PUMA:
antiProton Unstable Matter Annihilation

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Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

- ☑ **PUMA concept**
- ☑ Physics cases @ CERN
- ☑ Sensitivity to physics cases
- ☑ Technical development

Antiprotonic Atom

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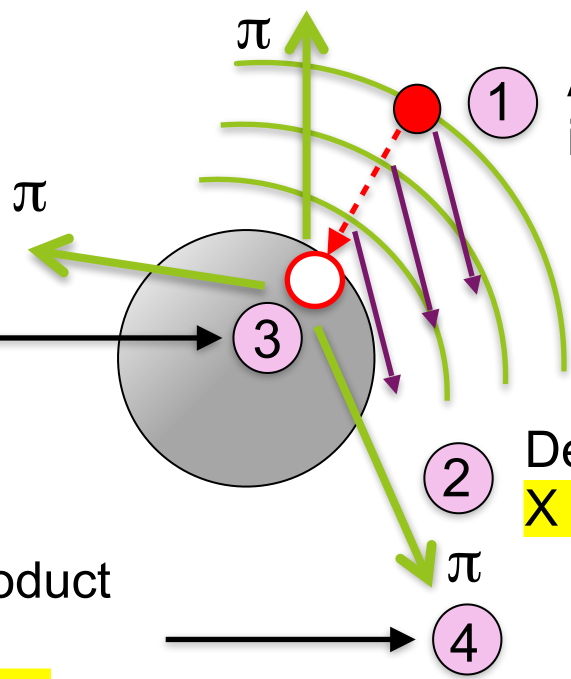
Past works at BNL and CERN on antiproton annihilation with stable nuclei

Antiprotonic Atom



1. Antiprotons captured into atomic orbital.

2. Decay into lower atomic orbital. X rays & Auger electrons

3. $\bar{P}$ reaches at the density tail of nuclei. Annihilate with p or n.

4. Annihilation product: Multiple pions, Residual nucleus

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

C,To,Ta,Pb@ BNL, W. N. Bugg *et al.*, PRL 31, 475 (1973)

$\bar{P}$ annihilates at the density tail of nuclei

Antiproton - Nuclei annihilation

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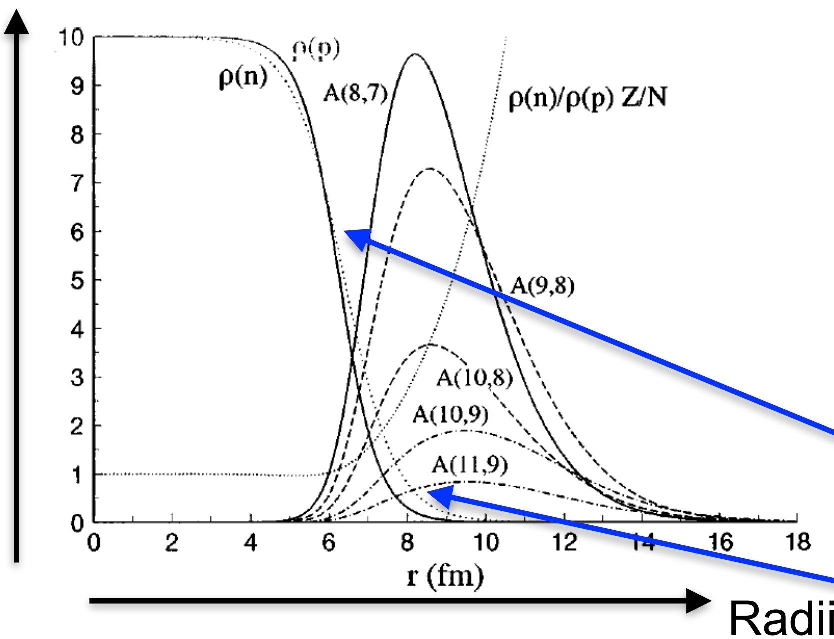
- ☑ X-ray measurement shows the annihilation takes place at the surface
- ☑ Isotope shift effect between ^{172,176}Y -> N/P ratio at the density tail

Arb. Unit [Density/Absorption Probability]



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

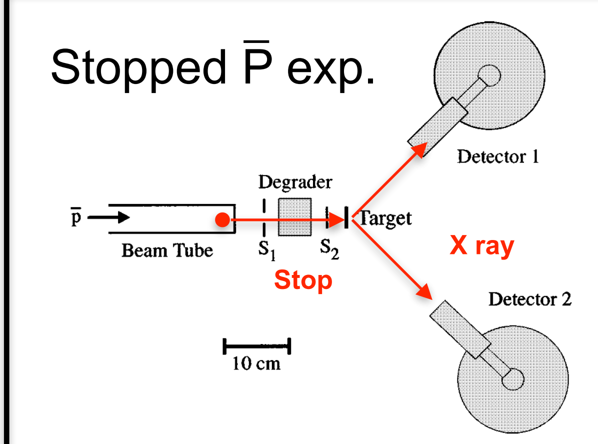


FIG. 1. Schematic view of the experimental setup: S_1, anti-counter, and S_2, counter of the telescope.

Scattering experiments probe: Middle of diffuseness

Annihilation takes place: "Density tail of nuclei"

$\overline{\mathrm{P}}$ can be an unique probe to investigate the density tail of nuclei

Antiproton - Nuclei annihilation

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☑ Residual nuclei measurement also exists

TABLE II. Number of antiprotons stopped in each target, (A_t-1) nuclei with $Z'=Z_t-1$ and with $N'=N_t-1$, half-lives $T_{1/2}$, and γ energies E_γ of lines which were used for the evaluation.

Target	Number of stopped $\bar{p}$ (10^8)	Z' and N' nucleus		$T_{1/2}$	E_γ (keV)
^{48}Ca	8.3	^{47}K	$\bar{\text{P}}$P	17.5 s	2013, 586, 565
		^{47}Ca	$\bar{\text{P}}$N	4.54 d	1297, 489, 807
^{100}Mo	8.3	^{99}Nb		15.0 s/2.6 m	138/254, 351, ...
		^{99}Mo		65.9 h	740, 181, ...
^{104}Ru	4.2	^{103}Tc		54.2 s	346, 136, ...
		^{103}Ru		39.26 d	497, 610
^{112}Sn	9.3	^{111}In		7.7 m/2.80 d	537/245
		^{111}Sn		35.3 m	762, 457, ...
^{116}Cd	3.9	^{115}Ag		18.0 s/20.0 m	389, 361, 113/213, 472, ...
		^{115}Cd		2.23 d/44.6 d	336, 528/934, 1290
^{124}Sn	8.5	^{123}In		5.98 s/47.8 s	1130, 1019/126
		^{123}Sn		40.1 m/129.2 d	160/1089

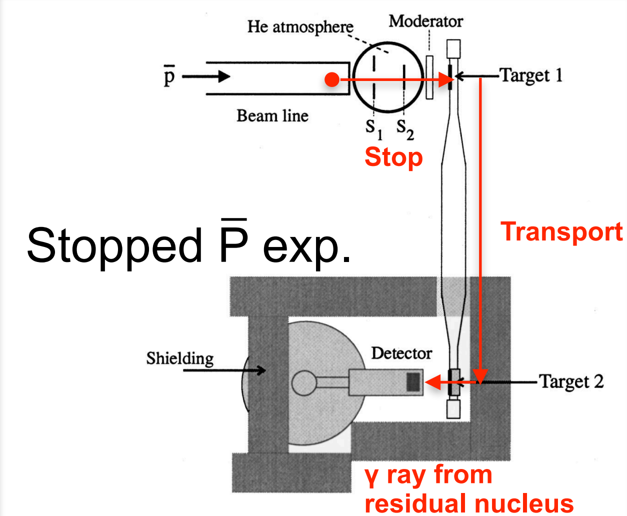

FIG. 1. Schematic view of the setup for irradiation and activation measurement of short-lived isotopes. S_1 and S_2 are anticounter and counter of the scintillation-counter telescope, respectively.

Target	$\frac{N(\bar{p},n)}{1000\ \bar{p}}$	$\frac{N(\bar{p},p)}{1000\ \bar{p}}$	$\frac{N(\bar{p},n)}{N(\bar{p},p)}$	$f_{\text{halo}}^{\text{periph}}$	$\frac{N(A_t-1)}{1000\ \bar{p}}$
^{48}Ca	76 (38)	29 (15)	2.62 (30)	2.97 (34)	105 (53)
^{100}Mo	66 (6)	23.4 (15)	2.82 (23)	3.24 (26)	90 (8)
^{104}Ru	55 (16)	19 (6)	2.9 (4)	3.4 (5)	75 (21)
^{112}Sn	52 (9)	66 (11)	0.79 (14)	1.01 (18)	118 (12)
^{116}Cd	130 (31)	26 (9)	5.0 (21)	5.6 (23)	156 (55)
^{124}Sn	98 (15)	19.6 (15)	5.0 (6)	5.4 (6)	118 (9)

Counting number of residual nucleus

$\bar{\text{P}}$ can be an unique probe to investigate the density tail of nuclei

Antiproton - Nuclei annihilation

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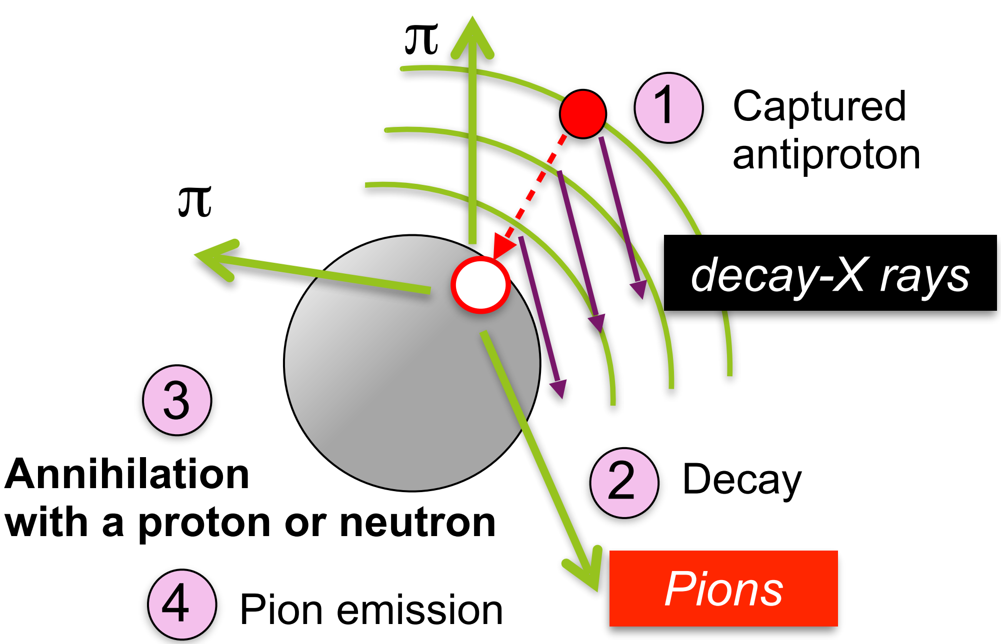
- ☑ PUMA propose pion measurement
- ☑ Possibility to access short-lived nuclei

Antiprotonic Atom → ***Multi Pion final state***



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

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

$\overline{P}$-P =Total Charge 0

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

$\overline{P}$-N =Total Charge -1

Compiled from BNL & LEAR@CERN data

Pion measurement has sensitivity to Isospin.

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Landscape of Radioactive nuclei

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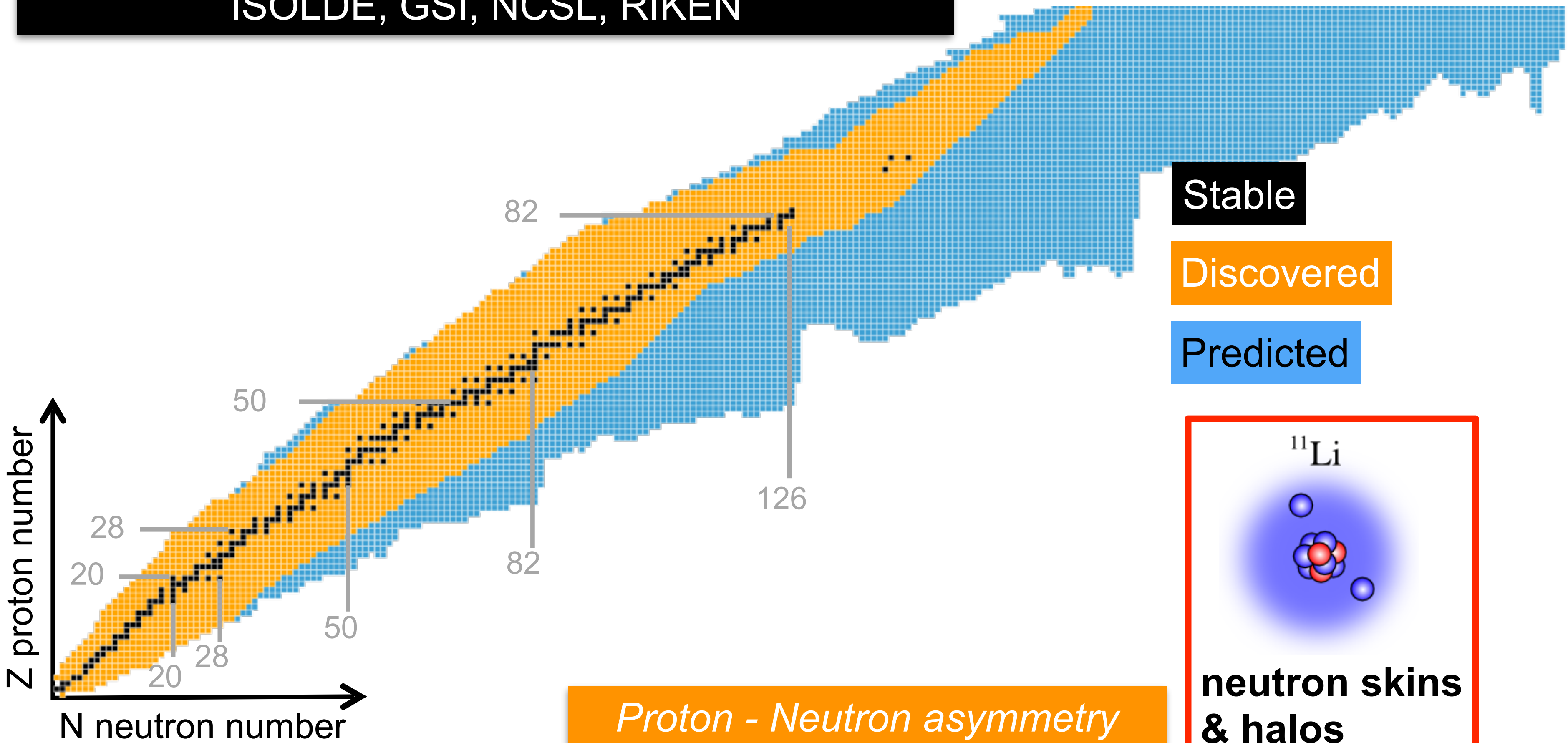
Most of the nuclei became only recently accessible by the unstable nuclei facility like ISOLDE, GSI, NCSL, RIKEN



neutron skins & halos

PUMA's target

Proton - Neutron asymmetry
->
New many-body phenomena

Physics cases: Neutron skins and halos

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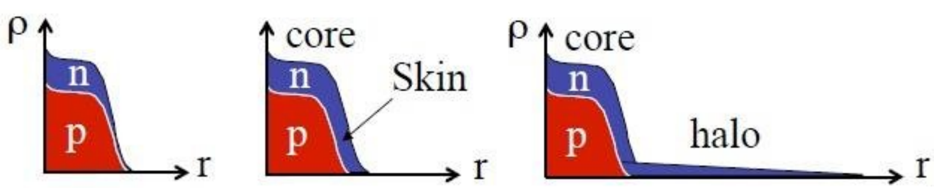
- ☑ Neutron Skins and Halos have been extensively studied, but…
- ☑ Still one of the major topics in unstable nuclei

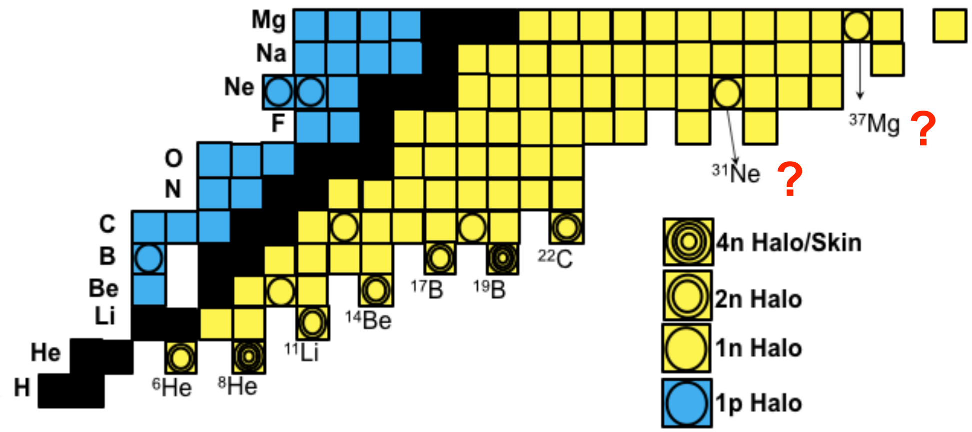
Neutron Skin Thickness

$$\boxed{\Delta r_{np} = \langle r_n \rangle - \langle r_p \rangle}$$



Matter radius (n-radius) is difficult to access via hadronic or weak probe.

Neutron Halos



Mod. from T. Aumann and T. Nakamura Phys. Scr, T152. (2013)

Halos are not known well (at all) beyond mass 30, while predicted.
-> But no conclusive experimental evidence so far.

Antiprotonic atom can provide new information on surface phenomena

Day-one physics program @CERN

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Nucleus	$T_{1/2}$	Statistics 1 day beam	Expected N_n/N_p (Mean field prediction)
H, D, ^{3}He, ^{4}He	stable	high statistics	reference measurements at ELENA
^{7}Li, ^{16}O, Ar, …	stable	high statistics	reference measurements at ELENA
^{6}He	807 ms	10^7	Neutron halo > 100
^{8}He	119 ms	4×10^6	Thick skin 70(10)
^{9,11}Li	178 ms 8 ms	> 10^6 2×10^3	Neutron halo (^{11}Li) > 100
^{17,18}Ne	109 ms 1.7 s	10^4	Proton halo < 0.10
$^{26-30}$Ne $^{28-32}$Mg	>3 ms	> 10^2	Neutron halo > 100
$^{104-138}$Sn	>140 ms	>10^2	Progression of skin: From 1.0(2) to 4.0(6)

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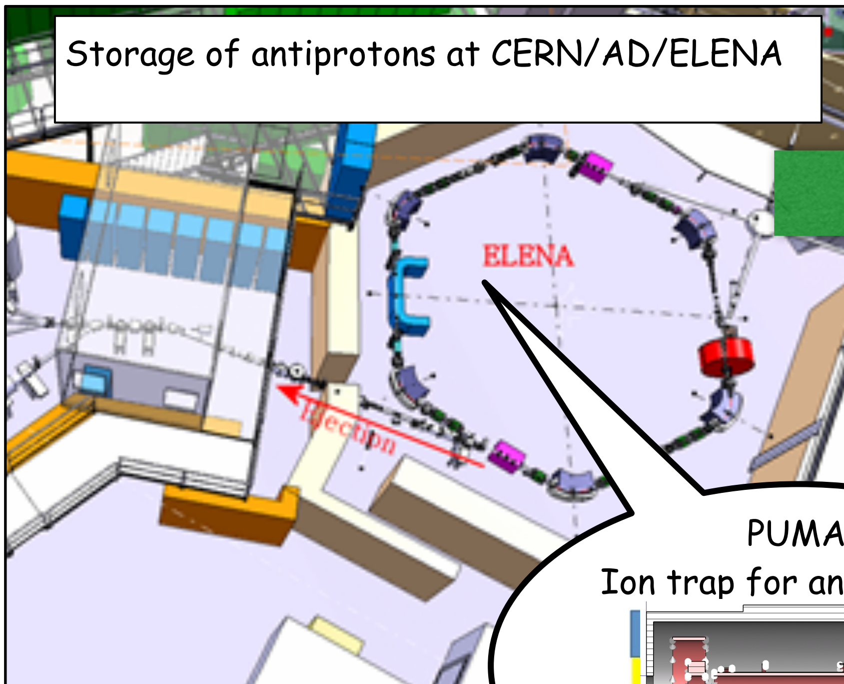
PUMA: antiProton Unstable Matter Annihilation

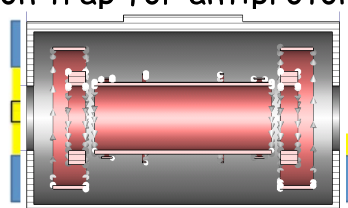
- ☑ Radioactive nuclei: short life (from msec)
- ☑ Transfer Antiprotons to Radioactive Nuclei

Transport billions of antiprotons from ELENA to ISOLDE

Storage of antiprotons at CERN/AD/ELENA



PUMA
Ion trap for antiprotons



Transport the antiprotons…

… to ISOLDE at CERN
for short-lived nuclei annihilation.

PUMA - a Transportable Ion Trap System

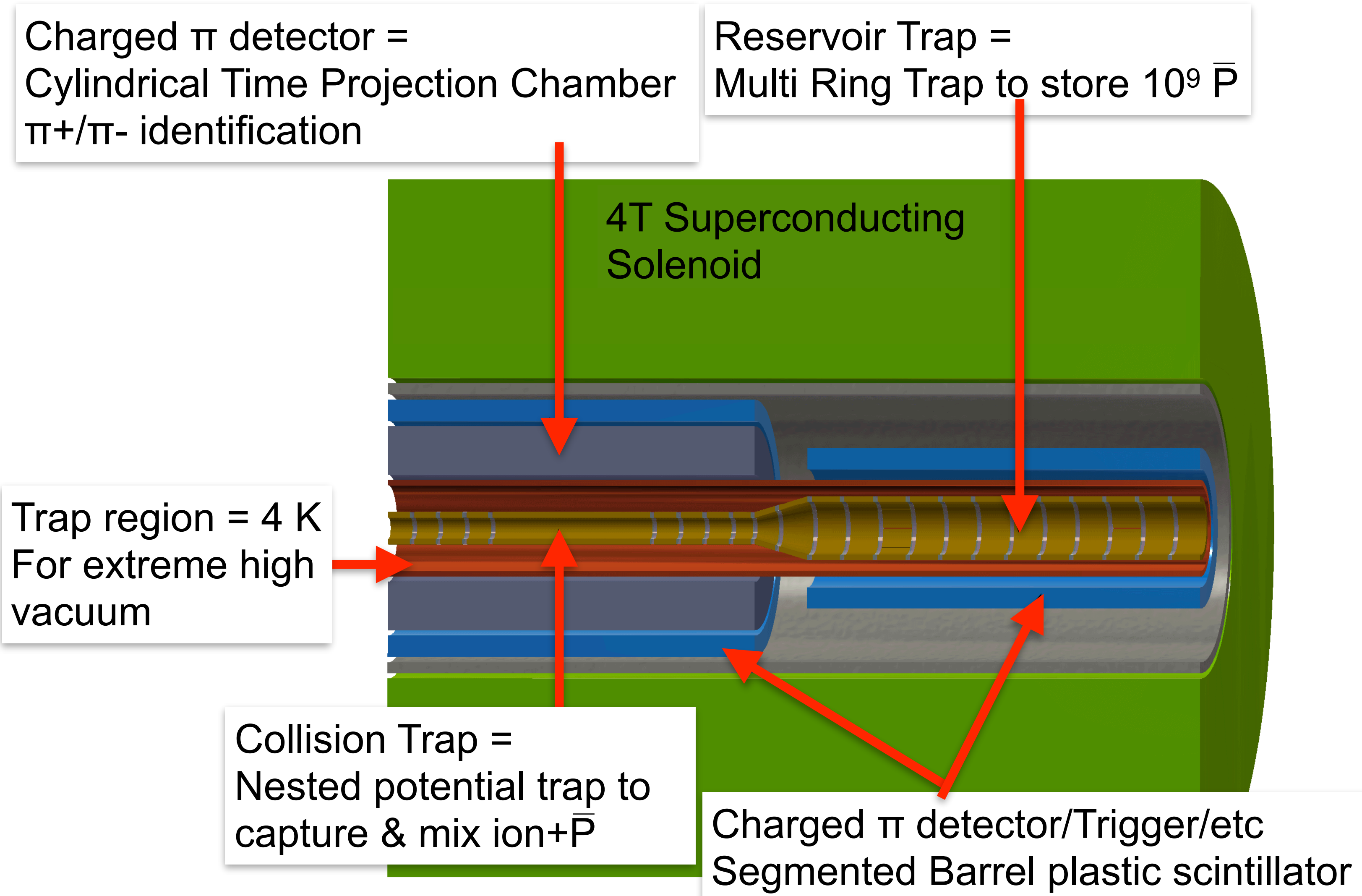


Figure: J. Fisher and A. Schmidt

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Uncertainties

- Systematic
  - Annihilation site, Cascade
  - Multi pion final states
  - Final state interactions of π^{-0+}

→ Theoretical input is needed!

- Statistic
  - Beam intensity
  - Half life of nuclei
  - Trapping efficiency

Antiprotonic atom a bit more in detail

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- ☑ Atomic cascade calculations is necessary to determine annihilation site
- ☑ An example: cascade scheme from kaonic atom

Capture n orbit

Auger e^- decay region

X ray decay region

Last observed transition 100% absorption

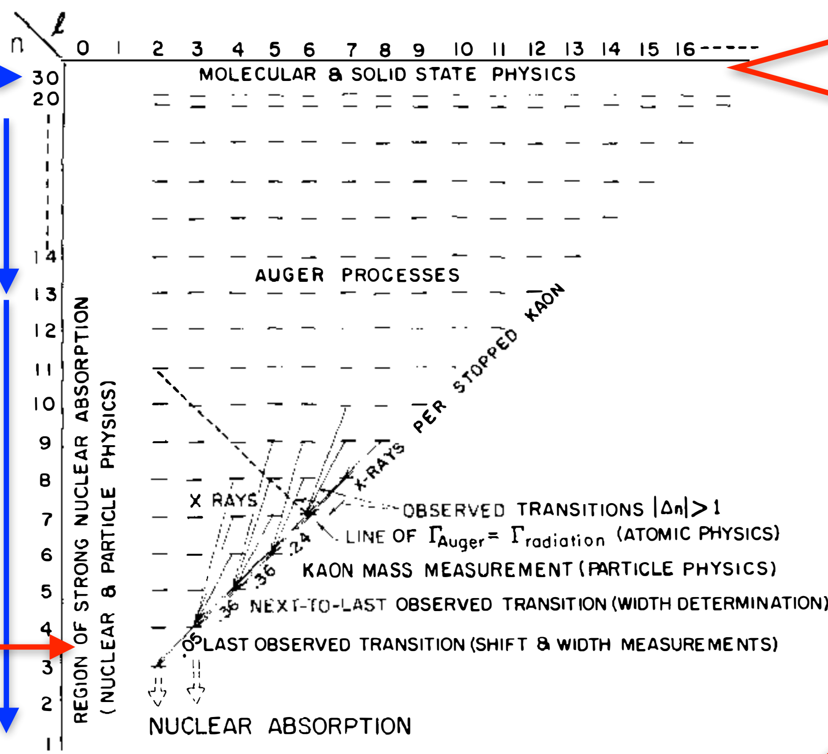

Figure 7 Schematic diagram of kaonic ${}^{32}_{16}$S atoms showing some of the features of the cascade and nuclear absorption. The cascade was started at $n = 30$ where the angular momentum distribution of kaons was assumed to be proportional to $2l+1$ and l_{max} equaled $n-1$. Regions of applicability of various disciplines in physics are indicated.

	m/m_e	n@capture
μ^-	206.8	14
π^-	273.1	23
K^-	966.1	31
pbar	**1836.2**	**43**

Nuclear absorption region: Overlap of atomic & nuclear process

- ☑ Annihilation probability has distribution.
- ☑ Reliable cascade code to determine annihilation site.
- ☑ $\bar{P}$-nucleus (optical) potential as an input

R. Seki and C. E. Wiegand, Ann. Rev. Nucl. Sci. **25**, 241 (1975)

Pion final state a bit more in detail

- Multiple pion final state: Data in good agreement with statistical model
- Initial state at annihilation: Heavier mesons

- Crystal Barrel at LEAR
- $\langle N_{charge}\rangle=3$, $\langle N_{neutral}\rangle=2$
- $\langle N_{total}\rangle=5$, Gaussian distribution

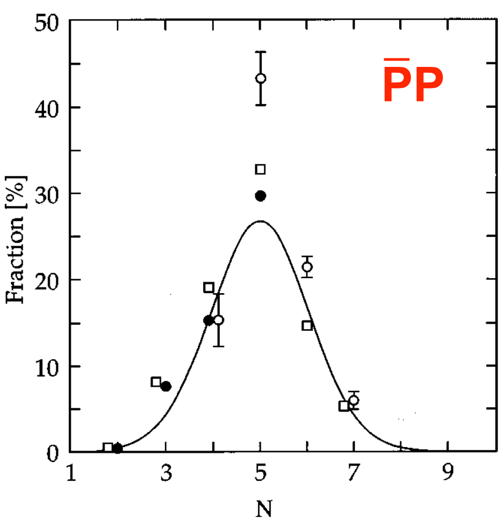

FIG. 1. Pion multiplicity distribution for $\bar{p}p$ annihilation at rest in liquid hydrogen: □, statistical distribution; ●, data; ○, estimates from Ghesquière (1974). The curve is a Gaussian fit assuming $\langle N\rangle=5$.

C. Amsler, Rev. Mod. Phys. **70**, 4 (1998)

- Initial state

	B				Reference
e^+e^-	3.2	±	0.9	10^{-7}	Bassompierre *et al.* (1976)
$\pi^0\pi^0$	6.93	±	0.43	10^{-4}	Amsler *et al.* (1992a)‡
	4.8	±	1.0	10^{-4}	Devons *et al.* (1971)
$\pi^+\pi^-$	3.33	±	0.17	10^{-3}	Armenteros and French (1969)
$\pi^+\pi^-$	3.07	±	0.13	10^{-3}	Amsler *et al.* (1993b)‡
$\pi^0\eta$	2.12	±	0.12	10^{-4}	Amsler *et al.* (1993b)‡
$\pi^0\eta'$	1.23	±	0.13	10^{-4}	Amsler *et al.* (1993b)‡
$\pi^0\rho^0$	1.72	±	0.27	10^{-2}	Armenteros and French (1969)
$\pi^\pm\rho^\mp$	3.44	±	0.54	10^{-2}	Armenteros and French (1969)
$\eta\eta$	1.64	±	0.10	10^{-4}	Amsler *et al.* (1993b)‡
$\eta\eta'$	2.16	±	0.25	10^{-4}	Amsler *et al.* (1993b)‡
$\omega\pi^0$	5.73	±	0.47	10^{-3}	Amsler *et al.* (1993b) [a]‡
	6.16	±	0.44	10^{-3}	Schmid (1991) [b]‡
$\omega\eta$	1.51	±	0.12	10^{-2}	Amsler *et al.* (1993b) [a]‡
	1.63	±	0.12	10^{-2}	Schmid (1991) [b]‡
$\omega\eta'$	0.78	±	0.08	10^{-2}	Amsler *et al.* (1993b)‡
$\omega\omega$	3.32	±	0.34	10^{-2}	Amsler *et al.* (1993b)‡
$\eta\rho^0$	4.81	±	0.85	10^{-3}	[c]
	3.87	±	0.29	10^{-3}	Abele *et al.* (1997a)‡
$\eta'\rho^0$	1.29	±	0.81	10^{-3}	Foster *et al.* (1968a)
	1.46	±	0.42	10^{-3}	Urner (1995)‡
$\rho^0\rho^0$	1.2	±	1.2	10^{-3}	Armenteros and French (1969)
$\rho^0\omega$	2.26	±	0.23	10^{-2}	Bizzarri *et al.* (1969)
K^+K^-	1.01	±	0.05	10^{-3}	Armenteros and French (1969)
K^+K^-	0.99	±	0.05	10^{-3}	Amsler *et al.* (1993b)‡
K_SK_L	7.6	±	0.4	10^{-4}	Armenteros and French (1969)
K_SK_L	9.0	±	0.6	10^{-4}	Amsler *et al.* (1995c)‡

<Final state>: Multiple π^{-0+} state
<Initial state>: Heavier mesons possible: K^{+-LS},η',,,
- Possibly interact with residual nucleus
- Possibility to study hypernuclei etc…

Final state interactions (FSIs)

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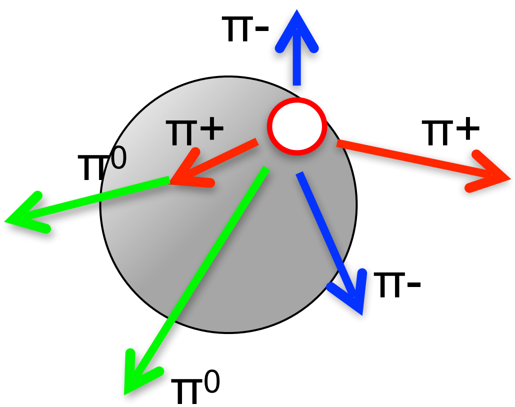
- ☑ Produced pions can interact with residual nucleus
- ☑ FSIs change total charge of pions/event (Σ) and charged pion multiplicity/event (N)

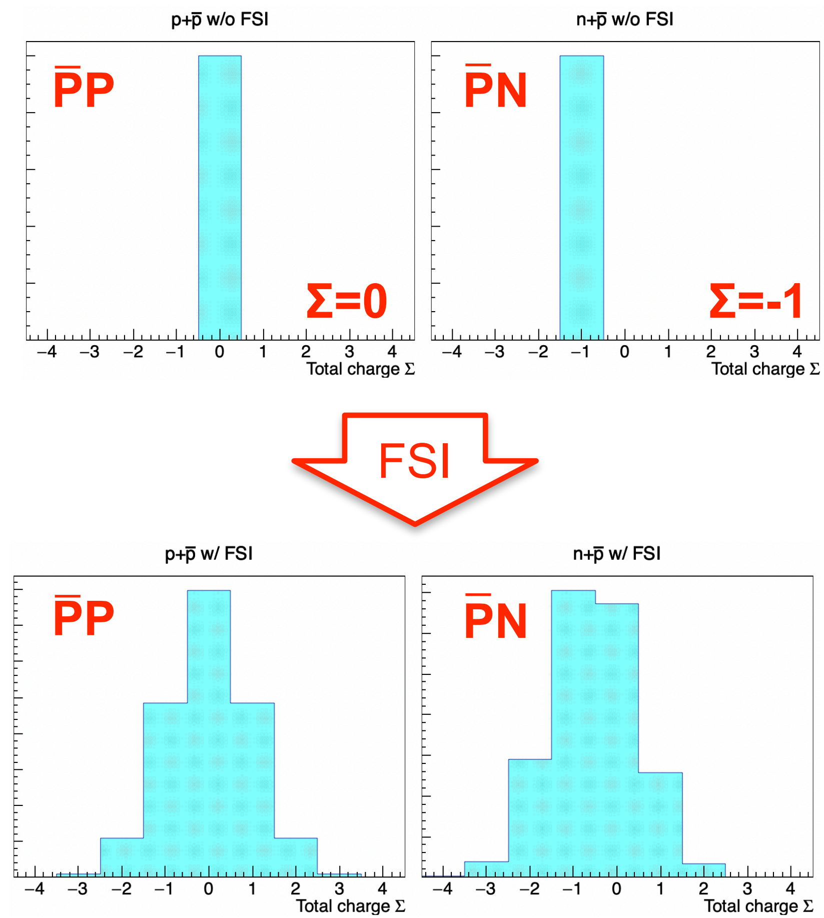
Observable   Observable

$\bar{P}P$ annihilation



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

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



- ☑ Not negligible at the nuclear surface
- ☑ An estimated value:
  - ☑ π^{-+} -> X (missing) : ω=10~20 %
  - ☑ π^0 -> π^{-+} : λ=10 %
- ☑ Event by event correction not possible
- ☑ Statistical analysis necessary

Correcting FSIs

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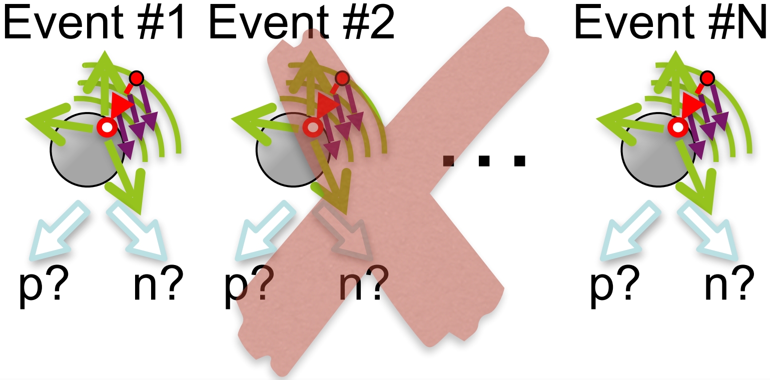
☑ Event-by-event analysis does not work



☑ Analyze Σ-N matrix ***M*** -> Reconstruct

M. Wada and Y. Yamazaki, AIP Conf. Proc. **793**, 233 (2005)

M

TABLE 3. Simulated histogram of the multiplicity of charged pions (row) and the total charge per event (column) under a typical experimental condition: $R_{n/p} = 1.0$, $\varepsilon_+ = \varepsilon_- = 0.6$, $\omega_+ = \omega_- = 0.1$, $\lambda_+ = \lambda_- = 0.1$. The number of total annihilation event is 10^5.

$M \backslash \Sigma_c$	-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

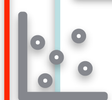
$M = a^*\bar{P}P + (1-a)^*\bar{P}N$ ***a:*** P/N ratio at surface

✓ Formalism of analysis: Extract '***a***'

☑ Find '***a***' using machine learning

Supervised learning

Input



Exp. data:
M with
unknown '***a***'

Neural network

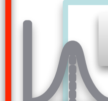
Fit

Teaching data

Monte-Carlo:
M with
known '***a***'

Prepare sufficient sample
a in [0,1]

Output



n-p ratio '***a***'

Sensitivity

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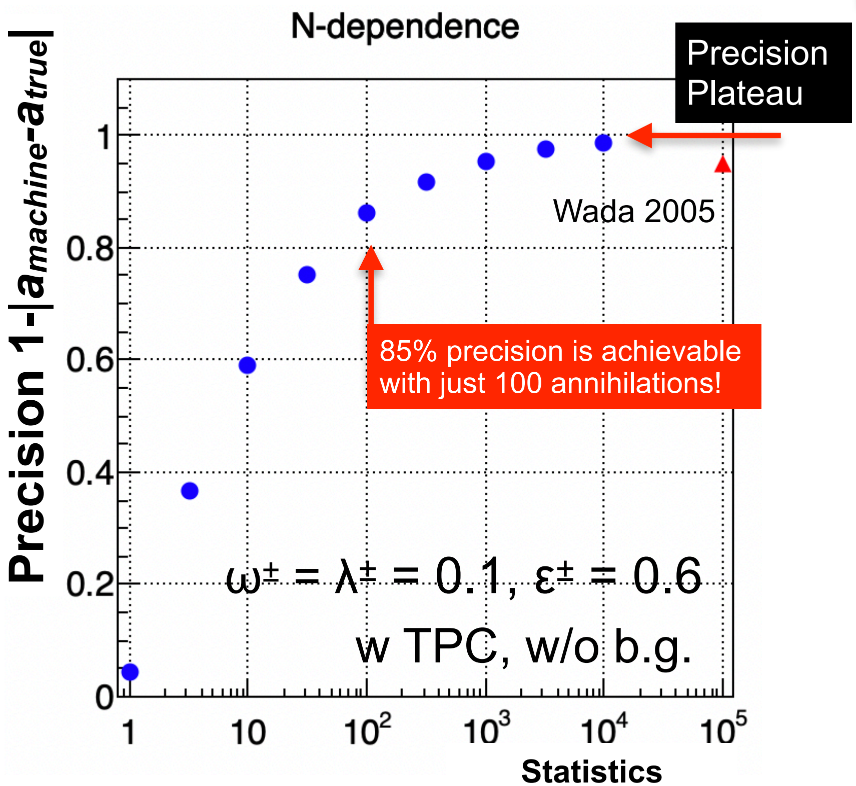
☑ Benchmarking machine learning using a Monte-Carlo test data

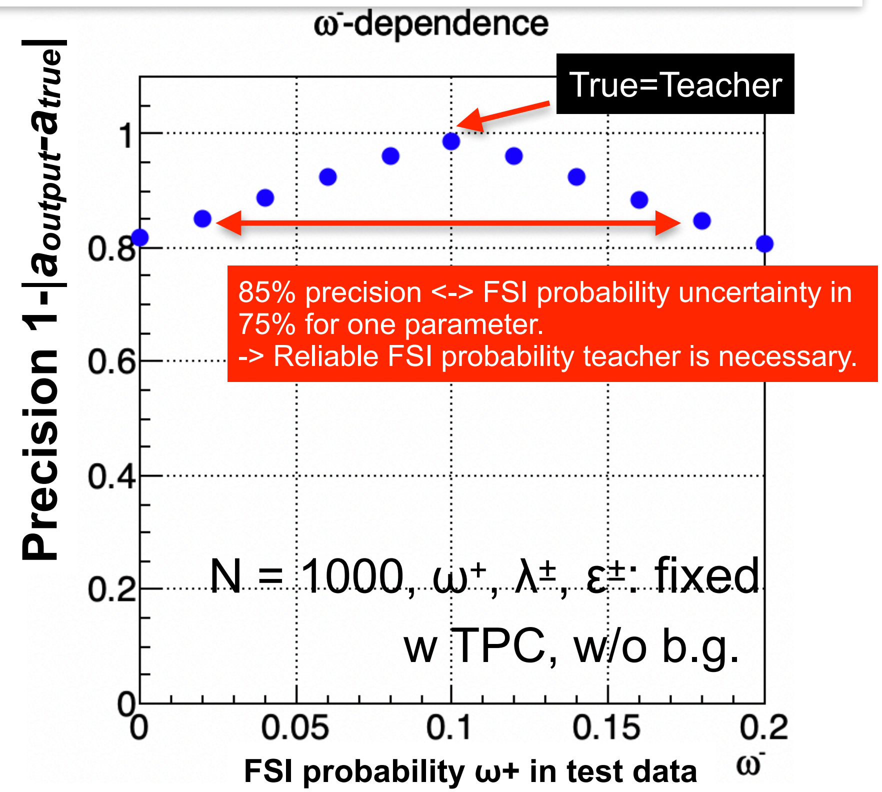
Statistics vs machine learning precision

☑ '*a*' determination precision depends on statistics
☑ N=10^4 annihilation event in a ***M*** matrix = plateau



FSI uncertainty vs machine learning precision

☑ Uncertainty in FSI probability affect precision
☑ Teaching data: charge exchange probability ω^+=0.1
☑ Test data: ω^+= 0 to 0.2



Upgrade plan to improve sensitivity

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- Further upgrade of PUMA planned
- Decay x-ray measurement =
  Rich information of annihilation site, but statistics necessary
- Recoil nucleus measurement = Background suppression (discuss later)

- Example: Decay X ray scheme of antiprotonic ^{172,176}Y

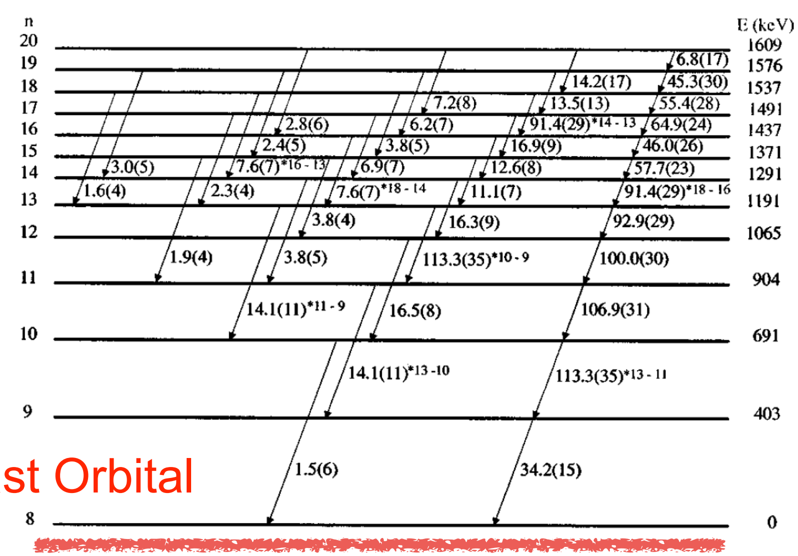

FIG. 4. Measured intensities of antiprotonic x-ray transitions in ^{172}Yb, normalized to the transition $n=12\rightarrow 11$; admixed transitions are marked with an asterisk. E: Level energy relative to the level $n=8$

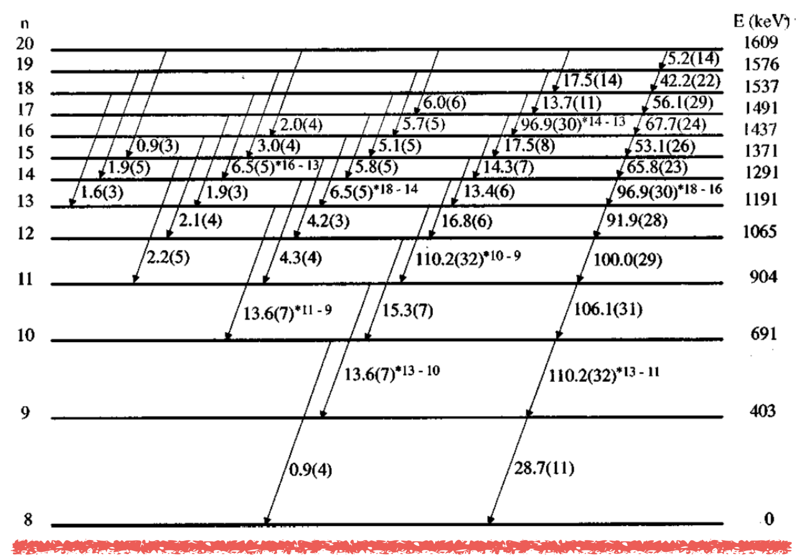

FIG. 5. Measured intensities of antiprotonic x-ray transitions in ^{176}Yb, normalized to the transition $n=12\rightarrow 11$; admixed transitions are marked with an asterisk. E: Level energy relative to the level $n=8$.

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

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PUMA - a Transportable Ion Trap System

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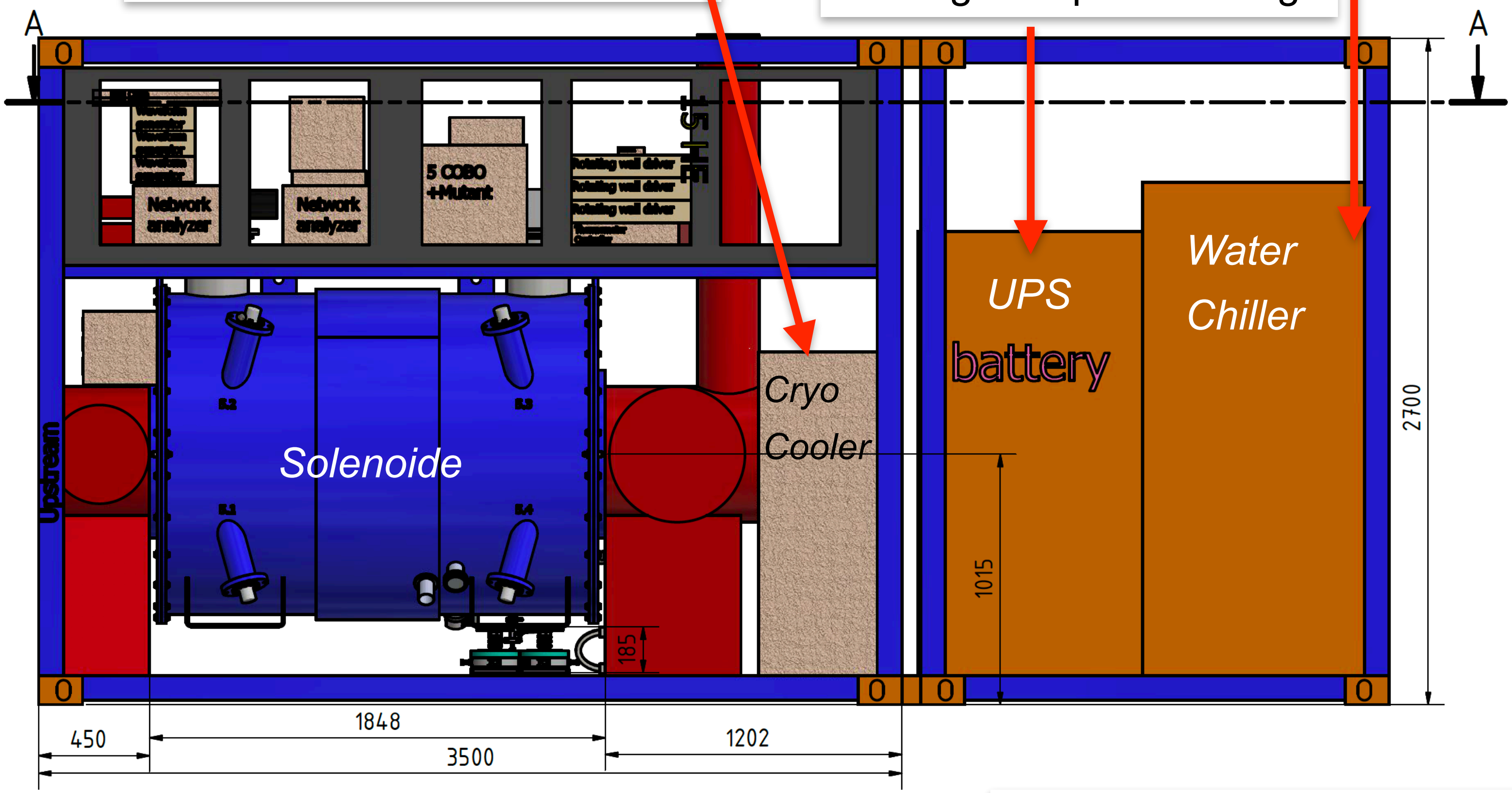
- ☑ Transportable trap that meets constrains from environment (ELENA / ISOLDE)
  C.H. Tseng and G. Gabrielse, Hyperfine Interactions 76, 381 (1993)

Transporting Frame

A chiller to supply cooling water
During transportation

Cryocoolers for He-free system

UPS against power outage



(+ Diesel Power Generator on Truck)

PUMA - a Transportable Ion Trap System

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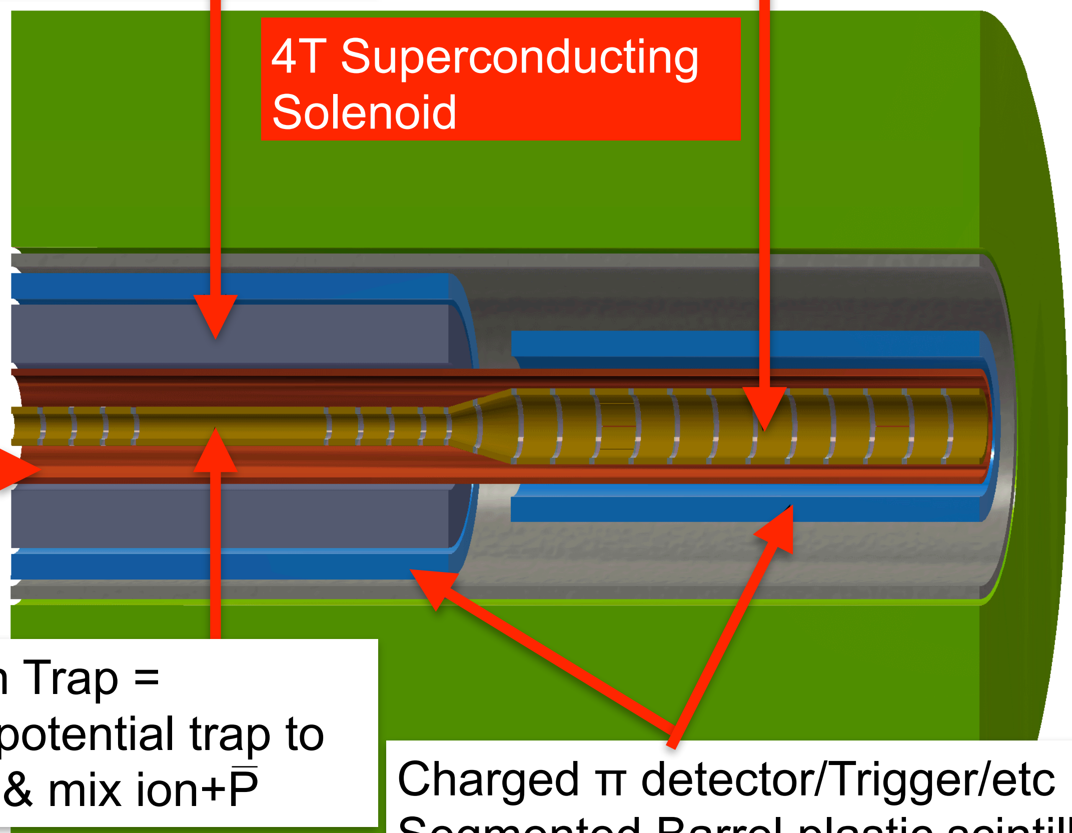
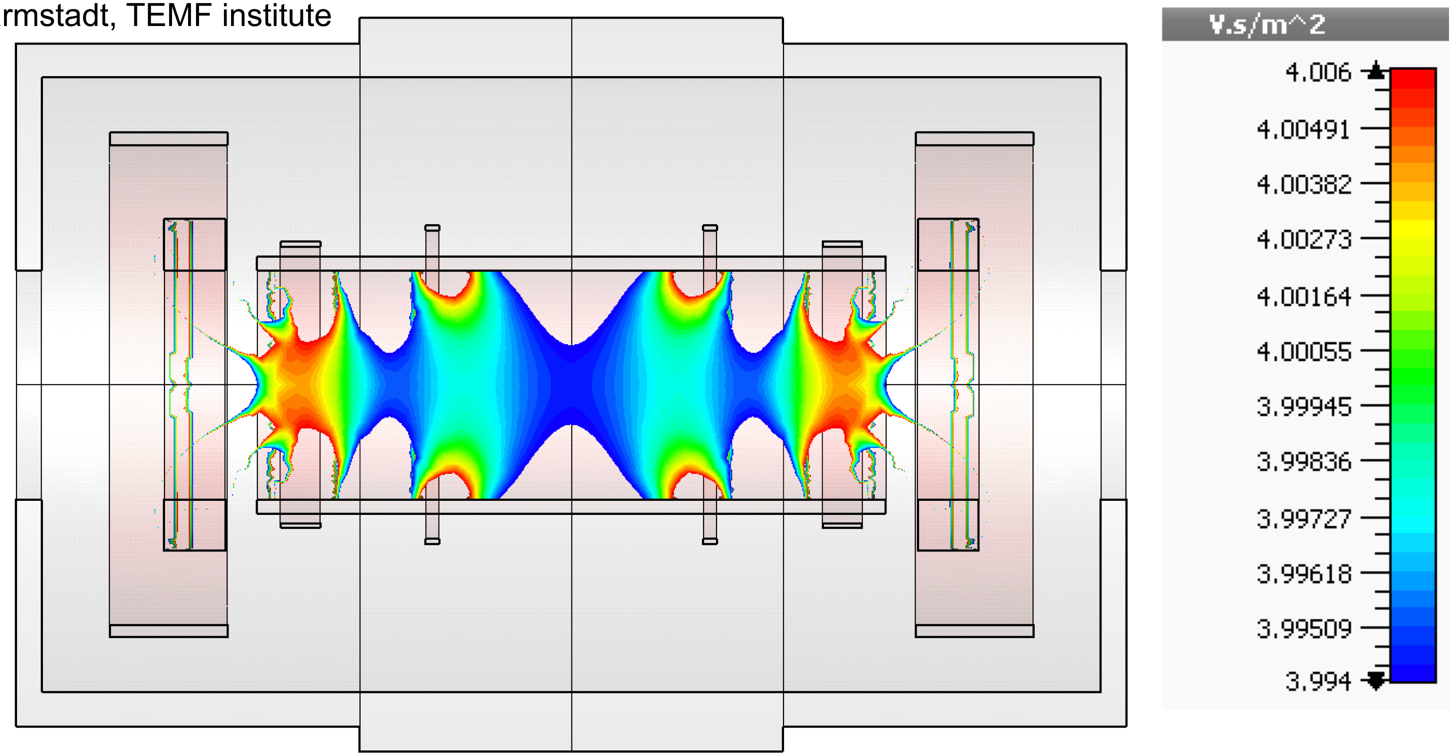


Figure: J. Fisher and A. Schmidt

PUMA - Design of Solenoid

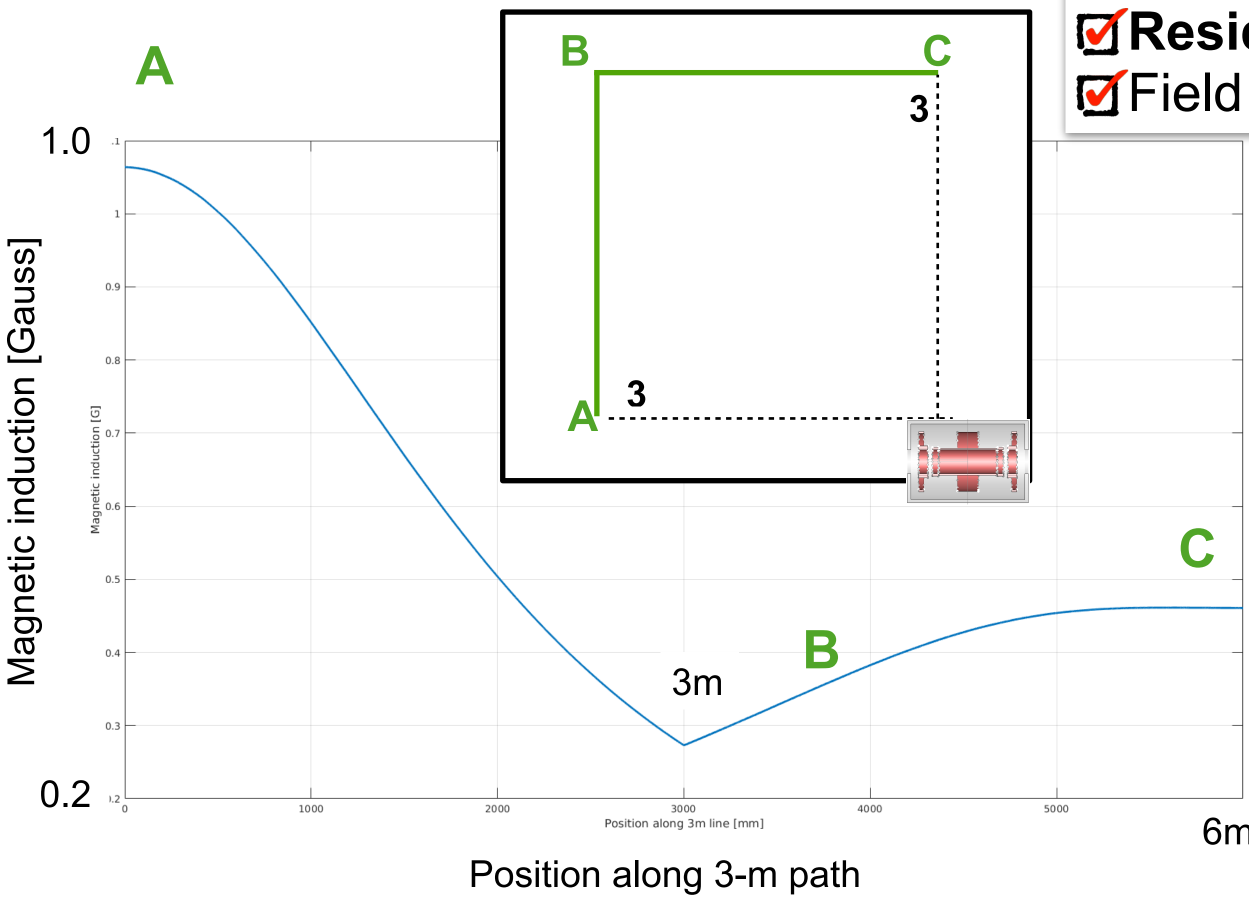
- Solenoid- Required to minimize residual field for ELENA experiments
- Specific Coil design - simulated by TEMF @ TU Darmstadt
- 4 T - Superconducting - homogeneous at trap region
- Under construction by Nöel-Bilfinger in Würzburg
- Delivery in early 2020

TU Darmstadt, TEMF institute



Residual field

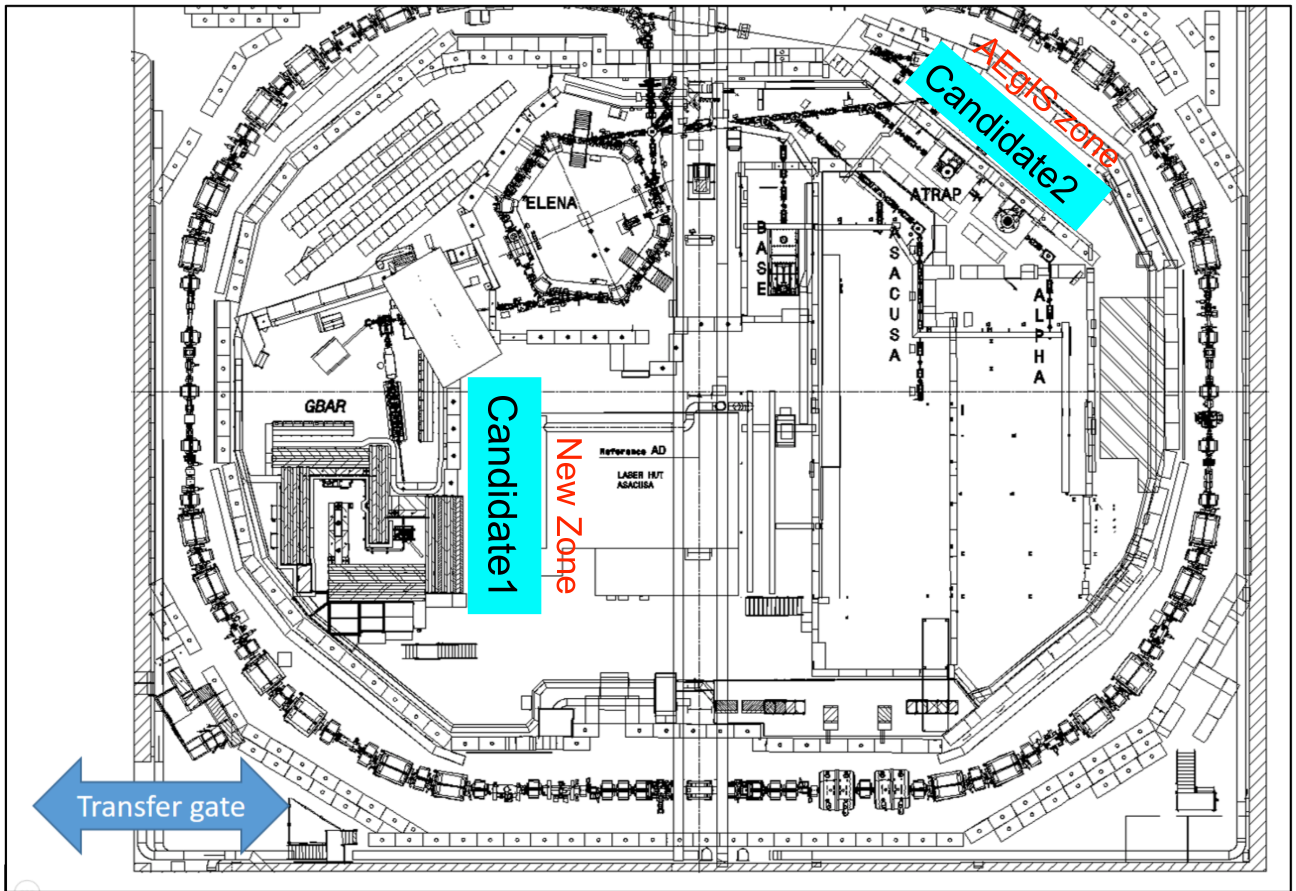
- ☑ Transportable solenoid: necessary to minimize residual field at ELENA
- ☑ Constraints on coil design



- ☑ **Active & passive shielding**
- ☑ **Residual field**:
- ☑ Field **< 2 G** at 3 m

Locations at ELENA

- Current AEgIS area or new area between GBAR and ASACUSA.
- CERN will make decision IF our proposal will be accepted.



Locations at ISOLDE

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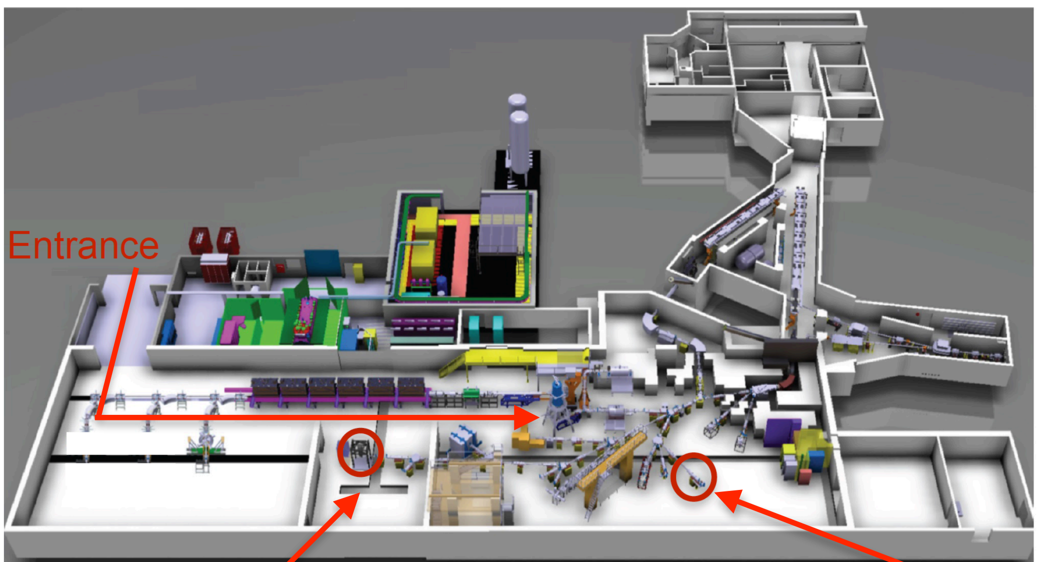
☑ Requirement for the beam line: Coupling to MR-TOF, low energy (<3keV) etc..

Location not decided yet
Two options discussed so far
Vacuum at ISOLDE: up to 10^{-6} mb due to gas cooling (RFQ, Helium)



Candidate B
Not used at the moment

Candidate A
Traveling setup

PUMA - a Transportable Ion Trap System

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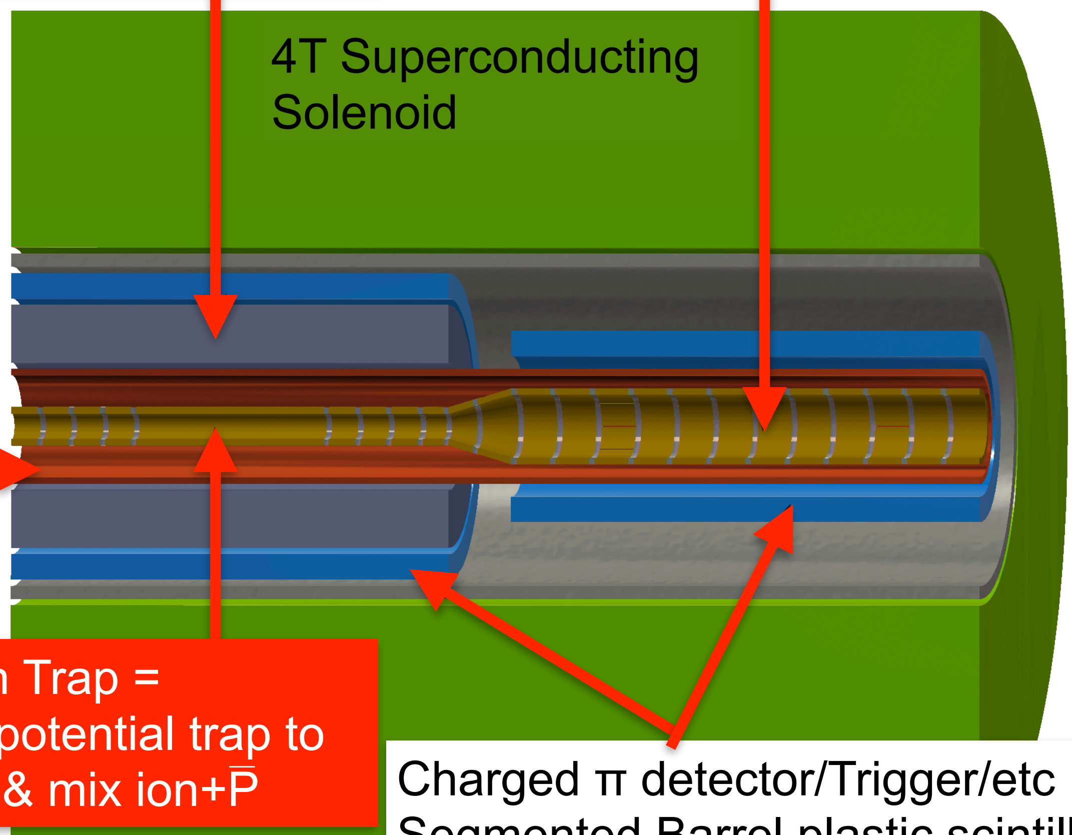


Figure: J. Fisher and A. Schmidt

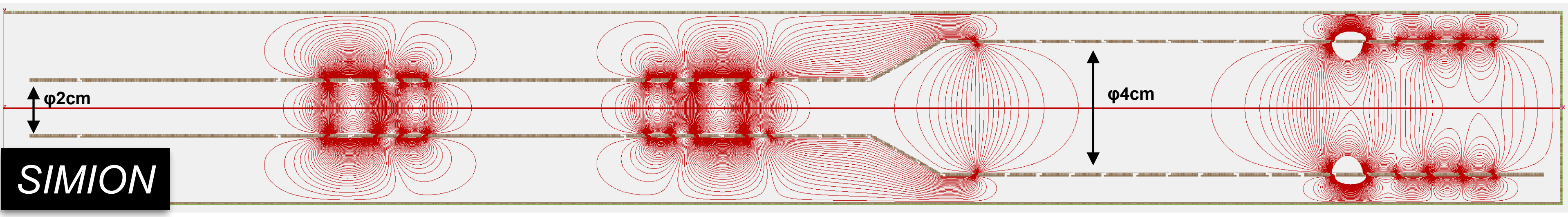
PUMA - Design of Ion Trap

- ☑ Consists of Collision and Storage Trap
- ☑ Pulsed Drift Tube before traps to optimize injection energy
- ☑ Collision Trap - 2cm diameter, Nested potential to trap $\bar{P}$ and A simultaneously
- ☑ Storage Trap - 4cm large diameter to limit space charge $<10^7/cm^3$

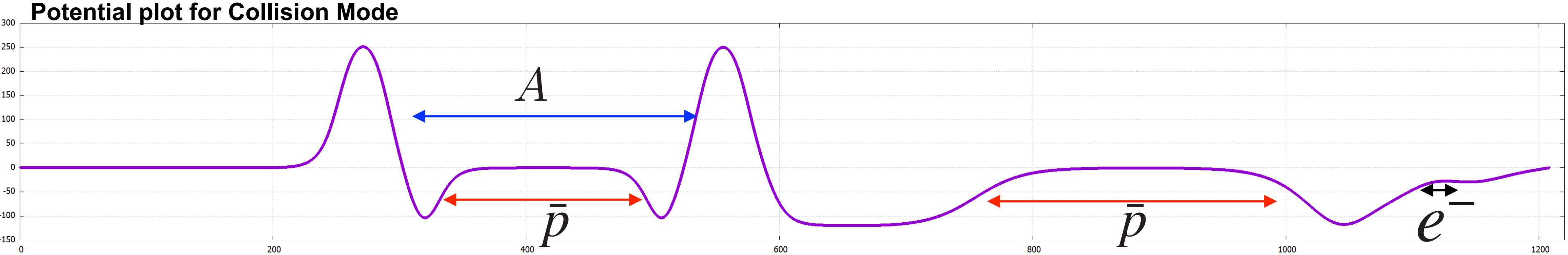
Pulsed Drift Tube
Slow down nuclei

Collision Trap
Nested Potential to mix $\bar{P}$-A

Storage Trap
Load, cool down, store 10e9 $\bar{P}$

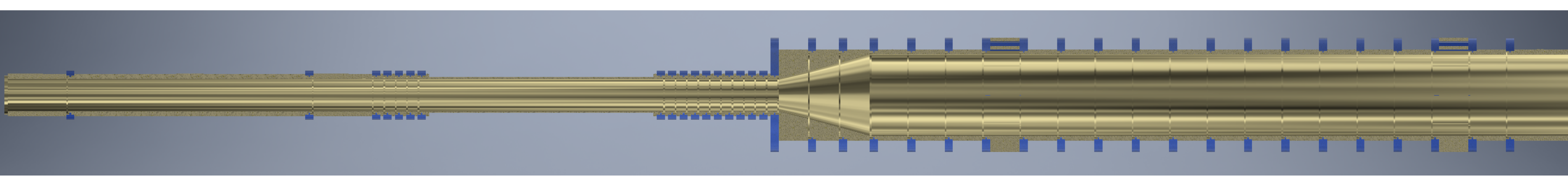


Potential plot for Collision Mode



Total length ~120 cm

Magnetic field homogeneous region ~ 80 cm



Trapping scheme

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Key Techniques

Pulsed Drift Tube

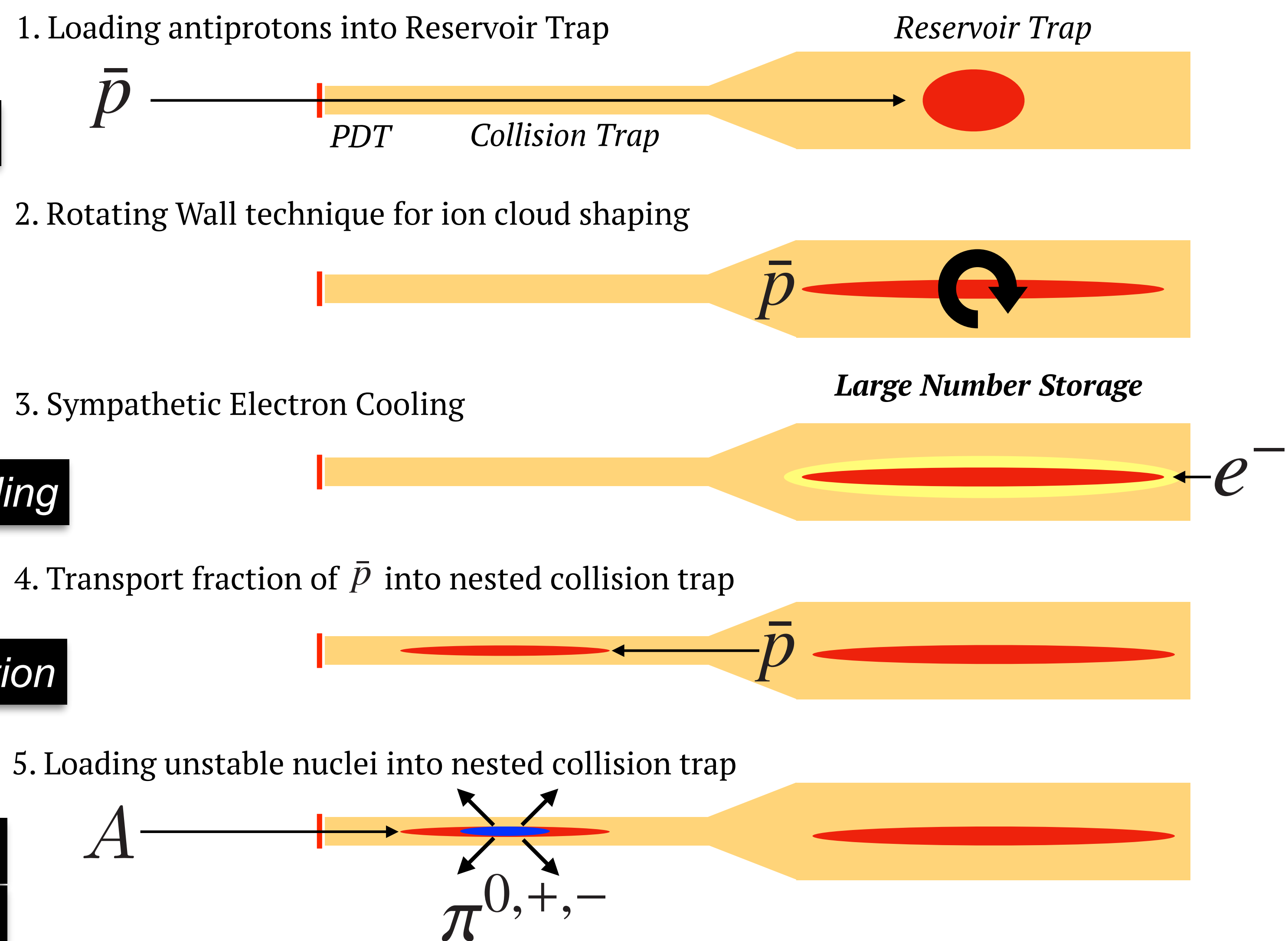
Rotating Wall

Sympathetic Cooling

Fractional Extraction

Nested Potential

Pulsed Drift Tube

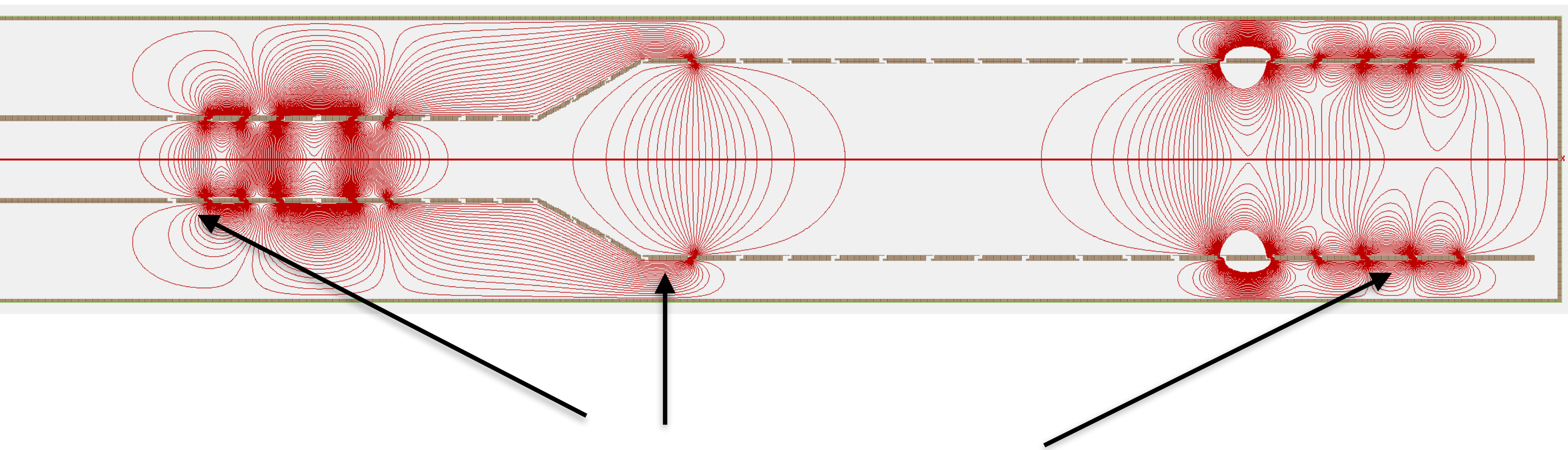


PUMA - Ion Detection

- ☑ Ion diagnostics - destructive & non-destructive
- ☑ Non-destructive - Induced charge detection circuit
- ☑ Destructive imaging - MCP + phosphor screen + CCD readout
- ☑ Destructive number count - Faraday cup

Collision Trap
Nested Potential to mix $\bar{P}$-A

Storage Trap
Load, cool down, store 10e9 $\bar{P}$



Electrodes with non-destructive detection circuit

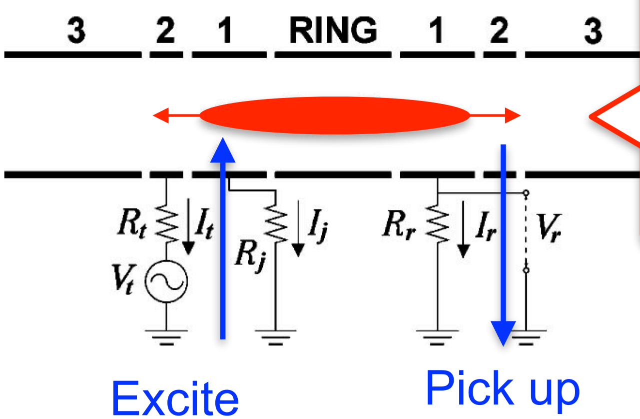
PUMA - Plasma Mode Diagnostics

- ☑ $\overline{\text{P}}$ cloud behaving as non-neutral plasma in a harmonic well
- ☑ Frequency of excited mode ~ diagnostics of plasma

Excite n-n collective mode using RF

Complete nondestructive diagnostic of nonneutral plasmas based on the detection of electrostatic modes

M. Amoretti,[1,a)] G. Bonomi,[2] A. Bouchta,[2] P. D. Bowe,[3] C. Carraro,[1,4] C. L. Cesar,[5] M. Charlton,[6] M. Doser,[2] A. Fontana,[7,8] M. C. Fujiwara,[9] R. Funakoshi,[9] P. Genova,[7,8] J. S. Hangst,[3] R. S. Hayano,[9] L. V. Jørgensen,[6] V. Lagomarsino,[1,4] R. Landua,[2] E. Lodi Rizzini,[10] M. Macrí,[1] N. Madsen,[11] G. Manuzio,[1,4] G. Testera,[1] A. Variola,[1] and D. P. van der Werf[6] (ATHENA Collaboration)



Plasma behaves as a part of a serial LCR circuit

Equivalent 'n-n plasma' LCR circuit

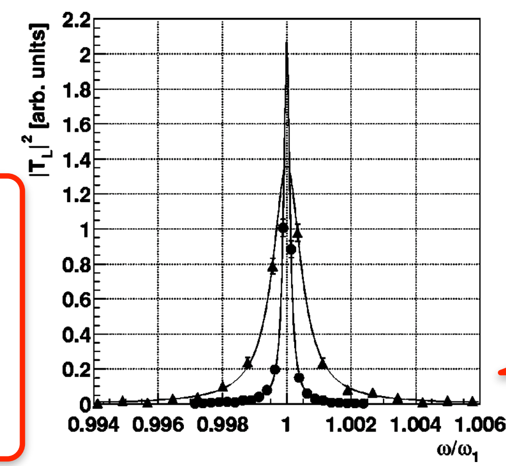


FIG. 4. Examples of the measured $|T_L|^2$ as a function of the ratio between ω and the corresponding ω_1 value. The data refer to electrons stored in the catching trap. Bullets (•) correspond to $N=5.8\times10^7$ and triangles (▲) to $N=2.6\times10^8$. The solid lines are the best fit functions [Eq. (23)].

Quality Factor of serial LCR plasma circuit = number of particles

- ☑ Excite plasma [(1,0) axial oscillation mode] using RF
- ☑ Receive the indices signal from the plasma

- ☑ Plasma is a part of LCR serial circuit
- ☑ Quality factor gives the number of particles in the plasma
- ☑ (Relative) temperature measurement also possible

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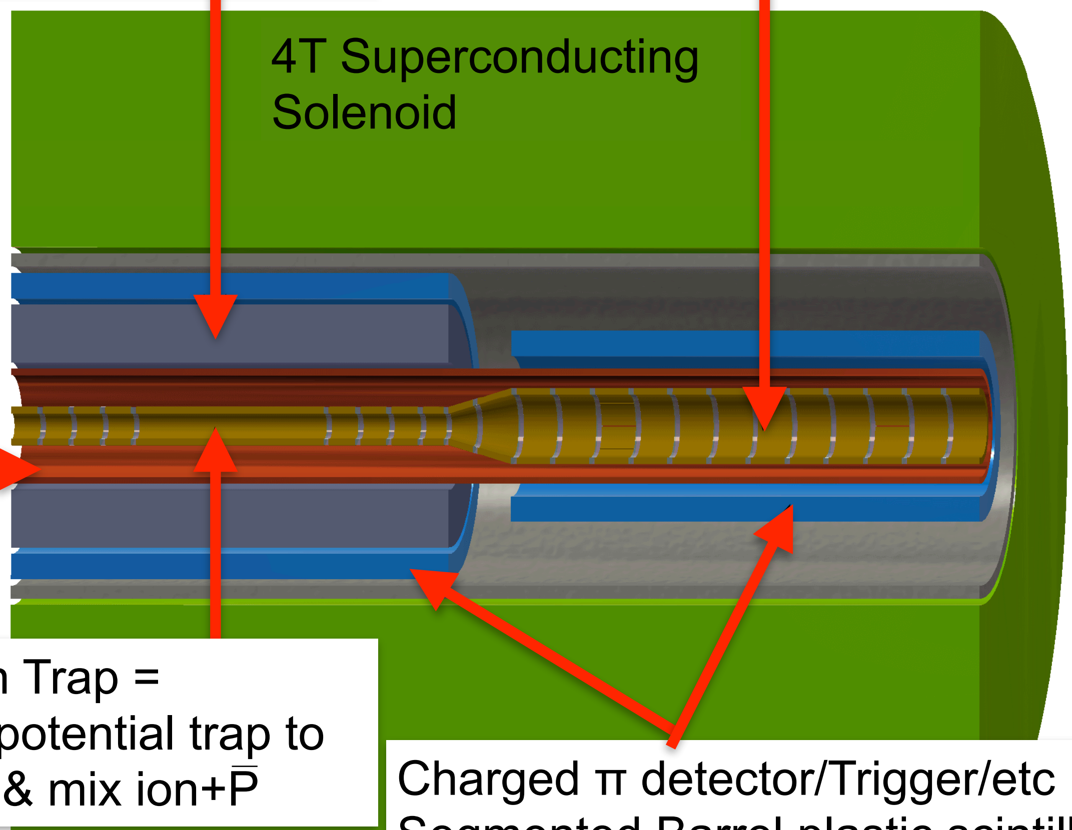

Figure: J. Fisher and A. Schmidt

Required vacuum

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☑ Extreme vacuum is necessary to keep $\bar{\mathrm{P}}$ alive for a long term

Considering the perfect gas law $P = \rho \times k_B T$

cf. S. Ulmer, BASE
cf. G. Gabrielse, ATRAP

$$P_H(\text{mbar}) = 7.8 \times 10^{-11} \times \frac{T(\text{K})}{\tau(\text{s})}$$

Empirical formula: cryopumping vs $\bar{\mathrm{P}}$ lifetime

At 5 K, if P = 10^{-12} mbar, tau = 6 minutes
if P = 10^{-17} mbar, tau = 450 days

The residual rate R_2 of annihilations in PUMA is therefore

$$R_2 = \frac{N_{\bar{p}}}{\tau} = N_{\bar{p}} \times 2 \times 10^{10} \times \frac{P}{T}$$

At 5 K, for N = 10^7 antiprotons
if P = 10^{-12} mbar, R_2 = 4 10^4 s^{-1}
if P = 10^{-17} mbar, R_2 = 0.4 s^{-1}

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Required vacuum

☑ Extreme vacuum also necessary to improve S/N ratio

Physics event rate in the antiproton cloud: R_1

$$R_1 = \rho_{\bar{p}} \times \sigma \times N \times \frac{v}{L}$$

The signal over background is better than 1 only if:

$$\frac{R_1}{R_2} > 1 \Longleftrightarrow P < \frac{\sigma \times N \times v}{V \times T \times 7.8 \times 10^{-11}}$$

Signal to noise ratio:
PA annihilation rate vs
$\bar{P}$gas annihilation rate

One extreme case: ^{11}Li

Capture cross section from ^{11}Li [Cohen, PRA 69] = 8.10^{-16} cm^2 at 50 eV in the laboratory (Ecm=0.15 a.u.)
V=pi*0.2^2*5 = 0.6 cm^3, T=5 K, N=10 v=3*10^6 cm.s^{-1} (^{11}Li at 50 eV)

R_1 is about 1 s^{-1} (<R1> = 10 /min), one gets the condition for proper operation: P<1.6 10^{-17} mbar.

Cryopumping - isotherms

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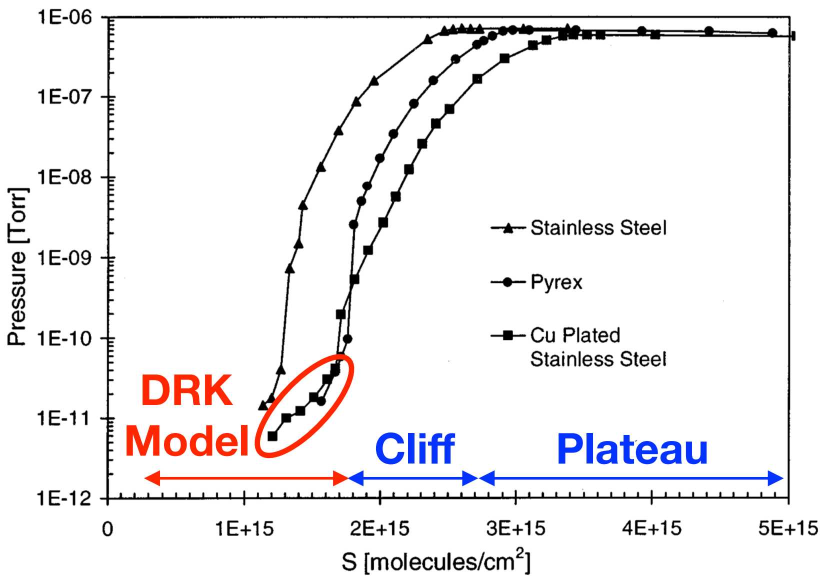
- ☑ Isotherms = equilibrium between adsorbed molecules & pressure
- ☑ Data exists down to 10^{-12} mbar

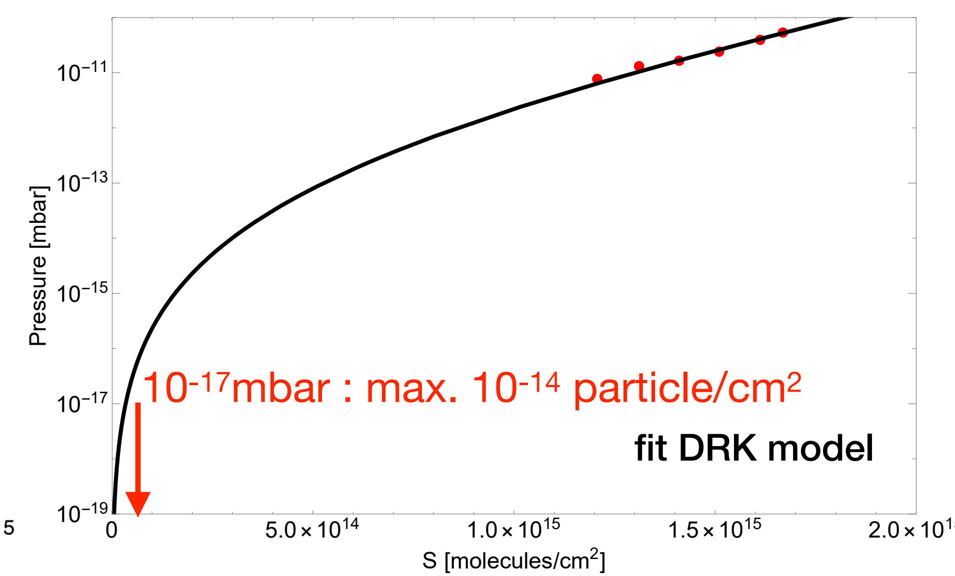
H_2 adsorption isotherms at 4.2 K



Monolayer Evaporation Equilibrium

E. Walle´n: Adsorption isotherms of He and H_2 Journal of Vacuum Science & Technology A 15, 265 (1997); doi: 10.1116/1.580523

Extrapolation to 10^{-17} mbar



- ☑ Extrapolate into lower pressure using DRK model
- ☑ Maximum particle you can introduce = Lifetime of 10-17 mbar vacuum
- ☑ Molflow simulation to estimate lifetime ongoing

Extreme high vacuum: A conductance simulation for ISOLDE beam line

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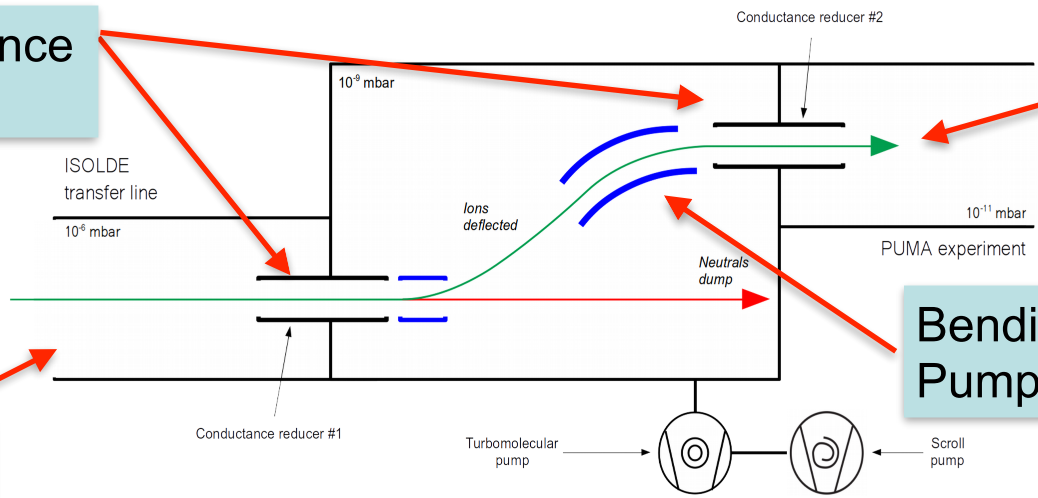
- ☑ Differential pumping to isolate ISOLDE 10^{-6} and PUMA 10^{-12} mbar vacuum
- ☑ Simulation based on molecular flow conductance: Molflow (CERN)

Conductance barrier

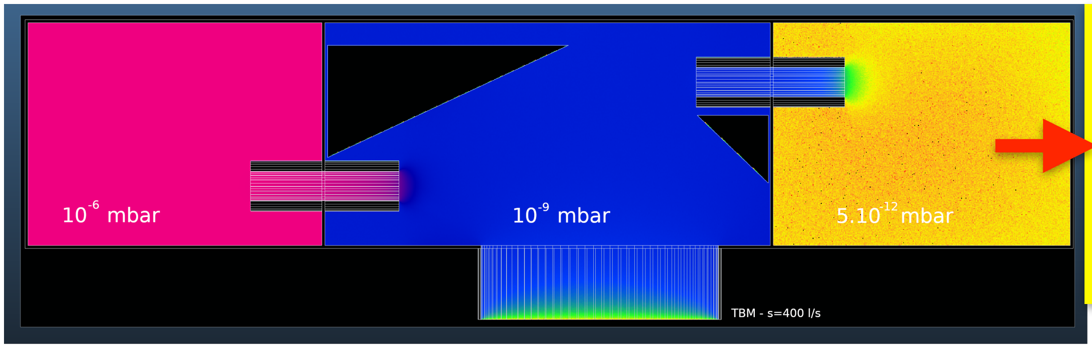
PUMA entrance 10^{-12}mbar



Bending charged particle/ Pumping neutral particle

ISOLDE vacuum 10^{-6} mbar

Molfow simulation/ Conductance scheme = possible



PUMA 4 K trap vacuum 10^{-17} mbar

L=70cm

Reducing Conductance : A development of cryogenic gate valve & conductance barrier

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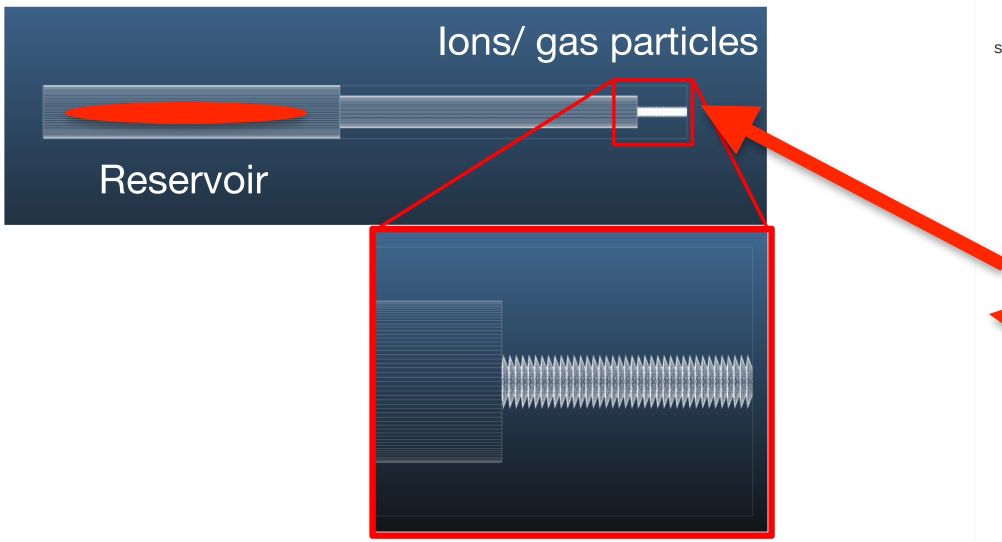
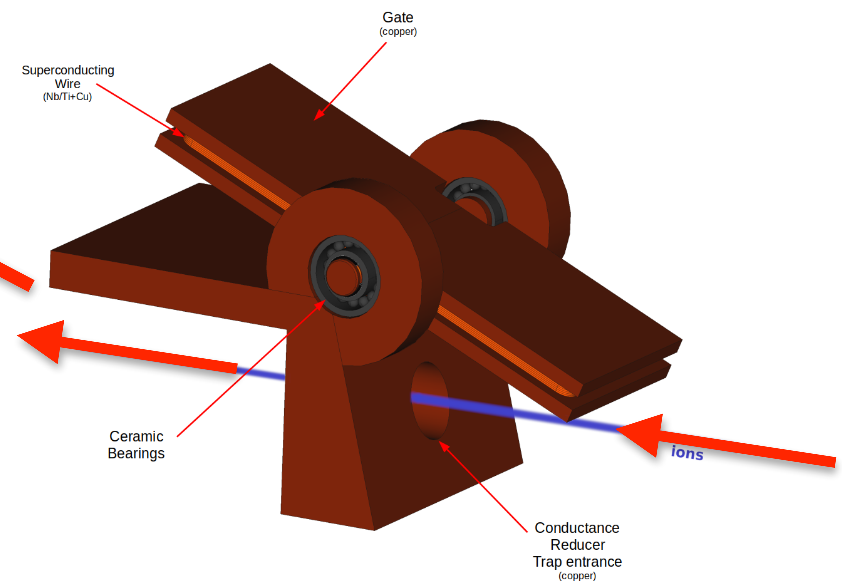
☑ Extreme vacuum also necessary to improve S/N ratio

Conductance barrier



- ☑ Reduce conductance
- ☑ Saw-Structure
- ☑ Reflect incoming gas particles
- ☑ Simulation to search for the best shape

Cryogenic gate valve



- ☑ Reduce conductance
- ☑ Motion driven by a current loop in B-field
- ☑ Open/Close time: ~100 ms
- ☑ Under development

PUMA - a Transportable Ion Trap System

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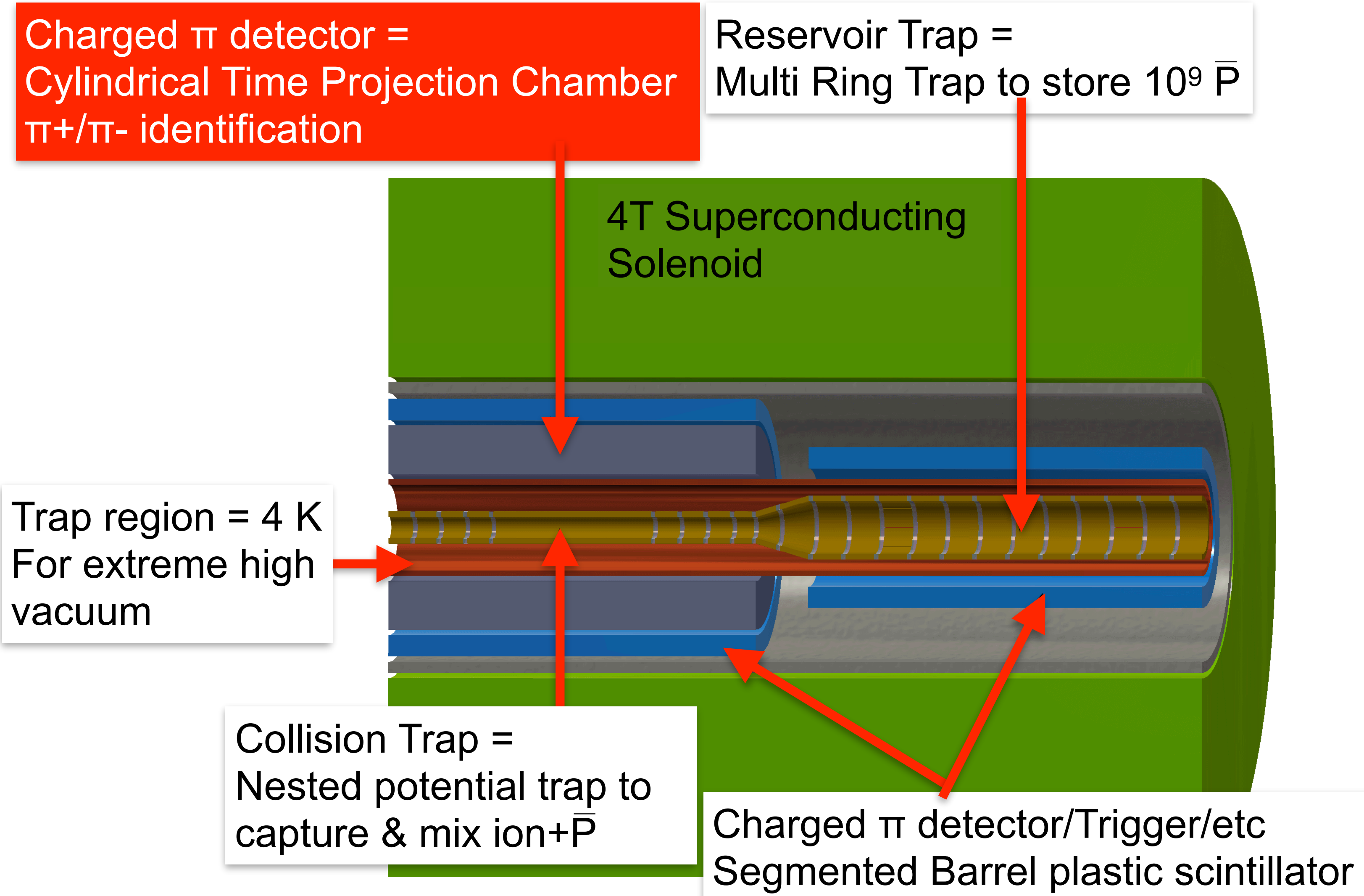
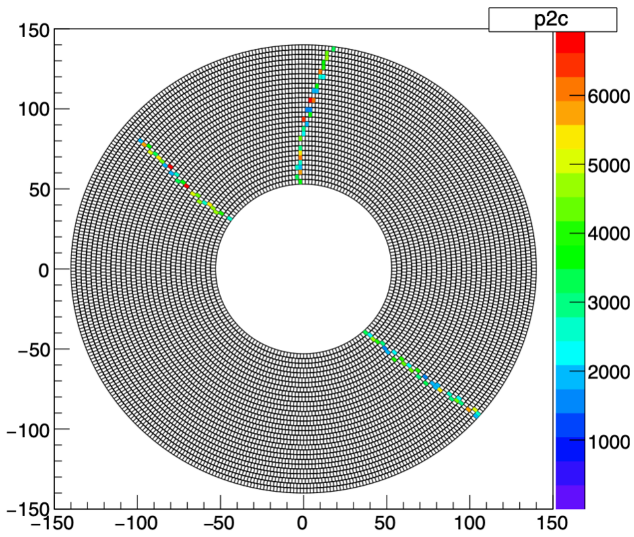


Figure: J. Fisher and A. Schmidt

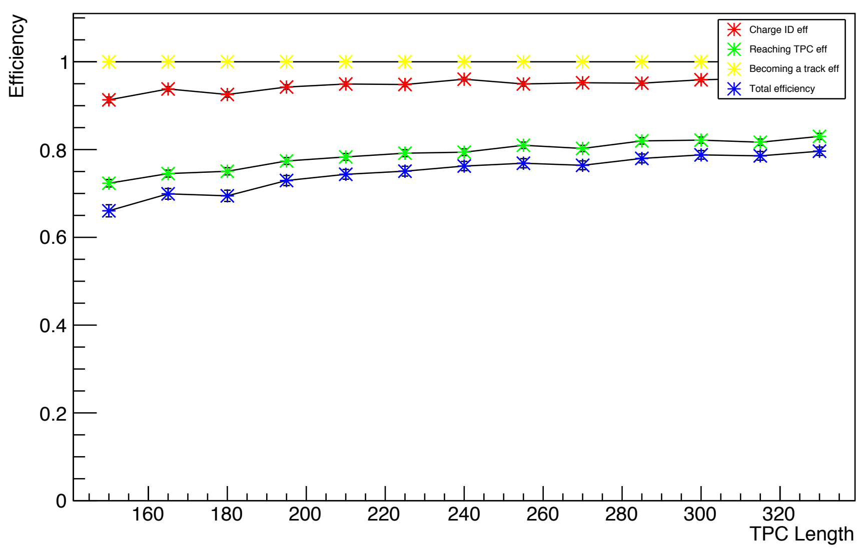
PUMA - Charged pion detection

- ☑Cylindrical Time Projection Chamber (TPC): Geant4 simulation
- ☑ID pion charge (π+ or π-) based on the curvature of the track in B-field
- ☑Optimization study to maximize detection efficiency

Event monitor of an annihilation



Efficiency vs TPC axial length



Summary

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- **PUMA**: Starting program at CERN / ELENA and ISOLDE
- Antiprotons to probe the **surface phenomena of short-lived nuclei**
- **Neutron halos and thick neutron skins** in medium mass short-lived nuclei.
- **Transport trapped antiprotons from ELENA to ISOLDE.**
- First physics experiments expected in **2022 at ELENA.**
- **Test setup to be built @ TU Darmstadt within 2019.**
- **Proposal plan to be submitted within this year.**

PUMA - Test Setup

- Test Setup to be built at TU Darmstadt
- Poster Session by J. Fischer & A. Schmidt. (Thursday)

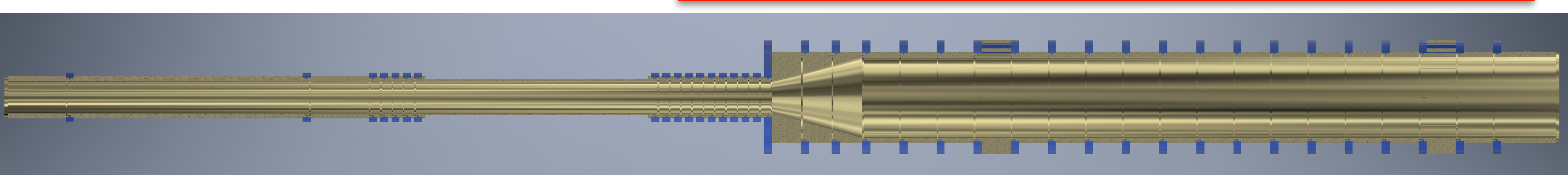
- Reservoir Trap:
- “infinite” storage of many charged particles (e^-, P).

- Destructive Diagnostics:
- Micro channel plate & Faraday cup.

- Non-destructive diagnostics:
- Plasma diagnostics based on induced charge.

- Cryogenic Ready:
- Keep trap 4K to be used as cryo pump. - Crucial to achieve UHV for antiprotons to survive.

Test 3T-Solenoid just installed



Collaboration

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J. Carbonell, A. Corsi, F. Flavigny, H. De Gersem, G. Hupin, Y. Kubota, R. Lazauskas, S. Malbrunot, N. Marsic, W. F. O. Müller, S. Naimi,
N. Nakatsuka, A. Obertelli, N. Paul, P. Pérez, E.C. Pollacco, M. Rosenbusch, R. Seki, T. Uesaka, F. Wienholtz

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