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The main goal of the AEgIS experiment at CERN is to test the weak equivalence principle for antimatter. We will measure the Earth's gravitational acceleration g with antihydrogen atoms being launched in a horizontal vacuum tube and traversing a moiré deflectometer. We intend to use a position sensitive device made of nuclear emulsions (combined with a time-of-flight detector such as silicon μ−strips) to

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measure precisely their annihilation points at the end of the tube. The goal is to determine g with a 1% relative accuracy. In 2012 we tested emulsion films in vacuum and at room temperature with low energy antiprotons from the CERN antiproton decelerator. First results on the expected performance for AEgIS are presented.

1. The AEgIS experiment

The main goal of the AEgIS experiment (CERN/AD6) is to test the weak equivalence principle (WEP) using antihydrogen ($\overline{H}$). This principle of the universality of free fall has been tested with tremendous precision for matter, but not with antimatter particles, due to major technical difficulties related to stray electric and magnetic fields. In contrast, the electrically neutral $\overline{H}$ atom is an ideal probe to test the WEP and the antiproton decelerator at CERN is a worldwide unique antihydrogen factory. In AEgIS the gravitational deflection of $\overline{H}$ atoms launched horizontally and traversing a moiré deflectometer will be measured with a precision of 1% on $|\Delta g|/g$, using a position sensitive annihilation detector [1]. The required position resolution should be a few μm to achieve the 1% goal.

As we discuss in this paper, the antihydrogen annihilation point can be determined in a novel application of emulsion films [2] using the techniques applied to the OPERA experiment [3]. This is the first time that nuclear emulsions will be used in vacuum. The vertical precision on the measured annihilation point will be about 1 μm, an order of magnitude better than proposed originally with silicon μ−strip detectors [1]. Fig. 1 shows the principle of the experiment and the estimated number of annihilations needed to reach a given precision on $\overline{g}$, as a function of position resolution.

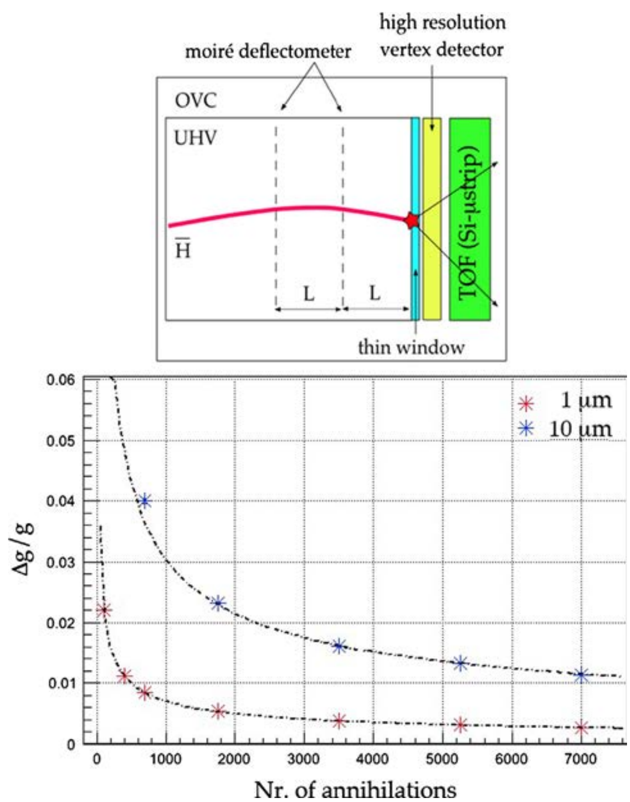

Fig. 1. Top: Schematics of the AEgIS detectors. The vertex detector is made of nuclear emulsions. The time-of-flight detector (TOF) is needed to measure the velocities of the $\overline{H}$ atoms. The thin window limits the position resolution (due to multiple scattering), but is needed to separate the ultra-high vacuum (UHV) part from the outer vacuum region (OVC) containing the emulsion films. Bottom: $\Delta g/g$ vs. number of particles for a vertex resolution of 1 μm (red) and 10 μm (blue). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

2. Nuclear emulsions

Nuclear emulsions [4] are photographic films with extremely high spatial resolution, better than 1 μm. A track produced by a charged particle is detected as a sequence of silver grains (Fig. 2), where about 36Ag grains per 100 μm are created by a minimum ionizing particle. The intrinsic spatial resolution is about 50 nm. In recent experiments such as OPERA [3], large area nuclear emulsions were used thanks to the impressive developments in automated scanning systems.

For AEgIS, we developed nuclear emulsions which can be used in ordinary vacuum (OVC, 10^{-5}–10^{-7} mbar). This opens new applications in antimatter physics research. We performed exposures with stopping antiprotons in June and December 2012. A sketch of the experimental setup is shown in Fig. 3. The emulsion detector consisted of five sandwiches made of emulsion films deposited on both sides of (200 μm thick) plastic substrates ($68 \times 68 \times 0.3$ mm^3).

A thin foil will be needed in the gravity measurement as a window to separate the $\overline{H}$ beam line at UHV pressure from the

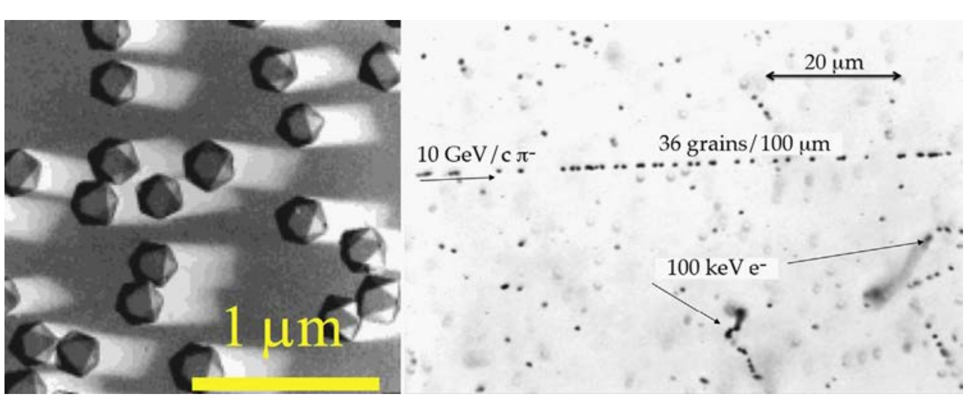

Fig. 2. Left: AgBr crystals in emulsion layers observed with a scanning microscope. Right: A minimum ionizing track from a 10 GeV/c pion.

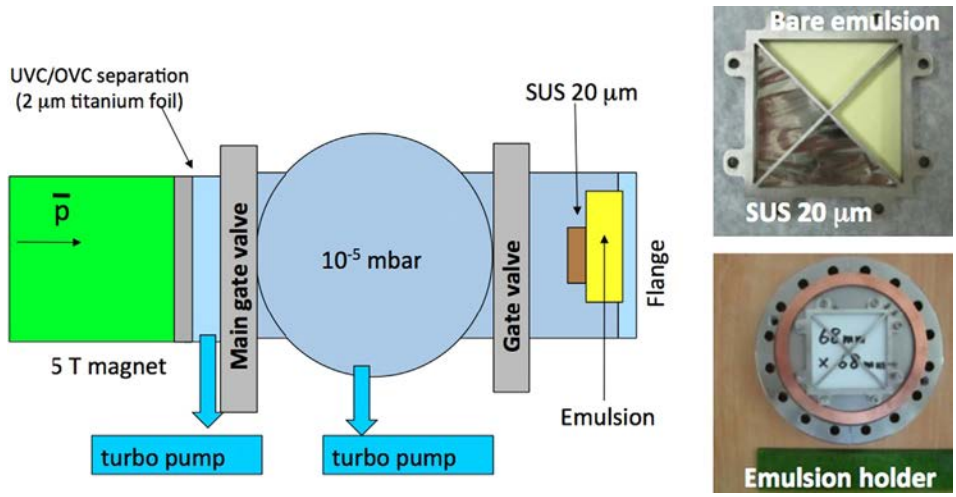

Fig. 3. Left: Experimental setup. Right: Picture of the vacuum flange holding the emulsion stack attached by a crossed bar frame.

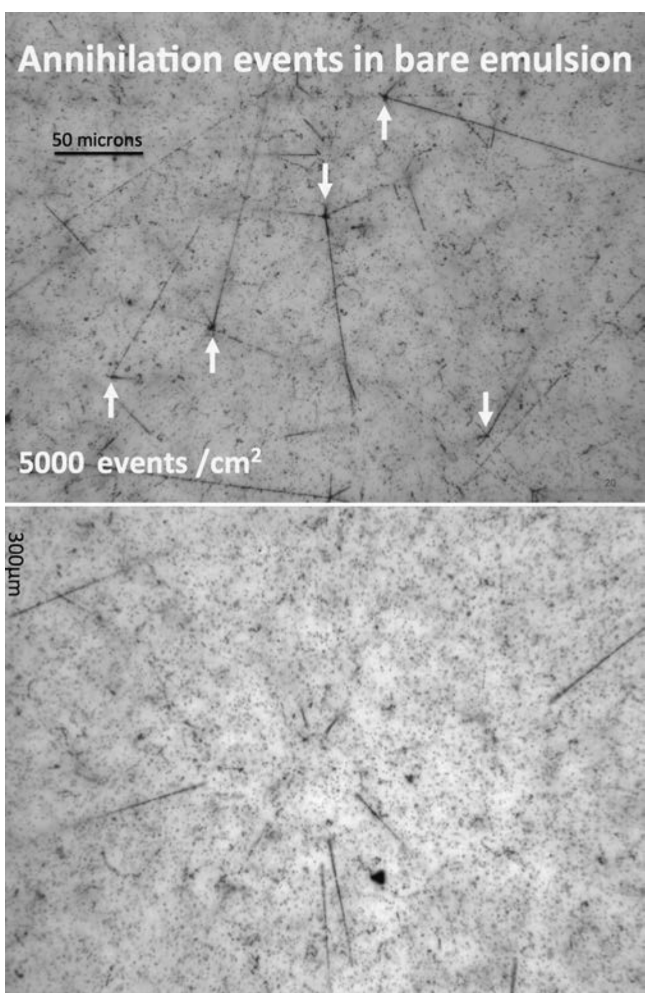

Fig. 4. Top: Typical antiproton annihilation vertices in the bare emulsion. Bottom: Tracks observed behind a thin silver foil in which the antiprotons annihilate.

OVC section containing the emulsion detector. Thus for the tests half of the emulsion surface was covered by a 20 μm (SUS) stainless steel foil, while direct annihilation on the emulsion surface could be investigated from the other half.

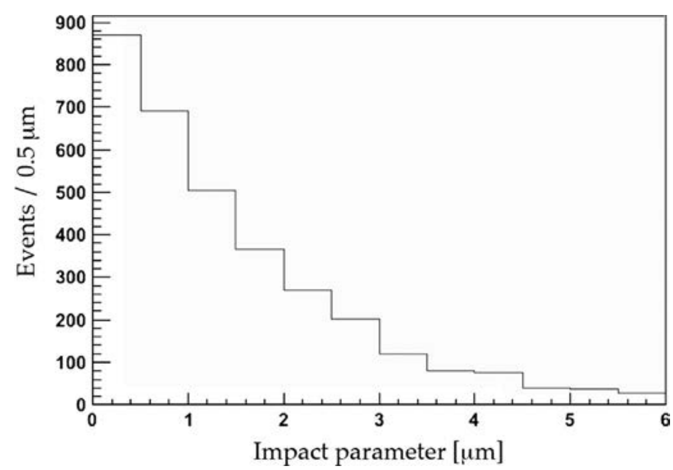

Fig. 5. Impact parameter resolution with a 20 μm stainless steel window.

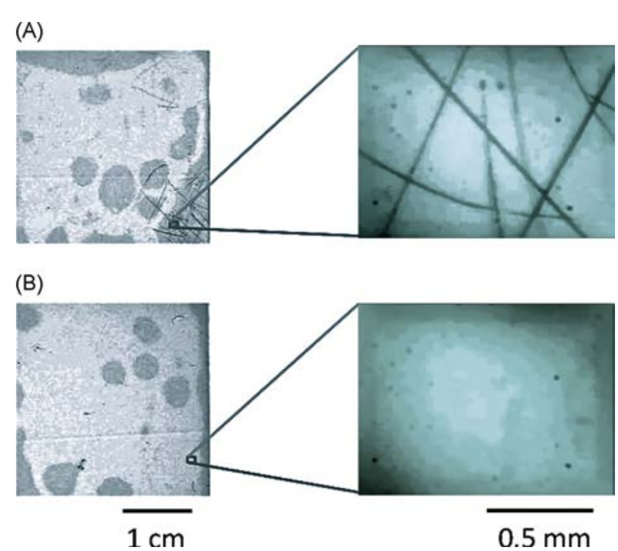

Fig. 6. Emulsion films kept during 3.5 days in vacuum show cracks (A) which can be avoided by treating the films with glycerine before exposure (B).

The 3D tracking and annihilation vertex reconstructions were performed at the University of Bern using the automatic scanning facility developed for OPERA [5]. Annihilation stars were observed

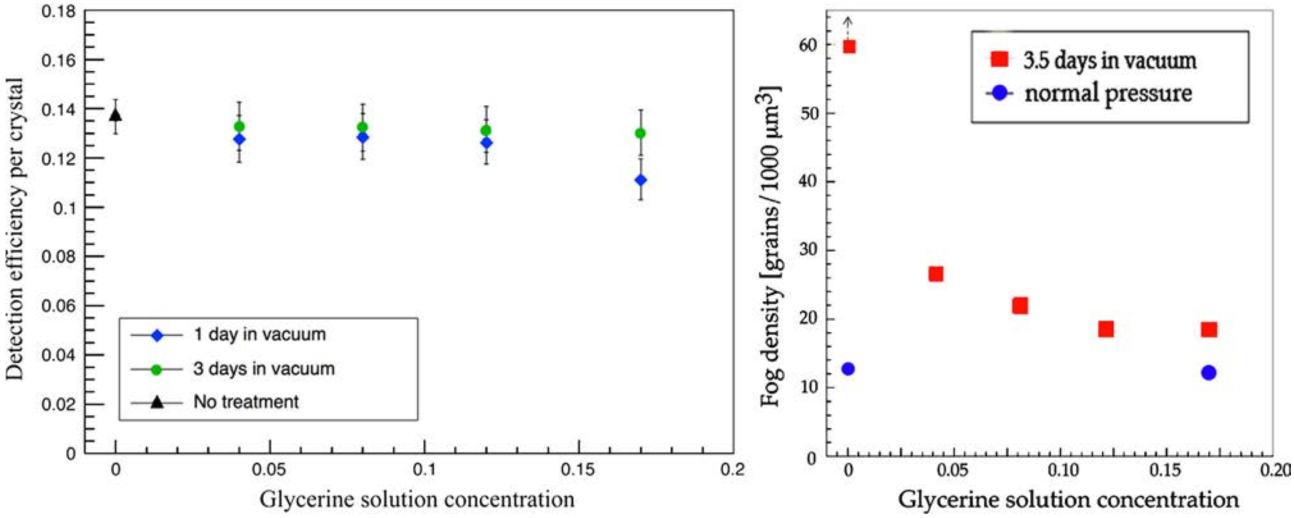

Fig. 7. Left: Crystal sensitivity vs. glycerine concentration. Right: Fog density (number of noise grains per 10^3 μm^3) vs. glycerine concentration for films kept in vacuum for 3.5 days (squares), compared films kept at atmospheric pressure (dots).

Table 1
Comparison between the reference films (OPERA) and the new emulsions from Nagoya University.

Gel type	Development time (min)	Grain density (grains/100 μm)	Fog density (grains/μm^3)
OPERA	25	30.3 ± 1.6	10.1 ± 0.7
Nagoya 1	20	47.7 ± 2.0	1.9 ± 0.2
Nagoya 2	25	55.1 ± 2.6	3.0 ± 0.3

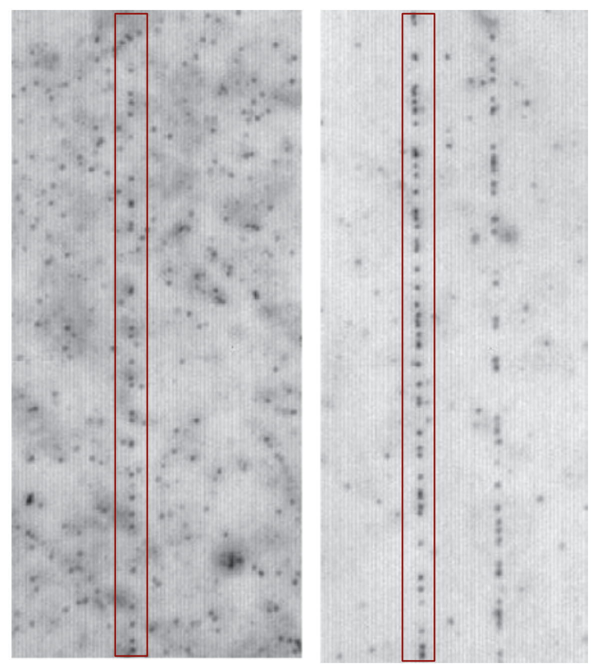

Fig. 8. A 10 GeV/c pion track in the reference film (OPERA, left) and in a highly sensitive one (right).

in the bare region not covered by the steel foil. A typical antiproton annihilation vertex in the emulsion layer is shown in Fig. 4 (top).

In December 2012 we also carried out measurements with a series of thin foils of varying compositions (Al, Si, Ti, Cu, Ag, Au, Pb) to determine the relative contributions from protons, nuclear fragments and pions as a function of atomic number. Fig. 4 (bottom) shows for instance the scanning of a 0.3×0.3 mm^2 surface of a 5 μm thick silver foil. Tracks emerging from the annihilation vertex are clearly observed. The emulsions were exposed for up to several hours, leading to vertex densities of typically 0.5 vertices per mm^2. Note that the maximum track density that can easily be dealt with by the scanning facility is around 10^3 tracks per mm^2, so that emulsions could be placed in the final apparatus for several days before being replaced.

Tracks from nuclear fragments, protons, and pions were reconstructed and the distance of closest approach between pairs of tracks was calculated. Fig. 5 shows the distribution of the distance of closest approach projected into the vertical direction (impact parameter), which is a measure of the resolution with which the annihilation point will be determined in the gravity measurement. The figure shows that with *e.g.* a 20 μm steel window a resolution of ≃1 μm on the vertical position of the annihilation vertex can be achieved.

3. Development of emulsions for AEgIS

We have tested the properties of nuclear emulsions in vacuum [2] which to our knowledge had not been studied before. Water loss in the gelatine which surrounds the AgBr crystals can produce cracks in the emulsion layer, thus compromising the mechanical stability (required at the μm level). We therefore developed a

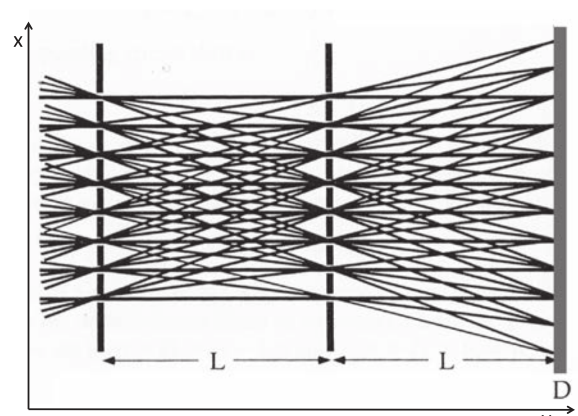

Fig. 9. Principle of moiré deflectometer.

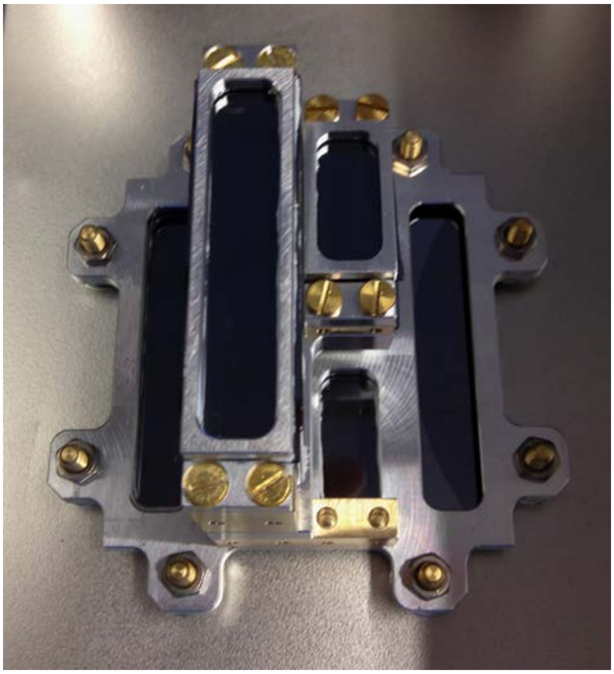

Fig. 10. Photograph of miniature moiré deflectometer.

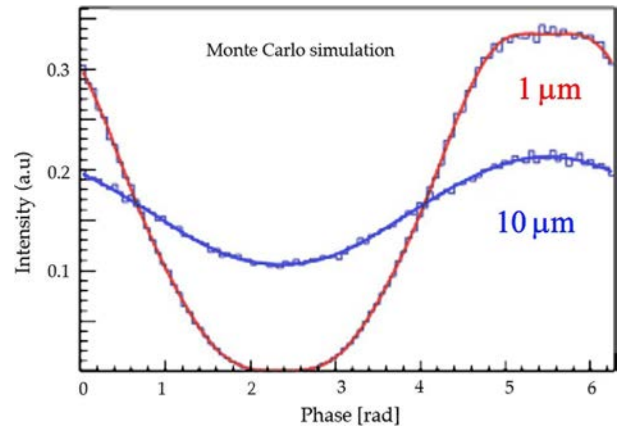

Fig. 11. Simulated intensity distribution of reconstructed vertices with position resolutions of 1 μm (red) and 10 μm (blue). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

treatment with glycerine which can efficiently prevent the elasticity loss in the emulsion (see Fig. 6). However, glycerine treatment changes the composition of the emulsion layer and we therefore had to determine the detection efficiency per AgBr crystal. This was performed with minimum ionizing pions in a 6 GeV/c CERN beam. The result (Fig. 7) does not indicate any changes in the efficiency, which is typically 13% for glycerine concentrations below 20%. However, the thermally induced background – the so-called fog density – increases for glycerine treated emulsions.

Annihilation products from annihilating antiprotons (or $\overline{H}$ atoms) are emitted isotropically, in contrast to the $\tau-$decay products measured in the OPERA experiment, which are forward boosted. The efficiency of our automatic scanning system therefore needs to be improved for tracks traversing the emulsion layers at large incident angles. We are also investigating new emulsion gels with higher sensitivity to increase the detection efficiency for minimum ionizing particles. They were developed at Nagoya University (Japan) and coated onto glass substrates in Bern. Glass is well suited for highest position resolutions thanks to its superior environmental stability (temperature and humidity), as compared to plastic. A comparison between the OPERA films and the new Nagoya gels is shown in Table 1, while Fig. 8 compares minimum ionizing pion tracks between the two types of gel. The Nagoya 2 gel is roughly twice as sensitive as the OPERA one and shows a much lower fog density.

4. Proof of principle using a miniature moiré deflectometer

In AEgIS [1] the Rydberg excited $\overline{H}$ atoms will be accelerated by an electric field before traversing the deflectometer [6] consisting of two identical gratings separated by a distance L of typically 40 cm (Fig. 9). The annihilation intensity will be measured along the vertical direction x with emulsions located at the same distance L from the second grating. The displacement Δx of the moiré intensity pattern due to gravity will be measured. The $\overline{H}$ beam is not monochromatic and therefore Δx depends on the time of flight of the $\overline{H}$ atoms through the relation $\Delta x = \overline{g}T^2$, where T is the time of flight between the two gratings. The start of TOF is given by the switch off time of the electric field for Stark acceleration and the stop by the $\overline{H}$ annihilation time measured by the silicon $\mu-$strips (see Fig. 1) that associate a time of flight to each annihilation vertex.

A proof of principle was performed in December 2012 with emulsion films irradiated with antiprotons passing through a small moiré deflectometer. A photograph of the deflectometer is shown in Fig. 10. The device contained several pairs of gratings with different spacings, as well as gratings in direct contact with the films. The simulation in Fig. 11 shows as an example the expected interference pattern at the emulsion layer, generated by a pair of gratings (12 μm slit, 40 μm pitch, separated by $L = 25$ mm). The antiproton data is being analyzed and preliminary results are quite encouraging.

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