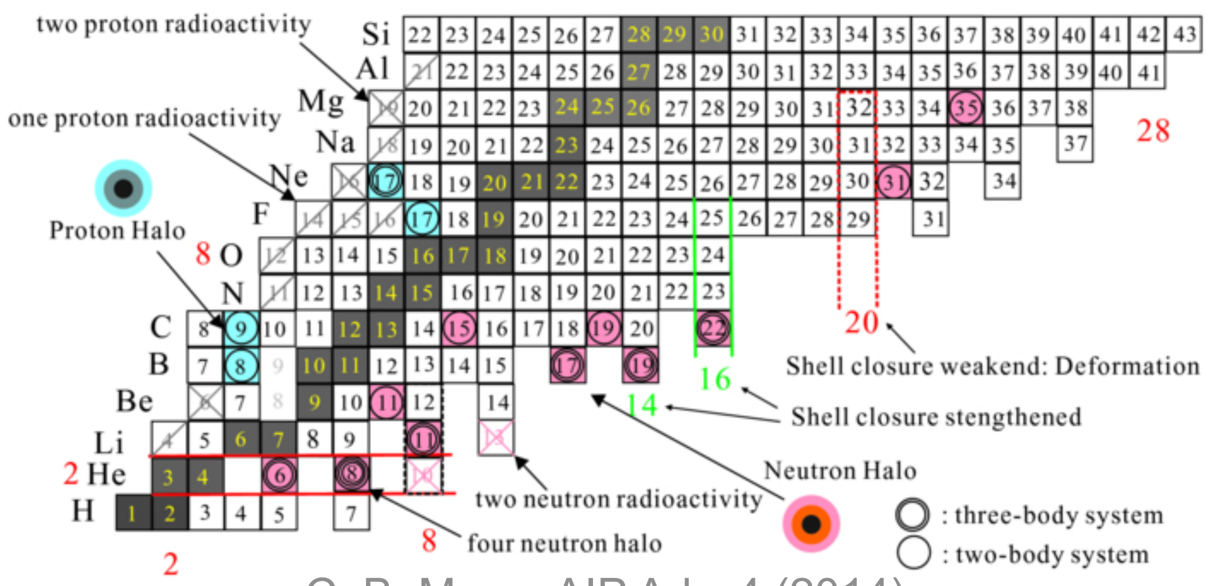
PROBING NUCLEONIC DENSITIES WITH ANTIPROTONS

Clara Klink
for the PUMA collaboration
07.04.2024

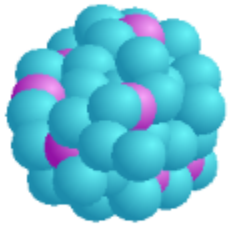
Motivation: Nuclear structure of exotic nuclei



C. B. Moon, AIP Adv. 4 (2014)

- Exotic nuclei can exhibit halo structure and neutron skins
- Reflects in neutron and proton densities: $\rho_Z(r)$ and $\rho_N(r)$
- Relates to the equation of state of nuclear matter

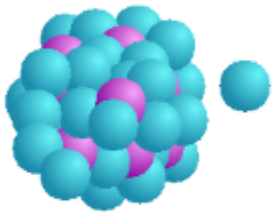
Skin



- If N > Z, $\rho_N(r)$ exceeds $\rho_Z(r)$ on the nucleus' surface
- Characterised by thickness

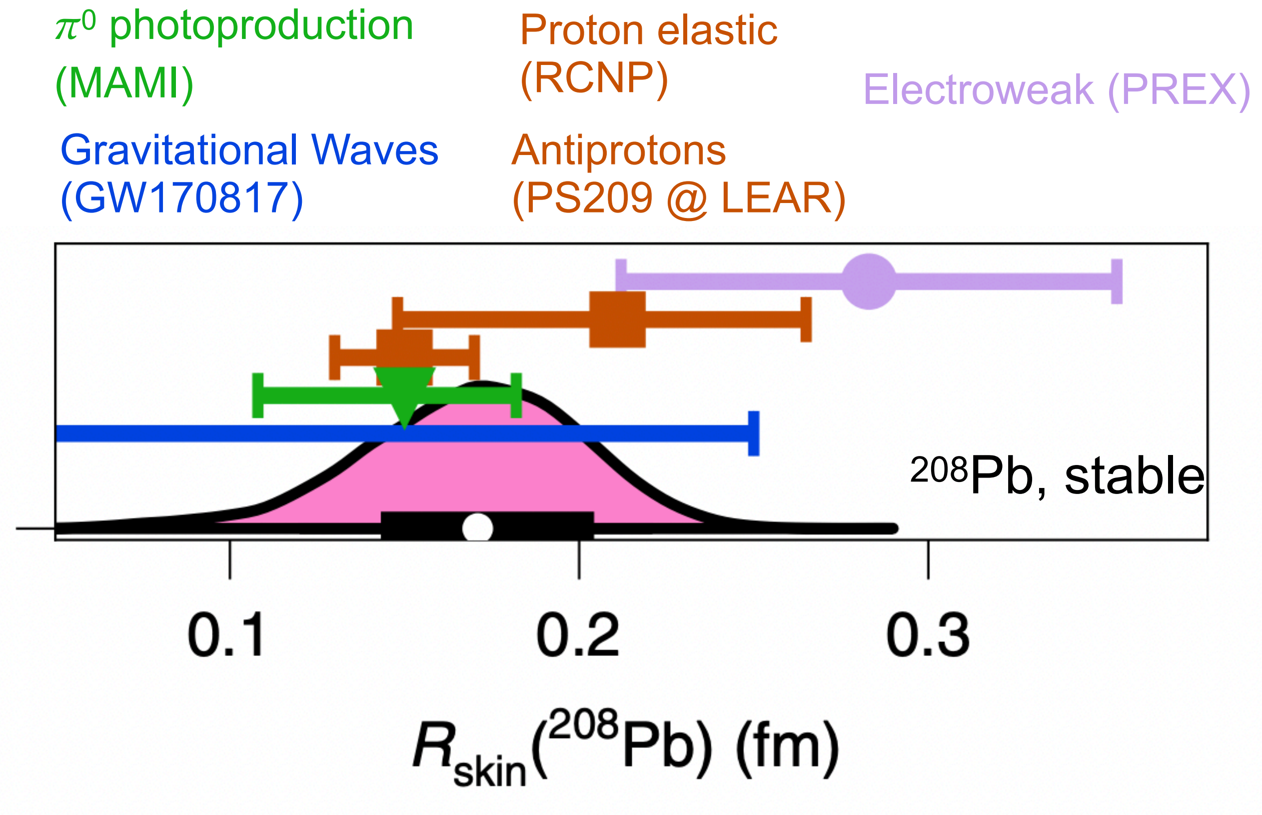
$$\Delta r_{np} = \; < r_n^2 >^{\frac{1}{2}} \; - < r_p^2 >^{\frac{1}{2}}$$

Halo



- Drip line nuclei (N ≫ Z or Z ≫ N)
- Weakly bound halo of orbiting proton(s) or neutron(s):
  $\rho_{N/Z}(r)$ extends far from expected r_{nucl}
- Halo ^{11}Li has ~ r_{nucl} as ^{208}Pb

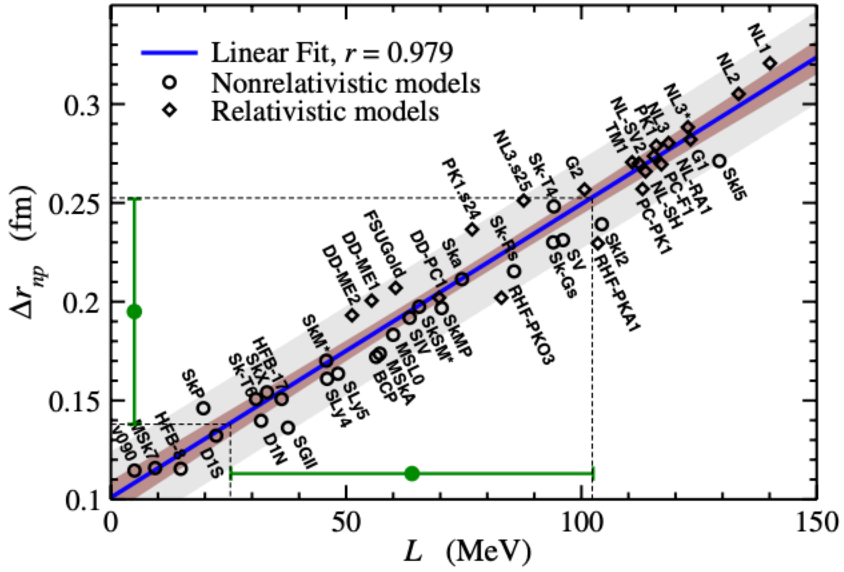
Neutron Skin Thickness of Pb-208



Hu et al., Nat. Phys. (2022) and Refs. therein

$$E(\rho, \alpha) = E(\rho, \alpha = 0) + E_{sym}(\rho)\alpha^2 + O(\alpha^4),$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2$$



Roca-Maza et al., PRL (2011)

Motivation: How do we probe the nuclear densities?

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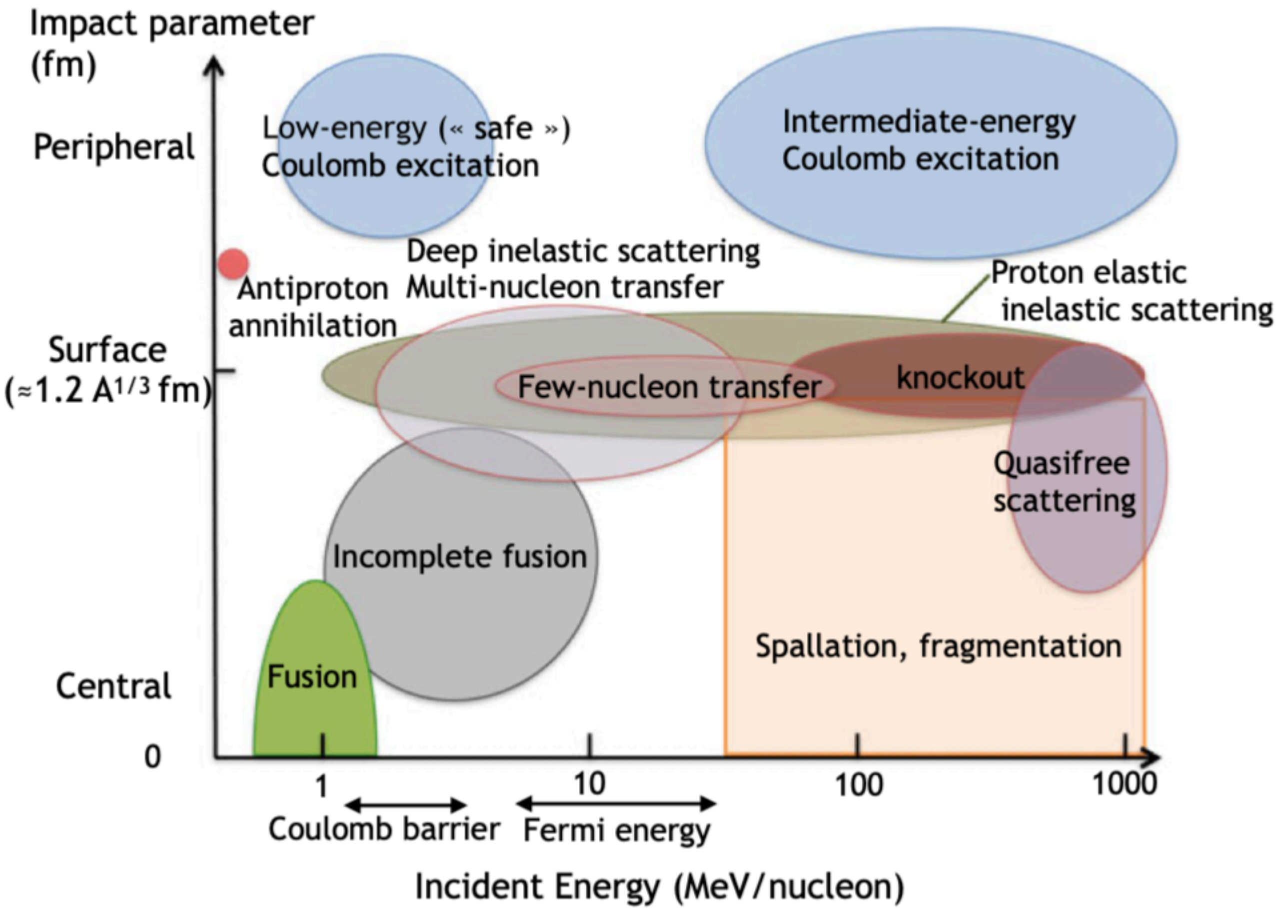
A. Obertelli, “Modern Nuclear Physics”, (2021)

We require a technique which:

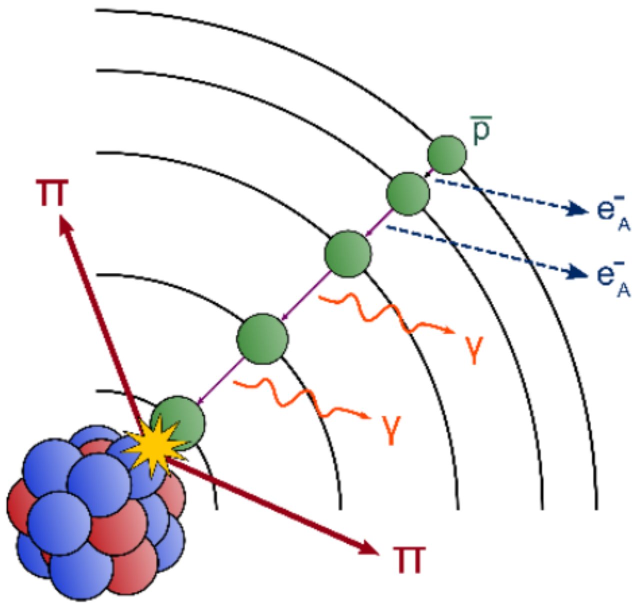
- **Probes the surface:** appropriate technique to access surface has to be chosen
- **Probes the neutron fraction:** Traditionally relies on hadronic probes (→large and uncontrolled uncertainties)
- **Probes radioactive nuclei**

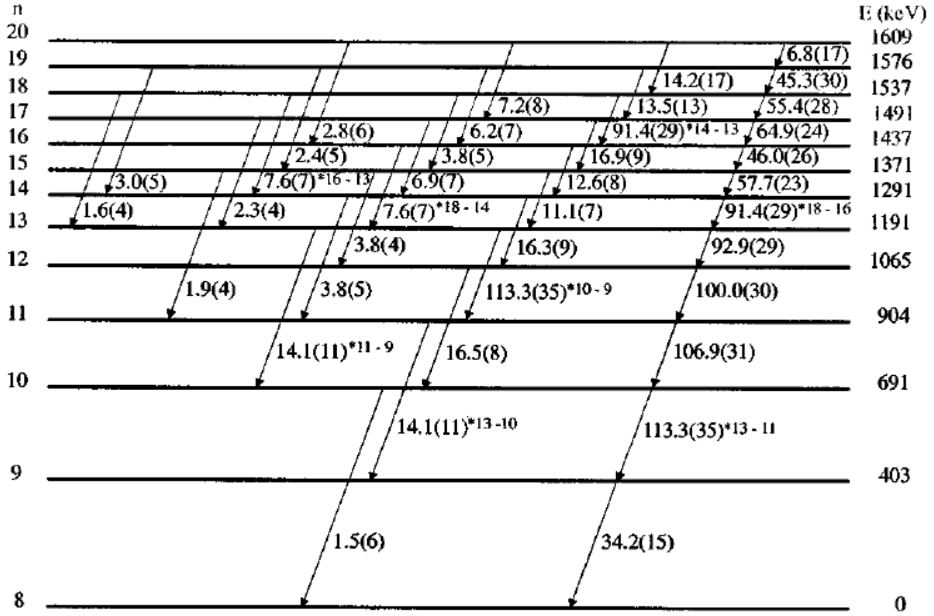


antiProton Unstable Matter Annihilation (PUMA)

Proposed technique: Low-energy antiprotons as a probe

Capture in excited antiproton orbital → Cascade: Auger transitions → Cascade: radiative transitions → Annihilation with surface nucleon → Final-state interactions of emitted mesons





R. Schmidt, PRC (1998)

antiProton Unstable Matter Annihilation (PUMA)

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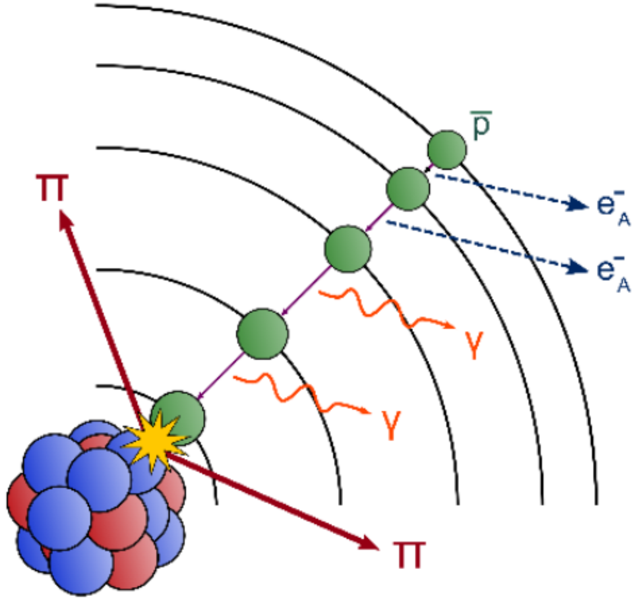

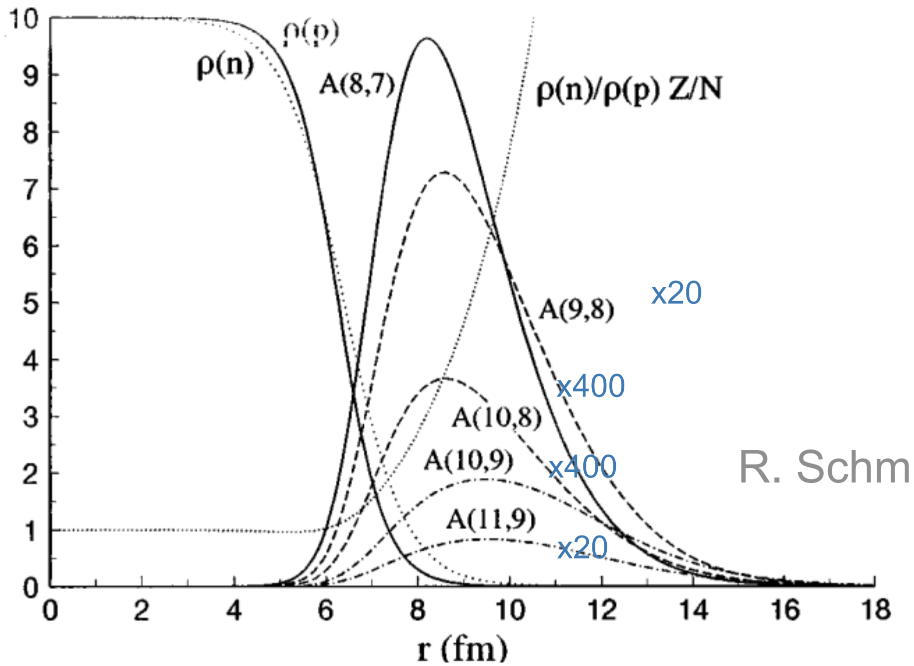

R. Schmidt, PRC (1998)

antiProton Unstable Matter Annihilation (PUMA)

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antiproton-proton		antiproton-neutron	
Pion Final State	**Branching**	**Pion Final State**	**Branching**
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0,233	$\pi^-\pi^-\pi^+k\pi^0(k>1)$	0,397
$\pi^+\pi^-\pi^+\pi^-\pi^0$	0,196	$\pi^-\pi^-\pi^+\pi^0$	0,17
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	0,166	$\pi^-k\pi^0(k>1)$	0,169

Conservation of total charge & energy

→ carried by final-state mesons (mostly pions)

$$\sum_\pi q_\pi = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases} \qquad \sum_\pi q_\pi \text{ of all events} \rightarrow \frac{N_n}{N_p} \rightarrow \frac{\rho_n}{\rho_p}$$

$$f_{halo} = \frac{N_n}{N_p} \cdot \frac{Z}{N} \cdot \frac{Ima(\bar{p}p)}{Ima(\bar{p}n)}$$

- Expected Sensitivity: 10%, dominated by final state interactions
- First application of method:
  Buggs et al., PRL (1973)
- Application to RI proposed:
  Wada and Yamasaki, NIM B (2004)

Where to find antimatter and exotic nuclei?

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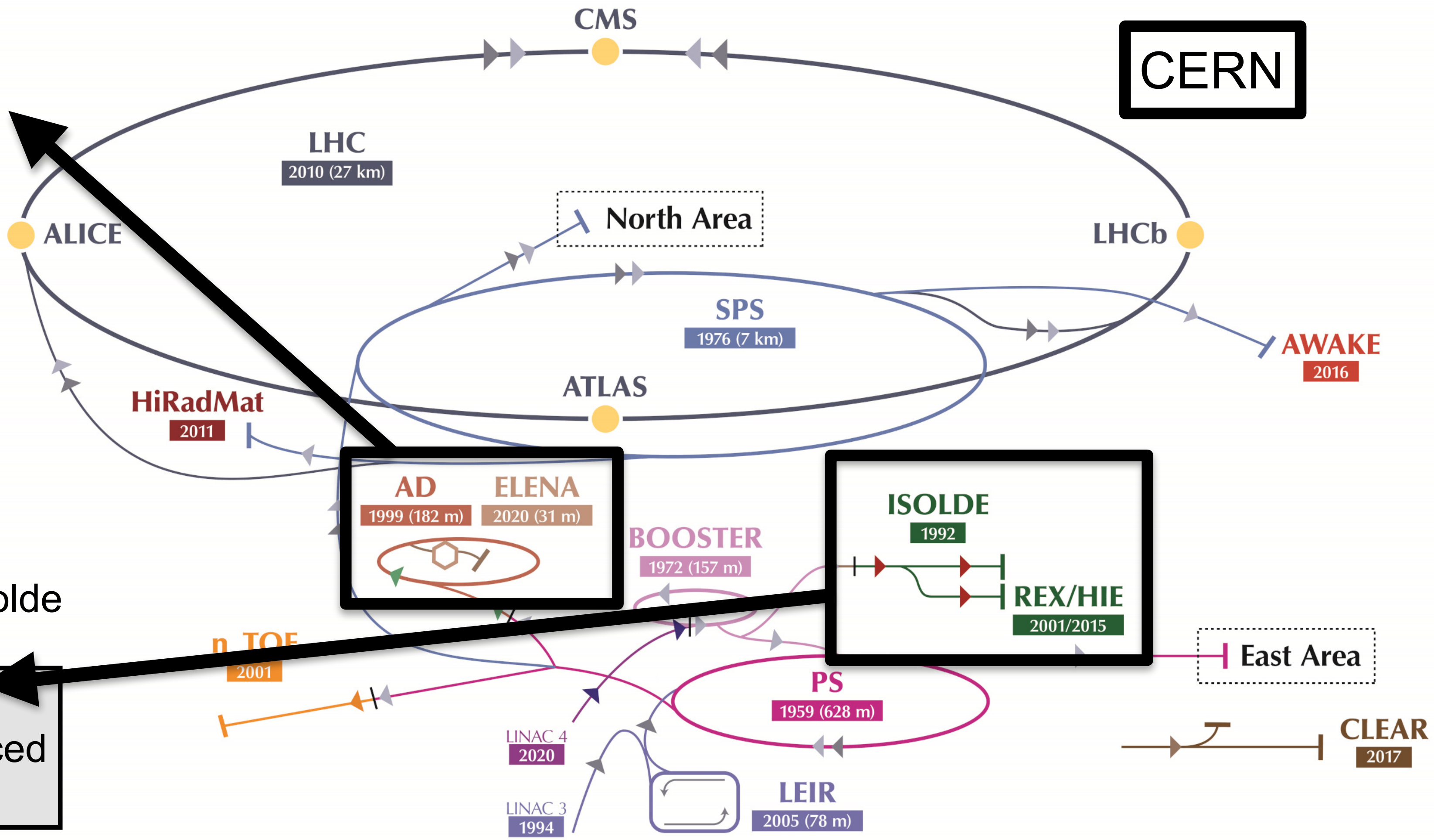
https://home.cern/science/accelerators/antiproton-decelerator

ISOLDE

https://home.cern/science/experiments/isolde

Radioactive Ion Beam Facility
> 1300 isotopes of > 70 elements produced
1000 researchers on ~ 90 experiments



Transporting Antiprotons from AD to ISOLDE

- There is no connecting beam line between the 2 facilities

- Requirements:
  → a transportable ion trap with sufficient storage capabilities
  → XHV vacuum conditions for the storage of antiprotons ($20\,cm^{-3}$)
  → a detection system for monitoring annihilation rates during the transport

<u>Good news:</u>

- Long antiproton trapping time already achieved.
  Ex. BASE: > 50 years

- Transportation of antiprotons is also a core component of BASE-STEP (PI: C. Smorra, Mainz)

PUMA Penning Trap

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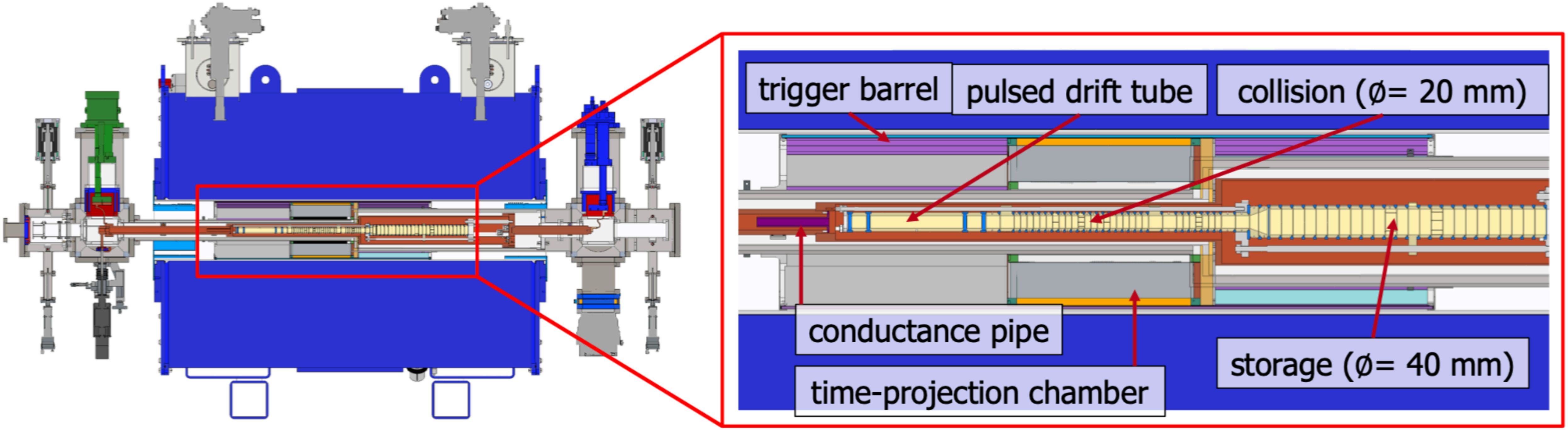
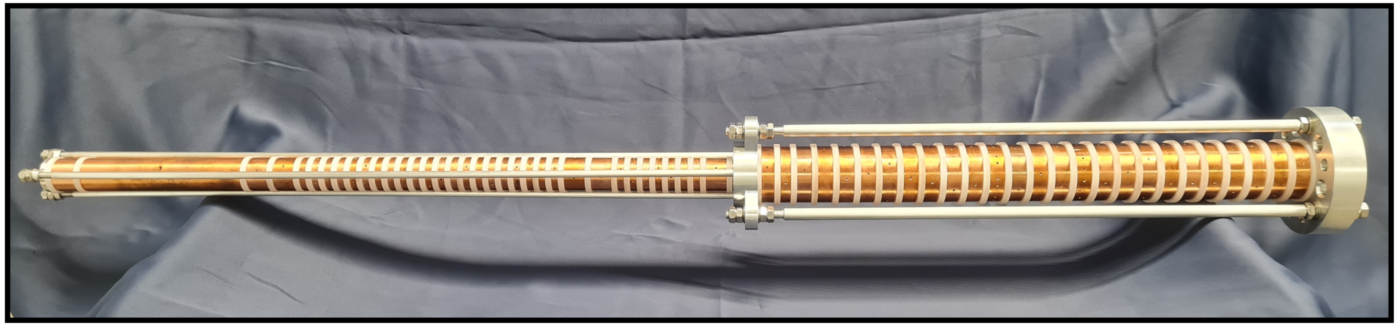
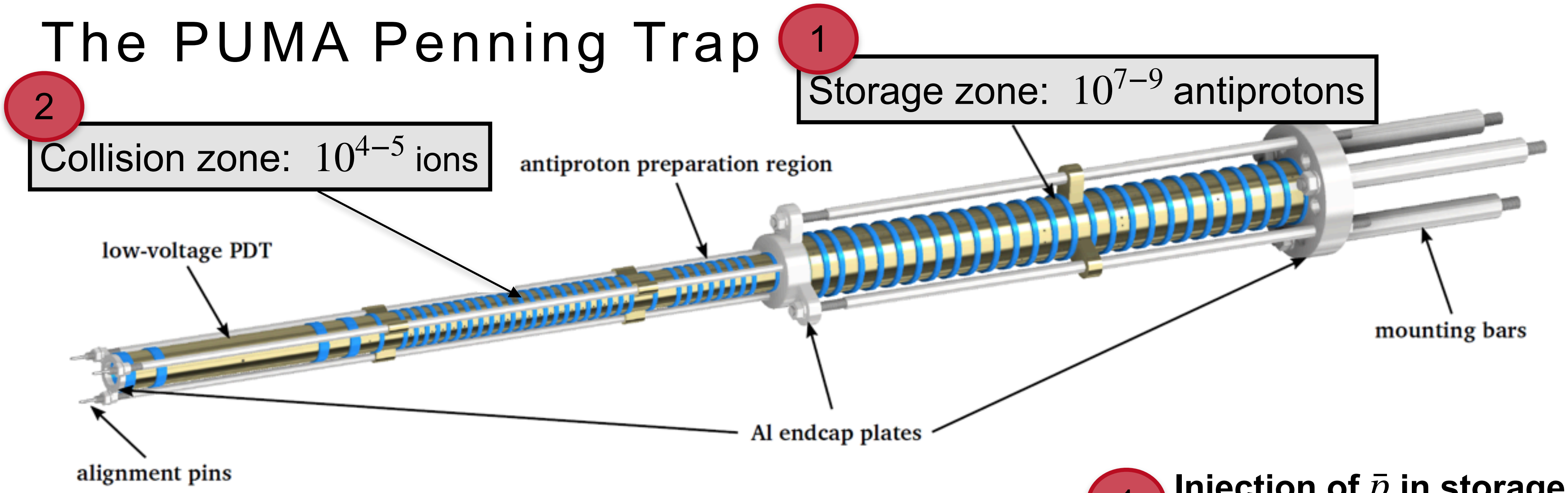
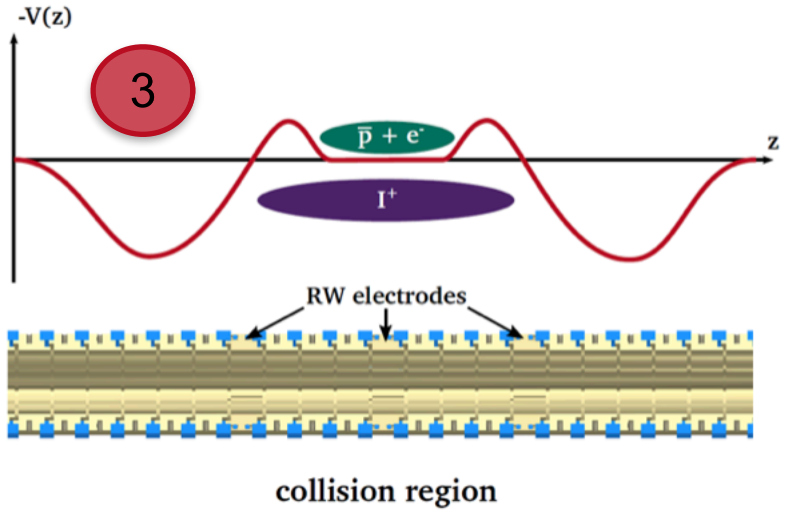
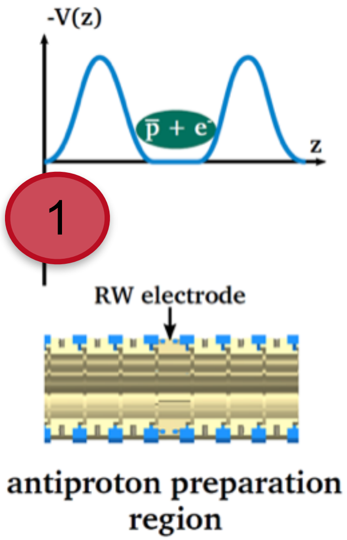




The PUMA Penning Trap







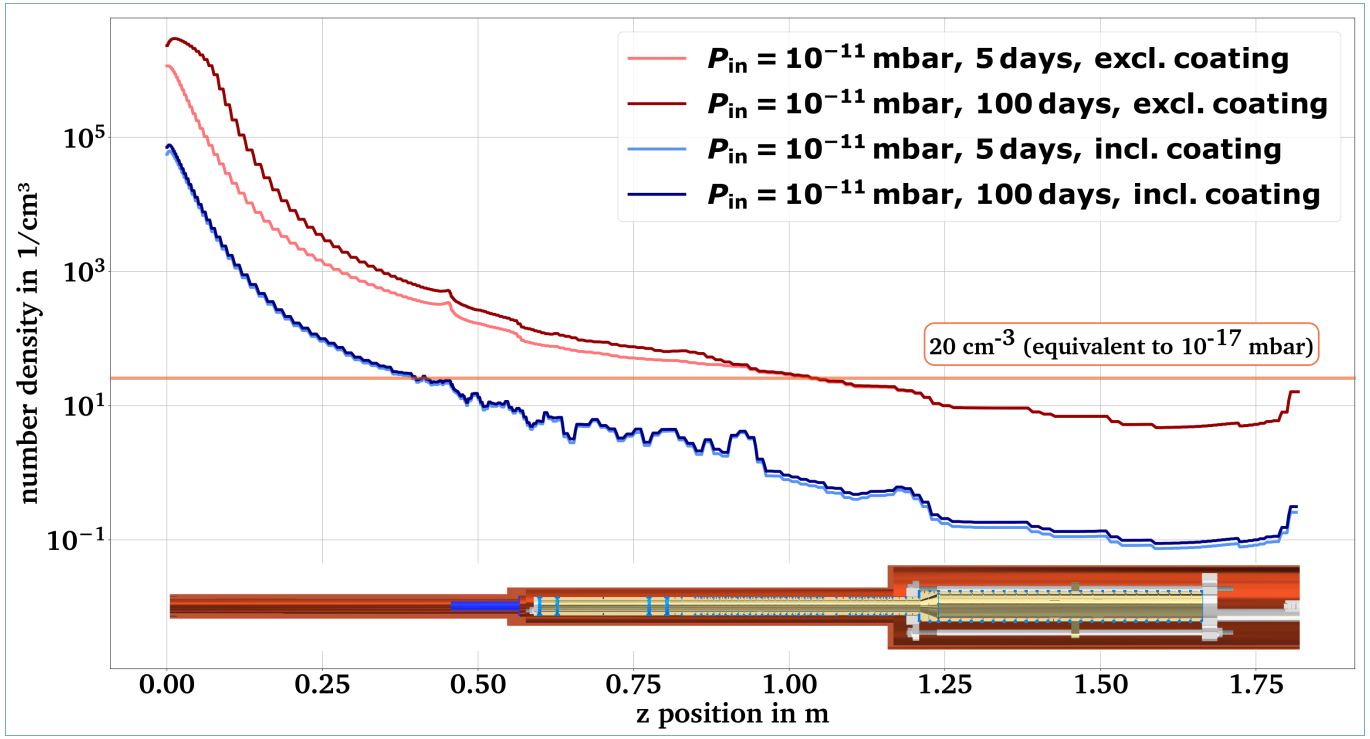
1 **Injection of $\bar{p}$ in storage zone:** application of rotating wall technique and electron cooling

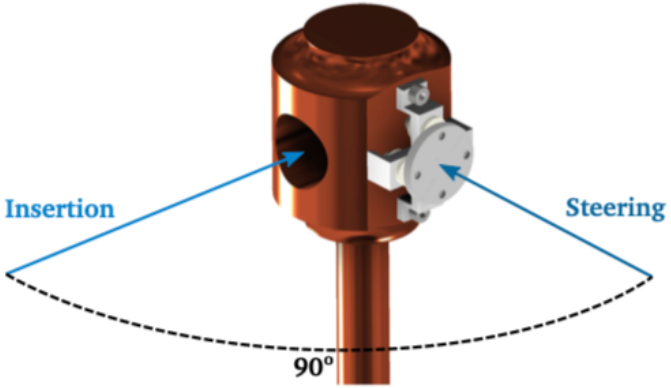
2 **Trapping of ions in collision zone:** immediately or after transport

3 **Mixing of antiproton plasma with ion cloud:** ions bounce at potential walls and traverse the plasma

Vacuum

- Experimental cycle incl. transport to ISOLDE: ~30 days → storage time τ limited by residual gas pressure
- τ [days] ~ $6 \cdot 10^{-16} \cdot T$[K] / P[mbar] → $P_H < 10^{-16} mbar \sim 20\, cm^{-3}$
  PUMA collaboration, PUMA, antiProton Unstable Matter Annihilation, Eur. Phys. J. A. **55:88** (2022)
- Cryogenic temperatures (4.2 K) in trap required → Cryopumping





Rotating Beam Shutter
- Open / Close configuration
- Pickup Plate for Steering
- Mounted on x-y-z table

Pion Detection - Time Projection Chamber / Barrel

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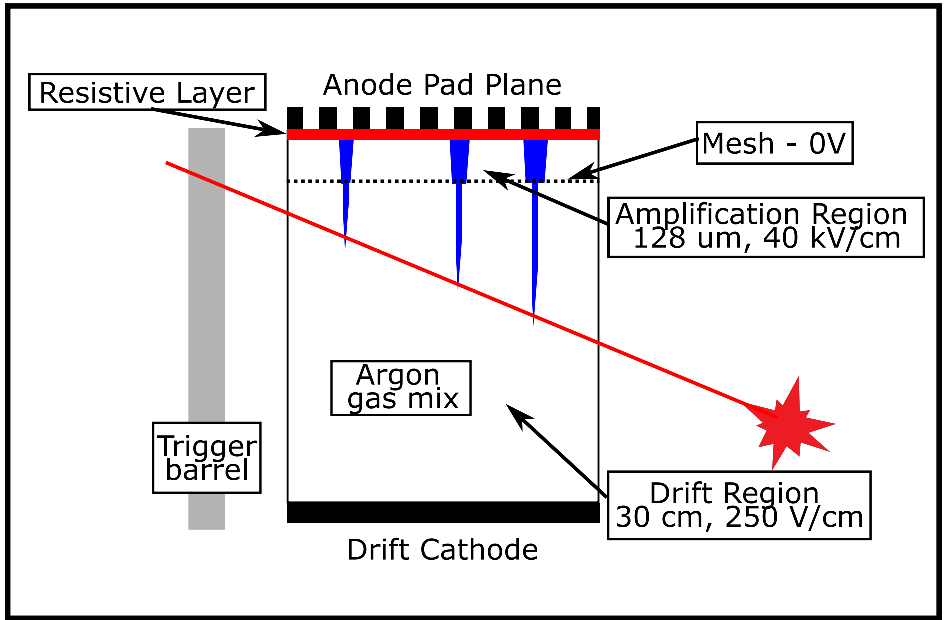
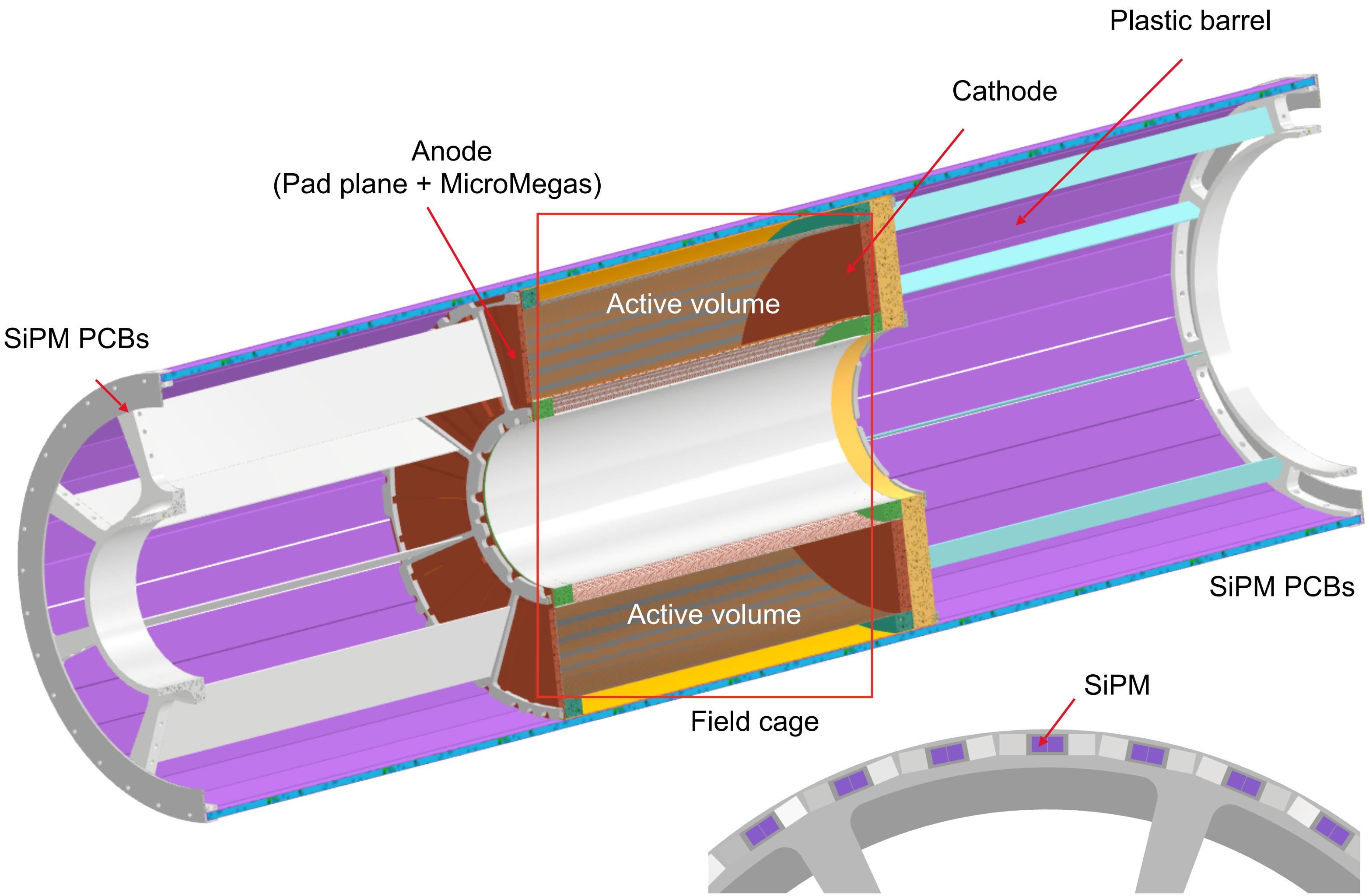
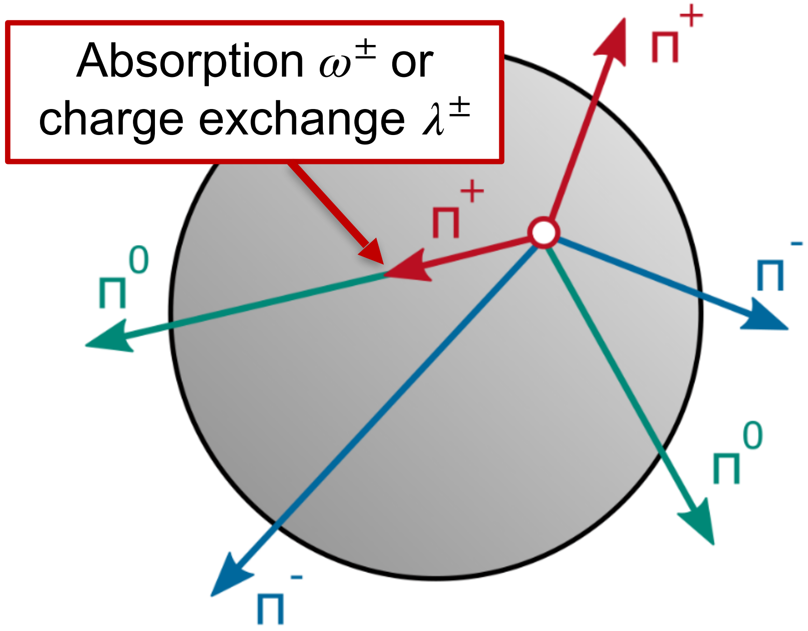


Resistive Micromegas; resolution < 400 μm
Detection efficiency: 85 % (simulations)
Energy resolution: 14.07 +- 0.31 % (Cu XRF)

<u>Front-end electronics</u>
TPC: TDCM/ARC with STAGE chip (CEA)
Trigger Barrel: TRB3 (GSI)



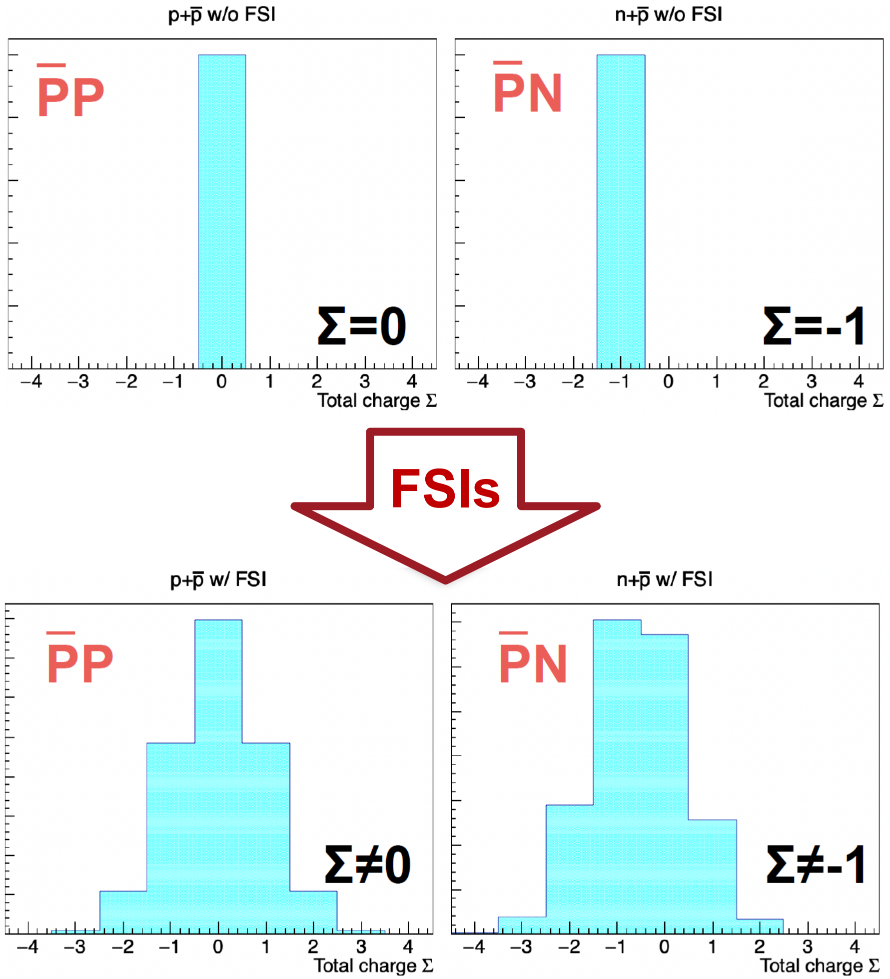
Final State Interactions



Initial state:
(π+,π-,π0) = (2,2,1)
Σ = 0, M = 4

Final state:
(π+,π-,π0) = (1,2,2)
Σ = -1, M = 3

Y. Kubota et al., in preparation (2024)



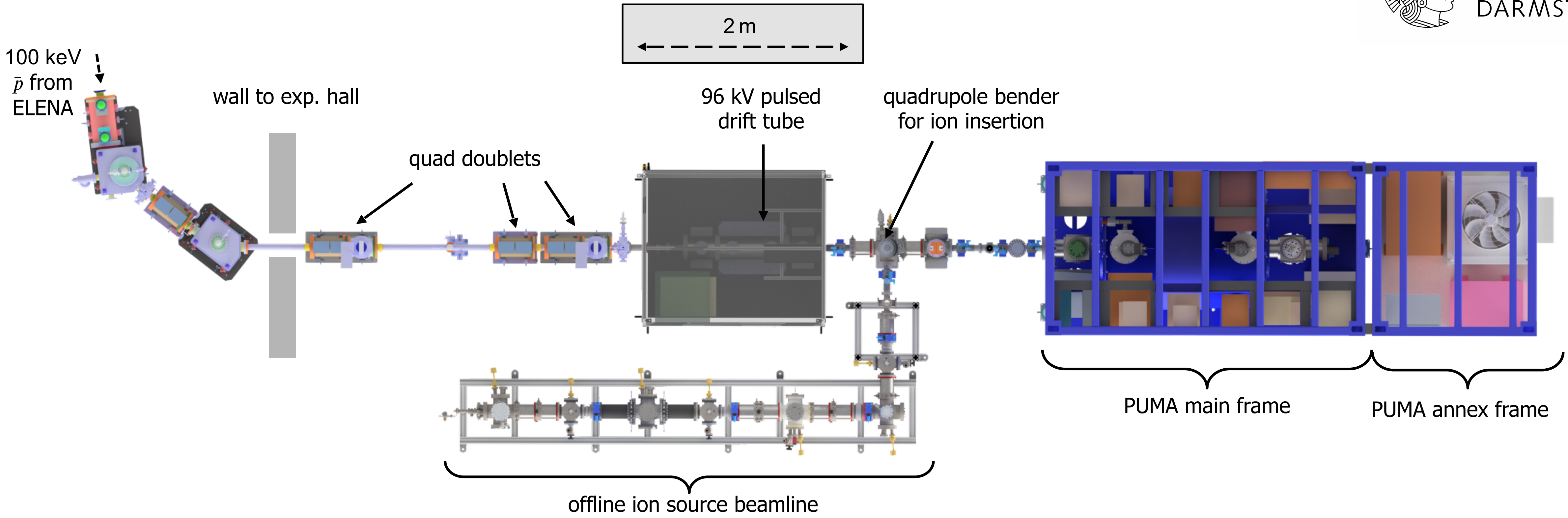
Event-by-Event analysis not possible

→ statistical analysis dependent on Σ and M considering $\omega^{\pm}$ and $\lambda^{\pm}$

Main limitation for detection sensitivity:

Simulations: 10% in $\frac{N_n}{N_p}$

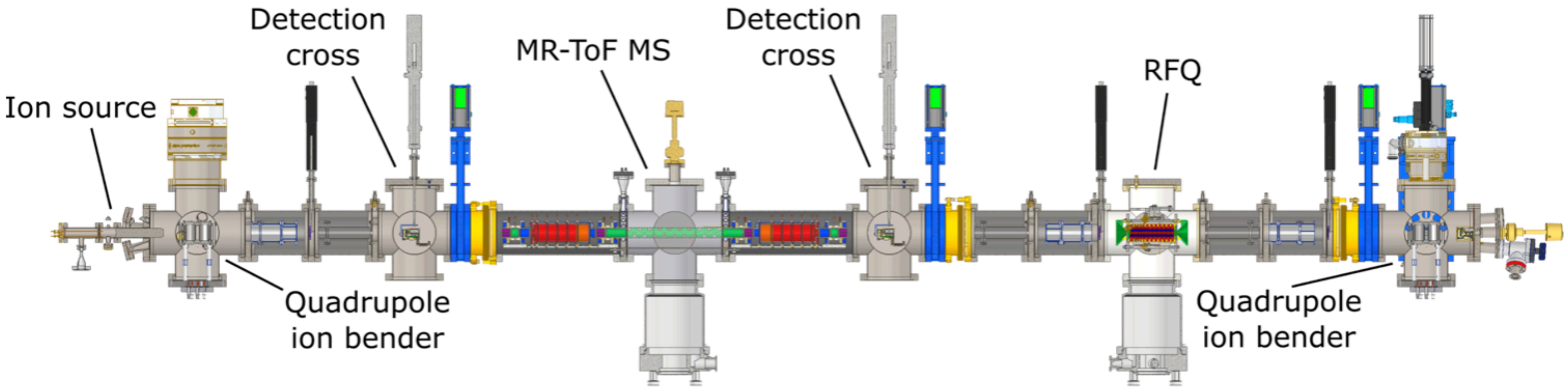
Deceleration and offline ion source



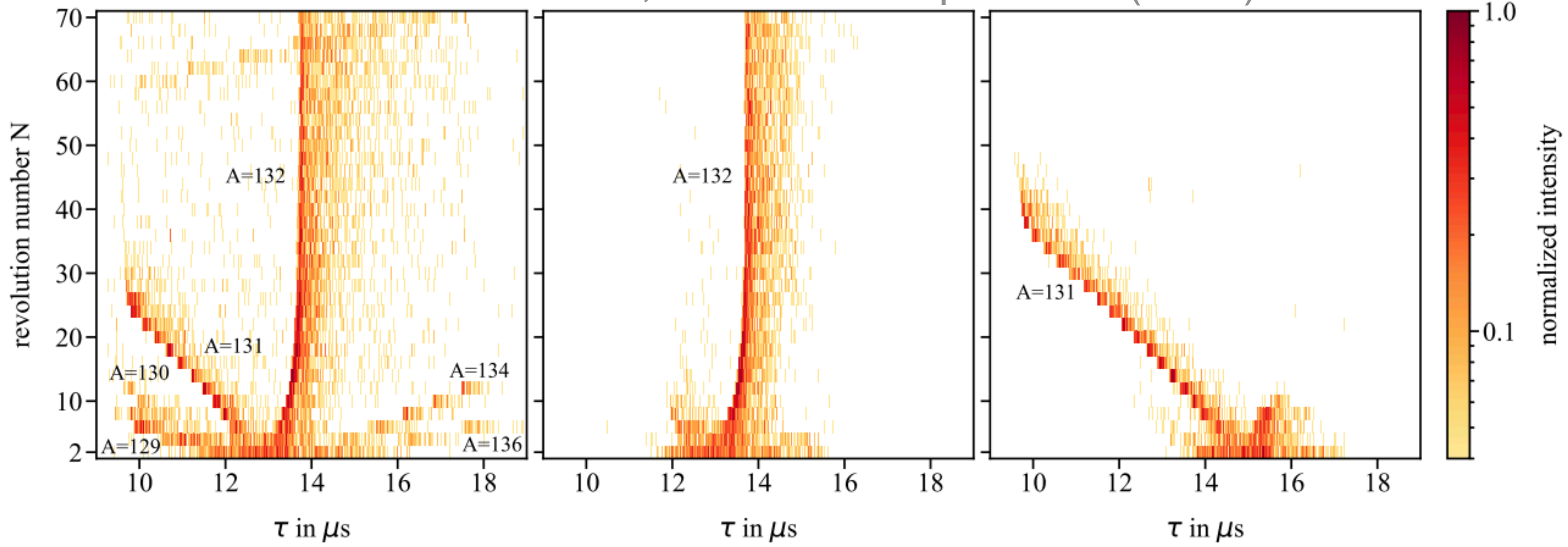
- Deceleration of $\bar{p}$ from 100 keV to 4 keV by pulsed drift tube (PDT)
- First experimental campaign at AD with stable isotopes
- Dedicated beam line: mass separation with MR-ToF, stacking and cooling in Paul Trap

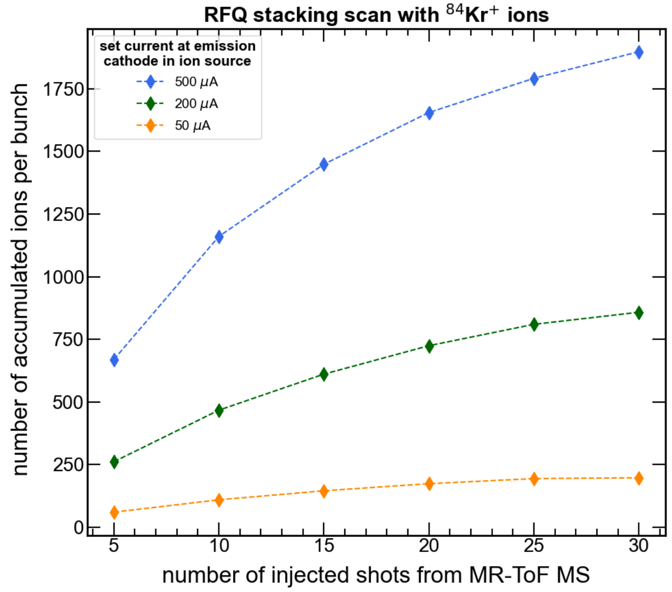
Offline Ion Source Beamline

- Ion Generation
- Isotope Separation
  → isotopic purity in trap
- Accumulation and Bunching
  → $\sim 10^3$ ions in RFQ



M. Schlaich et al., Int. J. Mass Spectrom. (2023)





First Experimental Campaigns

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Starting in 2024:

- Characterise pion detector (TPC) & benchmark simulations: p, d
- Evolution of final state interactions with nucleon number: $^{3,4}He,\ ^{20,21}Ne,\ ^{16}O,\ ^{40}Ar,\ ^{132}Xe$
- Study isospin dependence along isotopic chains: $^{124-136}Xe$

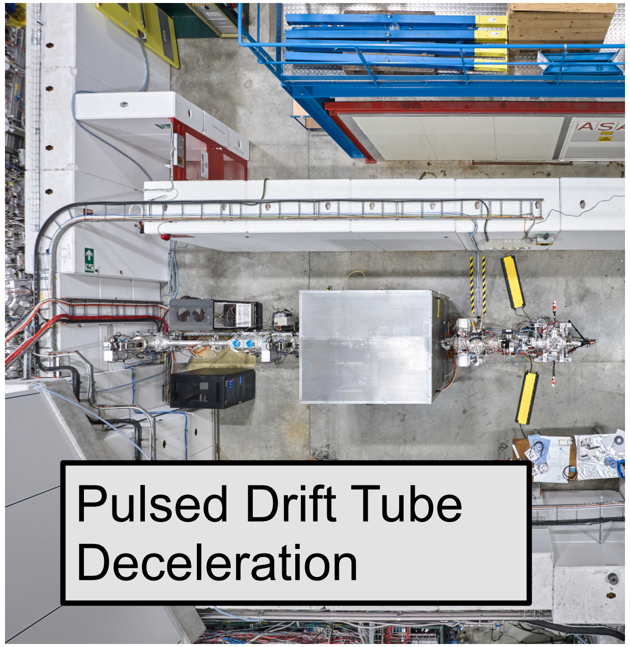
After LS3:

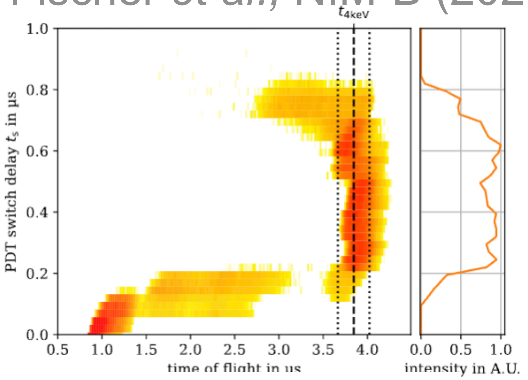
- Future step: laser ablation source for $^{40-48}Ca,\ ^{112-124}Sn,\ ^{208}Pb$ (see talk of M. Schlaich)

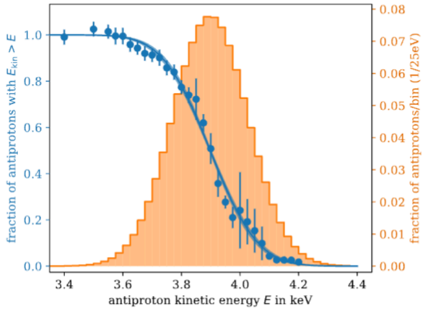
Current Status

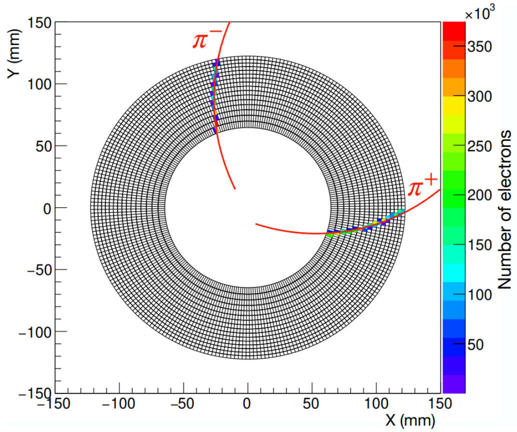
Installation and first measurements at AD/ELENA in 2024

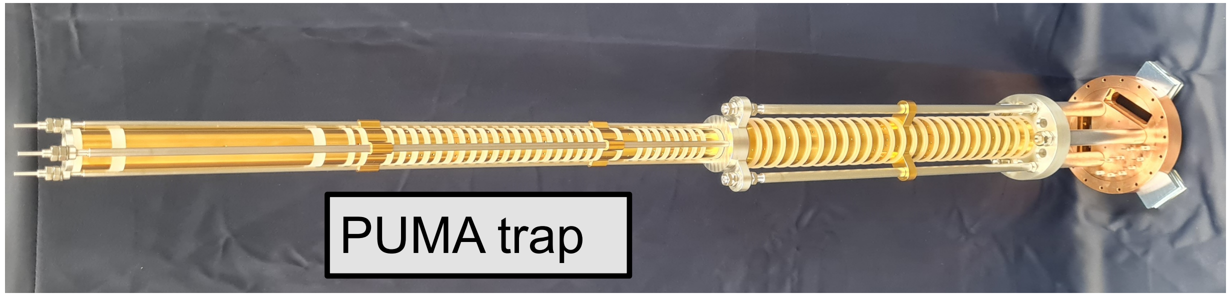
J. Fischer *et al.*, NIM-B (2024)



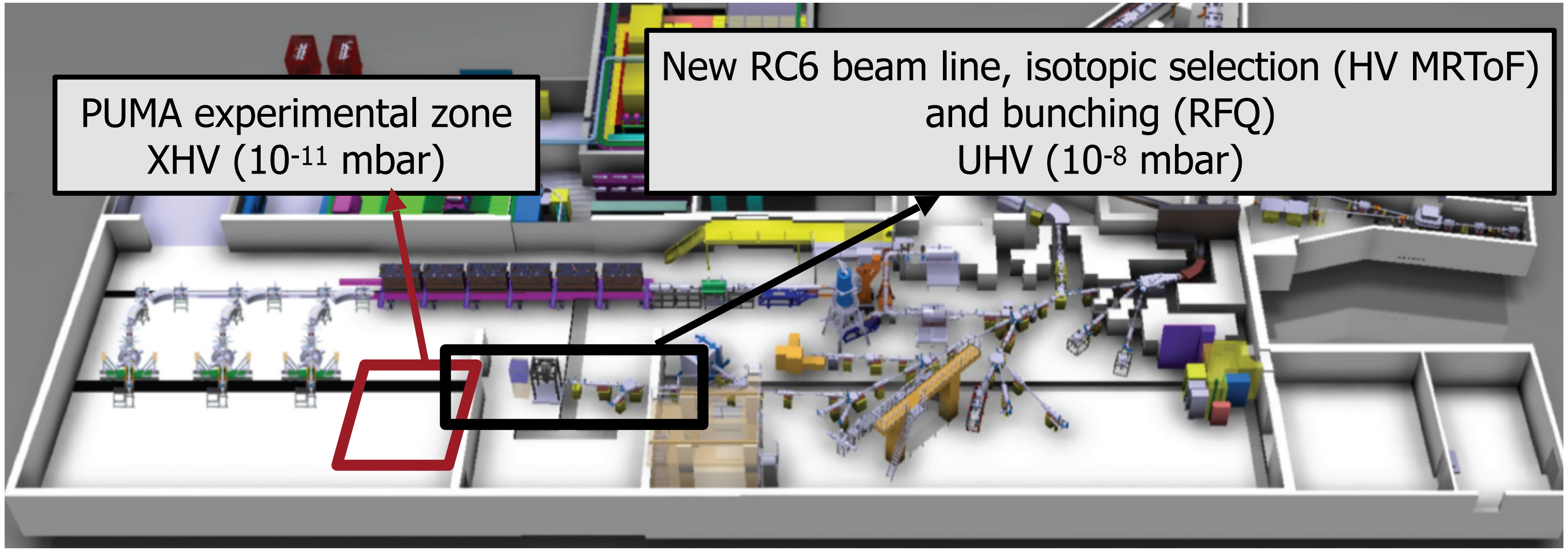








PUMA at ISOLDE



First Physics Cases

<u>2025:</u>

Continue efforts from gas studies at AD:

- neutron-rich Xe isotopes (neutron skin along isotopic chains)
- neutron-rich and deficient Ne (halo structure)

Summary and Outlook

- **PUMA** is a new experiment at CERN accepted in 2021
- It aims at **low-energy antiprotons to probe the tail of the nuclear density distribution**
- Observable: **neutron-to-proton-ratio,** which allows to investigate nuclear phenomena like Halo nuclei and neutron skins of stable (ELENA) and exotic isotopes (ISOLDE)
- Transport of $\bar{p}$ from ELENA to ISOLDE
- First $\bar{p}$ in PUMA experimental zone: **operation of 96kV PDT confirmed**
- First experiments at ELENA in 2024, first low-energy RIB experiments at ISOLDE in 2025

The PUMA collaboration

T. Aumann, N. Azaryan, W. Bartmann, A. Bouvard, O. Boine-Frankenheim, A. Broche, F. Butin, D. Calvet, J. Carbonell, P. Chiggiato, H. De Gersem, R. De Oliveira, T. Dobers, F. Ehm, J. Ferreira Somoza, J. Fischer, M. Fraser, E. Friedrich, M. Gomez-Ramos, J.-L. Grenard, G. Hupin, K. Johnston, C. Klink, M. Kowalska, Y. Kubota, P. Indelicato, R. Lazauskas, S. Malbrunot-Ettenauer, N. Marsic, W. Müller, S. Naimi, N. Nakatsuka, R. Necca, D. Neidherr, A. Obertelli, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, L. Riik, D. Rossi, H. Scheit, M. Schlaich, R. Seki, A. Schmidt, L. Schweikhard, S. Sels, E. Siesling, T. Uesaka, M. Wada, F. Wienholtz, S. Wycech, C. Xanthopoulou, S. Zacarias

This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA)

Vacuum

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- Experimental cycle incl. transport to ISOLDE: ~30 days
  → storage time τ limited by residual gas pressure

- τ [days] ~ $6 \cdot 10^{-16} \cdot T$ [K] / P [mbar] → $P_H < 10^{-16} mbar$

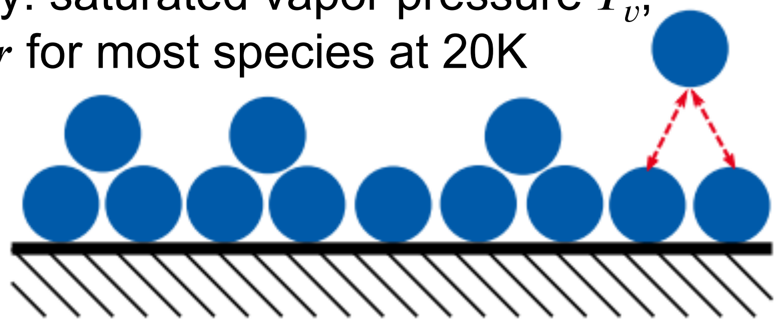
PUMA collaboration, PUMA, antiProton Unstable Matter Annihilation, Eur. Phys. J. A. **55:88** (2022)

- Cryogenic temperatures (4.2 K) in trap required → Cryopumping

Cryocondensation

- Attraction of similar molecules at low T
→ limited by thermal conductivity of condensate

- Keyproperty: saturated vapor pressure P_v,
P_v < $10^{-11} mbar$ for most species at 20K

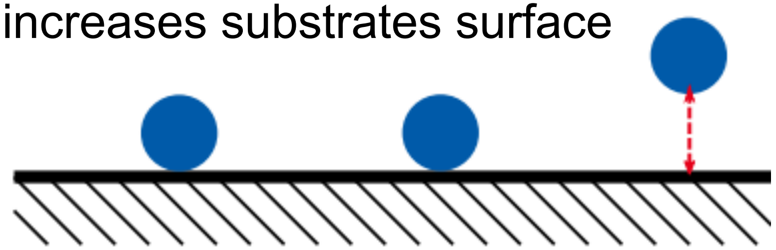


Cryosorption

- Attraction between gas molecules and substrate

- If adsorbed quantity smaller than 1 monolayer:
  $P_H \ll P_v$

- Carbon layer increases substrates surface



Antiproton Decelerator (AD) & Extra Low Energy Antiprotons (ELENA)

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Input: $1.5 \cdot 10^{13}$ p at 26 GeV/c on target

approx. $3 \cdot 10^{7}$ $\bar{p}$ arrive in AD

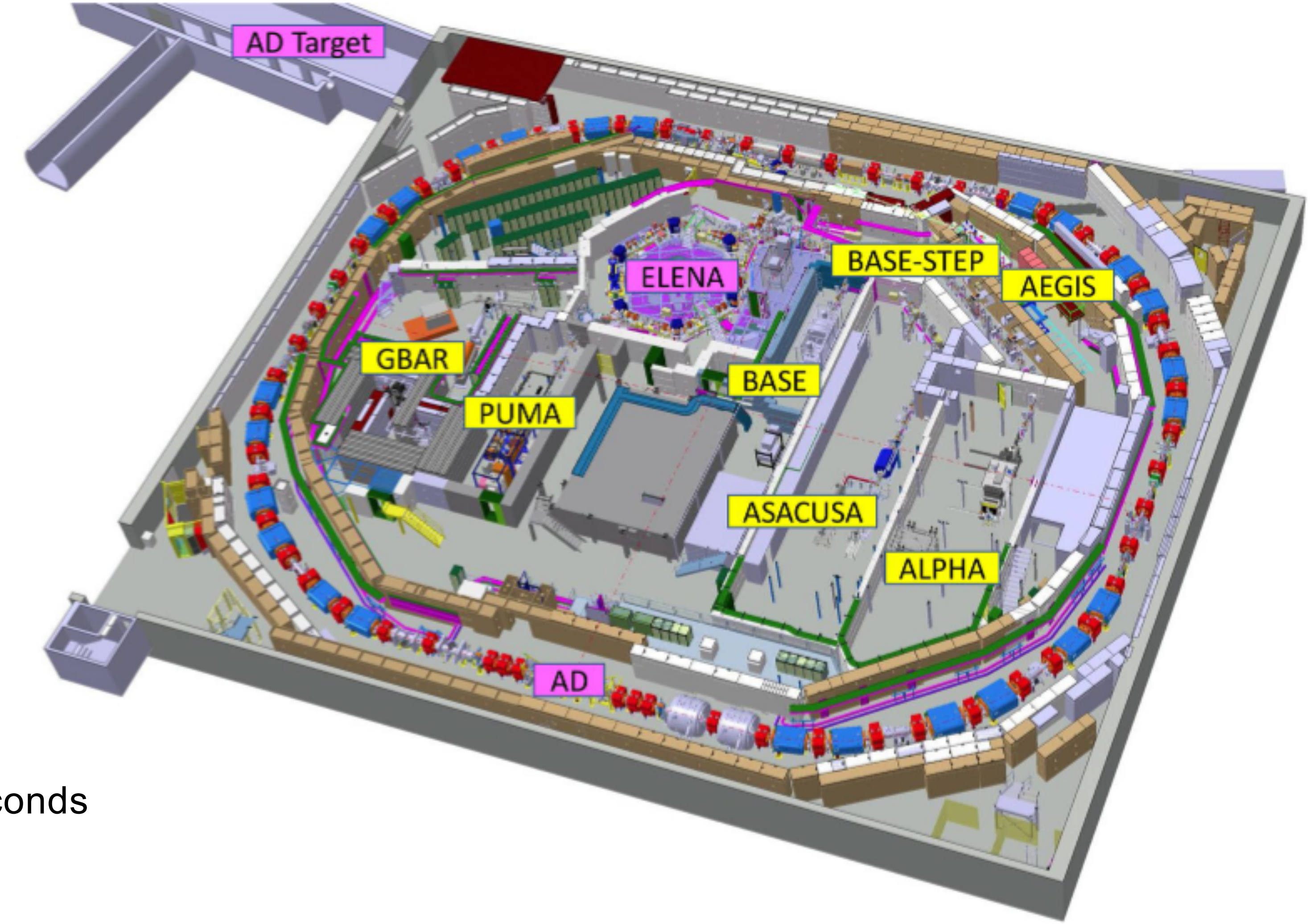
Deceleration of $\bar{p}$:

- 5.3 MeV in AD
- 100 keV in ELENA (since 2018)

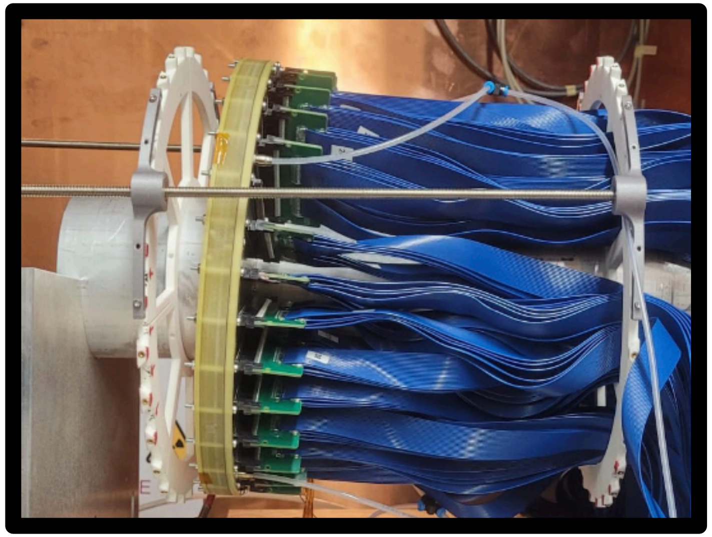
Duty cycle of ELENA:

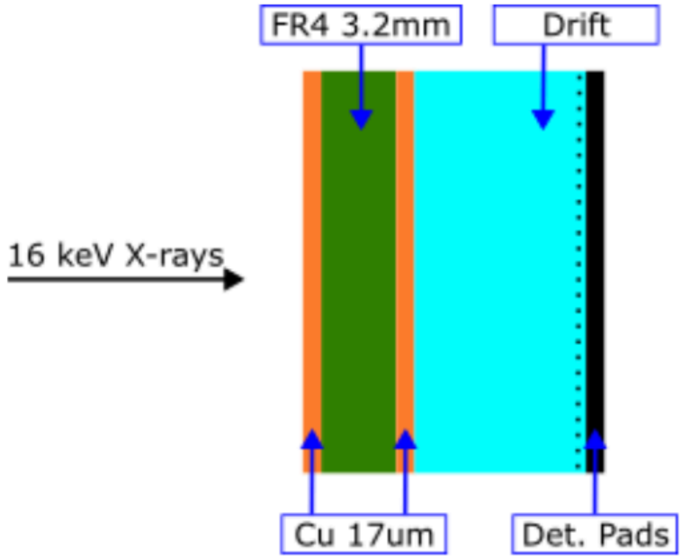
4x $4 \cdot 10^{6}$ bunches every 110s

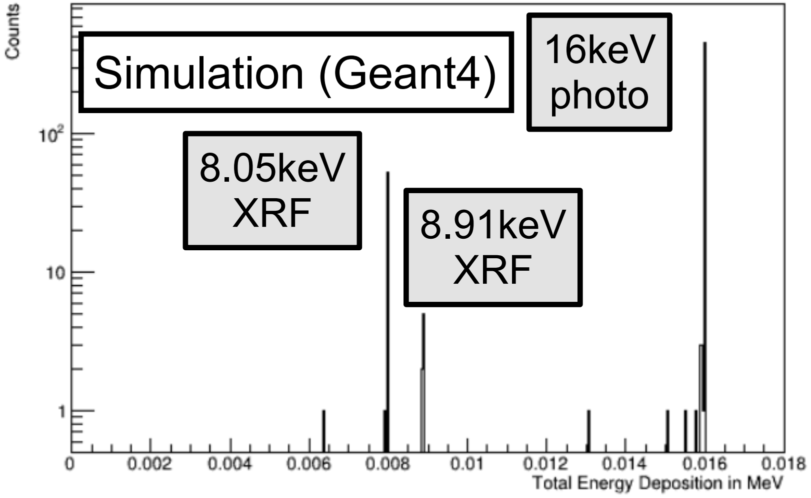
Possibility to use 100 keV H- every 20 seconds

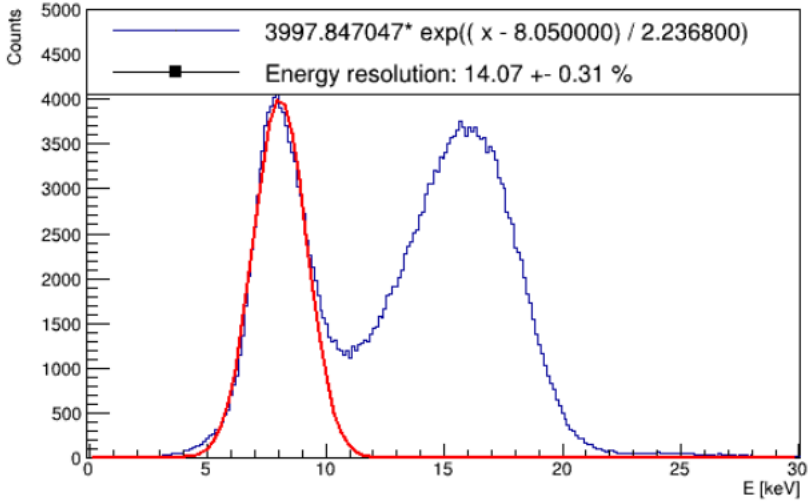


First run with reduced detection setup



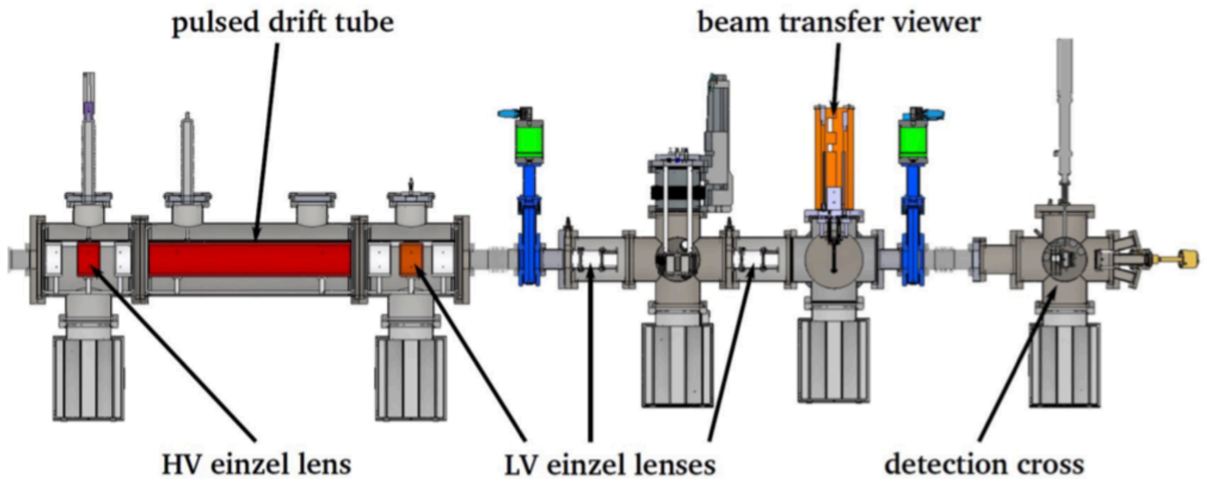


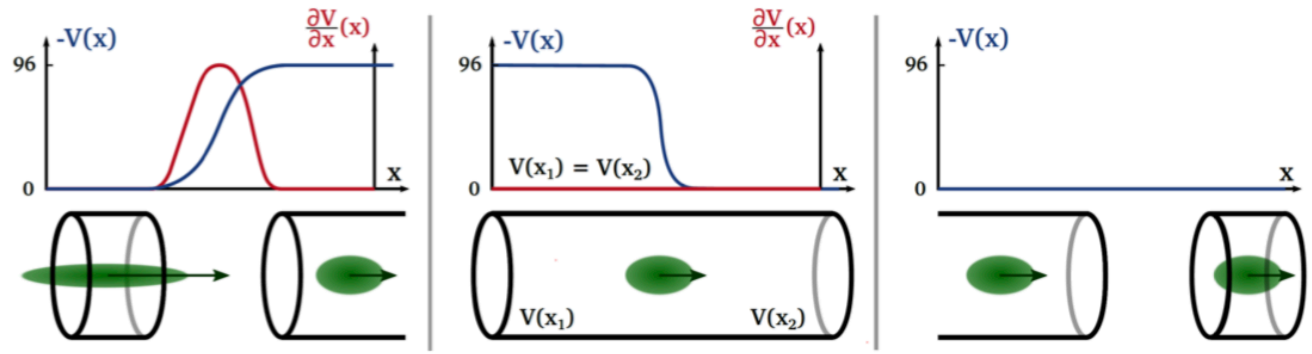


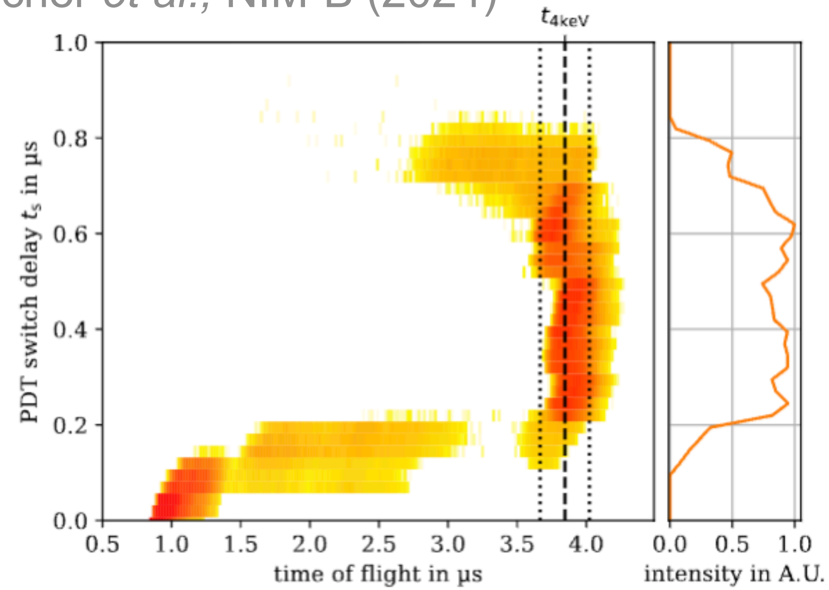


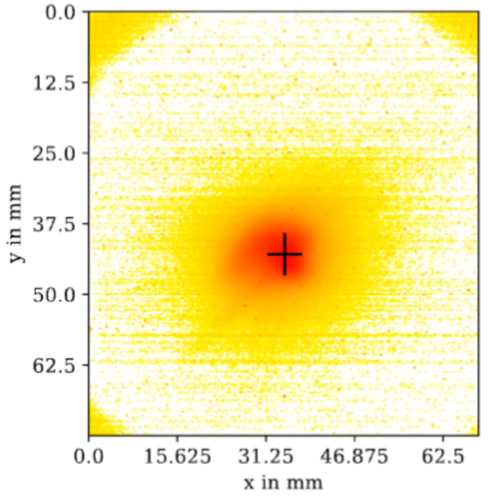
Deceleration of Antiprotons - 100 keV to 4 keV

J. Fischer *et al.*, NIM-B (2024)



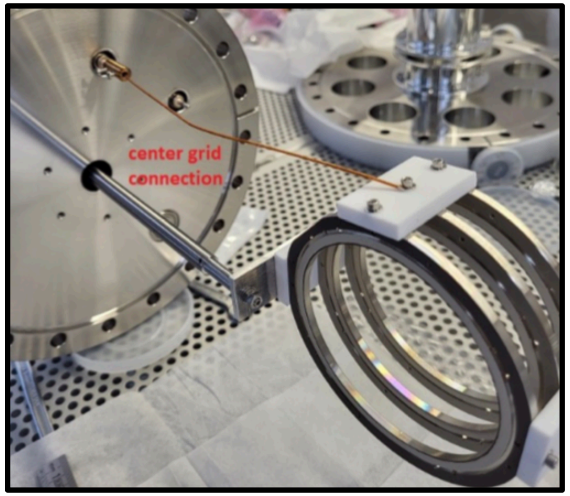


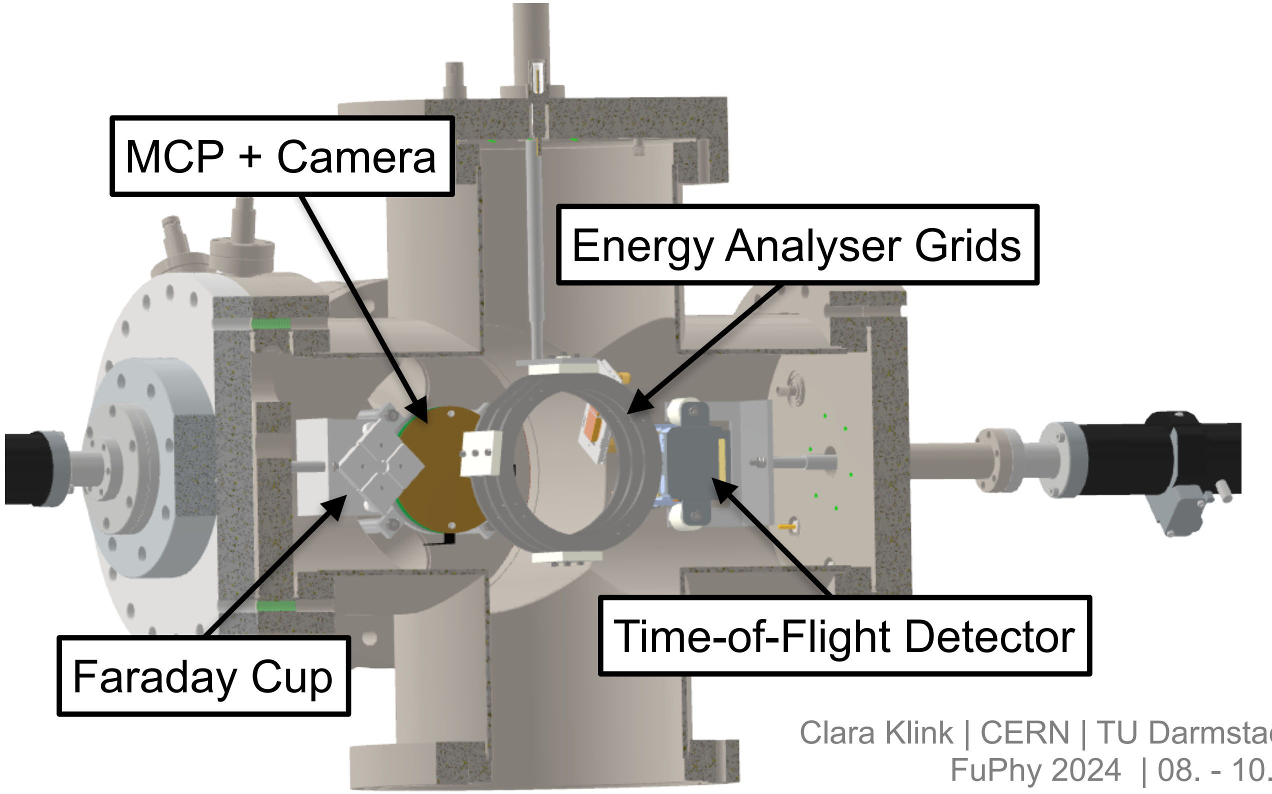




Beam Characterization after PDT

- Transmission approx. 55 (3)% (simulations: 100%)
- Energy after deceleration 3.898(3) keV
- Energy spread 127(4) eV (σ) (simulations: 100 eV)





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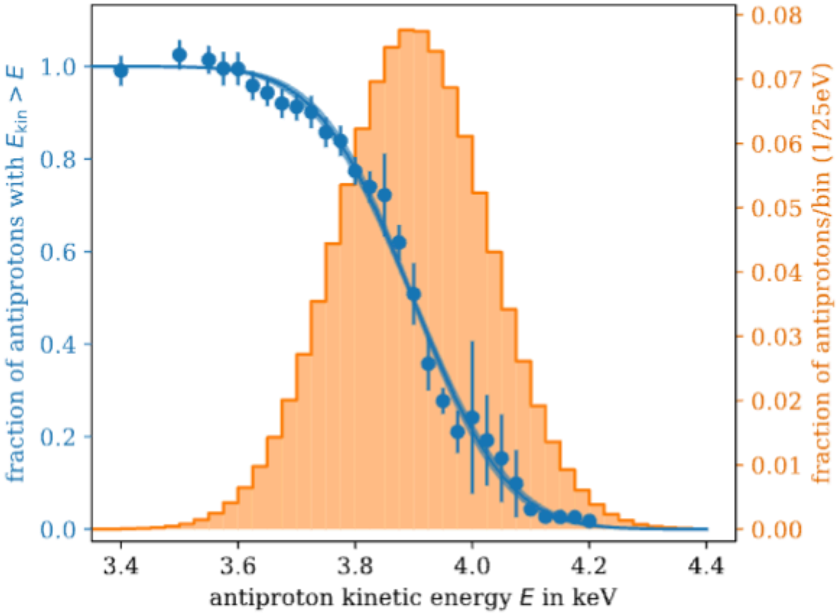

Multi-Reflection Time-of-Flight Spectrometer

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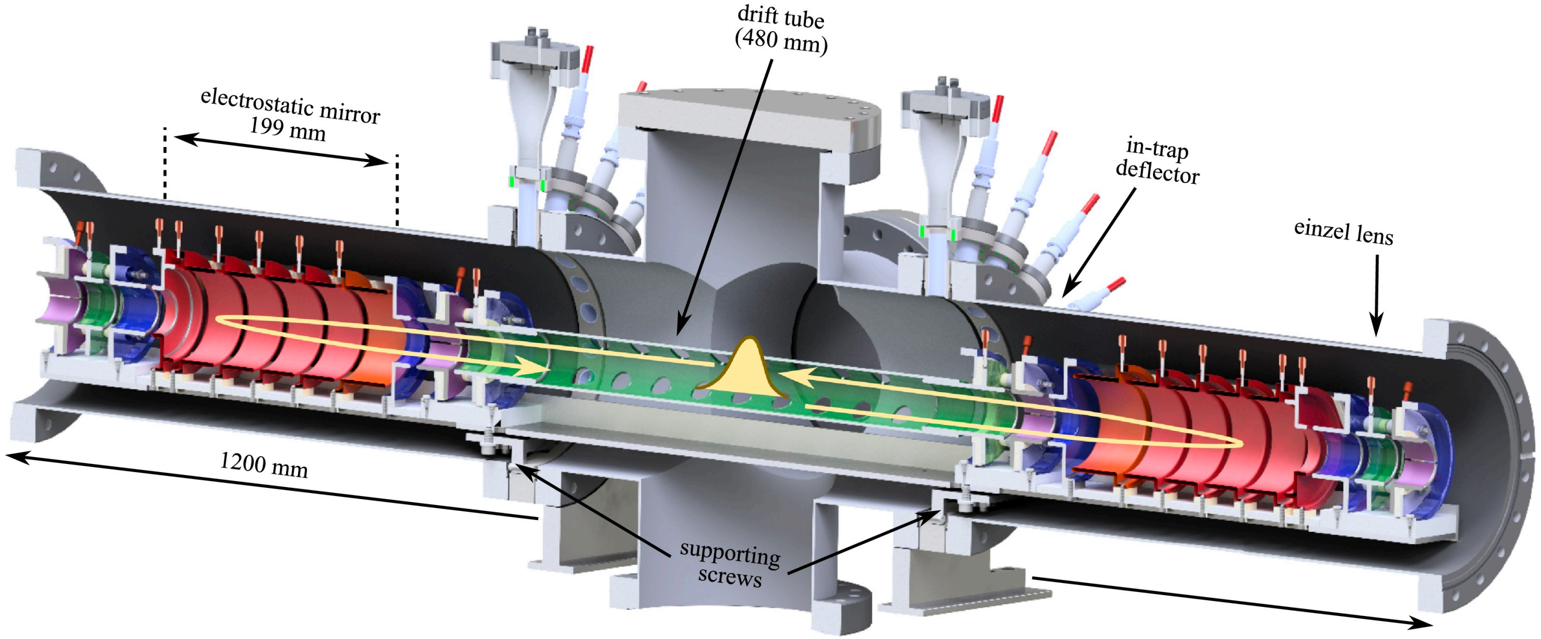
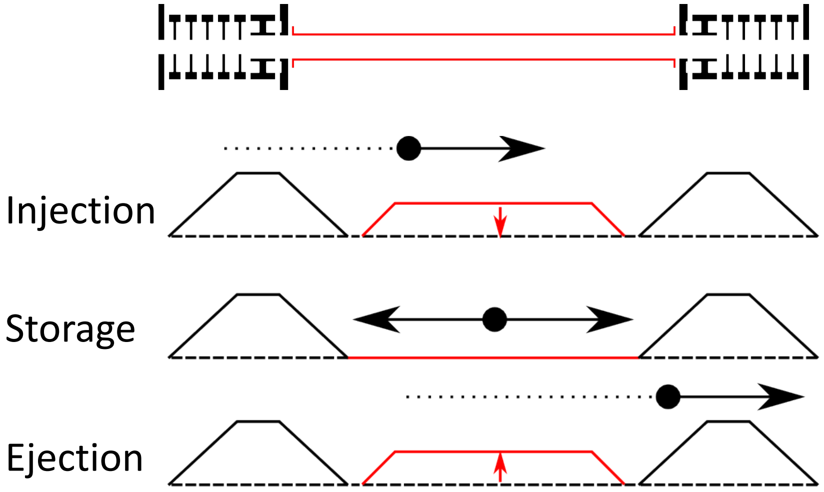


$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t} = \frac{t_0 + nT}{2\sqrt{\Delta t_0^2 + (n\Delta T)^2}}.$$

Time of Flight → t; Revolutions → n; Revolution Time → T; Bunch Width → Δt; Time Dispersion → ΔT

$$\lim_{n\to\infty} R = \frac{T}{2\Delta T}$$

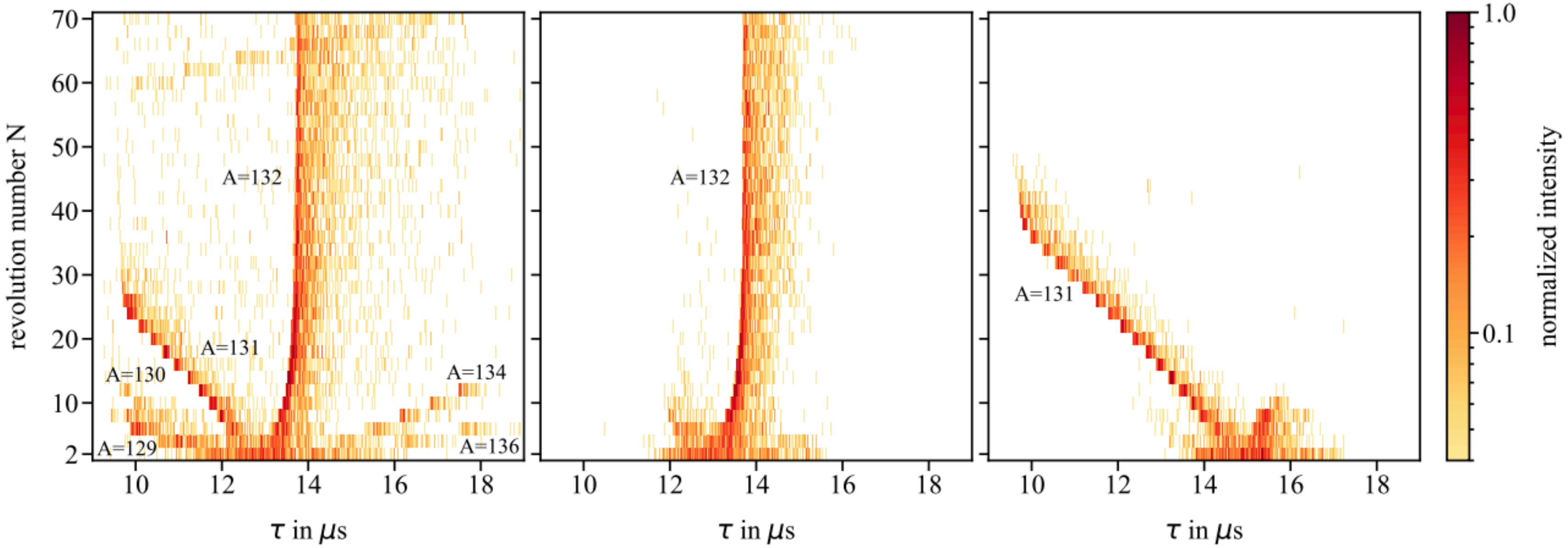
in-trap lift



- Reflect ions between electrostatic mirrors
  → length of flight path is mass dependent
- Main limitation for mass resolving power R is bunch width Δt:
  → optimise mirror electrode potentials to focus
- Trapping by in-trap lift

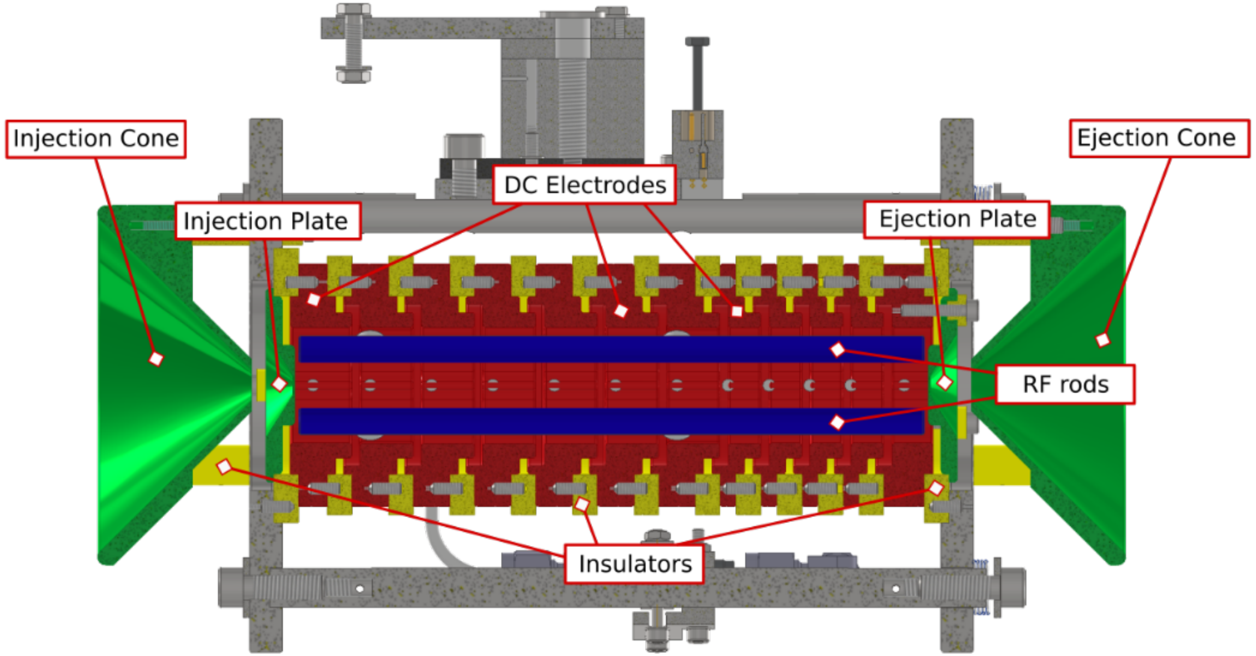
The Darmstadt Design

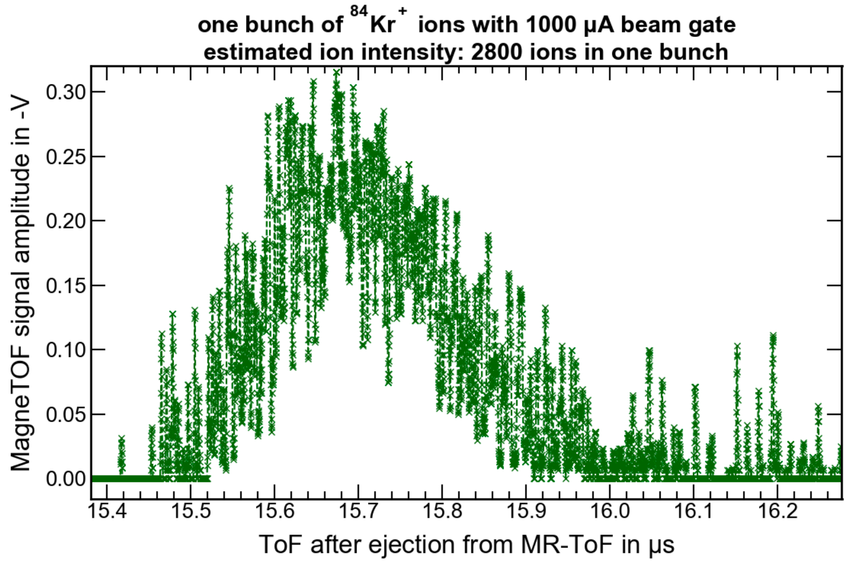
M. Schlaich et al., Int. J. Mass Spectrom. (2023)

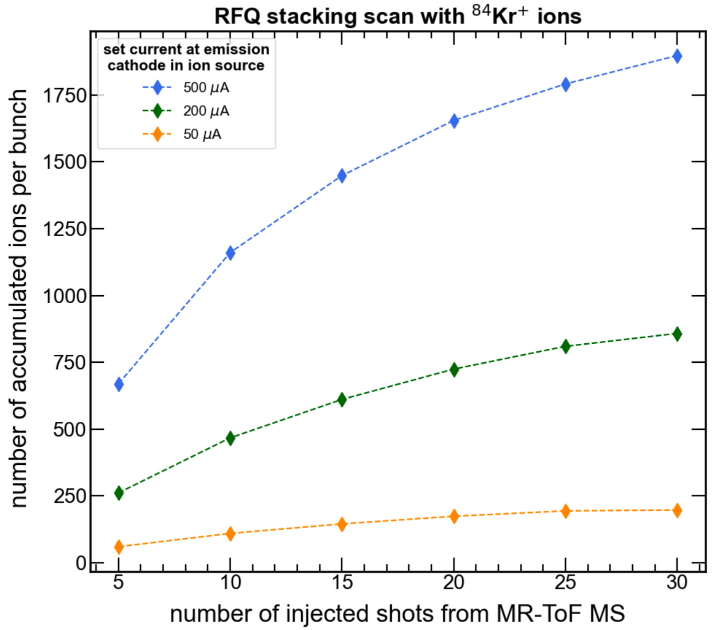


- Based on design of University of Greifswald - modified electrode shape and increased diameter
- Used by 7 institutes in MR-ToF collaboration
- Mass resolving power of $5 \cdot 10^4$ reached after 150 revolutions (limited by energy spread)

Paul Trap - MIRACLS Design

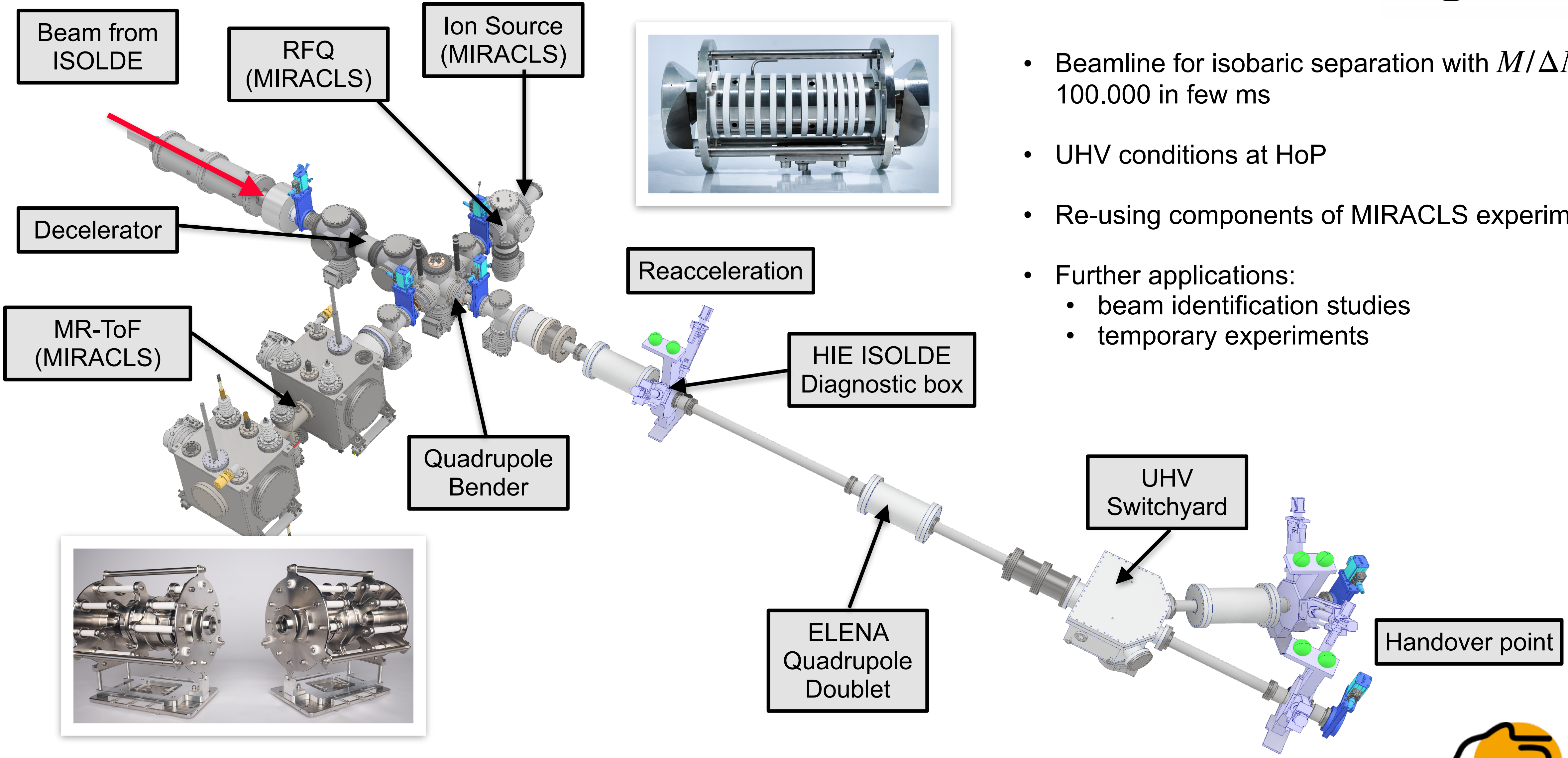






- Linear Paul Trap with 12 DC Electrodes to form potential well, RF rods create confining field
- Used by 4 institutes in Paul Trap collaboration
- Accumulation and Bunching + Cooling using buffer gas injection

RC6 transfer beam line



- Beamline for isobaric separation with $M/\Delta M$ > 100.000 in few ms
- UHV conditions at HoP
- Re-using components of MIRACLS experiment
- Further applications:
  - beam identification studies
  - temporary experiments

Front-end electronics and DAQ

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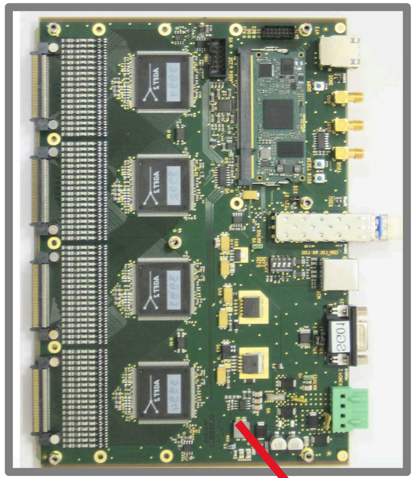
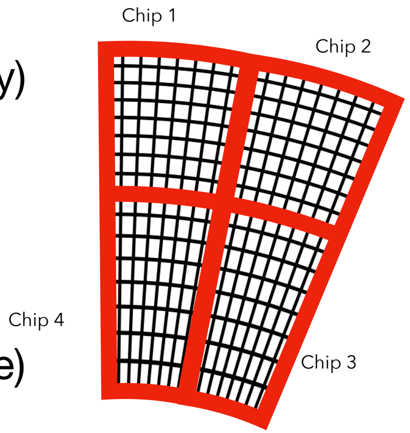


Front-end: STAGE asic (D. Calvet, CEA Saclay)
64 protected channels/chip

ARC (Another Readout Card): 4 STAGE
16 ARCS, 1 ARC to read 256 channels

TDCM (Trigger and Data Concentrator Module)

DAQ Converter (B. Löher, GSI):
hex to root files -> DAQ Interface



Sr-90 Source on reduced detector setup