New high-precision nuclear mass studies by the first MRTOF mass spectrometer at the BigRIPS facility

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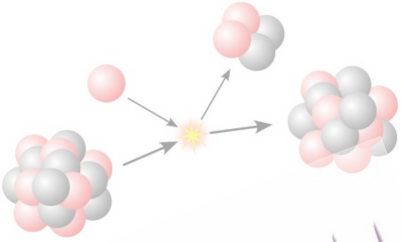
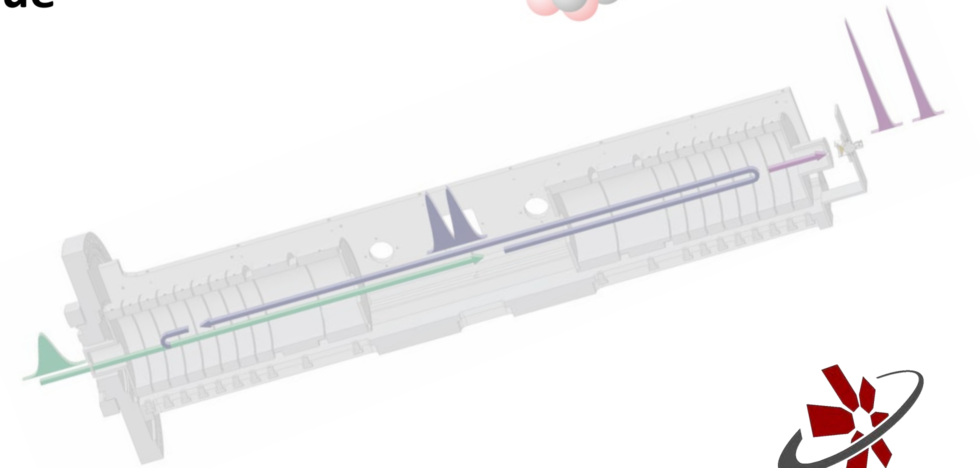
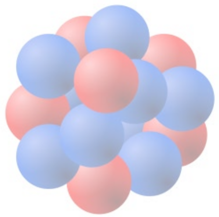
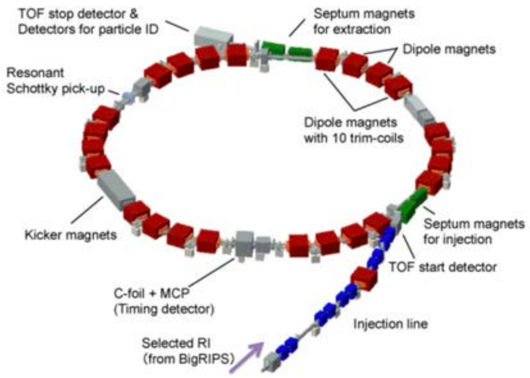


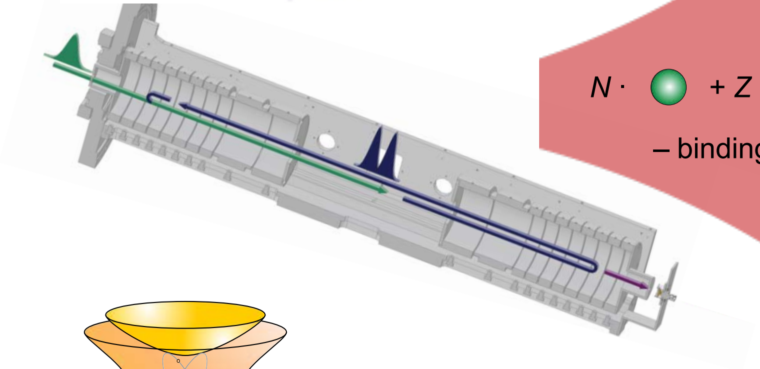
- **Nuclear mass spectrometry**
- **Multi-reflection time-of-flight technique**
- **The SLOWRI-ZD MRTOF experiment**
- **Technological advances**
- **2020 online commissioning**

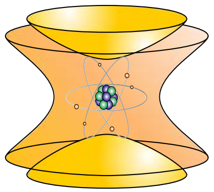


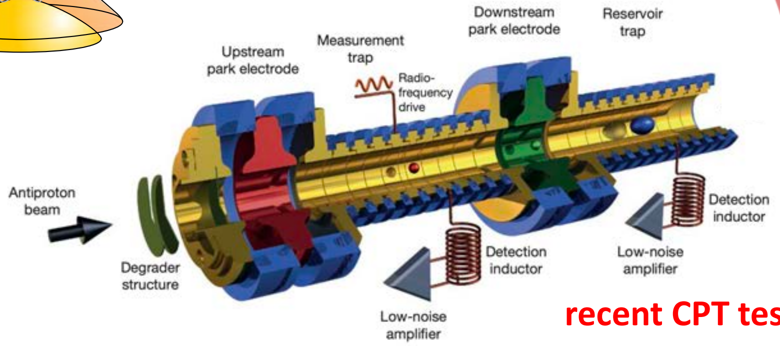


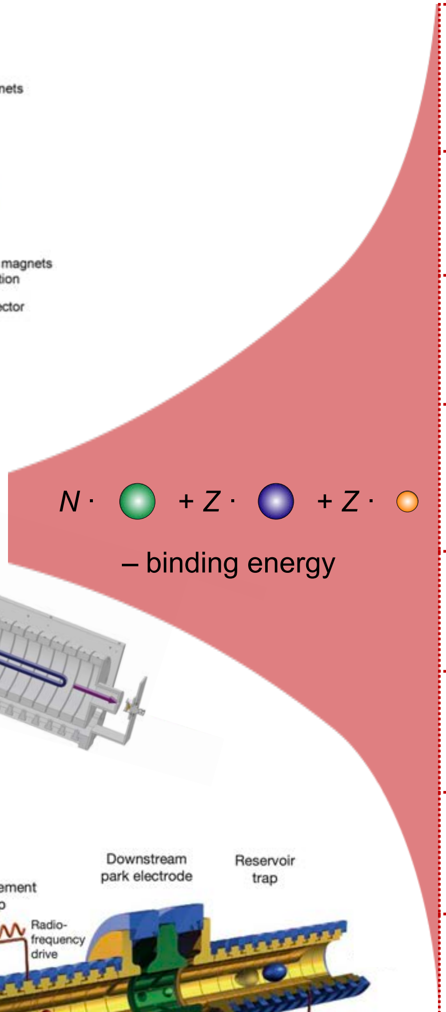
Physics using mass spectrometry







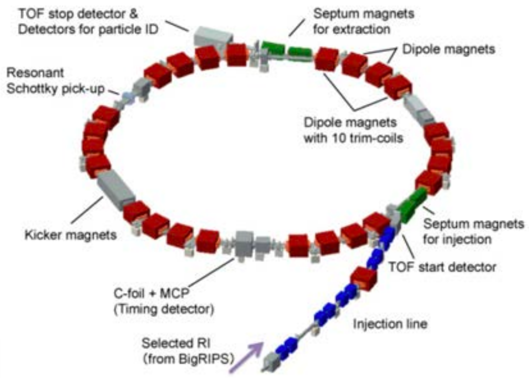


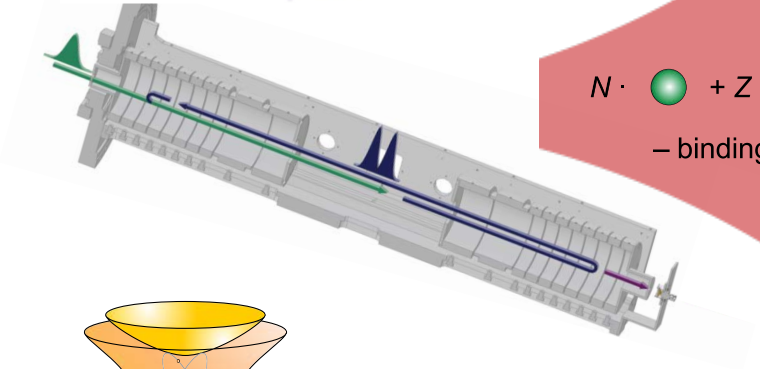


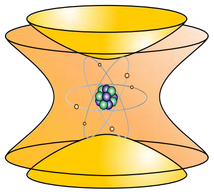
Physics application	δm/m
General physics & chemistry	$\lesssim 10^{-5}$
Nuclear structure and Astrophysics - separation of isobars	$\lesssim 10^{-6}$
Isomer studies and Astrophysics - separation of isomers	$\lesssim 10^{-7}$
Weak interaction studies	$\lesssim 10^{-8}$
Metrology - fundamental constants	$\lesssim 10^{-9}$
CPT tests	$\lesssim 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\lesssim 10^{-11}$

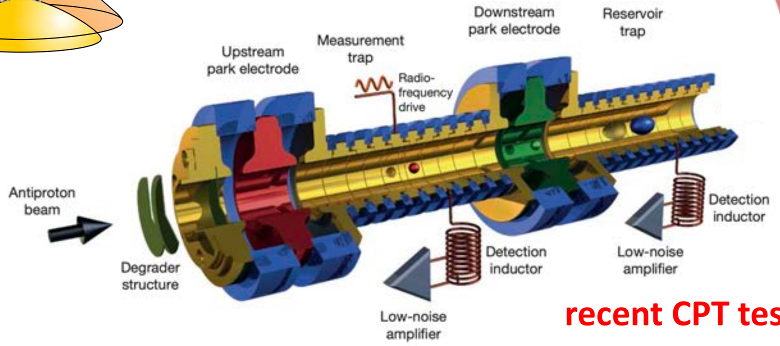
recent CPT tests on 10^{-12} level: S. Ulmer *et al.*, Nature 524, 196 (2015)

Physics using mass spectrometry









$N \cdot$ ( ) $+ Z \cdot$ ( ) $+ Z \cdot$ ( )

– binding energy

Physics application	δm/m
General physics & chemistry	$\lesssim 10^{-5}$
Nuclear structure and Astrophysics - separation of isobars	$\lesssim 10^{-6}$
Isomer ... Astrophysics **MRTOF at present** ... of isomers	$\lesssim 10^{-7}$
Weak i... **MRTOF future goal**	$\lesssim 10^{-8}$
Metrology - fundamental constants	$\lesssim 10^{-9}$
CPT tests	$\lesssim 10^{-10}$
QED in highly-charged ions - separation of atomic states	$\lesssim 10^{-11}$

recent CPT tests on 10^{-12} level: S. Ulmer *et al.*, Nature 524, 196 (2015)

Shell evolution studies

What can we learn from ground-state masses about the nuclear shell evolution?

S_p S_n

Odd-Even Staggering

$$S_n(Z,N) = E(Z,N-1) - E(Z,N)$$

Estimators for the pairing gaps

$$\Delta^3(N) = \frac{(-1)^N}{2}[E(N-1) - 2E(N) + E(N+1)]$$

S_{2p} S_{2n}

Two-nucleon separation energies

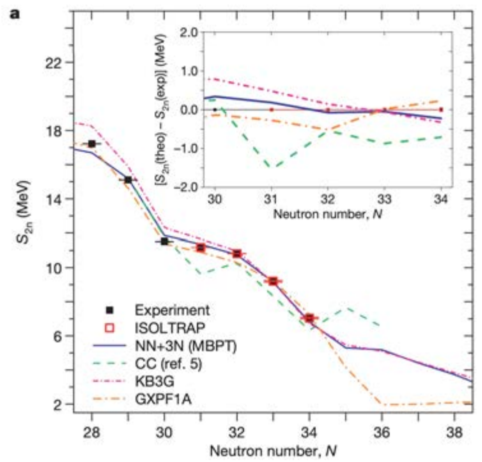
$$S_{2n}(Z,N) = E(Z,N-2) - E(Z,N)$$
$$S_{2p}(Z,N) = E(Z,N) - E(Z-2,N)$$

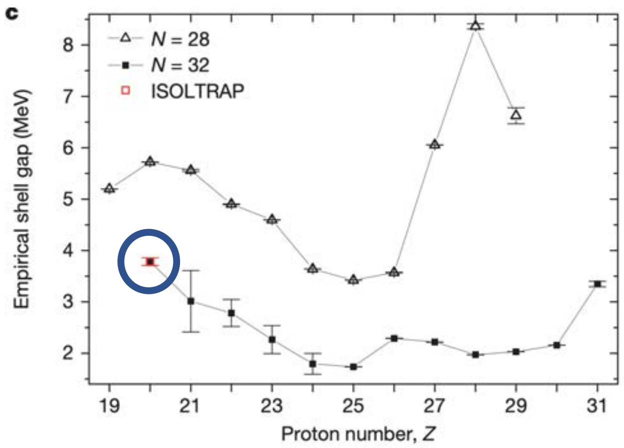
Shell gaps, test of magicity

$$\delta_{2p}(Z,N) = S_{2p}(Z,N) - S_{2p}(Z+2,N)$$
$$\delta_{2n}(Z,N) = S_{2p}(Z,N) - S_{2p}(Z,N+2)$$

Input for theory to reveal possible nuclear valence orbit configurations, collectivity and deformations. **New extrapolations into the terra incognita**

Mass measurements of exotic nuclei



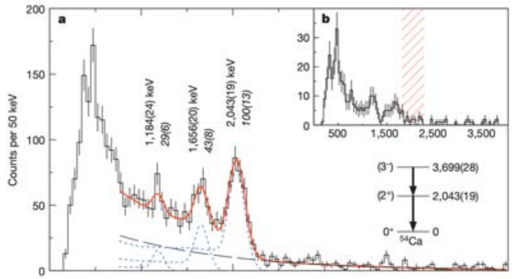


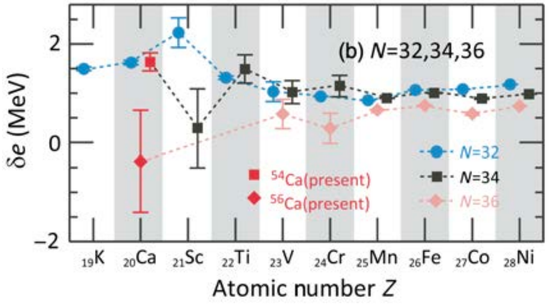
Nuclear structure example:

Study of nuclear tensor force

T. Otsuka, Rev. Mod. Phys. 92, 015002 (2020)

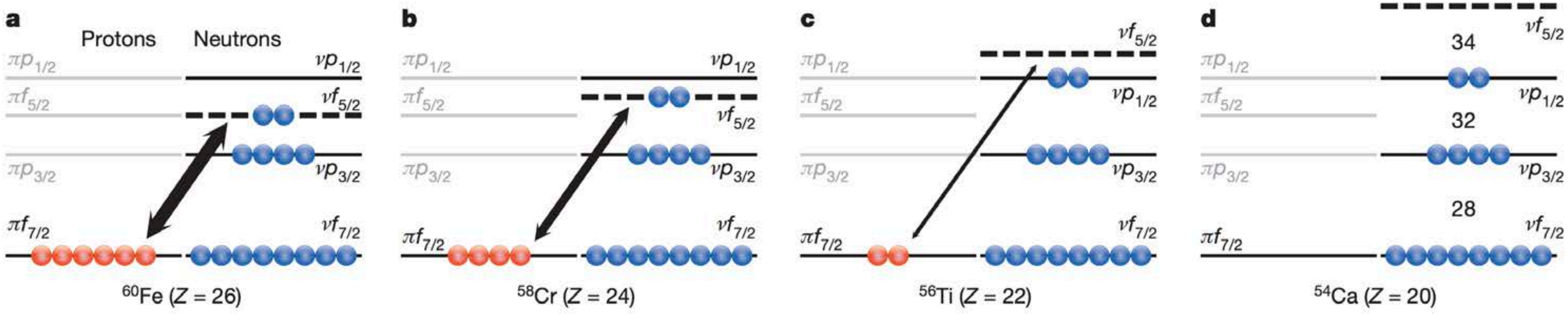
N = 32





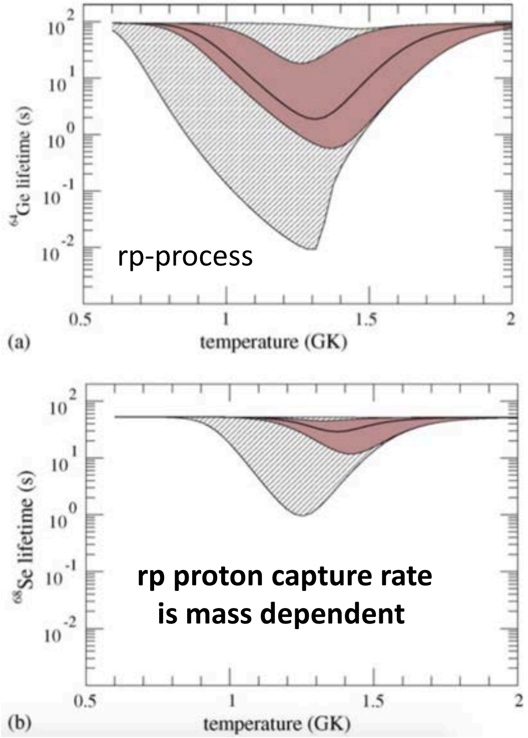
N = 34

F. Wienholtz *et al.*, Nature 498,346 (2013)
D. Steppenbeck *et al.*, Nature 502, 207 (2013)
S. Michimasa et al., PRL 121, 022506 (2018)

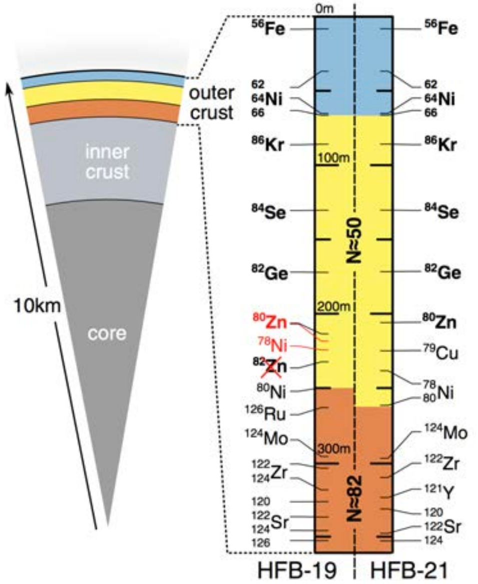


Mass measurements of exotic nuclei

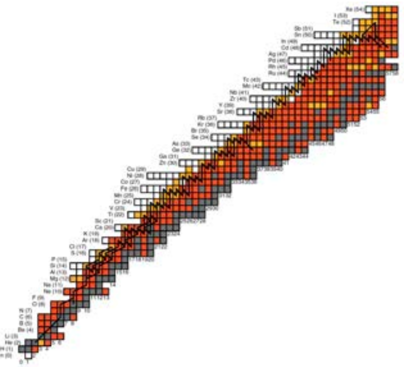
Astrophysical examples



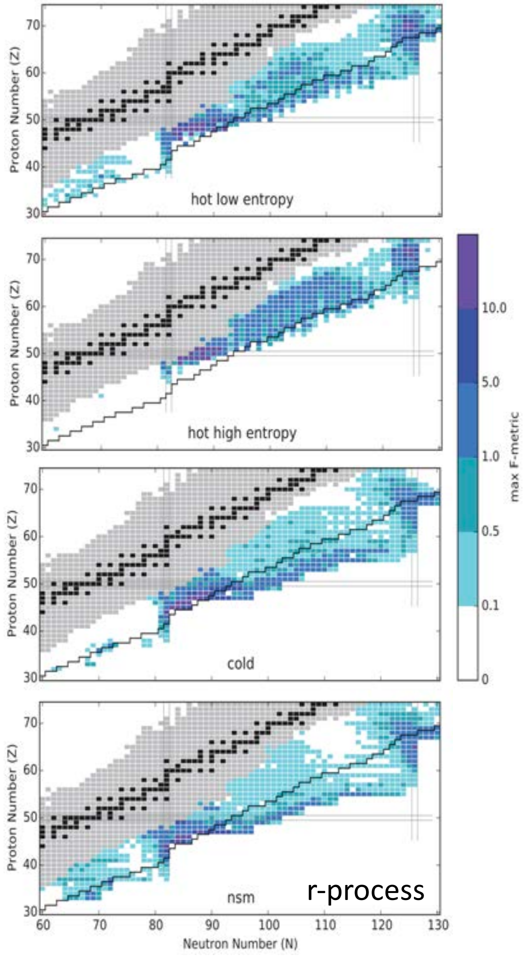
rp proton capture rate is mass dependent



R. N. Wolf *et al.*, Phys. Rev. Lett. 110, 041101 (2013)



H. Schatz, Int J. Mass spectrom. 251, 293 (2006),
Int J. Mass spectrom. 349-350, 181 (2013)



M. R. Mumpower *et al.*, Phys. Rev. C 92, 035807 (2015)

$$\frac{Y(Z,N+1)}{Y(Z,N)} \propto \frac{G(Z,N+1)}{2G(Z,N)} \frac{N_n}{(kT)^{3/2}} \exp\left[\frac{S_n(Z,N+1)}{kT}\right]$$

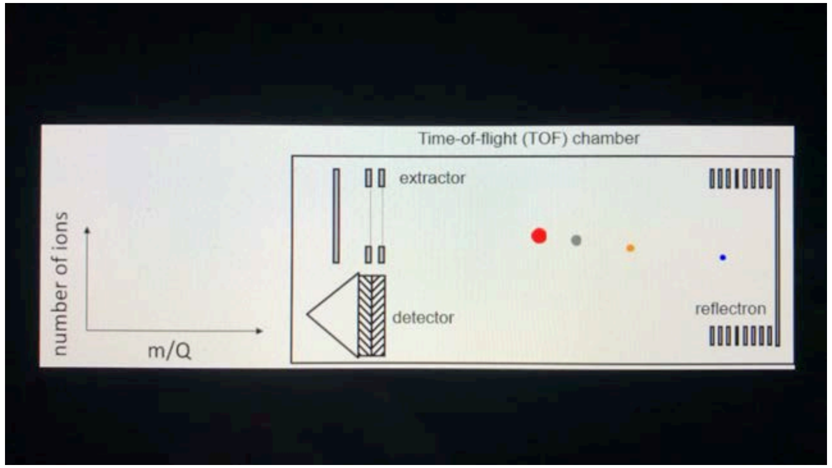
High precision and accuracy needed!

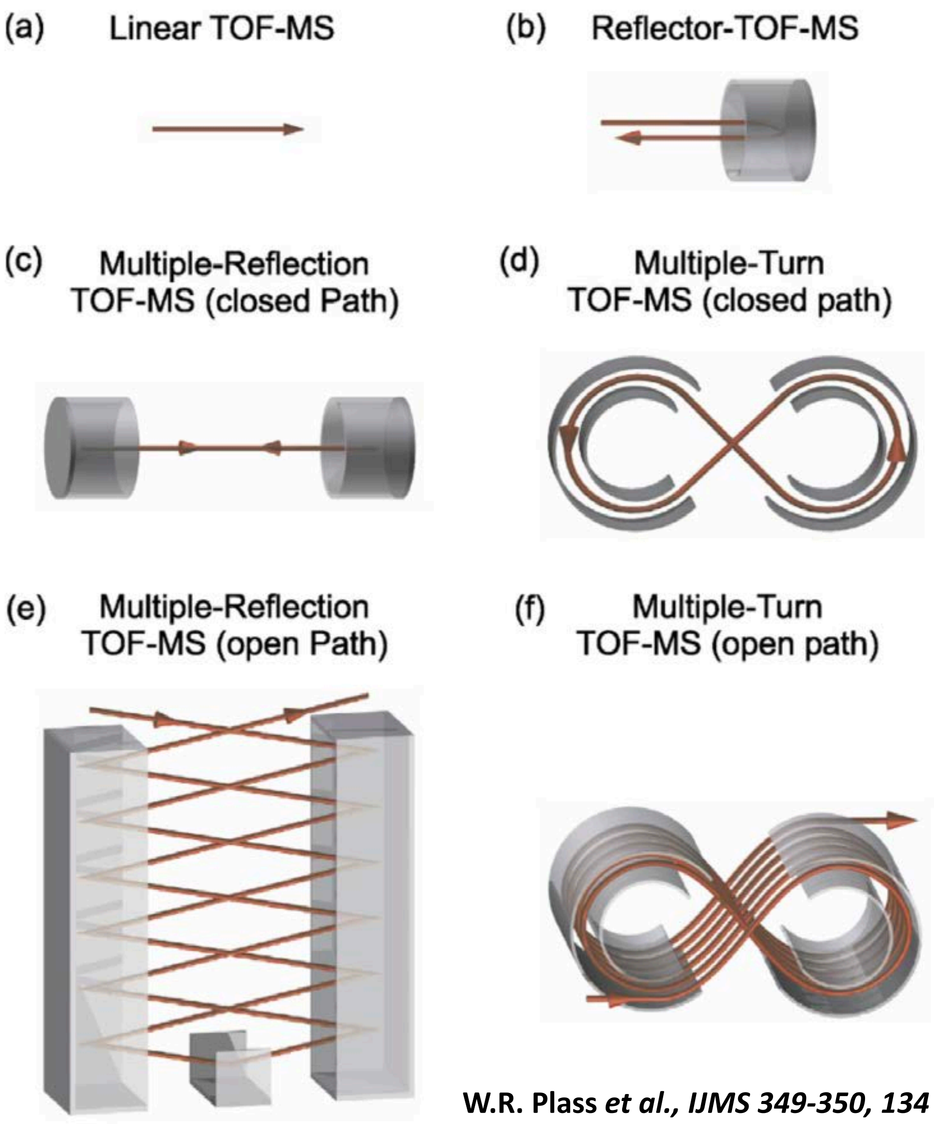
Time-of-flight mass spectrometry

Mass resolving power:

- **linear TOF-MS: m/Δm > 100**
- **reflector-TOF-MS: m/Δm > 5,000**
- **MRTOF-MS: m/Δm > 100,000**

Δm = 2Δt = FWHM of ion TOF distribution

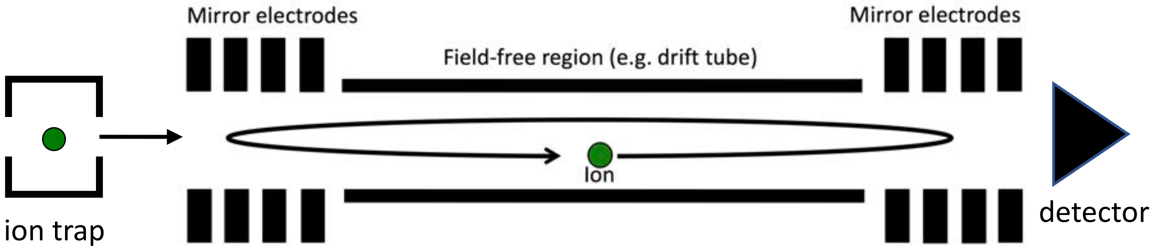




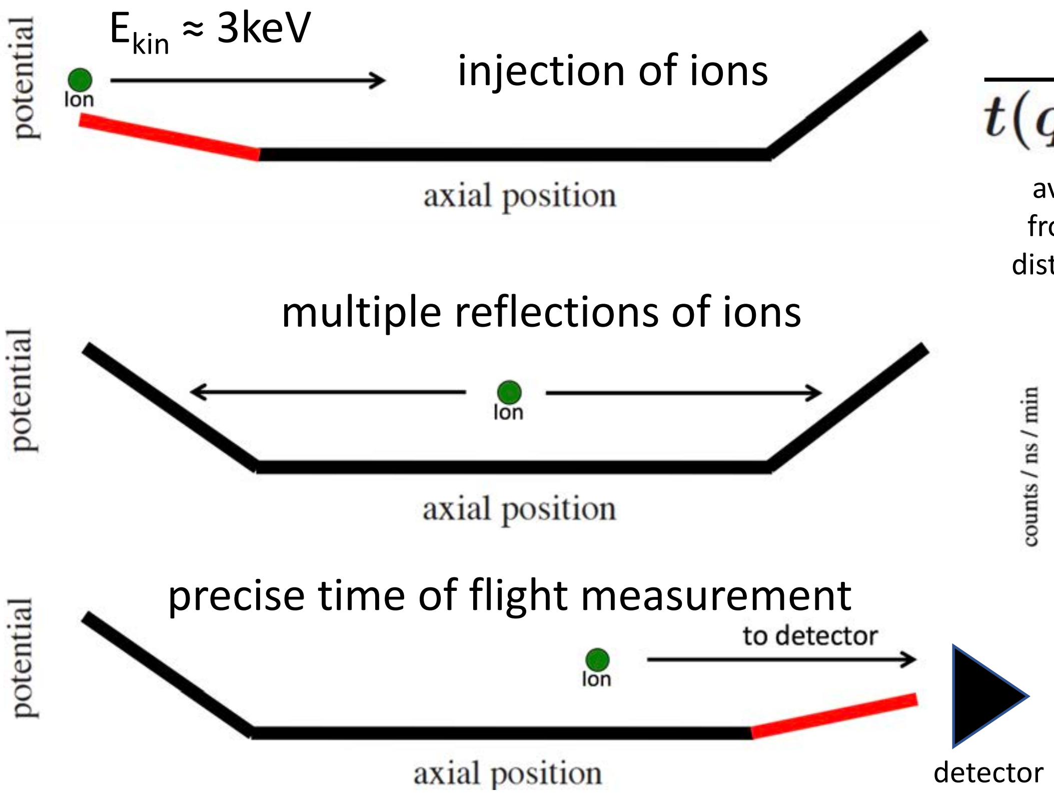
W.R. Plass *et al., IJMS 349-350, 134 (2013)*

The multi-reflection time-of-flight (MRTOF) technique

H.Wollnik and M. Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)



Total time of flight predominantly determined by the electrostatic term of the system

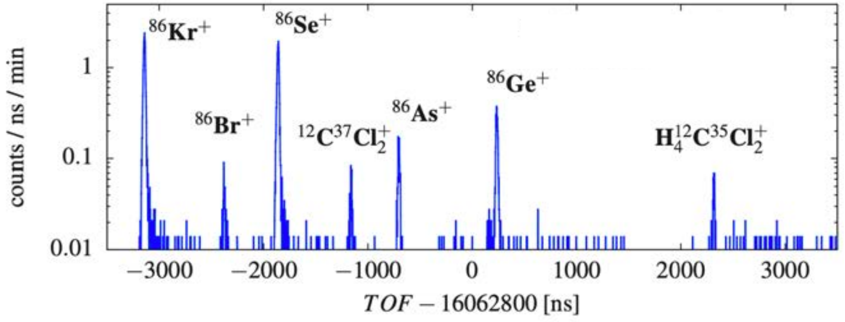


device constant

$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}}$$

average from ion distribution

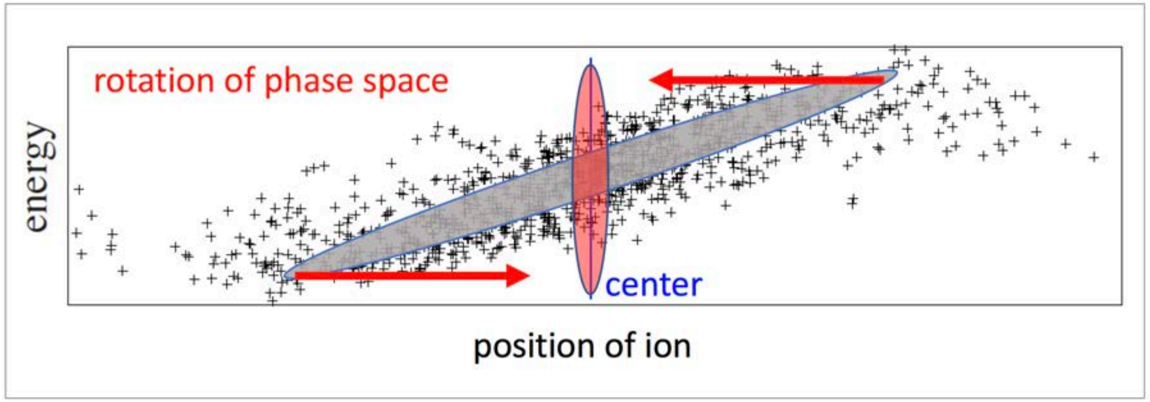
electrostatic contribution



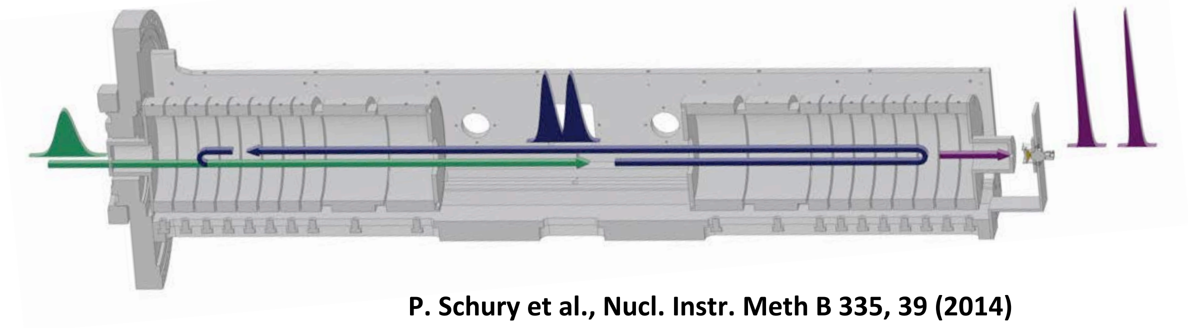
Ion focusing

- Axial potential shape allows to modify the phase space of the ions via the penetration depth into the ion mirror

- Narrow time-of-flight focus achieved at the detector
  → high resolution by long flight path

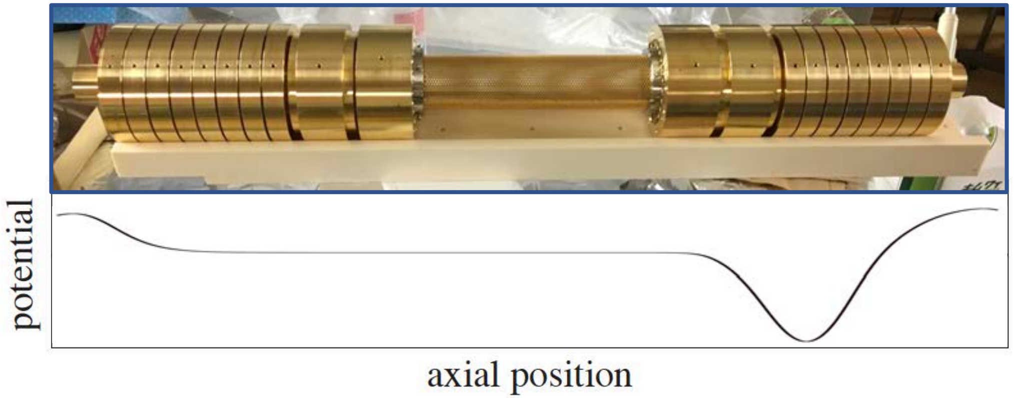


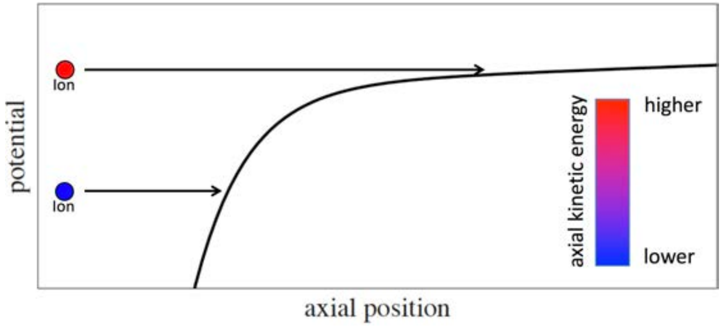
MRTOF mass spectrograph



P. Schury et al., Nucl. Instr. Meth B 335, 39 (2014)

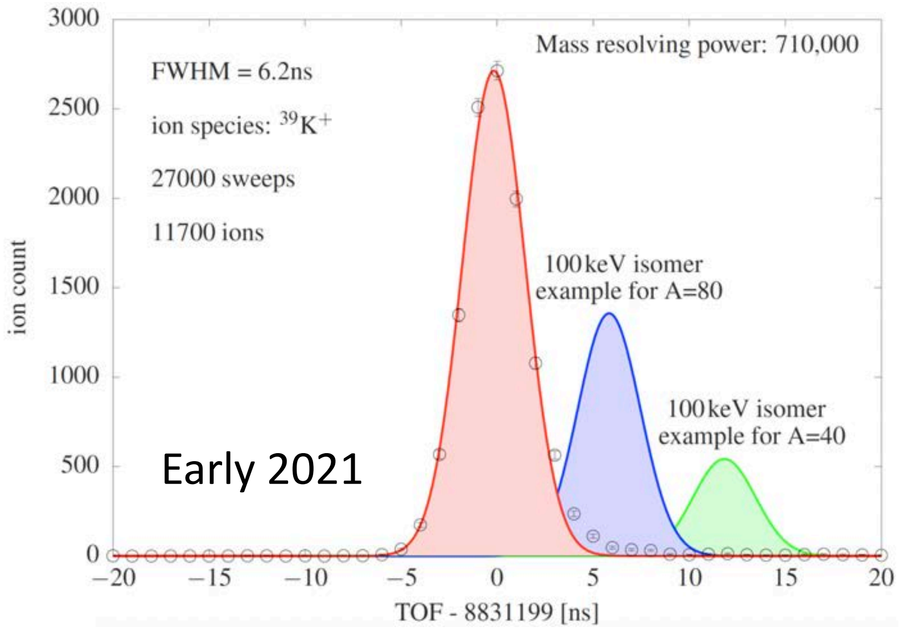
M. Rosenbusch et al., Nucl. Instr. Meth B 463, 184 (2020)



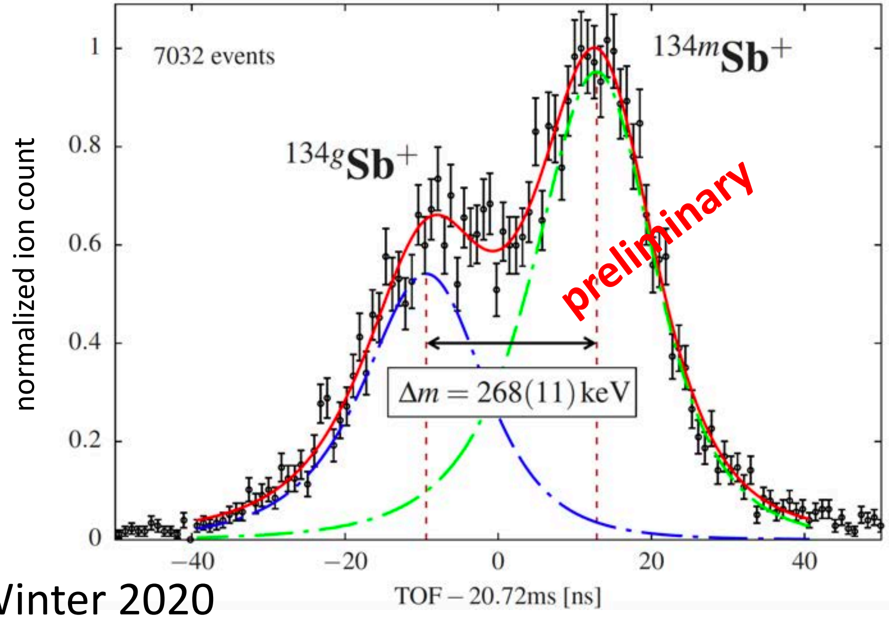


MRTOF-MS Advantages

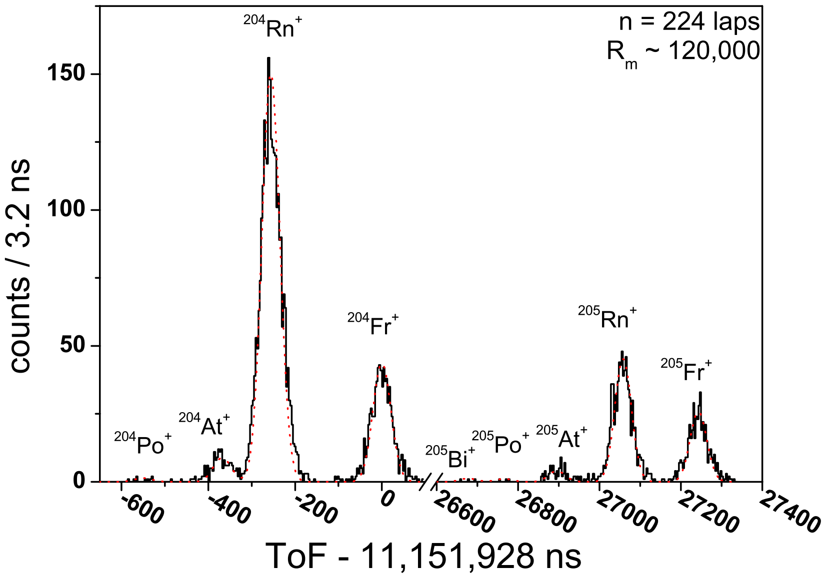
- Measurement duration is short: < 10-20ms per cycle
  → short lived isotopes accessible
- Several isotopes can be measured at the same time
  → efficient use of expensive accelerator time
- High mass resolving power **m/Δm > 500,000**
  → nuclear isomer separation possible



Early 2021

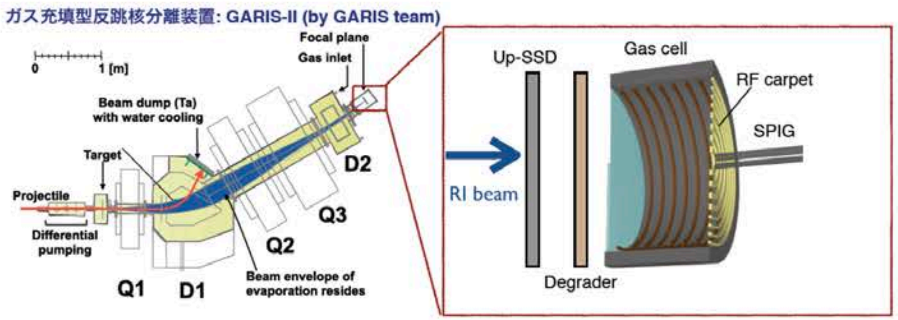


Winter 2020



P. Schury et al., Phys. Rev. C 95, 011305(R) (2017)

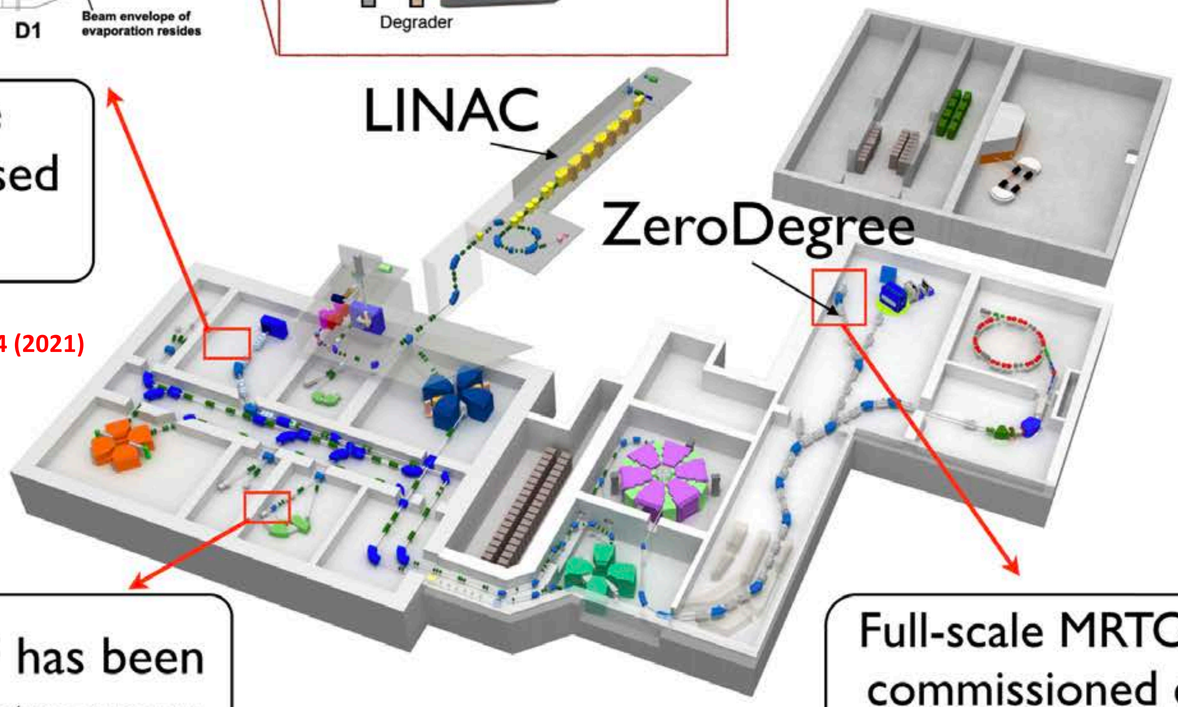
Current MRTOF facilities at RIBF



GARIS-III MRTOF coming soon

Original full-scale MRTOF primarily used for SHE studies

First SHN recently measured!
P. Schury *et al.*, Phys. Rev. C 104, L021304 (2021)

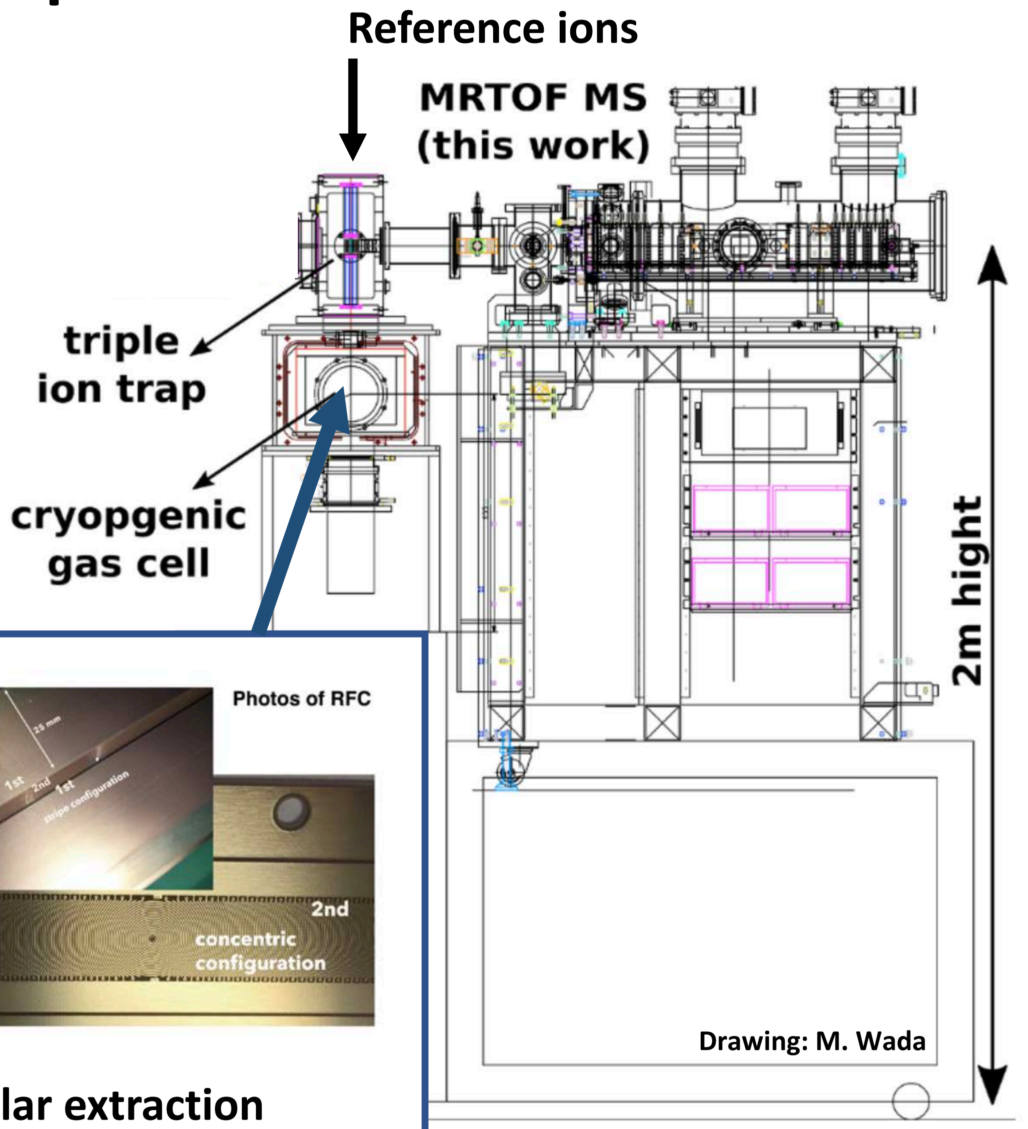


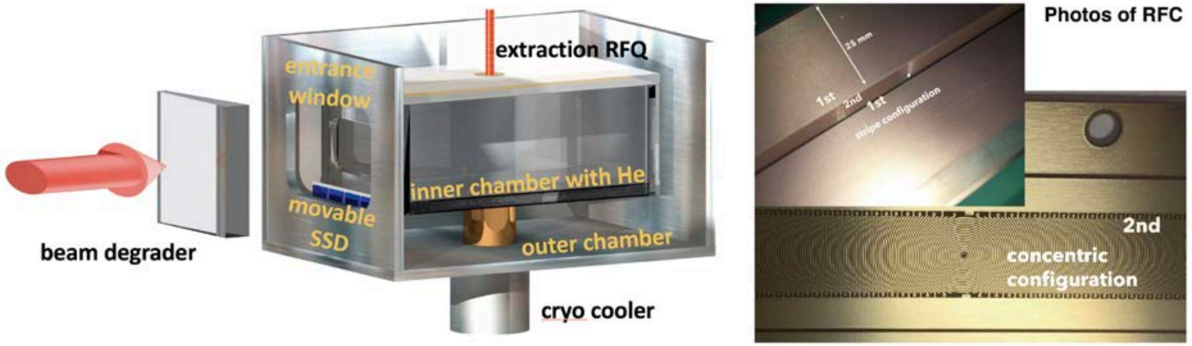
Half-scale MRTOF has been useful in mass-spectroscopy-assisted laser spectroscopy

Full-scale MRTOF has been commissioned commensal to in-beam gamma-ray spectroscopy

The SLOWRI-ZD MRTOF experiment

- Ions stopped in a cryogenic gas cell
- Extraction and transport to a trap chamber with triple-trap system
- Preparation/cooling of ions in central flat ion trap
- Ions are forwarded to MRTOF-MS and injected
- After multiple reflections → ejection and time-of-flight detection



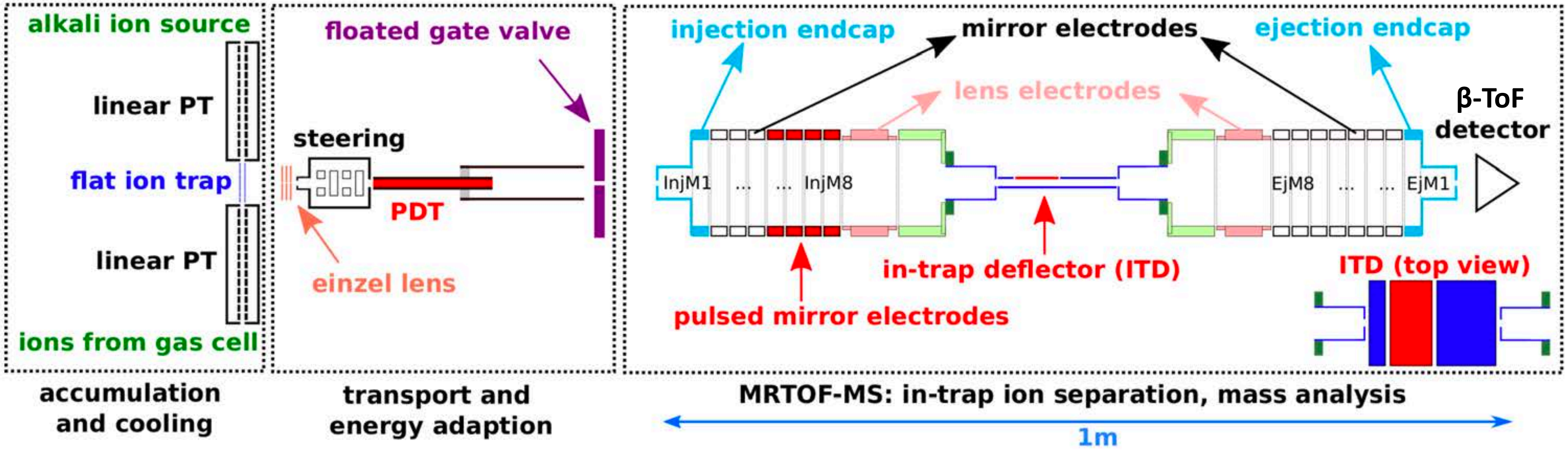


New gas cell design for perpendicular extraction

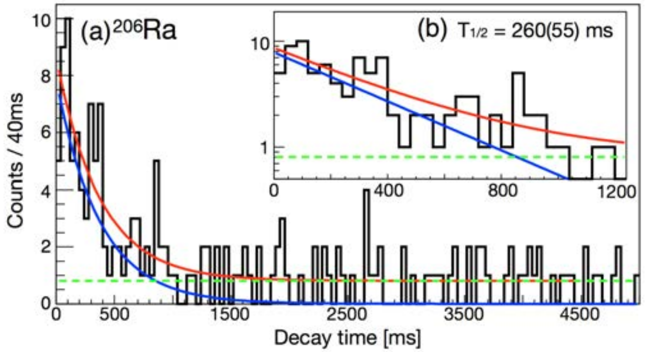
A. Takamine, S. Iimura, D. Hou

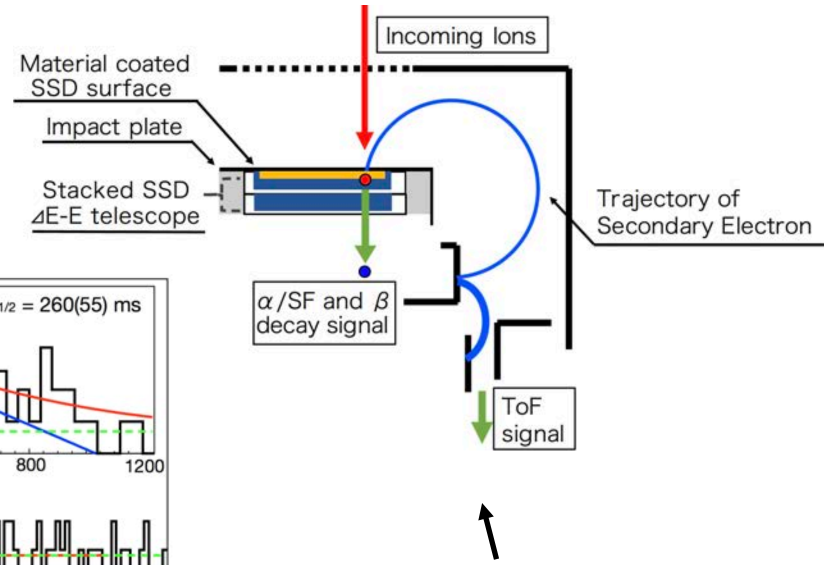
M. Rosenbusch *et al.*, Nucl. Instr. Meth B 463, 184 (2020)

The SLOWRI-ZD MRTOF experiment



- Energy adaption available by pulsed drift tube
- In-trap ion separation available (two methods tested)
- Beta-ToF detection available

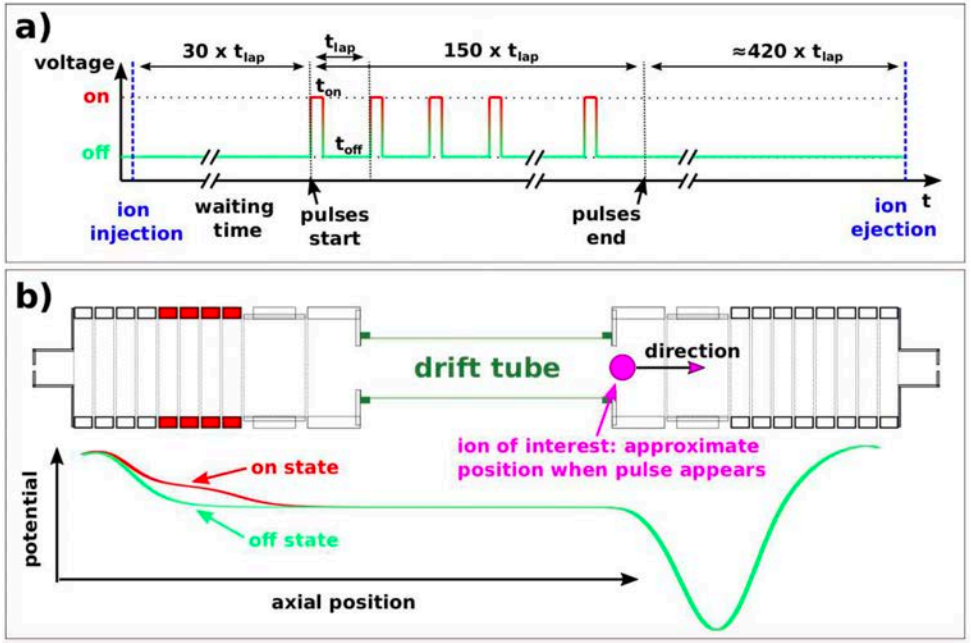




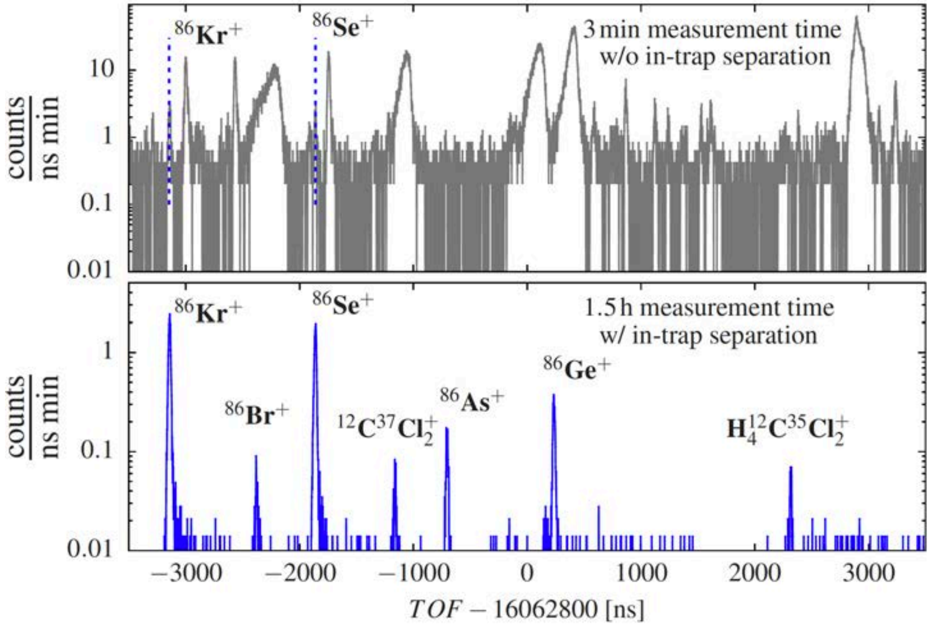
T. Niwase *et al.*, Nucl. Instrum. Meth. A 953, 163198 (2020).
P. Schury *et al.*, Phys. Rev. C 104, L021304 (2021).
T. Niwase *et al.*, Phys. Rev. C, under review (2021). (arxiv 2108.06245)

Technological advances: CGITS

- Molecular contaminants from gas cell ionized by high-energy beam
- In-trap ion separation essential to isolate ions of interest
- Concentric-Geometry In-Trap Separation (CGITS) was successfully employed



used during commissioning 2020



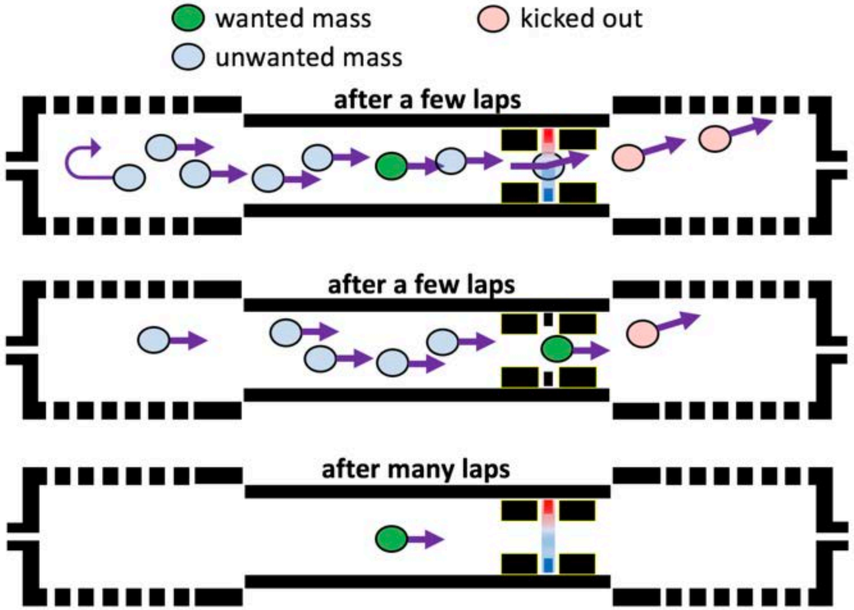
First MRTOF in-trap cleaning with deflector:
Y. Toker *et al.*, J. Instrum. 4, P09001 (2009).

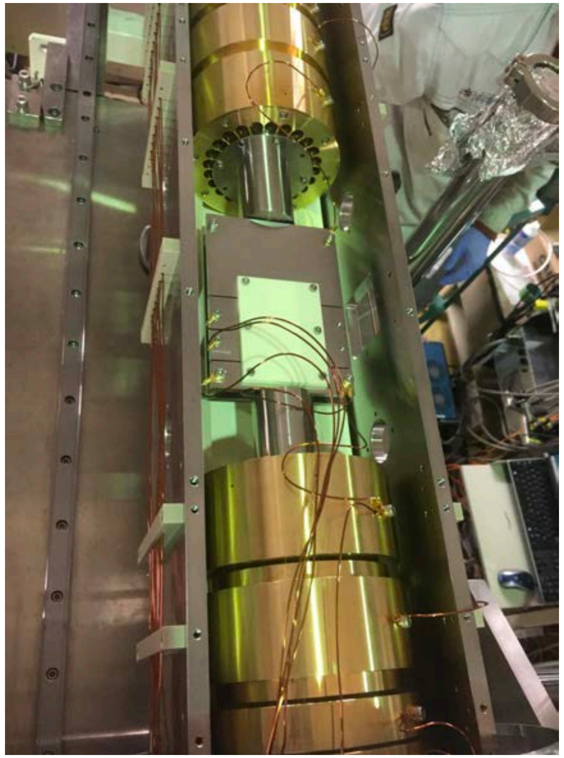
Usage of mirror endcaps:
J. T. Johnson *et al.*, Anal. Chem. 91, 8789 (2019).

Further application and development of deflector:
T. Dickel *et al.*, Nucl. Instrum. Meth. 777, 172 (2015).
P. Fischer *et al.*, Rev. Sci. Instrum. 89, 015114 (2018).

Technological advances: In-trap deflector

- Selective kick-out now possible
- Selective protection of several masses now possible
- Proper design: Kick out of unwanted ions with weak 30V pulse





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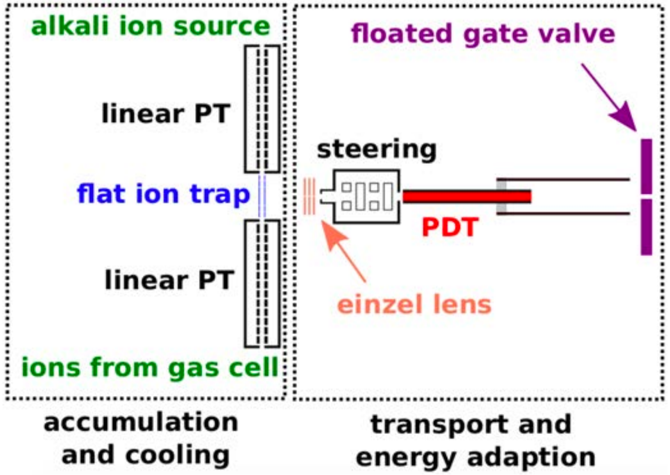
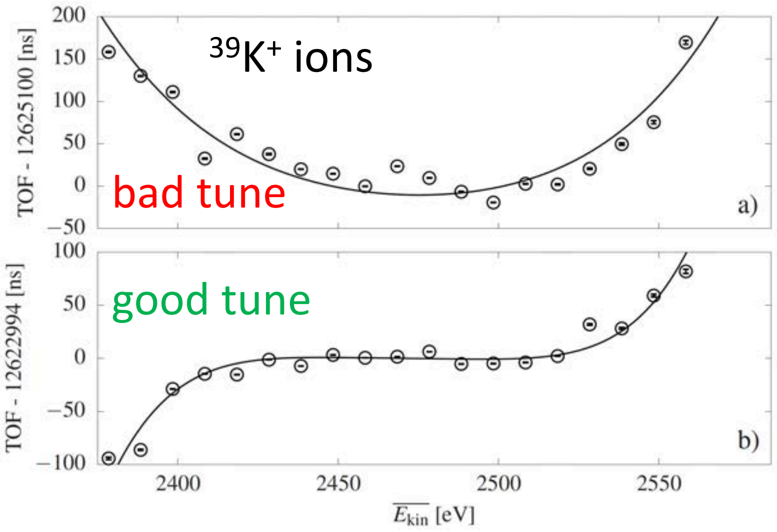
P. Fischer *et al.*, Rev. Sci. Instrum. 89, 015114 (2018).

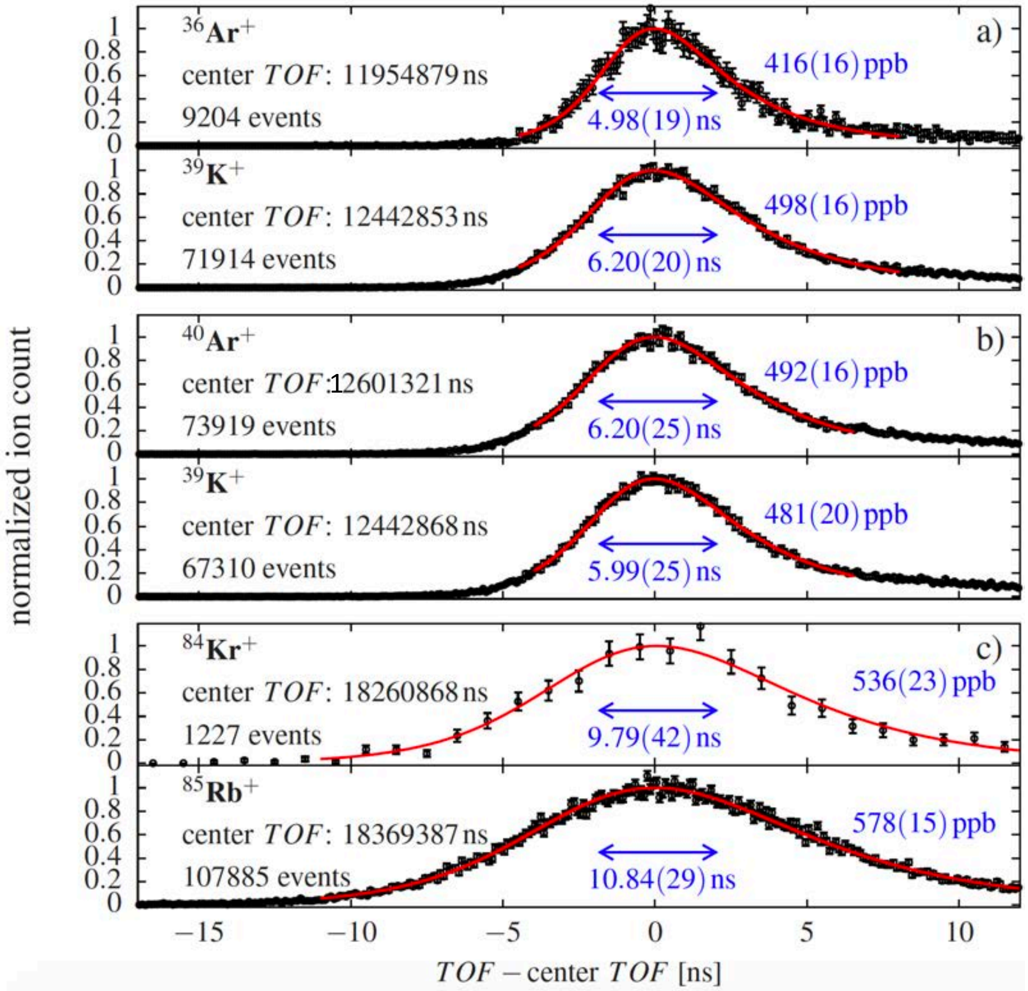
Technological advances: Tuning method and high MRP





wide energy range

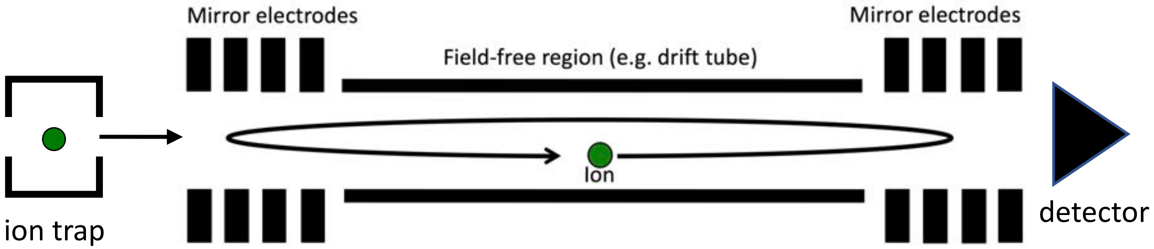
1 hour measurement (each)



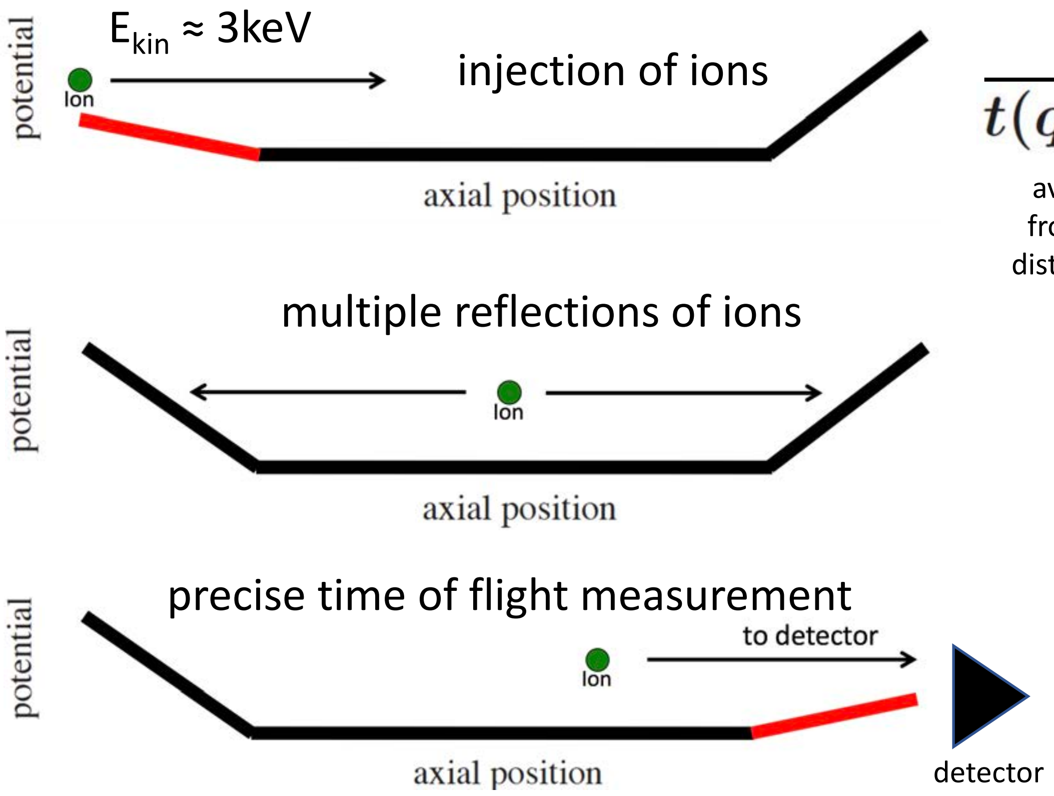
m/Δm > 1,000,000 for A=40
m/Δm > 900,000 for A=80

The multi-reflection time-of-flight (MRTOF) technique

H.Wollnik and M. Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)



Total time of flight predominantly determined by the electrostatic term of the system



device constant

$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}} + t_0 + t_{\mathrm{NS}}(q,m) + t_{\mathrm{other}}(q,m)$$

average from ion distribution

- $A \cdot \sqrt{\frac{m}{q}}$: electrostatic contribution
- t_0: offset time
- $t_{\mathrm{NS}}(q,m)$: non-static fields
- $t_{\mathrm{other}}(q,m)$: ion-trap physics and ToF detect.

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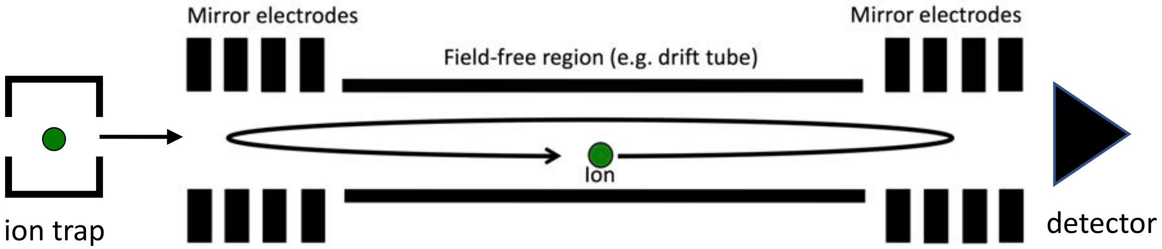
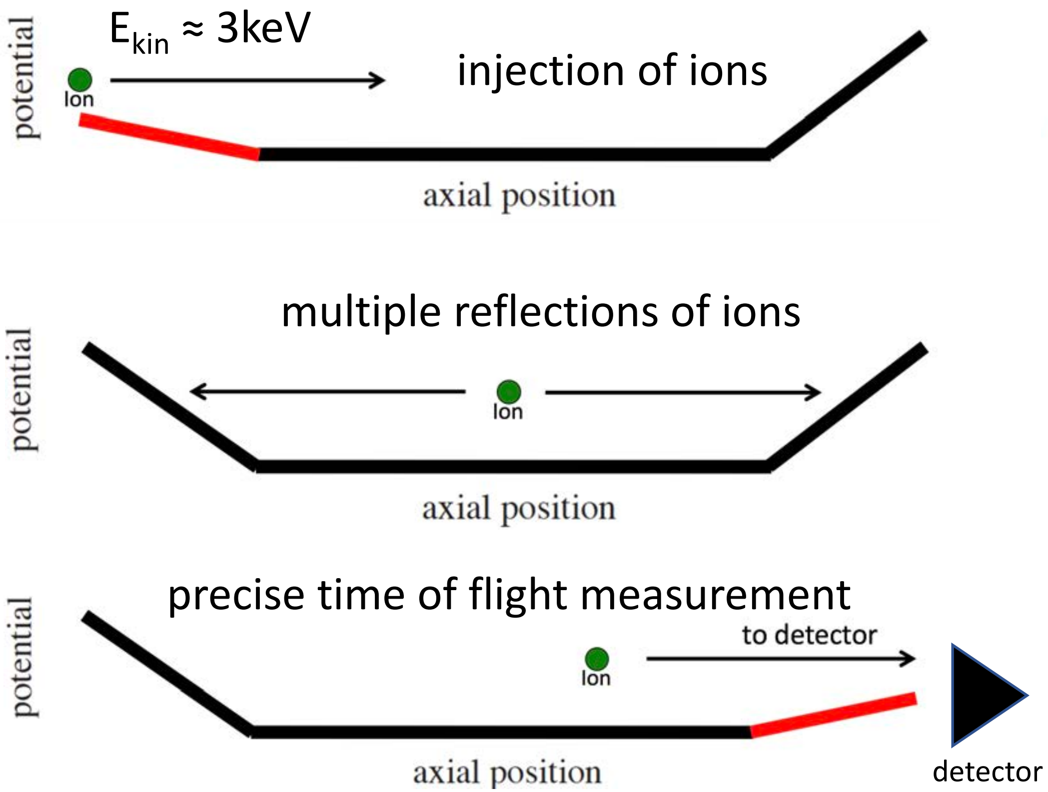
H.Wollnik and M. Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)



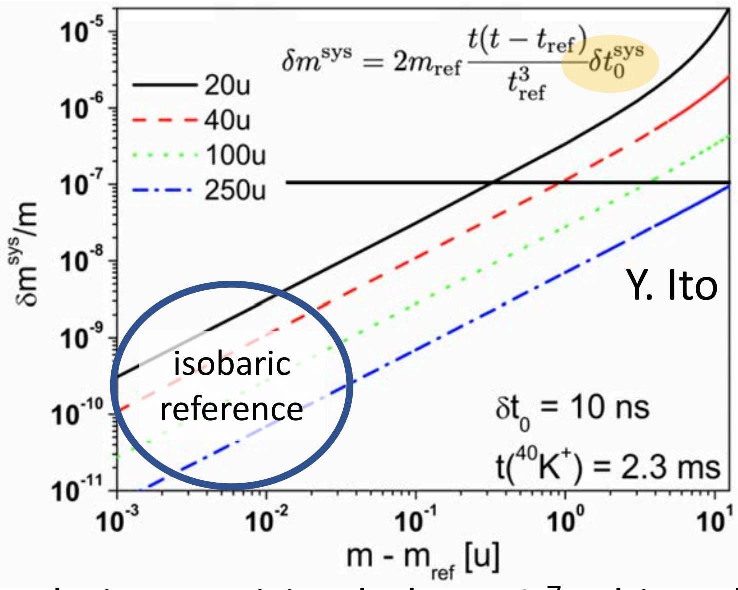
Ions of well known mass and exotic ions
→ comparison of times-of-flight for the same number of laps



electrostatic contribution

offset time

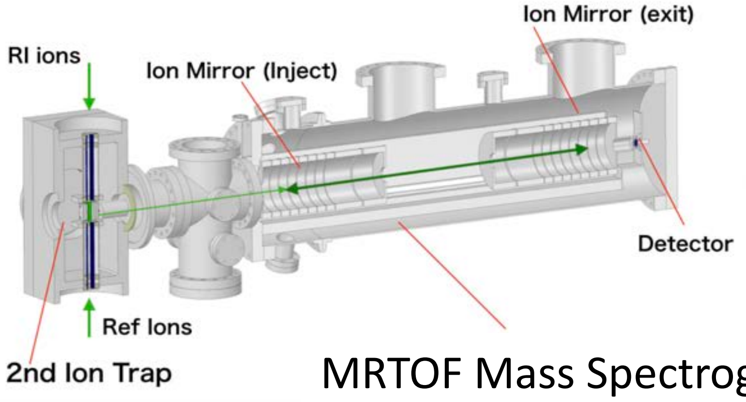
$$\frac{m}{m_{ref}} = \frac{q_{ref}}{q}\left(\frac{t + t_0}{t_{ref} + t_0}\right)^2$$



relative precision below 10^{-7} achieved

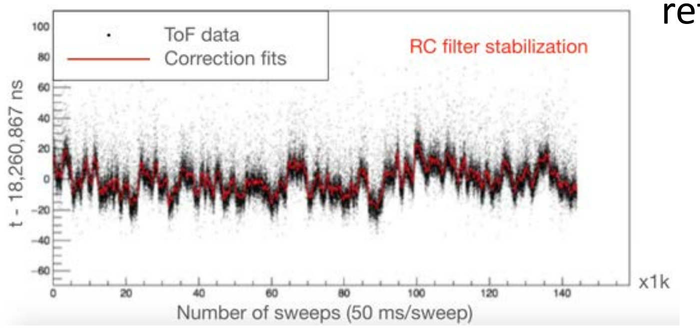
Technological advances: Wideband accuracy

MRTOF voltage fluctuations/drifts (solved)



MRTOF Mass Spectrograph

- Iimura Shun is developing improved drift correction algorithm to compensate for remaining drifts



reference ions / online ions

$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}}$$

average from ion distribution

$$+ \quad t_0$$

$$+ \; t_{NS}(q,m)$$

non-static fields

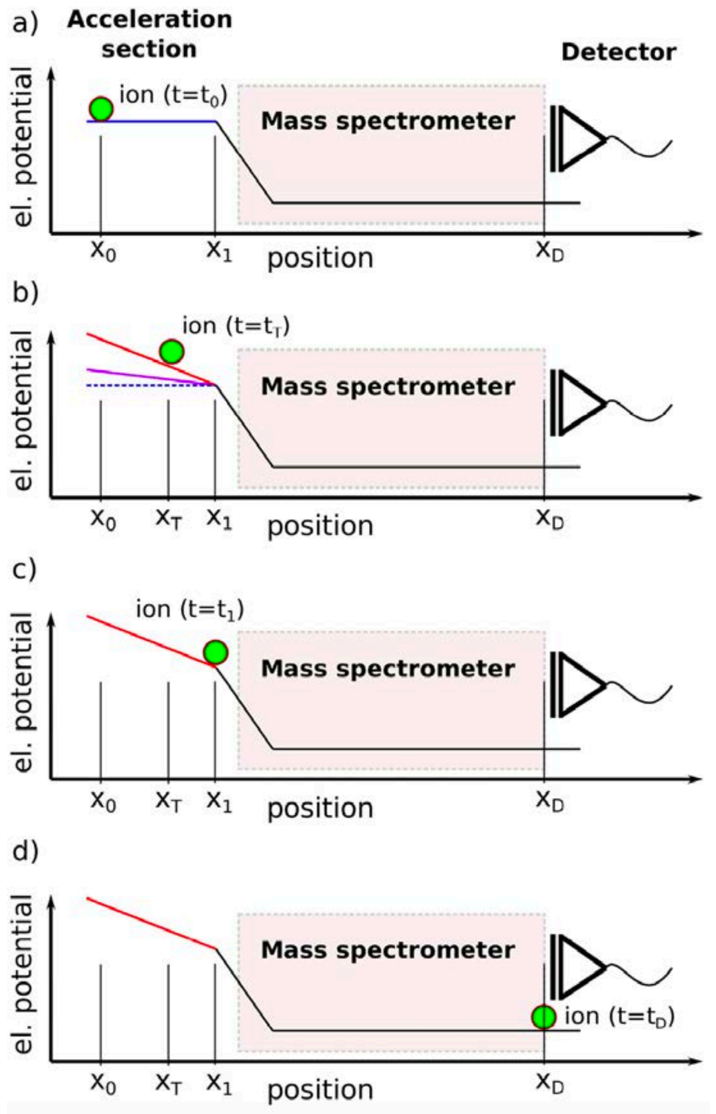
$$+ \; t_{other}(q,m)$$

Time-dependent ejection field of ion trap

Radiofrequency trapping field of ion trap

Micro-ramping of MRTOF mirrors

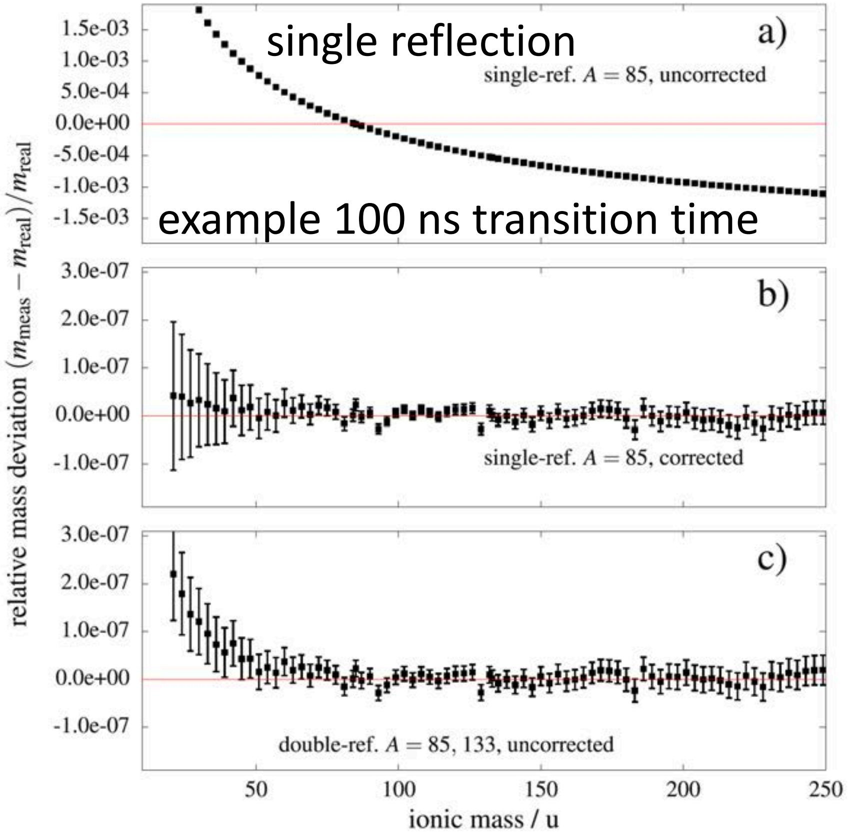
Technological advances: Time-dependent ejection



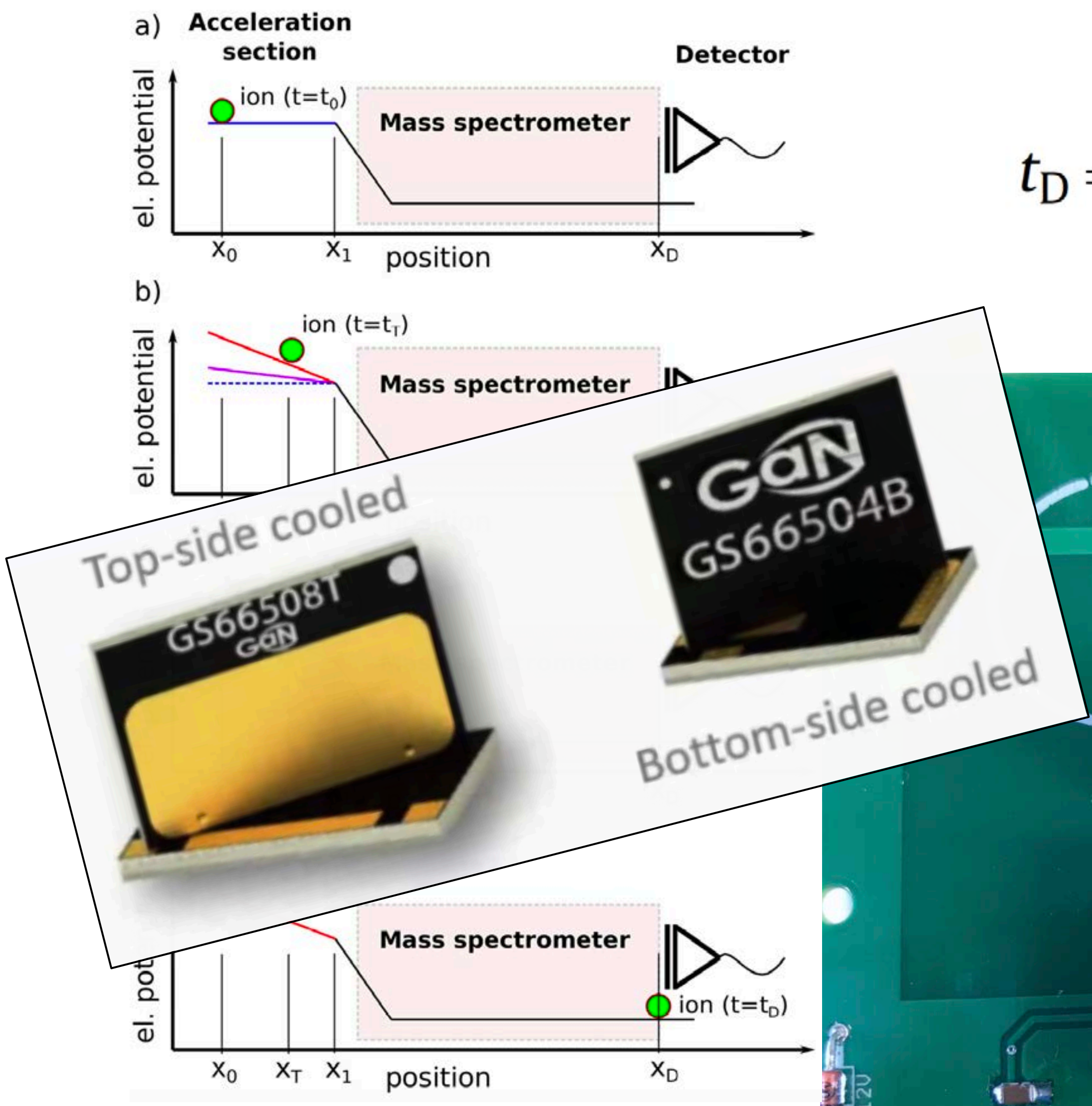
M. Rosenbusch *et al.*, Int. J. Mass Spectrom. 456, 116346 (2020)

non-static fields

$$t_D = t_0 + \frac{t_T}{2} + \alpha\sqrt{\frac{m}{q}} + \beta\sqrt{\frac{q}{m}}$$

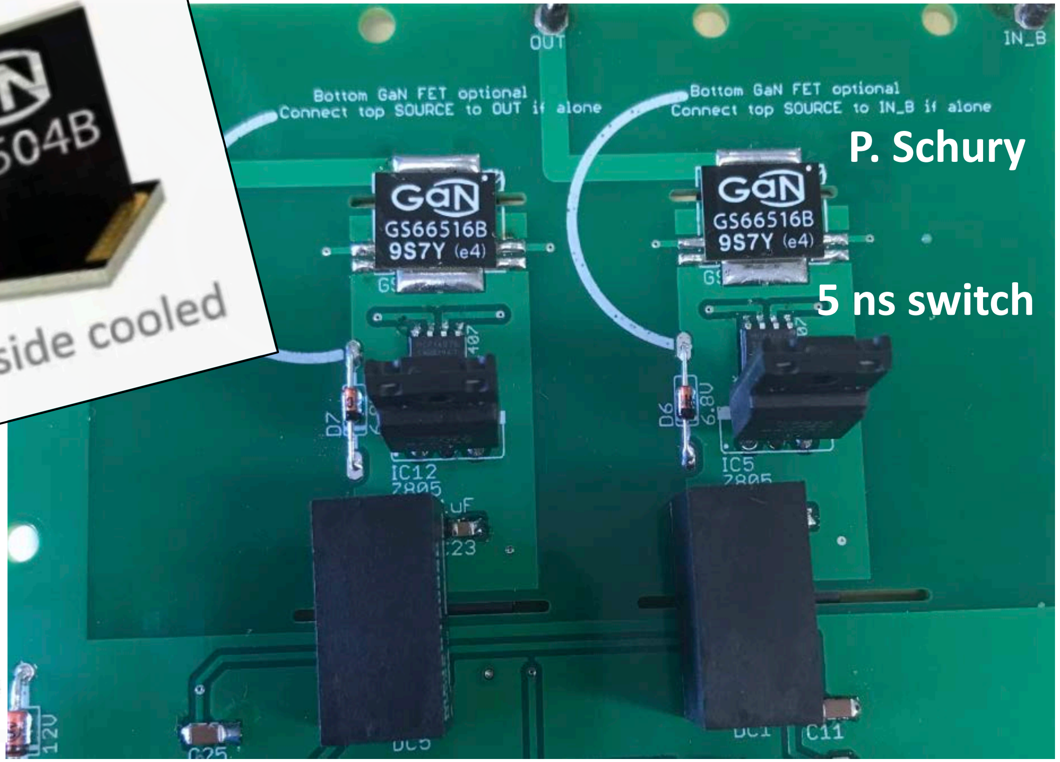


Technological advances: Time-dependent ejection

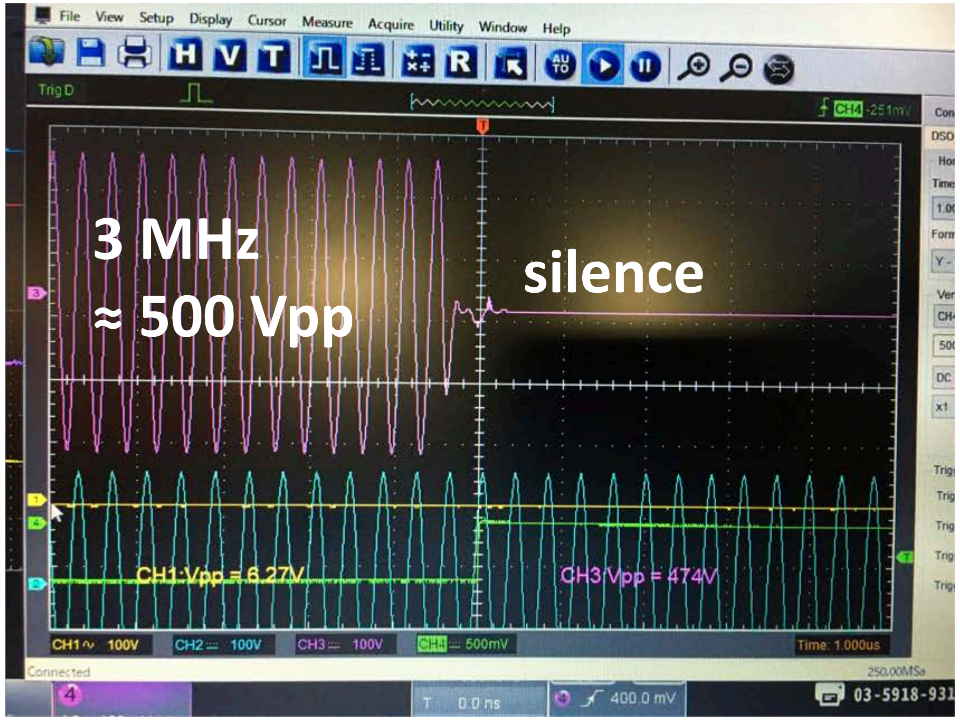


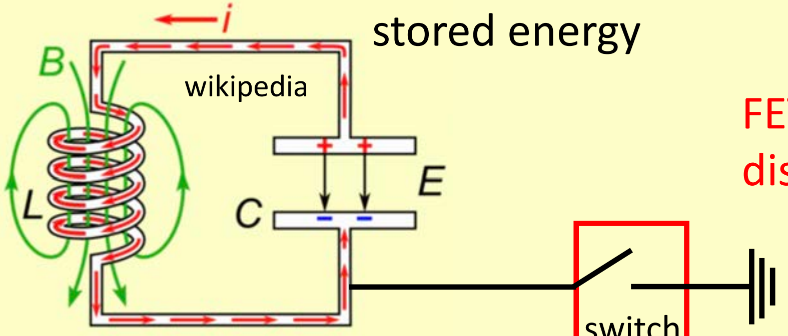
non-static
fields

$$t_D = t_0 + \frac{t_T}{2} + \alpha\sqrt{\frac{m}{q}} + \beta\sqrt{\frac{q}{m}}$$



Technological advances: RF shunting





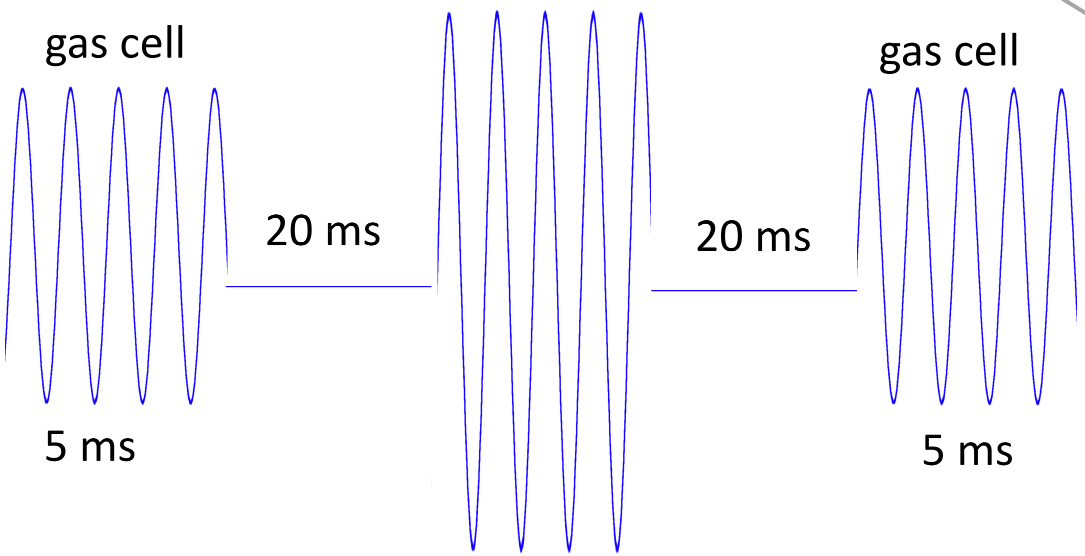
stored energy

FET switch to ground
disturbs resonance

solution not so easy

Technological advances: Ion trap RF adaption

RF amplitude switch for GC/reference ions



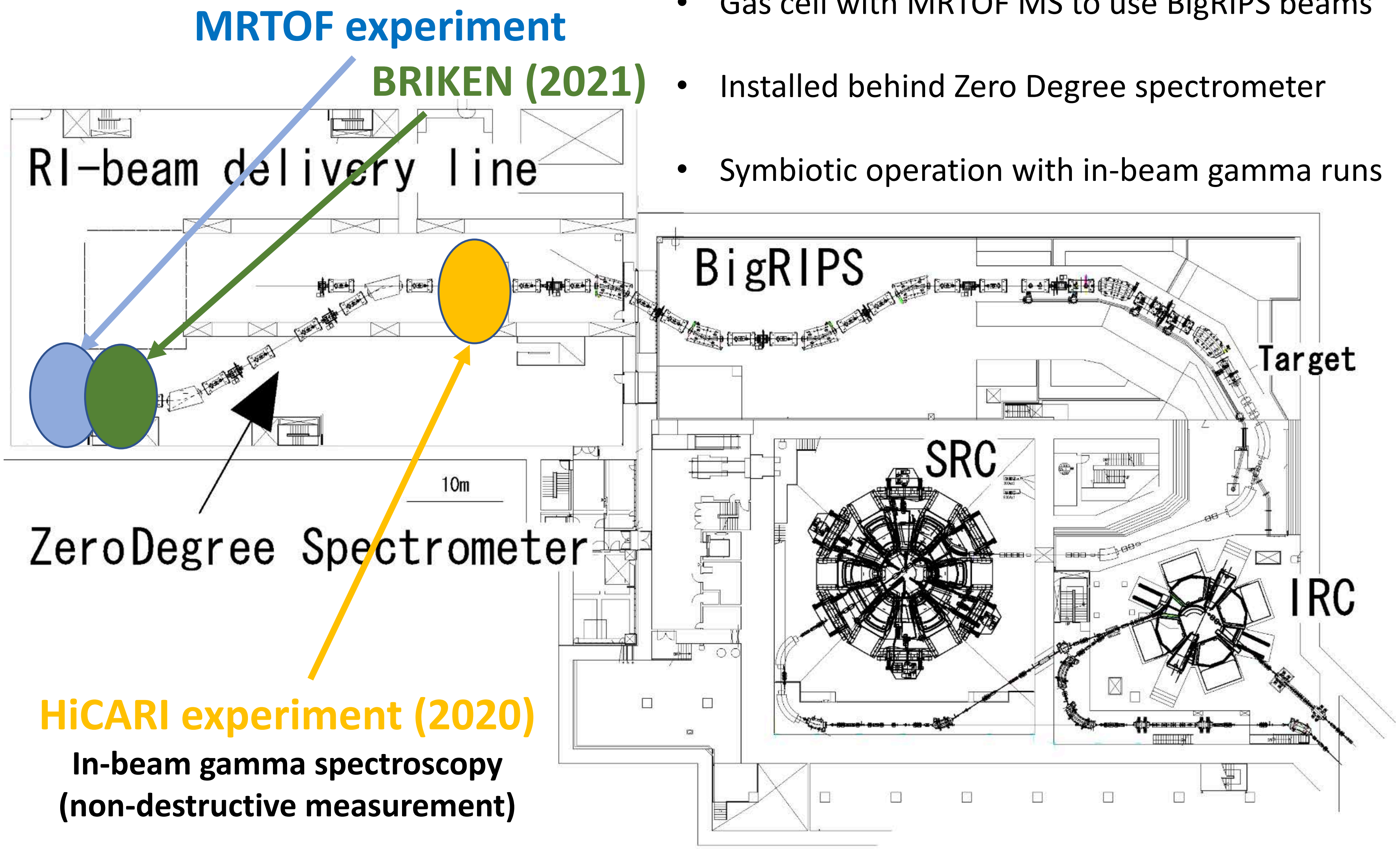
$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}} + t_0 + t_{\mathrm{NS}}(q,m) + t_{\mathrm{other}}(q,m)$$

$\overline{t(q,m)}$: average from ion distribution

$t_{\mathrm{other}}(q,m)$: ion-trap physics

2020 online commissioning

- Gas cell with MRTOF MS to use BigRIPS beams
- Installed behind Zero Degree spectrometer
- Symbiotic operation with in-beam gamma runs

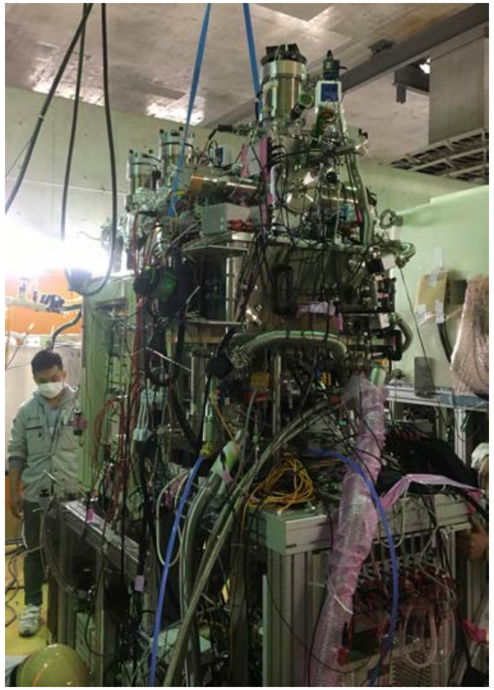


2020 online commissioning

- Transport to the BigRIPS F11 position in October 2020

- Test of apparatus in online condition beginning of November, identification of chemical compounds obtained from the gas cell

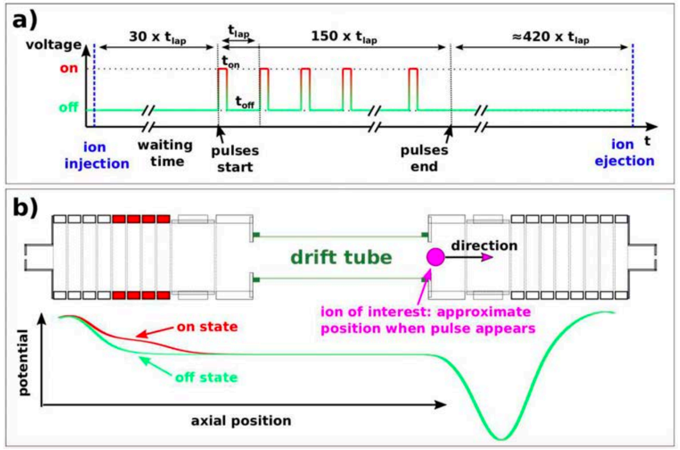
- Taking part in different experiments of the HiCARI group by receiving parasitic beam during November and December 2020



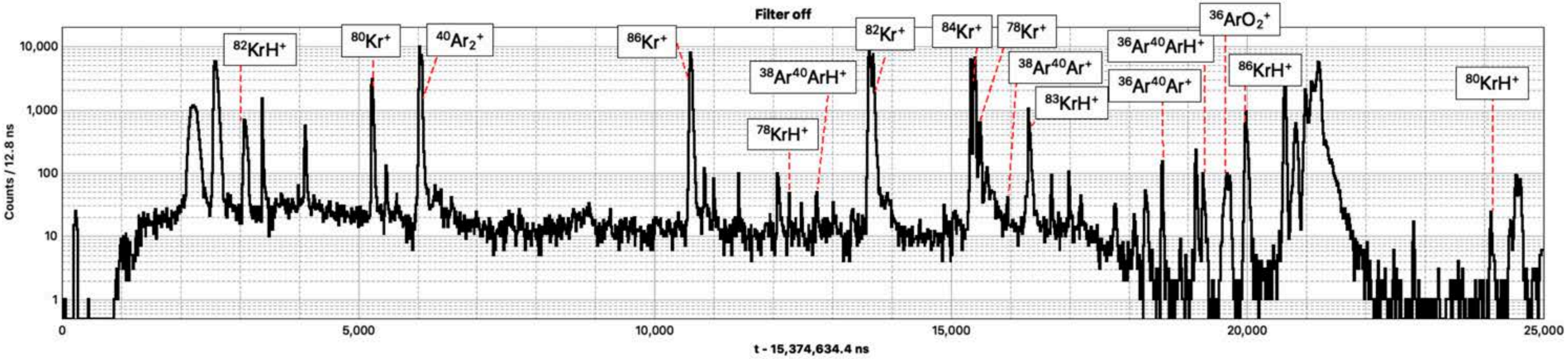
2020 online commissioning

Challenges:

- Molecular contamination in general
- Discharges in Gas Cell
- Chemical reactions in the Gas Cell (unstable efficiency)

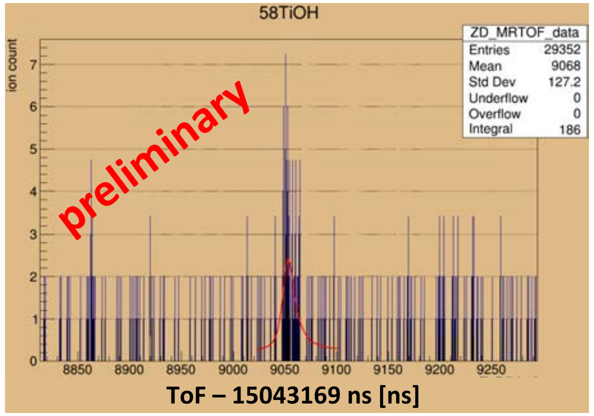


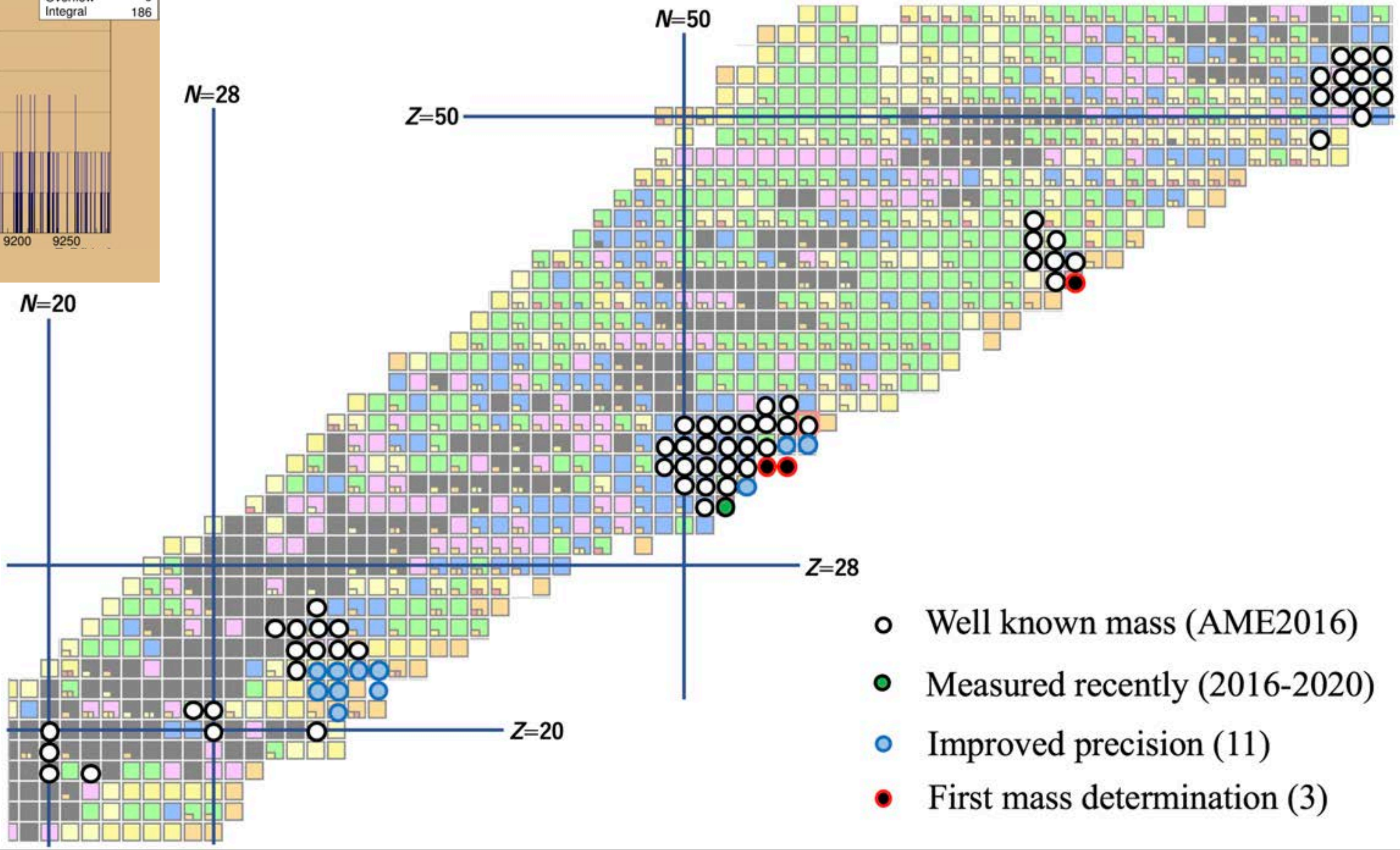
- Quite strong pulses from CGITS cleaning
- Decision: we trust only isobars



ZD MRTOF system: 2020 online commissioning

- Mass measurements in four different regions of the nuclide chart
- Three nuclear masses measured for the first time
- Eleven nuclear masses improved in precision
- Total system efficiency measured (0.3% - 1.5%)

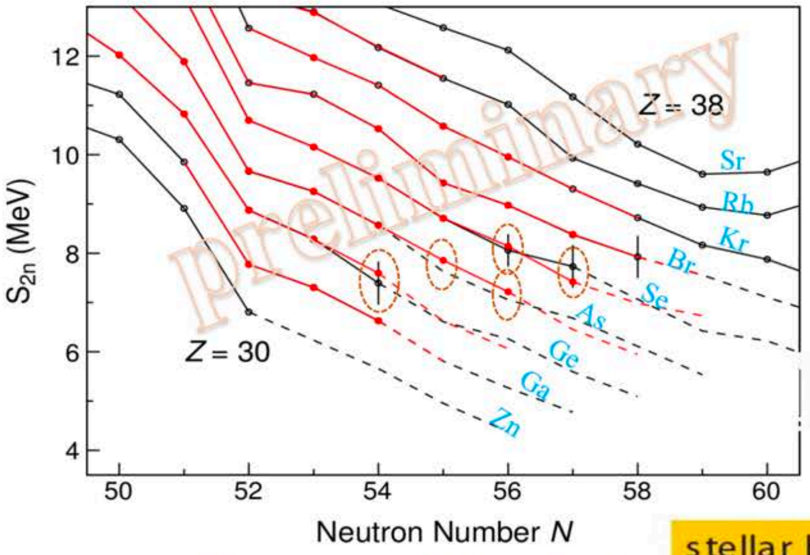




2020 online commissioning

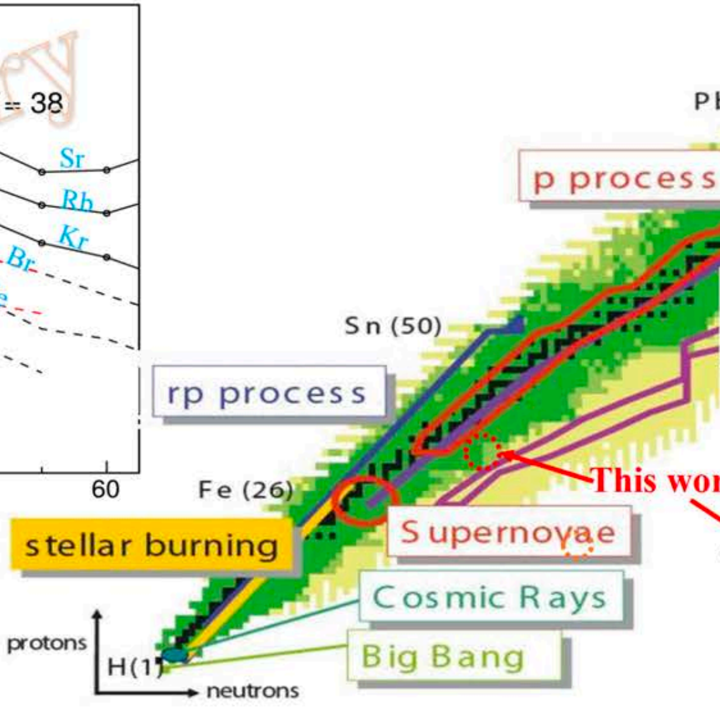
^{88,89}As measured for the first time!

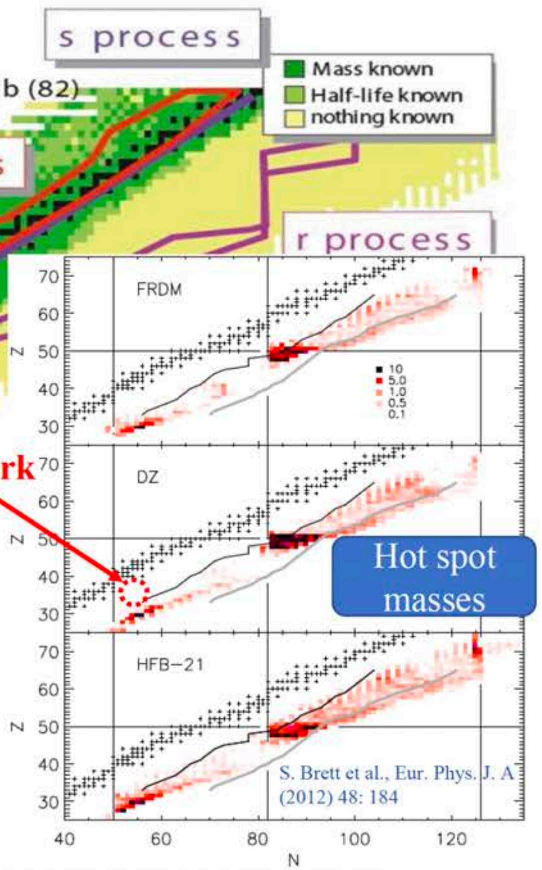
Mass reveals Nuclear structure



- Uncertainty could be reduced by more than a factor of ten
- S_{2n} curves are confirmed to be smooth

Mass as a key input in Astrophysics



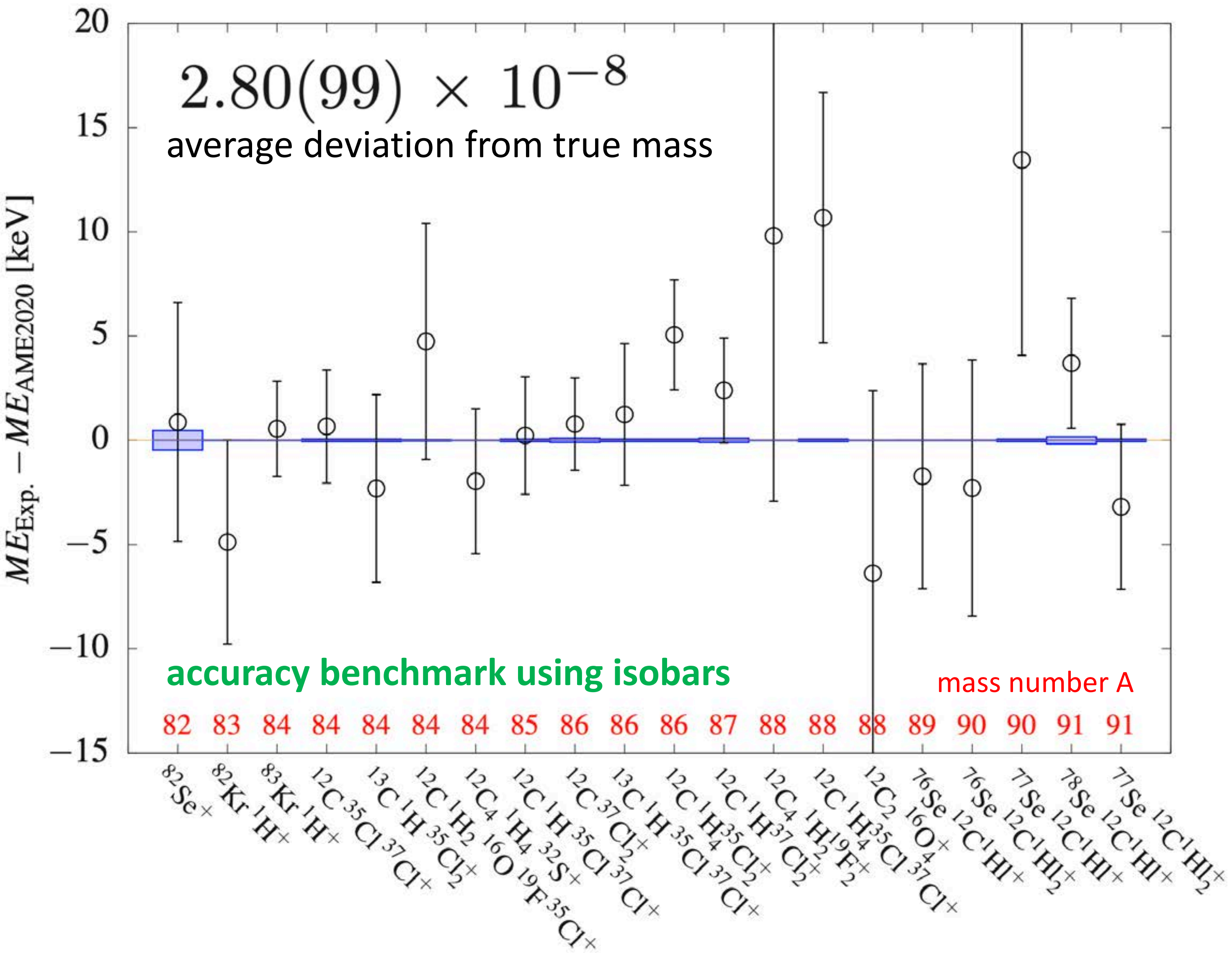


Masses of exotic nuclei with short live time could be evaluated by MRTOF (^{89}As~66ms)

S. Brett *et al.*, Eur. Phys. J. A (2012) 48: 184

slide by W. Xian

2020 online commissioning



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Collaborators