Antiproton Interferometry and the Aharonov-Bohm effect

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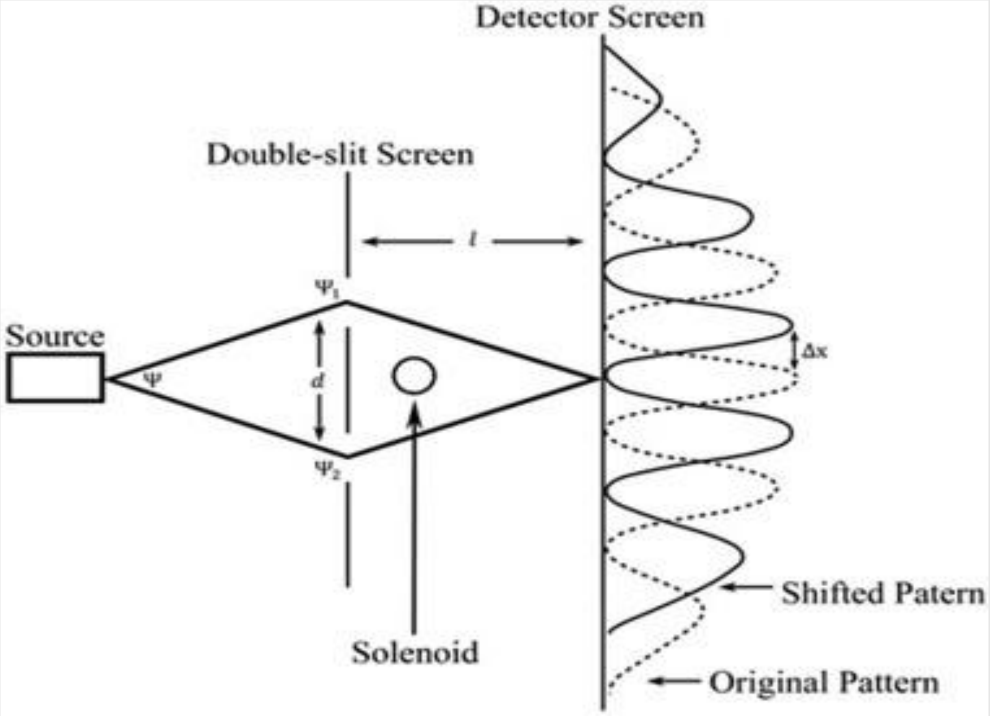
1 Antiproton Interferometry

2 Aharonov-Bohm (AB) effect
for the Antiproton

Slow Antiproton beam @ASACUSA



Interference with Antiprotons

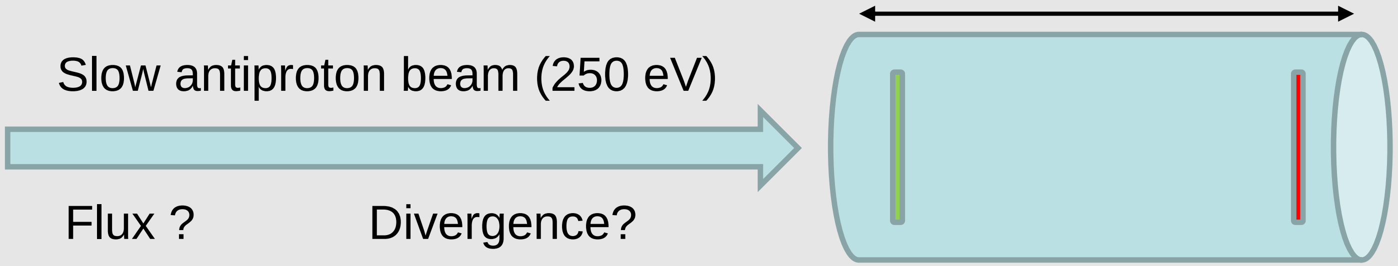
- Why?
- As a preparation step for AB

Direct tests of wave-like nature of particles

- C.J. Davisson, L.H. Germer, *Proc. Natl. Acad. Sci. 14 (1928) 317*. → Electron
- G.P. Thomson, A. Reid, *Nature 119 (1927) 890*. → Electron
- A.V. Overhauser, R. Colella, *Phys. Rev. Lett. 33 (1974) 1237*. → Neutron
- P.G. Merli, G.G. Missiroli, G. Pozzi, *Am. J. Phys. 44 (1976) 306.* → Electron — Single Particle
- I.J. Rosberg, A.H. Weiss, K.F. Canter, *Phys. Rev. Lett. 44 (1980) 1139*. → Positron
- A. Zeilinger, R. Gaehler, C.G. Shull, W. Treimer, W. Mampe, *Rev. Mod. Phys. 60 (1988) 106*. → Neutron — Single Particle
- J.F. Clauser, S. Li, *Phys. Rev. A 49 (1994) R2213*. → Potassium
- M. Arndt, O. Nairz, J. Vos-Andreae, C. Keller, G. van der Zouw, A. Zeilinger *Nature 401 (1999) 680*. → C-60 Fullerene — Single Particle
- S. Sala, A. Ariga, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, C. Pistillo, P. Scampoli, *Science Adv. 5 (2019) eaav7610*. → Positron — Single Particle

1 Interference with Antiprotons

Never directly observed up to now, see S.R. Mueller et al., New Jou. Phys. 22 (2020) 073060

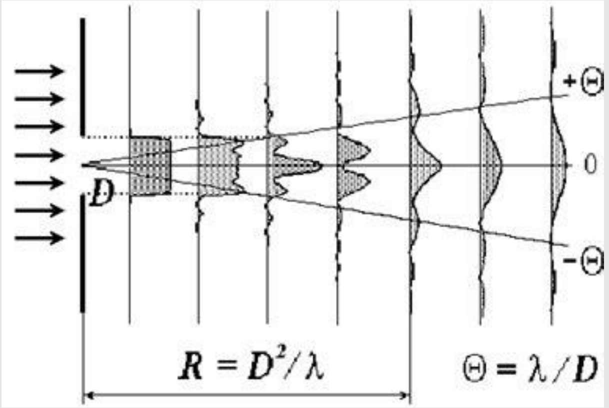


To use the same technique as in QUPLAS (Talbot-Lau) one would need 5 eV antiprotons

Problems

- Efficiency at very low energy
- Beam flux (divergence)
- Magfield deflection because of low p

Possibilities with nominal beam



d = 200, R = d^2/λ = 2 cm

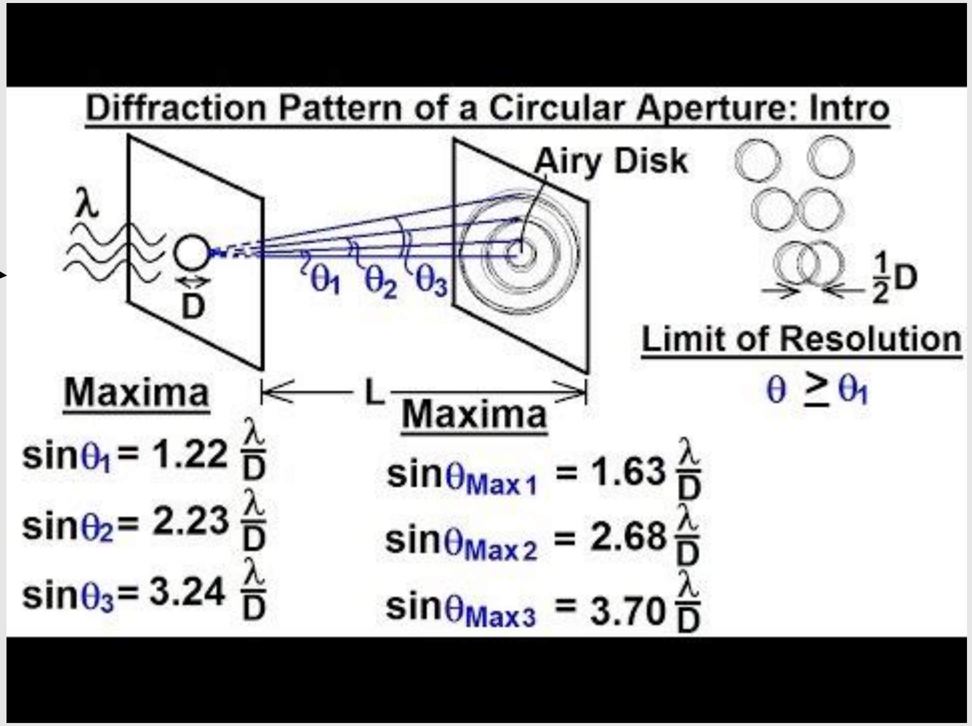
T = 250 eV → λ = 2 pm

Available de Broglie wavelength

Can be built by UNIMORE collaborators

d = 200 nm
$\theta = \lambda/d$ = 10 µrad → $\Delta = L\theta$ = (0.5 m) 10^{-5} = 5 µm

1) Just diffraction from a circular aperture (resolution needed already available)

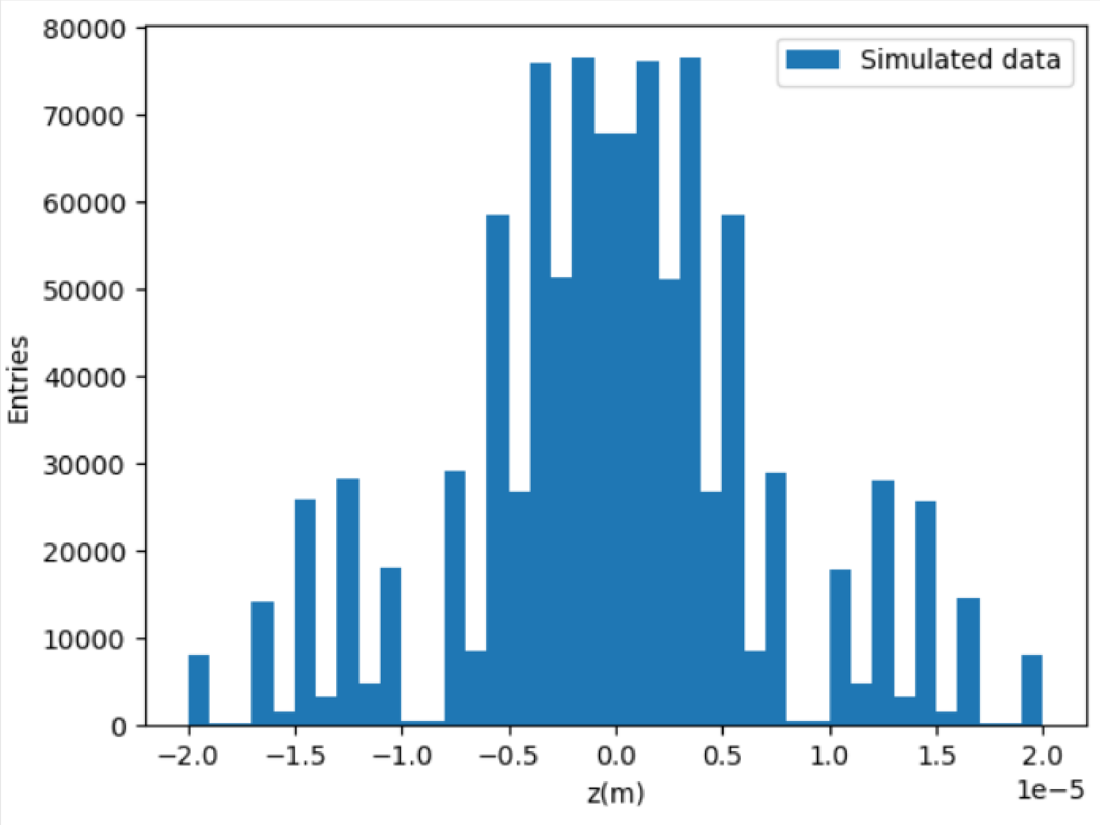


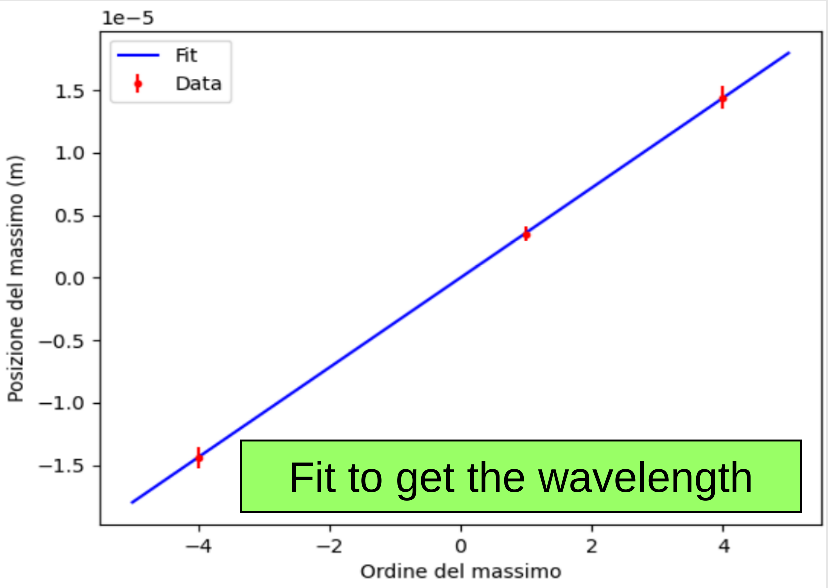
2) Double-slit Young style?

Similar to what was done for neutrons:
- A. Zeilinger et al, Rev. Mod. Phys. 60 (1988) 1067
- R. Gaeler et al., Am. J. Phys. 59 (1991) 316

A Grating configuration

N = 1000 slits
Slit = 200 nm
Interslit = 1 μm



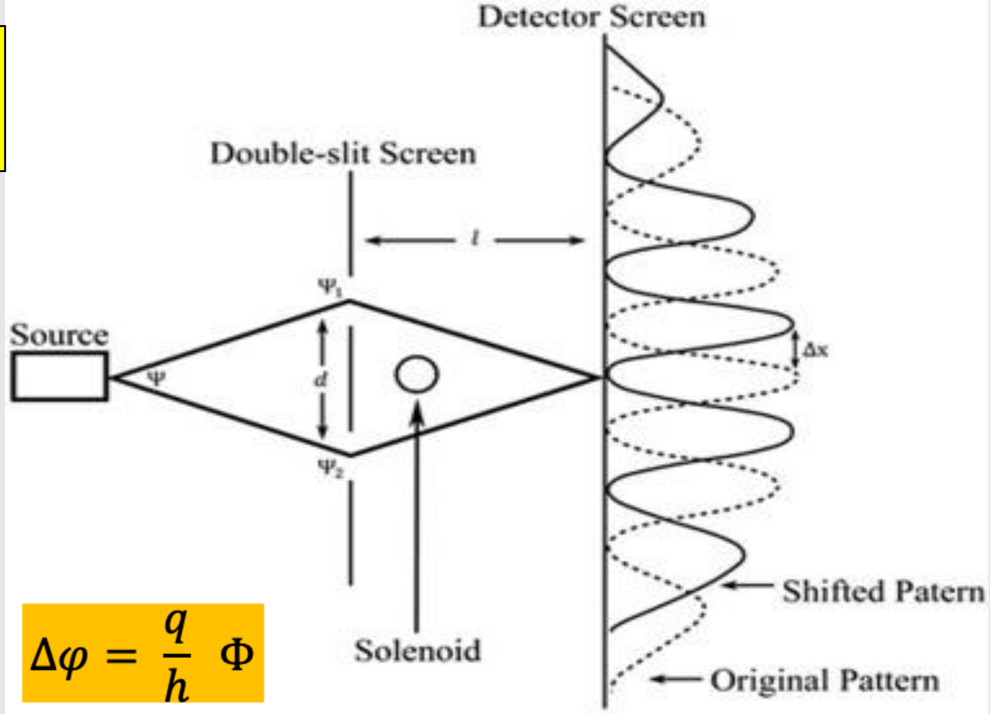


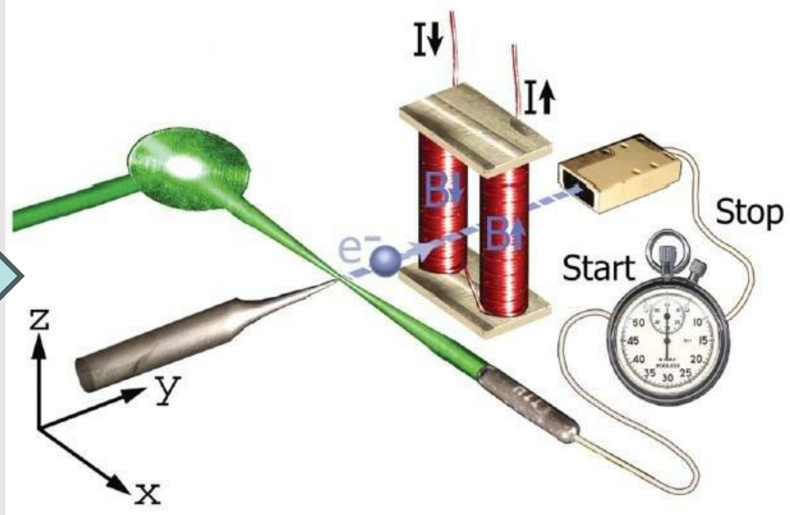
Expected Pattern for a total of 10^6 antiprotons collected
1 micron resolution of the detector embedded

- Energy spread
- Beam divergence
- Magfield effects

2 The AB Effect with Antiprotons

- 1949 Ehrenberg and Siday hinted at the possibility that the electromagnetic potentials can produce observable effects in the «electron refractive index»
- 1959 Aharonov and Bohm gave a more complete explanation (distinguishing electric and magnetic effects). Title: Significance of Electromagnetic Potentials in the Quantum Theory
- 1984 Berry introducing the general concept of topological phase in Quantum Systems
- 1986 Demonstration of magnetic AB effect with electrons by Tonomura and collaborators
- 2007 Caprez and collaborators demonstrated the absence of magnetic (longitudinal) forces in an AB setup
- 2016 Experimental realization in the form proposed by Ehrenberg and Siday, by Pozzi and collaborators (see figure)





Why antiprotons?

- Time delays in arrival (longitudinal force) ruled out
- Deflection as indicator of «Quantum Force» has been predicted by some models (Shelankov, Keating & Robbins)
- Accurately measure the transverse position on the screen

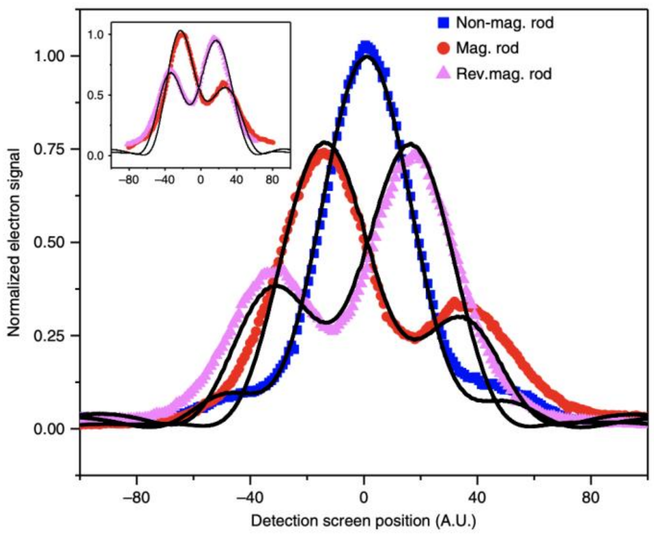


Fig. 7 Symmetry reversal. Electron diffraction patterns are detected in the far-field at 300 keV for an aperture that holds a nanorod (same rod as in Fig. 6). Three diffraction patterns corresponding to measured phase steps of 1.32 π, 0.58 π, and 0 were recorded. The temperature of the magnetized rod was increased to reach these phase steps. The inset gives magnetization reversal by an external magnetic field

- Never done with any other particle than the electron
- Never done with an antiparticle (positron in QUPLAS?)
- Never done with a hadron (CVC test, electric charge)
- Some LR asymmetry seen in Nat. Comm. 10 (2019) 700.

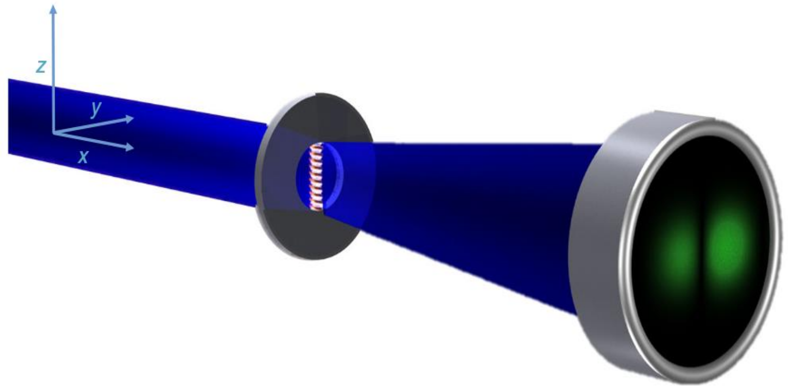
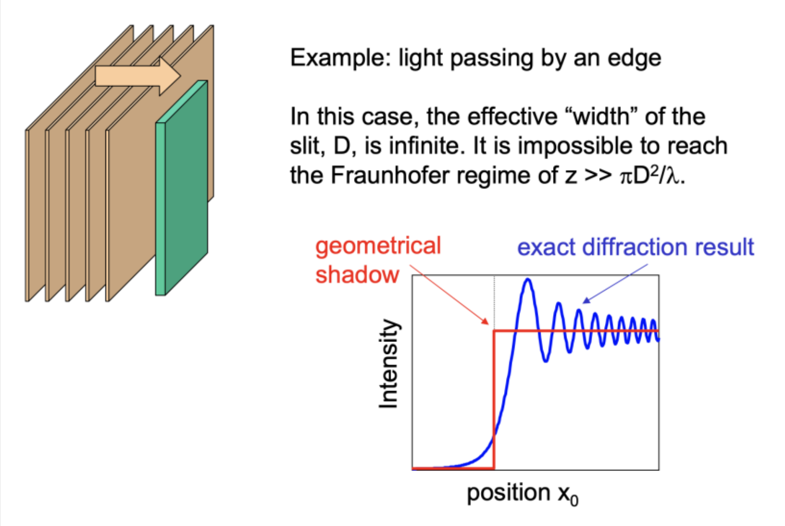


Fig. 1 Physical system schematic. An electron beam (blue) diffracts from an aperture that holds a magnetic flux line, here represented by a solenoid. The solenoid is opaque to the electrons, and the electrons pass through an area where there is no magnetic or electric field, and thus no classical force. The non-zero expectation value of position, represented by a left-right asymmetry in the strength of the detected electrons (green), indicates the presence of a quantum "force" for the Aharonov-Bohm physical system

How AB with antiprotons ?

- Increase the flux by inversion of
- «Infinite» uniform magnetized bar (nanorod)
- Emulsion detector



Thank you for your attention

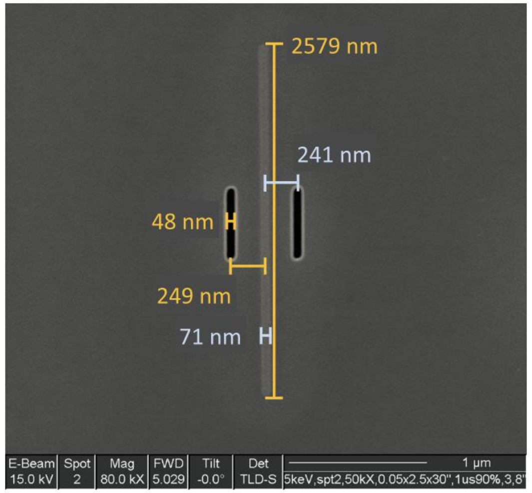
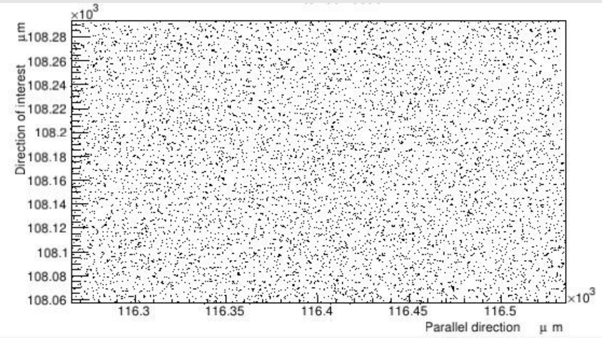
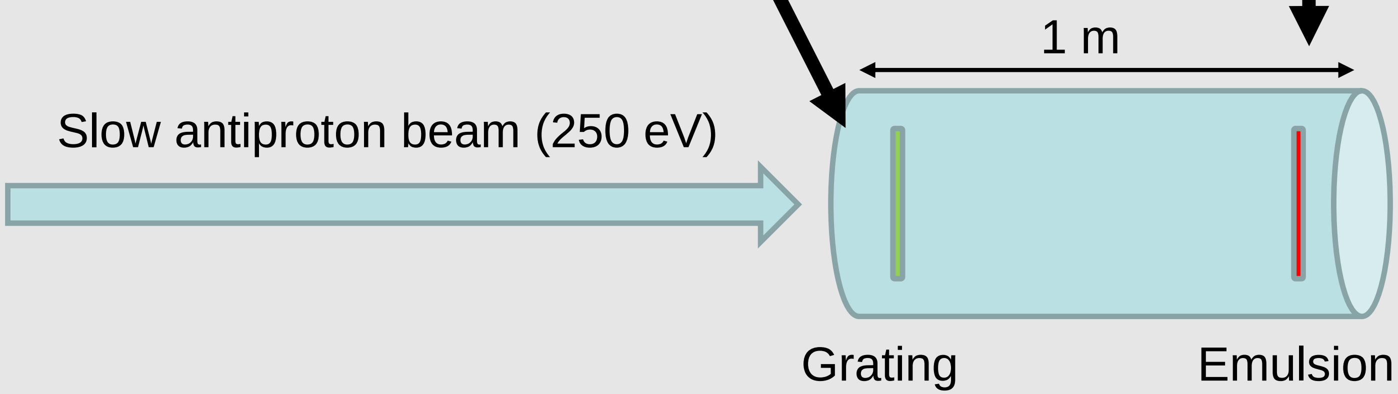


FIG. 4. SEM image of the two slits and Co nanorod. The Co nanorod is the vertical bar in the centre with length 2579 nm. The slits are the dark features on either side of the Co nanorod.





Backup Slides

Open issues

Much lower energy than in Aegis antiproton deflectometry paper (~150 keV):
- Nature Comm. doi:10.1038/ncomms5538

Preliminary test: emulsion exposure to antiprotons

- Response (efficiency)
- Response (is space resolution kept?)

Conclusions

- Very likely it can be done with «modest» effort
- It will be a «little» first time ever!

Measurement of Emulsion efficiency to slow antiprotons
For positrons:

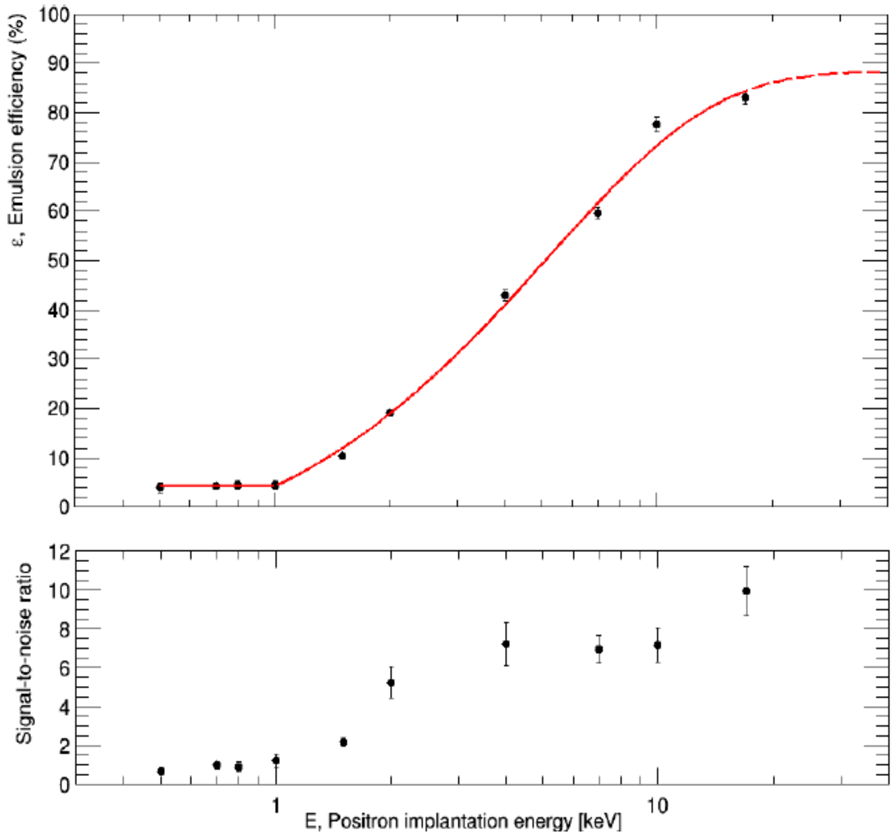


Figure 5. Emulsion detection efficiency (top) and signal to noise ratio (bottom) as a function of the positron implantation energy.

L. Anzi et al. JINST 15 (2020) P03027

Beam at 250 eV

From Angela, Marcus

V = 200 mm/μs

High transmission but
Collimation needed

Other energies possible

Output:

σ_x = 2.45 mm
σ_y = 2.74 mm
Transmission = 97.56 %