MCP Detectors for Picosecond Timing

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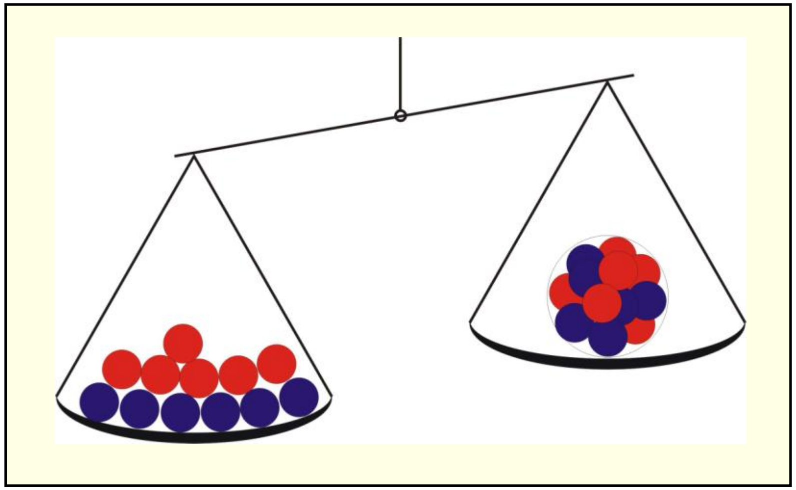
HELMHOLTZ GEMEINSCHAFT

Overview

- Motivation
  Mass Measurement of Exotic Nuclei
- MCP Detectors for TOF-MS
- MCP Detectors for Storage Ring MS
  Timing
  Detection Efficiency
  Rate Capability
- Conclusions

Motivation: Mass Measurements of Exotic Nuclei



The mass of a nucleus reflects its binding energy and hence its stability and structure

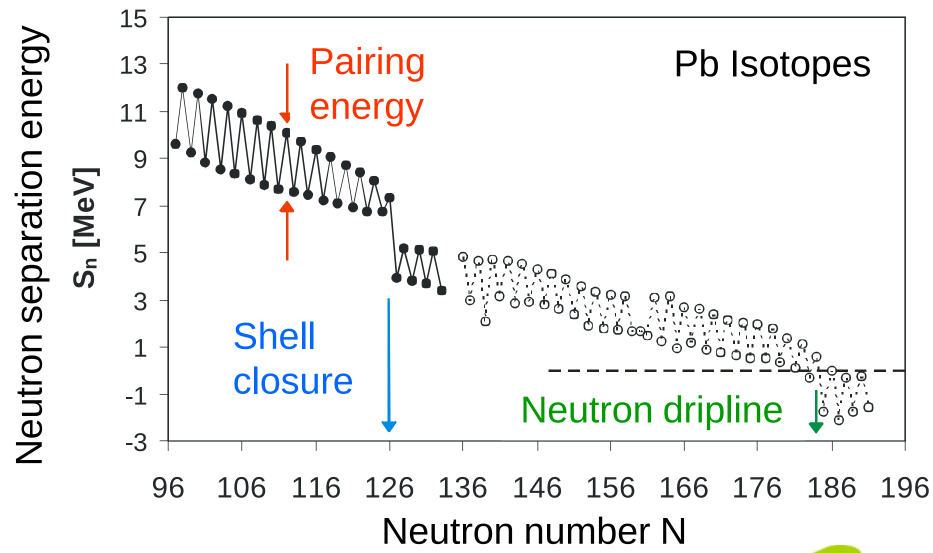
Nuclear Mass $M(N, Z) = Z \cdot m_p + N \cdot m_n - B(N, Z)/c^2$

Z = Proton number, N = Neutron number, A = N + Z = Mass number, B = Binding Energy

Motivation: Mass Measurements of Exotic Nuclei

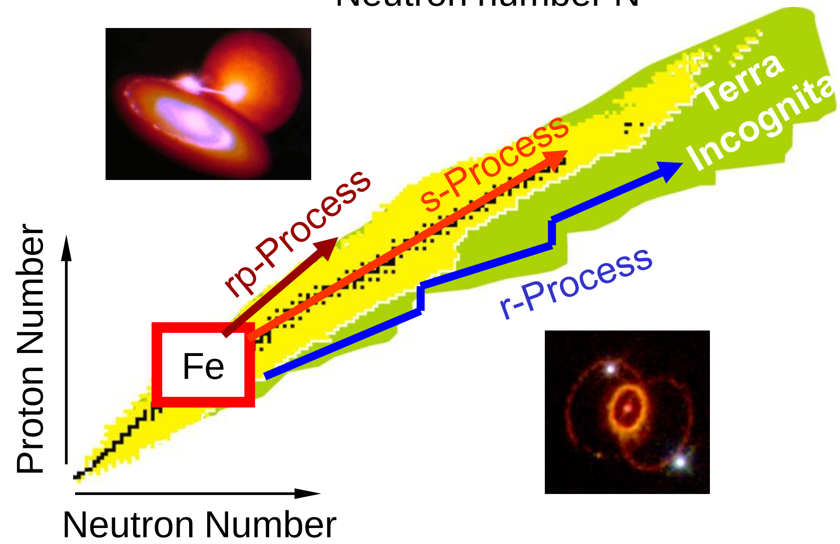
Nuclear Structure

- binding, separation energies
- pairing
- shell closures
- deformation
- location of driplines
- halo nuclei
- nuclear / mass models



Nuclear Astrophysics

- nucleosynthesis pathways
- elemental abundances
- explanation of astrophysical observations (e.g. x-ray bursts)



Required Resolving Power: $m/\Delta m = 10^5$ (Isobars)

Required Accuracy: $\delta m/m \leq 10^{-6}$ viz. 100 keV

Production of Exotic Nuclei

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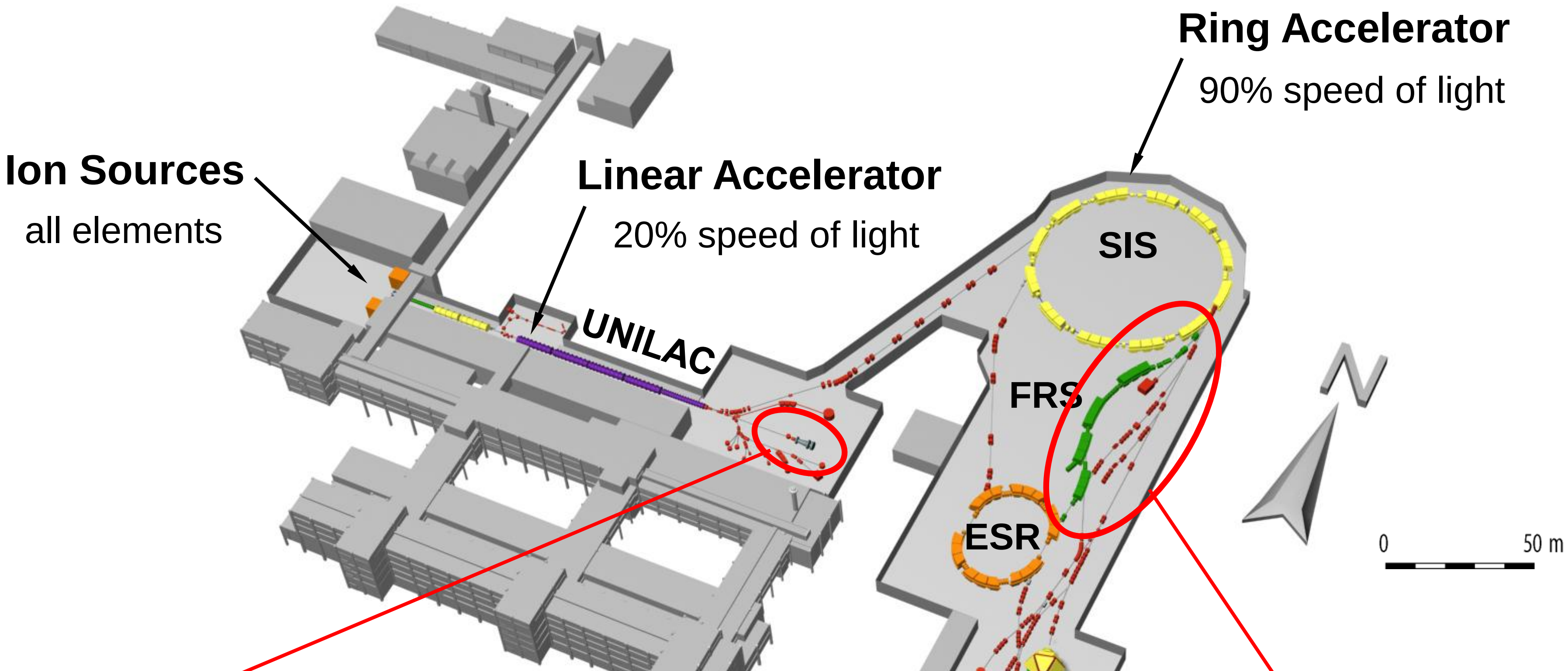
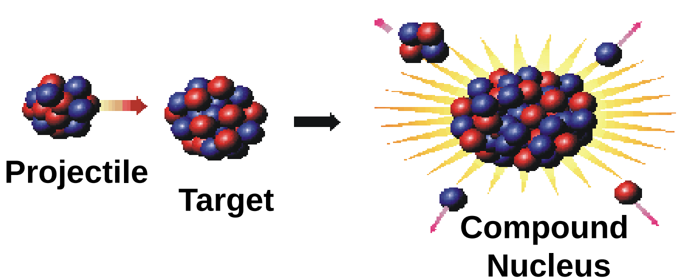
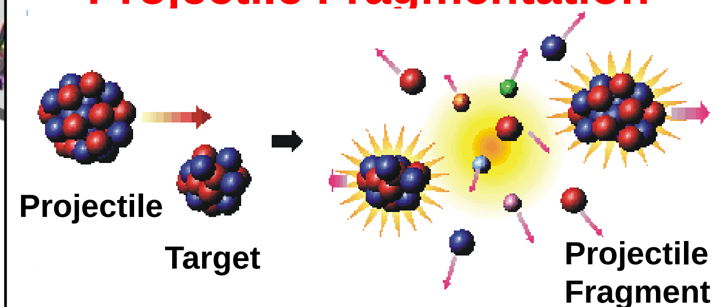


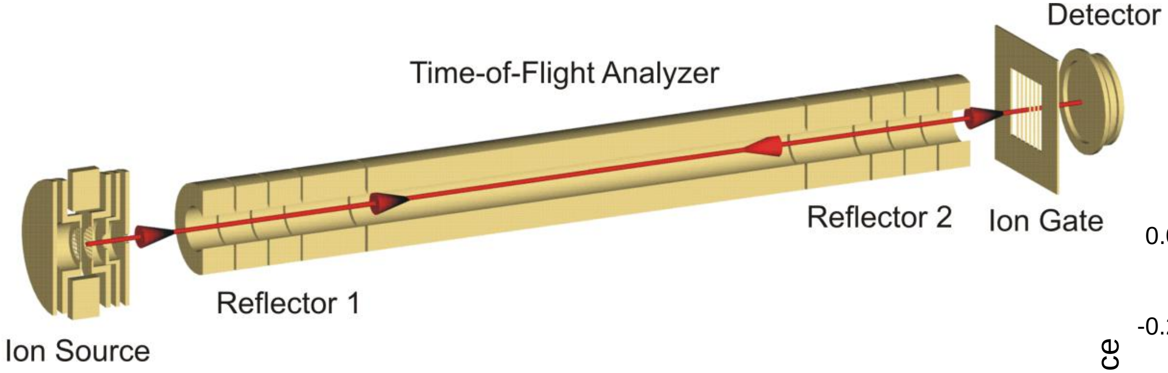
SHIP Facility: Fusion-Evaporation



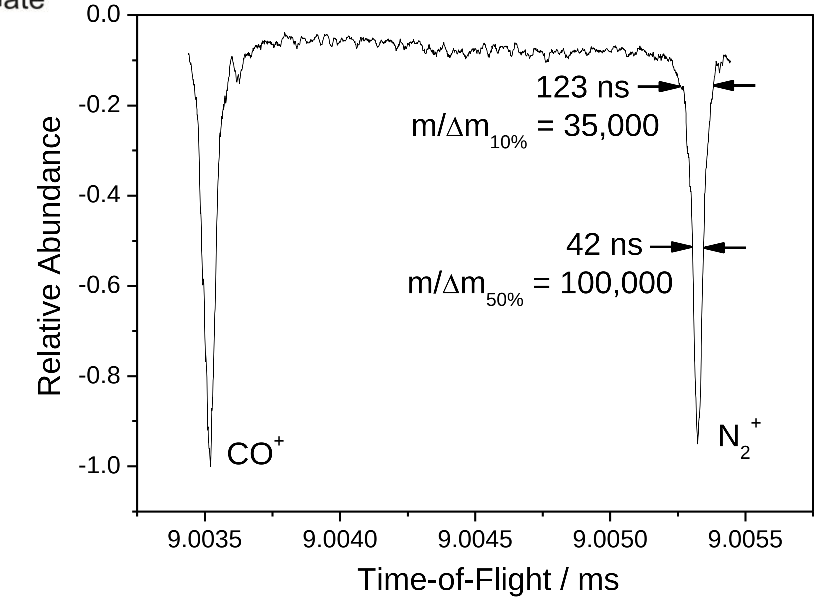
FRS Facility: Projectile Fragmentation



Multiple-Reflection Time-of-Flight Mass Spectrometer



Isobaric pair
CO (27,99437 u)
N_2 (28,00560 u)



Analyzer length: 30 cm, Ion energy: 1.5 keV

T. Dickel, Diplomarbeit, Justus-Liebig-Universität Gießen, 2006
W.R. Plaß et al., Nucl. Instrum. Methods B 266 (2008) 4560

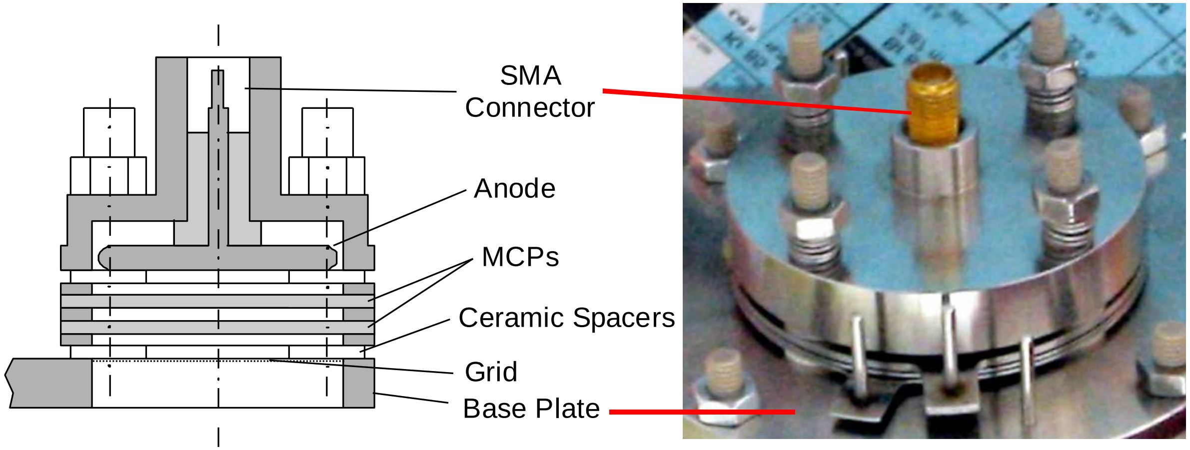
Advantages

- High resolving power (> 10^5)
- High ion capacity (> 10^6 / s)
- Short measurement time (~ ms)
  → access to very exotic nuclei

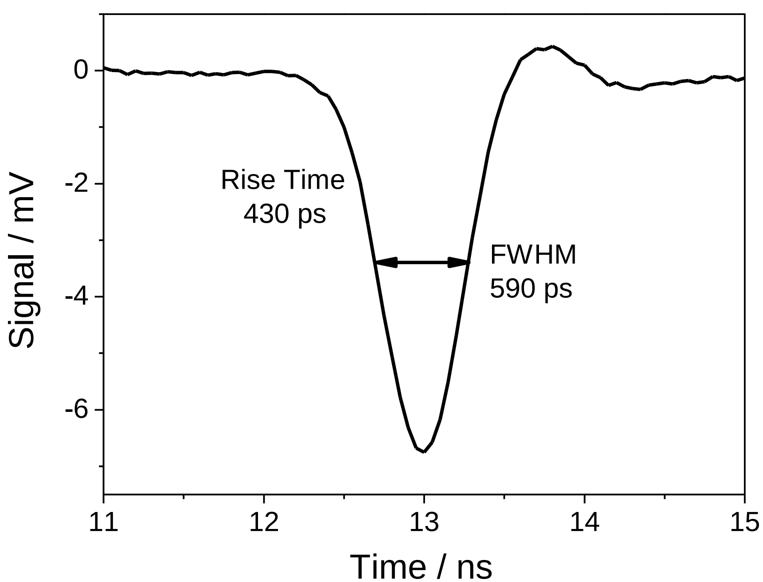
Applications

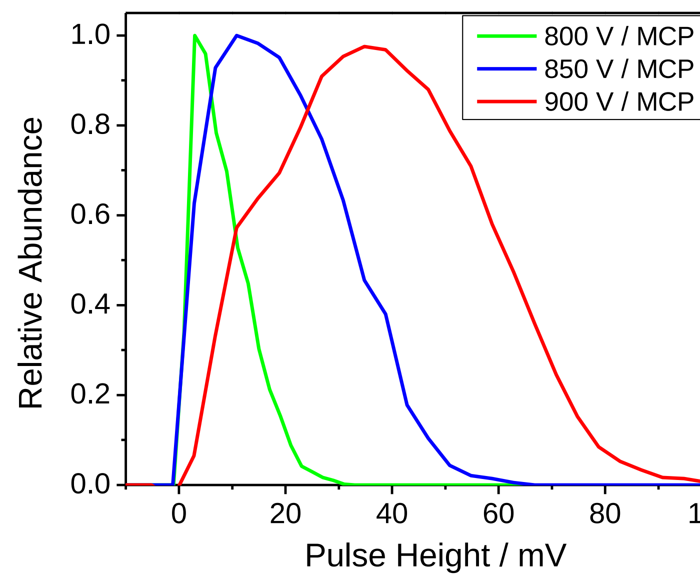
- Direct mass measurements
- Isobar separation (e.g. ^{100}Sn)

MCP Detector for TOF-MS



2 MCPs, Chevron arrangement
Active diameter: 18 mm
Channel diameter: 10 μm
Length / diameter: 40:1
Resistance: ~ 300 MΩ





T. Dickel, N. Kuzminchuk

Isochronous SEM for TOF-MS

SEM with isochronous
inter-dynode electrode transfer:
Crossed electric and magnetic fields

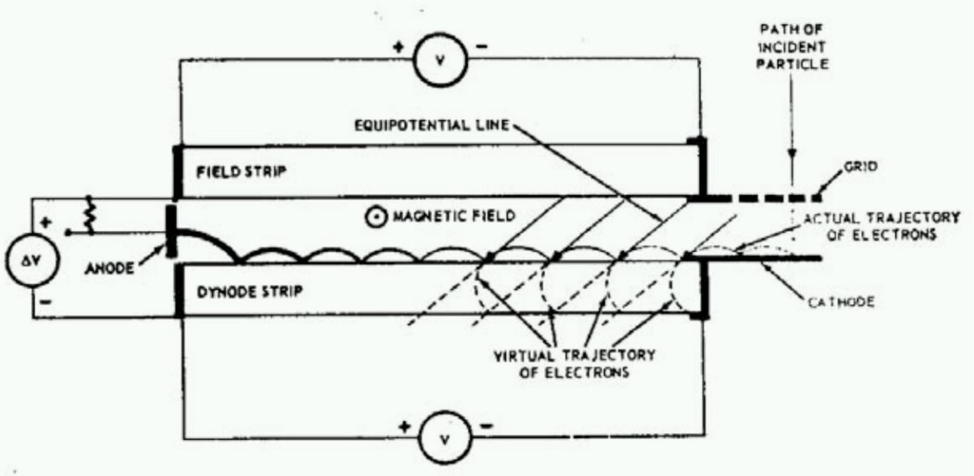
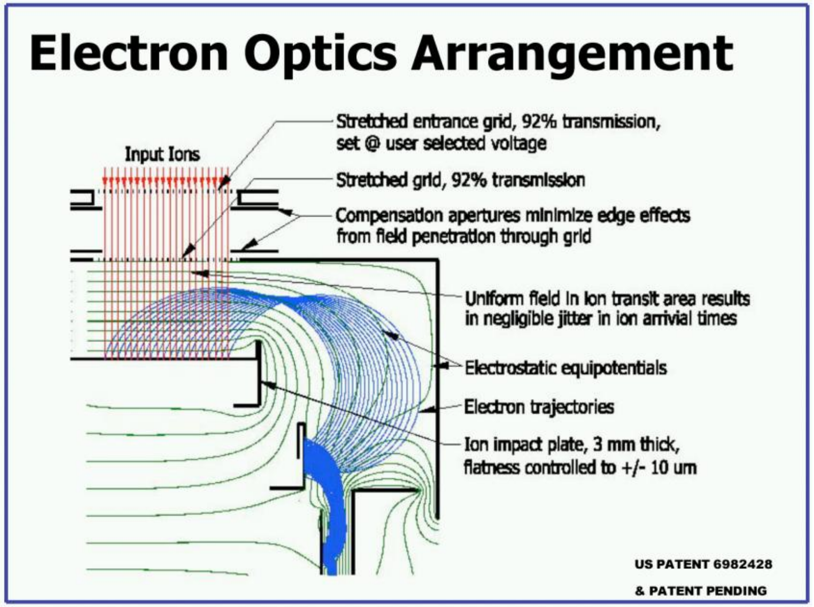


FIG. 2. Electron trajectories in resistance strip magnetic multiplier.

G.W. Goodrich, W.C. Wiley, Rev. Sci. Instrum. 32 (1961) 846

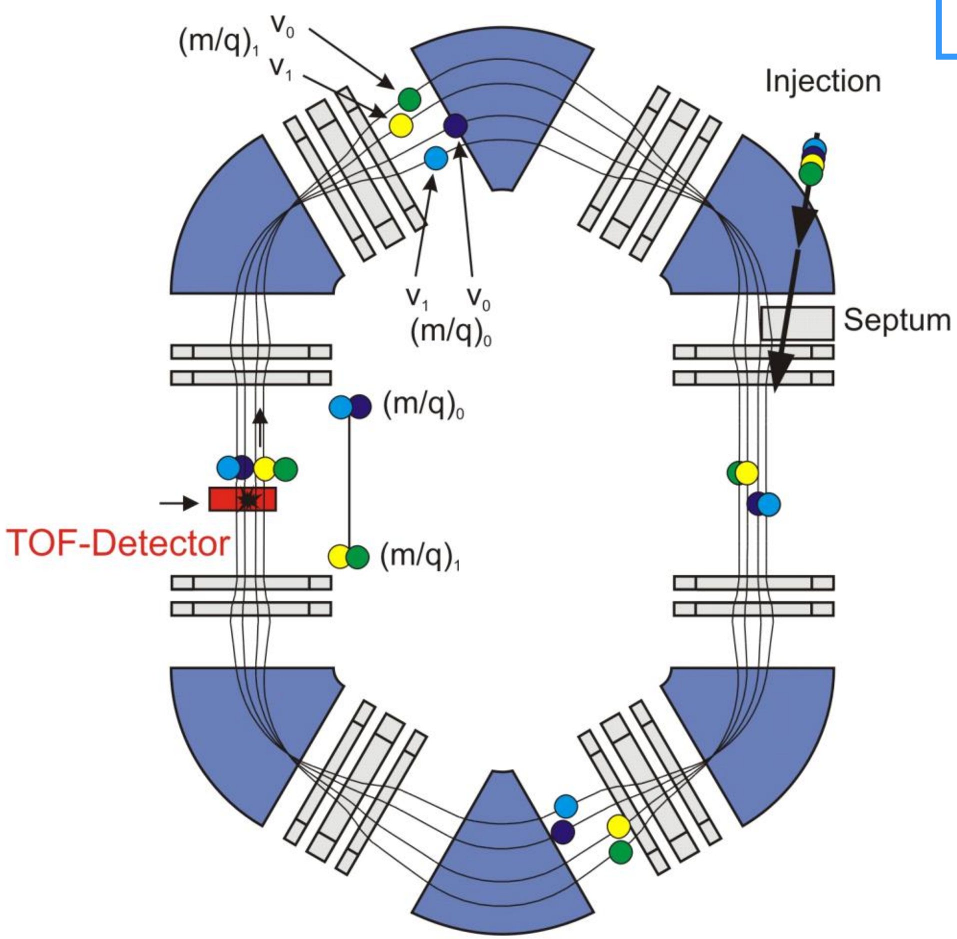
Isochronus SEM with
larger input aperture:
Inhomogenous magnetic field



Performance Characteristics (Manufacturer)
Peak Width (FWHM): < 0.5 ns
Detection Efficiency: ~ 80%
Max. Operating Pressure: 10^{-4} mbar
Input Aperture: 15 mm x 33 mm

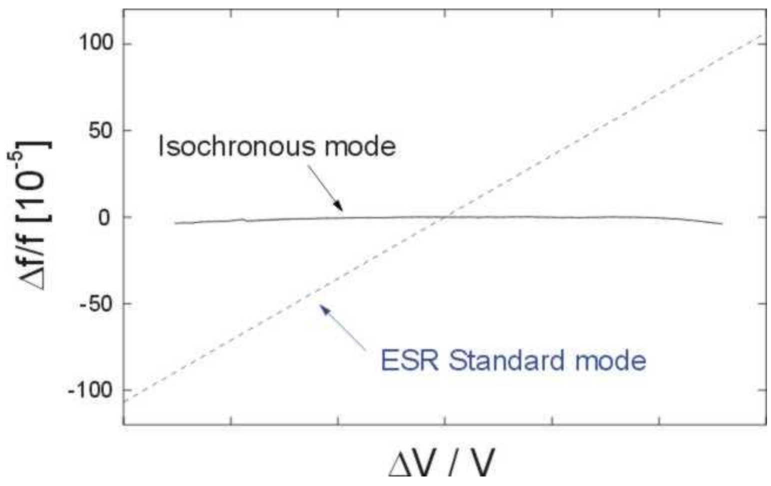
D. Stresau et al., Proc. 54th ASMS Conference, 2006

Isochronous Mass Spectrometry (IMS) in the ESR



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

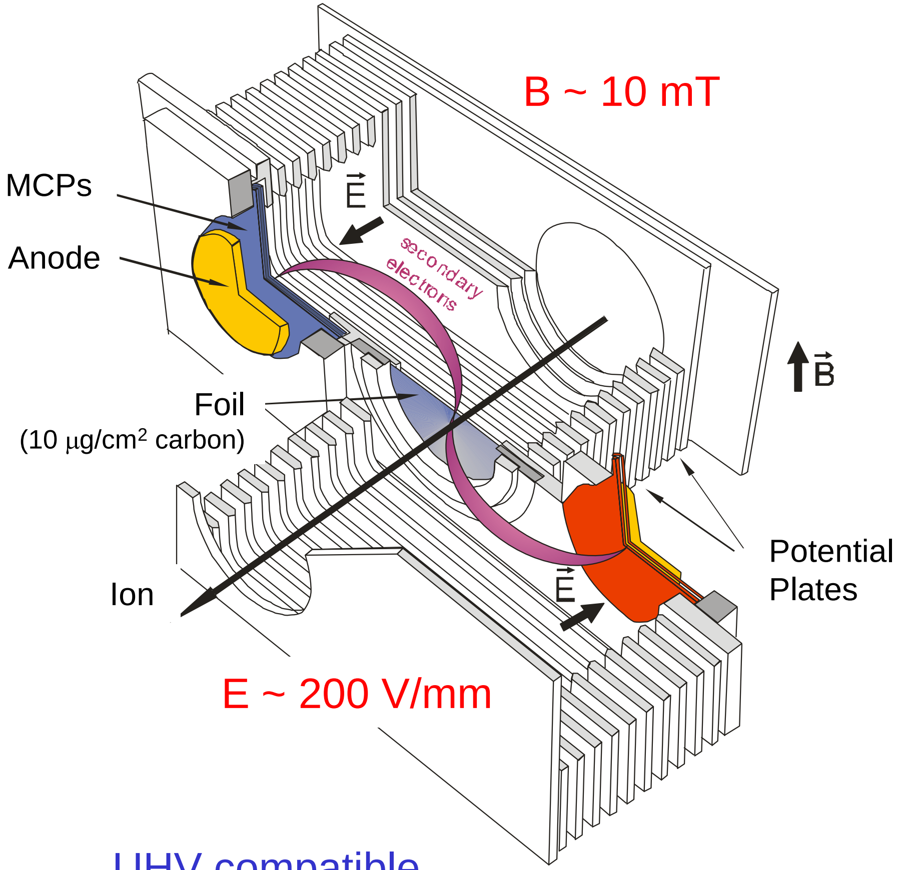
$\gamma \rightarrow \gamma_t$



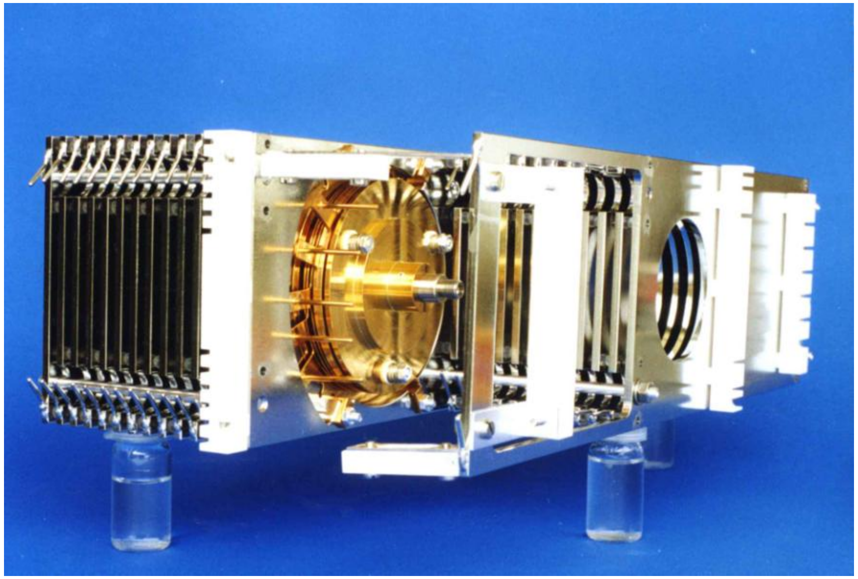
ESR is operated in an isochronous mode (transition point)

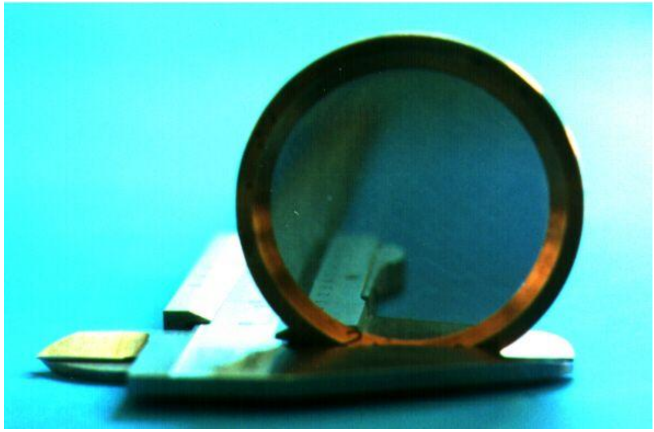
→ dependence of frequency on velocity almost disappears

TOF Detector for IMS in the ESR



UHV compatible
(< 10^{-11} mbar)

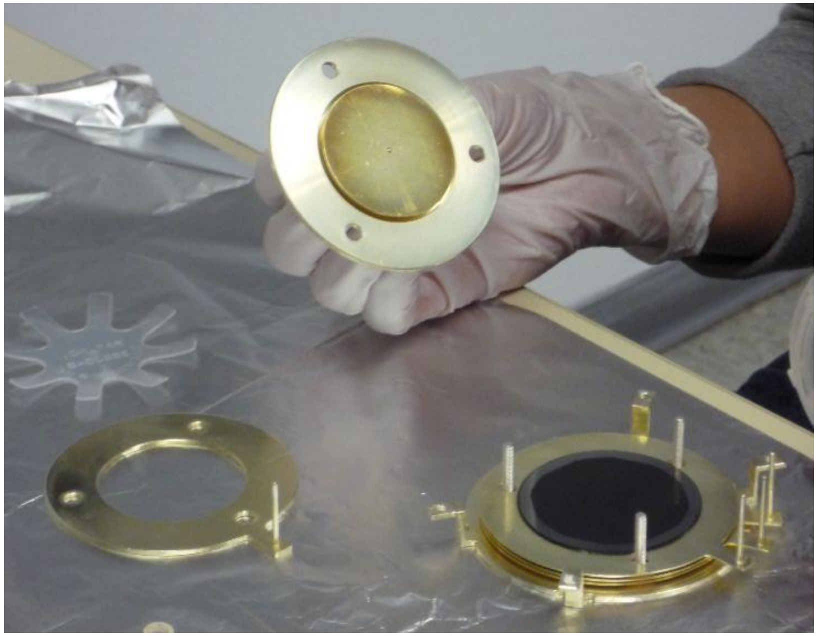




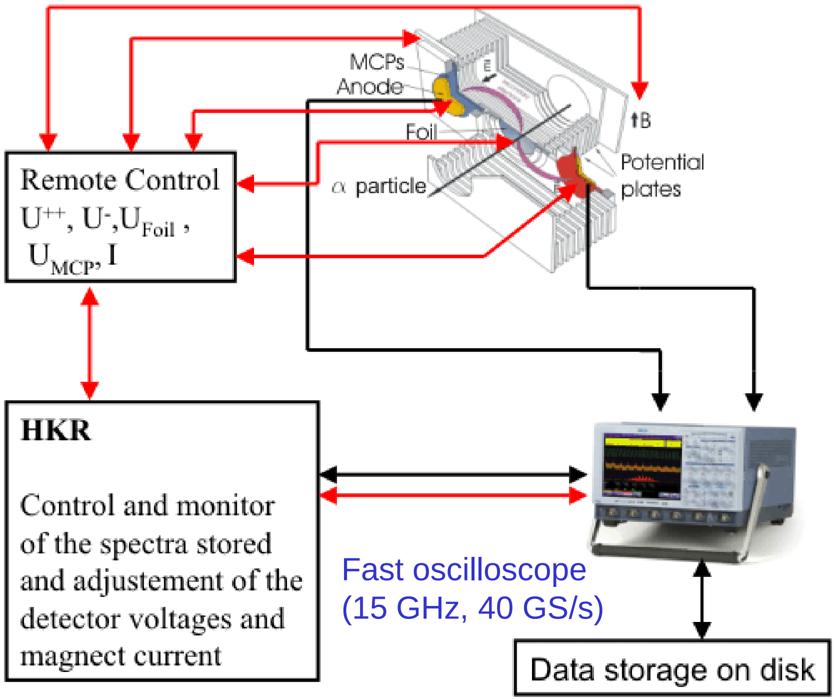
Carbon Foil

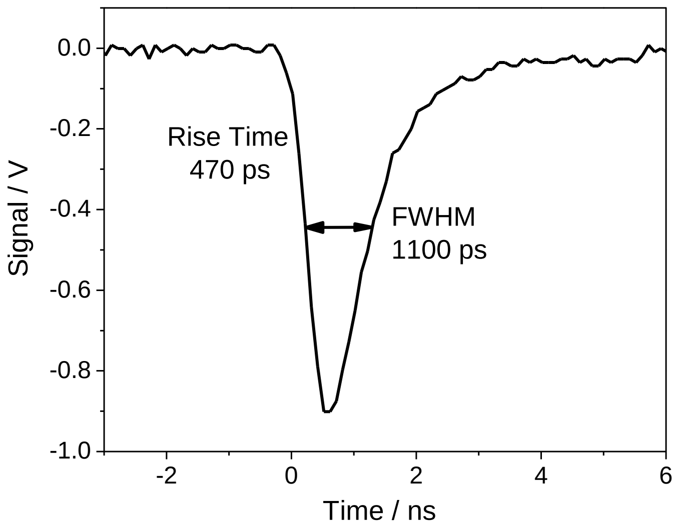
J. Trötscher et al., NIMB 70 (1992) 455

IMS TOF Detector: MCP Detectors and Data Acquisition



2 MCPs, Chevron arrangement
Active diameter: 40 mm
Channel diameter: 10 μm
Length / diameter: 60:1
Resistance: ~ 30 MΩ





N. Kuzminchuk

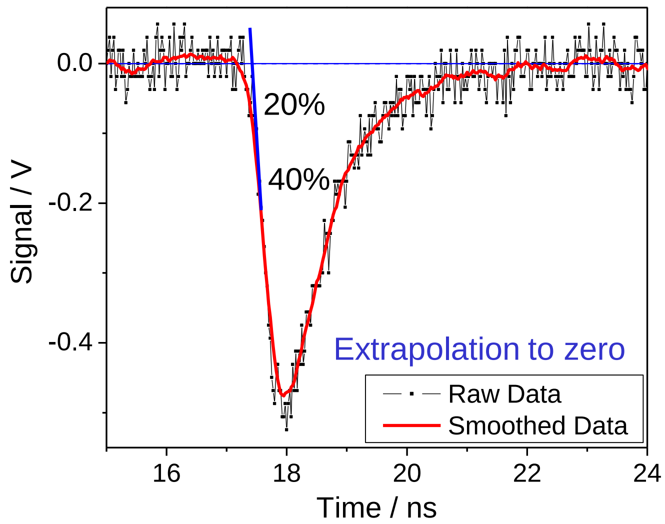
IMS TOF Detector: Timing Precision

Event timing analysis (in software):

1. Data smooting

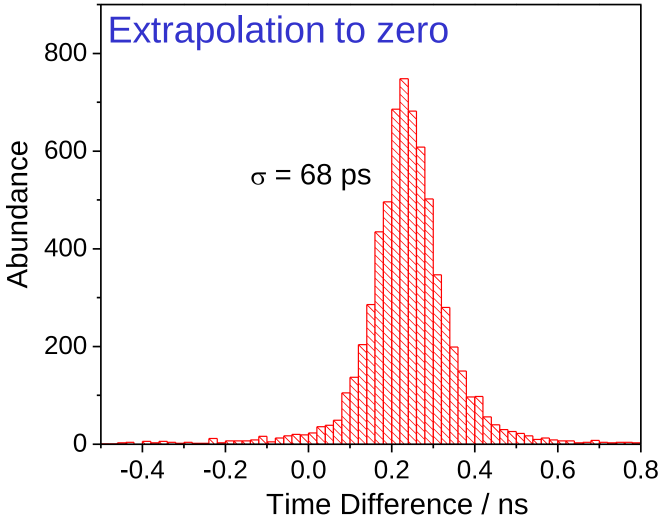
2. Determination of event time

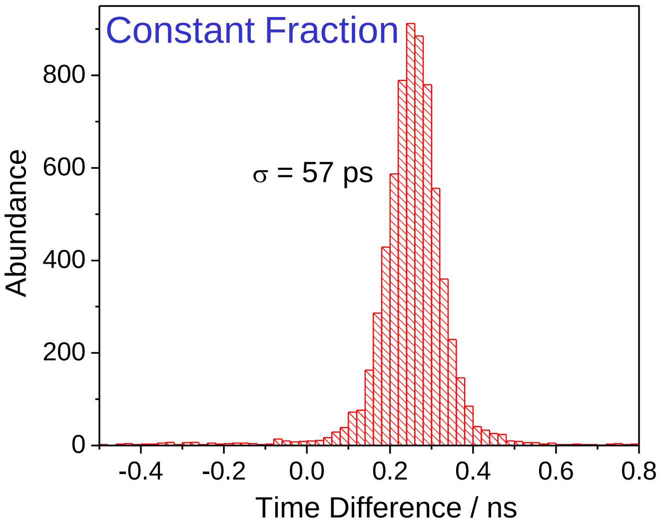
- Extrapolation to zero
- Constant Fraction



Determination of the timing precision by coincidence measurement

(forward and backward channels)





Timing precision per detector:

σ_{det} = 40 ps

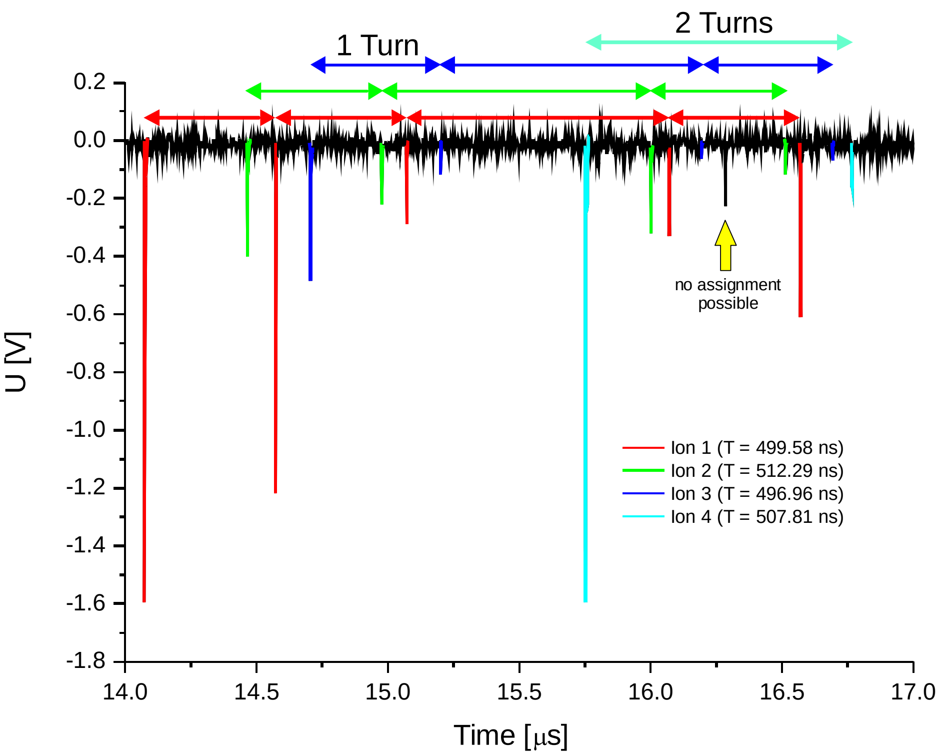
Limitation: electron transit in

- the detector
- the MCPs

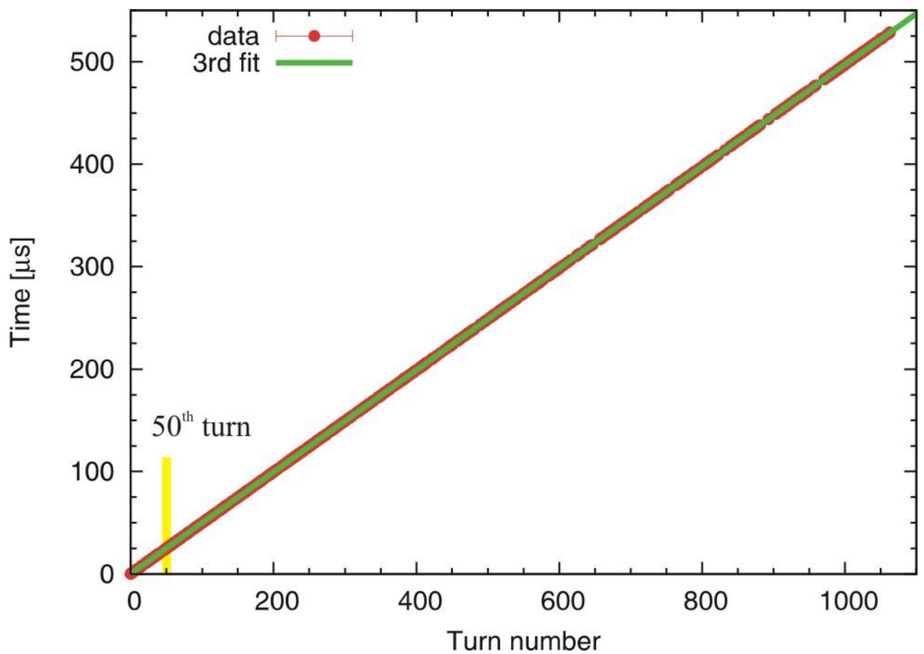
N. Kuzminchuk, B. Sun

IMS Data Analysis

Identification of Individual Ions



Determination of Revolution Times

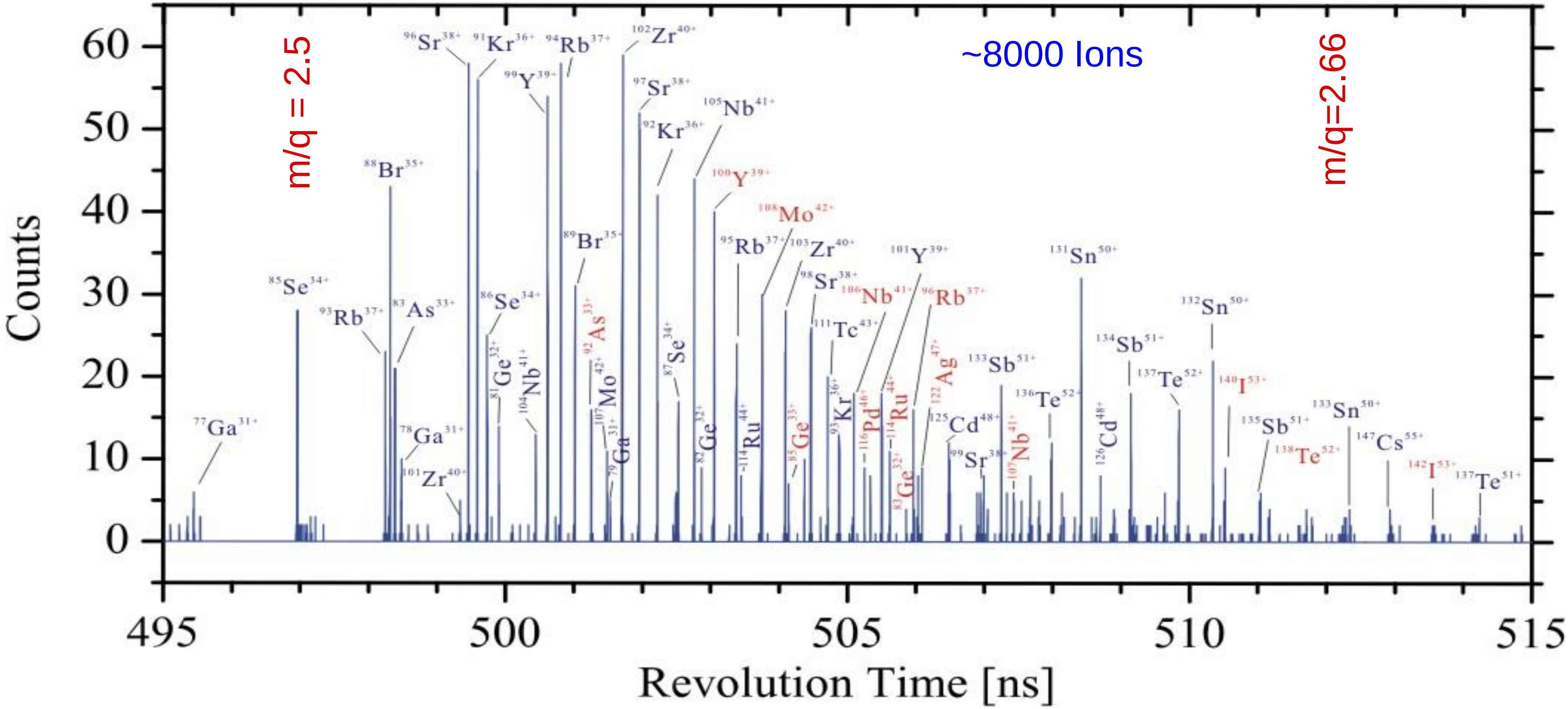


Revolution time: ~ 500 ns

Uncertainty: ~ 0.1 … 1 ps

R. Knöbel, B. Sun

Performance of IMS

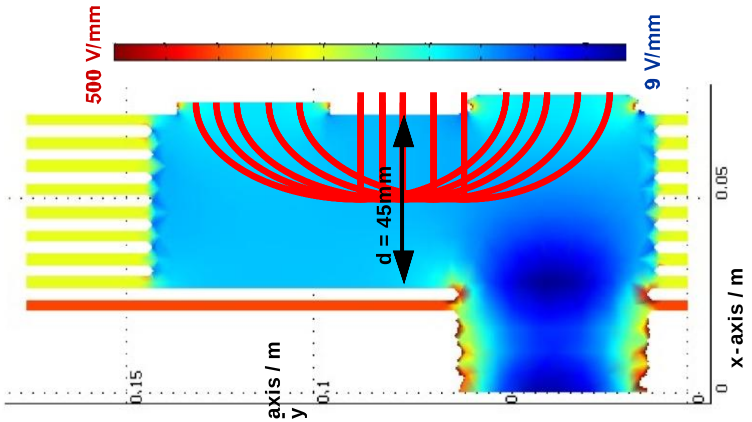


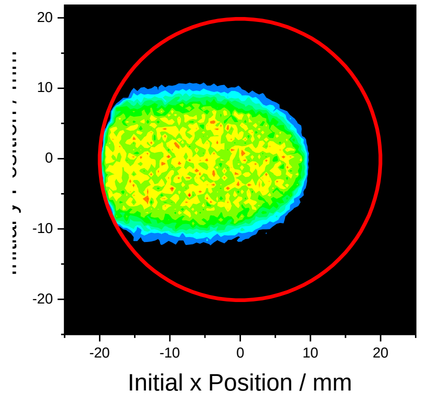
Resolving Power: $2 \cdot 10^5$
Accuracy: 100 keV
Duration: ~ 50 μs
Sensitivity: Single Ions

B. Sun, R. Knöbel

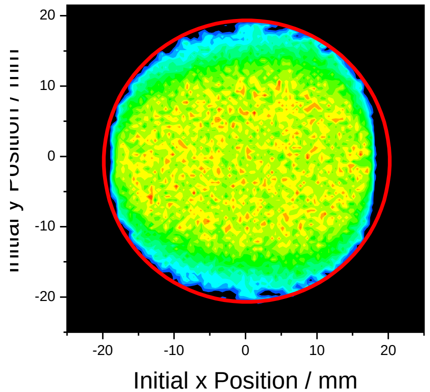
IMS TOF Detector: Detection Efficiency

Optimization of electron transport by simulations



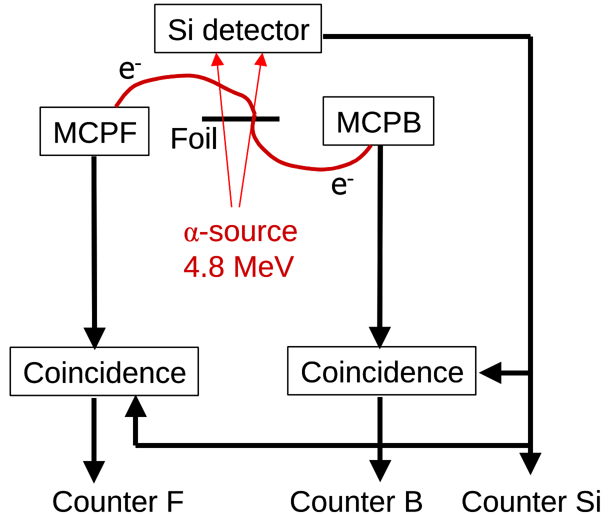


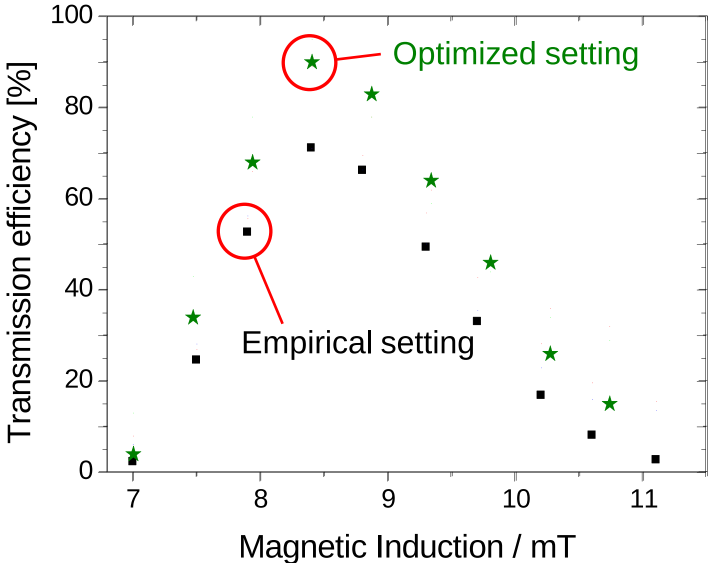
Empirical setting
(J. Trötscher , Dissertation, JLU Gießen 1993)



Setting optimized by simulations
(B.Fabian, PhD thesis, JLU Gießen 2008)

Verification by experiment



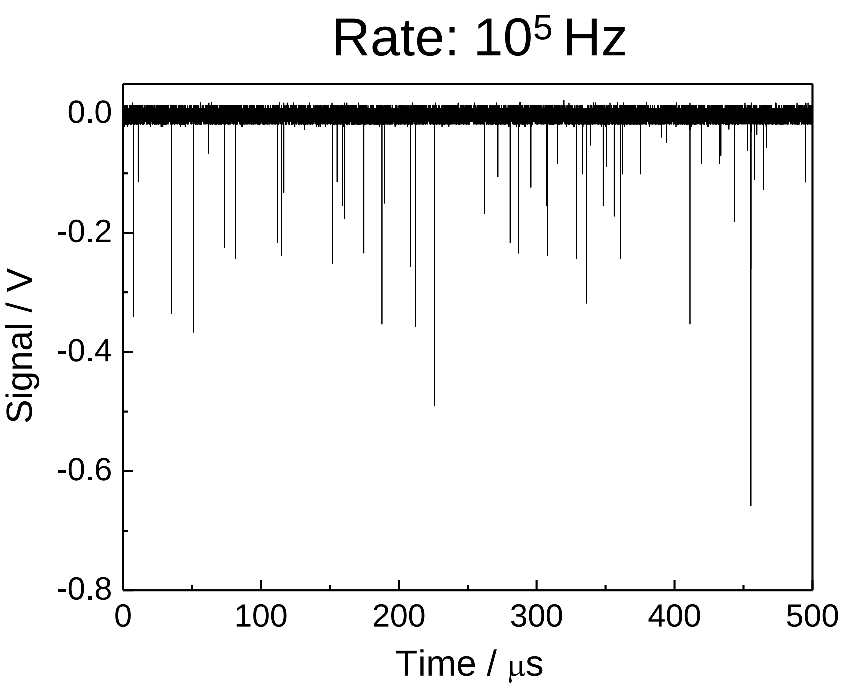


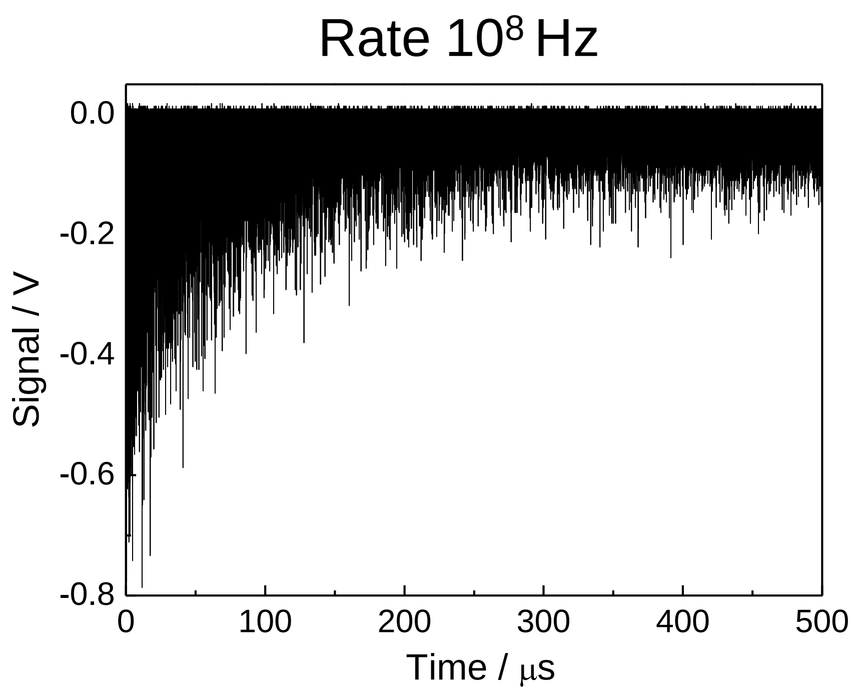
B. Fabian

IMS TOF Detector: Rate Capability

Revolution time detector in the ESR needs high rate capability

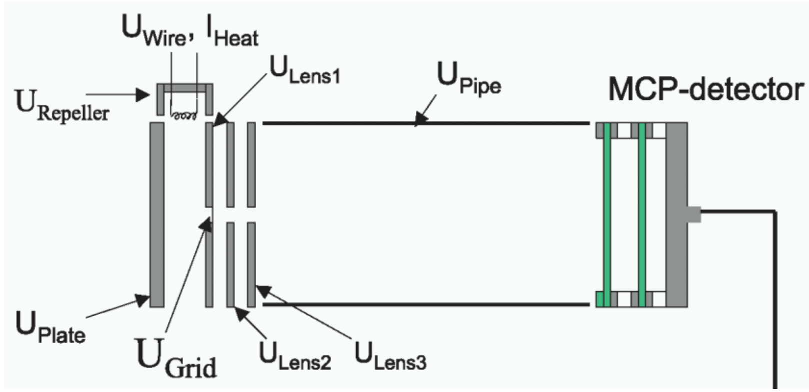
Revolution frequency: ~ 2 MHz
→ 50 particles generate 10^8 hits / s



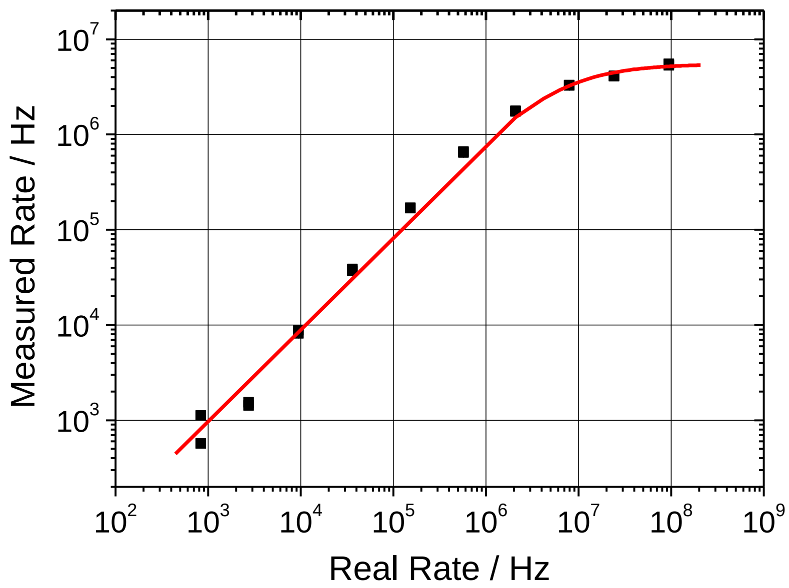


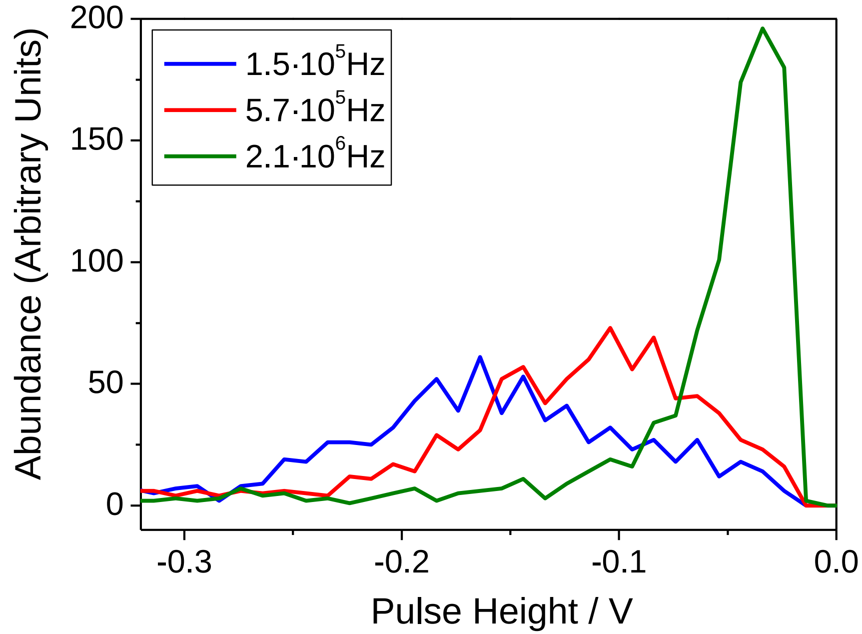
B. Fabian, Dissertation, Justus-Liebig-Universität Gießen, 2008

IMS TOF Detector: Rate Capability



Beam width = 15 mm





$$f_{\exp} = \frac{f}{1 + \frac{f}{N^{eff}} \cdot \tau}$$

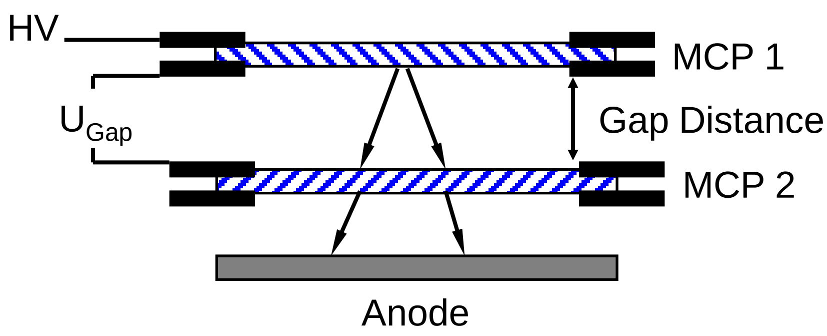
τ = 2.3 ms (Recharge time)

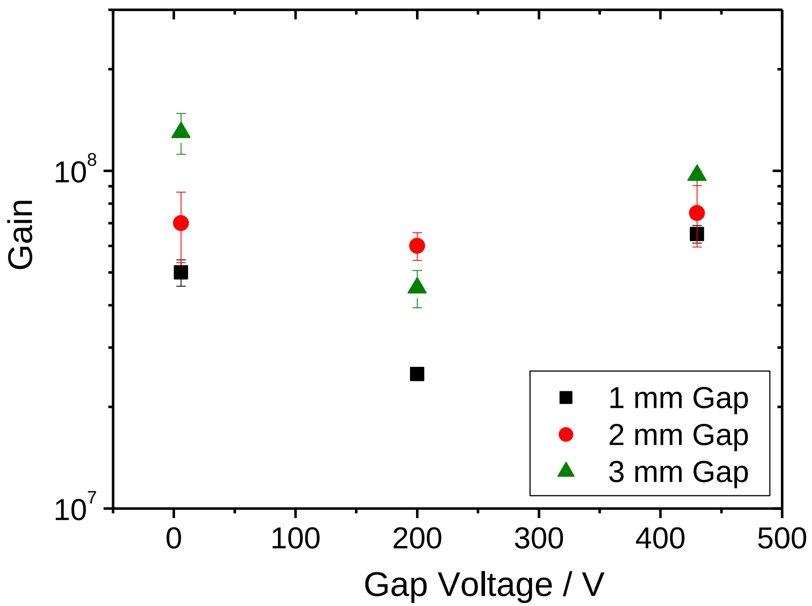
G.F. Fraser, Nucl. Instrum. Methods A 306 (1991) 247

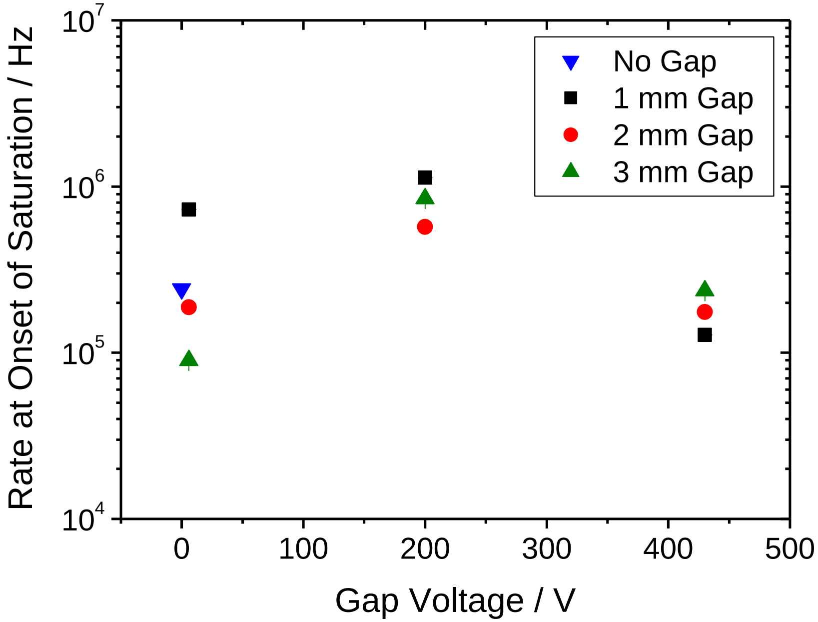
B. Fabian, Dissertation, Justus-Liebig-Universität Gießen, 2008

IMS TOF Detector: Optimization of the Rate Capability

Variation of MCP gap distance and gap voltage







Increasing number of secondary channels ←

Increasing electron impact energy →

Compromise between gain and rate capability required

N. Kuzminchuk, B. Fabian

Conclusions and Outlook

Direct mass measurements: important tool for

- structure of exotic nuclei
- nuclear astrophysics

Novel mass measurement methods

- Isochronous mass spectrometery (IMS)
- Multiple-reflection time-of-flight mass spectrometry (MR-TOF-MS)

MCP detectors for IMS and MR-TOF-MS

- Peak width: 0.5 …1 ns

Detector and data acquisition for IMS

- Data acquisition by fast-sampling digital oscilloscopes
- Event timing analysis in software: CFD and extrapolation to zero
- Timing precision: 40 ps, < 1 ps for multiturn measurement
- Optimization of transmission efficiency by simulation and experiments
- Investigation of rate capability (>10^6 Hz)

Next steps

- MCPs with 5 μm channel diameter (timing, rate capability)
- Detector design for improved timing
- Position-sensitive detection (delay line detector)

Acknowledgements

Timo Dickel[1], Benjamin Fabian[1,2], Natalia Kuzminchuk[1,2]
Hans Geissel[1,2], Ronja Knöbel[1,2], Christoph Scheidenberger[1,2],
Baohua Sun[1,3], and the FRS-ESR Collaboration

[1] Justus-Liebig-Universität Gießen
[2] Gesellschaft für Schwerionenforschung Darmstadt
[3] Peking University, Beijing, China

Funding: HGF und GSI (VH-NG 33), GSI F+E (GIMET2), BMBF (06GI185I)

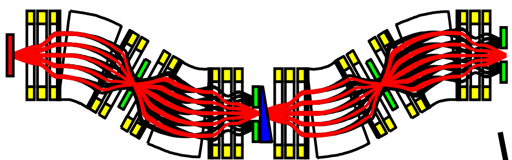
Methods for Mass Spectrometry of Exotic Nuclei

Production and Separation

Projectile Fragment Separator

Projectile Fragmentation / Fission

50 – 1000 MeV/u

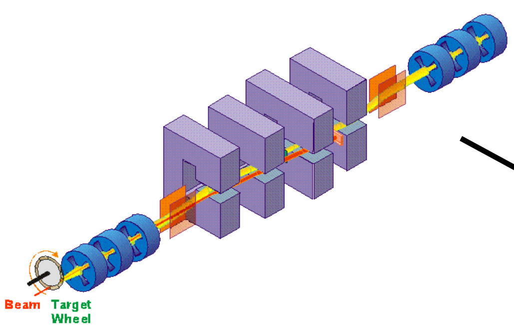


50 – 1000 MeV / u

Wien Filter

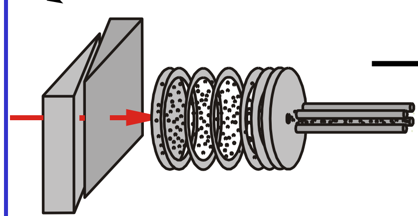
Fusion-Evaporation

5 MeV / u



Stopping

Gas-Filled Stopping Cell



1 eV – 10 keV

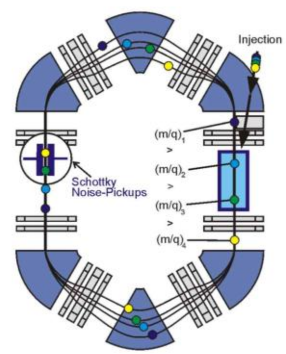
Mass Spectrometry

Schottky MS

Electron Cooling

Measurement ~ 10 s

$m/\Delta m = 10^6$

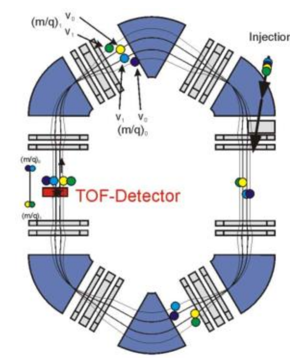


Isochronous MS

Isochronous

Measurement ~ 100 μs

$m/\Delta m = 10^5$

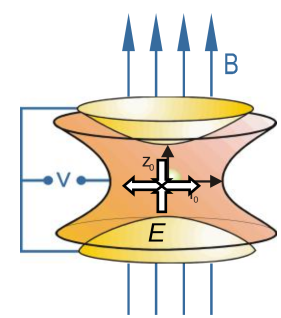


Penning Trap MS

Buffer Gas Cooling

Measurement ~ 1 s

$m/\Delta m = 10^6 – 10^7$



Time-of-Flight MS

Isochronous

Measurement ~ 1 – 10 ms

$m/\Delta m = 10^5$