Enhancing trappable antiproton populations through an induction unit followed by frictional cooling

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Talk presented by A. Sessler

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Motivation

Particular Motivation

To prepare a paper so Max and I could attend this conference. In the course of thinking about what we should work on we came up with this subject, which – actually -- turns out to be in our opinion rather interesting, and you shall see if you agree..

- **Basic thoughts**
  Increase the anti-proton flux prior to the construction of ELENA.
- That is, a fast, and rather inexpensive way, to proceed during the ELENA construction period.
- Currently, starting with more trapped antiprotons does not necessarily yield more trapped anti-hydrogen atoms, but as theoretical understanding and experimental control of trapping and mixing improve, the option to start with an order of magnitude more antiprotons might be quite useful.

•**Caveats**

The ideas to be presented here are very preliminary.

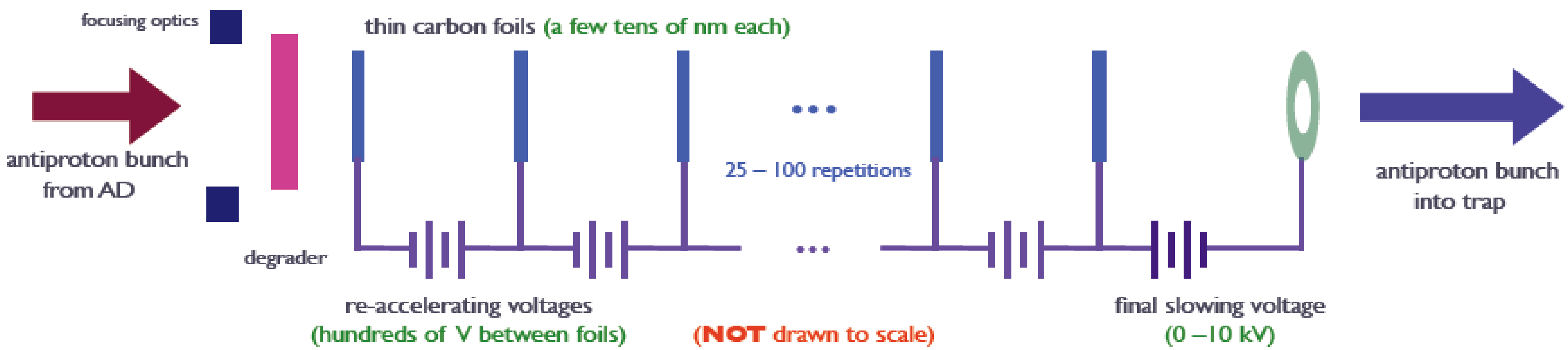
Back-of-the-envelope ***estimates*** and some Monte Carlo ***simulations*** suggest that a reasonably simple and compact design would result in an increased antiproton trapping by about one order-of-magnitude.

Multiple-scattering may be significant, and strong solenoidal fields are probably required.

More detailed simulations will be needed to verify preliminary results and optimize performance.

Overview of the Concept

- a large mismatch exists between the average kinetic energy of antiprotons exiting the AD and the kinetic energy of antiprotons that can be trapped
  - ~5.3 MeV vs. ~3 keV
- to enhance yields, one must first increase the number of antiprotons in the region of phase space that subsequently can be trapped:
  - particles must have sufficiently low kinetic energy
  - and sufficiently low divergence angle (outside solenoid) and/or gyro-radius (inside solenoid)
- at sufficiently low velocities inside matter, antiprotons experience a stopping power due to collisions that is approximately *linear* in the particle velocity
- this "viscous drag"-like damping force can be exploited to try to produce:
  - longitudinal slowing: bringing down the average kinetic energy/longitudinal momentum
  - longitudinal cooling: decreasing the RMS spread in kinetic energy/longitudinal momentum
  - *possibly* transverse cooling: controlling the RMS divergence angle/gyro-radius
- we propose using a series of thin carbon foils separated by re-accelerating electrostatic gradients in order to slow and cool a portion of the antiproton beam after it exits the degrader....



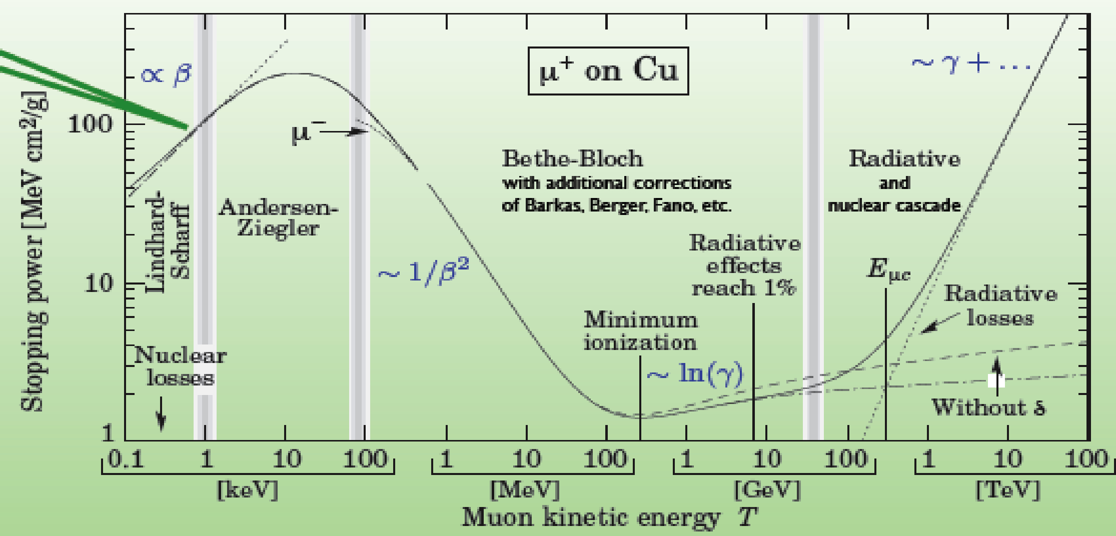
Stopping Power & Frictional Cooling

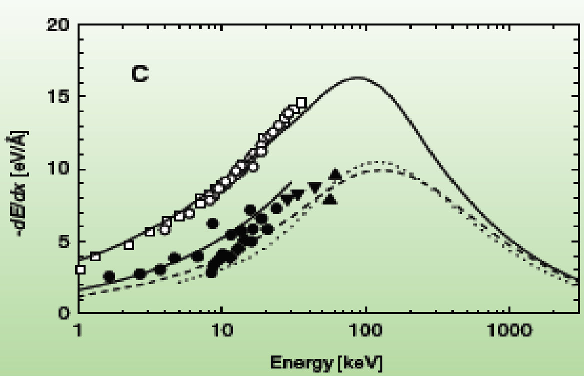
adiabatic "frictional" regime

at particle velocities below bound electronic velocities in atoms and above a low threshold where nuclear recoil losses are important, the **average force** is approximately *proportional to the speed and directed opposite the velocity*, leading to an approximately **linear damping**

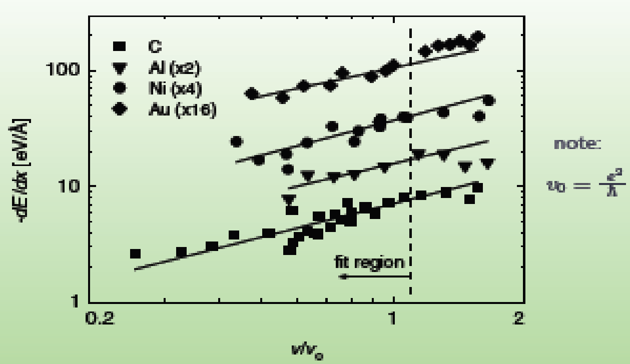
frictional cooling was first discussed in the context of muons, specifically to cool antimuons for various high-precision measurements including anomalous magnetic moments, or the hyperfine structure of muonium

typical $-\left\langle \frac{1}{\rho}\frac{dE}{dx} \right\rangle$ for charge particles in solid matter (from reference [1])





measured low-velocity stopping power in solid carbon for protons (open symbols) and antiprotons (filled symbols)



measured antiproton stopping power normalized to Bohr velocity on log-log plot (both plots fro reference [12])

although the general features of the stopping power curves are similar, the magnitude of the damping forces in a given medium differ for a particle and its anti-particle, due primarily to material polarization (as well as exchange effects)

This **Barkas Effect** was first observed for pions, but is clearly evident for protons and antiprotons...

Comments

- anywhere stopping power is *positive*, collisional energy losses lead to ***slowing*** on average:
- decrease in *average* kinetic energy
- decrease in *average* longitudinal momentum
  (the only component with non-zero average)
- if damping foils are alternated with longitudinal re-accelerating gradients, ***average*** longitudinal momentum of (a suitably low-energy portion) of beam can approach an equilibrium

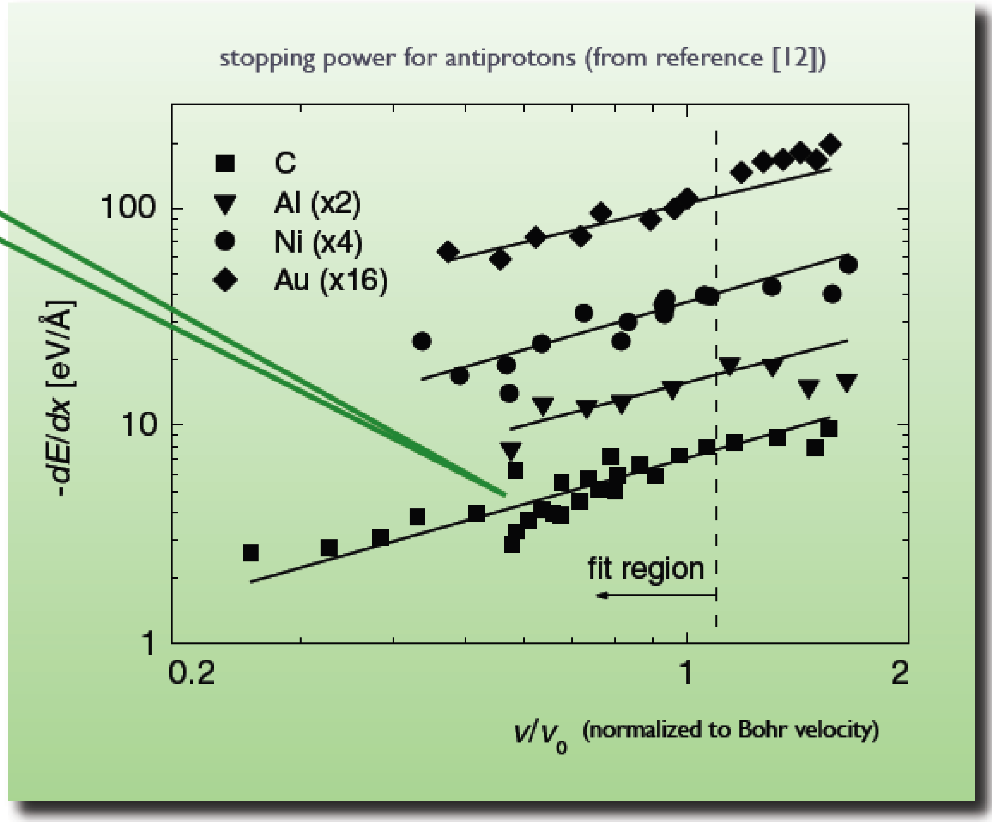
- equilibrium energy/momentum determined by balance of energy gains between foils and losses in foils
- note only particles in some sufficiently low initial energy range will have time to reach equilibrium
  over an energy range where stopping power ***increases monotonically*** with particle kinetic energy, particles can also be cooled longitudinally
- because faster particles experience more slowing
  so ***variance*** in energy or longitudinal momentum may be reduced *for particles within coolable energy range*
- but stochastic nature of collisions leads to unavoidable fluctuations in the number and extent of the individual energy/momentum transfers

Comments (Concl.)

- diffusion necessarily accompanies damping (fluctuation-dissipation theorem)
- leads to ***straggling***, or non-zero ***variance*** in energy changes
- interplay of momentum diffusion, damping, and deceleration determines achievable longitudinal cooling
- since damping forces point on average in direction opposite total momentum, but only longitudinal momentum is restored, particles may be ***cooled transversely*** as well
- in absence of fluctuations, this decreases the RMS divergence angle or (in a solenoidal field) the gyro-radius
- ***but*** *fluctuations* contribute a diffusive ***heating*** term, described by *multiple-scattering rates*
- ***multiple scattering*** between re-accelerations tends to increase heating term without improving cooling term
- some particles may be stopped or back-scattered, and hence ***lost*** from the beam
- ***lower-Z*** materials lead to lower multiple scattering rates — we are focusing on ***carbon***
- coupling between the angular, spatial, and energy drift/diffusion may complicate the Fokker-Planck dynamics
- but it appears that here the energy/angular coupling can be approximated simply
- various other effects may also occur, but are expected to be less important:
- space-charge emittance growth, intra-beam scattering, annihilation....

Antiproton Stopping Power

average stopping power estimated from data for antiprotons in carbon



we use these data to estimate the average stopping power as a function of kinetic energy:

$$\langle -\frac{dE}{dz} \rangle \approx 0.45\sqrt{E} \qquad \left[\frac{\text{eV}}{\text{nm}}\right]$$

where energy E is in eV for kinetic energies less than about 60 keV

Energy Straggling: Fluctuations in Energy Loss

dashed blue line shows predictions based on a semiclassical binary collision model

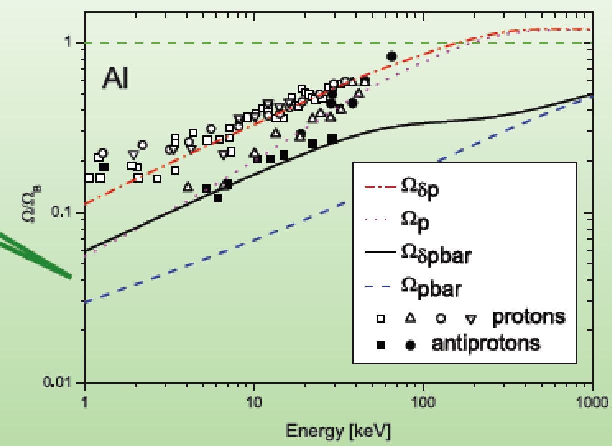
solid black line includes fitted effects of foil inhomogeneities

we use these data to make an estimate for the energy straggling term — on the order of **10% of the Bohr value** at low energies, and scaling linearly with particle speed:

$$\frac{d\Omega^2}{dz} \approx .05\,E \quad \left[\frac{\mathrm{eV}^2}{\mathrm{nm}}\right]$$

(E is in eV)

straggling for protons/antiprotons in aluminum foils (from reference [11])



Measured antiproton (■, 260 Å foil, ● 350 Å) and proton (△ 260 Å, ▽ 260 Å, □ 320 Å, ◯ 320 Å) fluctuation in aluminum, normalized to the Bohr straggling Ω_B.

Ω is the rms energy spread

data for antiprotons *in carbon* have not been reported,
but similar data for Al and Au (not shown) suggest *Z*-dependence is weak....

$\Omega_B^{\,2} = 4\pi\, Z\, e^4\, n\, t$, where Z is the foil atomic number and n is the foil density and t is the foil thickness

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Multiple Scattering and Angular Diffusion

data suggest that at kinetic energies of a few keV to a few tens of keV, the multiple scattering rates for *protons* are about **one order-of-magnitude lower** than the level suggested by the commonly-used Molière analytic estimate

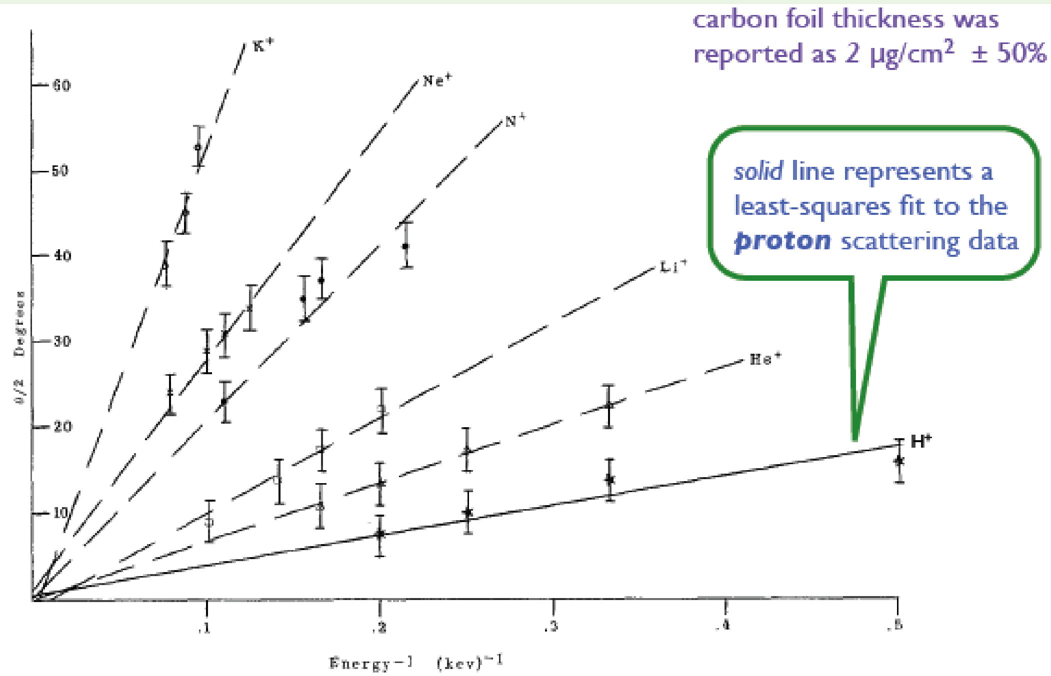
Barkas Effect suggests that *antiprotons* might suffer ***even less*** angular diffusion from multiple scattering, but the magnitude of the Barkas effect is uncertain....

multiple scatter estimated as: $\frac{d\sigma_\theta^2}{dz} \approx \kappa \frac{2.3 \cdot 10^5}{E^2} \left[\frac{\text{rad}^2}{\text{nm}}\right]$

for some $\kappa \leq 1$

from the graph, we estimate $\kappa \approx .04$ for protons in carbon

angular divergence vs. inverse incident energy for ions in thin carbon foils (reference [3])



Dependence of the angular width of the scattered distribution on the reciprocal of the incident ion energy. The lines shown are a least squares fit to the experimental data. The solid line is drawn through the hydrogen data points.

data for *antiprotons* in carbon have not been reported to our knowledge....

Although scattering is expected to be *weaker* for *antiprotons* than *protons*, in absence of theoretical model or experimental data, we **conservatively** use values in the range $0.10 \leq \kappa \leq 1.0$

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Simple model

Homogeneous media with homogeneous electric field to compensate average energy losses, in the low-energy limit where the energy loss dE_{fr}/dx is proportional to $E^{1/2}$ (i.e., velocity).

$$\frac{d\,\sigma^2}{d\,x} = -\frac{dE_{fr}}{E_{eq}\,dx}\,\sigma^2 + \frac{d\,\Omega_s{}^2}{E_{eq}{}^2\,dx} + \frac{1}{4}\left(\frac{dE_{fr}}{E_{eq}\,dx}\right)^{-1}\left(\frac{d\sigma_\theta{}^2}{d\,x}\right)^2$$

Cooling

Straggling heating

Scattering heating

Here, σ is the relative energy spread, E_{eq} is the energy where losses equal the energy gain in the applied electric field, and σ_θ is the multiple scattering angle. In the region of interest one can neglect the "straggling" term Ω_s.

In equilibrium

$$\sigma = \frac{1}{2}\left(\frac{dE_{fr}}{E_{eq}\,dx}\right)^{-1}\frac{d\sigma_\theta{}^2}{dx}$$

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From the experimental data:

Energy in eV , distance in nm and angles in radian

$\mathfrak{R}$ is the applied electric field

q is the charge of pbar

$$q\mathfrak{R} = \frac{dE_{fr}}{dx} + E_{eq}\frac{d\sigma_{\theta}^{2}}{dx}$$

$$\frac{dE_{fr}}{dx} == .45\sqrt{E_{eq}}\left[\frac{eV}{nm}\right]$$

$$\frac{d\Omega_{s}^{2}}{dx} = .05\,E_{eq}\left[\frac{eV^{2}}{nm}\right]$$

$$\frac{d\sigma_{\theta}^{2}}{dx} = \frac{\kappa\, 2.3\, 10^{5}}{E_{eq}^{2}}\left[\frac{1}{nm}\right]$$

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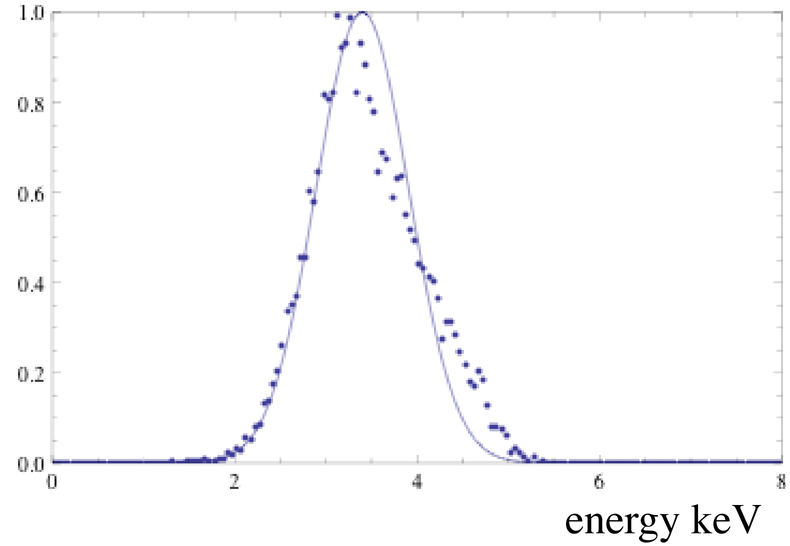
Results of simple model and Monte Carlo simulations

mean energy E_{eq} = 3.5 keV
RMS energy spread = 600 eV
RMS divergence angle = 0.4 radians
RMS spot size = 6 mm
losses = 18%
RMS time-spreading = 17 ns
pop. enhancement in 3 keV window
centered at 3.5 keV = 12X
70 carbon foils (20 nm each)
V = 540 V
total V ≈ 38 kV



Solid line is a Gaussian distribution with parameters as listed above.
Dots are from simulations using the experimental data from the previous slide.

Numerical Simulations

We consider four cases:

1. The Anti-proton De-accelerator (AD) giving 5 MeV anti-protons followed by a degrader foil (which is the present situation) and then followed by a frictional cooling section.
2. The AD with an induction accelerator operating from 5 MeV to 50 keV followed by a frictional cooling section.
3. The AD with an RFQ to 50 keV followed by a frictional cooling section.
4. The performance of ELENA. ELENA followed with a small degrader foil. No frictional cooling needed.

Monte Carlo Model

- initial conditions:
- energy distribution based on assumed output beam from degrader:
- degrading foil comparable in thickness to typical *range* of antiprotons at mean energy of AD output
- produces wide energy distribution
- but approximately ***uniform kinetic energy spectrum*** between 0 keV and ~300 keV
- an estimated ~4% of the original antiproton population in bunch will lie below 50 keV
- simulations considered sub-population of antiprotons with kinetic energy below 50 keV
- assumed a uniform energy distribution between 0 keV and 50 keV— at higher energies particles cannot be cooled
- focused on *relative enhancement* of population in a window around a few keV— absolute populations not needed
- transversely, used a gaussian beam with 2 mm spot size
- and 0.03 radian RMS divergence (likely too small, but largely irrelevant as it blows up after first foil anyway)

- other physical assumptions:
- non-relativistic kinematics
- 20 nm thick carbon foils
- equal DC voltage drop between successive foils
- ambient longitudinal magnetic field of magnitude 3.5 T everywhere
- annihilation was ignored
- tracked individual sample particle trajectories and collisions

- transport parameters:
- adopted stopping powers and straggling as in equilibrium theory
- tried various values of κ , e.g., 0.11, 0.25, 1.0
- performance:
- custom simulations were performed, because *ICOOL's* results were not reliable at low energies
- runs performed with about 105 sample particles
- targeted various final mean kinetic energies: ~3 keV, 5 keV, 10 keV
- chose number of foils and voltage drop to match target energy and to reach equilibrium

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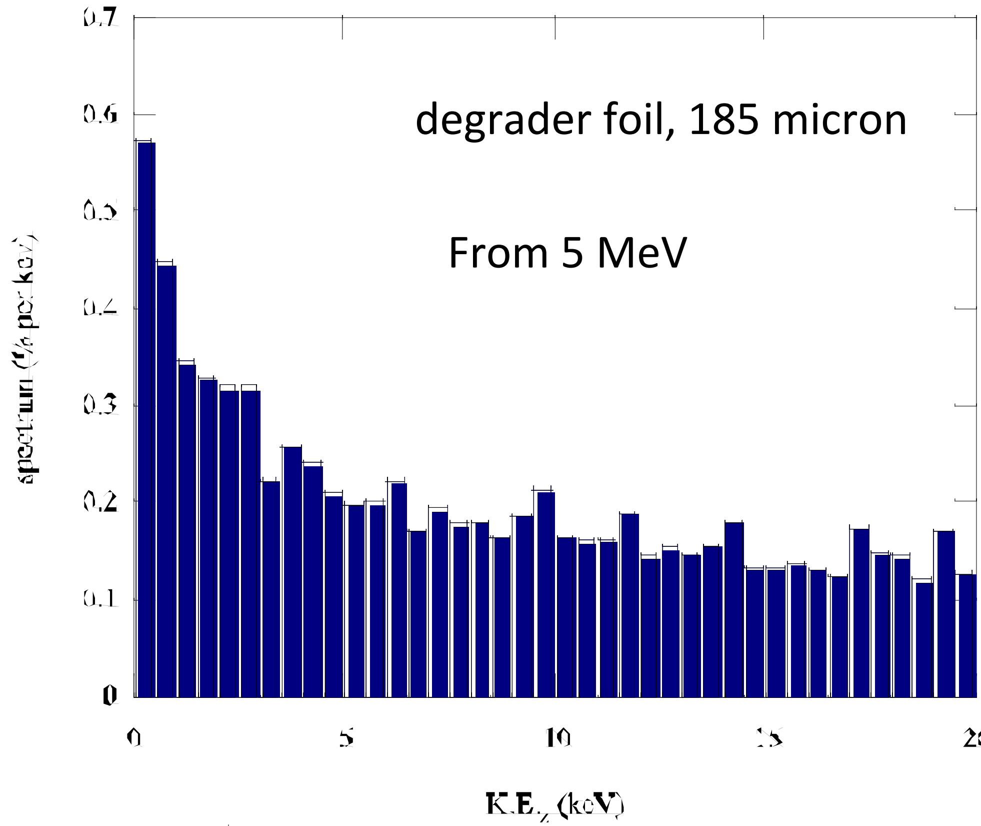
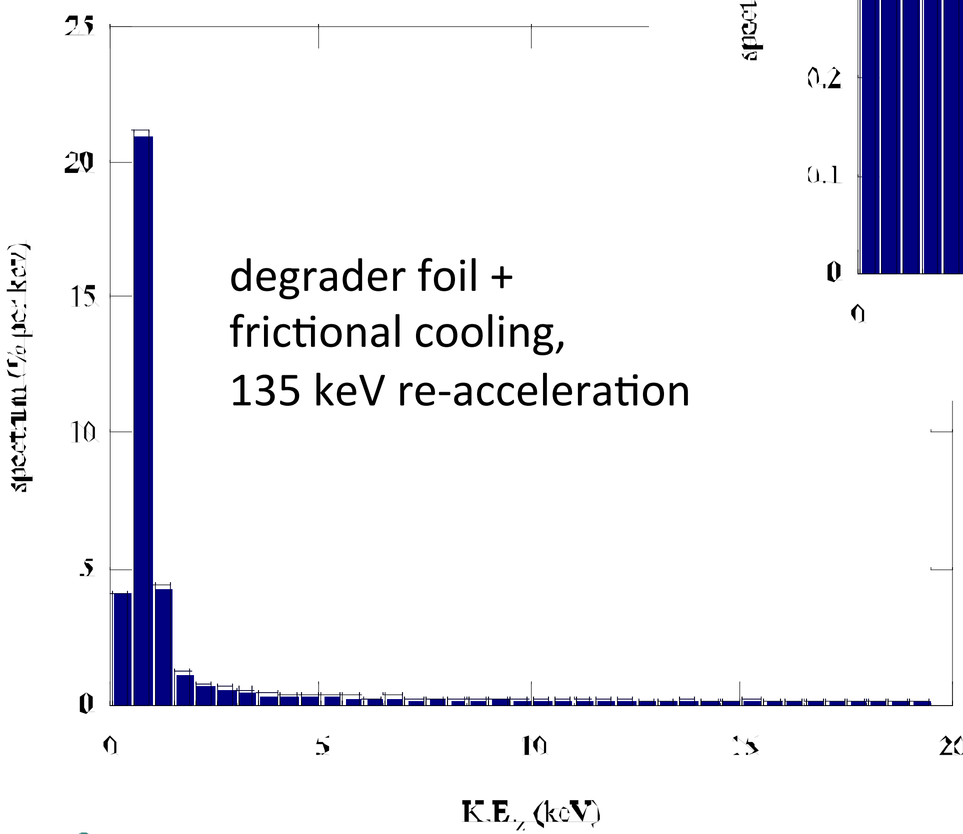
AD parameters

fraction of particles < 3 keV:
1.1%   degrader only
16%   frictional cooling
factor 14 improvement

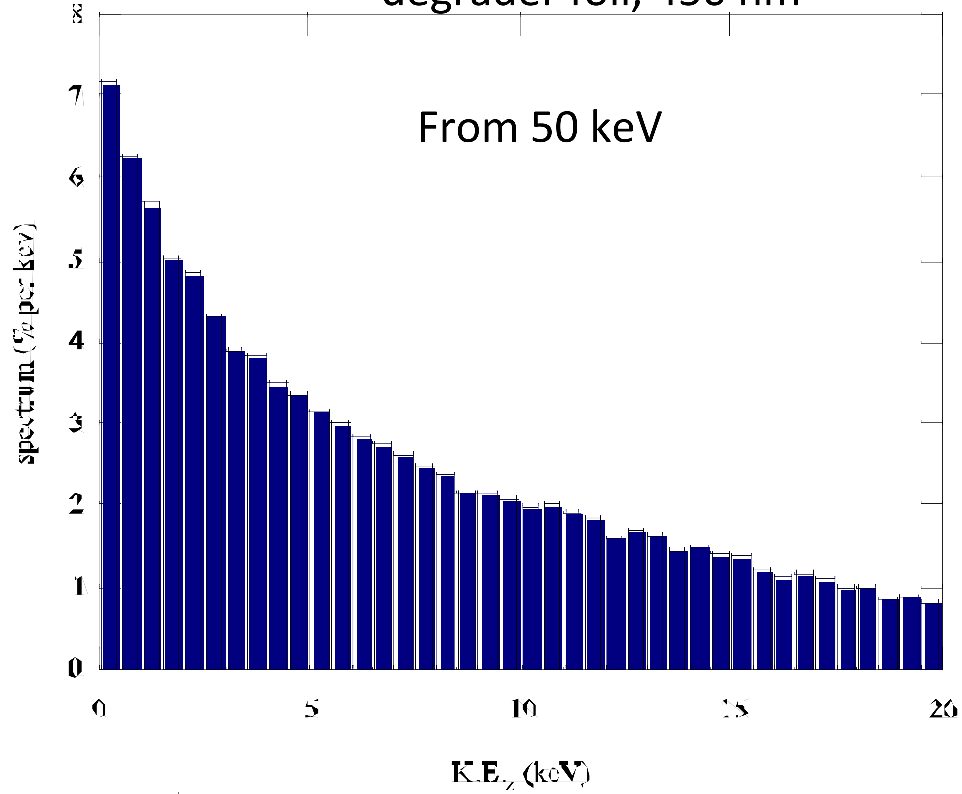


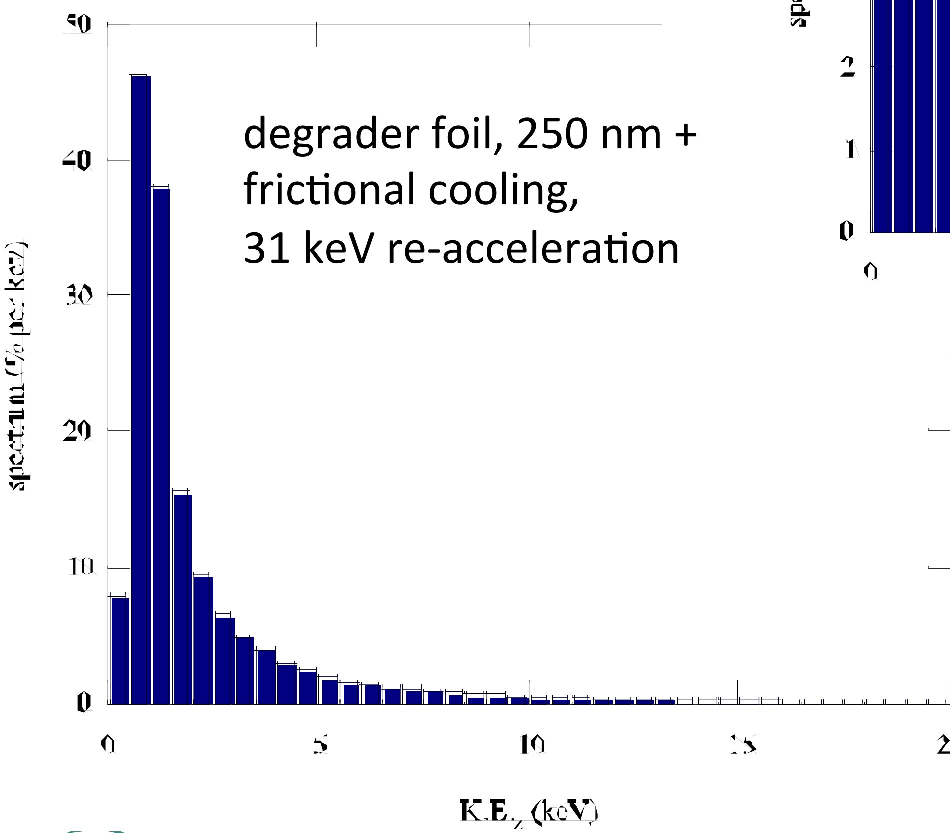


induction linac:

fraction of particles < 3 keV:
16%   degrader only
62%   frictional cooling
factor 4 improvement

degrader foil, 450 nm





The induction unit runs at 1 MeV/m for
The full AD pulse of (about) 200 ns.
Need about 5 m

It can run at 5 MeV/m for (about) 50 ns
(or ¼ of the AD pulse)

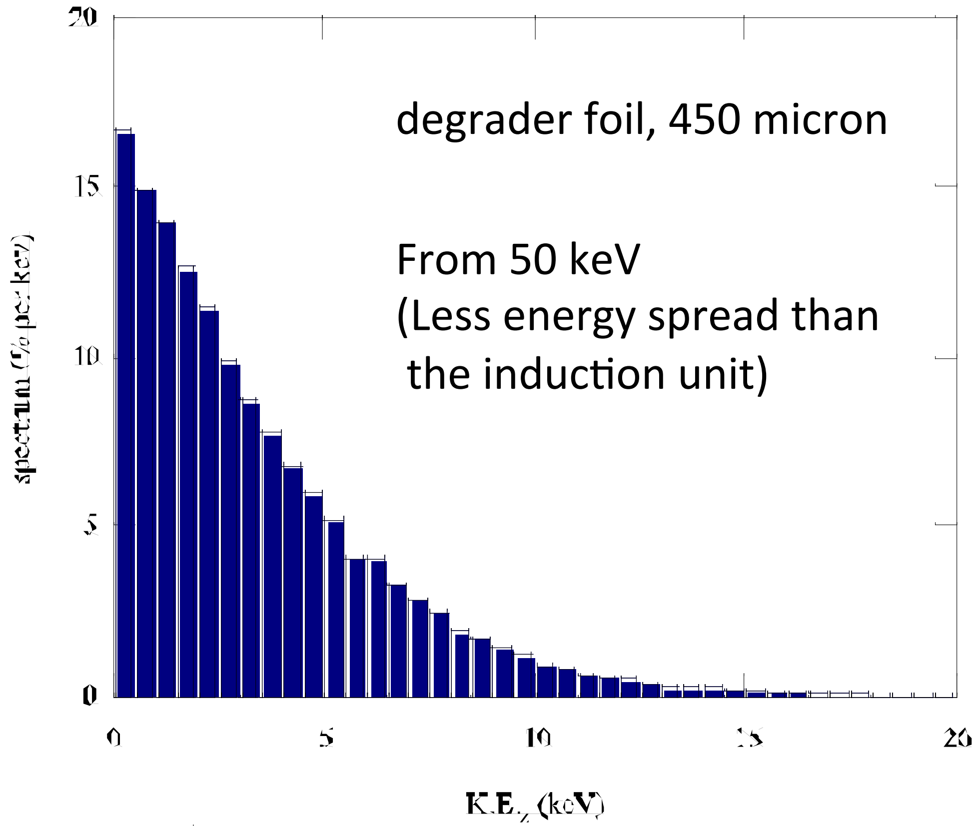
RFQ:

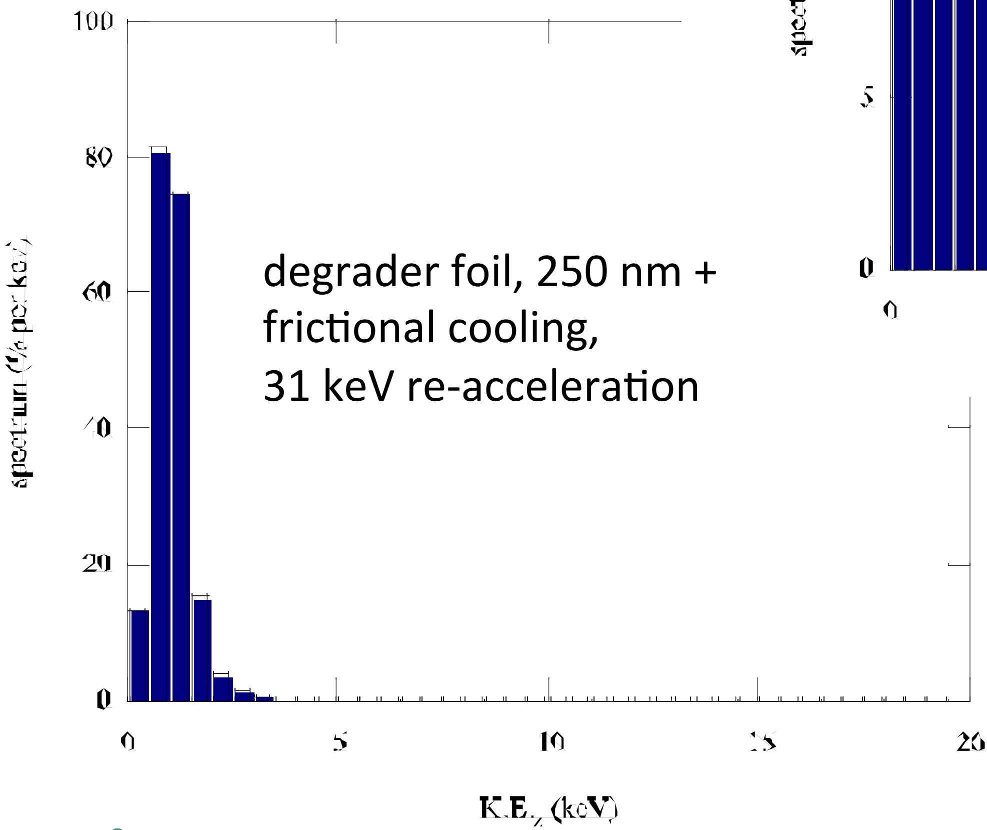
fraction of particles < 3 keV:

40% degrader only

95% frictional cooling

factor 2.5 improvement

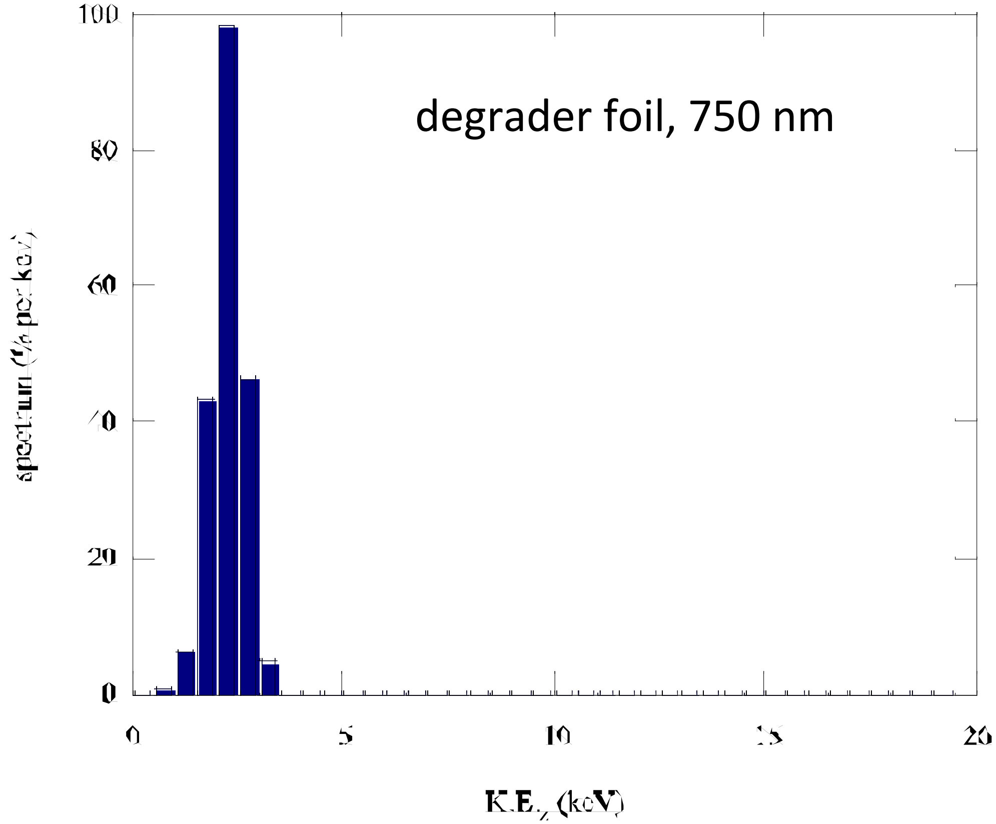




Elena parameters

fraction of particles < 3 keV:
98%   degrader only

No frictional cooling needed



Conclusions

A frictional cooling section can be easily made (fast and inexpensive) and it would significantly increase the flux to the anti-hydrogen experiments in the interim while ELENA is under construction and commissioning.

A frictional cooling section, in it own right, would be interesting; that is, it brings in new physics which might be of future importance and, furthermore, is a real-world application of the frictional cooling concept (which has been shown in-principle, but not yet in a practical device).

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Thank you for your attention!!

Any questions?
(They will be answered by Max. Your choice as to whether in Ukrainian or Russian)