PARTICLE REFRIGERATOR*

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Abstract

We describe an approach that can extend the utility of frictional cooling, originally developed for muon beams, to other particles and ions, producing beams of exceptionally low normalized emittance. Moreover, via this approach the small momentum acceptance typical of frictional cooling channels can be increased by two to three orders of magnitude, making it possible to handle much larger intensities with much higher transmission, while preserving the exceptionally low normalized emittance of the output. Simulation studies have been used to optimize the design and performance for a variety of ions and particles, and an inexpensive experiment has been designed to test and verify the concept and simulations, using alpha particles from a radioactive source.

BACKGROUND: FRICTIONAL COOLING

Frictional cooling [1] is based on the idea of opposing a velocity-dependent braking force, exerted on a charged-particle beam as it passes through matter, with an accelerating electric field. The result is that the particles in the beam are slowed down or speeded up until they come to an equilibrium momentum and energy, thus cooling the beam longitudinally. At the same time, the braking force reduces any random sideways motion of the beam particles, thereby cooling the beam transversely as well.

Frictional cooling is applicable over only a limited range in particle energy in which there is negative feedback: particles that at random happen to lose more energy than the average experience a reduced braking force, and those losing less than the average experience an increased one. This has two effects: it inherently reduces the momentum spread of a beam, and for a repeated series of absorbers and acceleration, it provides a stable equilibrium in momentum (and thus in kinetic energy). As can be seen in Figure 1, this negative feedback occurs just below the Bragg peak, for momenta in the vicinity of $p/mc = \beta\gamma < \sim 0.005$, where m is the particle's mass and c the speed of light in vacuum. (It also occurs above ~1 TeV/c, but that is not of any practical use.)

An important aspect of the energy loss in materials is the variance, known as straggling. In the frictional regime, straggling is important, and can be a significant fraction of the total energy loss, shown by the height of the distribution in Figure 2. This makes designing a frictional cooling channel more challenging, as particles which lose either too much or too little energy in a foil can leave the frictional regime and be lost.

* Work supported in part by USDOE STTR Grant DE-FG02-08ER86281.
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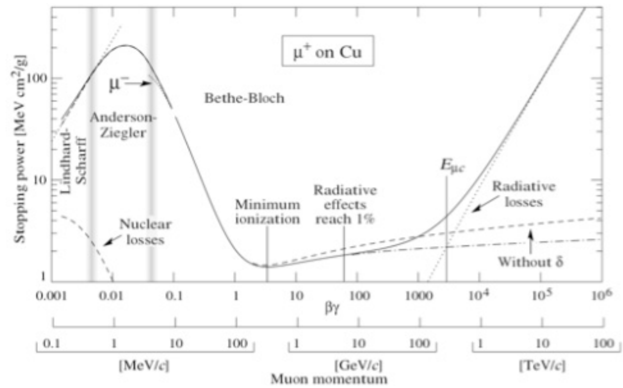

Figure 1: Muon stopping power in copper [2]; the frictional cooling range extends to slightly above the shaded band at $\beta\gamma \approx 0.005$.

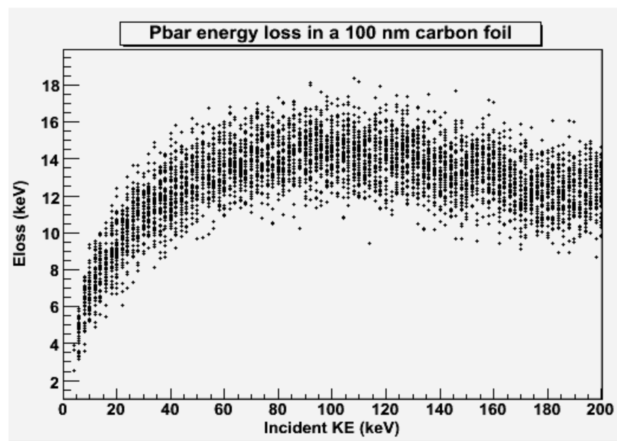

Figure 2: Energy loss and straggling in a 100 nm carbon foil for low energy antiprotons. For these particles, the frictional regime extends from 7 to 60 keV.

Frictional cooling of muons has been demonstrated experimentally by Mühlbauer et al. [1]. They operated a stack of 10 thin (20 nm) graphite foils in an electric field of about 2×10^5 V/m within a 5 Tesla solenoid magnetic field. They worked with muons having kinetic energies below 15 keV ($\beta\gamma < 0.017$); muon frictional cooling does not work at higher energies. The innovation that we are introducing is a method to extend the benefits of frictional cooling to considerably higher energies – up to several MeV.

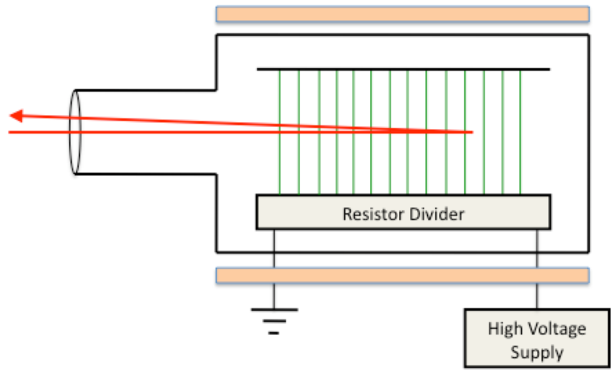

Figure 3: Schematic view of a Particle Refrigerator. The high voltage accelerates particles to the left. Particles (red) enter from the left, are decelerated to a stop by the electric field, and accelerate to the left within the frictional cooling channel. The thin foils are indicated in green, and many more are needed than are shown. The entire device is surrounded by a solenoid.

THE PARTICLE REFRIGERATOR

The "particle refrigerator" is essentially a frictional cooling channel with backwards injection. A schematic is shown in Figure 3. In this device, the incident particle beam is brought to a stop by the combined action of energy loss in thin foils and a D.C. decelerating electric field. Those particles stopping between foils then turn around and are accelerated back towards the channel entrance, emerging at or near the equilibrium energy of the frictional channel. As the D.C. potential difference can be several megavolts, the incident beam can have an energy spread of several MeV, because although particles with different initial energies turn around at different places, after turnaround they are all are within the acceptance of the frictional cooling channel. They then emerge from it at or near the equilibrium kinetic energy *of the channel*.

INITIAL SIMULATION RESULTS

We have successfully simulated this device using the Geant4-based G4beamline code [3] for a variety of particle and ion species, including muons, antiprotons, and alpha particles. In one example, the input kinetic-energy distribution of an alpha-particle beam was uniform from 0.1 to 3 MeV; Figure 4 shows that the emerging beam has an r.m.s. energy spread of only 16 keV. The transverse emittance of the beam remains approximately constant (not shown), but the normalized transverse emittance is reduced substantially.

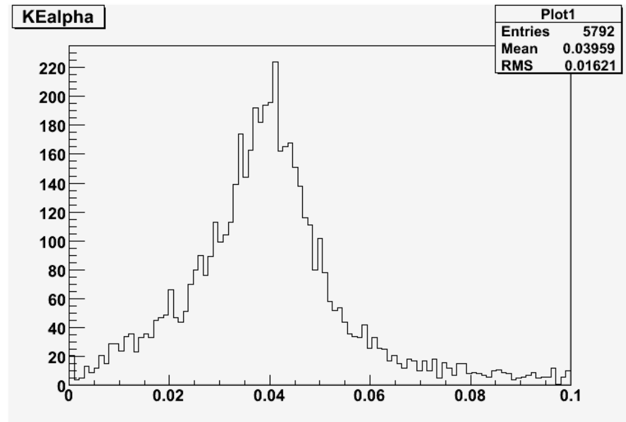

Figure 4: Distribution in kinetic energy of alpha particles emerging from a particle refrigerator simulated using G4beamline [3]. Units are MeV.

This device is also quite efficient: of 10,000 simulated alpha particles incident on the particle refrigerator, 58% survived, the rest being stopped in the carbon foils (where they annihilate). The simulated particle refrigerator in this case consists of 167 graphite foils of 100 nm thickness, each separated from the next by 1 cm and by 15 kV in potential. A total potential difference of 2.5 MV is thus required, well within the voltage range of, e.g., Van de Graaff generators.

EFFECTS OF CHARGE FOR IONS

Note that the energy loss rate of particles in matter depends on both their mass and their charge. For the frictional cooling channel to work, the potential difference from one foil to the next must be selected to equal the energy lost in one foil, for particles with kinetic energy in the middle of the channel's acceptance. Thus the particle refrigerator's high voltage and foil thickness must be carefully tuned for the particular particle species of interest. For ions this means that a specific charge state must be selected and the voltage difference per foil adjusted appropriately. Particles gain energy from the E field proportional to their charge q, but they lose energy in the foils proportional to q^2. Thus, ions in higher charge states will stop in a foil, while ions in lower charge states will be accelerated out of the frictional regime to higher energy (~ MeV, compared to the frictional channel's ~ keV).

Selecting or Increasing the Charge State of Ions

This device combines many foils with an accelerating voltage, and puts the beam through considerably more material than a conventional stripping foil. For some desired charge states that may be enough – tune the refrigerator for that state and only keep ions which emerge in the frictional channel momentum range (dump the remaining lower-charge particles which have much higher momentum; higher-charge particles will have stopped). For a system in which timing is not important and there is insufficient material for efficient stripping, one could arrange for a momentum selection at the output to recycle the high momentum ions back into the refrigerator (i.e. those that are insufficiently stripped); these are always within its momentum acceptance. Such repeated recycling ensures the ions will either strip as desired or be lost. Even though the beam traverses a lot of material, at the output its transverse emittance and momentum spread remain those of the frictional cooling channel, and are quite low; the time spread clearly increases markedly. This obviously works better for higher charge states than for low ones, and is limited to charge states reachable by stripping at the few-MeV energies involved. This is a new idea that still has many details to be investigated.

KNOCK-ON ELECTRONS

A difficulty that must be worked through is the generation and acceleration of knock-on electrons. Due to their much lighter mass, any electrons knocked out of the foils by the beam particles are rapidly accelerated to energies well outside their frictional-cooling regime (thus the stopping power of the foils is much lower for them than for the beam particles). As they traverse the foil stack, they can knock out additional electrons, generating a cascade. Mühlbauer et al. [1] indeed observed about 100 electrons emerging from their 10-foil stack for each incident muon, corresponding to about a 60% knock-on probability per foil. Extrapolating this to the 167-foil example, for an intense beam a spark could be generated, shorting out the accelerating voltage and possibly damaging the foils. (Note that this is significantly fewer electrons than would be generated in a gaseous medium – the frictional regime is within the breakdown region of all gases.)

We have a number of ideas in mind to overcome this difficulty. Quantitatively, the effect will depend on the foil thickness, with thicker foils being less effective at generating electron cascades than thinner ones. Additionally, electrons will follow magnetic-field lines much more closely than the slower-moving particles of the beam. They can thus be deflected in cusp fields or wigglers and guided into absorbers that are outside the beam aperture. Detailed simulations as well as prototype studies will be required to assess which combinations of these as well as other techniques will be most effective.

AN ALPHA-PARTICLE EXPERIMENT

Simulations are not enough to prove that the idea is viable, and we intend to perform an inexpensive experiment to validate both the general idea and the simulations. To keep it simple and inexpensive, we will use an alpha source and relatively low high-voltage supplies. We will put a thin degrader just after the source to increase the flux near 100 keV. With suitable collimation of the source, there should be no need for an expensive solenoid; alternatively, a small solenoid could be built or borrowed. The basic layout of the experiment is shown in Figure 5.

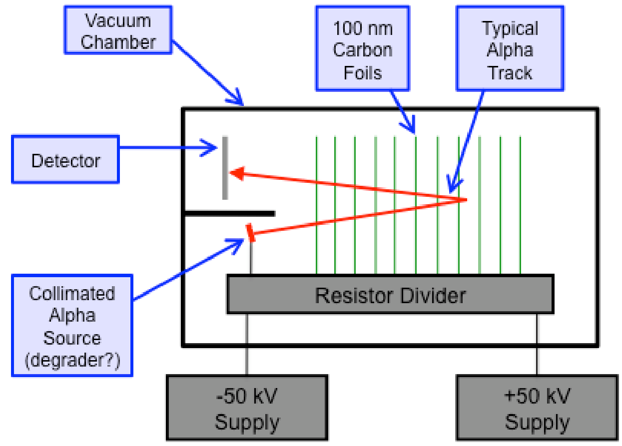

Figure 5: An inexpensive alpha-particle experiment; just 11 foils are needed.

CONCLUSION

The particle refrigerator is a new concept for the cooling of low-energy charged particle beams. As it increases the acceptance of a frictional cooling channel almost a thousandfold, it makes the exceptionally small emittance of such a channel practical for high-brightness beams. This is potentially of interest for the trapping of antiprotons in an atomic trap, the creation of unstable ion beams, as well as preparing muon beams for a neutrino factory, muon collider, or stopping-muon experiments.

REFERENCES

[1] M. Mühlbauer et al., Hyp. Interact. 119:305, 1999.
[2] Particle Data Group, C. Amsler et al., Physics Letters B667, 1 (2008).
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