ISOLDE Workshop and Users Meeting 2024, CERN, 27.11.2024

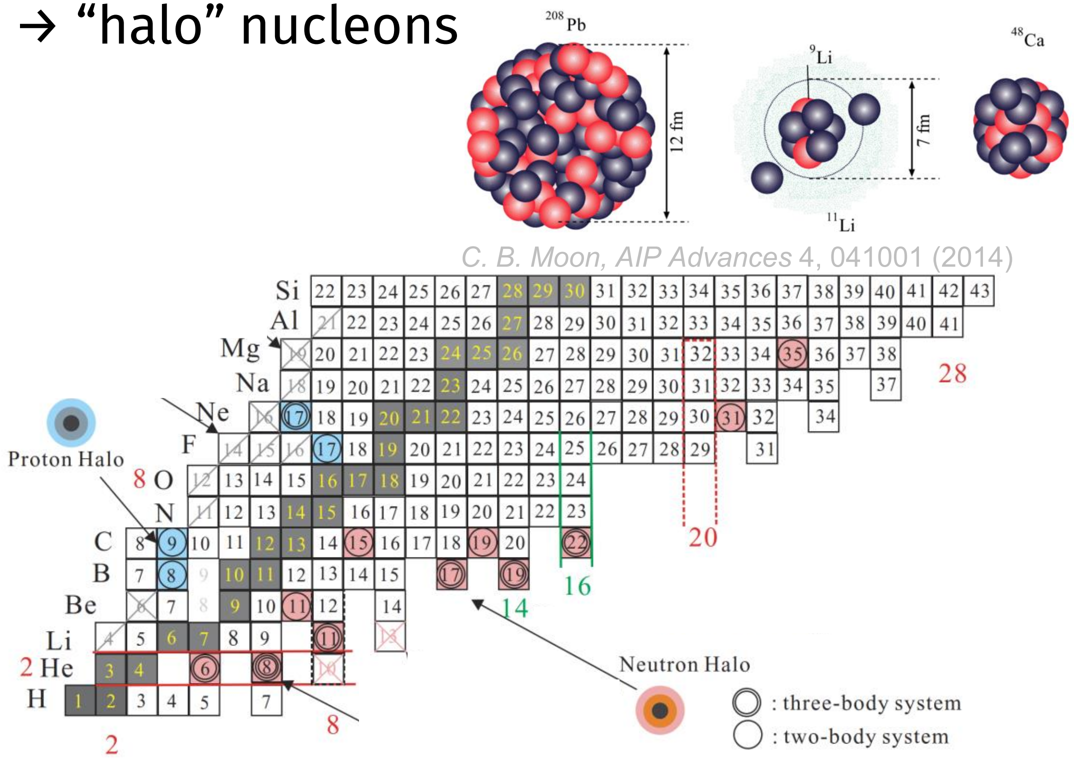
Status of PUMA at ISOLDE

Lukas Nies for the PUMA collaboration
European Organization for Nuclear Research

Nucleon distribution on the surface of nuclei

Halo Nuclei

- Dripline nuclei with a large N or Z excess
- One or more nucleons orbit the nucleus → "halo" nucleons

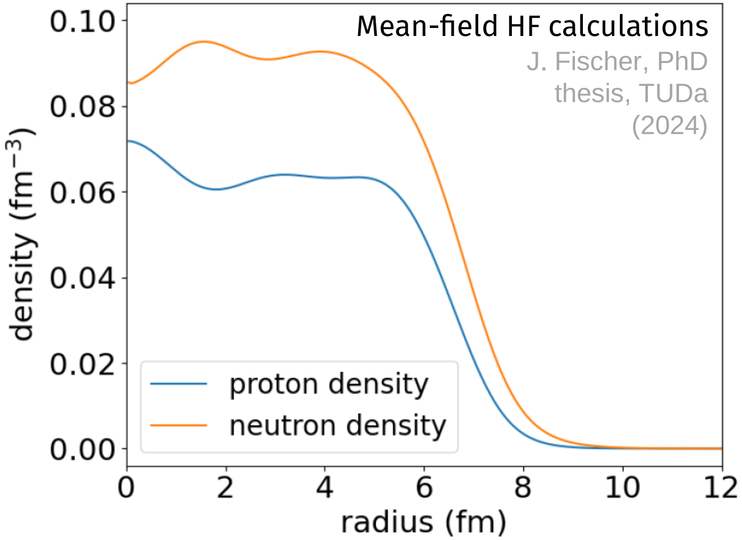


C. B. Moon, AIP Advances 4, 041001 (2014)

Neutron skins

- Neutron excess in most nuclei least to larger neutron density throughout nucleus
- On surface, larger neutron density tail leads to neutron skin with thickness

$$R_{skin} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle} \sim 0.1 - 0.25 \text{ fm for } {}^{208}\text{Pb}$$



Lukas Nies
ISOLDE Collaboration

Nucleon distribution on the surface of nuclei

Halo Nuclei

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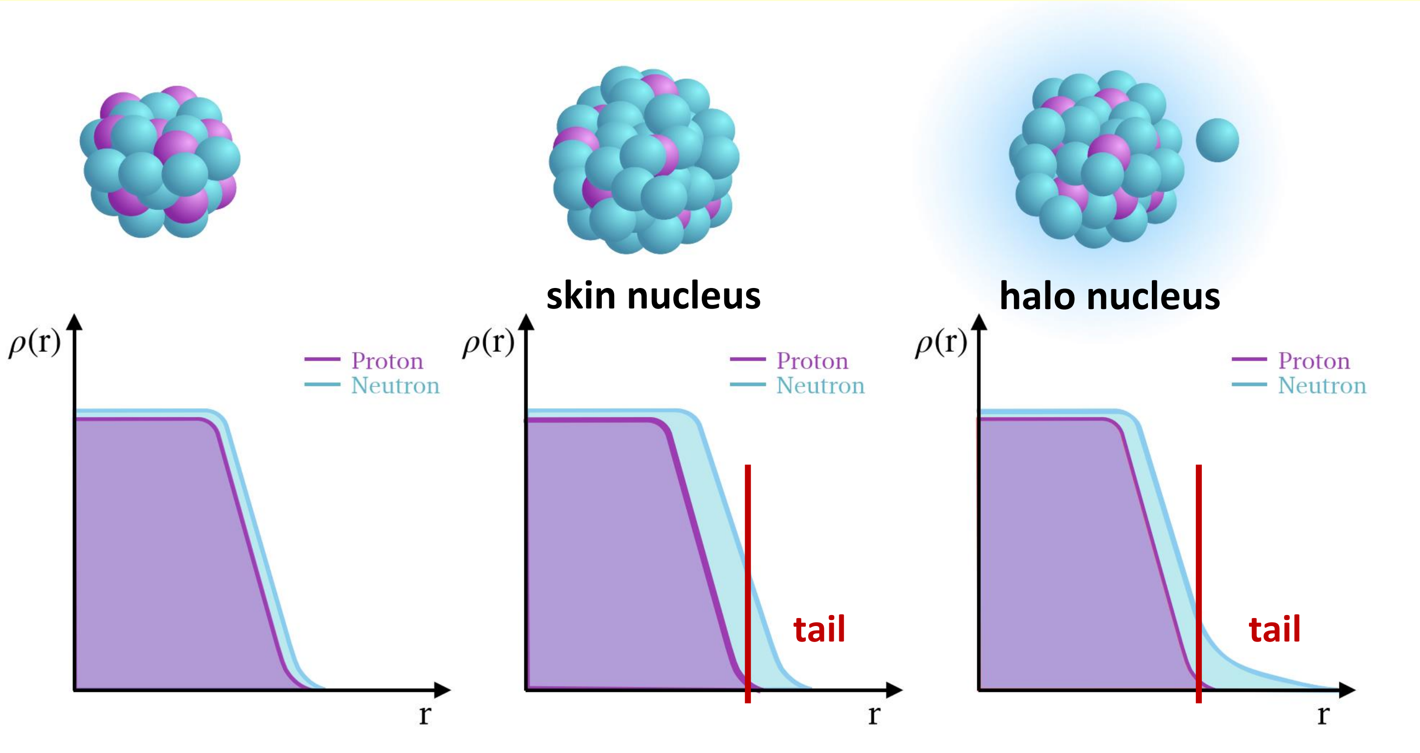


PUMA aims to develop a technique that

→ Probes the nuclear density tail

→ Determines the neutron fraction

→ Is applicable to radioactive nuclei

2 8 : two-body system

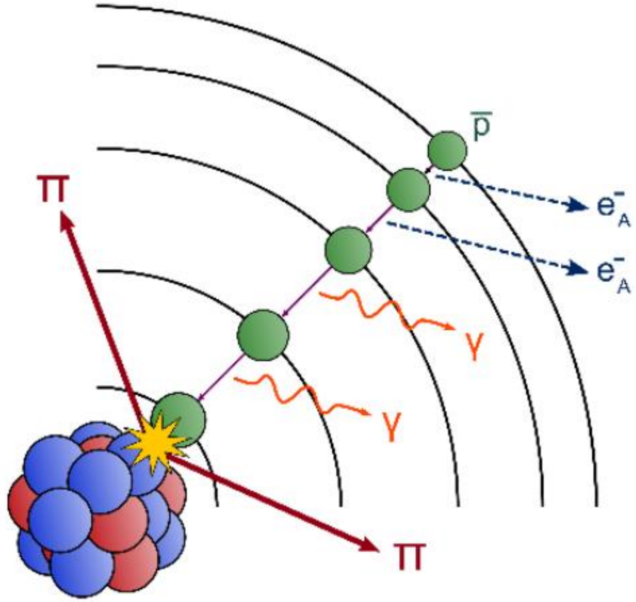
0 2 4 6 8 10 12
radius (fm)

Lukas Nies
ISOLDE Collaboration

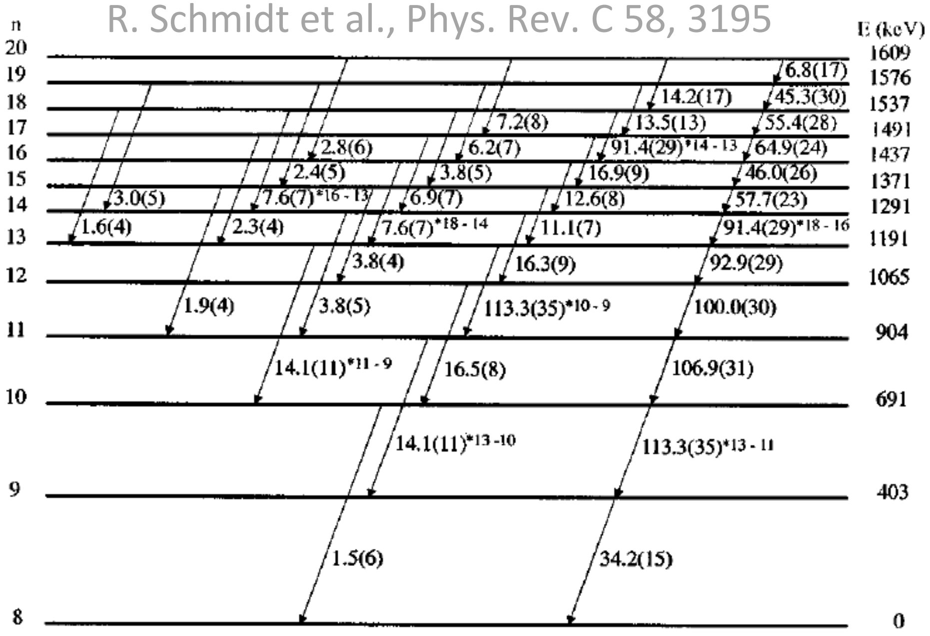
antiProton Unstable Matter Annihilation (PUMA)

Technique: Low-energy antiprotons as a probe for nuclear structure

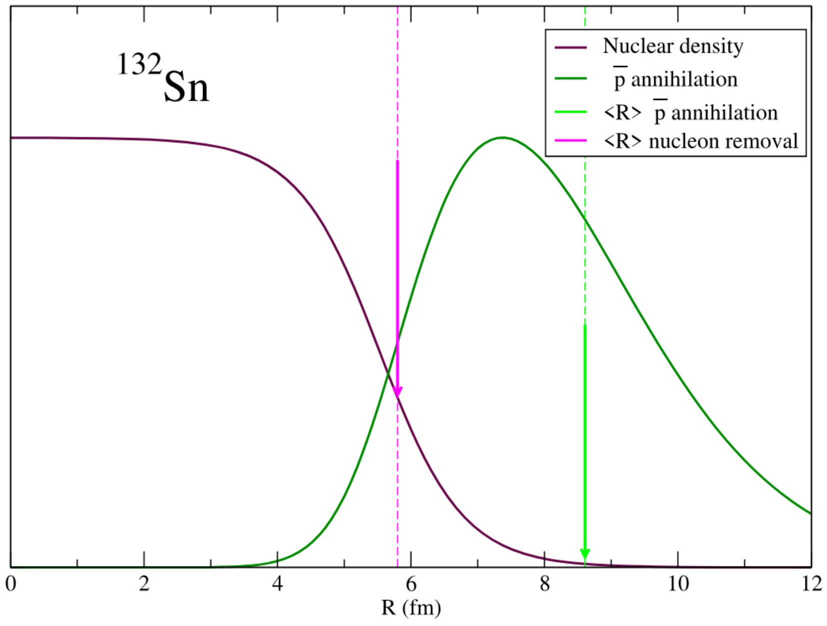
Capture in excited antiproton orbital → Cascade: Auger transitions → Cascade: radiative transitions → Annihilation with surface nucleon → Final-state interactions of emitted mesons



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



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



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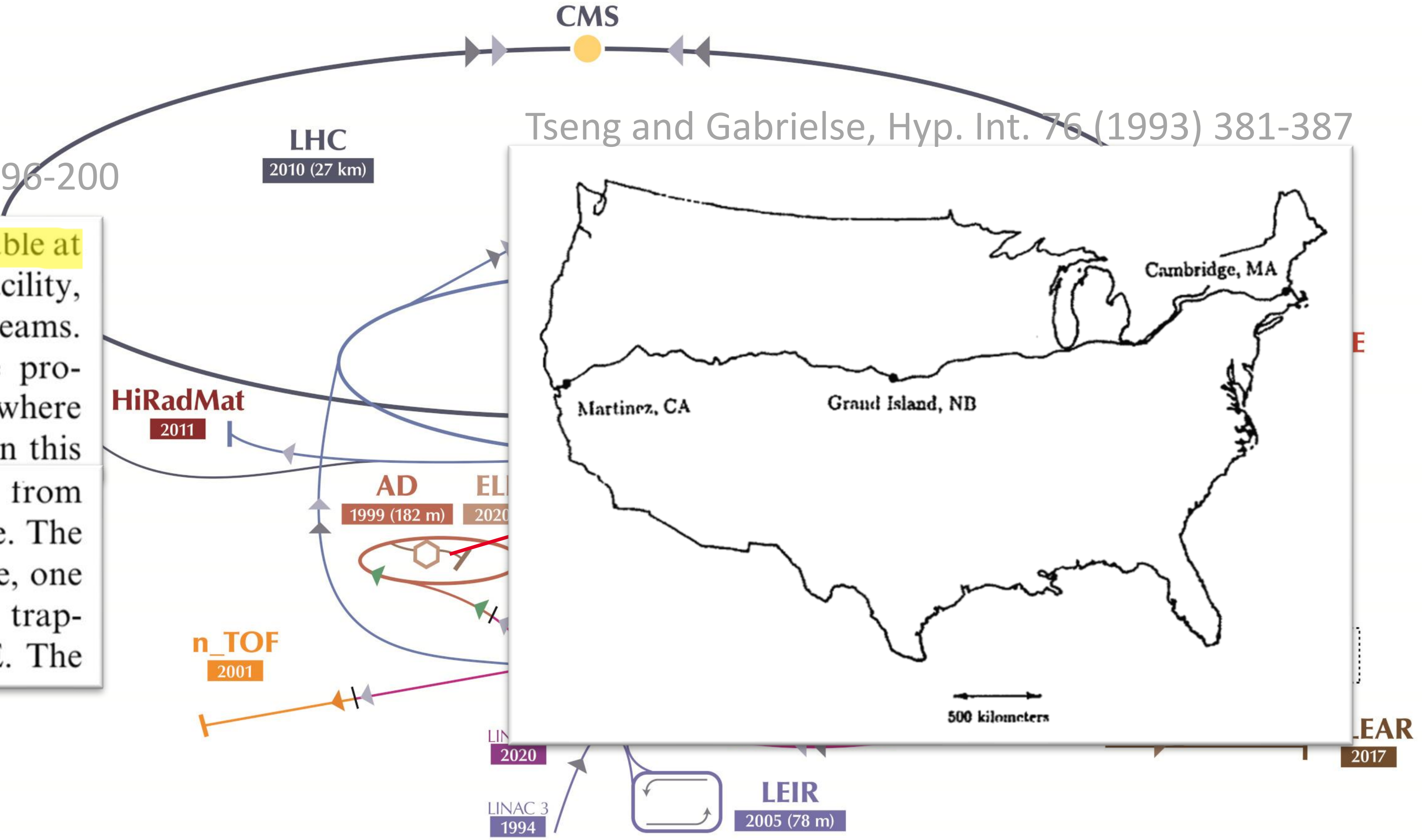
antiProton Unstable Matter Annihilation (PUMA)

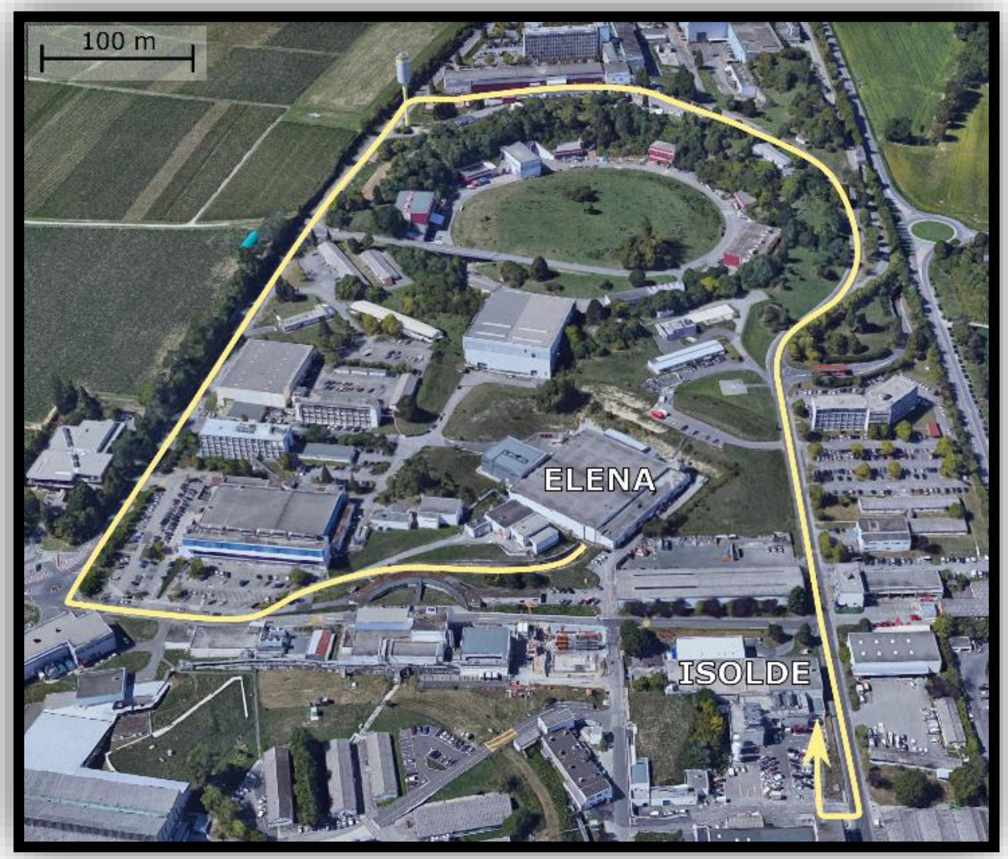


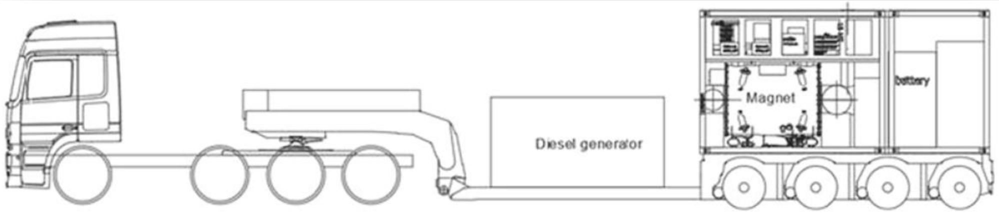
Wada and Yamazaki, NIM B 214 (2004) 196-200

> 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

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

The Transport: Cinema vs. Reality





- There is no connecting beam line between the 2 facilities
- Requirements:
  - → a transportable ion trap with sufficient storage capabilities (10^9 p̄)
  - → XHV vacuum conditions for the storage of antiprotons
  - → a detection system for monitoring annihilation rates during the transport

Movie

Reality

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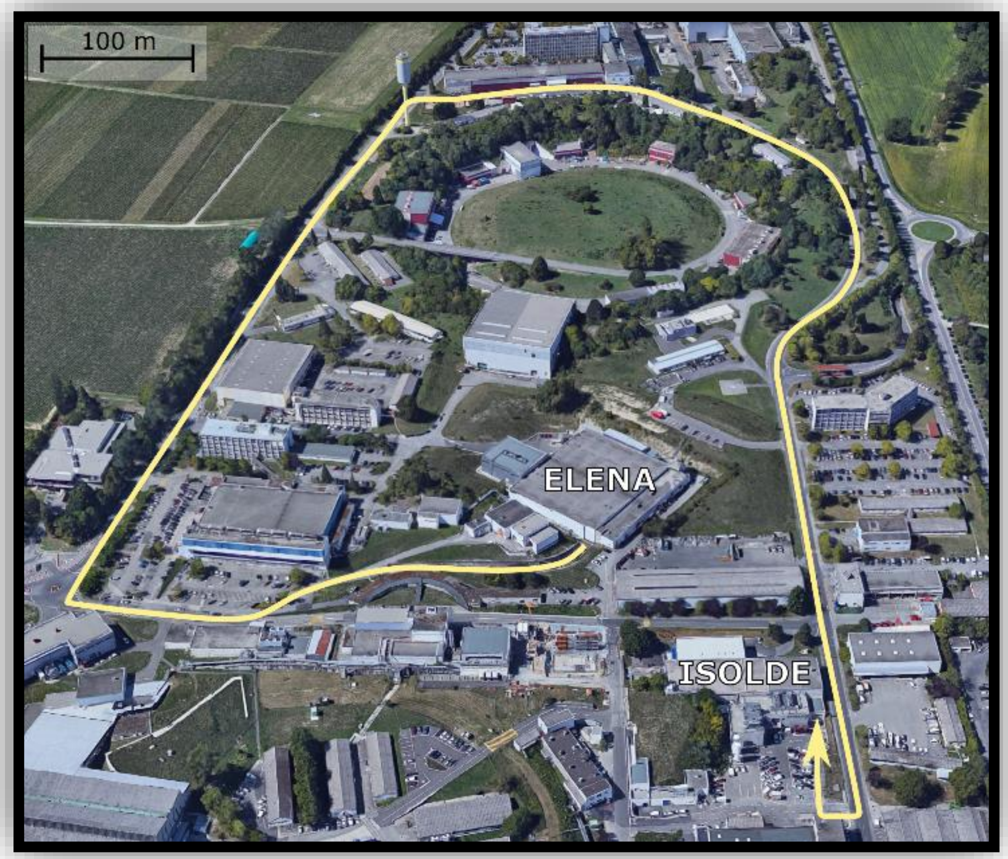
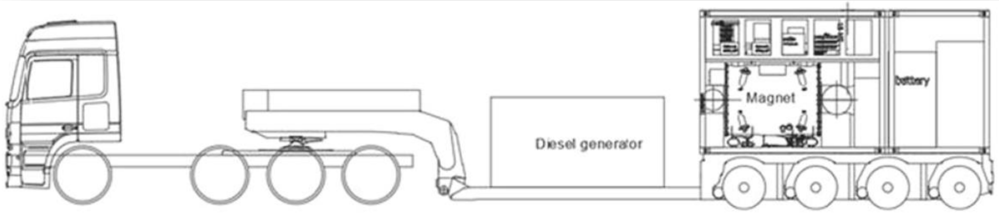
ISOLDE Collaboration

The Transport: Cinema vs. Reality





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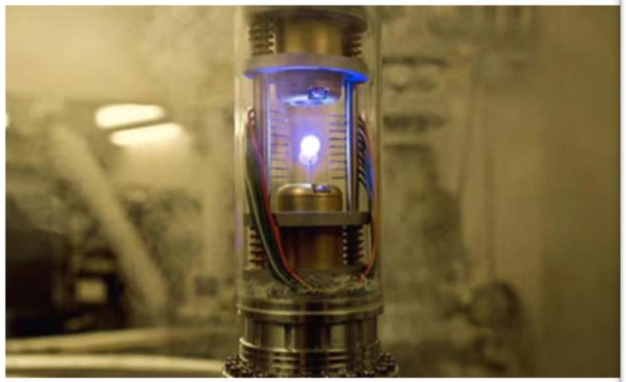


Movie

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)

Reality

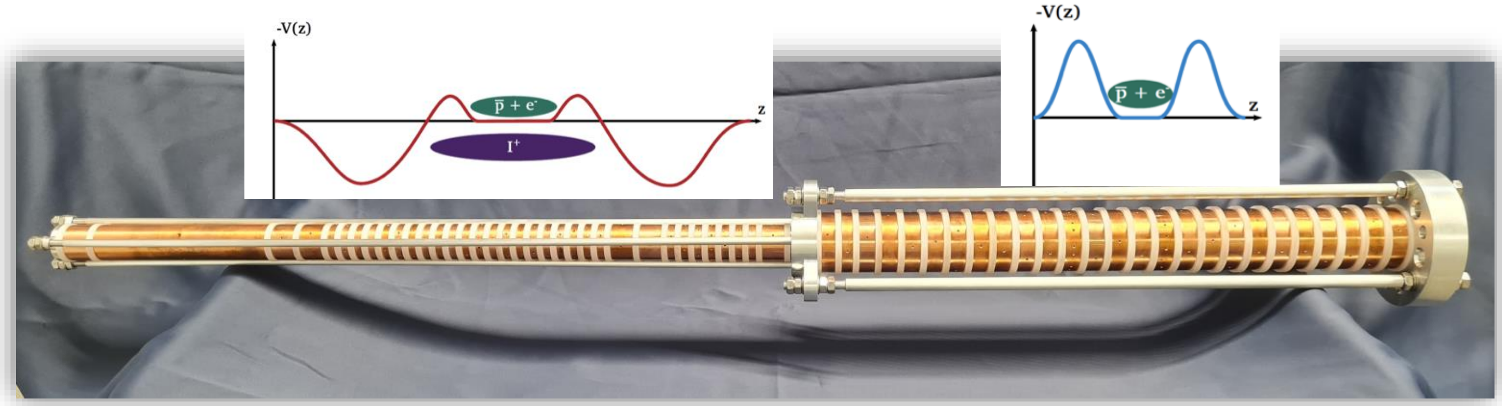
Lukas Nies
ISOLDE
Collaboration

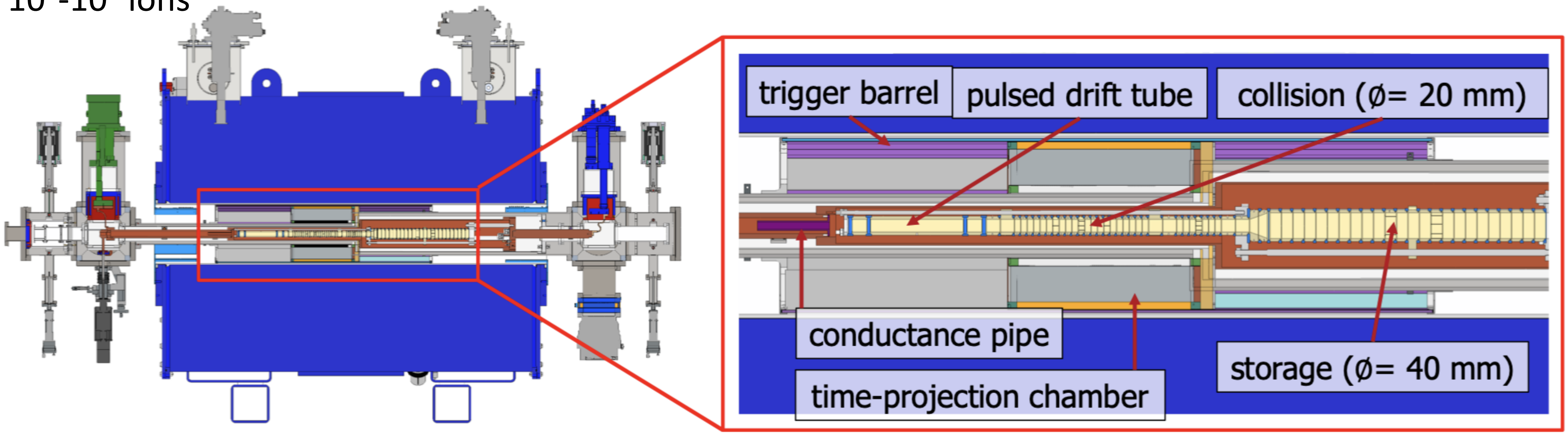
The Penning traps

- 4T superconducting NbTi magnet
- Cryogen-free design: cold mass of about 1750 kg

Objectives

- Store 10^7 antiprotons (1st stage)
- Store 10^9 antiprotons (2nd stage)
- Inject 10^4-10^5 ions





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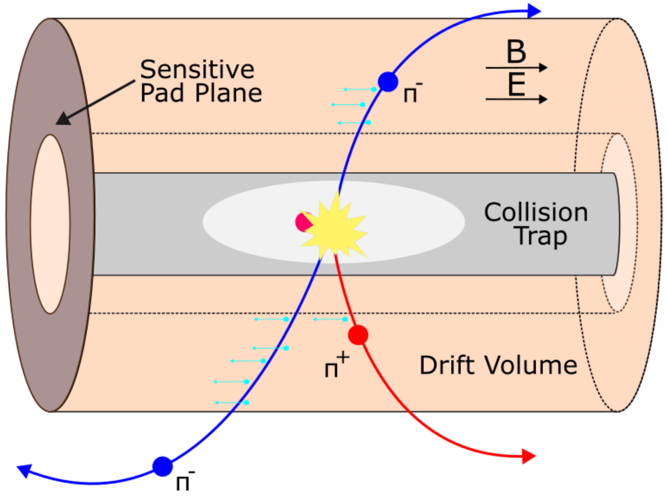
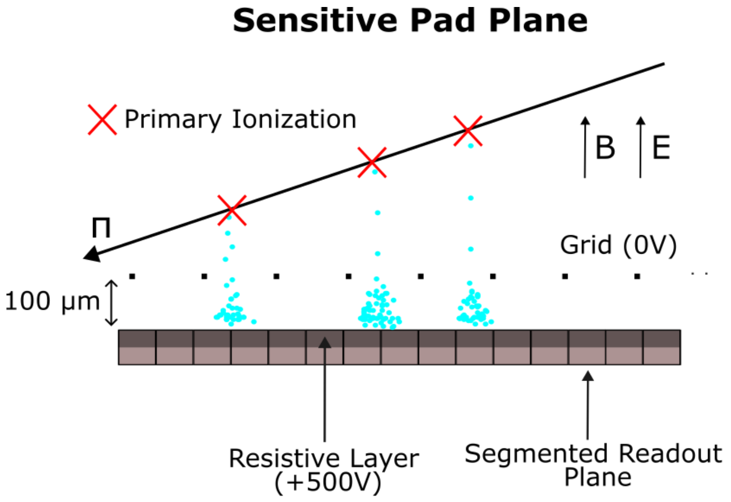
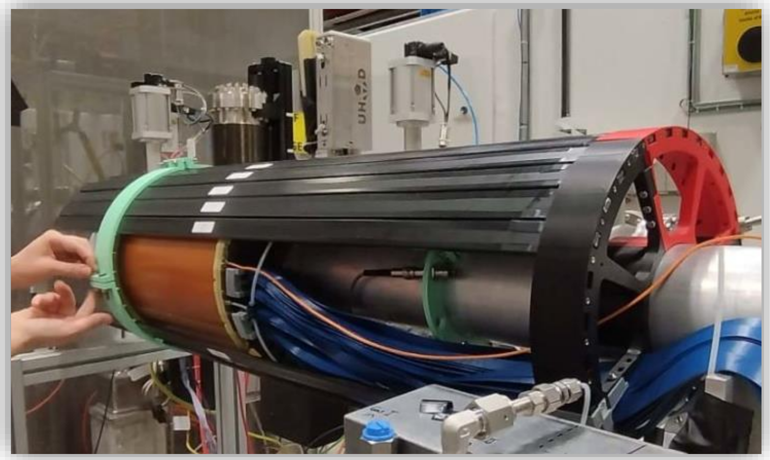
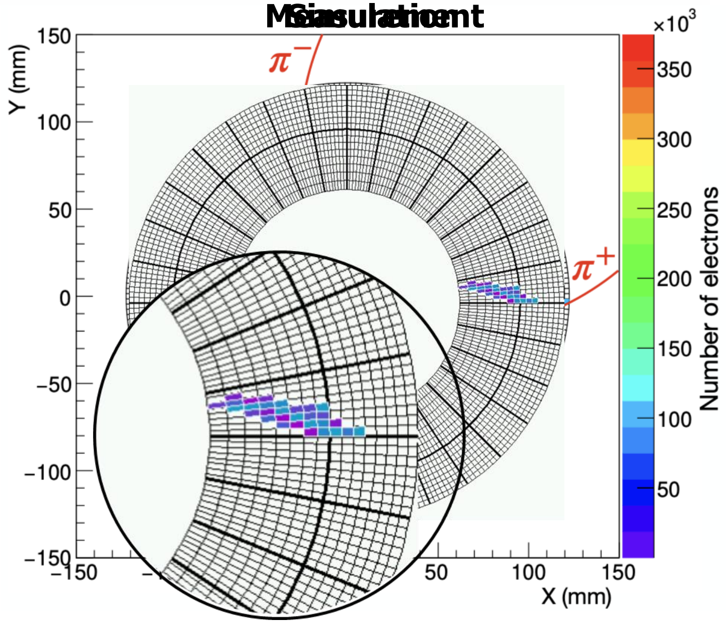
The Particle detectors



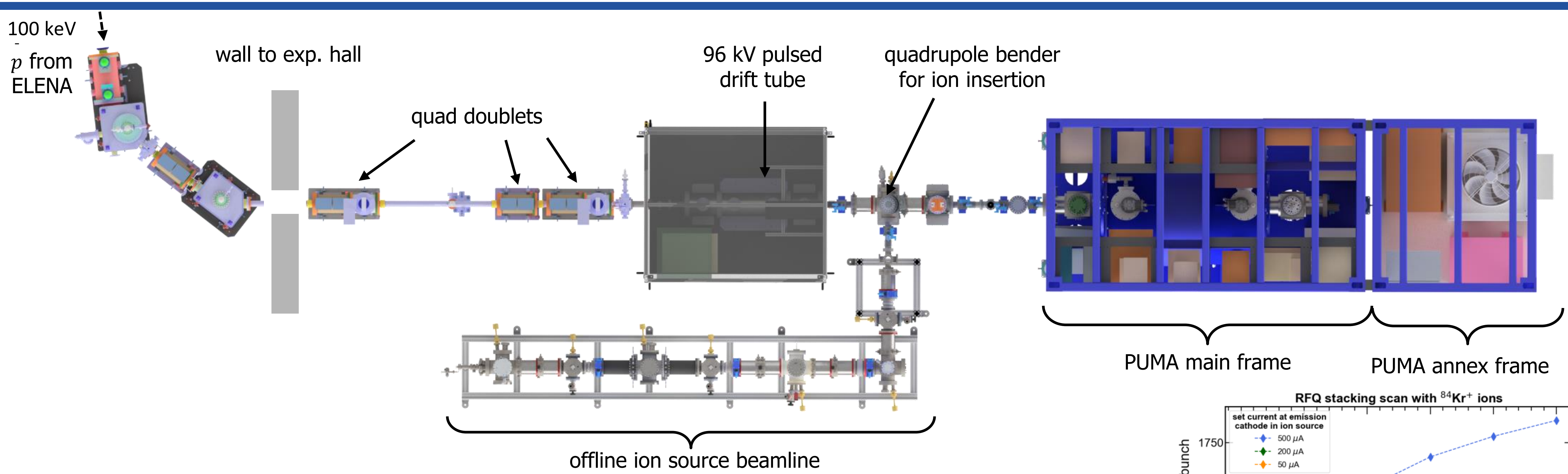


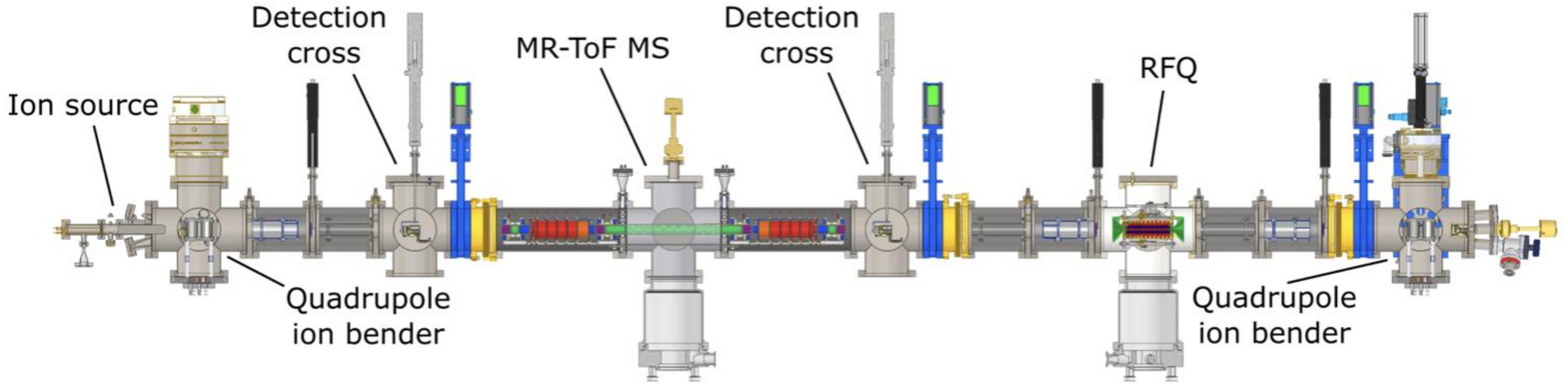


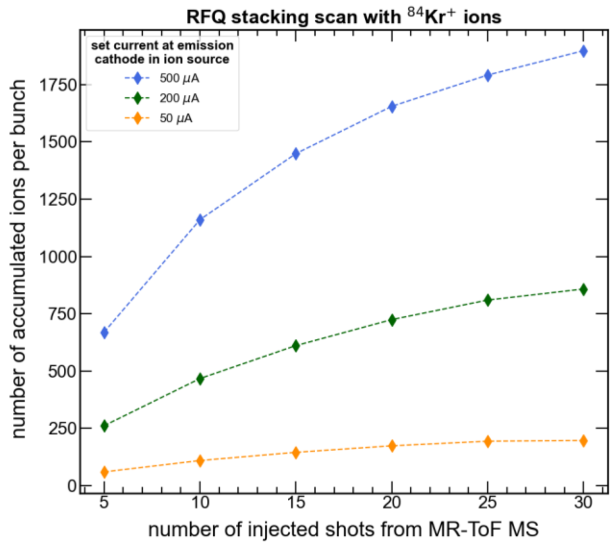


- Time Projection Chamber with trigger plastic barrel
- TPC developed at CERN → currently finalized
- Resistive micromegas → resolution < 400 µm
- ARC front end with stage chips (CEA, also used for T2K)

PUMA at ELENA

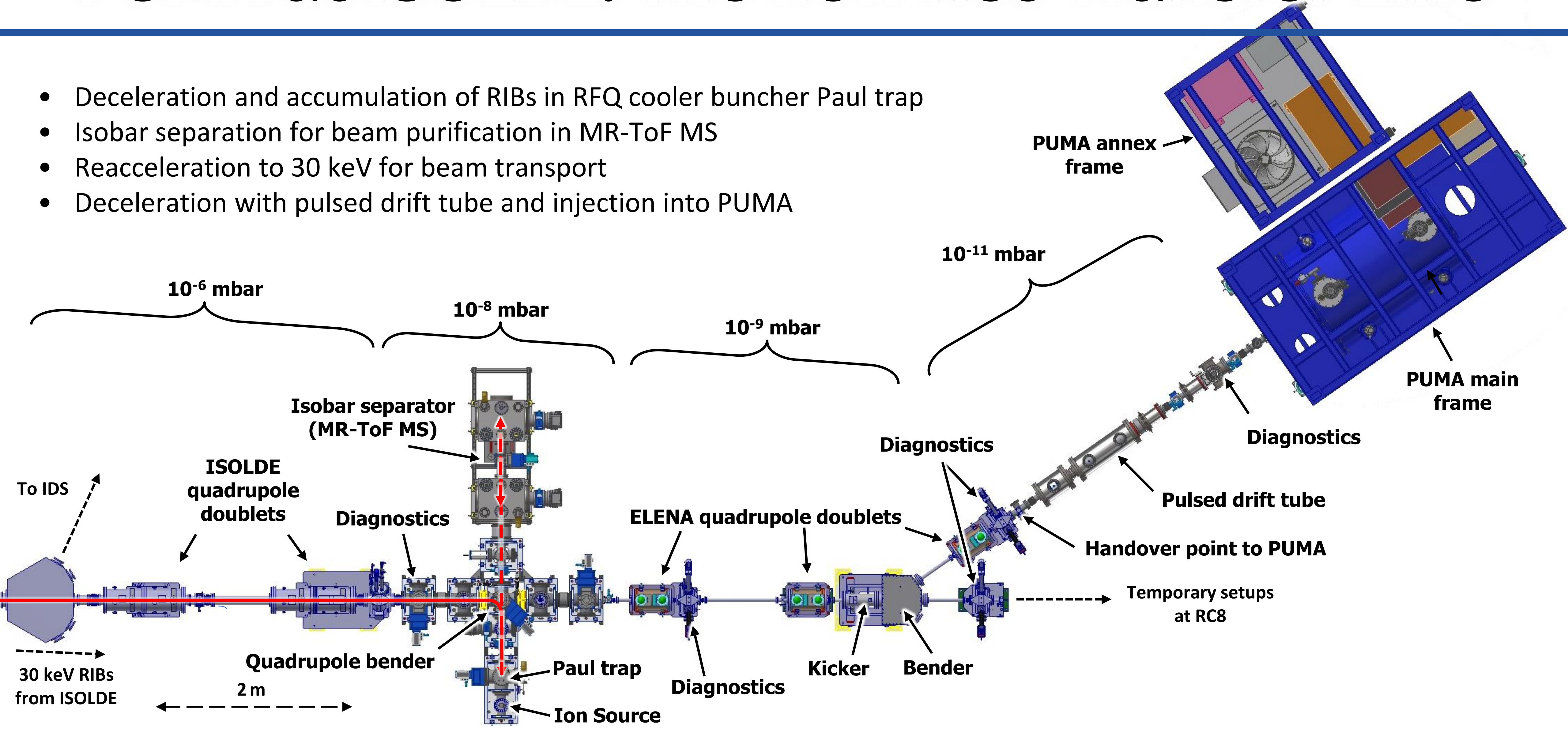






PUMA at ISOLDE: The new RC6 Transfer Line

- 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



Lukas Nies
ISOLDE Collaboration

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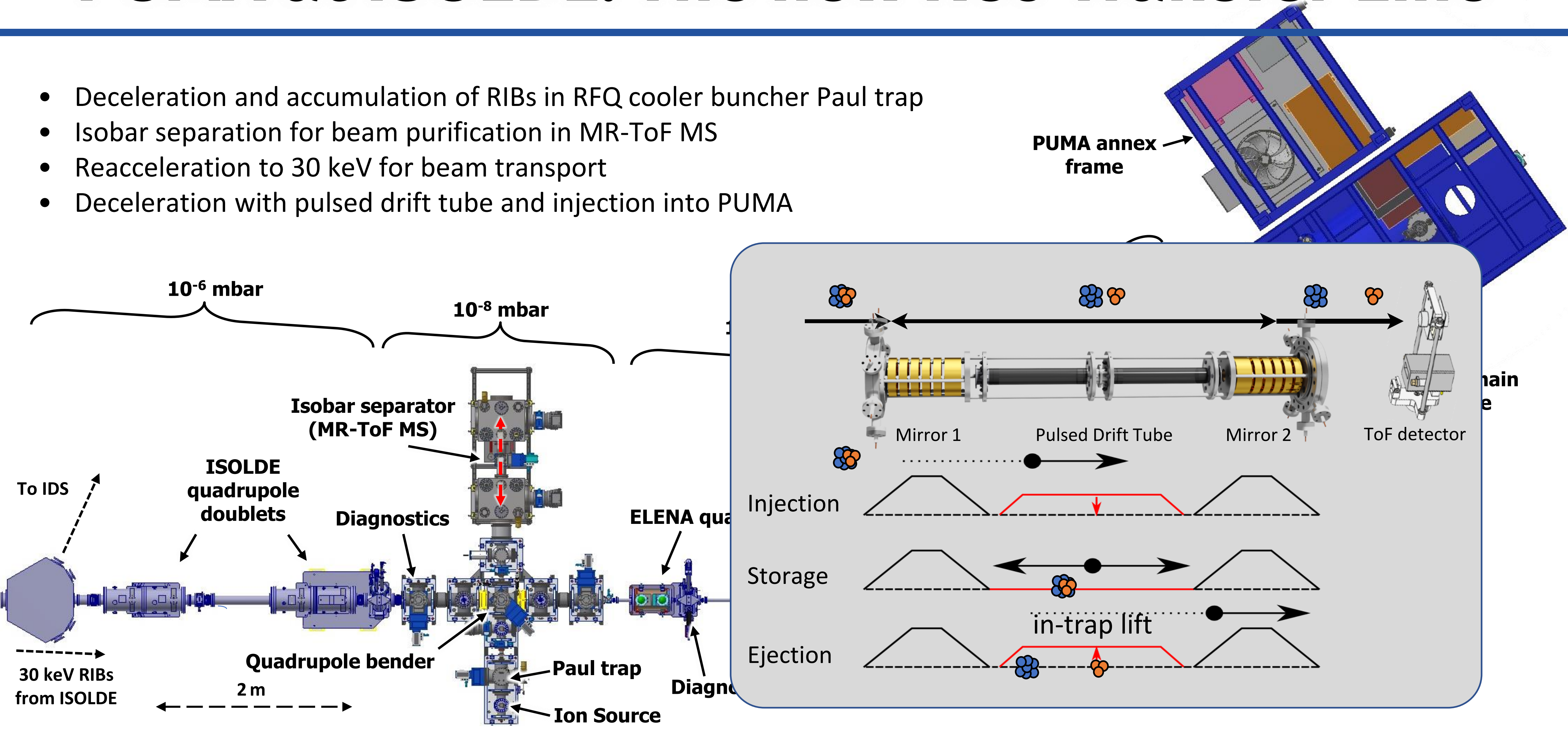

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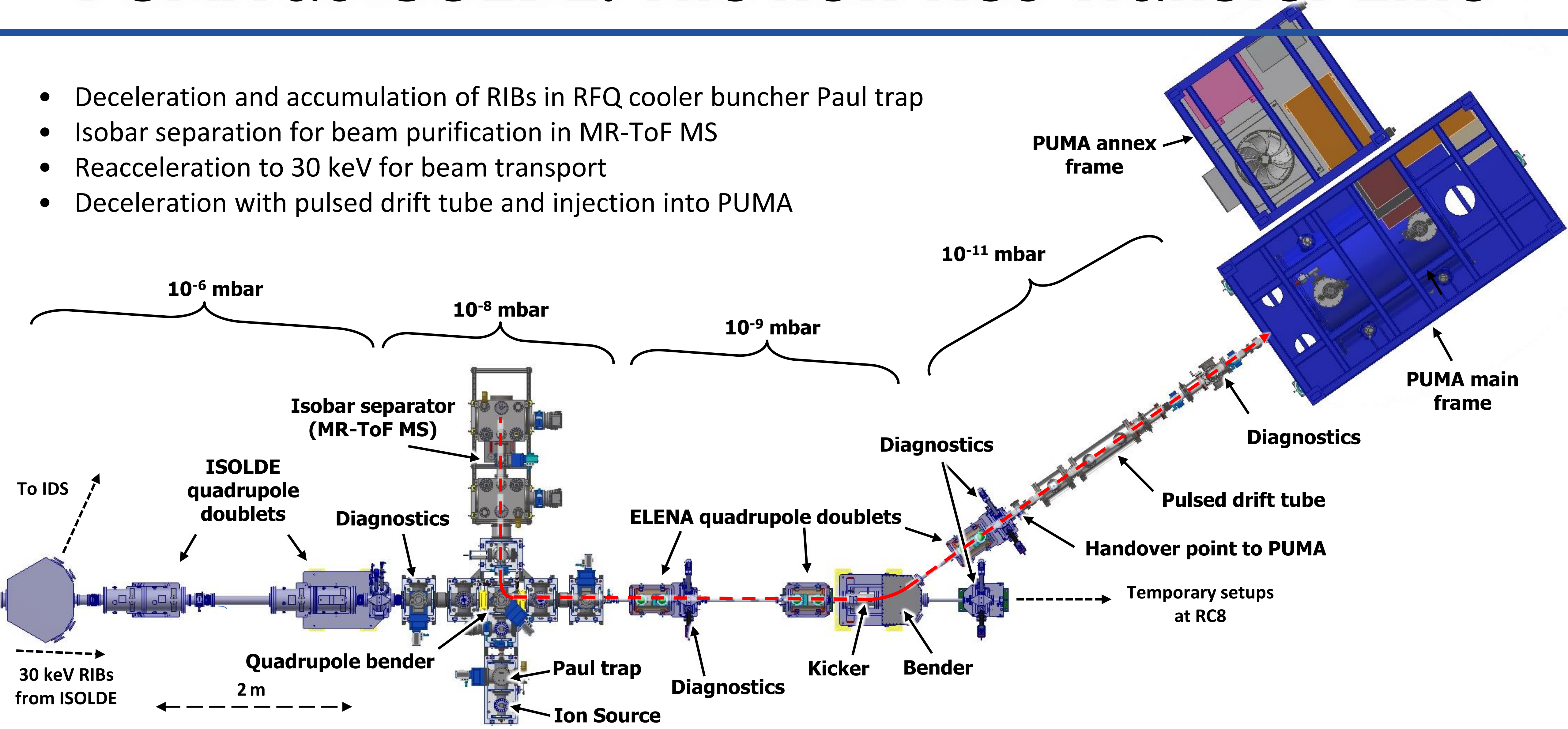

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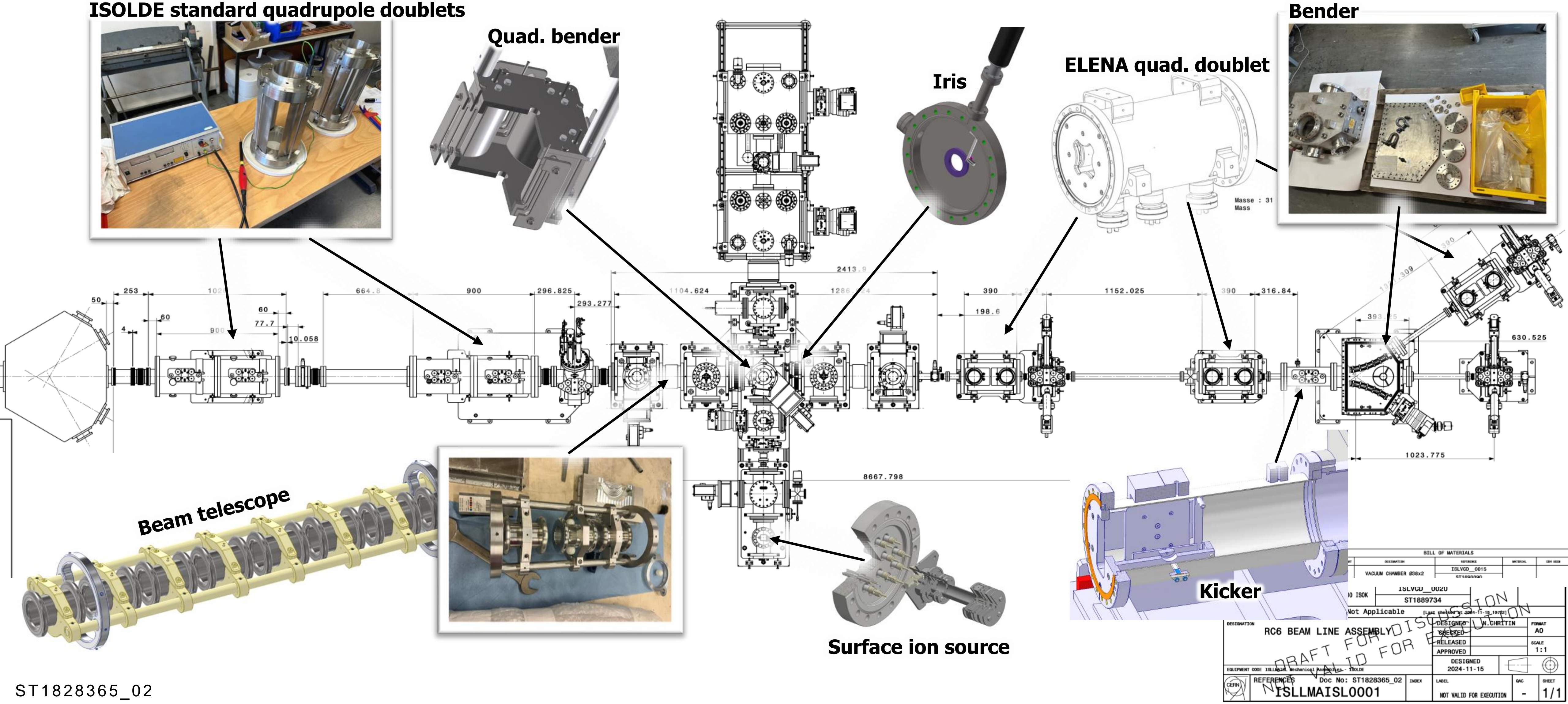
PUMA at ISOLDE: Optics, ion source



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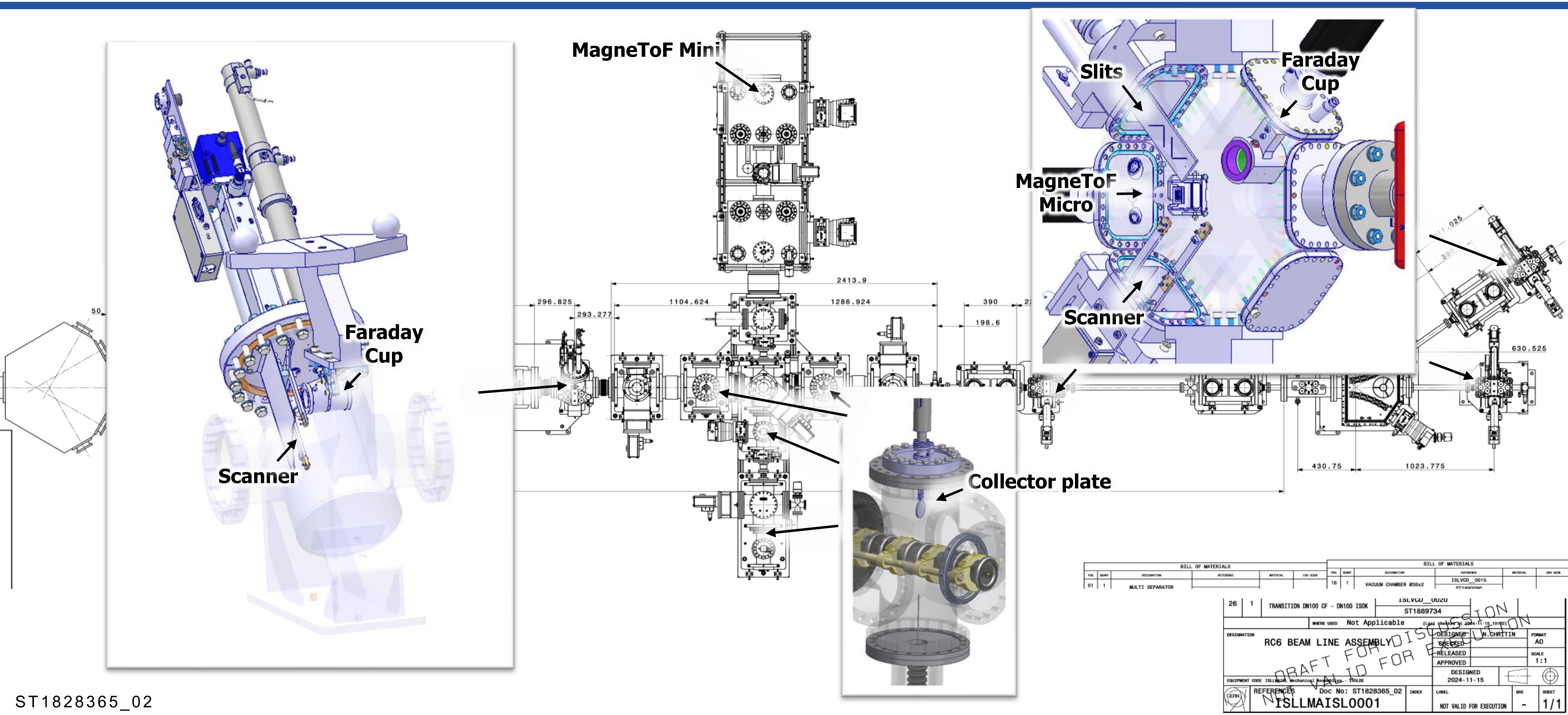
PUMA at ISOLDE: Diagnostics



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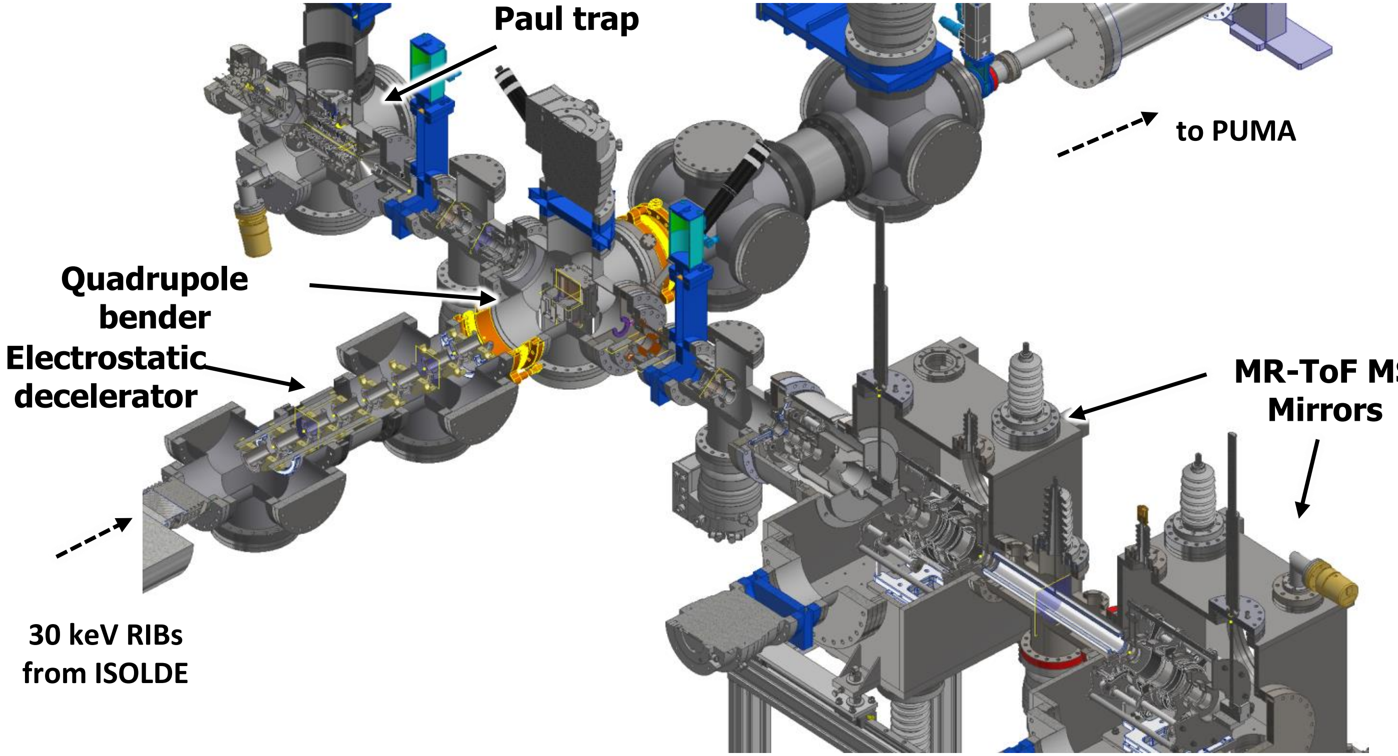
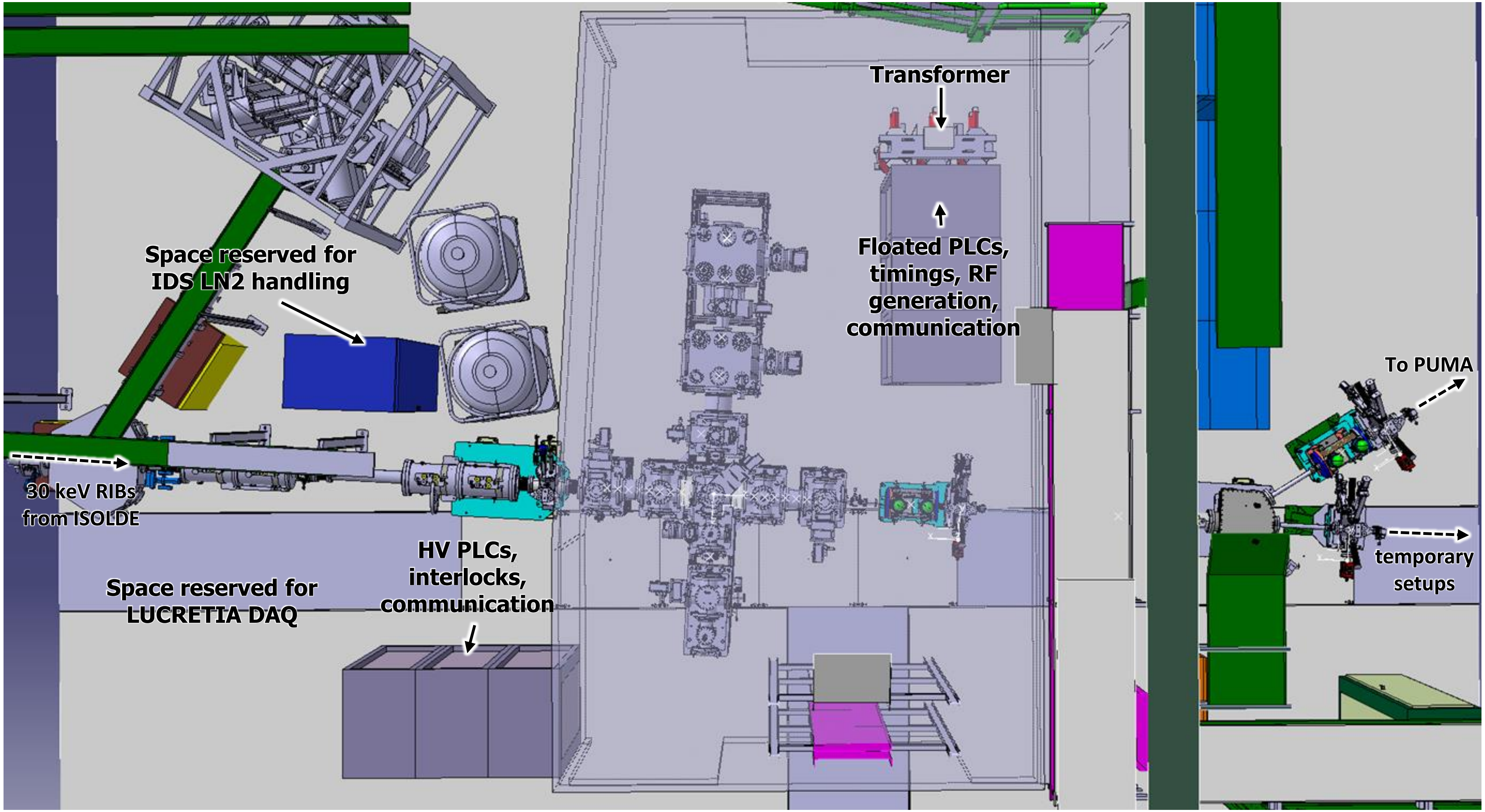
Isobar Separator: Expected Capabilities

- **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 (being investigated)
- **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



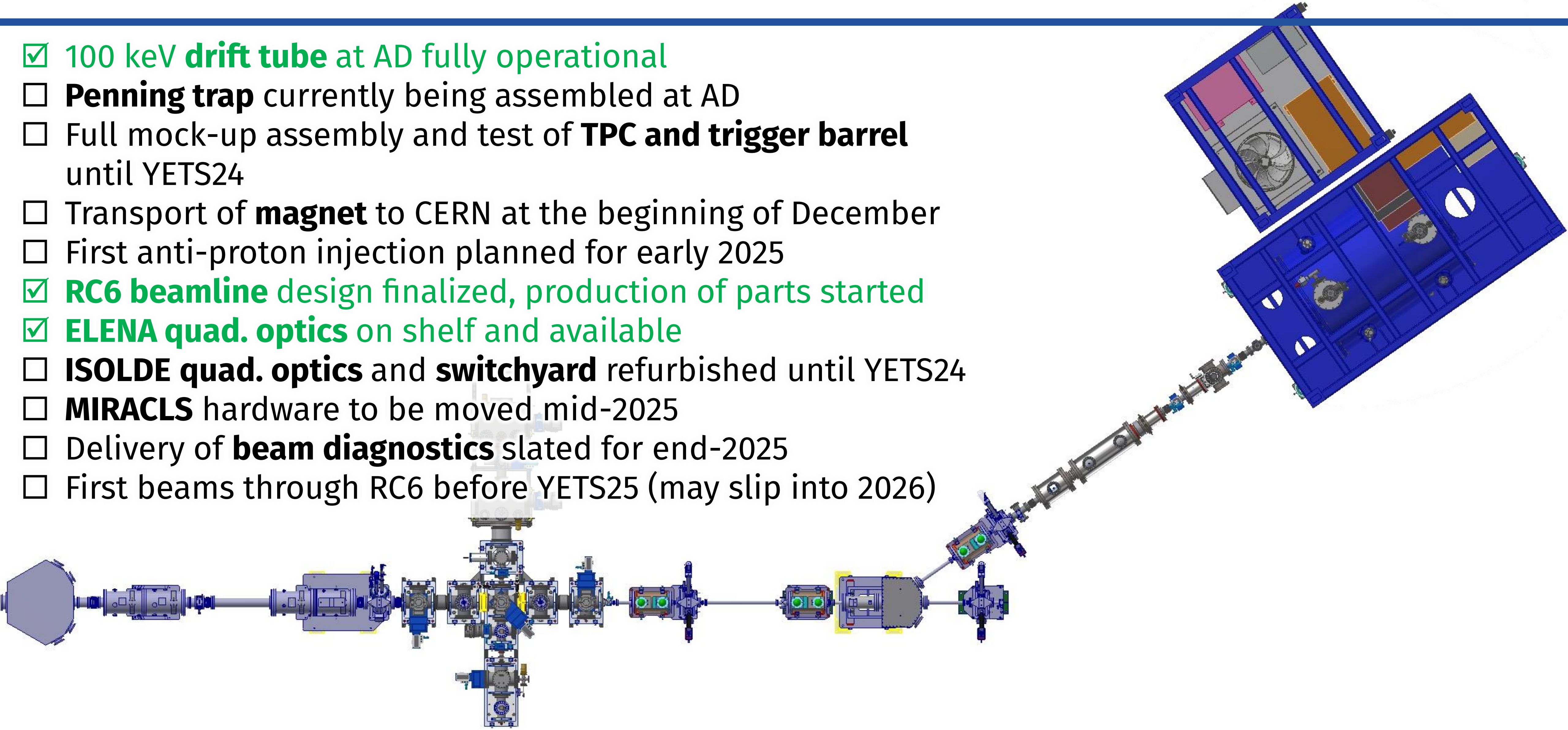
PUMA at ISOLDE: RC6 Integration



Lukas Nies
ISOLDE Collaboration

Outlook and Timeline

- ☑ 100 keV **drift tube** at AD fully operational
- ☐ **Penning trap** currently being assembled at AD
- ☐ Full mock-up assembly and test of **TPC and trigger barrel** until YETS24
- ☐ Transport of **magnet** to CERN at the beginning of December
- ☐ First anti-proton injection planned for early 2025
- ☑ **RC6 beamline** design finalized, production of parts started
- ☑ **ELENA quad. optics** on shelf and available
- ☐ **ISOLDE quad. optics** and **switchyard** refurbished until YETS24
- ☐ **MIRACLS** hardware to be moved mid-2025
- ☐ Delivery of **beam diagnostics** slated for end-2025
- ☐ First beams through RC6 before YETS25 (may slip into 2026)



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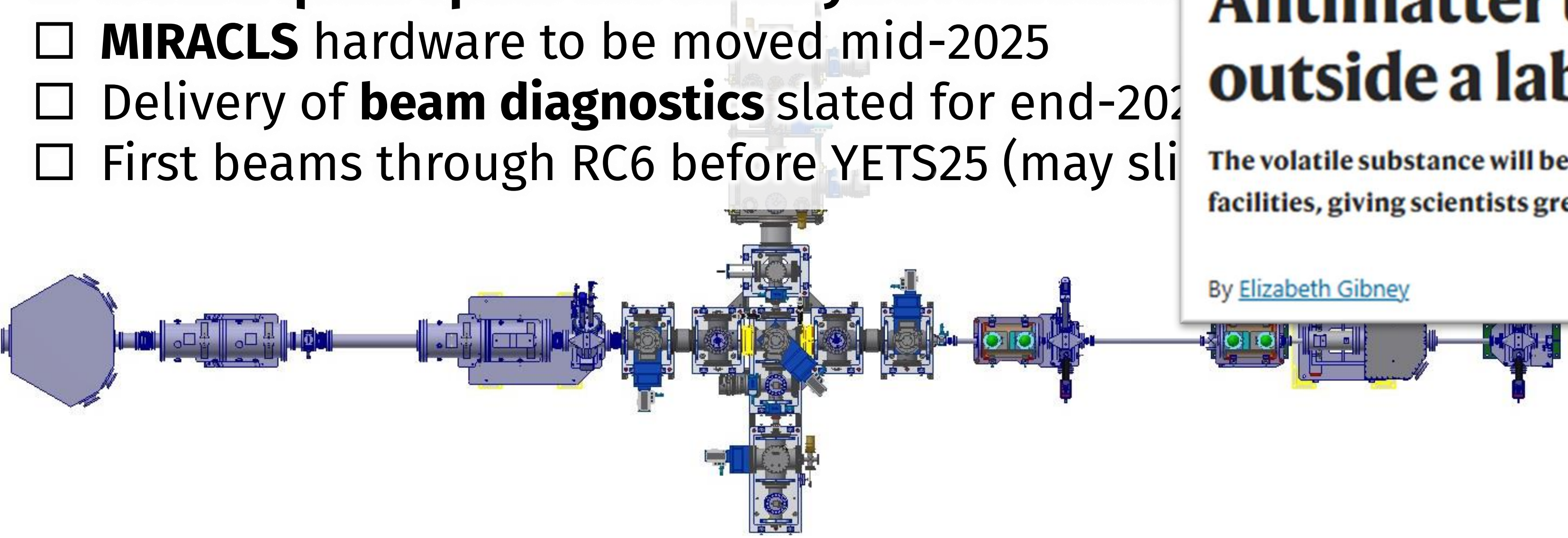

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NEWS | 26 November 2024

Antimatter to be transported outside a lab for first time – in a ~~van~~ truck!!

The volatile substance will be driven across the CERN campus in trucks to different facilities, giving scientists greater opportunities to study it.

By Elizabeth Gibney

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, **R. Holz**, 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, **L. Nies**, **A. Obertelli**, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, L. Riik, D. Rossi, **R. Sangani**, 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**

The ISOLDE-RC6 Team

O. Aberle, W. Andreazza, P. Arrutia, N. Azaryan, V. Barozier, W. Bartmann, M. Bissel, A. Boucherie, C. Capelli, N. Chritin, N. David, Q. Demassieux, J. A. Ferreira Somoza, I. Kozsar, Grzegorz Kruk, M. Kowalska, S. Lechner, F. M. Maier, S. Malbrunot-Ettenauer, A. Martinez De Zuazo Martinez, P. Martins, S. Mataguez, A. Michet, **L. Nies**, M. Nieto, B. Ninet, C. Pasquino, E. Piselli, R. Rinaldesi, A. Roitman, **E. Siesling**, J. Tassan-Viol, M. Vilén, F. Wienholtz

Backup

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!

PUMA aims to:

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

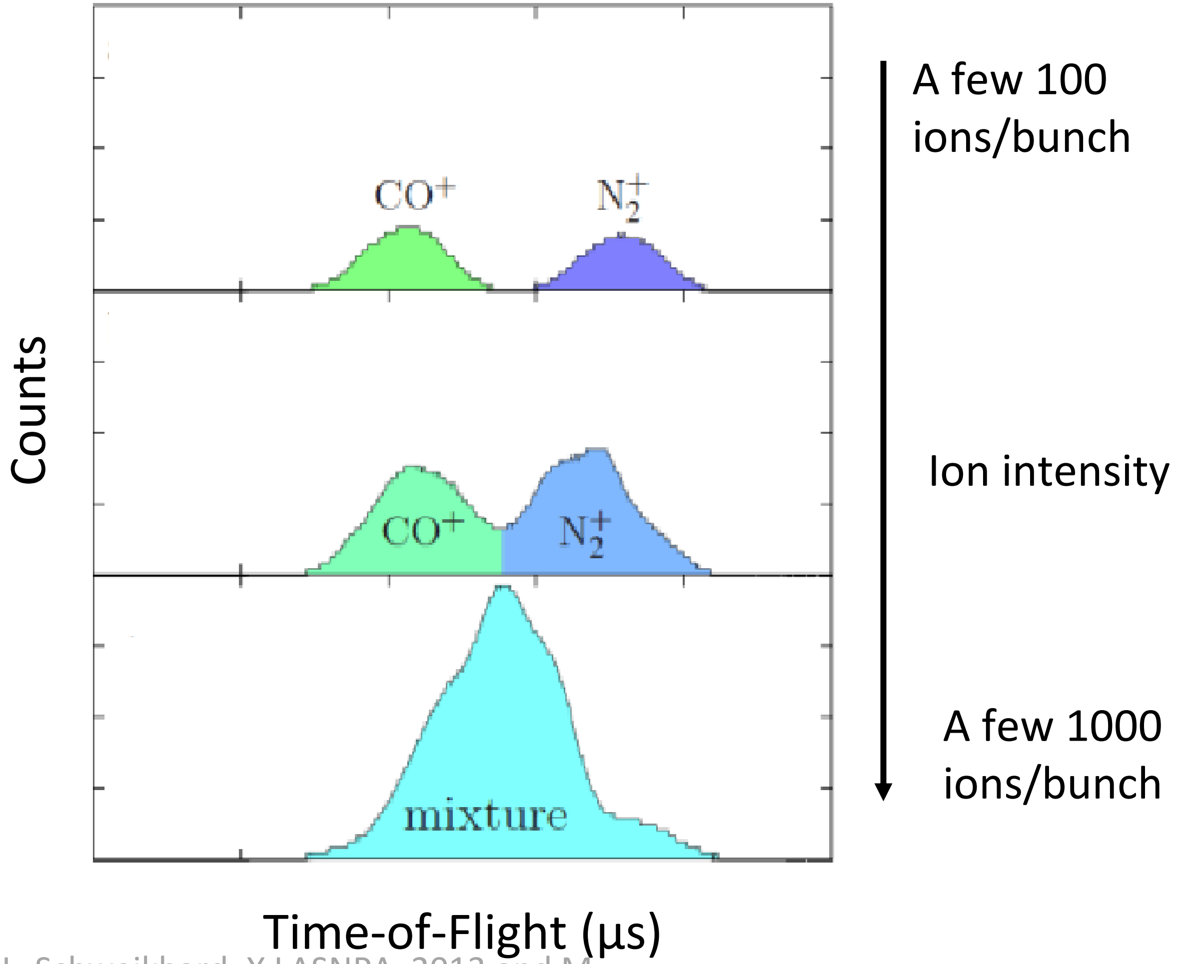
antiproton-proton		antiproton-neutron	
Pion Final State	**Branching**	**Pion Final State**	**Branching**
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0,233	$\pi^-\pi^-\pi^+k\pi^0(k>1)$	0,397
$\pi^+\pi^-\pi^+\pi^-\pi^0$	0,196	$\pi^-\pi^-\pi^+\pi^0$	0,17
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	0,166	$\pi^-k\pi^0(k>1)$	0,169

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

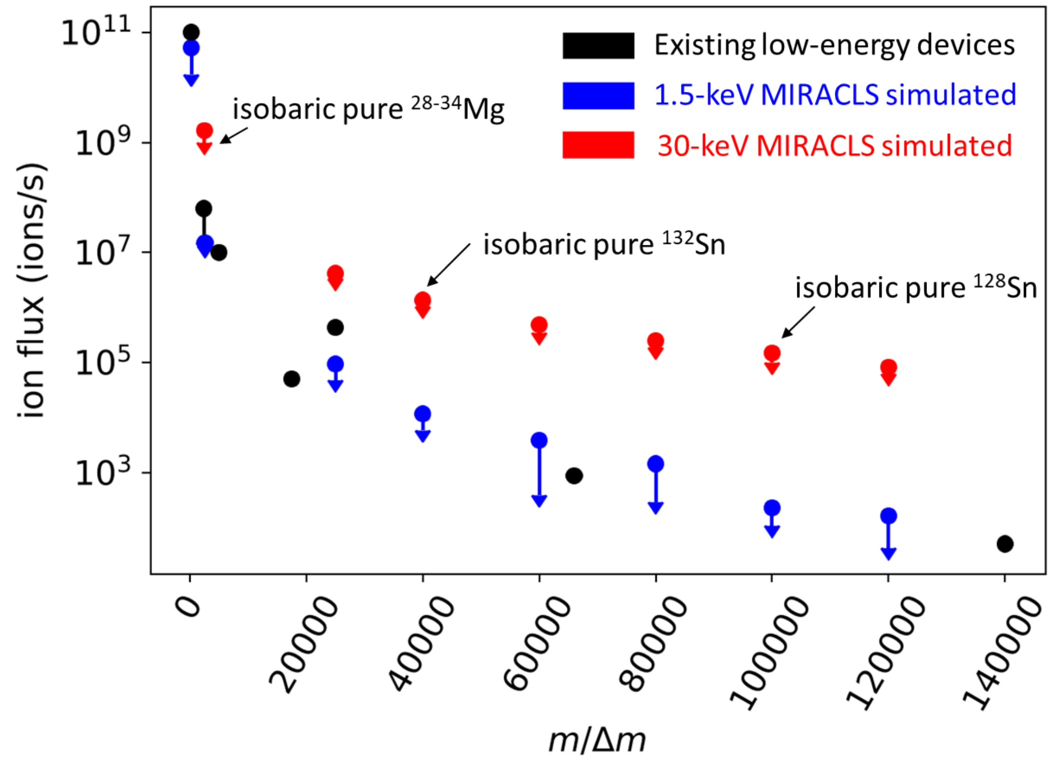
T. Aumann et al., Eur. Phys. J. A (2022) 58 :88

Space Charge Limit on Ion Flux

Experimental studies with m/Δm ≈ 2500:



L. Schweikhard, X LASNPA, 2013 and M. Rosenbusch, AIP Conf. Proc. 1521, 53–62 (2013)



- Coulomb interaction of stored charges leads to smearing of bunch structure
- Ion optical simulations show: higher beam energy yields higher ion flux

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

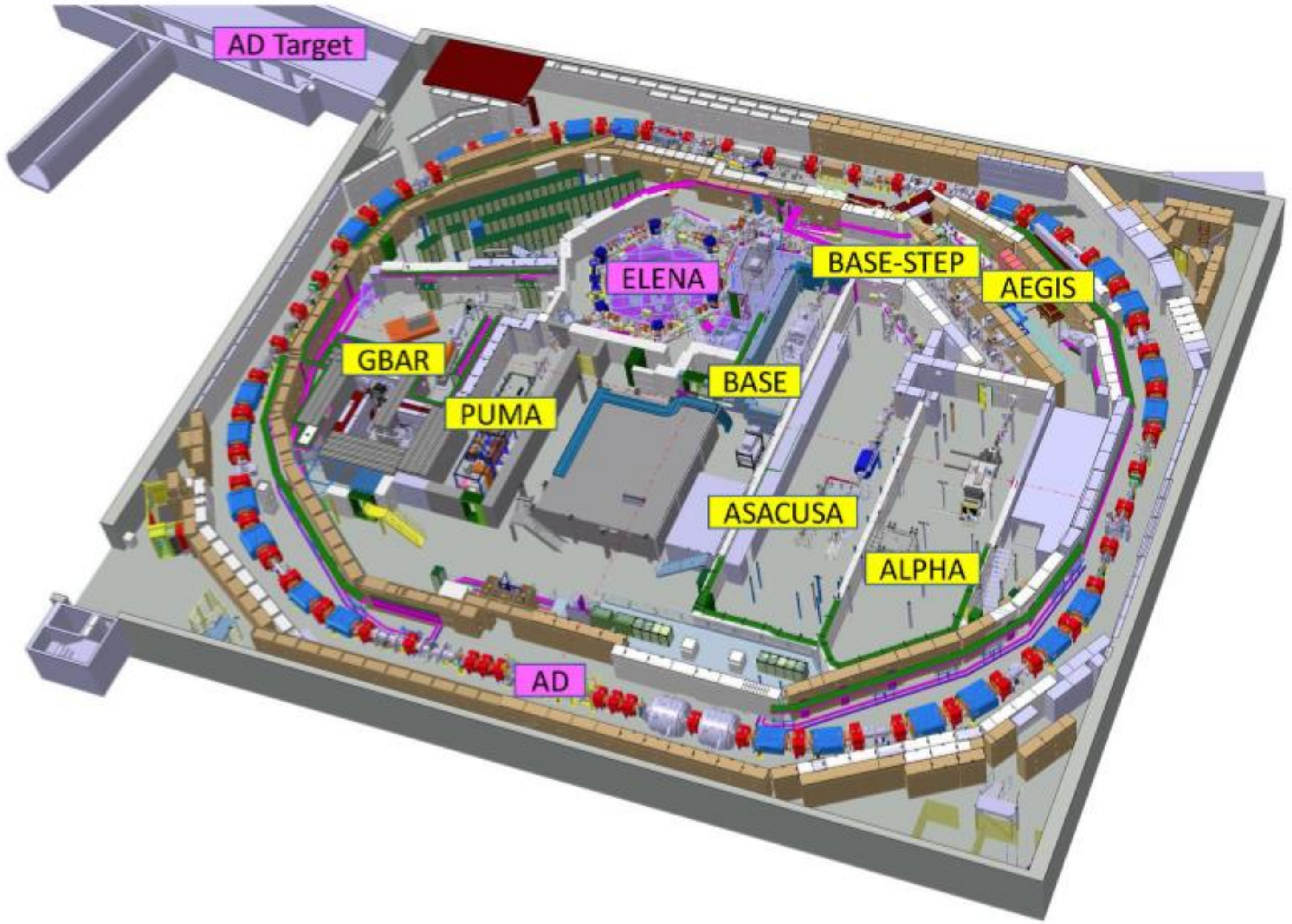
Deceleration of $\bar{p}$:

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

Duty cycle of ELENA:

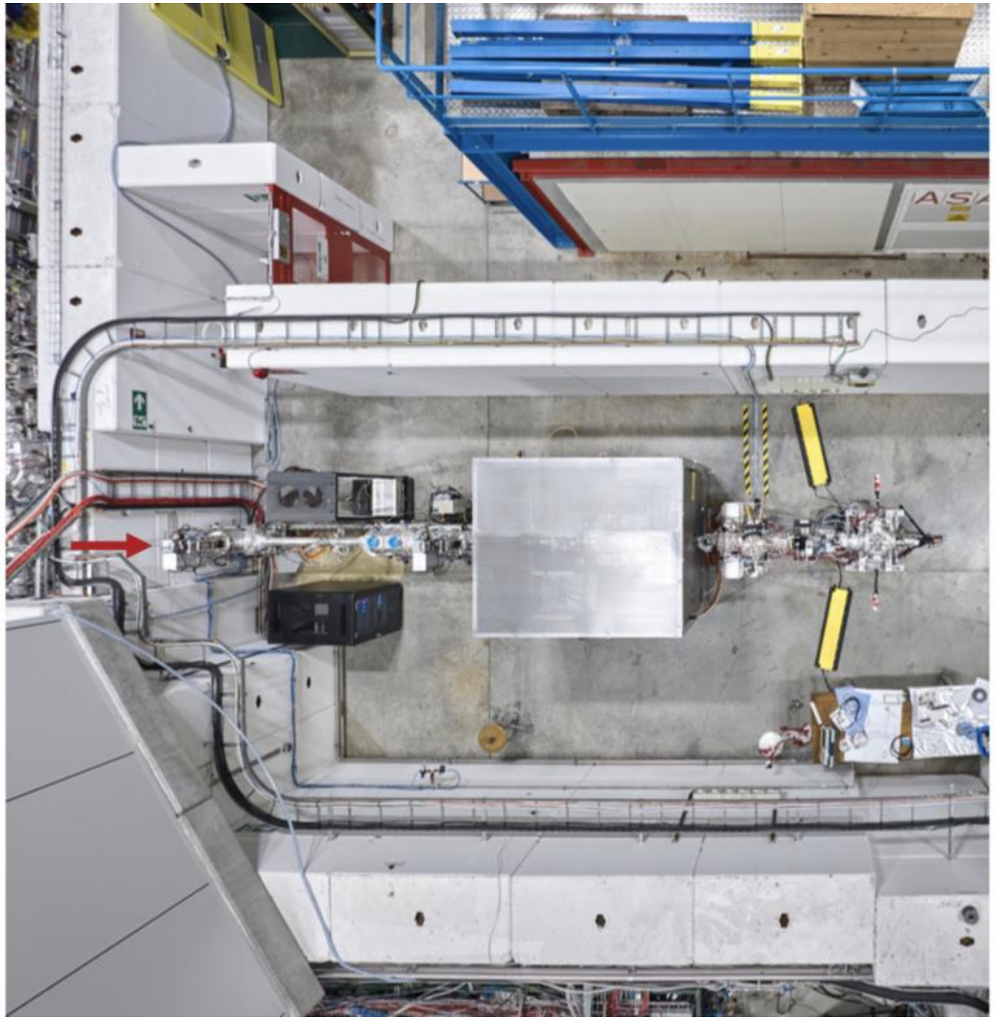
4x $4 \cdot 10^{6}$ bunches every 110s

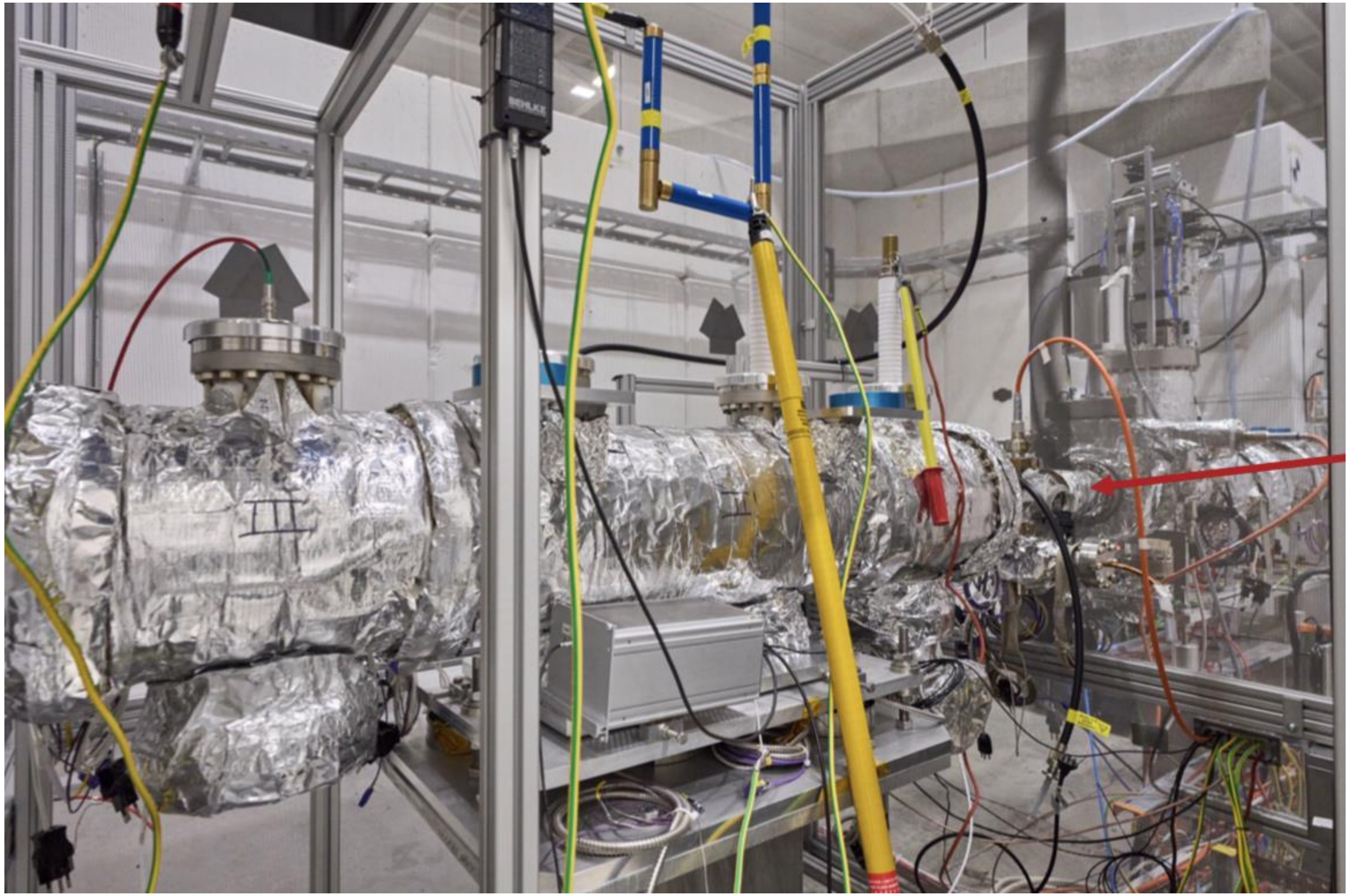
Possibility to use 100 keV H- every 20 seconds



Slide by C. Klink (BE-EA)

PUMA at the AD

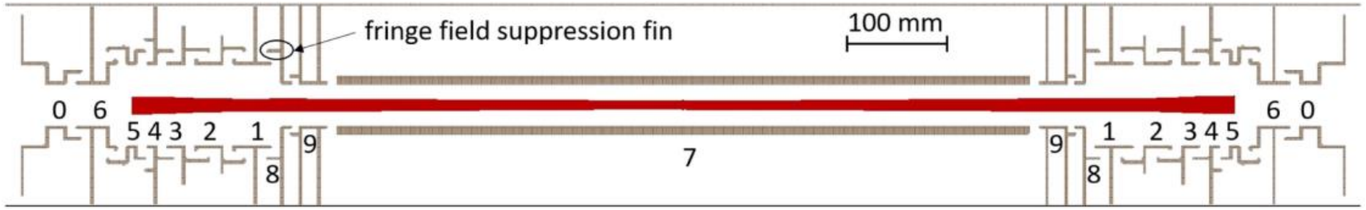


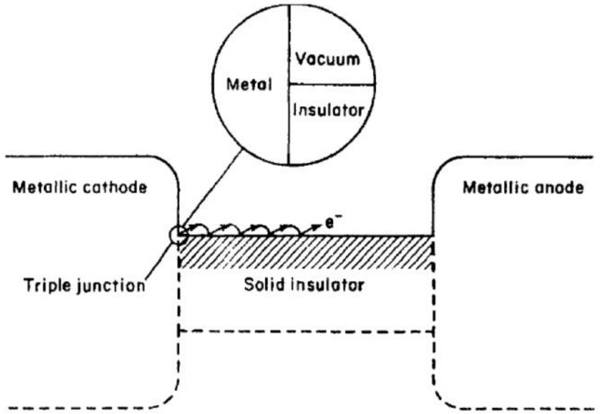


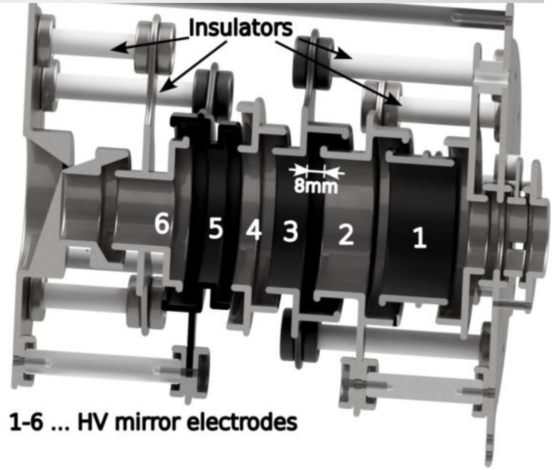
Slide by C. Klink (BE-EA)

Towards a High-Flux MR-ToF device

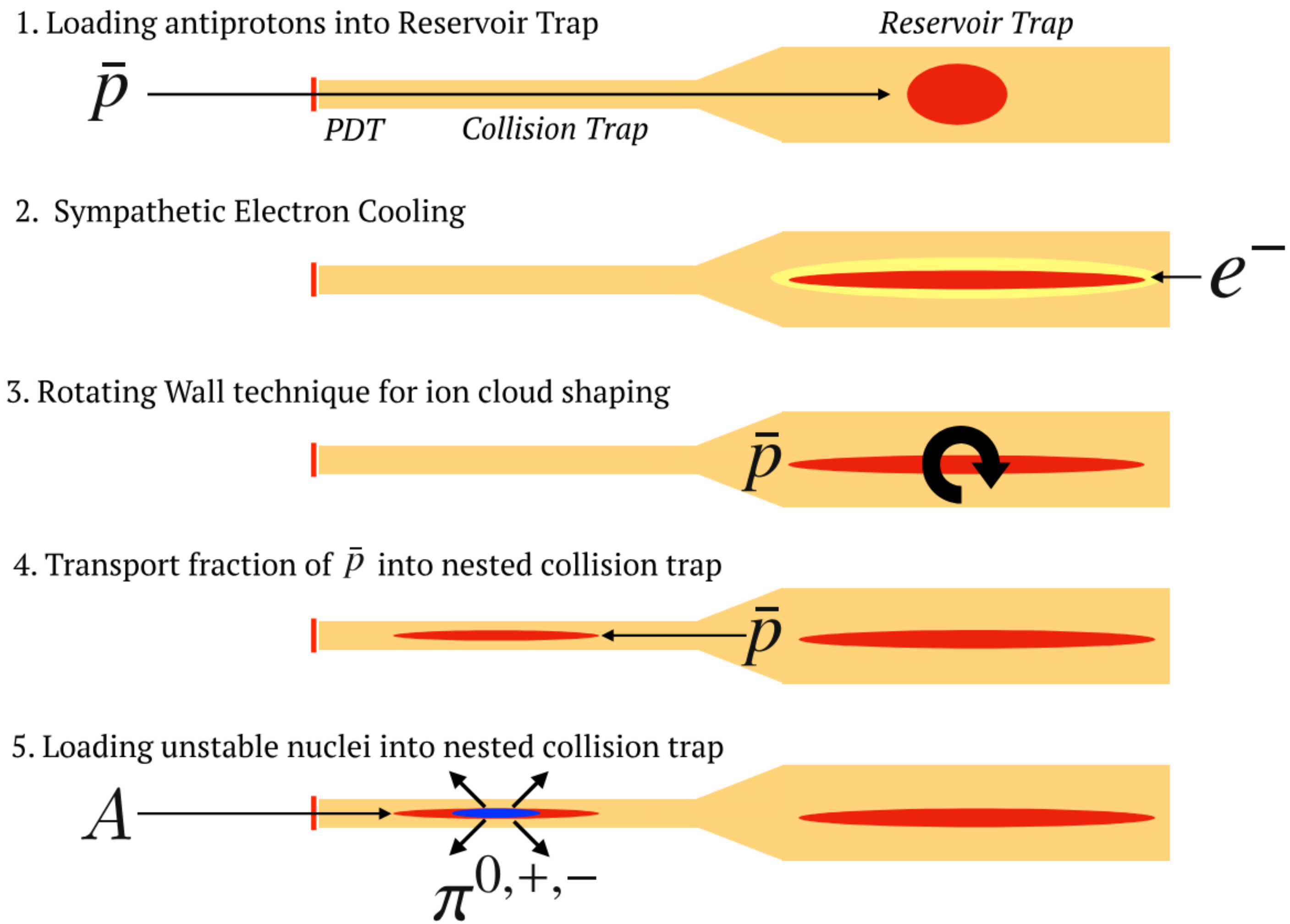
- Two main challenges:
  - Triple junction
  - Vacuum gap
- Cup design for triple junction held 60 kV in test setup
- Discharge between electrode vacuum gap at 12 to 21 kV limited MR-ToF operation to < 10 keV in 2023
- Recent upgrade: Electropolishing of all electrodes
- Both mirrors **stable for 11 keV** beam energy and max. 35 kV between 2 electrodes during the last 12 months
- Tests for **18 keV beam energy** show stable mirrors for 2 days, after which the test was ended







Mixing Matter and Antimatter

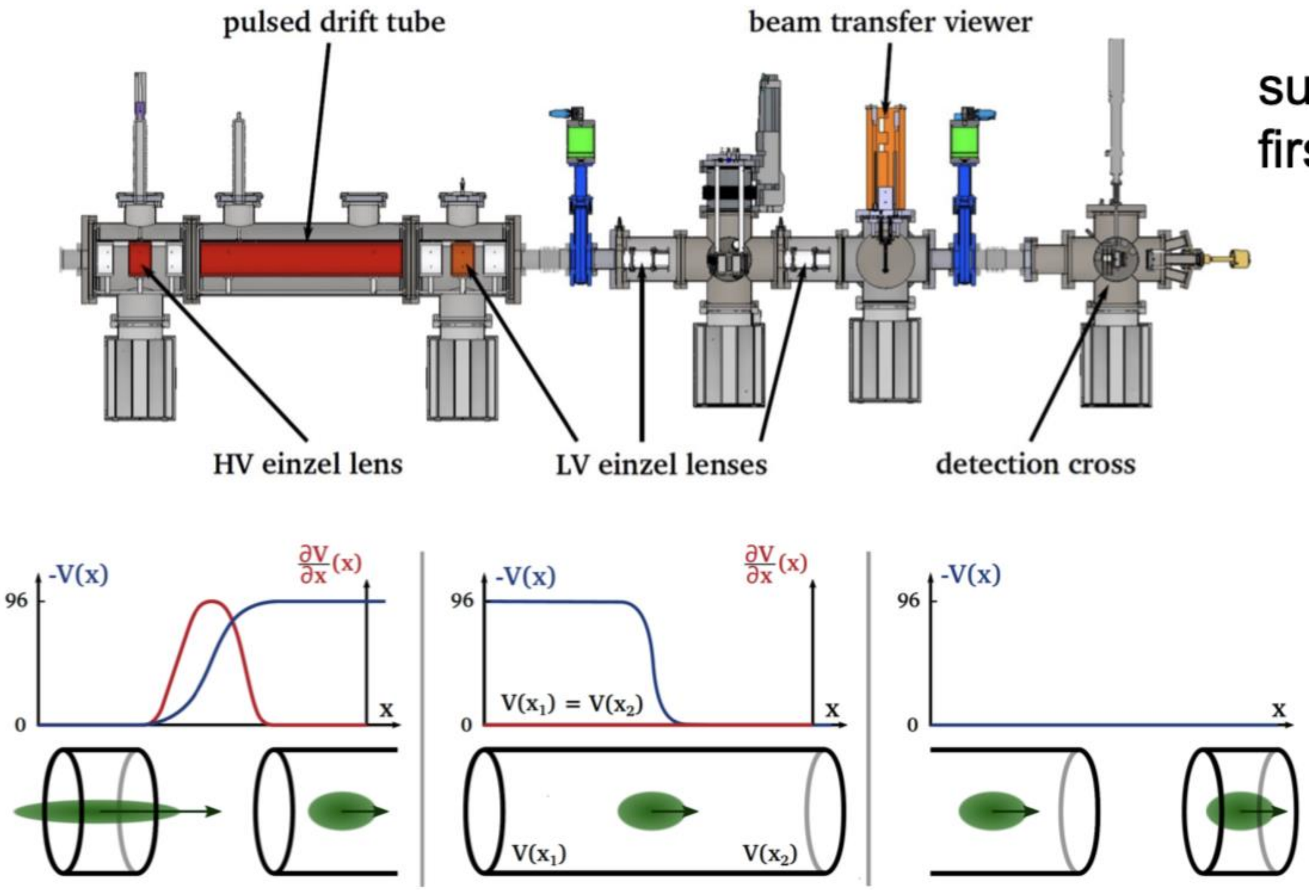


T. Aumann et al., Eur. Phys. J. A (2022) 58 :88

- 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

Pulsed Drift Tube for p̄

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



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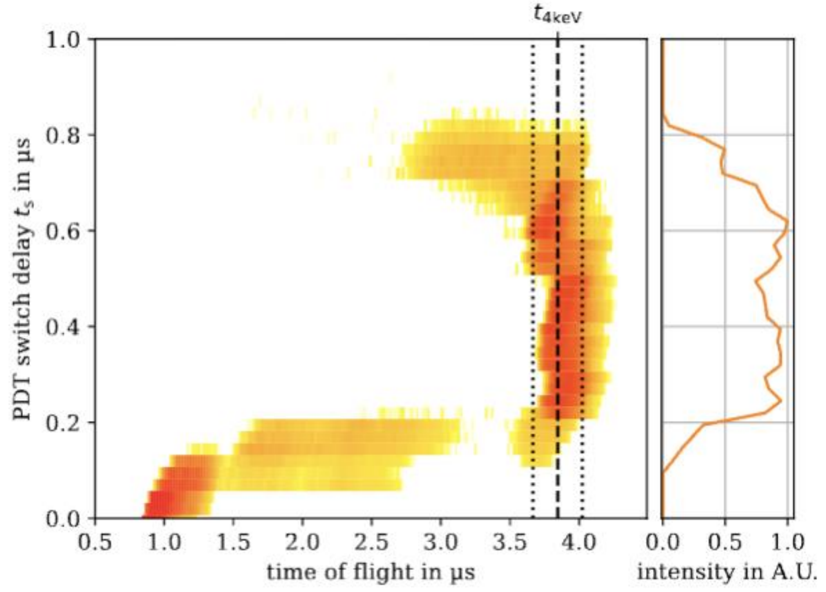
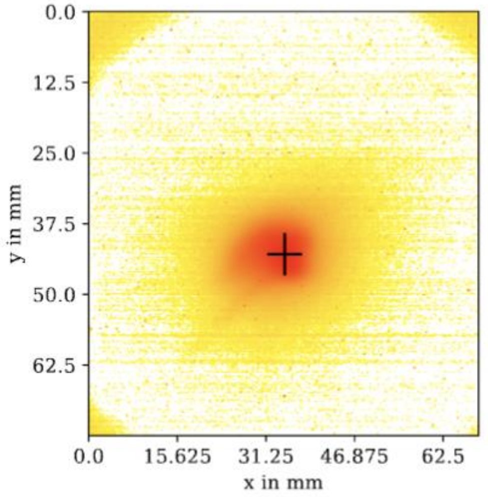
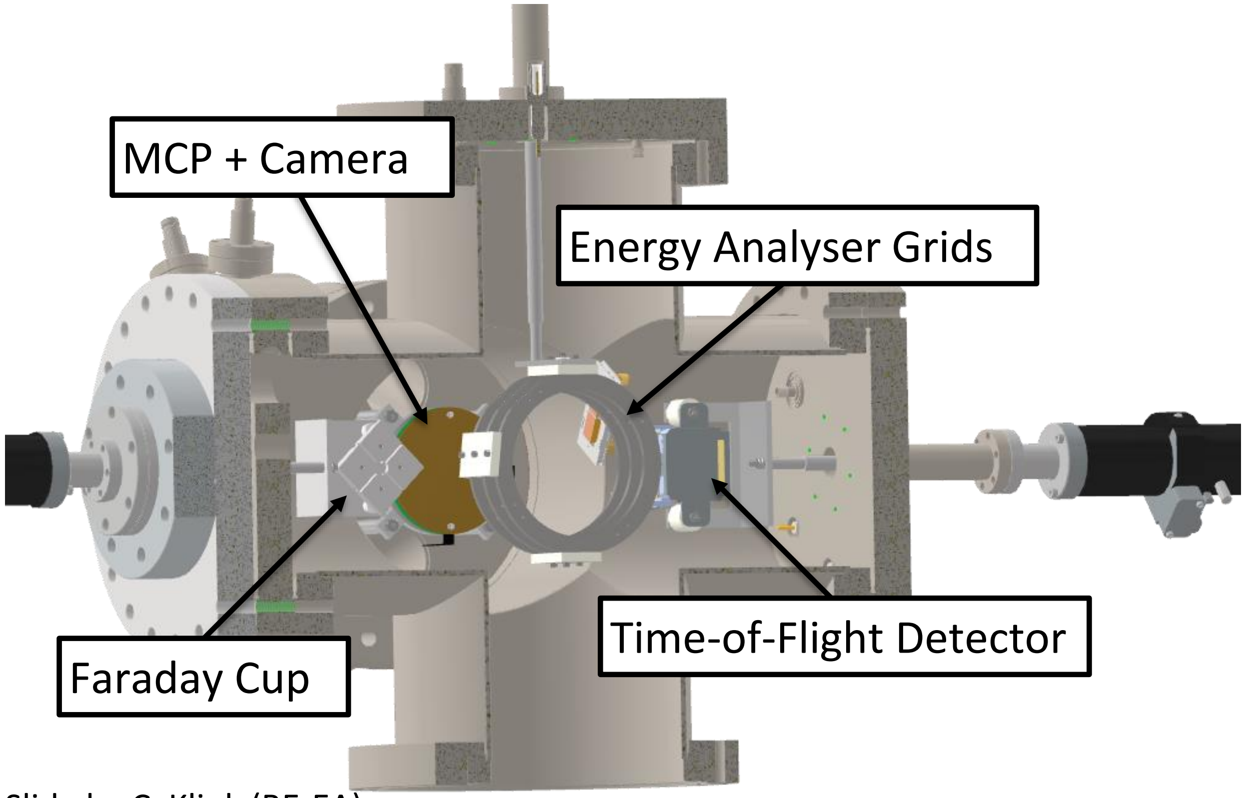


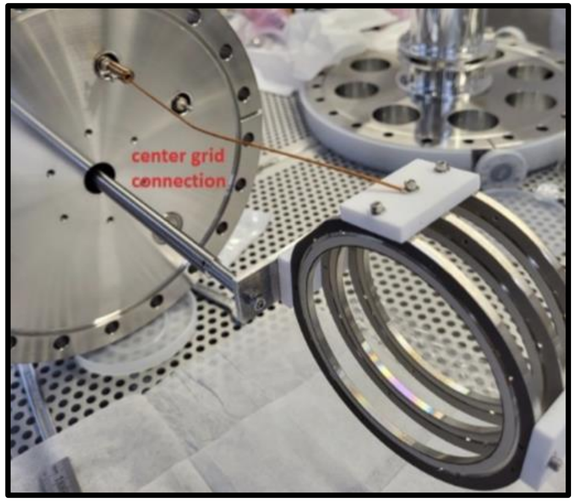


Slide by C. Klink (BE-EA)

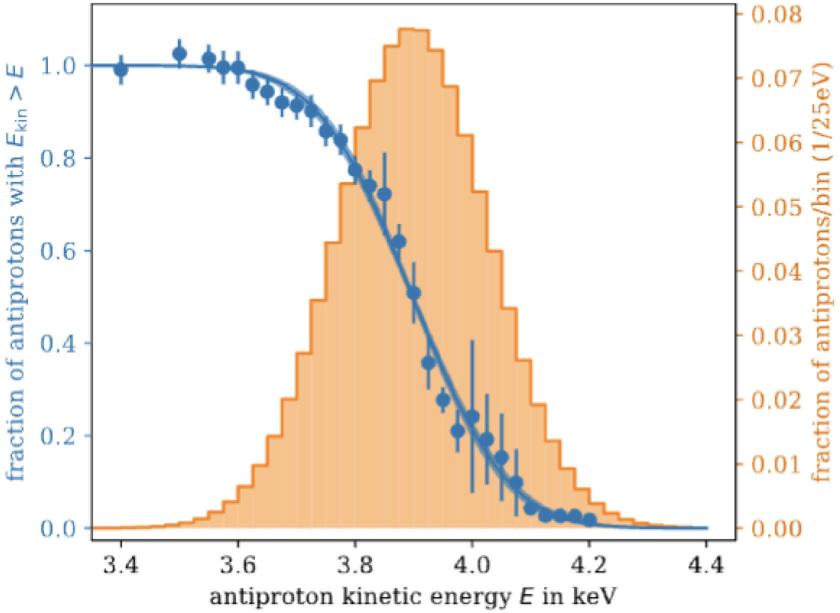
Beam diagnostics

- 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)



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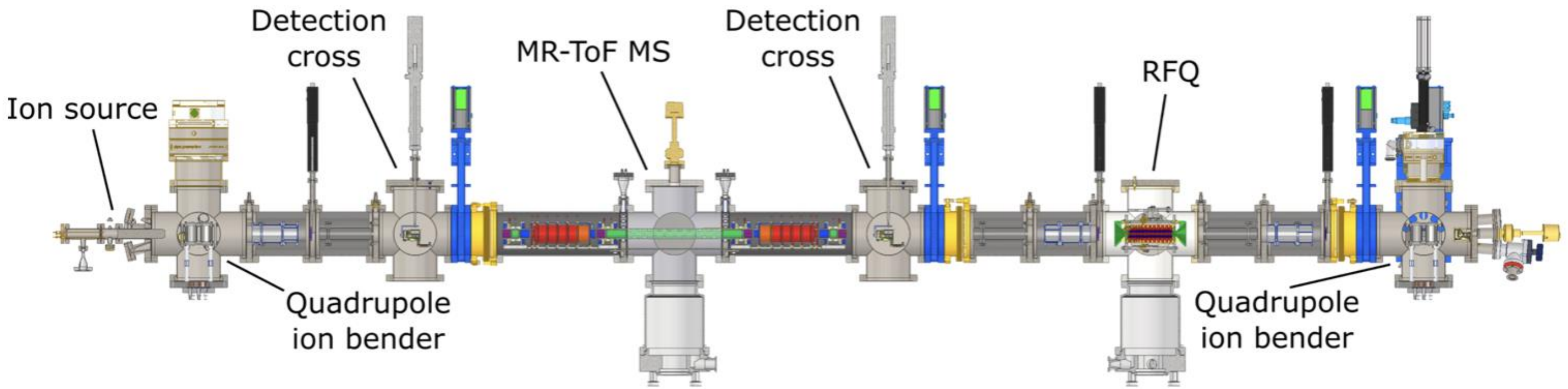
Offline ion source at AD

- 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 $\rightarrow$ $\sim 10^3$ ions in RFQ



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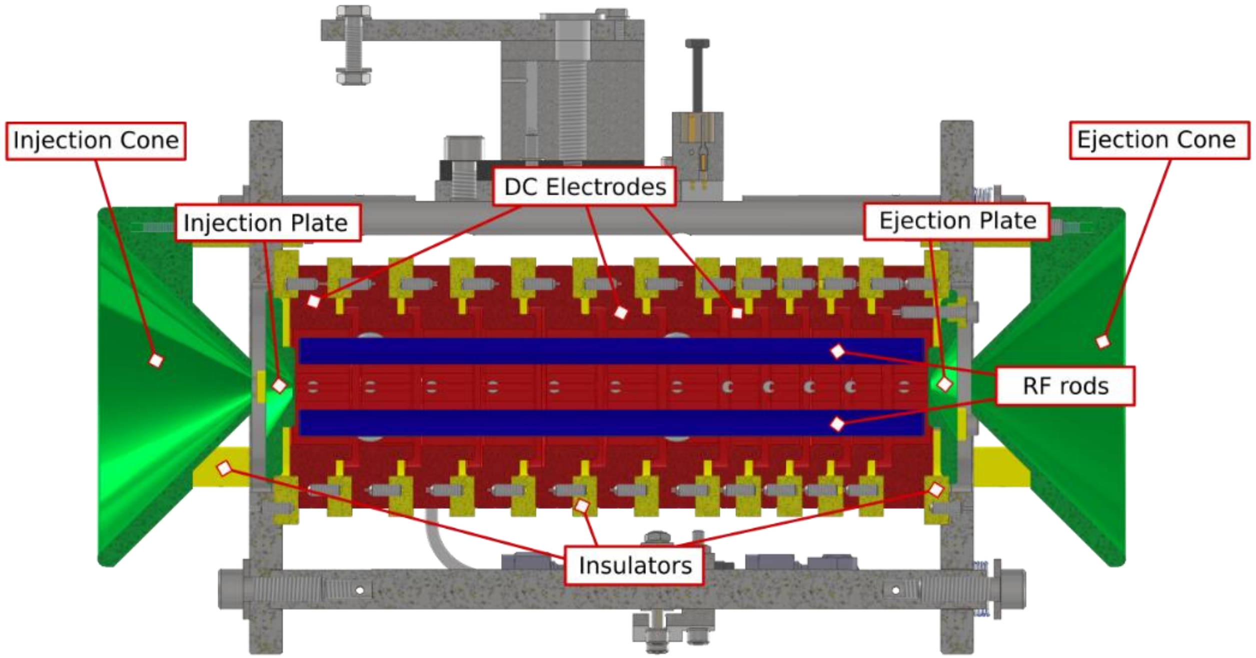
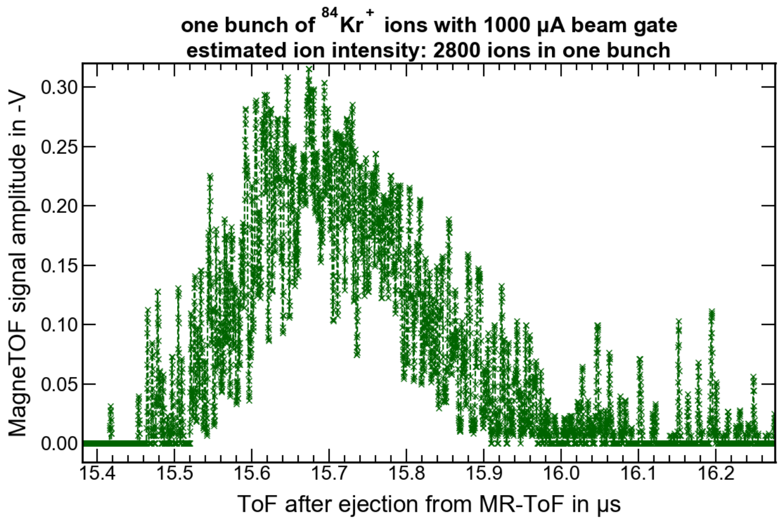
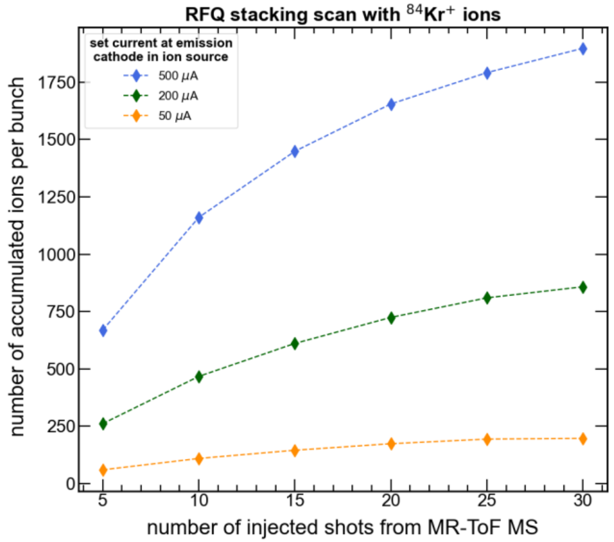
Multi-Reflection Time-of-Flight Separator







- 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)