PUMA

Exotic Nuclei & Antiprotons

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Outline

1) **Why** antiprotons for short-lived nuclei?

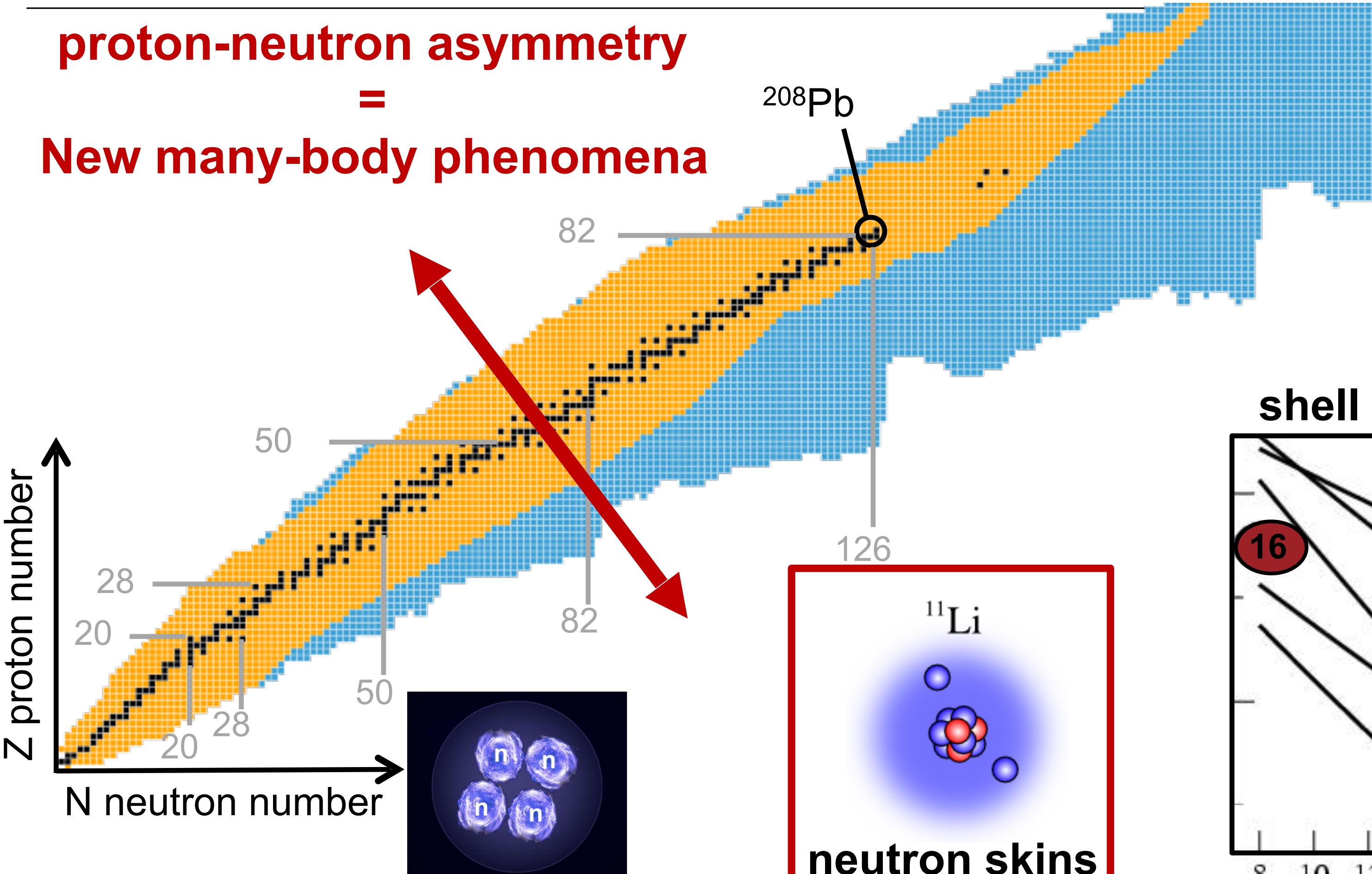
2) The **concept**

3) **Agenda, collaboration**

4) **Magnet** design

Radioactive nuclei

proton-neutron asymmetry
=
New many-body phenomena

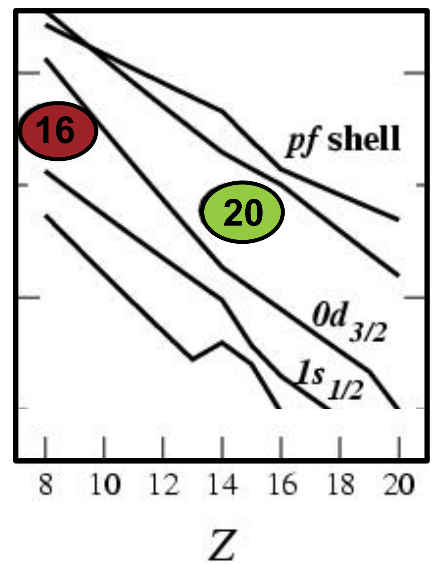


multi-neutron systems

neutron skins & halos

hypernuclei

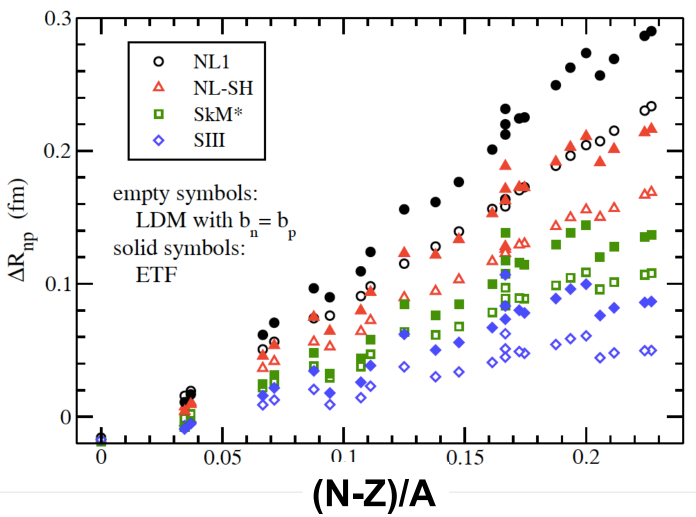
shell evolution



Neutron skins and halos

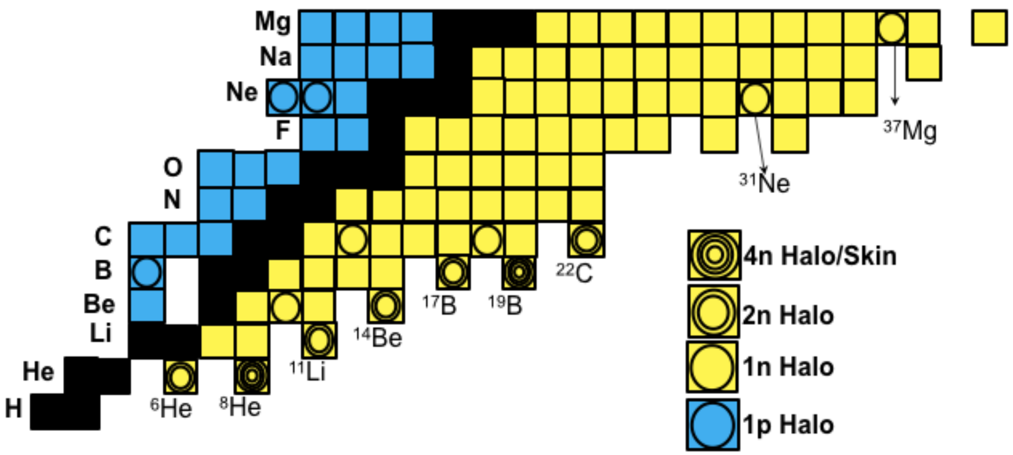
neutron skin thickness

$$\Delta r_{np} = \langle r_n \rangle - \langle r_p \rangle \approx \langle r_m \rangle - \langle r_c \rangle$$



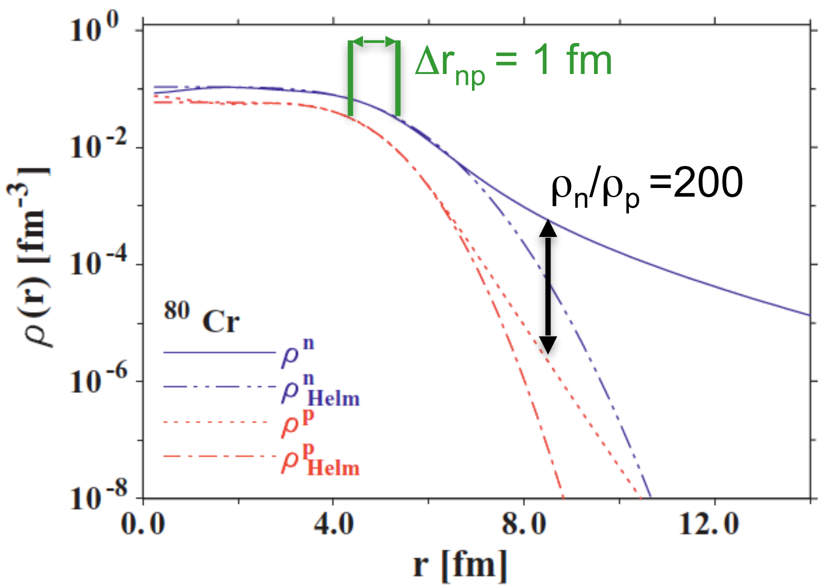
X. Vinas *et al.*, Eur. Phys. J A 50, 27 (2014)

neutron and proton halos



- **neutron skins and halos** have been extensively studied
- structure phenomenon difficult to characterise and to measure accurately
- skins also motivated by the Nuclear Equation of State (EOS)
- **Halos** not known well (at all) beyond mass 15, while predicted

Antiproton annihilation: a probe for the nuclear density tail



From V. Rotival et al., PRC 79 (2009)

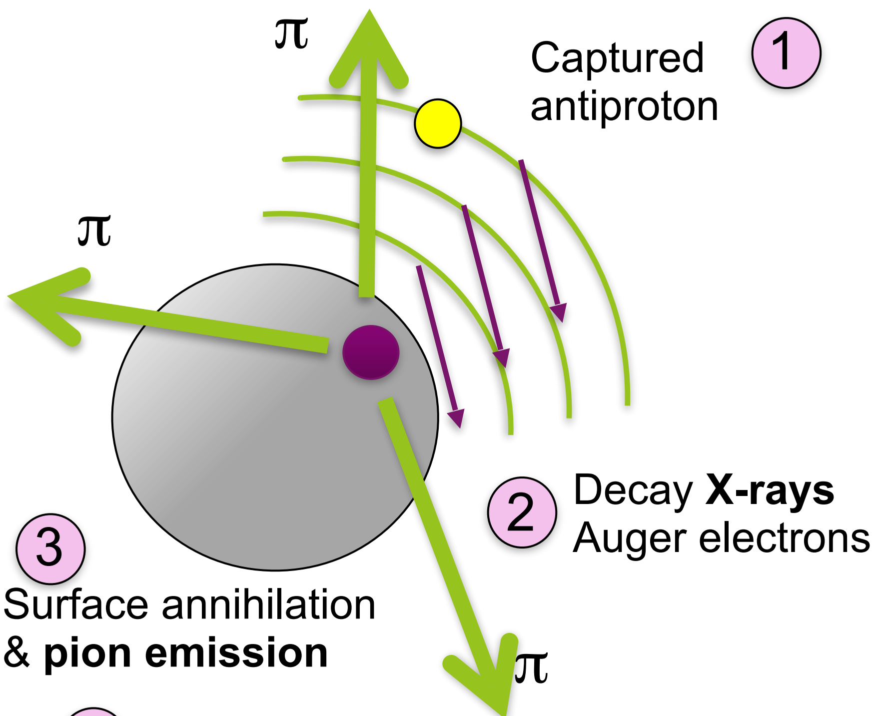
What would be an ideal probe?

- ❑ **isospin** sensitivity: selectivity of protons and neutrons
- ❑ sensitivity to the **tail** of the nuclear density, where the skin/halo are
- ❑ **effective** for short-lived and low-rate production nuclei

Low-energy antiprotons as a probe for radioactive nuclei!

[was proposed at FAIR, see FLAIR presentation by E. Widmann]

Antiproton annihilation: a probe for the nuclear density tail



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Cascade & **residue production**, decay

Brookhaven NL: W. M. Buggs et al., Phys. Rev. Lett. 31, 475 (1973)

Antiproton-proton, $\overline{p}p$ [43]

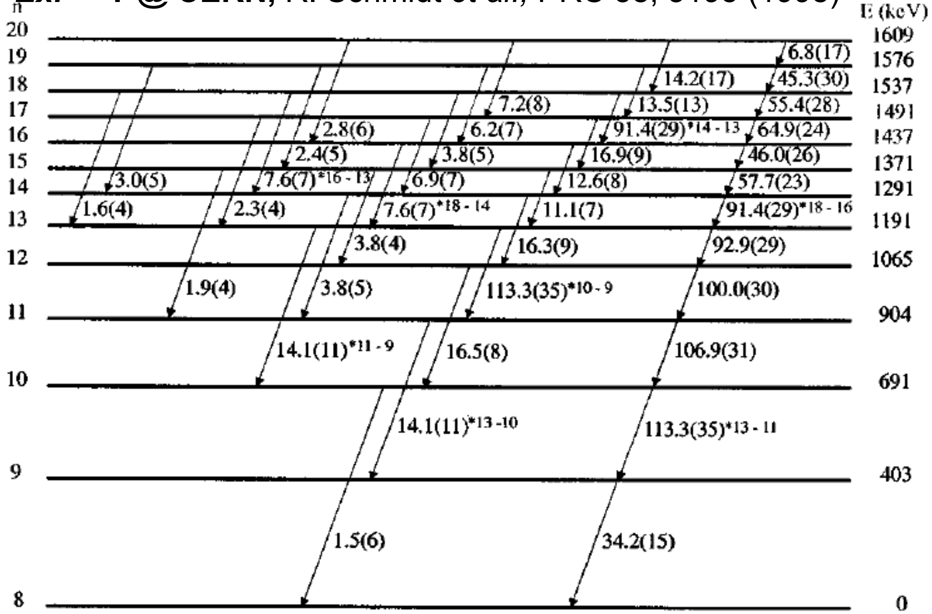
Pion final state	Branching ratio
$\pi^0\pi^0$	0.00028
$\pi^0\pi^0\pi^0$	0.0076
$\pi^0\pi^0\pi^0\pi^0$	0.03
$\pi^+\pi^-$	0.0032
$\pi^+\pi^-\pi^0$	0.069
$\pi^+\pi^-\pi^0\pi^0$	0.093
$\pi^+\pi^-\pi^0\pi^0\pi^0$	0.233
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	0.028
$\pi^+\pi^-\pi^+\pi^-$	0.069
$\pi^+\pi^-\pi^+\pi^-\pi^0$	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

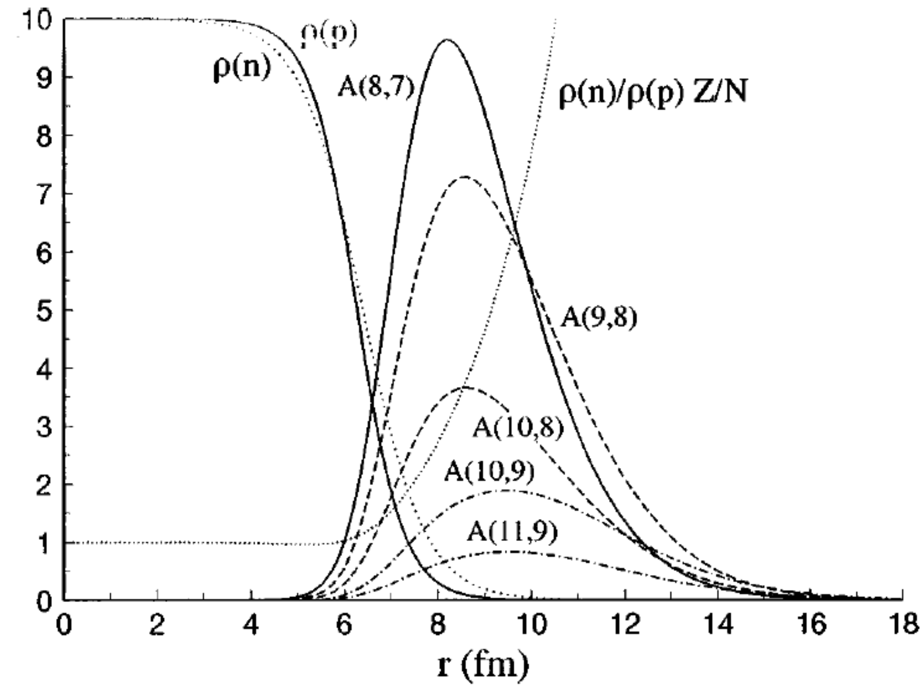
Antiproton-neutron, $\overline{p}n$ [46]

Pion final state	Branching ratio
$\pi^-\pi^0$	0.0075
$\pi^- k\pi^0$ $(k > 1)$	0.169
$\pi^-\pi^-\pi^+$	0.023
$\pi^-\pi^-\pi^+\pi^0$	0.17
$\pi^-\pi^-\pi^+ k\pi^0$ $(k > 1)$	0.397
$\pi^-\pi^-\pi^-\pi^+\pi^+$	0.042
$\pi^-\pi^-\pi^-\pi^+\pi^+\pi^0$	0.12
$\pi^-\pi^-\pi^-\pi^+\pi^+ k\pi^0$ $(k > 1)$	0.066
$\pi^-\pi^-\pi^-\pi^-\pi^+\pi^+\pi^+ k\pi^0$ $(k \geq 0)$	0.0035

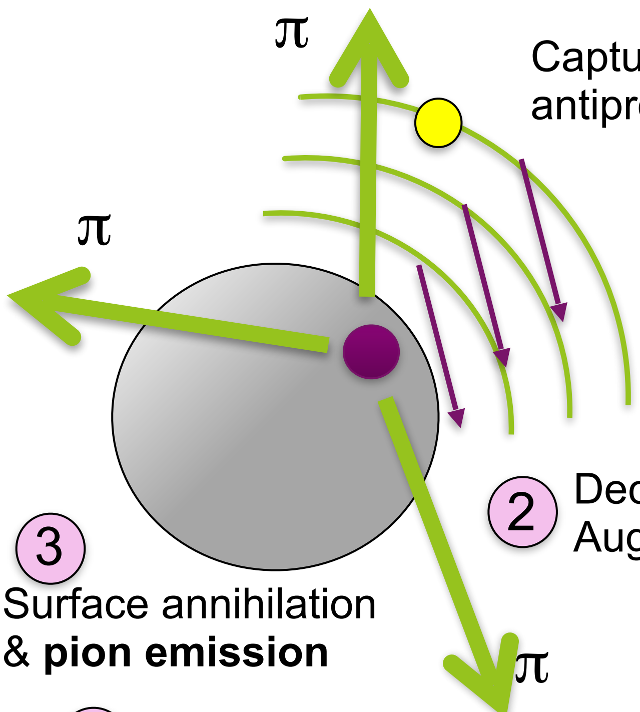
Antiproton annihilation: a probe for the nuclear density tail

***Ex.* ^{172}Y @ CERN,** R. Schmidt *et al.,* PRC 58, 3195 (1998)





Antiproton annihilation: a probe for the nuclear density tail



1. Captured antiproton
2. Decay **X-rays**
   Auger electrons
3. Surface annihilation
   & **pion emission**
4. Cascade & **residue production**, decay

- Features:
  - **High cross section** (Mbarns) **at low energy** (100 eV)
  - **Net electric charge conservation**
    -1: neutron annihilation
    0: proton annihilation
- Sensitive to **neutron-proton density ratio at surface**

Emitted pions, Multiplicity M, Total charge Σ	⟵ FSI ⟶	$\frac{N_n}{N_p}$	⟵ theory ⟶	$\left.\frac{\rho_n}{\rho_p}\right\|_{surface}$
Measured		**Extracted**		**Calculated**

M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

PUMA: Pbar Unstable Matter Annihilation

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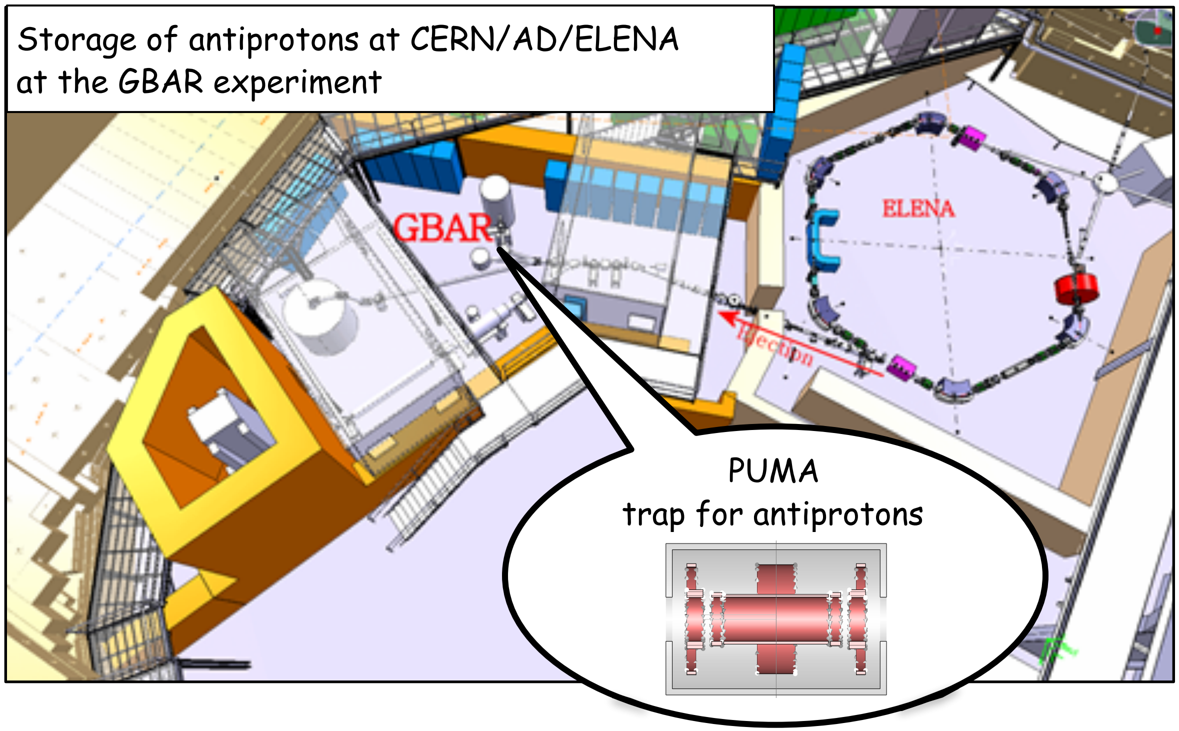
- ❑ Transport antiprotons from ELENA (CERN) to ISOLDE
- ❑ Device to be build (funded from 01/2018, for 5 years)
- ❑ First experiment at ISOLDE foreseen in 2022
- ❑ Pioneer experiment with antiprotons as a probe for short-lived nuclei

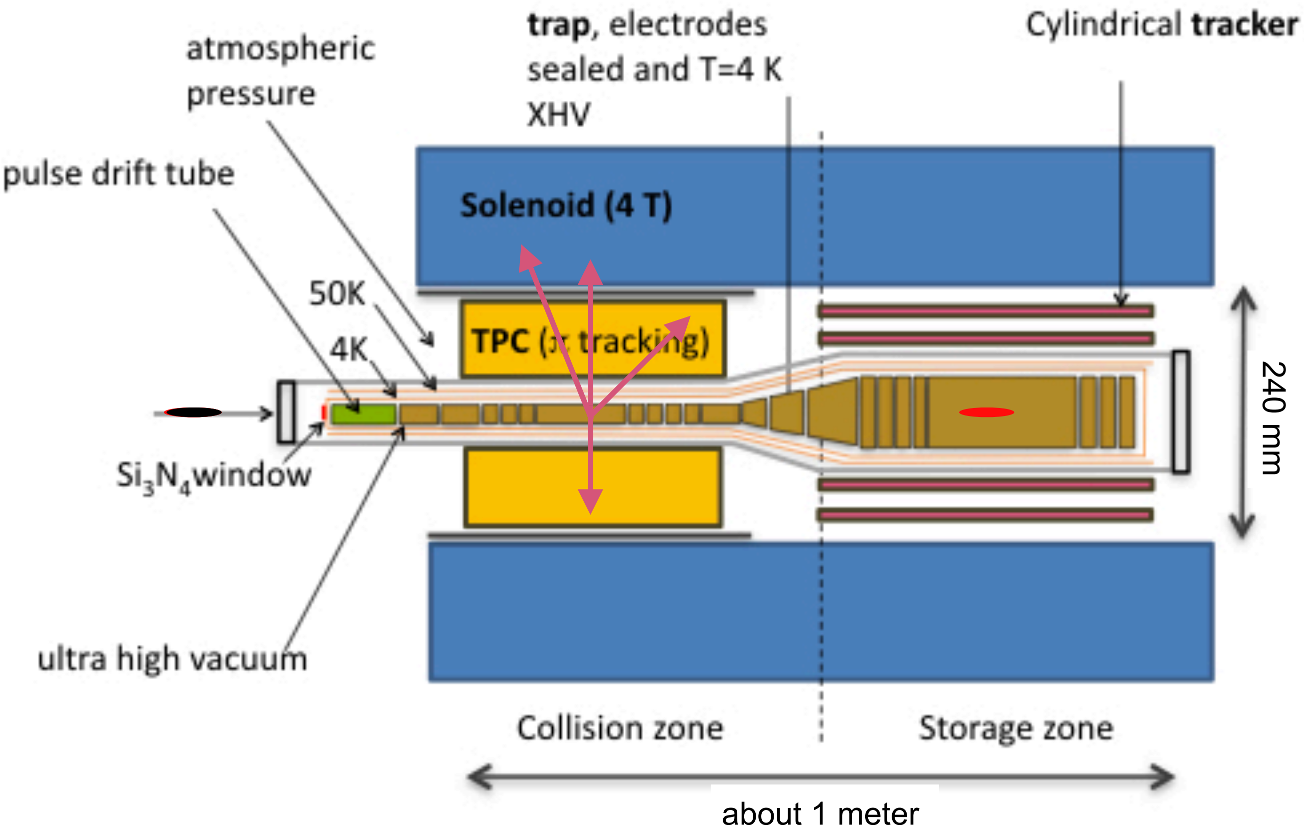
Storage of antiprotons at CERN/AD/ELENA
at the GBAR experiment

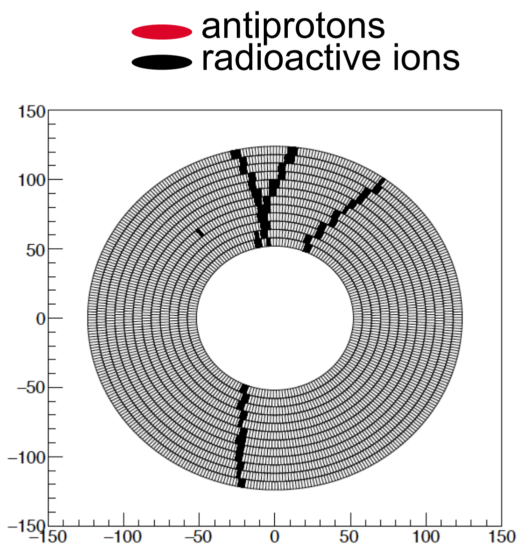


Transport the antiprotons…

… to ISOLDE at CERN
for unstable ion annihilation.

PUMA: a magnetic bottle for antiprotons





Physics cases

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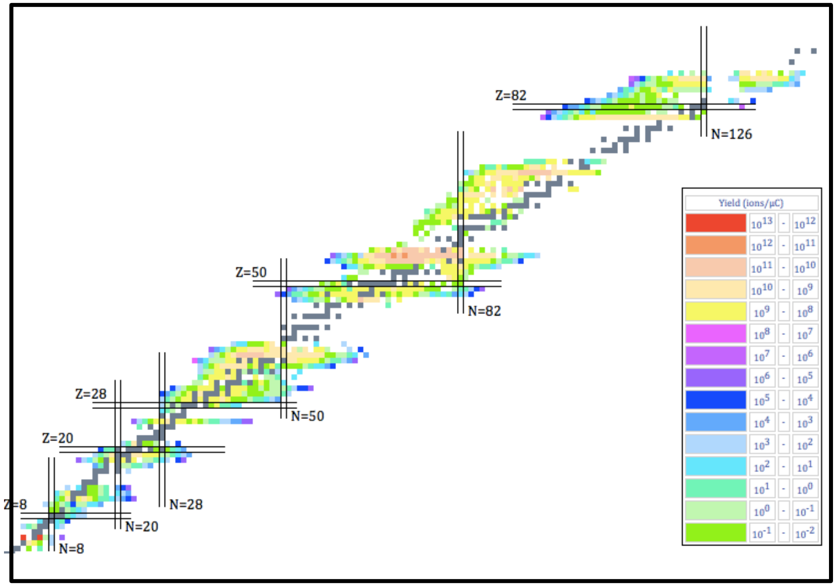

Production rates at ISOLDE

Nucleus	$T_{1/2}$	Statistics 1 day beam	Expected N_n/N_p
^{6}He	807 ms	10^7	Neutron halo > 100
^{8}He	119 ms	$4.\ 10^6$	Thick skin 70(10)
^{11}Li	8 ms	$2\ 10^3$	Neutron halo > 100
^{17}Ne	109 ms	10^4	Proton halo < 0.010
^{31}Ne	3 ms	$5.\ 10^2$	Neutron halo > 100
$^{104-138}$Sn		$>10^3$	Progression of skin: From 1.0(2) to 4.0(6)

Targeted accuracy: <15%
(FSI corrections, statistics)

- ❑ Example of yield estimate:
- capture cross section is **10^{-16} cm^2** (100 Mbarns, 100eV relative E)
- **10^7 cm^{-2} antiproton** « target », 6-cm long
- **trapping time of 10 ms**
- **1000 pps production rate** of radioactive Ion (20 ions / bunch, every 20 ms)
- under these specific conditions: annihilation rate of **few per minute** (few 10^2 / day)

Challenges

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- **Cryostat** suited for ultra-high vacuum (<10^{-17} mbar) and insertion of low-energy ions
  - sealed by thin entrance window (20 nm, proposed solution Si3N4)
  - 4K
  - ions & antiprotons cooling

C. Smorra *et al.,* Int. Jour. Mass. Spec. **189**, 19 (2015)

- Trapping of **10^9 antiprotons**

- **Transportable trap** that meets contrains from environment (GBAR / ISOLDE, costs)

C.H. Tseng and G. Gabrielse, Hyperfine Interactions **76**, 381 (1993)

- **Final state** interaction correction uncertainties

M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

Agenda and collaboration

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PUMA phases

- **2018-2020**: 2 years
  - solenoid magnet
  - trap & cryostat
  - detection
- **2020-2021**: 2 years
  - operation
- **2022-…**: 1 year ++
  - installation at CERN
  - first measurements

Milestones

2018: LoI to CERN

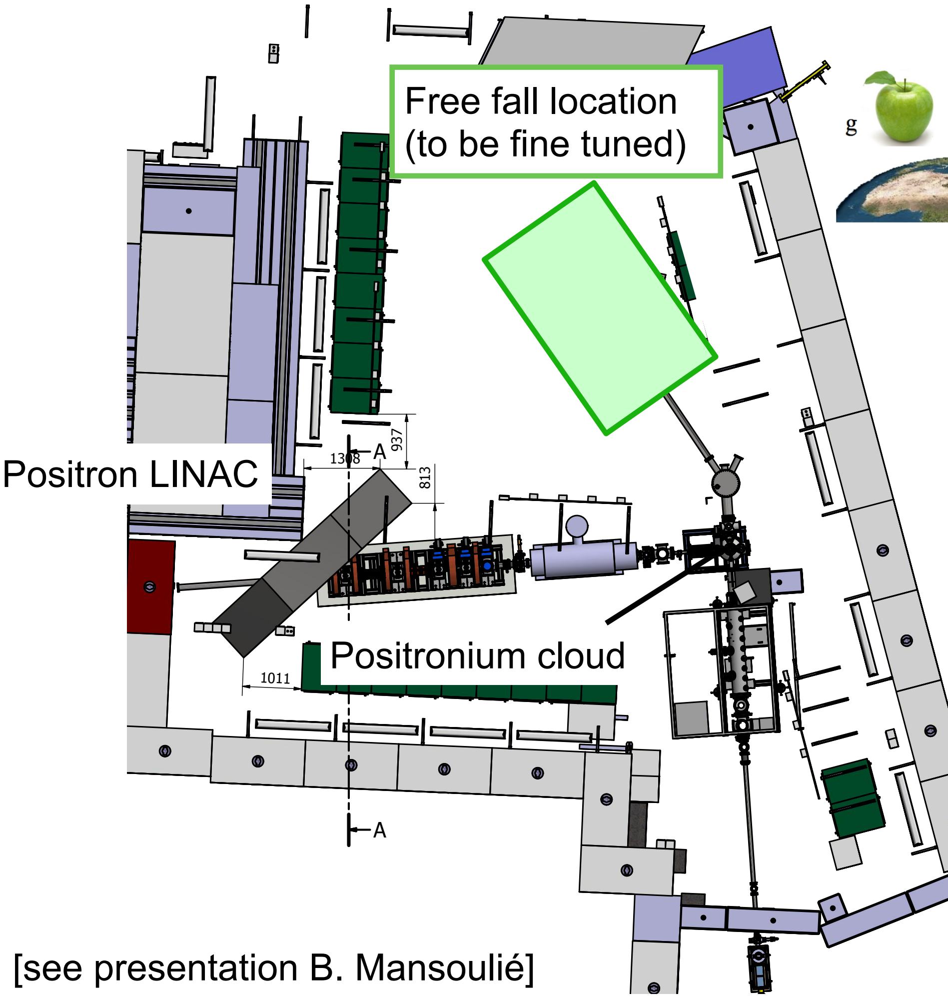
2020: Proposal to CERN

2021: Validation with protons / stable ions at TU Darmstadt

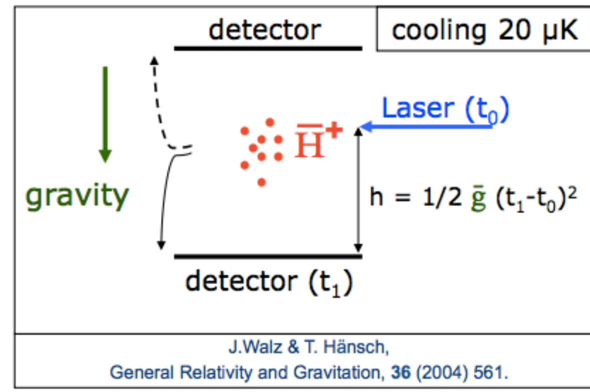
2022: Trapping of antiprotons
First ion-antiproton annihilations

Collaboration (today): TU Darmstadt, RIKEN, CEA, IPN Orsay
Scale: 6 staff (2.5 FTEs), 2 PD, 1 PhD (+ 2 more positions to come)

GBAR @ ELENA



[see presentation B. Mansoulié]

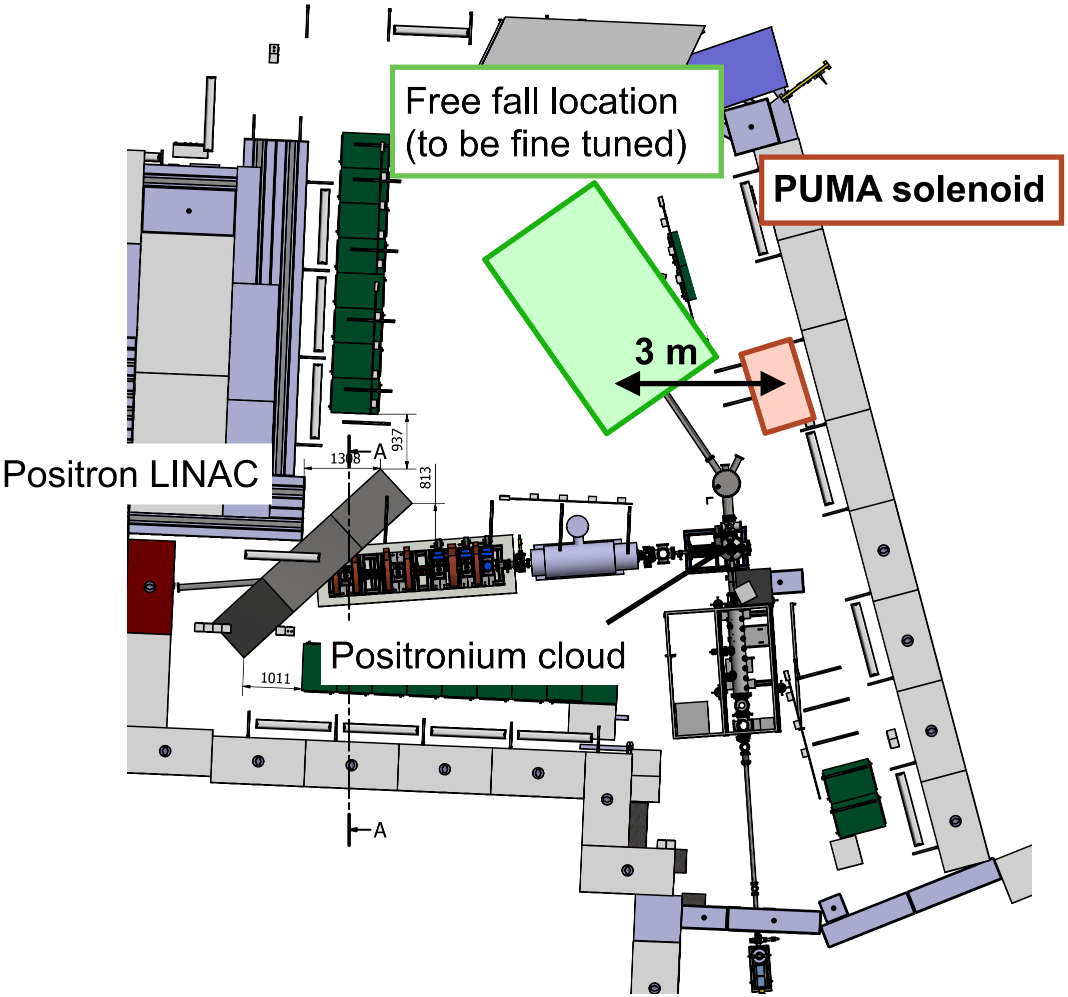


- Produce ion $\bar{H}^+$
- Sympathetic cooling 20 microK
- Photo-detachment
- Measurement of free fall

any **B gradient** creates a force due to magnetic moment of positron

0.02 Gauss / m = 0.1% accuracy

Solenoid magnet location and constrains



4 Tesla,
active & passive shielding
Transportable

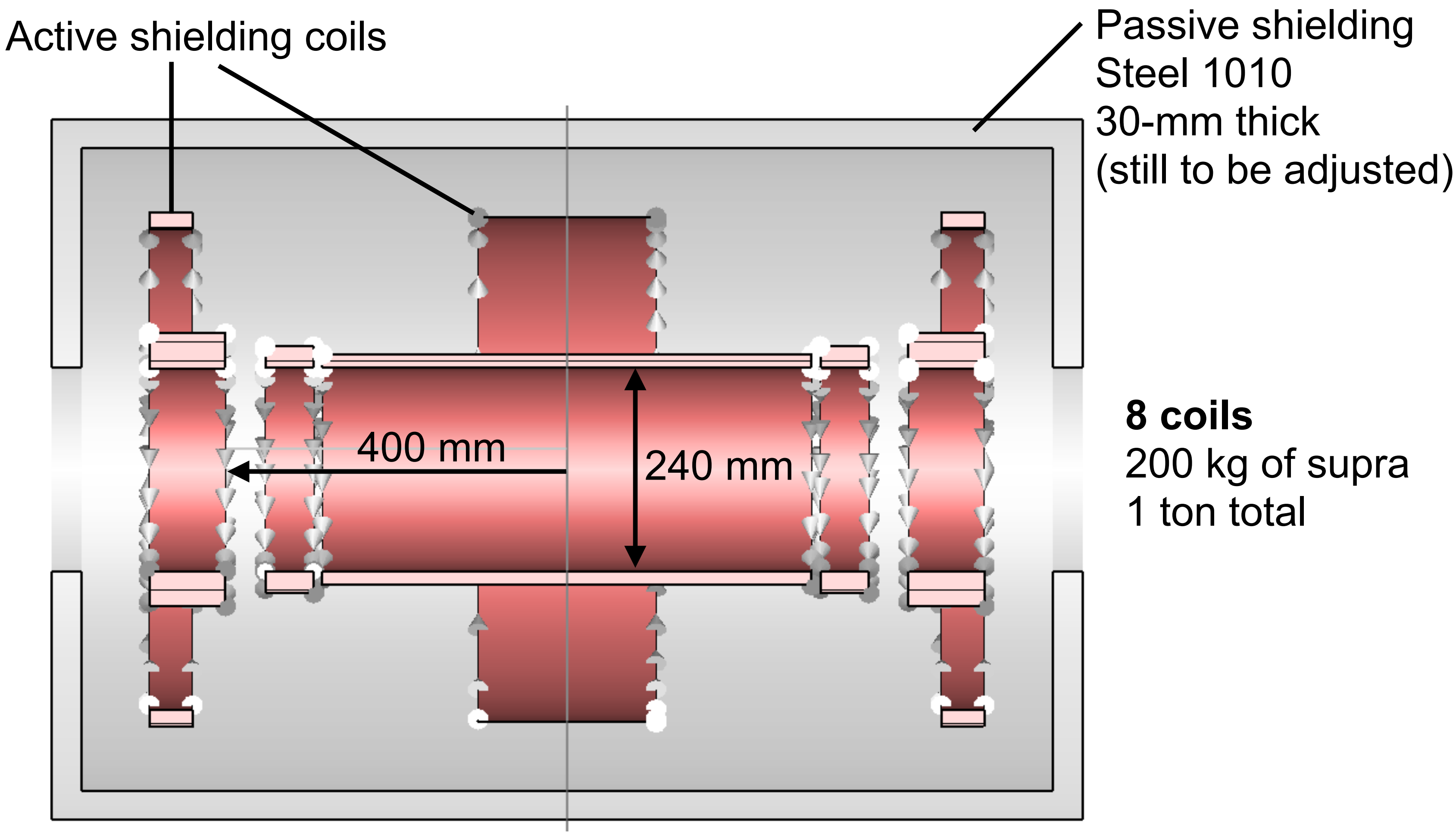
NbTi, **200 A / mm²**

Active region (warm bore):
Length = **800 mm**
Diameter = **210 mm**

Homogeneity:
<0.2% in trapping region
<2% in detection region

Residual field at free fall region:
Gradient **< 0.2 G / m** at 3 meters
Field **< 2 G** at 3 meters

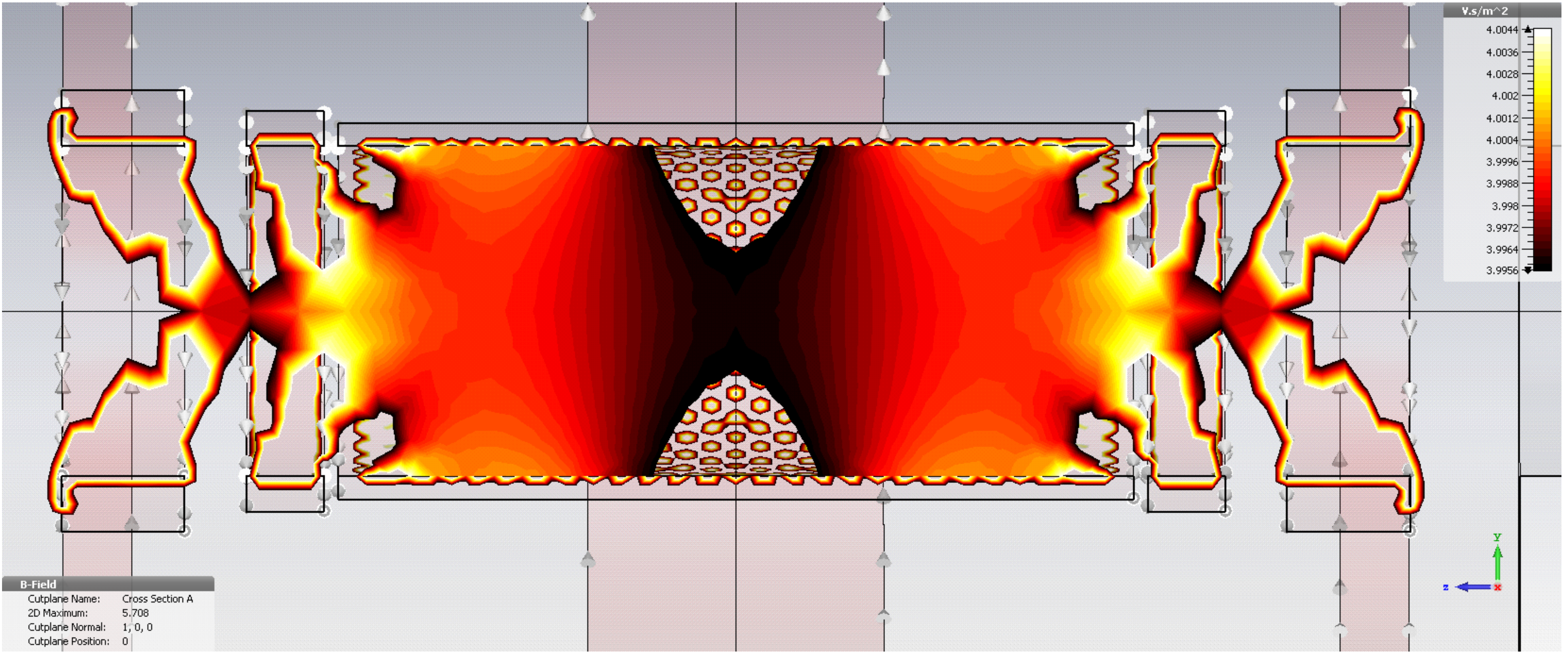
Solenoid magnet design



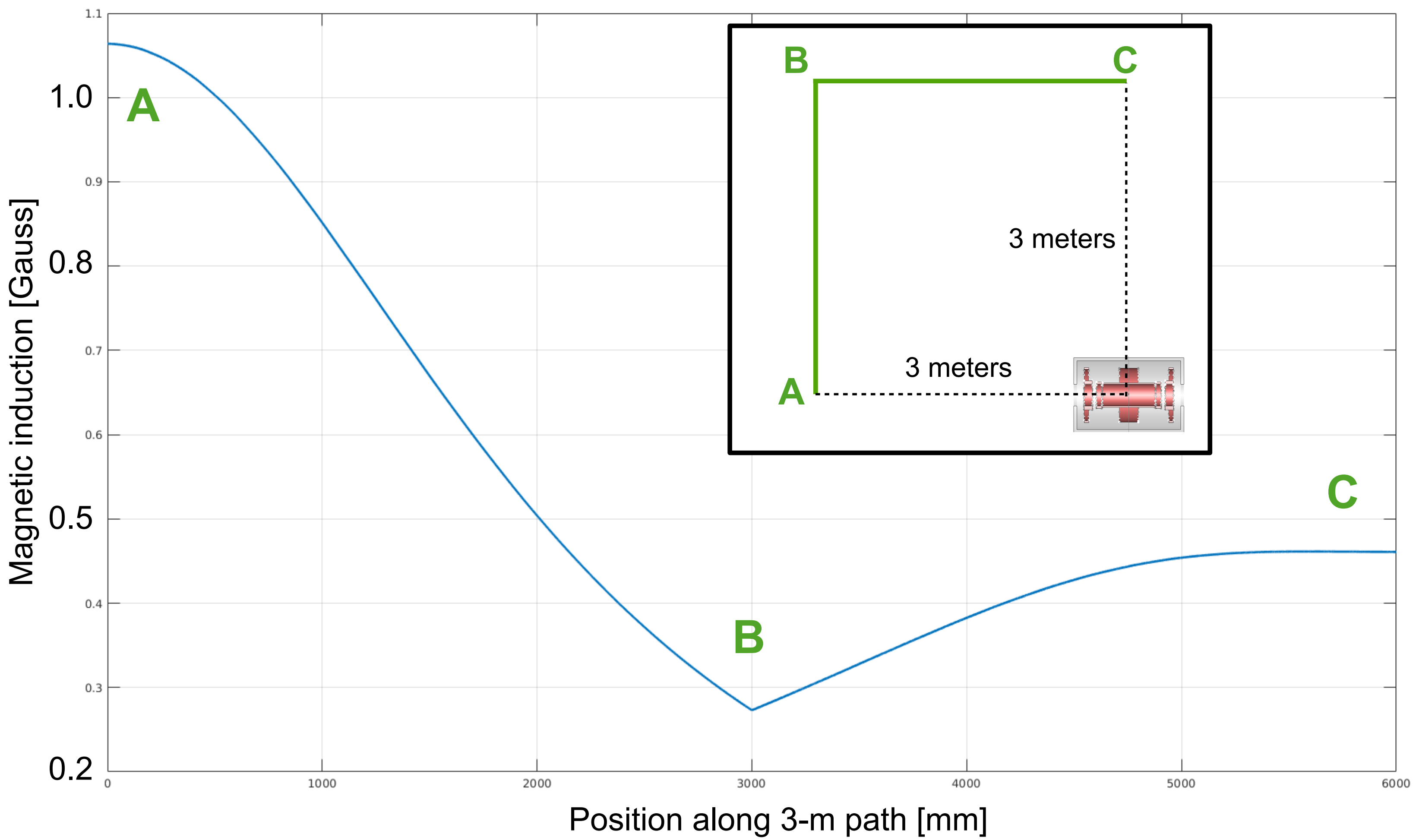
8 coils
200 kg of supra
1 ton total

Solenoid magnet design

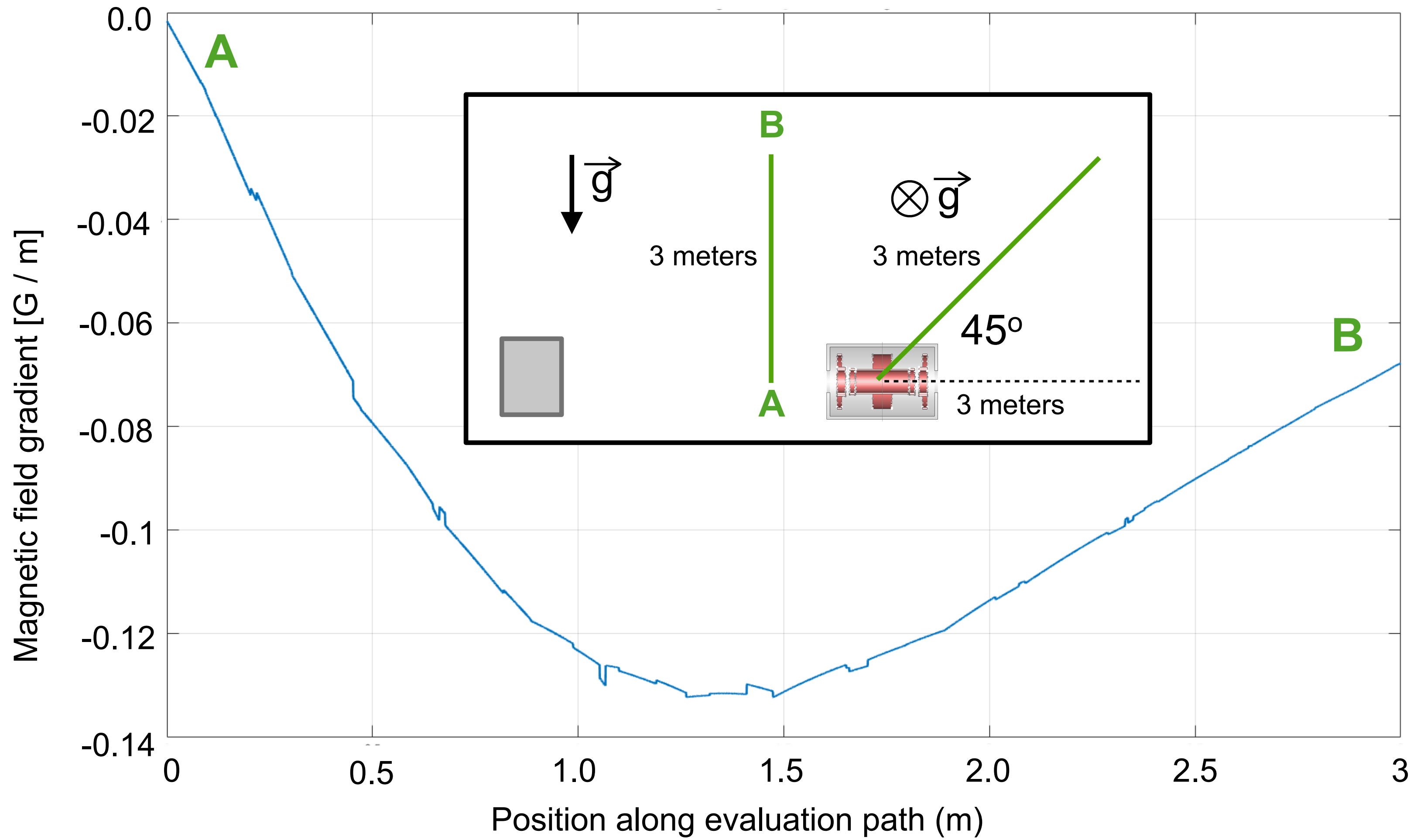
Field homogeneity shown for +- 0.11%



Residual magnetic field



Field gradient



Summary

- **PUMA**: new program at CERN / ELENA and ISOLDE
- Low-energy antiprotons to probe for the **nuclear density tail of short-lived nuclei**
- H**alos and thick neutron skins** searched in medium mass short-lived nuclei
- T**ransport trapped antiprotons from ELENA to ISOLDE**
- Solenoid, trap, cryostat and detection to be designed and built (not started)
- Official start on 02.01.2018, LoI submitted to SPSC and INTC (dec. 2017)
- In collaboration with **GBAR**
- First physics experiments expected in **2022**
- **Potential** for nuclear physics beyond halos and skins

Sensitivity to final state interactions

M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004)

$M\backslash\Sigma_c$	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	
0	0	0	0	0	0	0	0	0	0	0	(11386)*
1	0	0	0	0	17223	0	11233	0	0	0	28456
2	0	0	0	7530	0	21437	0	2844	0	0	31811
3	0	0	1029	0	11901	0	6591	0	179	0	19700
4	0	44	0	1904	0	4394	0	519	0	5	6866
5	1	0	99	0	979	0	451	0	13	0	1543
6	0	2	0	75	0	133	0	14	0	0	224
7	0	0	1	0	7	0	3	0	0	0	11
8	0	0	0	1	0	1	0	0	0	0	2
9	0	0	0	0	1	0	0	0	0	0	1
	1	46	1129	9510	30111	25965	18278	3377	192	5	88612

- Pions may re-interact with residual nucleus
  Stable nuclei: probability 20-50%

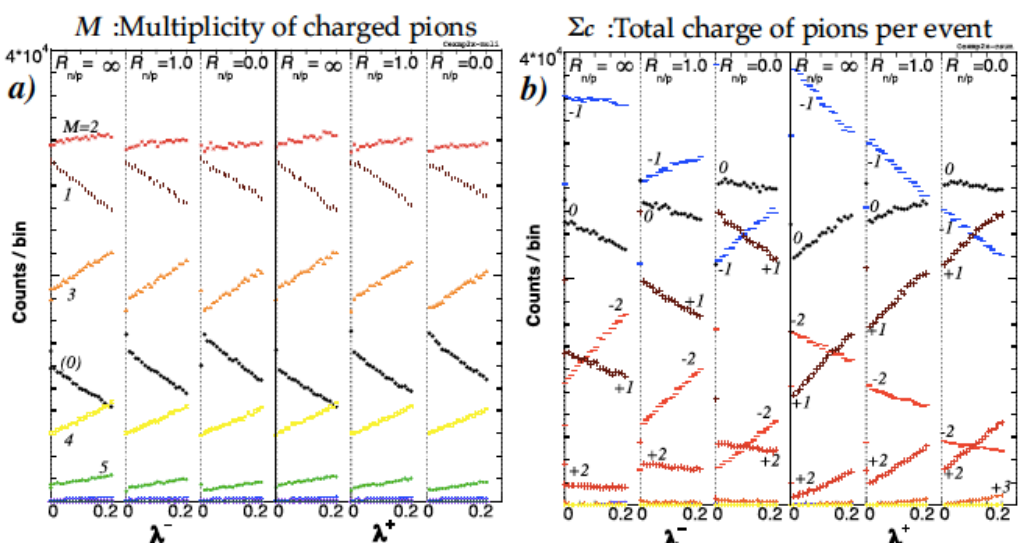
- Solution: analyse charged pion multiplicity (M) AND sum charge (Sigma_c)

- treatment of final state interactions:

λ^+: π^0 + p -> π^+ + n
λ^-: π^0 + n -> π^- + p
ω^+: π^- + p -> π^0 + n
ω^-: π^+ + n -> π^0 + p

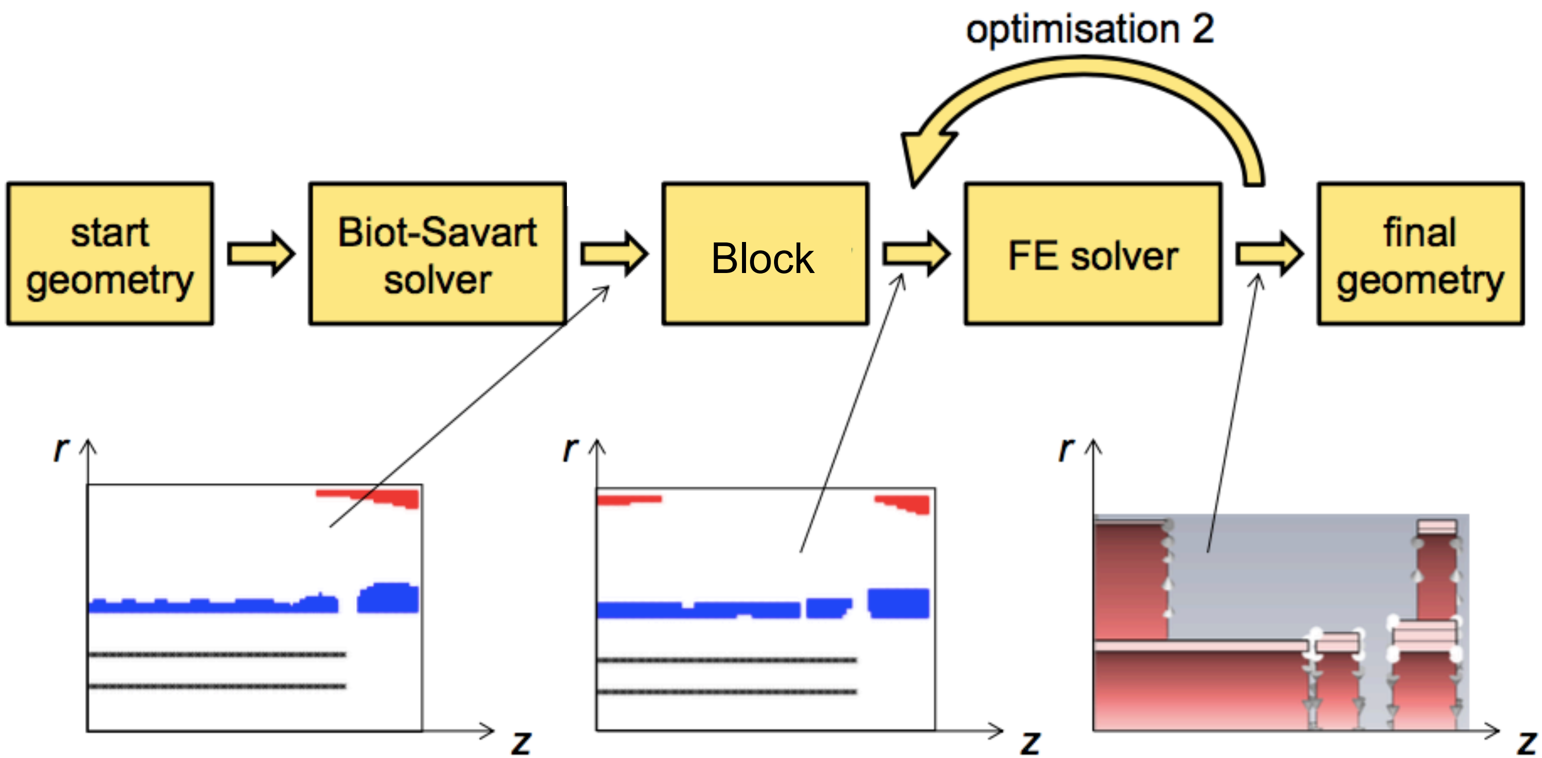
- analysis of M-Sigma matrices should lead to N(pbar-n)/N(pbar-p) with good accuracy and precision (**<5%** for 10^5 annihilations)

- new and systematic analysis based on simulated Monte-Carlo annihilations in progress (A. Corsi *et al.*)



Solenoid magnet constrains

Optimization:
N. Marsic, TU Darmstadt



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Refs. Xu et al., “Homogeneous magnet design using liner programming”
Wu et al., “Optimal design of a 7 T highly homogeneous superconducting magnet for a Penning trap”