000 1050 1100 1150
250 300 350 400 450 500
Frequency (31Hz/bin)
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
Signal Power (a.u.)


Time after injection (32ms/bin)
1450 1500 1550 1600 1650 1700 1750
300 320 340 360 380 400 420
Frequency (31Hz/bin)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 4.5
Signal Power (a.u.)


Time after injection (32ms/bin)
0 20 40 60 80 100 120 140
200 250 300 350 400 450 500 550
Frequency (31Hz/bin)
0 0.1 0.2 0.3 0.4 0.5 0.6 0.8
Signal Power (a.u.)


Time after injection (32ms/bin)
1200 1250 1300 1350 1400 1450
280 300 320 340 360 380 400 420 440 460
Frequency (31Hz/bin)
0 0.2 0.4 0.6 0.8 1.0 1.2
Signal Power (a.u.)

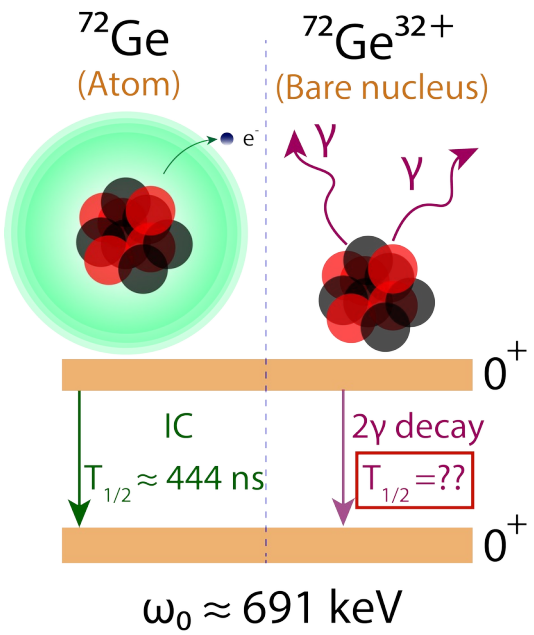
Electromagnetic nuclear de-excitations

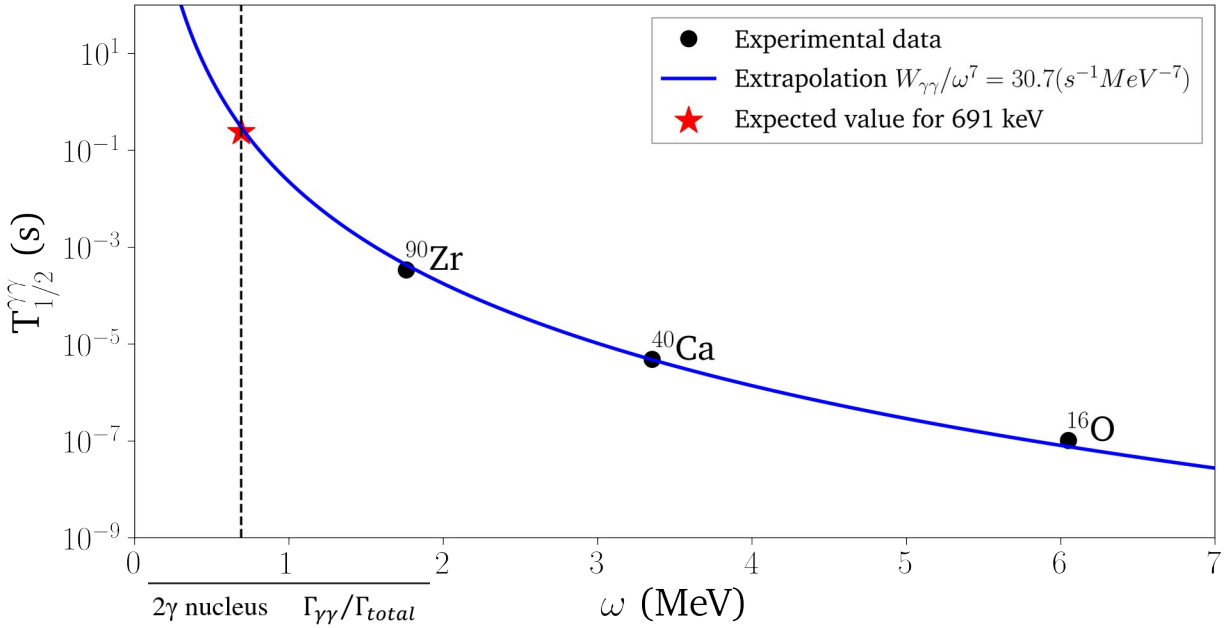


D. Freire-Fernández, PhD Thesis, Uni Heidelberg (2024)

Two photon decays

- First order process is inhibited due to $0^+ \rightarrow 0^+$, second order process → 2 gamma decay
  - Nuclear theory information (shape coexistence, neutron skin depth, etc...)
- Up to now measured using gamma spectroscopy: ^{16}O, ^{40}Ca, ^{90}Zr
- Estimation for ^{72m}Ge partial decay half-life





2γ nucleus	$\Gamma_{\gamma\gamma}/\Gamma_{total}$
^{16}O	$6.6(5)\cdot10^{-4}$
^{40}Ca	$4.5(10)\cdot10^{-4}$
^{90}Zr	$1.8(1)\cdot10^{-4}$

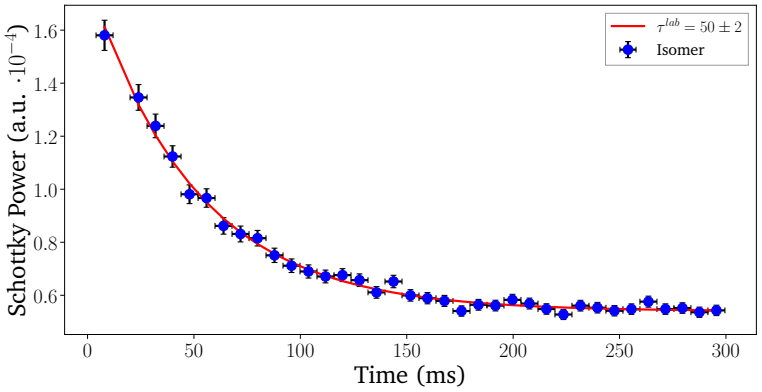
J. Schirmer et al. Phys. Rev. Lett. 53 (1984)

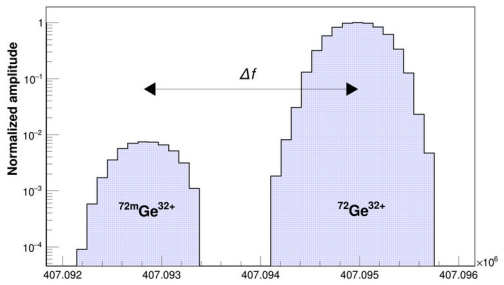
J. Kramp et al., Nucl. Phys. A 474 (1987)

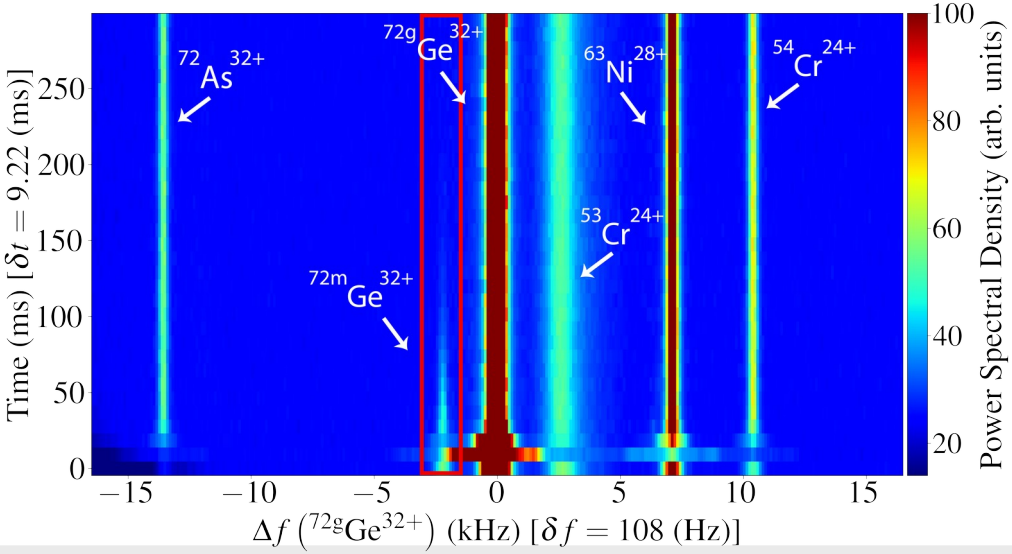
D. Freire-Fernández, PhD Thesis, Uni Heidelberg (2024)

New combined Schottky + IMS (S+IMS) method

- Halflife measurement of ^{72m}Ge (2021)
- Spokesperson: W. Korten @ CEA and Yu. A. Litvinov @ GSI
  - D. Freire-Fernández, R. Chen, S. Litvinov, H. Weick, S. Sanjari and the E0143 collaboration
- $T_{1/2}^{rest}$=23.9(6) ms, 692.8(19) keV
- 10 times shorter than prediction

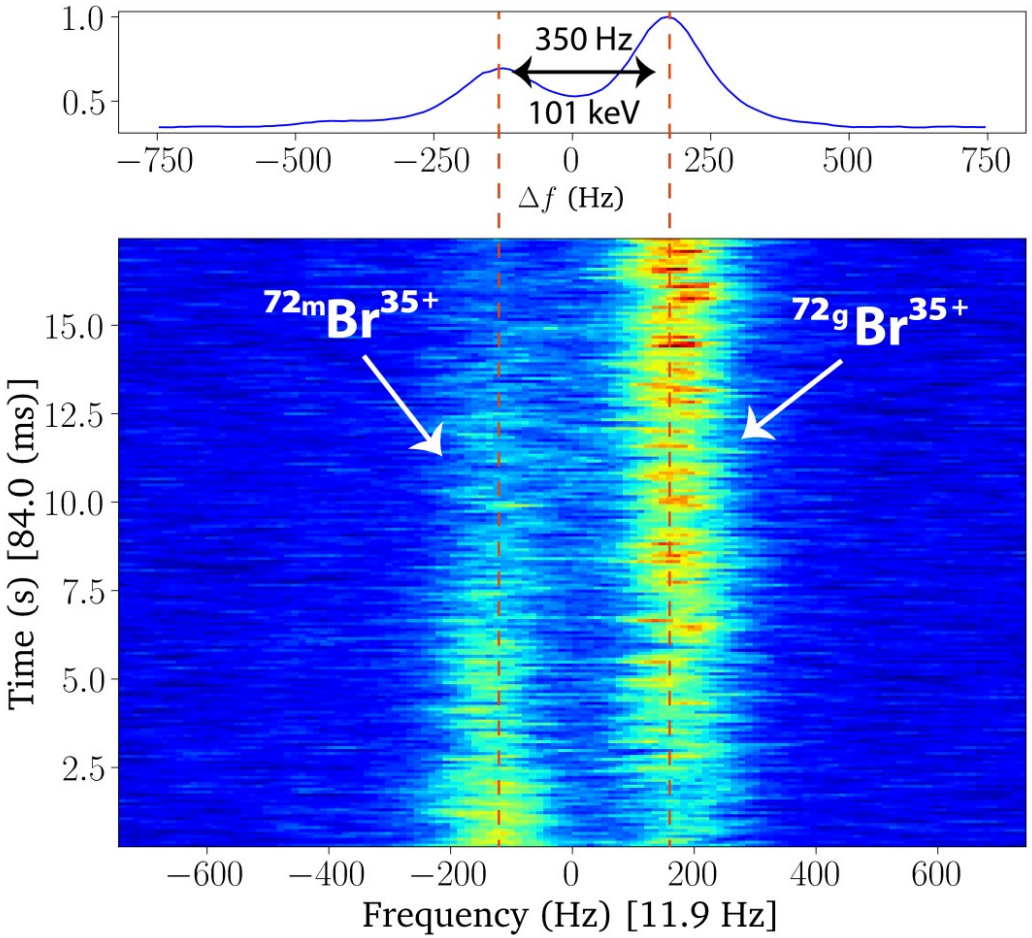






D. Freire-Fernández, et. al. PRL 133, 022502 (2024)

- Low lying isomer ^{72m}Br (Spring 2021)
  - Unprecedented mass resolution of 9.1 x 10^5
  - ~100keV

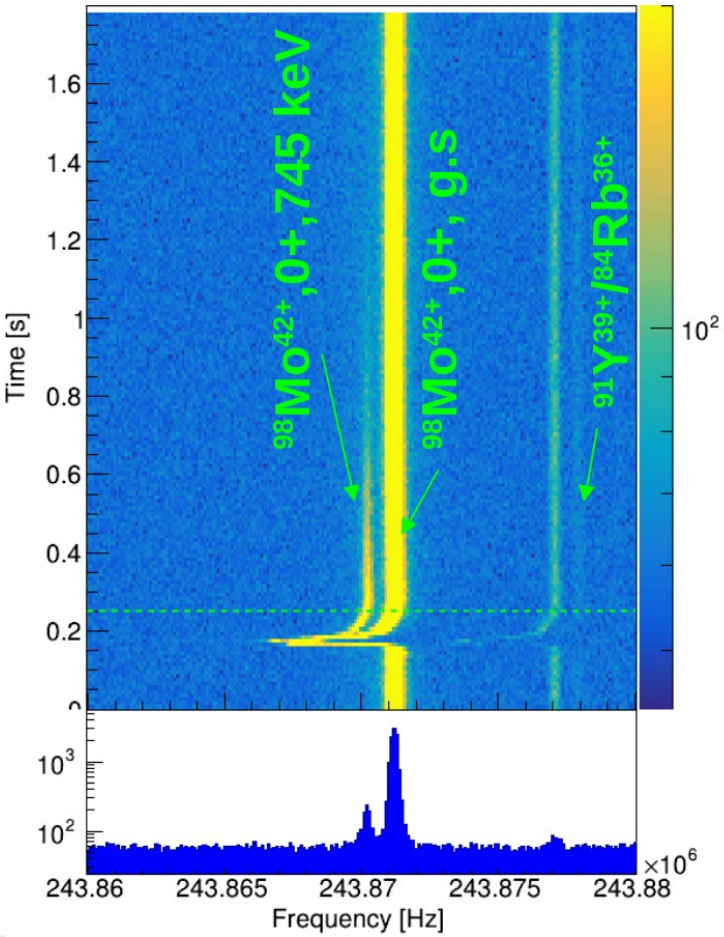


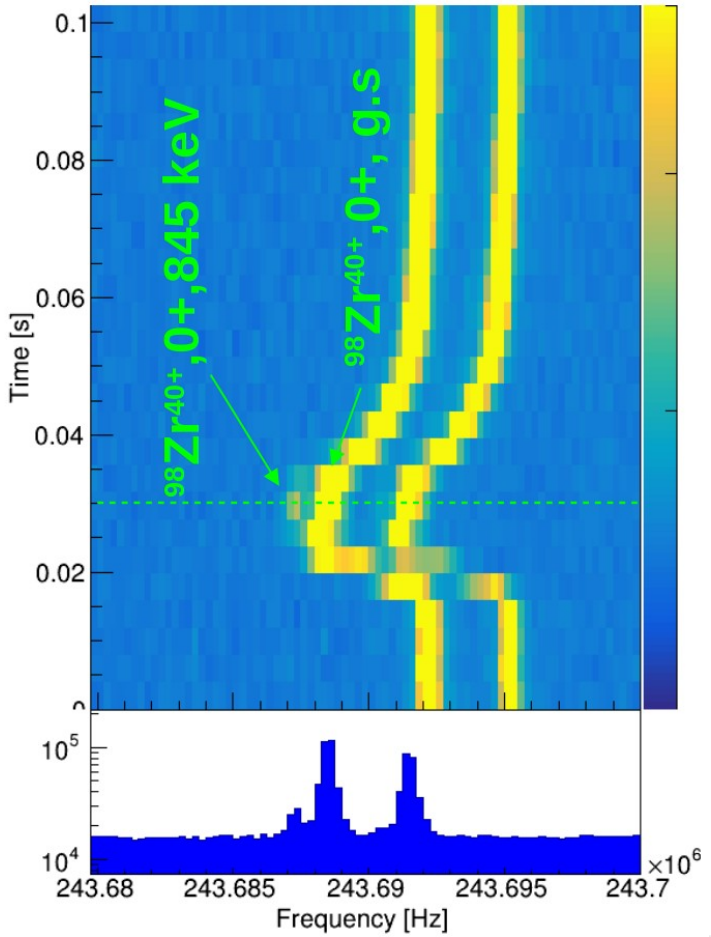
D. Freire-Fernández, PhD Thesis, Uni Heidelberg (2024)

New measurement of ^{98m}Mo and ^{98m}Zr

- Pushing limits down to ~ 3 ms!
- First part of G22-00018 Experiment (May 2024)
- Uncorrected spectra

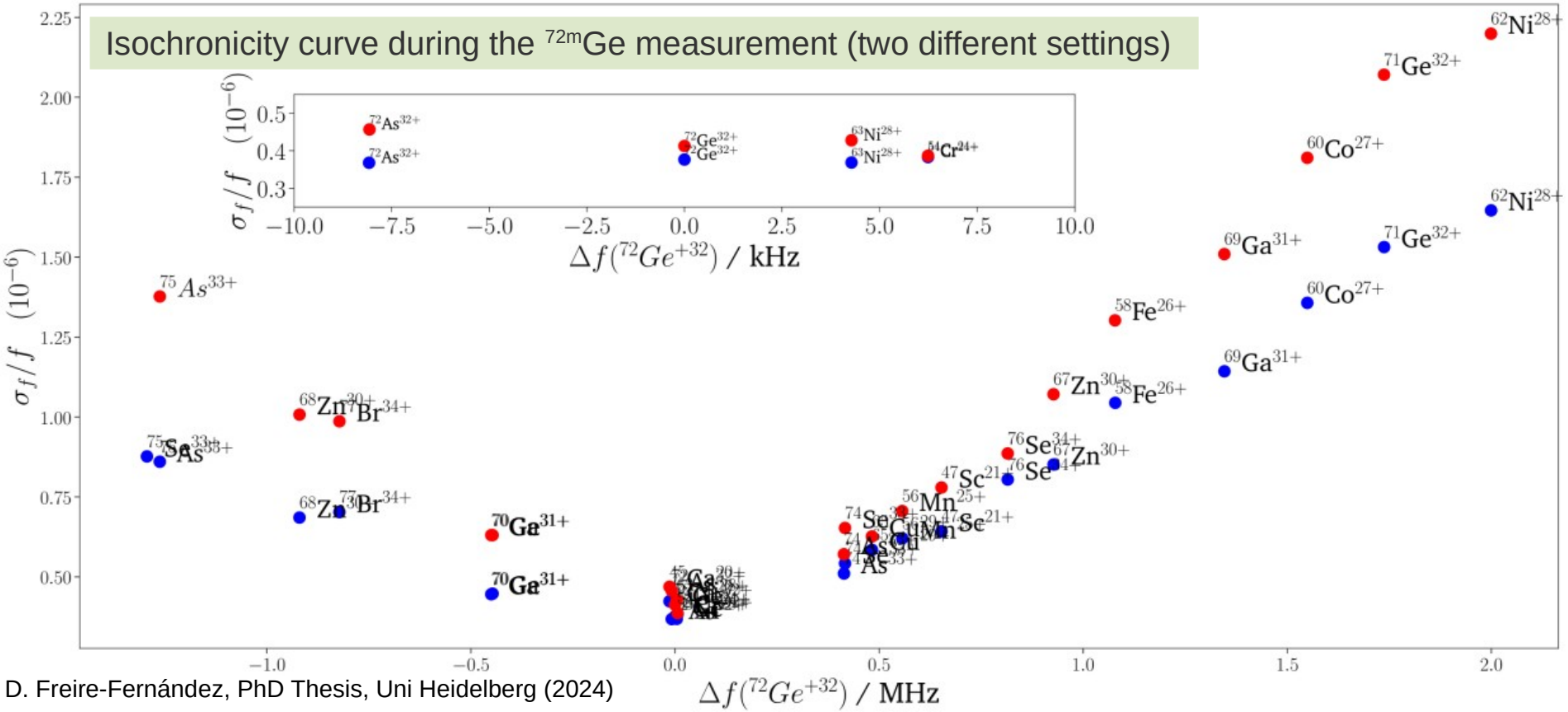
Preliminary!





Plans for further increase of accuracy

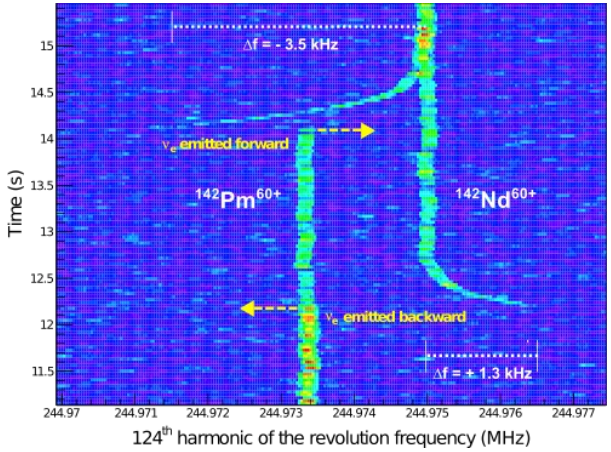
- The isochronous condition is only valid in a very narrow range
  - Causing peak broadening → Increase of Δf/f → Decrease of mass resolving power → Increase of error bar



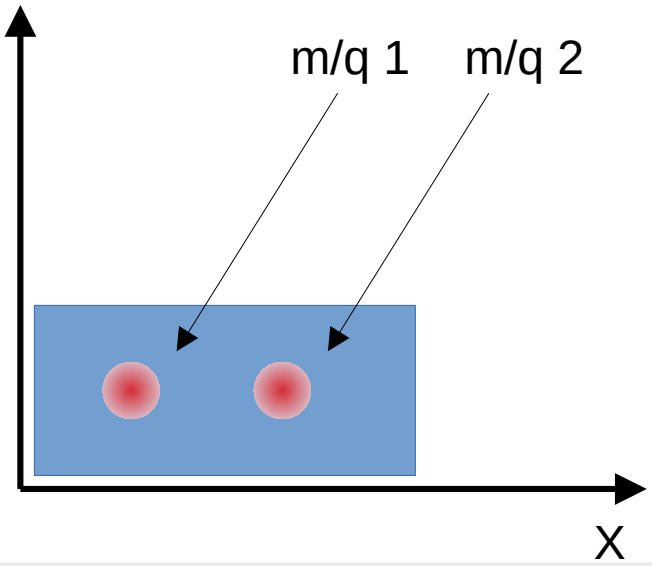
D. Freire-Fernández, PhD Thesis, Uni Heidelberg (2024)

5D analysis

- Up to now: **Power**, **Frequency** and **Time**
- Towards **5 dimensional** analysis:
  - **Phase**: Signal phase between several detectors
  - **Position** (a.k.a. Rho, Brho or velocity)
- Correct for the mass formula
  - Fitting 2nd order pol: good for ID but not for mass measurements
    - Due to reduced resolution!

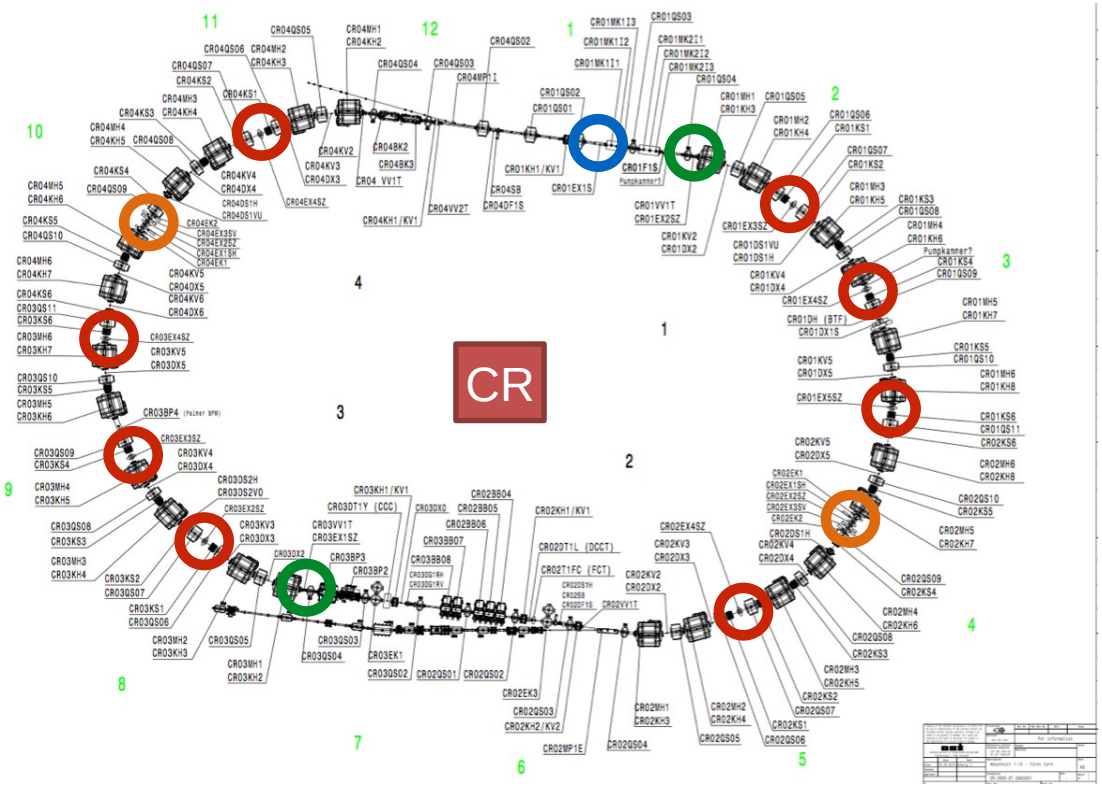


$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{(m/q)} + \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v}{v}$$



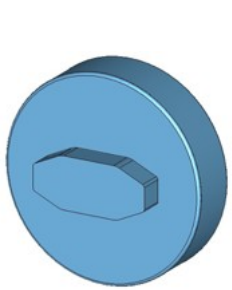
Phase measurement

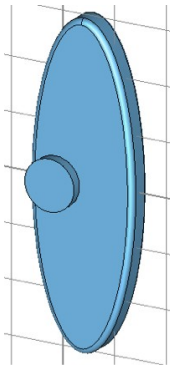
- Correlating signals from different detectors, including the phase information
  - Similar techniques in ion-traps and communications eng.
- Currently work in progress
  - Also many thanks 🙏 to Dr. Qian Wang (IMP Lanzhou, currently guest scientist at GSI)

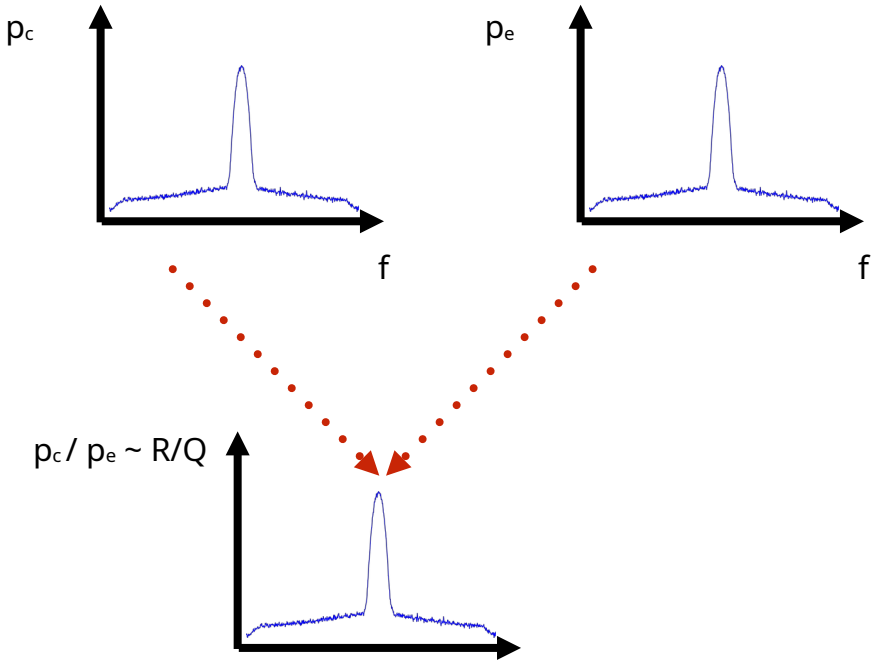


Possible Schottky detector locations in future Collector Ring (CR) @ FAIR

Idea using cavity doublet

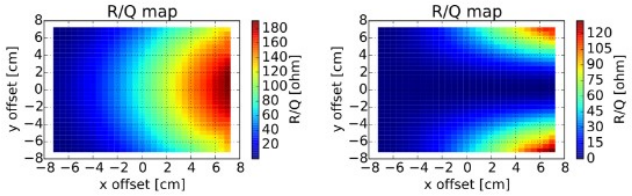




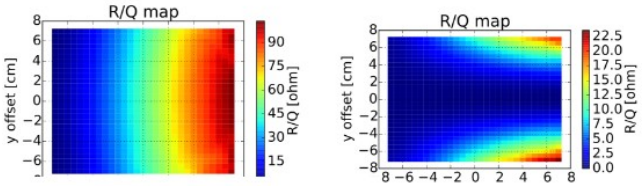


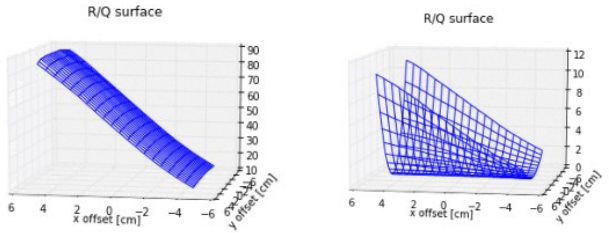
- Position determination
  - Comparison with circular reference
  - Same Depth (TTF)
  - Same f_0

Circular



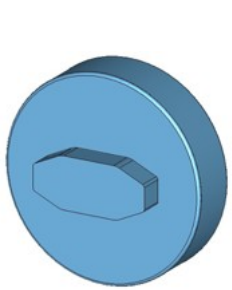
Elliptical

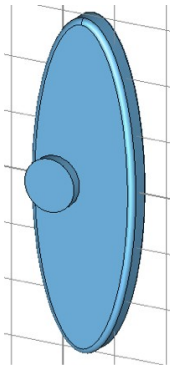


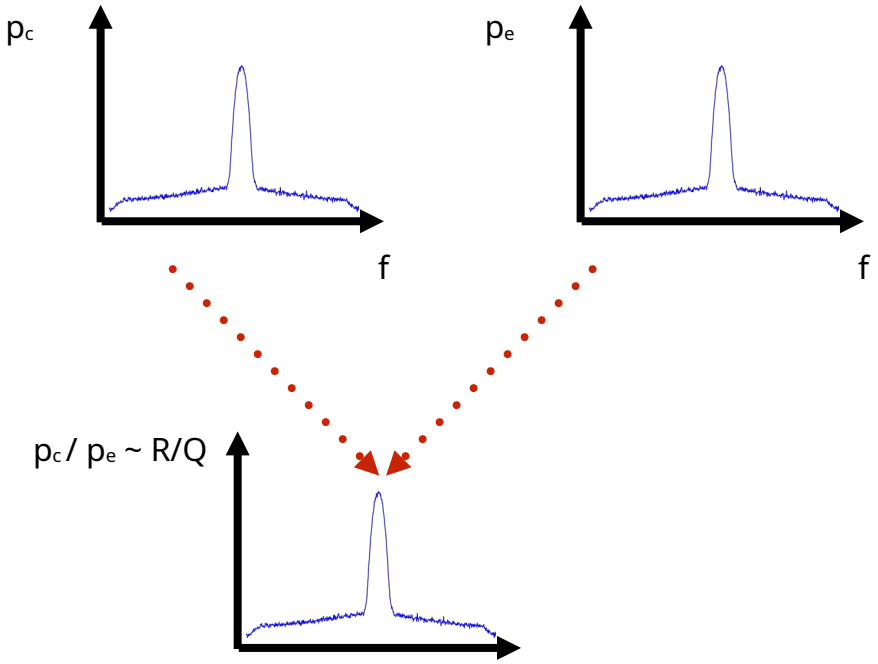


S. Sanjari et. al. Phys. Scr. 014060 (2015)
X. Chen et. al. Hyperfine Interact. (2015) 235:51
D. Dmytriiev, PhD Thesis, 2021

Idea using cavity doublet

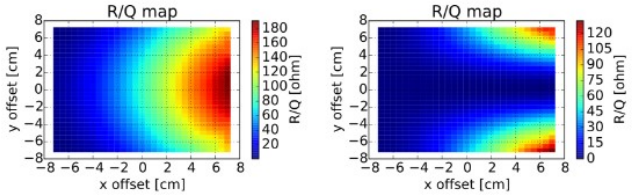




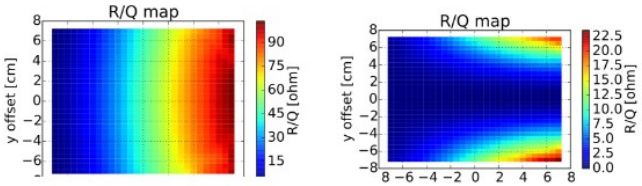


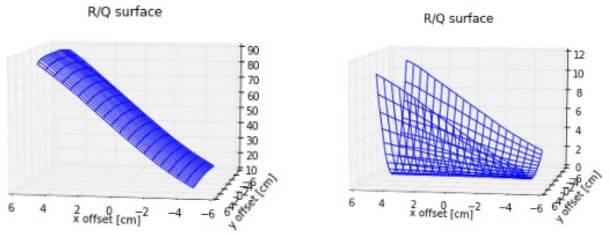
- Position determination
  - Comparison with circular reference
  - Same Depth (TTF)
  - Same f_0

Circular



Elliptical





S. Sanjari et. al. Phys. Scr. 014060 (2015)
X. Chen et. al. Hyperfine Interact. (2015) 235:51
D. Dmytriiev, PhD Thesis, 2021

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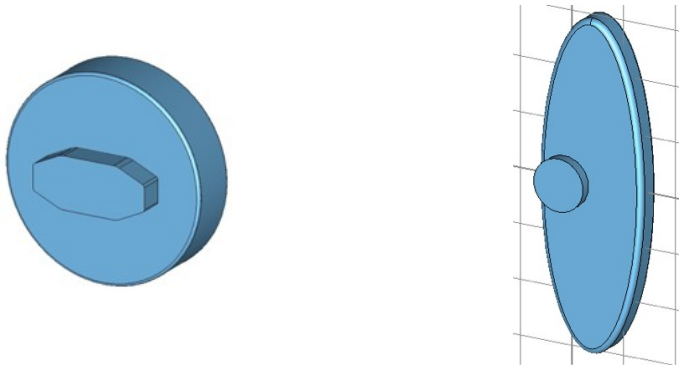
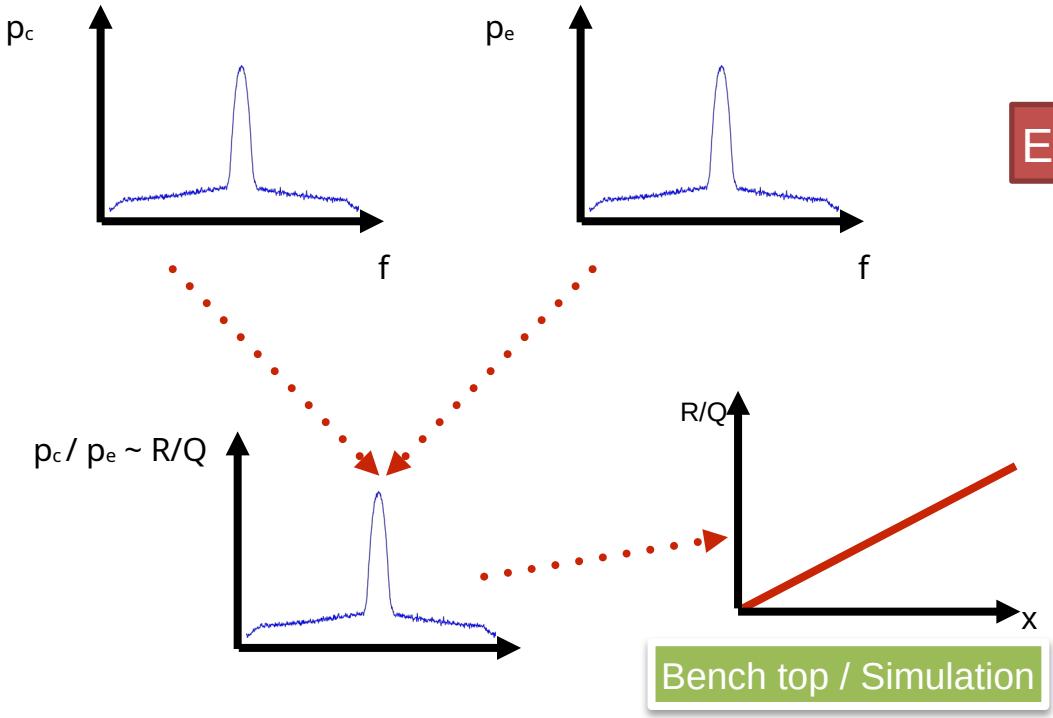
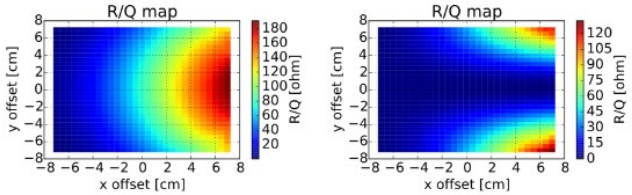
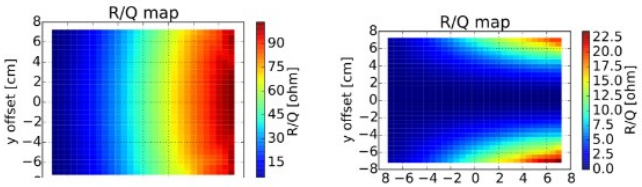


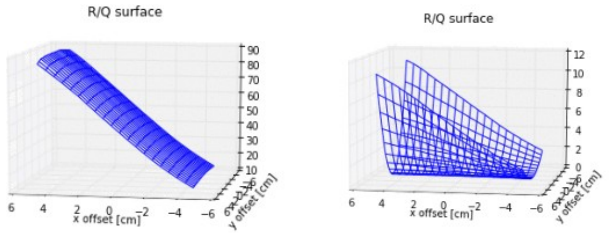


Circular



Elliptical





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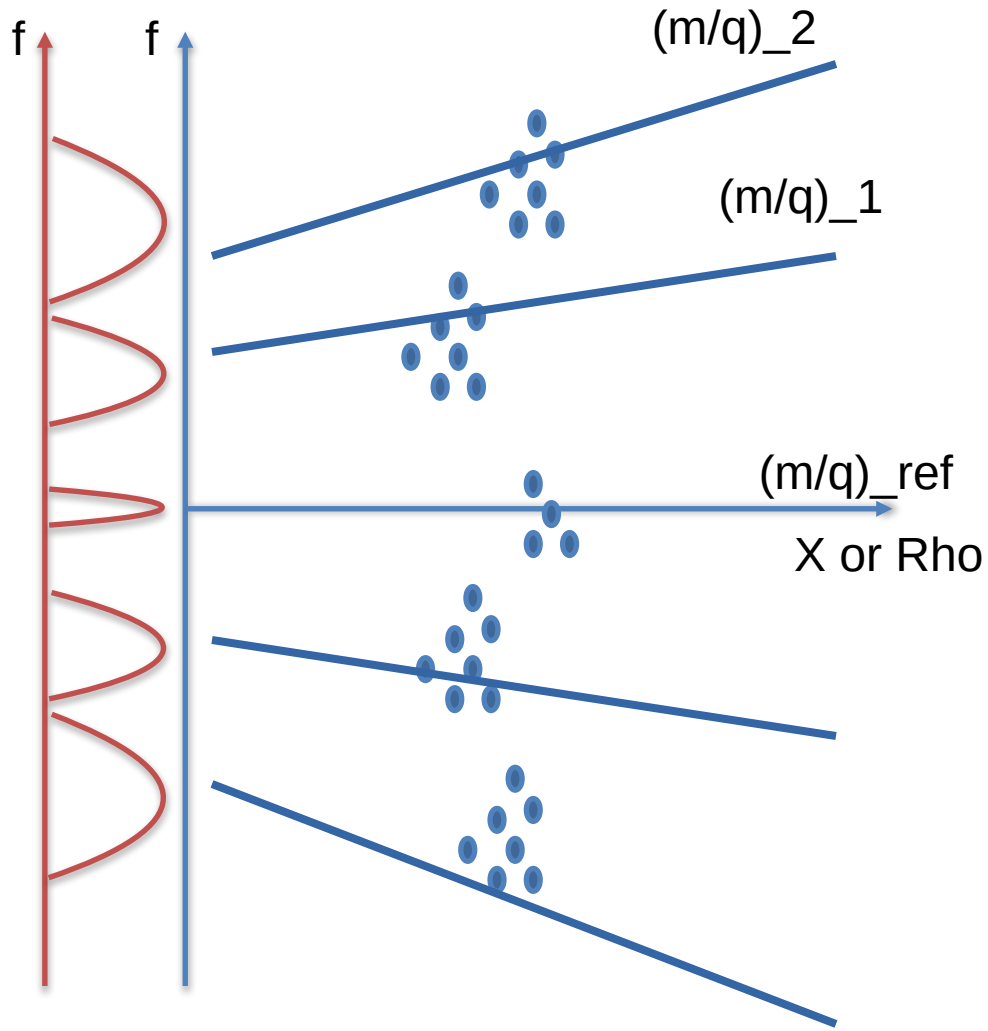
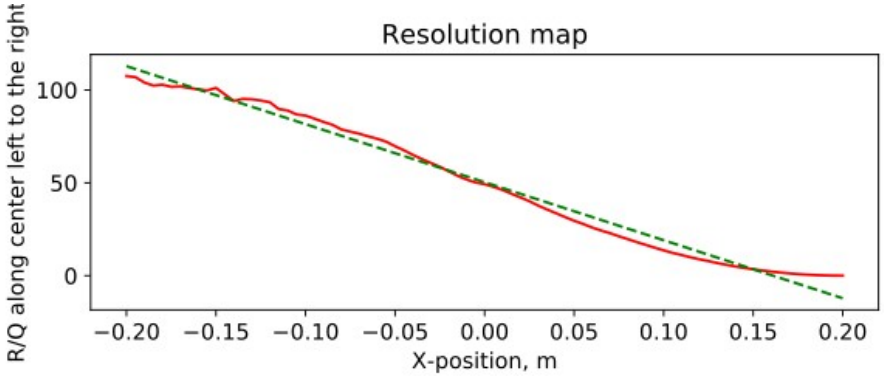


- Bin for bin comparison
  - Results in **f - x** diagram
  - Additional dimension
- Calculation method:
  - Frequency peaks from original spectrum
  - Δf from the error of the slope of the fit
  - Standard mass measurement methods

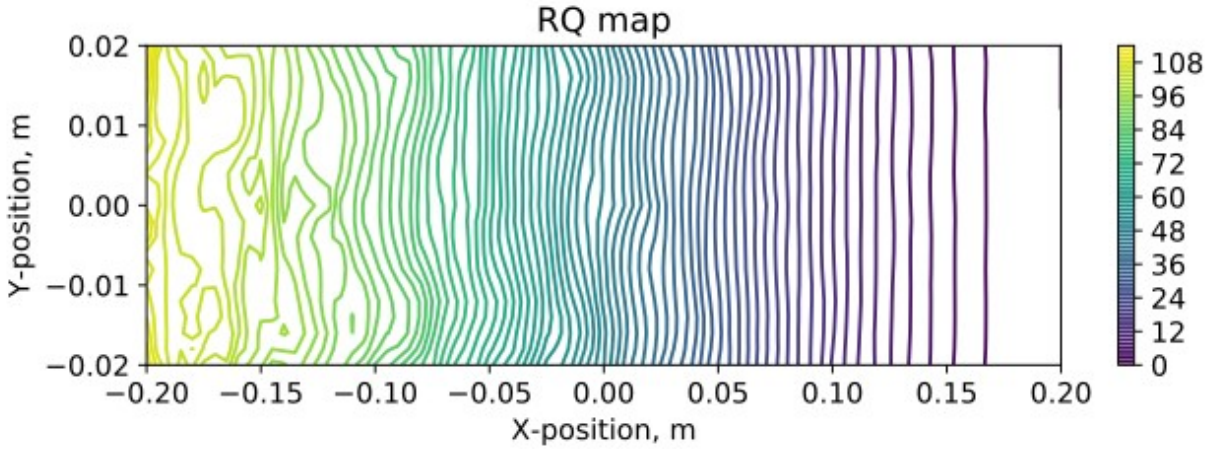
Image / idea: Yuri A. Litvinov

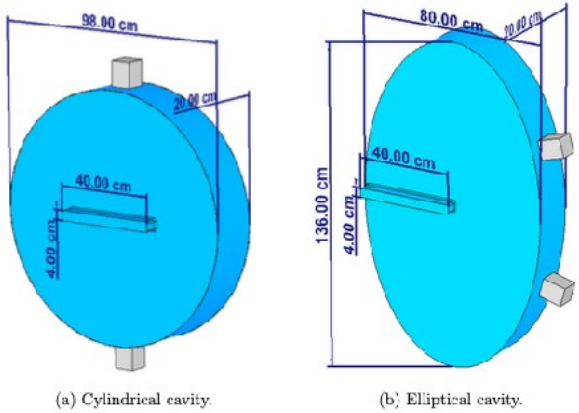
Cavity doublet for R3@RIKEN

- Design of a new cavity doublet for R3-RIKEN



(b) Linearity of the R/Q gradient for the line of the vertical symmetry





(a) Cylindrical cavity. (b) Elliptical cavity.

D. Dmytriiev et. al., NIM-B: 463, pp. 320-323 (2020)

D. Dmytriiev, PhD Thesis (2021).

Cavity doublet for R3@RIKEN

- Design GSI Darmstadt in cooperation with MPIK Heidelberg (Max Planck Institute for Nuclear Physics)
- First beam tests are planned for DEC-2024
- Many thanks 🙏 to our friends 🤝 at RIKEN Nishina Center:

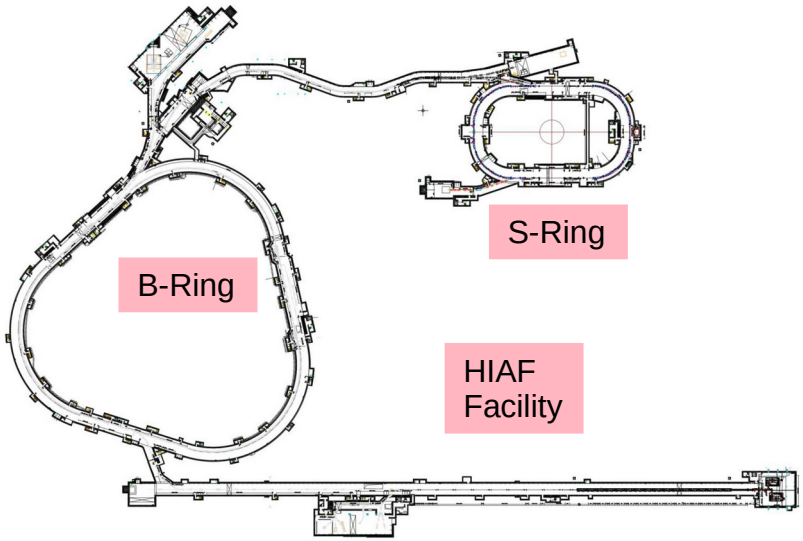
  - PhD Student: George Hudson-Chang
  - Dr. Sarah Naimi (also with IJCLAB @ IN2P3)
  - Dr. Yoshitaka Yamaguchi
  - Dr. Tetsuya Ohnishi
  - Prof. Takayuki Yamaguchi
  - Many other colleagues

Sanjari et. al., Publication in preparation ...

Package arrived in Japan
installation September 12th!

Future plans

- Collaboration: Schottky detectors for S-Ring @ HIAF facility in Huizhou (Guangdong Province):
  - Very promising for mass and lifetime measurement of RIB: High vacuum, high energy, beam diagnostics
- Development by our friends 🤝 @ IMP-Lanzhou:
  - Dr. Qian Wang
  - Dr. Guangyu Zhu
  - Ze Du
  - Peilin He
  - Dr. Xinliang Yang
  - Prof. Junxia Wu
  - Prof. Wang Meng



Picture: Dr. Qian Wang

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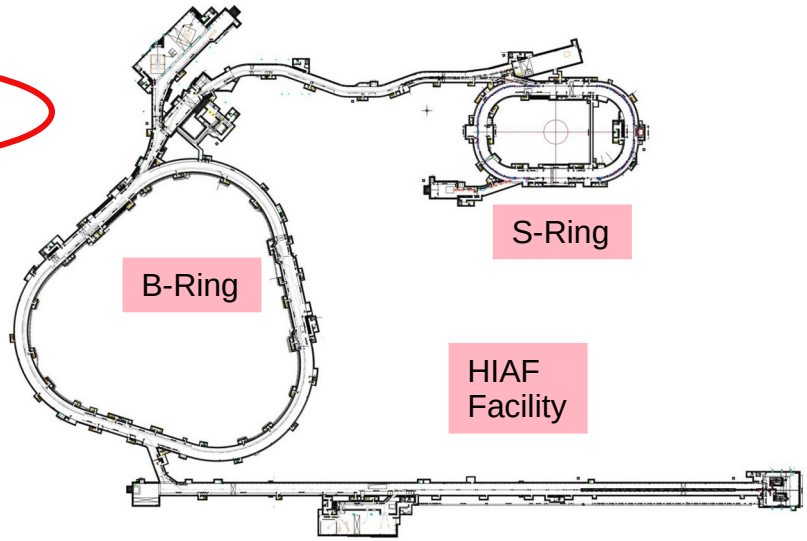
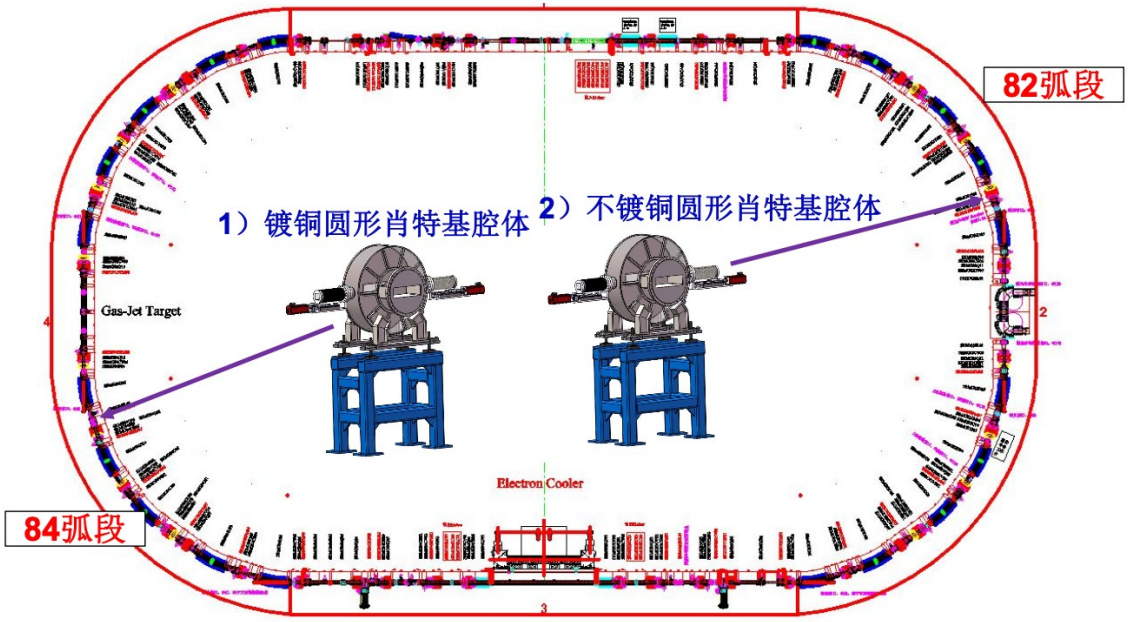
Next Talk!



Picture: Dr. Qian Wang

SRing肖特基腔体布局

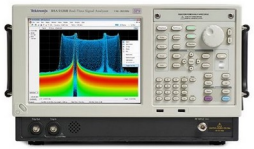
- Two cavities:
  - High and low Q
- (Isomeric) lifetime measurements (hopefully) in 2025
- Unique possibility of testing the phase measurement method
- Placeholders for elliptical cavities
  - Plans for addition of complimentary position method in 2026

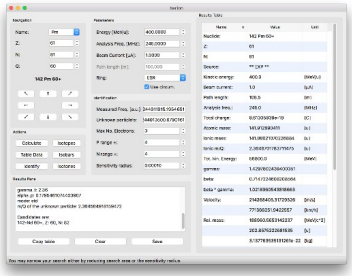


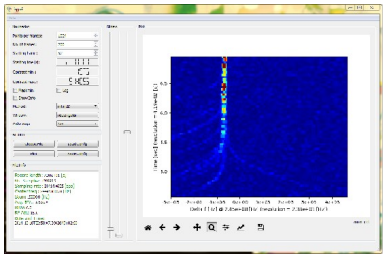
Picture: Dr. Zhu Guangyu 朱光宇 and Qiu Zishuai 邱子帅

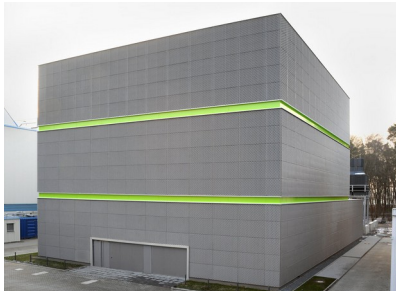
Data acquisition and analysis

- Moving away from commercial solutions:
  - Spectrum analyzers
  - Long term time capture device NTCAP (C. Trageser, PhD Thesis, 2018)
- Towards open hardware open source:
  - GNURadio based Software Defined Radios
  - Scalability, easy maintenance
- Analysis code published on GitHUB
  - Python (+ROOT) based framework
  - IQTools / IQGUI (for different DAQs)
  - Barion (Ion calculations)
  - RionID (D. Freire-Fernandez et. al.)
  - Other recent tools for identification / mass measurement
- HPC and some first attempts at ML









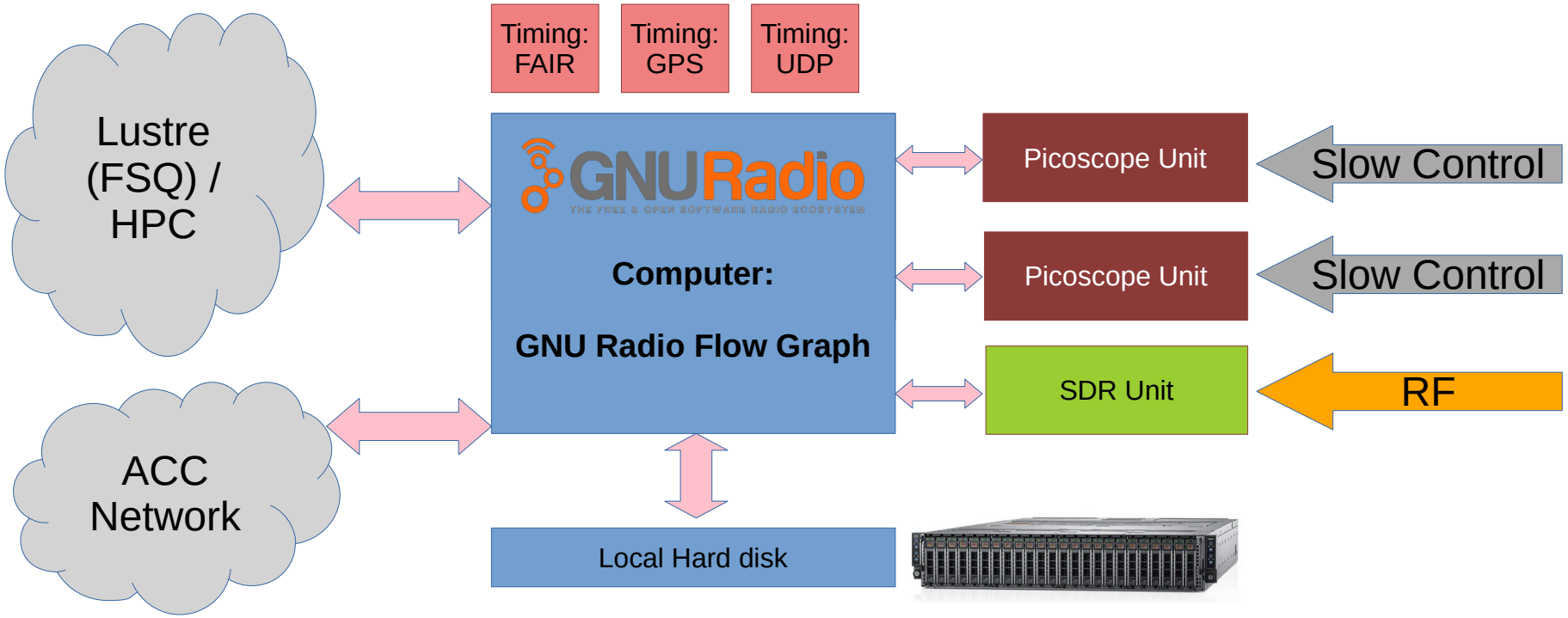
GSI Green IT Cube

R. Steinhagen, A. Krimm et. al. @ GSI

D. Dmytriiev et al 2020 J. Phys.: Conf. Ser. 1668 012014

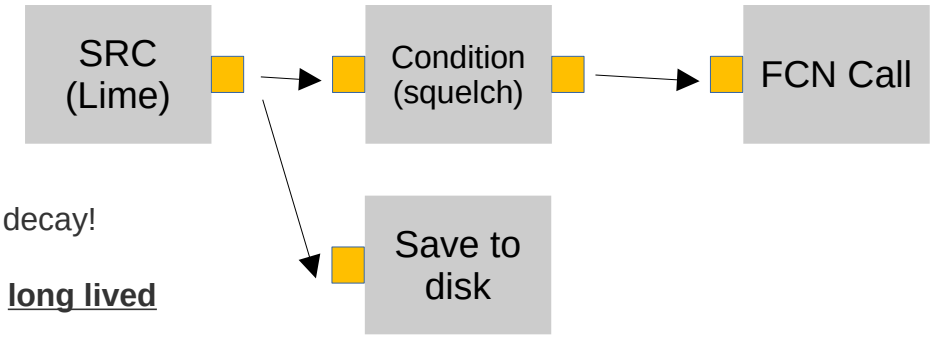
Optimizations of data flow

- Optimizations for future DAQ and experimental data flow



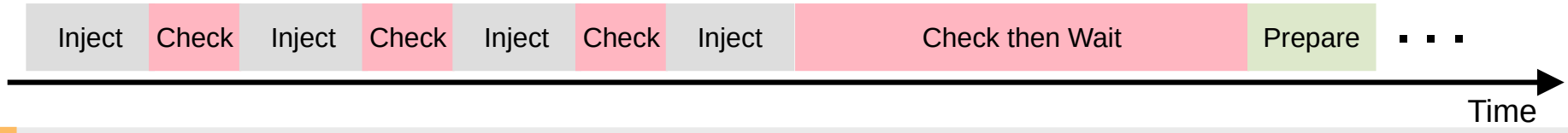
Outlook for 2025

- Experiment proposal (G-22-00203) during the ^{208}Pb beam time block:
  - Mass & half-life measurements in the neutron-rich N≈116 region (around ^{188}Hf)
  - Spokesperson: Yuri A. Litvinov
- Optimization of beam time:
  - Recording is always running
  - Re-inject if there are no isomers, otherwise wait until decay!
- Unique way to efficiently tackle **low yield** (1 in 1.5 days) and **long lived** unstable nuclear states!
- Much easier offline processing!
  - Empty injections are easily discarded → reduction of error



Current scheme:

Future plan:



Thank you!

謝謝！