Antiprotonic radioactive nuclear atoms for nuclear structure studies

Collaboration : under construction

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M. Wada, Y. Yamazaki
and the Exo+pbar collaboration

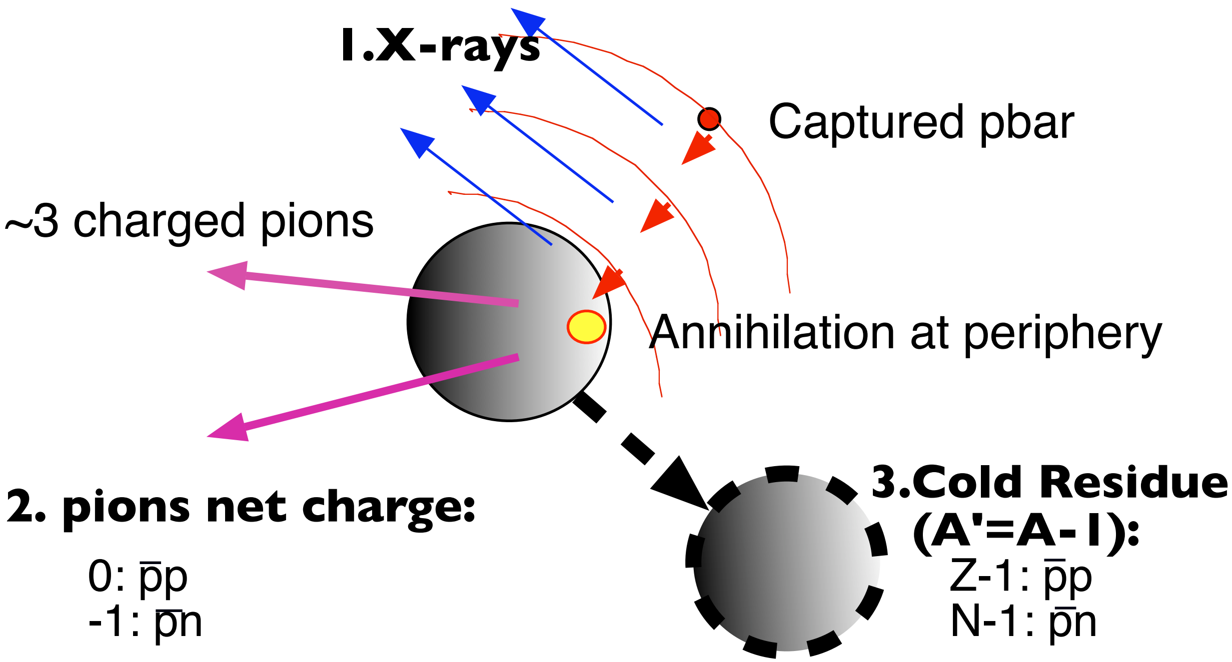
Proposed Experiment for GSI/FAIR and RIKEN/SLOWRI

1. **Introduction**
2. **Proposed Experiment**
3. **Infrastructure**
4. **Summary**

Nuclear Size, Form of Unstable Nuclei

Methods	***quantity to be determined***	***fund. interaction***	***for RI-beam***	
Optical spectroscopy (IS)	rel. $\left\langle R_C^2 \right\rangle^{1/2}$	Ele. Mag.	○ >10^2/s	*Used for many unstable nuclides of good elements. Only sensitive for protons.*
Microwave spectroscopy(hfs)	$\Delta\text{hfs} \rightarrow \varepsilon_{BW} \rightarrow \left\langle R^2_{valenceN} \right\rangle^{1/2}$	Ele. Mag.	○ 100 in trap	*Bohr-Weisskopf effect -> Distrib. Nucl. Magnetization Only for a few elements (Be, Mg,..)*
muonic X-ray	abs. $\left\langle R_C^2 \right\rangle^{1/2}$ $\text{hfs} \rightarrow \varepsilon_{BW} \rightarrow \left\langle R^2_{valenceN} \right\rangle^{1/2}$	Ele. Mag.	? >10^9 atoms	*Absolute value of charge rms radii and DNM. Short life-time of muon -> hard for RIB.* Strasser
Electron scattering	$\rho_C(r),\ \rho_{Mag}(r)$	Ele. Mag.	? >10^6?	*Charge & magnetic form factors, universal ele-mag probe. Small cross section -> hard for RIB.* Suda
Interaction cross section	$\sigma_I \Rightarrow \left\langle R_N^2 \right\rangle^{1/2}$	Strong	○ >0.01/s	*Nuclear matter size. Model is required to determine nuclear rms radii.* Ozawa
Proton elastic scattering	$\rho_N(r)$	Strong	○ >10^3/s	*Nuclear matter distribution. Model is required to determine nuclear matter distribution.* Terashima
(Momentum distrib. in fragmentation)	$\sigma P_{\text{removed nucleon}} \Rightarrow \text{halo}$	Strong	○ >1/s	*Direct evidence of halo structure, combined with rms radii.* Ozawa
(Mass)	$S_{2n}, S_n, \ldots$	Strong	○ >1/d	*Small binding energy -> loosely bound nucleon(s)*
antiprotonic atom	$r_N, \rho_n/\rho_p\vert_{\text{surface}}$	Strong	○ >10^3/s	*Different abundance of protons & neutrons at surface. Nuclear matter radii via X-ray.* Wada

Antiprotonic radioactive atoms (Exo+pbar)



A new probe for nuclear structure study of unstable nuclei

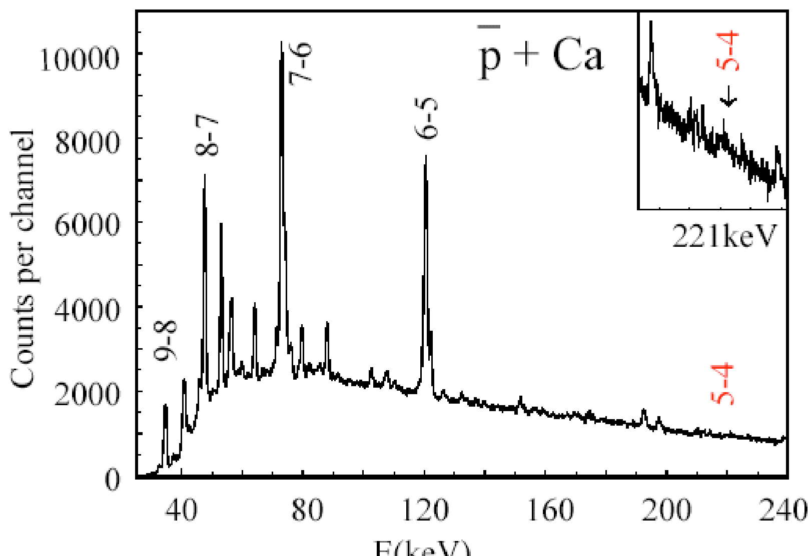
*** annihilation at** $\rho = 0.001 \sim 0.05\rho_0$

*** pbar distinguishes p and n**

physical quantity	***observable***	***method***	***for RIB****	***previous works for stable nuclei***
nuclear size	X-ray (min. n,l)		?	Trzcinska et al, PRL87(2001) 82501
p,n abundance at nuclear surface	pion net charge	calorimetric		Bugg et al, bubble chamber exp. for C,Ti,Ta,Pb. PRL31(1973)475
		statistical	O	
	cold residue	gamma-ray		Jastrebski et al, Nucl. Phys A558(1993)405c
		recoil momentum PI	O	
surface nucleon's momentum	cold residue	recoil momentum	?	

* *radioactive nuclei require efficient detection methods*

X-rays from Antiprotonic Atoms



F.J.Hartmann et al., Phys.Rev.C (to be published)

Trzcinska et at, PRL 87(2001)82501

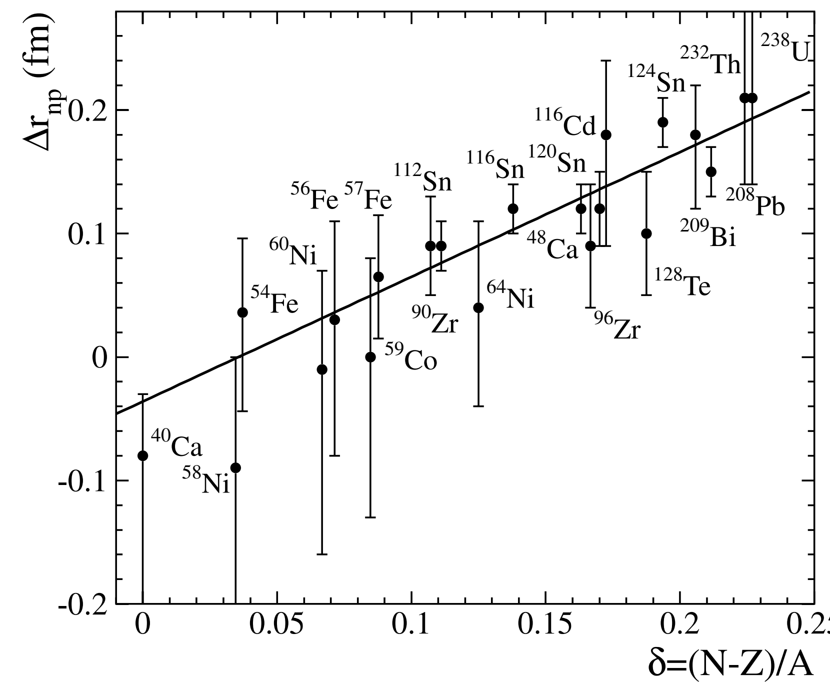


FIG. 4. Difference Δr_{np} between the rms radii of the neutron and proton distributions as deduced from the antiprotonic atom x-ray data, as a function of $\delta = (N - Z)/A$. The proton distributions were obtained from electron scattering data [41] (Sn nuclei) or from muonic atom data [38,42,43] (other nuclei). The full line represents the linear relationship between δ and Δr_{np} as obtained from a fit to the experimental data.

Xray

↓ *final n,l, Shifts, Broadening*

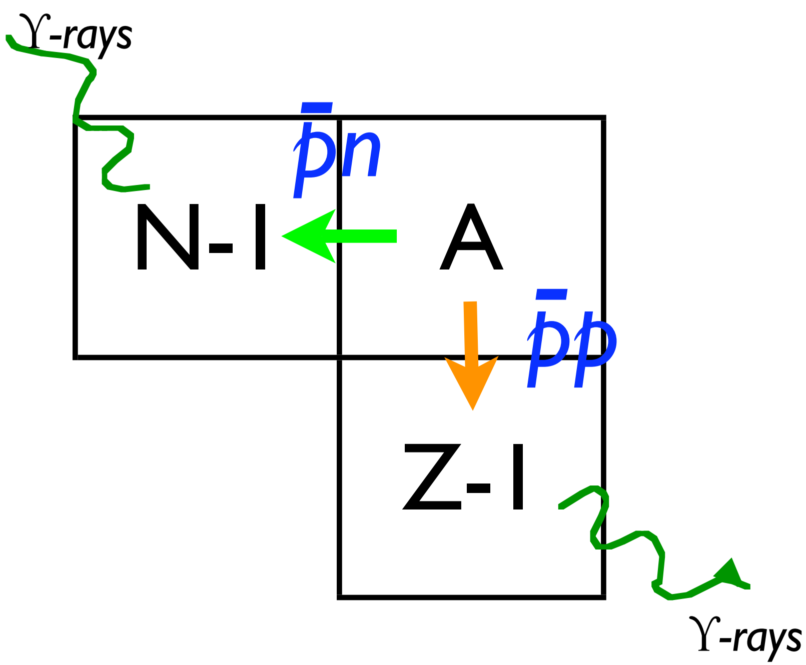
<u>Matter Radius: r_{np}</u>

↓ *subtract charge radii from e-scattering*

r_{np} - r_c → r_n

Stable Nuclear Atoms!

A-1 Cold Residue by Radiochemistry



Identification of Cold Residues by g-rays

$$f_{nhalo}^{periph} = \frac{N(N-1)}{N(Z-1)} \cdot \frac{Z}{N} \cdot \frac{\sigma_{\bar{p}p}}{\sigma_{\bar{p}n}}$$

periph: pion must miss daughter nucleus

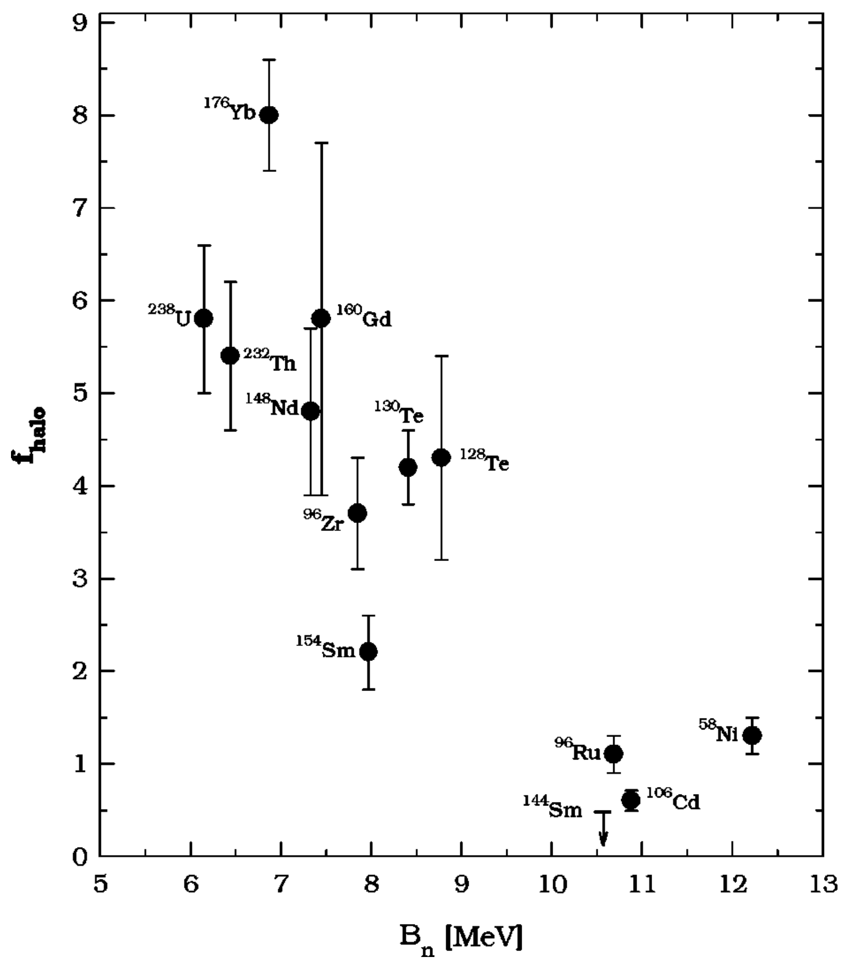


FIG. 3. Neutron halo factor (defined in the text) as a function of the target neutron separation energy B_n.

Lubinski et al, PRC57(1997)2962

π^- / π^+ ratio in bubble chamber

Evidence for a Neutron Halo in Heavy Nuclei from Antiproton Absorption*

W. M. Bugg, G. T. Condo, and E. L. Hart
The University of Tennessee, Knoxville, Tennessee 37916

and

H. O. Cohn and R. D. McCulloch
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 19 April 1973)

PRL 31(1973)475

From a study of stopping antiprotons in a variety of elements located in a hydrogen bubble chamber, we find evidence for the existence of a neutron fringe in heavy nuclei.

TABLE IV. "Halo factor" analysis.

Element	$N(\pi^-) - N(\pi^+)$	$N(\bar{p}n)$	$N(\bar{p}p)$	$\frac{N(\bar{p}n)}{N(\bar{p}p)}$	$\frac{N(\bar{p}n)}{N(\bar{p}p)}\Big\vert_c$	$\frac{N}{Z}$	Halo factor
C	2302	2586	4089	0.632	1.00	1.00	1.00
Ti	881	1067	1111	0.960	1.52	1.18	1.29 ± 0.21
Ta	1006	1276	931	1.371	2.17	1.48	1.46 ± 0.24
Pb	947	1216	534	2.270	3.59	1.54	2.34 ± 0.50

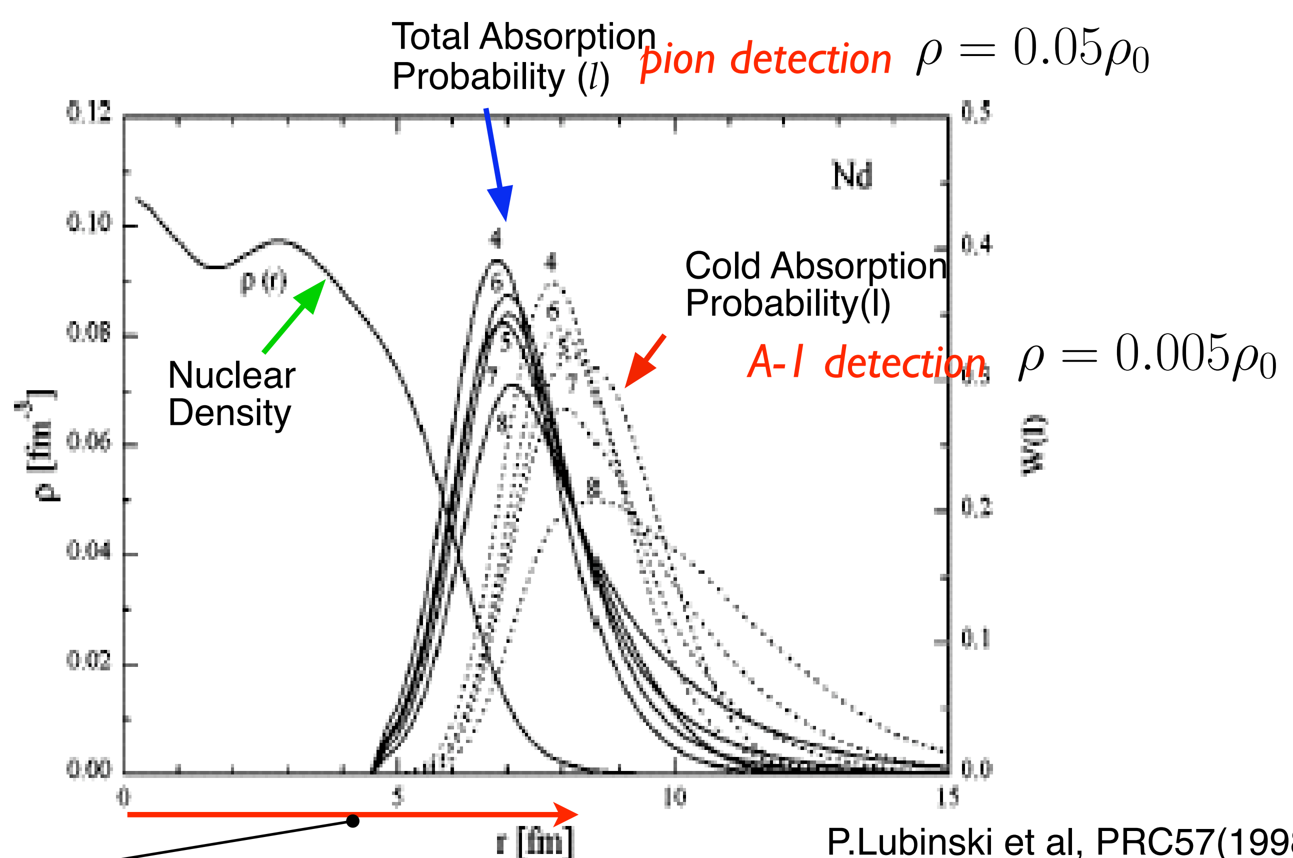
Charged Pion Ratio

"Calibrate" Rnp by C-12

$$R_{\rm np} \equiv \sigma_{\bar{p}n}/\sigma_{\bar{p}p} \approx 0.63$$

$$f_{n\rm halo} = \frac{N(\bar{p}n)}{N(\bar{p}p)} \cdot \frac{Z}{N} \cdot \frac{\sigma_{\bar{p}p}}{\sigma_{\bar{p}n}}$$

What is the sensitive Radius ?



P.Lubinski et al, PRC57(1998)2962.

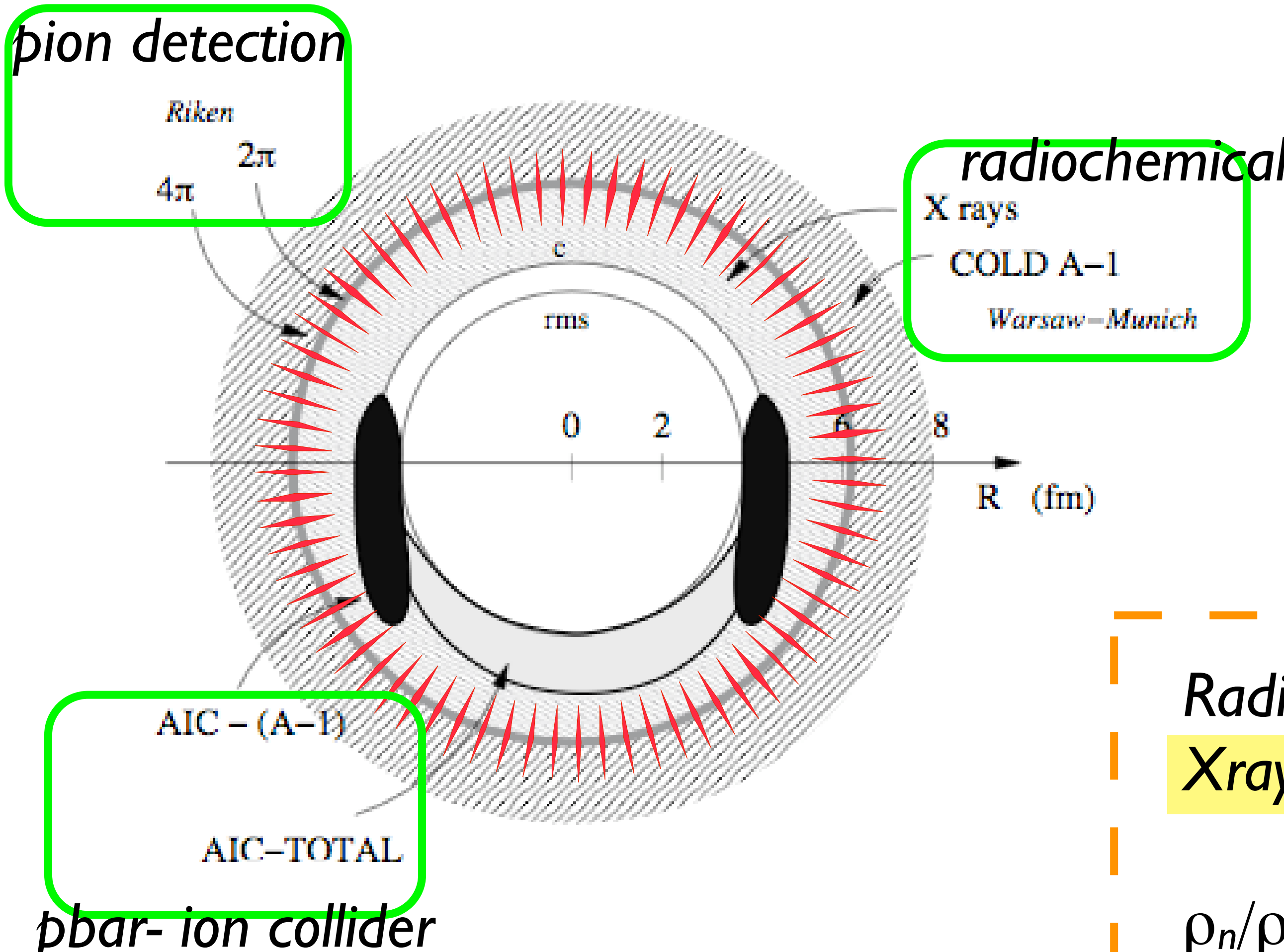
X-ray determines $R_{annihilation}$

Intermediate-Energy Collision (AIC) **<<** *Total Absorption (pion detection)* **<<** *A-1 Cold Residue*

Closer ⟷ ***Farer***

p̄ capture probability densities in Sn region

Wycech, preliminary



Antiproton beam (in AIC)

Radius:

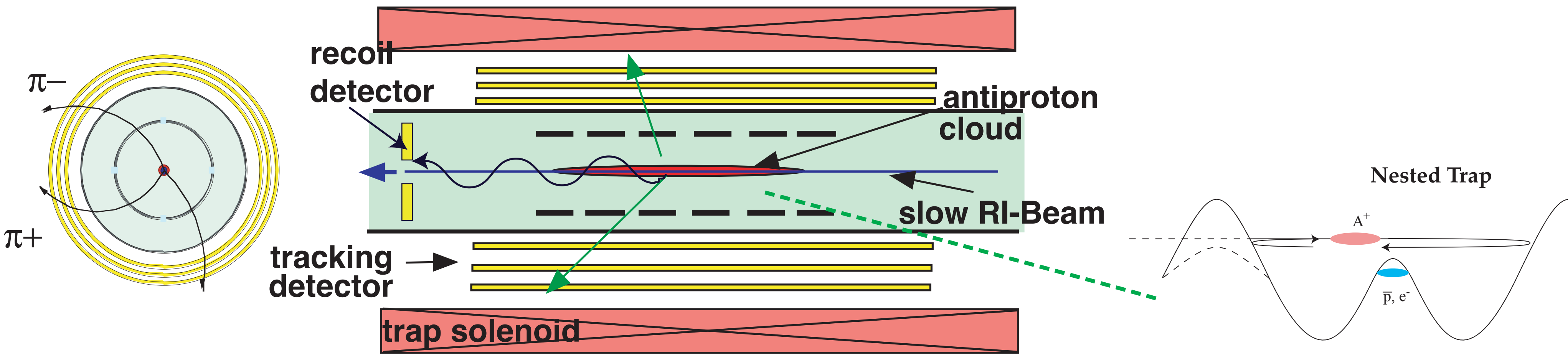
Xrays >> $\sigma_{absorption}$

ρ_n/ρ_p:

A-1 cold >> *pion* >> *A-1 AIC*

Exo + pbar

Extension of Bugg's Experiment (pion detection) but for Radioactive Nuclei in Nested Penning Trap where pbar is Target



M.Wada, Y.Yamazaki, NIM B214 (2004) 196-200

$$\frac{N(\pi^-)-N(\pi^+)}{N(\pi^-)+N(\pi^+)} \text{ or } \frac{N(\pi^-)}{N(\pi^+)} \Rightarrow \frac{N(\bar{p}n)}{N(\bar{p}p)} \Rightarrow \left.\frac{\rho(n)}{\rho(p)}\right|_{\text{@ annililation}}$$

Statistical Evaluation (next slide)

Using R_{np} κ from Calibration or Theory

$$\frac{\rho_n}{\rho_p} = \frac{N(\bar{p}n)}{N(\bar{p}p)} \cdot \frac{1}{R_{np}}\kappa$$

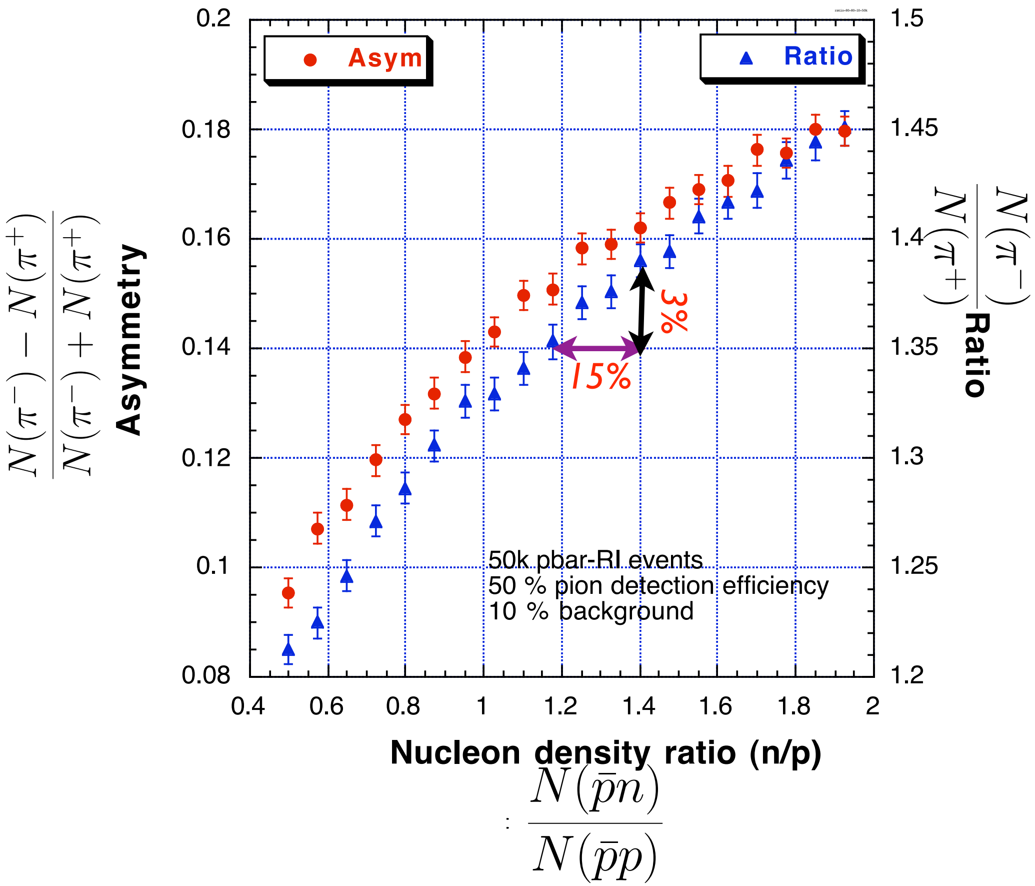
$$R_{\rm np} \equiv \sigma_{\bar{p}n}/\sigma_{\bar{p}p} \approx 0.63$$

κ *: Correction for pion's charge exch. & absorption*

These Correction factors can be evaluatable from Total-charge distrib. per event. (Wycech)

Key features of Exo+pbar

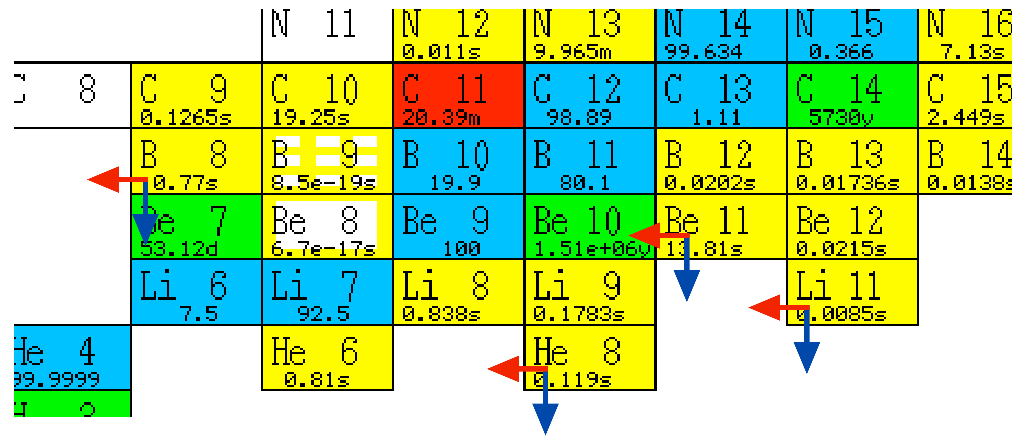
Expected Asymmetry or Ratio of pions
as function of $\bar{p}n/\bar{p}p$ annihilation ratio



~5% accuracy of $\frac{N(\bar{p}n)}{N(\bar{p}p)}$

with 50 k pbar-RI atoms

pion detection is universal for any nuclides

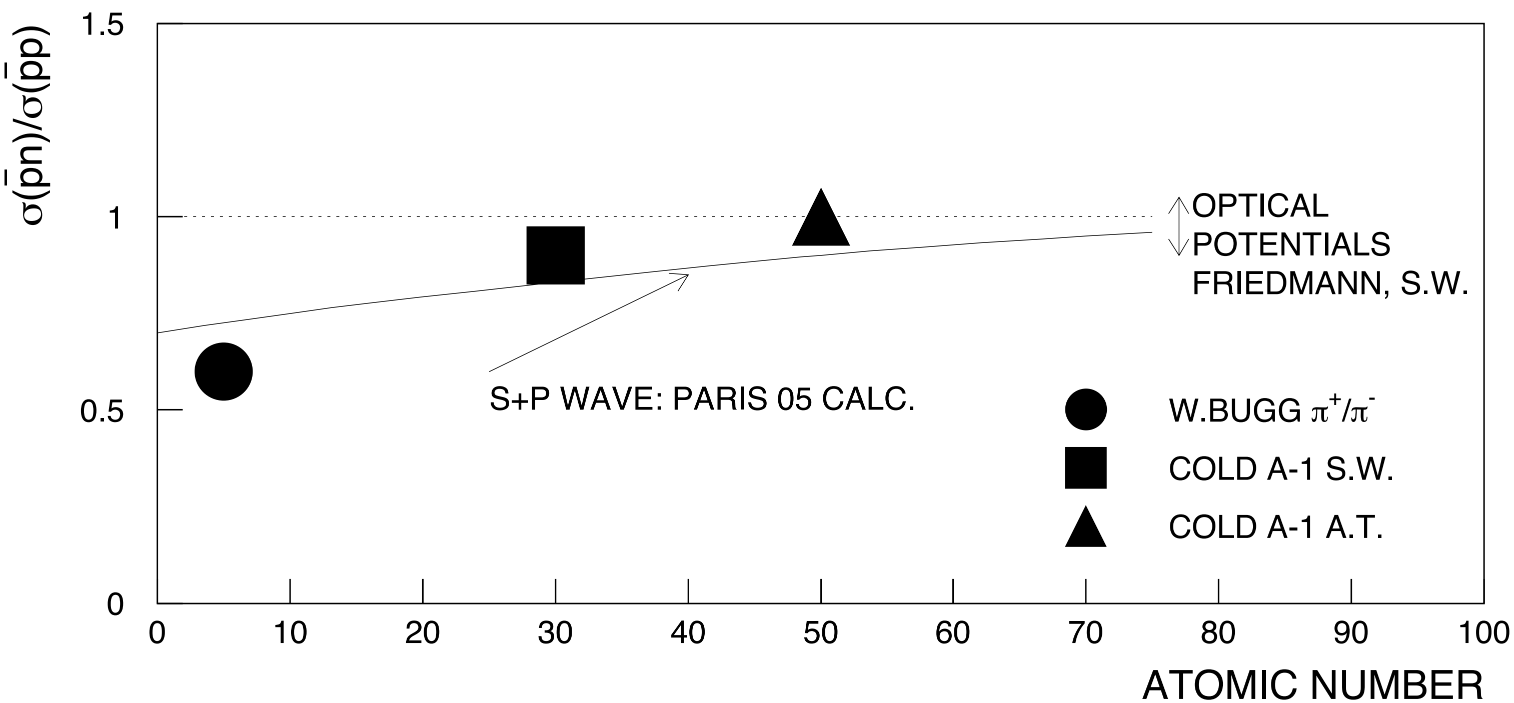


Interesting Nucleides are often close to drip-line

pions are always observable, while
cold residues are often particle unbound

$R_{np} \equiv \sigma_{\bar{p}n}/\sigma_{\bar{p}p}$ in atomic states

Wycech, private comm.



Feasibility of Exo+pbar

1. Event rate

5M pbar (target) + 1 k atom/s Li-11, 10ms cycle : a hardest case assumption

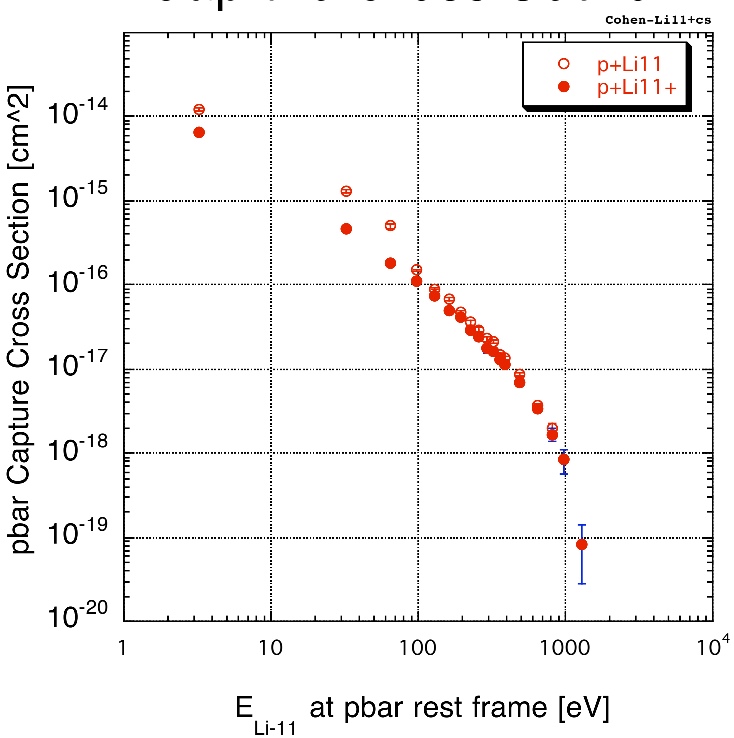
$$R = \sigma_{\bar{p}A} N_{\bar{p}} I_{\rm RI}$$
$$= 4\times10^{-16}[{\rm cm}^2]\cdot 5\times10^{8}[{\rm cm}^{-2}]\cdot 10[{\rm atoms}]\cdot 5\times10^{3}[/10{\rm ms}]$$
$$= 1\times10^{-2}[\bar{\rm p}{\rm RI}/10{\rm ms}]$$

Beam Intensity:
10 atoms in 10 ms

Collision Number:
5000 pass in 4 cm length
in 10 ms

Target Density:
5M pbar in 1mm²

Capture Cross Section



Cohen PRA69(2004)022501

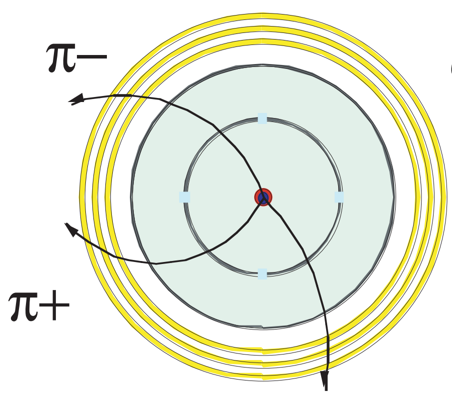
Expected Yield:

$$\bar{\rm p}^{11}{\rm Li}^{2+} : 1 \text{ atom/s}$$

Yield is proportional to the cycle time:
High Yield for Long-lived Nuclei.

Feasibility of Exo+pbar

2. particle identification



$\pi^+\pi^-$: Deflection direction in solenoid by multilayer PSD

$$E_{\pi^\pm} = 100 \sim 250\text{MeV},\ \rho = 12 \sim 23\text{cm}@5\text{T}$$

3. background event elimination

A. Other charged particles (noise)

proton: (scattered by pion) multiplicity ~ 1

discrimination via $\Delta E,\ TOF,\ B\rho$

B. pions from background gas

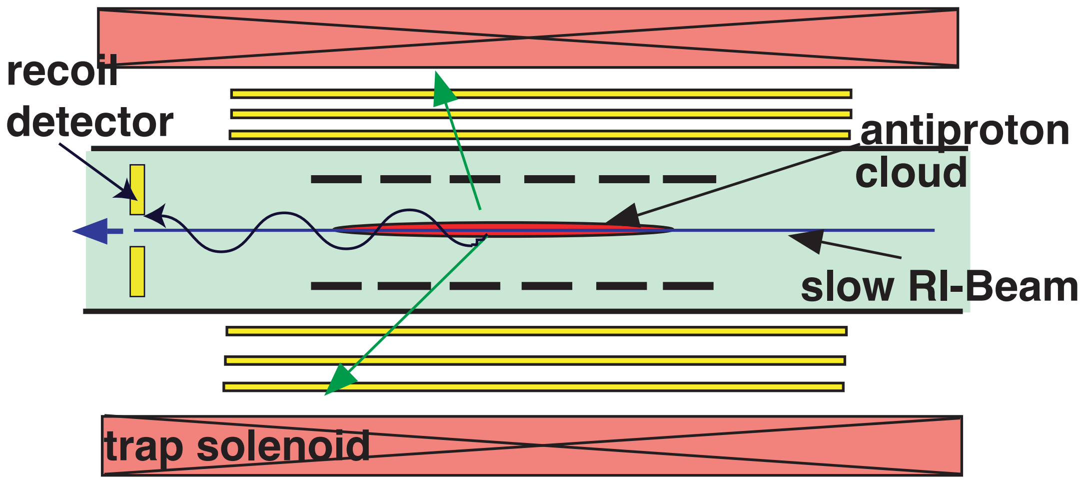
pbar+hydrogen -> no recoil nuclei

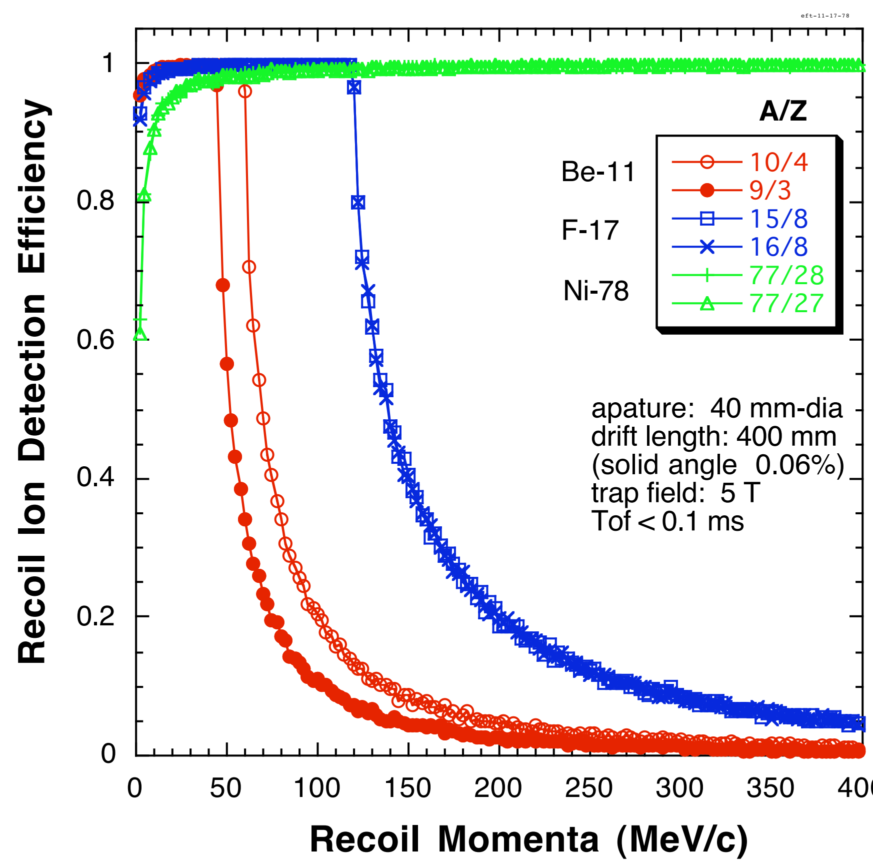
coincidence recoil nuclei detection → *(next slide)*

True Event Identification by Recoil Nuclei

Background gas in UHV: Hydrogen Molecule → No Recoil in annihilation

$T_{1/2}$ of pbar trapping ~ 1 day → 100 /s natural annihilation for 10^7 pbar





High Detection Efficiency due to
High Magnetic Field and Fully Stripped Ion

Developments to be done

1. Universal Slow RI-Beams (slowri@RIKEN, LEB@GSI) *being progress*

2. Antiproton trap (asacusa@CERN-AD) *being progress*

3. Pbar-RI atom formation trap, Detectors, DAQ *design & evaluation*

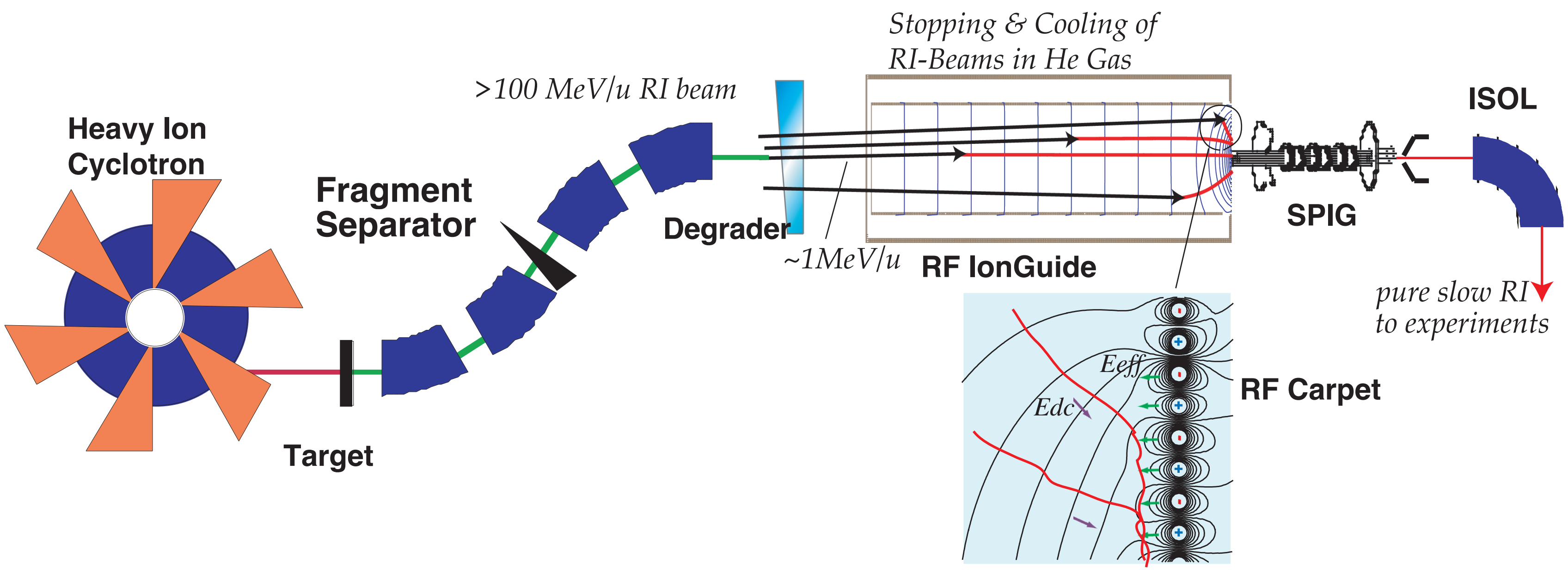
4. Construction: Super High Vacuum, long BTL, etc *design & evaluation*

5. Theoretical Foundation *being progress (Wycech)*

$R_{np} \equiv \sigma_{\bar{p}n}/\sigma_{\bar{p}p}$, *intrinsic annihilation probability*

absorption and charge exchange of pions

SLOWRI@RIKEN-RIBF
Universal Slow RI-Beam Facility

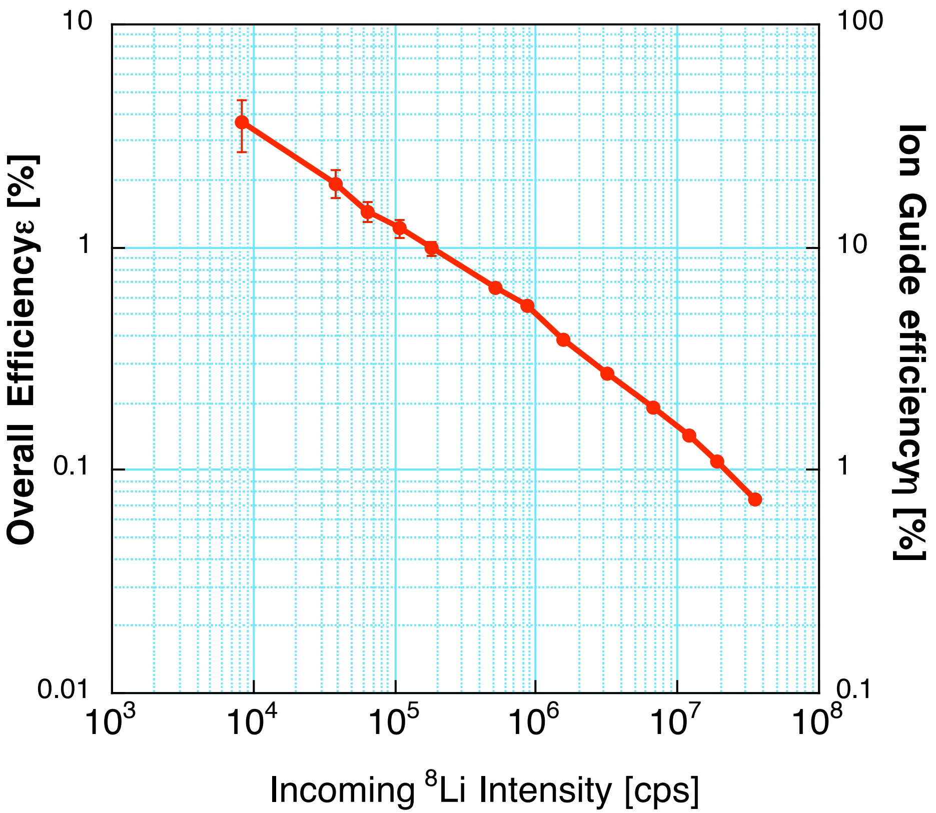


BigRIPS
+
RF Ion Guide

@RIBF

1. Wide Range of Nuclides
   No Chemical Processes in Production & Separation
2. High Purity
   No Isobar No Isotone Contamination
3. Small Emittance
   ~1π mm mrad (5 keV), ~10 eVμs Short Bunch
4. Variable Energy Range
   1-50 keV Slow Beam, <1eV Trapped RI, 1MeV/u (future option)
5. Human Accesibility during On-line Exp.

Present Performance of the RF Ion Guide



Overall Efficiency: ~5% max
(Ionguide Efficiency: ~33% max)
Yield of 8Li: 24 kcps max

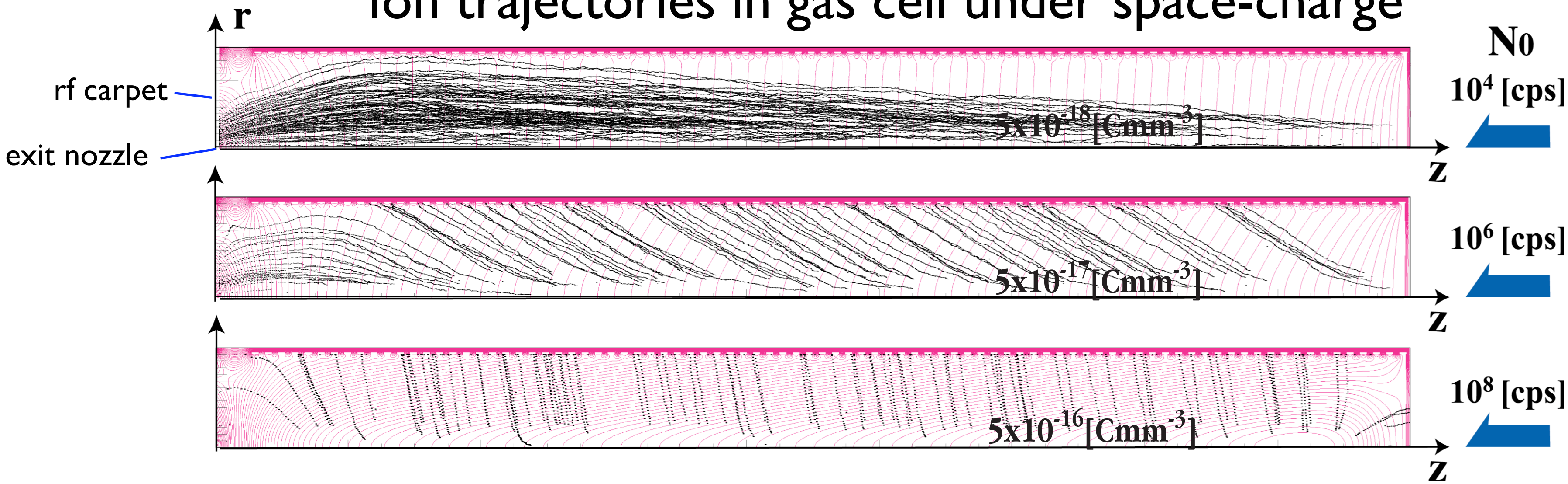
$$efficiency \propto 1/\sqrt{Intensity}$$

Space-Charge effect

$$charge\ density \propto \sqrt{Intensity}$$

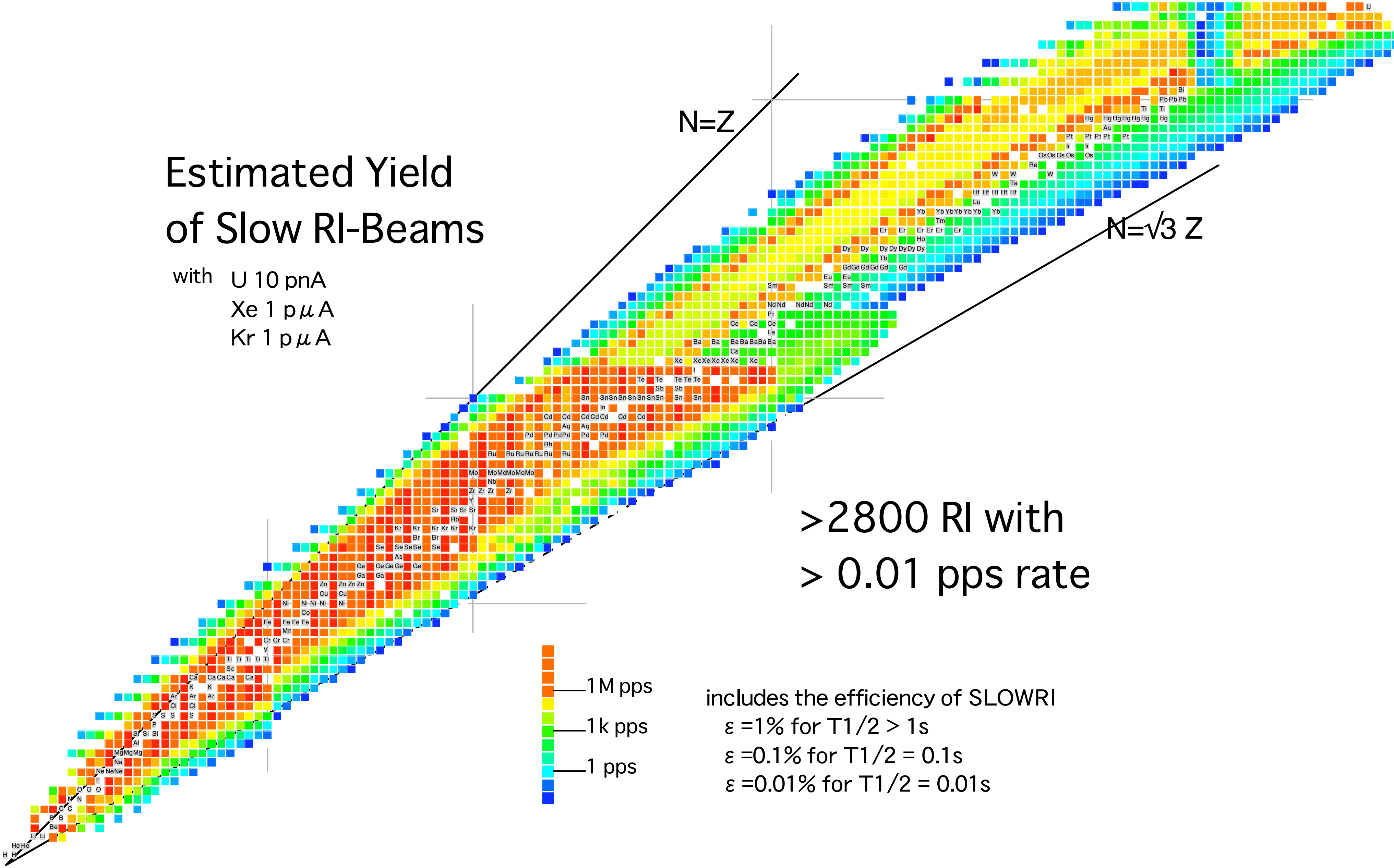
$$efficiency \propto 1/charge\ density$$

Ion trajectories in gas cell under space-charge



Estimated Yield of Slow RI-Beams

with U 10 pnA
Xe 1 pμA
Kr 1 pμA

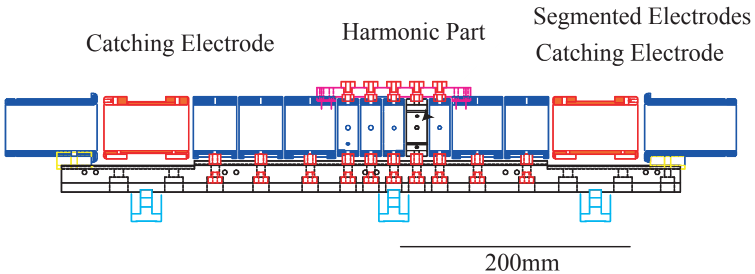


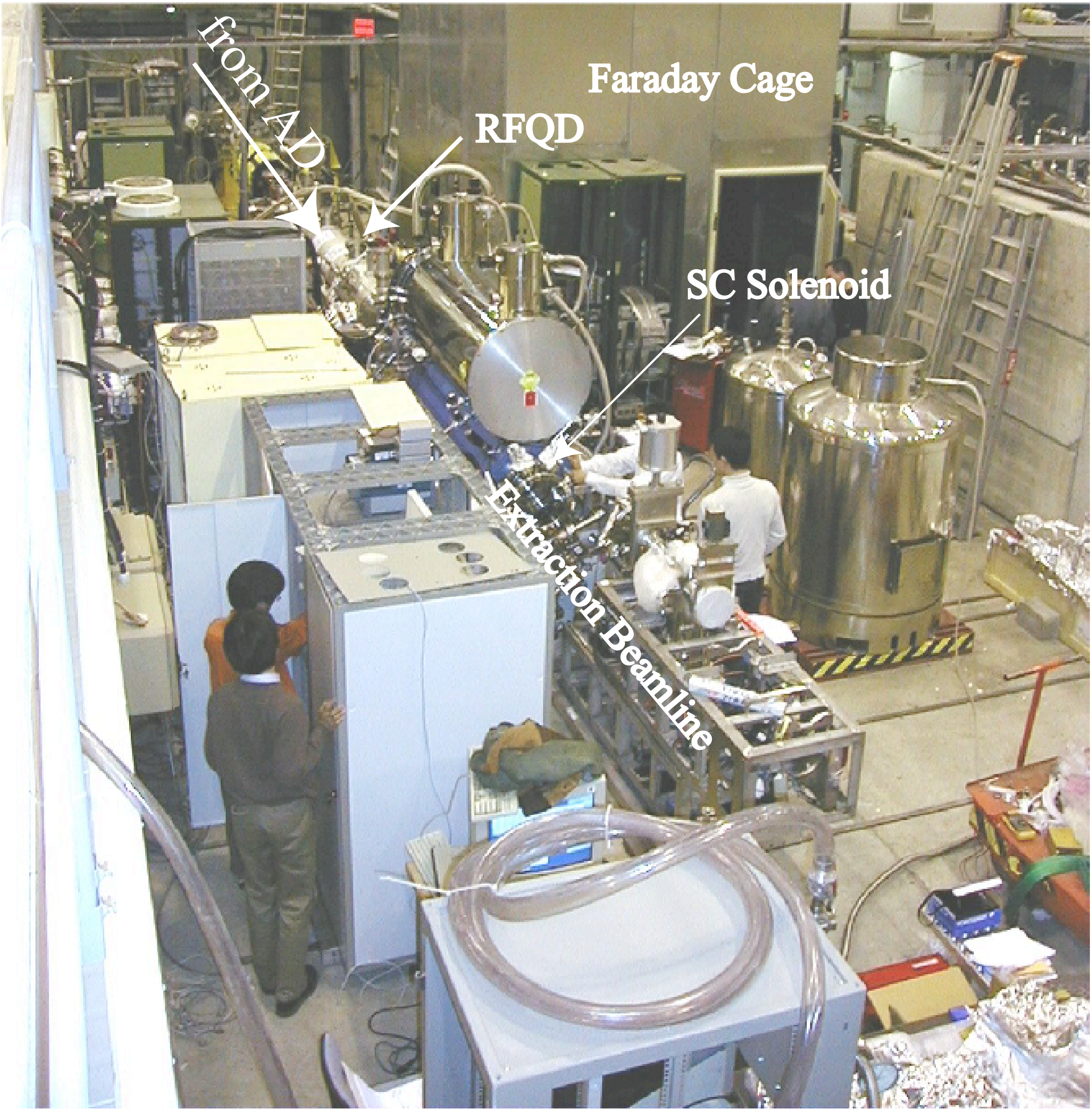
>2800 RI with > 0.01 pps rate

includes the efficiency of SLOWRI
ε =1% for T1/2 > 1s
ε =0.1% for T1/2 = 0.1s
ε =0.01% for T1/2 = 0.01s

pbar accumulation trap @cern

MUSASHI beamline
of ASACUSA Project





* 5x10^6 antiprotons
are stored
* Lifetime ~ several hours ?

Kuroda et al

Phys. Rev. Lett. 94, 023401(2005)

Possible Experimental Locations

1. @CERN AD
   ISOLDE (RI-Beam) → L.E. Beam Transport → AD (pbar)

2. @CERN ISOLDE
   CERN AD(pbar) Portable Trap → ISOLDE (RI-Beam)

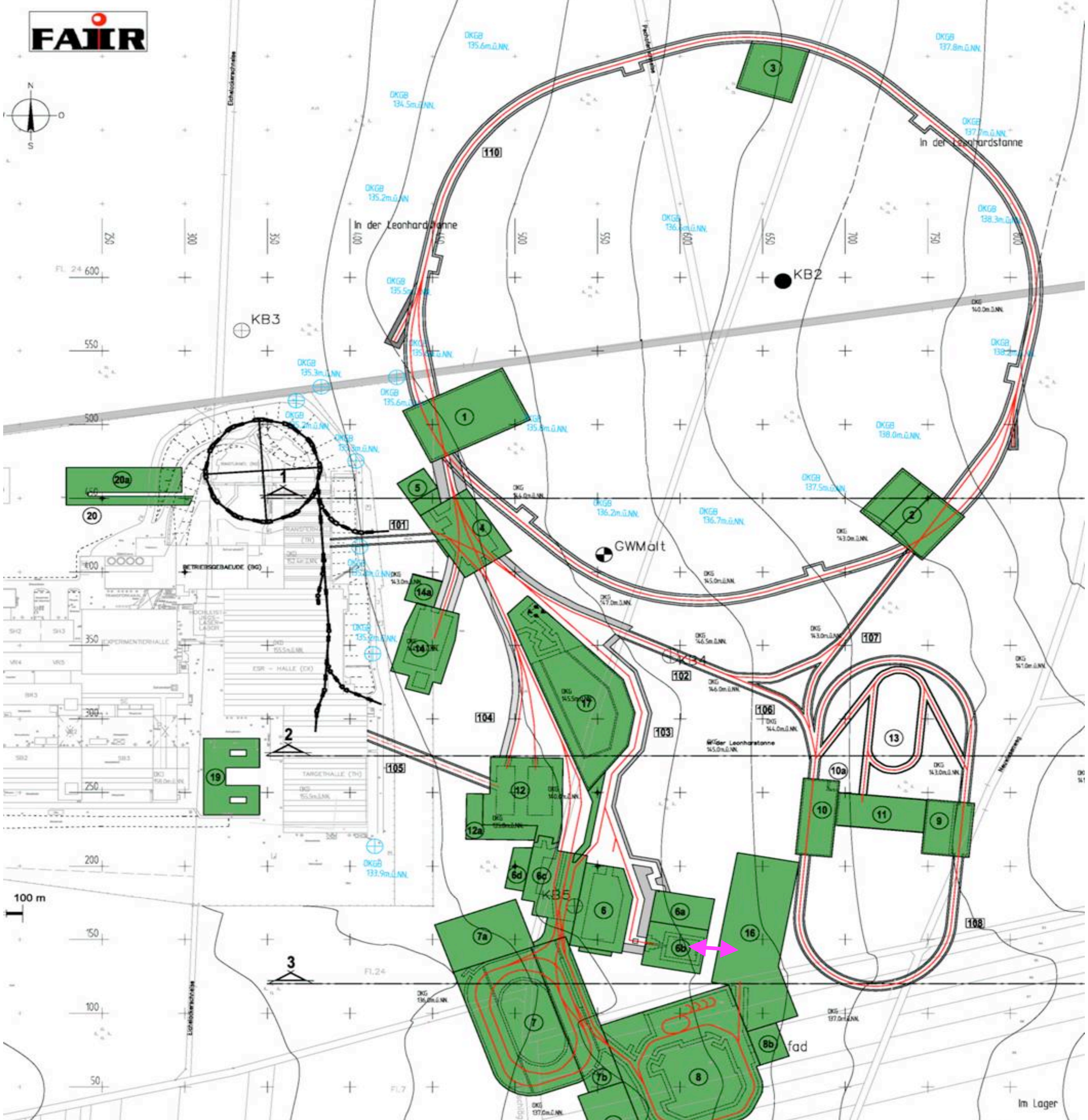
Loading/Unloading ~2 hours

+ 10 hours ?

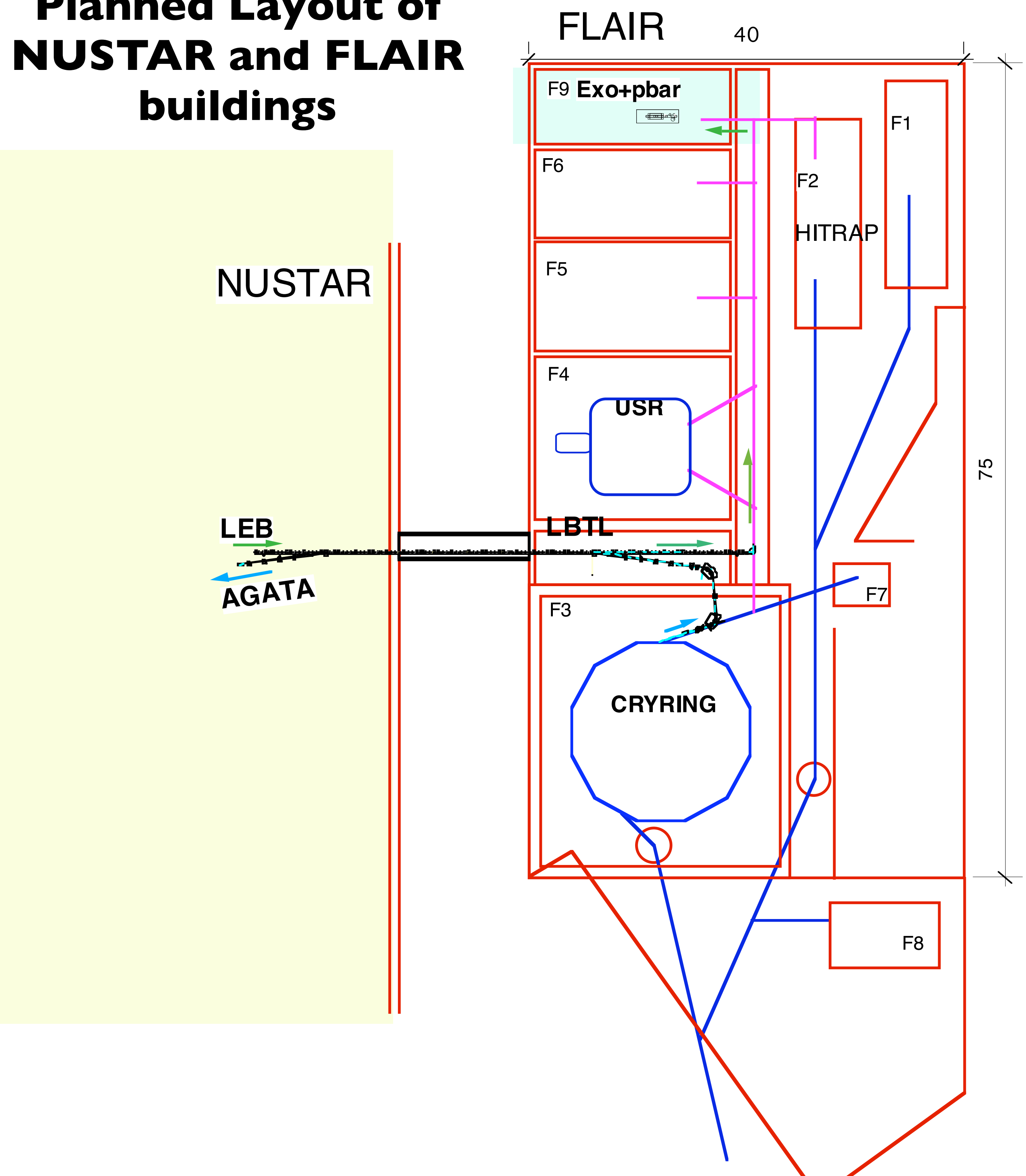
3. @RIKEN
   CERN AD(pbar) Portable Trap → RIKEN-RIBF(RI-Beam)

Syverian Railway (1 week)

4. @GSI FAIR
   SuperFRS-LEB (RI-Beam) BTL → FLAIR (pbar)


FAIR
N
O
S
In der Leonhardstanne
KB2
KB3
GWMalt
KB4
KB5
110
101
102
103
104
105
106
107
108
1
2
3
4
5
6
6a
6b
6c
6d
7
7a
7b
8
8b
9
10
10a
11
12
12a
13
14
14a
16
17
19
20
20a
BETRIEBSGEBAEUDE (BG)
EXPERIMENTIERHALLE
ESR - HALLE (EX)
TARGETHALLE (TH)
100 m
Im Lager
fad

Planned Layout of NUSTAR and FLAIR buildings



Slow RIB:

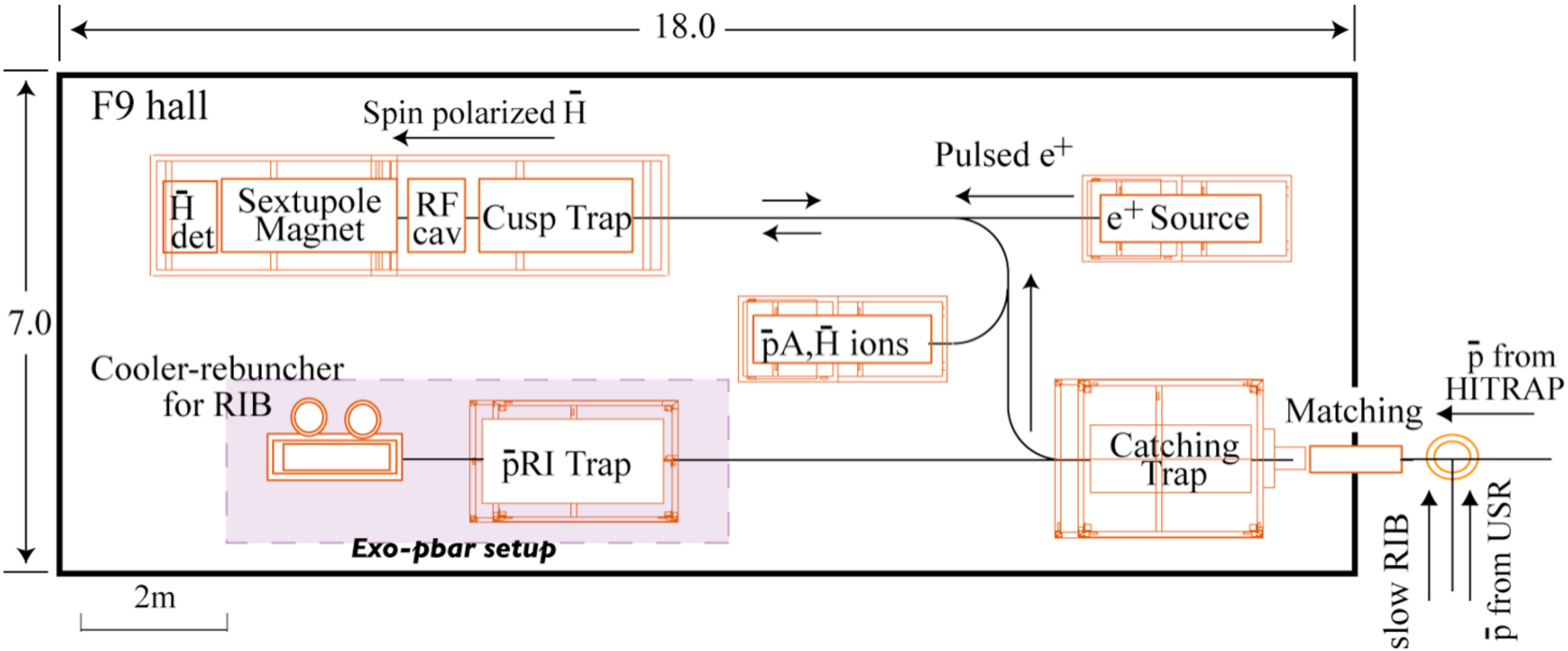
SuperFRS -
LEB (gas catcher) -
LBTL -
FLAIR common BTL -
Exo+pbar

Antiproton:

NESR -
CRYRING (LSR) -
USR -
FLAIR common BTL -
Exo+pbar

Highly charged 6MeV/u RIB,
300 keV antiprotons,
can be transported from
FLAIR to NUSTAR

Planned Layout of
F9 hall of FLAIR buildings



Loading pbar (~ once per day)
Buch inject Slow RI ions (after re-bunching and cooling)
with a short cycle (> ~10 ms)

Comparison of two proposals

	Exo+pbar in trap	**AIC** in collider ring
Observable	$N(\pi^+)/N(\pi^-)$	•σ_T, (σ_n, σ_p) •N(N-1)/N(Z-1) A-1 cold residue
Physical Quantity	•$\rho(n)/\rho(p)$ at surface ($\rho \approx 0.05\rho_0$)	•$\rho(n)/\rho(p)$ at rms •$\langle r_N \rangle$ ($\langle r_n \rangle$,$\langle r_p \rangle$) •Recoil momenta quasi free
Object Nucleus	•universal drip-line nuclei, short-lived nuclei •10^3/s @ LEB for $T_{1/2}$>10ms (5×10^6 pbar in trap)	•A>50 for shottky (A>20 for recoil?) •$T_{1/2}$ > 1s beam cooling •no dirpline nuclei no cold residue •10^5 ions in ring (10^9 pbar in ring)

summary

- Antiprotonic Radioactive Atom will be a new probe for nuclear structure studies.
- Exo+pbar @ FAIR or (pbar-RI @RIKEN) would be unique & feasible experiments.
- Exo+pbar & AIC are complementary.
- Future Option
  - X-ray measurements
  - Hyper-Radioactive Nuclei ?