TITAN; TRIUMF Ion Trap for Atomic and Nuclear science (TITAN EBIT, rapid charge breeder for exotic nuclei)

Jens Dilling, TRIUMF & UBC

OUTLINE

- ‘Modern’ nuclear physics, motivation and goals.
- High precision mass measurements
- ISAC @ TRIUMF (the source of exotics)
- The TITAN system, the need for an EBIT and the requirements
- Conclusions & Outlook

20 years of EBIT. Nov 12-16 2006

TRIUMF ISAC

UBC THE UNIVERSITY OF BRITISH COLUMBIA

‘Modern’ Nuclear Physics
& the BIG questions

1. **What binds protons and neutrons into stable nuclei and rare isotopes?**
2. **What is the origin of simple patterns in complex nuclei?**
3. **When and how did the elements from iron to uranium originate?**
4. **What causes stars to explode?**

Rare exotic nuclei: (radioactive isotopes)

Increase of ‘playground’ by a factor of 20 allows systematic measurements

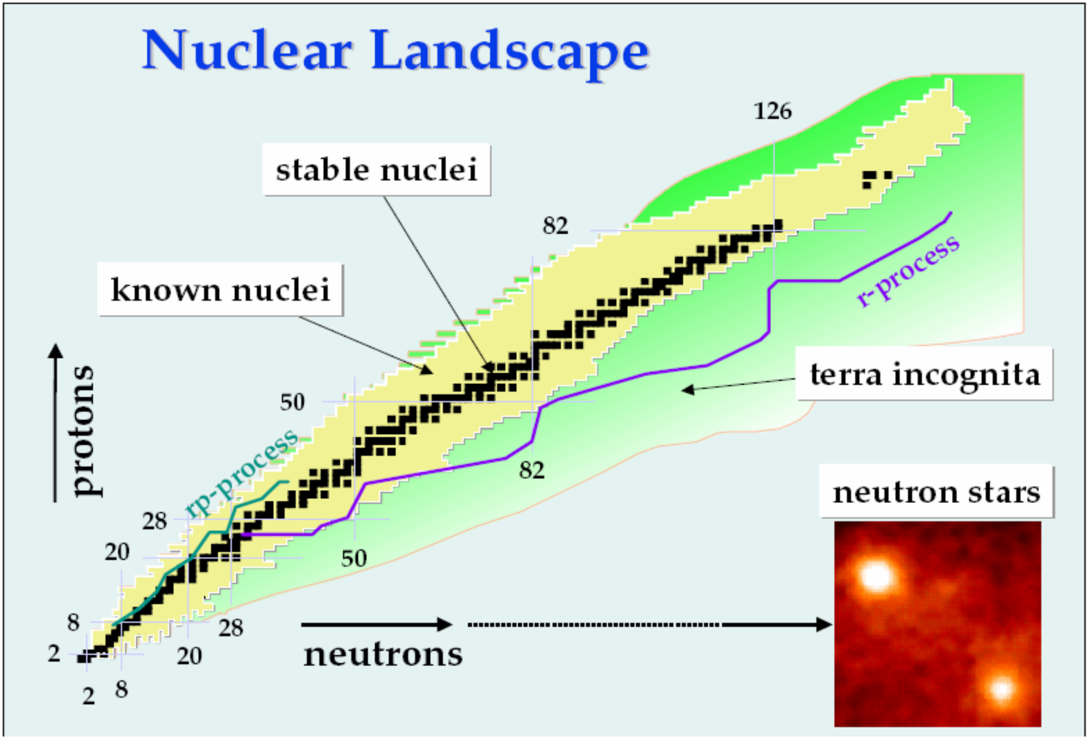
Reach regions important for the questions, and where nobody else can go

Experimental techniques refined.

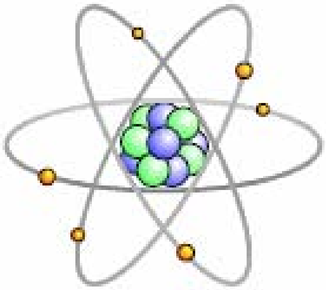
Era of precision experiments:

Atomic masses, nuclear half-lives, spins radiative captor cross sections, charge radii, magnetic moments…

ion traps, laser traps, laser spectroscopy, beta,-gamma spectroscopy, recoil spectrometer, …



Mass Measurements: For Nuclear Physics



= N · 🟢 + Z · 🔵 + Z · 🟠

- binding energy

Fundamental Property

Test of nuclear models and formulas

Nuclear Structure

Shell closures, pairing,
deformation
Halos

Reaction and decays

Q-values, boundaries on exotic decays

Limits and Islands

Driplines and Superheavies

Nuclear Astrophysics

r- and rp-process

Fundamental tests

Symmetries
Weak interaction: CVC hypothesis,
search for scalar and tensor currents

Unitarity of the Cabbibo, Kobayashi, Maskawa (CKM) Matrix

Weak eigenstates

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

Mass eigenstates

Contribution to the unitarity:

V_{ud} (nuclear β-decay) = 0.9740(5)

V_{us} (kaon-decay) = 0.2196(12)

V_{ub} (B meson decay) = 0.0036(5)

⬇

(non-)unitarity of CKM-matrix

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9968 \pm 0.0014$$

i.e. CKM not unitary at the 98% confidence level

(btw: if E865 Brookhaven and E832 Fermilab included-> Unitarity OKAY,
if NA48 CERN included-> again 2.4 σ difference).
J.C. Hardy and I.S. Towner PRL 94, 092502 (2005)

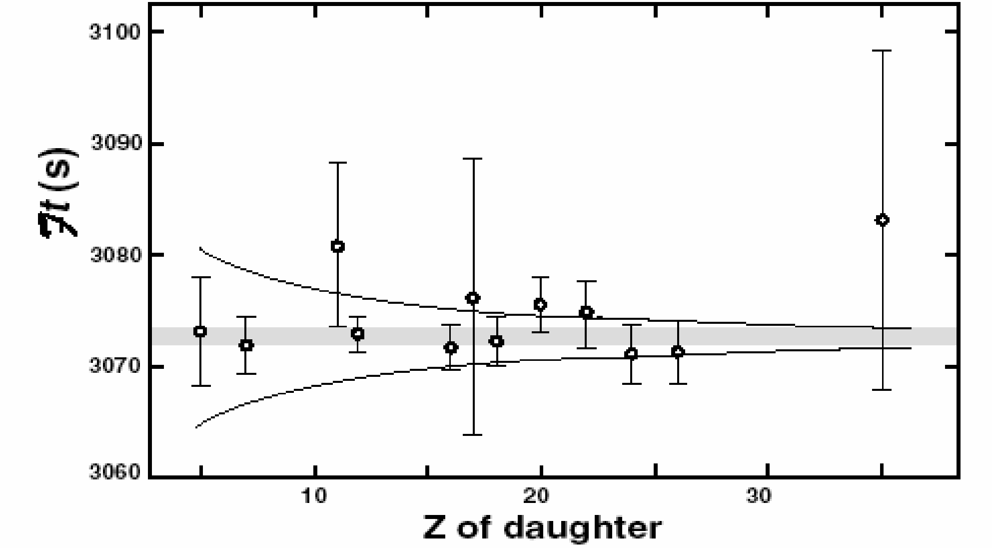
Nuclear β-decay contribution

$$FT \equiv ft(1+\delta_R)(1-\delta_C) = \frac{K}{2G_F^2 V_{ud}{}^2 (1+\Delta_R^V)} = (CVC)\ const.$$

f is stat. rate function

t is partial half-life ($t_{1/2}$ and BR)

$$K/(\hbar c)^6 = 2\pi^3 \hbar \ln 2/(m_e c^2)^5 = (8120.271 \pm 0.012)\cdot 10^{-10}\ GeV^{-4} s$$



$$FT(average) \equiv ft(1+\delta_R)(1-\delta_C)$$
$$= \frac{K}{2G_F^2(1+\Delta_R)V_{ud}^2} = 3072.2(8)$$

with $\chi^2/\nu = 0.6$

where:

δ_C : Coulomb (isospin) correction

δ_R : nucleus-dependent radiative corrections

Δ_R : nucleus-independent radiative corrections

δ_R : dominant part is QED calc.

considered very reliable!

δ_C : depending on nuclear structure

(model dependent)

Precision experiments: f. ex.:

^{74}Rb($T_{1/2}$ = 65 ms): δm = ~6 keV

Need: δm = < 2 keV δm/m < 1·10^{-8}

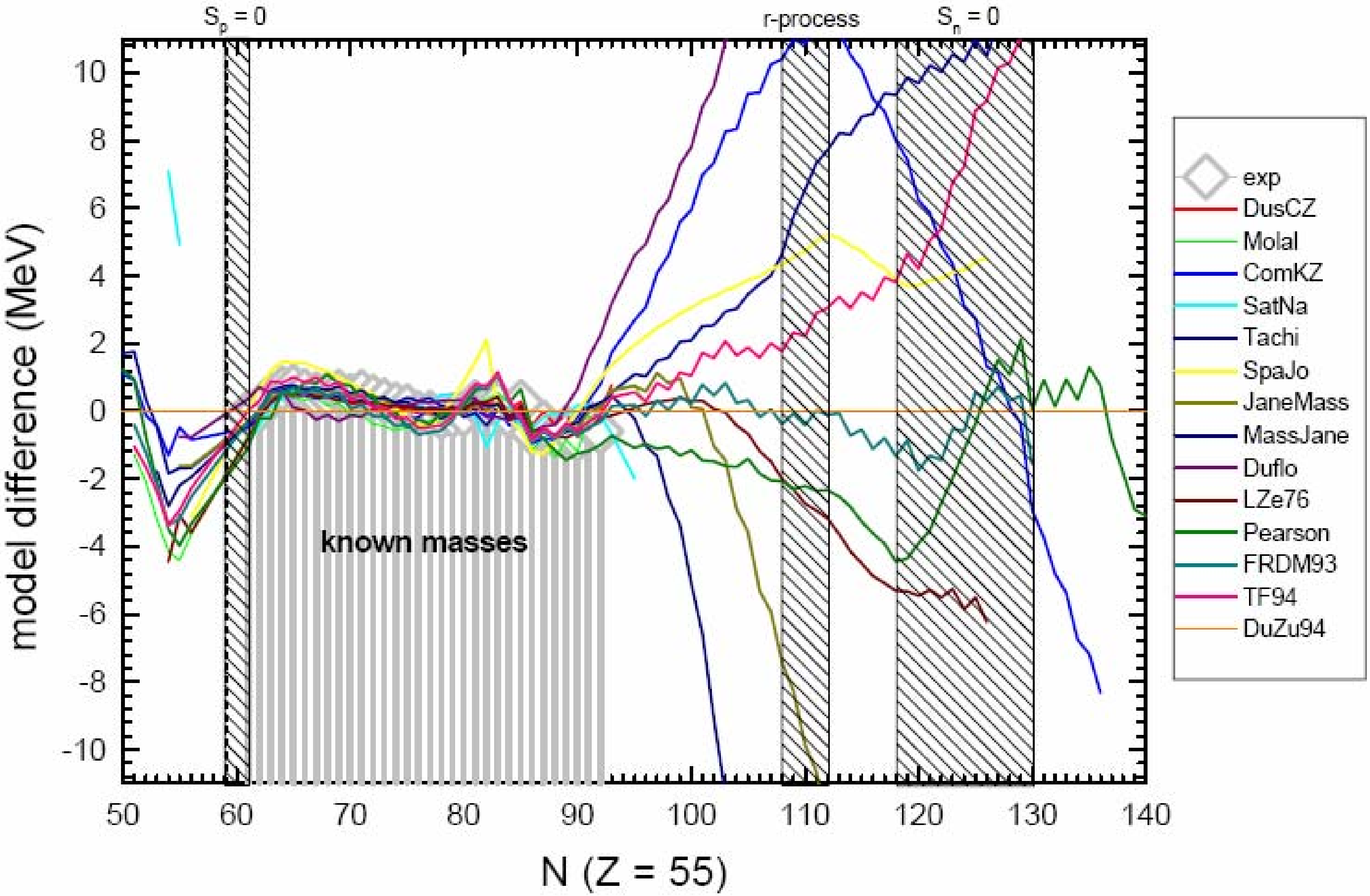
Motivation for mass measurements

- Nuclear astrophysics (need data near the r & rp process path).
- Nuclear structure, shell model, deformation, limit of existence.
- Halo nuclei.
- CKM matrix unitarity.
- Etc…

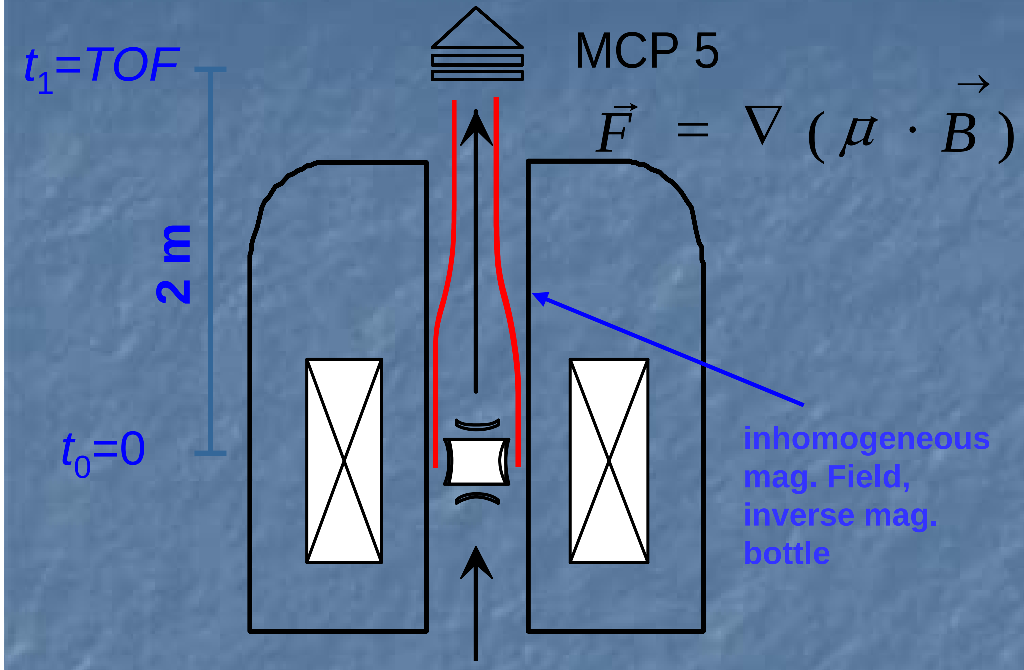
- NEED precise and accurate data on short-lived isotopes at low productions rate!

- Why not models?

Can't we use models?

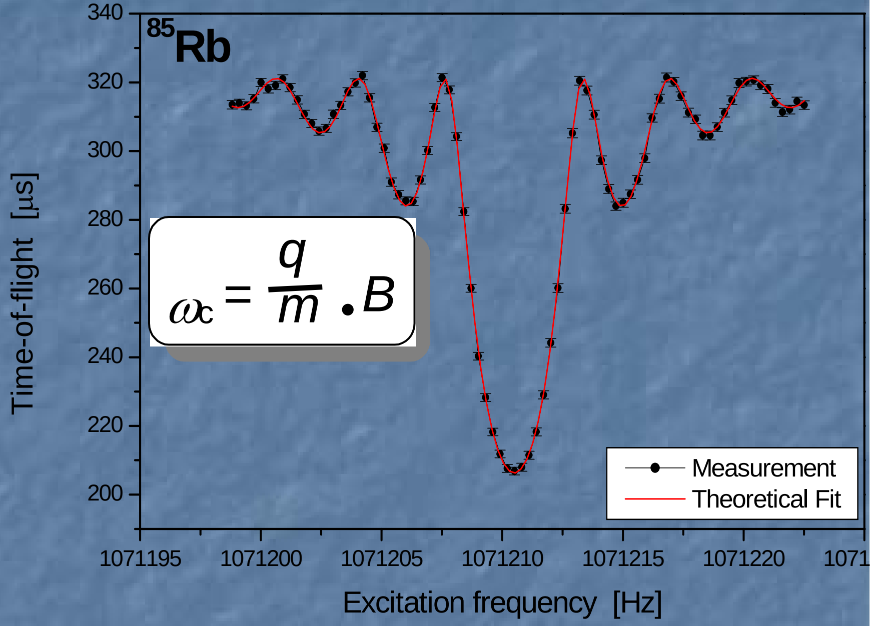


Mass measurement via time-of-flight



$$\vec{F} = \nabla(\mu \cdot \vec{B})$$

inhomogeneous mag. Field, inverse mag. bottle



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

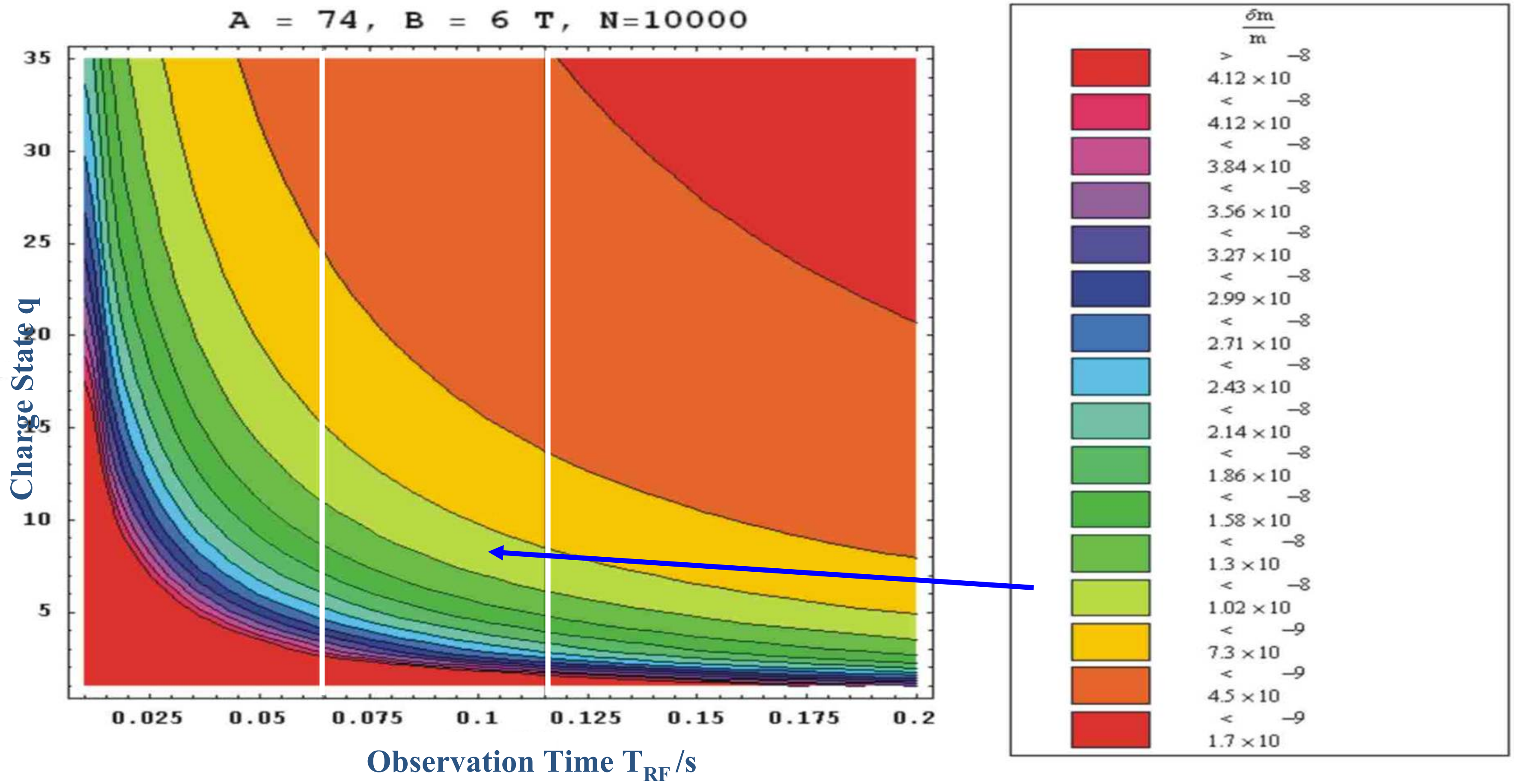
$$E_{pot} = -\vec{\mu} \cdot \vec{B} \qquad E_{rad} = \mu B$$

Determine atom mass from frequency ratio with a well known reference

Time-of-flight cyclotron resonance detection → suited for radioactive isotopes

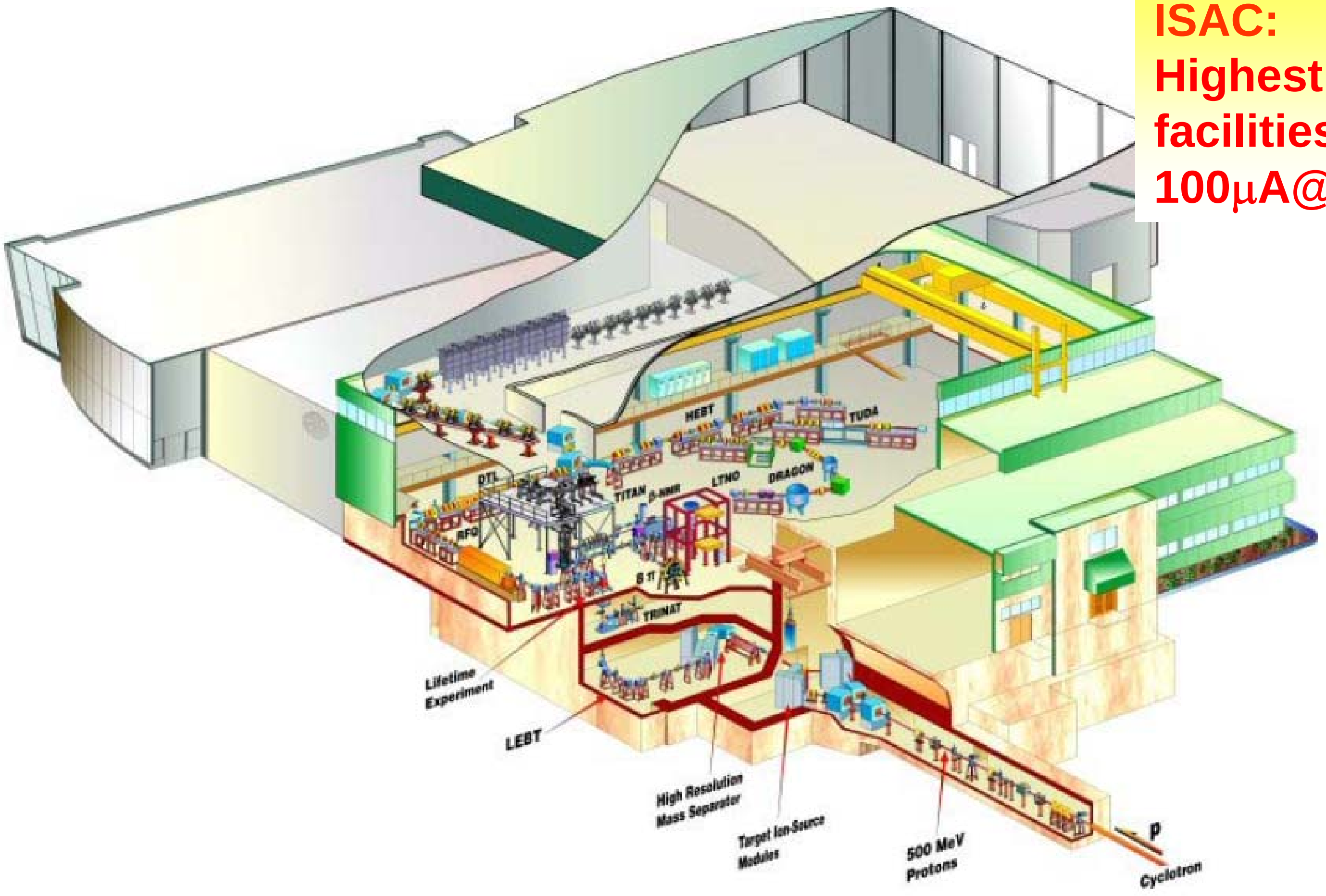
Accuracy of Penning Trap Mass Measurements

$$\nu_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B \qquad \frac{\delta m}{m} \approx \frac{m}{T_{RF}\cdot q\cdot B\cdot\sqrt{N}}$$



Use Highly Charged Ions.

We need exotics: ISAC@TRIUMF



ISAC:
Highest yields for On-Line facilities, we go up to 100μA@500MeV DC proton

Ion-sources:

- Surface ☑
- Resonant-Laser source on-line ☑
- Negative, off-line test ☑
- FEBIAD, off-line test ☑
- ECR, on-line tests and checks ☑ (changes needed)
- Targets:
- High power target tested on-line and reached 50kW on target ☑
- Actinide target task force: Plan to do tests next year

Yields: ^{11}Li 5*10^{4}/s, ^{74}Rb 2*10^{4}/s, ^{62}Ga 2*10^{3}/s

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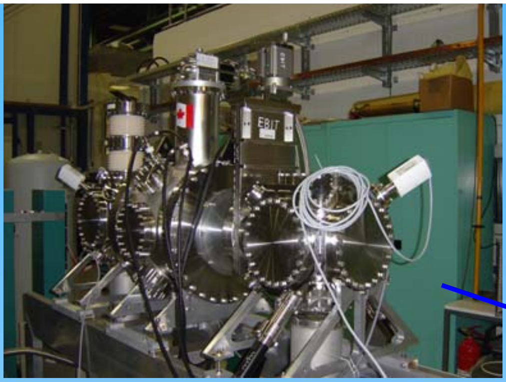
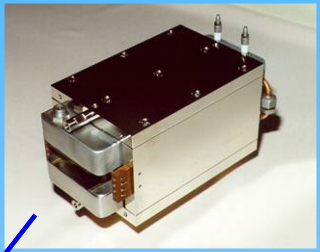


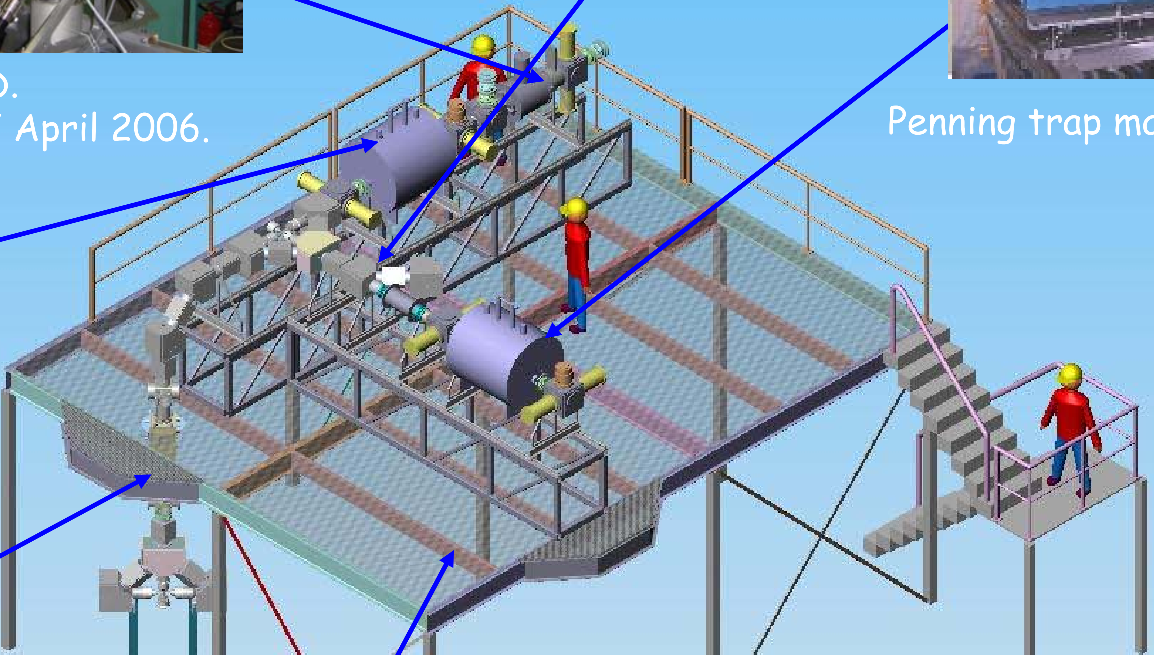
EBIT built at MPI-HD.
Delivered to TRIUMF April 2006.

McGill

Wien filter
(R=500)

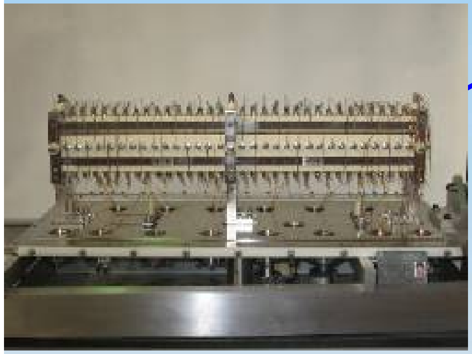


Penning trap magnet



Cooler trap for HCI
under construction in
Manitoba

university of manitoba



RFQ operational off-line

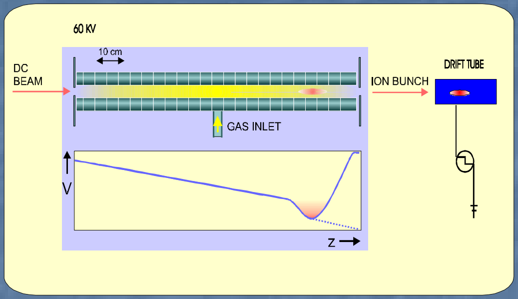
TRIUMF
ISAC

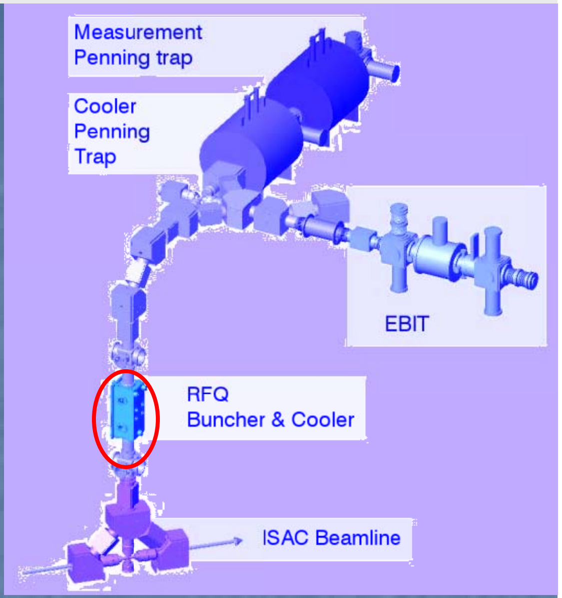
TITAN platform finished
at ISAC

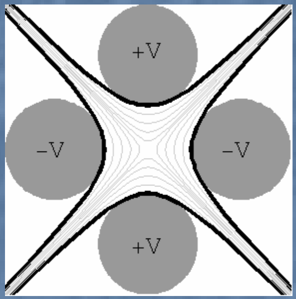
The TITAN system is under construction and will be operational for mass measurements at ISAC 2007.

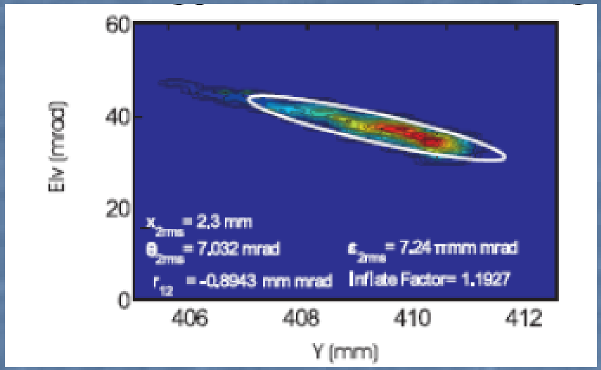
Isotopes with $T_{1/2} \approx 10$ ms
$\delta m/m < 1 \cdot 10^{-9}$

RFQ cooler and buncher (RFCT)









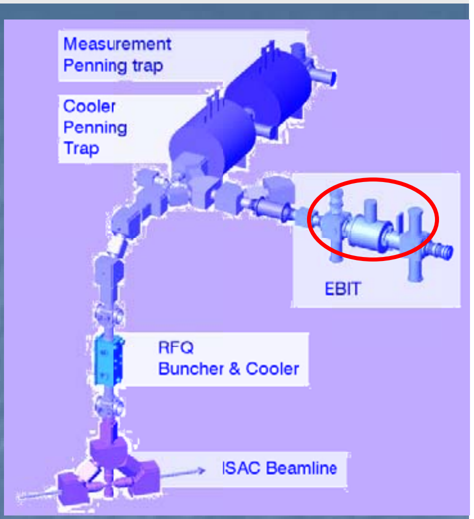
The RFCT allows to convert the DC ISAC beam into bunches (~1-10 μs) of excellent beam quality.

Ready for experiments!

Transversal $\varepsilon_{95\%} = 7.24\ \pi$ mm mrad @ 4 keV
He gas: 4.9 mTorr
Cooling Time: 10 ms
RF: 400V @ 659 kHz
DC Slope: -3V over DCs 1-21 with DC1 = 2V
Trap depth: -30V

Corresponds to an beam quality improvement of a factor of >50.

TITAN EBIT charge breeder



- Fast c

$$R_{q_i} \propto \frac{\boxed{I_e^2}\, l\, B}{v_e\, r_c \sqrt{k\, T_c}\, q_i \sum_{j=0}^{q_i} \frac{1}{\sigma_j^{\mathrm{EI}}}} \left[\frac{\mathrm{ions}}{\mathrm{s}}\right]$$

Currell & Fussmann, IEEE Trans. Plas. Sci., **33**, 2005

po

magnetic field

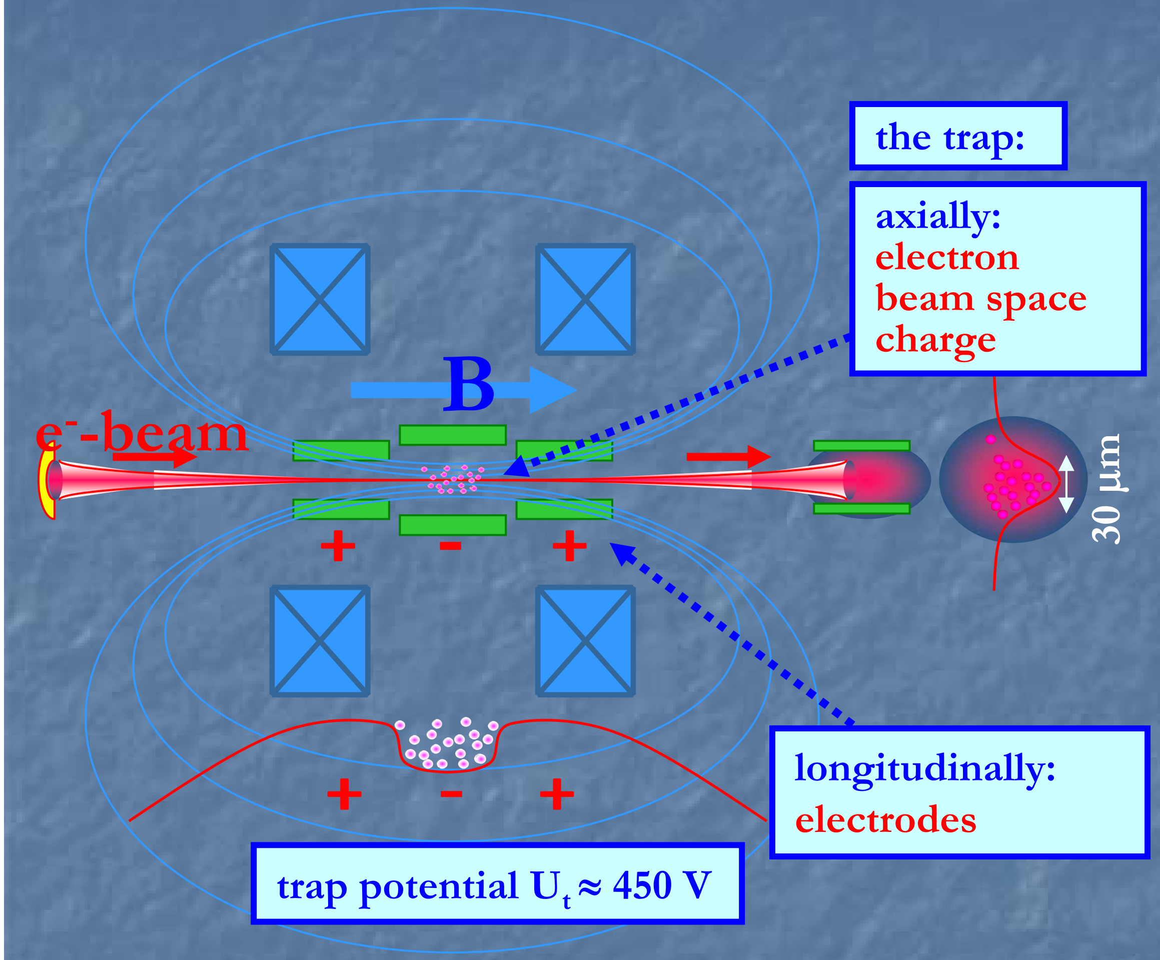
compression

$$\begin{aligned}\frac{dn_i}{dt} = {} & \boxed{n_e v_e}[\sigma^{\mathrm{EII}}_{i-1\to i}\, n_{i-1} - (\sigma^{\mathrm{EII}}_{i\to i+1} + \sigma^{\mathrm{RR}}_{i\to i-1} + \sigma^{\mathrm{DR}}_{i\to i-1}) n_i \\ & +(\sigma^{\mathrm{RR}}_{i+1\to i} + \sigma^{\mathrm{DR}}_{i+1\to i}) n_{i+1}] \\ & -\cancel{n_0 v}_{\mathrm{ion}}[\sigma^{\mathrm{CX}}_{i\to i-1}\, n_i - \sigma^{\mathrm{CX}}_{i+1\to i}\, n_{i+1}]\end{aligned}$$

Charge changing processes
- Electron impact ionization
- Radiative recombination
- Dielectronic recombination
- Charge exchange

- Efficient Ion Injection, Extraction, Separation, and Capture into a Penning trap

EBIT system for charge breeding

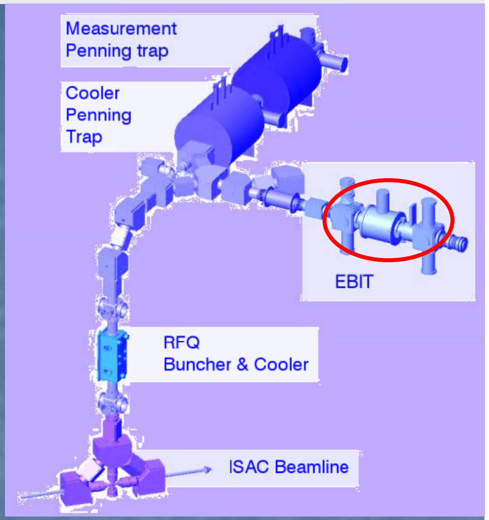


the trap:

axially:
electron beam space charge

longitudinally:
electrodes

trap potential $U_t \approx 450$ V



Magnetic field: 6 Tesla

Electron beam energy: up to 70 keV

Electron beam current: 5 A

Beam radius (80% current): ~30-50 µ m

Central current density: $1.1\cdot10^{5}$ A/cm^{2}

Ionization time (Sn, q: $1\rightarrow2$) 0.16 µ s

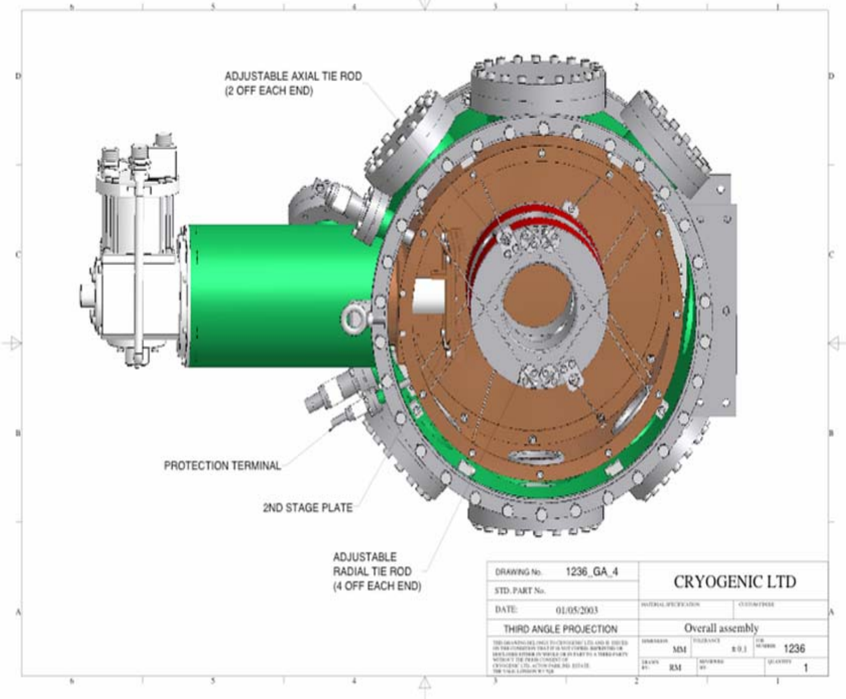
Total electron charges: $8\cdot10^{10}$

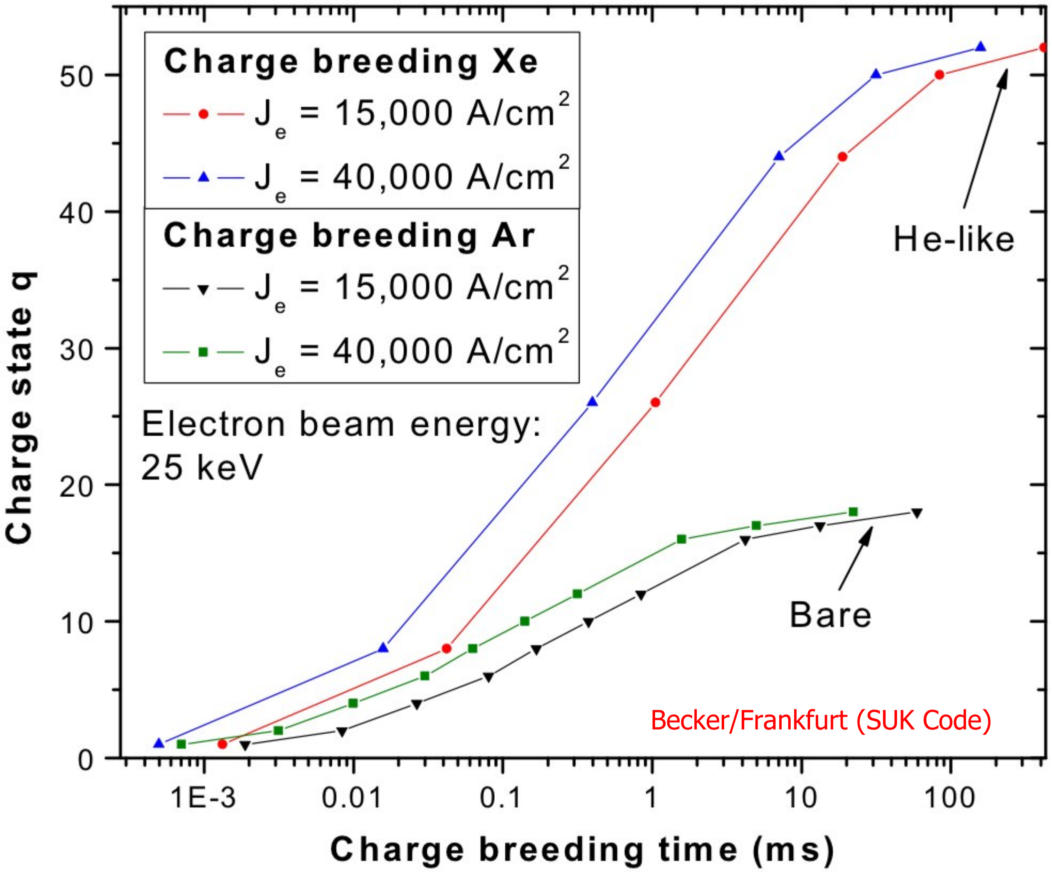
Built in collaboration with the MPI for Nuclear Physics in Heidelberg/Germany.

Max-Planck-Institut
für Kernphysik

Expected Performance of the TITAN EBIT

Trapping potential: U_e = 450 V @ 5 A
Ion acceptance: ε = >20 π mm mrad @ 3 keV
Injection efficiency: $\eta \approx$ 50 % -100 %
Ionization time (Sn): τ = 3 ms (q = 40+, Ne-like)
τ = 34 ms (q = 48+, He-like)
Space charge limit: 10^9 ions for Sn^{40+}
Charge state abundance: 25 ... 90 %





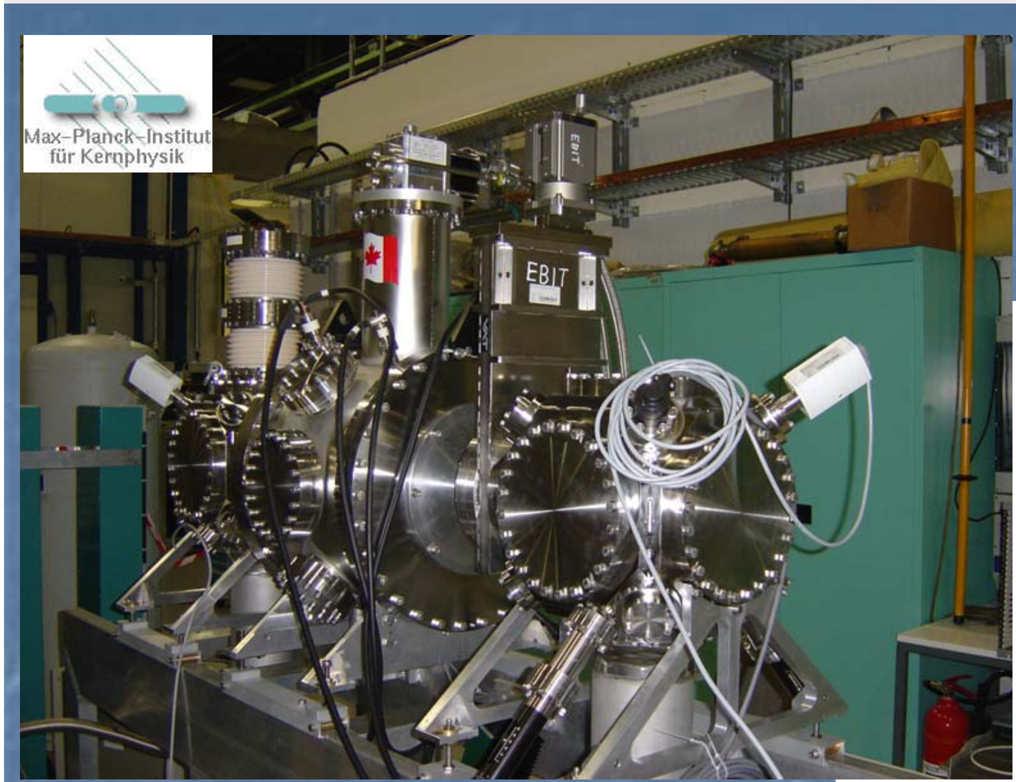
Becker/Frankfurt (SUK Code)

- For charge state distribution: reached 90% in one charge state: for example at Ba^{46+} (Ne-like) PRL 60(1988)1715.
- Manipulation of the distribution by varying the electron-energy and the trapping time.

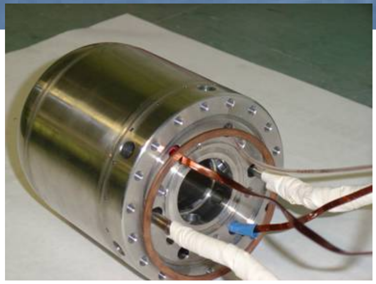
Cryogen free! Smaller, no preferred orientation.

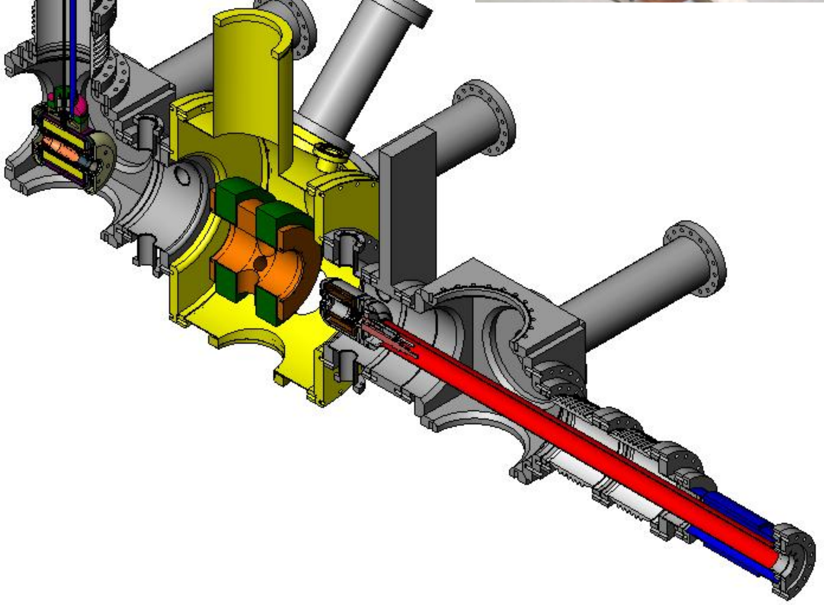
Excellent performance of magnet, vacuum (cryo-cold system)!

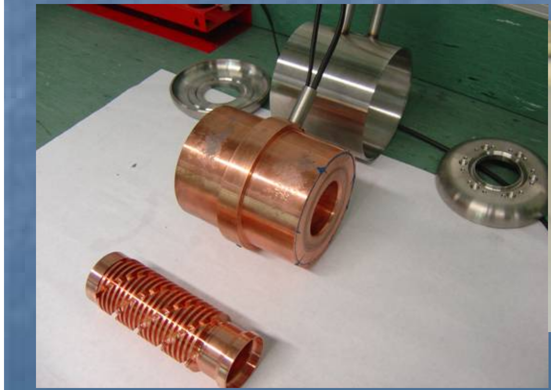
TITAN EBIT @ Heidelberg



Three different E-guns (0.5A, 1.5A, 5A) assembled, reached 400mA @ 27 keV.







Collector cooling tested up to 5 kW.

G. Sikler et al, European Phys. Journal A 25 (2005) 1.63

J. Dilling et al Int. J. Mass Spec 251 (2006) 198-203

TITAN on the move

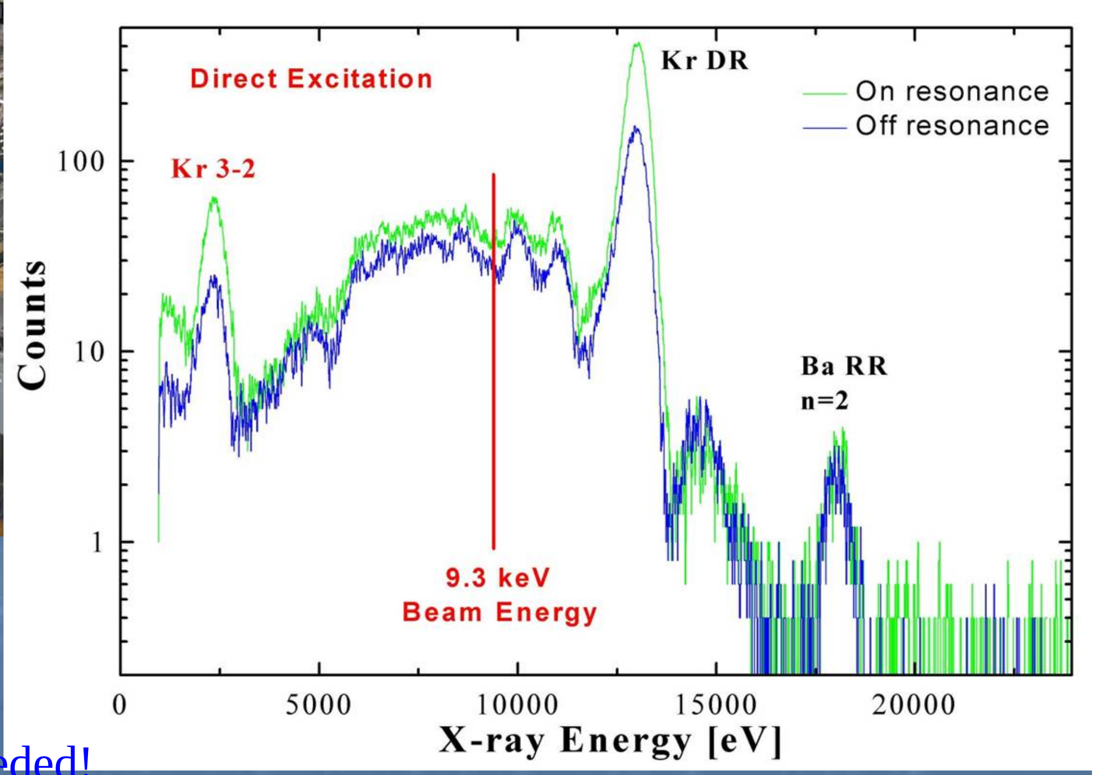
TITAN EBIT arrived!

TITAN EBIT @ TRIUMF

Fully functional test set-up.

Very stable operation, excellent magnet field control.

Tested to 400 mA @ 27 keV.



X-ray spectrum of Kr.
Prove of charge breeding.
NEXT: test with external ions
emittance measurements are much needed!
Optimization of system with stable ions. Use spectroscopy on-line as diagnosis.

Ready for experiments ! (Awaiting your ideas…)

Conclusions, status and challenges

- TITAN is getting ready for first experiments using HCIs exotics.
- Exciting times for Nuclear Physics, with potential to really tackle the BIG QUESTIONS

- The TITAN EBIT is operational at present at 400 mA @ 27 keV, and can go to 5 A @ 80 keV (the 5 A are possible but will require some work…).
- The TITAN EBIT is coupled to an offline plasma source, has a gas-injector, and is of course coupled to ISAC, the worlds most intense source of exotic nuclei.
- Need to optimize injection and extraction!
- The TITAN EBIT allows access to virtually all sub-uranium elements, but in addition, to many isotopes of the specific element.
- The TITAN EBIT is built for flexible use and has 7 (six when gas injector is used) access-ports radial for detectors and spectrometers.
- Challenge will be the energy spread of ions coming out of the EBIT (G Gwinner’s talk).

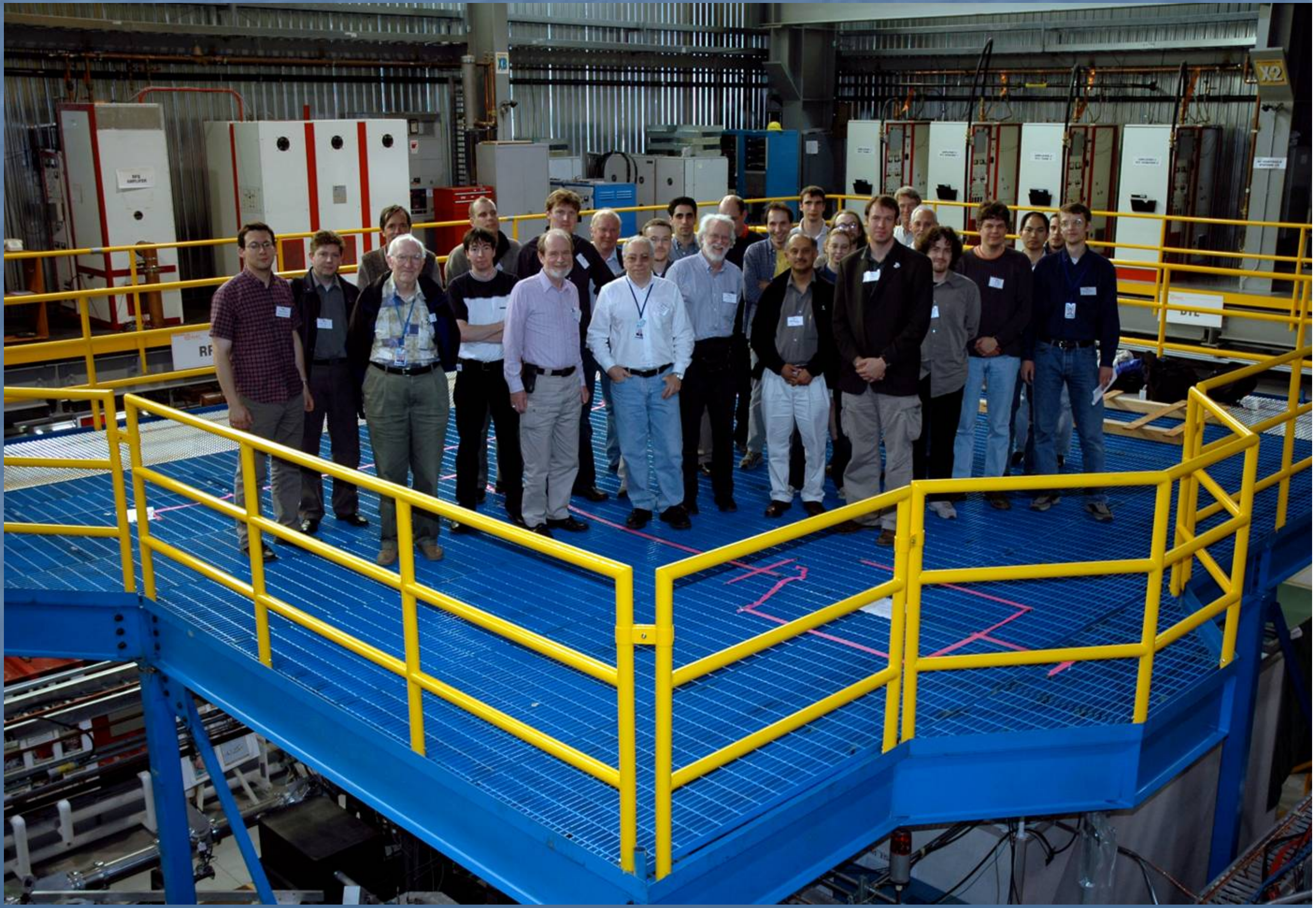
TITAN collaboration:

R. Baartman, P. Bricault, F. Buchinger, J. Crawford, J Dilling, P. Delheij, G. Drake, G. Gwinner, J. Lee, B. Moore, M Pearson, K. Sharma, R. Thompson, W. Van Weijngaarden J. Crespo, J Ullrich & J Vaz, V. Rijkov, G. Sikler, A. Lapierre (PDFs), M. Smith, L. Blomley, M. Brodeur, Z. Ke, M. Froese, C Champagne (students)

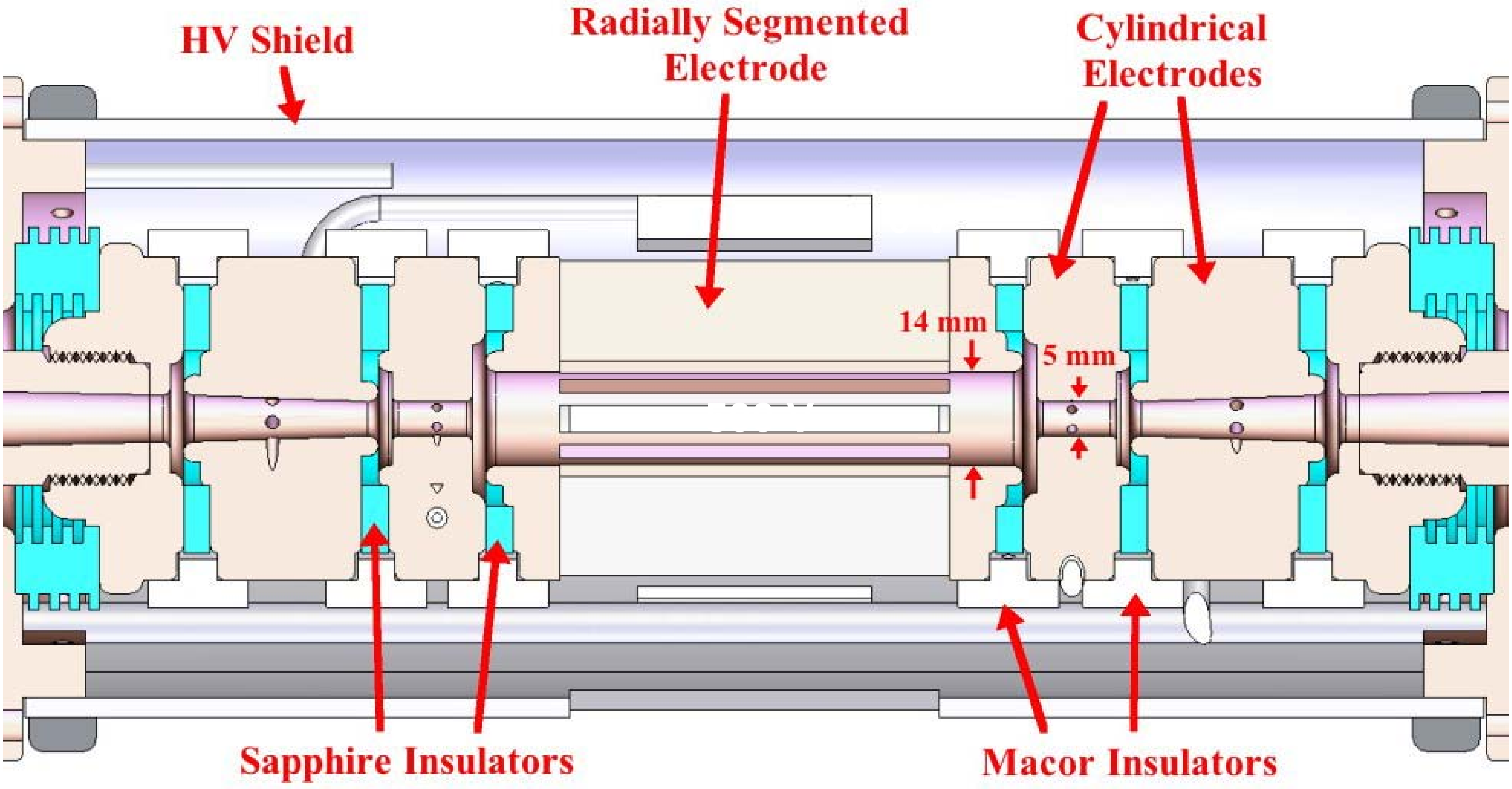
TRIUMF
McGill
U Manitoba
York
Windsor
Calgary.
MPI-HD

And maybe you?
www.triumf.ca/titan

Thank you
for your attention!

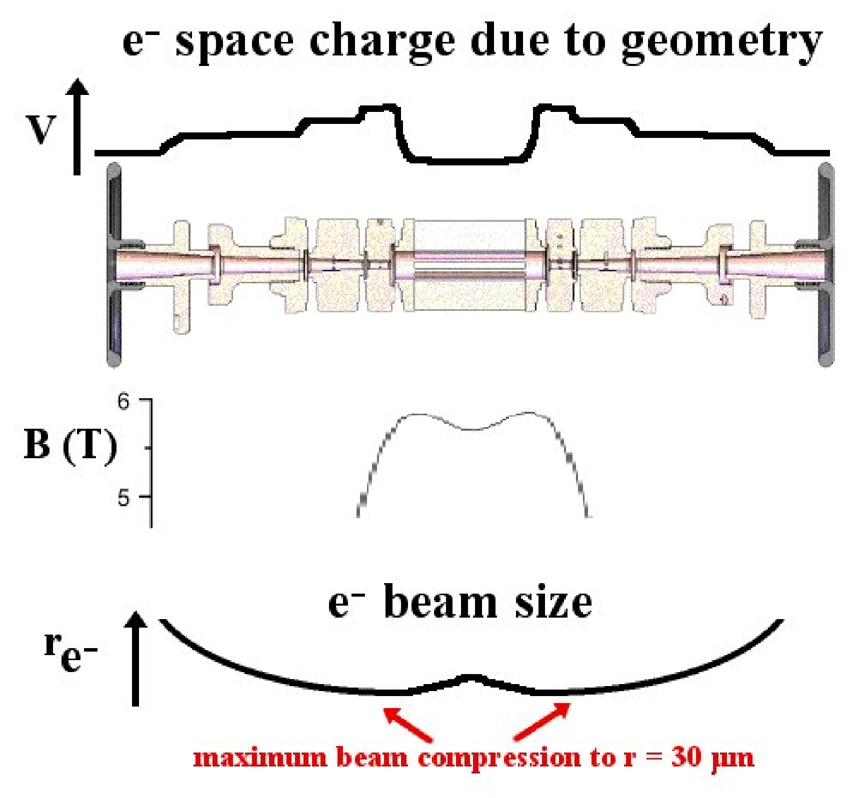


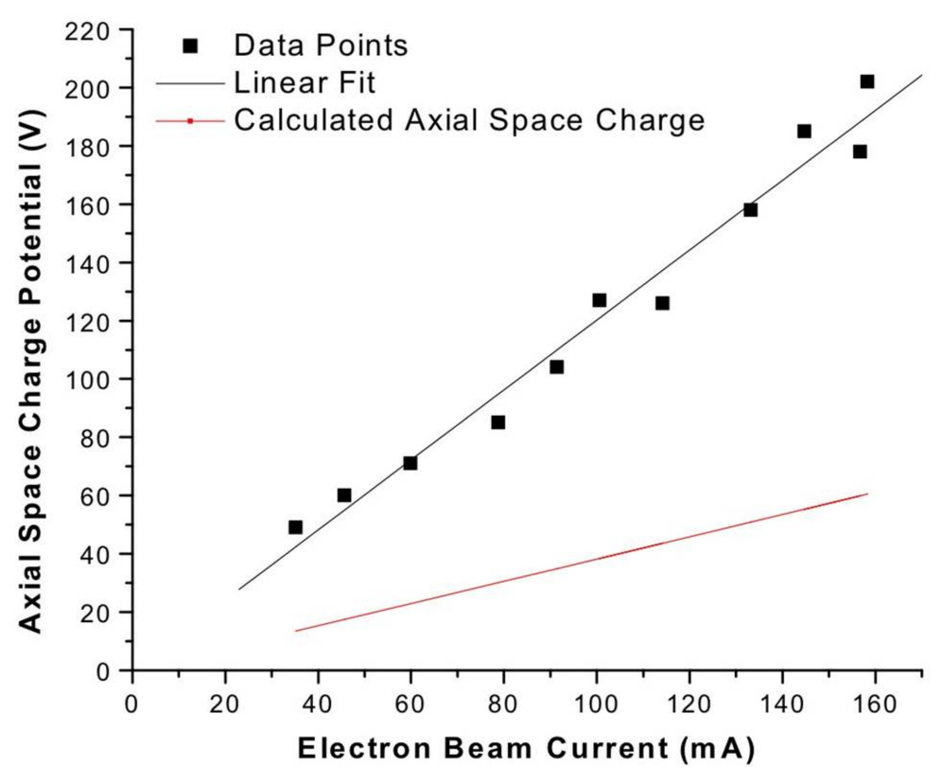
Trap Cross-section



Axial Space Charge

- Conclusions
  - More effective ion trapping
  - Further study



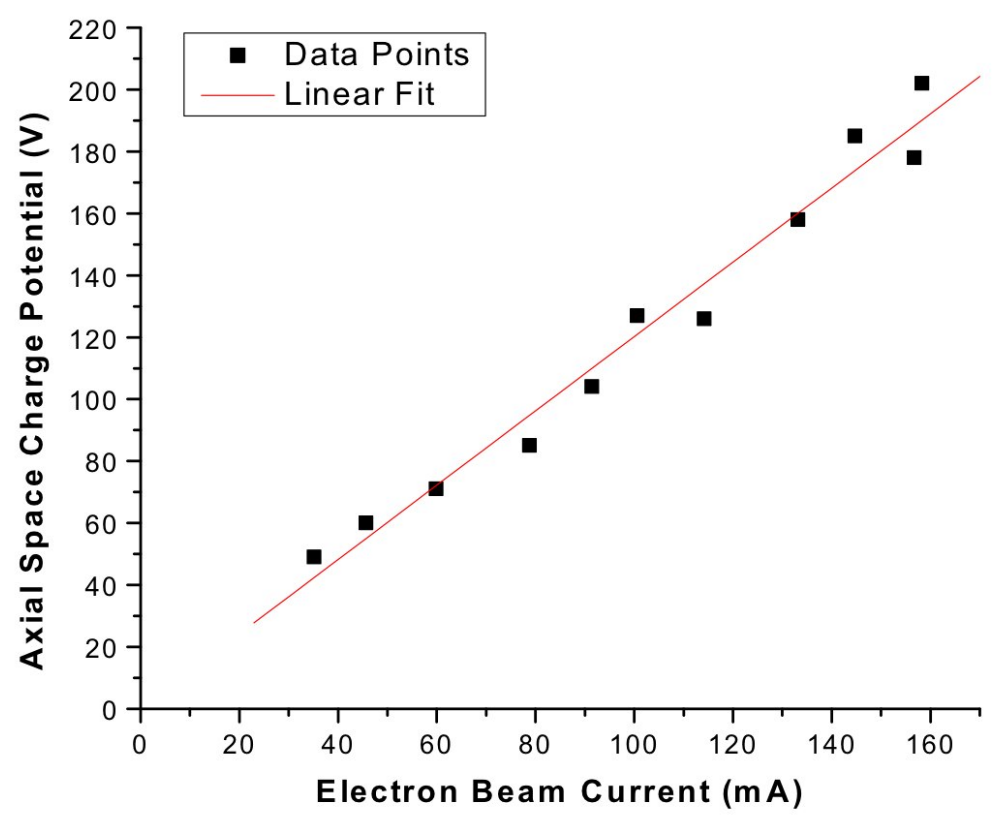


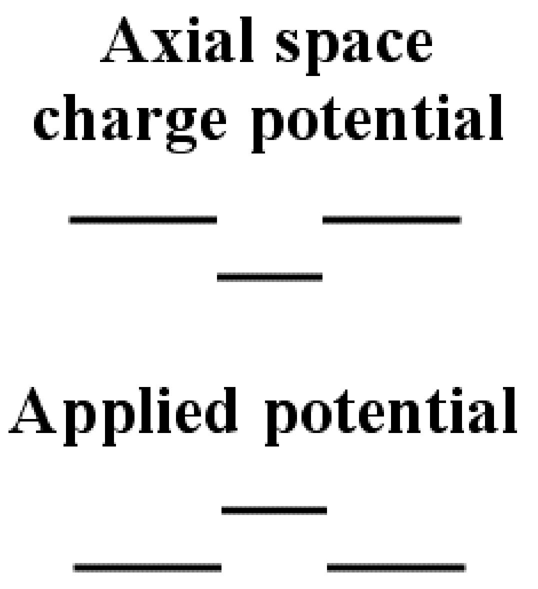
$$V_{\mathrm{SpC}}(r \geq r_H) = \frac{I_e}{2\pi\epsilon_0 v_e}\ln\left(\frac{r}{r_{\mathrm{trap}}}\right)$$

$$V_{\mathrm{SpC}}(r \leq r_H) = \frac{I_e}{4\pi\epsilon_0 v_e}\left[\left(\frac{r}{r_H}\right)^2 + \ln\left(\frac{r_H}{r_{\mathrm{trap}}}\right)^2 - 1\right]$$

Axial Space Charge

- Effects extracted ion temperature





Axial space charge potential

Applied potential

- $k_b T_{ion} \approx 0.1\ q\ V_{well}$

- Agrees with spectral line width measurements from the SuperEBIT and the HD EBIT