CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS
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The TITAN EBIT & Prospects of Experiments with Radioactive Highly Charged Ions

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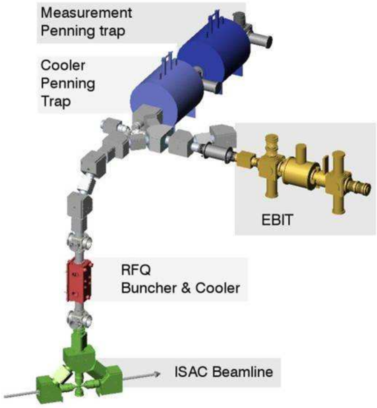
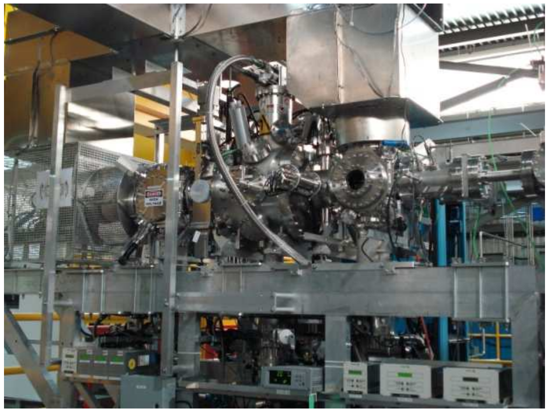
TRIUMF, U of BC, UT Munich, U of Manitoba, MPI-K (Heidelberg)



Outline

- TITAN facility @ TRIUMF
- TITAN EBIT
- Recent results: Trapped RAI's and HCI's
- Prospects of experiments



LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES
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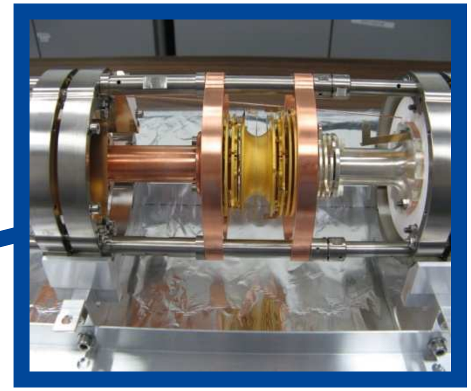
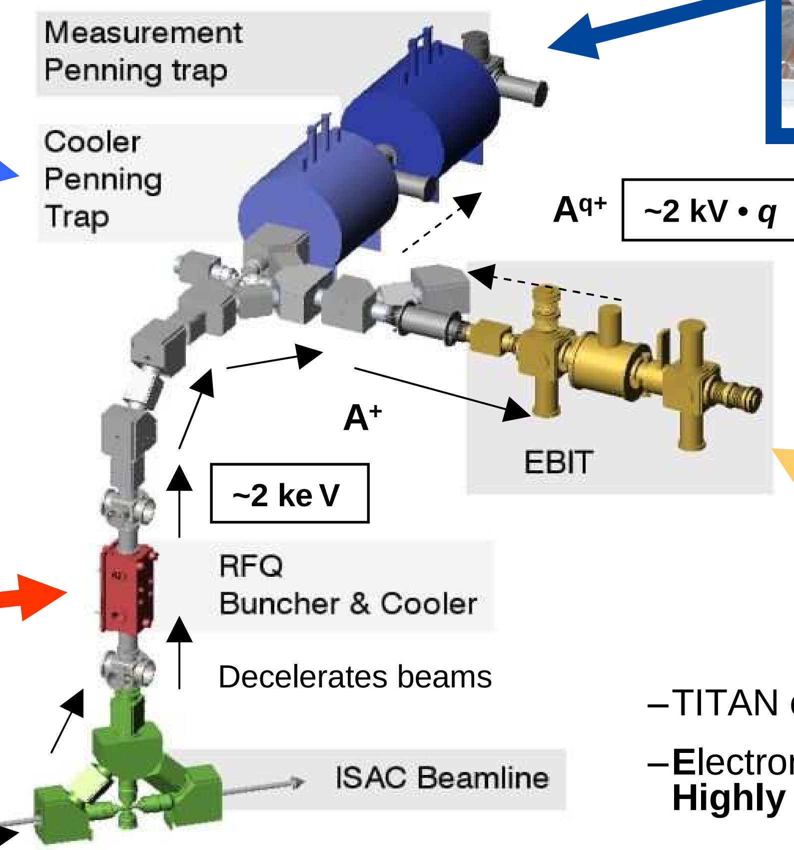
What is TITAN ?

TRIUMF's **I**on **T**rap for **A**tomic & **N**uclear Physics

- Facility to perform **high-precision atomic mass measurements.**
- **Main motivations:** Mass measurements on **short-lived isotopes** (level of precision: $\Delta m/m<10^{-8}$)



Under construction: Installation planned for Dec. 2009

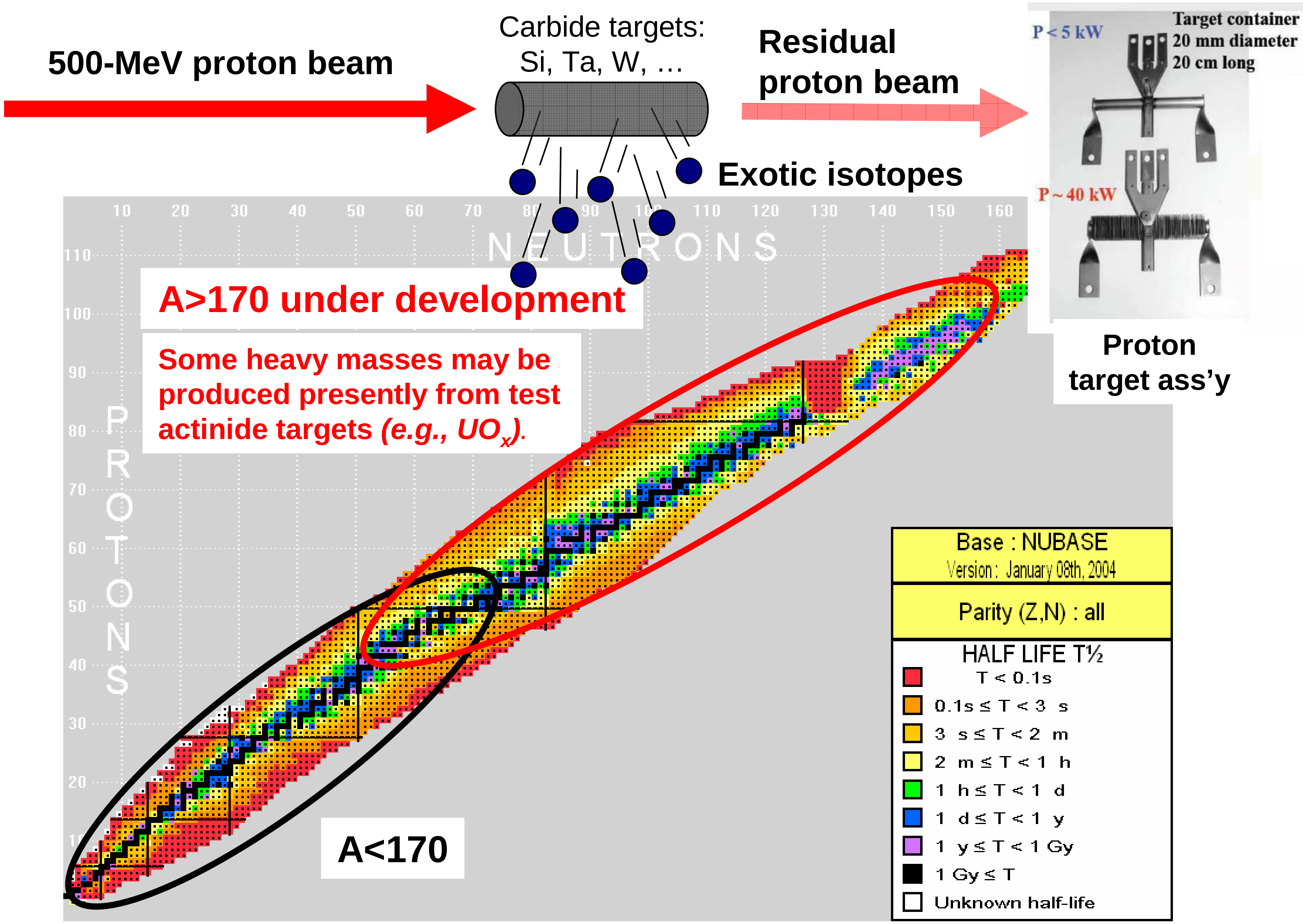


~20 - ~60 keV A+

- TITAN composed of **3 ion traps** *(presently)*
- **E**lectron **B**eam **I**on **T**rap (**EBIT**): Produces **Highly Charge Ions**

Radioactive isotopes from an **ISOL** facility (TRIUMF ISAC).

Production of Radioactive Isotopes → ISOL



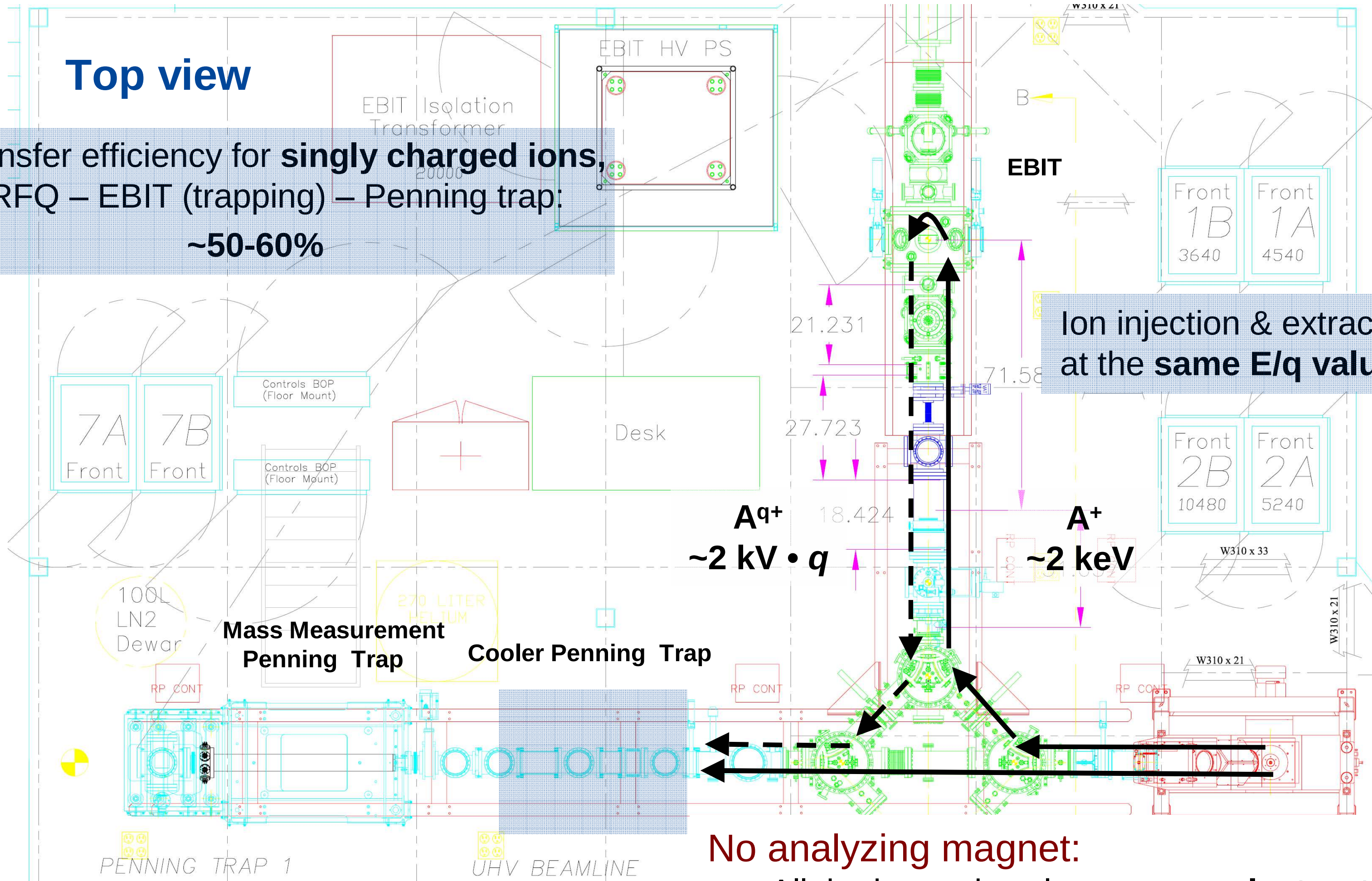
TITAN Facility

Ion beams from the RFQ can be sent to the Penning trap or the EBIT.

Top view

Transfer efficiency for **singly charged ions,** RFQ – EBIT (trapping) – Penning trap:

~50-60%



Ion injection & extraction at the **same E/q value**

No analyzing magnet:

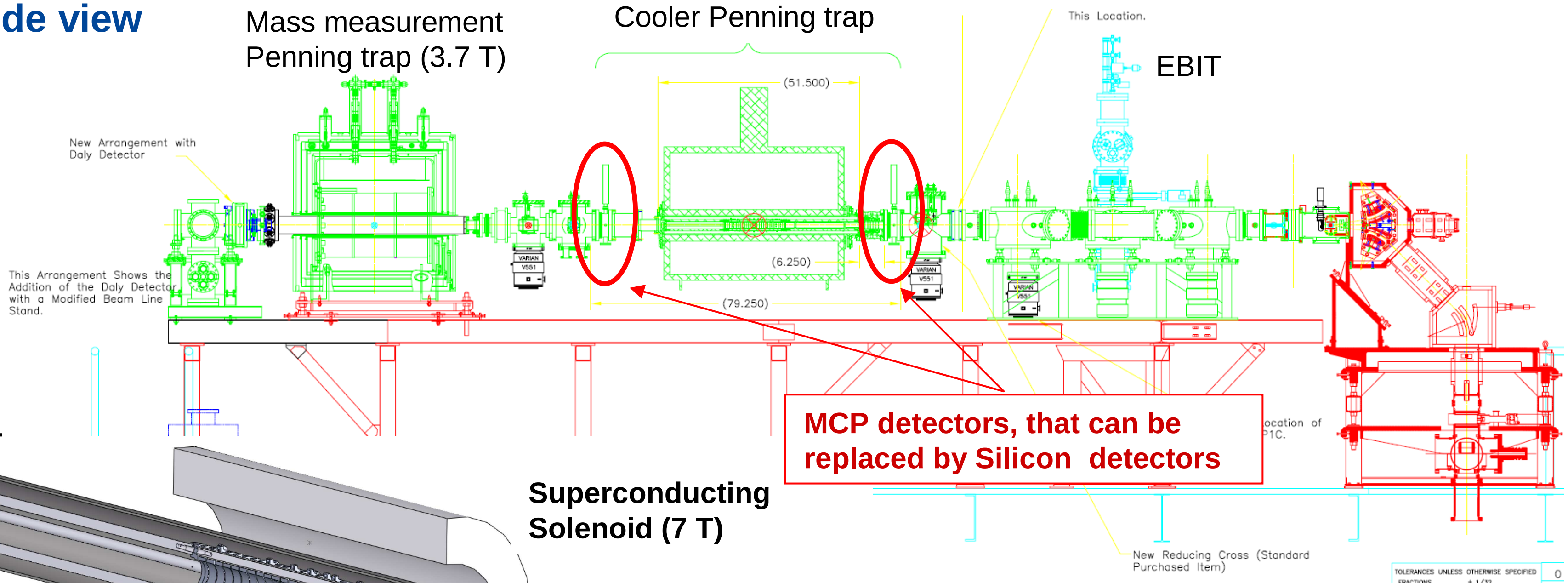
– All the ion optics elements are **electrostatic.**

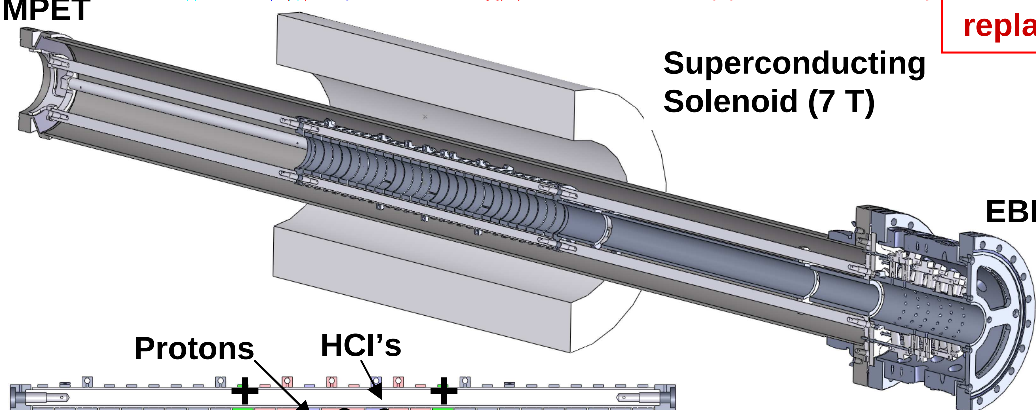
– Different **m/q ratios resolved by time of flight.**

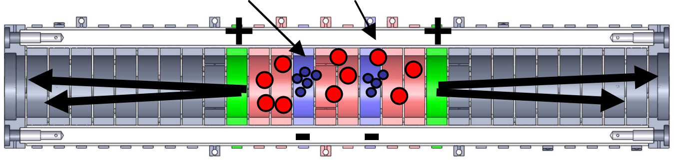
Cooler Penning Trap

Main purpose: Increase the precision of measurements by phase-space cooling HCI's with low-energy *protons* or *electrons* to 1 eV/q prior to mass measurements.

Side view







β or α guided out of the trap by trap magnetic field

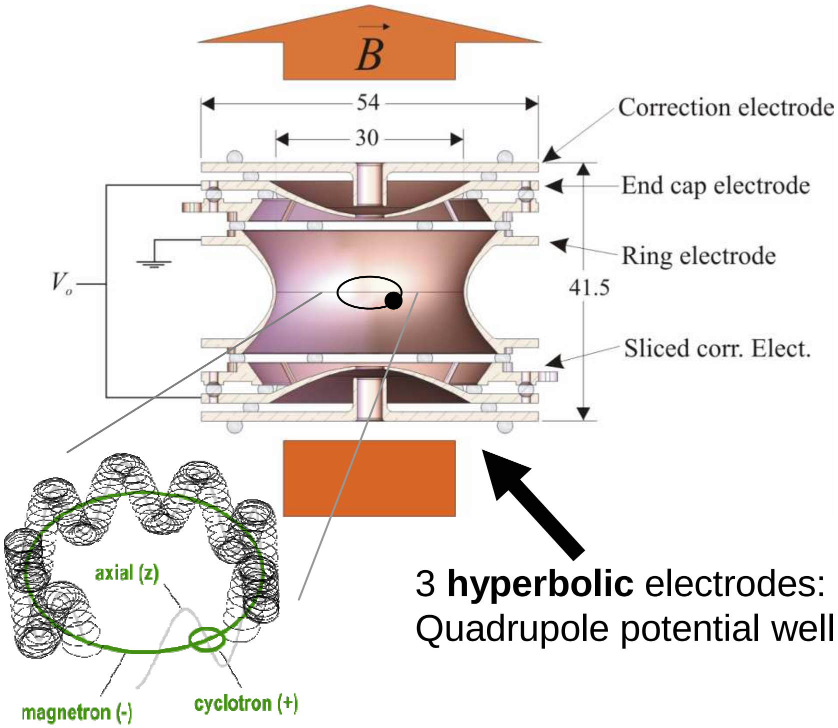
Nested Penning trap: Coaxial cylindrical trapping electrodes

Singly or highly charged ions can be trapped → **In-trap decay spectroscopy**

- Look for β's or α's produced in the decay of trapped radioactive isotopes.
- After RF cleaning, extract the daughters of decaying mother ions.

High-Precision Mass Measurements

Hyperbolic Penning trap



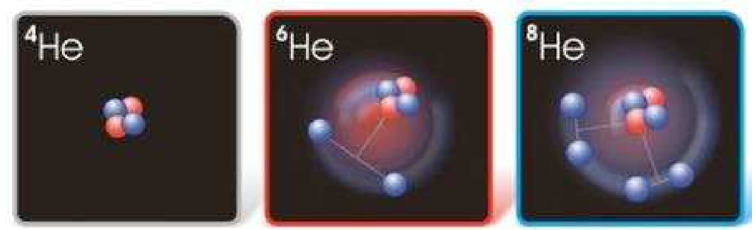
3 **hyperbolic** electrodes:
Quadrupole potential well

The TITAN Penning trap system is now operational

Mass of Halo nuclei

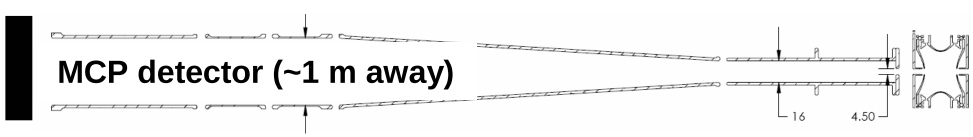
(nuclei with orbiting valence nucleons)

He-6	6.01888587(72) u
He-8	8.03393440(16) u
Li-11	11.04372361(69) u
Be-11	11.02166155(62) u



Time-**O**f-**F**light **I**on **C**yclotron **R**esonance:

- TOF of ions extracted onto a MCP after RF excitation of ion motions @ the ion cyclotron frequency.



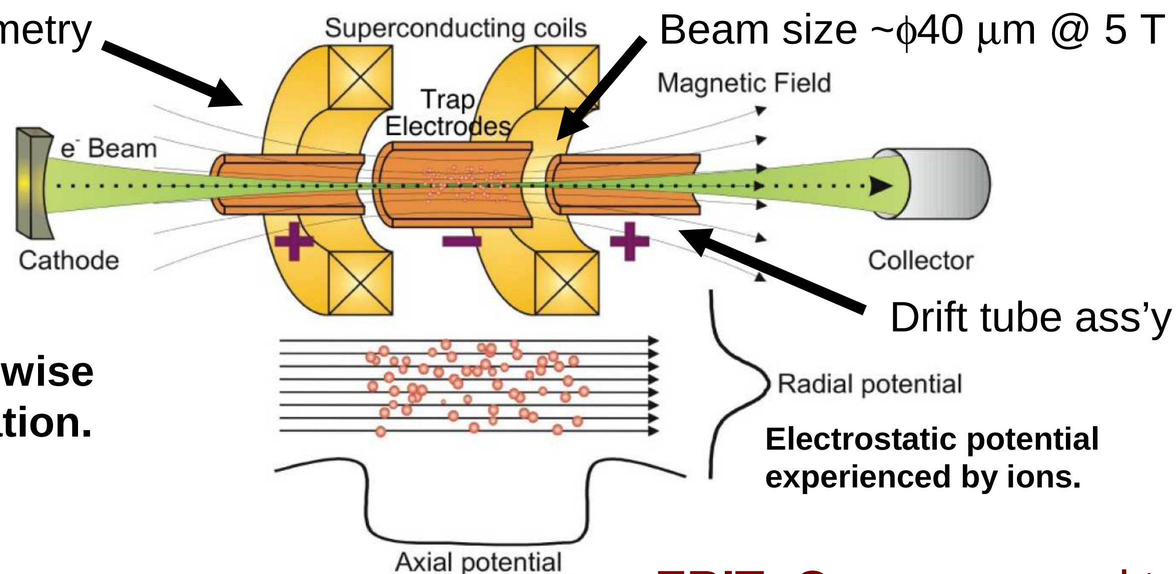
Singly or highly charged ions can be trapped → **In-trap decay spectroscopy:**

- β's or α's guided by the magnetic field & detected by a silicon detector out of the trap.
- Extract the daughters of decaying mother ions after RF cleaning (mother).

What is an Electron Beam Ion Trap ?

An EBIT is and Ion trap that…

– **Produces & traps highly charged ions (HCI's)** with of a high-current density electron beam**.**



HCIs produced by sepwise electron-impact ionization.

Ions are trapped:

Axially (B-field axis)

1) Electrostatic potentials to drift tubes *(quadrupole potential. well).*

Radially

1) Electron beam space charge potential.
2) Axial magnetic field (HCI's trapped with no electron beam for ~sec's)

EBIT: Open-accessed trap for spectroscopy**:**

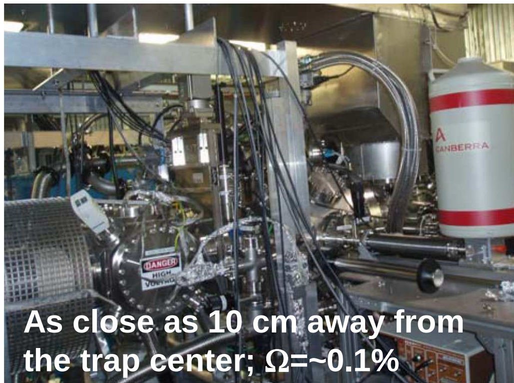
– X-ray spectroscopy
– Visible spectroscopy
– Electron capture recombination

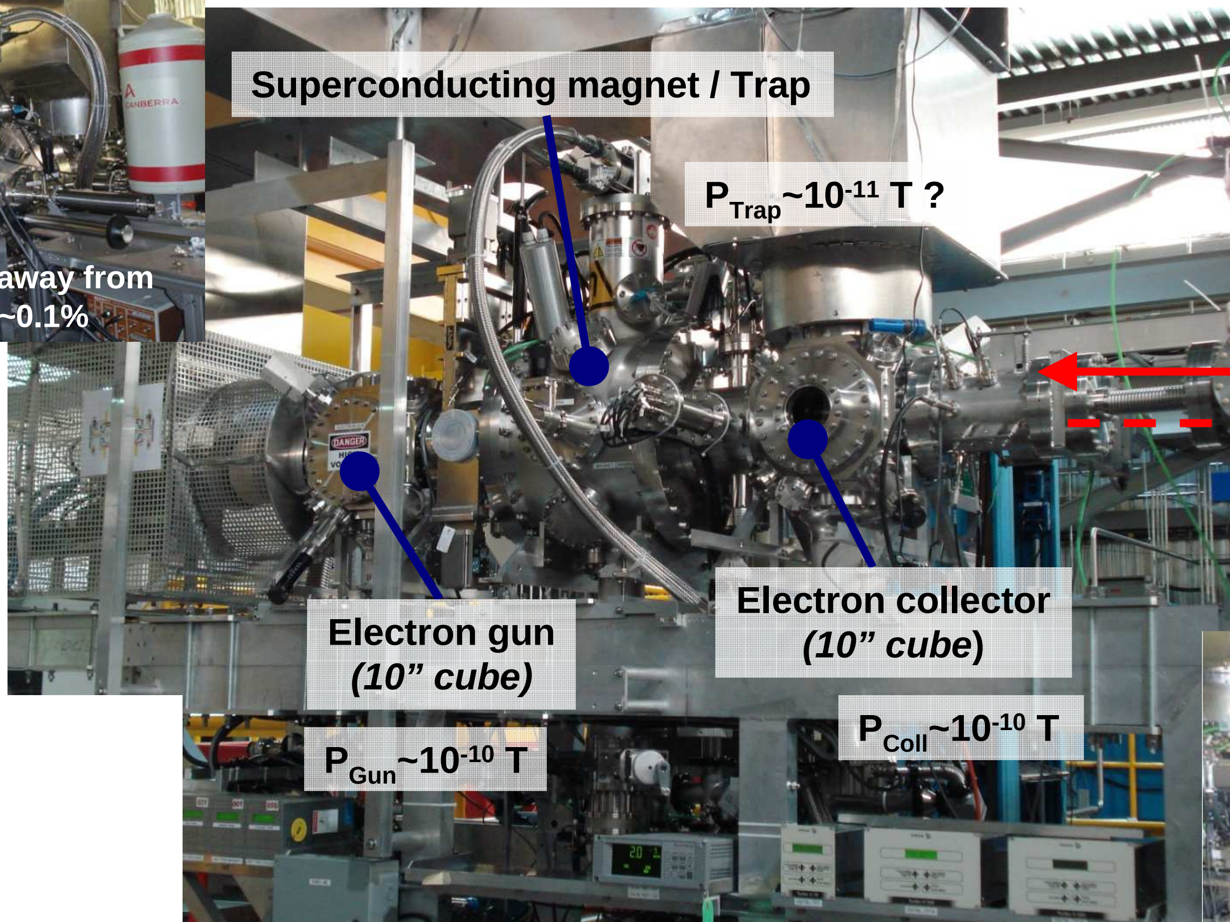
In-trap decay spectroscopy of radioactive ions

TITAN EBIT

Twin of the **FLASH EBIT** *(next talk; built at the MPI-K)*

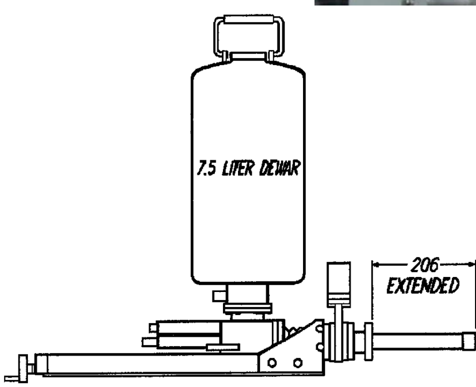
LeGe X-ray detector
~ 3 – 100 keV





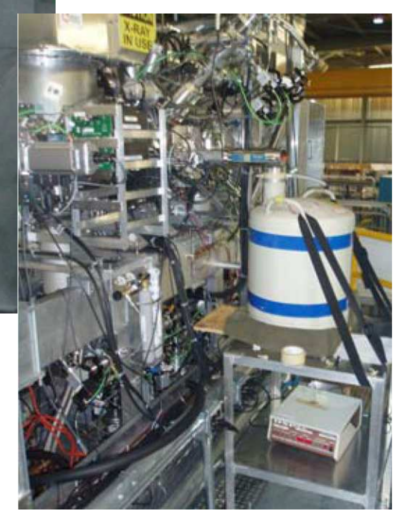
A^+
Injection
~ 2 keV

A^{q+}
Extraction
~ 2 kV_{Ext} x q



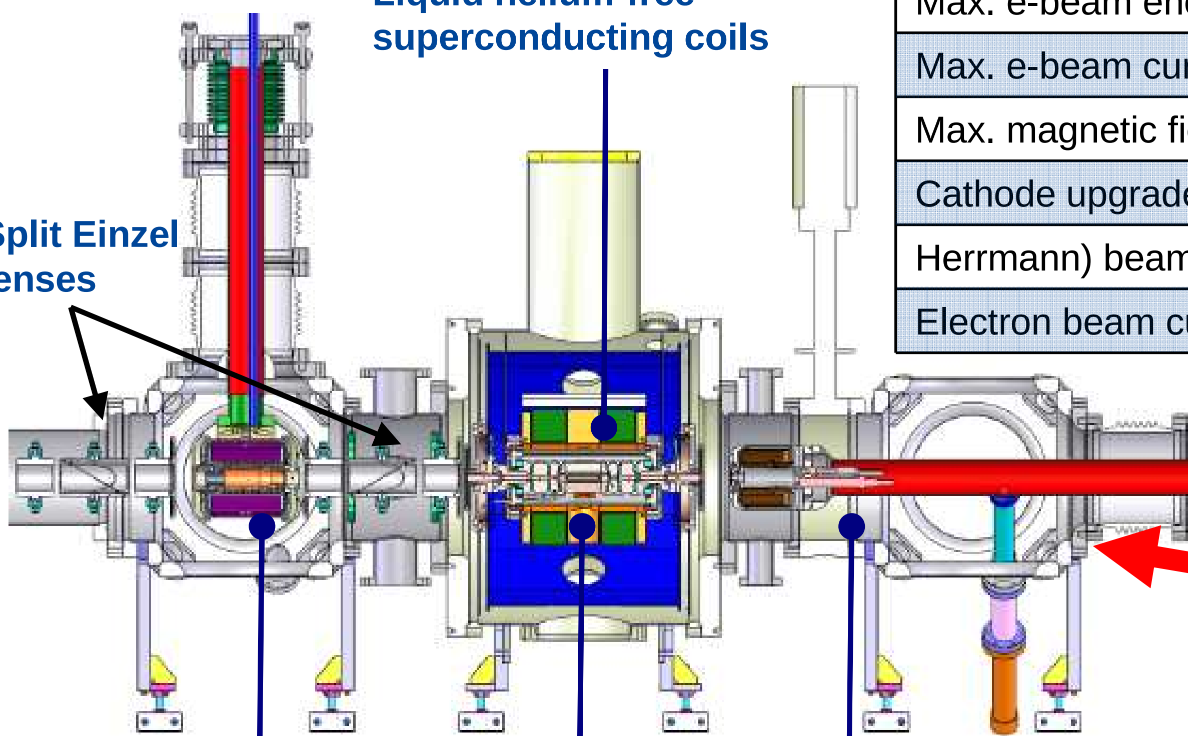
2.5 m

Coaxial Ge X-ray detector
~ 5 – 300 keV



TRIUMF

Rendered Cut of the TITAN EBIT



Design values

Max. e-beam energy	~70 keV
Max. e-beam current	500 mA
Max. magnetic field strength	6 T
Cathode upgrades	1 A & **5 A**
Herrmann) beam diameter (FWHM)	~40 µm
Electron beam current density	~10^5 A/cm^2

The gun & collector must be biased at high voltages to reach high electron beam energies.

Number of trapped ions: 10^6-10^8

Electron number density: ~5x10^{22} e/cm^2/s

Beam energy spread: ~50 eV

Highest charge state: ~ He-like U^{90+}

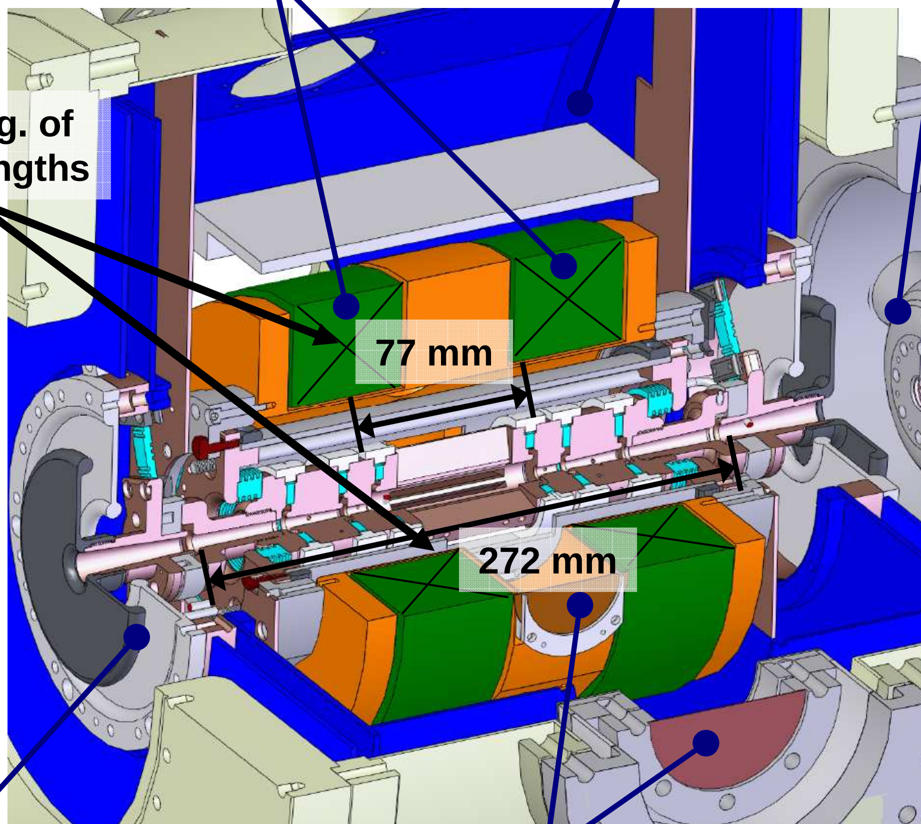
The Trap

Superconducting coils (Nb_3Sn) @ ~4 K

Thermal shield @ ~30 K

Electron gun

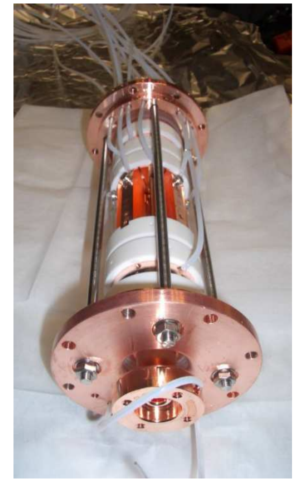
Trap config. of various lengths



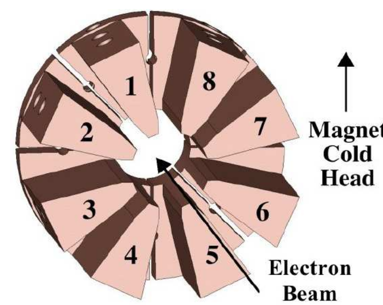
9 cylindrical drift tubes

Be windows

7 access viewports for spectroscopy



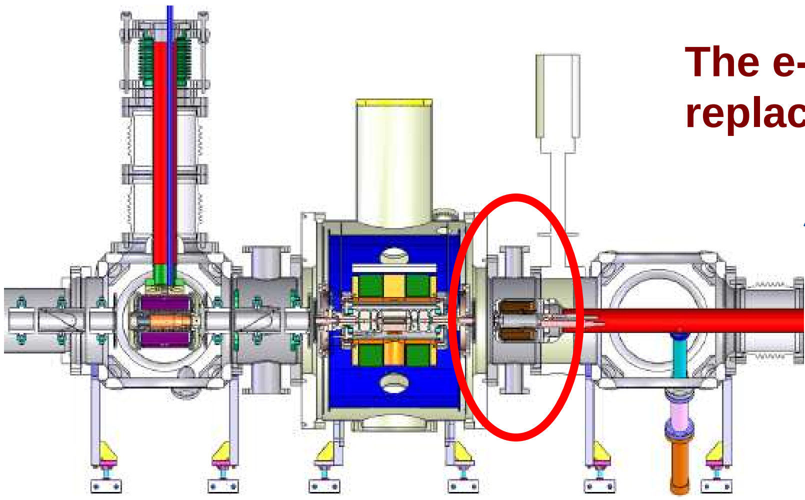
TITAN-EBIT special feature



8-fold segmented central drift tube:

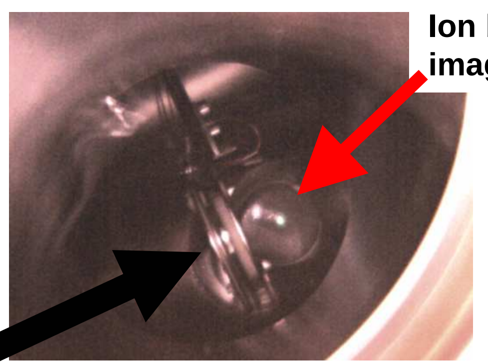
- Clean ion contaminants with RF field.
- Study the trap content by **I**on **C**yclotron **R**esonance.

Retractable Electron Gun



The e-gun can be replaced by detectors.

Silicon detector for β or α-decay measurements



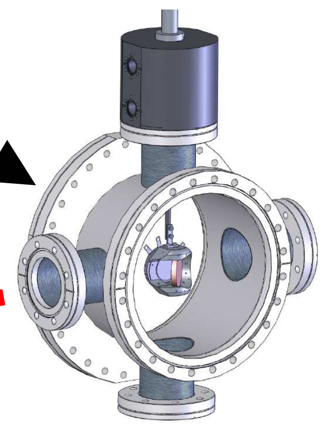
Ion beam image

Li-ion beam **Radius: ~1.5mm**

MCP w/ phosphor screen placed between the trap & electron gun for alignment of singly charged ion beams (injection).

Ion beam

Ion beam image from a mirror



Back view

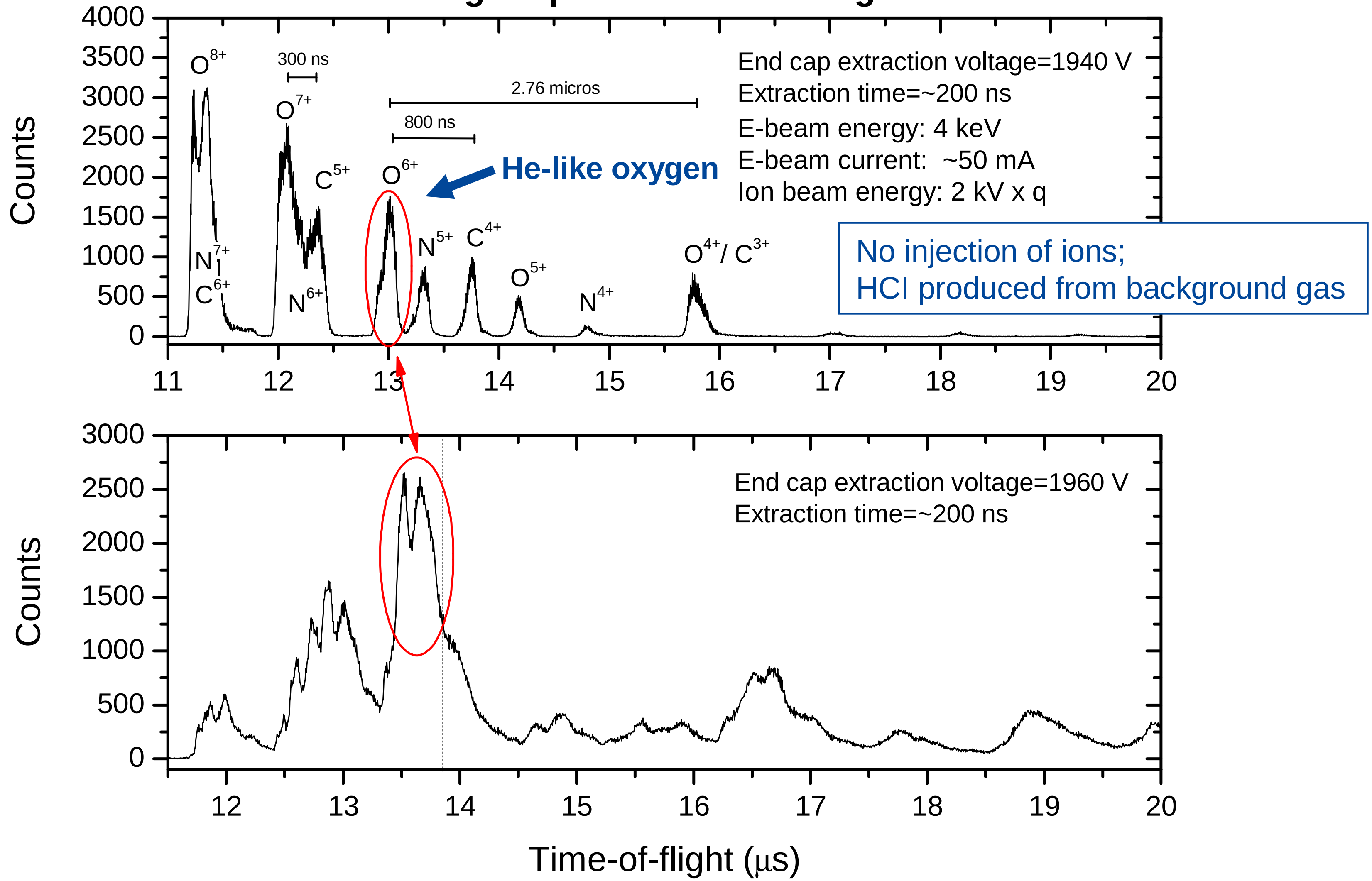
Front view

MCP w/ phosphor screen to have an image injected beams with a CCD camera.

Charge Breeding & Extraction

Since Nov. 2008, we can extract HCI’s from the EBIT…

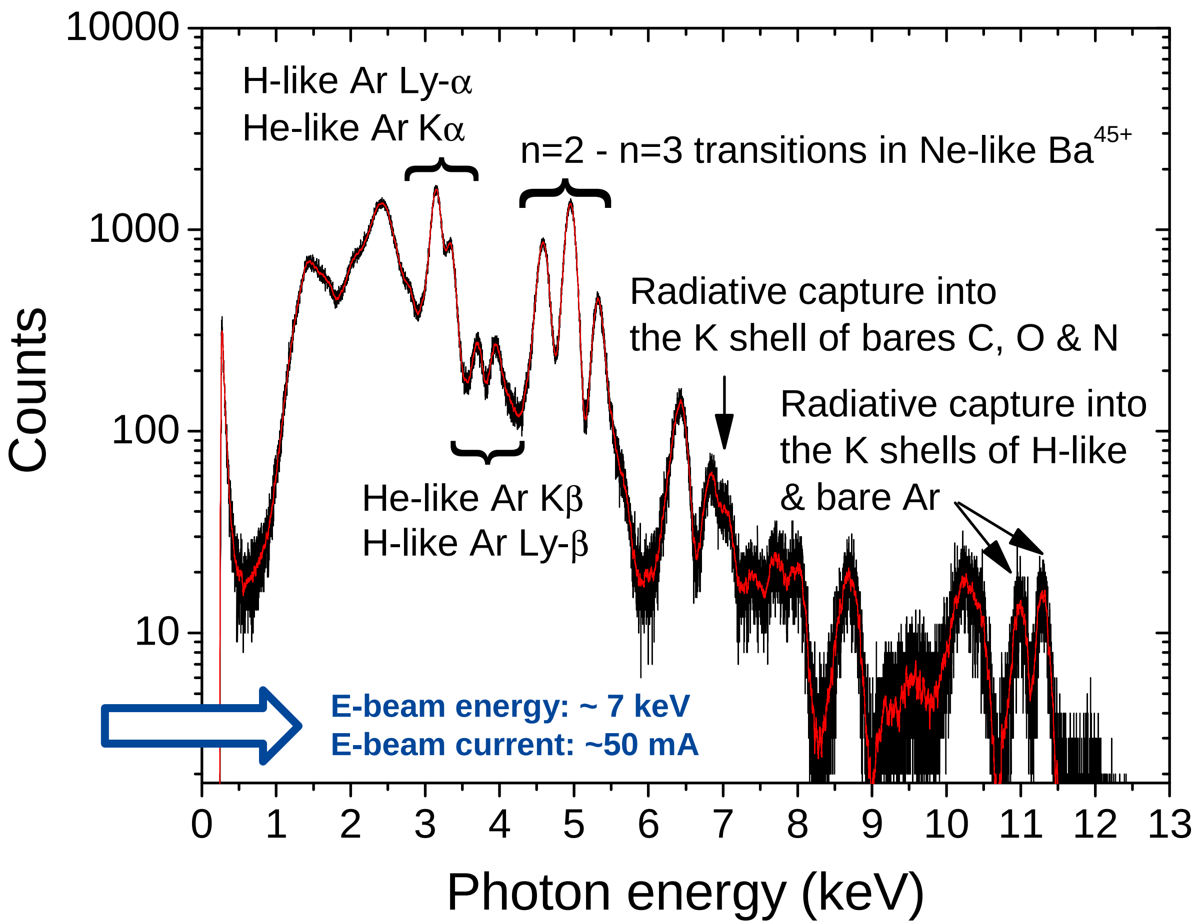
Time-of-flight spectra of residual gas ions



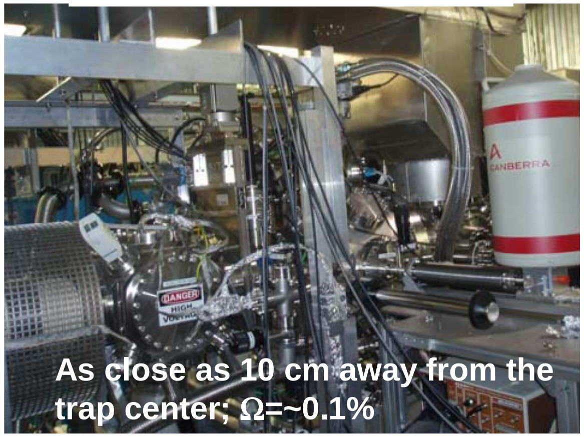
X-ray Spectroscopy

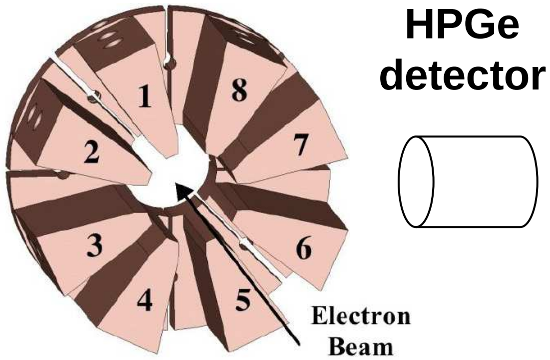
The geometry of the coils (*Helmholtz*) allows visible access to trapped ions for spectroscopy.

X-ray spectrum of residual gas ions



LeGe X-ray detector

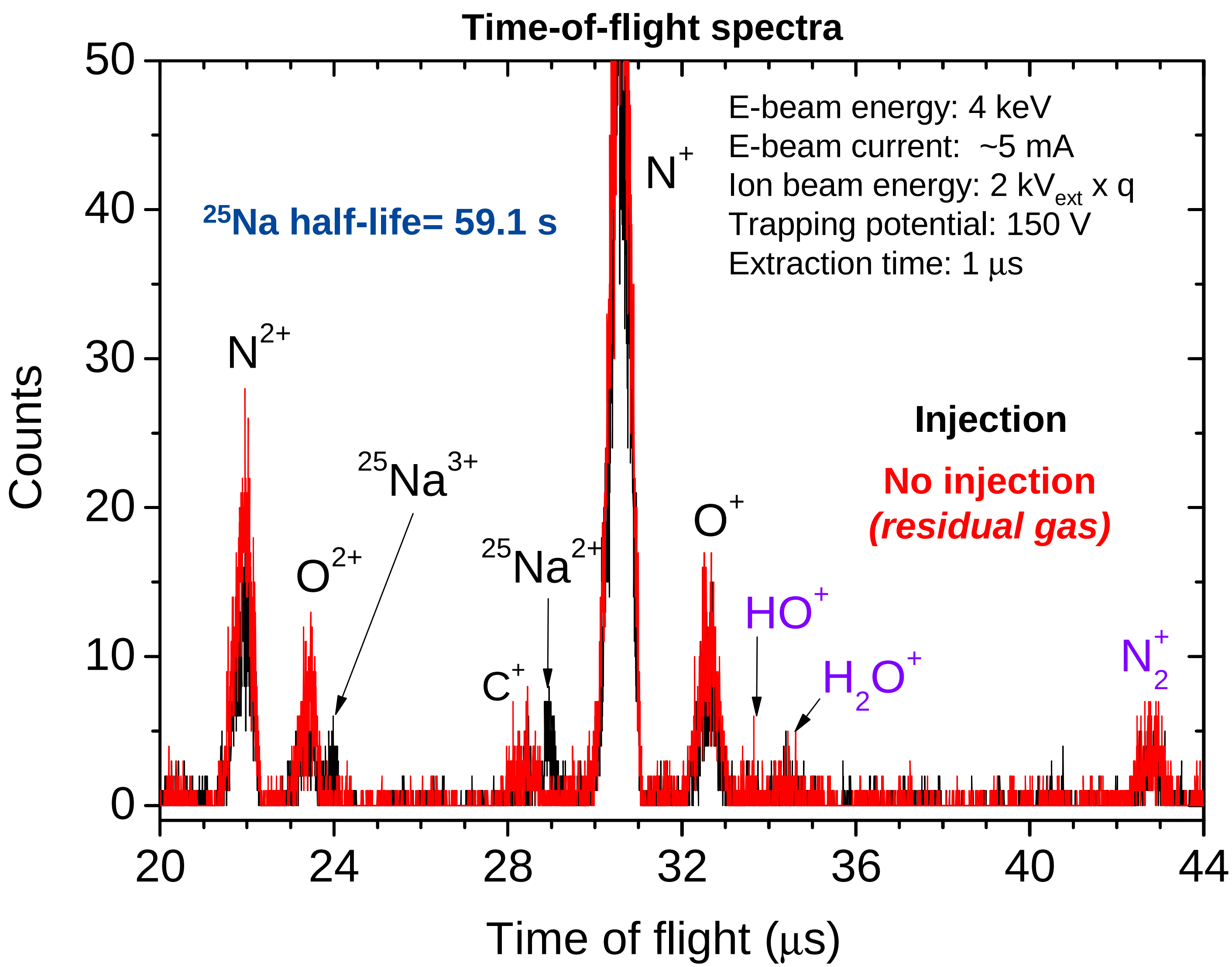




HPGe detector

Charge Breeding of a Radioactive Isotope

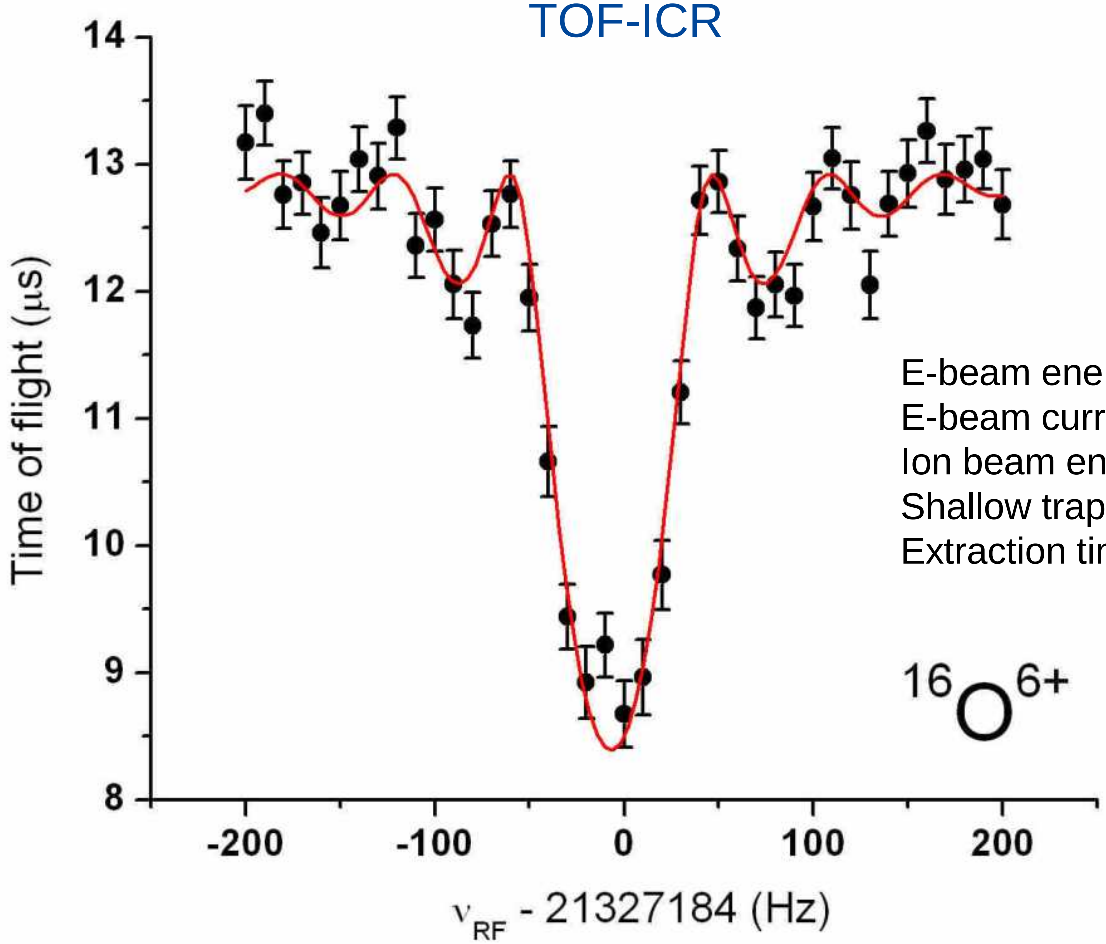
In April 2009, injected & charge bred our first radioactive ion (Na-25) into the EBIT



Mass Measurement of a HCI

He-like O^{6+} mass measurement with the TITAN Penning trap

TOF-ICR



E-beam energy: 4 keV
E-beam current: ~50 mA
Ion beam energy: 2 kV x q= 12 keV
Shallow trapping potential: 150 V
Extraction time: 200 ns

$^{16}O^{6+}$

Prospects of Experiments with Radioactive Highly Charged Ions

Outline

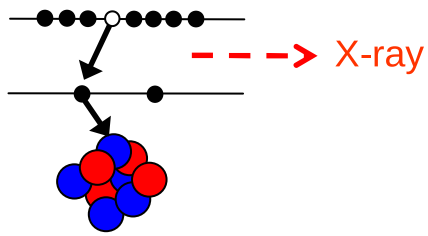
- Results of nuclear-decay electron capture measurements in singly charged ions
- Measuring the energy of the 7.5 eV Th-229 isomer
- Nuclear Excitation by Electron Capture (NEEC)

EBIT with NO Electron Beam

Program @ TITAN: Electron Capture Branching Ratio Measurements in *Singly Charged Ions*

Nuclear-decay Electron Capture (EC):

$$p + e^- \rightarrow n + \nu_e$$



After EC, the daughter emits X-rays, as a result of decays of electrons filling shell vacancies.

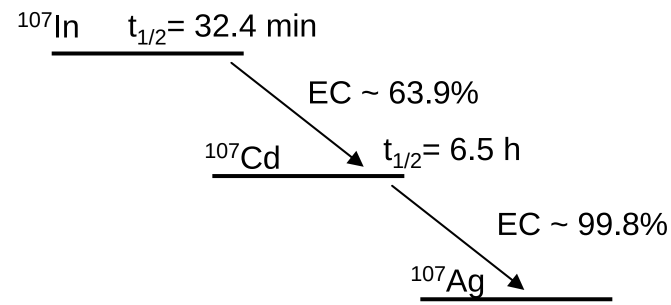
EC-BR measured from **X-ray yields**.

- EC-BR used to evaluate ββ- and 0νββ-decay nuclear matrix elements *(benchmark theory).*
- If 0νββ decay is observed, such matrix elements can be used to infer the **neutrino mass**.

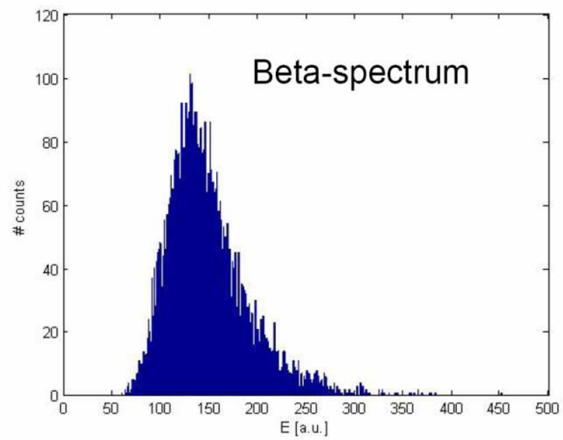
Candidates for EC-BR measurements:

^{82m}Br→^{82}Se, ^{110}Ag→^{110}Pd, **^{100}Tc (EC: 0.003%)→^{100}Mo**

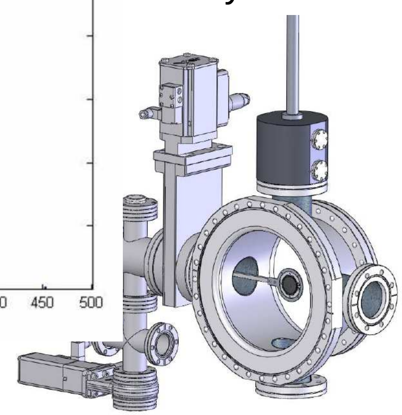
Proof-of-principle experiment: ^{107}In



β's from implanted ions on an Al foil in front of the Si det.

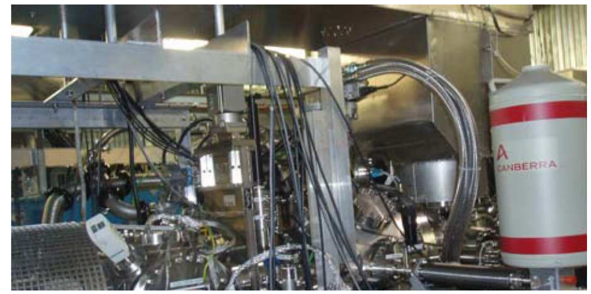


Replaced the gun by silicon detector for β-decay measurements

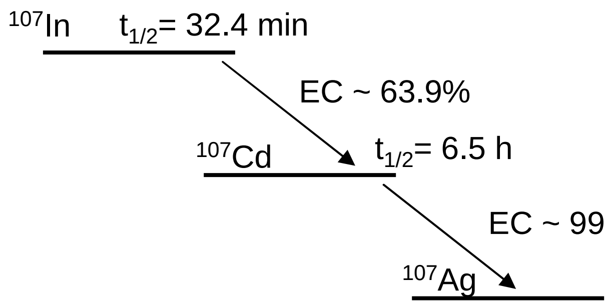


EBIT with NO Electron Beam

LEGe X-ray detector (~0.02% solid angle)



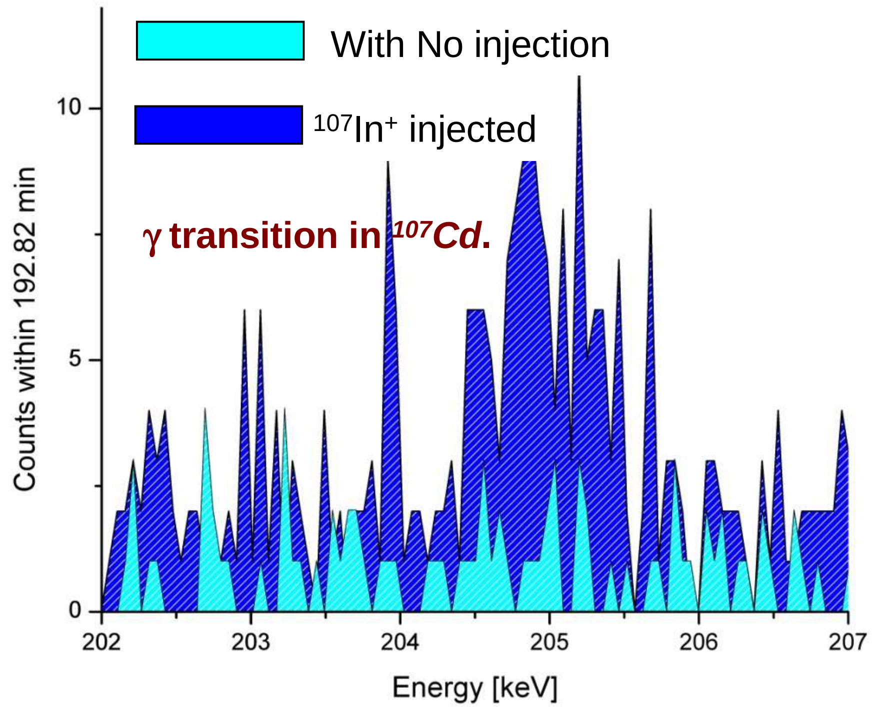
Proof-of-principle experiment: ^{107}In



What we expect to see in X-ray spectra:
→ K_α & K_β lines in ^{107}Cd.

Ground state decay X-rays from EC (64%):

	Energy (keV)	Intensity (%)
XR l	3.13	3.92 % 17
XR kα2	22.984	14.1 % 7
XR kα1	23.174	26.4 % 13
XR kβ3	26.06	2.29 % 11
XR kβ1	26.095	4.41 % 21
XR kβ2	26.644	1.14 % 6

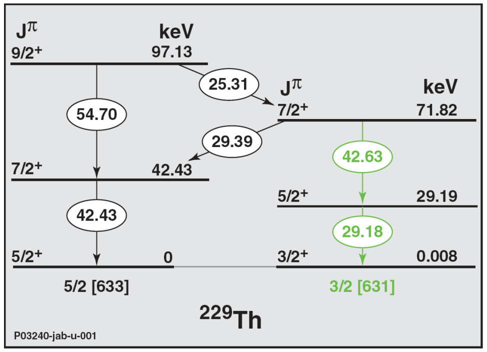


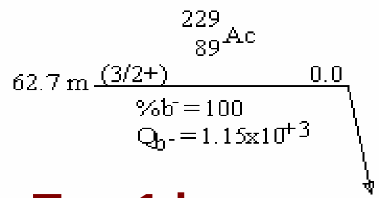
Low-Energy ^{229}Th Isomer

^{229}Th isomer measured @ 7.5 eV ± 1 eV (*talks tomorrow*)
Beck *et al.* PRL 98 142501 (2007)

Lifetime of the isomer (*neutral* atom) calculated ~10 μs
Karpeshin & Trzhaskovskaya PRC 76 054313 (2007)

We could measure precisely the isomer energy with EBIT!





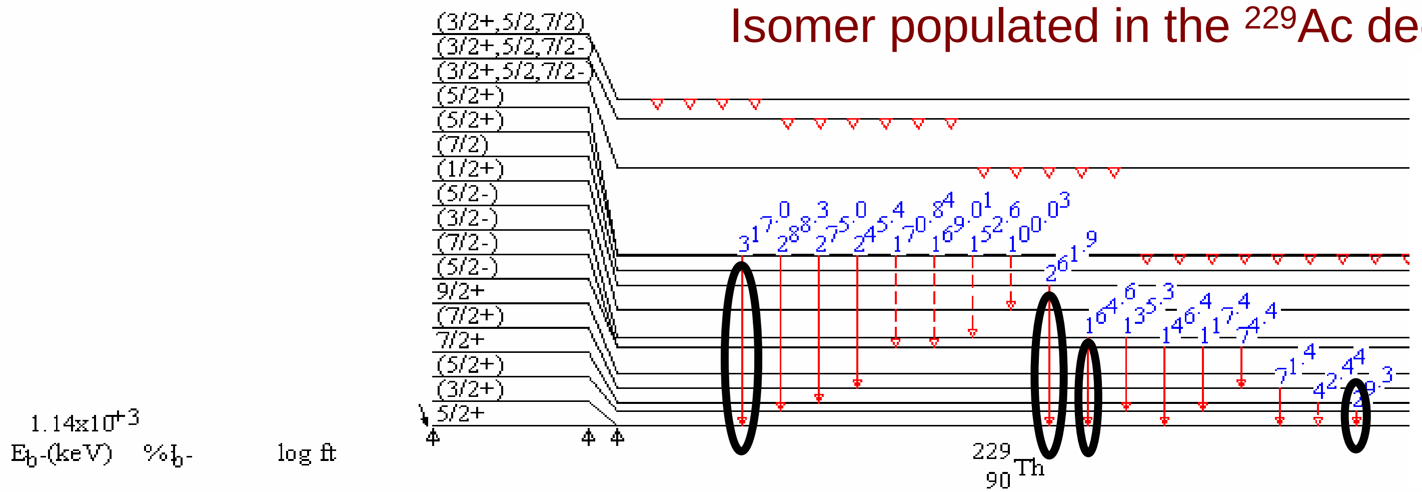
$T_{1/2}$~1 hour

PROBLEM: Isomer would decay in the ISOL target before being extracted → **Diffusion time ~ ms – s**

SOLUTION: Produce & Trap *singly charged* ^{229}Ac

^{229}Ac decays to ^{229}Th by β- decay

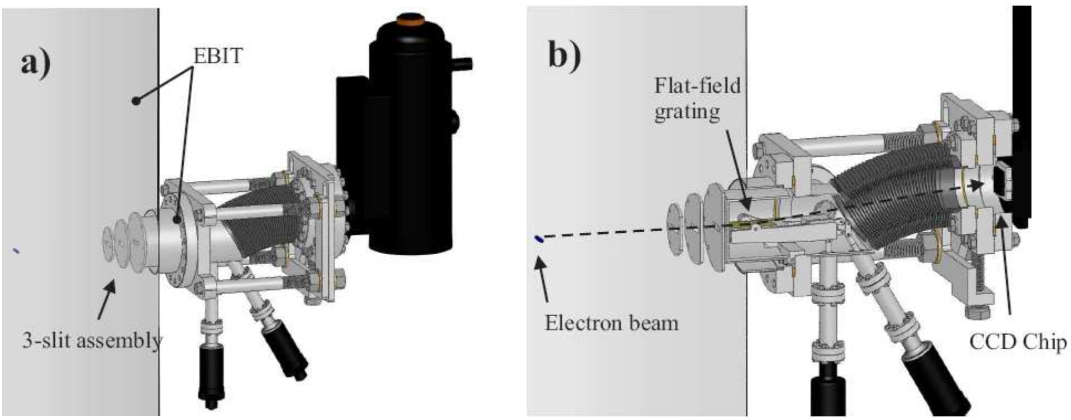
Isomer populated in the ^{229}Ac decay.

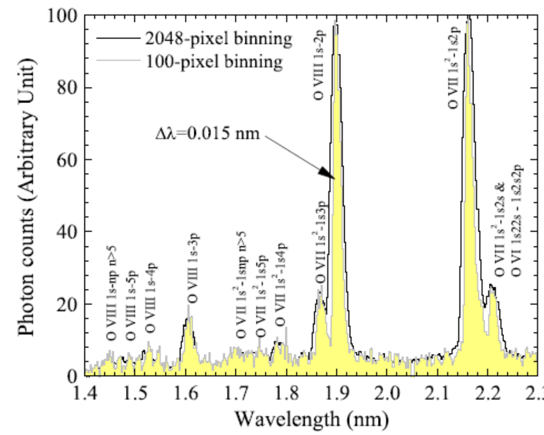


Some γ transitions populating the isomer…

Low-Energy ^{229}Th Isomer

Vacuum ultraviolet (VUV) spectroscopy of singly charged ^{229}Th





Relative precision ΔE/E<0.01 → ~0.1 eV out of 7.5 eV ?

The lifetime of the isomer in HCI's *(hyperfine quenching)*

TABLE I. Energies of the hfs levels and mean lifetimes of the $M1$ transitions to the $F=2$ (low) state and to the $F=3$ state (in brackets) for $E_{isom}=10$ eV, and for three charge states of the ^{229}Th ion.

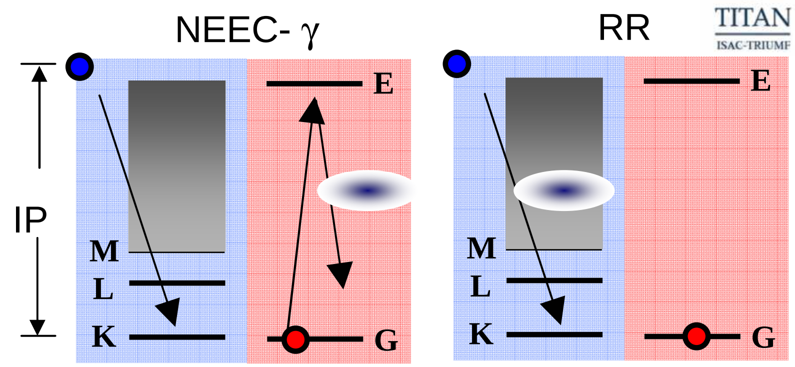
Ions		H-like		Li-like		Na-like	
State	F	E_F (eV)	τ (s)	E_F (eV)	τ (s)	E_F (eV)	τ (s)
$\|4\rangle$	1	10.12	0.010	10.02	0.72	10.004	8.3
$\|3\rangle$	2upp	9.96	0.007	9.99	0.44	9.997	5.0
			(0.010)		(0.54)		(6.0)
$\|2\rangle$	3	0.39	0.065	0.05	36.5	0.015	1.4×10^3
$\|1\rangle$	2low	−0.58		−0.07		−0.020	

K. Pachucki et al. PRC 64, 064301 (2001)

Nuclear Excitation by Electron Capture

NEEC

- Free electron is captured into electronic bound state & a nuclear state is simultaneously excited.
- Nuclear state de-excites by IC or γ emission.
- Best atomic systems to observe NEEC are HCI's; nuclear transitions are in the keV range.



$E_{nuclear} = E_{ebeam} + IP$

$E_{max\ cross\text{-}section} \sim 2.7\ IP$

$E_{max\ ebeam} \sim 75$ keV

$E_{nuclear} \leq 100$ keV

RR is ~10^4 more likely than NEEC !

Challenging to observe:

- **Weak resonance strengths ~10^{-26} cm^2 eV.**
- γ's masked by rad. recombination X-rays (same energy).
- IC electrons buried within the e-beam (same energy).

RR is observable in an EBIT, what about NEEC ?

E-beam current	**500 mA**	**5 A**
E-number density	5x10^{22} e/cm^2/s	5x10^{23} e/cm^2/s
He-like ions	~10^6	~10^7
Expected count rate	**~10 / min**	**~1000 / min ~ 17 / sec**

7 X-ray detectors → Ω ~ 2%

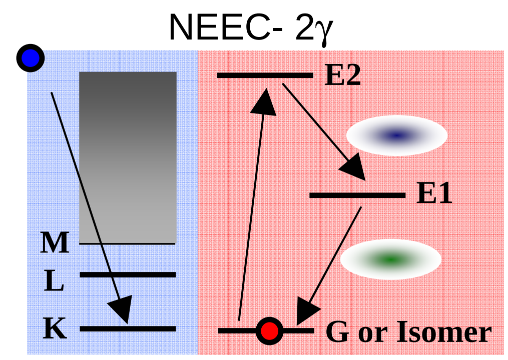
Nuclear Excitation by Electron Capture

TRIUMF

TITAN ISAC-TRIUMF

2-level systems are not ideal to observe NEEC

– **NEEC γ's are concealed by RR x-rays**



Best option: 3-level systems & detect γ's

– **Short-lived nuclear states → "Strong" strengths**

– Isomer excitation → "Weak" strengths *(small trans. probabilities to GS)*

– Exciting from an Isomer → Low production yields in the ISOL targets

3-level candidates with short-lived nuclear states: for capture into the L shell of He-like ions

Element	Z	Mass u	Nucleus Half-life	He-like IP keV	Li-like IP keV	Max. C-S keV	E-beam Energy keV	Upper Level keV	Half-life ns	Inter. Level keV	Half-life ns	Gamma_UtoI keV	Gamma_ItoG keV
Sm	62	151	90 y	52.73	13.26	35.80	52.57	65.83	0.4	4.82	35.00	61.01	4.821
Sm	62	151	90 y	52.73	13.26	35.80	56.44	69.70	0.5	4.82	35.00	64.88	4.821
Dy	66	161	Stable	60.33	15.23	41.11	28.60	43.82	0.83	25.65	29.10	18.15	25.65
Dy	66	161	Stable	60.33	15.23	41.11	59.34	74.57	3.14	25.65	29.10	48.91	25.65
Os	76	187	Stable	82.24	20.92	56.47	53.42	74.33	0.02	9.75	2.38	64.58	9.746
Os	76	187	Stable	82.24	20.92	56.47	54.13	75.04	0.02	9.75	2.38	65.29	9.746
Pt	78	187	2.35 h	87.15	22.20	59.94	52.37	74.57	0.5	9.27	1.00	65.30	9.27
Pt	78	187	2.35 h	87.15	22.20	59.94	52.37	74.57	0.5	25.54	0.70	49.03	25.54

Good!

We are looking for other candidates…

TRIUMF

Nuclear Excitation by Electron Capture

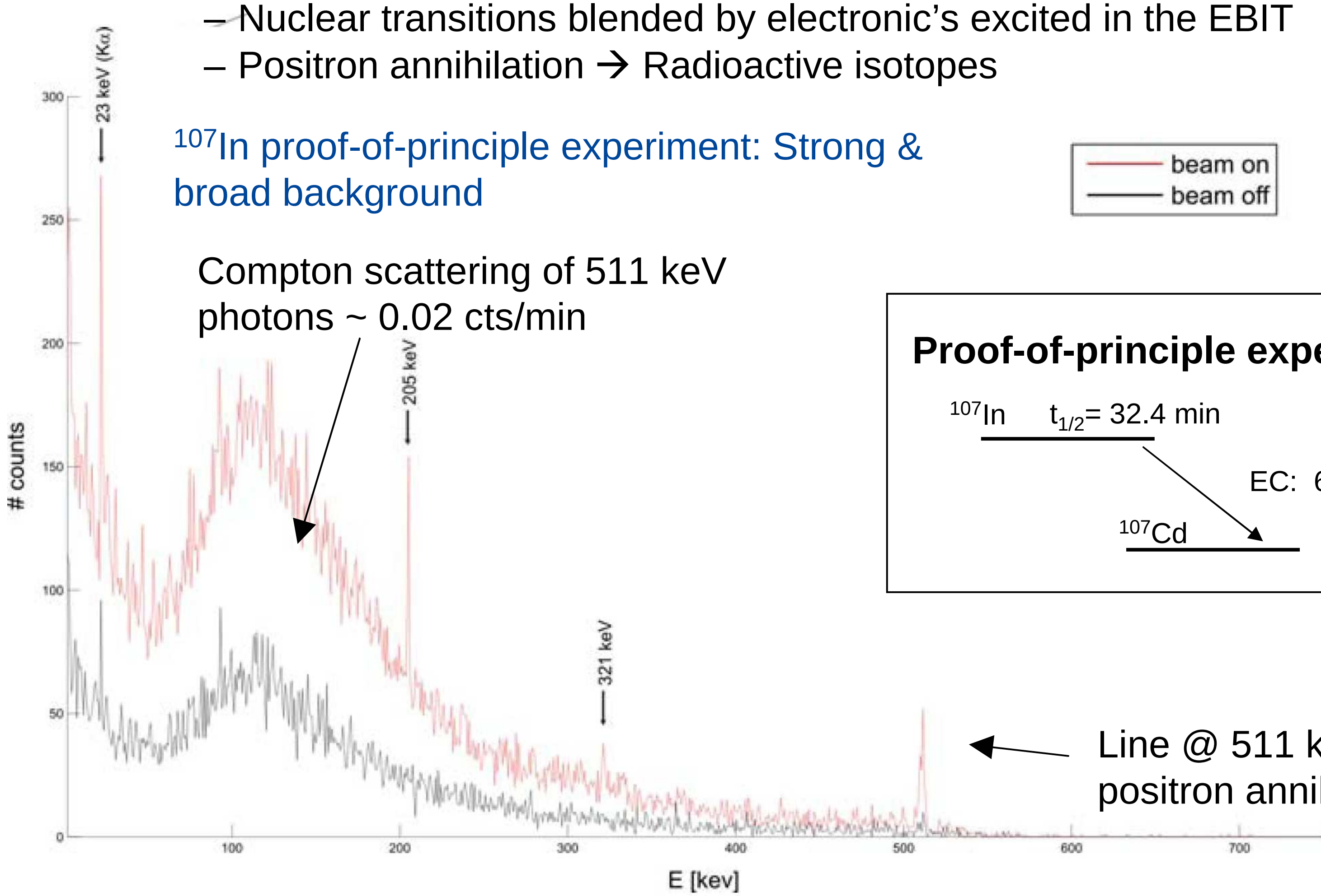
TITAN
ISAC-TRIUMF

A good candidate for NEEC must yield a low background level.

Sources of background:

– Nuclear transitions blended by electronic's excited in the EBIT
– Positron annihilation → Radioactive isotopes

^{107}In proof-of-principle experiment: Strong & broad background



Compton scattering of 511 keV photons ~ 0.02 cts/min

Line @ 511 keV: positron annihilation

Proof-of-principle experiment: ^{107}In

^{107}In $t_{1/2}$= 32.4 min

EC: 64% & β+: 36 %

^{107}Cd

Summary

- TITAN facility @ TRIUMF: High-precision mass measurements.
- 3 traps for in-trap decay spectroscopy of singly and highly charged radioactive ions.
- Observed nuclear-decay EC events in the EBIT with NO beam.
- Future opportunities with the EBIT:
  - Measure the energy (high precision) of the Th-229 isomer.
  - Observe NEEC (high current density & large solid angle).

Members / Collaborators

TITAN Group: Jens Dilling, Paul Delheij, Gerald Gwinner, Alain Lapierre, Maxime Brodeur, Thomas Brunner, Stephan Ettenauer, Aaron Gallant.

Former members: Chris Champagne, Ryan Ringle, Vladimir Ryjkov, Mathew Smith, Zunjian Ke,…

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- U. of Manitoba
- McGill U.
- Muenster U.
- MPI-K
- GANIL
- U. of Calgary
- U. of Windsor
- Colorado School of Mines
- UBC