THE PUMA EXPERIMENT

Motivation, objectives, and current status of the apparatus

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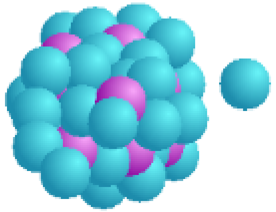
59th International Winter Meeting on Nuclear Physics | 23 – 27 Jan 2023, Bormio, Italy

24.01.2023

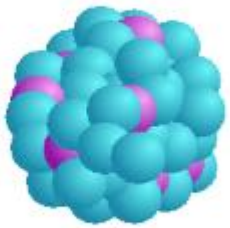
Halos and Neutron Skins

Halo Nucleus



- Core nucleus orbited by weakly-bound neutrons or protons
- $\rho_{n/p}(r)$ extends far from expected r_{nucl}, e.g. Halo ^{11}Li has $\sim r_{nucl}$ as ^{208}Pb
- QM: nucleons tunnel through the nucleus' potential barrier

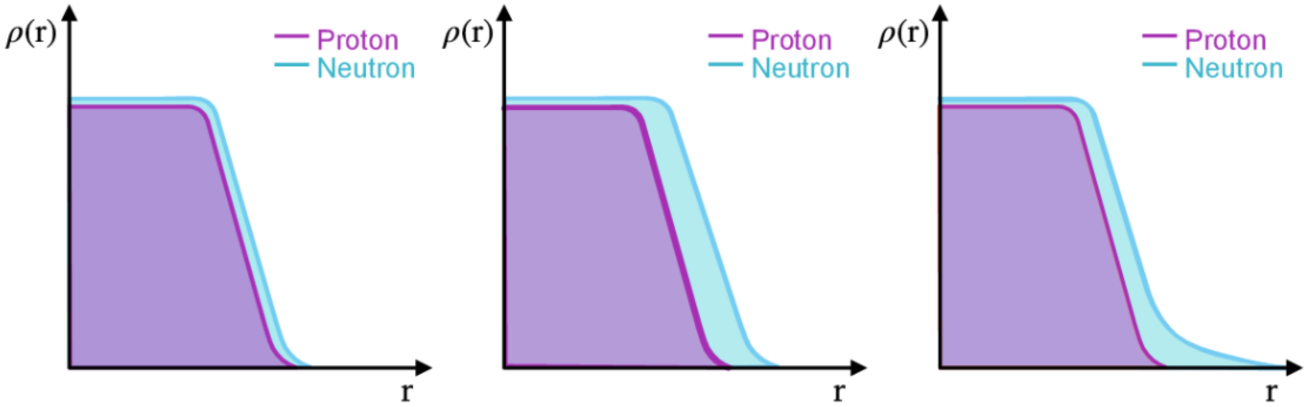
Neutron Skin



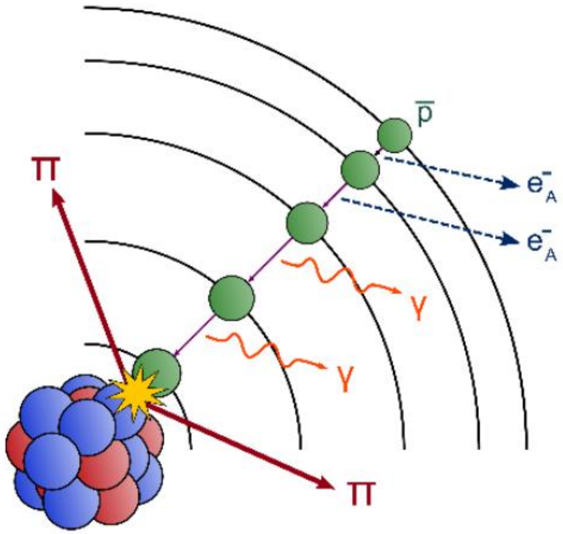
- $\rho_n(r)$ exceeds $\rho_p(r)$ significantly on the surface
- Characterized by thickness: $\Delta r_{np} \sim 0.2 fm$ for ^{208}Pb

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

- shell closures, possibly low-density pure neutron matter



antiProton Unstable Matter Annihilation (PUMA)



- $\bar{p}$: probe for surface of nuclear structure

- $\bar{p}$ captured in excited antiprotonic orbital & annihilate in tail $\rho_{n/p}(r)$

- Conservation of total charge & energy
  → carried by final-state pions

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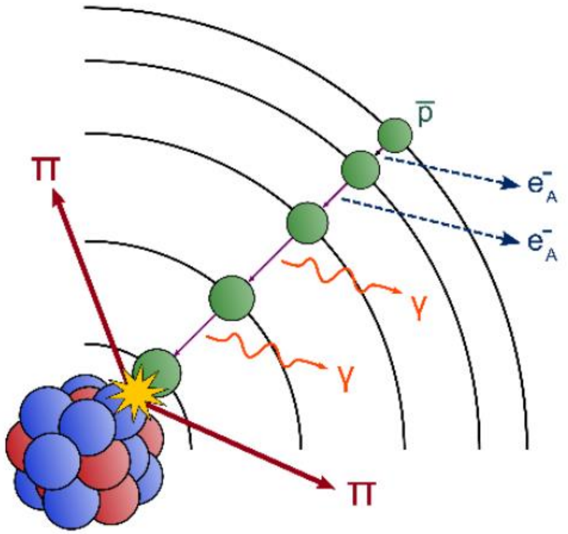

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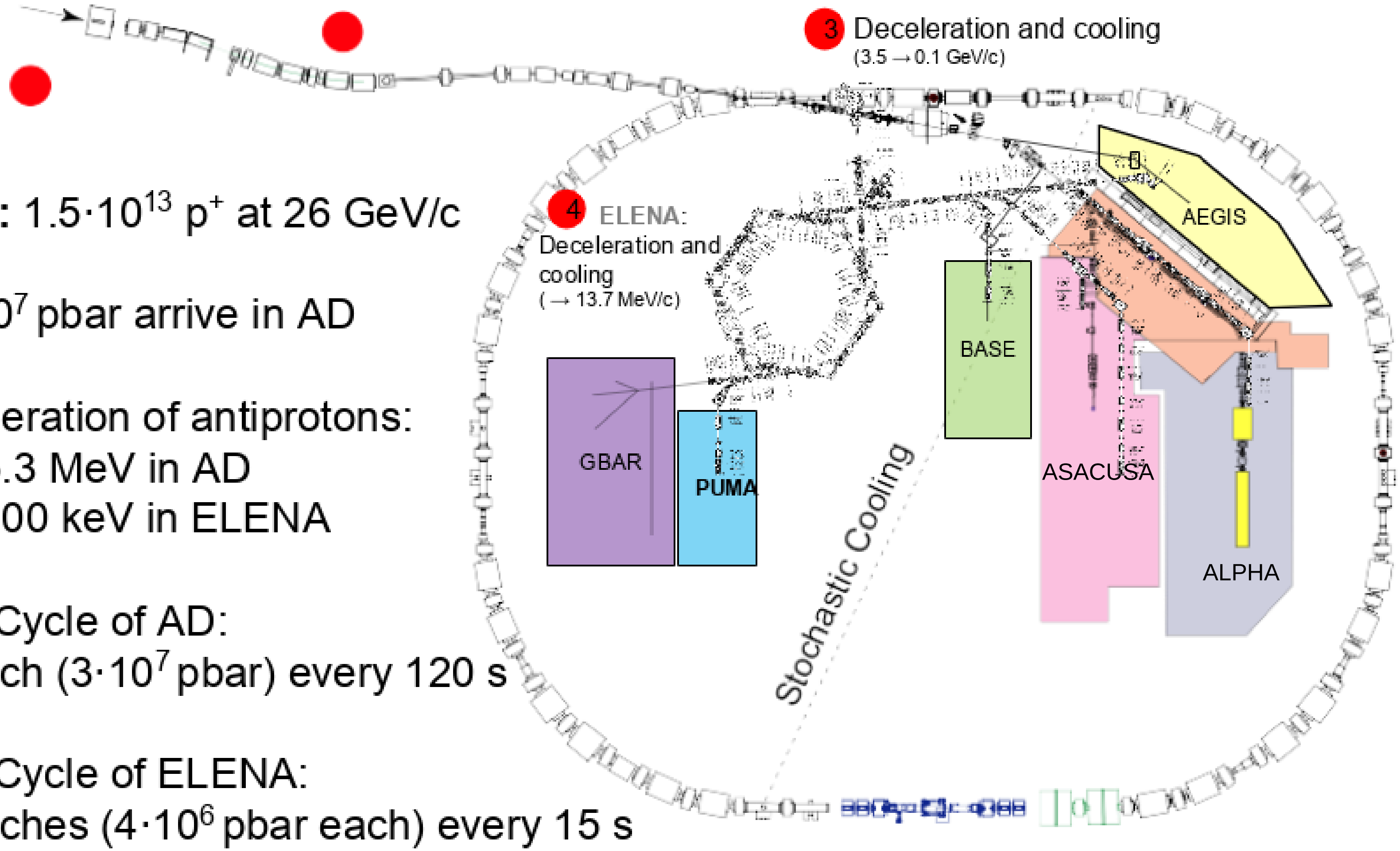
antiproton-proton		antiproton-neutron	
Pion final state	Branching	Pion final state	Branching
$\pi^0\pi^0$	0.00028	$\pi^-\pi^0$	0.0075
$\pi^0\pi^0\pi^0$	0.0076	$\pi^- k\pi^0 (k > 1)$	0.169
$\pi^0\pi^0\pi^0\pi^0$	0.03	$\pi^-\pi^-\pi^+$	0.0023
$\pi^+\pi^-$	0.0032	$\pi^-\pi^-\pi^+\pi^0$	0.17
$\pi^+\pi^-\pi^0$	0.069	$\pi^-\pi^-\pi^+ k\pi^0 (k > 1)$	0.397
$\pi^+\pi^-\pi^0\pi^0$	0.093	$\pi^-\pi^-\pi^-\pi^+\pi^+$	0.042
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233	$\pi^-\pi^-\pi^-\pi^+\pi^+\pi^0$	0.12
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028	$\pi^-\pi^-\pi^-\pi^+\pi^+ k\pi^0 (k > 1)$	0.066
$\pi^+\pi^-\pi^+\pi^-$	0.069	$\pi^-\pi^-\pi^-\pi^-\pi^+\pi^+\pi^+ k\pi^0 (k \geq 0)$	0.0035
$\pi^+\pi^-\pi^+\pi^-\pi^0$	0.196		
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	0.166		
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$	0.042		
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	0.021		
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0$	0.019		

$$\sum_{\pi} q_\pi = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$

➢ $\sum_\pi q_\pi$ of all reactions $\leftrightarrow \frac{N_n}{N_p} \leftrightarrow \frac{\rho_n}{\rho_p}$ (density tail)

Antimatter Decelerator (AD) and Extra Low ENergy Antiproton (ELENA)

- **Input:** $1.5 \cdot 10^{13}$ p^{+} at 26 GeV/c
- ~ $3 \cdot 10^{7}$ pbar arrive in AD
- Deceleration of antiprotons:
  - 5.3 MeV in AD
  - 100 keV in ELENA
- Duty Cycle of AD:
  1 bunch ($3 \cdot 10^{7}$ pbar) every 120 s
- Duty Cycle of ELENA:
  4 bunches ($4 \cdot 10^{6}$ pbar each) every 15 s



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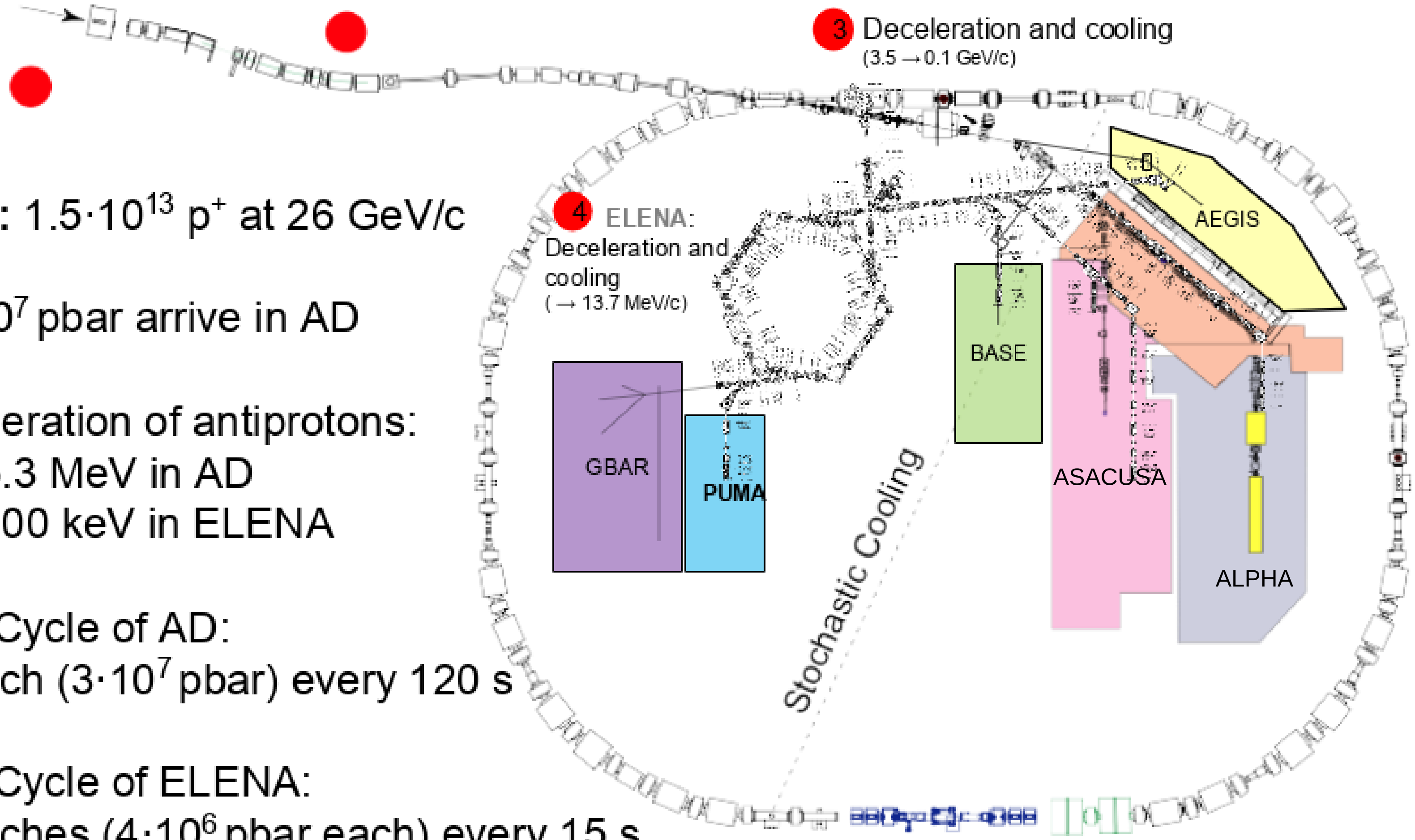
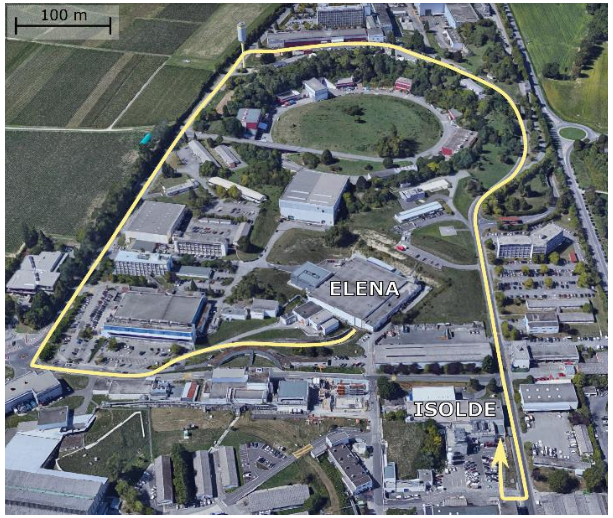


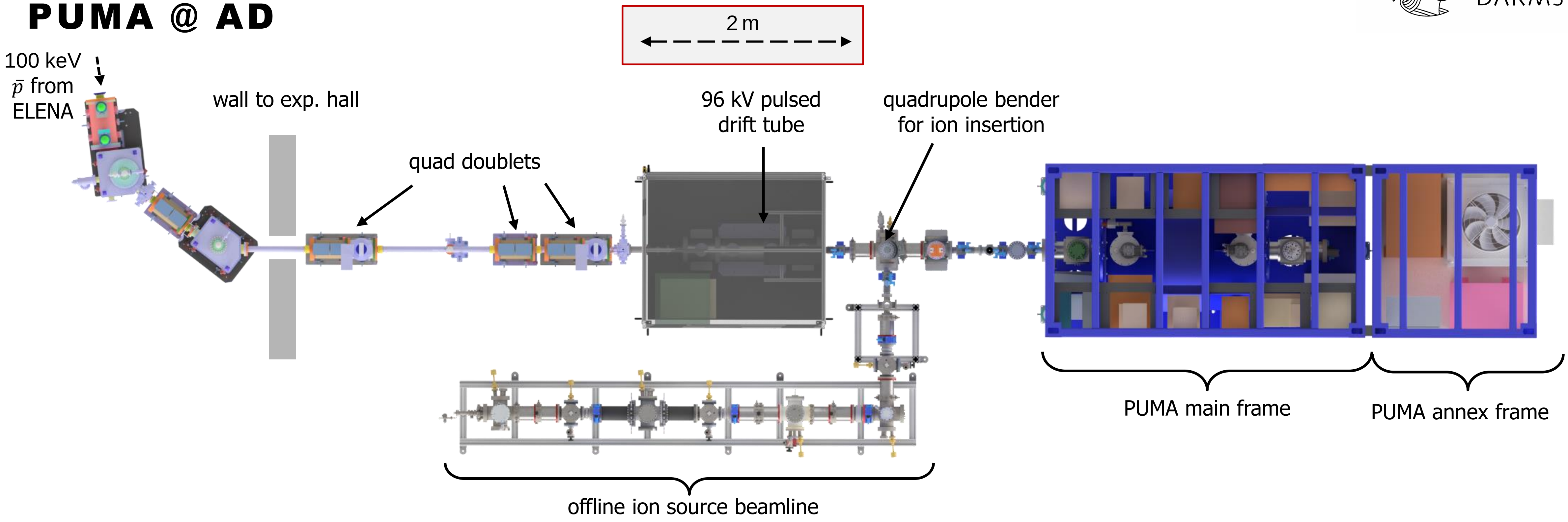


First Physics Cases

- **at AD/ ELENA:** investigation of neutron skin evolution of stable isotopic chains
  - gas ionization source: $^{36\text{-}40}$Ar, $^{128\text{-}132,134,136}$Xe
  - laser ablation source: $^{40\text{-}48}$Ca, $^{110\text{-}126}$Sn, ^{208}Pb
- **at ISOLDE:** investigation of thick skins and halos in unstable nuclei

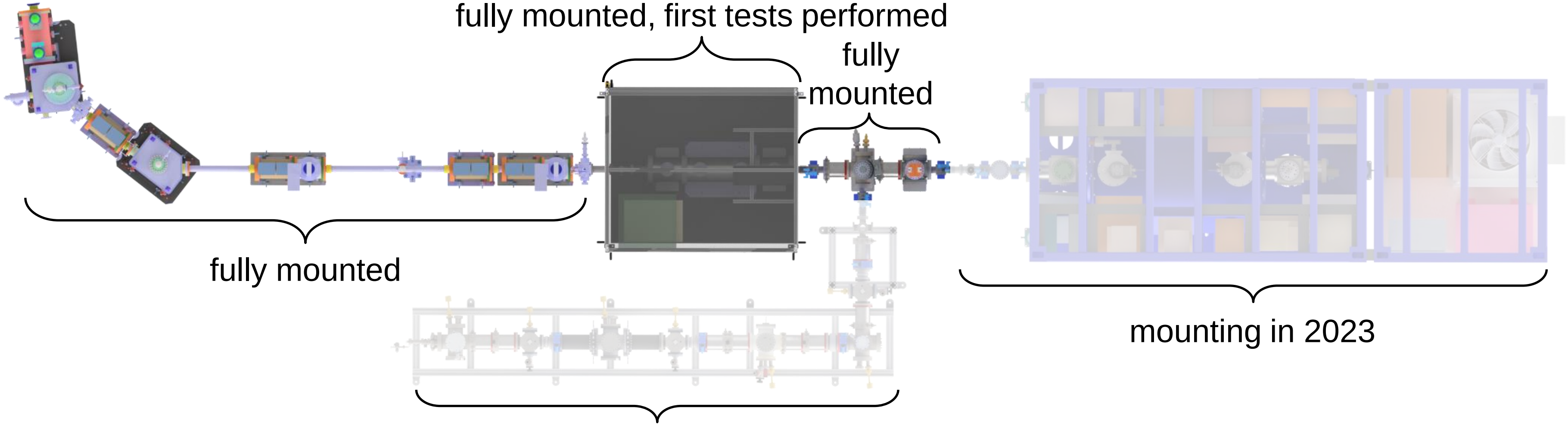
Nucleus	Half-life $T_{1/2}$	Statistics (1 day of beam)	Expected phenomena
^{6}He	807 ms	10^{8}	neutron halo
^{8}He	119 ms	$4{\cdot}10^{7}$	thick neutron skin
^{17}Ne	109 ms	10^{5}	proton halo

PUMA @ AD



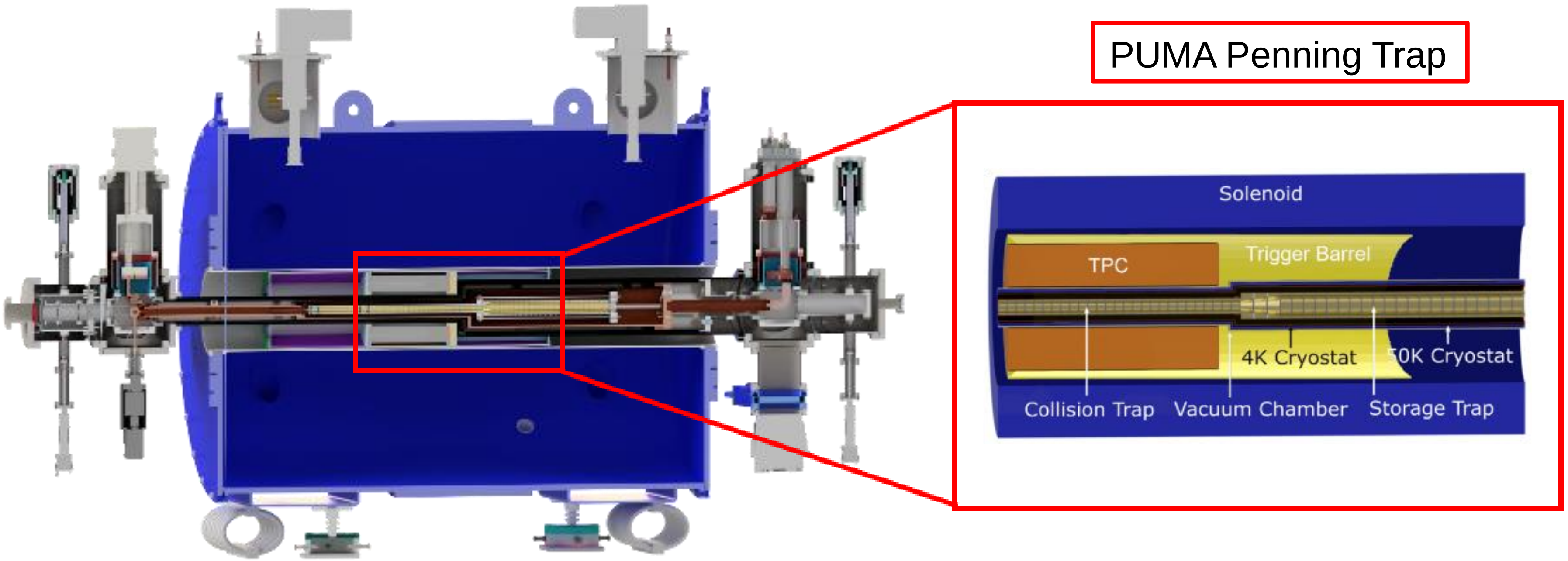
- deceleration of $\bar{p}$ from 100 keV to 4keV by pulsed drift tube (PDT)
- operation cycle: 1 bunch (~ $4{\cdot}10^6$ $\bar{p}$) every 120 s → aiming for 10^9 $\bar{p}$
- mass-separated (MR-ToF) & bunched (RFQ) ions from offline ion source

PUMA @ AD


fully mounted, first tests performed
fully mounted
fully mounted
mounting in 2023
mounting in 2023, currently tests at TUDa

THE PUMA TRAP & VACUUM

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



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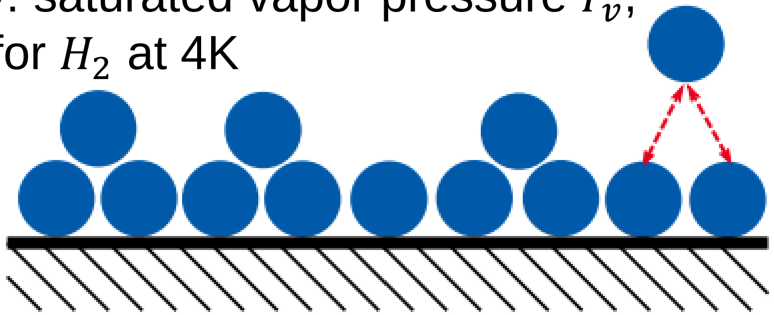
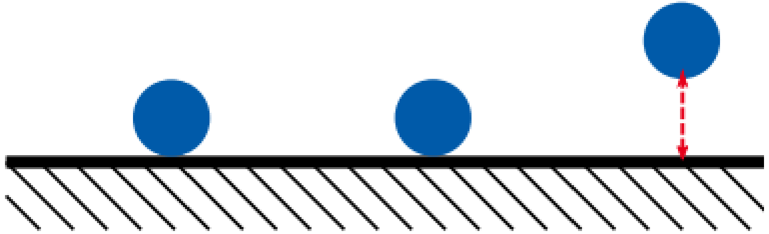
Cryocondensation

- Attraction of similar molecules at low T
  → limited by thermal conductivity of condensate
- Key property: saturated vapor pressure P_v,
  P_v ~$10^{-7} mbar$ for H_2 at 4K



Cryosorption

- Attraction between gas molecules and substrate
- If adsorbed quantity smaller than 1 monolayer:
  $P_H \ll P_v$

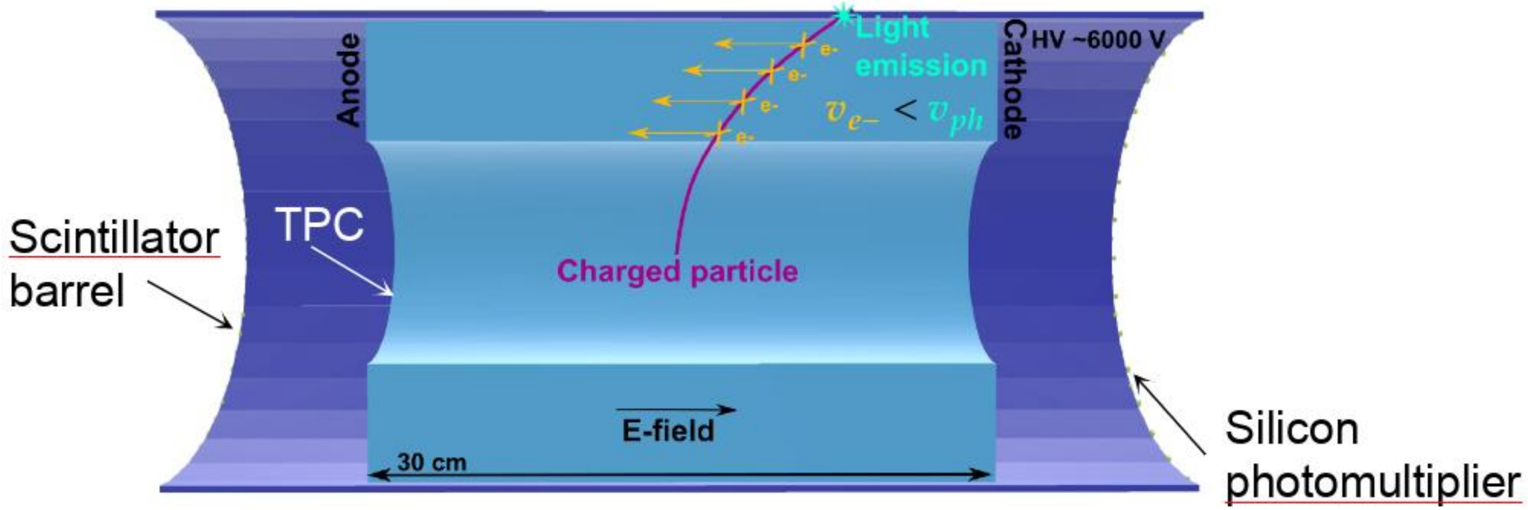


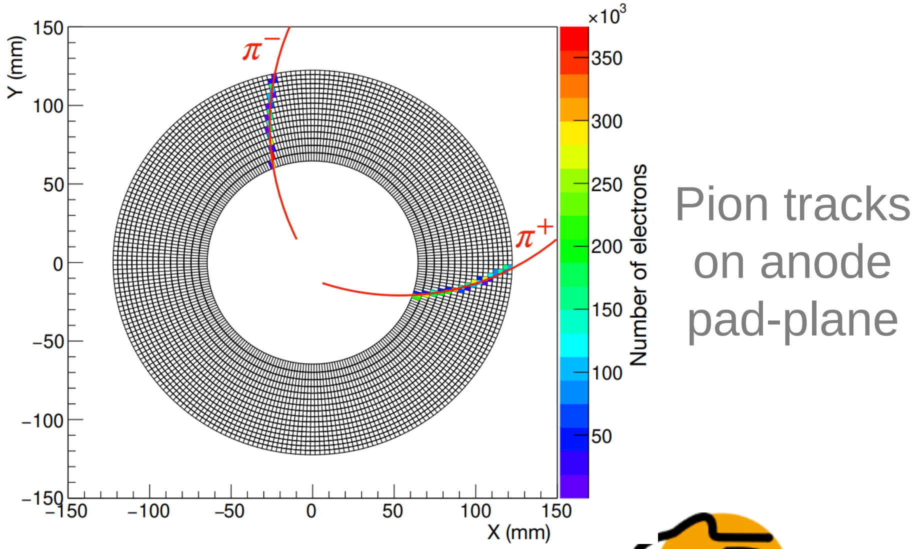
DETECTION SYSTEM

- Time Projection Chamber (TPC) and Trigger Plastic Barrel
  - TPC allows for 2D-pion vertex reconstruction
  - Trigger adds timing information → 3D-track
- Currently designed at CERN, first tests 2023

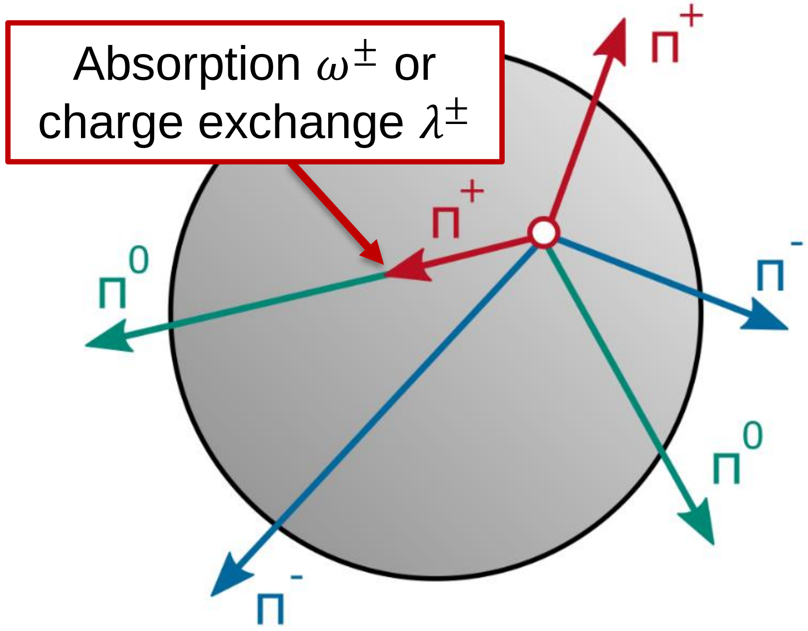
Requirements:

- Reliability (long term without maintenance).
- >60% detection efficiency.
- Resolution 400 μm.
- E field = 200 V/cm (ie: Cathode @ -6kV).
- Field uniformity.
- Minimization of sparks and microsparks.

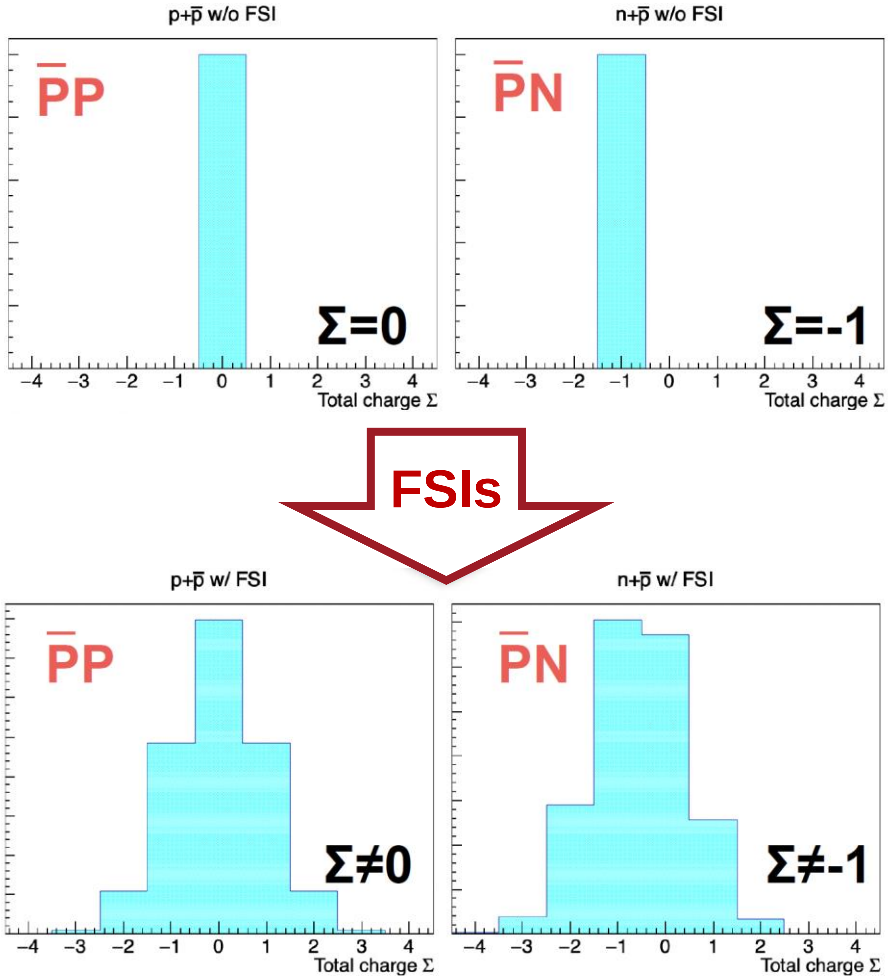




FINAL STATE INTERACTIONS



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



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

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

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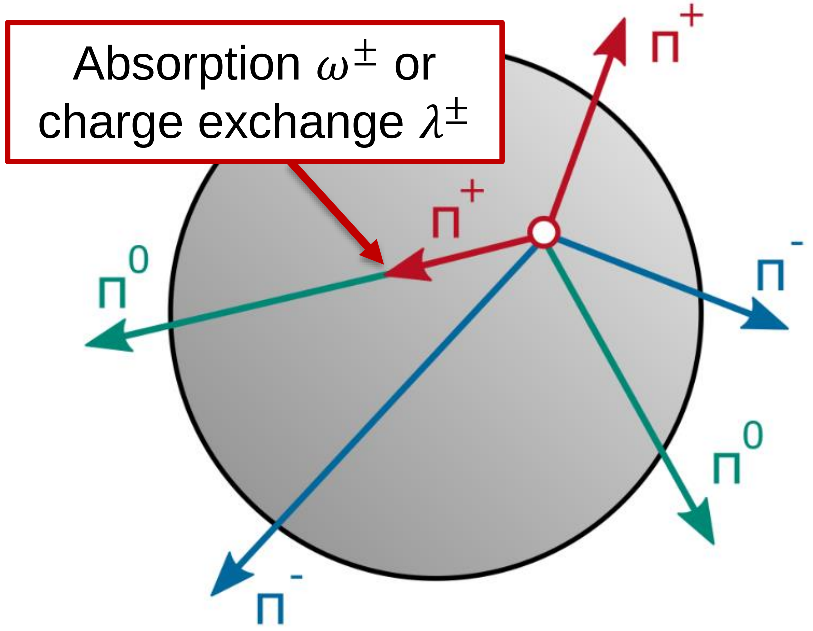

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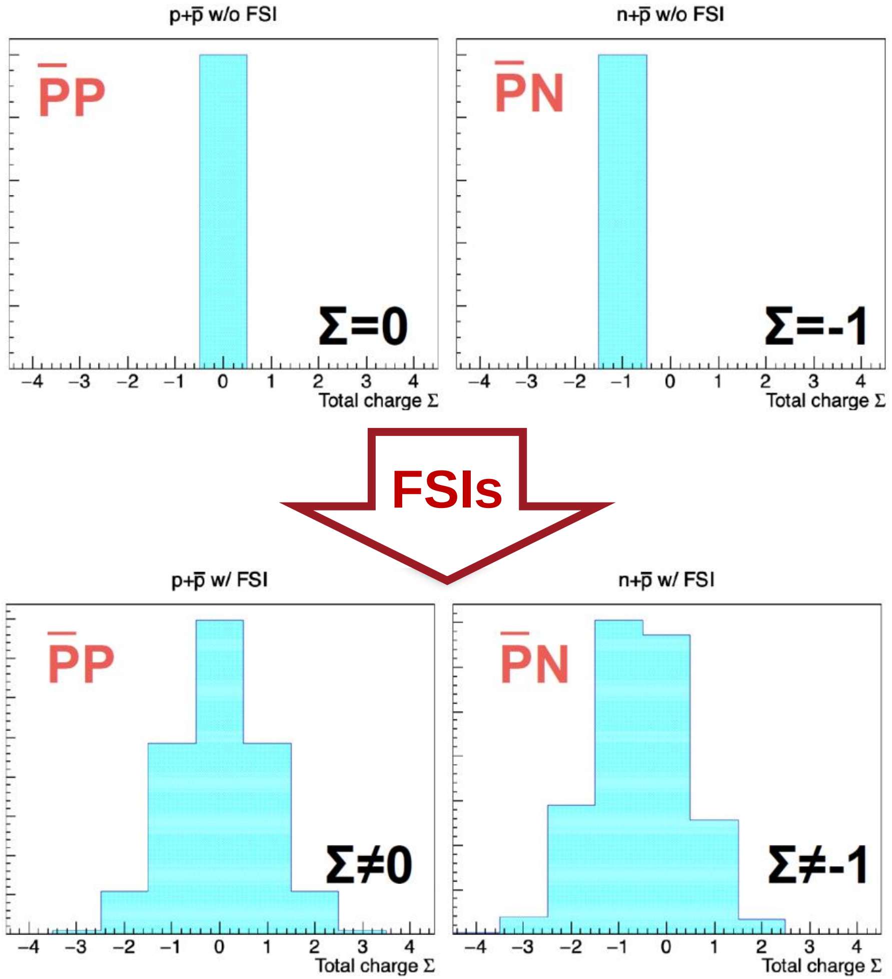


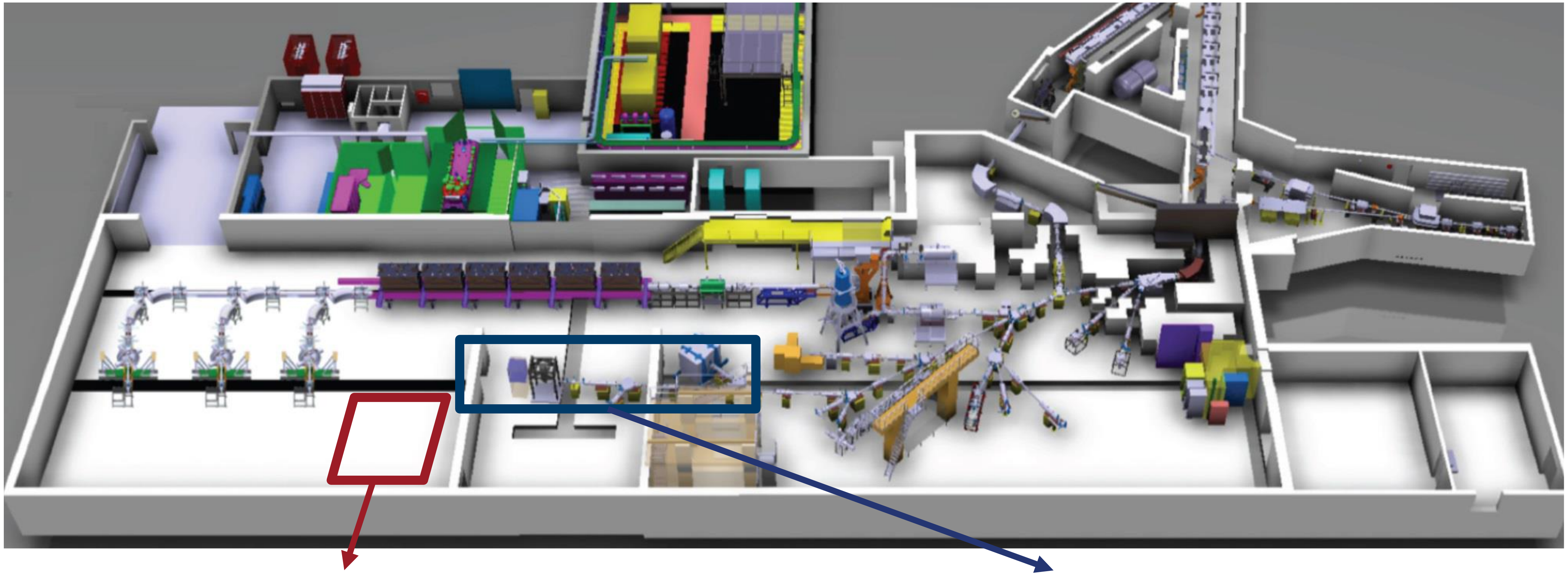
Event-by-Event analysis not possible

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

Main limitation for detection sensitivity:
Simulations: 10% in $\frac{N_n}{N_p}$

PUMA @ ISOLDE

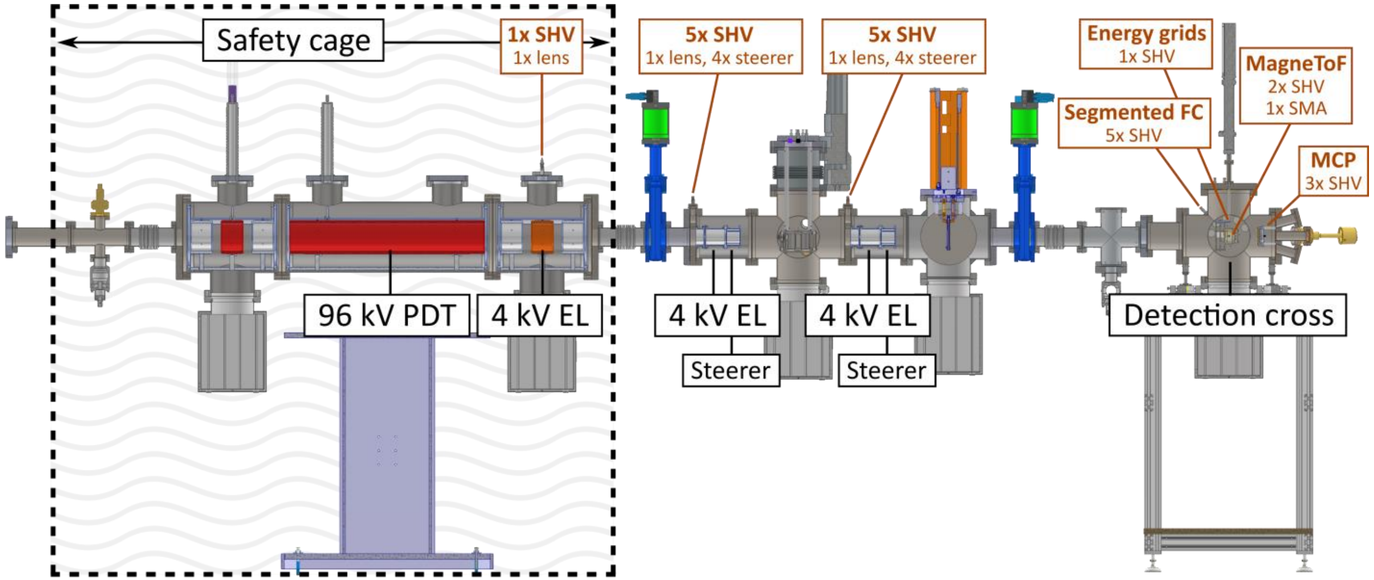
Beamline under design, first experiments foreseen in 2024

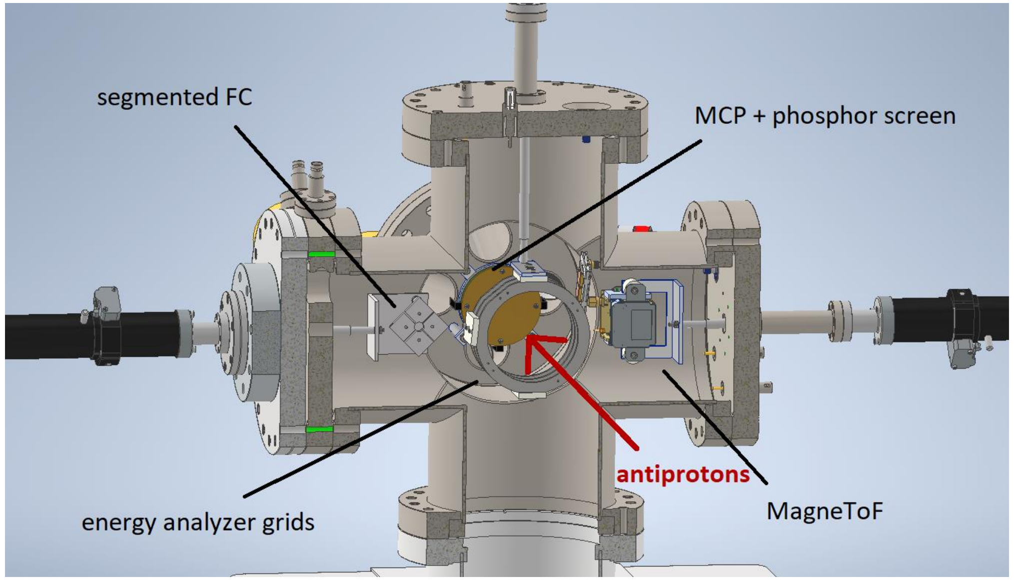


PUMA experimental zone
XHV (10^{-11} mbar)

low-energy 4keV beamline
isotopic selection (MR-ToF) and bunching (RfQ)
UHV (10^{-8} mbar)

DECELERATION OF ANTIPROTONS TO 4KEV IN NOV. 2022





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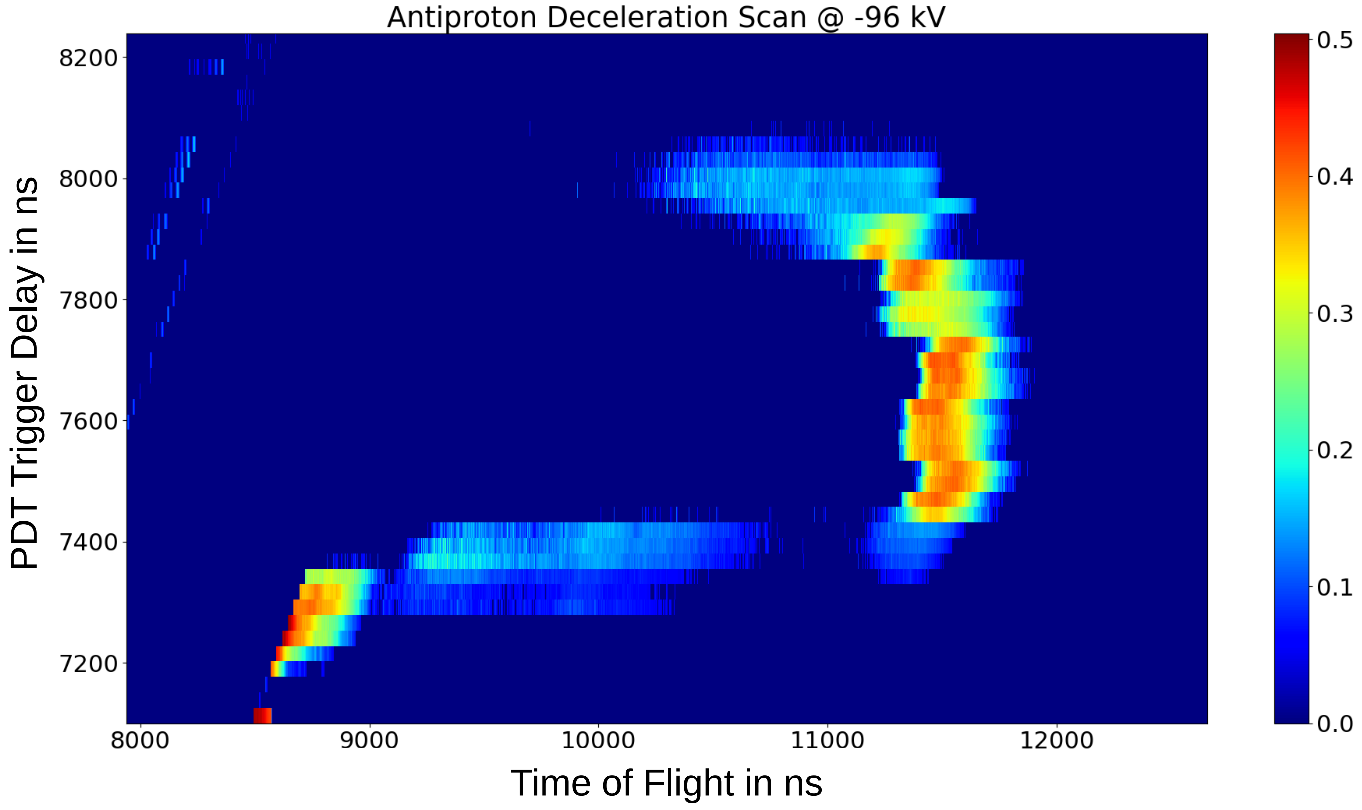
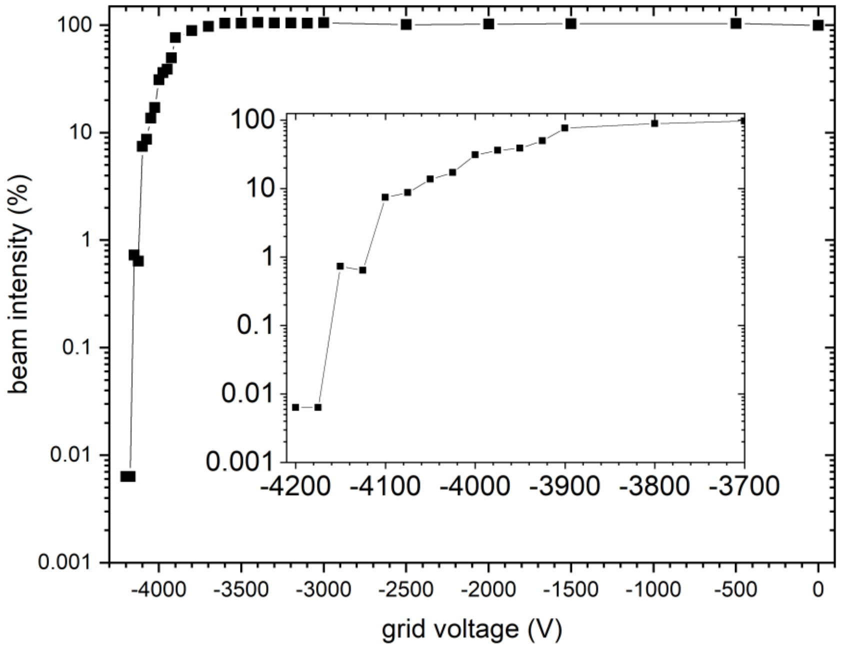




successful deceleration from 100 keV to 4 keV & first $\bar{p}$ in the PUMA experimental zone

SUMMARY & OUTLOOK

- **PUMA** is a new experiment at CERN accepted in 2021
- It aimes 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 in November 2022: **operation of 96kV PDT confirmed**
- First experiments at ELENA in 2023, first low-energy RIB experiments at ISOLDE in 2024

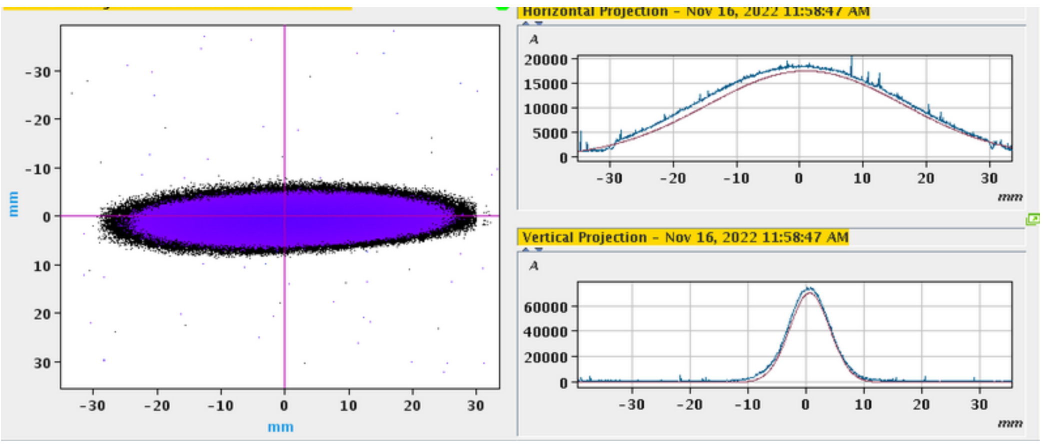
THE PUMA COLLABORATION

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
With contribution from B. Loeher, GSI

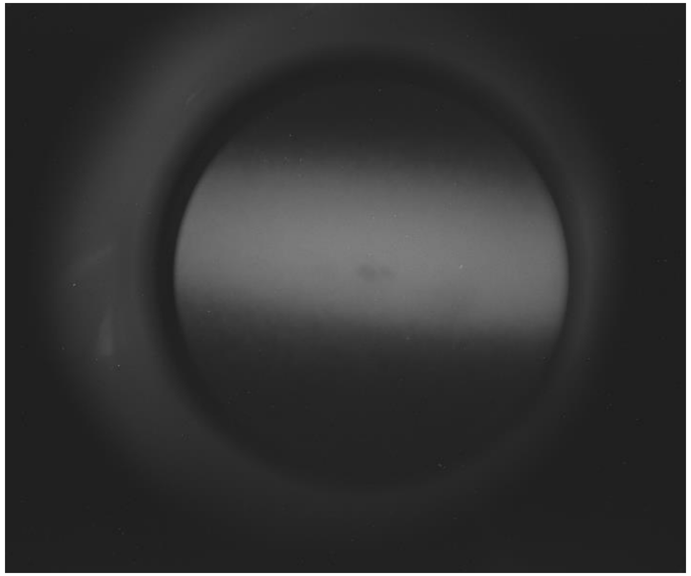
TECHNISCHE UNIVERSITÄT DARMSTADT | CERN | IJCLab Irène Joliot-Curie | LKB | IPHC | TRIUMF | Alexander von Humboldt Stiftung/Foundation | erc

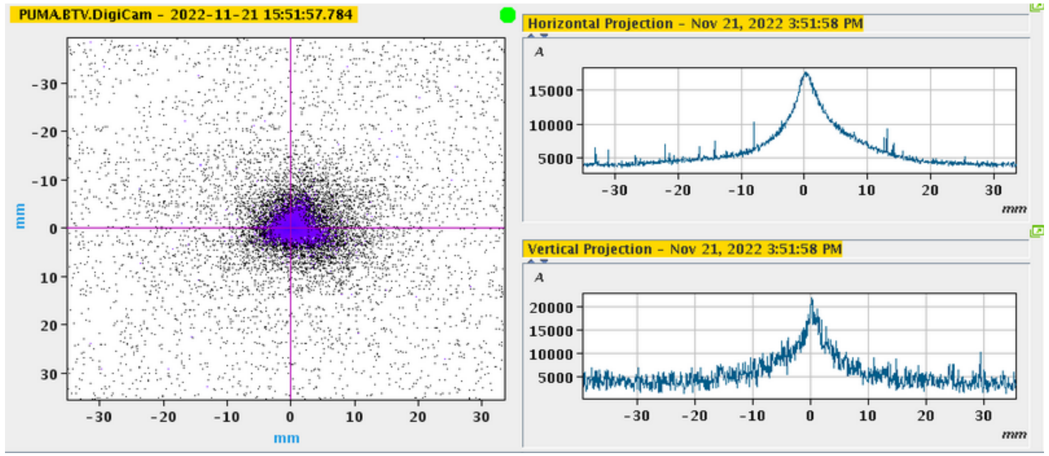
This work has been sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA)

SOME PICTURES OF PBAR BUNCHES

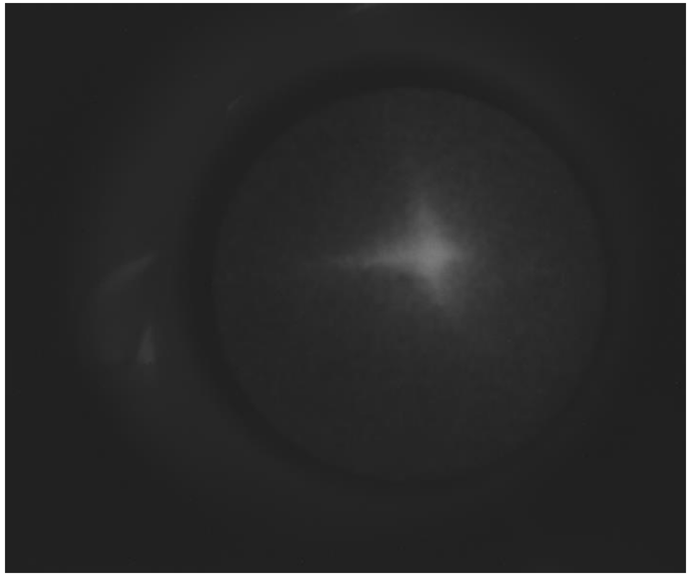


100 keV





4 keV



HOW TO DEAL WITH FSI

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

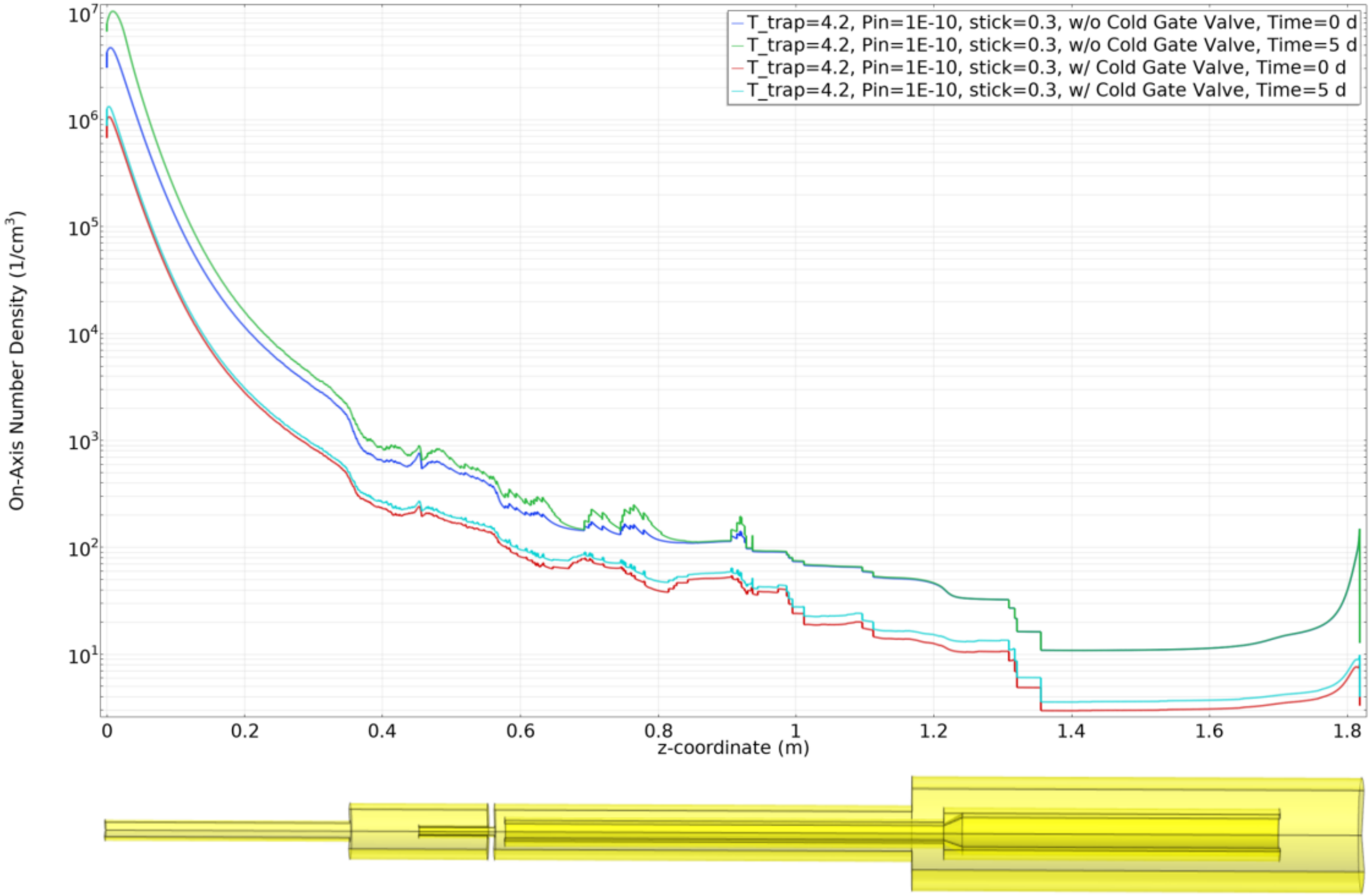
$M \setminus \Sigma$	-5	-4	-3	-2	-1	0	$+1$	$+2$	$+3$	$+4$
0	0	0	0	0	0	1384	0	0	0	0
1	0	0	0	0	2696	0	4079	0	0	0
2	0	0	0	1403	0	18331	0	2188	0	0
3	0	0	284	0	12946	0	13783	0	280	0
4	0	27	0	2993	0	23029	0	2035	0	18
5	2	0	313	0	6414	0	4189	0	111	0
6	0	21	0	634	0	2116	0	232	0	3
7	0	0	20	0	312	0	142	0	5	0
8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

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

VACUUM SIMULATIONS

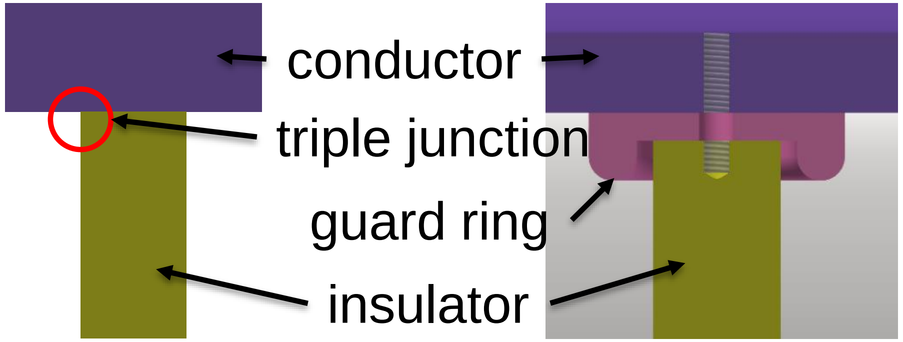
Desired: $P_H < 10^{-16} mbar$ resp. $n_{gas} = 20\ cm^{-3}$



100 KV IS A LOT

challenges

- good vacuum, < 10^{-10} mbar
- personal safety
- electrical safety
- fast switching times, ~ 100 ns
- RC circuit, $\tau = RC$



ansatz

- NEG, aluminium, Macor
- safety cage, interlock
- no edges, triple junctions
- MOSFET switch
- low resistance, high current

Best advice from GBAR: **Slow rising of voltage before switching prevents sparking**