CERN-INTC-2024-055 ; INTC-P-712
77th INTC, 12.11.2024

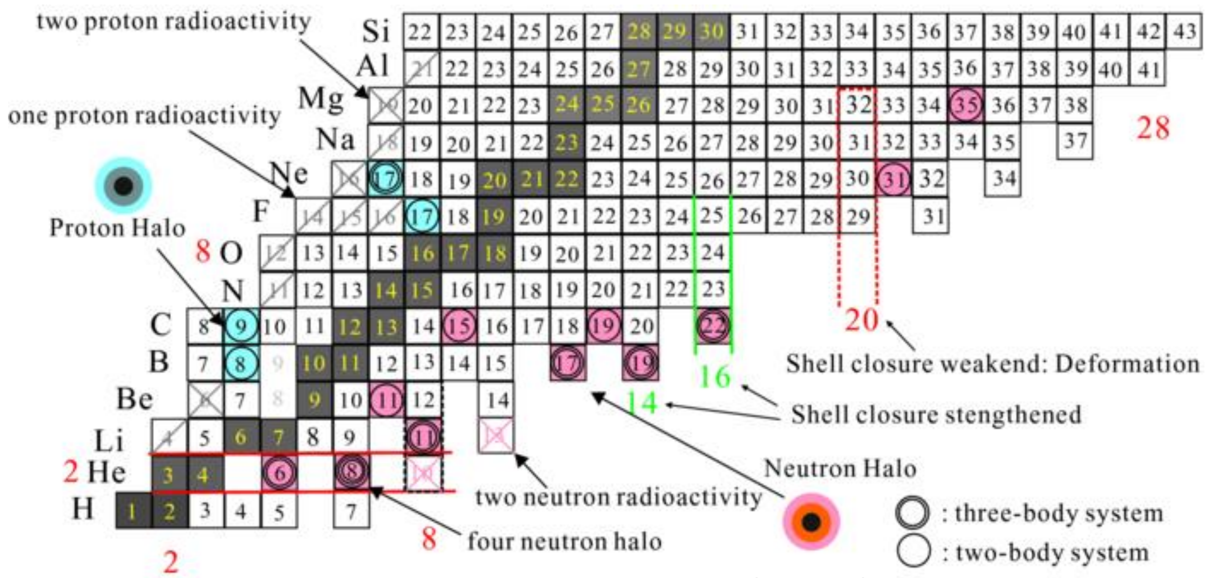
The first PUMA Experiment

Investigation of the nucleon distribution on the surface of unstable xenon isotopes

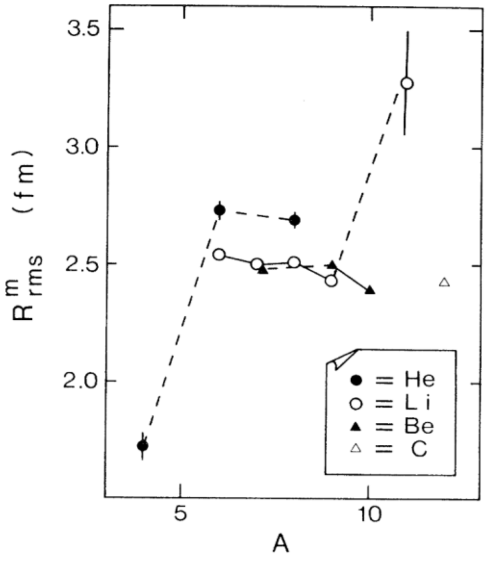
Lukas Nies[1] **and Frank Wienholtz**[2] ***for the PUMA Collaboration***
[1]CERN, Switzerland
[2]TU Darmstadt, Germany

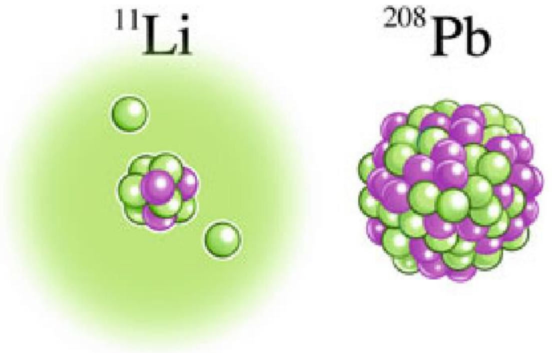
Nucleon Skins and Halos

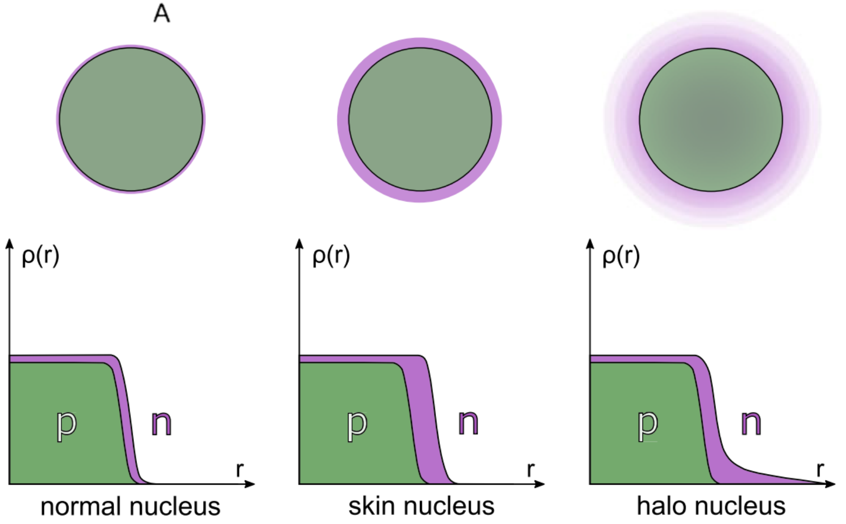
I. Tanihata et al., PRL **55**, 2676 (1985)
A. Obertelli, H. Sagawa, Mod. Nucl. Phys. (2021)



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 $\rho_N(r)$

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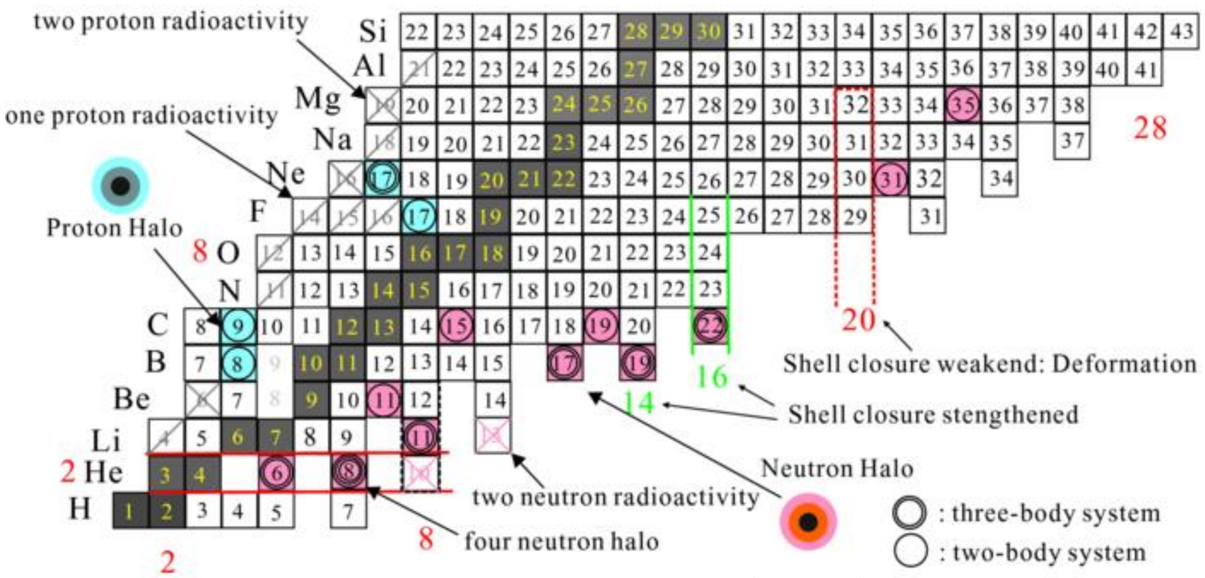

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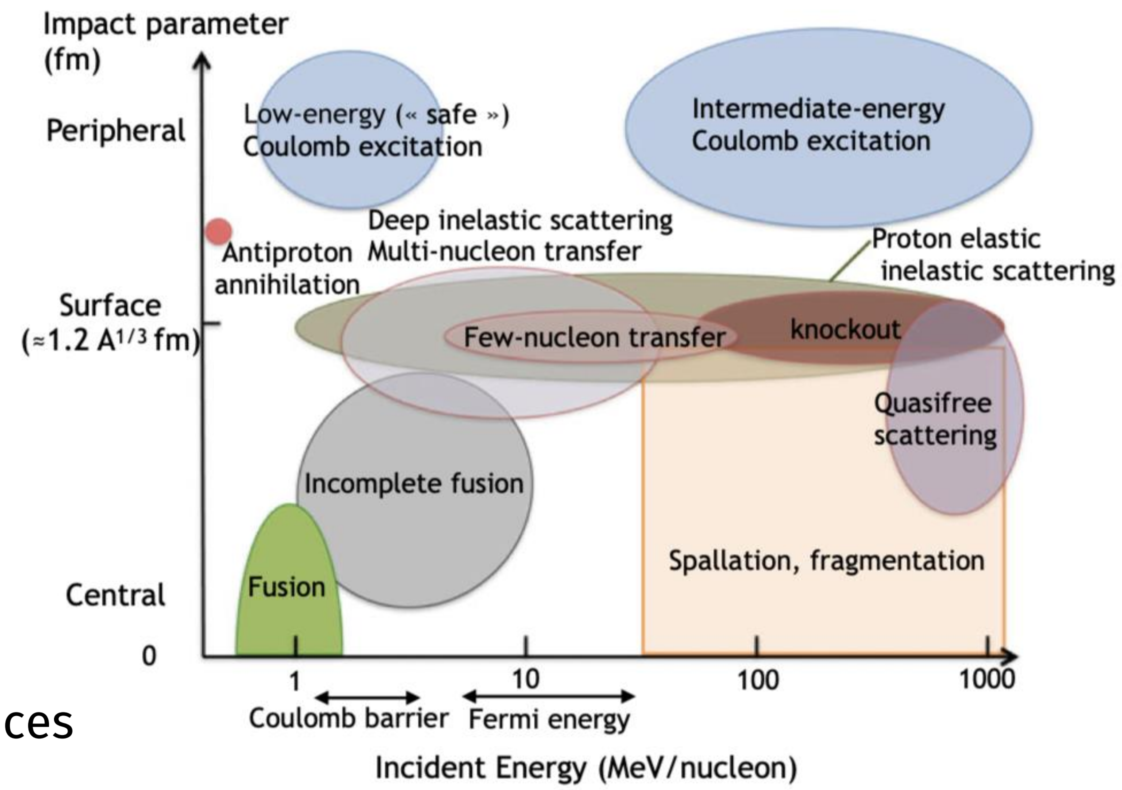


- Exotic nuclei can exhibit **halo structure** and **neutron skins**
- Reflects in neutron and proton densities: $\rho_Z(r)$ and $\rho_N(r)$
- Has so far only been probed at high energies or large distances

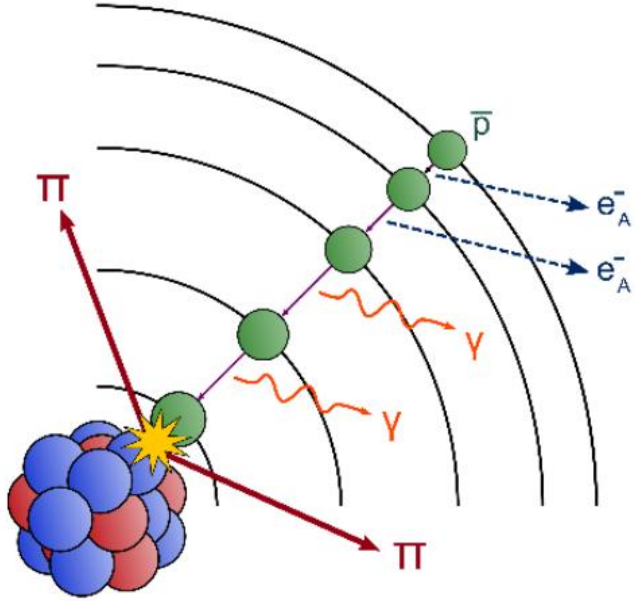
➔ Requires technique that:

- probes **tail** of matter distribution
- probes **neutron fraction**
- is **applicable to unstable nuclei**

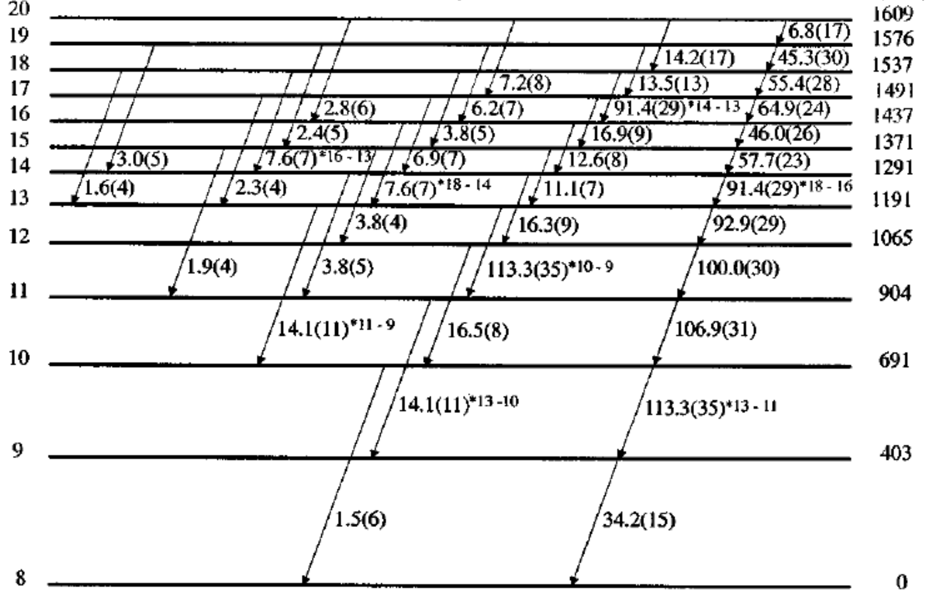
antiProton Unstable Matter Annihilation (PUMA)

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

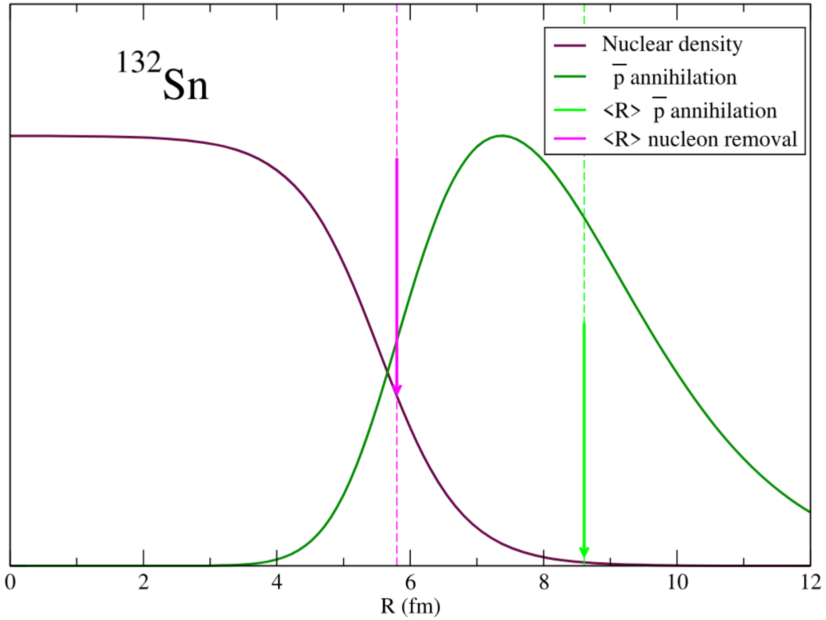


R. Schmidt et al., Phys. Rev. C 58, 3195



LEAR at CERN

T. Aumann et al., Eur. Phys. J. A (2022) 58 :88



Slide by C. Klink (BE-EA)

antiProton Unstable Matter Annihilation (PUMA)

Technique: Low-energy antiprotons as a probe

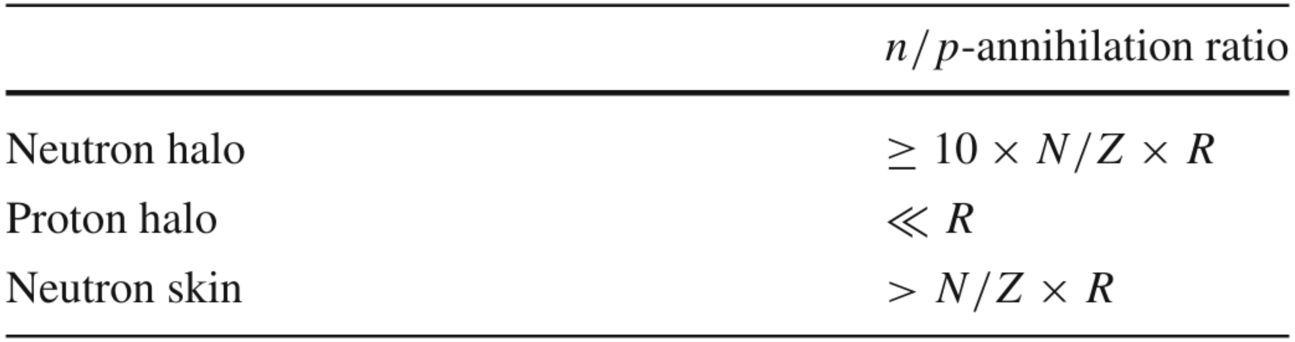
- First application of method by Bugg et al., PRL **31,** 475 (1973) at BNL, USA
- New observable: proton-to-neutron annihilation ratio *R,* related to Halo factor
- Application to RIBs first proposed by Wada and Yamasaki, NIM B **214** (2004) 196-200

… but never applied!

<u>PUMA aims to:</u>

1. Provide **new nuclear observable *R***
2. Characterize **nuclear density tails** (skins, halos, …)
3. Find **new p and n halos**
4. Understand <u>**development of n-skins**</u>

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

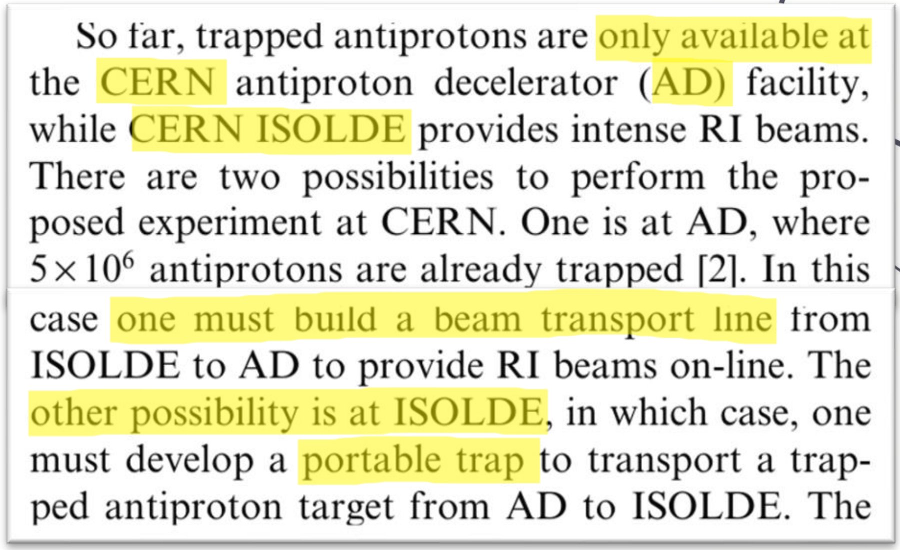


	n/p-annihilation ratio
Neutron halo	$\geq 10\times N/Z\times R$
Proton halo	$\ll R$
Neutron skin	$> N/Z\times R$

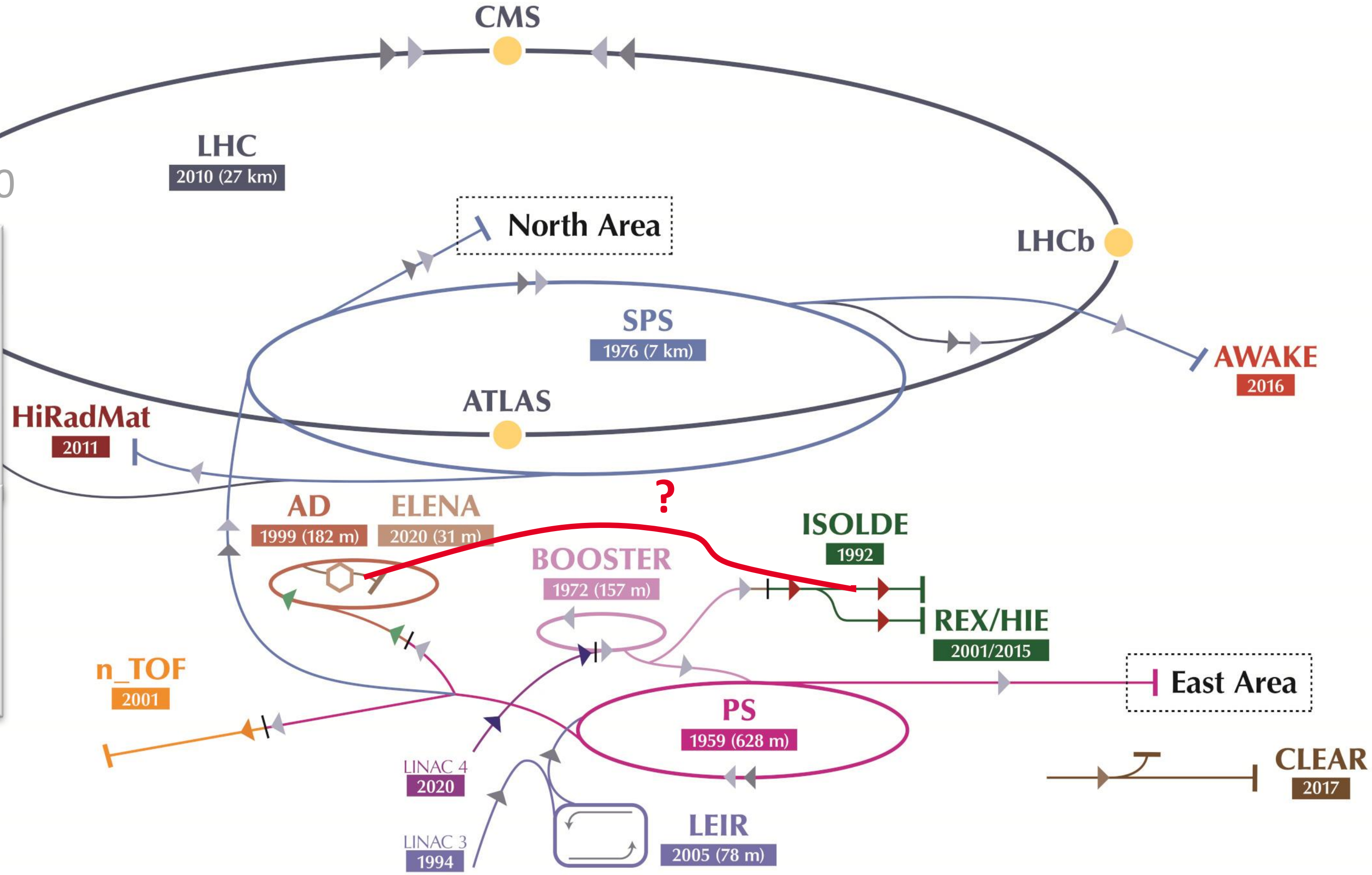
T. Aumann et al., Eur. Phys. J. A (2022) 58 :88

Where to find p̄ and unstable matter?

Wada and Yamazaki, NIM B 214 (2004) 196-200



So far, trapped antiprotons are only available at the CERN antiproton decelerator (AD) facility, while CERN ISOLDE provides intense RI beams. There are two possibilities to perform the proposed experiment at CERN. One is at AD, where 5×10^6 antiprotons are already trapped [2]. In this case one must build a beam transport line from ISOLDE to AD to provide RI beams on-line. The other possibility is at ISOLDE, in which case, one must develop a portable trap to transport a trapped antiproton target from AD to ISOLDE. The



Where to find $\bar{p}$ and unstable matter?

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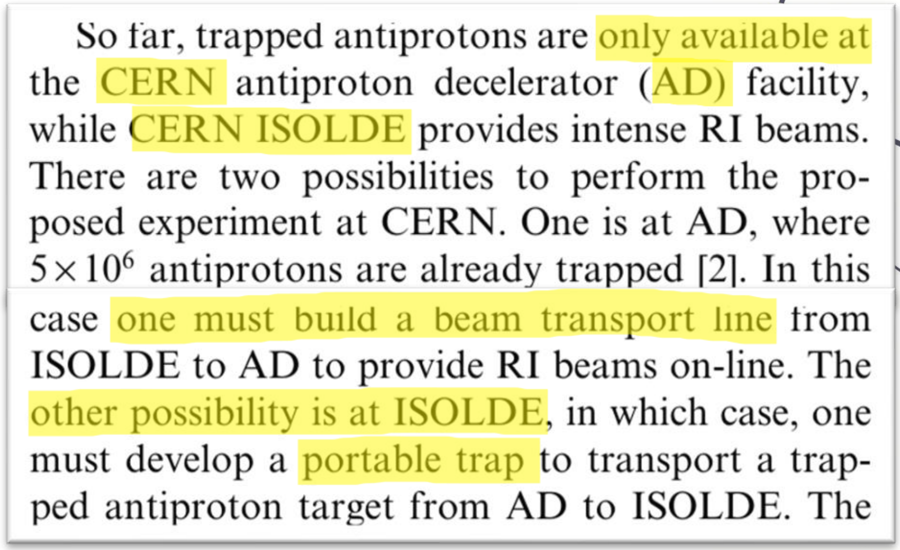

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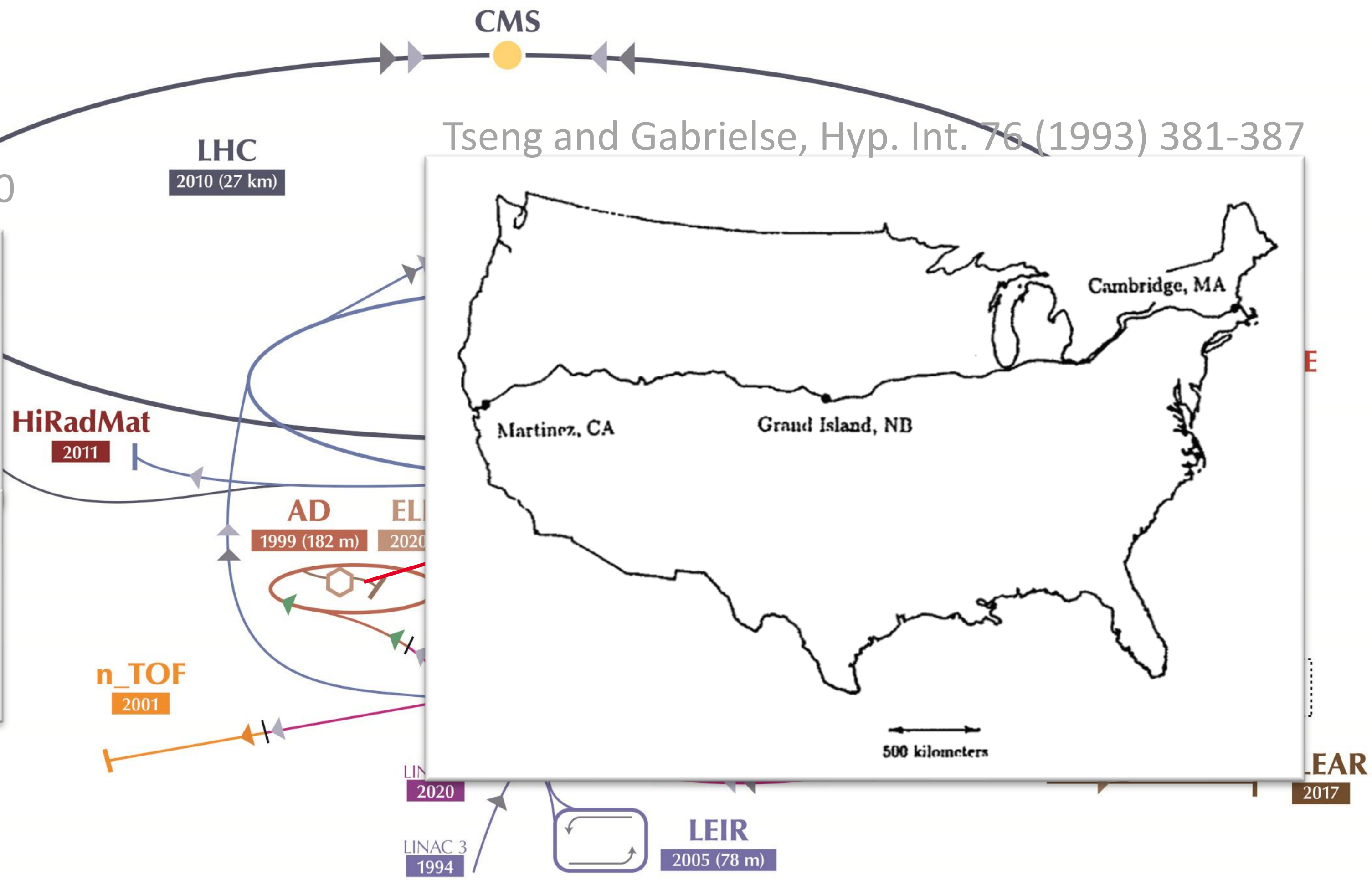
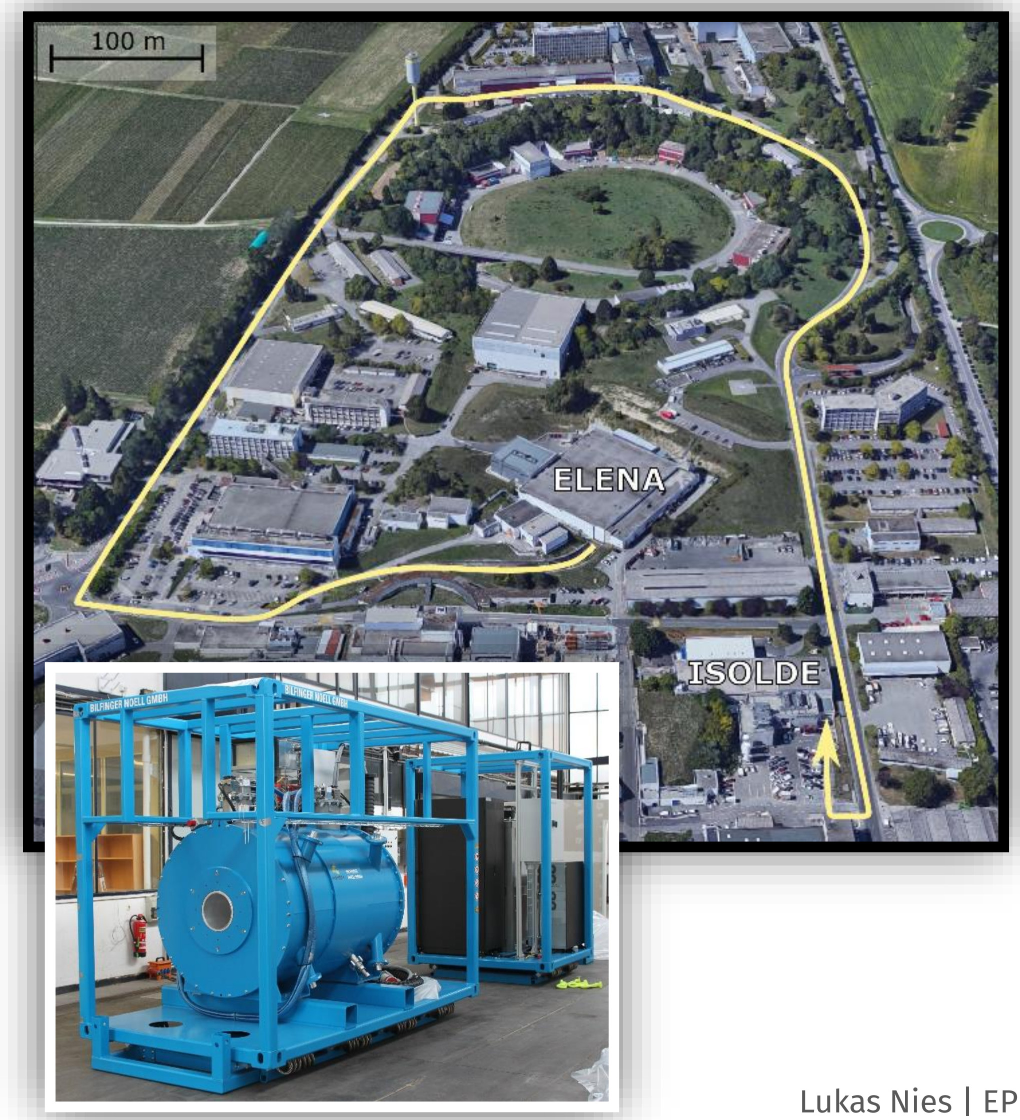


Tseng and Gabrielse, Hyp. Int. 76 (1993) 381-387

Transporting Antiprotons from AD to ISOLDE



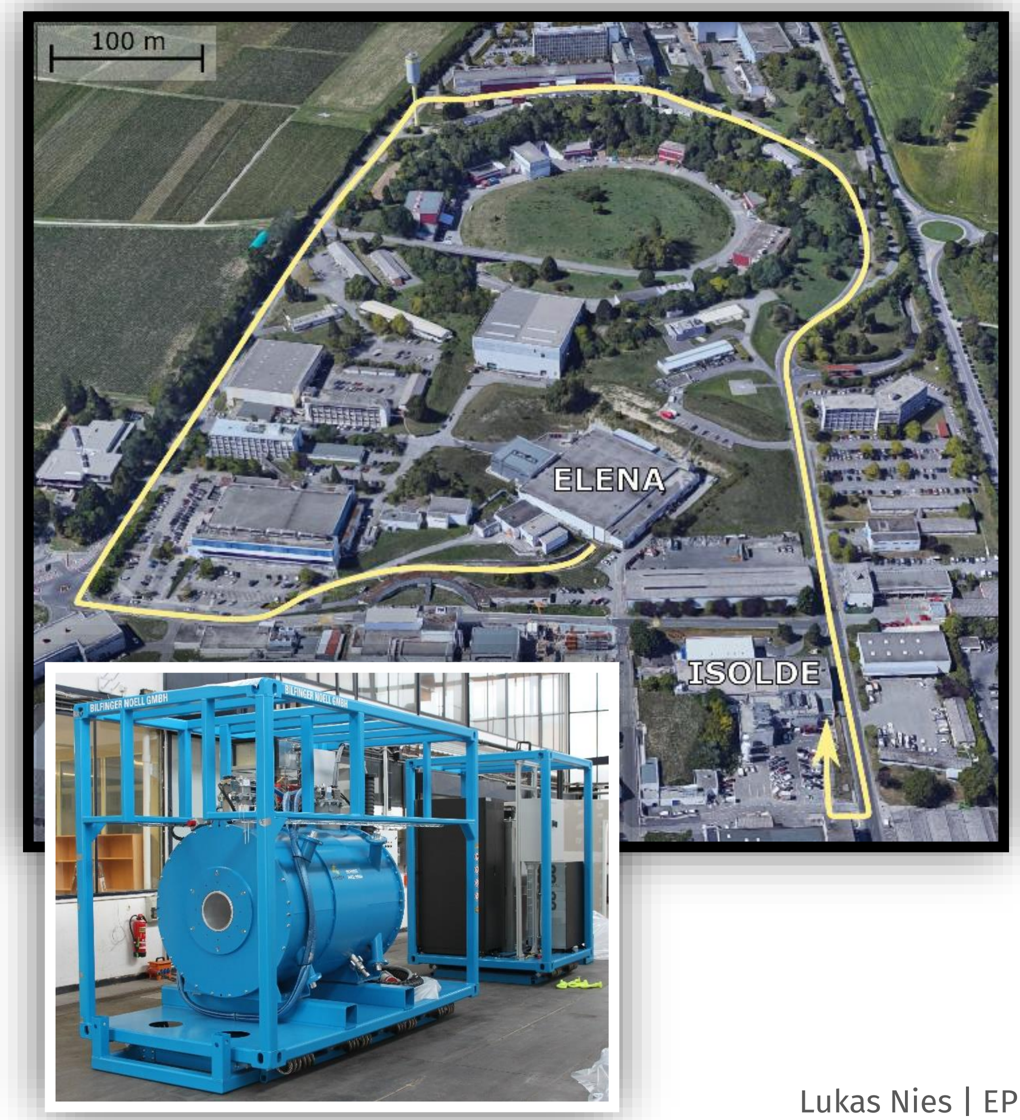
Slide by C. Klink (BE-EA)

- There is no connecting beam line between the 2 facilities
- Requirements:
  - → a **transportable ion trap** with sufficient storage capabilities (eventually up to 10^9 $\bar{p}$)
  - → **XHV vacuum conditions** for the storage of antiprotons
  - → a **detection system** for monitoring annihilation rates during the transport
  - → a very soft, slow transport

Good news:

- Long antiproton trapping time already achieved.
  Ex. BASE: > 400 days (S. Sellner et al., New J. Phys. 19 083023, 2017)
- Transportation of antiprotons is also a core component of BASE-STEP (PI: C. Smorra, Mainz, Rev. Sci. Instrum. 94, 113201 (2023))

Transporting Antiprotons from AD to ISOLDE



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Good news:

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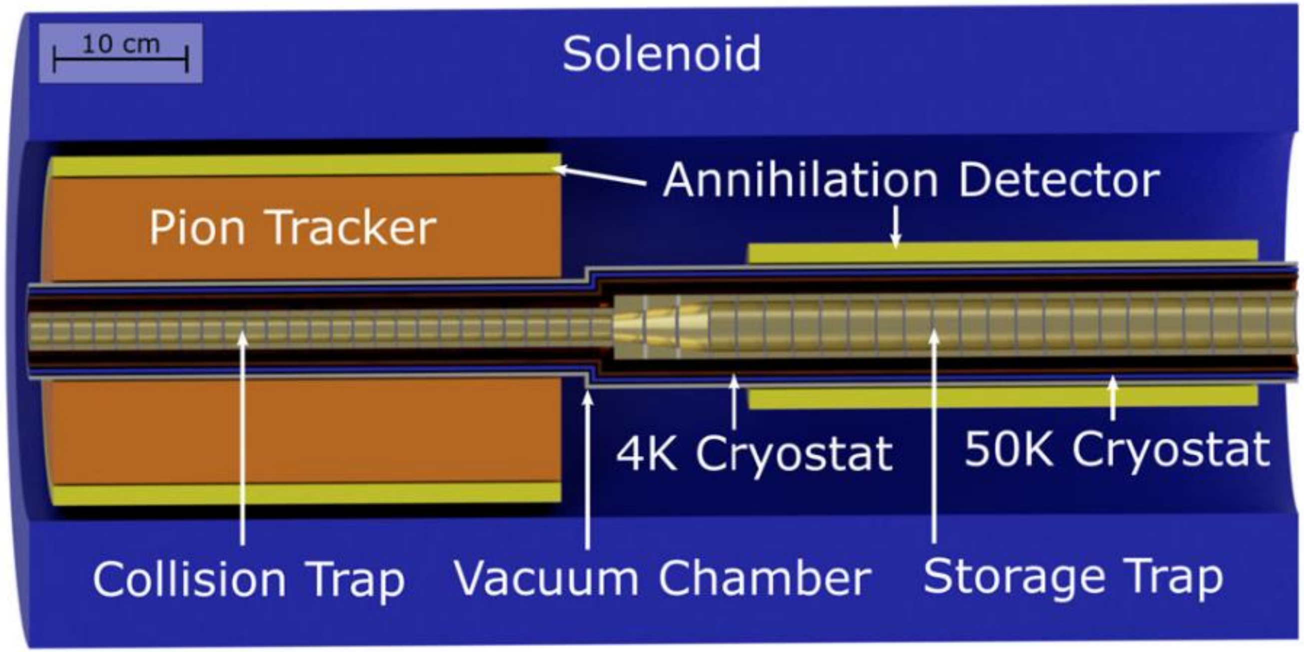
  Ex. BASE: > 400 days (S. 083023, 2017)
- Transportation of antiprot BASE-STEP (PI: C. Smorra, 113201 (2023))

CERN Courier October 2024

The transportable trap being carefully loaded in the truck before going for a road trip across CERN's main site. (Image: CERN)

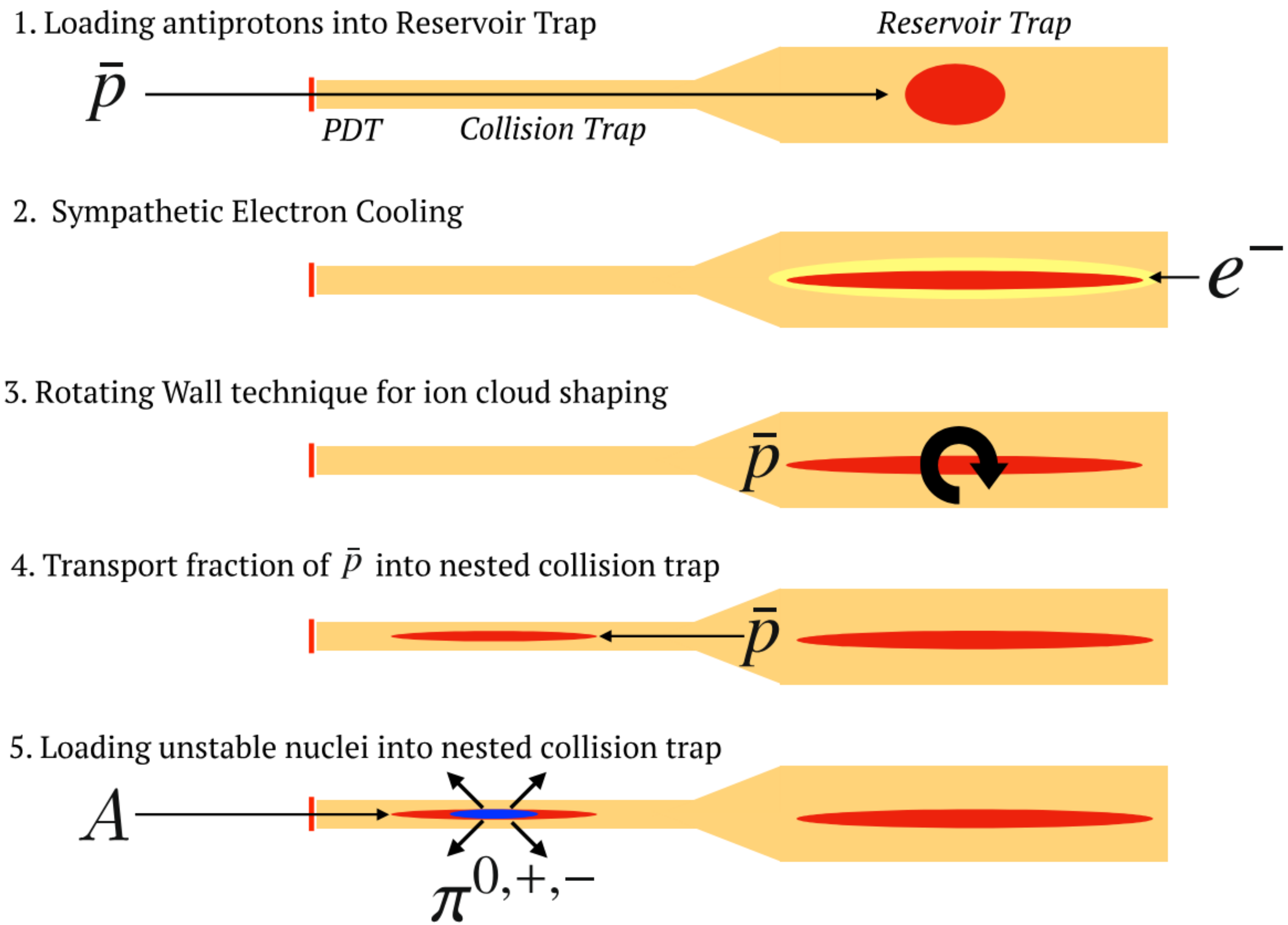
Slide by C. Klink (BE-EA)

The PUMA Magnet and Penning Traps



- **4T NbTi** superconducting magnet (Bilfiniger Noell)
- Cryogen-free design: **1750kg cold mass**, cool-down time 25 days for 4K
- Quench would increase equilibrium temperature by 40K
- $\bar{p}$ plasma confined in **Penning traps**
- Ring electrodes made from OFE copper with silver and gold plating

Mixing Matter and Antimatter

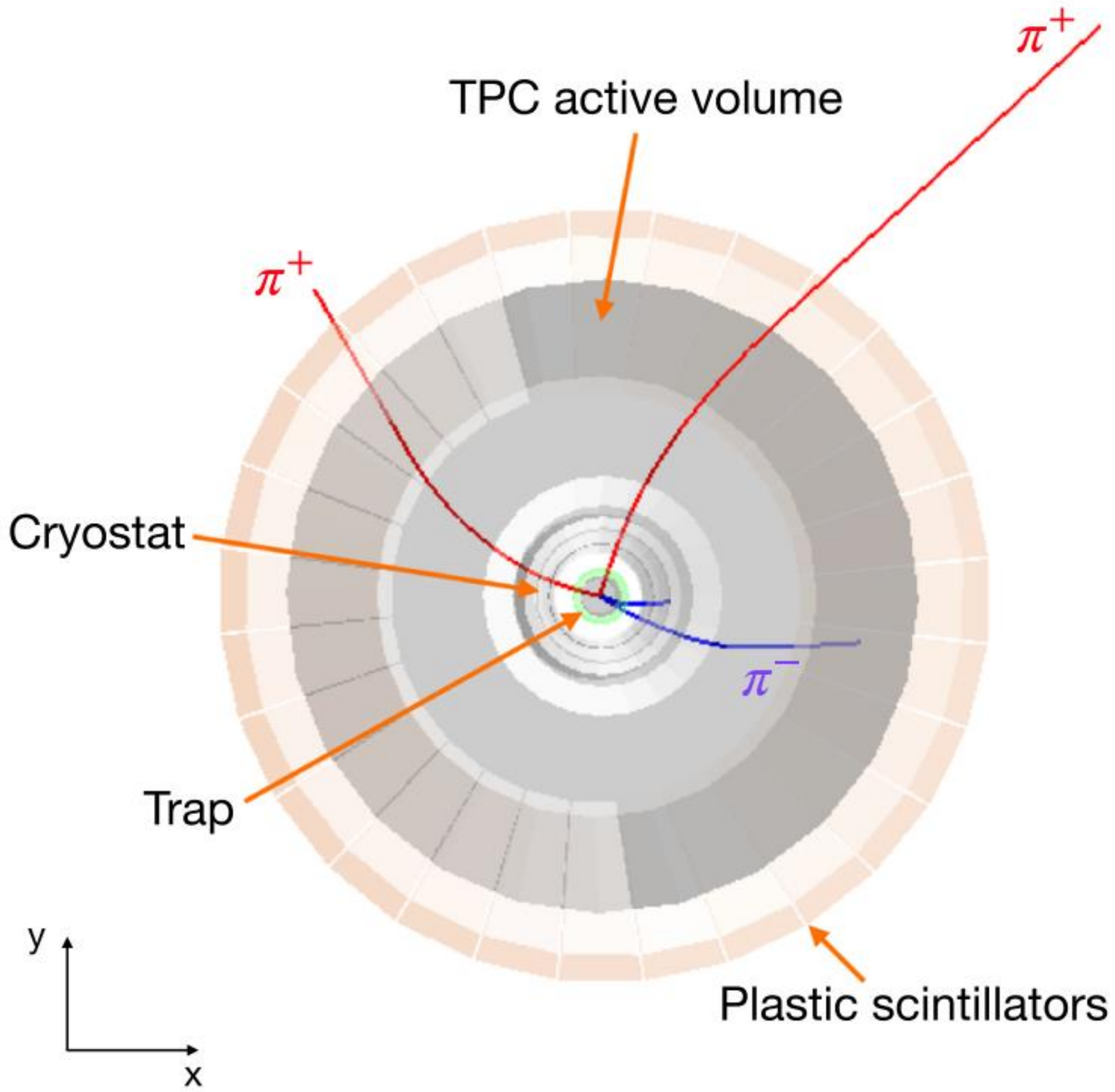


T. Aumann et al., Eur. Phys. J. A (2022) 58 :88

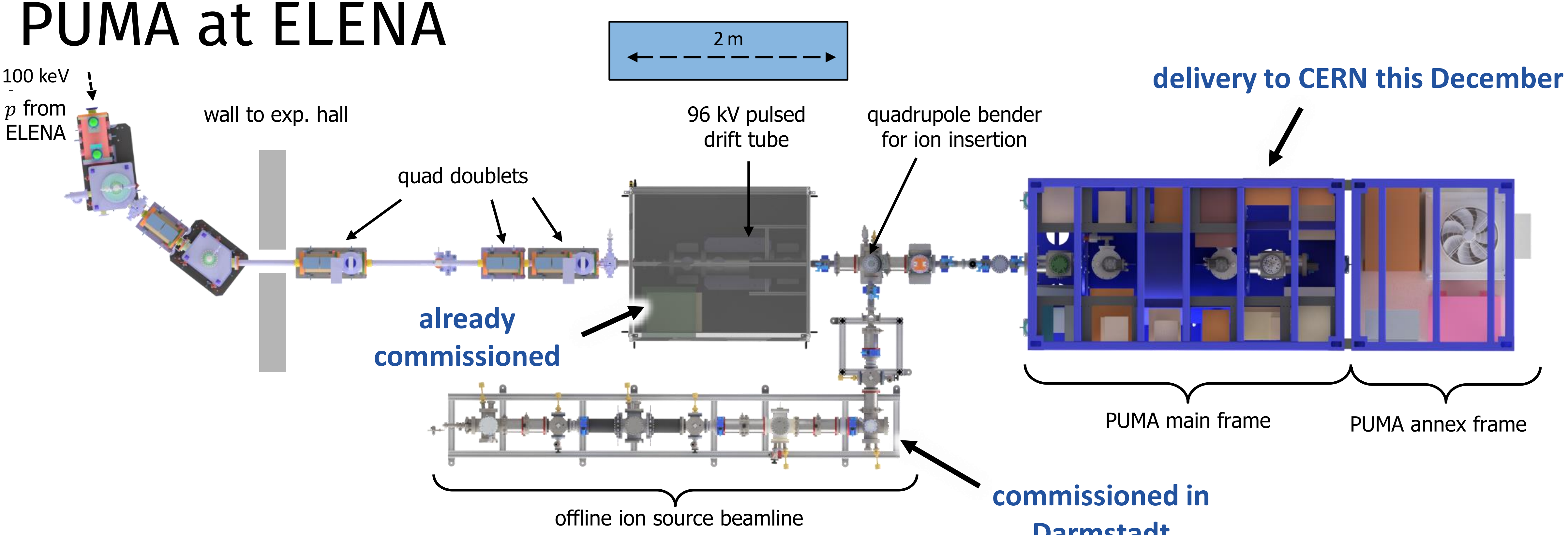
- Fill trap with electrons from field emission source
- e^- cool down to ambient temperature through cyclotron radiation
- p̄ capture in reservoir trap
- Sympathetic cooling through Coulomb interaction
- Use rotating wall technique to controll radial expansion of p̄
- Fraction of p̄ is transported into nested collision trap
- Loading of unstable ions into nested trap potential
- Mixing and annihilation of p̄ and ions, promoted by RF heating

The particle detectors

- Collision trap surrounded by particle detectors for event reconstruction
- Time-Projection-Chamber (TPC) for charge-reconstruction (curving trajectories for charged particles in B field)
- Plastic barrel used for event triggering and also to estimate vacuum conditions inside the container
- Background rejection of cosmic muons through energy and geometry considerations
- Already commissioned, installation planned for November 2024



PUMA at ELENA



2 m

100 keV $\bar{p}$ from ELENA

wall to exp. hall

quad doublets

96 kV pulsed drift tube

quadrupole bender for ion insertion

delivery to CERN this December

already commissioned

PUMA main frame

PUMA annex frame

offline ion source beamline

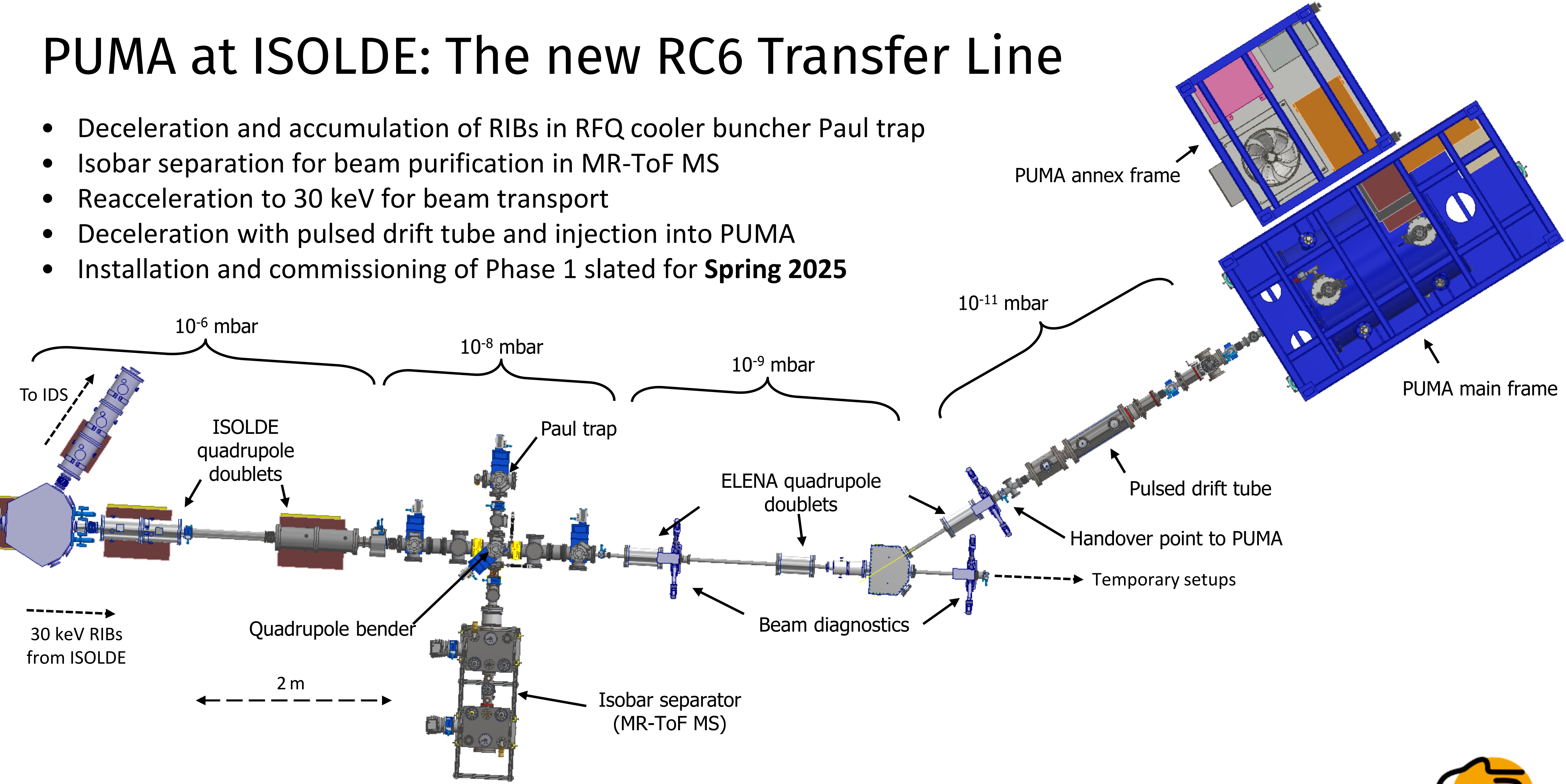
commissioned in Darmstadt

- deceleration of p̄ 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 MS, stacking and cooling in Paul Trap

Slide by C. Klink (BE-EA)

PUMA at ISOLDE: The new RC6 Transfer Line

- Deceleration and accumulation of RIBs in RFQ cooler buncher Paul trap
- Isobar separation for beam purification in MR-ToF MS
- Reacceleration to 30 keV for beam transport
- Deceleration with pulsed drift tube and injection into PUMA
- Installation and commissioning of Phase 1 slated for **Spring 2025**



Why xenon?

1. Large range of stable xenon isotopes available at ELENA (A= 124,126,128-132,134,136) to be studied before extending to radioactive nuclei
2. Predicted sensitivity to small variation of neutron skin thickness is high
3. Investigation of sensitivity to nuclear shape effects such as quadrupole deformation and triaxiality
4. Large range of radioactive xenon isotopes available at ISOLDE in rate above 10^5/s (A=115-144)
5. Xenon (Z=54) has large p̄-capture cross-section due to large number of electrons
6. Excellent beam purity of ISOLDE beam with VD7 cold plasma source -> isobaric mass separation not needed for this case

-> INTC-P-712 as pathfinder and commissioning experiment for future studies of neutron skins, nucleon halos, etc…

Rate estimations

- **Coupled differential equations** for radioactive decay and annihilation losses:

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = -\lambda_s N_i N_{\bar{\mathrm{p}}} - \frac{\ln 2}{t_{1/2}} N_i \qquad N_{\mathrm{i}}(t) = N_{\mathrm{i}_0} \exp\left(-\left(\lambda_{\mathrm{s}} N_{\bar{\mathrm{p}}}(t) + \frac{\ln 2}{t_{1/2}}\right) t\right)$$

$$\frac{\mathrm{d}N_{\bar{\mathrm{p}}}}{\mathrm{d}t} = -\lambda_s N_i N_{\bar{\mathrm{p}}} - \lambda_b N_{\bar{\mathrm{p}}}. \qquad N_{\bar{\mathrm{p}}}(t) = N_{\bar{\mathrm{p}}_0} \exp\left(-\left(\lambda_{\mathrm{s}} N_{\mathrm{i}}(t) + \lambda_{\mathrm{b}}\right) t\right)$$

- **Signal rate** given by annihilation rate:

$$\Gamma_{\mathrm{s}}(t) = \eta \lambda_{\mathrm{s}} N_{\mathrm{i}} N_{\bar{\mathrm{p}}} = 2.8 N_{\bar{\mathrm{p}}}(t) N_{\mathrm{i}}(t) \times 10^{-11}\,\mathrm{Hz}$$

$$= 2.8 N_{\mathrm{i}_0} N_{\bar{\mathrm{p}}_0} \exp\left(-\left(\lambda_{\mathrm{s}} N_i + \lambda_s N_{\bar{\mathrm{p}}} + \lambda_{\mathrm{b}} + \frac{\ln 2}{t_{1/2}}\right) t\right) \times 10^{-11}\,\mathrm{Hz},$$

- **Measurement time**:

$$T = \frac{N_{\bar{\mathrm{p}}A} \cdot \tilde{t}}{\int_0^{\tilde{t}} \Gamma_{\mathrm{s}}(t)\,\mathrm{d}t}$$

cycle time

- With annihilation rate constant:

annihilation cross-section ~10^{-16}

kinetic energy ~100eV

$$\lambda_{\mathrm{s}} = \frac{\sigma_{\bar{\mathrm{p}}\mathrm{A}}}{A} \cdot \sqrt{\frac{2E}{m_{\mathrm{N}}}} \cdot \frac{1}{l}$$

plasma length ~5cm

Mass ~130u

geometric cross-section ~$0.25\mathrm{cm}^2$

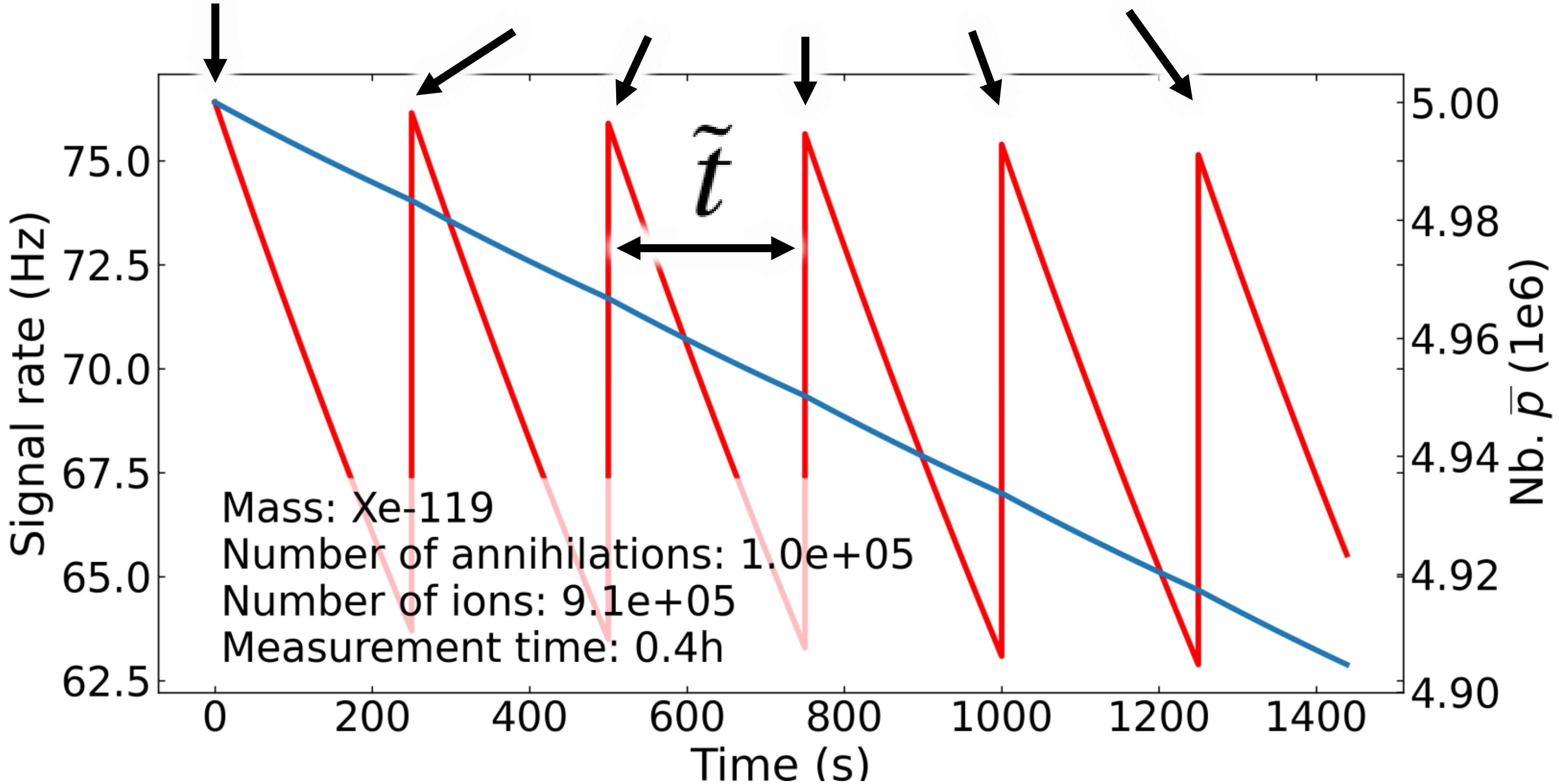
Measurement cycle – Half-lifes >> s

- Loading of ions only when annihilation rate drops below certain treshold to keep measurement fast
- Losses mainly due to annihilation

$$\Sigma < 1x10^6$$

Loading initial 5x10^5 ions

Topping up with 8x10^4 ions every 300s



Mass: Xe-119
Number of annihilations: 1.0e+05
Number of ions: 9.1e+05
Measurement time: 0.4h

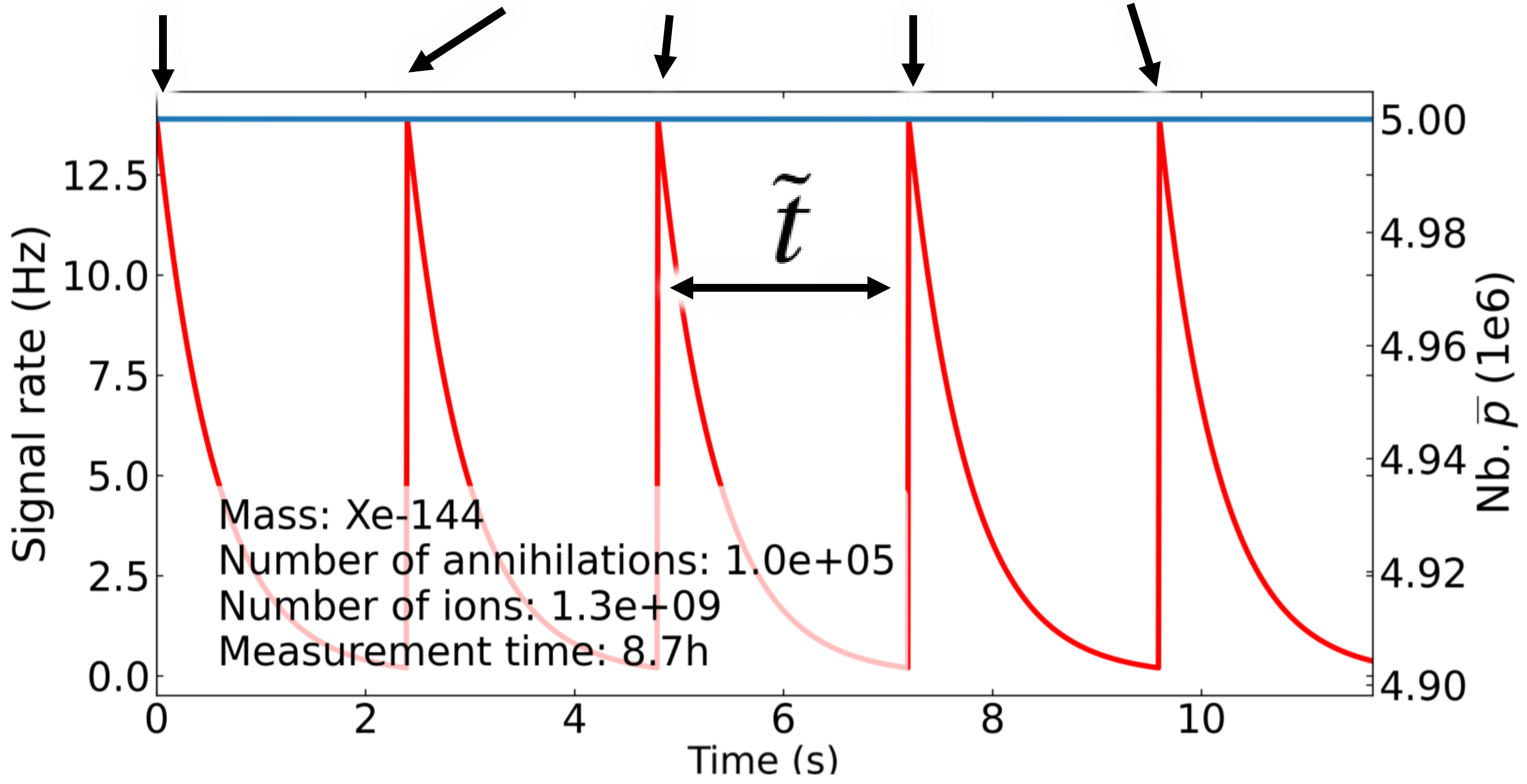
Measurement cycle – Half-lifes ~ s

- Loading of ions as often as PSB delivers protons on target
- Losses mainly due to radioactive decay

$$1x10^7 < \Sigma < 1x10^{10}$$

Loading initial 1x10^5 ions

Topping up with 1x10^5 ions every 2.4s on average



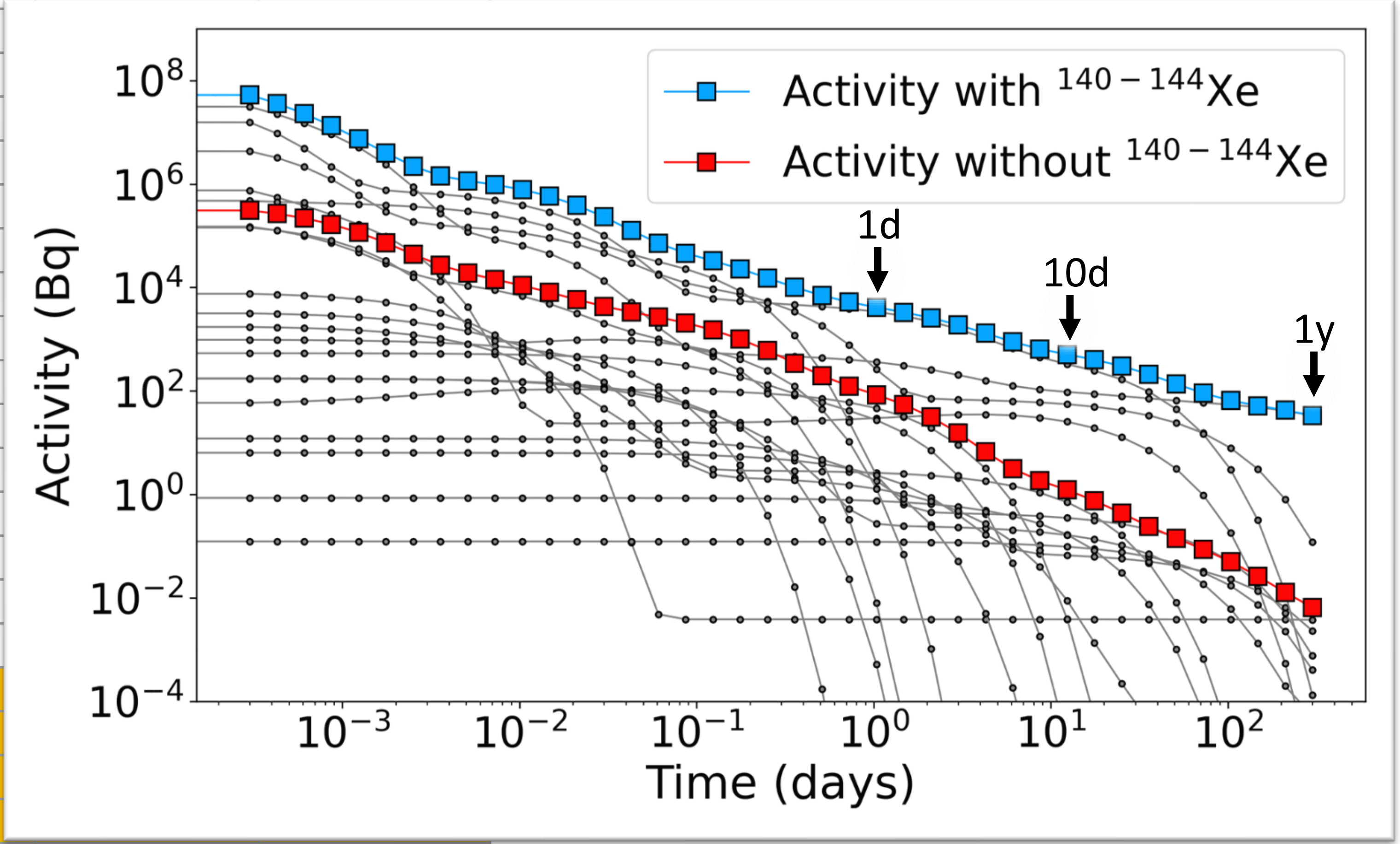
Total ion count and activity over time

Isotope	Half-life	Number of ions	H*(10) (uSv)	Rate after 1h (Bq)	Rate after 1d (Bq)	Rater after 30d (Bq)
115Xe	18	2.5e7	3.3e-3	3.3e3	0	0
116Xe	59 s	8.1e6	8.6e-4	9.6e2	1.7e0	0
117Xe	61 s	8.1e6	7.0e-4	8.0e2	2.4e0	0
118Xe	3.8 min	1.1e6	1.4e-4	6.4e1	2.6e0	9.2e-2
119Xe	5.8 min	9.1e5	1.7e-5	1.9e1	1.3e0	0
120Xe	46.0 min	6.0e5	6.8e-5	1.0e2	8.1e-4	0
121Xe	40.1 min	6.1e5	6.2e-5	9.2e1	2.8e-1	8.6e-2
122Xe	20.1 h	5.7e5	3.0e-4	1.1e2	4.8e1	0
123Xe	2.08 h	5.8e5	5.6e-5	4.1e1	2.9e0	0
125Xe	16.87 h	5.6e5	1.2e-4	6.24e1	2.5e1	5.5e-1
127Xe	36.3 d	5.6e5	4.5e-6	1.3e-1	1.2e-1	7.1e-2
133Xe	5.2 d	5.6e5	2.5e-6	8.5e-1	7.51e-1	1.62e-3
135Xe	9.14 h	5.7e5	6.86e-6	9e0	1.9e-0	0
137Xe	3.8 min	2.7e6	2.30e-5	1.6e-1	3.9e-3	3.9e-3
138Xe	14.1 min	1.2e6	1.58e-4	2.2e2	0	0
139Xe	39.7 s	1.3e7	1.71e-4	1.4e3	1.2e-3	0
140Xe	13.6 s	3.7e7	5.12e-3	2.3e1	3.0e1	**9.8e0**
141Xe	1.73 s	2.9e8	1.91e-1	3.06e4	2.91e2	**3.8e1**
142Xe	1.23 s	4.1e8	6.25e-2	4.5e4	2.9e0	2.41e-1
143Xe	511 ms	9.4e8	2.64e-2	4.8e4	3.45e3	**1.3e2**
144Xe	388 ms	1.3e9	1.18e-1	5.5e3	3.7e2	**7.6e1**

Total ion count and activity over time

Isotope	Half-life	Number of ions	H*(10) (uSv)	Rate after 1h (Bq)	Rate after 1d (Bq)	Rater after 30d (Bq)
115Xe	18	2.5e7	3.3e-3	3.3e3	0	0
116Xe	59 s	8.1e6	8.6e-4	9.6e2		
117Xe	61 s	8.1e6	7.0e-4	8.0e2		
118Xe	3.8 min	1.1e6	1.4e-4	6.4e1		
119Xe	5.8 min	9.1e5	1.7e-5	1.9e1		
120Xe	46.0 min	6.0e5	6.8e-5	1.0e2		
121Xe	40.1 min	6.1e5	6.2e-5	9.2e1		
122Xe	20.1 h	5.7e5	3.0e-4	1.1e2		
123Xe	2.08 h	5.8e5	5.6e-5	4.1e1		
125Xe	16.87 h	5.6e5	1.2e-4	6.24e1		
127Xe	36.3 d	5.6e5	4.5e-6	1.3e-1		
133Xe	5.2 d	5.6e5	2.5e-6	8.5e-1		
135Xe	9.14 h	5.7e5	6.86e-6	9e0		
137Xe	3.8 min	2.7e6	2.30e-5	1.6e-1		
138Xe	14.1 min	1.2e6	1.58e-4	2.2e2		
139Xe	39.7 s	1.3e7	1.71e-4	1.4e3		
140Xe	13.6 s	3.7e7	5.12e-3	2.3e1		
141Xe	1.73 s	2.9e8	1.91e-1	3.06e4		
142Xe	1.23 s	4.1e8	6.25e-2	4.5e4		
143Xe	511 ms	9.4e8	2.64e-2	4.8e4		
144Xe	388 ms	1.3e9	1.18e-1	5.5e3	3.7e2	**7.6e1**

Calculated total activity with Nucleonica



Revised shift count

Isotope	Half-life	Number of ions	Expected yield (/uC)	H*(10) (uSv)	Rate after 1h (Bq)	Rate after 1d (Bq)	Rater after 30d (Bq)	Req. shifts (8h) – Run LaCx	Req. shifts (8h) – Run UCx
115Xe	18	2.5e7	6.7e5	3.3e-3	3.3e3	0	0	1	
116Xe	59 s	8.1e6	6.5e6	8.6e-4	9.6e2	1.7e0	0	1	
117Xe	61 s	8.1e6	5.0e7	7.0e-4	8.0e2	2.4e0	0	0.5	
118Xe	3.8 min	1.1e6	5.9e7	1.4e-4	6.4e1	2.6e0	9.2e-2	0.5	
119Xe	5.8 min	9.1e5	7.1e7	1.7e-5	1.9e1	1.3e0	0	0.5	
120Xe	46.0 min	6.0e5	1.6e8	6.8e-5	1.0e2	8.1e-4	0	0.5	
121Xe	40.1 min	6.1e5	>1.0e8	6.2e-5	9.2e1	2.8e-1	8.6e-2	0.5	
122Xe	20.1 h	5.7e5	>1.0e8	3.0e-4	1.1e2	4.8e1	0	0.5	
123Xe	2.08 h	5.8e5	>1.0e8	5.6e-5	4.1e1	2.9e0	0	0.5	
125Xe	16.87 h	5.6e5	4.7e8	1.2e-4	6.24e1	2.5e1	5.5e-1	0.5	
127Xe	36.3 d	5.6e5	5.2e8	4.5e-6	1.3e-1	1.2e-1	7.1e-2	0.5	
133Xe	5.2 d	5.6e5	>6e8	2.5e-6	8.5e-1	7.51e-1	1.62e-3		0.5
135Xe	9.14 h	5.7e5	>6e8	6.86e-6	9e0	1.9e-0	0		0.5
137Xe	3.8 min	2.7e6	6.2e8	2.30e-5	1.6e-1	3.9e-3	3.9e-3		0.5
138Xe	14.1 min	1.2e6	5.7e8	1.58e-4	2.2e2	0	0		0.5
139Xe	39.7 s	1.3e7	5.0e8	1.71e-4	1.4e3	1.2e-3	0		0.5
124,126,128-132,134,136	stb	5.5e5	/	/	/	/	/	5.0 (no protons)	5.0 (no protons)
Yield measurements $^{115-120}$Xe from LaCx								0.5	
Optimization and systematic studies								6.0 (no protons)	6.0 (no protons)
Σ								**18**	**13.5 (-4.5)**

The PUMA Collaboration

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The ISOLDE-RC6 Team

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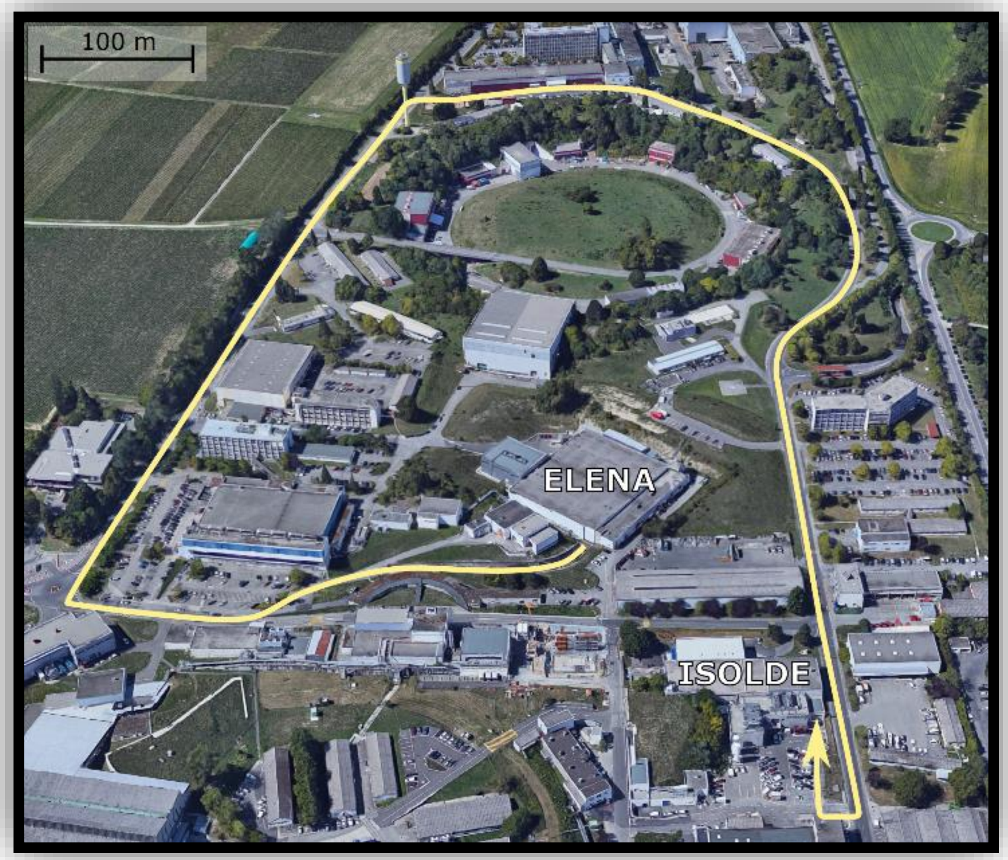
Summary

- **PUMA** is a new experiment at CERN accepted in 2021
- It aims at bringing together **low-energy p̄ and unstable nuclei to probe the tail of the nuclear density distribution**
- Observable: **neutron-to-proton-ratio**, which allows investigation of nuclear phenomena like Halo nuclei and neutron skins of stable (ELENA) and exotic isotopes (ISOLDE)
- Transport of p̄ from ELENA to ISOLDE
- Offline ion source beamline fully commissioned
- First experiments at ELENA and construction of RC6 beamline at ISOLDE slated for Spring 2025



Extra Low Energy Antiprotons (ELENA) at the Antiproton Decelerator (AD)

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

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

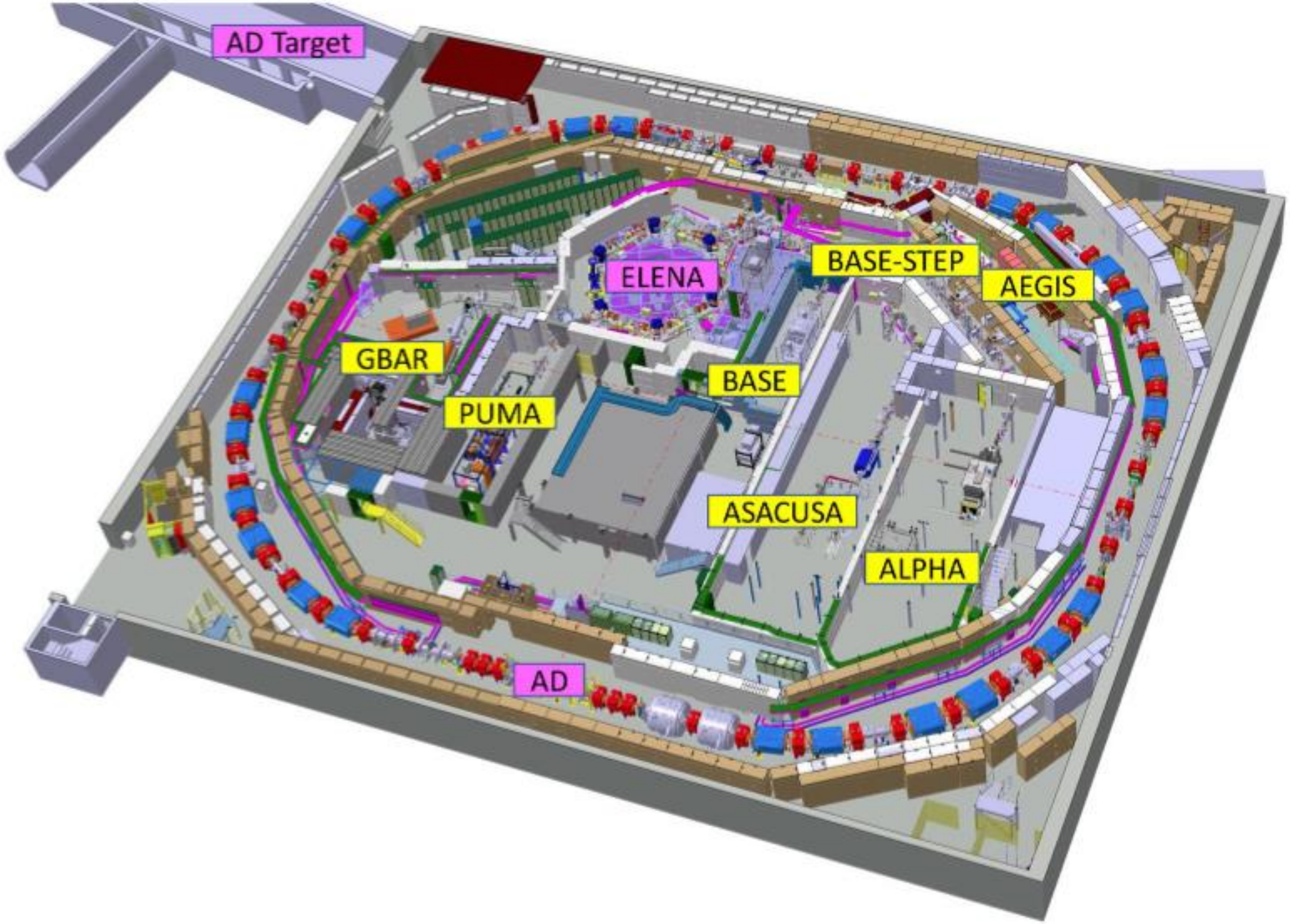
Deceleration of $\bar{p}$:

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

Duty cycle of ELENA:

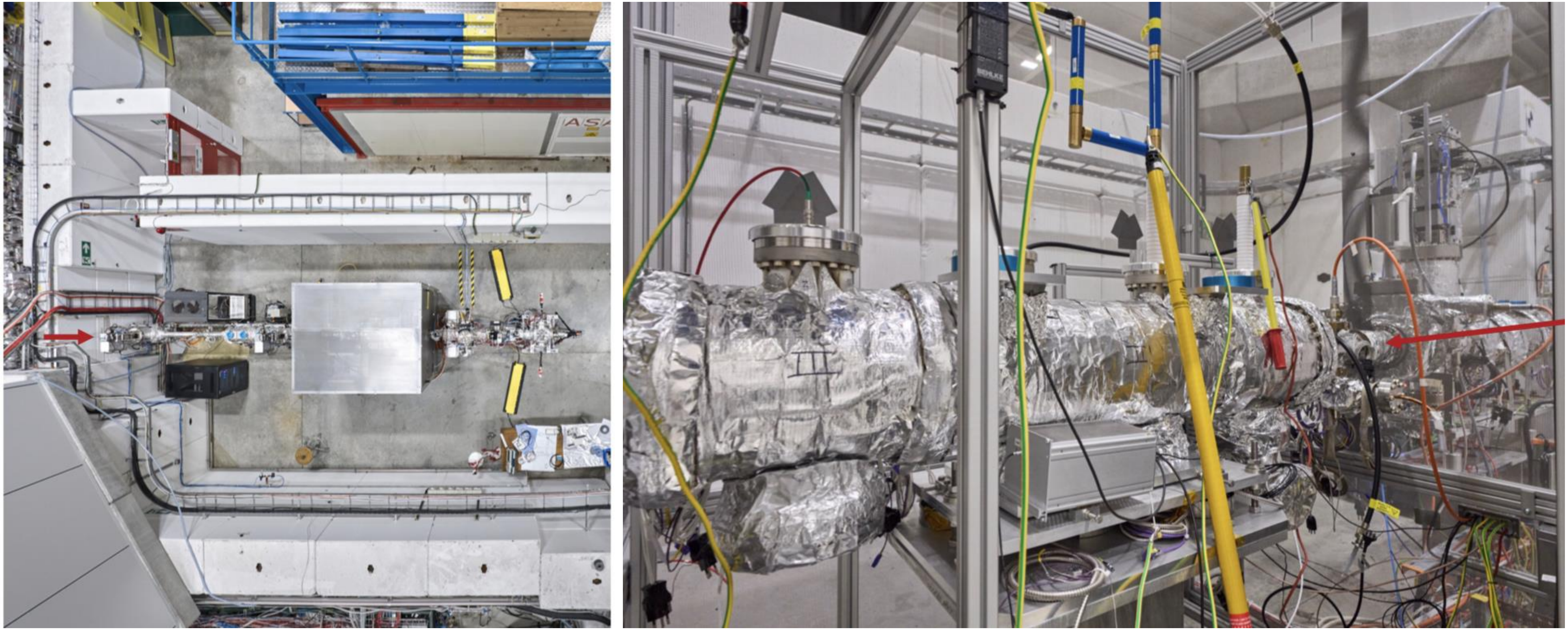
4x $4 \cdot 10^{6}$ bunches every 110s

Possibility to use 100 keV H- every 20 seconds



Slide by C. Klink (BE-EA)

PUMA at the AD



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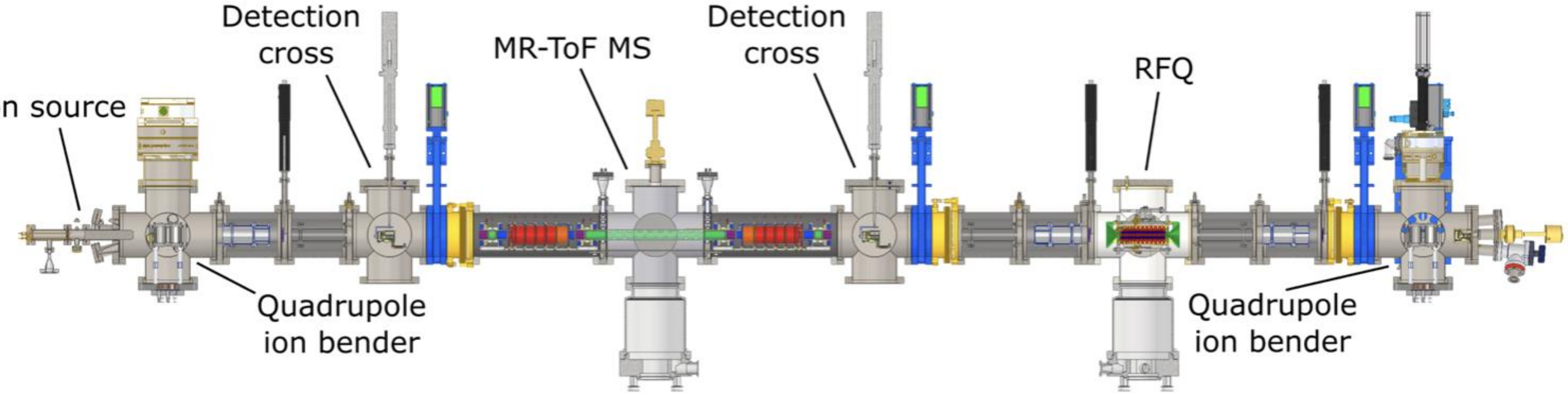
Offline ion source at AD

- Characterise pion detector (TPC) & benchmark simulations: p, d
- Evolution of results with changing nucleon number: ^{3,4}He, ^{20,21}Ne, ^{16}O, ^{40}Ar, ^{132}Xe
- Study isospin dependence along isotopic chains: $^{124\text{-}136}$Xe
- Future step: laser ablation source for: $^{40\text{-}48}$Ca, $^{112\text{-}124}$Sn, ^{208}Pb

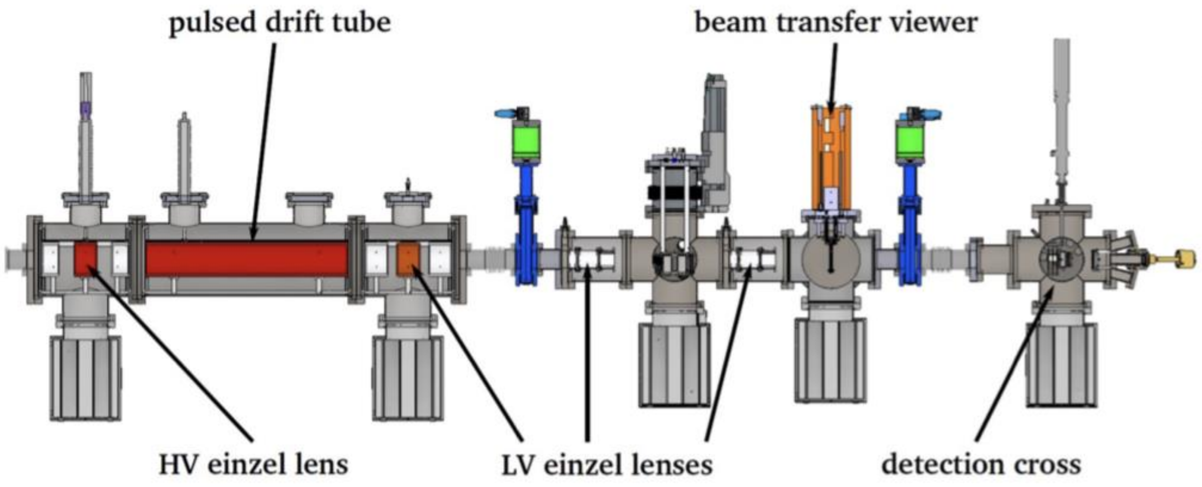
- Ion Generation
- Isotope Separation isotopic purity in trap
- Accumulation and Bunching → $\sim 10^3$ ions in RFQ



Slide by C. Klink (BE-EA)

Pulsed Drift Tube for p̄

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



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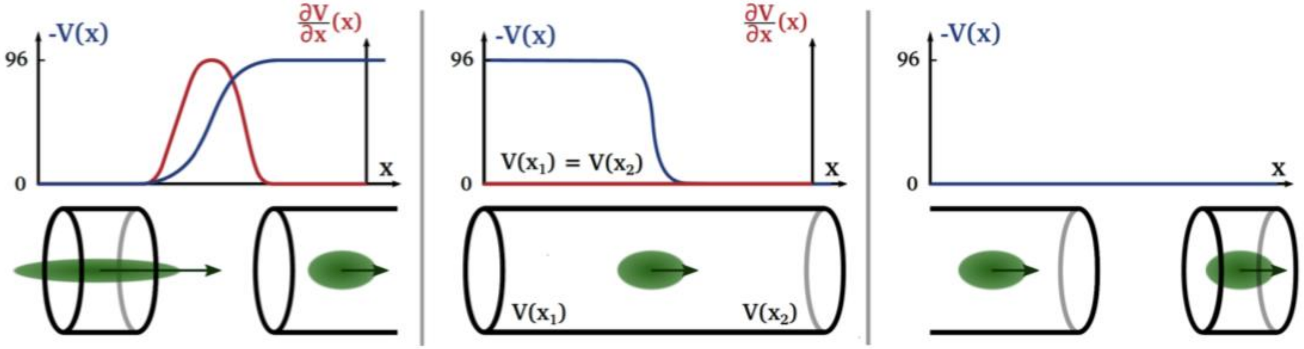
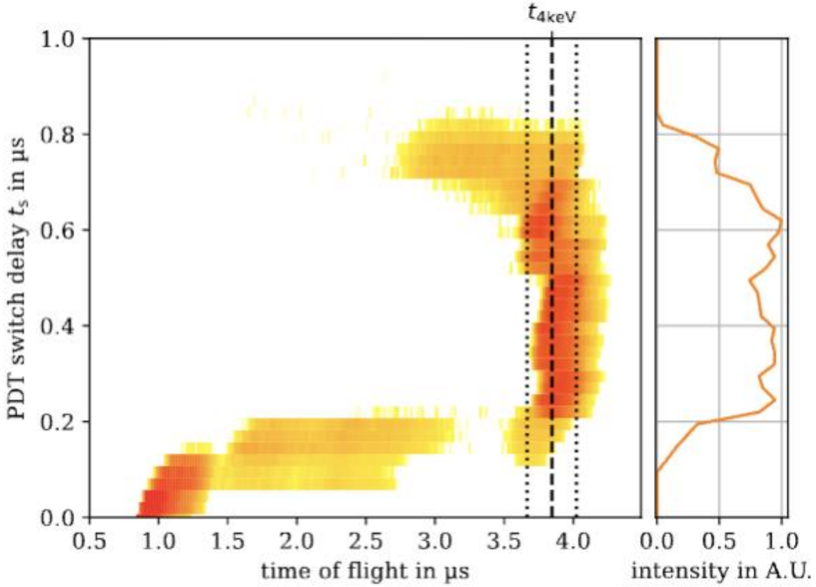
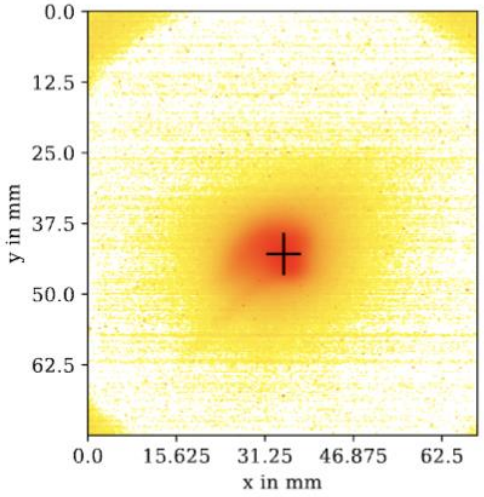


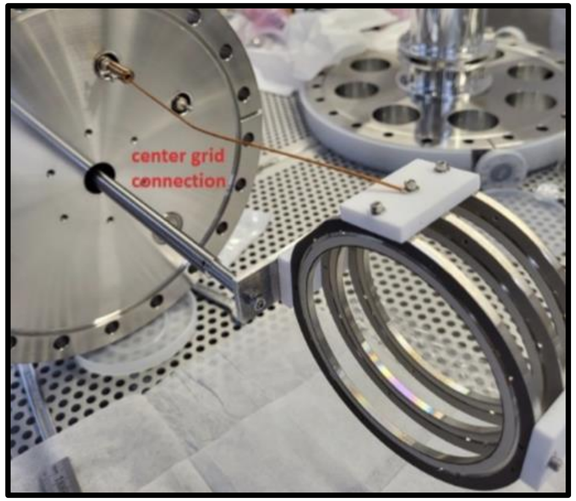


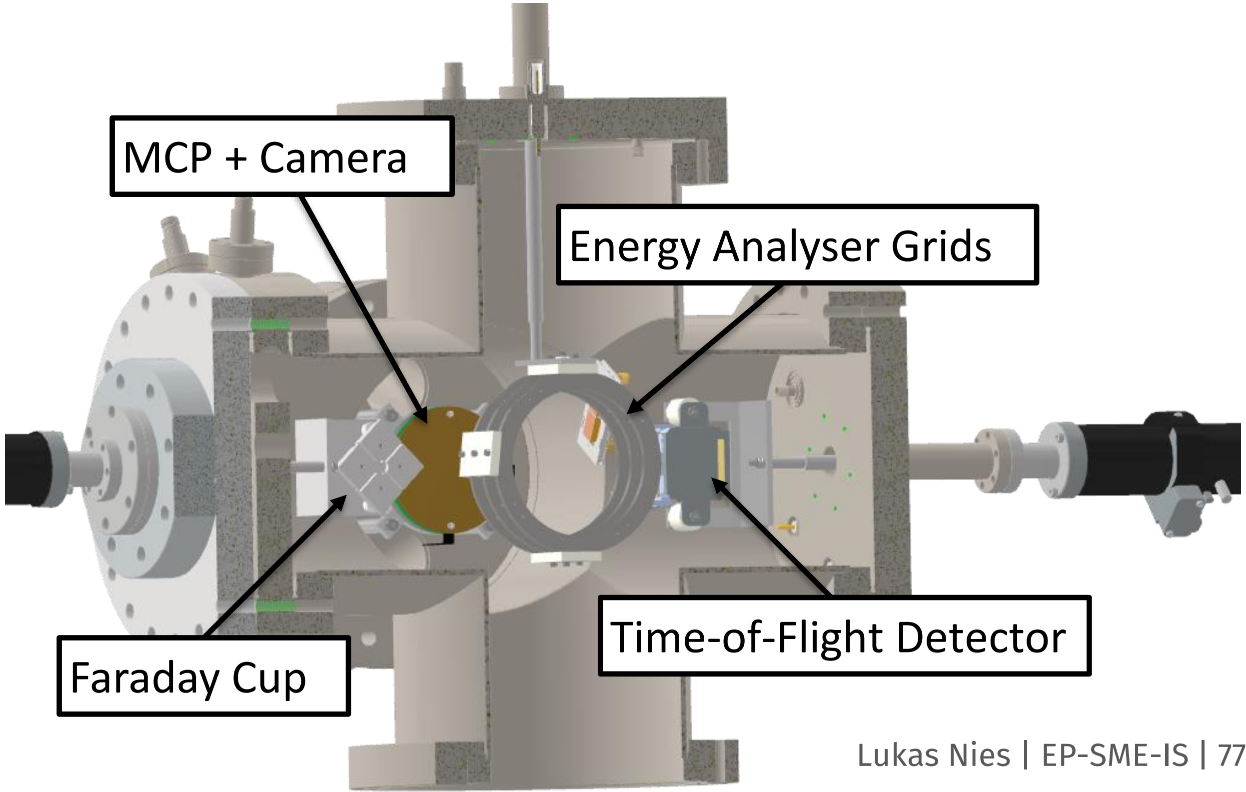


Slide by C. Klink (BE-EA)

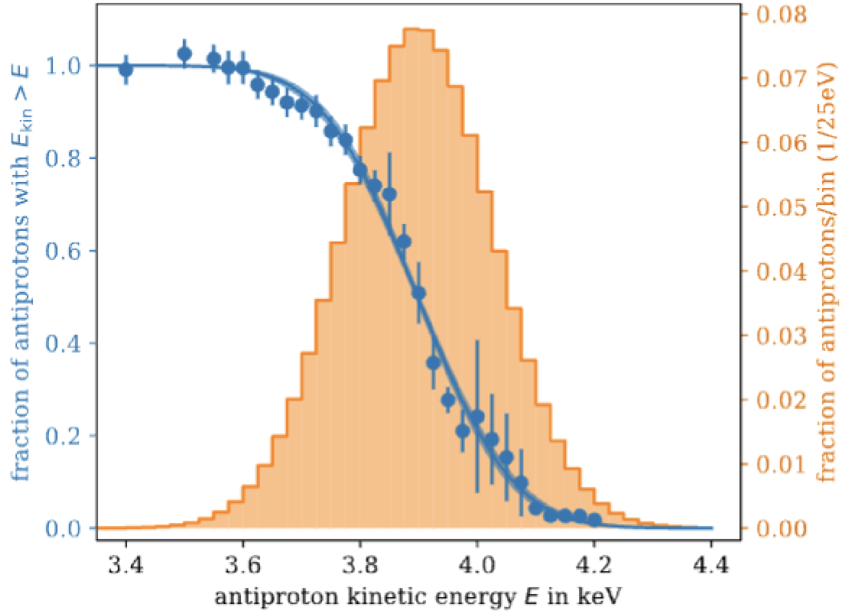
Beam diagnostics

- Transmission approx. 55 (3)% (simulations: 100%) due to lack of lensing (only one of four lenses available at time of measurement)
- Energy after deceleration 3.898(3) keV
- Energy spread 127(4) eV (σ) (simulations: 100 eV)





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

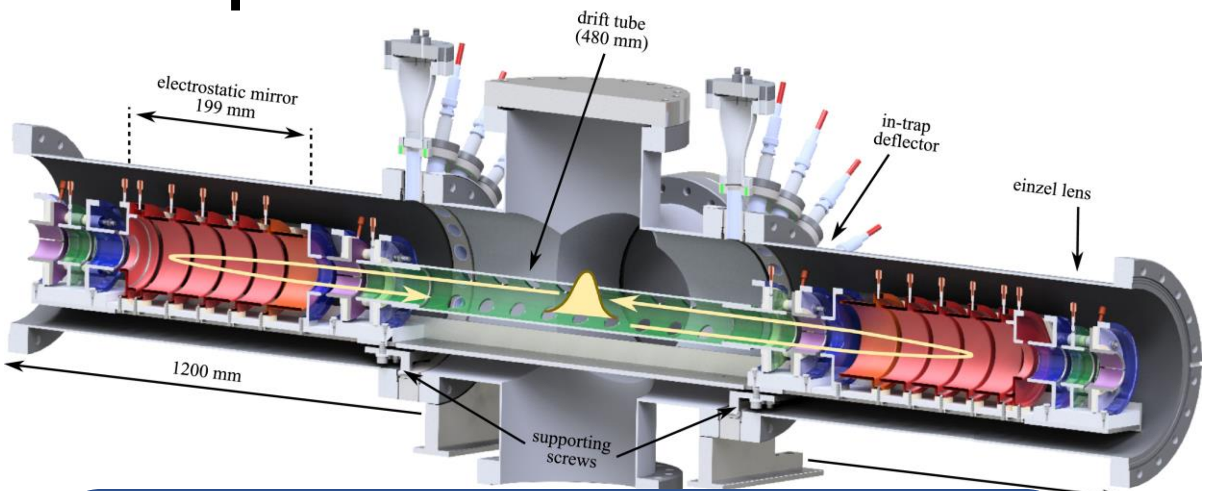


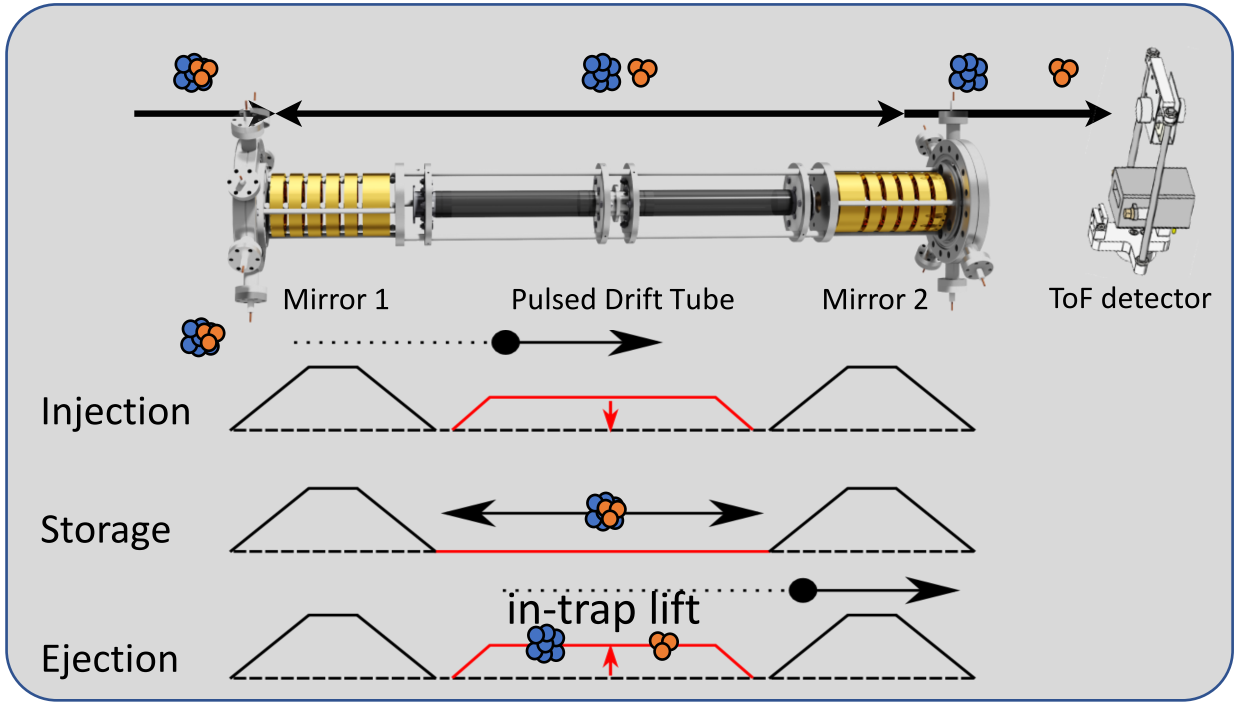
Slide by C. Klink (BE-EA)

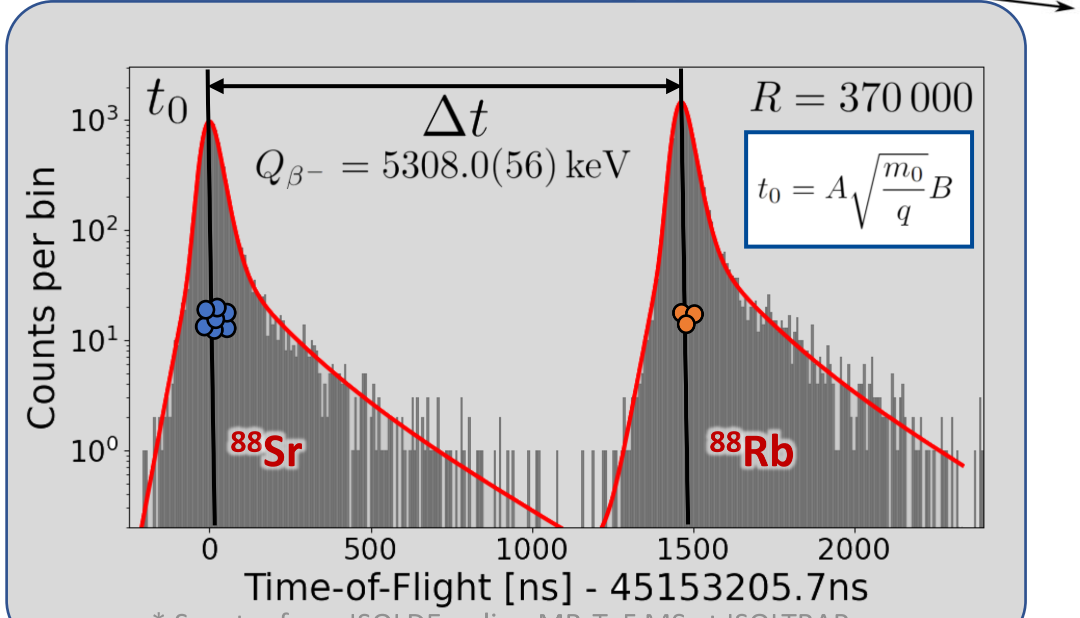
Multi-Reflection Time-of-Flight Separator

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

- Reflect ions between electrostatic mirrors: several kilometers of distance travelled
- Main limitation for mass resolving power R is bunch width Δt
- TU Darmstadt now used by 7 institutes in MR-ToF MS collaboration -> based on U. Greifswald design

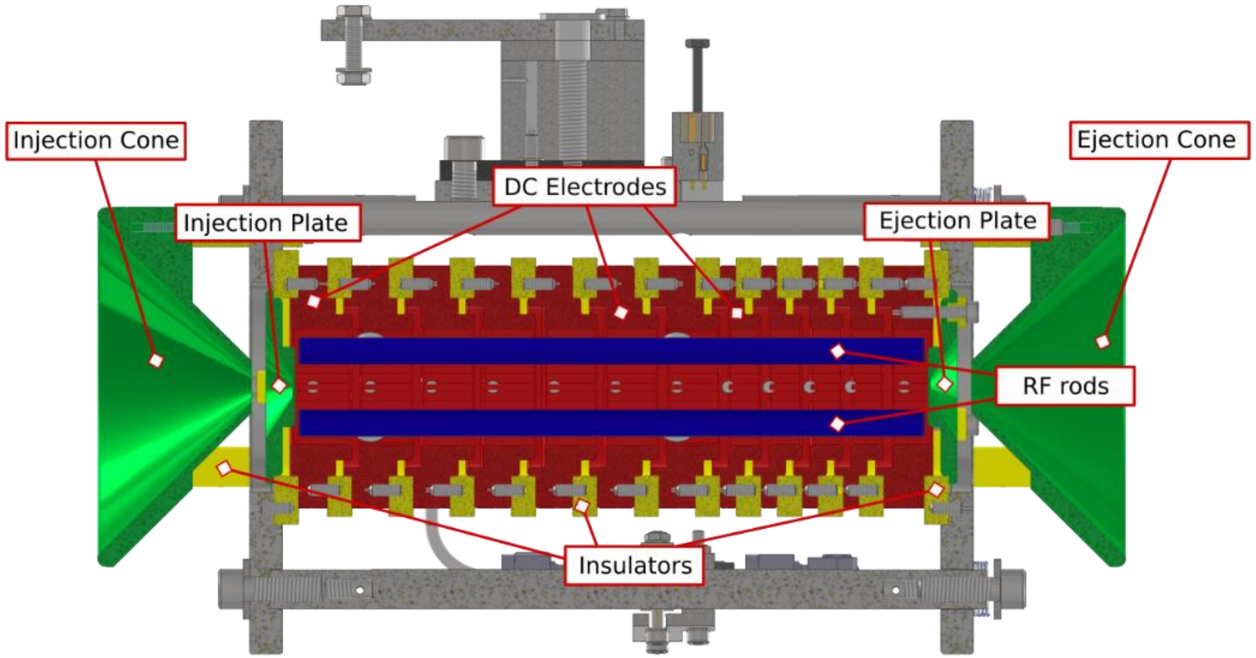


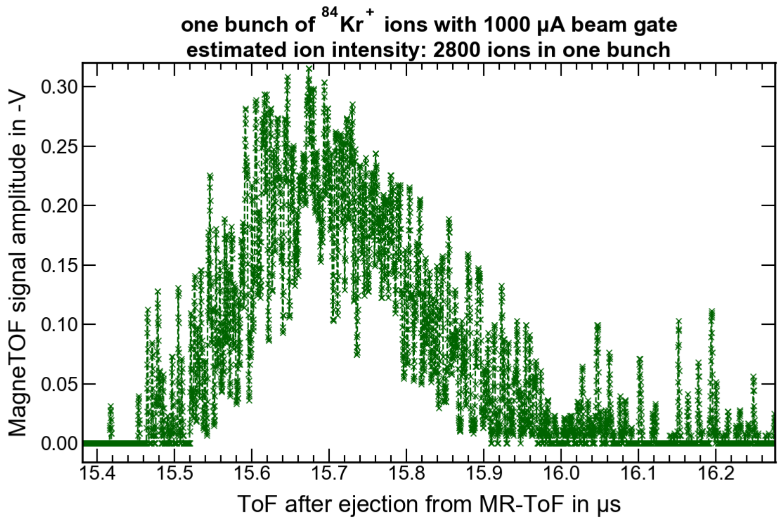


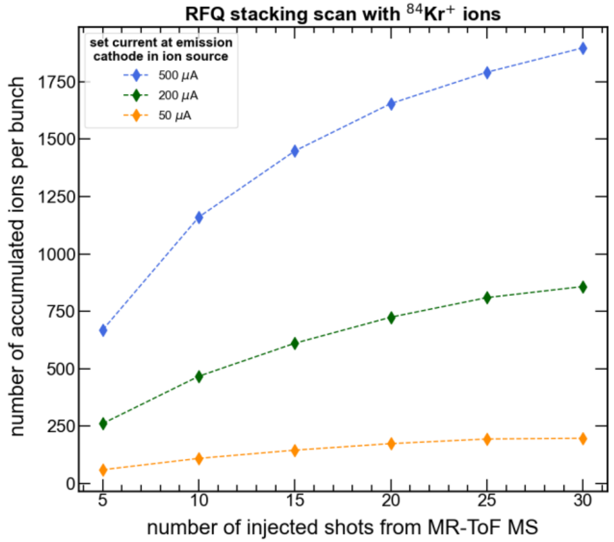


* Spectra from ISOLDE online MR-ToF MS at ISOLTRAP

Multi-Reflection Time-of-Flight Separator







- 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

Slide by C. Klink (BE-EA)

PUMA at ISOLDE: The new RC6 Transfer Line

- **Isobaric separation** with resolving powers $M/\Delta M > 100{,}000$ in only a few milliseconds
- **Ultra-high vacuum** with $< 10^{-10}$ mbar at hand-over-point
- **Higher throughput** predicted as compared to other multi-reflection separators
- Possibility of **back-extraction** into central beamline
- **Beam identification** studies for target and ion source developments
- **Collection** of samples benefiting from high flux and high separation powers
- **Temporary experiments** requiring $< 10^{-10}$ mbar vacuum