TRIUMF

Ion trapping capabilities at TRIUMF

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TRIUMF Quantum Computing Retreat

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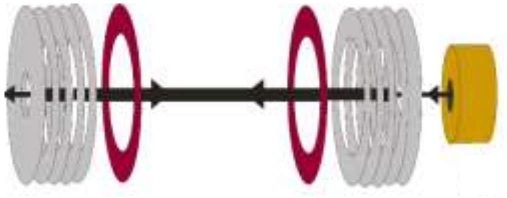
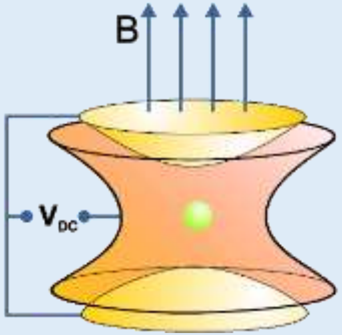
3 ion-trapping flavors are found at TRIUMF.

Multi-reflection / electrostatic



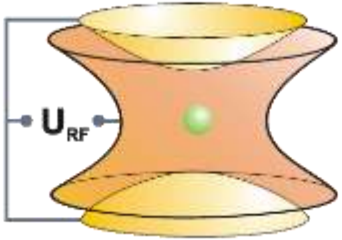
pair of electrostatic mirrors

Penning traps



magnet + electrostatic field

Paul traps



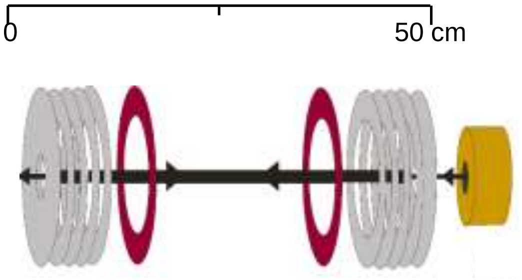
oscillating (RF) electric field

Differences between atomic origins and adaptation for radioactive ion beams (RIB).

	AMO	Nuclear
Precision $\delta m / m$ is	$<10^{-12}$	10^{-6}-10^{-9}
Ions are	stable	$T_{½} \geq$ few ms
Ion produced by	surface ion laser	accelerator facility reactor facility fission source
Beam energy	< 5 keV	> 20 keV
Cold	< K	~ eV

Ion traps prepare & measure RIB.

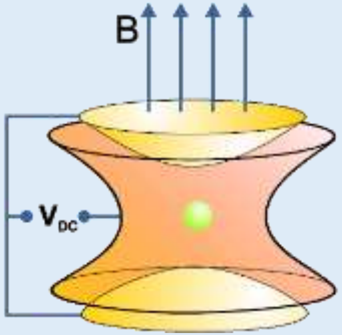
Multi-reflection / electrostatic



pair of electrostatic mirrors

→ mass measurements
→ beam purification
→ decay spectroscopy

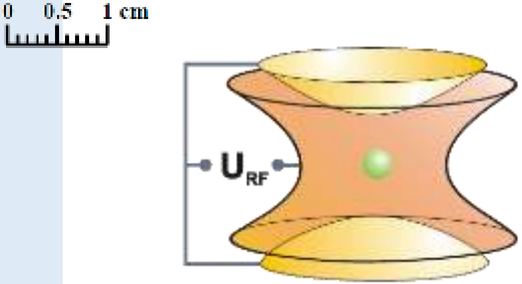
Penning traps



magnet + electrostatic field

→ mass measurements
→ decay spectroscopy
→ beam purification
→ charge breeding

Paul traps



oscillating (RF) electric field

→ beam preparation
→ beam purification
→ decay spectroscopy

At TRIUMF, three groups use ion traps.

ALPHA
particle physics

Penning trap

TITAN
nuclear physics

linear Paul trap
Penning trap
EBIT
electrostatic trap

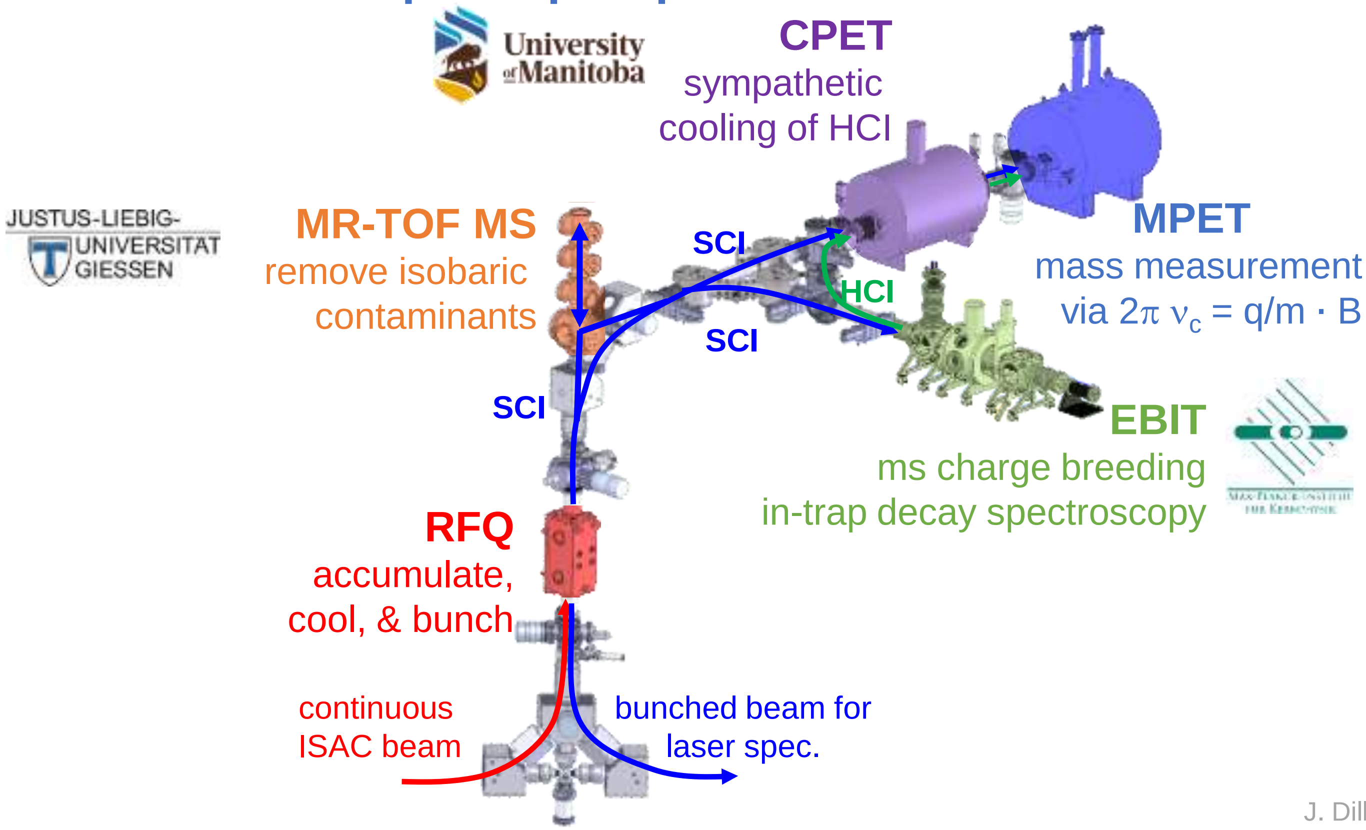
CANREB
accelerator physics

linear Paul trap
EBIT

ALPHA: cerncourier.com/a/keeping-antihydrogen-the-alpha-trap;

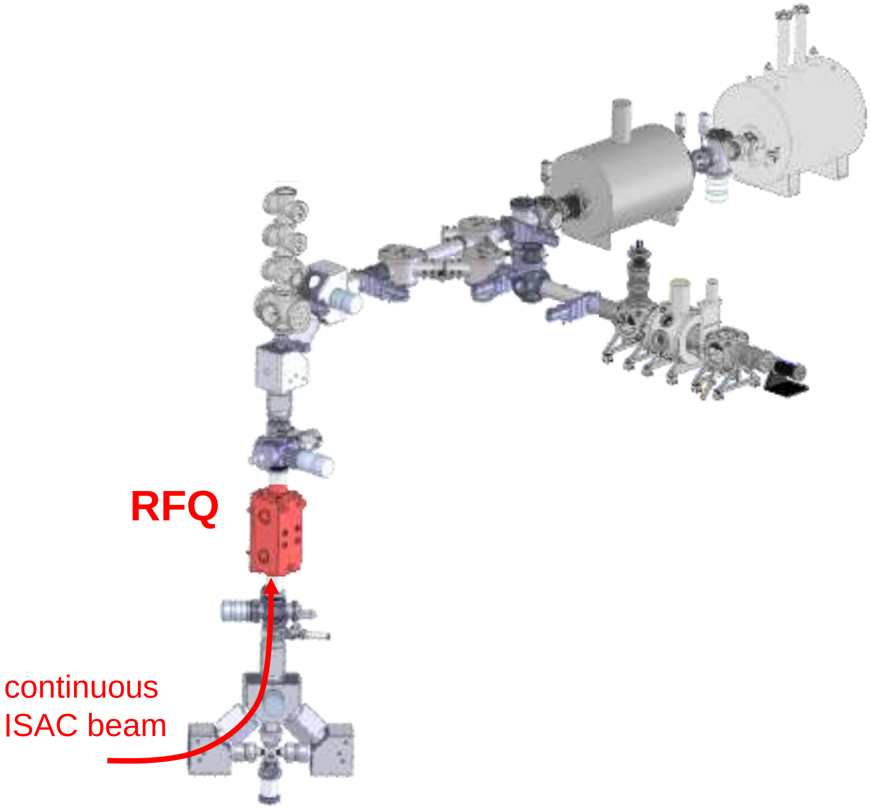
TITAN is TRIUMF's Ion Trap for
Atomic and Nuclear science.

TRIUMF's Ion Trap for Atomic and Nuclear science, uses 5 ion trap to prepare & measure RIB.



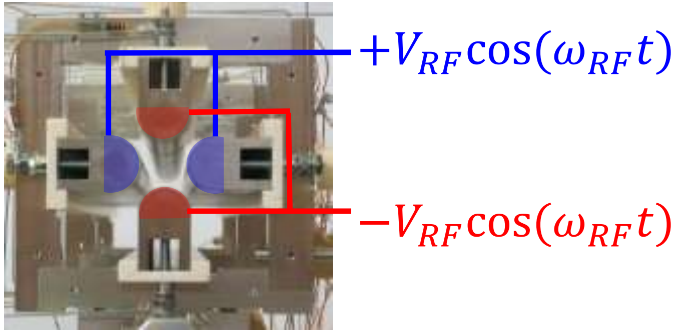
J. Dilling *et al.*, NIMB **204** (2003) 492

TITAN prepares the beam in the RFQ.

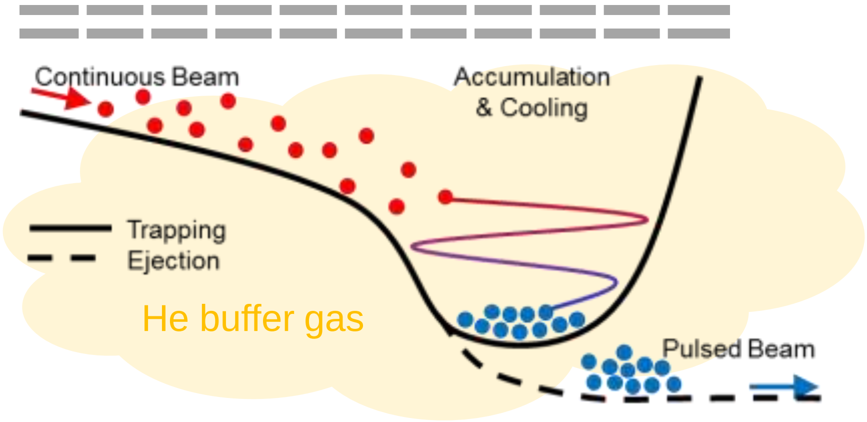


J. Dilling *et al.*, NIMB **204** (2003) 492

The buffer-gas-filled linear Paul trap accumulates, cools, & bunches the RIB.



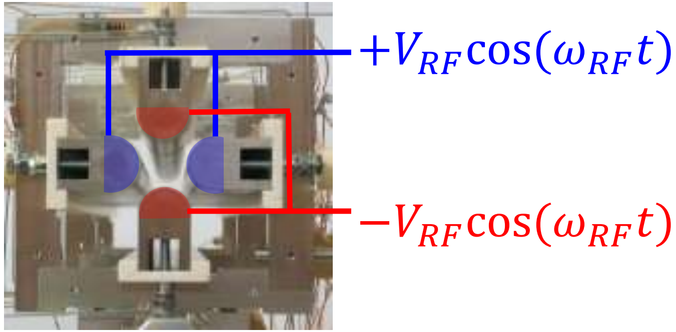
- RadioFrequency Quadrupole → transverse confinement
- Segmentation → axial trapping
- Buffer gas → cooling

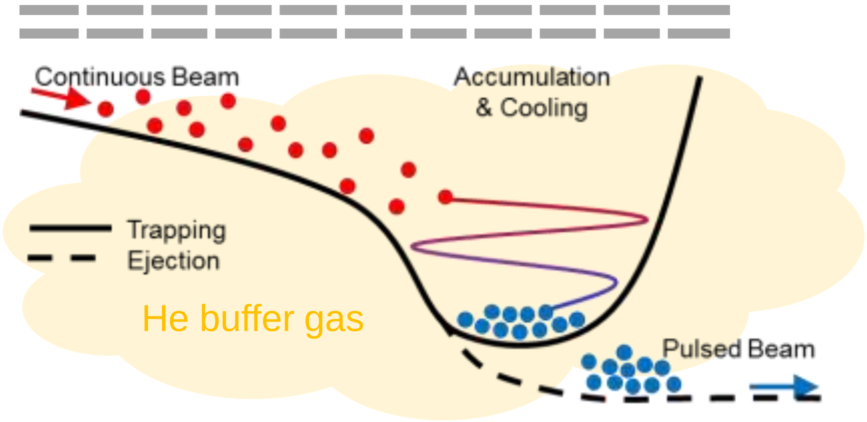


T. Brunner *et al.*, NIMA **676** (2012) 32

The buffer-gas-filled linear Paul trap accumulates, cools, & bunches the RIB.

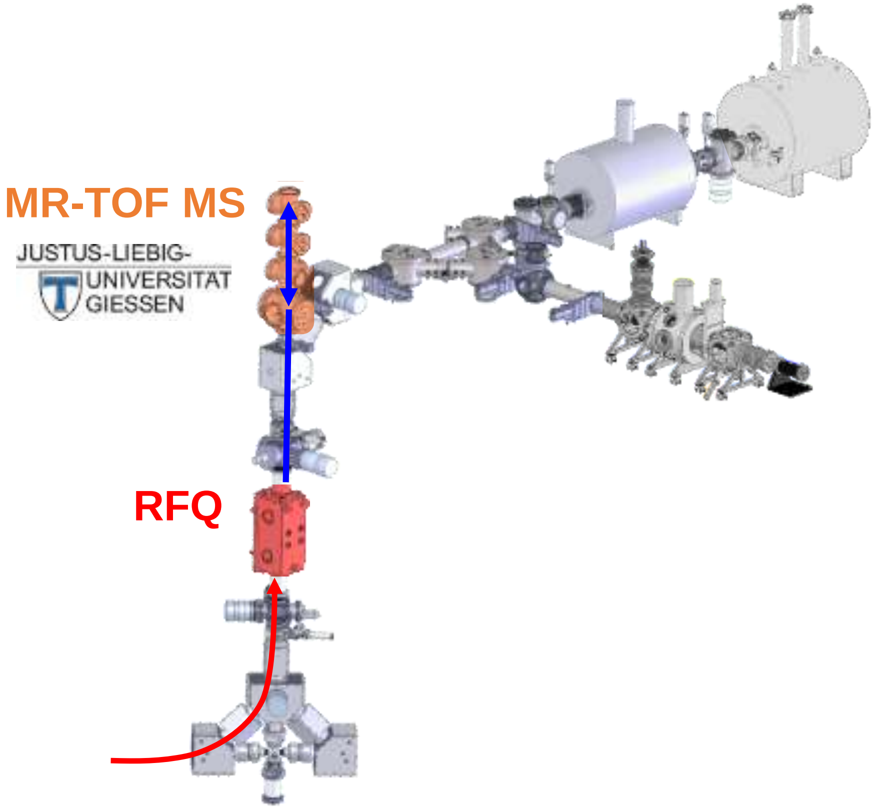
- Space-charge limit of ~10^5 e with good emittance
- Longitudinal emittance of a few eV µs depending on extraction slope
- Shortest duty cycle demonstrated 5 ms





T. Brunner *et al.*, NIMA **676** (2012) 32

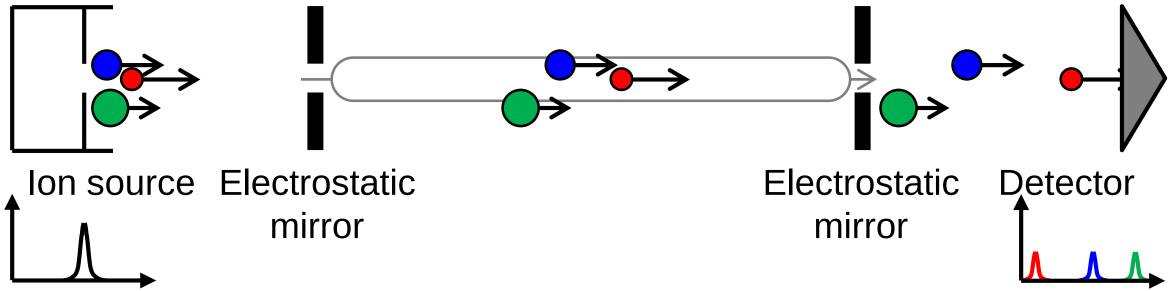
Broadband, fast mass measurements are performed in the MR-TOF-MS.



J. Dilling *et al.*, NIMB **204** (2003) 492

Multi-Reflection Time-Of-Flight Mass Spectrometers are based on simple kinematics.

$$TOF = \frac{L}{v} = \frac{L}{\sqrt{2E}} = \sqrt{\frac{m}{q}} \int \frac{dz}{\sqrt{2V(z)}}$$

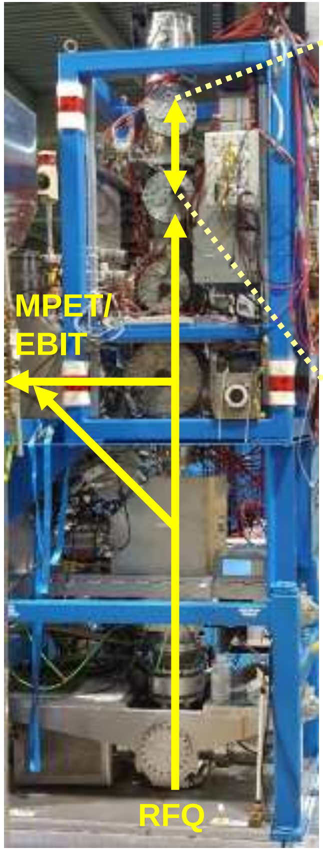


Separation increases with flight path → longer path length OR **multiple passes** on same path

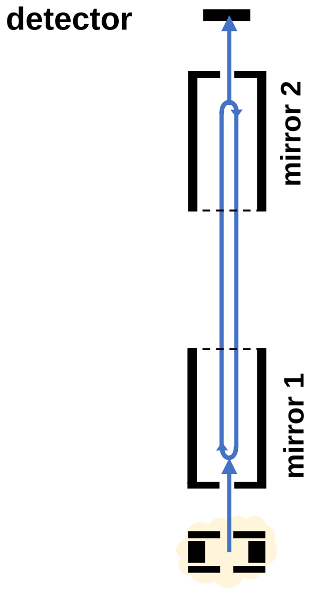
Precisions up to ~10^{-7}
and for half-lives as low as 2 ms (^{215}Po @Giessen-GSI)

TITAN MR-TOF-MS capabilities:

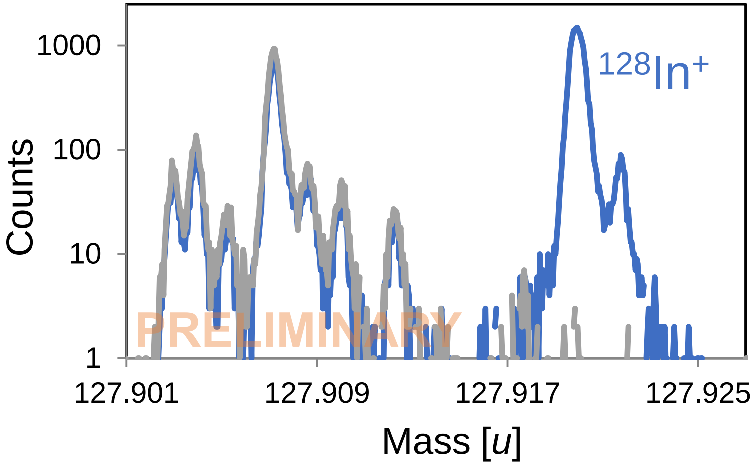
- Space charge: ≤10^6 pps
- Sensitivity: <0.1 pps
- Shortest $T_{1/2}$: 5 ms
- $\delta m/m$: > 5×10^{-8}
- Trap lifetime: 100s ms (singly charged)



MR-TOF was used to measure masses of astrophysically important, n-rich $^{125-134}$In.



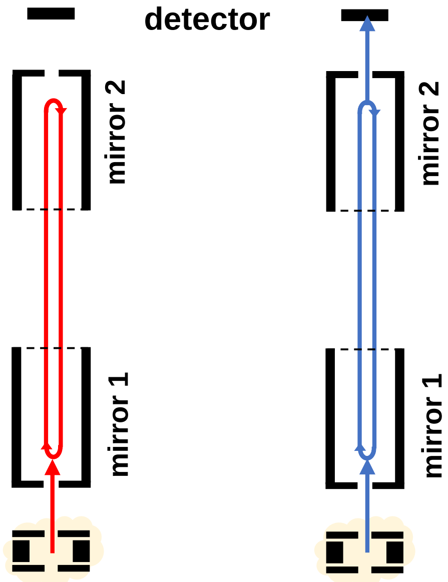
Cool, inject & separate by TOF



In laser ionization
no laser ionization

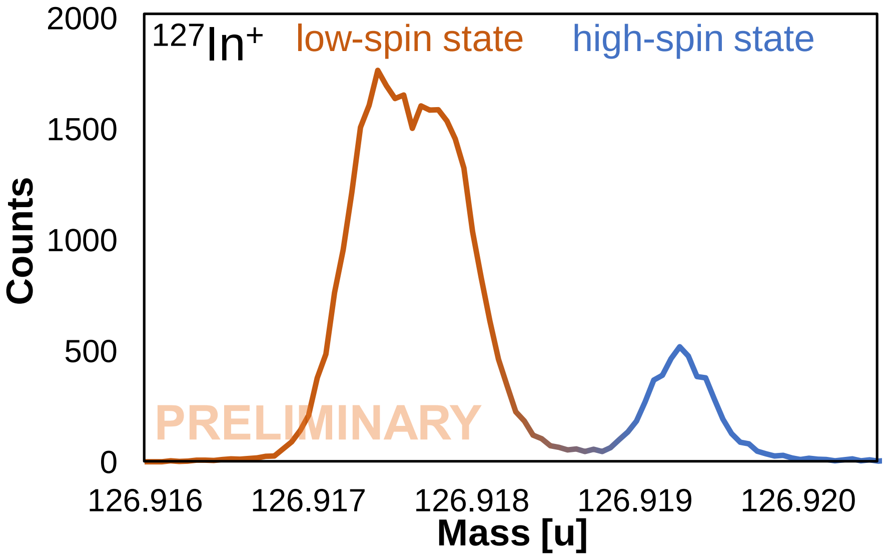
C. Izzo *et al.*, in preparation

“Re-trapping” technique makes MR-TOF-MS its own purifier.



1. Separate by TOF & recapture in injection trap

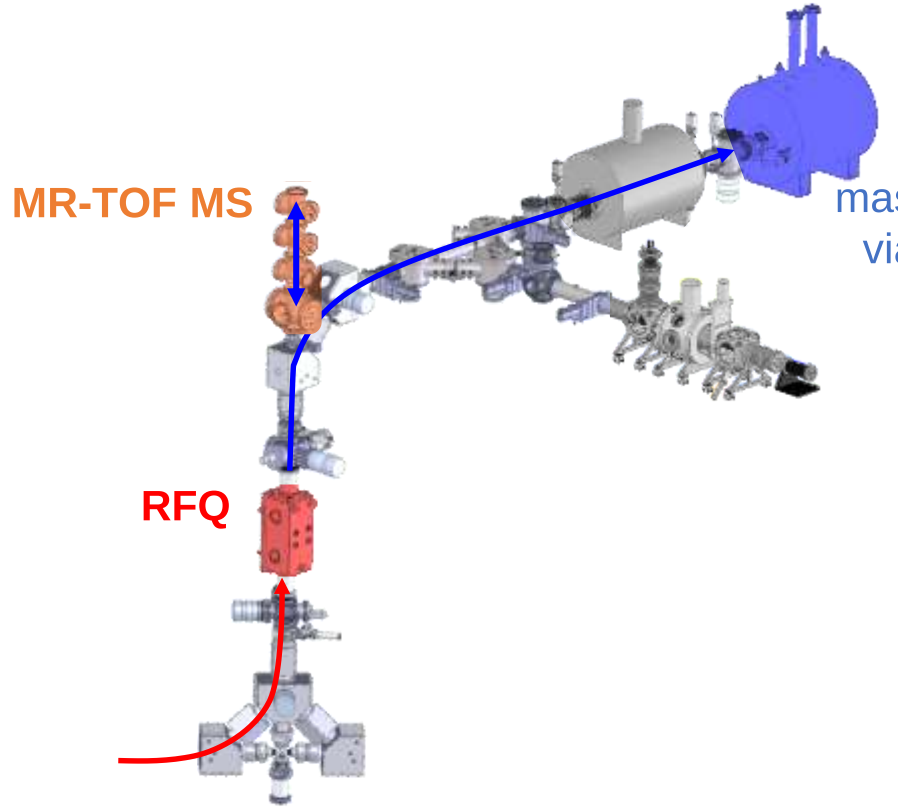
2. Re-cool, reinject & re-separate by TOF



C. Izzo *et al.*, in preparation

The highest precision & accuracy are achieved with Penning trap mass spectrometry.

The Measurement Penning Trap can achieve precisions of $\delta m/m$ ~10^{-9}.



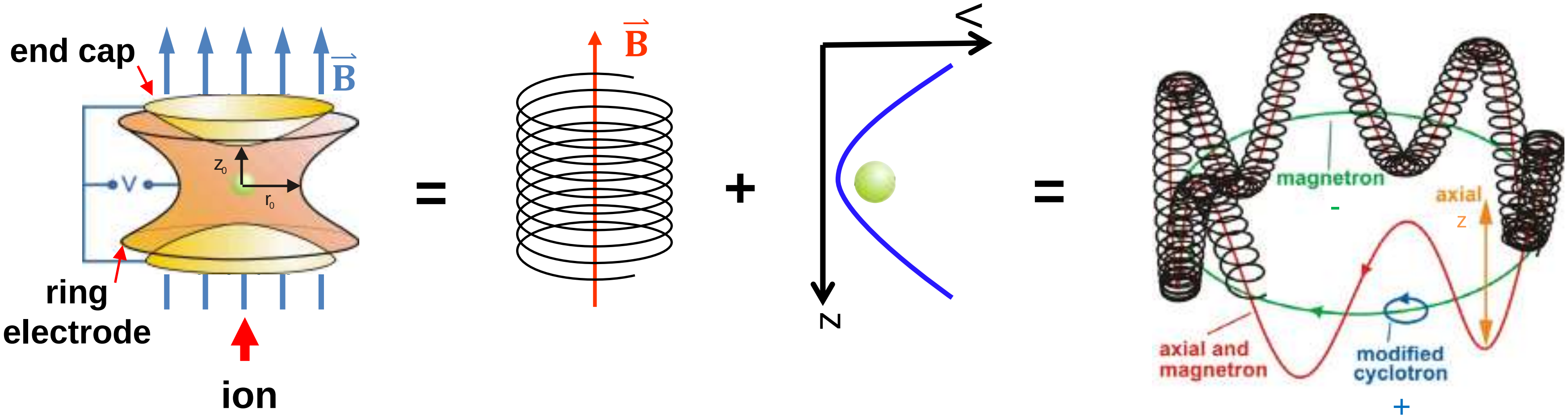
MPET
mass measurement
via $2\pi\,\nu_c = q/m \cdot B$

J. Dilling *et al.*, NIMB **204** (2003) 492

A Penning trap accesses the cyclotron frequency & therefore the ion's mass.

$2\pi\nu_c = (qe/\mathbf{m}) \cdot B$

$\nu_c = \nu_+ + \nu_-$



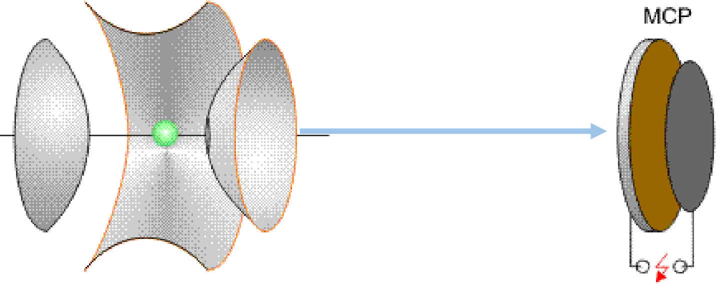
RIB mass measurements with precisions up to $\sim10^{-9}$
and for half-lives as low as 9 ms ($^{11}Li^+$ @ TITAN-TRIUMF)

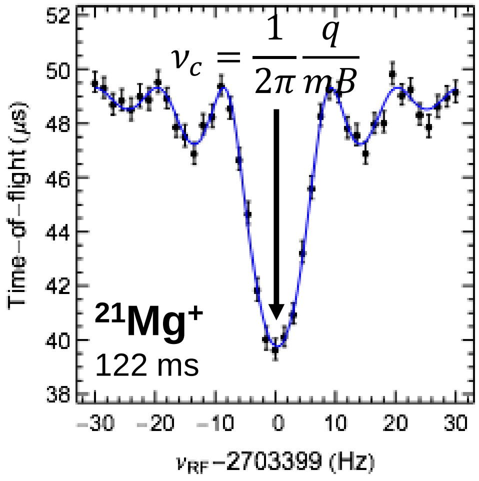
L.S. Brown & G. Gabrielse, Rev. Mod. Phys., 58 (1986) 233

Cyclotron frequency can be determined via

Time-of-Flight Ion Cyclotron Resonance

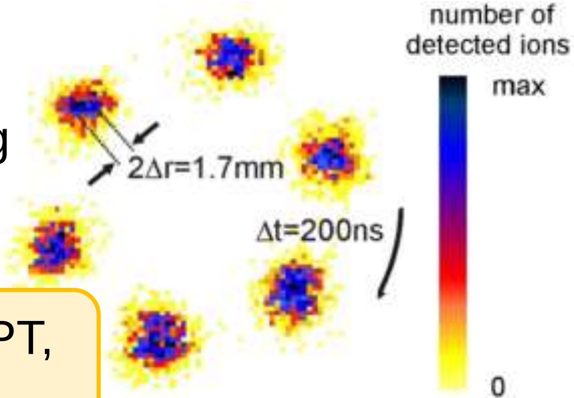
all RIB PTMS



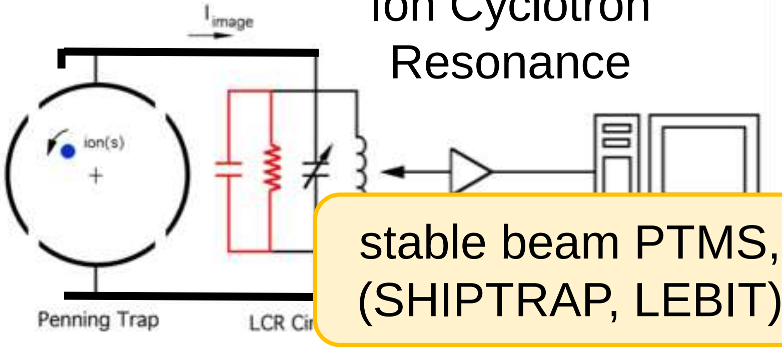


Phase-Imaging Ion Cyclotron Resonance

SHIPTRAP, CPT, JYFLTRAP, …



Fourier-Transform Ion Cyclotron Resonance



stable beam PTMS, (SHIPTRAP, LEBIT)

M. König, *et al.*, Int. J. Mass Spec. 142 (1995) 93; S. Eliseev, *et al.*, PRL 110 (2013) 082501; A.G. Marshall, *et al.*, Int. J. Mass Spec. 215 (2002) 59

Accuracy is understood in theory & practice.

Exact theoretical description

- Brown & Gabrielse, Rev. Mod. Phys. 58 (1986) 233
- G. Bollen, *et al.*, J. Appl. Phys 88 (1990) 4355
- M. Konig, *et al.* Int. J. Mass Spec. 142 (1995) 95
- M. Kretzschmarr, Int. J. Mass Spec. 246 (2007) 122

Accuracy & precision for non-ideal traps

- G. Bollen, *et al.*, J. Appl. Phys 88 (1990) 4355
- G. Gabrielse, Int. J. Mass. Spec. 279 (2009) 107

Corrections & stabilizations

- K. Blaum *et al.*, EPJ A 15 (2002) 245
- M. Brodeur *et al.*, IJMS 310 (2010) 20
- C. Droese *et al.*, NiMA 632 (2011) 15

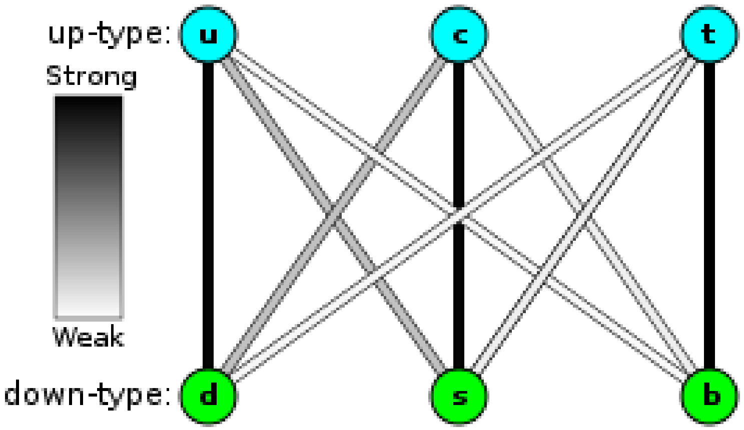
→ Verified via tests of stable nuclides

TITAN MPET capabilities:

- Space charge: ≤10^3 e
- Sensitivity: 100 pps
- Shortest $T_{1/2}$: 8 ms
- $\delta m/m$: ≥ 10^{-9}
- Trap lifetime: >2 s (singly charged)

The Cabibbo-Kobayashi-Maskawa matrix describes quark-mixing interactions.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{ub} & V_{us} \\ V_{cd} & V_{cb} & V_{cs} \\ V_{td} & V_{tb} & V_{ts} \end{pmatrix} \begin{pmatrix} d \\ b \\ s \end{pmatrix}$$



In the Standard Model, the CKM matrix describes a unitary transformation.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

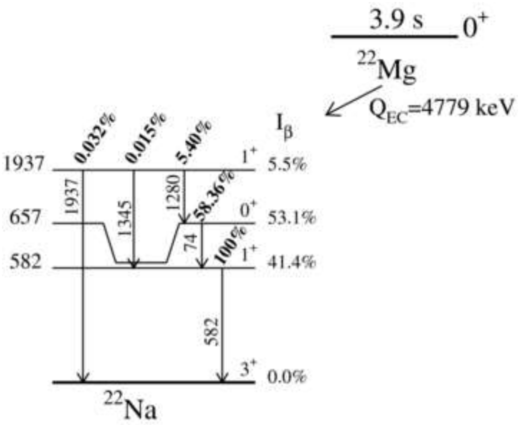
Top row is the most stringent test.

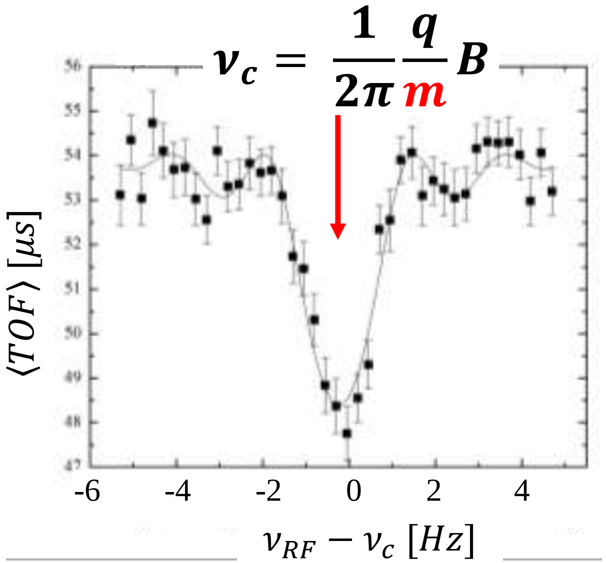
$|V_{ud}|$ dominates the top row.

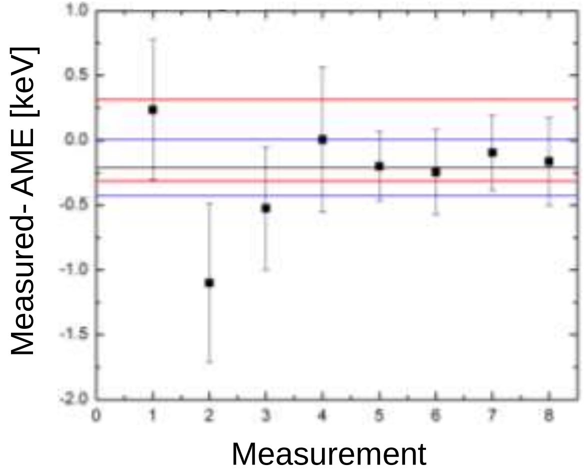
It is measured through the mass difference of superallowed β emitters and their daughters.

Figure: commons.wikimedia.org

The Q-value of ^{22}Mg, a superallowed β emitter, supports quark-mixing matrix's unitarity.







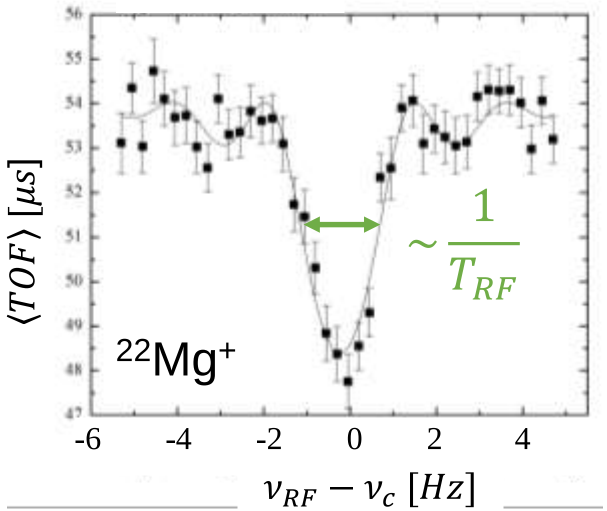
TITAN Q-value measured through TOF-ICR to 220 eV & agrees with literature .

Weighted average δQ = 160 eV, 30% more precise

M.P. Reiter, *et al*, PRC 96 (2017) 052501

How can higher performance be achieved?

Higher charge states increases precision, reduces exp. requirements, or boosts resolving power.



$$\frac{\delta m}{m} \propto \frac{m}{q e\, B\, T_{RF} \sqrt{N}}$$

N = statistics → limited by production

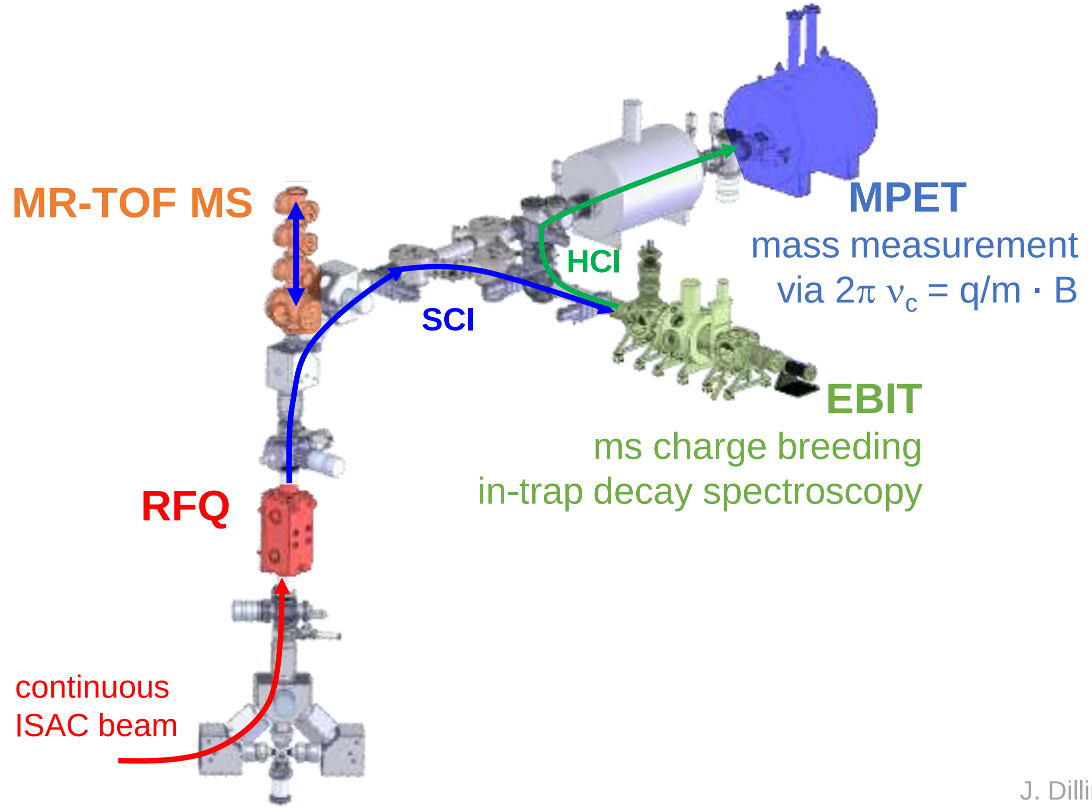
T_{RF} = measurement time → limited by $T_{1/2}$

B = magnetic field → limited by technology

q = charge state → limited by Z

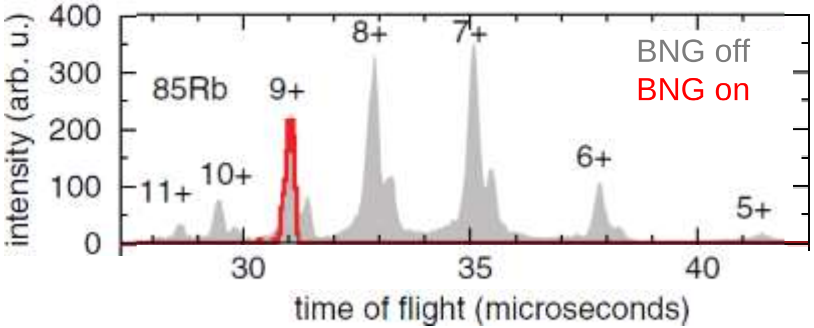
M.C. Simon, *et al*, RSI 83 (2012) 02A912

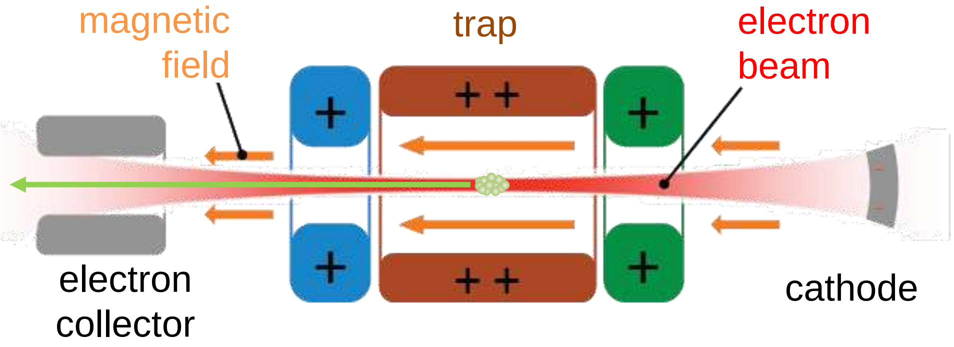
The Electron Beam Ion Trap performs fast charge breeding.



J. Dilling *et al.*, NIMB **204** (2003) 492

The EBIT charge breeds through successive electron impact.





EBIT = Penning trap + electron beam

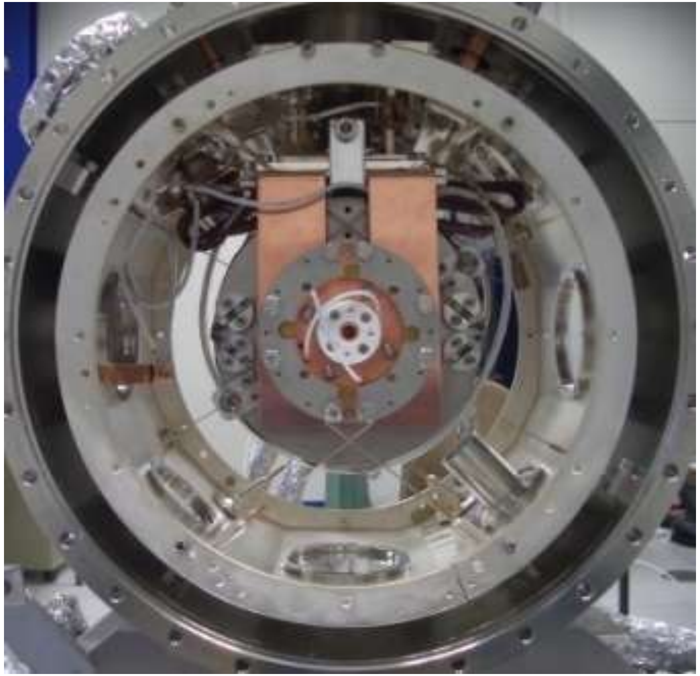
Charge-state distribution depends on Z, electron beam energy, electron current density, & charge breeding time.

EBIT also used for beam purification and storage during decay & recapture.

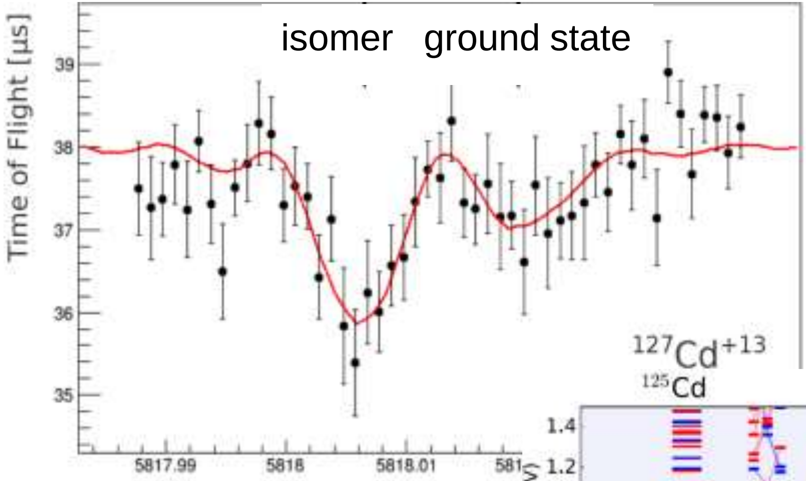
A. Lapierre, *et al.*, NIMA **624** (2010) 54

TITAN EBIT capabilities:

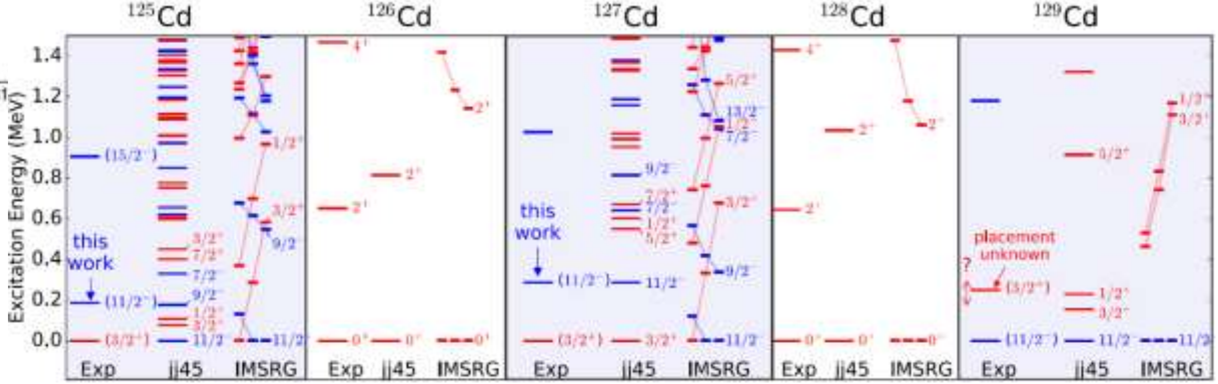
- Space charge: ≤10^9 e
- Sensitivity: 1000 pps
- Shortest $T_{1/2}$: 65 ms
- Max $E_{e\ beam}$: 65 keV
  - Max current: 5 A
  - Highest charge state: ${}_{55}Cs^{33+}$ at 5 keV
- Trap lifetime: > few min



High charge states resolve isomers & reveals details of nuclear structure.



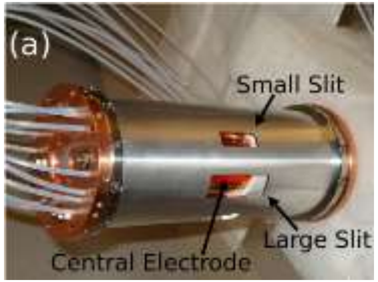
Excited state structure revealed in indium and odd-A cadmium isotopes approaching the closed shell N = 82.

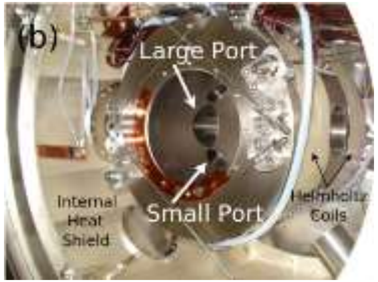


D. Lascar, *et al.*, PRC, 96 (2017) 044323; C. Babcock, *et al.* PRC 97 (2018) 024312

The EBIT also boast 7 radial ports,
optically accessing trapped ions.

The EBIT's optical access allows nuclear decay spectroscopy.





Magnetic field redirects β particles → no positron-annihilation radiation.

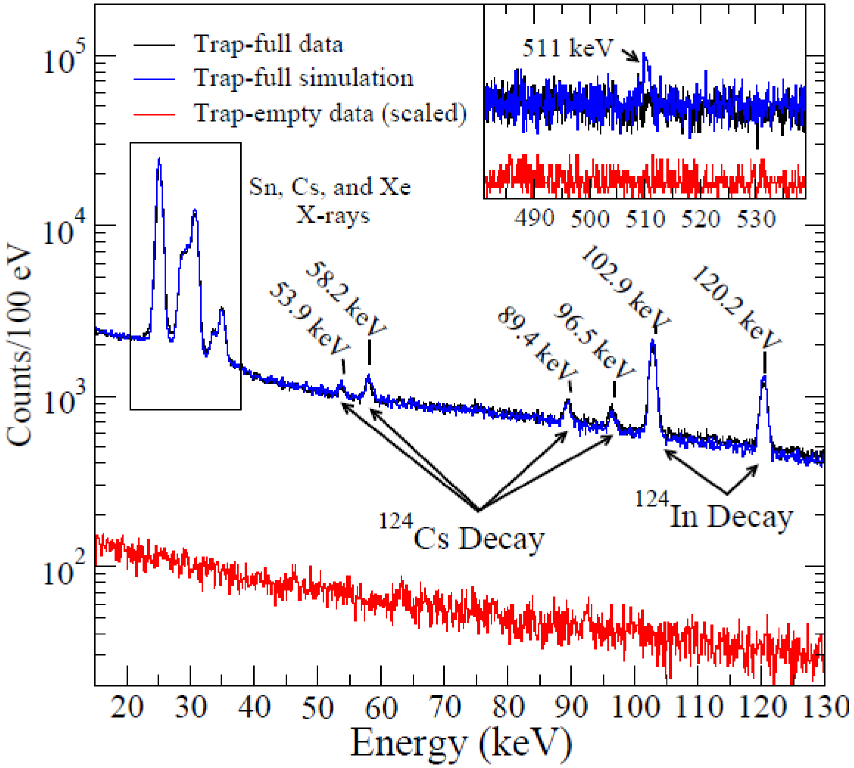
Electron beam deepens confinement → extends trap lifetime.

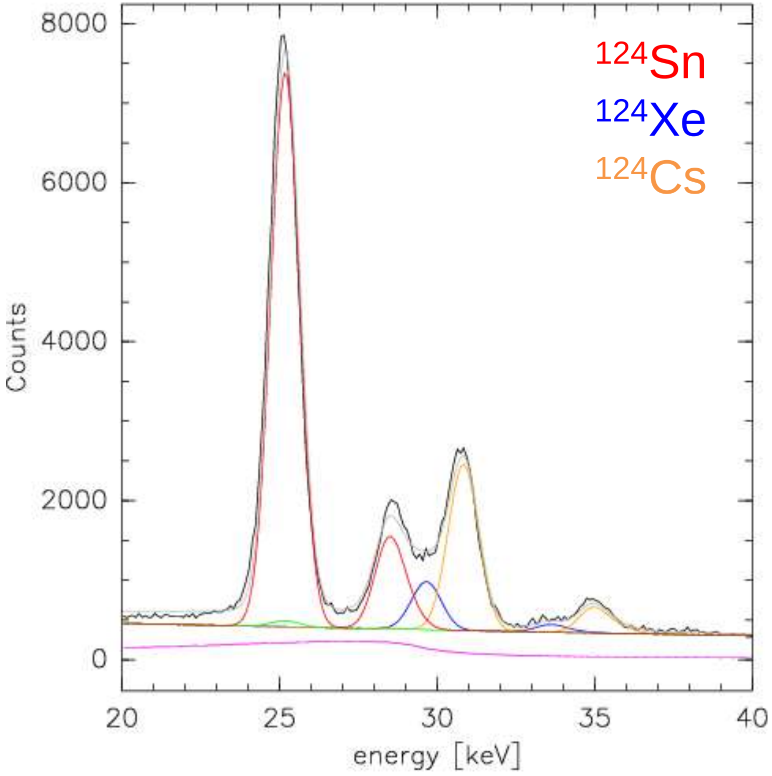
Science program:

- originally benchmarking 0ν2EC nuclear matrix elements
- changes in nuclear properties as function of charge state for astro
- nuclear excitation by electron capture

A. Lennarz, *et al*, Phys. Rev. Lett. 113 (2014) 082502; K.G. Leach *et al.*, NIMA, 780 (2015) 91

EBIT's backing-free environment and reduced β background enhance certain measurements.





A. Lennarz, *et al*, Phys. Rev. Lett. 113 (2014) 082502; K.G. Leach *et al.*, NIMA, 780 (2015) 91

TRIUMF builds & develops ion traps for short-lived species.

- radioactive ion beams (TITAN, CANREB)
- anti-hydrogen (ALPHA)
- with strong “other” technical support (detectors, controls, DAQ, cryo, HV, …)

TITAN focuses on nuclear-physics studies.

- mass measurements (Penning trap, MR-TOF)
- in-trap decay spectroscopy (in EBIT or trap assisted)
- beam purification & preparation (MR-TOF, EBIT, Penning trap)

Subatomic-physics vs. quantum computing

- substantial differences (species of interest, energy regime, detection technique, physical dimensions, …)
- substantial overlap (single-ion sensitivity, ion manipulation, optical access, …)

TRIUMF

Discovery,
accelerated