FLAIR

A Facility for Low-Energy Antiproton and Ion Research

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on behalf of the FLAIR collaboration

UNIVERSITY OF LIVERPOOL

DITANET

The Cockcroft Institute of Accelerator Science and Technology

Outline

- Why cooled low-energy antiprotons ?
- Present situation: AD @ CERN
- The future: FLAIR
  - *General scheme*
  - *The low-energy storage ring (LSR)*
  - *The ultra-low-energy storage ring (USR)*

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Atomic Physics & Fund. Interactions

Examples from LoI

Structure + Fundamental interactions

- Precision spectroscopy of $\bar{H}$(1s-2s)
- Hyperfine spectroscopy of $\bar{H}$
- p/$\bar{p}$ mass & H/$\bar{H}$ gravity measurements
- g-factor of $\bar{p}$

Structure & Dynamics

- Hyperfine spectroscopy of $\bar{p}$He+
- Precision spectroscopy of $\bar{p}$He+
- Life-time of metastable states in $\bar{p}$He+

Dynamics

- Formation of $\bar{p}$He+: n,l distributions
- Formation of antihydrogen
  - $\bar{p}$ + e+: radiative recombination, stimulated by laser
    three-body recombination, in strong magnetic fields
  - $\bar{p}$ + PS: kinematical e+ capture in the presence of a laser field
- $\bar{p}$ collisions with atoms and molecules
  - energy loss
  - total single and multiple ionization cross sections
  - fully differential cross sections for single, double, multiple ionization

Nuclear and Particle Physics with Antiprotons

...

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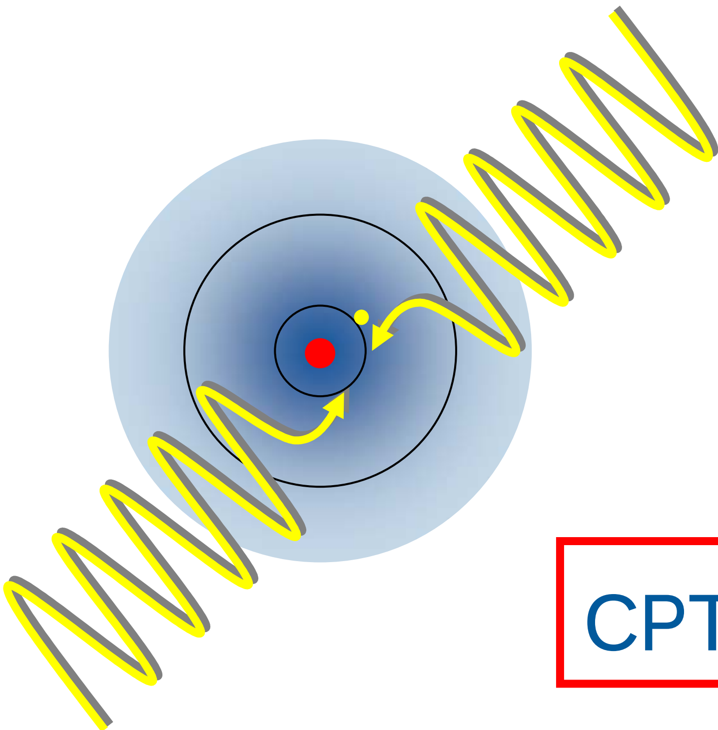
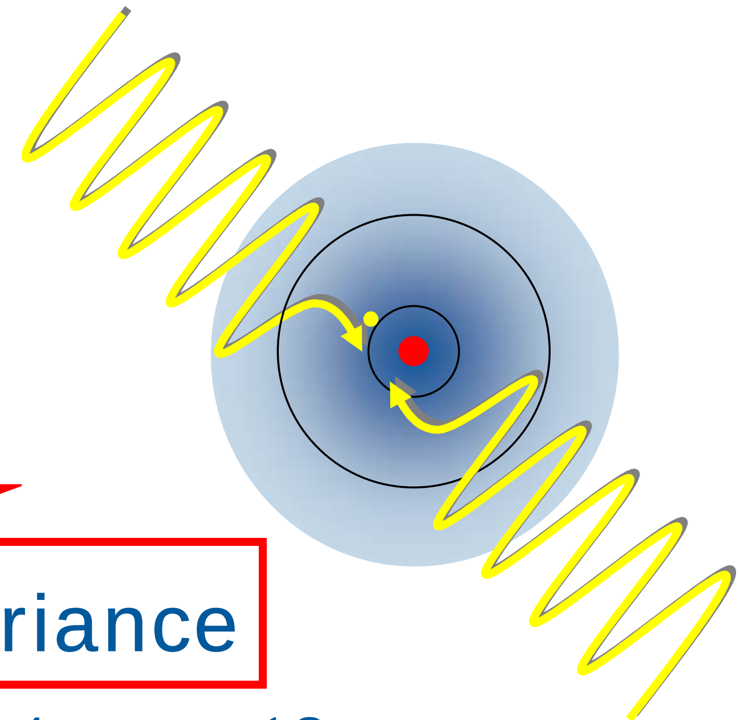
Same Structure ?

Hydrogen **Anti-Hydrogen**





CPT Invariance

$$\Delta E / E \approx 10^{-14} \ldots . 10^{-18}$$

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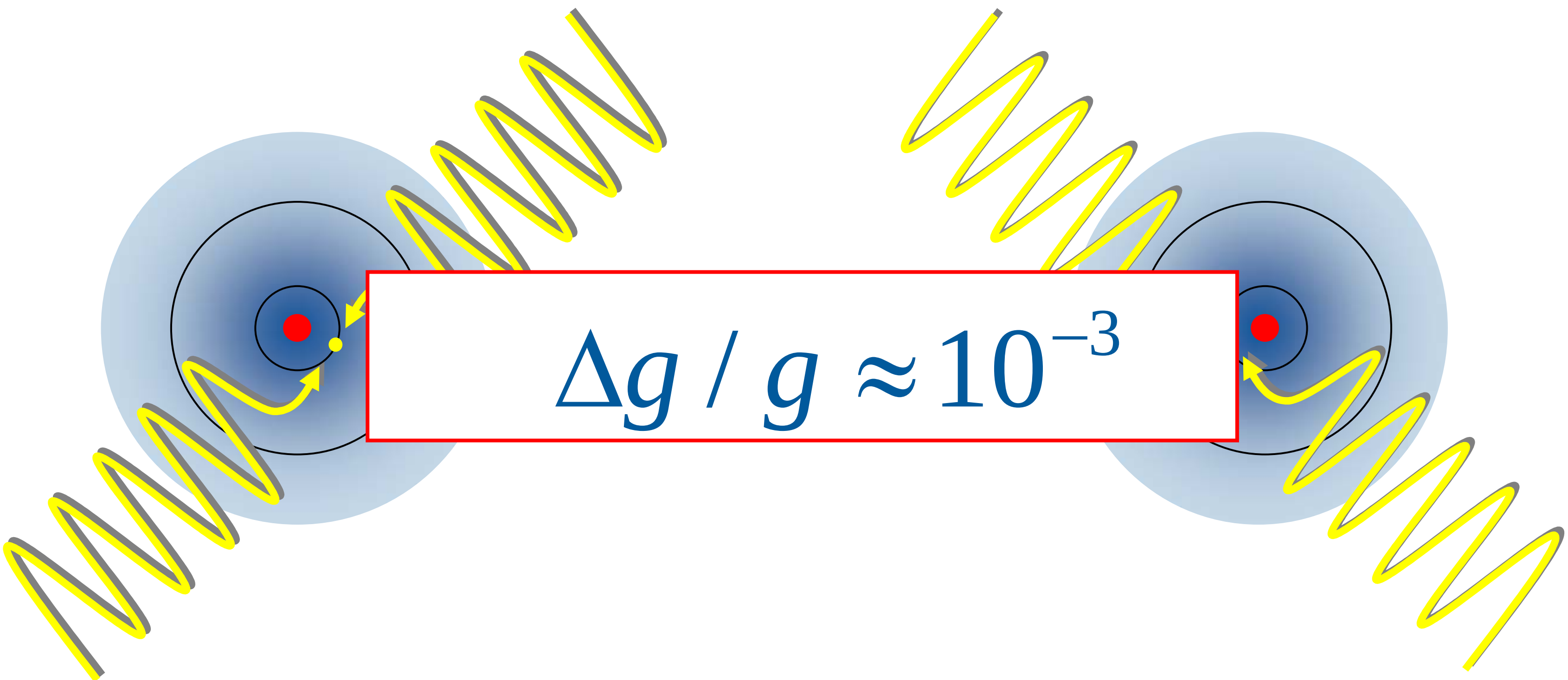
Same Weight ?

Hydrogen **Anti-Hydrogen**



$$\Delta g / g \approx 10^{-3}$$

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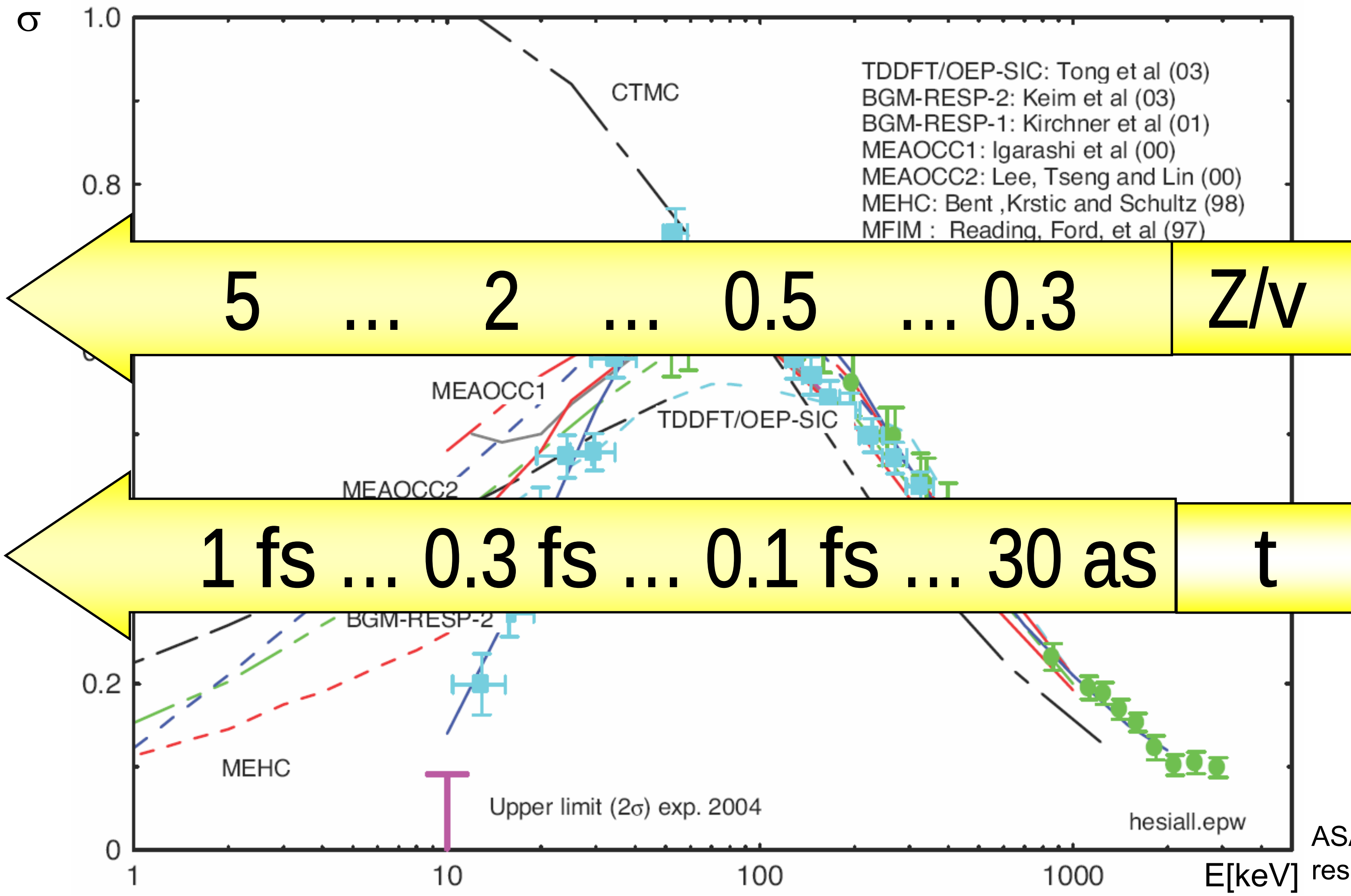
Dynamics: He + pbars



ASACUSA results

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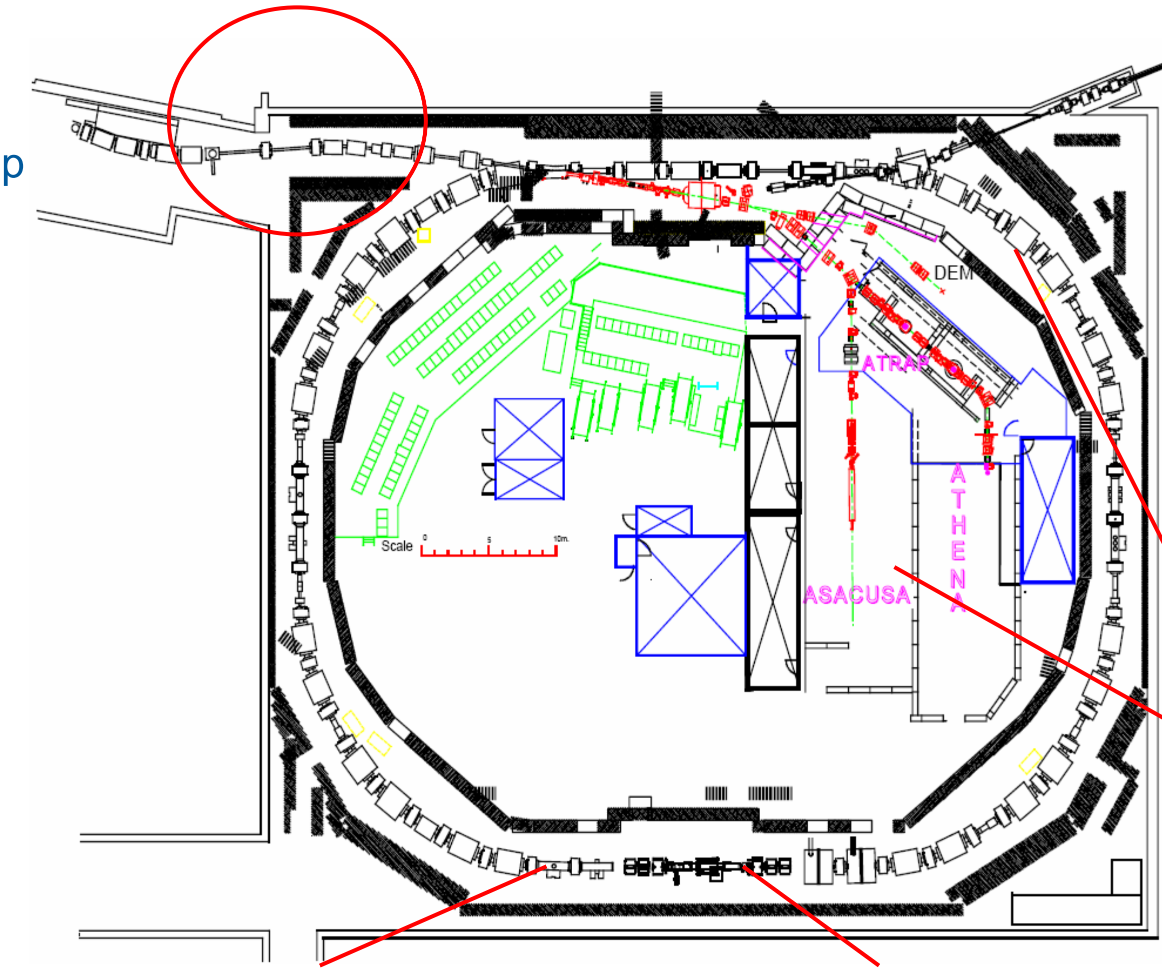
Present Situation: AD @ CERN

Target Area

26 GeV/c p
➡ 3.57 GeV/c $\bar{p}$

<u>Yield</u>: $4 \cdot 10^{-6}$

p



Experiments

Stoch. Cooling

e^- Cooler

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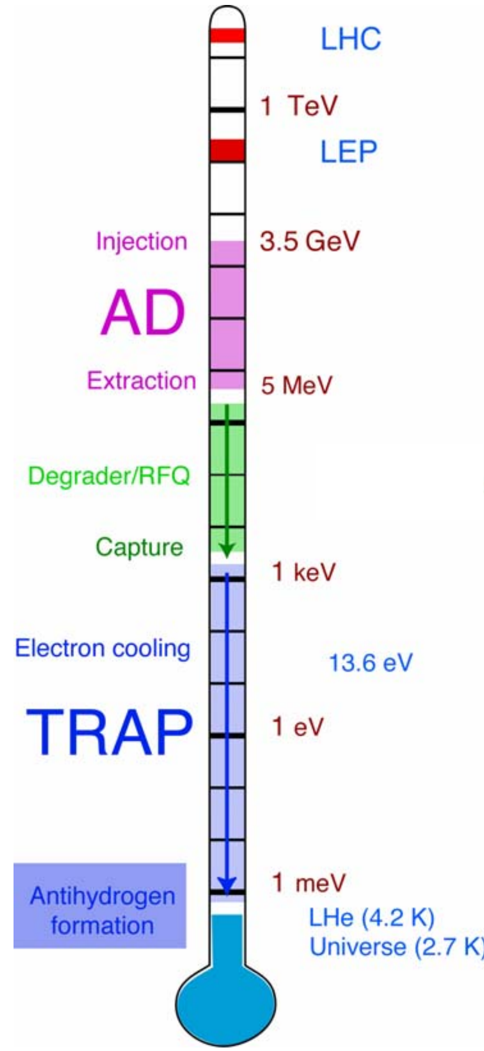
Challenges

Antiprotons are created at
high energies. (GeV)

H-atom is a weakly-bound system:

E (1s) = - 0.000 000 013 6 GeV

Deceleration & Cooling required !



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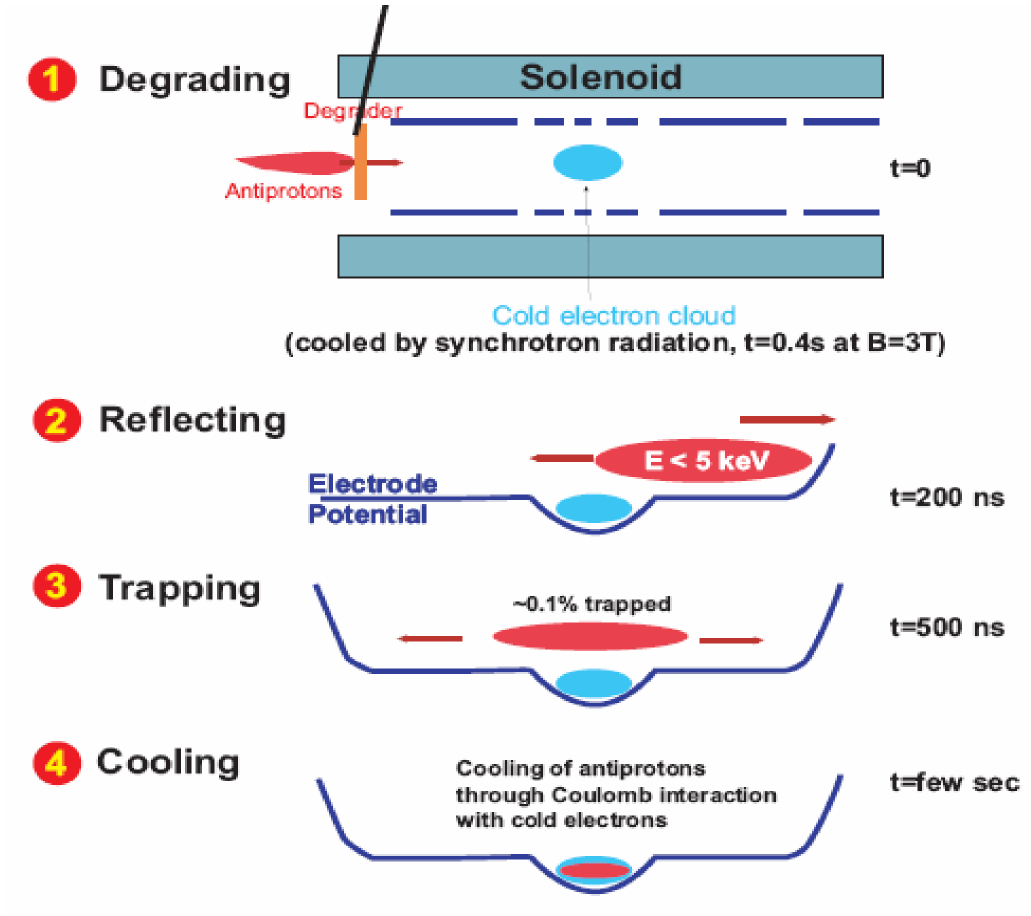
Problem: 5 MeV Too High For Trapping !



- > 99.9 % of pbars lost in degrader.

  ~ 10.000 pbars/shot

- ASACUSA: RFQ-D

  ~ 2.000.000 pbars/shot

  Still: large ΔE/E, $\varepsilon_{x,y}$

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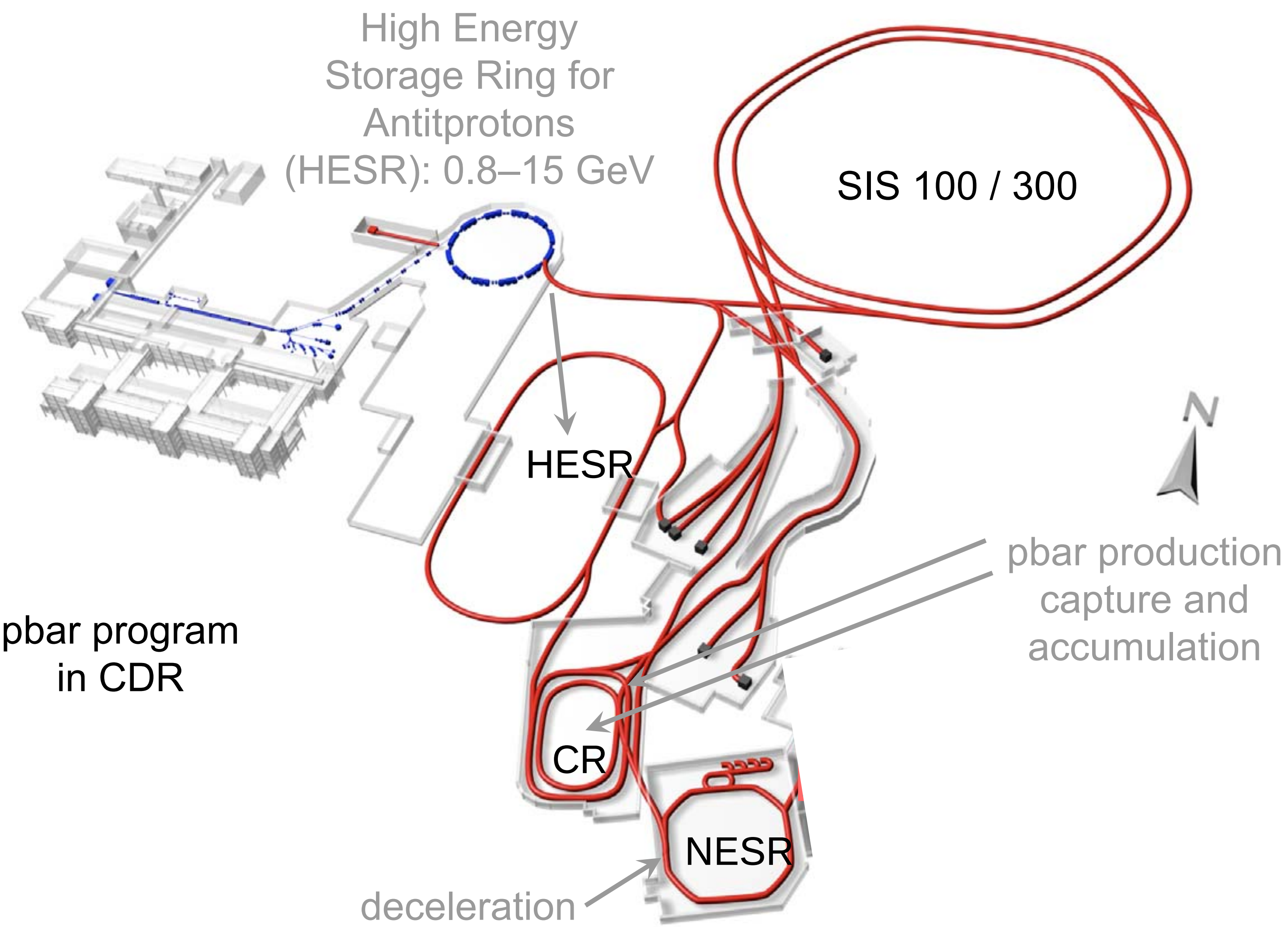
Antiprotons at FAIR



pbar program
in CDR

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Idea: FLAIR

- ***Austria*** (SMI, Vienna,TU)
- ***Canada*** (York, TRIUMPF)
- ***Denmark*** (Aarhus, ISA)
- ***Germany*** (GSI, Dresden, Frankfurt, MPQ, Giessen, MPI-K, FJZ, Mainz, Tübingen, Berlin)
- ***Hungary*** (KFKI, ATOMKI, Debrecen)
- ***India*** (VECC)
- ***Italy*** (Brescia, Firenze, Genova)
- ***Japan*** (RIKEN, Tokyo)
- ***Netherlands*** (Amsterdam, FOM)
- ***Poland*** (Warsaw, Soltan Inst.)
- ***Russia*** (JINR, Moscow, VNIIM, St. Petersburg, Troitsk, Moskva)
- ***Sweden*** (MSL, Stockholm)
- ***UK*** (Queens, Wales)
- ***USA*** (Harvard, Pbar Labs, New Mexico, Texas, Indiana)

Spokesman: E. Widmann, SMI, Vienna

150 Scientists

15 Countries

50 Institutions

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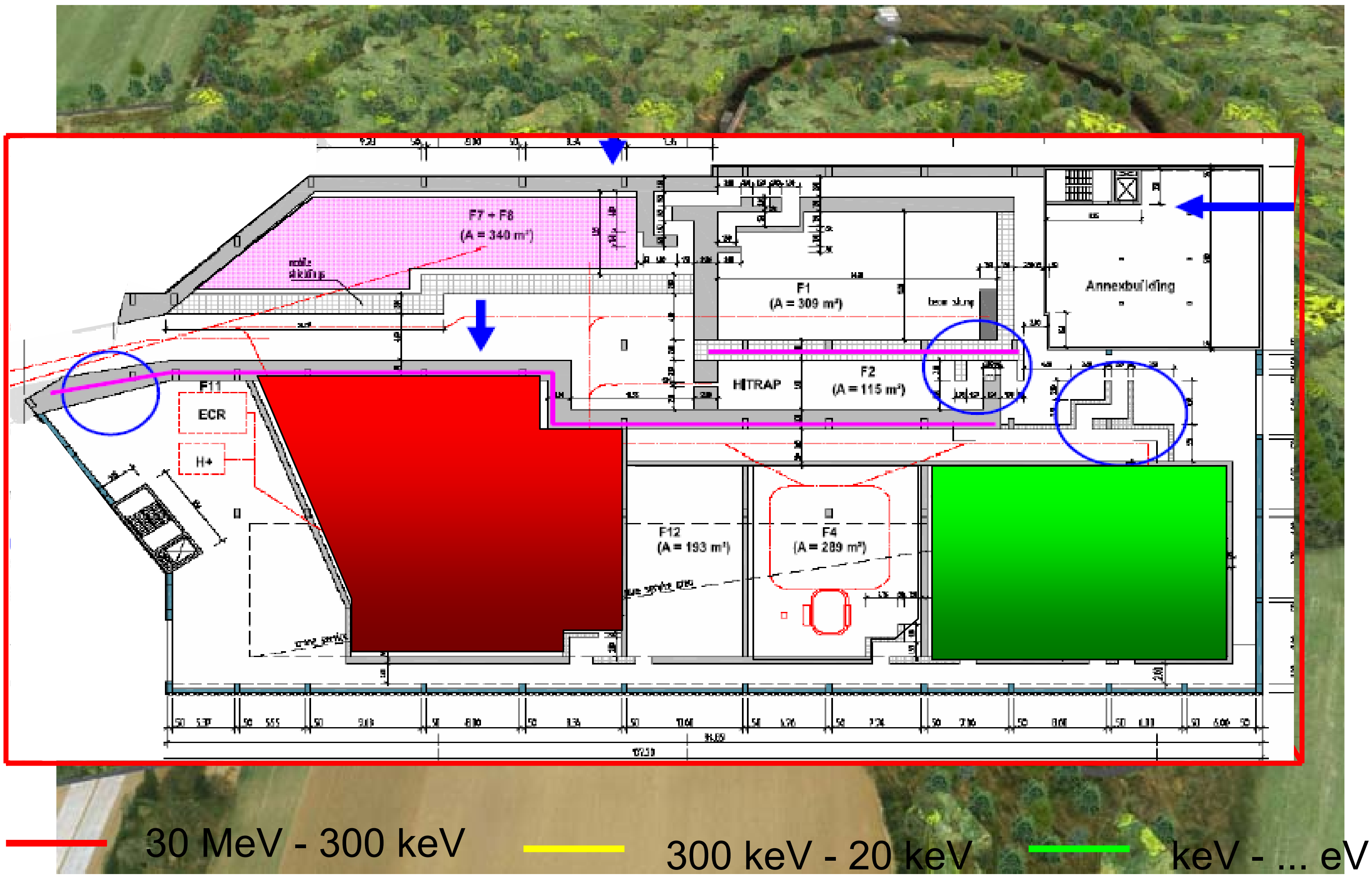
FLAIR @ Facility for Antiproton and Ion Research



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FLAIR Rings

$2 \cdot 10^7$/s

Ring		Energy Range	# pbars	
NESR	*20 sec*	800 – 30 MeV	$4 \cdot 10^8$	
LSR *$1.5 \cdot 10^8$*	*E=300 keV*	30 – 0.3 MeV	R_{eff} $R_{extr.}$	$= 2 \cdot 10^{13}$ 1/s $= 7 \cdot 10^6$ 1/s
USR *10^7*	*E=20 keV*	300 – 20 keV	R_{eff} $R_{extr.}$	$= 1 \cdot 10^{12}$ 1/s $= 5 \cdot 10^5$ 1/s

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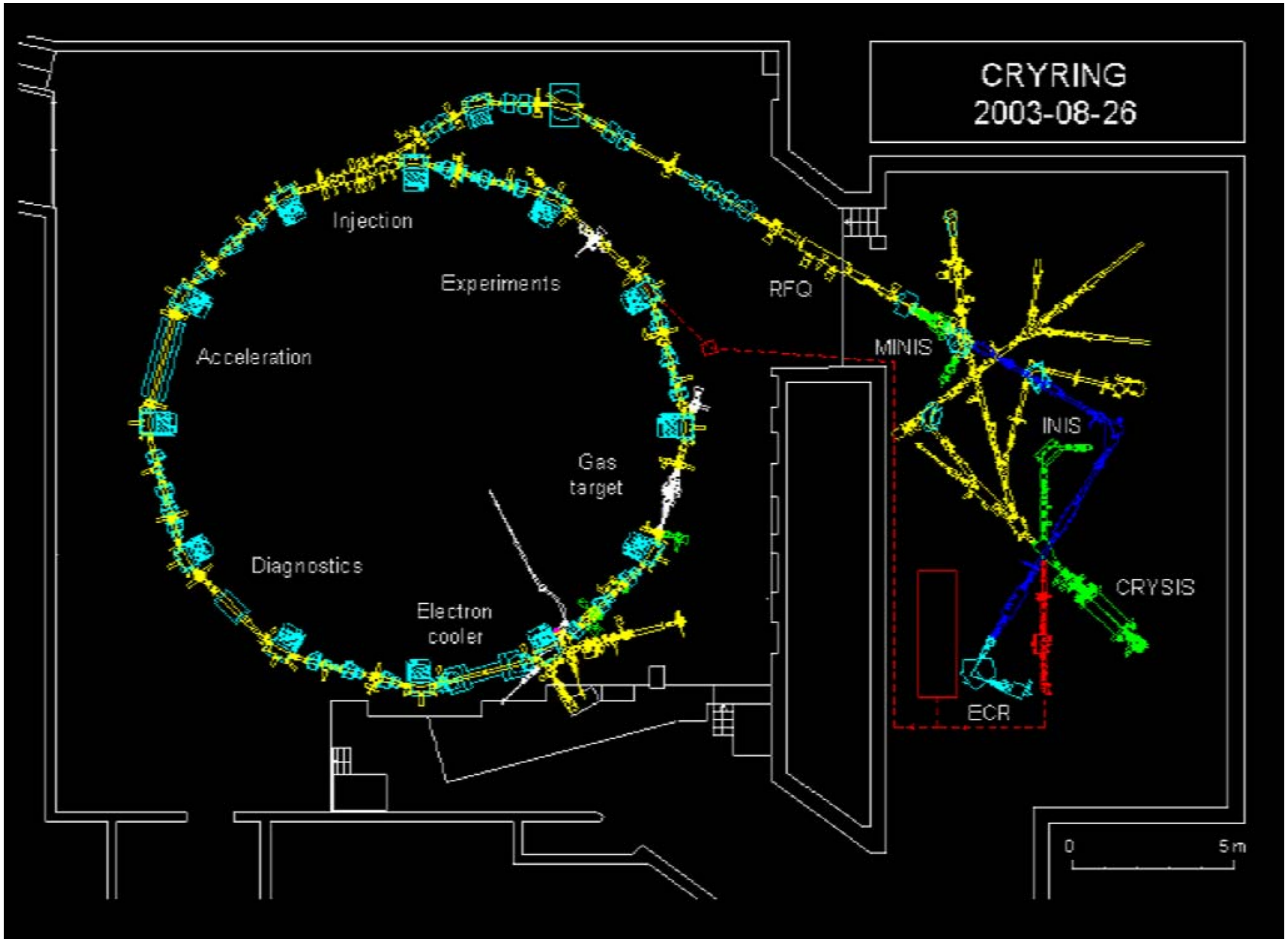
CRYRING



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CRYRING Timeline

- Design and construction started in 1986
- First beam stored in January 1991
- Electron cooler started in May 1993
- Start of experimental programme in June 1993
- ..
- Continuous improvements of power supplies, electron cooling, ion sources, diagnostics, control system, vacuum system …
- ..
- Swedish Research Council decided to stop funding in June 2003
- First discussions about transfering CRYRING to FAIR in summer 2003

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Ions that have been stored...

Singly charged positive atomic ions: H^+, D^+, $^{3}He^+$, $^{4}He^+$, $^{7}Li^+$, $^{9}Be^+$, $^{11}B^+$, $^{12}C^+$, $^{14}N^+$, $^{16}O^+$, $^{40}Ar^+$, $^{40}Ca^+$, $^{45}Sc^+$, $^{48}Ti^+$, $^{56}Fe^+$, $^{83}Kr^+$, $^{84}Kr^+$, $^{86}Kr^+$, $^{88}Sr^+$, $^{129}Xe^+$, $^{131}Xe^+$, $^{132}Xe^+$, $^{138}Ba^+$, $^{139}La^+$, $^{142}Nd^+$, $^{151}Eu^+$, $^{197}Au^+$, $^{208}Pb^+$

Multiply charged positive atomic ions: $^{4}He^{2+}$, $^{11}B^{2+}$, $^{12}C^{2+}$, $^{12}C^{3+}$, $^{12}C^{4+}$, $^{12}C^{6+}$, $^{14}N^{2+}$, $^{14}N^{3+}$, $^{14}N^{4+}$, $^{14}N^{7+}$, $^{16}O^{2+}$, $^{16}O^{3+}$, $^{16}O^{4+}$, $^{16}O^{5+}$, $^{16}O^{8+}$, $^{19}F^{6+}$, $^{19}F^{9+}$, $^{20}Ne^{2+}$, $^{20}Ne^{5+}$, $^{20}Ne^{7+}$, $^{20}Ne^{10+}$, $^{28}Si^{3+}$, $^{28}Si^{11+}$, $^{28}Si^{14+}$, $^{36}Ar^{8+}$, $^{36}Ar^{10+}$, $^{36}Ar^{12+}$, $^{36}Ar^{13+}$, $^{40}Ar^{9+}$, $^{40}Ar^{11+}$, $^{40}Ar^{13+}$, $^{40}Ar^{15+}$, $^{48}Ti^{11+}$, $^{58}Ni^{17+}$, $^{58}Ni^{18+}$, $^{84}Kr^{33+}$, $^{126}Xe^{36+}$, $^{129}Xe^{36+}$, $^{129}Xe^{37+}$, $^{136}Xe^{39+}$, $^{136}Xe^{44+}$, $^{207}Pb^{53+}$, $^{208}Pb^{53+}$, $^{208}Pb^{54+}$, $^{208}Pb^{55+}$

Singly charged postive molecular ions: H_2^+, HD^+, H_3^+, D_2^+, H_2D^+, $^{3}HeH^+$, $^{3}HeD^+$, $^{4}HeH^+$, D_3^+, He_2^+, LiH_2^+, D_5^+, BH_2^+, CH_2^+, NH_2^+, OH^+, CH_5^+, NH_4^+, H_2O^+, H_3O^+, HF^+, ND_3H^+, ND_4^+, D_3O^+, C_2H^+, CN^+, $C_2H_2^+$, HCN^+, $C_2H_3^+$, $HCNH^+$, $C_2H_4^+$, CO^+, N_2^+, $^{13}CO^+$, N_2H^+, $C_2H_5^+$, NO^+, $D^{13}CO^+$, CH_3O^+, CF^+, O_2^+, $CH_3NH_3^+$, CH_3OH^+, $CH_3OH_2^+$, H_2S^+, CD_3O^+, PD_2^+, $N_2H_7^+$, $D_2{}^{32}S^+$, $CD_3OH_2^+$, CD_3OD^+, $H_5O_2^+$, $D_2{}^{34}S^+$, $CD_3OD_2^+$, $^{13}CD_3OD_2^+$, $C_3H_4^+$, $D_5O_2^+$, $C_3D_3^+$, $N_2D_7^+$, $C_3H_7^+$, NaD_2O^+, CO_2^+, HCS^+, DN_2O^+, CO_2D^+, $NO^+{\cdot}H_2O$, O_3^+, $CD_3OCD_2^+$, $C_3D_7^+$, CF_2^+, $NO^+{\cdot}D_2O$, DC_3N^+, $CD_3OCD_3^+$, $N_3H_{10}^+$, DC_3ND^+, $CD_3ODCD_3^+$, $H_7O_3^+$, COS^+, $N_2O_2^+$, $D_7O_3^+$, $N_3D_{10}^+$, $C_4D_9^+$, $S^{18}O_2^+$, ArN_2^+, $H_9O_4^+$, $CD_3COHNHCH_3^+$, $CD_3CONHDCH_3^+$, $C_6D_6^+$, $H_{11}O_5^+$, $C_2S_2H_6^+$, $C_2S_2H_7^+$, $H_{13}O_6^+$

Multiply charged positive molecular ions: N_2^{2+}

Negative atomic ions: H^-, Li^-, F^-, Si^-, S^-, Cl^-, Se^-, Te^-

Negative molecular ions: CN^-, C_4^-, Si_2^-, Cl_2^-

Range of energies per nucleon: 38 eV/u – 92 MeV/u

Range of total energies: 5 keV – 1.4 GeV

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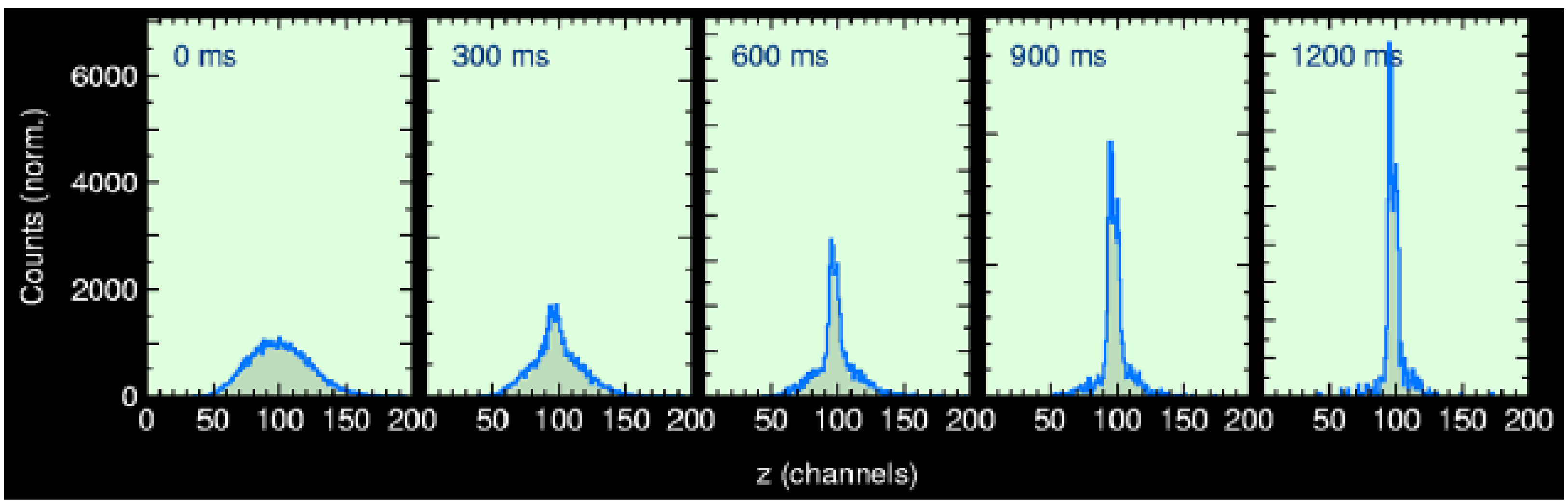
Electron Cooling of H^-

- Beam energy: 3 MeV
- Electron current: 18 mA
- Initial beam width (FWHM): 9 mm
- Initial emittance 10 π mm mrad
- Final beam width (FWHM): 1.5 mm
- Final emittance 0.25 π mm mrad



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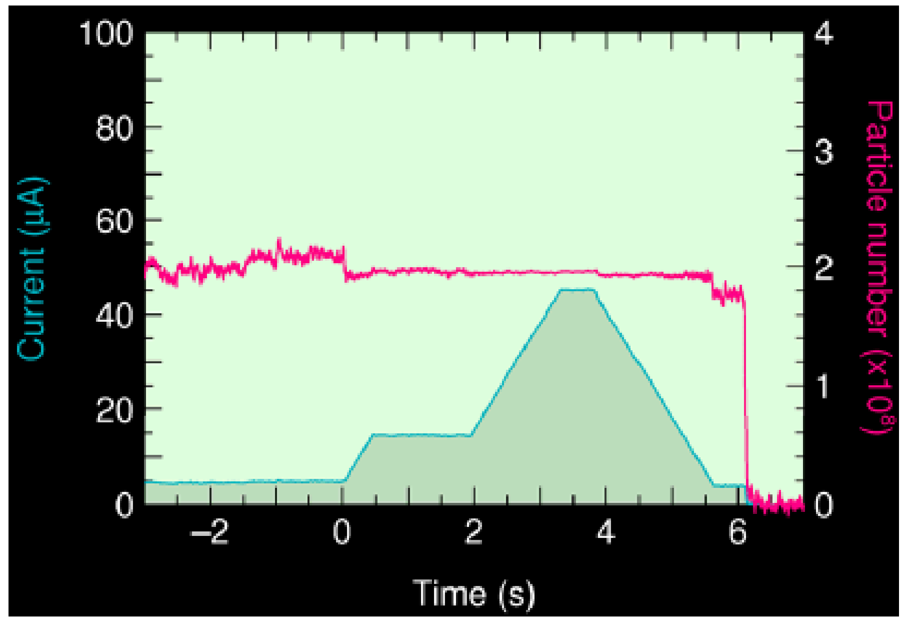
Test: Deceleration of Protons

Injection at 300 keV, cooling at 3 MeV,
acceleration to 30 MeV, deceleration to 300 keV

Energy	Particles
300 keV	2.11×10^8
3 MeV	1.96×10^8
30 MeV	1.96×10^8
300 keV	1.77×10^8

Transmission

Whole cycle:	84%
30 MeV - 300 keV:	90%



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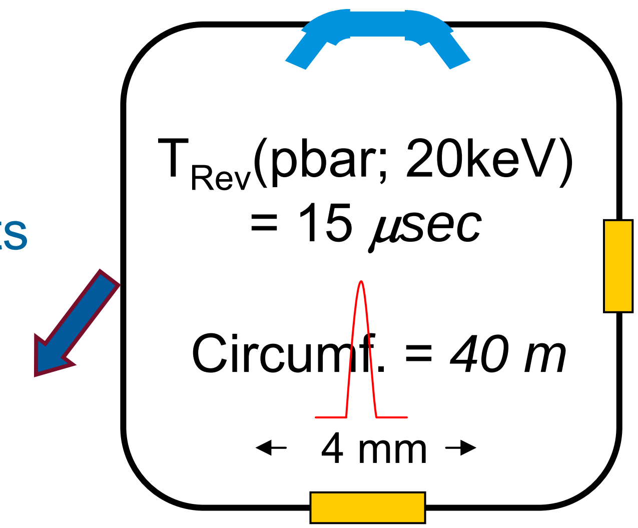
USR - Goals

- Variable to lowest energies
  - 300 keV ~ 20 keV
- High luminosity for in-ring experiments
- Well-defined extracted beams:
  - Small emittance
  - Small momentum spread
- Multi-user operation:
  - 2 straight sections for in-ring experiments
  - Slow and fast extraction
  - Additional beam lines possible
- Central requirements
  - Δt ~ 500 nsec for Injection in traps
  - Δt ~ 2 nsec / 10^4 ions for collision studies



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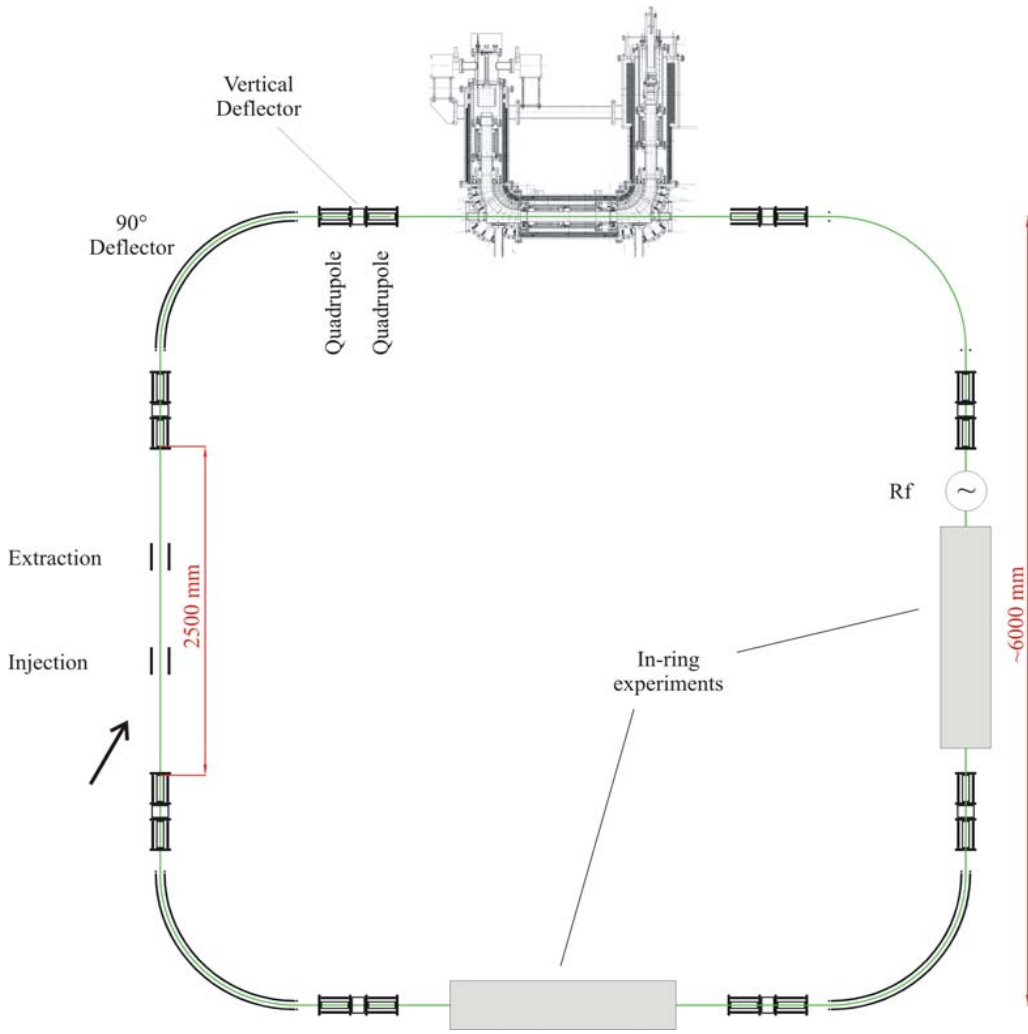
USR: First Design in 2005



Welsch, C.P., et al.
Nucl. Instrum. Methods A **546**
405–417 (2005)

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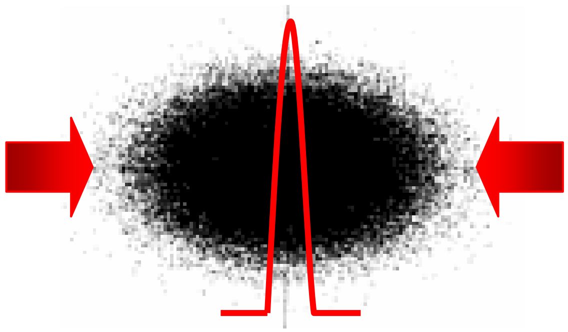
USR – Ring Re-Design 2009



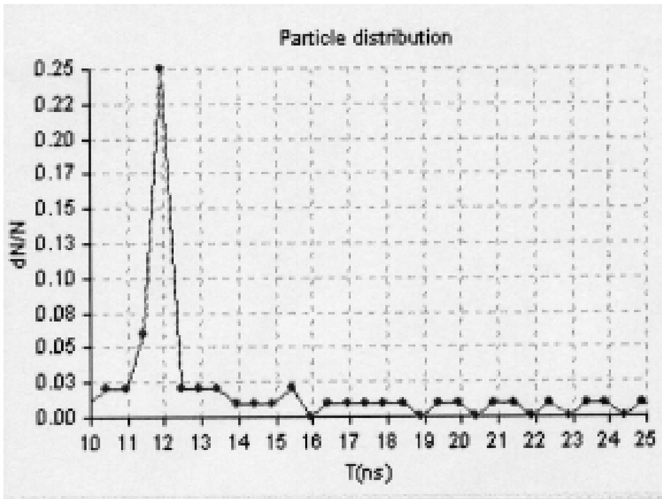
ns Bunching

How to realize nanosecond bunches ?

How to do beam extraction ?

<u>Steps</u>:

- General feasibility
- 1-D simulation
- Full study



A. Papash, C.P. Welsch, Part Phys. Nucl. Letters **3** (2009)

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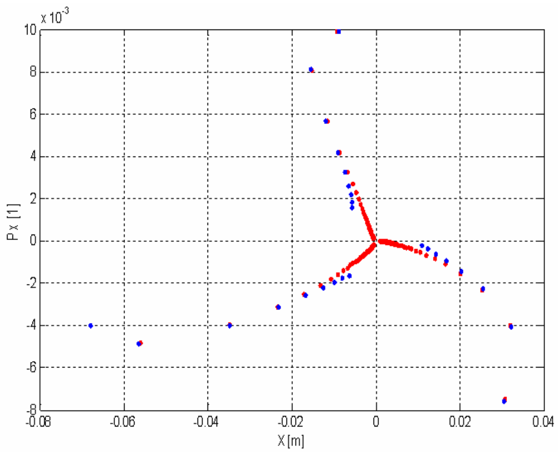
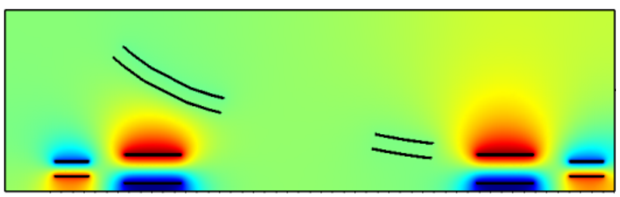
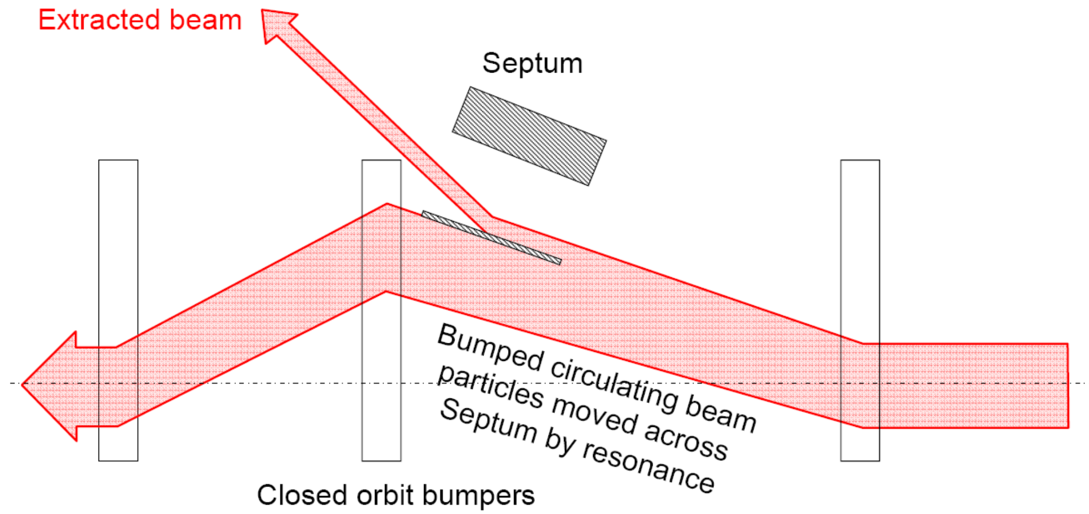
USR - slow/fast Extraction





Highly-flexible Beam Extraction



Motivation: Nuclear physics-type experiments.

➡ First time in electrostatic ring !

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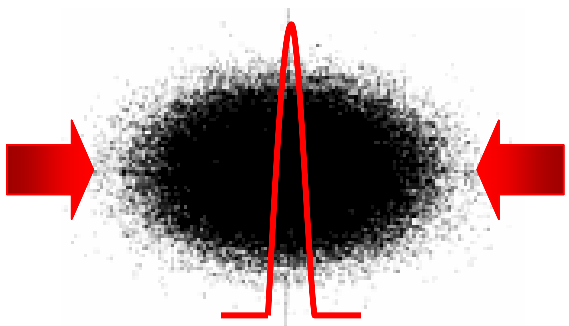
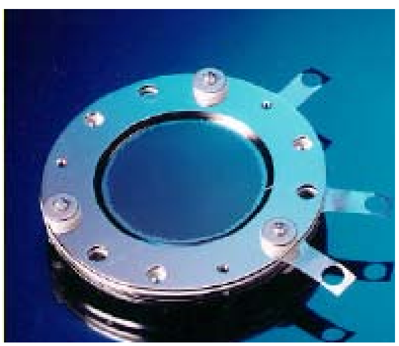
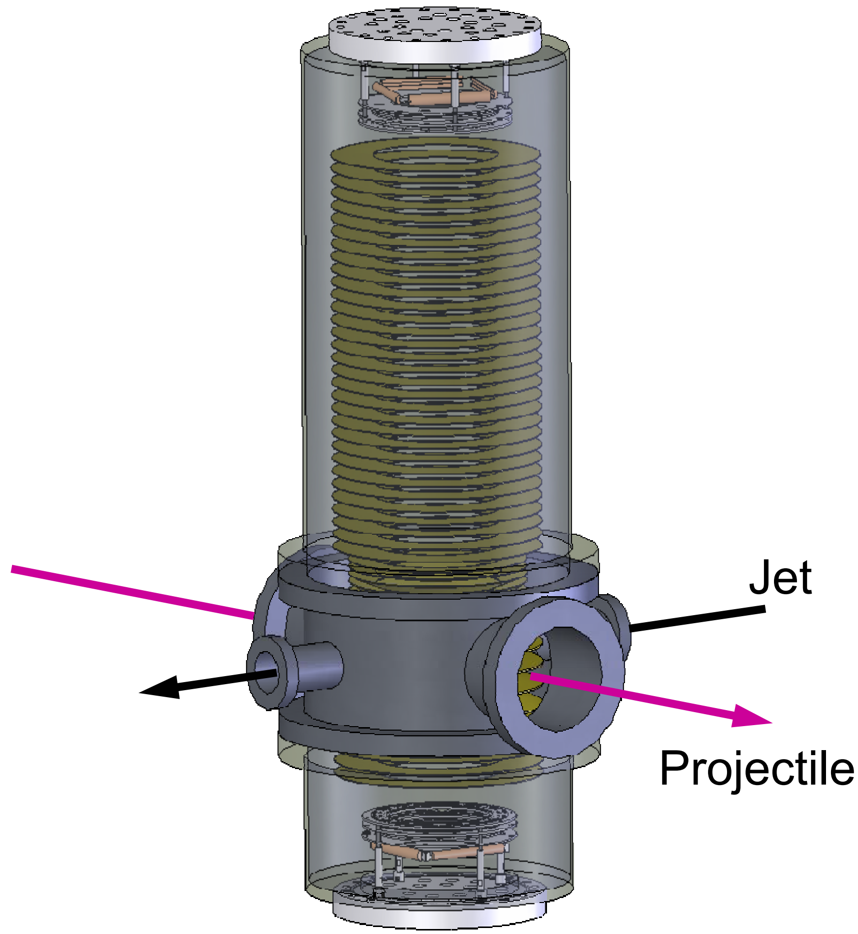
QUASAR Group Activities



ns Bunching



Diagnostics



In-ring Reaction Microscope

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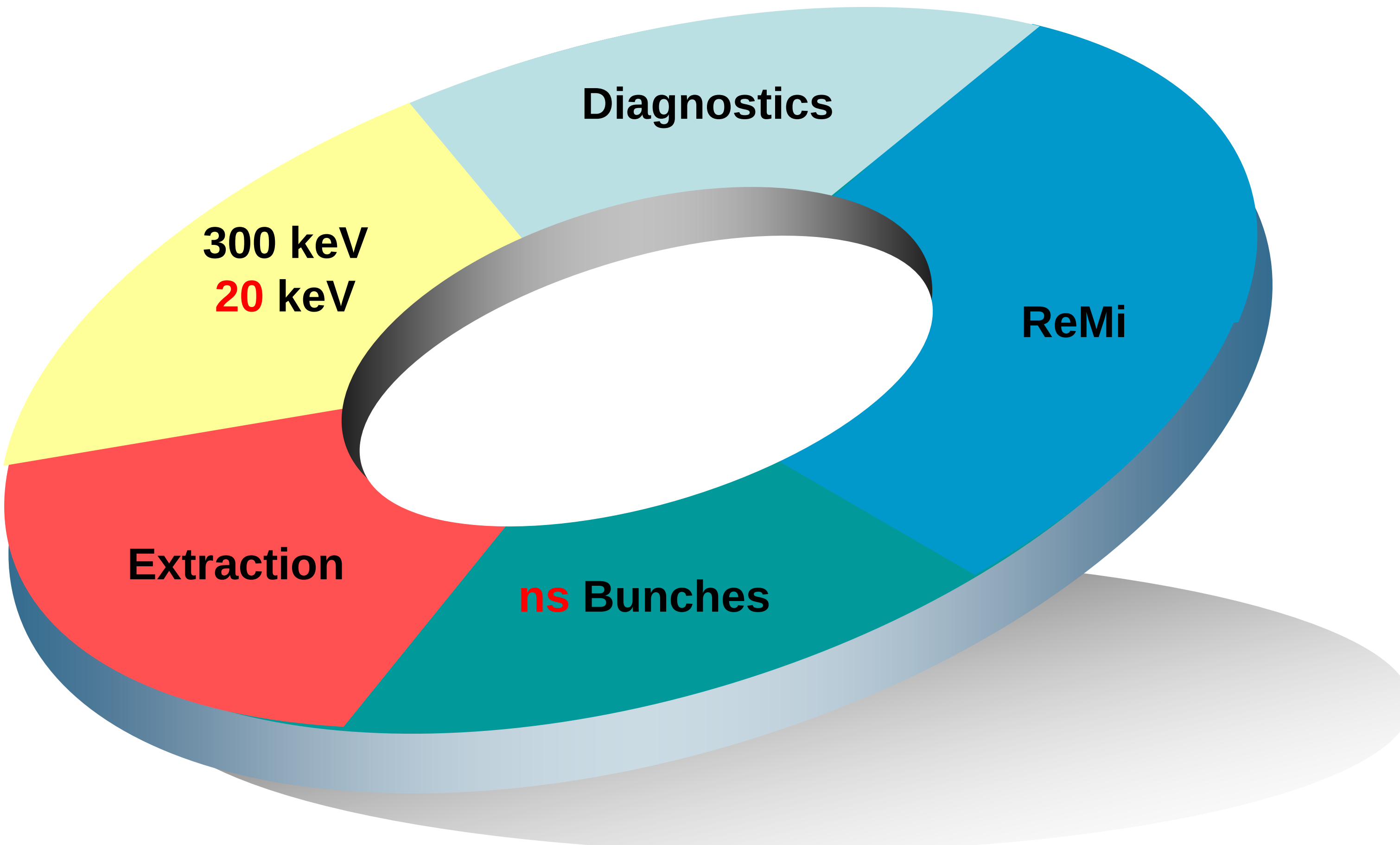
USR - Challenges



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Conclusion

- *"Cooled antiprotons in the 20 keV range will revolutionize low-energy antiproton physics."*
- DC beams enable nuclear and particle physics type experiments *(not possible at AD)*
- Availability of radioactive ion beams (RIB) offers new synergies *(beamline required !)*

Now: Beam diagnostics for FLAIR !

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More Information

http://www.oeaw.ac.at/smi/flair

LEAP

16.-19.9.2008, Vienna, Austria

http://www.msl.se

http://www.quasar-group.org

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