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Mass measurements: Experiment (1)

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and

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Outline

- Definitions and scale
- Required accuracy
- Deflection type spectrometers
- Time-of-flight spectrometers
- Cooling of radioactive ions
- Ion traps spectrometer
- Schottky technique in storage rings
- Q-value measurements by reaction and decay
- Consistency check

Basic considerations

- Atomic mass unit
  - $u = m(^{12}C)/12 = 931494.009\ keV/c^2$

- Mass of the constituents
  - $m_n = 939.565\ MeV/c^2 = 1.00866491574(56)\ u$
  - $m_p = 938.272\ MeV/c^2 \Rightarrow m(^1H) = 1.00782503207(10)\ u$
  - $m_e = 0.51100\ MeV/c^2$

- Mass of a nucleus
  - mass of constituents plus binding energy (usually negative … not always)

$$B = \{m(A,Z) - Z\,(m_p+m_e) - N\,m_n\}\,c^2$$

  - huge amount of stored energy
  - binding energy is about 8 MeV/*u*, that is 8/938 ~ 0.7% of the total rest mass energy. That is the fraction that can be released by nuclear reactions … still enough to power the sun and other stars.

$$B(^{12}C)/c^2 \sim 6X(1.0087 + 1.0078) - 12X1 \sim 0.099\ u \sim 0.8\%\ of\ m(^{12}C)$$

Binding energy and mass excess

- **Binding energy is the energy that is released when a nucleus is assembled from neutrons and protons**

$$m(Z,N) = Zm_p + Nm_n - Bc^2$$

  - **Once B is known, the mass of the nucleus is determined**
  - **B is roughly ~A**

- **Masses are usually tabulated as atomic masses**

$$m = m_{nuc} + Z\,m_e - B_e/c^2$$

Nuclear Mass
~ 1 GeV/c² per A

Electron Mass
511 keV/c²

Electron Binding Energy
13.6 eV (H)
to 116 keV (K-shell U) / Z

Most tables give atomic mass excess Δ in MeV: $\Delta(A,Z) = (M(A,Z) - Am_u)c^2$

(with $m_u = M(^{12}C)/12 = 931.478$ MeV/c² and for ^{12}C: $\Delta = 0$)

The Q-value for A+B → C can then be expressed as: $Q = \Delta(A) + \Delta(B) - \Delta(C)$

Required accuracy

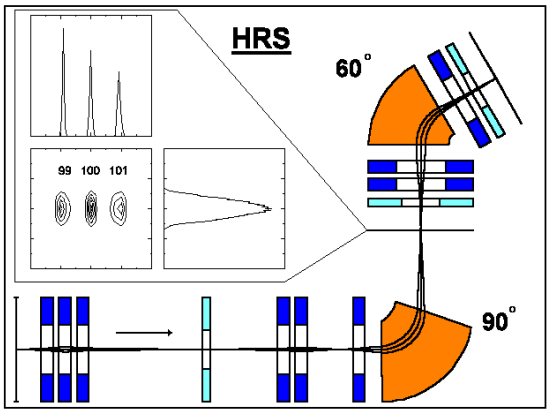
- Mass resolution and accuracy of the measurement determines the physics you are sensitive to (A~100)

$\Delta m/m$	Mass accuracy	physics
~ 10^{-2}	~ 1GeV/c^2	number of nucleons
~ 10^{-3}	~ 100 MeV/c^2	atom vs molecule
~ 10^{-5}	~ 1MeV/c^2	isobar
~ 10^{-6}	~ 100 keV/c^2	nuclear mass calculations
~ 10^{-7}	~ 10 keV/c^2	astrophysics, nuclear structure
~ 10^{-8}-10^{-9}	~ 0.1-1 keV/c^2	superallowed decay, $\beta\beta$-decay
~ 10^{-10}-10^{-11}	~ 1-10 eV/c^2	electronic binding energy
~ 10^{-12}	~ 0.1 eV/c^2	vibrational energy

- For nuclear physics and astrophysics, the requirement is typically 10^{-6} to 10^{-9} accuracy.

Tools of the trade

- **Tools of various size, cost and accuracy … no direct relationship between these quantities**



Deflection type separator

TOF spectrometer: SPEG

TOF or Schottky: ESR

Penning trap spectrometer

Accuracy is not the full story

- **Specific applications might have other requirements besides accuracy**
  - ***mass models are not that accurate***
    - **No mass model has predictive accuracy better than 300 keV/c² … e.g. comparison to 310 masses measured at the FRS**

$$\sigma_{rms}^2 = \frac{1}{N}\sum_{i=1}^{N}(m_i^{exp} - m_i^{theory})^2$$

Mass model	σ_{rms} /keV
FRDM	372
FRLDM	696
Spanier-Johanson	1210
Myers-Swiatecki	395
Duflo-Zucker	668
HF+BCS	960
HFB	650

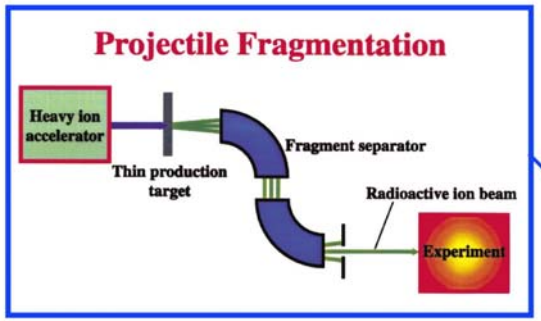
  - **to progress, models need anchor points very far from stability … they need reach, i.e. sensitivity**
- **Specific nuclei versus representative cases**
  - **in some cases, only that nuclei will do**
    - ***superallowed emitters, waiting point nuclei, …***
  - **need measurement technique matched to the production of that specific nuclei**

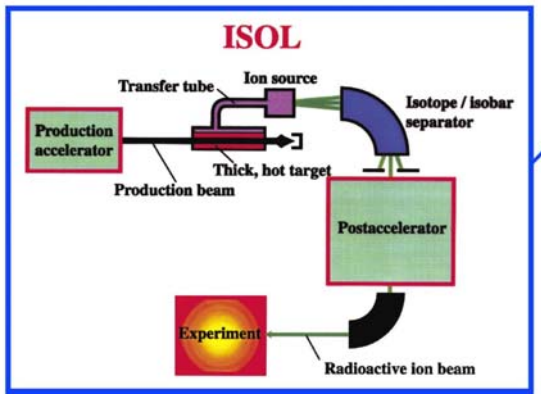
Production methods for beams of short-lived isotopes: beam properties determine the measurement techniques applicable

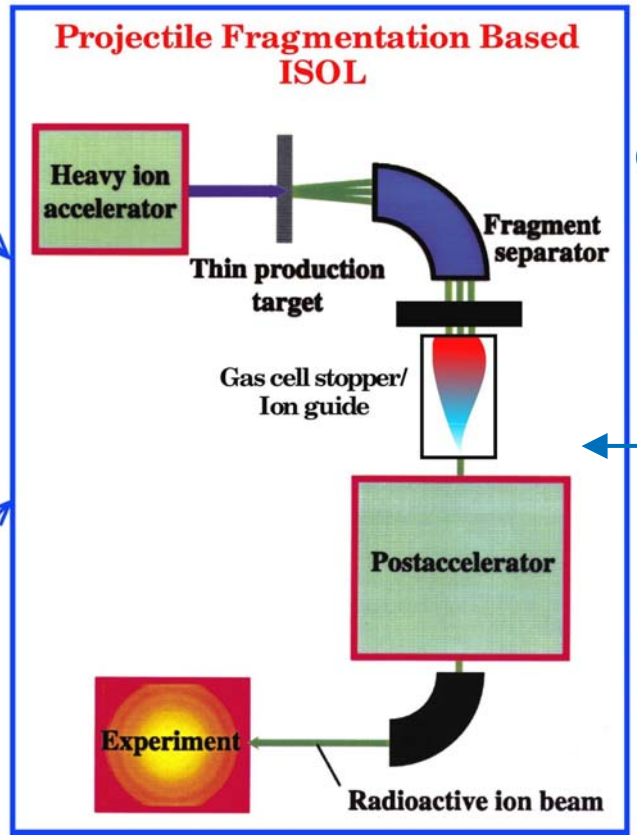
- Fast Extraction Times (~msec)
- Chemical independence
- Isobar separation

GSI, RIKEN, MSU, GANIL

ISAC II, REX-ISOLDE, HRIBF







In-flight generated beam stopped and cooled to ISOL beam energies and properties

Fusion-evaporation: ANL, GSI

Fragmentation: GSI, MSU, RIKEN

Mass measurement approaches

- **Indirect**
  - **Decay (2 or 3 body final state)**

    $A \rightarrow B + b$ $\qquad$ $Q_b = m_A - m_B - m_b$
  - **Reaction**

    $a(A,B)b$ $\qquad$ $Q = m_A + m_a - m_B - m_b$
  - **Quantum mechanics**

    $\nu_e \leftrightarrow \nu_u$ $\qquad$ $K \leftrightarrow \bar{K}$

- **Direct (less indirect)**
  - **Deflection spectrometer**
  - **Time-of-flight spectrometer**
  - **Cyclotron frequency measurement**

Method of choice depends on production method, yield, lifetime, and accuracy required.

Beginnings of nuclear mass spectrometry

- Pioneering work by J.J. Thomson around the early 1900s using a positive ray parabola apparatus (mass resolution of about 10!)

- Mass spectrometry field really started with A.J. Dempster (1918) and F.W. Ashton (1919)
  - Deflection type mass spectrometer
    - *Ion source at voltage V*

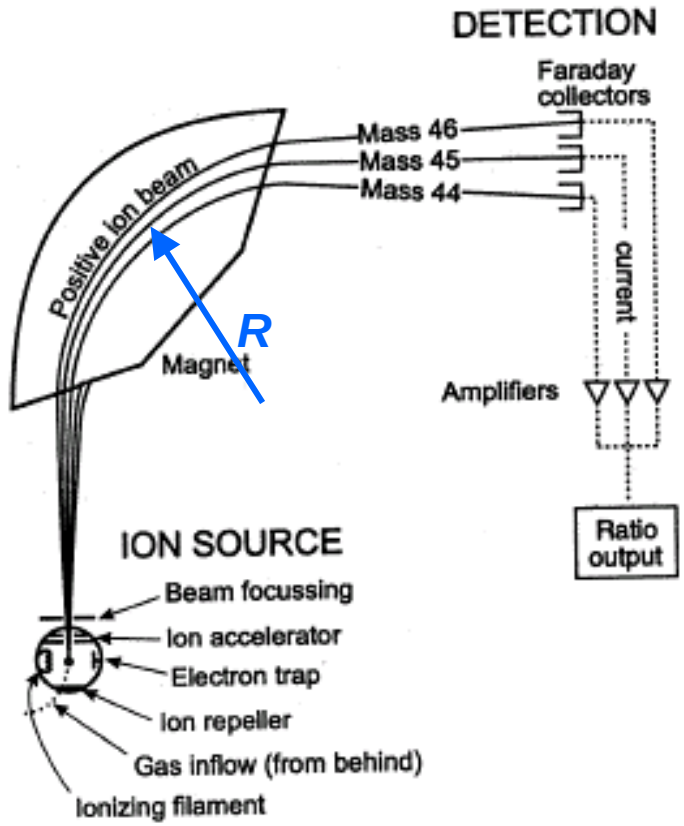
$$E = eV = mv^2/2$$

    - *Magnetic sector with field B*

$$F_c = mv^2/R = q\vec{v} \times \vec{B} = qvB$$

Brho

$$BR = \frac{mv}{q} = \frac{p}{q} = \frac{\sqrt{2mE}}{q}$$



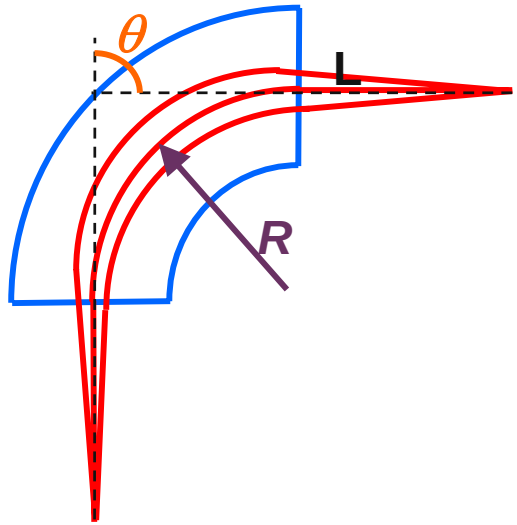
Deflection type spectrometer: dispersion

- **Radius of curvature depends on p/q**

$$R = \frac{mv}{qB} = \frac{p}{qB} = \frac{\sqrt{2mE}}{qB}$$

  - **different masses will have different R**
  - **image is displaced laterally**

$$d \sim L\,\delta\theta \sim K\,\delta R$$



- **Dispersion in mass, momentum and energy**
  - ***from equation above:***

$$\frac{\delta R}{R} = \frac{\delta p}{p} = \frac{\delta m}{2m} = \frac{\delta E}{2E}$$

mass dispersion = energy dispersion = ½ momentum dispersion

  - ***momentum dispersion typically in cm/%***
  - ***cannot separate mass and energy dispersion***

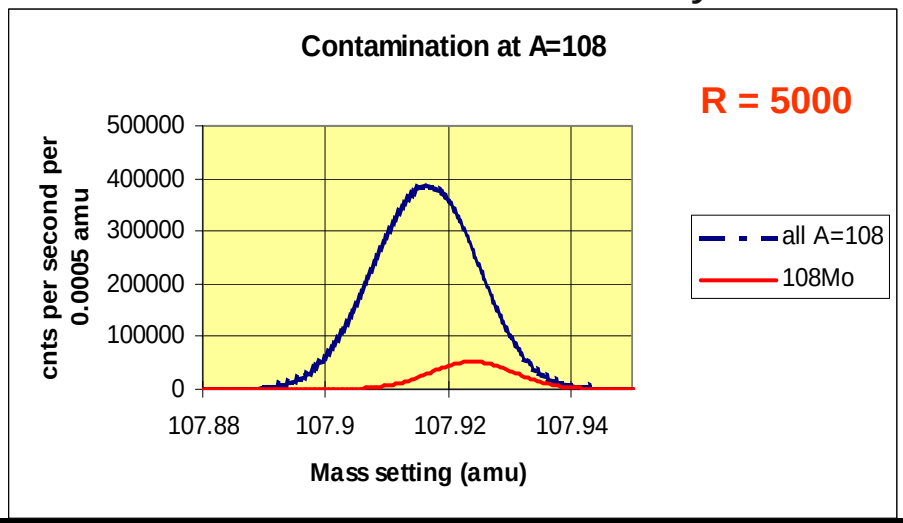
Deflection spectrometer: resolution and accuracy (1)

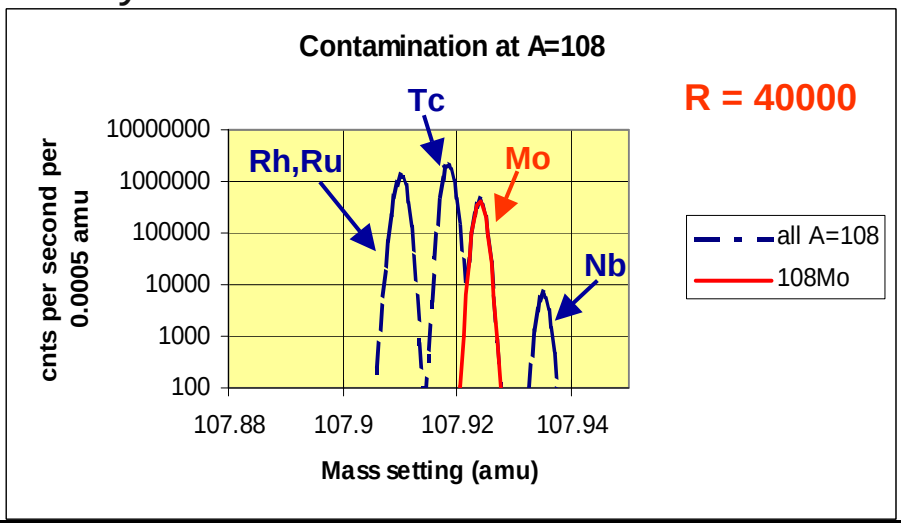
- Resolution is a measure of how well a spectrometer can separate different mass peaks:

$$R = \left(\frac{peak\ width}{dispersion} \right)^{-1} = \left(\frac{f(\varepsilon, \delta E, D)}{D} \right)^{-1}$$

with: ε = *emittance*, δE = *energy spread*, D = *dispersion*

  - *Magnetic field imperfections or optical aberrations can limit resolution*
  - *resolution not only a function of the spectrometer*
    - *energy spread will limit resolution*
    - *better transverse beam emittance can improve resolution*
- Resolution provides selection
  - Can't measure it if you can't identify it!



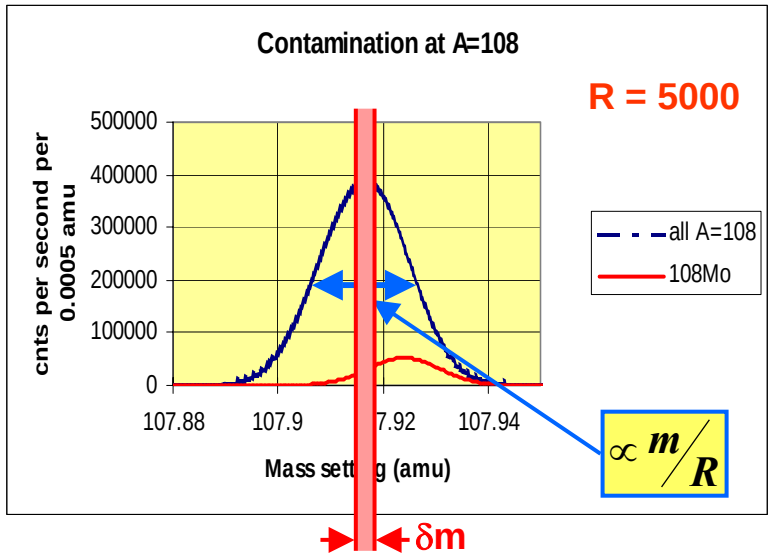


Deflection spectrometer: resolution and accuracy (2)

- Precision … and hopefully accuracy
  - Precision: how well you can determine the centroid of the peak

$$\delta m \propto \frac{m}{R\sqrt{N}}$$

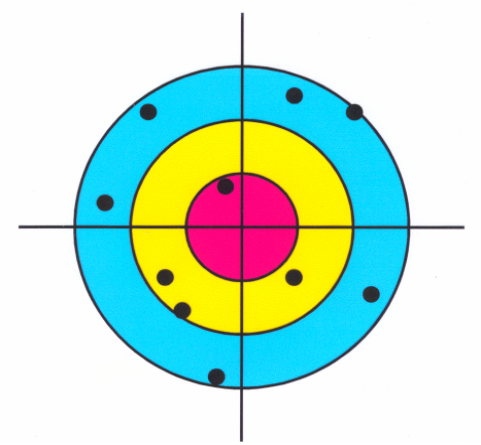
with: δm = mass uncertainty
R = mass resolution
N = counts in the peak



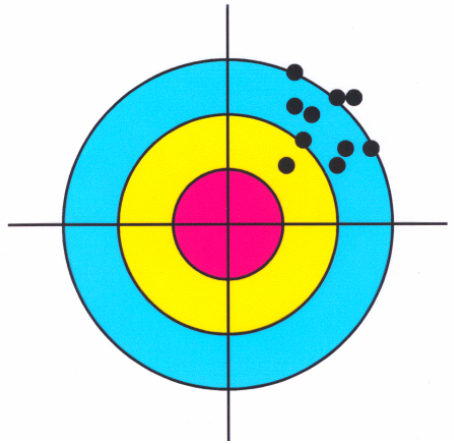
  - Accuracy: how well you can relate that centroid to a mass value

- Systematic errors
  - voltage and magnetic field calibration and stability
  - plasma potential, …. anything that can affect the energy of the ions

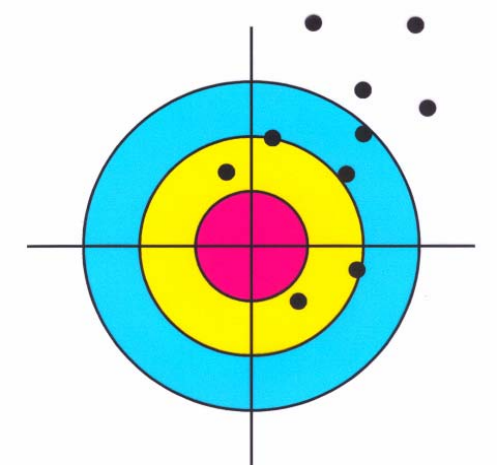
Difference between precision and accuracy



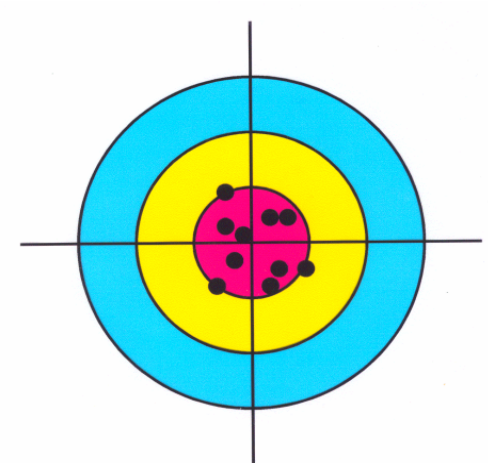
low precision, high accuracy



high precision, low accuracy



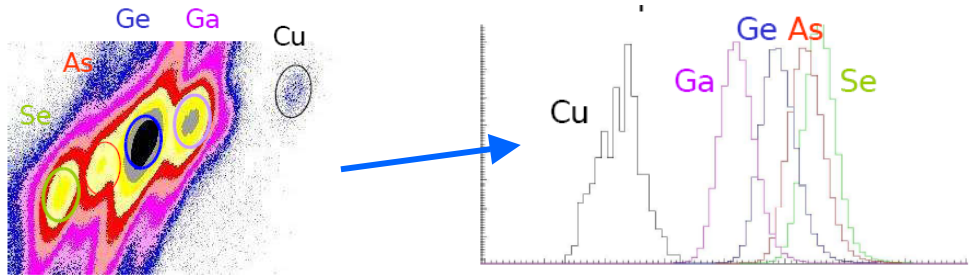
low precision, low accuracy



high precision, high accuracy

Deflection spectrometer: resolution and accuracy (3)

- **Practically achievable resolution**
  - **Ashton (1918): flat field magnet → R ~ 130**
    Chalk River (1980s): n=1/2 magnet → R ~ 7000-20000
    CARIBU (now): 2 flat field magnets → R ~ 20000
  - **limitations**
    - ***Field homogeneity***
    - ***Field and voltage stability***
    - ***Beam properties***
- **Achieved accuracy**
  - **Chalk River → ~10^{-6} accuracy on short-lived isotopes**
    - ***decay tagging to improve isobar identification***
  - **Oak Ridge → ~10^{-5} accuracy on short-lived isotopes**
    - ***energy loss to identify isobars***



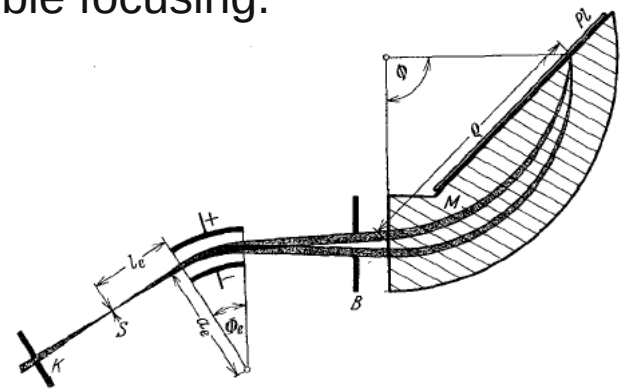
Double focusing spectrometer

- Main limitation of deflection type spectrometer is the intrinsic energy dispersion
- Electrostatic sectors have energy dispersion but no mass dispersion

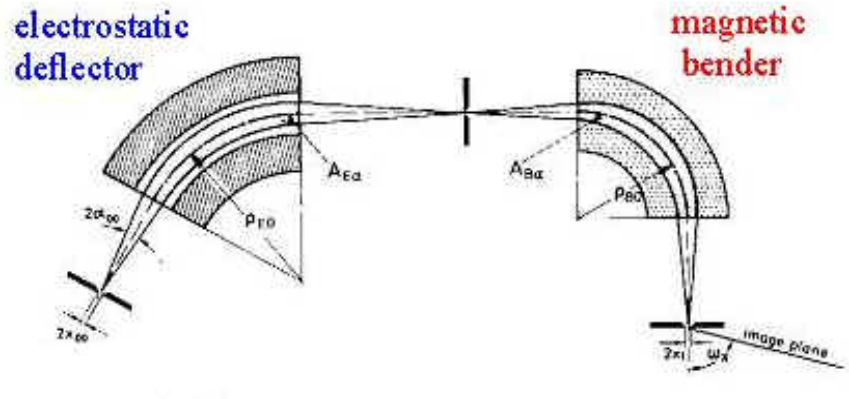
$$F_c = mv^2/R = qE \quad \rightarrow \quad dR/R = dE/E$$

electric field — *energy* — ***and no mass dispersion***

- Adding an electrostatic sector of equal energy dispersion to a deflection type spectrometer can remove the energy dispersion and significantly enhance the resulting mass resolution. Spectrometer is then focusing in angles and energy … double focusing.



Mattauch-Herzog spectrometer (1934)



Minnesota, Manitoba I and II (1970s - …)

Double focusing spectrometer (2)

- Achieved resolution
  - m/Δm ~ 50000 to 500000 in about a dozen devices

- Precision/accuracy
  - high resolution but limited stability
    - magnetic field fluctuations
      - *temperature variations, electronic noise, …*
      - *$\Delta B/B < 10^{-6}$ is hard when not closed loop superconducting*
    - voltage fluctuations, …
  - Solve by fast peak matching and averaging
    - jump from one peak to the other at the rate faster than the fluctuations
  - Accuracy of ~ 2-3 X 10^{-9} with Argonne, Minnesota and Manitoba II spectrometers

- Still subject to systematic errors due to ion source effective potential

Time-of-flight mass spectrometer

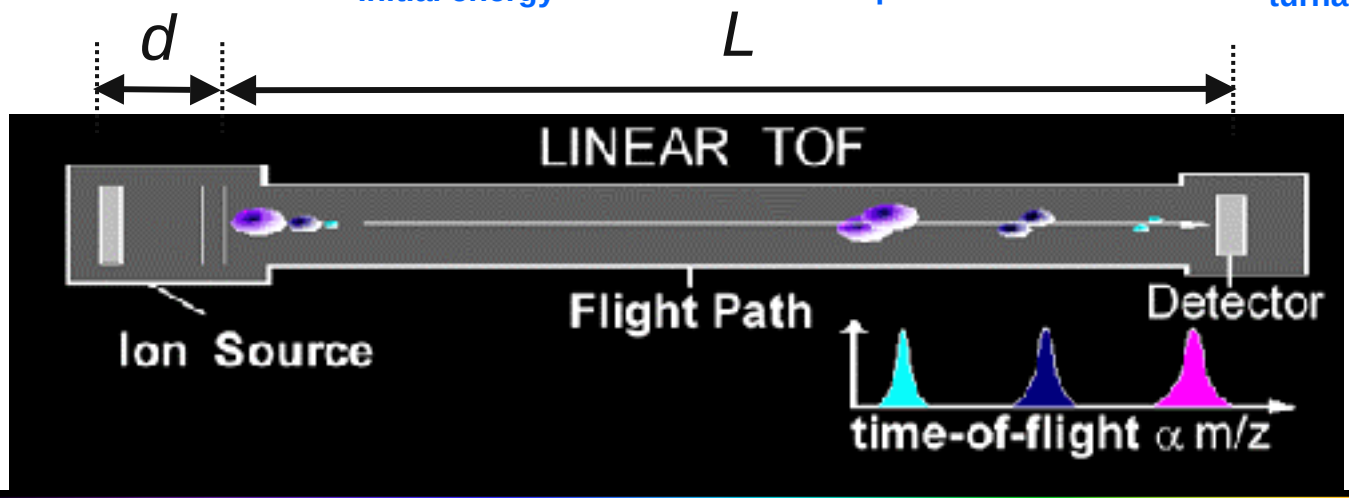
- Basic TOF spectrometer (first proposed by Stephens in 1946)
  - charged particle in an electric field E of length d gains energy V_0 and drift over distance L before reaching a detector
    - *For ions initially at rest we get :*

$$t = t_s + t_D \quad ; \quad t = \left(\frac{2md}{eE}\right)^{\frac{1}{2}} + L\left(\frac{m}{2eV_0}\right)^{\frac{1}{2}} \longrightarrow \boxed{\frac{\Delta m}{m} = \frac{2\Delta t}{t}}$$

    - *If the ions starts with an initial energy U_o at position s_0:*

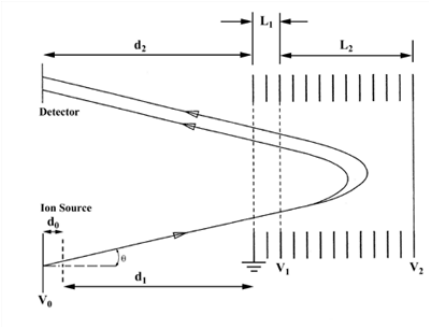
$$t = t_s + t_D + t_0 \quad ; \quad t = \frac{(2m)^{\frac{1}{2}}}{eE}\left[(U_0 + eEs_0)^{\frac{1}{2}} \mp U_0^{\frac{1}{2}}\right] + \frac{(2m)^{\frac{1}{2}} D}{2(U_0 + eEs_0)^{\frac{1}{2}}} + t_0$$

Initial energy — Initial position — turnaround time



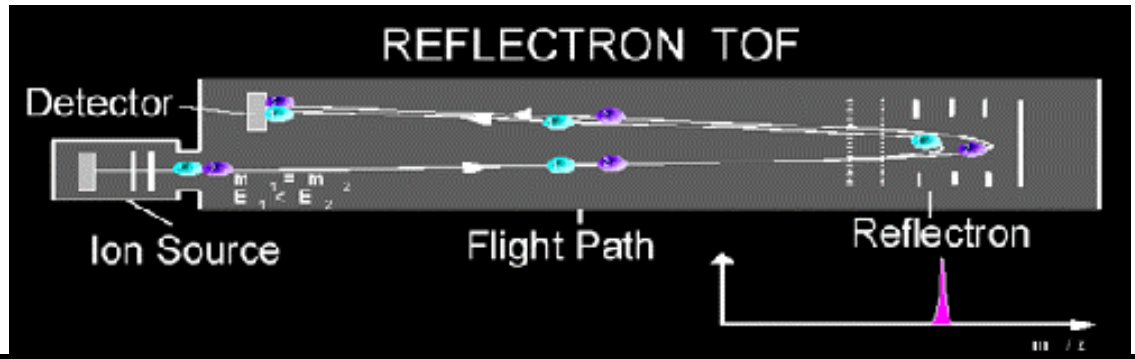
Time-of-flight mass spectrometer

- Reflectron TOF spectrometer
  - correct for initial energy spread by having higher energy ions go through a longer path inside an electrostatic reflector

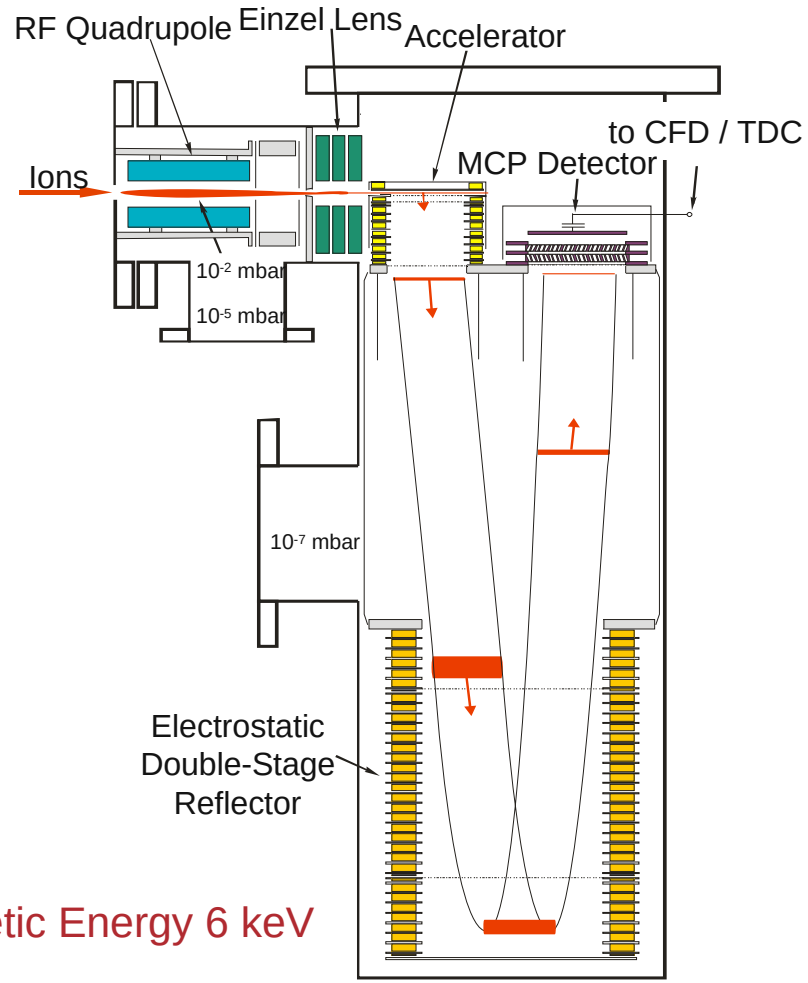


  - still get a simple a simple mass-tof relationship after calibration, but with better resolution

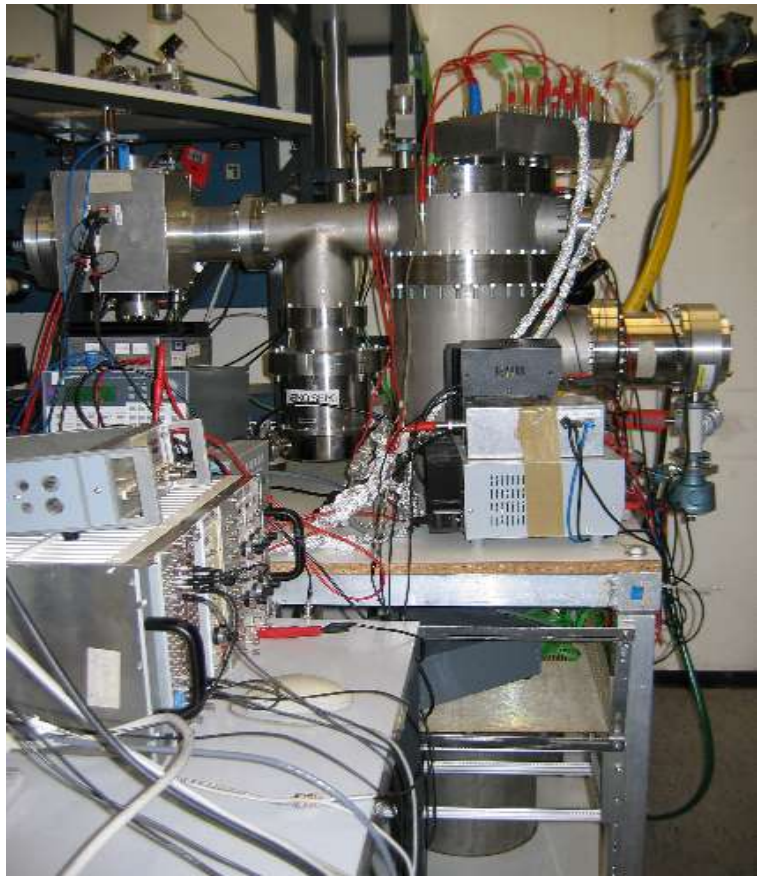
$$m = q(at + b)^2$$



Ortho-TOF mass spectrometer



Kinetic Energy 6 keV



1.7 m

(W.R. Plaß)

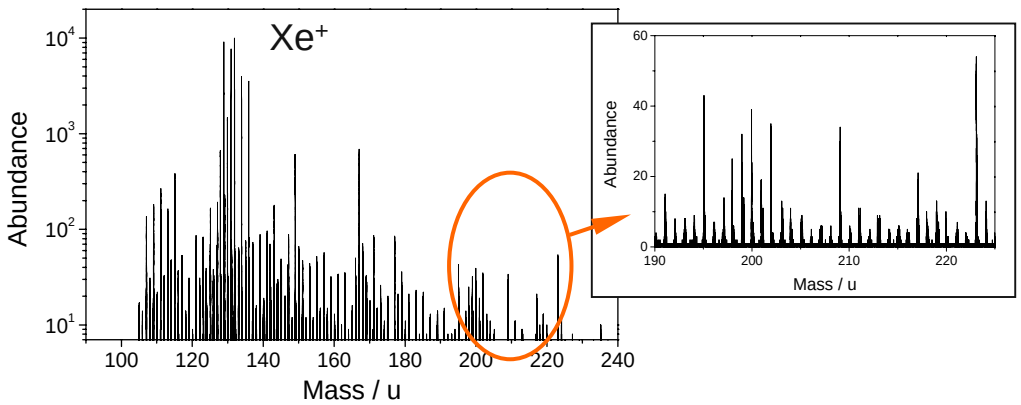
Mass Resolving Power: 10^4...$2 \cdot 10^4$
Mass Measurement Accuracy: 1-3 X 10^{-6}
Overall Efficiency (Cooling, Bunching, Mass Analysis, Detection): 1-3 %
Mass Measurement Cycle Duration: < 1 ms

Ortho-TOF spectrometer (2)

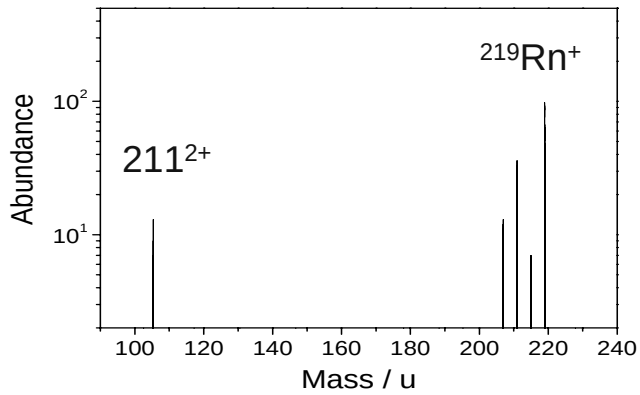
- advantage
  - full mass spectra can be observed in one shot
  - fast
  - no practical mass range limit
- disadvantage
  - requires a start signal → pulsed beam
  - requires a good quality low energy beam

Diagnosis of gas catcher purity

No cold trap, no baking

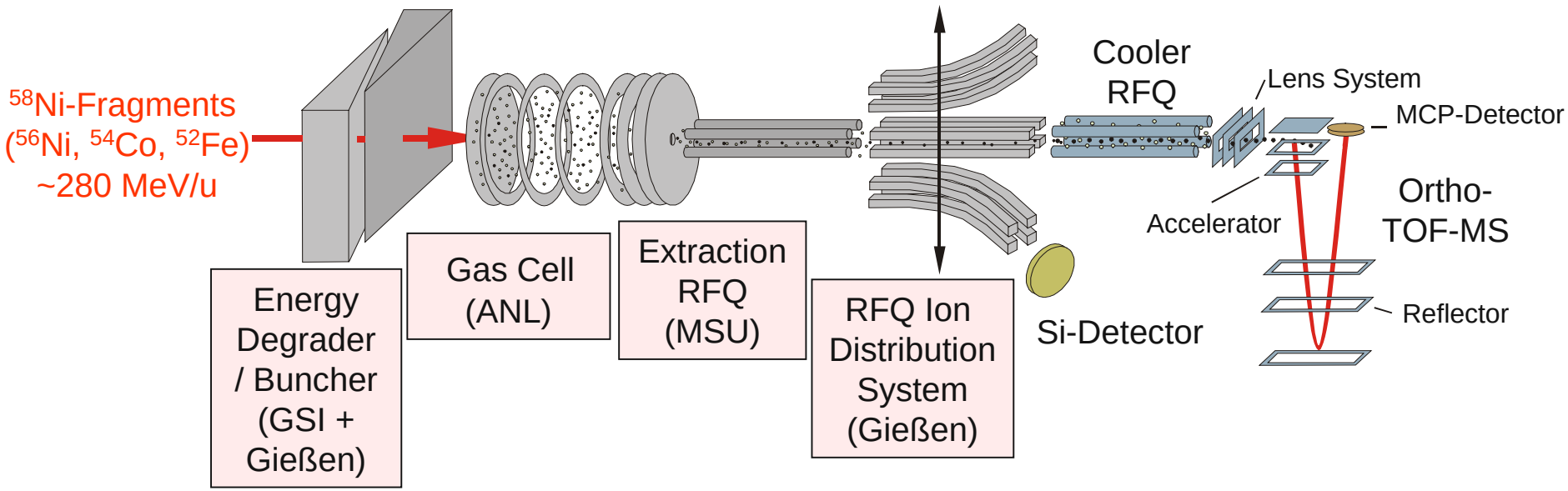


cold trap, after baking



Ortho-TOF spectrometer (3)

- Achieving the right beam properties to use such devices online can mean a significant investment in the front end at fast beam facilities

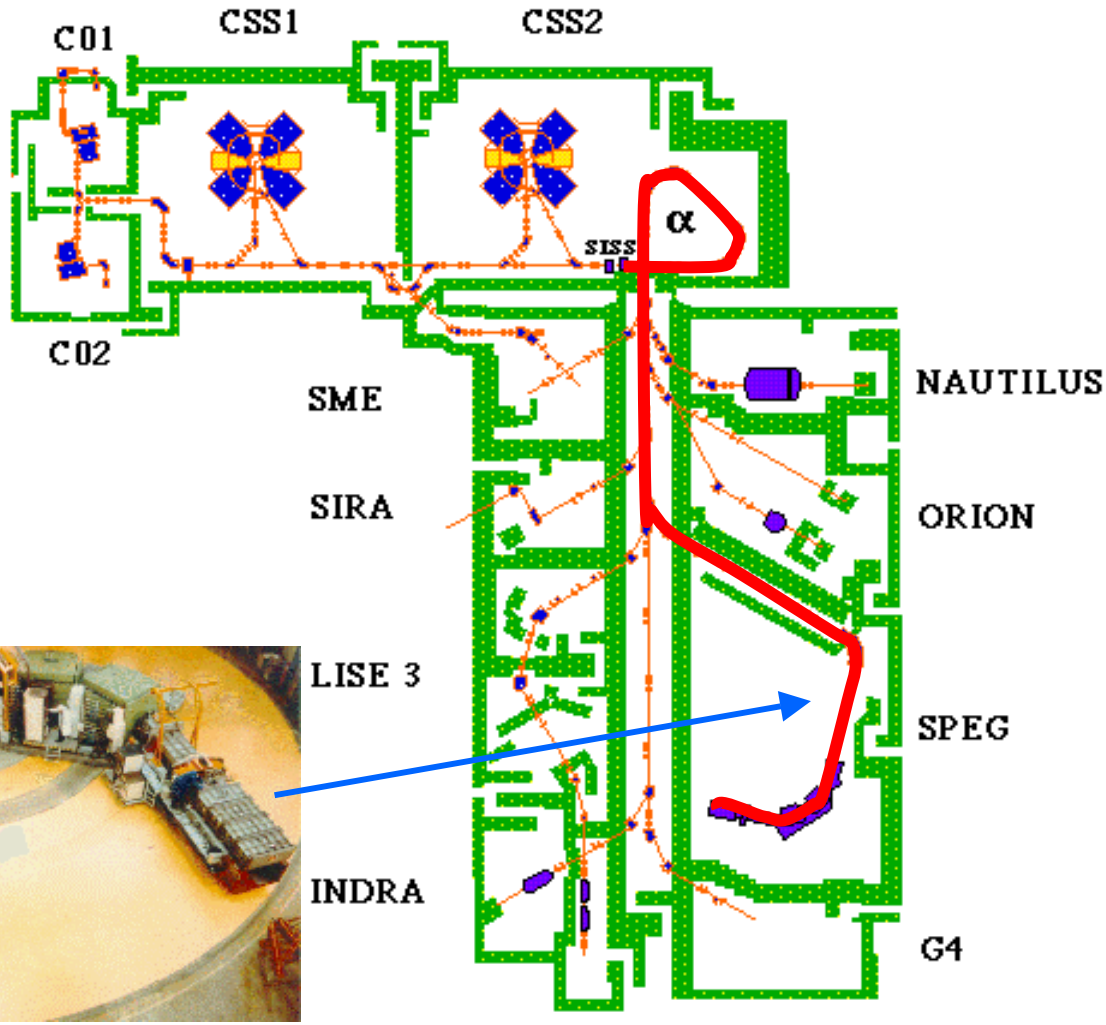


TOF spectrometer: SPEG at GANIL

- Use GANIL as a whole as a TOF spectrometer
- long flight path

  L ~ 82 m → tof ~ 1 μs
- momentum spread corrected by rigidity measurement in SPEG
- obtain mass from

  $B\rho = \gamma m_0 v/q$



TOF spectrometer: SPEG at GANIL (2)

- **Advantage**
  - well matched to GANIL energies (~ 90 MeV/u)
  - produce many species simultaneously
    - *calibration*
  - isotope with very short lifetime can be measured
  - extremely sensitive … far reach

- **Disadvantage**
  - limited resolution
    - *200 ps / 1 μs ~ 2 X 10^{-4}*
  - limited accuracy
    - *~ 10^{-5} - 10^{-6}*

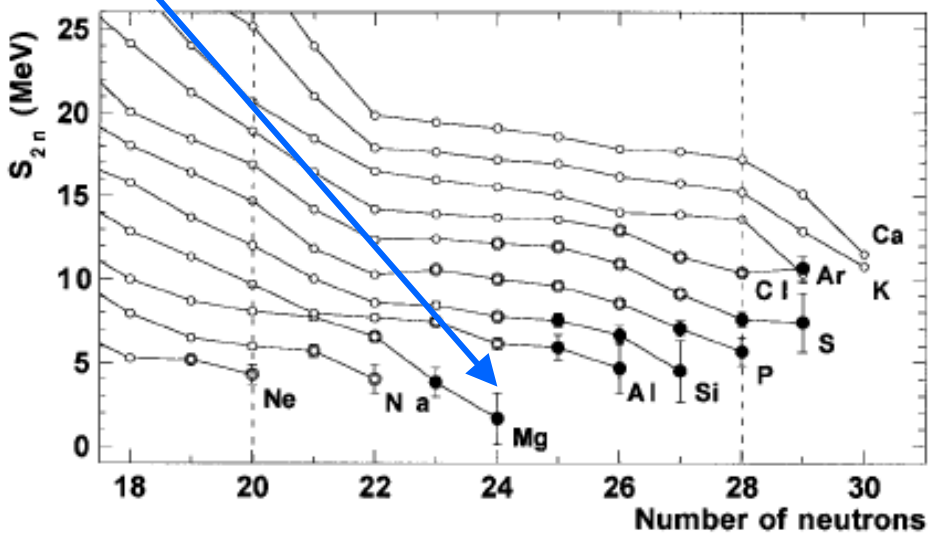
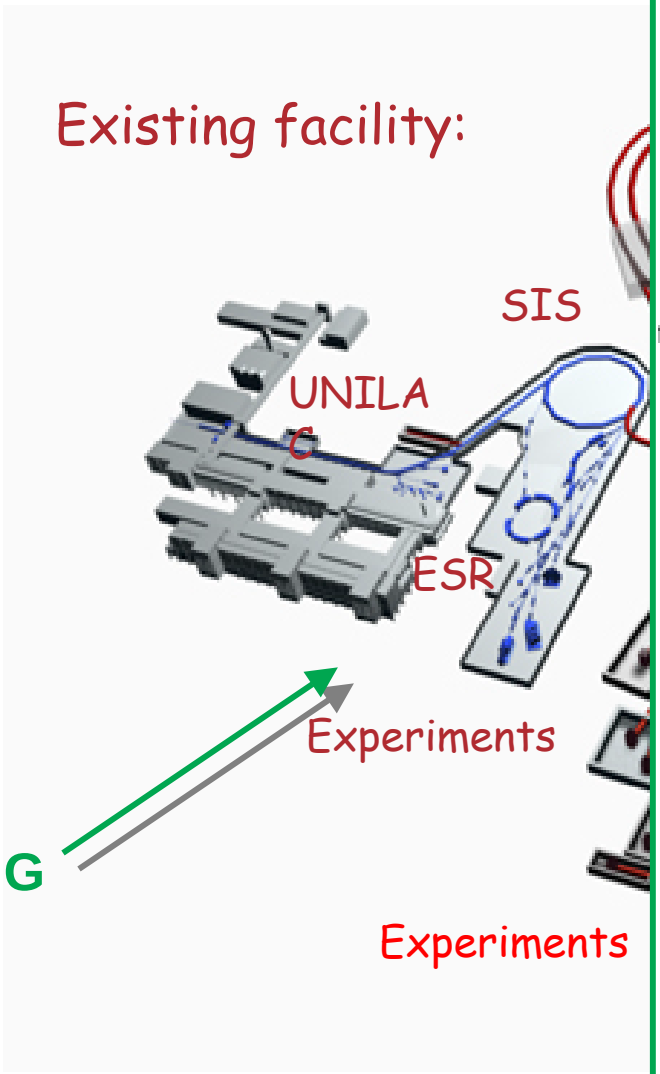
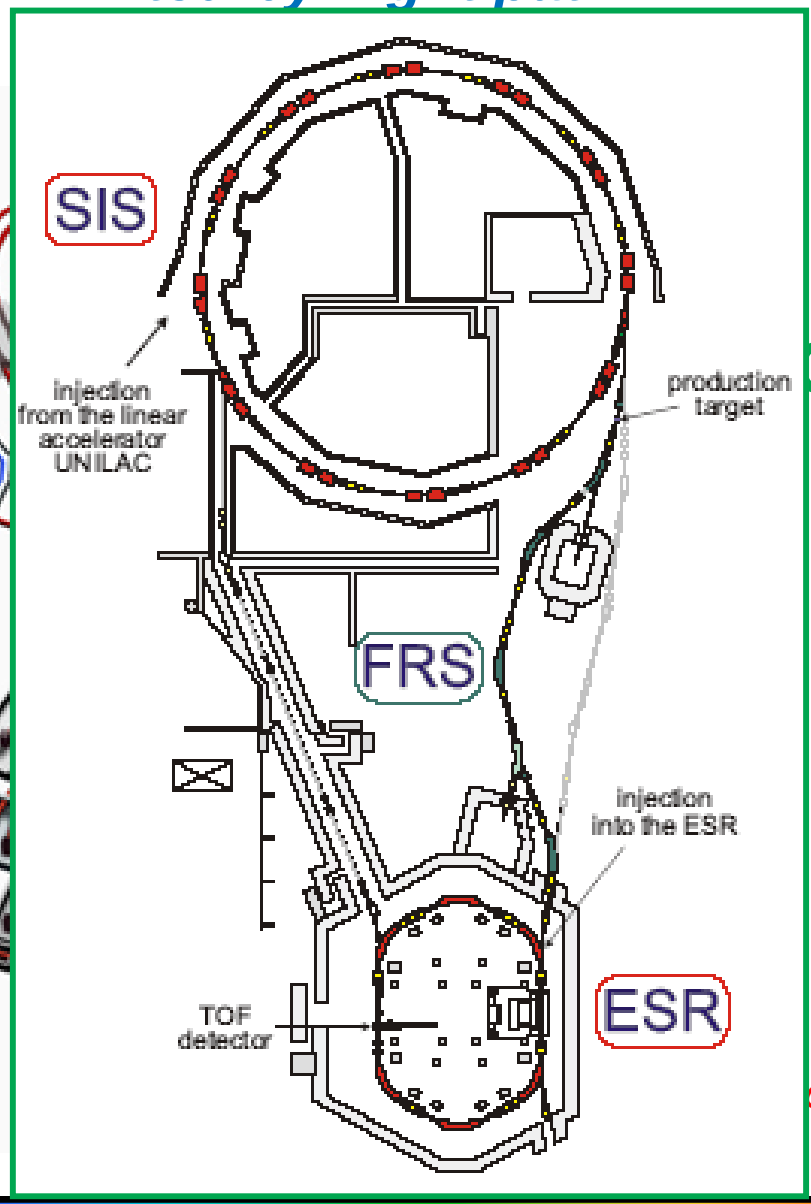


Figure 4. Experimental S_{2n} values in the region of the $N = 20$ and $N = 28$ shell closures. The circles correspond to values from [25], the bold circles to values for which the precision was improved and the full circles to masses measured for the first time.

TOF spectrometer: resolution limited by flight path





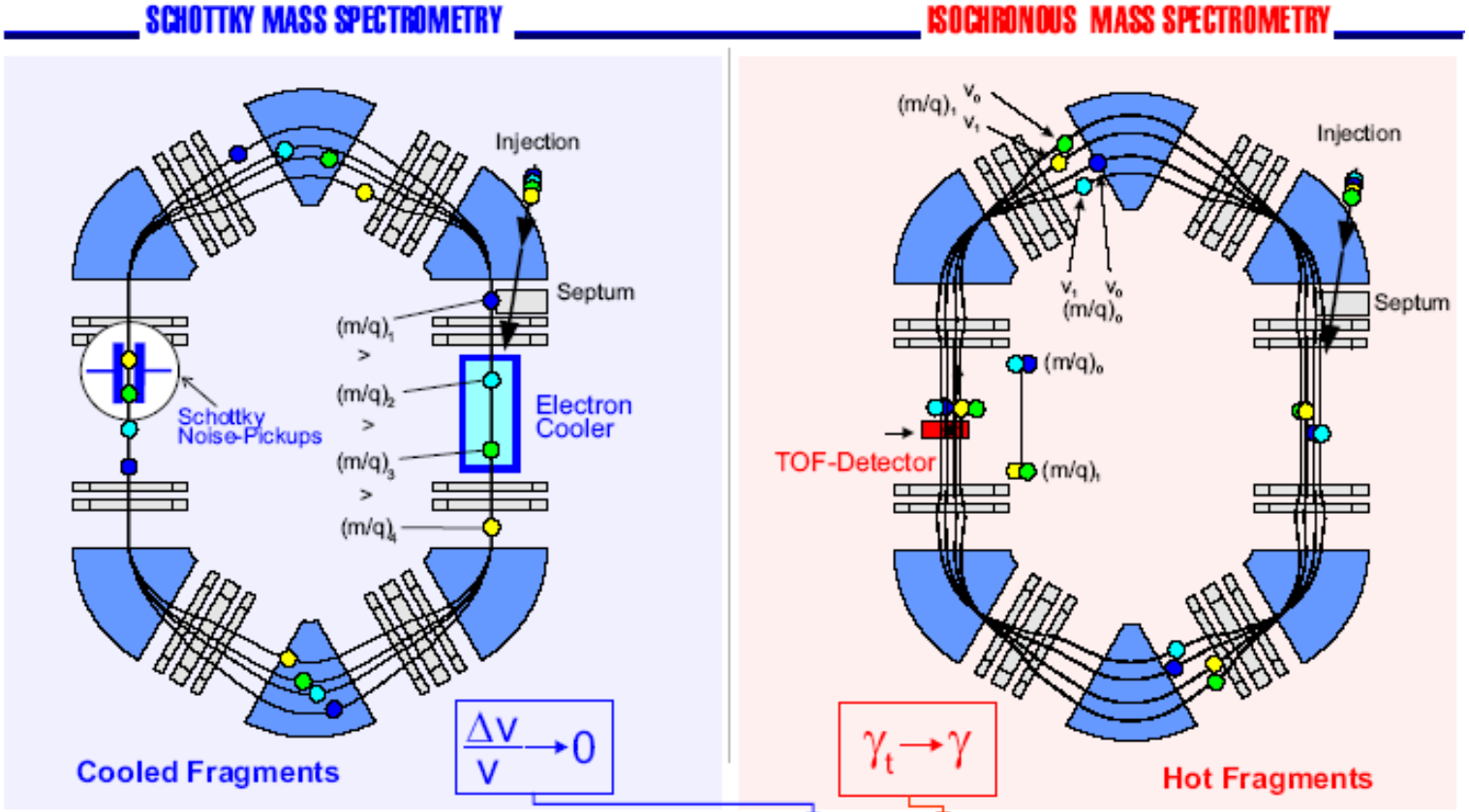
GER

cs)

TOF mass measurements at the ESR

- To get resolution in a TOF system, you need distance

→ *storage ring in isochronous mode* ←



$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

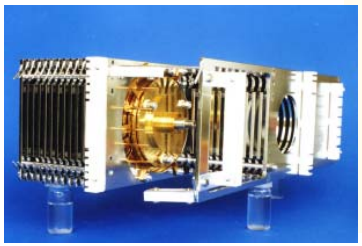
TOF mass measurements at the ESR (2)

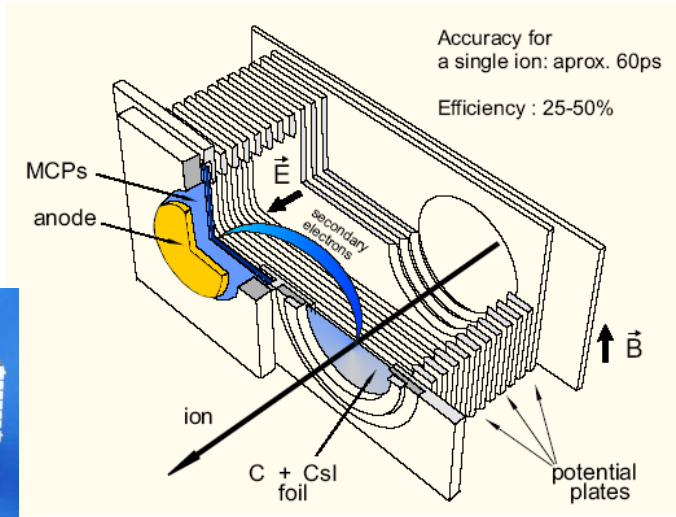
- Last term in frequency equation below must be made small
  - Reduce energy spread by cooling → introduce long delay
  - Run ring in isochronous mode → no cooling required

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right) \rightarrow 0$$

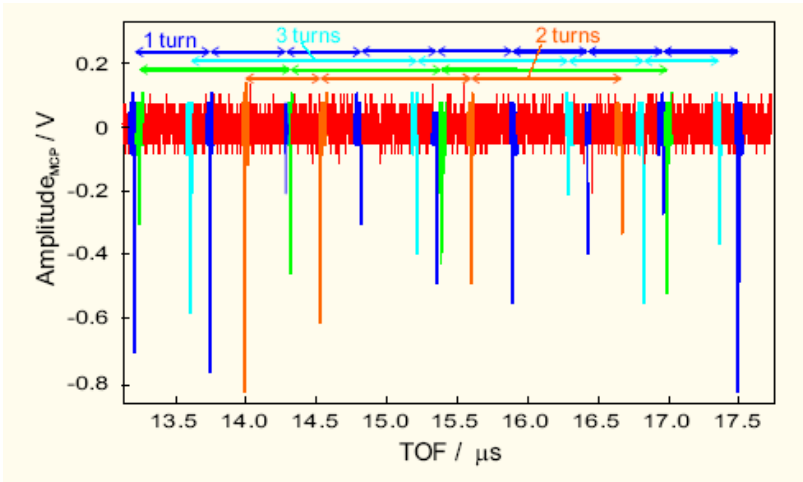
$\frac{\Delta v}{v} \rightarrow 0$ $\qquad$ $\gamma_t \rightarrow \gamma$

- Fast but need "transparent" detector (Schottky not applicable here)



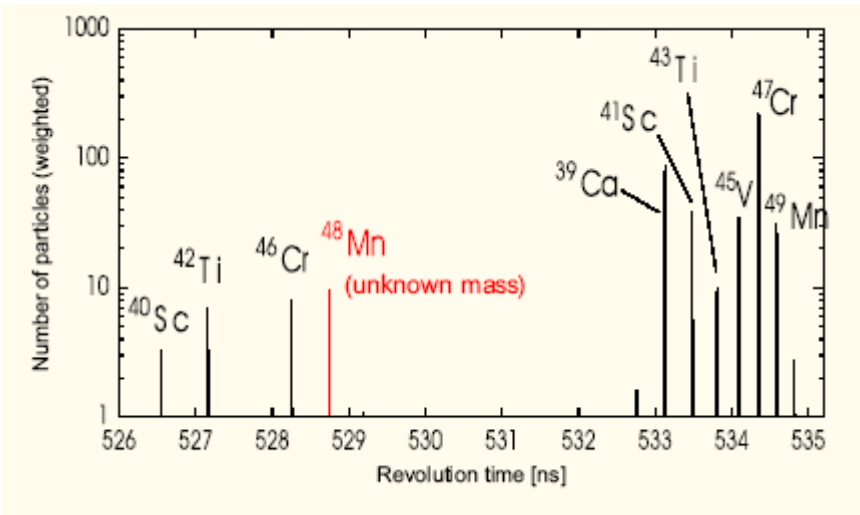


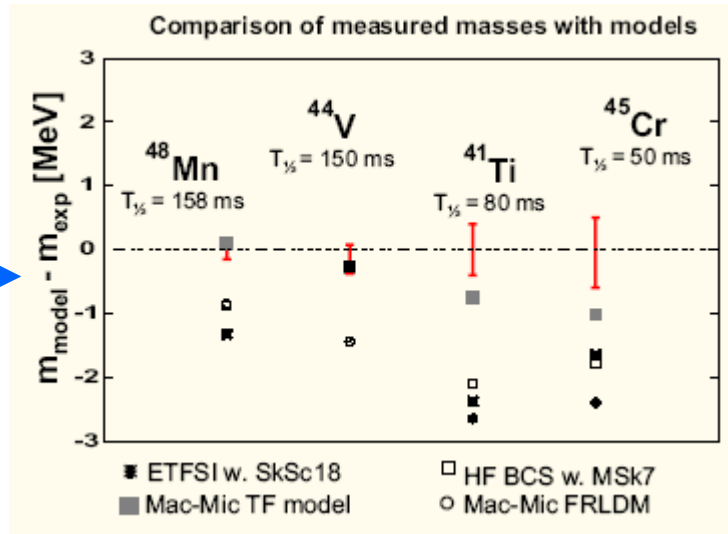
(J. Stadlman)



TOF mass measurements at the ESR (3)

- **Performance**
  - **resolution ~ 100000**
  - **essentially no lifetime limitation**
  - **limited accuracy ~ 10^{-6}**
  - **can access many masses simultaneously**
  - **well matched to the GSI facility**
  - **main limitation is acceptance into FRS**





(J. Stadlman)

Mass measurements and radioactive beam properties

- **Most of the mass measurement techniques we have seen so far have their resolution and ultimate accuracy affected by the beam properties**
  - **Resolution of deflection type spectrometer limited by energy spread and transverse emittance**
  - **Double focusing spectrometers affected by transverse emittance and variation of energy with species**
  - **Low energy TOF system affected by initial energy spread and requiring a pulsed beam structure**
  - **ESR TOF resolution and accuracy limited by the quality of the isochronicity of the ESR ring**

To obtain the utmost accuracy, cooling is required.

- **This not only improves the applications we have seen, it also opens the door to the highest accuracy ones:**

Ion traps and storage rings

Cooling: Physical considerations

- Liouville's theorem (paraphrasing)
  - phase-space density is conserved in a non-dissipative system
    - i.e.:

      angular spread X radial spread → constant

      time spread X energy spread → constant

- Cooling or bunching (reduction of transverse or longitudinal phase-space) therefore requires a dissipative system with the following conditions
  - "Cold" thermal bath (electrons, gas, laser beam, …)
  - Interaction of "ion beam" with the thermal bath
  - Sufficient acceptance of the bath and interaction time with the bath
  - Capability to extract from the bath without substantial reheating

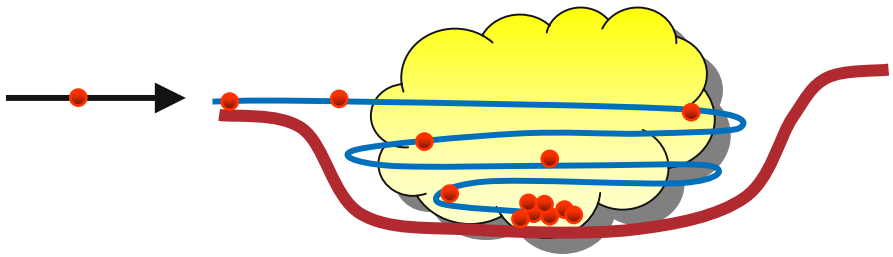
One road to fast and universal cooling/bunching

Collisions with a buffer gas in a guiding/trapping structure

- **gas provides thermal bath**
- **guiding/trapping structure provides large interaction time and localization**

Conditions to be met

- **enough stropping/cooling power to capture in longitudinal potential after one "interaction length"**
- **guiding/trapping potential/volume large enough to accept initial transverse emittance and energy spread after one "interaction length"**



Acceptance/stopping requirements for different radioactive ion sources

- **Radioactive ion source**

  1) poor quality ISOL beam

  Beam ~ 30 - 60 keV ; ΔE ~ 1 – 100 eV ; emittance ~ up to 100 π mm mrad

  approach: electrostatic deceleration to 100 eV, absorb remaining energy in gas … transverse guiding potential about 10-20 eV

  2) **fusion-evaporation reaction**

  Recoils energy ~ 0.2 - 5 MeV/u ; Δp/p ~ 1 - 15%

  typical: Sn @ 3MeV/u Range ~ 4.6 mg/cm^2 straggling ~ 0.2 mg/cm^2

  approach: remove most energy in solids, absorb final range straggling in gas… recoil spectrometer sets transverse size

  3) **fragmentation or in-flight fission reaction**

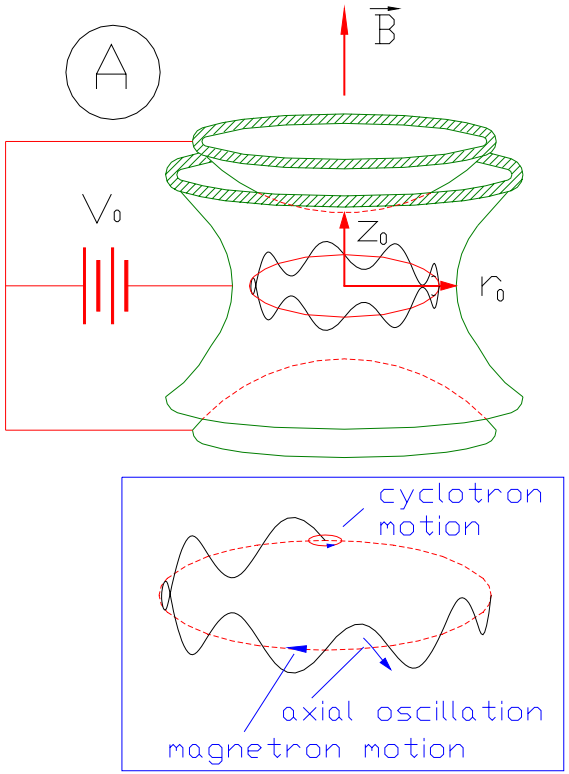
  Recoils energy ~ 100 - 1000 MeV/u ; Δp/p ~ 1-20%

  typical: Sn @ 250 MeV/u Range ~ 2.2 g/cm^2 straggling ~ 3 mg/cm^2

  approach: minimize energy spread, remove most energy in solids, absorb final range straggling in gas… fragment separator sets transverse size

Guiding/trapping structure(s)

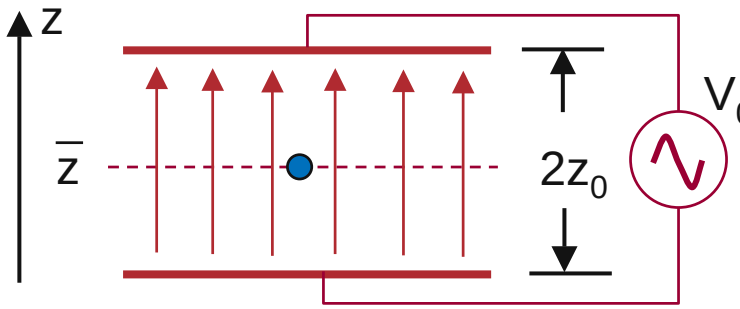
Penning Trap



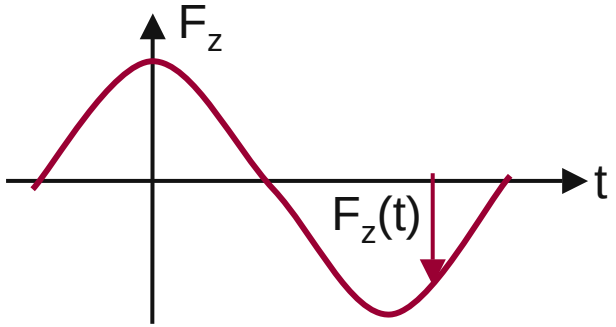
More of a measurement device … we will come back to it later

RF focusing(1)

Uniform RF field



$$E_0(z) = E_0(\bar{z})$$



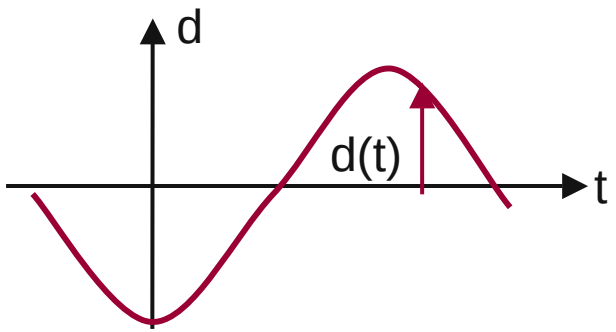
Basic harmonic motion

$$m\ddot{z} = F_z(t) = eE_0(z)\cos\Omega t$$

$$z(t) = \bar{z} + d(t)$$

$$d(t) = -d_0\cos\Omega t$$

$$d_0 = \frac{eE_0(\bar{z})}{m\Omega^2}$$

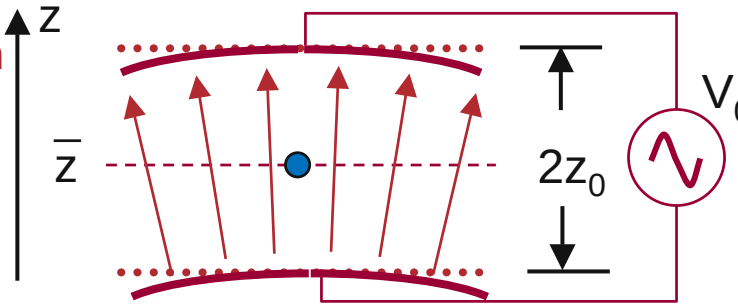


$$< F_z(t) >_{av} = eE_0(\bar{z}) < \cos\Omega t >= 0$$

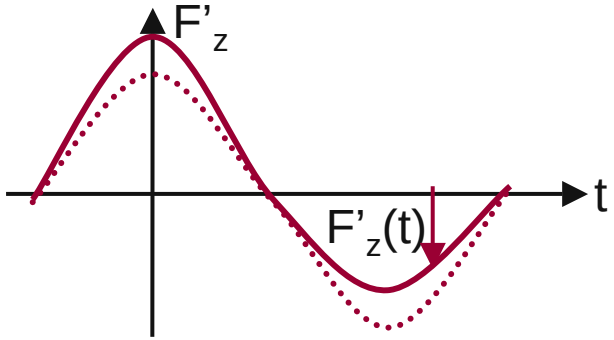
No net force when averaged over full RF cycle!

RF focusing(2)

Non-Uniform RF field



$$E_0(z) = E_0(\bar{z}) + \left(\frac{\partial E_0(\bar{z})}{\partial \bar{z}}\right) d$$

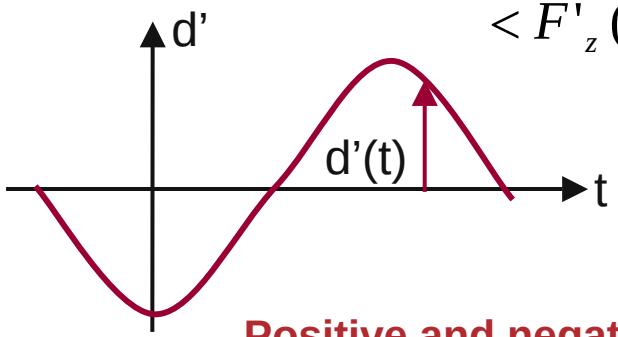


$$m\ddot{z} = F'_z(t) = eE_0(z)\cos\Omega t$$

$$z(t) = \bar{z} + d'(t)$$

$$d'(t) \cong d(t) = -d_0 \cos\Omega t$$

$$d_0 = \frac{eE_0(\bar{z})}{m\Omega^2}$$



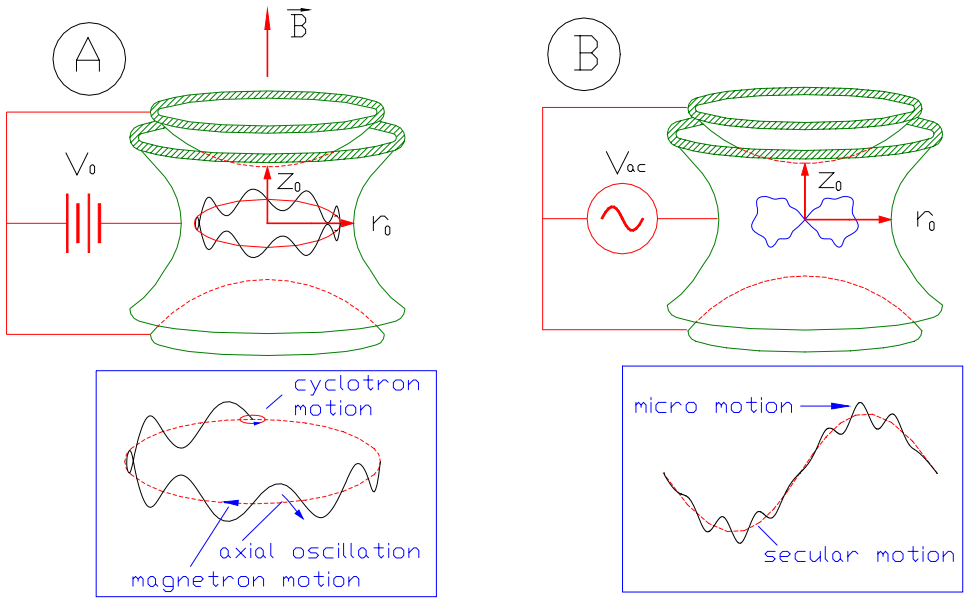
$$< F'_z(t) >_{av} = e\left(\frac{\partial E_0(\bar{z})}{\partial \bar{z}}\right) < d'\cos\Omega t >= \frac{-e^2 E_0(\bar{z})}{2m\Omega^2}\left(\frac{\partial E_0(\bar{z})}{\partial \bar{z}}\right)$$

$$F' = -e\frac{\partial V_{ps}}{\partial z} \quad \Rightarrow \quad V_{ps} = \frac{eE_0^2(z)}{4m\Omega^2}$$

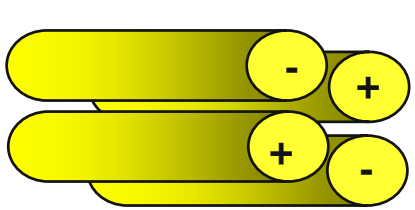
Positive and negative charges attracted to regions of lower RF amplitude!

Guiding/trapping structures

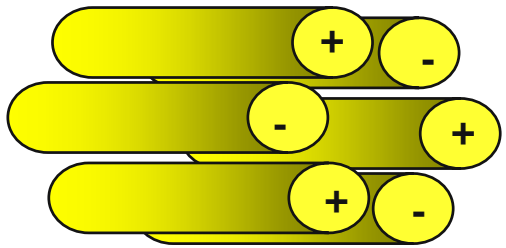
Penning Trap



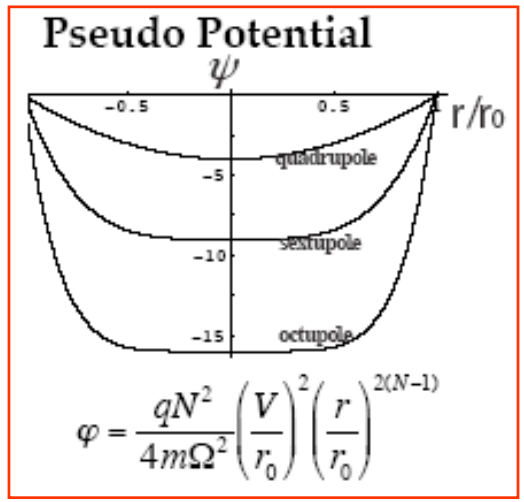
RFQ Trap



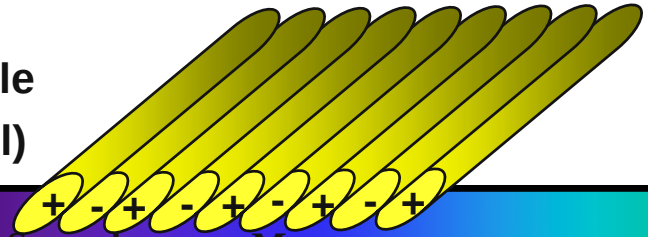
RF quadrupole



RF hexapole



Centipole (RF wall)



Low energy beam coolers

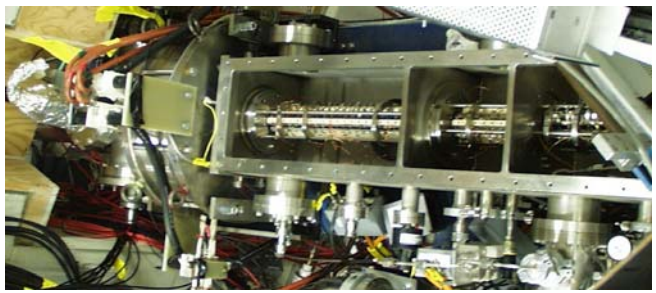
RF structures provide enough radial confinement and stopping length

First on-line attempt → Paul trap to bunch ISOLDE beam (R.B. Moore et al)

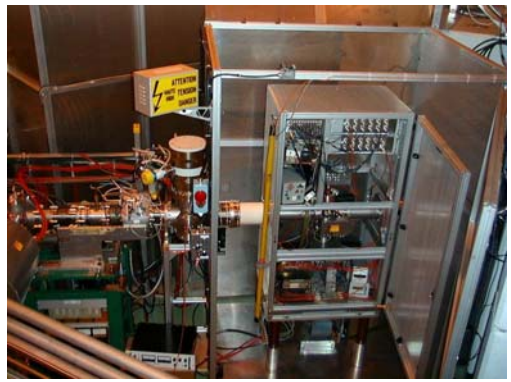
Linear RF structure provide more stopping length so higher efficiency

- **efficiency ~ 30-70% with beam deceleration**
  > 90% from a low energy beam
- **energy spread < 1eV**
- **Transverse emittance ~ 3 π mm mrad**

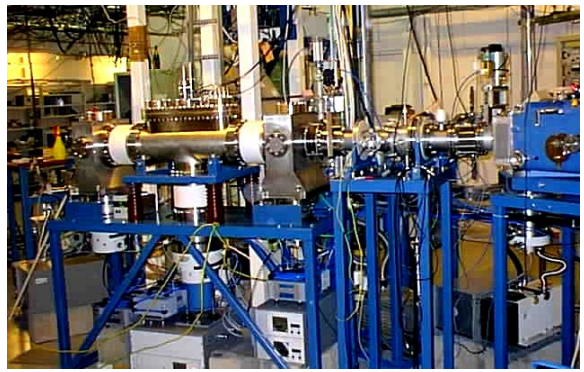
More than a dozen RFQ coolers in operation/construction in nuclear physics labs!



3 RFQ sections to extract from high gas flow region



Bunch low energy beam to match to experiment

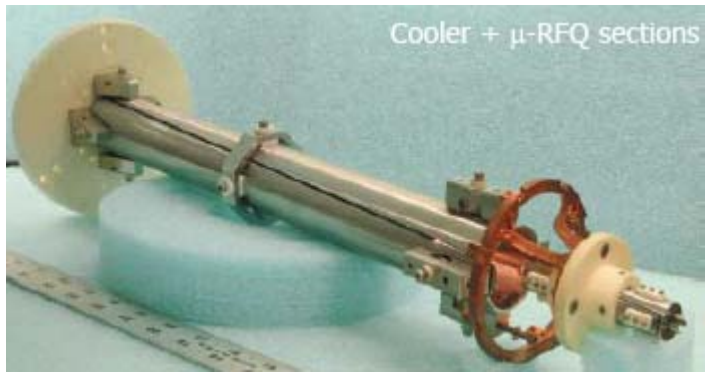


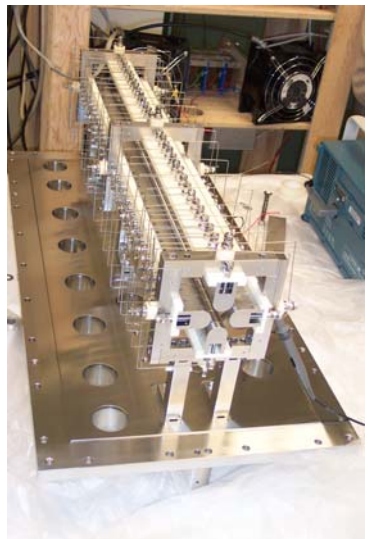
Reduce energy spread in DC mode

Further developments of low energy coolers

- **Decoupling of DC and RF drives** → **Wada et al for a while now but becoming more widespread**

- **Cooling of RF structure to liquid nitrogen temperature (MSU)**





- **Square wave RF drive (ISAC)**

- **Cooling for lighter species (CAEN)** → **Helium cooled**

Cooling/bunching of fusion-evaporation residues

Transverse emittance too high for any realistic small trapping device to handle (MV potential required)

Need a different approach

- **remove much of the energy before entering the device**
- **use gas to handle energy spread and range straggling**
- **once thermalized, use the fact that residues are ionized to guide them out selectively from stopping volume**

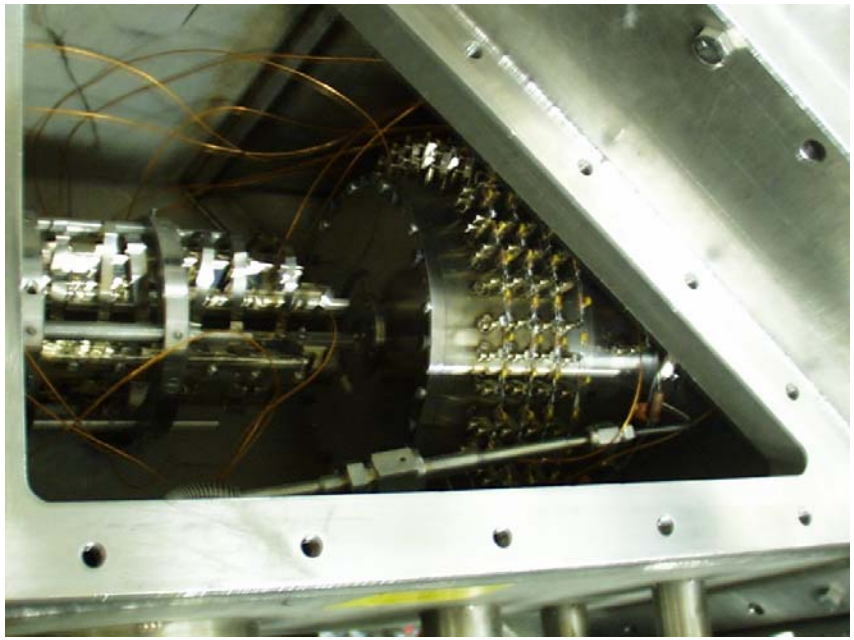
Gas volume requirement

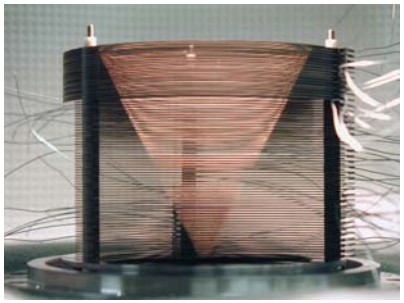
- **longitudinally roughly 0.1 – 1 mg/cm^2 He**
- **laterally depends on ion optics but typically 5 – 10 cm diameter**

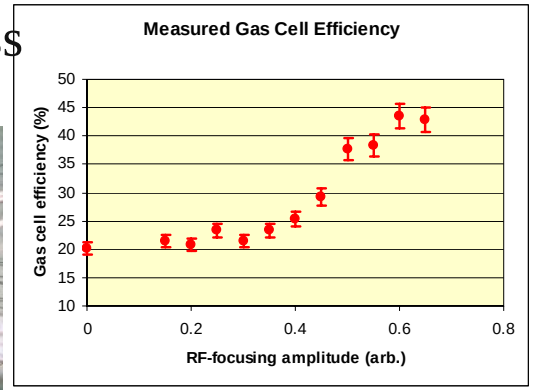
Too large a gas volume for a standard confining ion guide/trap!

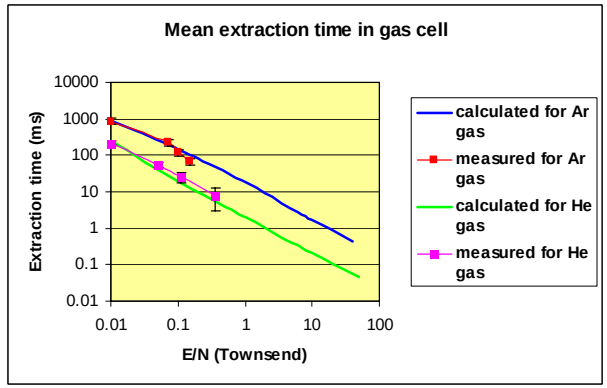
Gas catcher developed at the Canadian Penning Trap (CPT) at ATLAS

- 20 cm long gas cell with first generation RF cone
- ε ~ 45%
- mean delay time below 10 ms
- tested off-line with fission products and on-line with fusion–evaporation reactions
- routinely used for physics with CPT at Argonne for mass measurements on short-lived isotopes





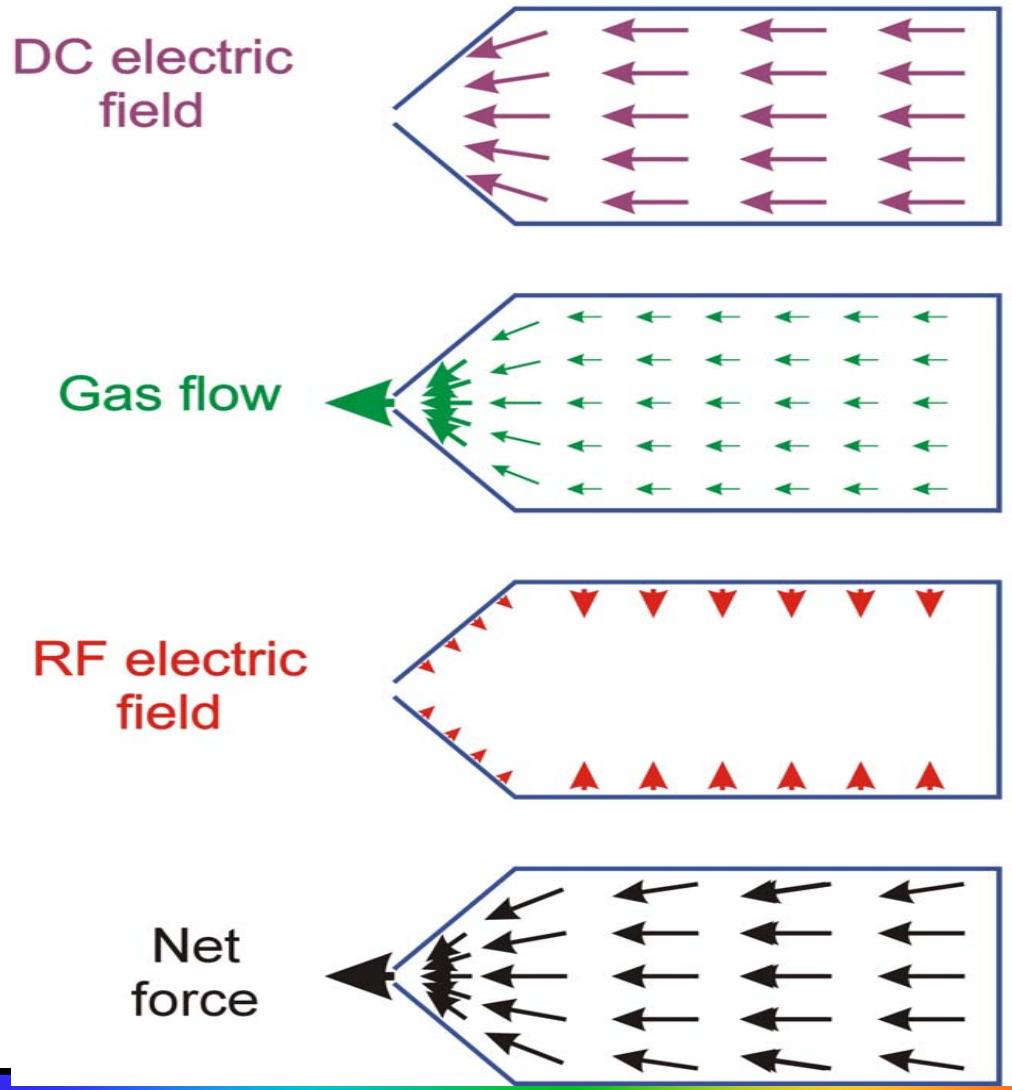




Forces in gas catcher system

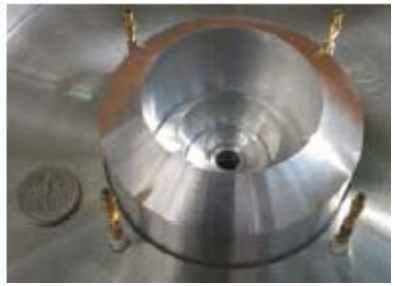
A combination of forces working together is required to obtain

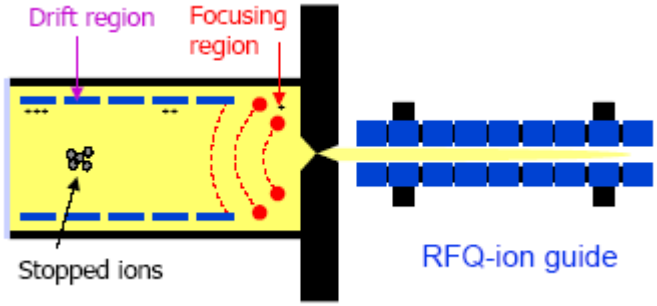
- Fast extraction times over the full volume
- High efficiency over the full volume
- Tolerance to high intensity



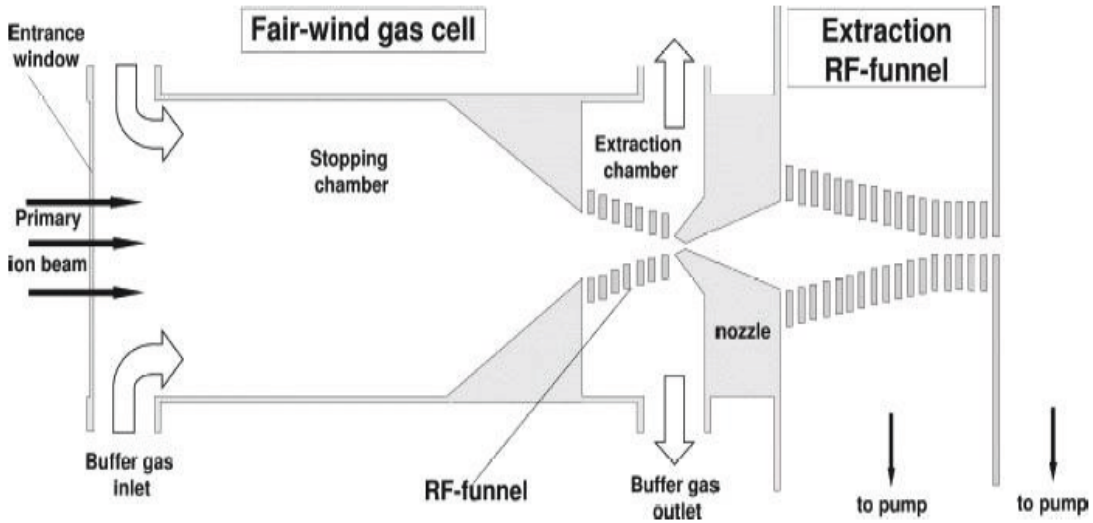
Other approaches being pursued

- No RF focusing, plain DC and gas flow



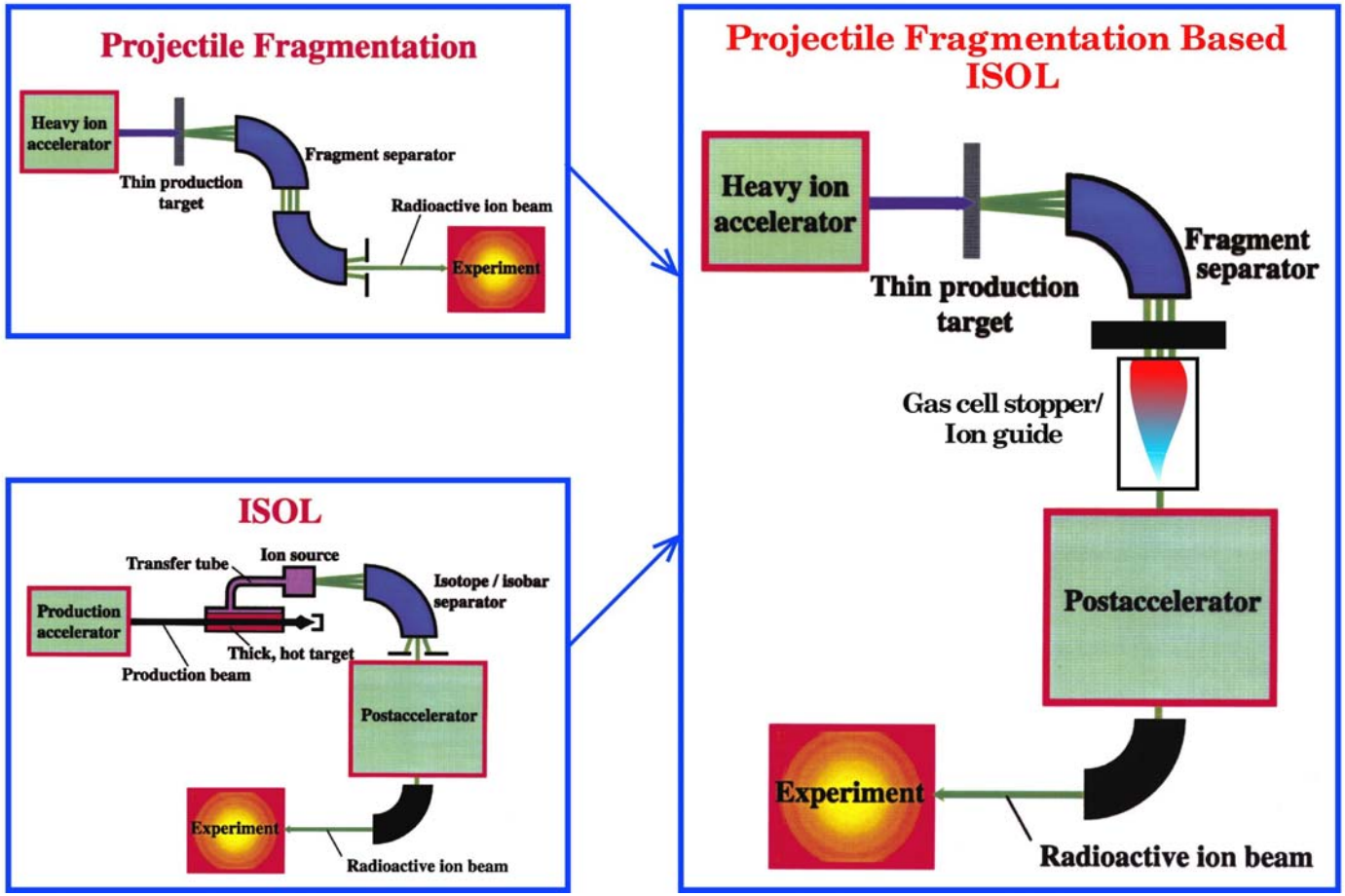


- Forced gas flow transport throughout catcher



Rare Isotope Production Schemes

- Fast Extraction Times (~msec)
- Chemical independence
- Isobar separation

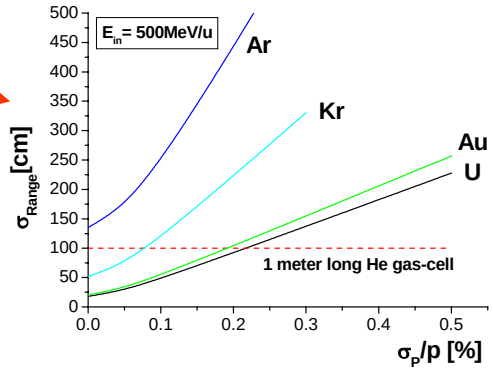


Cooling/bunching of fragmentation/in-flight fission residues

Transverse emittance too high for any realistic small trapping device to handle (multi MV potential required), range straggling too large also

Sn @ 250 MeV/u – 24 cm in 0.5 atm He

Same with Δp = 0.1% --- 70 cm



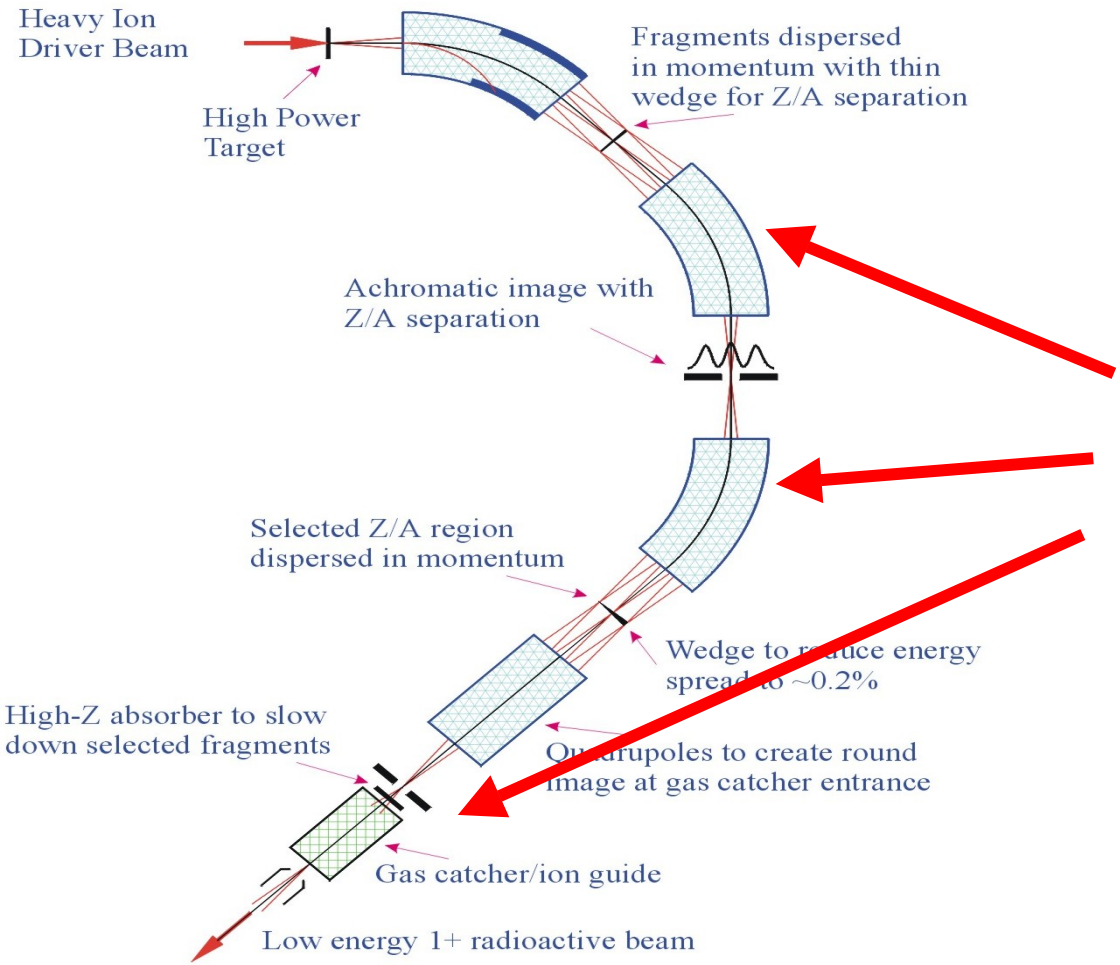
Need a more complex approach

- **must first reduce energy spread**
- **remove much of the remaining energy before entering the device**
- **use gas to handle residualrange straggling**
- **once thermalized, use the fact that residues are ionized to guide them out selectively from stopping volume**

Gas volume requirement

- **longitudinally roughly 2 – 20 mg/cm² He**
- **laterally depends on ion optics and achromatization**

Schematic layout for gas catcher and fragment separator



Schematic layout of fragment separator, achromatization stage and gas catcher system

Lateral dimension of large gas catcher

Lateral dimension of FRS gas catcher is determined by:

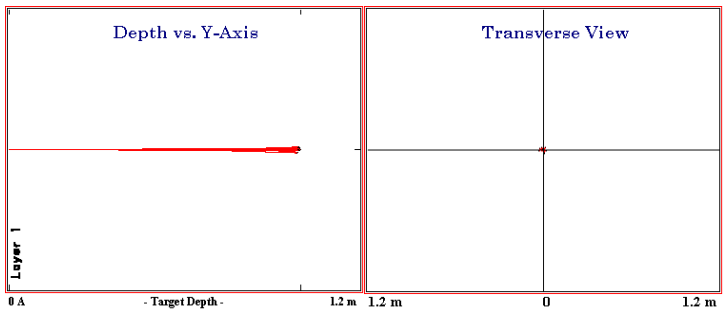
- Dispersion at wedge degrader
- Angular acceptance and magnification
- Angular straggling in deceleration

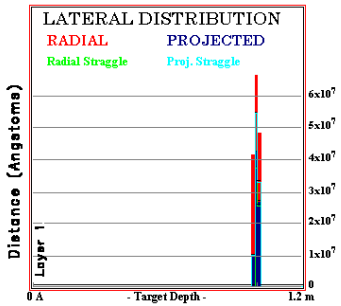
- FRS acceptance : ± 1% dp/p
- Dispersion required for achromatization: 7cm / %
- Angular acceptance : : ± 10 mrad
- Magnification : ~ 1.0 - 1.2
- Angular straggling:

Xe at 200 MeV/u → (Al degrader and window) → Xe at 6MeV/u → (He gas) → Xe stopped

Xe at 6MeV/u → angular straggling ~ 14 mrad

Xe stopped → lateral straggling ~ 5 mm





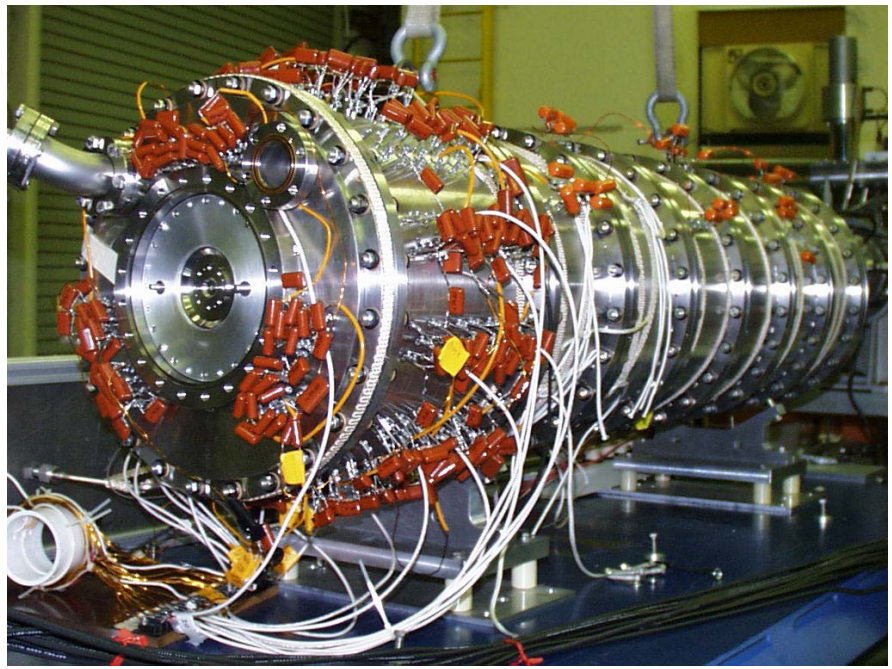
$\phi_{\text{gas catcher}}$ ~ 20-25 cm

Full scale RIA gas cell prototype

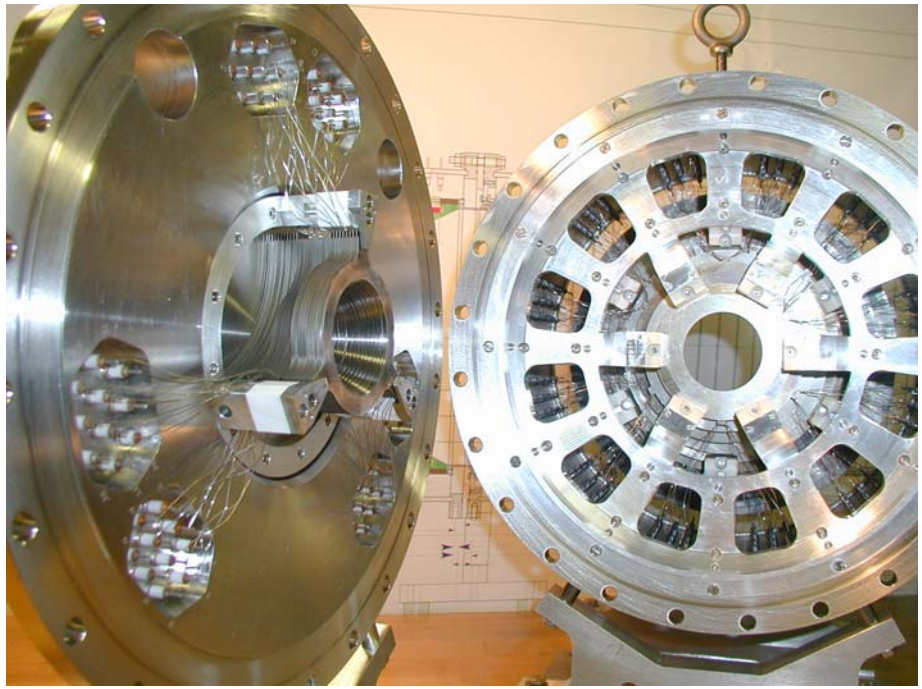
- **1.25 meter long(1.4 for GSI test), 0.25 meter inner diameter gas cell with same features as ¼ scale prototype**
- **over 7400 components, with more than 4000 prepared to UHV standards**

•Assembly completed FY02 DOE/NP Performance Target.

- **Characterization at low energy at ATLAS**
- **International collaboration testing full scale prototype at RIA energy at the fragment separator at GSI**



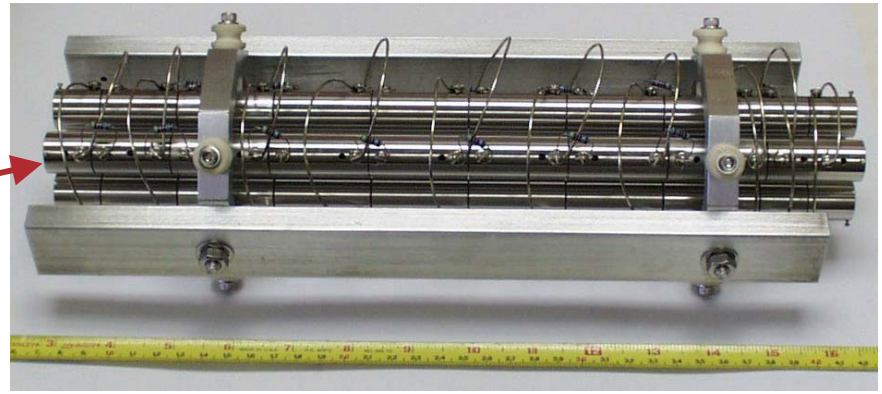
Completed large extraction RF cone



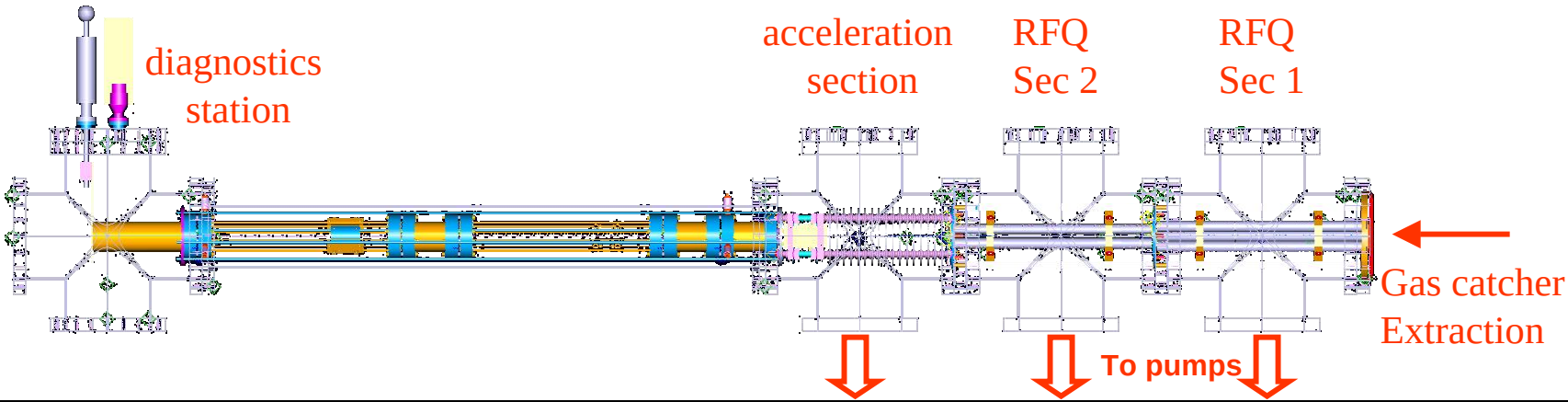
Extraction in the presence of large gas flow

Transport ions to lower pressure region via RF structures that guide ions while letting the gas escape and be pumped away.

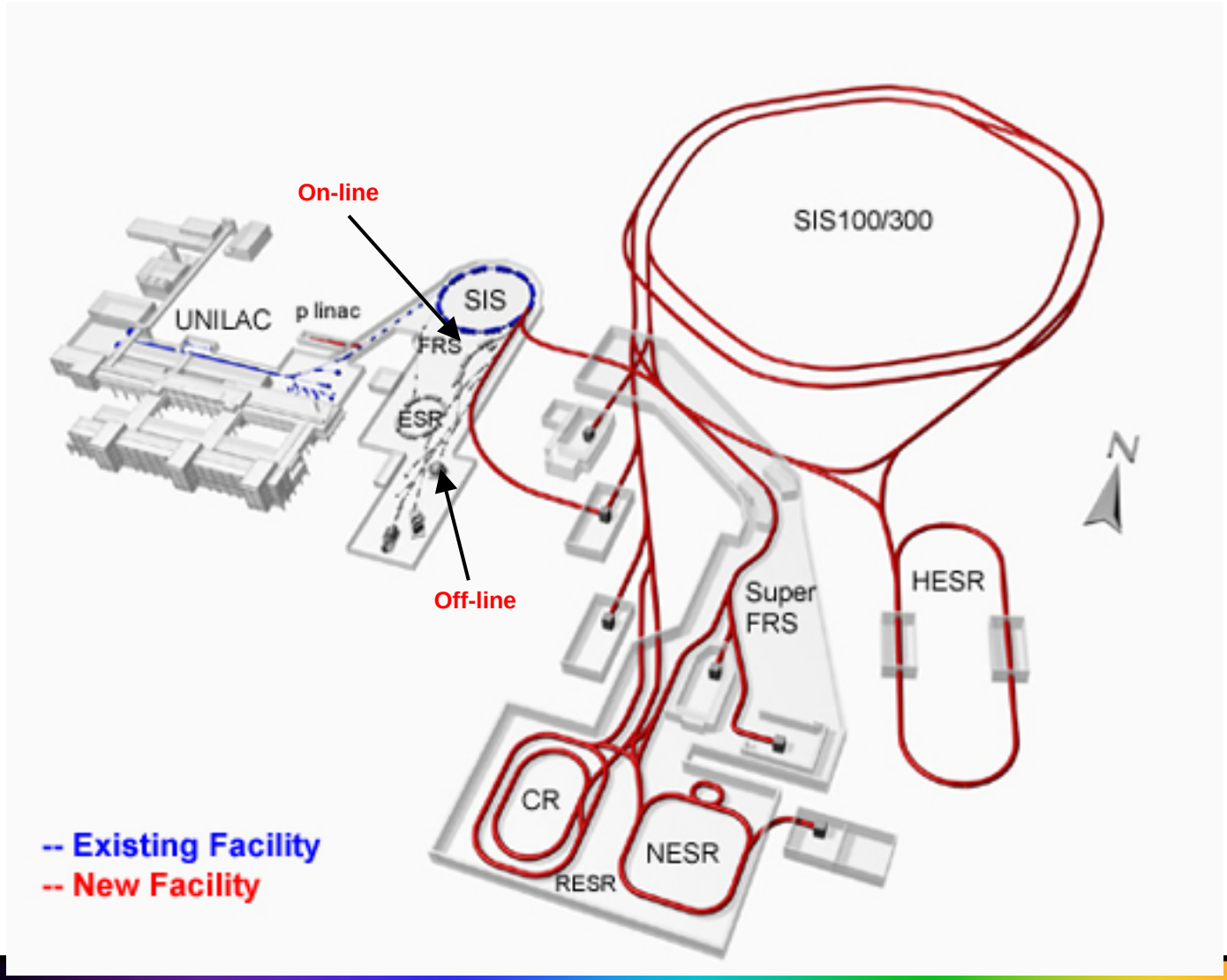
Section of segmented RFQ for ion transport and differential pumping



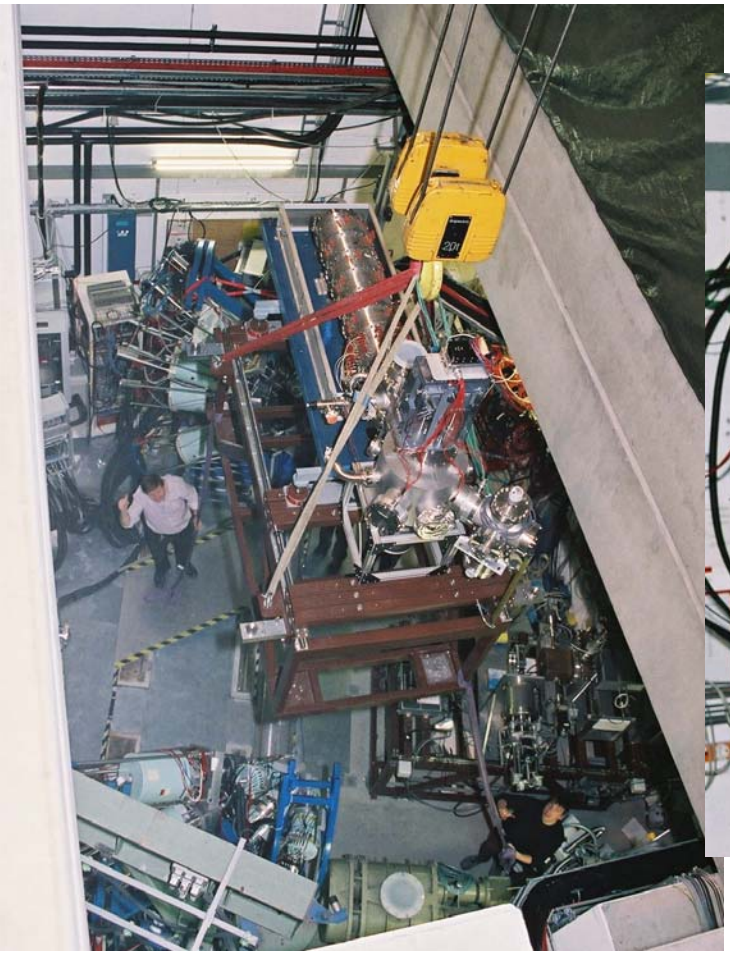
In DC mode, a limiting emittance (corresponding to roughly the gas temperature) is obtained after two such sections separated by small apertures (acceleration takes place in the lower pressure region after second section).

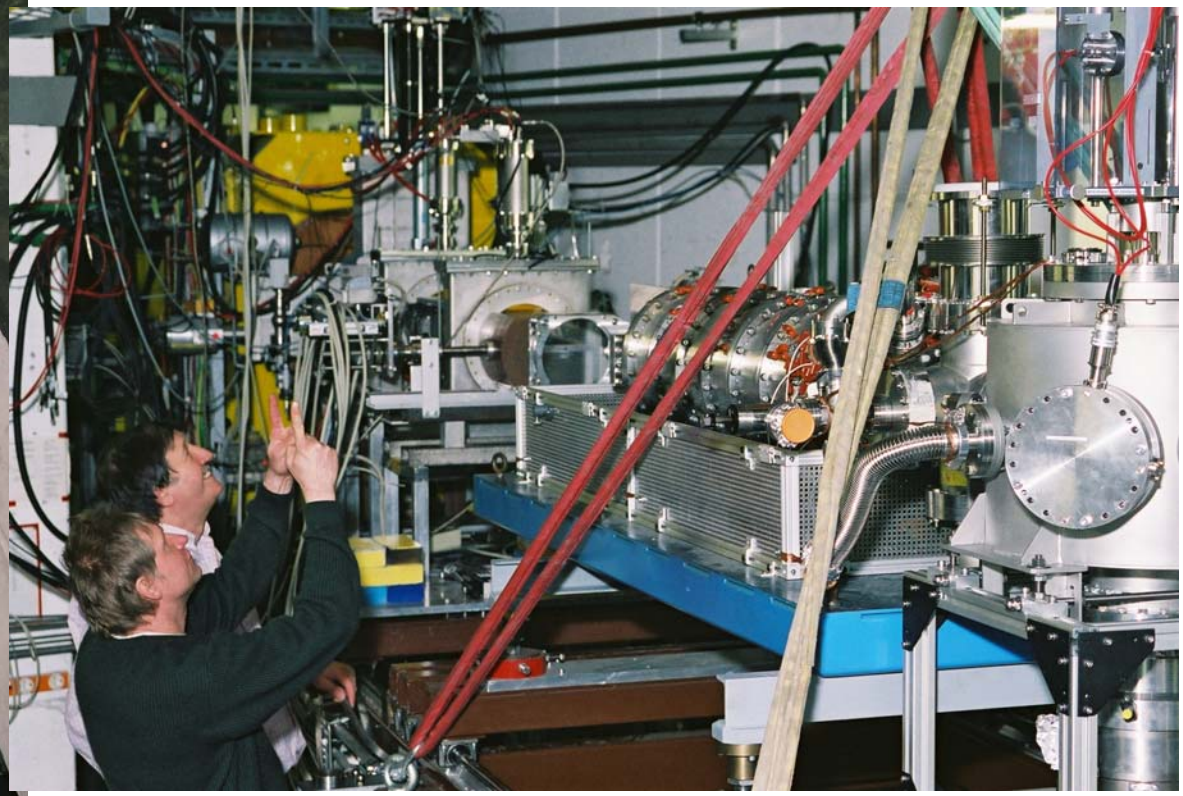


GSI Floor Plan

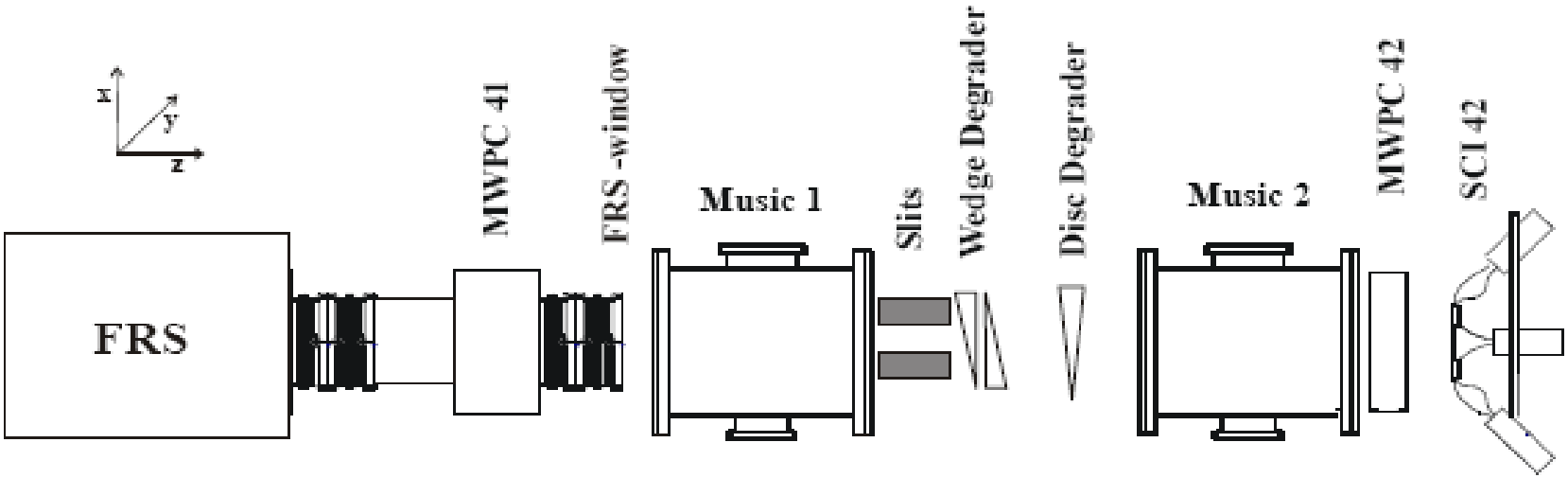


Installation of the RIA prototype gas catcher at the focal plane of the FRS

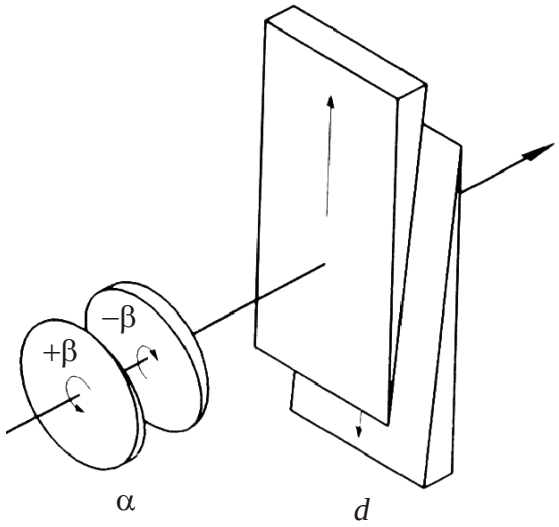




Detector system at F4 for particle identification



Precision Degrader System



Precision degrader system

Material:	Suprasil 2 (SiO_2)
Surface roughness:	less than 10 nm
Maximum shape deviation:	less than 1μm
Material homogenity:	better than 10^{-4}
Areal weight homogenity:	better than 0.2 mg/cm^2
Minimum thickness steps:	180 μg/cm^2

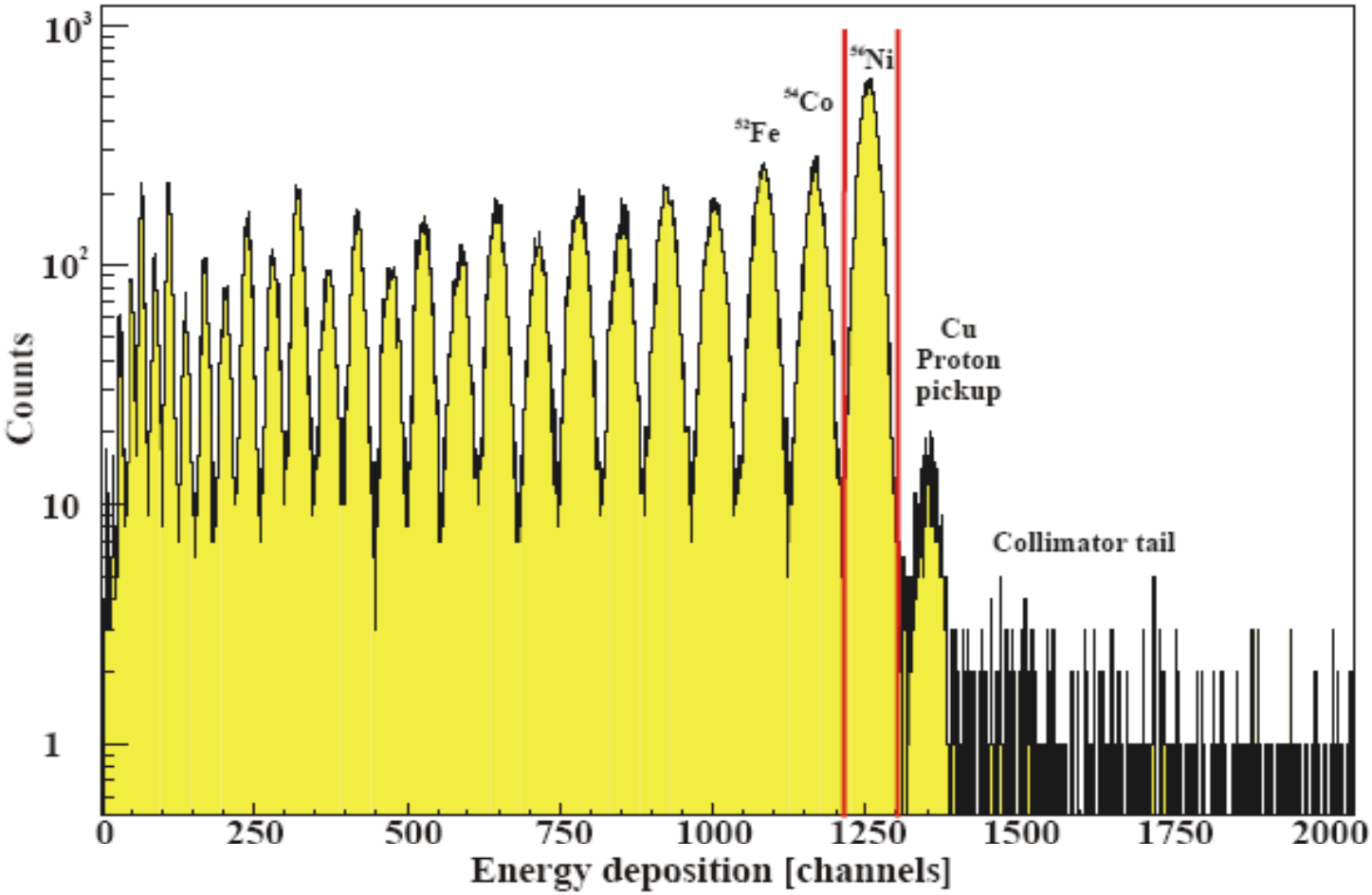
Velocity distribution of the beam limited by

*** ion-optical resolution of the buncher**

*** energy-loss straggling in degrader**

Practical limitation: inhomogenities

MUSIC Chamber Spectrum



MUSIC chambers Identify each individual ions

Radioactive ions extracted from the RIA prototype gas catcher at GSI (S258 experiment)

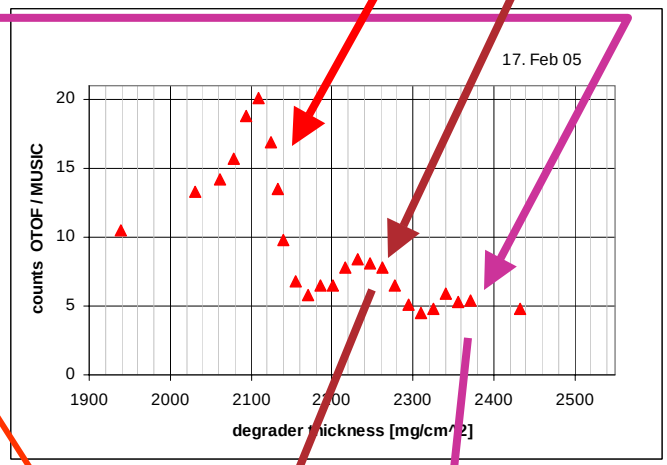
Energy loss in gas catcher by radioactive beam from FRS

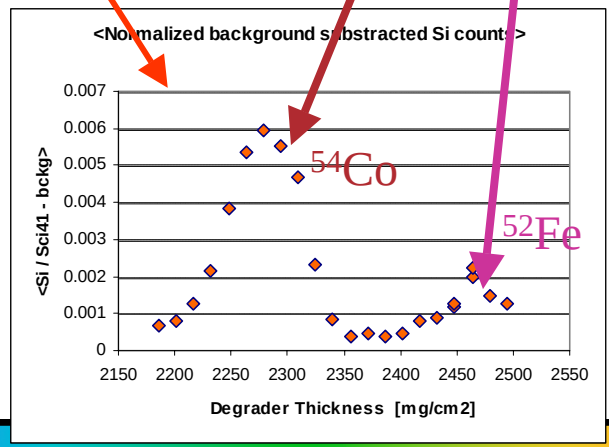
- Bragg peak from 56Ni beam
- Bragg peak from 54Co beam
- Bragg peak from 52Fe beam

~ 50 % of radioactive ions stopped in the gas catcher were extracted as a radioactive ion beam!

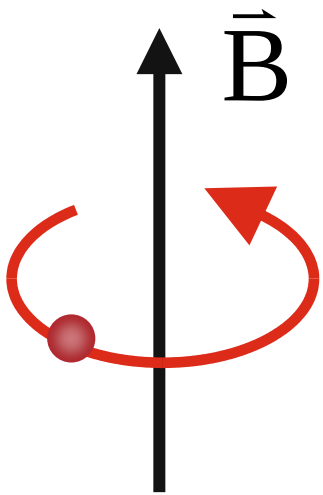
No saturation up to the maximum radioactive beam intensity (~ 10^6 ions per spill) that the FRS could deliver!

By tuning the degrader thickness, one can scan over the Bragg peak in the gas catcher, at the end of which the radioactive ions are stopped in the gas and extracted as a cooled low-energy radioactive ion beam





2d-confinement:Charged particle in a magnetic field

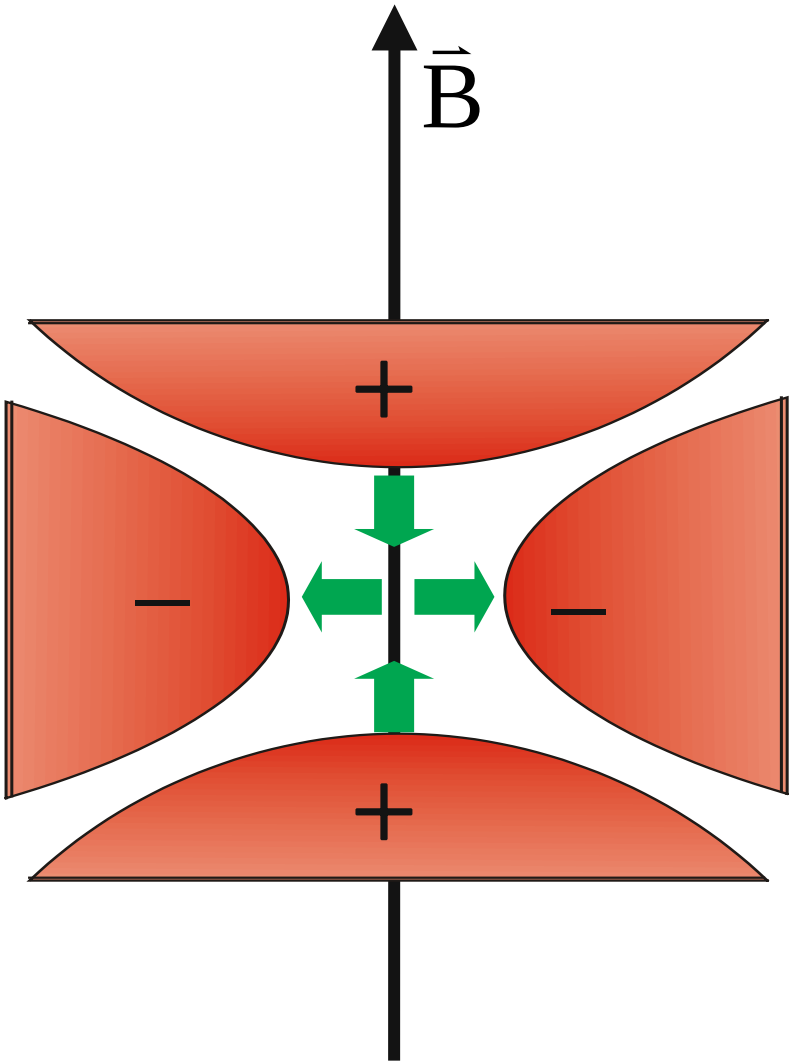


- Constant axial magnetic field
- particle orbits in horizontal plane

$$\omega_c = \frac{qB}{m}$$

- free to escape axially

3d-confinement: The Penning trap



- Add an axial harmonic electric field to confine particles

$$\varphi(\rho, z) = \frac{V}{4d^2}(2z^2 - \rho^2)$$

confining in z

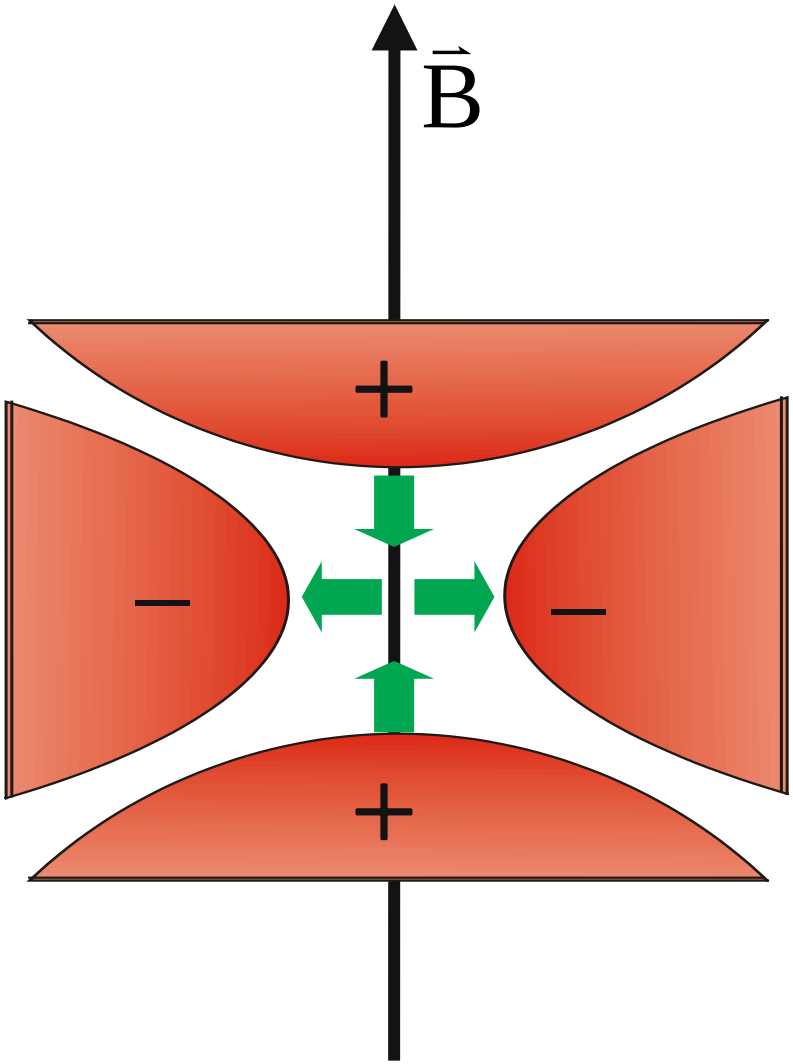
obeys Laplace $\nabla^2\varphi = 0$

- axial oscillations:

$$\omega_z = \sqrt{\frac{eV}{md^2}}$$

- axially confining potential comes with radially repulsive one

3d-confinement: The Penning trap



- radial motion now split into two eigenmodes

$$\frac{mv^2}{R} = qvB - qE_\rho = qvB - \frac{2VRq}{4d^2}$$

$$\omega^2 = \omega_c\omega - \frac{\omega_z^2}{2}$$

$$\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

confinement limit

- Radial motion split into two components by electric field:

→ω_+ : reduced cyclotron frequency

→ω_- : magnetron frequency

Precision measurements in a Penning trap

However:

$$\omega_c = \omega_+ + \omega_-$$

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

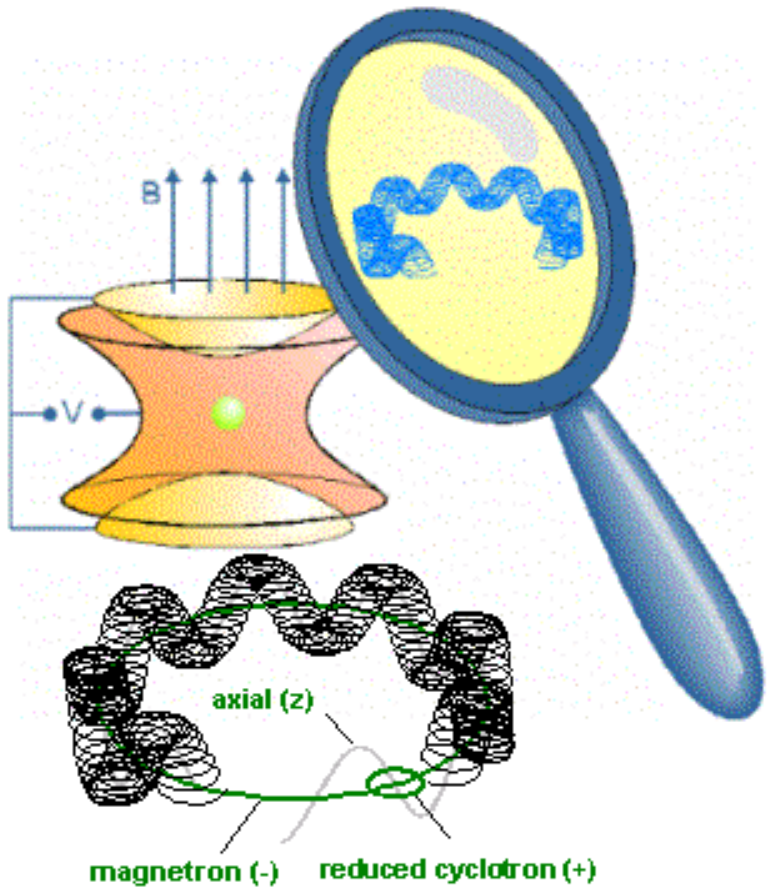
Recall:

$$\omega_c = \frac{qB}{\gamma m}$$

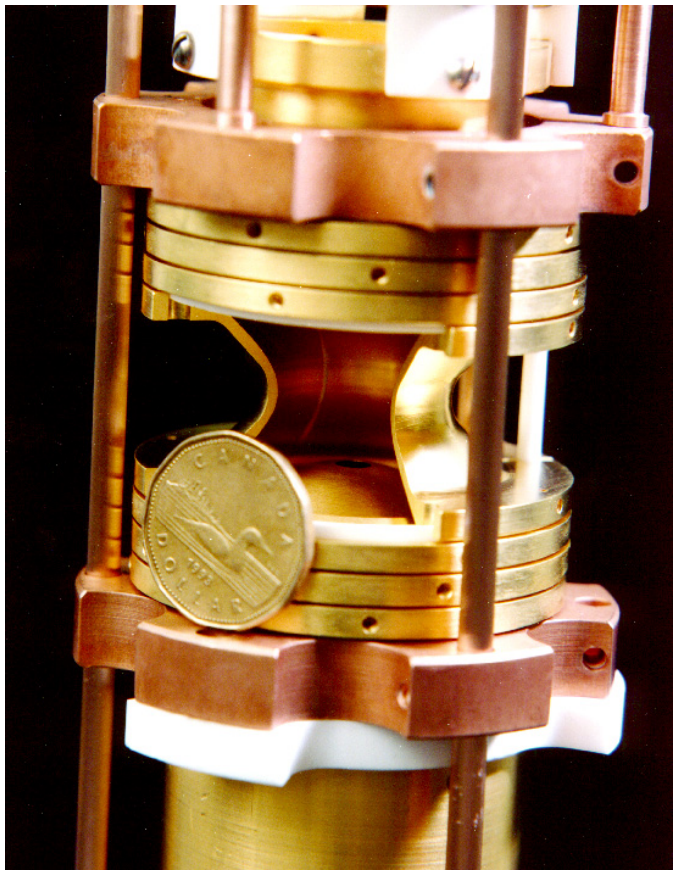
ω_c depends only on:

- **the mass**
- **the magnetic field**
- **not on the electric fields or the energy as long as γ is small**

Can use ω_c to make accurate and precise mass measurements



CPT mass spectrometer



Ion trap system located on-line at the ATLAS superconducting linac

High-accuracy mass measurements on short-lived isotopes via:

$$\omega_c = qB/m$$

Concentrate presently along N=Z line

- **Electroweak Interaction**
- **Nuclear Astrophysics**

Accuracy : 10^{-6} - 10^{-9}
Half-life limit : ~ 50ms
Resolution (Fourier limited) : ~ 10^{-6}

Superallowed Beta Decay

- *Precision tests of CVC*
- *Determination of weak vector coupling constant*
- *Unitary tests of the CKM matrix*

- For superallowed transitions between 0^+ T=1 states

$$Ft = ft\,(1+\delta_R)\,(1-\delta_C) = \frac{K}{2\,G_V^2\,(1+\Delta_R)}$$

from experiment; from calculations of radiative and charge-dependent effects

- Test need for physics beyond the standard model
  - G_v together with G_μ yield the V_{ud} quark mixing element of the CKM matrix

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

weak eigenstates — rotation matrix — mass eigenstates

- If matrix is not unitary then we need new physics
  - Additional Z bosons, Right-handed currents, SUSY…

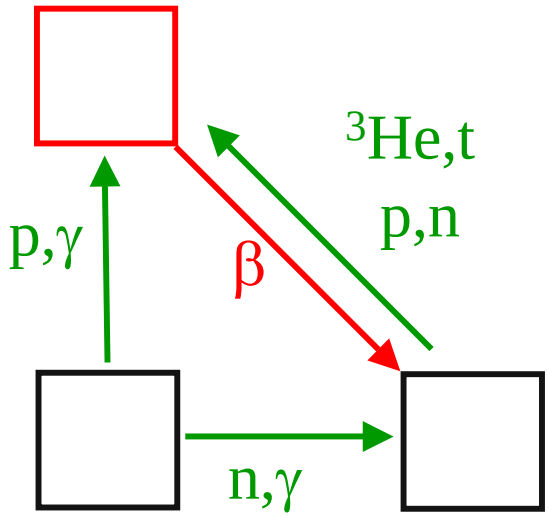
Big effect if R-parity violating … can be more than 0.0020

At loop level if R-parity conserving …. ~ 0.0007

Precision frontier --- superallowed Q-value measurements

- required precision (0.1 – 1 keV) cannot be reached by β endpoint measurement

•Standard approach: reaction threshold (neutron yield vs energy for p,n reaction) or gamma-ray energy … not applicable to new cases



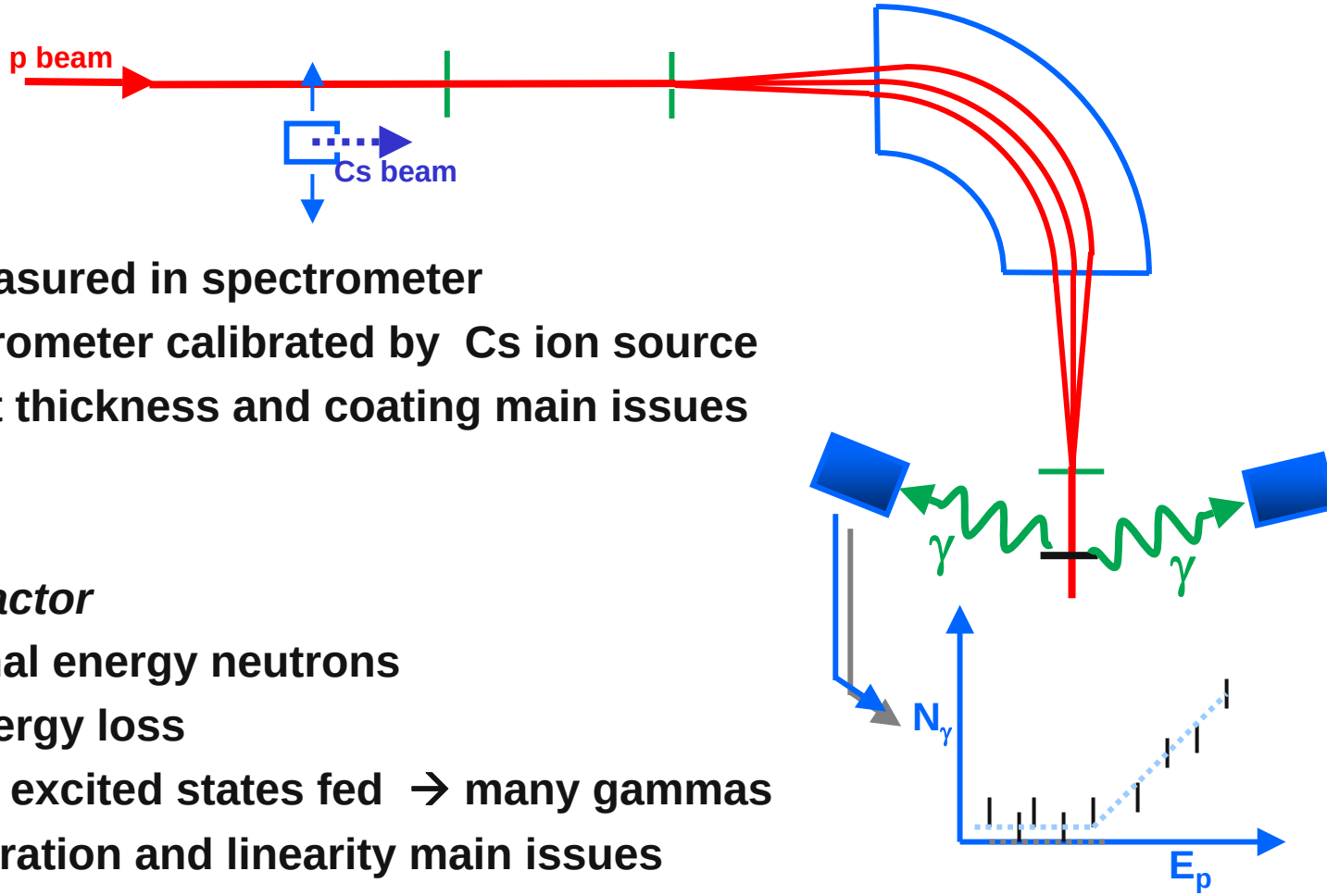
•new approach required

- •Penning trap mass measurements on short-lived isotopes
  - •Accuracy 10^{-7}-10^{-9}
  - •Lifetime limit ~ 50 ms
  - •Resolution 10^6

$\omega_c = qB/m$

Reaction threshold measurement

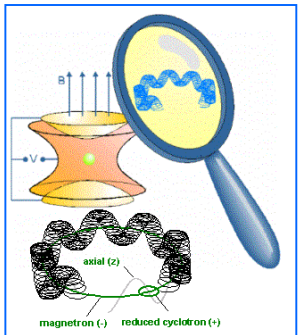
- Simple reaction to remove uncertainty from beam excitation
  - *(p,n) or (p,γ) with independently calibrated beam energy*



    - E_p measured in spectrometer
    - Spectrometer calibrated by Cs ion source
    - Target thickness and coating main issues

  - *(n,γ) at reactor*
    - Thermal energy neutrons
    - No energy loss
    - highly excited states fed → many gammas
    - γ calibration and linearity main issues

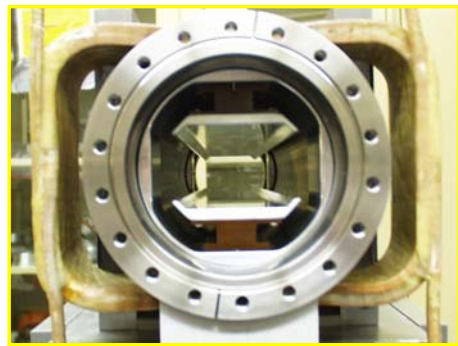
Overview of the CPT on-line mass spectrometer



transfer line

gas cell

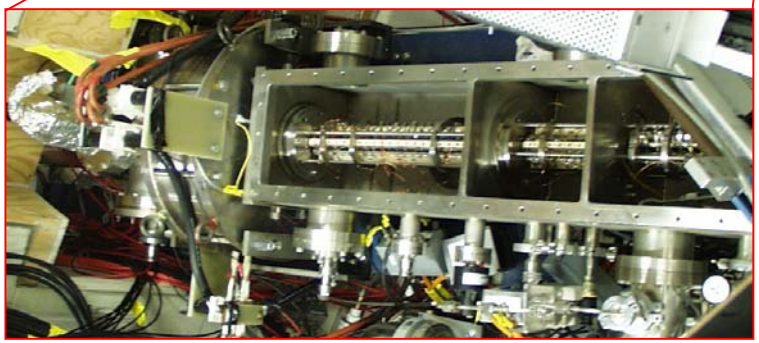
tunable degrader

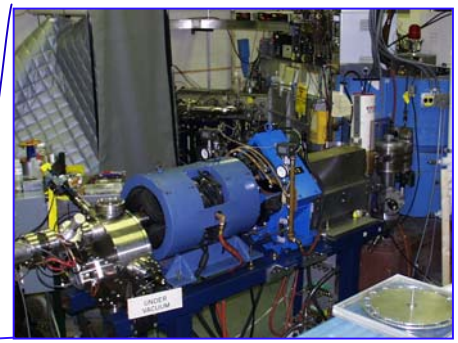


RFQ ion guide

isobar separator

Enge spectrograph





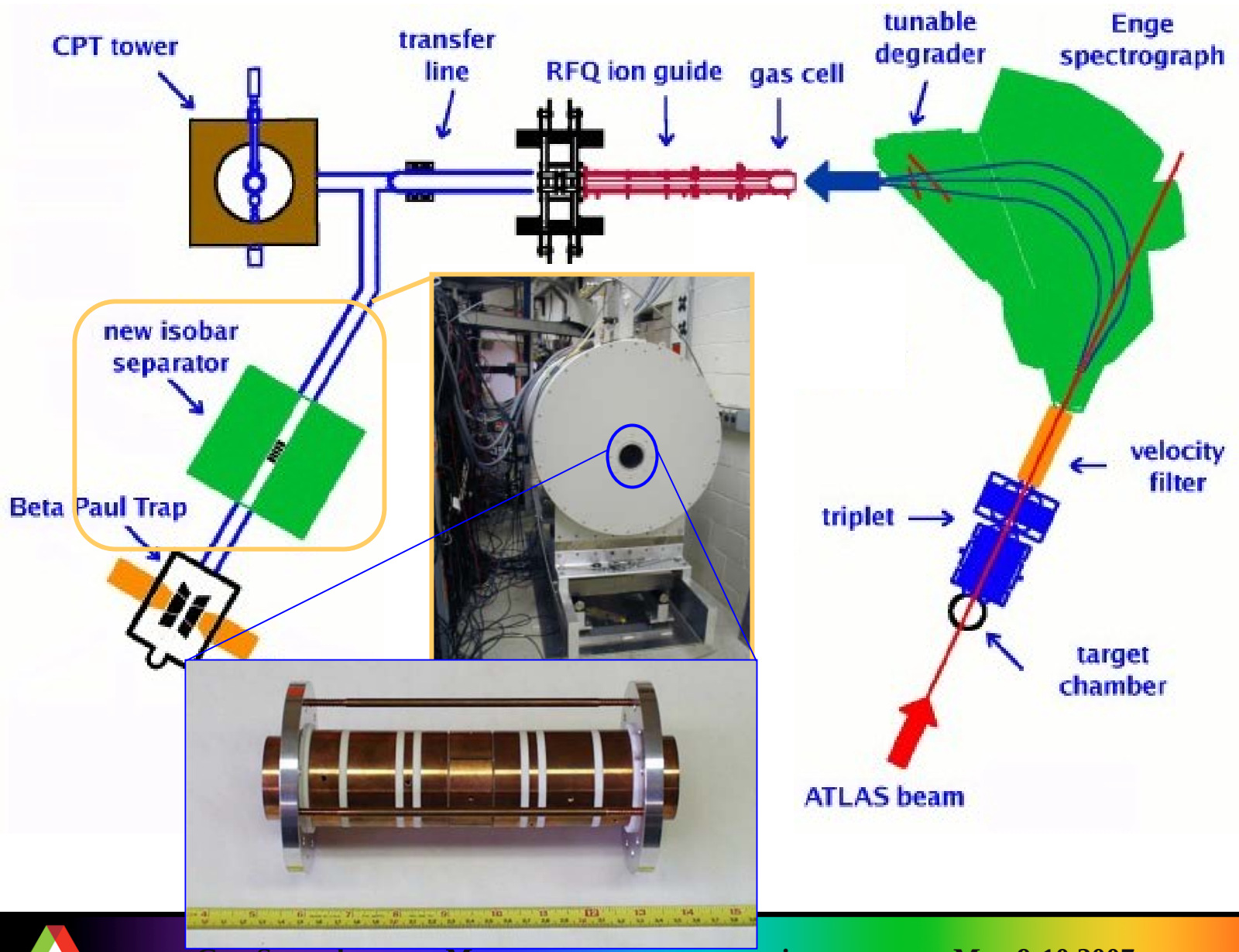
velocity filter

triplet

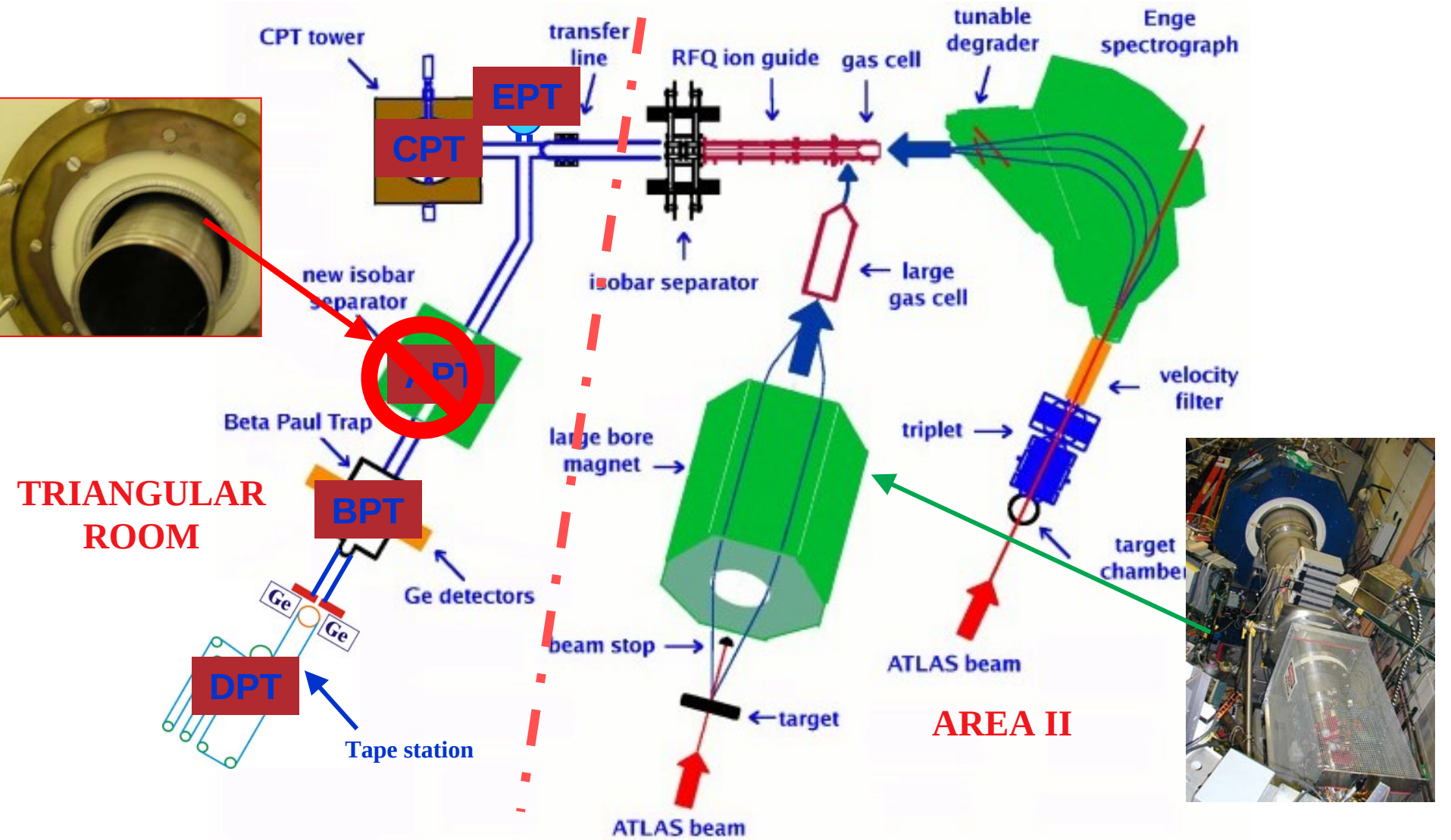
target chamber

ATLAS beam

Isobar separator for beam purification

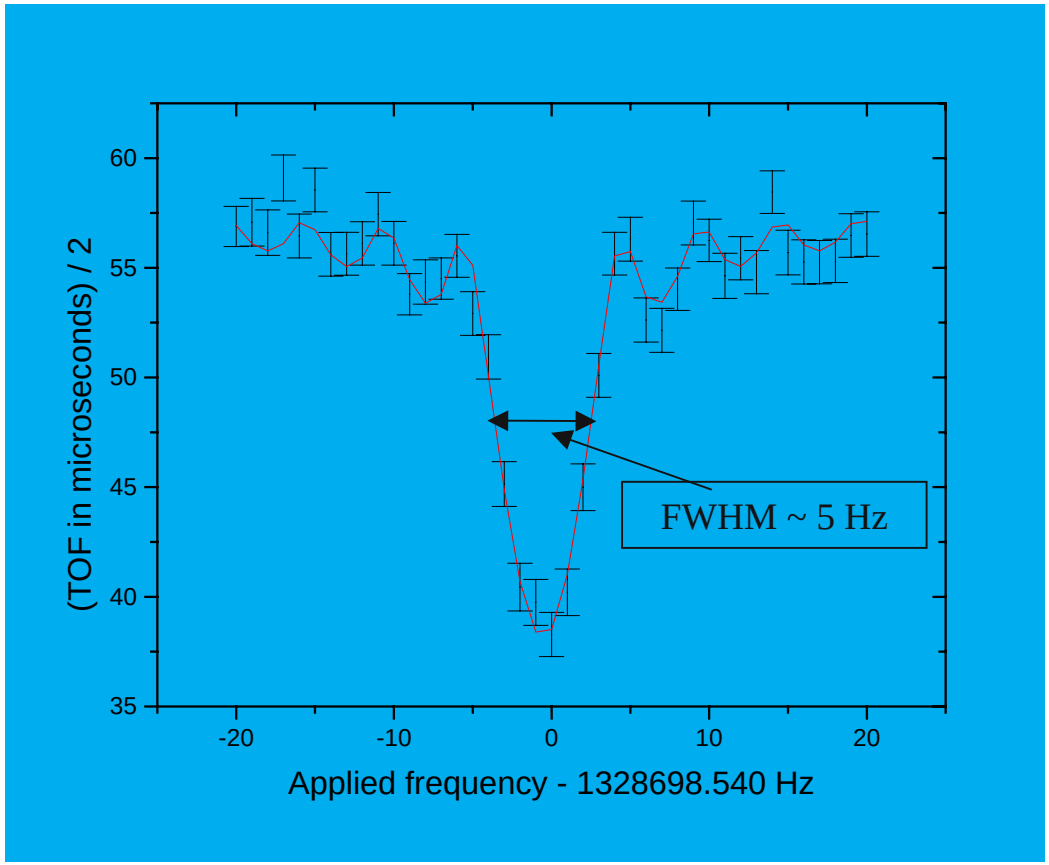


Fully evolved system giving access to all isotopes available at ATLAS … end of 2006



Sample TOF spectra

Calibration: $C_5 H_8$



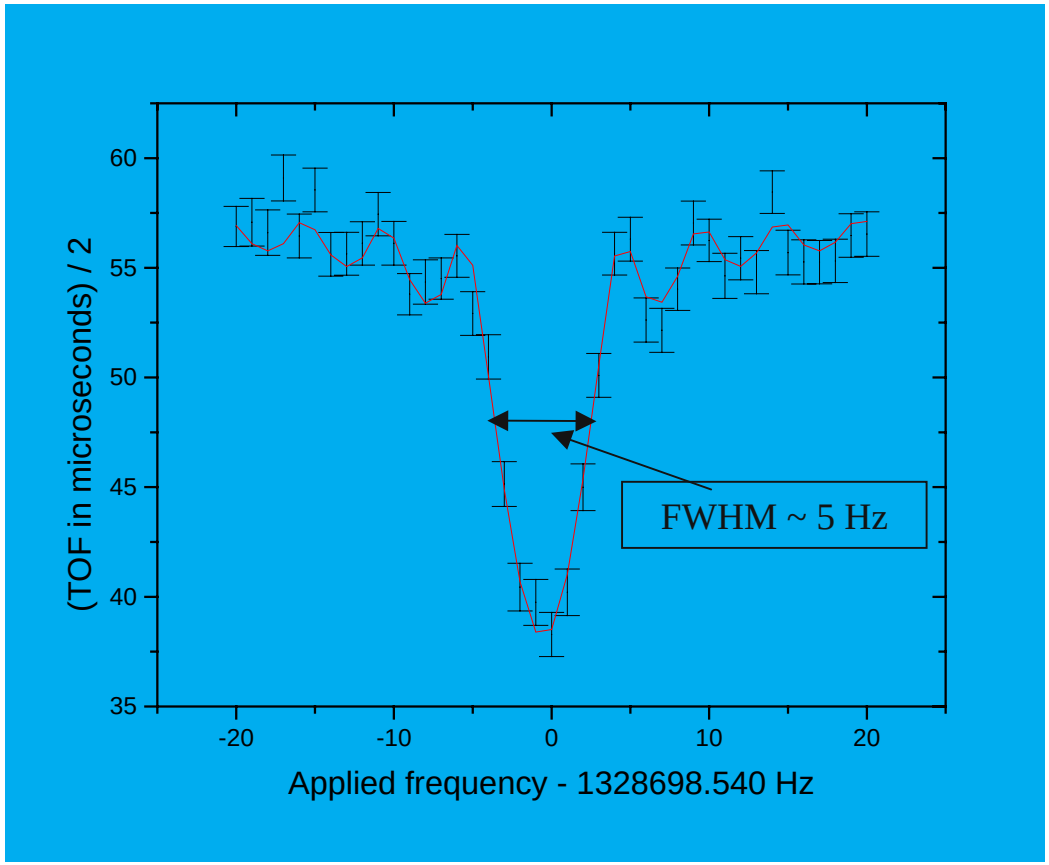
$$\omega_c = \frac{qB_c}{m_c}$$

Unknown: $\omega_? = \frac{qB_c}{m_?}$

$$\frac{Unknown}{Calibration} \Rightarrow m_? = \frac{m_c \omega_c}{\omega_?}$$

Sample TOF spectra

Calibration: $C_5 H_8$



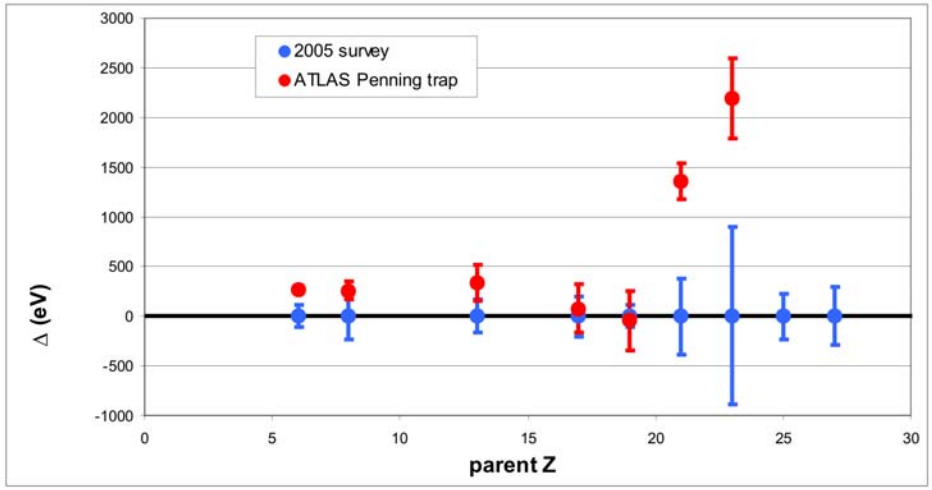
$$\text{Resolution} = \frac{\Delta\omega_{FWHM}}{\omega}$$

$$\Delta\omega_{FWHM} \sim \frac{0.9}{T_{RF}}$$

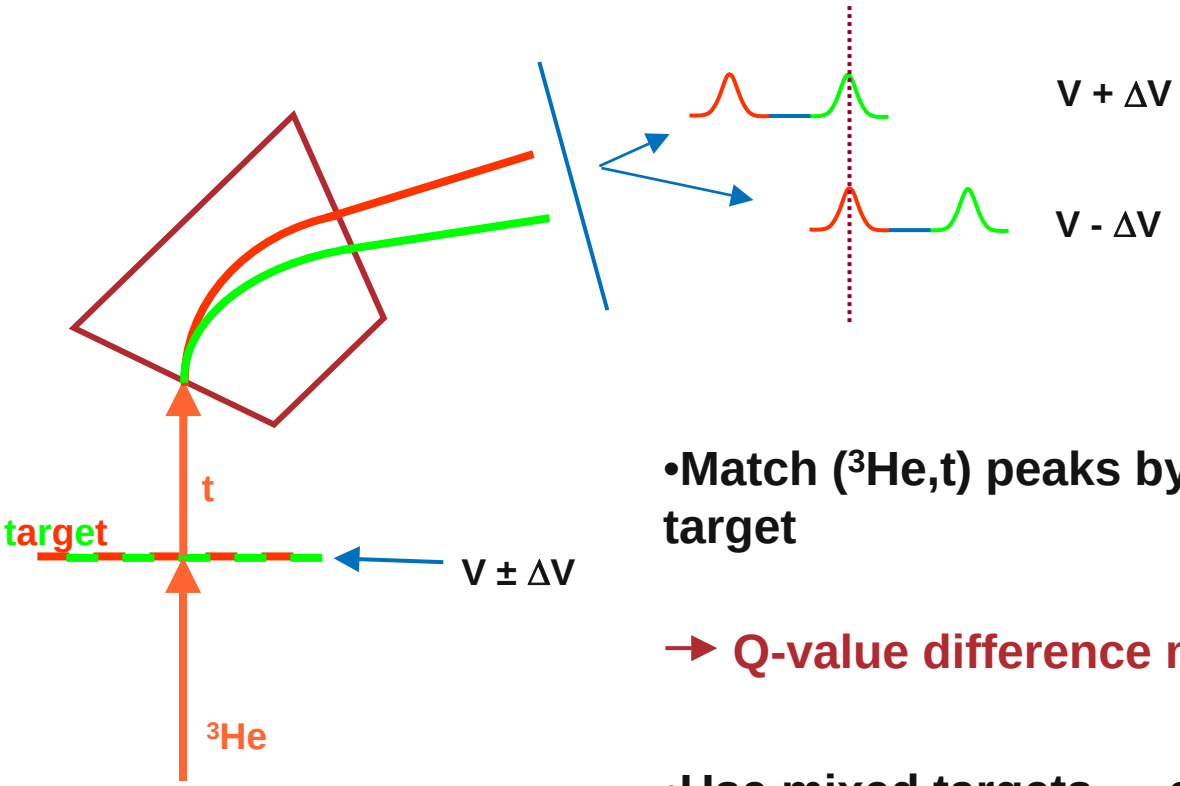
$$\text{Precision, } \frac{\text{m}}{\Delta\text{m}} \propto \frac{T_{RF} qB\sqrt{N}}{m}$$

Completing the Penning trap measurements of the nine highest precision superallowed emitters

- 7 of the 9 cases have now been measured at the CPT
  - ^{42}Sc was found, like ^{46}V, to be significantly higher than expected
  - Other cases are generally higher than last compilation but by smaller amounts
- Work at the accuracy frontier
  - extensive systematics check
  - absolute calibration during the experiment
  - highest accuracy ever achieved for online trap measurements
    - $\Delta Q(^{14}O) \sim 90$ eV
    - $\Delta Q(^{10}C) \sim 40$ eV
  - can now test atomic effects



Chalk River Q-value difference measurements



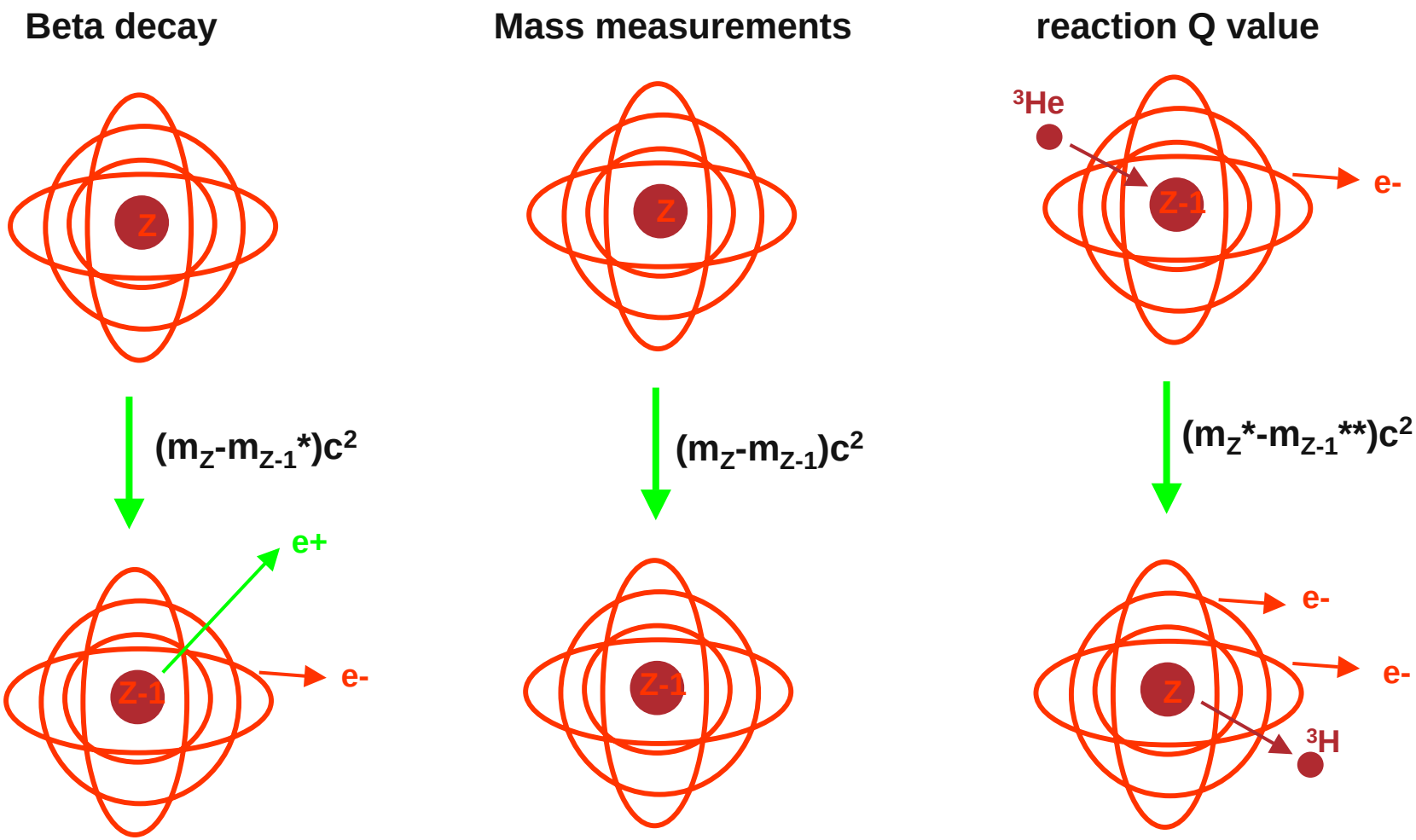
- Match (^{3}He,t) peaks by changing voltage on target

→ Q-value difference measured with a voltmeter ←

- Use mixed targets … essentially all sources of systematics drop out

- Most robust of the previously existing data

Atomic structure effects … are we measuring the same quantity?



Are we consistent with any of the reaction results?

- Our new results disagree with previous reaction values by 1σ for ^{14}O, about 7σ for ^{42}Sc … and about 4σ for our very recent ^{26m}Al result
- From the Chalk River Q value differences

  $Q(^{14}O) - Q(^{26m}Al) = 1401.68(13)$ keV

  $Q(^{26m}Al) - Q(^{42}Sc) = 2193.5(2)$ keV
- Our new value for ^{42}Sc shifts the Q value up by about 7 sigma, ^{14}O is only shifted slightly up. But the differences agrees with the difference measurements
  - Chalk River Q value difference → $Q(^{42}Sc) - Q(^{14}O) = 3595.18(24)$ keV
  - CPT results (preliminary) → $Q(^{42}Sc) - Q(^{14}O) = 3595.52(23)$ keV
- Can also predict the Q value of ^{26m}Al from the Q value differences and the CPT Q values for ^{14}O and ^{42}Sc … again we find excellent agreement with the CPT preliminary value for $Q(^{26m}Al)$.

It does not appear that the reaction approach is flawed … when done in the best conditions it agrees with the trap measurements.

Status - Outlook

•Enormous evolution in mass measurements techniques and hardware since the inception of the field roughly 100 years ago.

•Tools to make precision mass measurements to the accuracy required for astrophysics, nuclear structure and fundamental interaction studies have been developed and are operational.

•Main limitation at this point is access to the most exotic nuclei, but there is hope on the horizon with new large scale RIB facilities in preparation.