Perspectives of experiments with antiprotons merged with exotic nuclei at FAIR

Eberhard Widmann

NUSTAR week 2014

GSI Darmstadt, March 7, 2014

Stefan Meyer Institute for Subatomic Physics, Vienna

$\bar{p}$A proposals for FAIR

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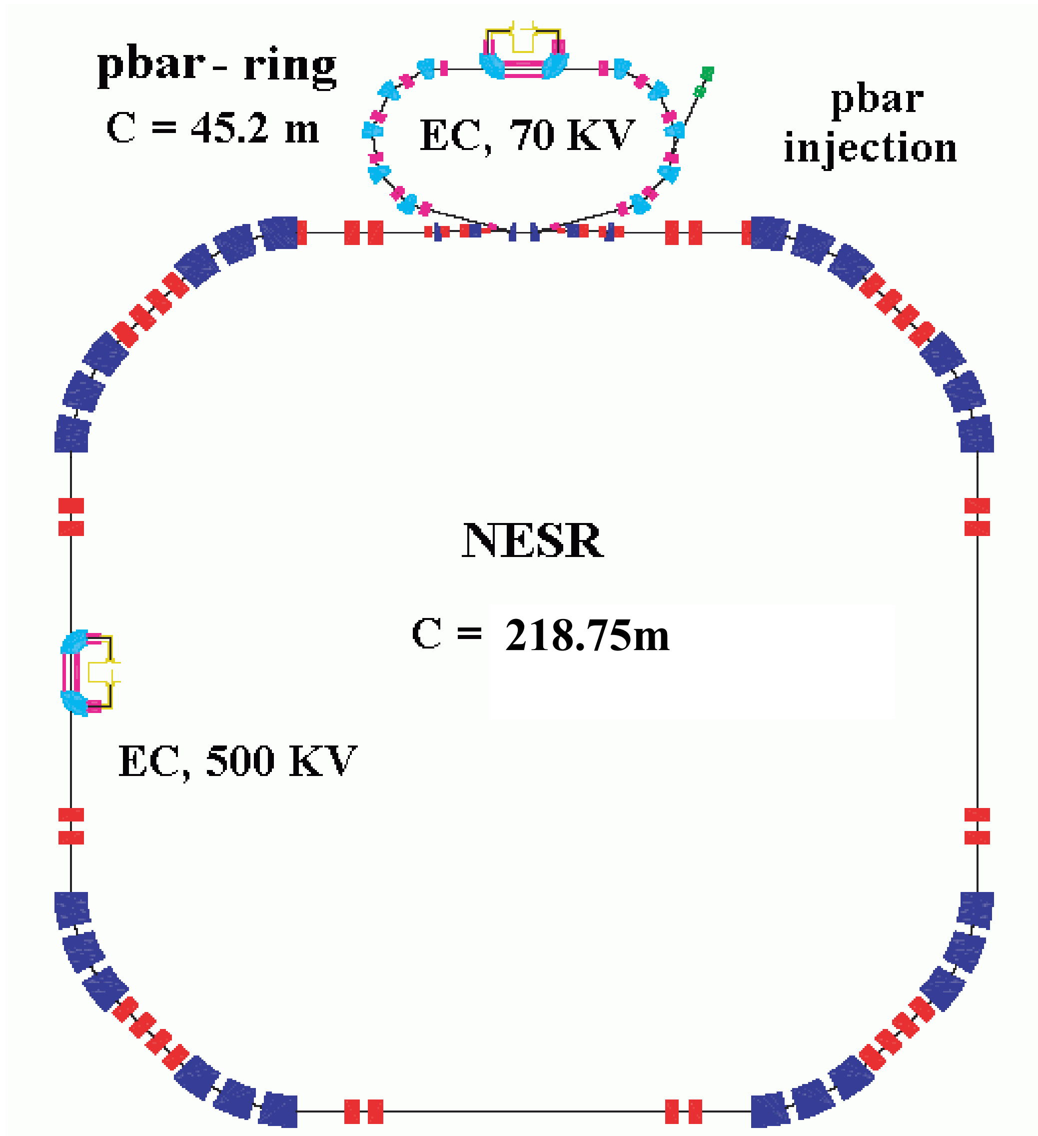
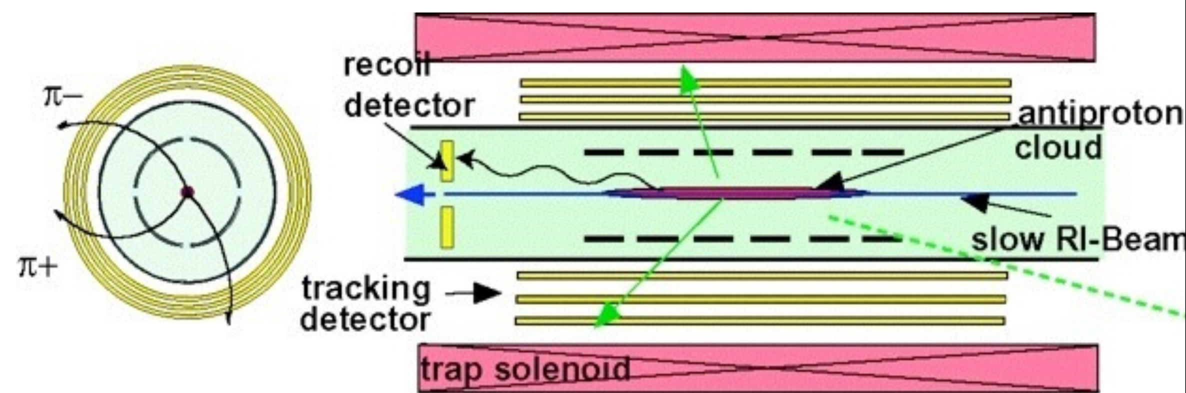
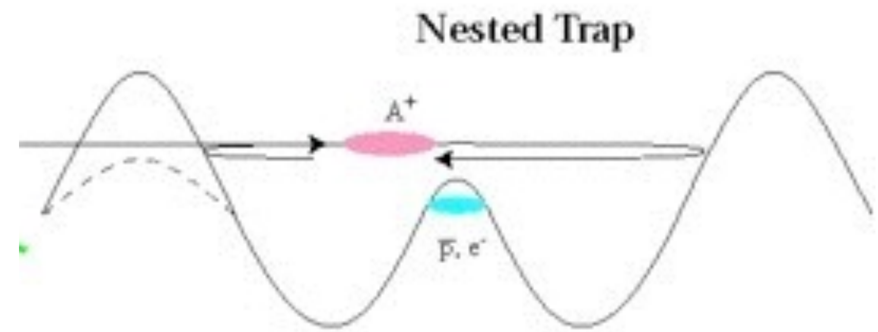
Antiproton Ion Collider
NESR + $\bar{p}$ ring



P. Kienle, NIM **B214**, 193 (2004)

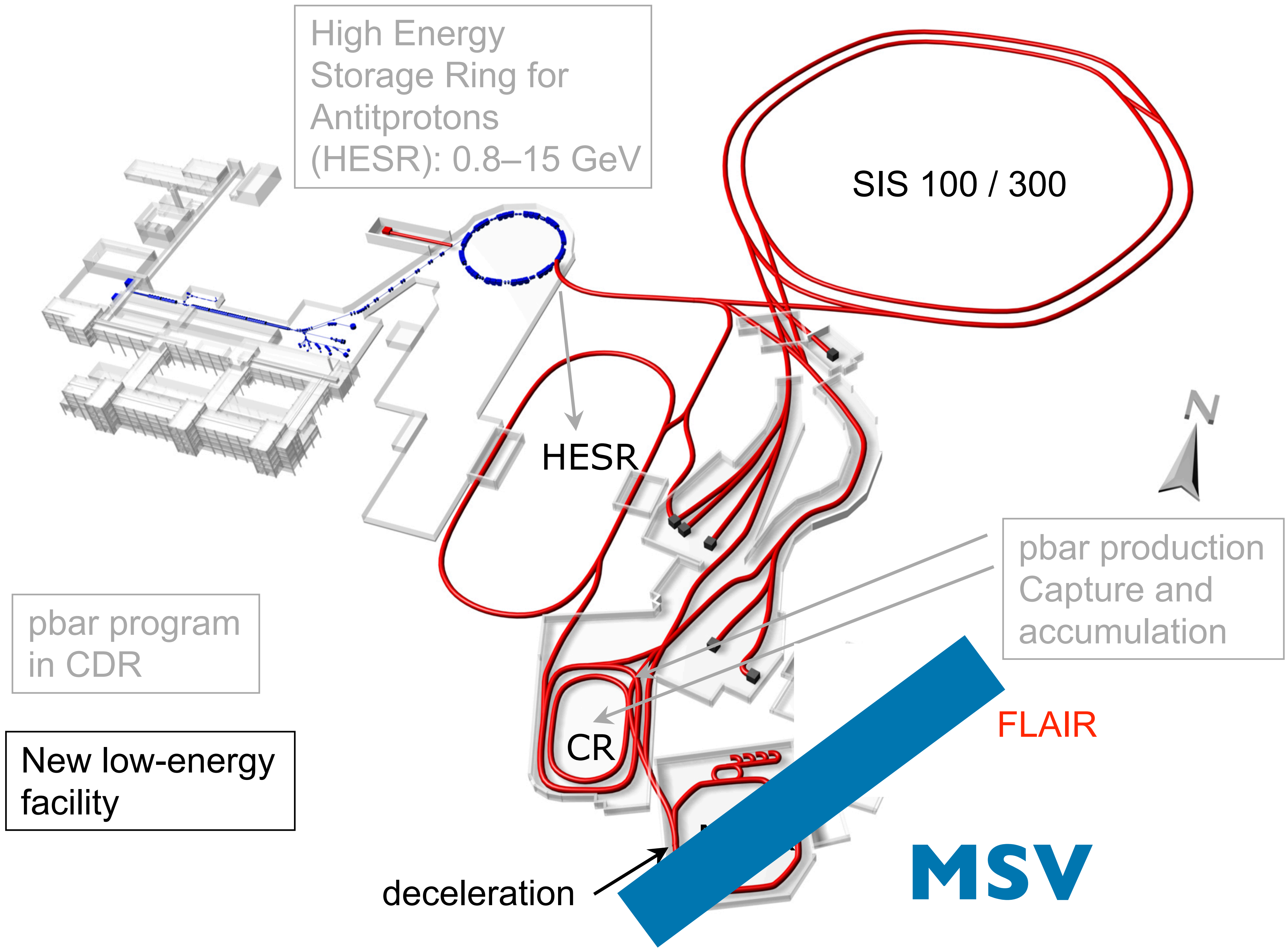
Exo+pbar
FLAIR + LEB-SFRS





M. Wada and Y. Yamazaki, NIM **B214**, 196 (2004)

Antiprotons at FAIR - BTR



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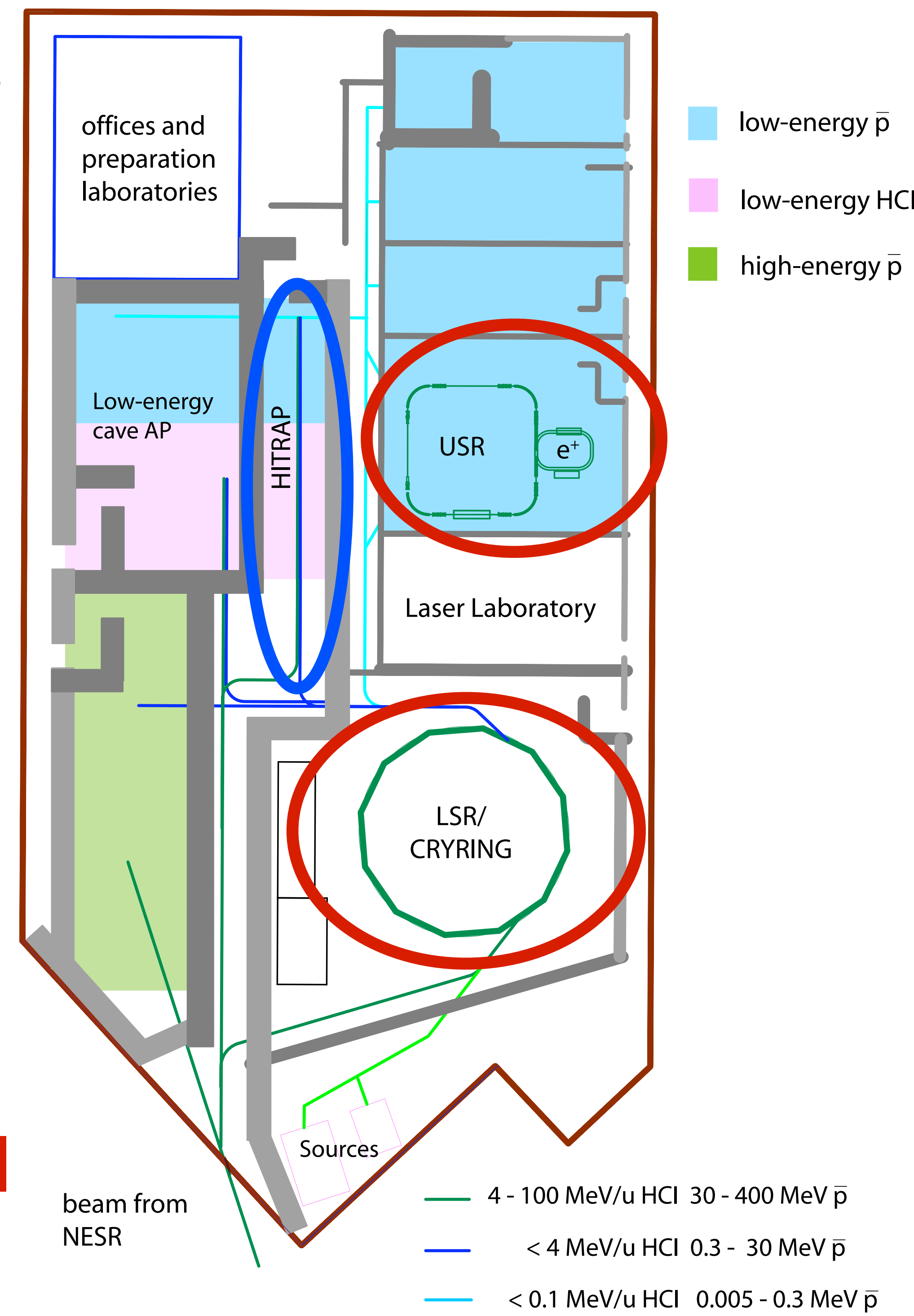
FLAIR@ FAIR - Baseline Technical Report 2005

- High brightness low energy beams
  - two storage rings with 300 keV (LSR) and 20 keV (USR)
  - electron cooling
    - $\varepsilon \sim 1\ \pi$ mm mrad
    - $\Delta p/p \sim 10^{-4}$
- Storage rings with internal targets for collision studies
- Slow and fast extraction
- Ion traps
  - HITRAP facility for HCI & pbar
- Many new experiments possible
- same facilities can be used for HCI



Factor 100 more pbar trapped or stopped in gas targets than now

Operation after ~2018

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ÖAW Austrian Academy of Sciences

CRYRING: a perfect match for LSR

- LSR is central "working horse" of FLAIR
  - Beam delivery for HITRAP, USR, experiments
- Choice of CRYRING (MSL, Stockholm)
  - Fitting energy range, electron cooling, fast ramping, internal target, low-energy injection from ion source for commissioning
  - Expertise: MSL staff has designed & built CRYRING
  - CRYRING will be contributed by Sweden as in-kind contribution to FAIR → **has been**

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Next-generation Low-energy Antiproton Facility

Feature	Solution
Higher intensity	Accumulation scheme
Fast and slow extraction	Coincidence experiments (nuclear physics)
Cooled beams down to < 500 keV	Storage rings
Availability of pbar and RI	FAIR

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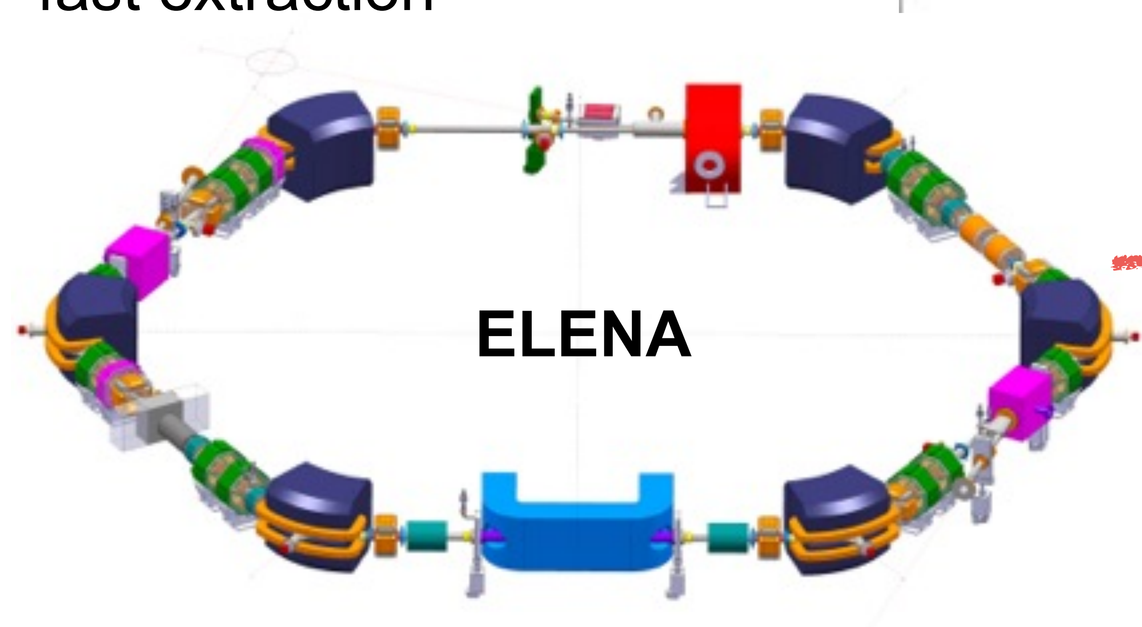
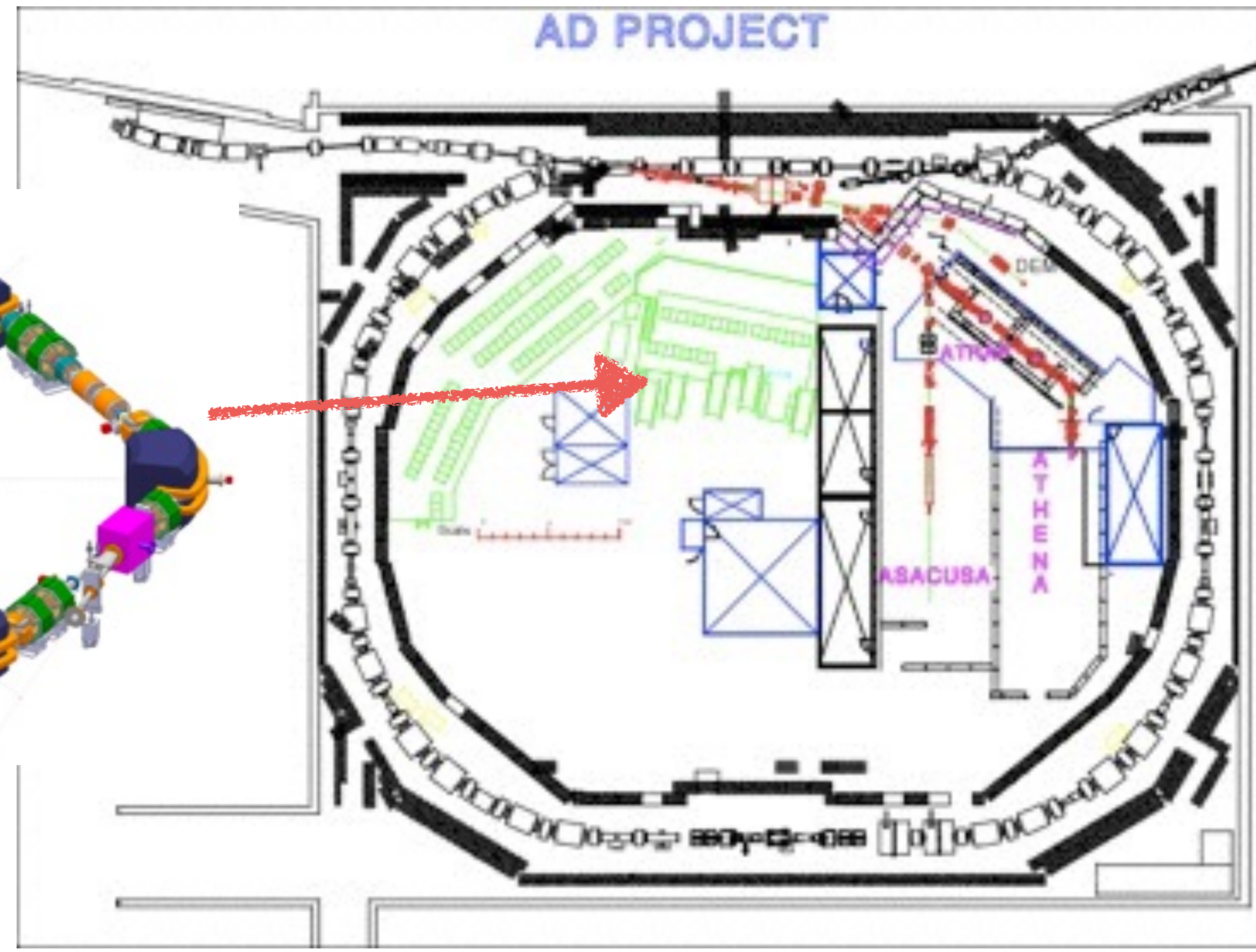
ELENA @ CERN-AD

100 keV
fast extraction





Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8
$\varepsilon_{x,y}$	4 / 4
$\Delta p/p$ of extracted beam, [95%], standard	8 ·10

Operation 2017 + 10−15 years

Low Energy Antiproton Physics @ FLAIR

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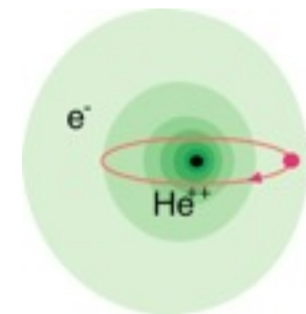
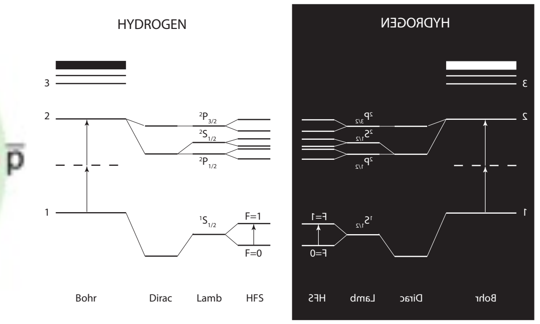
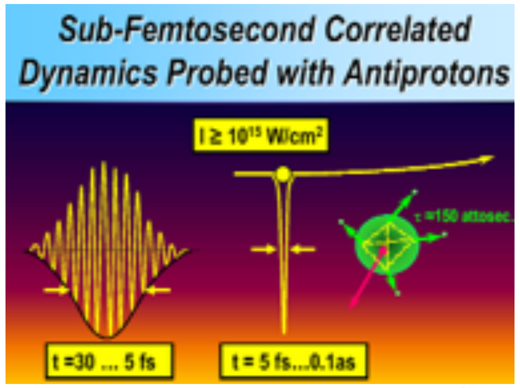
- Spectroscopy for tests of CPT and QED
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen

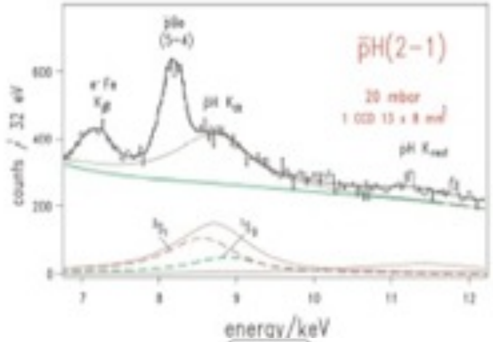


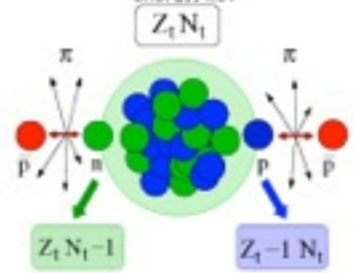


- Atomic collisions
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions

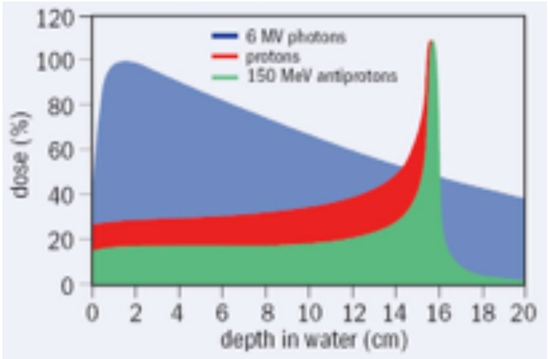


- Antiprotons as hadronic probes
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
  - Strangeness –2 production





- Medical applications: tumor therapy



FLAIR TDR - E.W CAMOP - Physica Scripta 72, C51-C56 (2005)

Modularized start version of FAIR

- Modularized start version 0-3
  - founded Oct. 2010
  - construction started
- FLAIR: Module 4 with NESR, SFRS-LEB
  - additional funding of ~100 M€ needed
    - *in 2005 prizes*
- Storage rings are a core feature of FAIR

: Modules 0 to 3 of FAIR. Module 0: green; module 1: red; module 2: yellow; module 3: orange.

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Austrian Academy of Sciences
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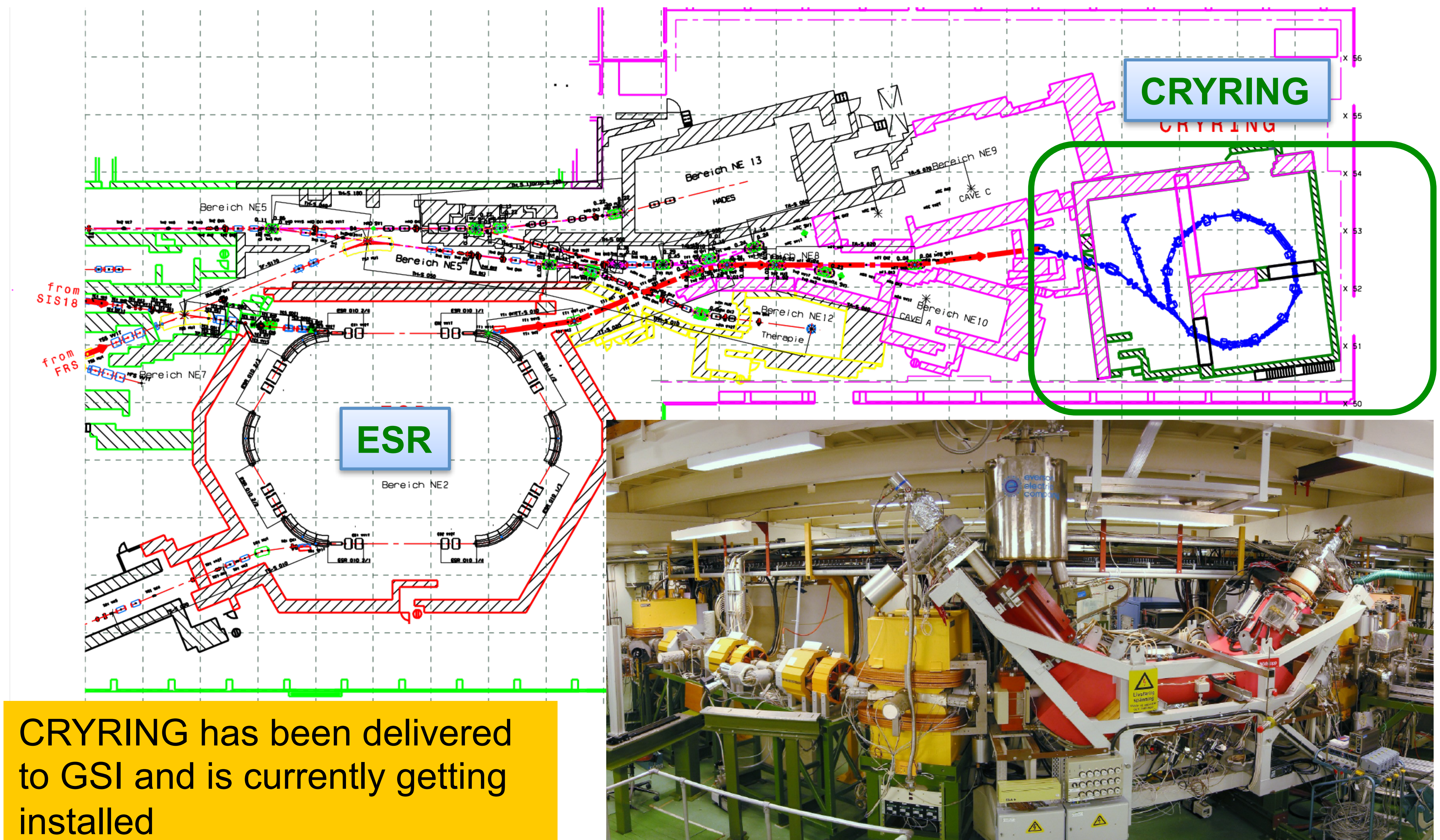
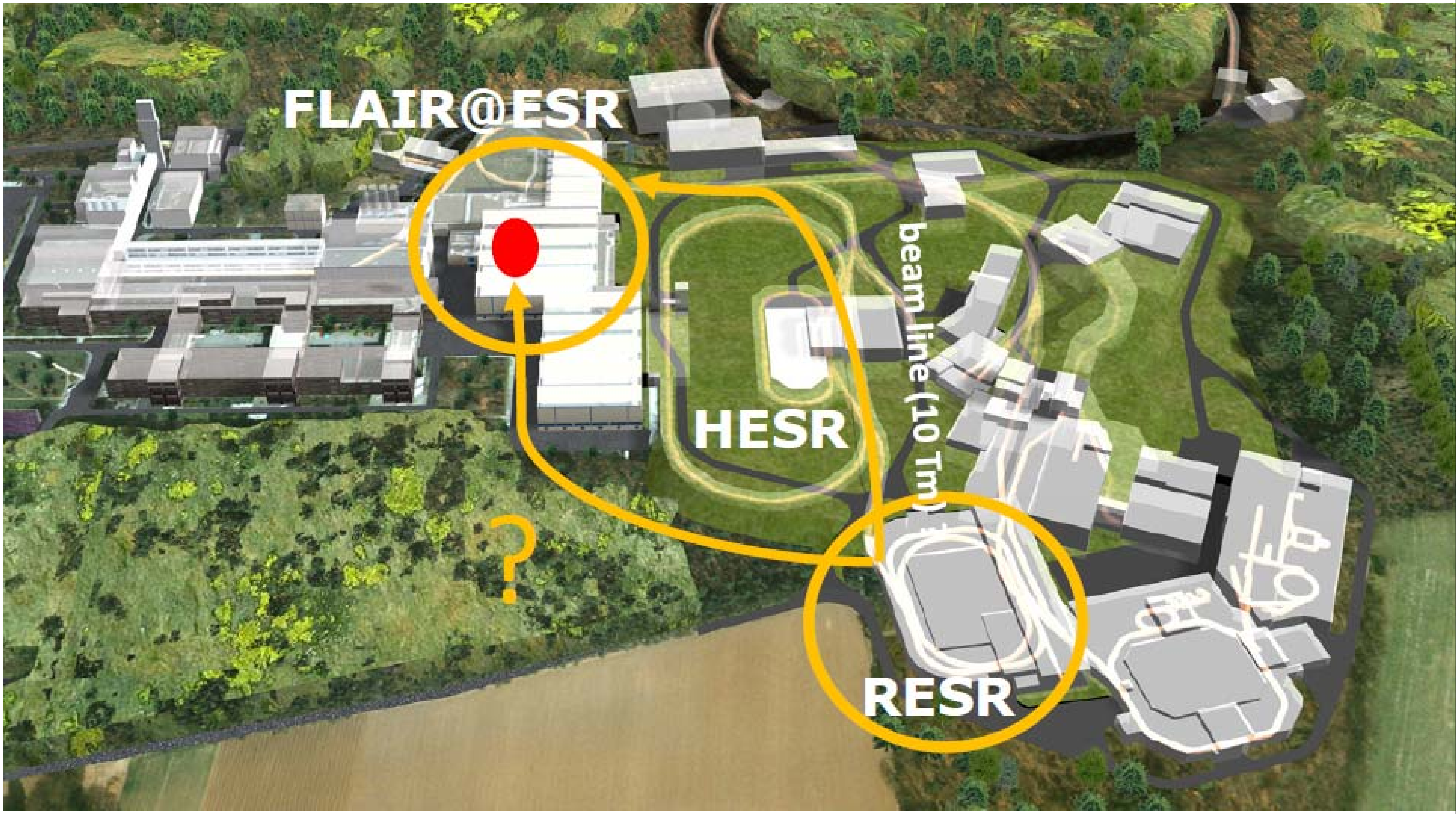
New idea: CRYRING@ESR:
phase 1 of FLAIR



CRYRING has been delivered to GSI and is currently getting installed

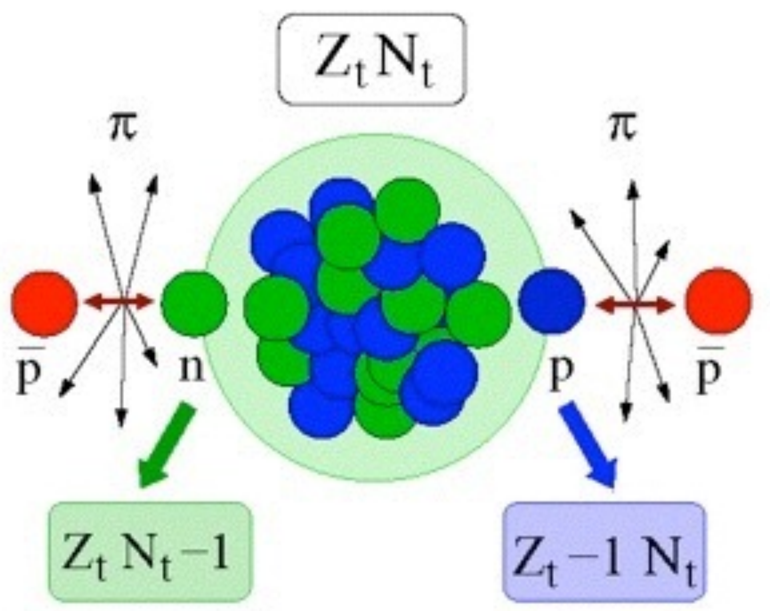
Vision: $\bar{p}$ / RI from CR/RESR to ESR?

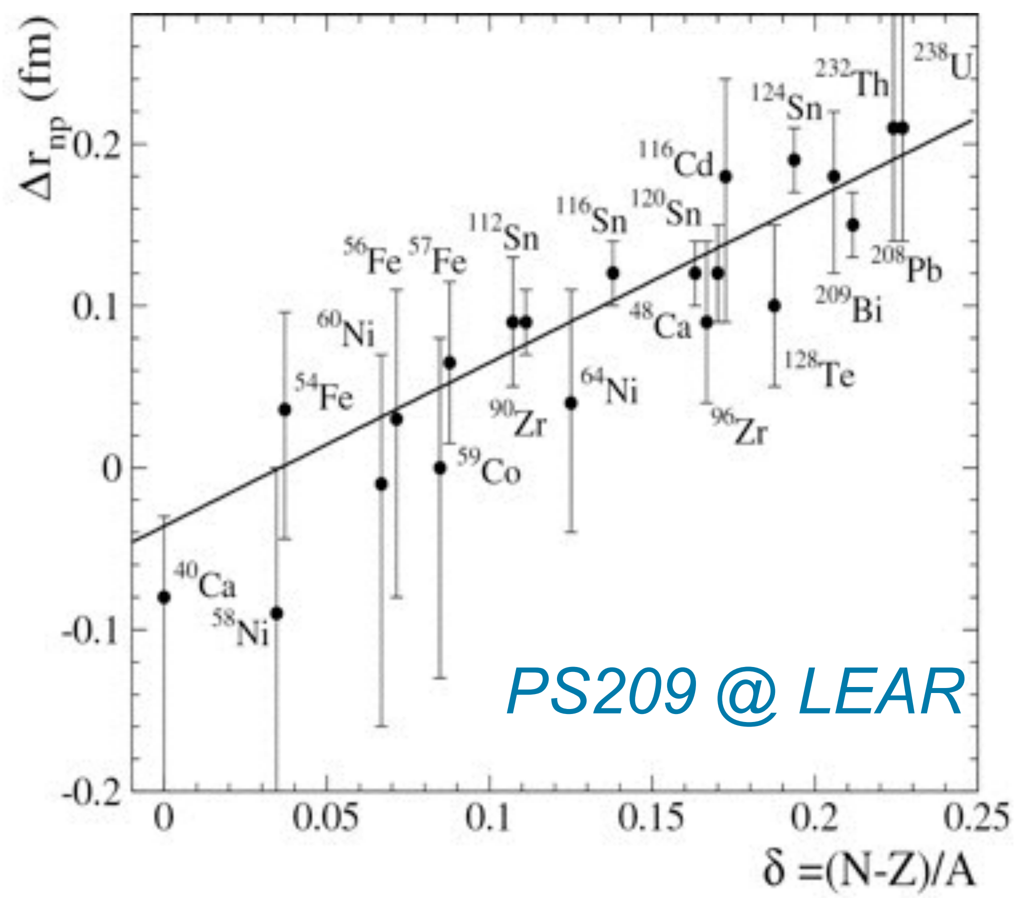


- Current ESR experimental hall could be used for full FLAIR program
  - without accumulation rates are similar to ELENA

Nuclear Periphery with antiprotonic Atoms

determination of the **halo factor** (f_{halo})





- Exotic atom formation -> cascade ->
  - Annihilation with outermost nucleons (<r>+ 2 fm)
- Measurement of neutron halo parameters
  - Radiochemical method, X-rays + model calculations
- Neutron diffuseness increases with neutron excess
- Extension to unstable nuclei interesting

A. Trzcinska, J. Jastrzebski et al. PRL 87 (082501) 2001

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First evidence for neutron halos

- charged pion 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

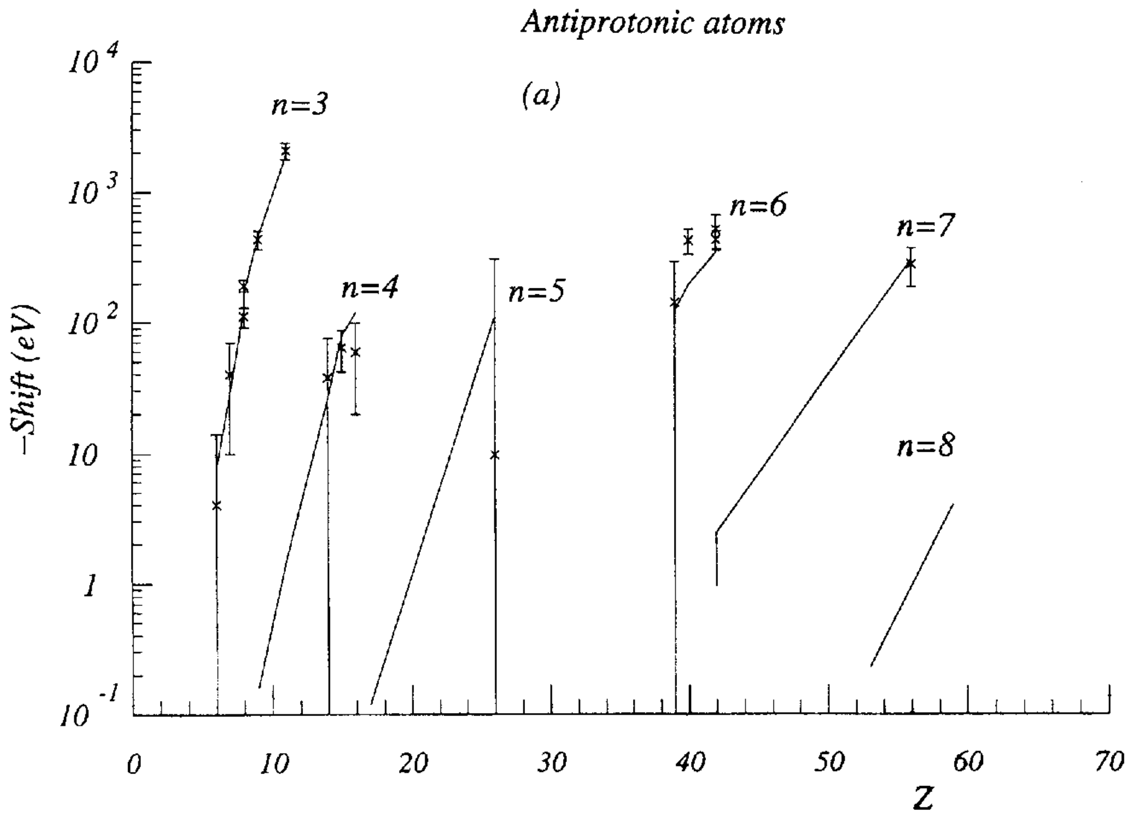
$$R_{\rm np} \equiv \sigma_{\bar{p}n}/\sigma_{\bar{p}p} \approx 0.63$$

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

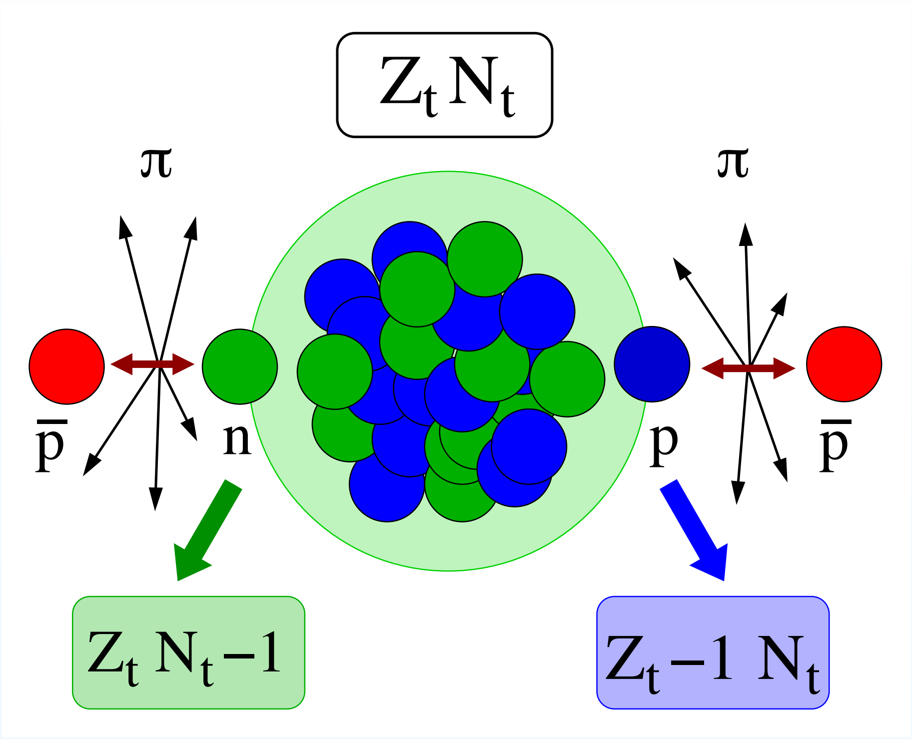
courtesy M. Wada

Nuclear radii

- Absorption measurements
  - matter radius: both r_n, r_p
- charge radius
  - electron scattering
  - muonic atoms
  - hyperfine structure isotope shifts
  - well established data base
- neutron radius
  - fewer reactions
  - largest contribution: antiprotonic atoms
    - radiochenical method
    - X-rays



Halo factors



in the experiment we measure:

$$\text{yields} \begin{cases} Y_{N_t-1} \sim \rho_n(r_{anih.}) \\ Y_{Z_t-1} \sim \rho_p(r_{anih.}) \end{cases}$$

$$f_{halo} = \frac{Y_{N_t-1}}{Y_{Z_t-1}} \cdot \frac{Z}{N} \cdot \frac{\text{Im}\, a_{p\bar{p}}}{\text{Im}\, a_{n\bar{p}}}$$

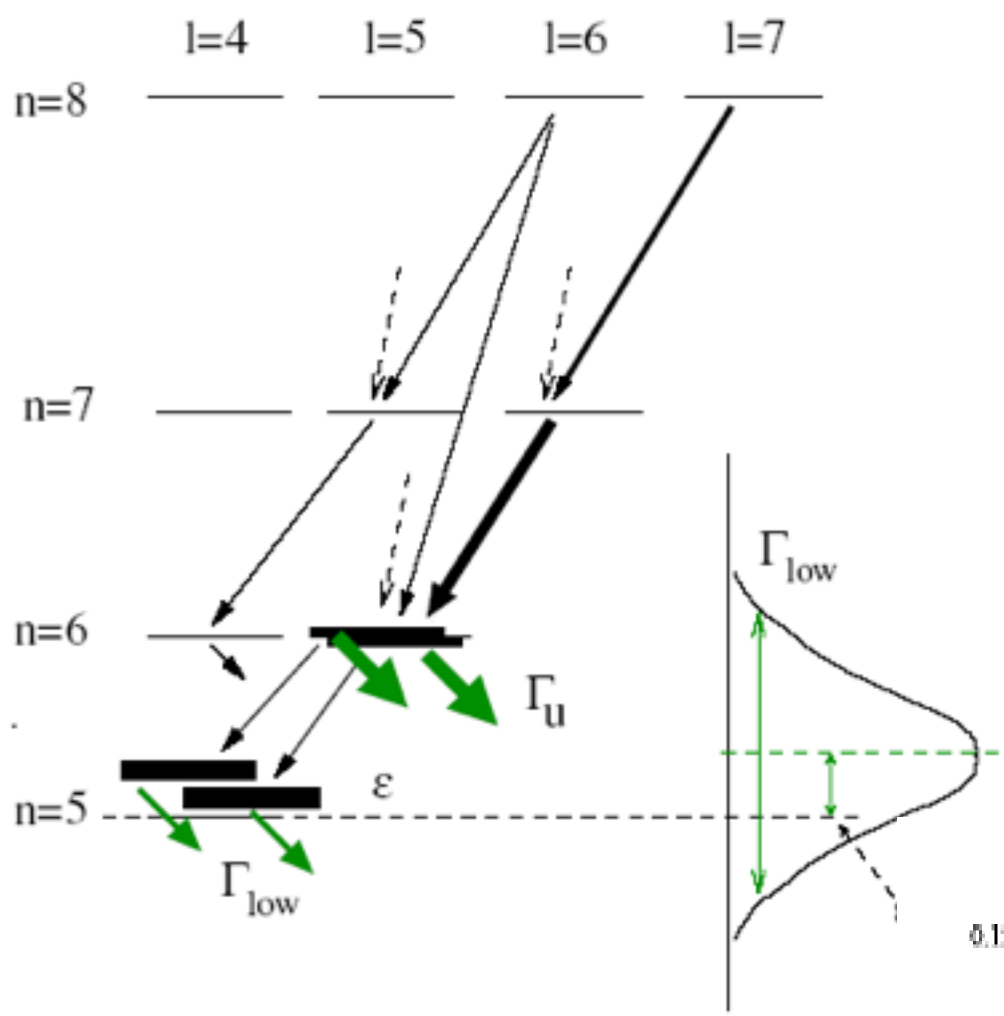
From light antiprotonic atoms

$$f_{halo} \sim \frac{\rho_n}{\rho_p} (\text{at annihilation place})$$

annihilation place $\simeq c_p + 2.5$ fm

courtesy A. Trzinska

Antiprotonic X-rays of heavy nuclei



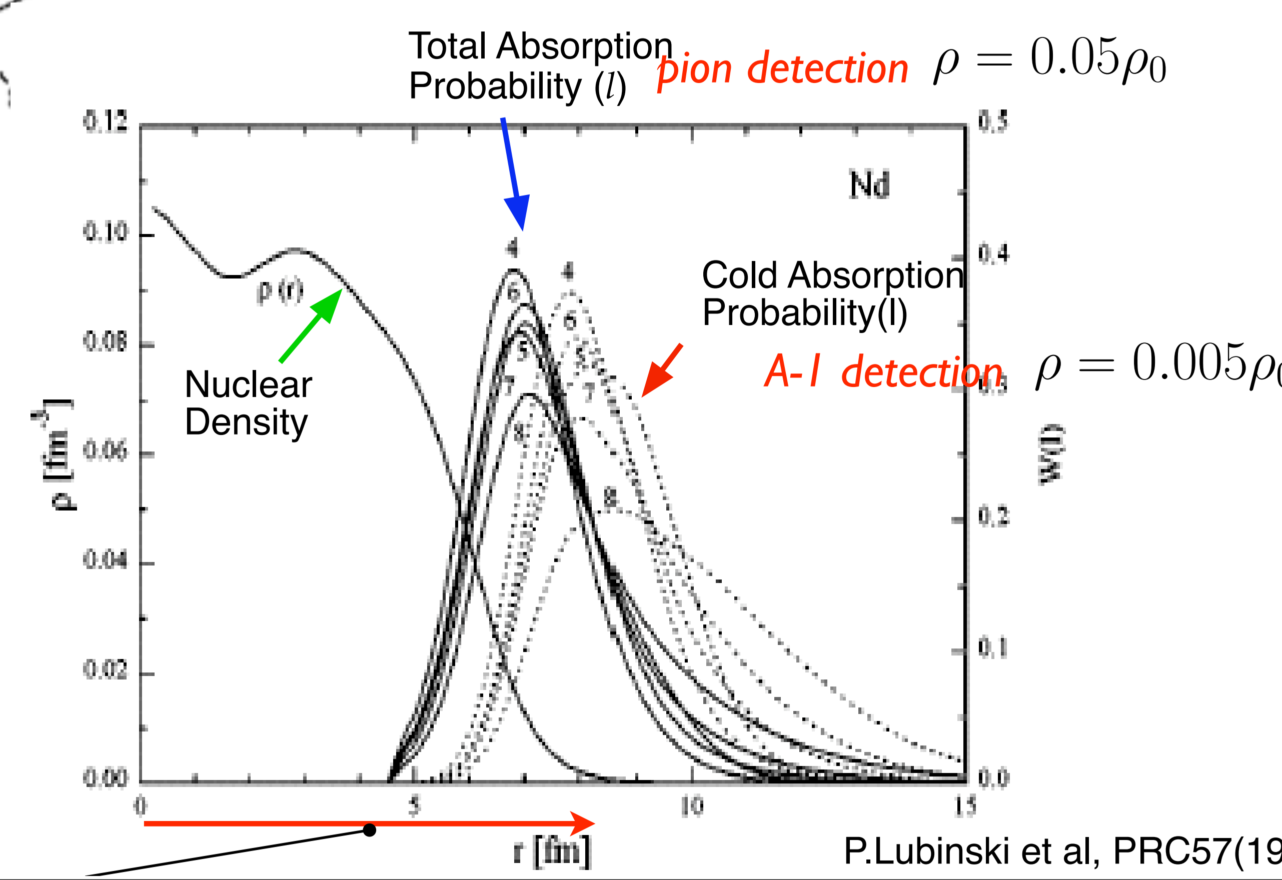
Strong interaction

⇓

levels **broadening** and **shift**

measured in experiment:

$\Gamma_{up}, \Gamma_{low}, \epsilon$



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

X-rays and nuclear density

strong interaction **widths** (Γ) and **shifts** (ϵ) are related to **the nuclear density**

$$\frac{\Gamma}{2} \sim \int \mathrm{Im}\, V(r)\ |\Psi_{nl}(r)|^2\, r^2\, dr$$

$$\frac{\epsilon}{2} \sim \int \mathrm{Re}\, V(r)\ |\Psi_{nl}(r)|^2\, r^2\, dr$$

$$V_{opt} = -\frac{2\pi}{\mu}\left(\bar{a}_n\, \rho_n(r) + \bar{a}_p\, \rho_p(r)\right)$$

$$\Rightarrow \Gamma, \epsilon \sim \rho$$

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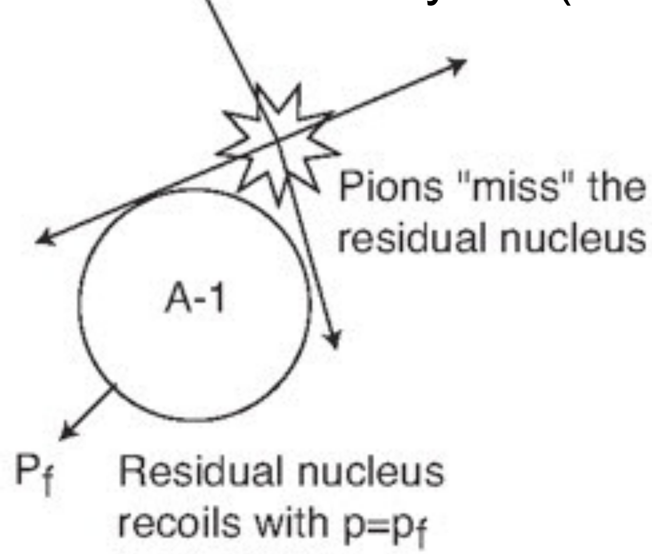
$\bar{p}$-RI in Traps for Nuclear Structure Study

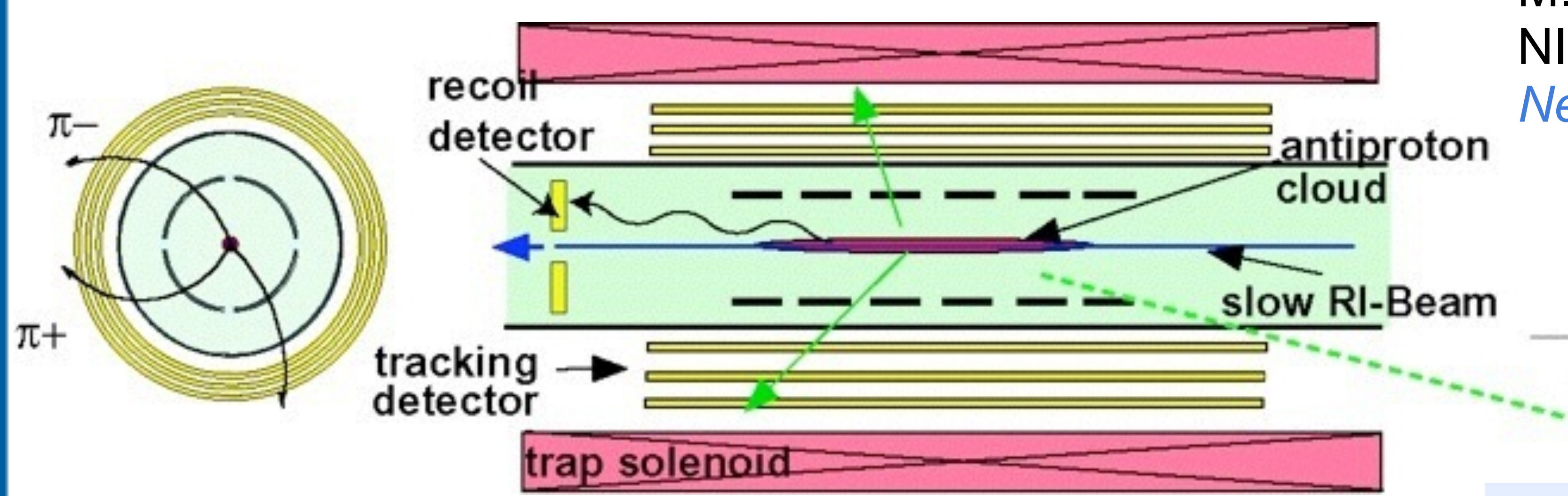
- pbar annihilates with outer-most nucleon at <r> + 2 fm

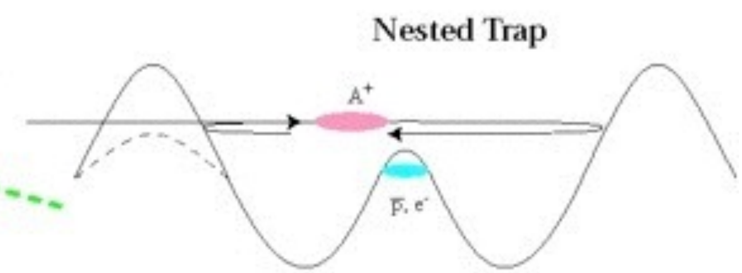
R. S. Hayano (Tokyo)



- Momentum distribution of recoil nuclei
  - Wave function of outer-most nucleon
- Charged pion multiplicity
  - Distinguish annihilation on p and n
  - Halo factors
  - Less model dependent than X-rays
- Antiprotons from FLAIR
- RI from LEB-SFRS gas catcher

M. Wada, Y. Yamazaki (Tokyo)
NIM B214 (2004) 196
Nested Penning trap





Exo+pbar

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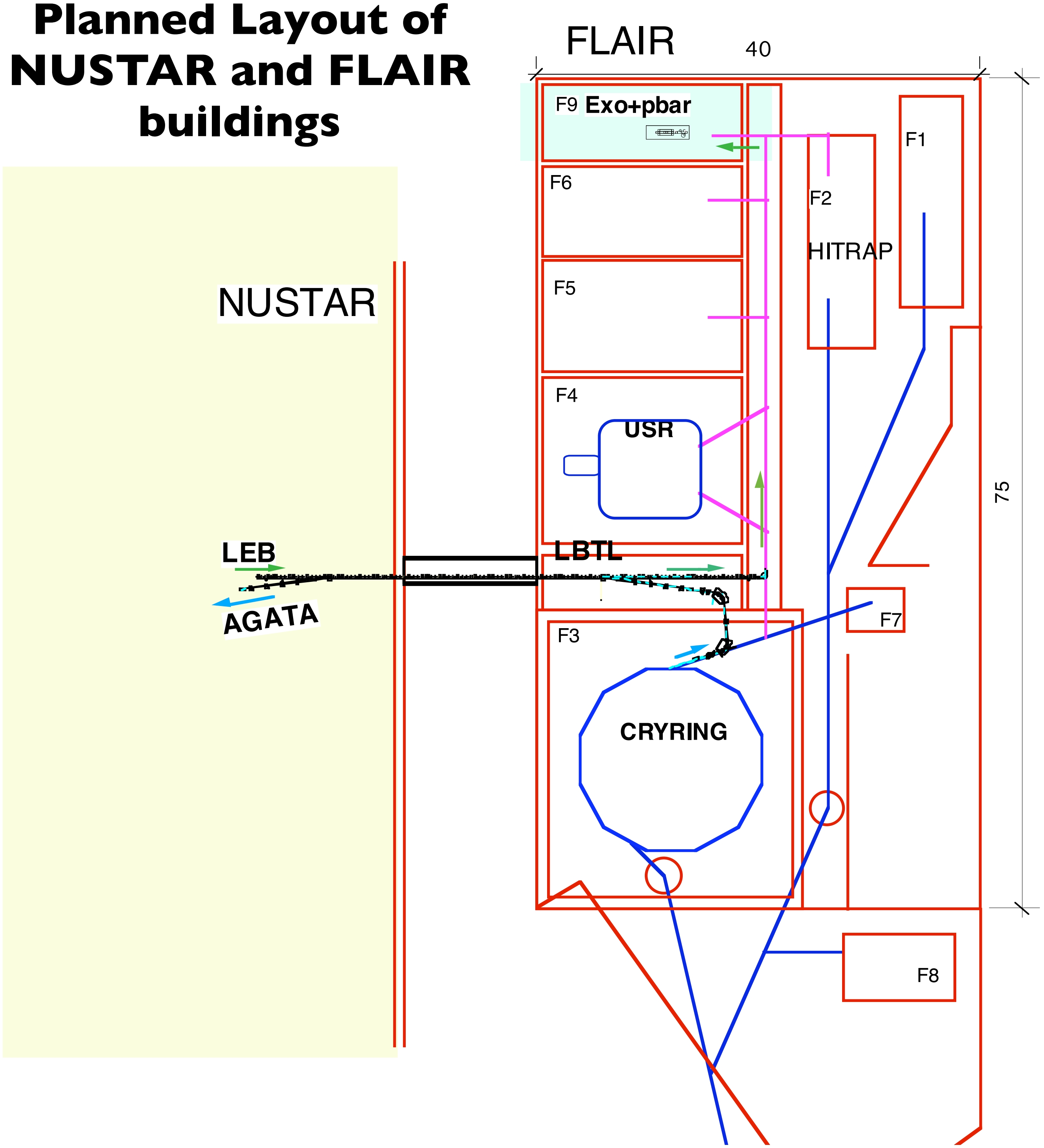
General layout

Planned Layout of NUSTAR and FLAIR buildings



M. Wada 2005

Slow RIB:

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

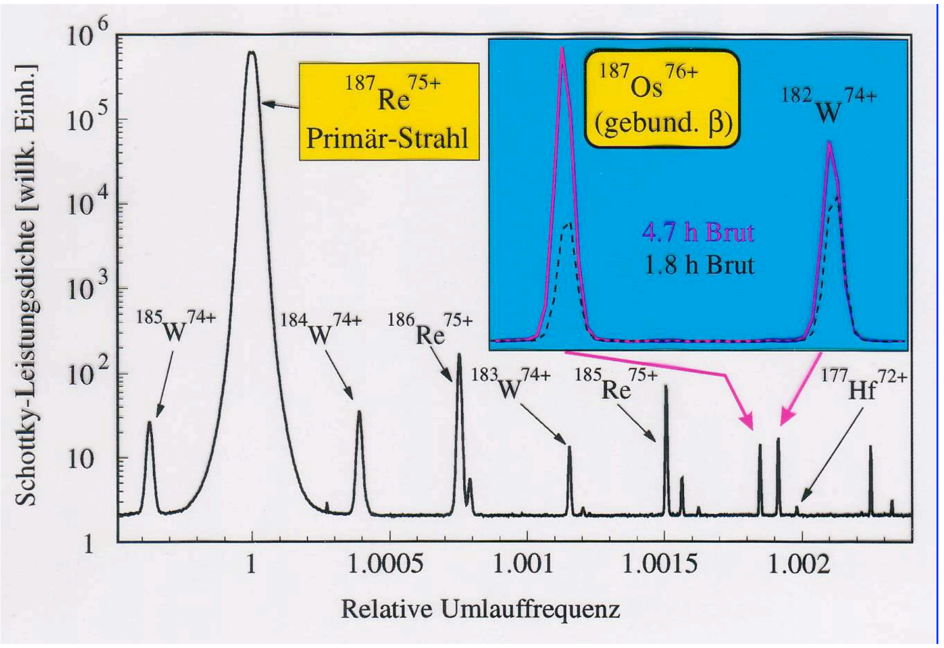
Antiproton:

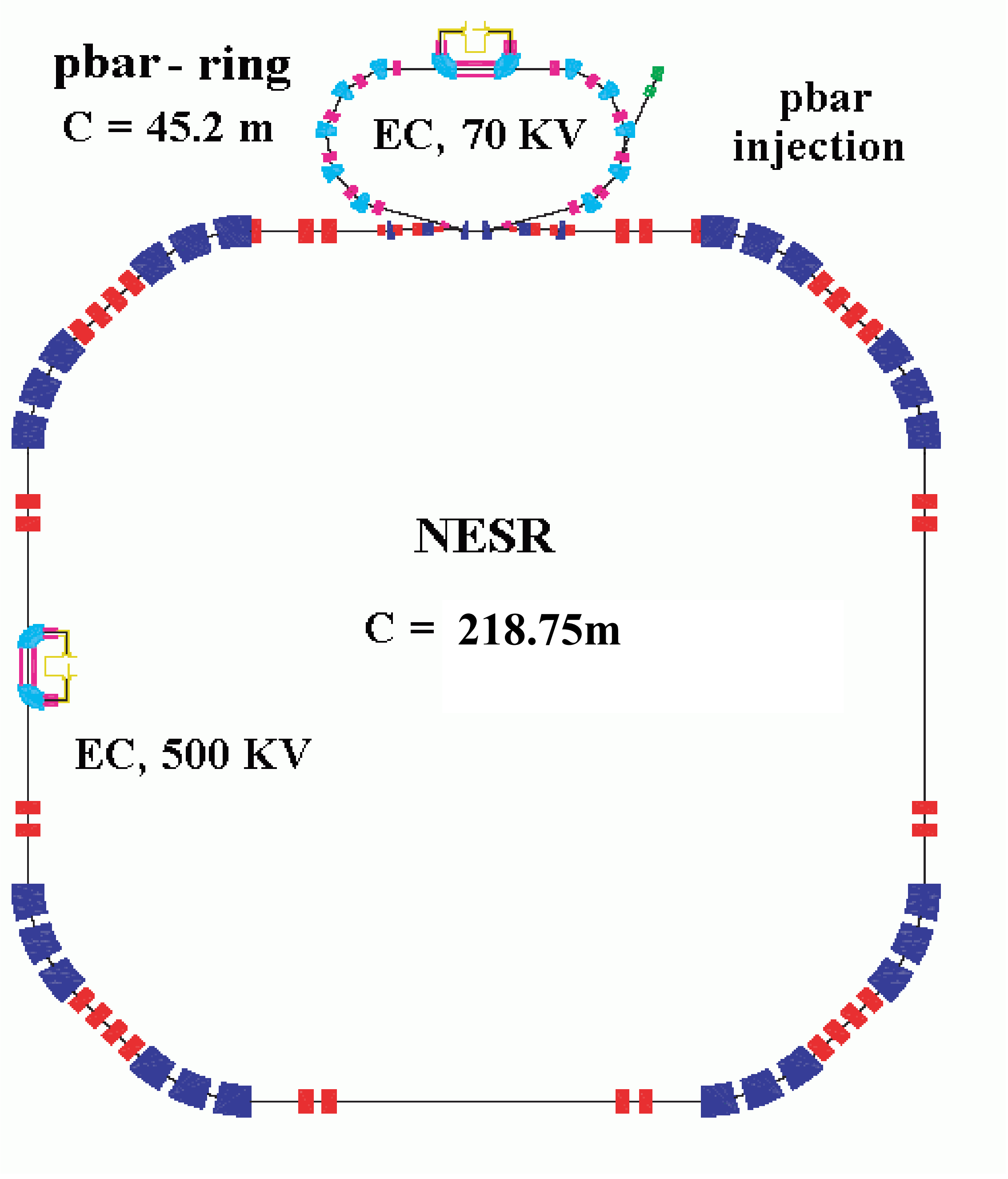
NESR -
CRYRING (LSR) -
USR -
FLAIR common BTL -
Exo+pbar

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

AIC layout

- make use of NESR & ELISE ring (now phase B of FAIR)
- medium energy antiproton - unstable heavy ion collisions for study of nuclear radii
- detection by Schottky method

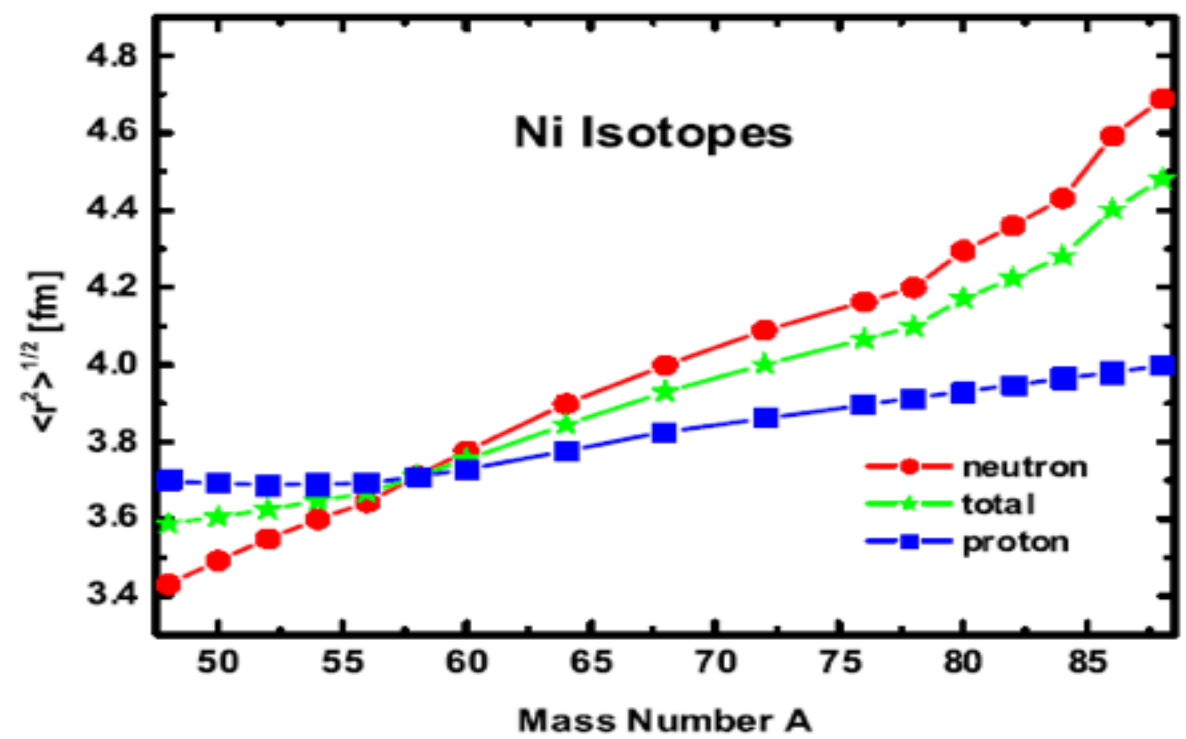


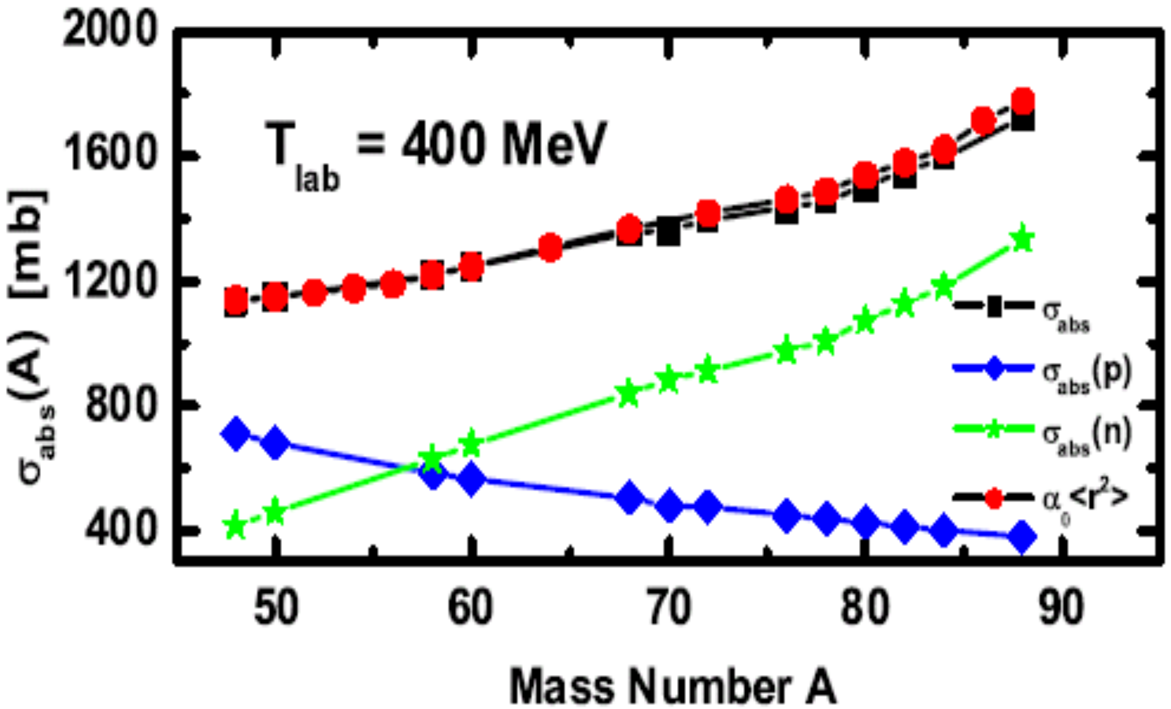


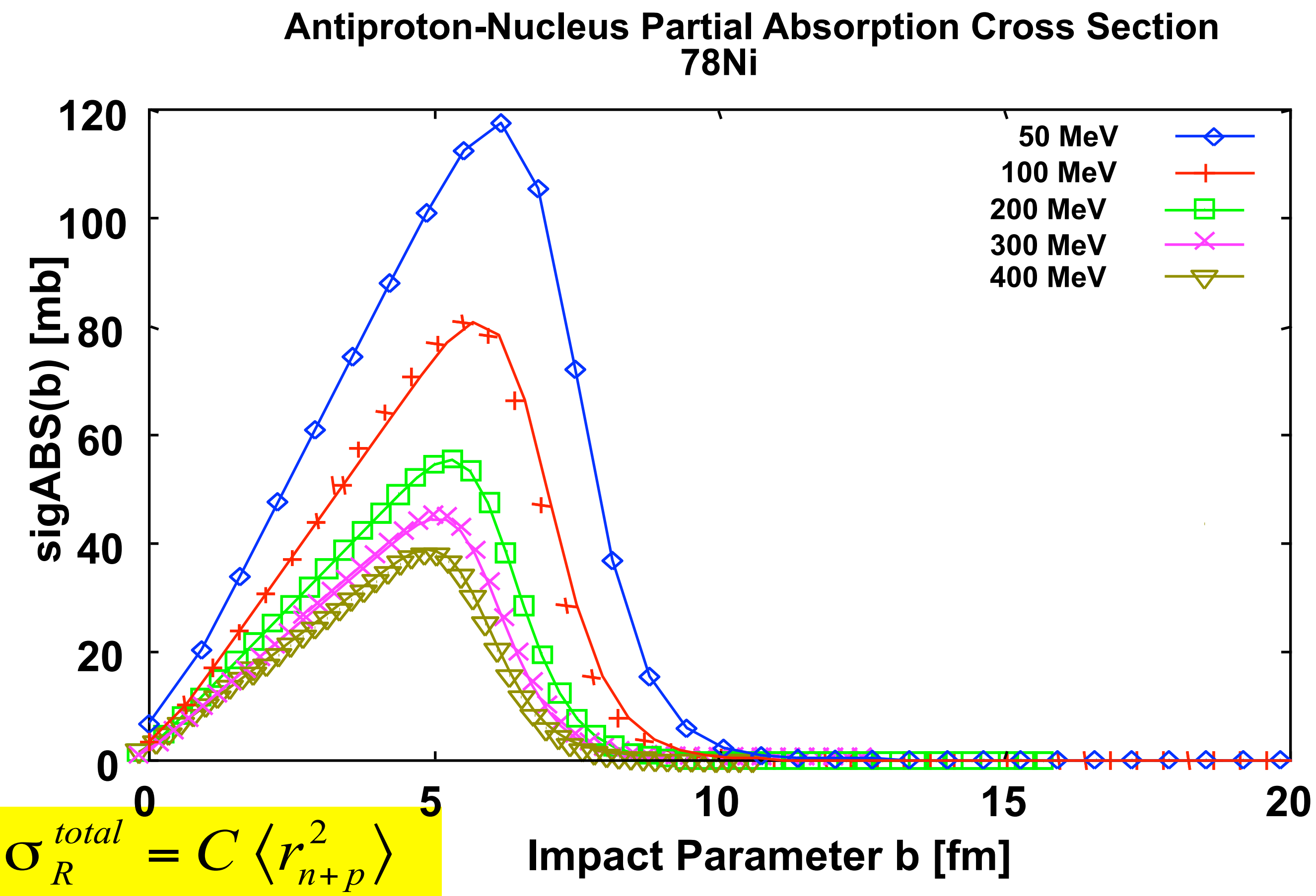
P. Kienle, NIM B 214 (2004) 193

p̄A annihilation cross section

Cross-section converges for high energies to value depend only on size of nuclei







$$\sigma_R^{total} = C \langle r_{n+p}^2 \rangle$$

$$\sigma_R^{n} = C \frac{N}{A} \langle r_n^2 \rangle$$

$$\sigma_R^{p} = C \frac{Z}{A} \langle r_p^2 \rangle$$

H. Lenske, P. Kienle,
Physics Letters B 647, 82–87 (2007)
nucl-th/0502065

Neutron distribution from $\overline{p}$

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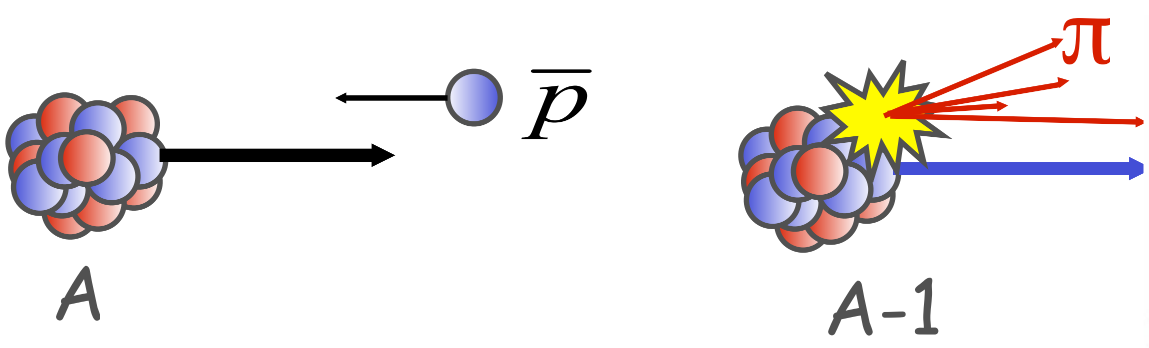
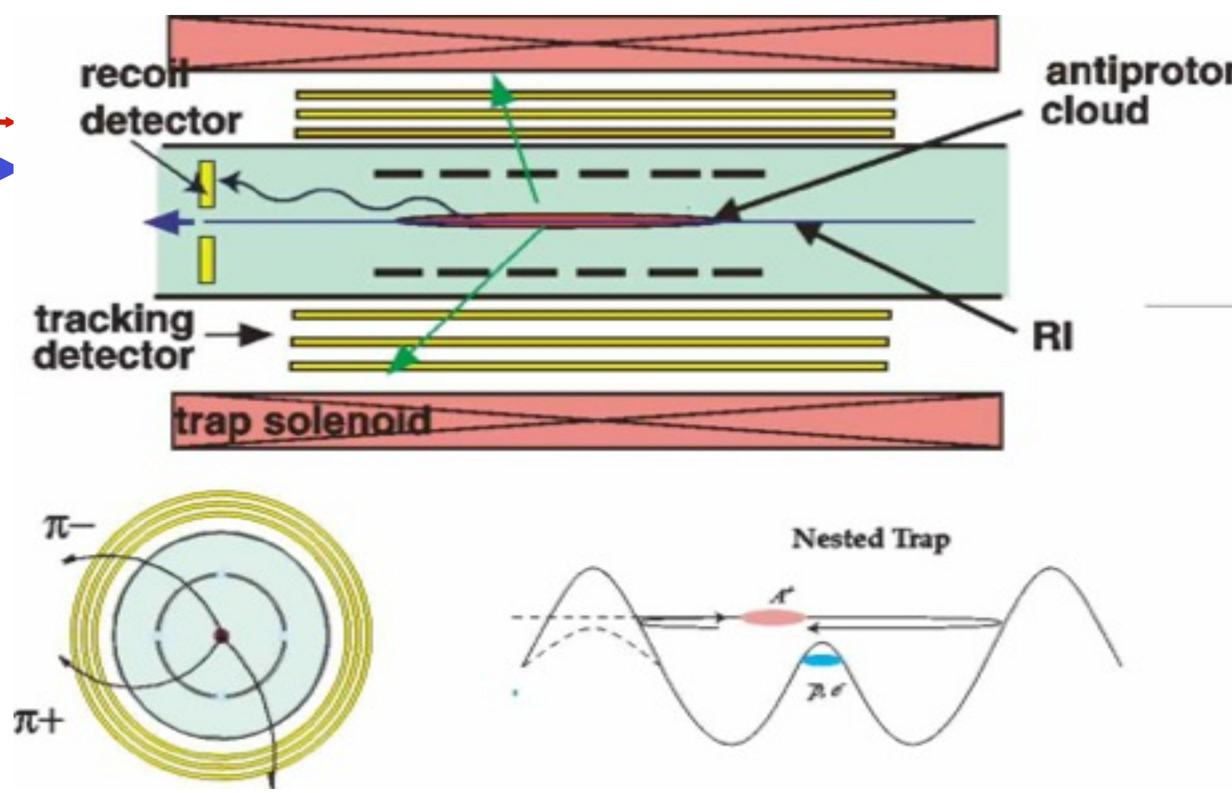
Antiproton Ion Collider (AIC)



- annihilation cross-section at high energies proportional to mean square radius
- count surviving A-1 nuclei

→ Proton and neutron radii in the same experiment

Exo+pbar



- antprotons in atomic orbits
- annihilation on tail of density distribution

→ Halo or Skin ?

Summary

- Antiprotons are unique tools to study neutron radii and halos
- Antiprotonic atoms provide largest data base for neutron radii for stable nuclei
- Extension to unstable nuclei extremely interesting
- FAIR offers unique chance
- AIC and Exo+pbar are complementary
- Needs:
  - low energy antiprotons: AIC 30 MeV, Exo+pbar: stopped
  - AIC: merged storage rings, 740 MeV/u RI
  - Exo+pbar: stopped $\bar{p}$ and RI in close proximity

Original proposals

FLAIR proposal 2004: Exo+pbar

1.8.3 Antiprotonic radioactive nuclides in traps

M. Wada, Y. Ishida, T. Nakamura, K. Okada, A. Takamine, N. Oshima, Y. Nakai, Y. Yamazaki, RIKEN, Wako, Japan
H. Geissel, W. Quint, C. Scheidenberger, M. Winkler, GSI, Darmstadt, Germany
J. Jastrzebski ,W. Kurcewicz, A. Trzcinska, Univ. Warsaw, Warsaw, Poland
J. Äystö, A. Jokinen, S. Kopecky, I. Moore, A. Nieminen, JYFL, Jyvaskyla, Finland

AIC TDR 2005

Beller, Peter [A] Bosch, Fritz[A] Cargnelli, Michael[B] Fabbietti, Laura [C] Faestermann, Thomas [C] Frankze, Bernhard [A] Fuhrmann, Hermann [B] Hayano, Ryugo S.[D] Hirtl, Albert[B] Homolka, Josef [C] Kienle, Paul [B,C] Kozhuharov, Christophor [A] Krücken, Reiner [C], Lenske, Horst [E] Litvinov, Yuri [A] Marton, Johann [B] Nolden, Fritz [A] Ring, Peter [C] Shatunov, Yuri [F] Skrinsky, Alexander N. [F] Suzuki Ken, [C] Vostrikov, Vladimir A. [F] Yamaguchi, Takayuki [G] Widmann, Eberhard [B] Wycech, Slawomir [H] Zmeskal, Johann [B]

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