Precision Measurements of Very-Short Lived Nuclei Using an Advances Trapping System for Highly-Charged Ions

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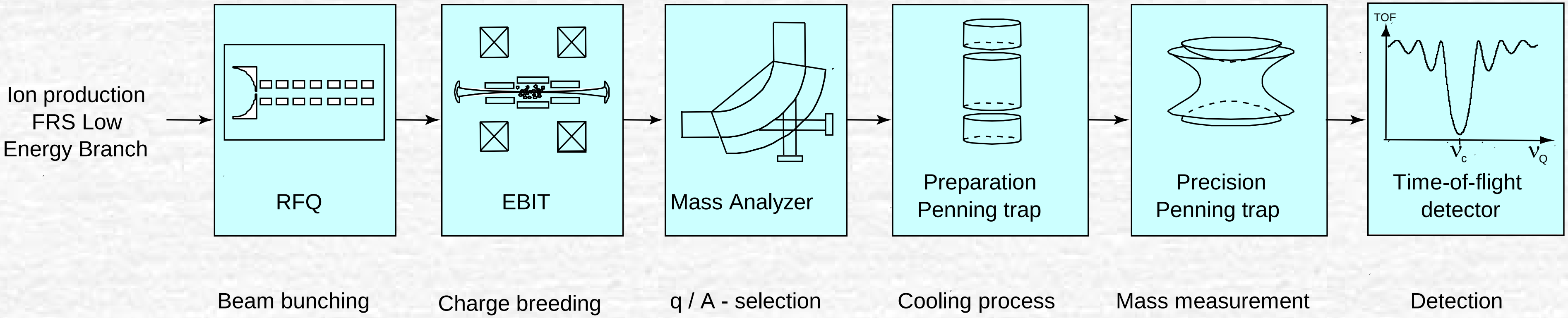
for the MATS Collaboration



The role of masses in nuclear physics

Absolute mass: $$B\left({}_{Z}^{A}X_{N}\right)=Zm_{H}c^{2}+Nm_{n}c^{2}-M\left({}_{Z}^{A}X_{N}\right)c^{2}$$

High-accuracy mass measurements allow one to determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus

Mass differencies:

First order derivatives

Nucleon (s.p) binding energy (drip-line definition)
Nucleon-pair binding energy (S_{2N})
Decay energy (Q_{β}, Q_{α})
Coulomb displacement energy (Isospin multiplets)

Second order derivatives

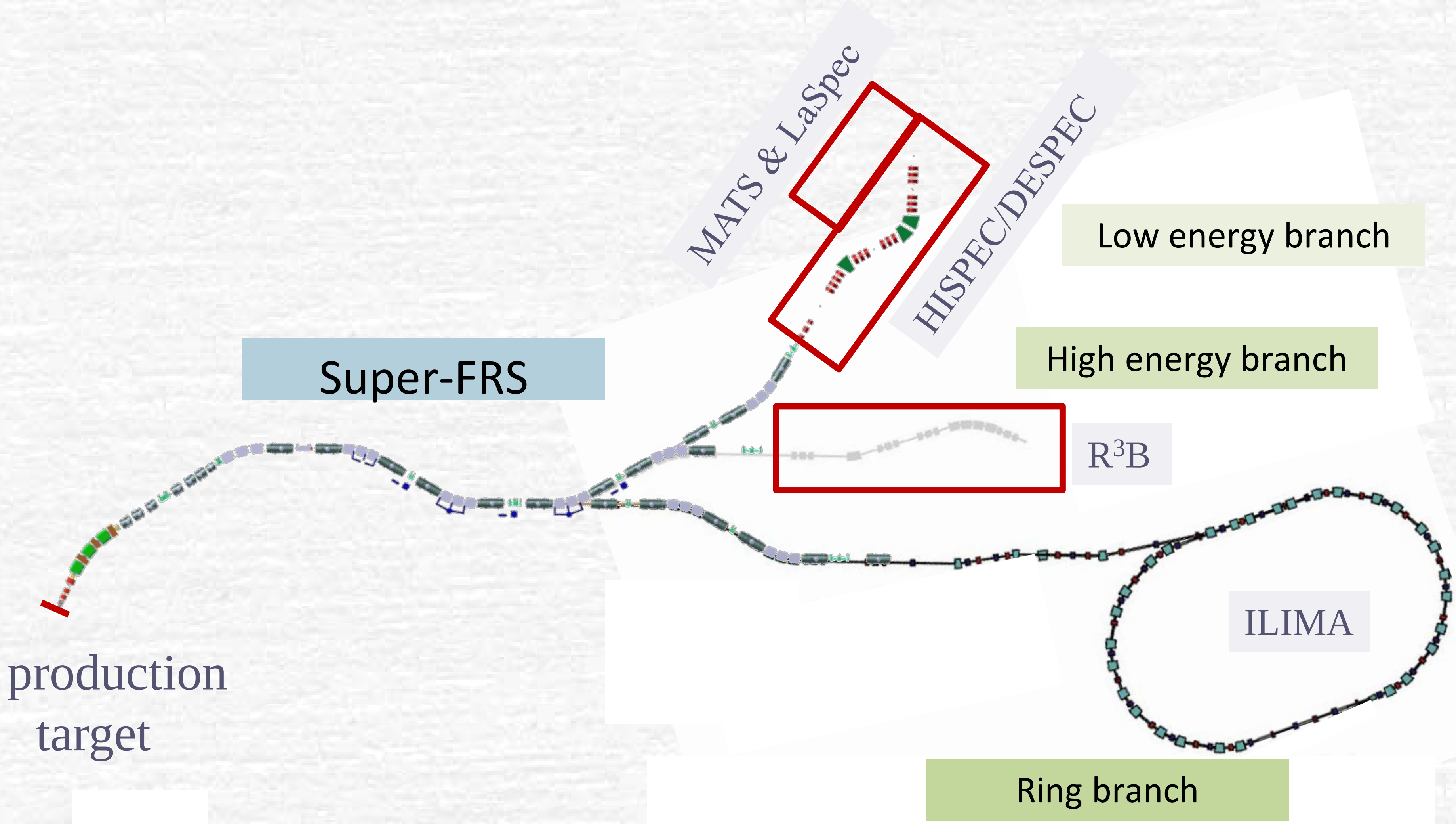
Pairing energy (odd-even staggering)
<u>Shell-gap energy – shell survival for exotic nuclei ?</u>

Research areas and relevant precision

(atomic masses and/or Q-values)

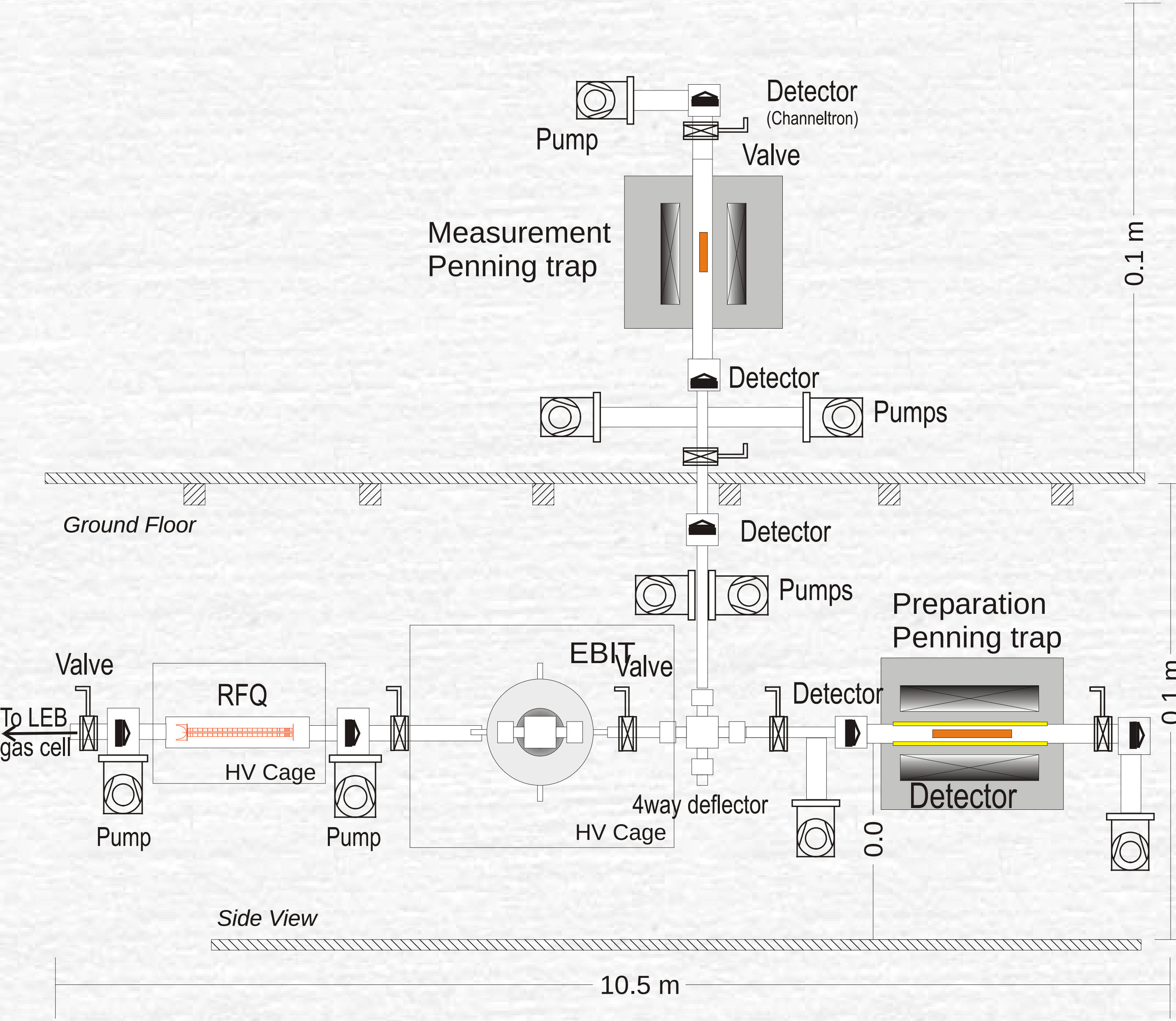
- **Nuclear structure (10-100 keV)**
  - Global correlations (100 keV)
  - Local correlations (10 keV)
    - shell structure, spin-orbit interaction, pairing, collectivity
  - Drip-line phenomena, halos, isomers (1 keV)
- **Nuclear astrophysics (≥ 1 keV)**
- **Charge symmetry in nuclei (≤ 1 keV)**
  - Isospin multiplets
  - Coulomb energy differences
- **Test of Standard Model (≤ 100 eV)** $\delta m/m < 1\cdot10^{-9}$
  - Nuclear β decay. Electroweak interaction
    - CVC theory and unitarity of CKM matrix
    - Double β decay

NUSTAR @ FAIR



MATS & LaSpec
HISPEC/DESPEC
Low energy branch
Super-FRS
High energy branch
R³B
ILIMA
production target
Ring branch

Setup



Detectors:
- FT-ICR
- TOF-ICR
- Si(Li) electron

Precision trap:
mass measure-ments

Cooler trap:
beam preparation
spectroscopy

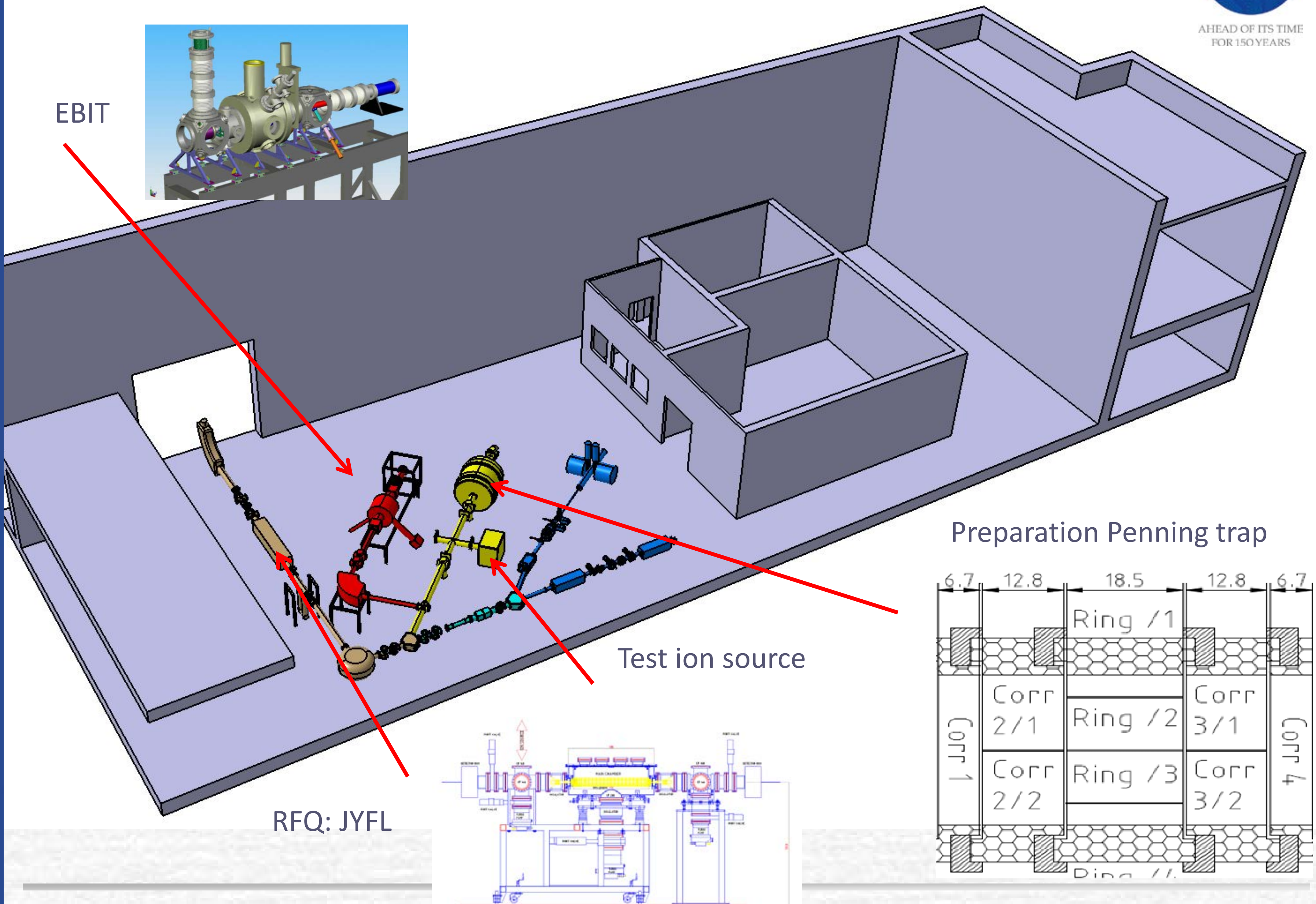
Magn. deflector:
q/m separation

EBIT:
charge breeding

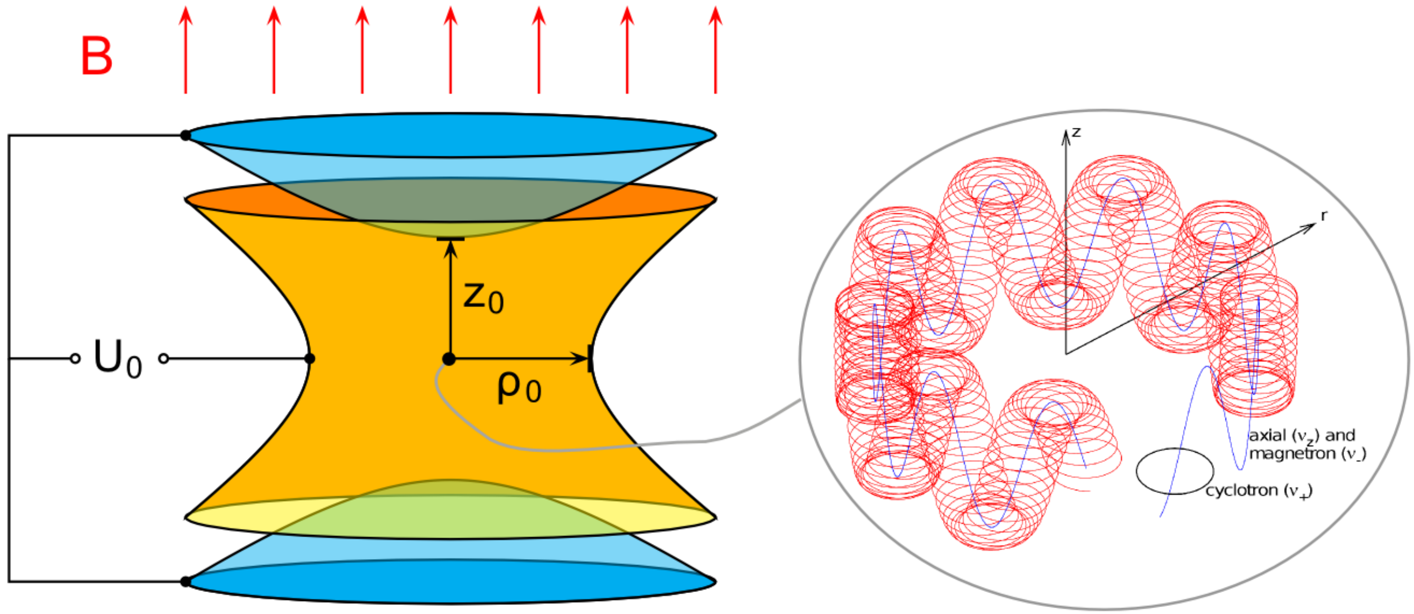
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

MATS & LaSpec at the LEB

MATS
AHEAD OF ITS TIME
FOR 150 YEARS

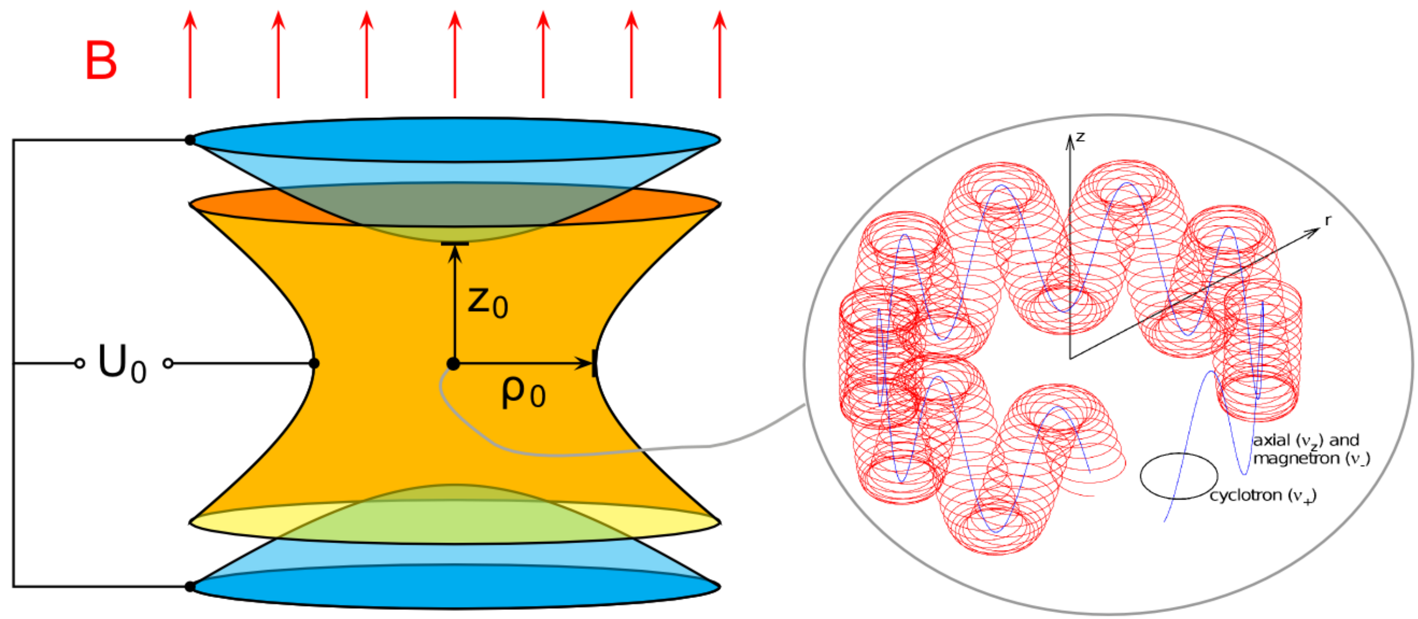


Penning trap – confining charged particles



- Strong homogenous B-field
- Quadrupolar electrostatic potential

Penning trap – confining charged particles



Three eigenmotions

- Axial ν_z
- Magnetron ν_-
- Modified cyclotron ν_+

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{U_0}{d^2}\frac{q}{m}}$$

$$\nu_\pm = \frac{1}{2}\left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

A=100, q=1, B=7 T

- $f_+ \approx$ 1 MHz
- $f_- \approx$ 1 kHz
- $f_z \approx$ 44 kHz

Penning trap – confining charged particles

FREE-CYCLOTRON FREQUENCY: $$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

$$\frac{f_{\mathrm{c,ref}}}{f_{\mathrm{c}}} = \frac{m - m_e}{m_{\mathrm{ref}} - m_e}$$

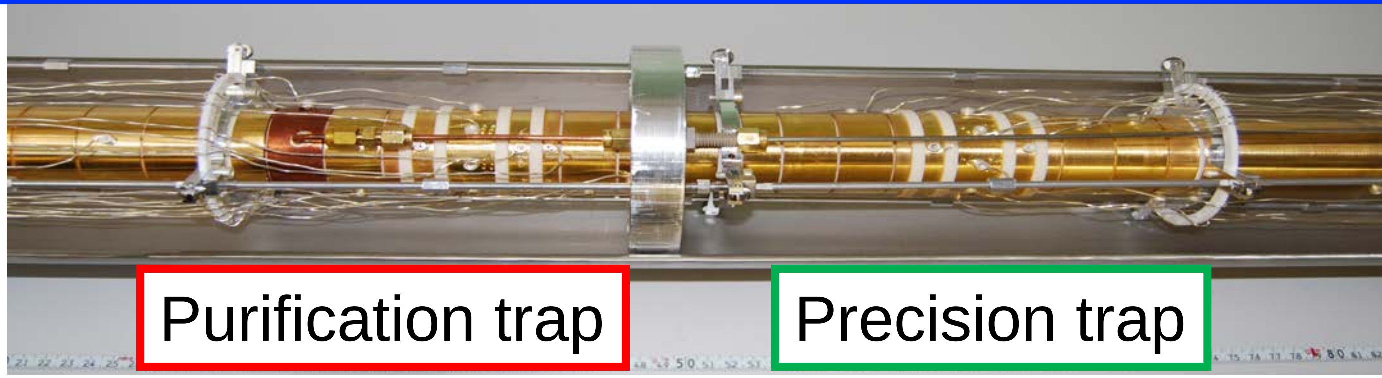
INVARIANCE THEOREM: $$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

Forgives some misalignments etc.

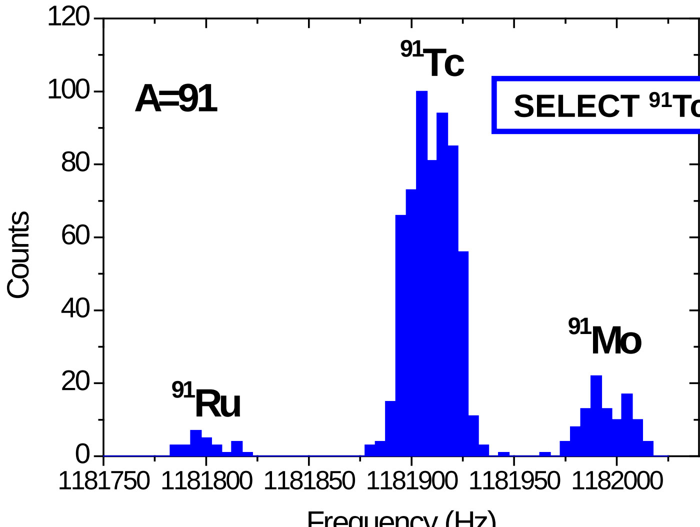
SIDEBAND FREQUENCY: $$\nu_c = \nu_- + \nu_+$$

For ideal trap but usually precise enough

Purification & measurement; JYFLTRAP

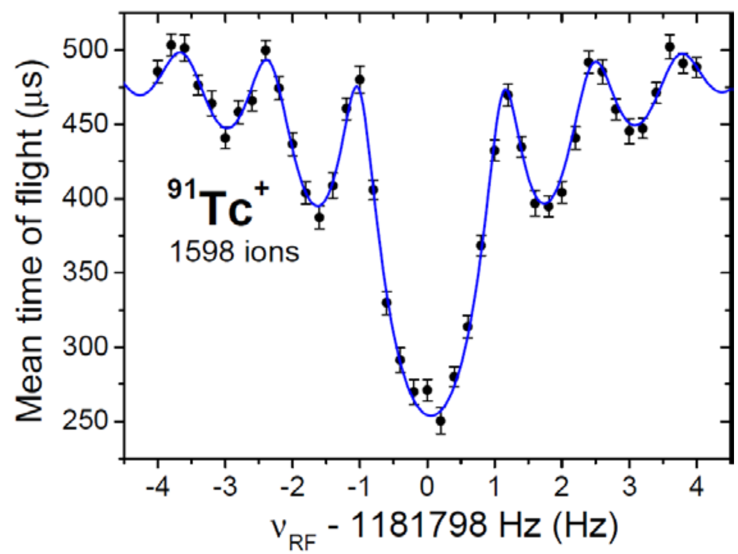


mass-selective buffer gas cooling



Routinely $M/\Delta M \sim 10^5$
Space charge limit $\sim 10^5$
Good/Bad ~ 10000

TOF-ICR method



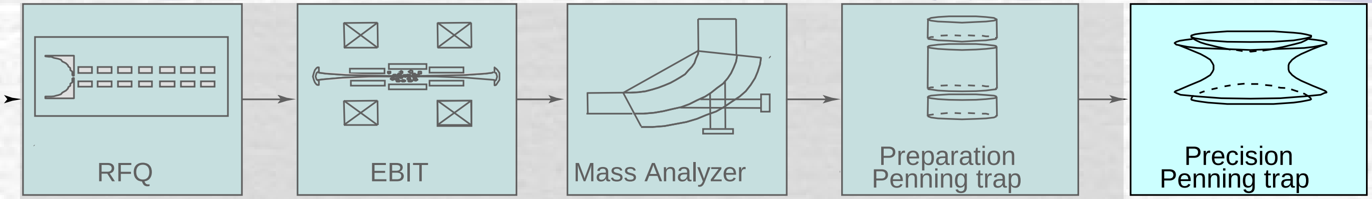
Basic equations for mass determination

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

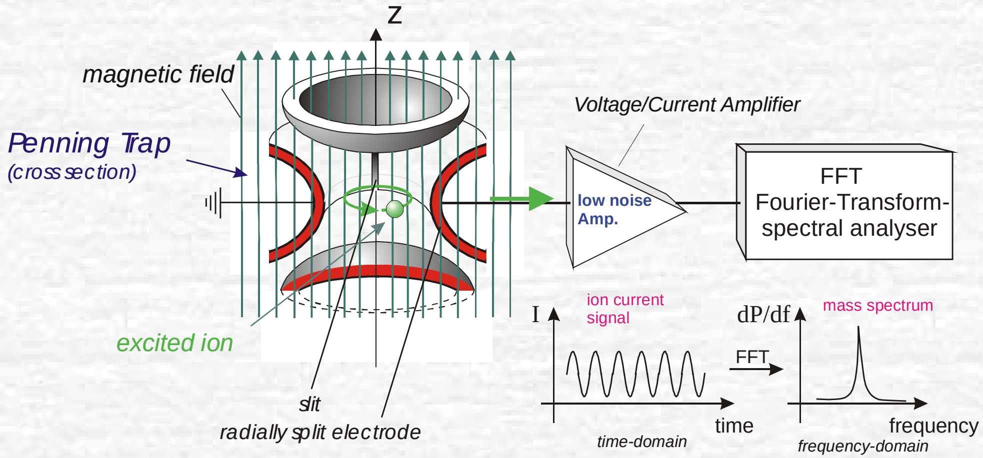
$$\frac{f_{c,ref}}{f_c} = \frac{m - m_e}{m_{ref} - m_e}$$

Routinely few keV
If required few tens of eV (**$\delta m/m < 1 \cdot 10^{-8}$**)

Single Ion FT-ICR

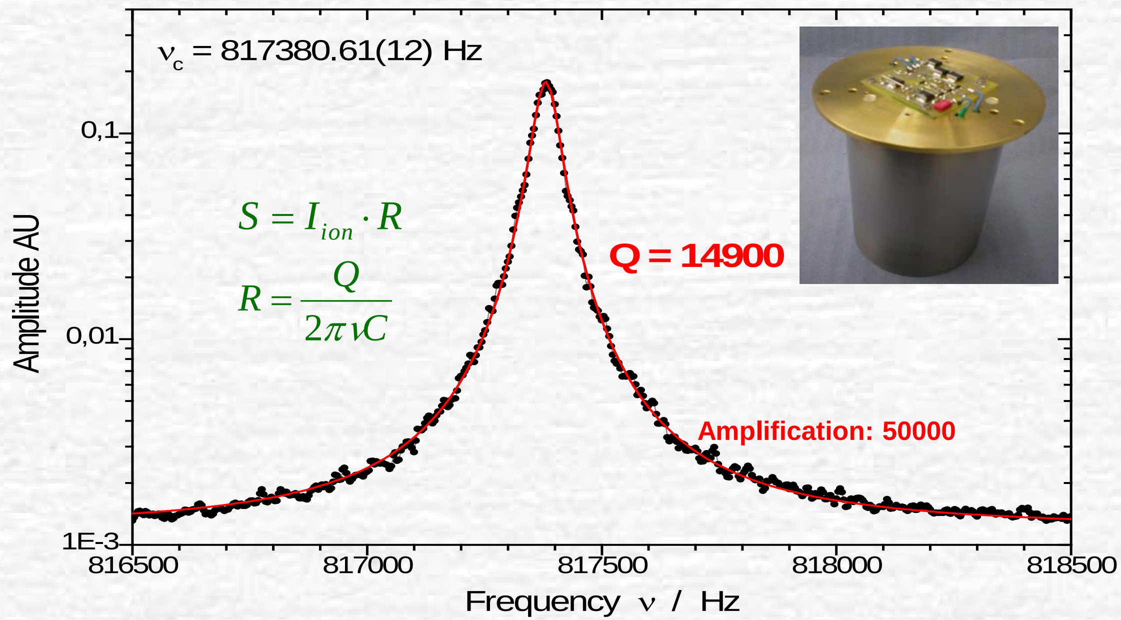


Universität Mainz, K. Blaum et al.

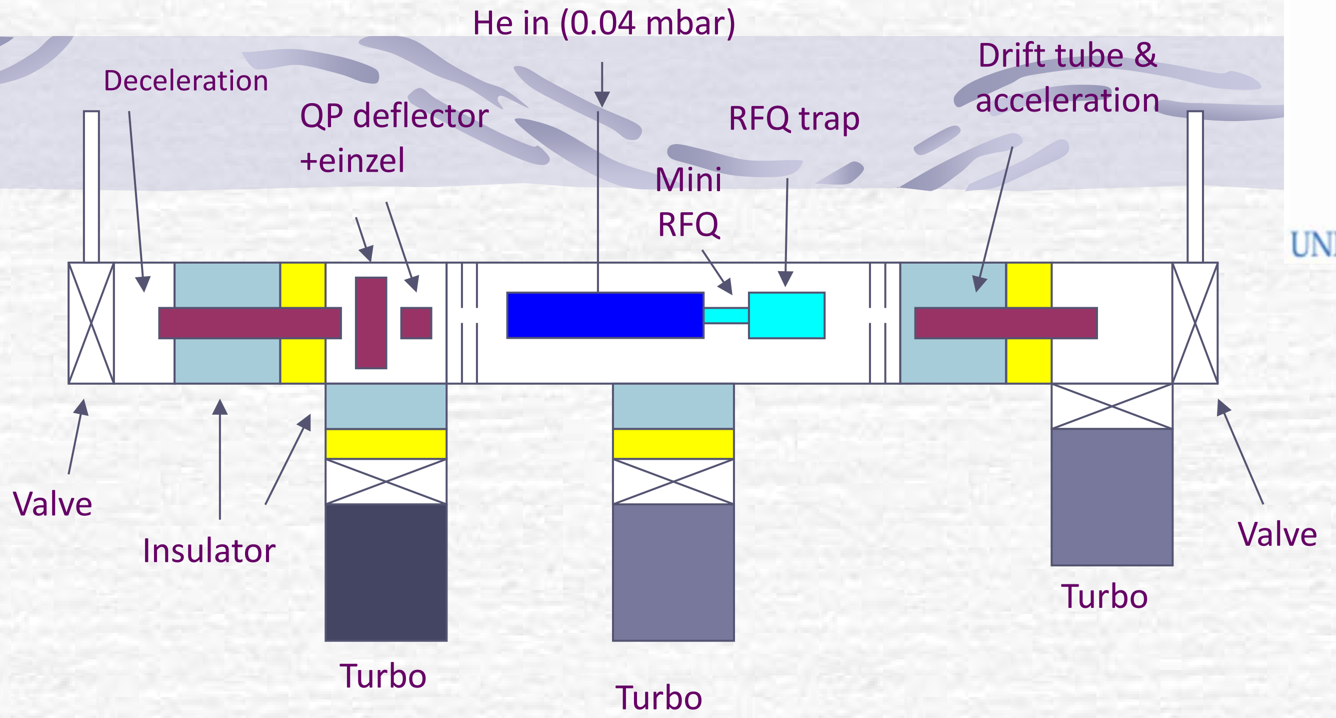


C. Weber et al., Eur. Phys. J A 25, 65 (2005)

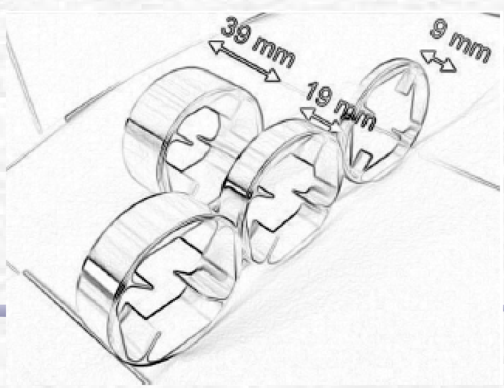
Resonance of the unloaded *LC*-circuit at *T* = 4K



3-stage rf cooler for MATS and LaSpec



Electrode design similar to ISCOOL



Simulation results:

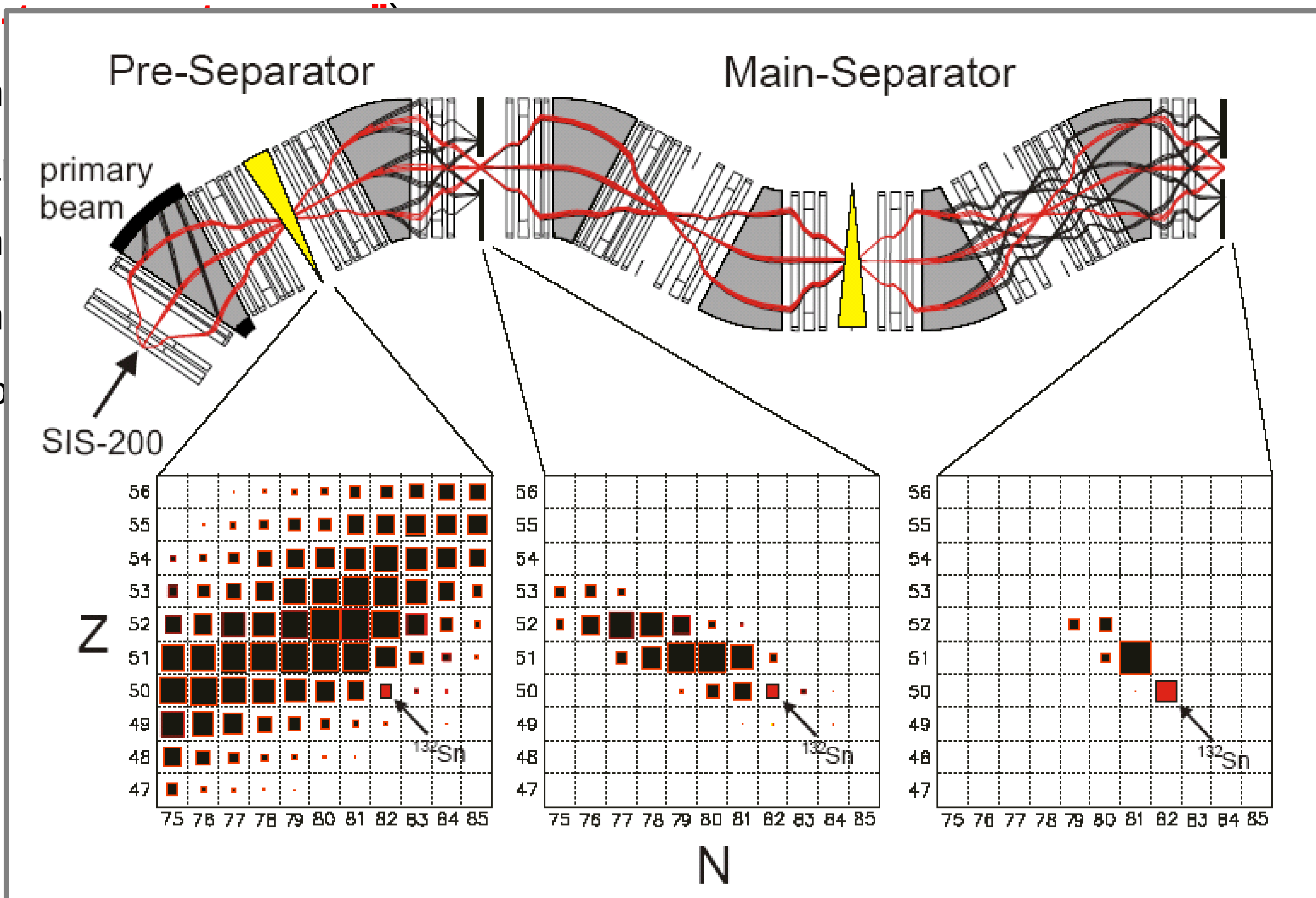
- Emittance ~6π mm mrad, ΔE~ 3 eV, δT ~3 μs for 2 keV pulse of ejected $^{133}Cs^{+}$ when using buffer gas at 80 K.
- 80% injection efficiency, when assuming parallel beam d=4 mm, (40 kV) before deceleration

Trap-assisted spectroscopy

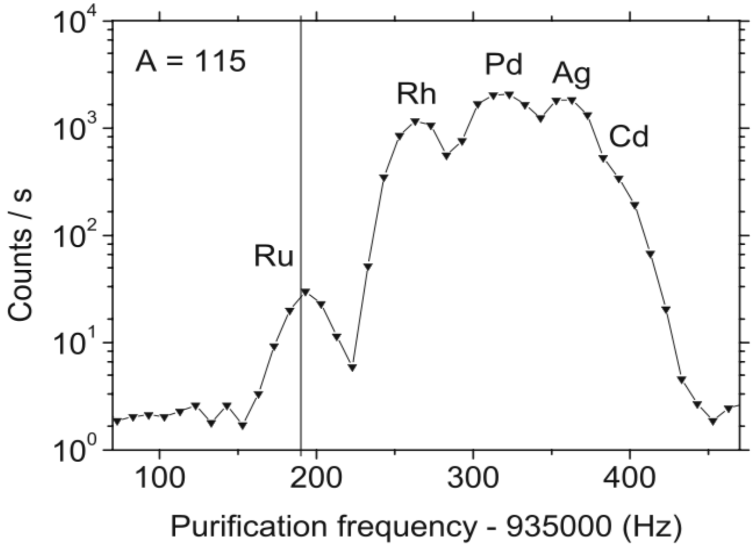
1. Ion beam/cloud manipulation to improve spectroscopic measurements (**"Post-trap spectroscopy"**)
   - Change of emittance, energy spread or time structure
   - Sample **purification** (**isobaric**/isomeric)
   - Change of the chemical element via decay in the trap
   - Change of the ionic state
2. Spectroscopy inside the trap ("in-trap spectroscopy")

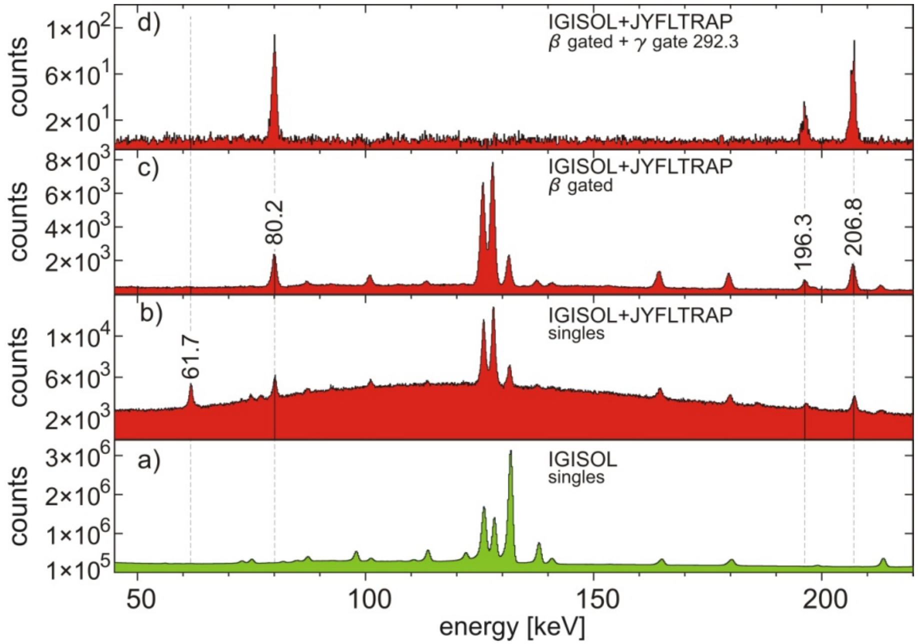
Trap-assisted spectroscopy

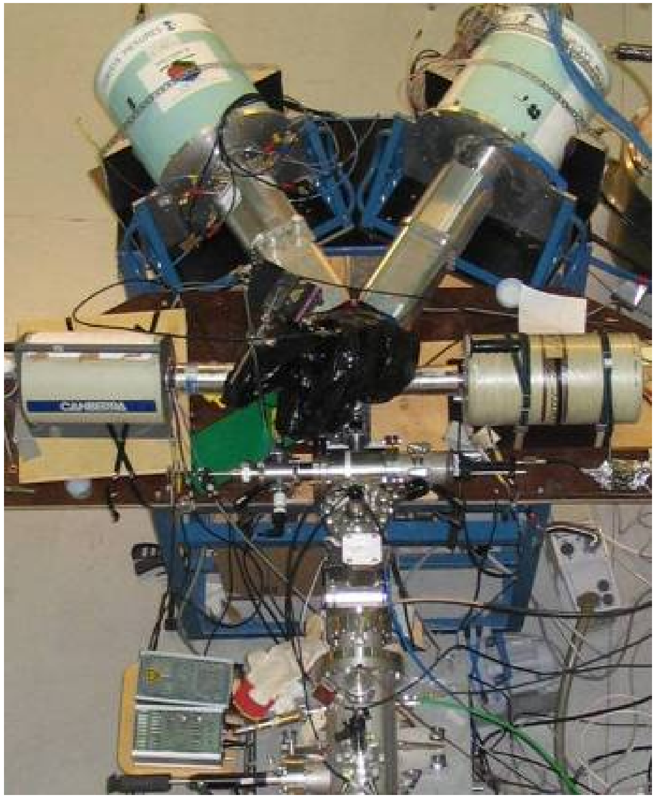
1. Ion beam/cloud manipulation to improve spectroscopic measurements (**"Post-**
   - o Ch
   - o Sa
   - o Ch
   - o Ch
2. Spectro



Example: Purification in A=115

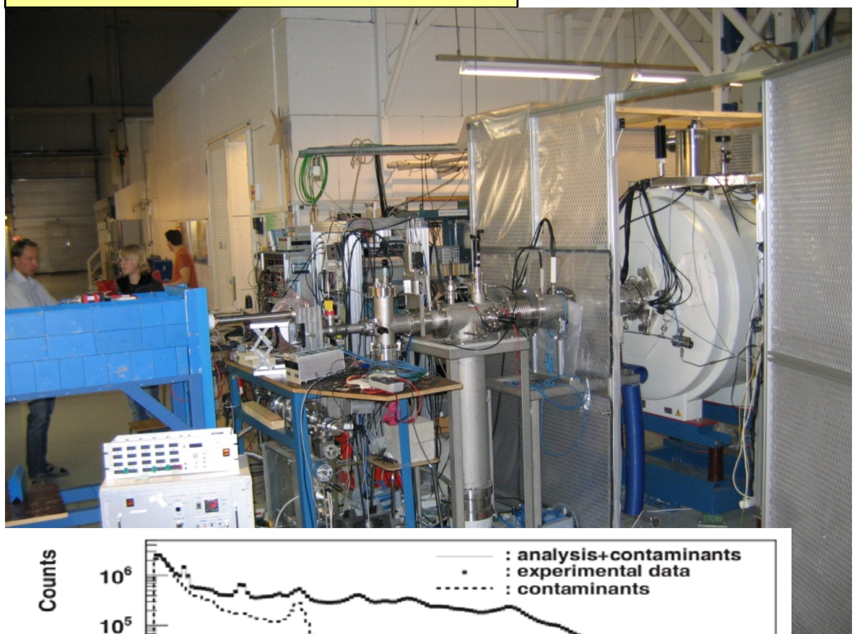


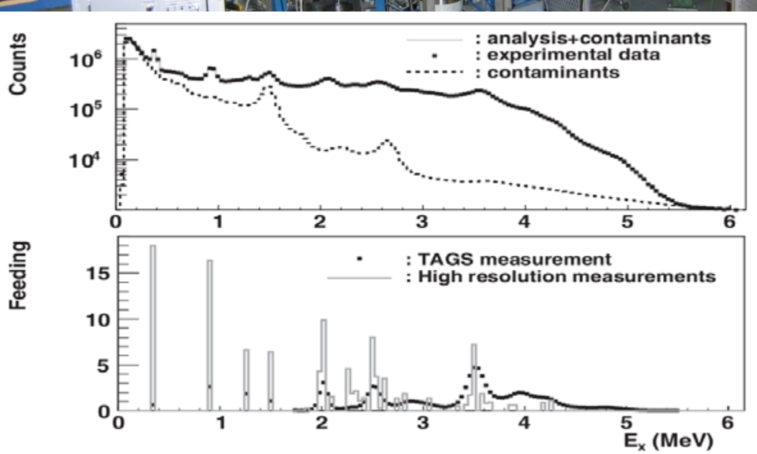




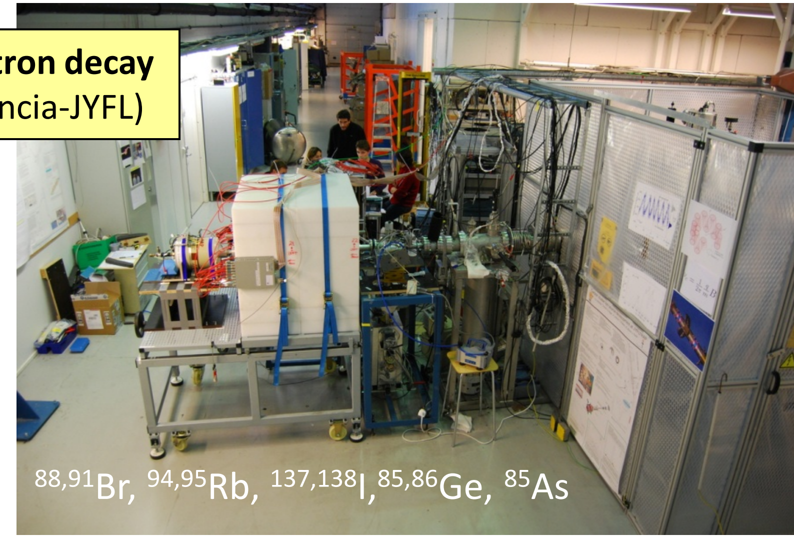
Pure samples for unselective instruments

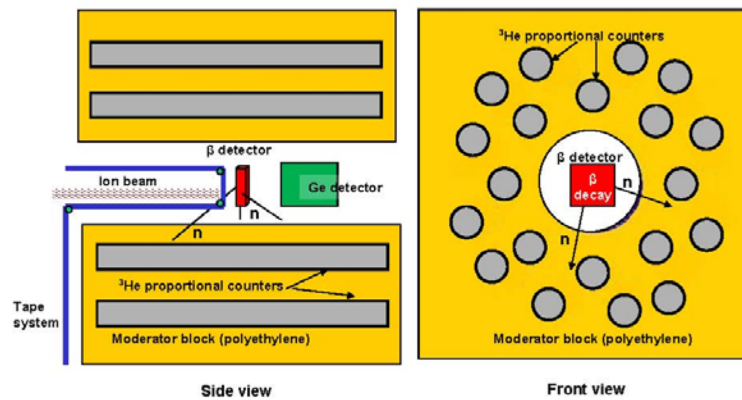
Total absorption spectroscopy
PRL 105 (2010) 202501
PRL 115 (2015) 062502
PRL 115 (2015) 102503





Beta-delayed neutron decay
Nuclear data (Valencia-JYFL)



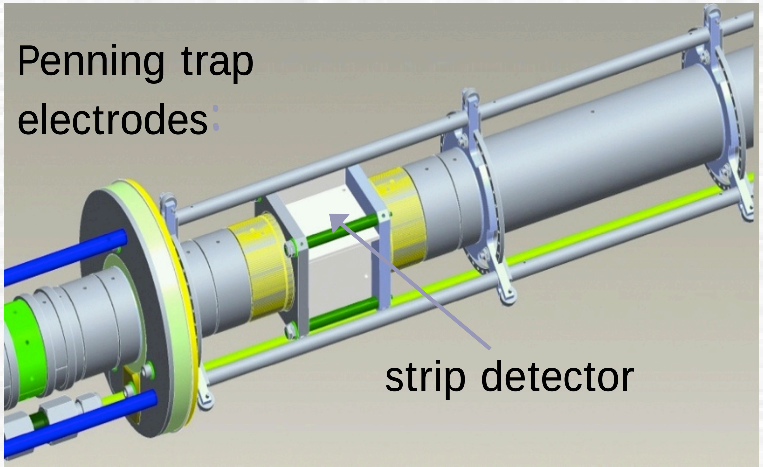


Collaboration:
CIEMAT (Madrid) – IFIC (Valencia) – Inst. Nucl. Res. (Debrecen) – LPC (Caen) – PNPI (St. Petersburg) – Univ. Jyväskylä (Jyvaskyla) – UPC (Barcelona) – Univ. Surrey (Surrey)

The Detector Trap (LMU Munich) [α-e coinc.]

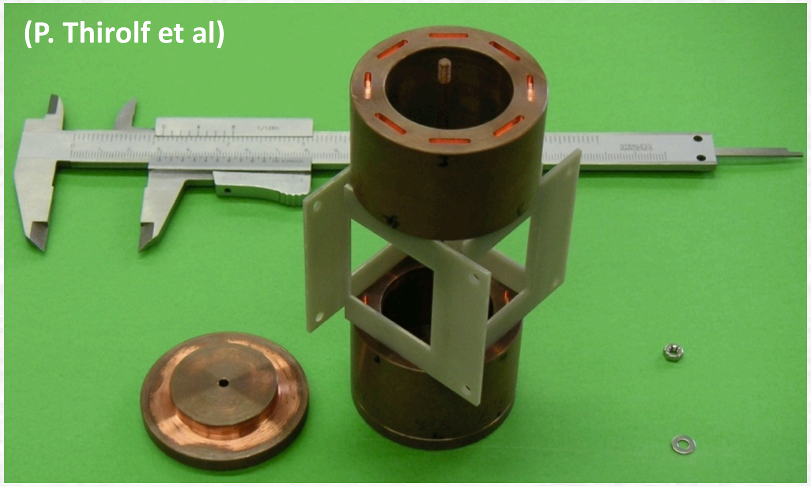
Characteristics:

- Replace inner Penning trap electrode by cubic setup of 4 Si-strip detectors
- Use detector bias for trapping potential

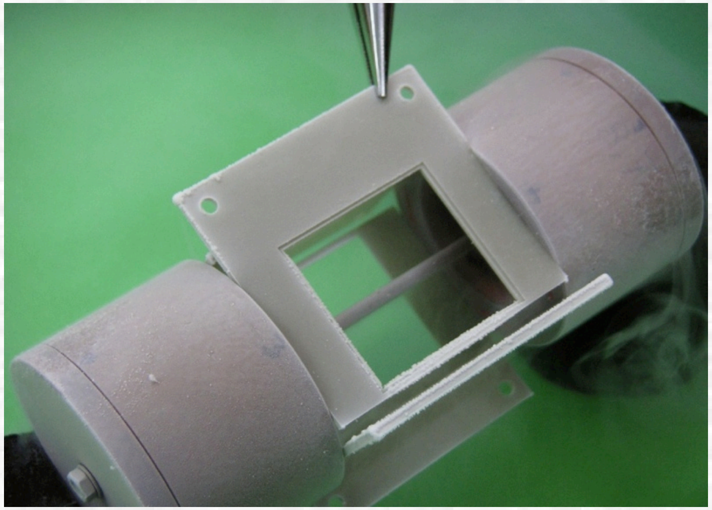


- Detector dimensions given by: space in magnet bore, required position resolution, efficiency optimization
- Detectors need to comply with UHV and cryogenic conditions

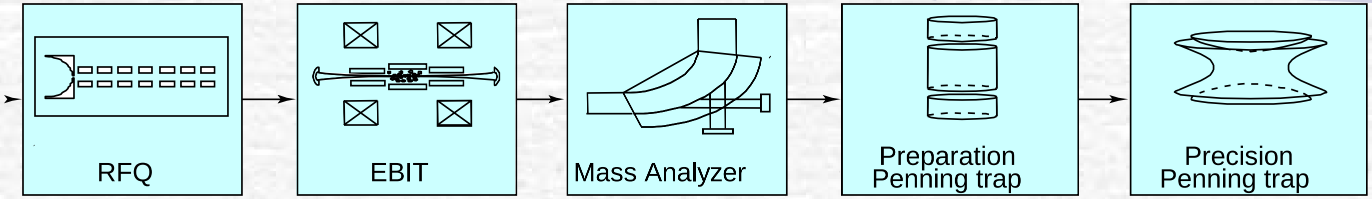
mock-up:
detector carrier boards between trap electrodes



cryotest:
lN_2 temperature, selection of groove dimensions



Summary



Design parameters:

Overall efficiency	1-5%
Maximum resolving power	10^8
Accessable half-life	10 ms
Relative mass uncertainty	10^{-9}

Status:

TDR published in EPJ A

Simulations ongoing

MATS will be an advances trapping system for mass spectrometry, laser spectroscopy, and in-trap decay spectroscopy with highly-charged, short-lived ions.

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Review

MATS and LaSpec: High-precision experiments using ion traps and lasers at FAIR

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