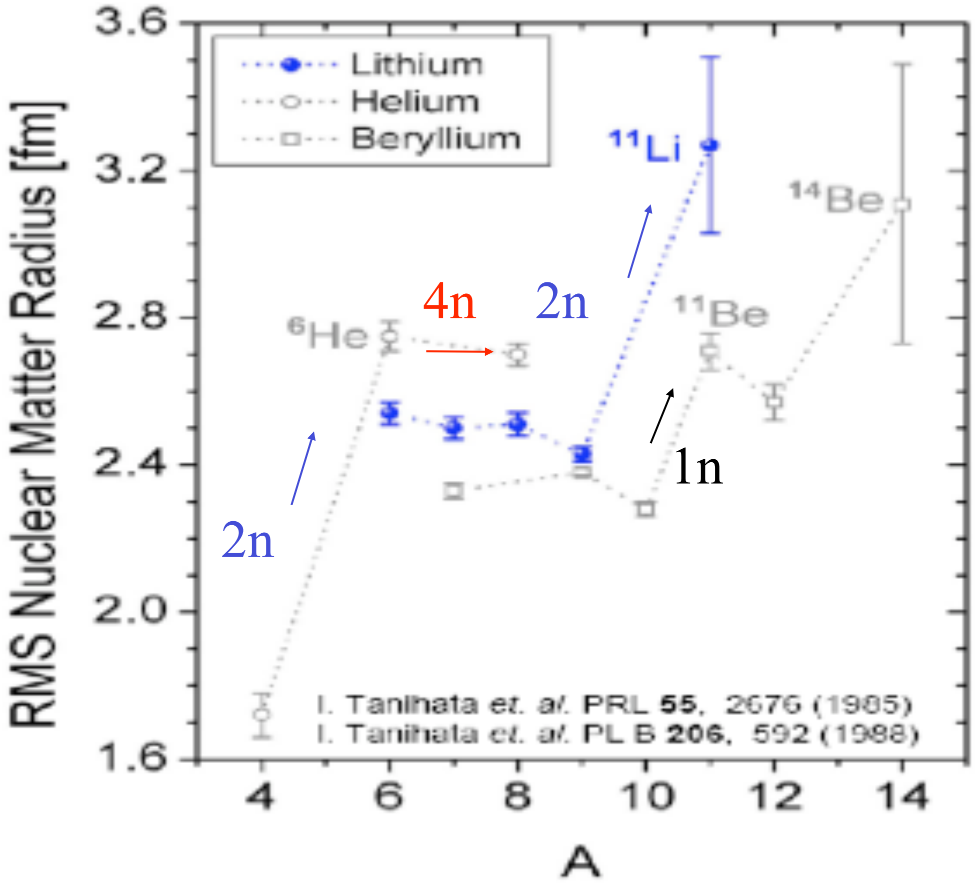
# Penning trap mass measurements of light, neutron-rich halo nuclei and recent developments at TITAN

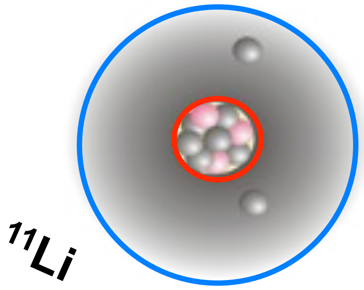
Ryan Ringle
RNB 8

# Properties of neutron halo nuclei



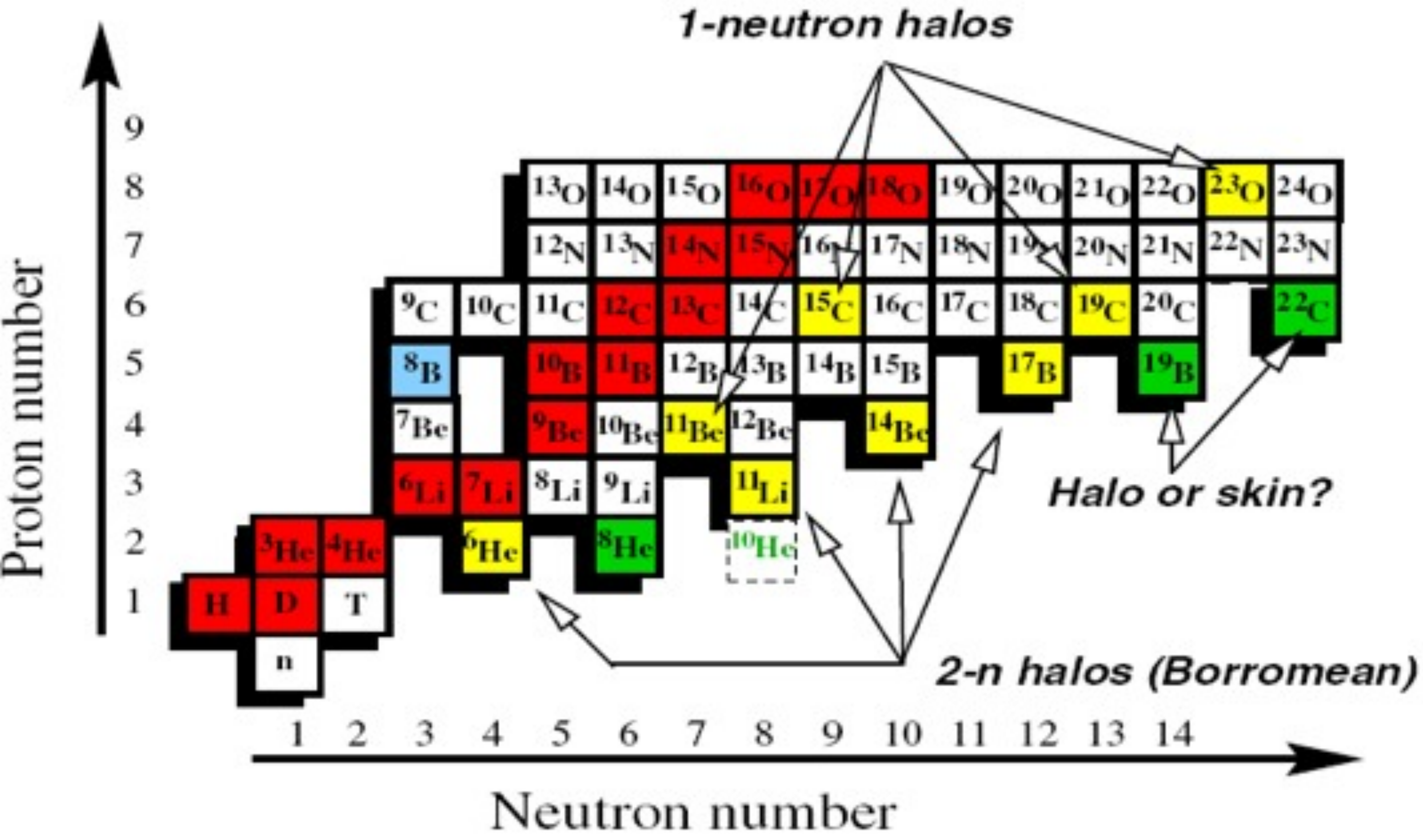
- very exotic (large n/p ratios)
- very large RMS matter distribution
- difference in matter and charge radii
- very small $S_n$ or $S_{2n}$

$^{11}$Li is a Borromean system



$^{9}$Li + n + n

Halo "=" $R_{Matter}$ - $R_{Charge}$



neutron halos occur along the drip line

→ half lives tend to be short

production tends to be low

$^{8}$He - 119 ms

$^{11}$Li - 8.8 ms

$^{14}$Be - 4.4 ms

Use the best tool for the job:

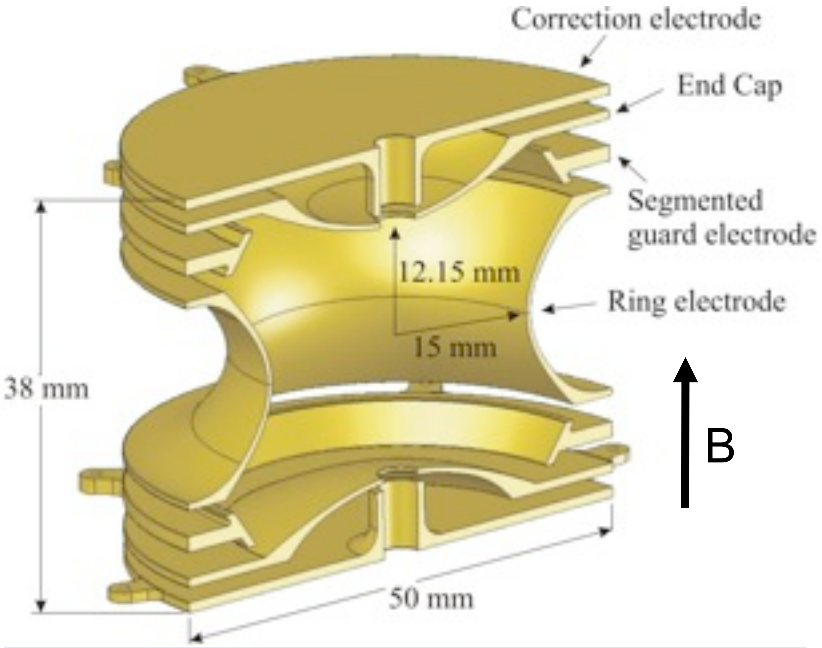
Penning traps

TITAN
ISAC•TRIUMF

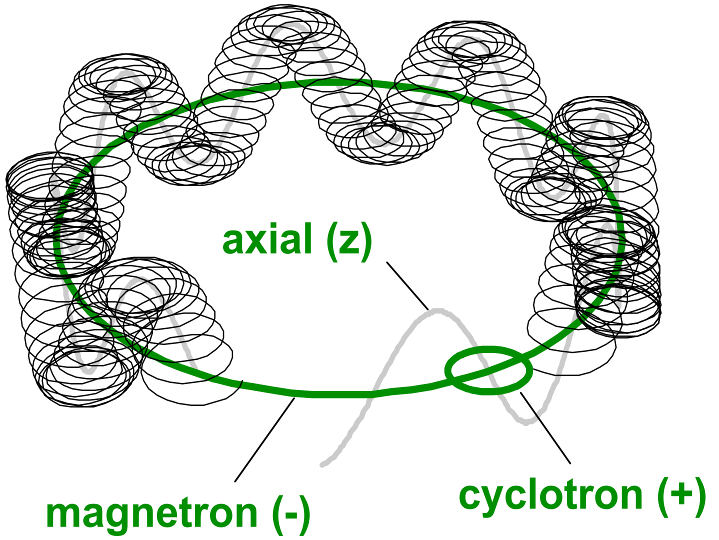
# Penning trap mass spectrometry of short-lived radioactive nuclides

Brown and Gabrielse, Rev. Mod. Phys. **58** (1986) 233

Bollen *et. al.*, J. Appl. Phys. **68** (1990) 4355



Linear Magnetic Field + Harmonic Electrostatic Potential



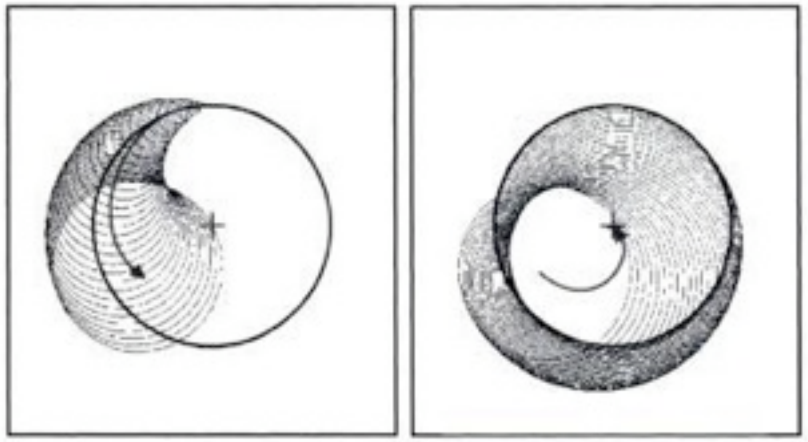
Three Harmonic Eigen-motions

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

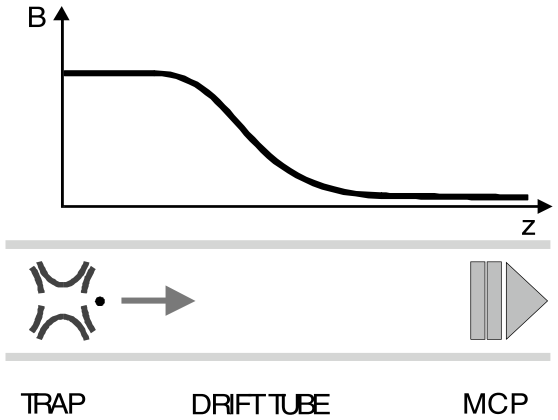
$$\omega_c = \frac{q}{m} B$$

$$\omega_+ >> \omega_-$$

The mass measurement is made by finding the true cyclotron frequency of the ion in the trap



Application of quadrupolar field converts magnetron motion into cyclotron motion

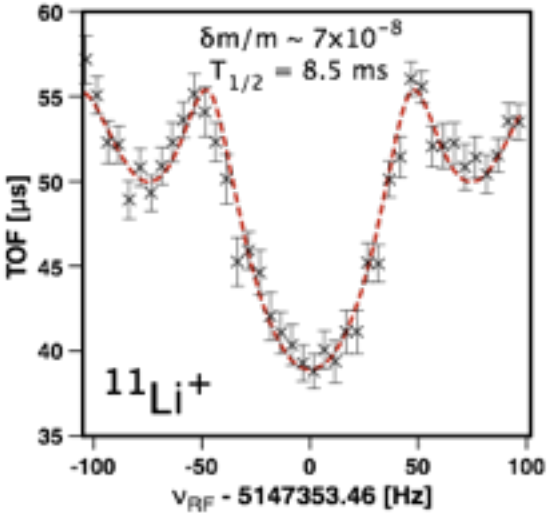


Extraction through magnetic field converts radial energy to longitudinal energy

Gräff *et. al.*, Z. Phys. A **297** (1980) 35

Bollen *et. al.*, J. Mod. Opt. **39** (1992) 257

König *et. al.*, IJMS **142** (1995) 95



Measurement of TOF gives cyclotron frequency and hence the mass

$$\frac{\delta m}{m} \propto \frac{m}{q T_{ex} B \sqrt{N}}$$

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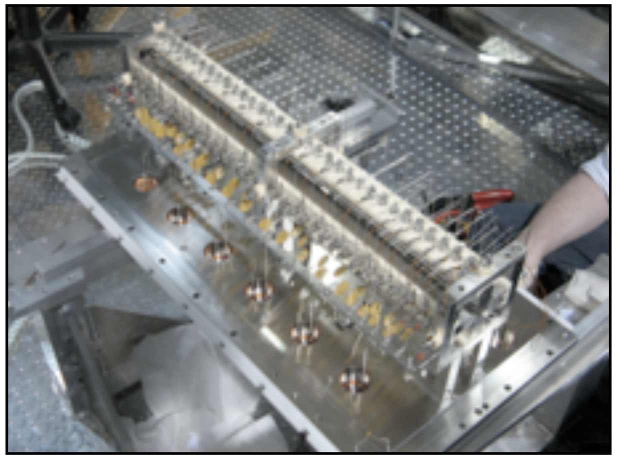
# The TITAN facility at ISAC

Dilling *et. al.*, IJMS **251** (2006) 198

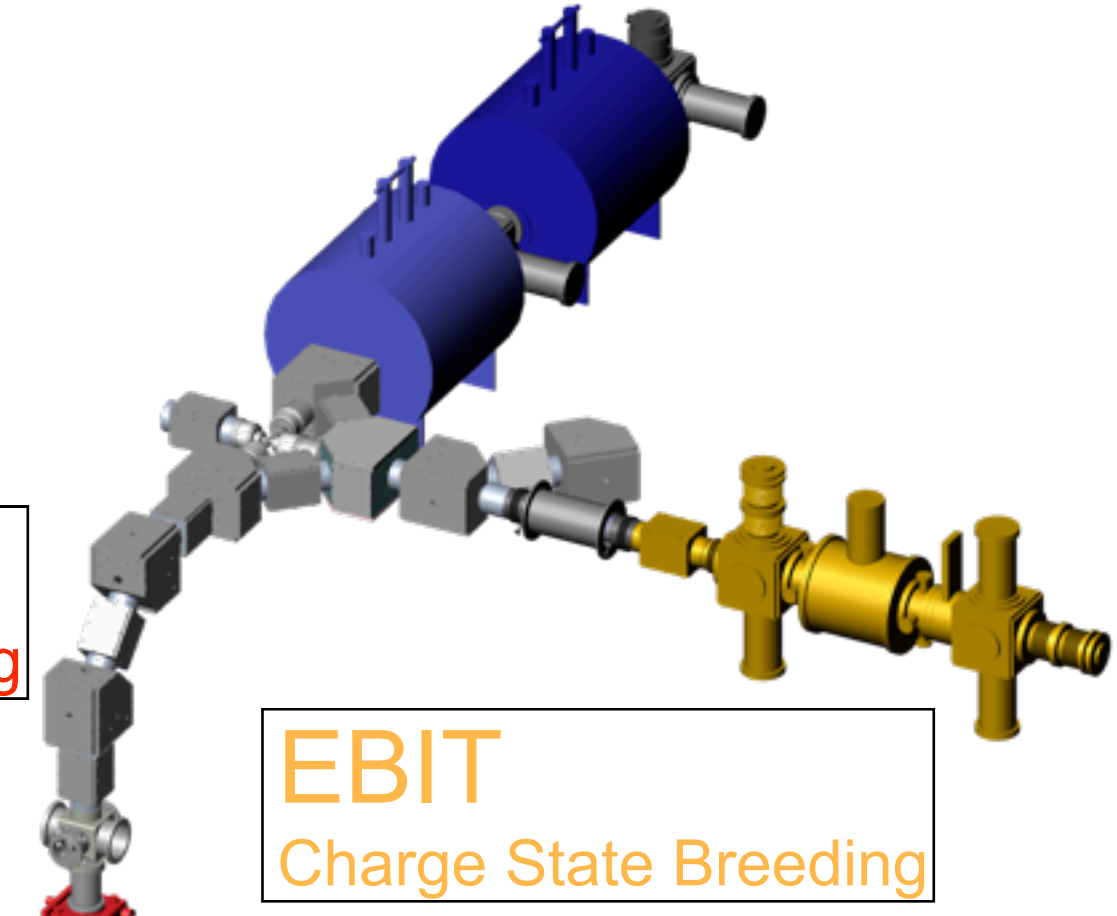
## Cooler Trap
Cooling HCI

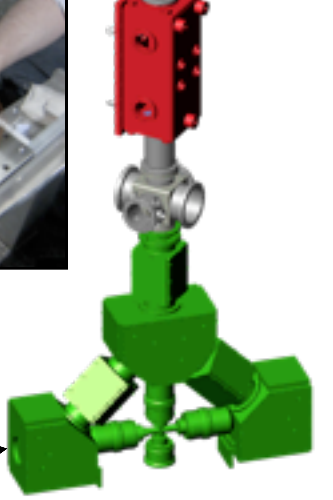
## RFQ
Cooling and Bunching



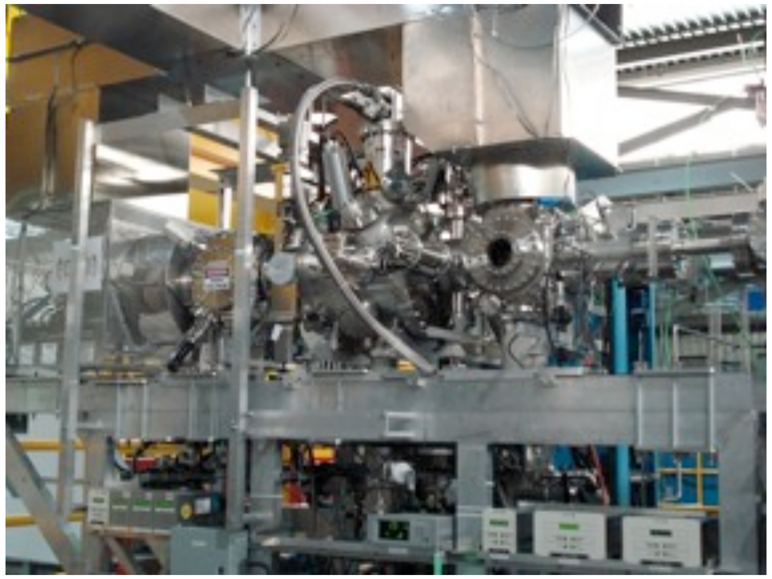
## ISAC Beam

(E ~ 20-60 keV)



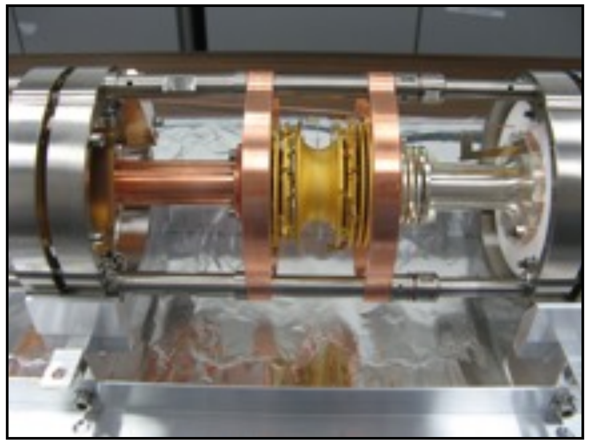


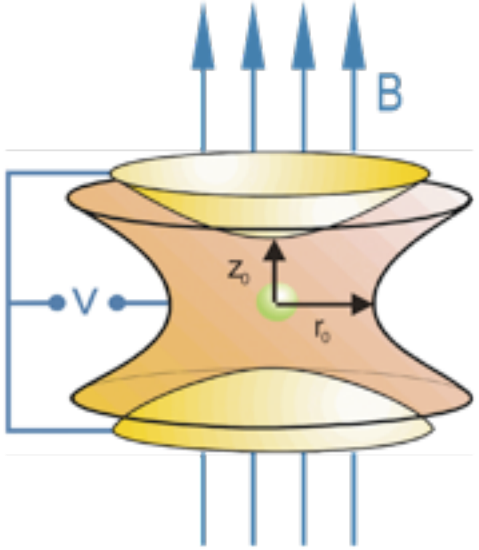
## EBIT
Charge State Breeding



(see poster by M. Brodeur)

## Penning Trap
Mass Measurement





$$\frac{\delta m}{m} \propto \frac{m}{\textcircled{q} T_{ex} B \sqrt{N}}$$

# TITAN - built for speed

## Fast DAQ/Controls

- MIDAS based data acquisition
- minimal software/hardware interaction during measurement
- free-running frequency modulated RF system
- DAQ/controls not limiting measurement repetition rate

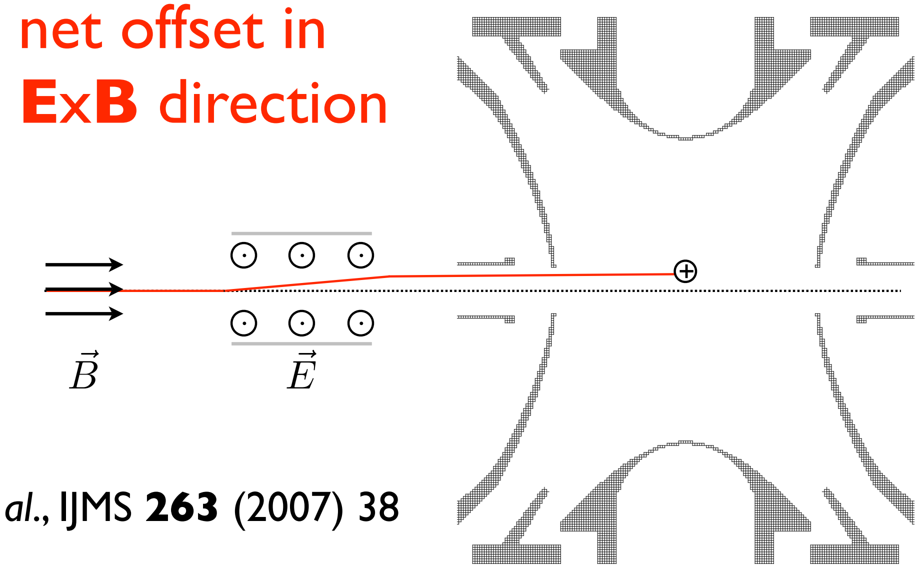
## Parallel Operation

- parallel loading of RFQ
- parallel sideband cooling in EBIT (no charge breeding)
- purified samples delivered to MPET on demand

## Fast Magnetron Preparation[1]

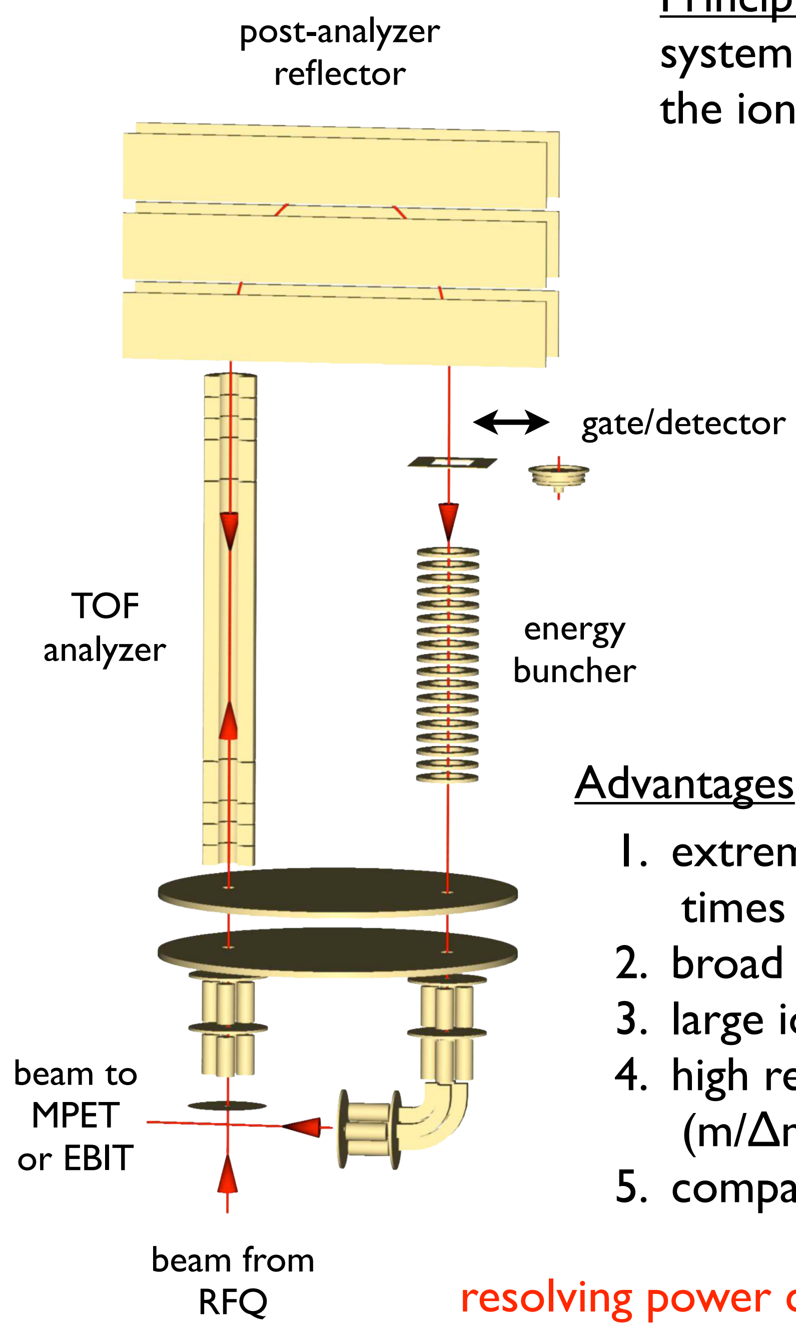
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

→ net offset in **ExB** direction



[1] R. Ringle *et al.*, IJMS **263** (2007) 38

## MR-TOF Isobar Separator (coming soon)



Principle: electrostatic mirror system drastically increases the ion flight path

Advantages:

1. extremely short measurement times (100 ns to 10 ms)
2. broad mass range
3. large ion capacity
4. high resolving power ($m/\Delta m$ ~ 100,000)
5. compact setup, inexpensive

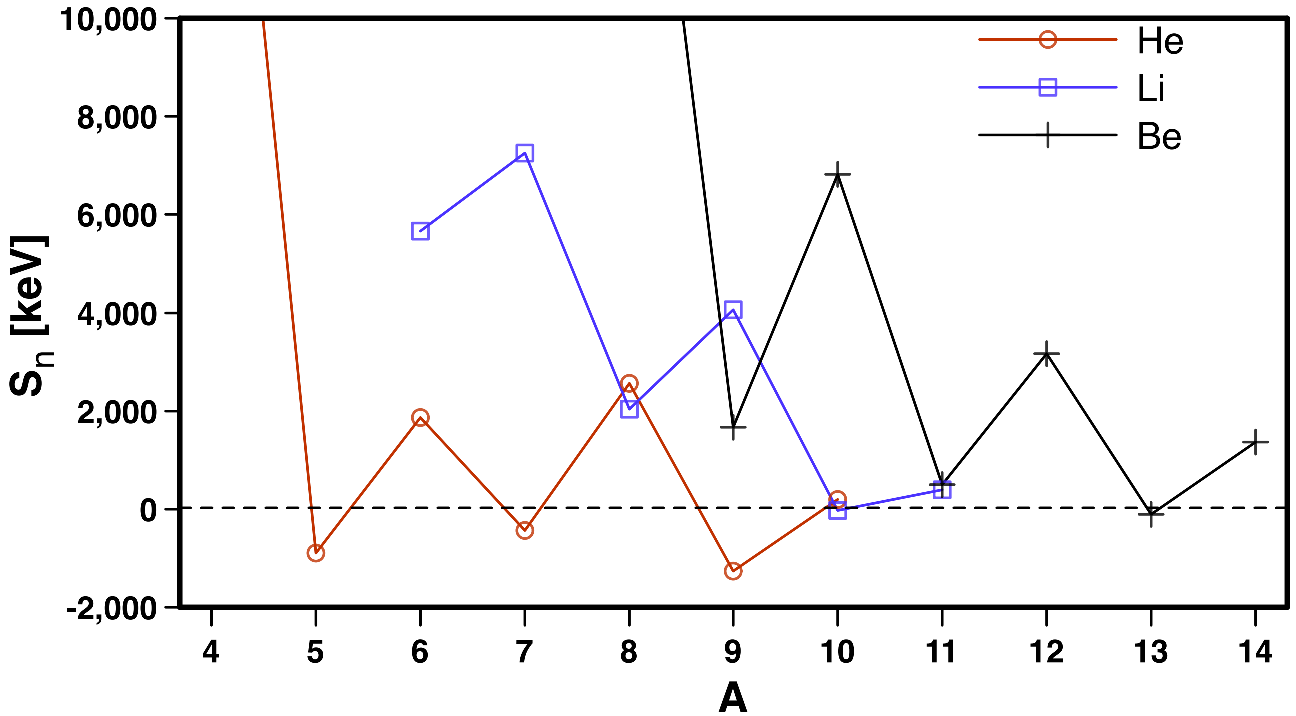
resolving power comparable to sideband cooling in a significantly shorter time

W.R. Plaß *et al.*, Nucl. Instr. Meth. B **266** (2008) 4560

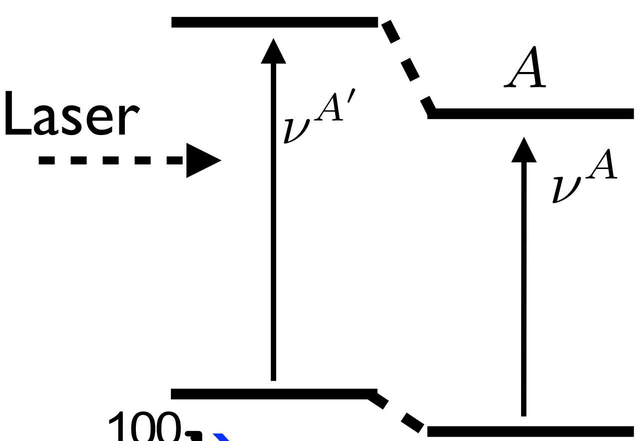
# What role do masses play?

Directly: determination of neutron separation energies

$$S_n(N,Z) = \boxed{M(Z,N-1)} + M_n - \boxed{M(Z,N)}$$



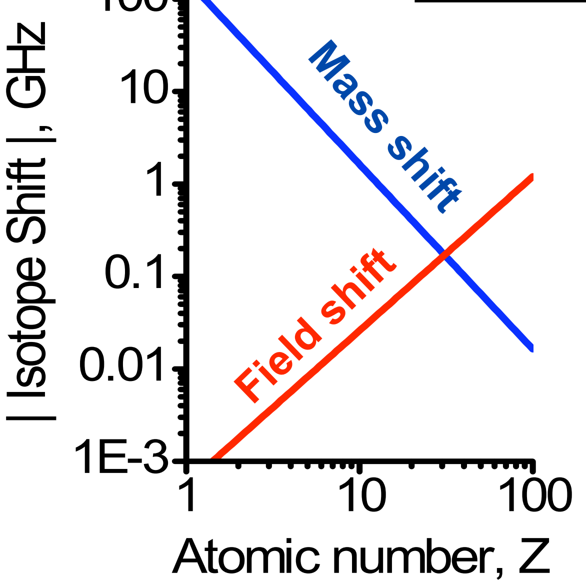
Indirectly: relative charge radius determination via isotope shifts



$$\overbrace{\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}}^{\text{Experiment}} = \overbrace{\delta\nu^{A,A'}_{MS} + K_{FS}}^{\text{Theory}} \cdot \delta < r_c^2 >^{A,A'}$$

mass shift

field shift



Mass precision < 1 keV required

Yan and Drake, PRL **91** (2003) 113004

Drake, Nucl. Phys. A **737** (2004) 25

Puchalski and Pachucki, PRA **78** (2008) 052511

| Halo nucleus | Reference | Lab | New mass? |
|---|---|---|---|
| $^{6}$He | Wang et. al., PRL **93** (2004) 142501 | ANL | ✓ |
| $^{8}$He | Mueller et. al., PRL **99** (2007) 252501 | GANIL | ✓ |
| $^{11}$Li | Sánchez et. al., PRL **96** (2006) 033002 | TRIUMF | ✓ |
| $^{11}$Be | Nörtershäuser et. al., PRL **102** (2009) 062503 | ISOLDE | ✓ |

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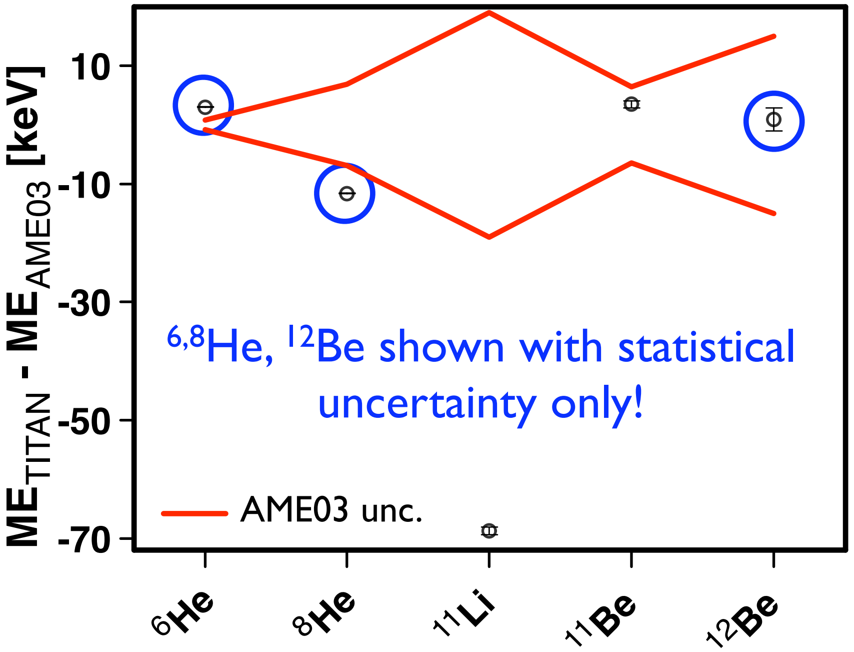
# Halo masses and charge radii



## Mass references

$^{6,8}$He: Brodeur et. al., in prep.

$^{8}$He: Ryjkov et. al., PRL **101** (2008) 012501

$^{11}$Li: Smith et. al., PRL **101** (2008) 202501

$^{11}$Be: Ringle et. al., PLB **675** (2009) 170

$^{12}$Be: Ettenauer et. al., in prep.

AME03: Audi *et. al.*, Nucl. Phys. A **729** (2003) 337

## Preliminary

New mass shift term calculations by G. Drake using new TITAN masses

atomic mass no longer a contributing source of uncertainty

$$\overbrace{\delta\nu^{A,A'} = \nu^{A'} - \nu^{A}}^{\text{Experiment}} = \overbrace{\boxed{\delta\nu_{MS}^{A,A'}} + K_{FS}\cdot\delta<r_c^2>^{A,A'}}^{\text{Theory}}$$

## *ab-initio* theory references

DCM $^{11}$Li: Tomaselli *et al.*, Nucl. Phys. A **690** (2001) 298

GFMC (AV18+UIX, AV8) $^{6}$He: Pieper, *et. al.*, PRC **64** (2001) 014001

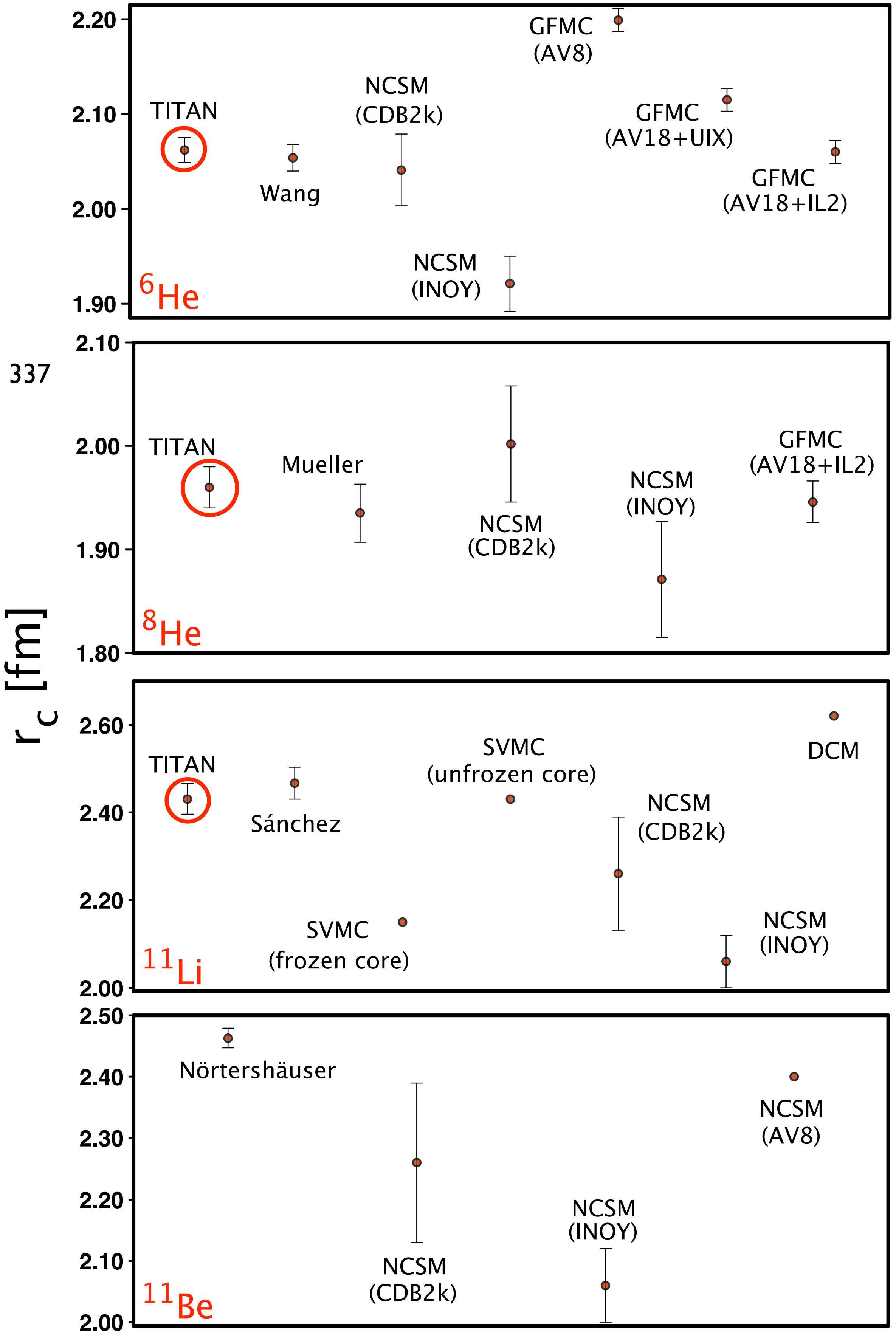
SVMC $^{11}$Li: Varga *et al.*, PRC **66** (2002) 3013

NCSM (AV8) $^{6}$He, $^{11}$Be: Forssén *et. al.*, PRC **71** (2005) 044312

GFMC (AV18+IL2) $^{6,8}$He: Pieper, Nucl. Phys. A **751** (2005) 516c

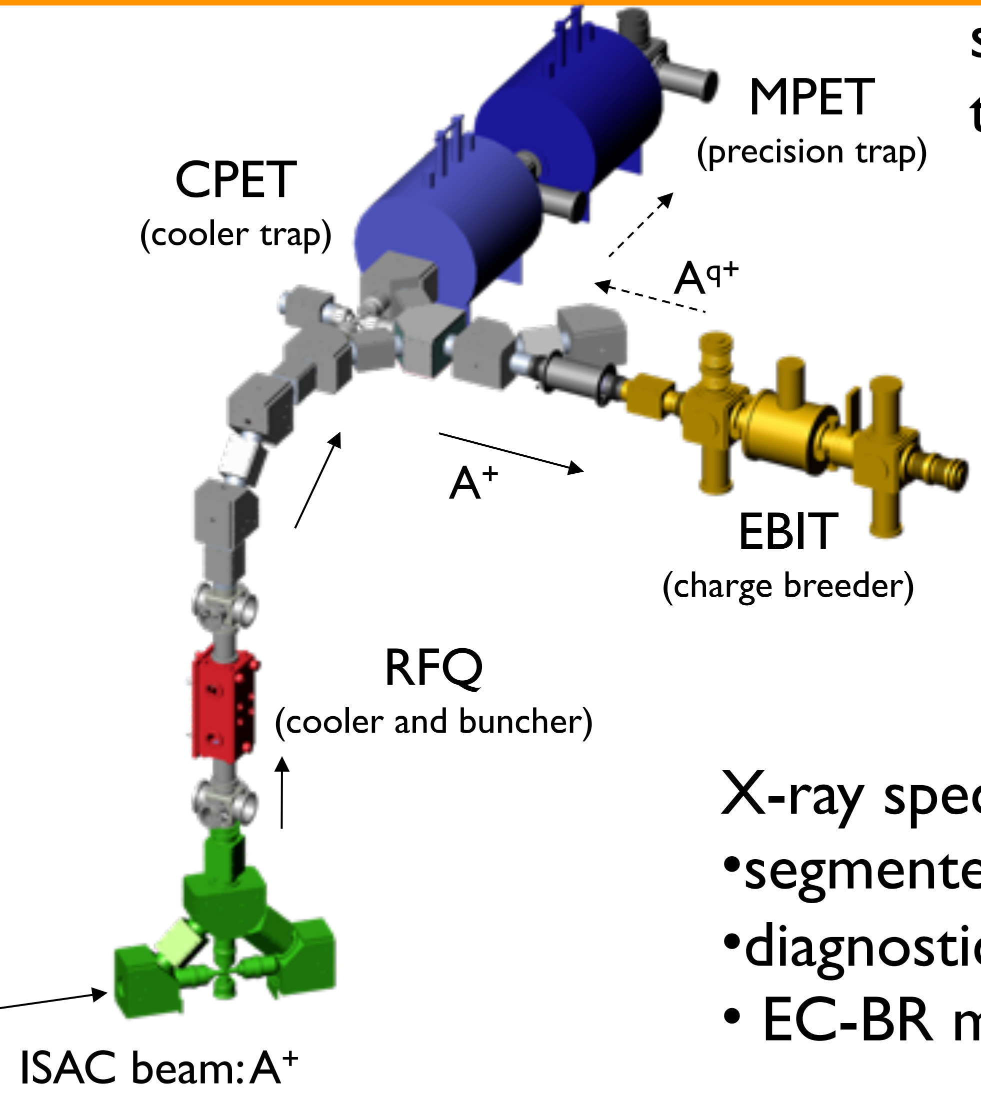
NCSM (CDB2k, INOY) $^{6,8}$He: Caurier and Navrátil, PRC **73** (2006) 021302(R)

NCSM (CDB2k, INOY) $^{11}$Li, $^{11}$Be: Forssén *et al.*, PRC **79** (2009) 021303(R)



# HCI's with the TITAN EBIT

(see poster by A. Lapierre)



MPET
(precision trap)

CPET
(cooler trap)

$A^{q+}$

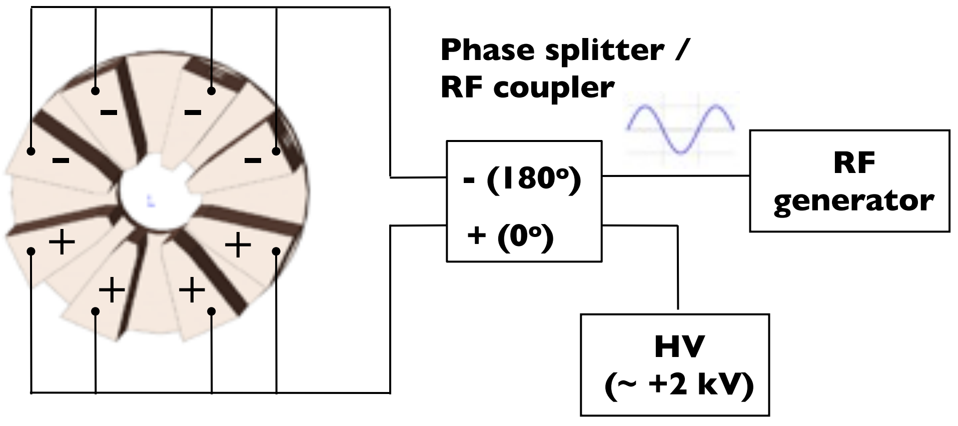
$A^{+}$

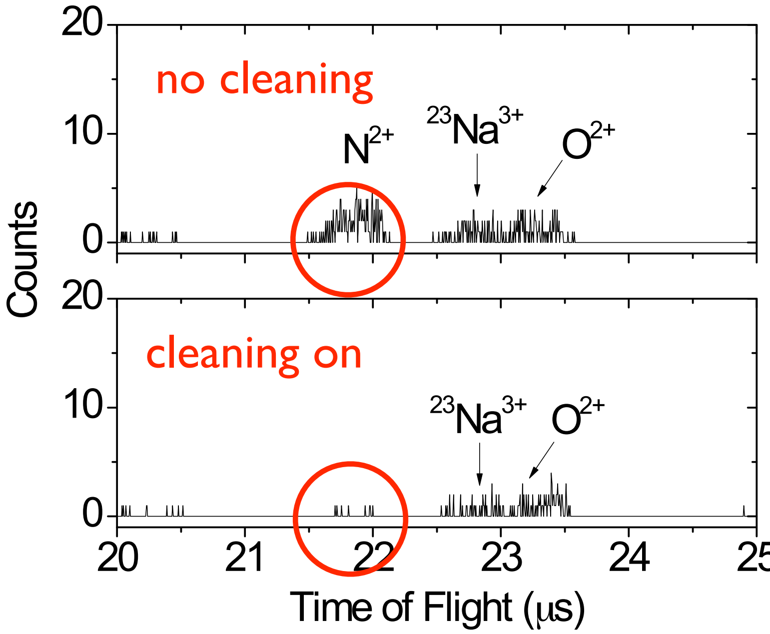
EBIT
(charge breeder)

RFQ
(cooler and buncher)

ISAC beam: $A^{+}$

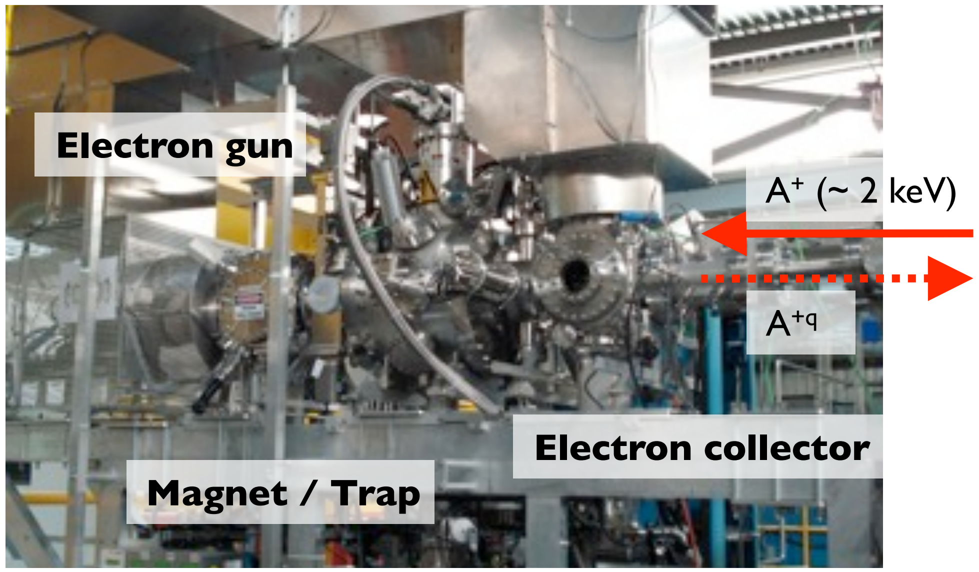
standard dipole excitation used to clean contaminants

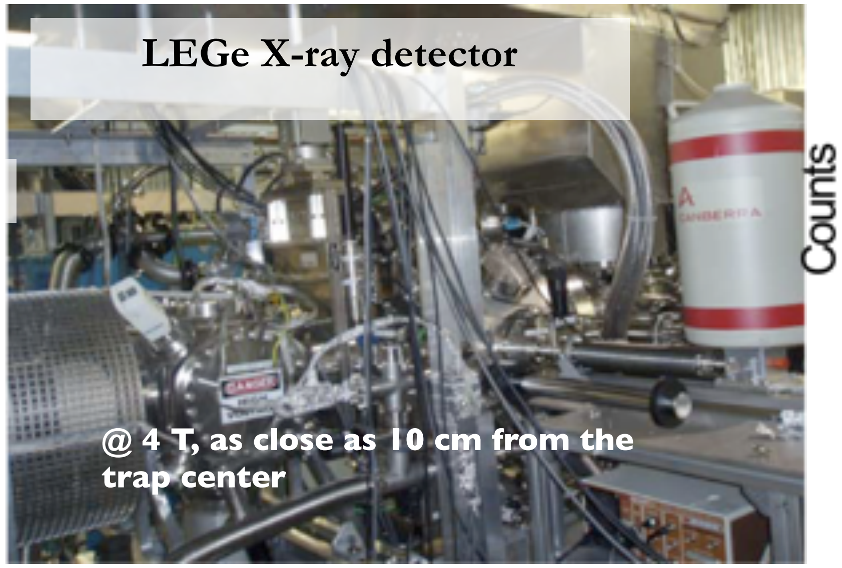


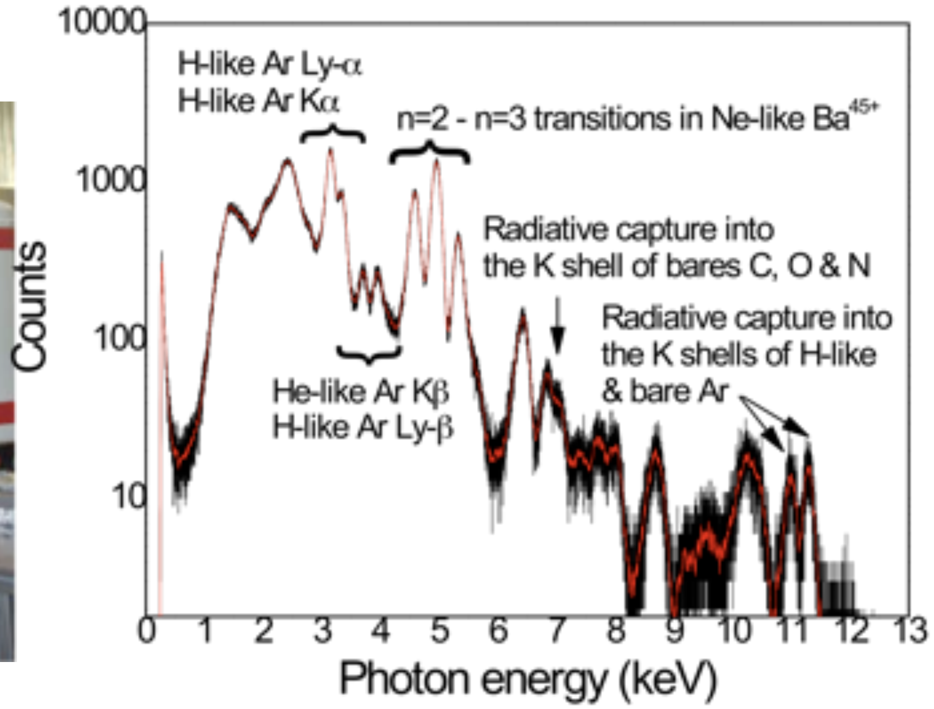


X-ray spectroscopy:

- segmented trap electrode for direct access to trap center
- diagnostics tool for charge breeding
- EC-BR measurement (see poster by T. Brunner)

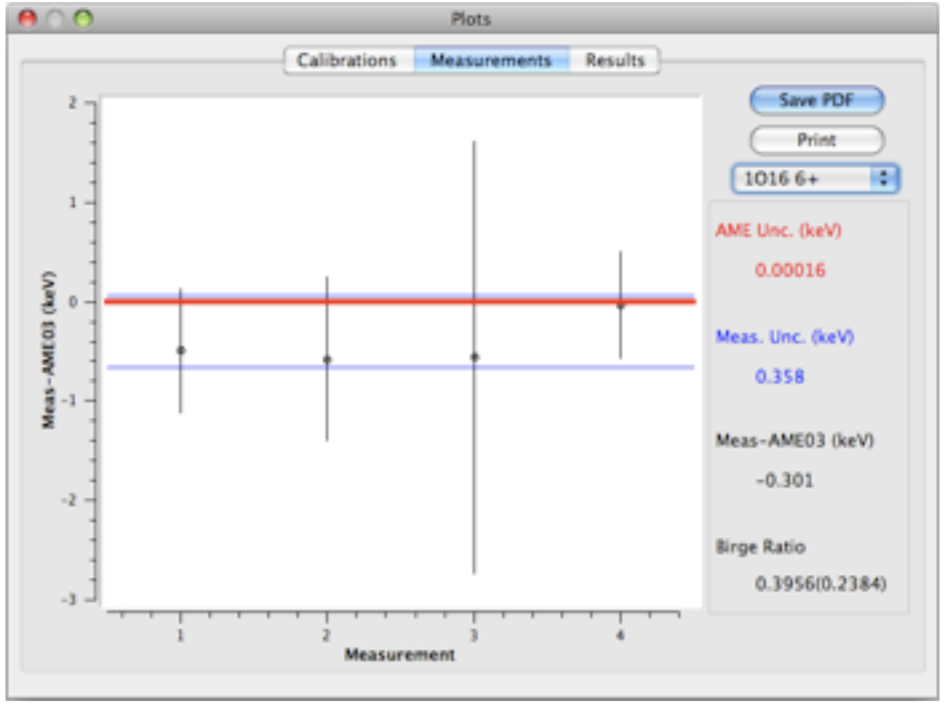






# HCI's with the TITAN EBIT

Preliminary



AME Unc. (keV)
0.00016

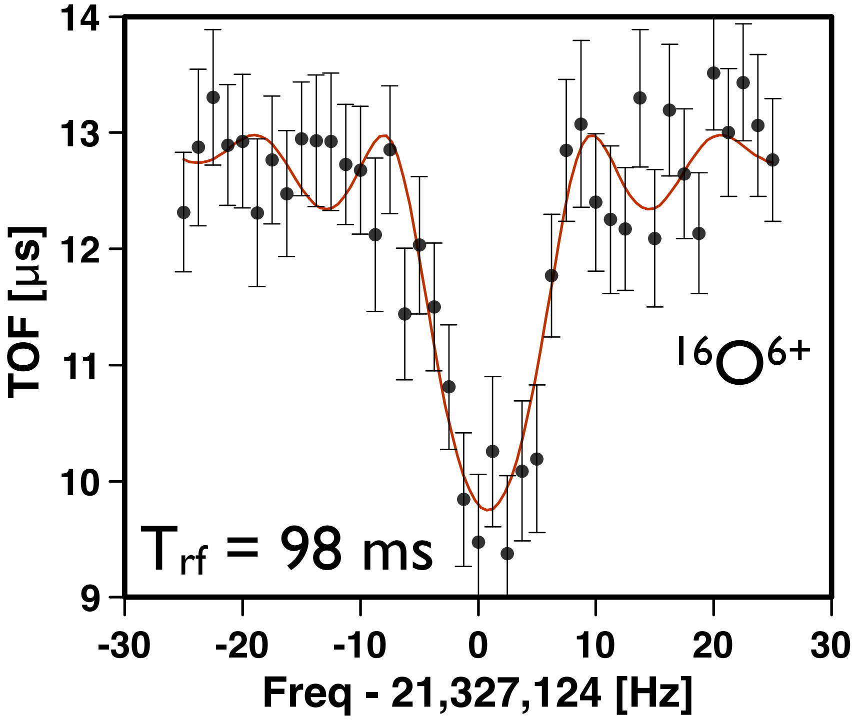
Meas. Unc. (keV)
0.358

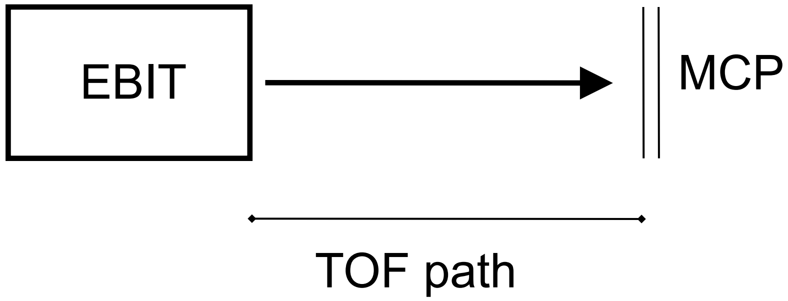
Meas-AME03 (keV)
-0.301

Birge Ratio
0.3956(0.2384)

$^{16}O^{6+}$ vs. $^{6}Li^{+}$

($^{6}Li^{+}$ from surface ion source)

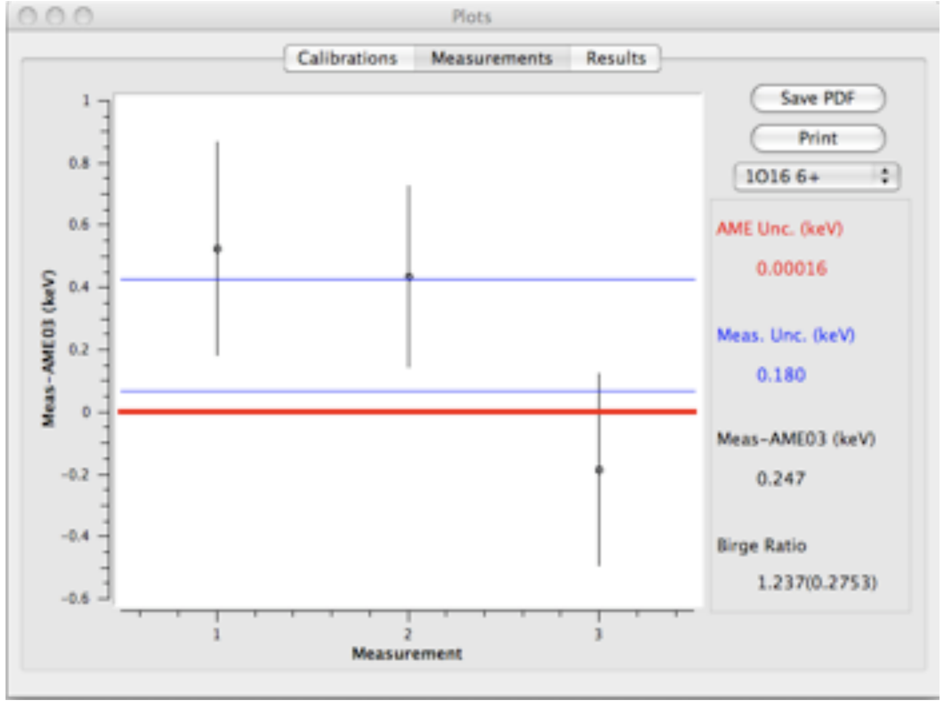



EBIT

MCP

TOF path

**TOF:** starts with extraction from EBIT



AME Unc. (keV)
0.00016

Meas. Unc. (keV)
0.180

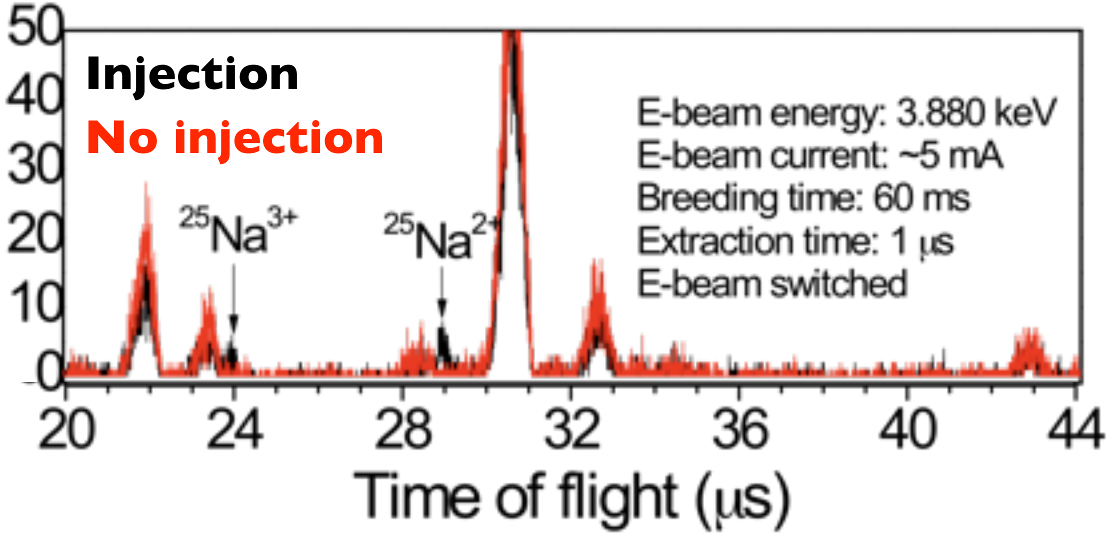
Meas-AME03 (keV)
0.247

Birge Ratio
1.237(0.2753)

$^{16}O^{6+}$ vs. $^{1}H^{+}$

must account for electron binding energies (~ 433 eV)

First radioactive HCI's from TITAN EBIT!

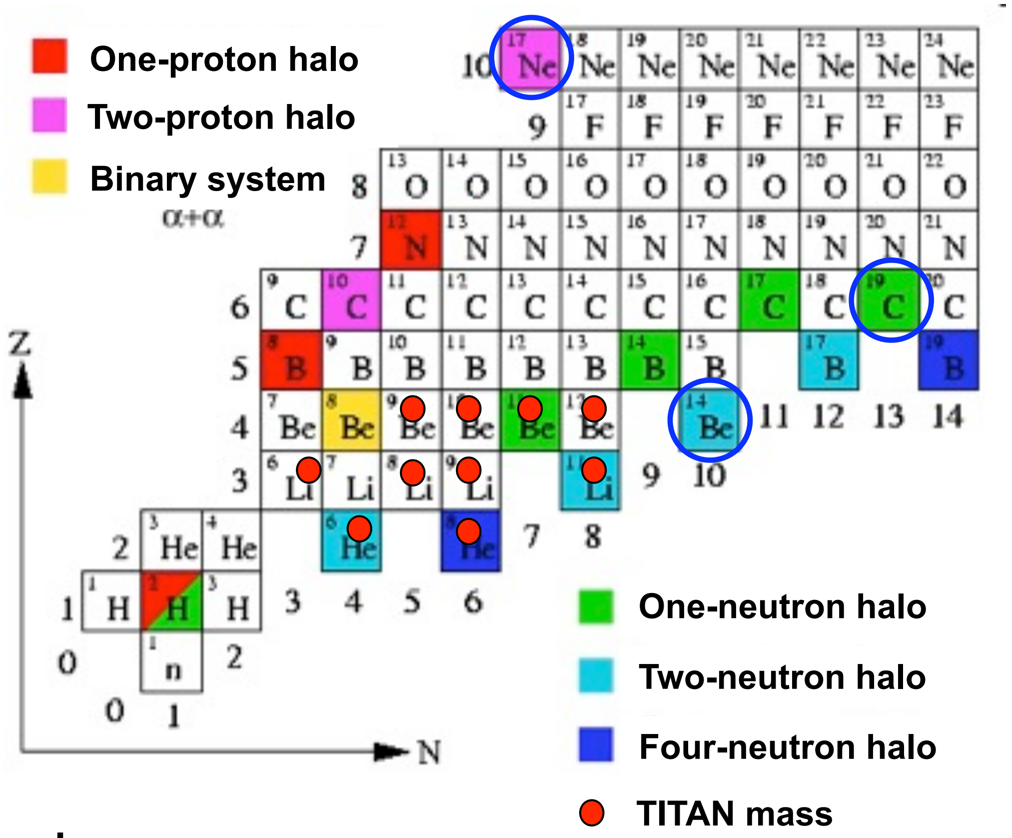


E-beam energy: 3.880 keV
E-beam current: ~5 mA
Breeding time: 60 ms
Extraction time: 1 μs
E-beam switched

# Summary and Outlook

## Halo nuclei

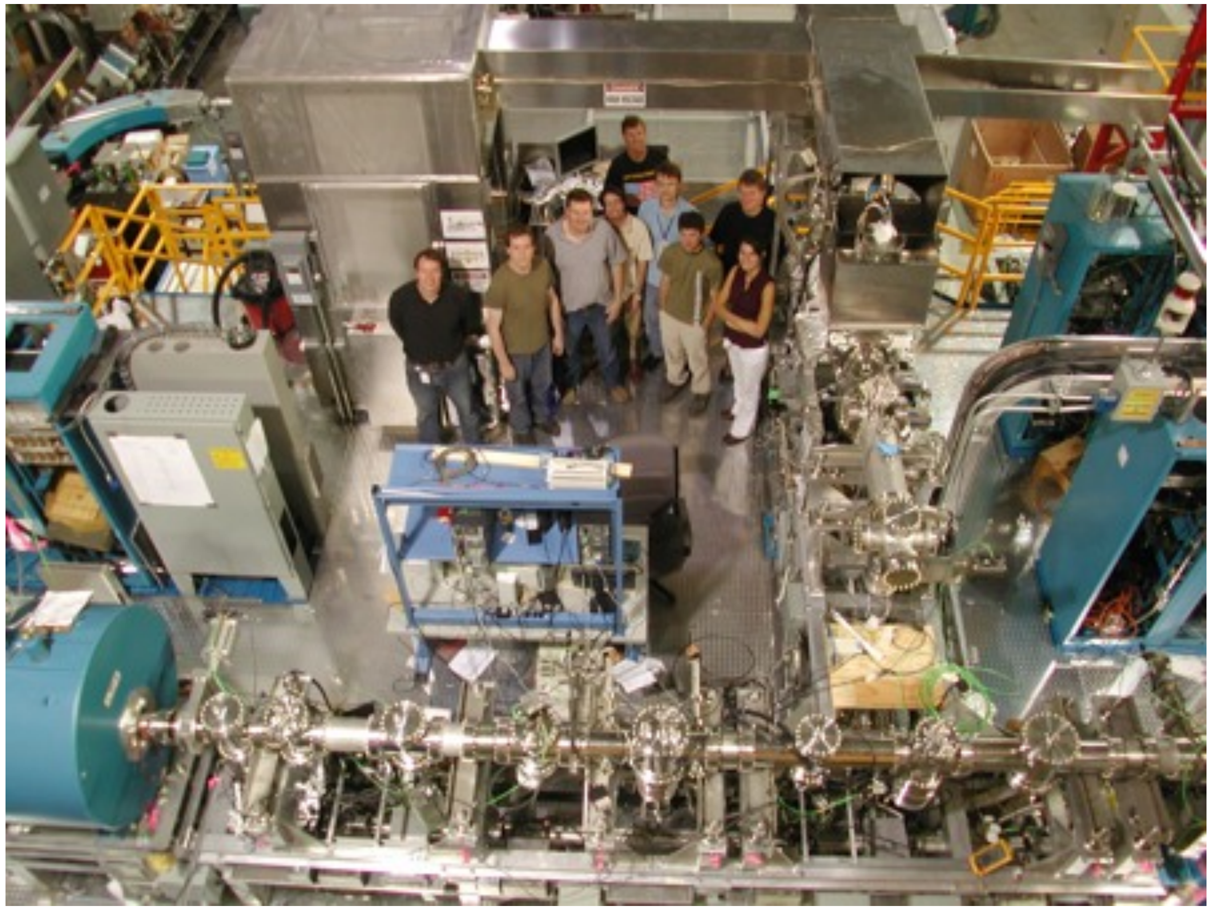
- High precision penning trap mass measurements of $^{6,8}$He, $^{11}$Li and $^{11}$Be have been performed with δm < 1 keV
- Mass values obtained with TITAN do not contribute a significant source of uncertainty to relative charge radius determinations
- Future halo mass measurement proposals include $^{19}$C (1n), $^{14}$Be (2n) and $^{17}$Ne (2p).



## Charge Breeding

- Stable HCI’s have been measured in the MPET
- Radioactive HCI’s have been produced
- Purification and identification techniques are being developed
- High-precision mass measurements of radioactive species later this year

# Collaborators



M. Brodeur, T. Brunner, S. Ettenauer, A. Gallant, M. Smith, A. Lapierre, R. Ringle,
V. Ryjkov, M. Good, P. Delheij, D. Lunney, and J. Dilling for the TITAN collaboration

| | |
|---|---|
| U. of Manitoba | U. of Calgary |
| McGill U. | U. of Windsor |
| Muenster U., | Colorado School of Mines |
| Max Plank Inst. of Heidelberg | TRIUMF |
| GANIL | UBC |