THE PUMA EXPERIMENT AT ELENA AND ISOLDE

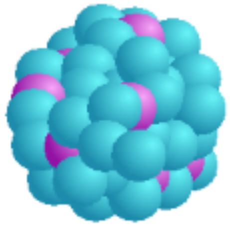
Clara Klink
for the PUMA collaboration
30.11.2023

Motivation

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Charge distribution in atomic nuclei:** accessible e.g. electron scattering
- **Neutron densities:** traditionally rely on hadronic probes -> large and uncontrolled uncertainties
- Interesting nuclear phenomena on the surface of asymmetric nuclei: densities relate to Equation of State

Skin

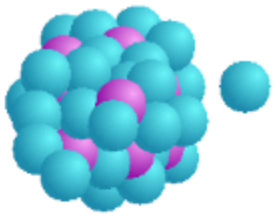


- If N > Z, $\rho_n(r)$ exceeds $\rho_p(r)$ on the nucleus' surface
- Characterized by thickness

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

- Δr_{np} ~ 0.2 fm for ^{208}Pb

Halo



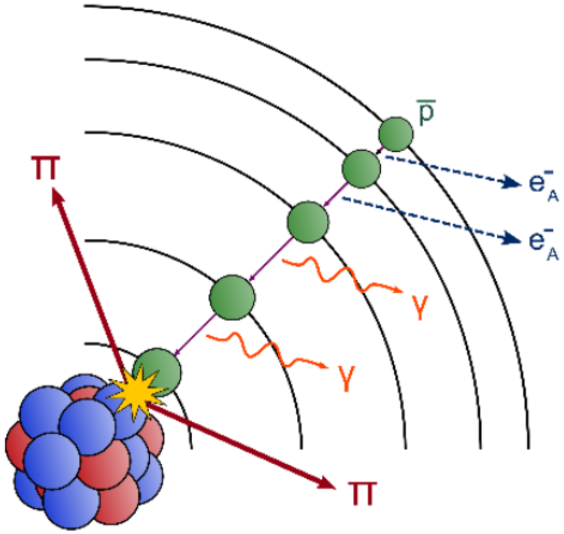
- Drip line nuclei (N ≫ Z or Z ≫ N)
- Weakly bound halo of orbiting proton(s) or neutron(s):

  $\rho_{n/p}(r)$ extends far from expected r_{nucl}

- Halo ^{11}Li has ~ r_{nucl} as ^{208}Pb

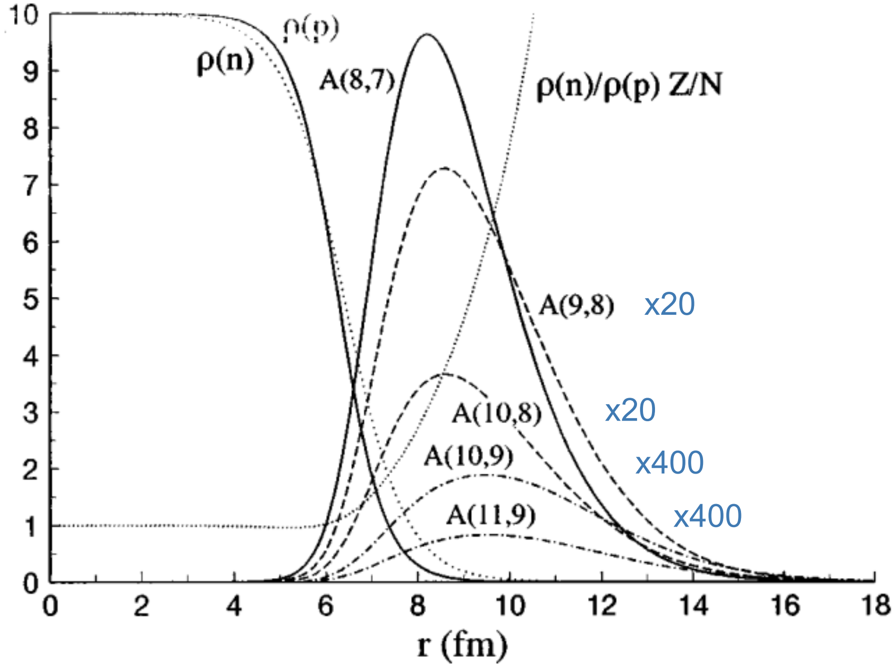
- A technique is required to probe proton <u>and</u> neutron densities in the tail of the nuclear density distribution function

antiProton Unstable Matter Annihilation (PUMA)



Proposed technique: low-energy $\bar{p}$ as probe

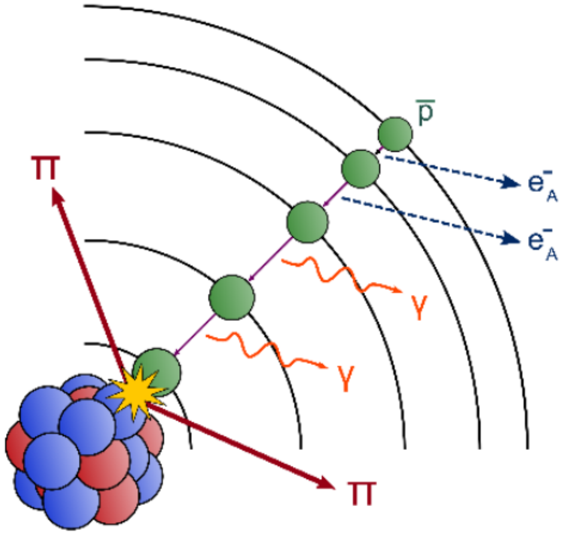
1) Capture in excited antiproton orbital
2) Decay cascade by Auger and radiative transitions
3) Annihilation with surface nucleon: 2-2.5 fm from half-density radius
4) Final-State interactions of emitted mesons



Schmidt et al., PRC (1998)

antiProton Unstable Matter Annihilation (PUMA)

TECHNISCHE UNIVERSITÄT DARMSTADT



Conservation of total charge & energy
→ carried by final-state mesons (mostly pions)

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

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

- First Application of Methode:
  Buggs et al., PRL (1973)
- Application to RI first proposed:
  Wada and Yamasaki, NIM B (2004)

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

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

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

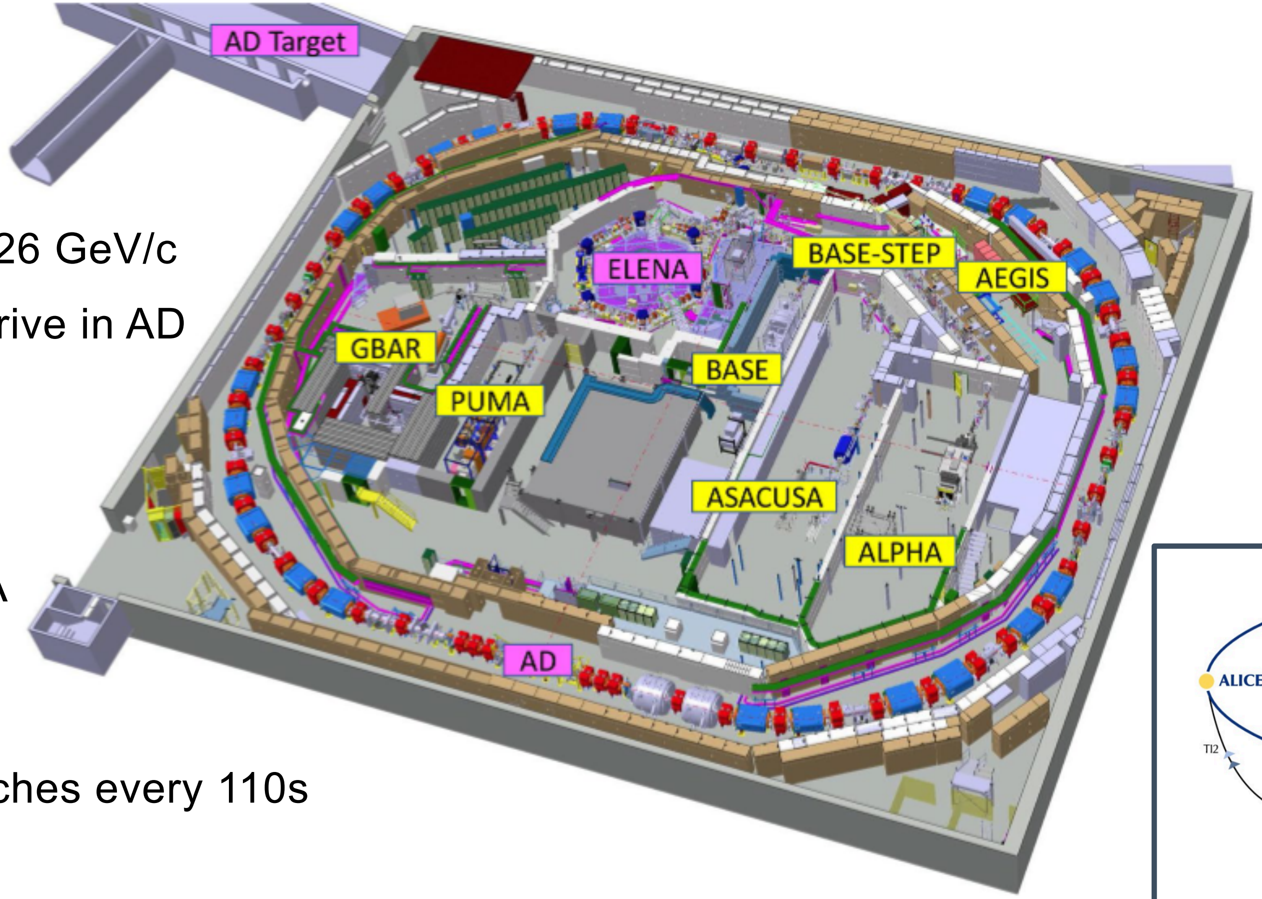
Deceleration of $\bar{p}$:

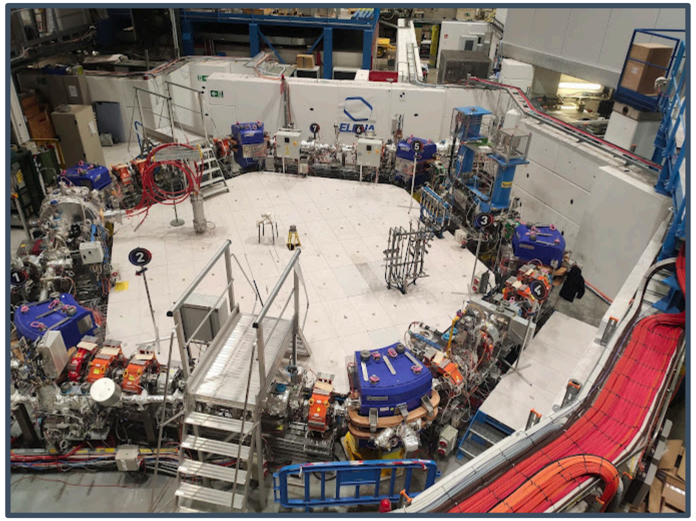
- 5.3 MeV in AD
- 100 keV in ELENA

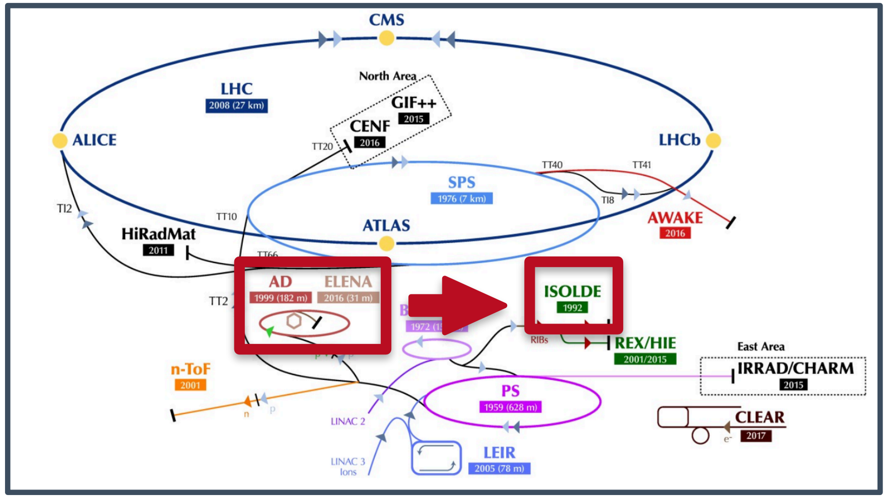
Duty cycle of ELENA:

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

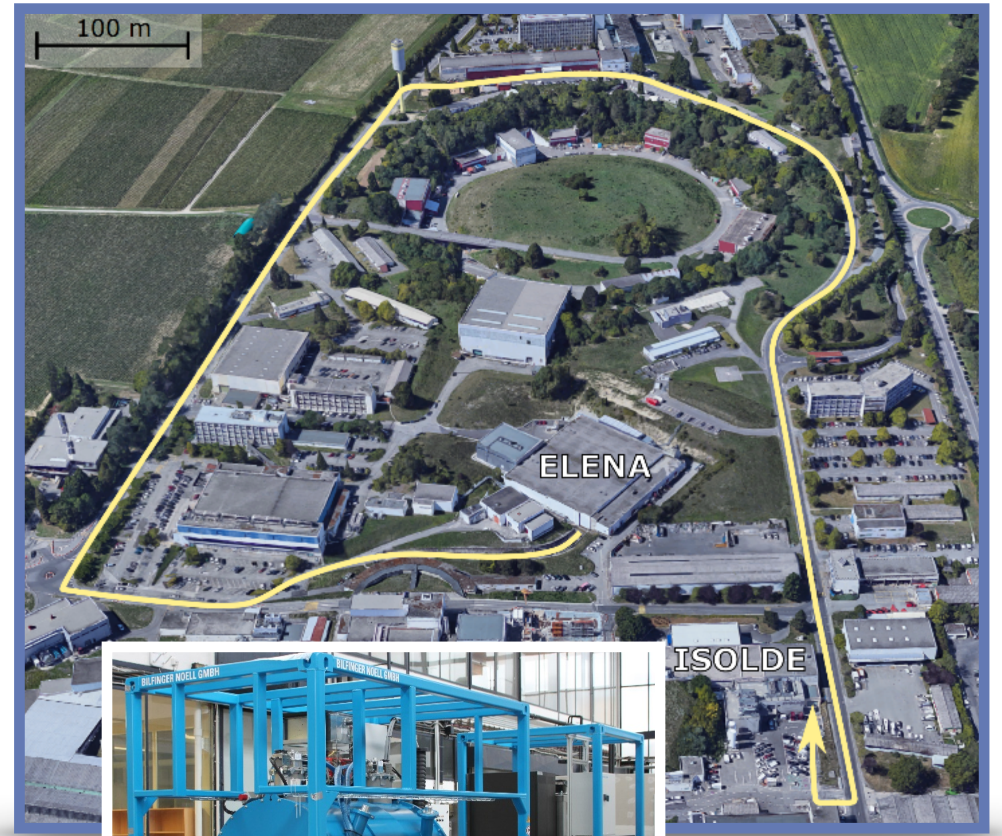
No RI at AD: transport $\bar{p}$ to ISOLDE in dedicated trap setup







Transporting Antiprotons



- 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]

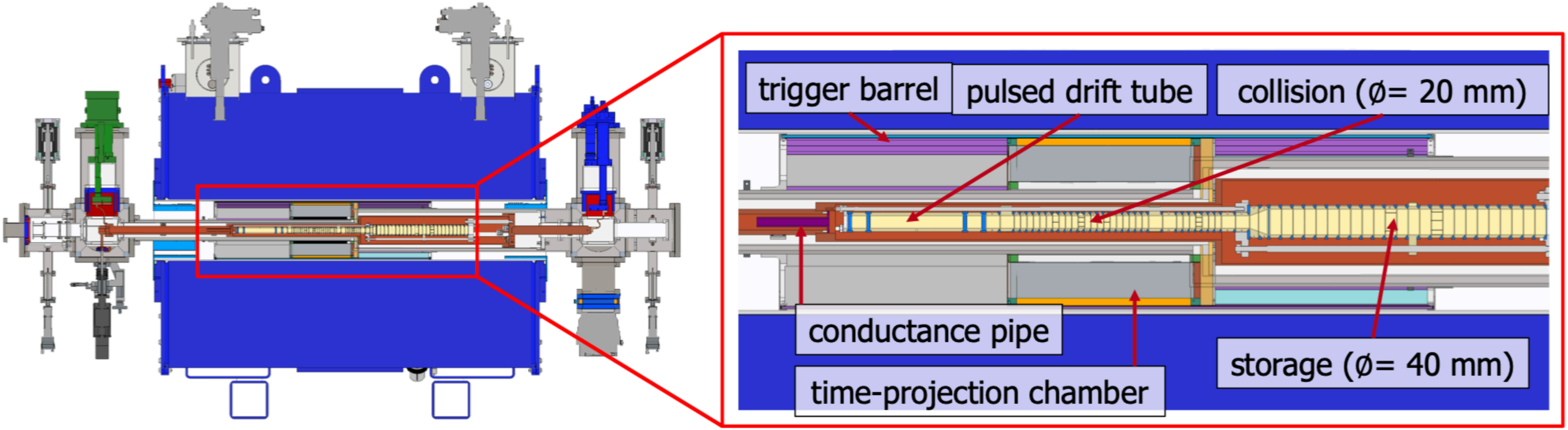
- targeted residual gas density: 20 cm^{-3} (10^{-17}mbar)

Transportation from ELENA to ISOLDE

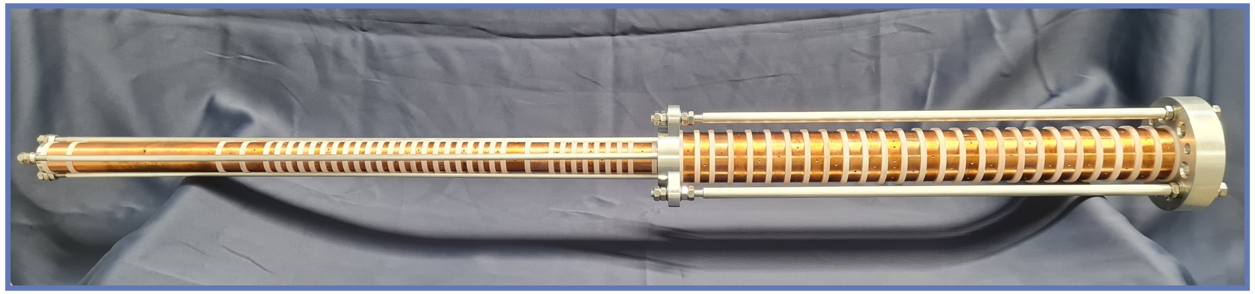
- Long antiproton trapping time already achieved.
  Ex. BASE: > 50 years

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

Traps and Detection for PUMA

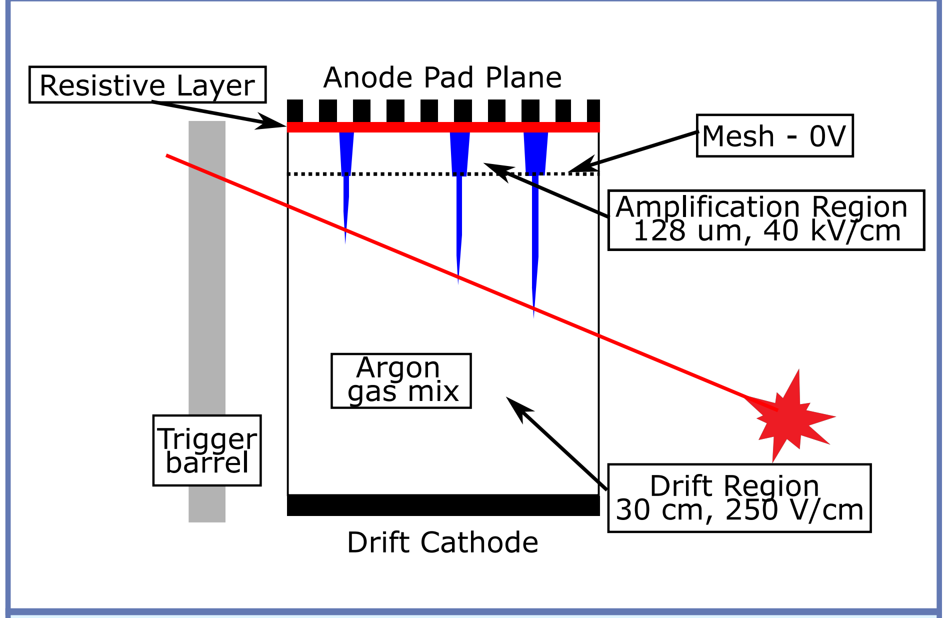


- Two trap sections: collision and storage
- Storage: 10^{7-9}antiprotons
- Collision: 10^{4-5} ions
- Expected yields: 100 Hz



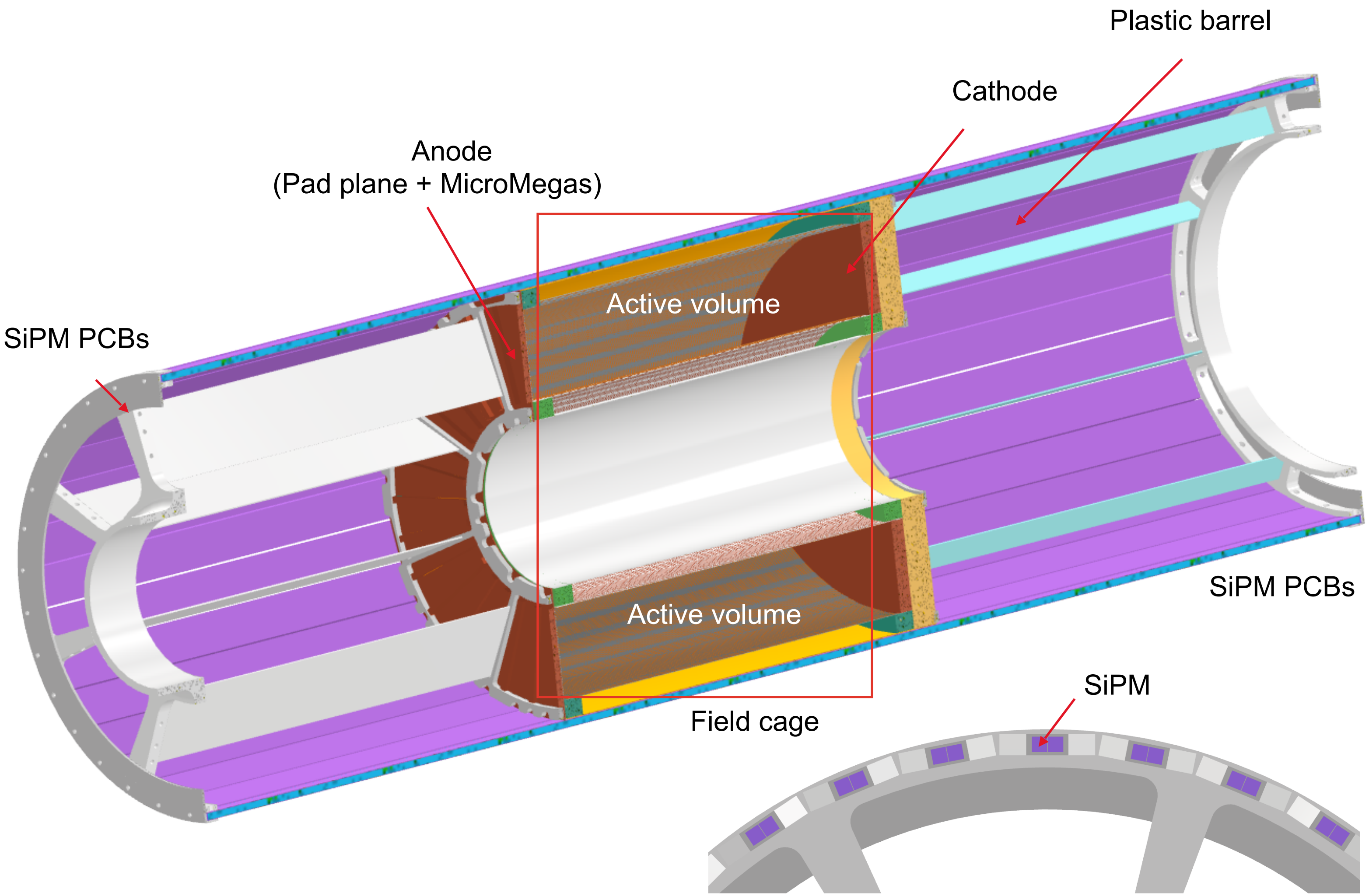
Pion Detection - Time Projection Chamber / Barrel

TECHNISCHE UNIVERSITÄT DARMSTADT

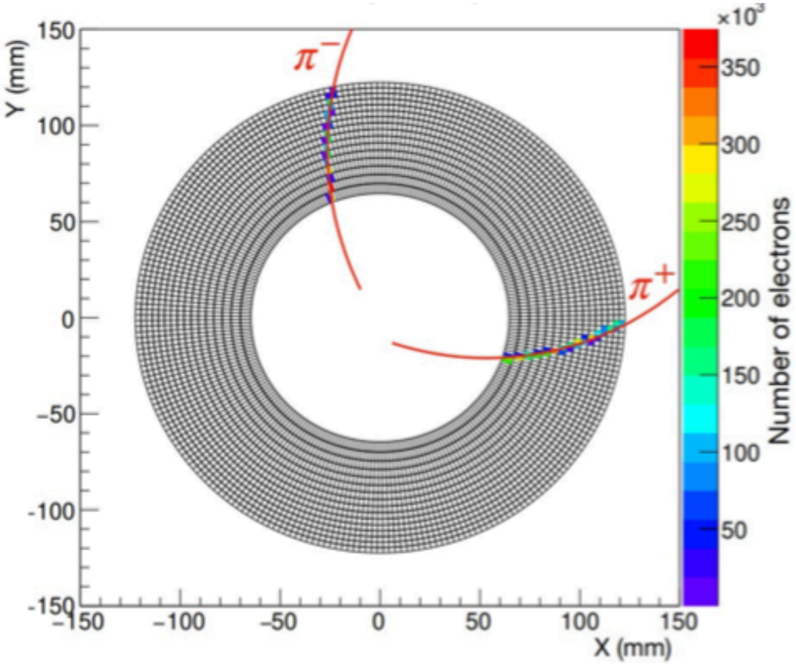


Resistive Micromegas; resolution < 400 μm
Detection efficiency: 85 % (simulations)

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

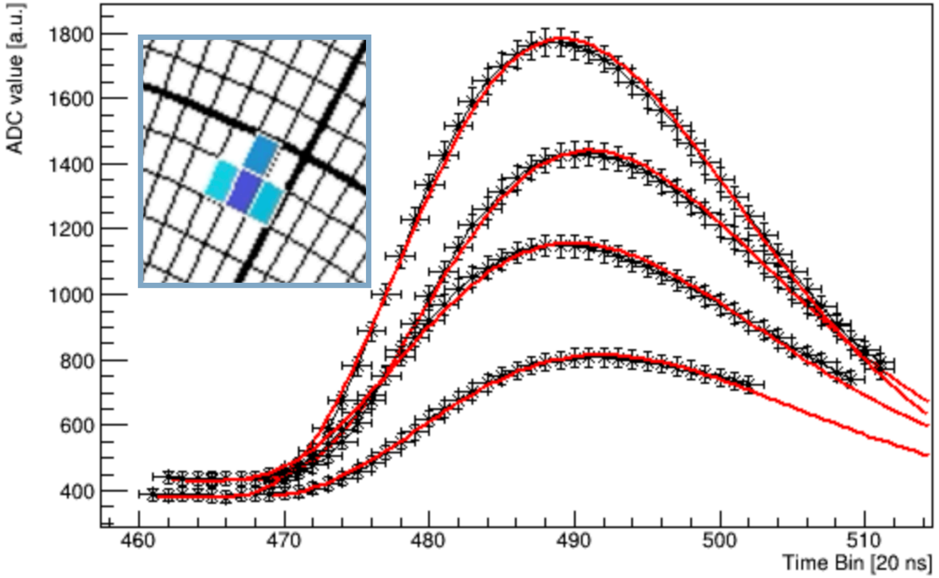


Pion Detection - Time Projection Chamber / Barrel



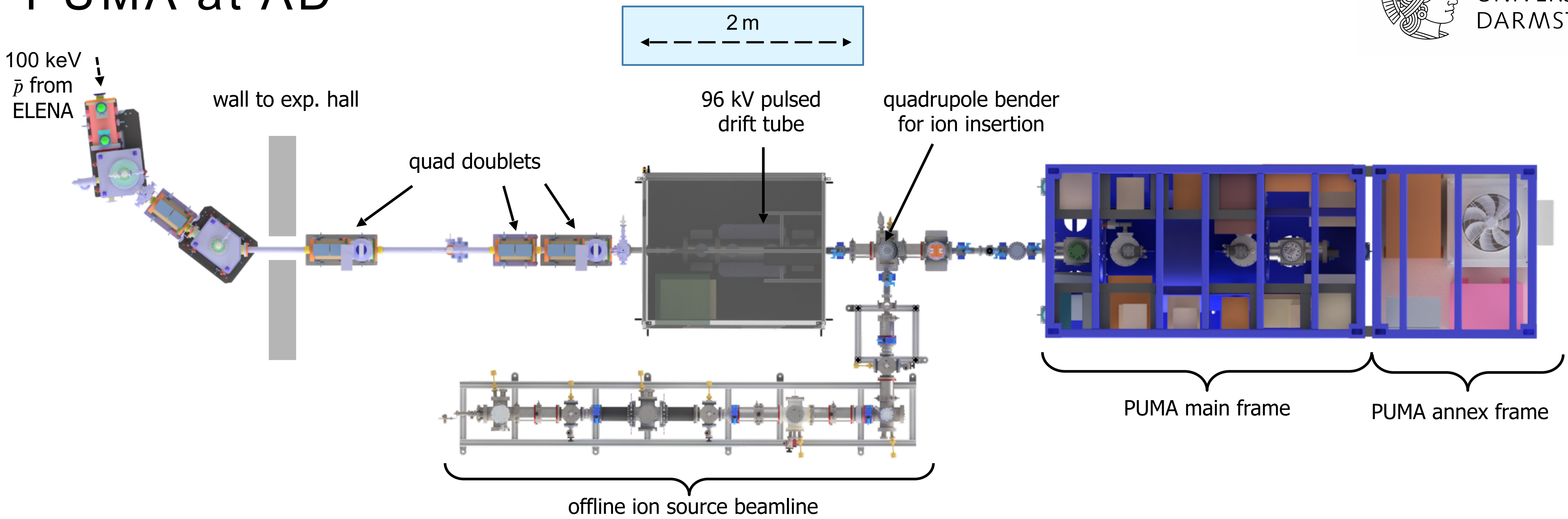
Simulated pion tracks on pad plane

Reduced detector setup for first pad plane tests



Example event reconstruction

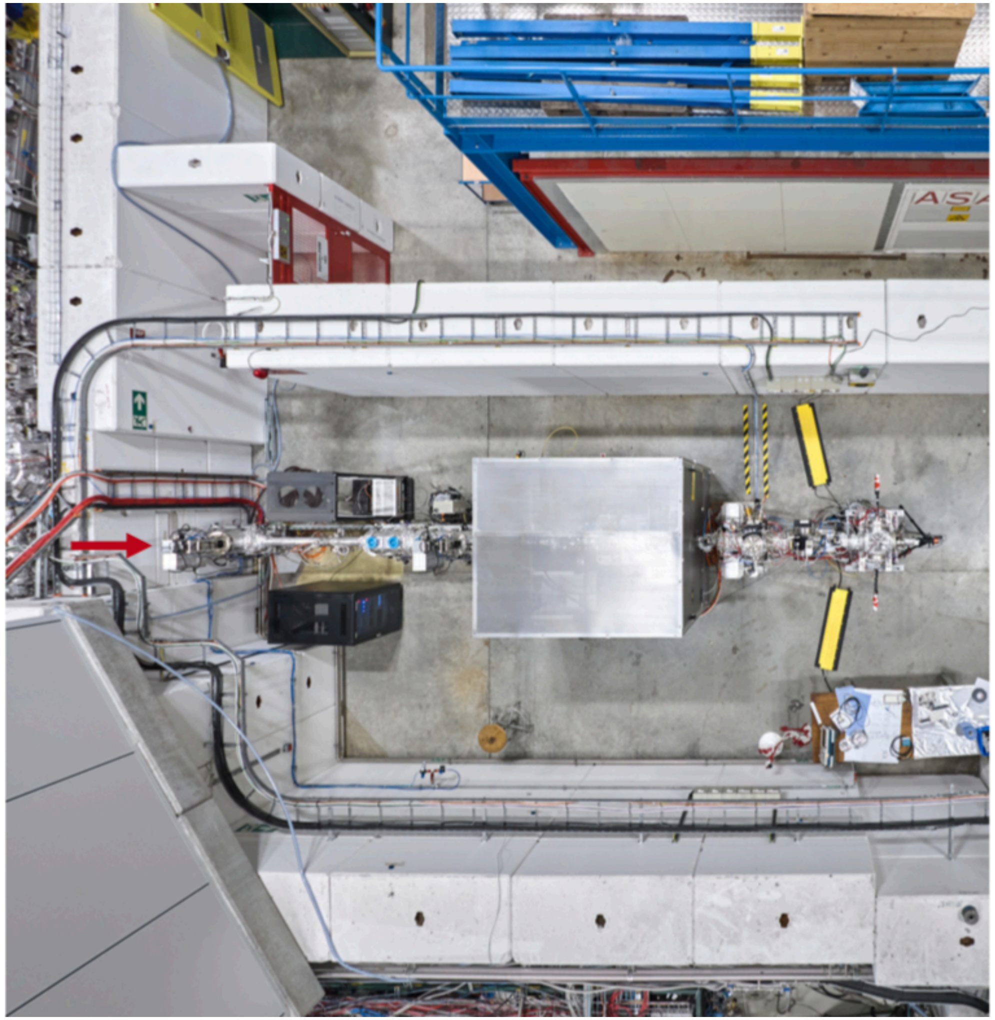
PUMA at AD

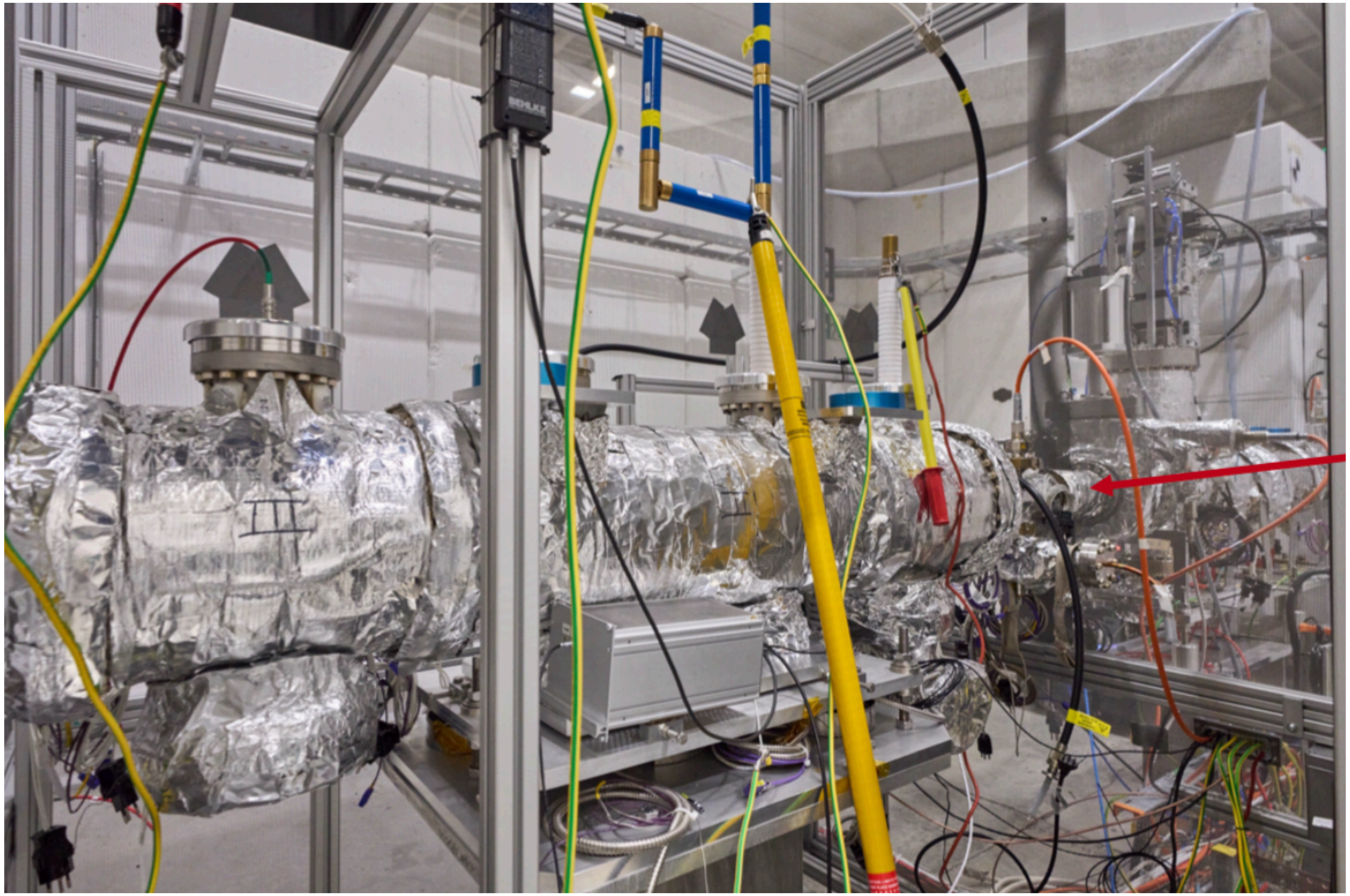


- deceleration of $\bar{p}$ from 100 keV to 4 keV by pulsed drift tube (PDT)
- First experimental campaign with stable isotopes from gas ion source
- Dedicated beam line: mass separation with MR-ToF, stacking and cooling in Paul Trap

PUMA at AD

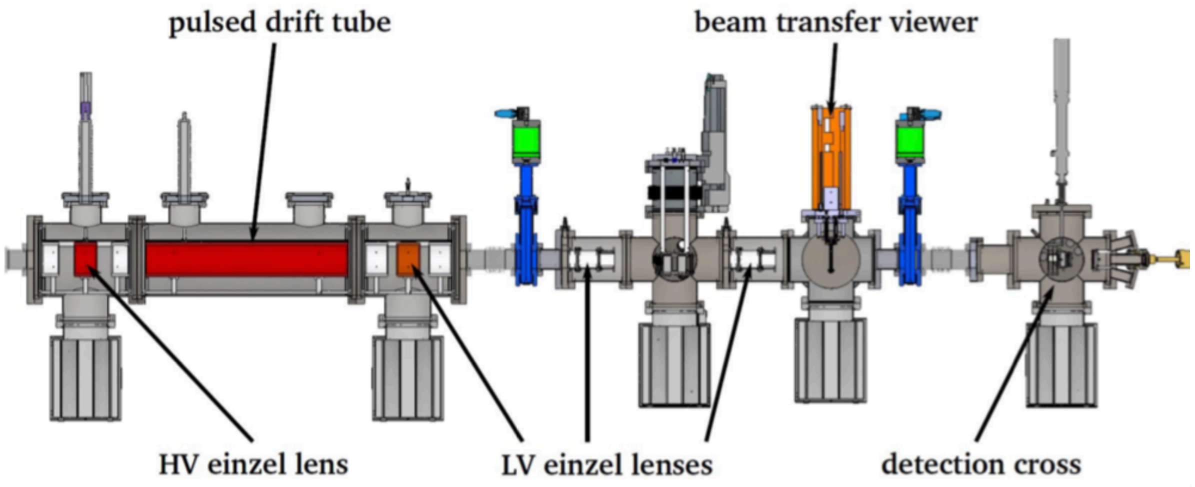
TECHNISCHE UNIVERSITÄT DARMSTADT



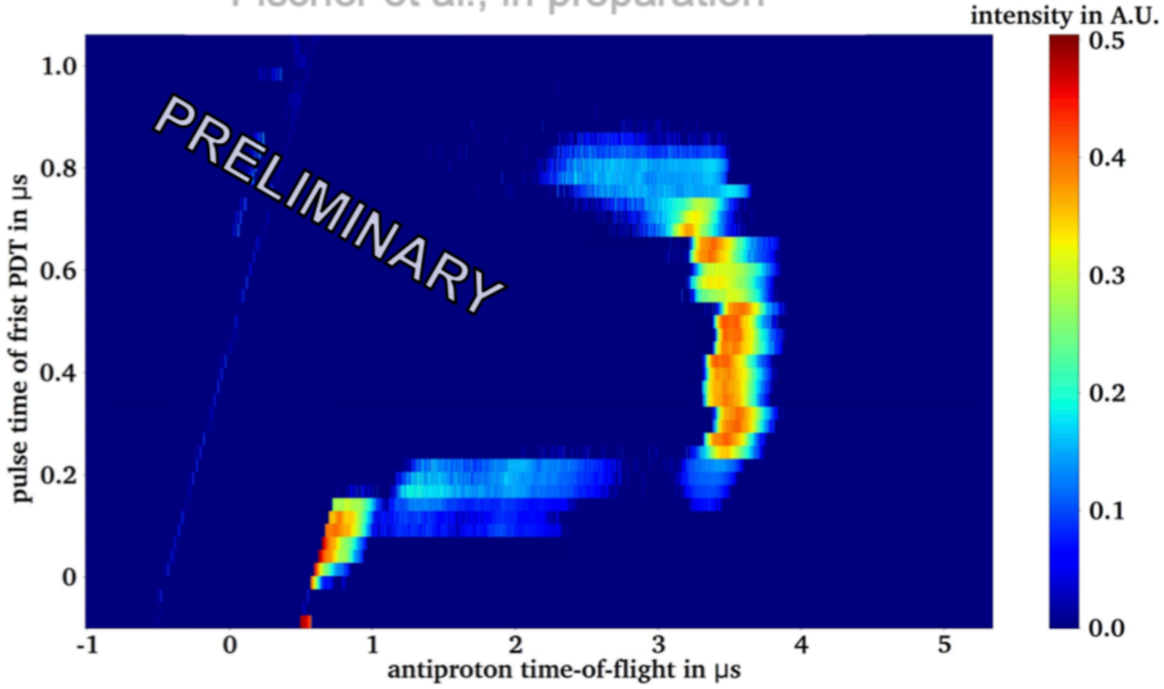


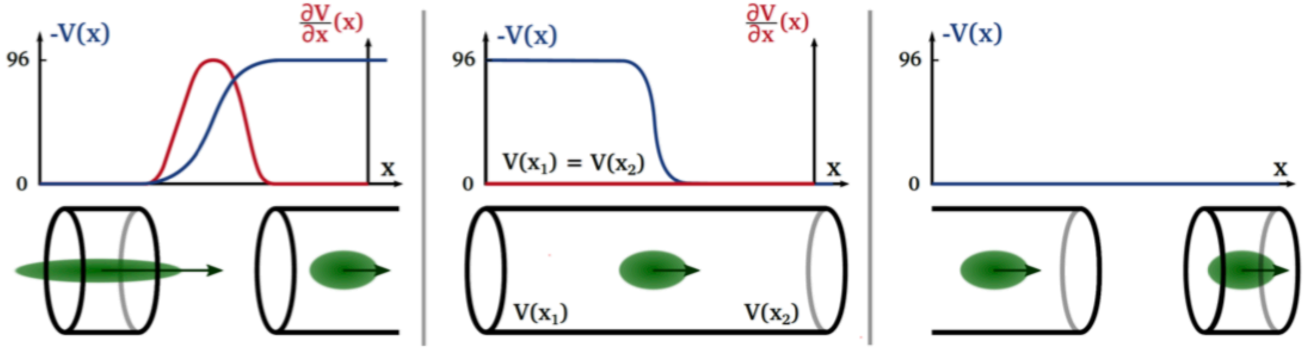
Clara Klink | CERN | TU Darmstadt – Institute for Nuclear Physics
ISOLDE Workshop and Users Meeting | 30 Nov 2023, CERN

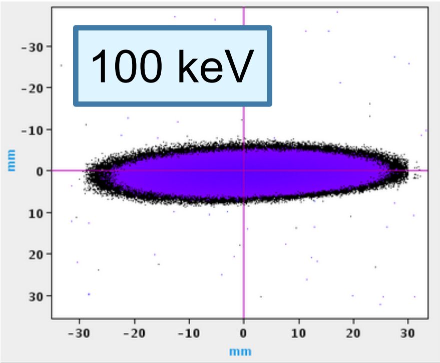
Deceleration of Antiprotons - 100 keV to 4 keV

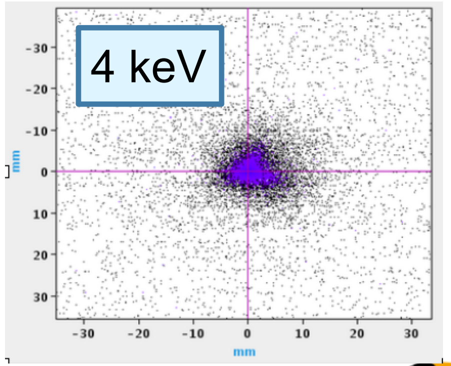


Fischer et al., in preparation



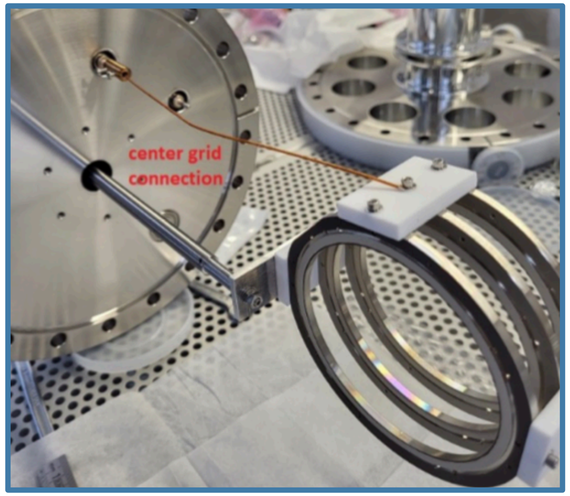


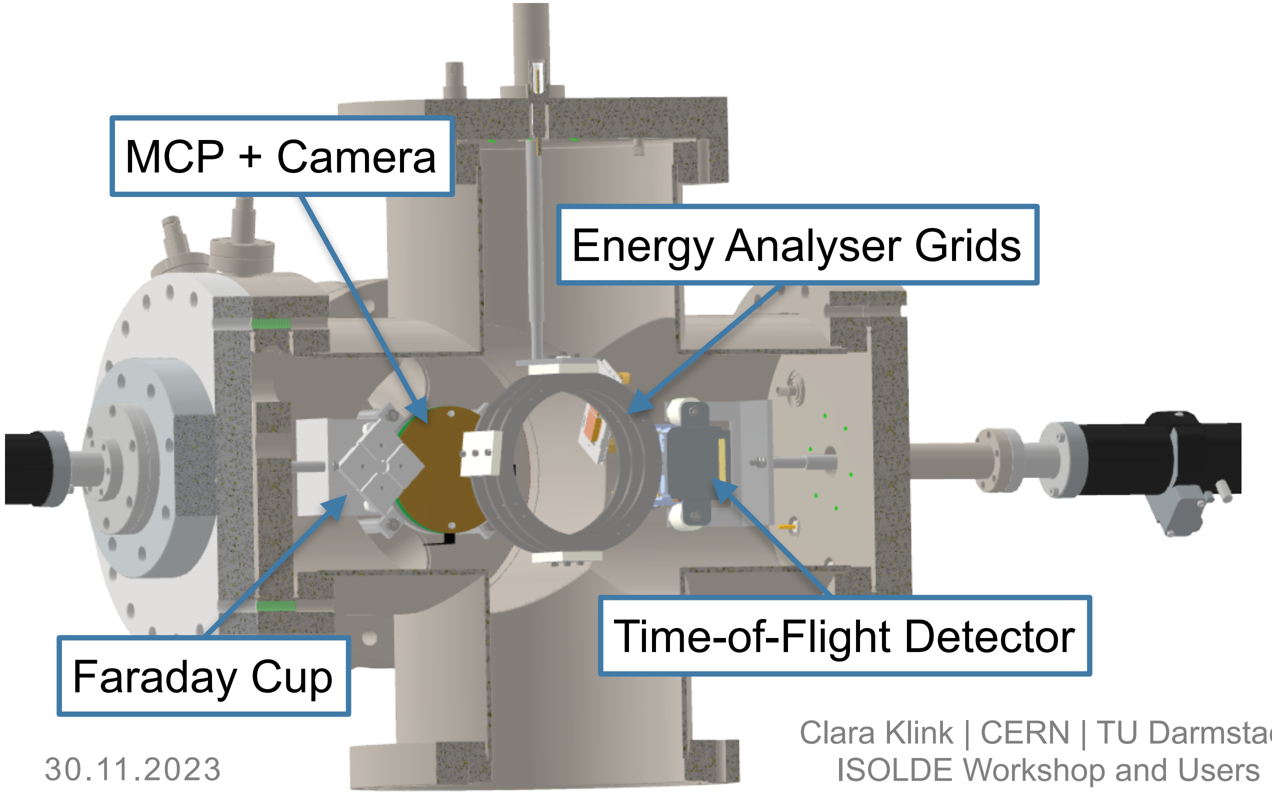




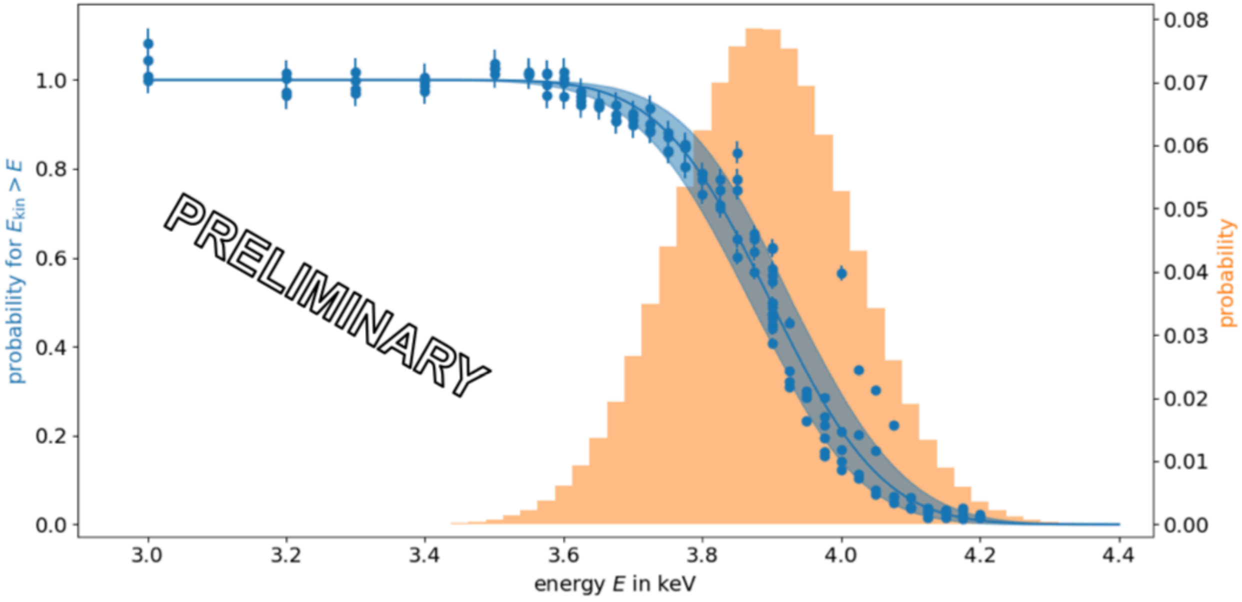
Beam Characterization after PDT

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



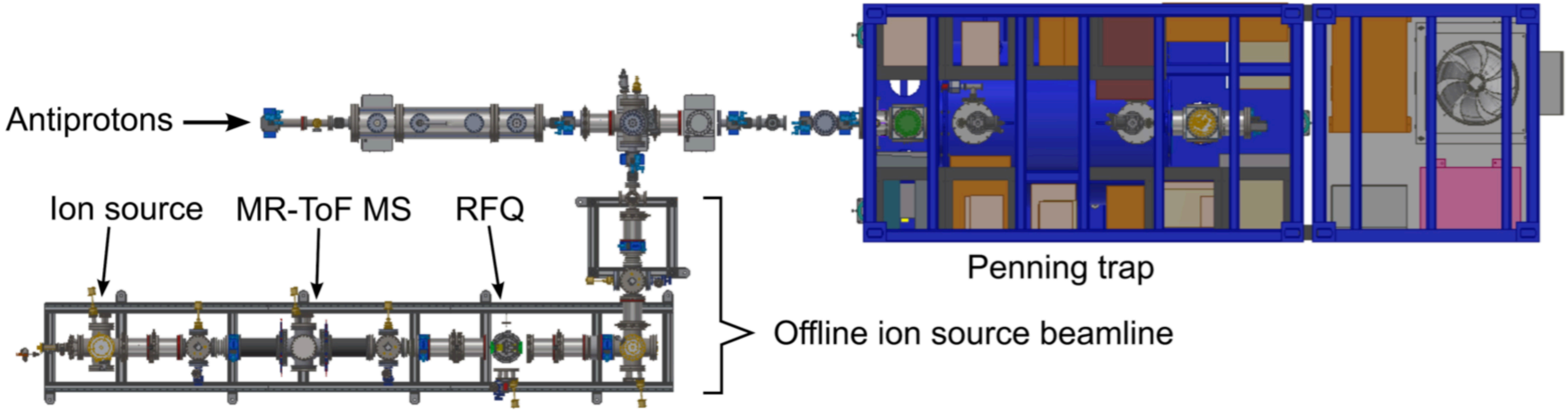


Fischer et al., in preparation



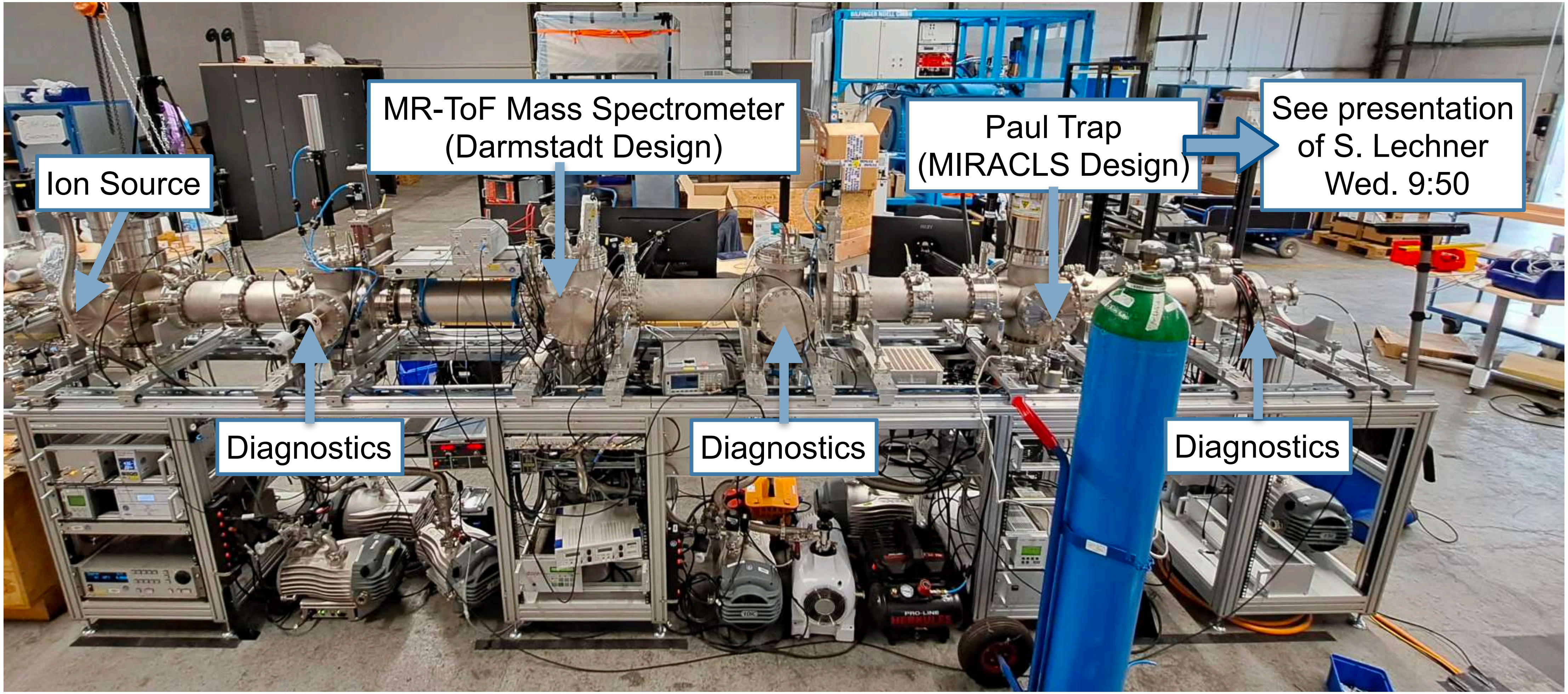
Offline Ion Source / First stable physics cases

- 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: $^{124-136}Xe$
- Future step: laser ablation source for $^{40-48}Ca,\ ^{112-124}Sn,\ ^{208}Pb$

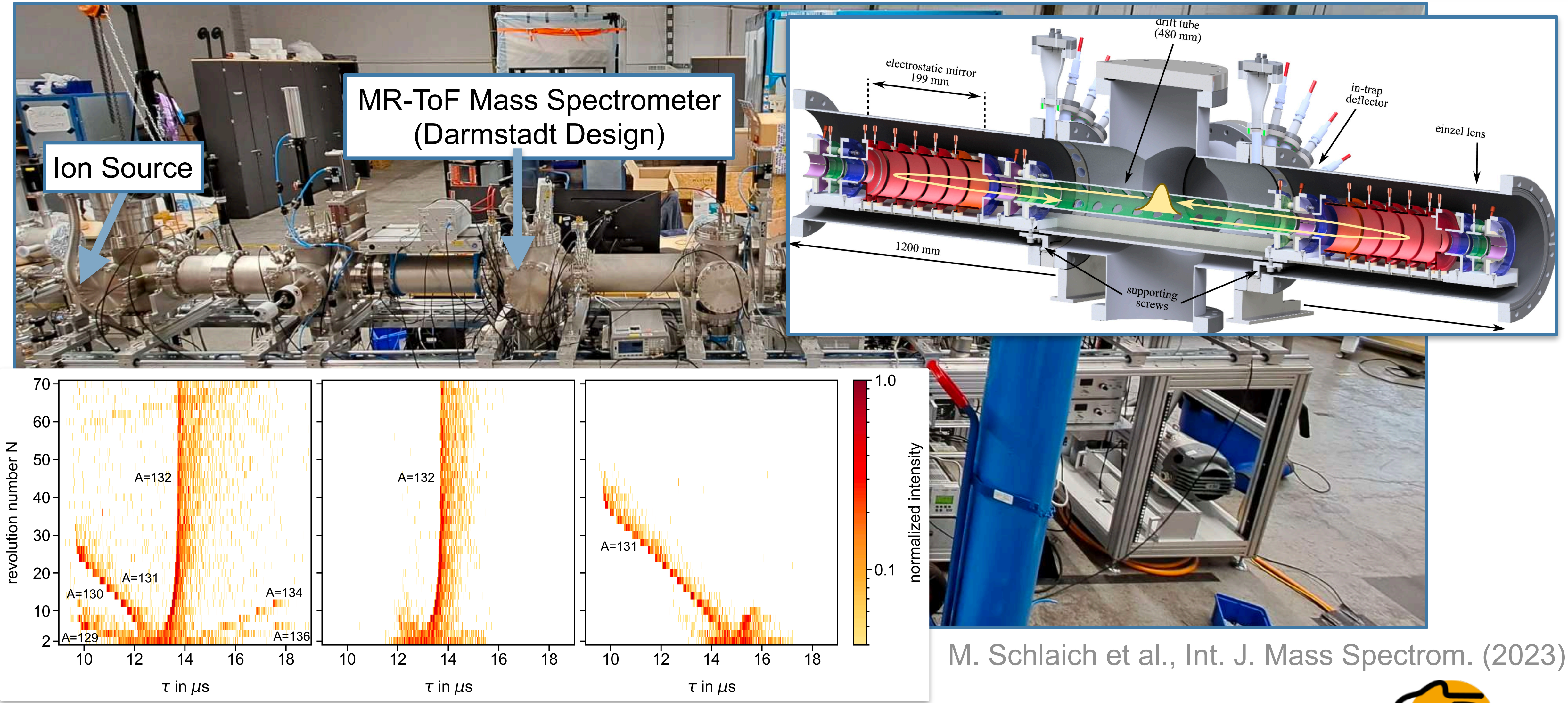


Offline Ion Source Beamline

TECHNISCHE UNIVERSITÄT DARMSTADT

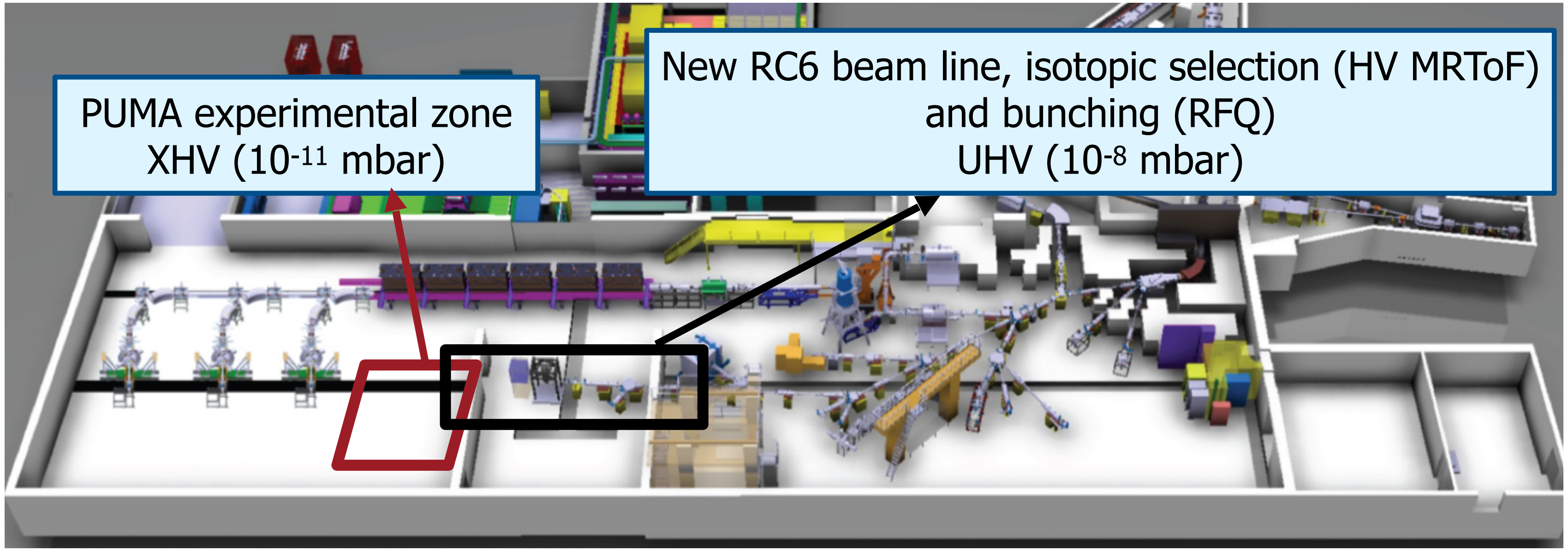


Offline Ion Source Beamline



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

PUMA at ISOLDE



First Physics Cases

<u>2025:</u>

- Continue efforts from gas studies at AD: neutron-rich Xe isotopes, neutron-rich and deficient Ne

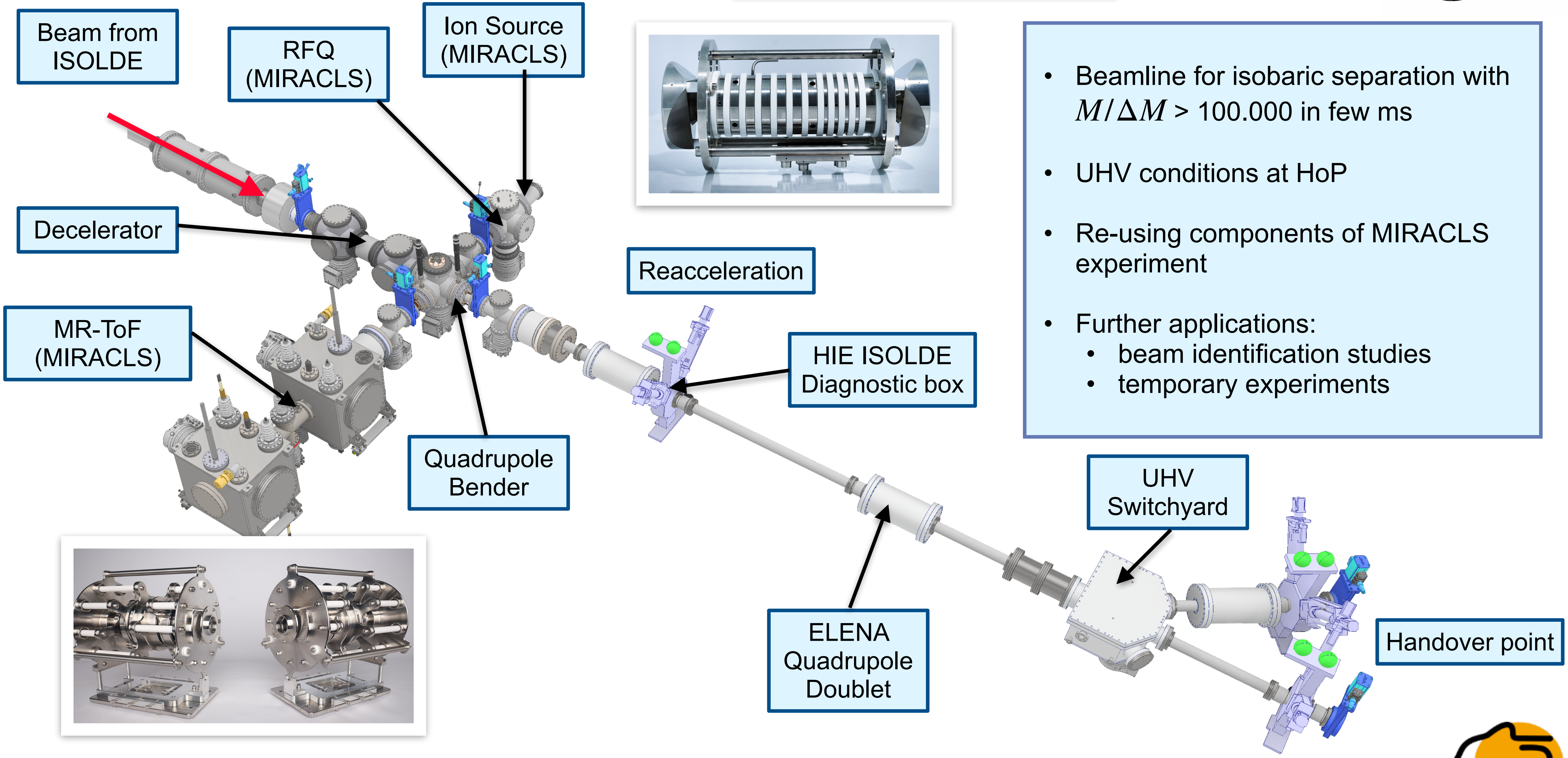
<u>After LS3:</u>

- New laser ablation source: e.g. Sn isotopic chain across $N = 82$, Ca isotopes

RC6 transfer beam line

Poster L. Nies

TECHNISCHE
UNIVERSITÄT
DARMSTADT



- 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

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 since November 2022: **operation of 96kV PDT confirmed**
- First experiments at ELENA in 2024, first low-energy RIB experiments at ISOLDE in 2025

The PUMA collaboration

TECHNISCHE UNIVERSITÄT DARMSTADT

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
With contribution from B. Loeher, GSI

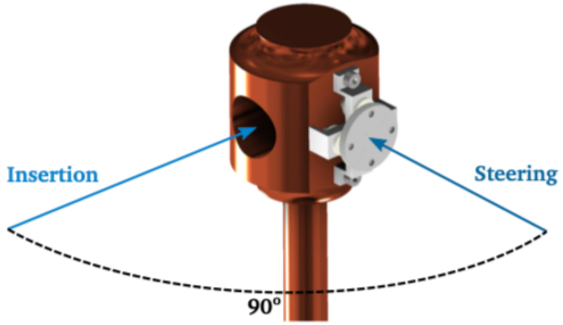
TECHNISCHE UNIVERSITÄT DARMSTADT | CERN | IJCLab Irène Joliot-Curie | LKB | IPHC | TRIUMF | Alexander von Humboldt Stiftung/Foundation | erc

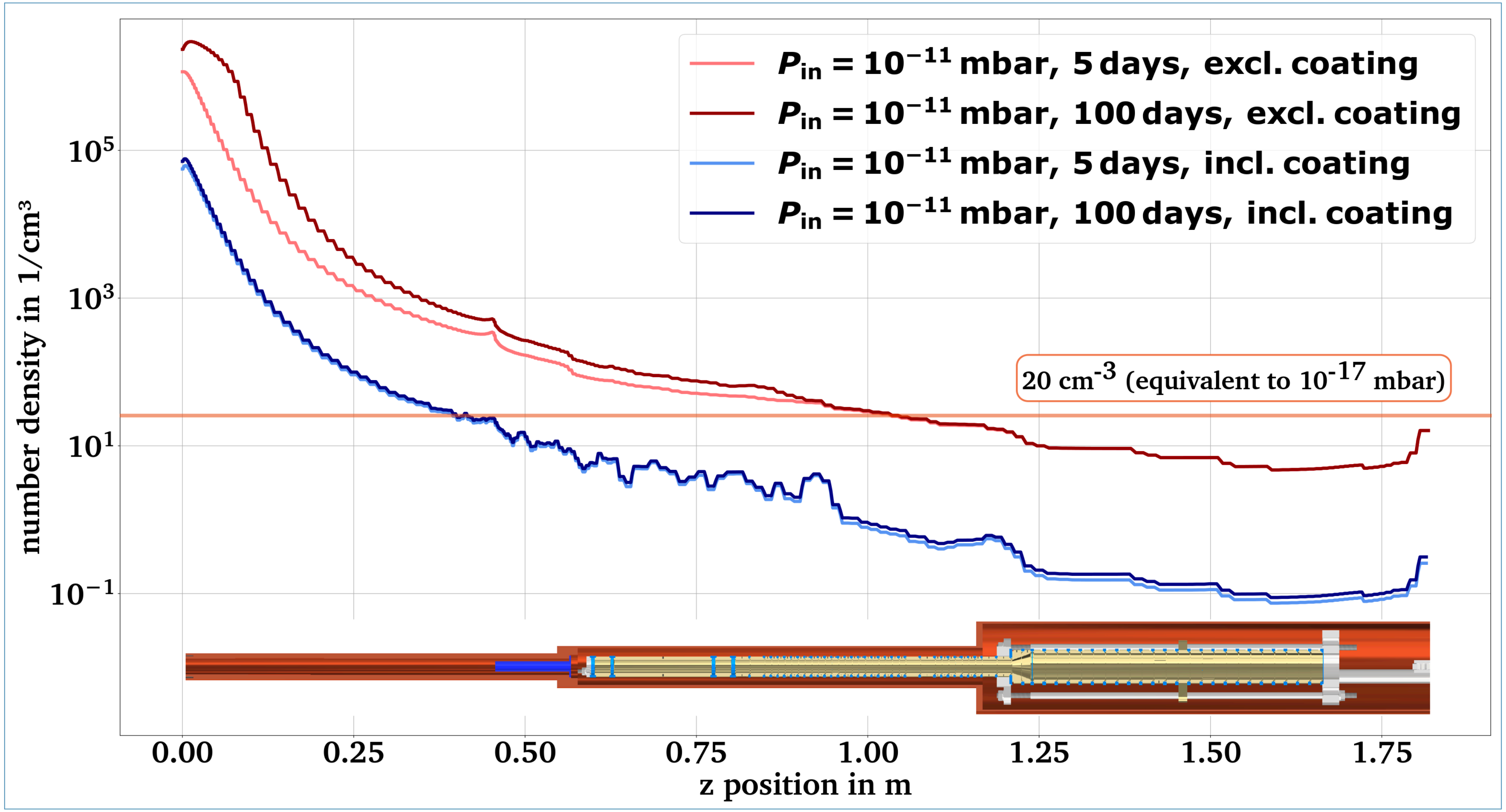
This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA)

Vacuum Simulations

TECHNISCHE UNIVERSITÄT DARMSTADT

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





THE PUMA TRAP & 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] → $P_H < 10^{-16} mbar$

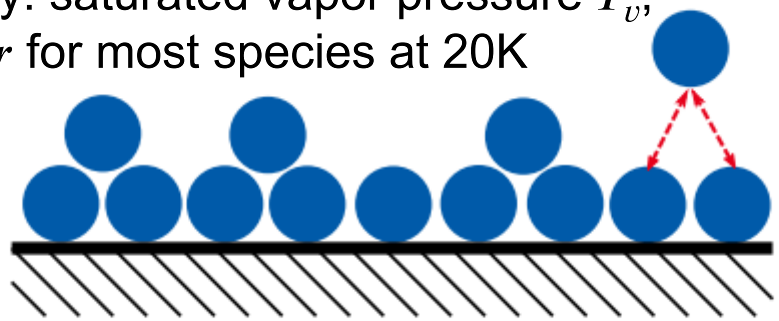
  PUMA collaboration, PUMA, antiProton Unstable Matter Annihilation, Eur. Phys. J. A. **55:88** (2022)

- 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

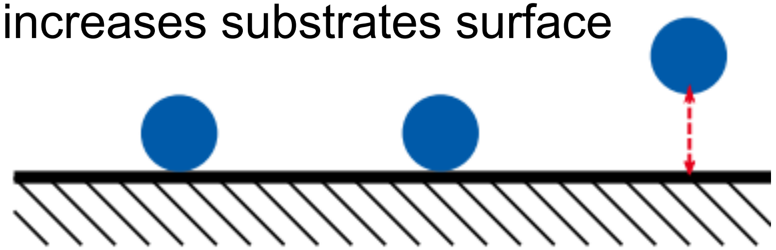


Cryosorption

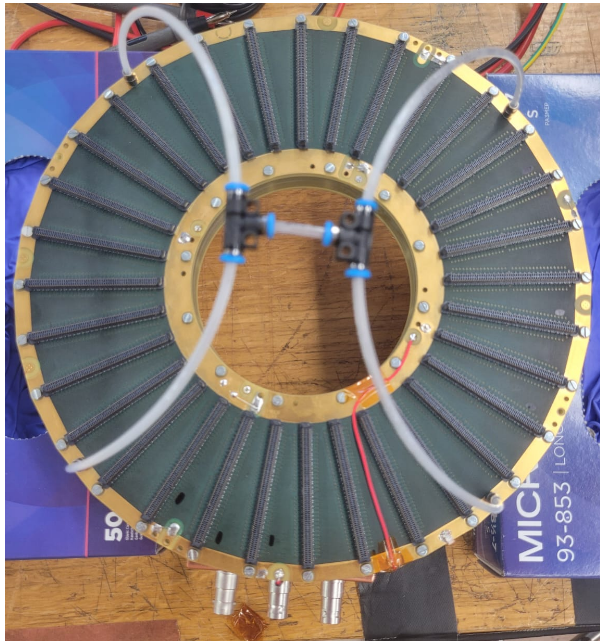
- Attraction between gas molecules and substrate

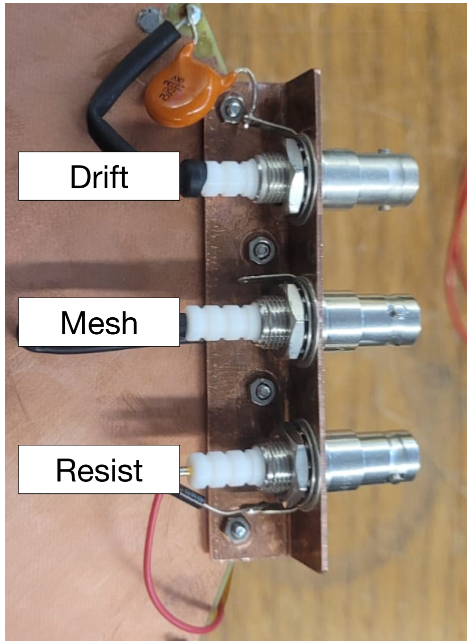
- If adsorbed quantity smaller than 1 monolayer:
  $P_H \ll P_v$

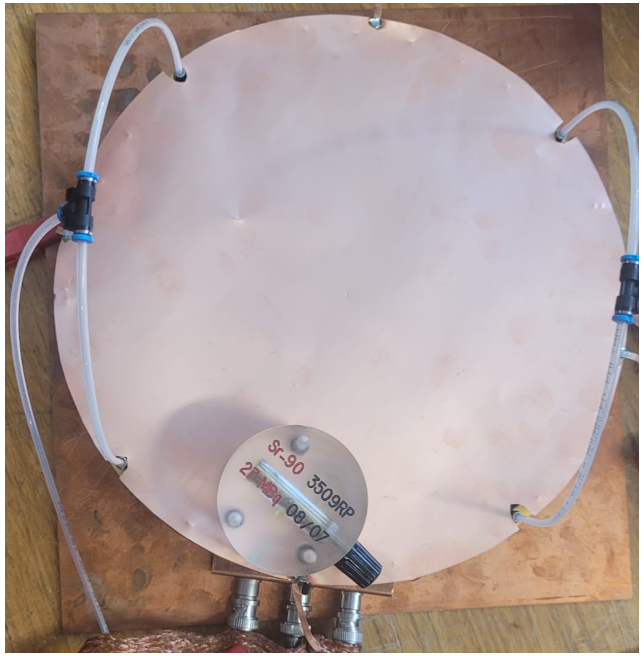
- Carbon layer increases substrates surface



PUMA TPC - Tests at GDD Lab - First Signal from Mesh



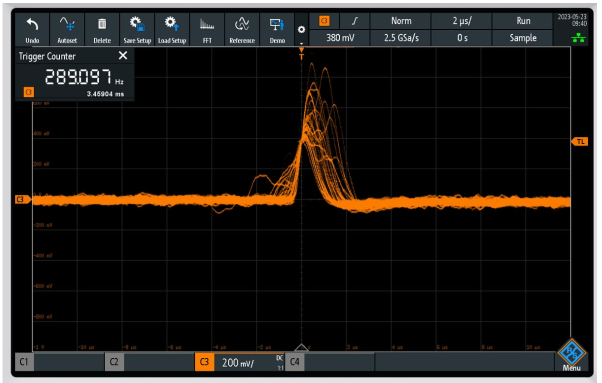




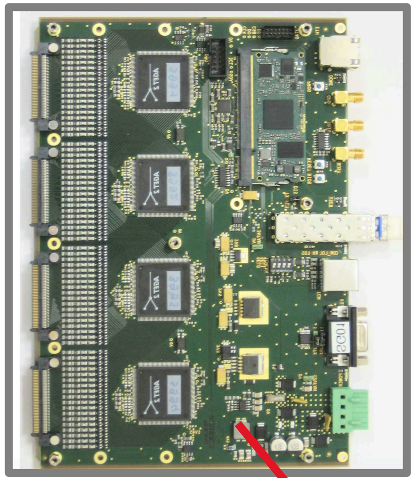
anode in flat “pancake” configuration:
Pad plane + MM + 1MΩ DLC RL
5 mm drift region, 100 um amplification region

-250V
+580V
0V

Gas mix: Ar-CO_2 (70/30), flow 5L/H
Signal read from Mesh



The PUMA Detection System - DAQ

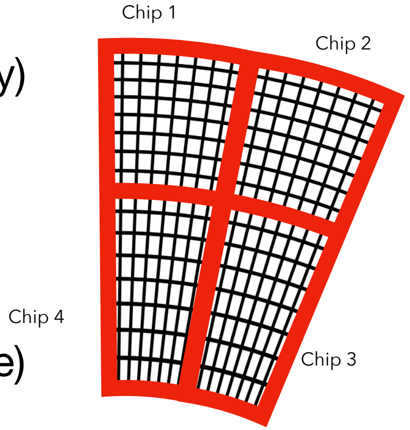


Front-end: STAGE asic (D. Calvet, CEA Saclay)
64 protected channels/chip

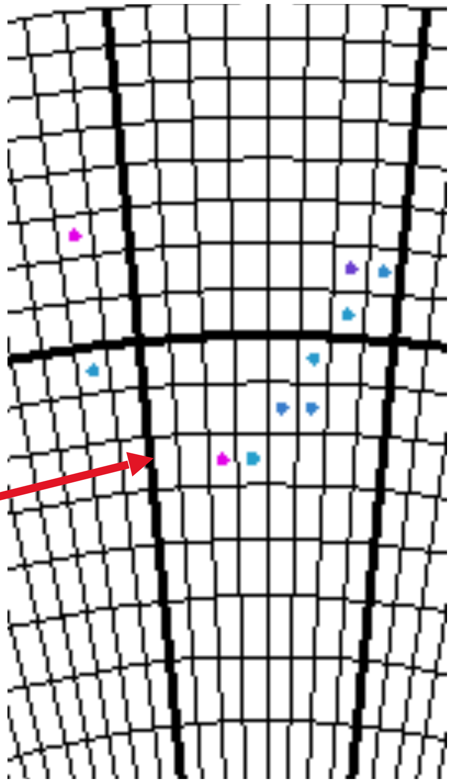
ARC (Another Readout Card): 4 STAGE
16 ARCS, 1 ARC to read 256 channels

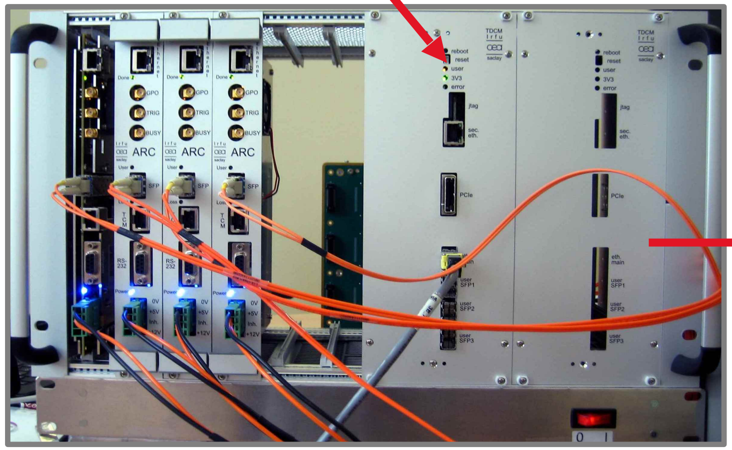
TDCM (Trigger and Data Concentrator Module)

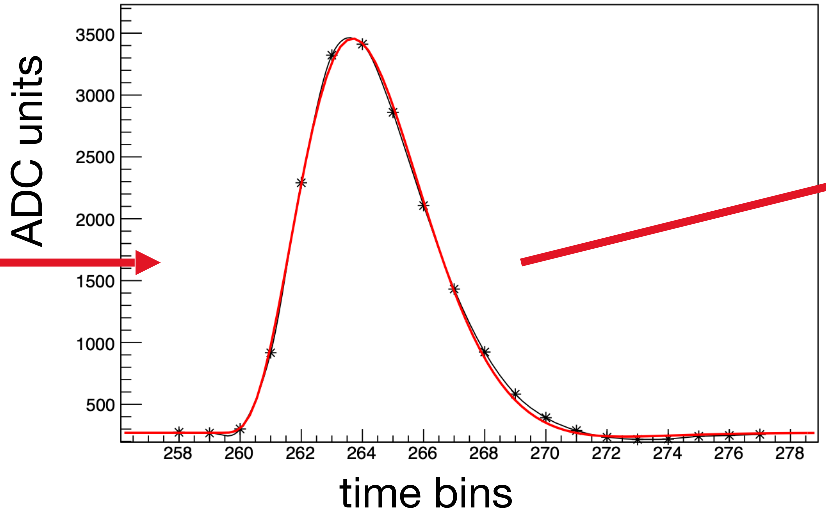
DAQ Converter (B. Löher, GSI):
hex to root files -> DAQ Interface



Sr-90 Source on reduced detector setup

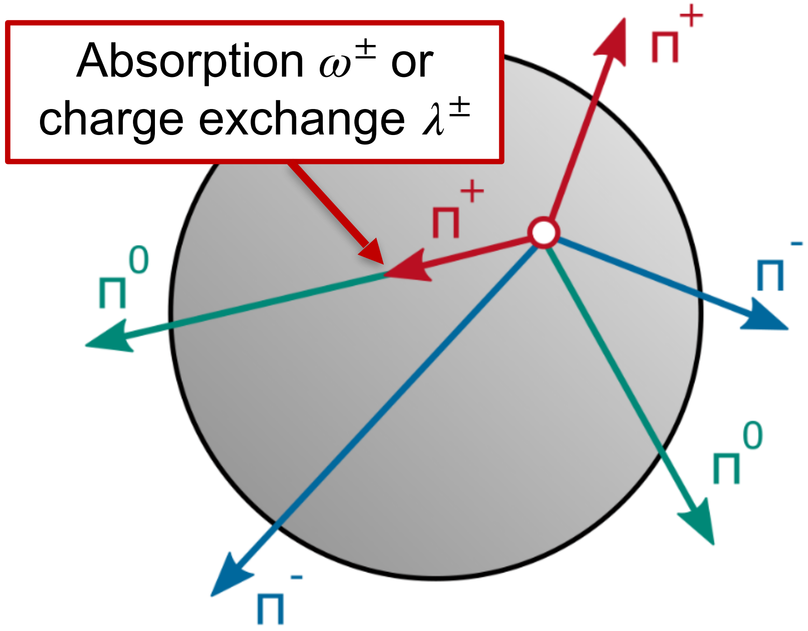






Clara Klink | CERN | TU Darmstadt – Institute for Nuclear Physics

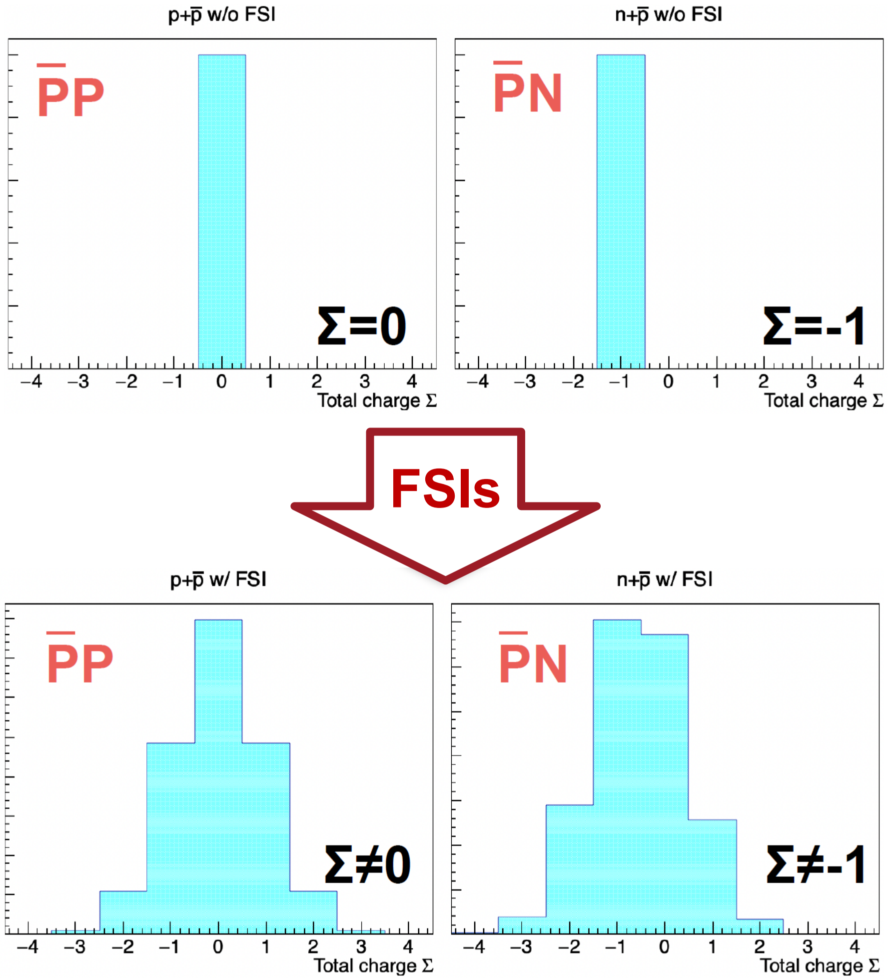
FINAL STATE INTERACTIONS



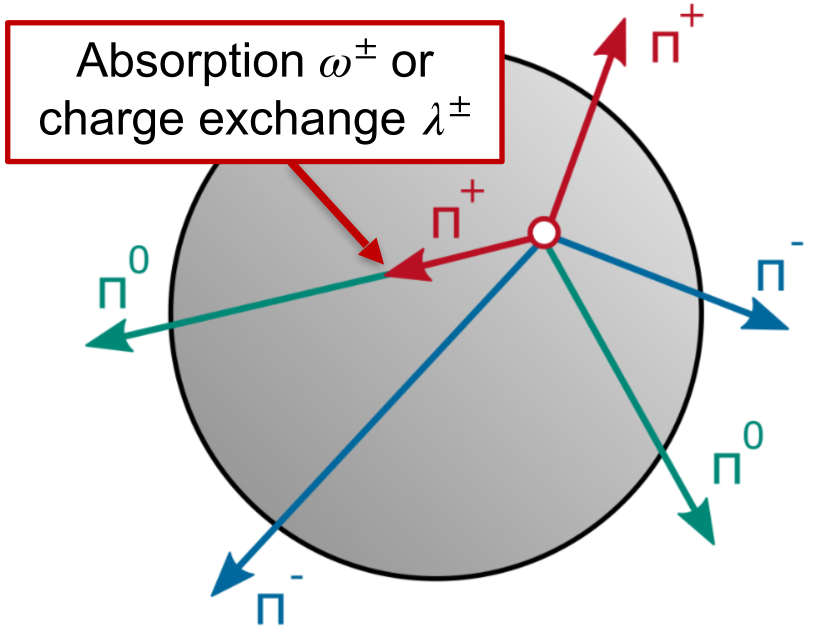
Initial state:
$(\pi^+,\pi^-,\pi^0) = (2,2,1)$
$\Sigma = 0$, $M = 4$

Final state:
$(\pi^+,\pi^-,\pi^0) = (1,2,2)$
$\Sigma = -1$, $M = 3$

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



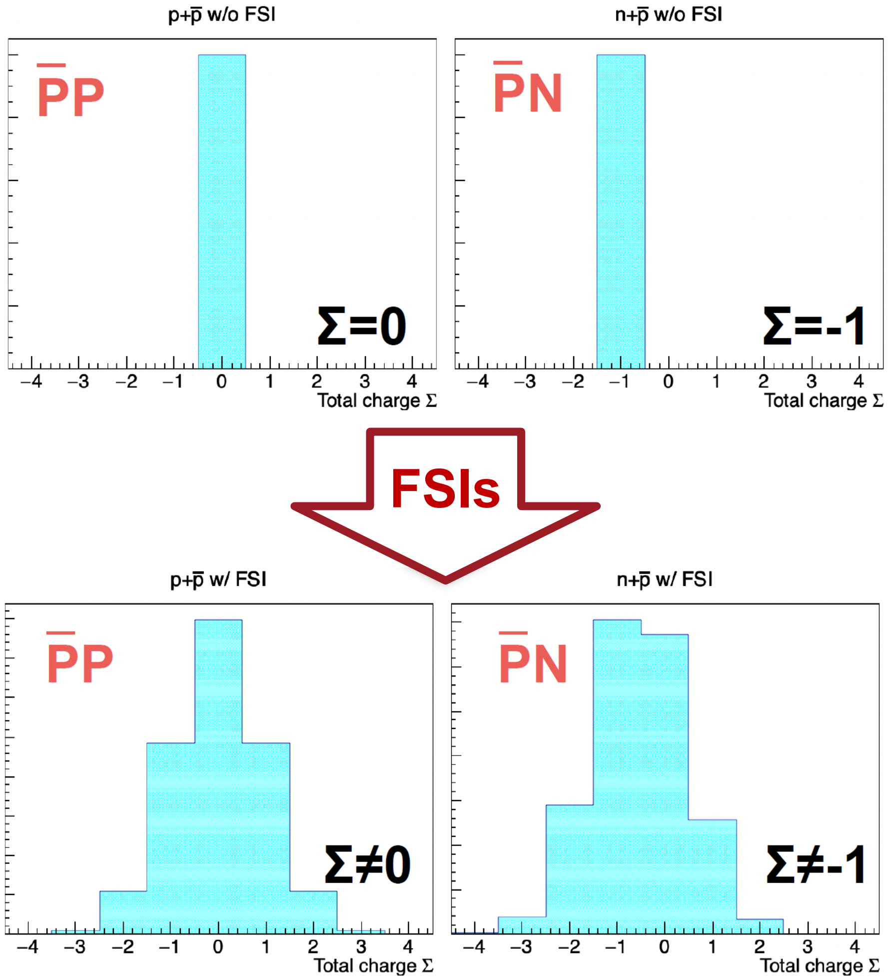
FINAL STATE INTERACTIONS



Initial state:
$(\pi^+, \pi^-, \pi^0) = (2,2,1)$
$\Sigma = 0$, M = 4

Final state:
$(\pi^+, \pi^-, \pi^0) = (1,2,2)$
$\Sigma = -1$, M = 3

Y. Kubota et al., in preparation (2023)



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 $\frac{N_n}{N_p}$

TECHNISCHE UNIVERSITÄT DARMSTADT

HOW TO DEAL WITH FSI

- Neural-Network-Approach:
  feed M-Σ matrix as input data for statistical analysis

$M \backslash \Sigma$	-5	-4	-3	-2	-1	0	$+1$	$+2$	$+3$	$+4$
0	0	0	0	0	0	1384	0	0	0	0
1	0	0	0	0	2696	0	4079	0	0	0
2	0	0	0	1403	0	18331	0	2188	0	0
3	0	0	284	0	12946	0	13783	0	280	0
4	0	27	0	2993	0	23029	0	2035	0	18
5	2	0	313	0	6414	0	4189	0	111	0
6	0	21	0	634	0	2116	0	232	0	3
7	0	0	20	0	312	0	142	0	5	0
8	0	0	0	3	0	4	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0

Example for simulation-based training data (INCL)

Benchmark tests on realistic intranuclear cascade model simulation:
- precision of ~ 93% reached

- Output: FSI coefficients for absorption and charge exchange & $\frac{N_n}{N_p}$