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The Particle Refrigerator

A promising approach to using frictional cooling for reducing the emittance of particle beams.

Applications using antiprotons, muons, and alphas are described.

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Introduction

- Frictional cooling has long been known to be capable of producing very low emittance beams
- The problem is that frictional cooling only works for very low energy particles, and its input acceptance is quite small in energy:
  - Antiprotons: KE < 50 keV
  - Muons: KE < 10 keV

Key Idea:

Make the particles climb a few Mega-Volt potential, stop, and turn around into the frictional cooling channel. This increases the acceptance from a few keV to a few MeV.

- So the particles enter the frictional cooling channel backwards; they come back out with the equilibrium kinetic energy of the channel regardless of their initial energy.
- Particles with different initial energies turn around at different places.
- The total potential determines the momentum (energy) acceptance.

Frictional Cooling

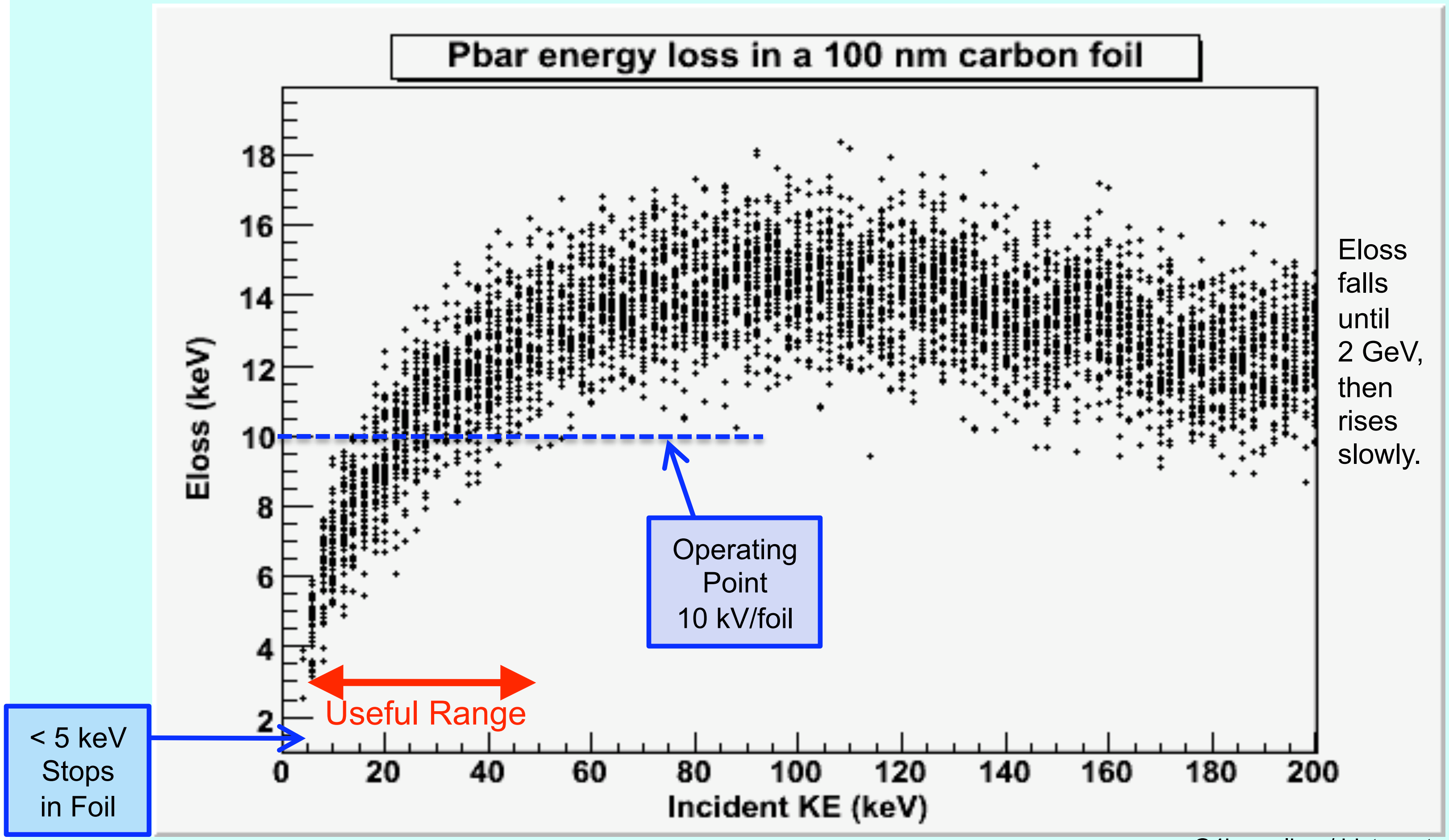
- A frictional cooling channel consists of either a continuous absorber or a series of thin foils, in a solenoid field to focus transversely, and in a dc electric field to restore energy lost in the absorber.
- In this regime, gas will almost certainly break down.
- Hopefully the solid foils will trap enough of the ionization electrons in the material to prevent a shower and subsequent breakdown.

Experiments not unlike this channel have been performed with ~10 foils and low rates.

There is much more work to be done before we will know if this will really work.

ANTIPROTONS

Characterization of a Thin Carbon Foil, Antiprotons

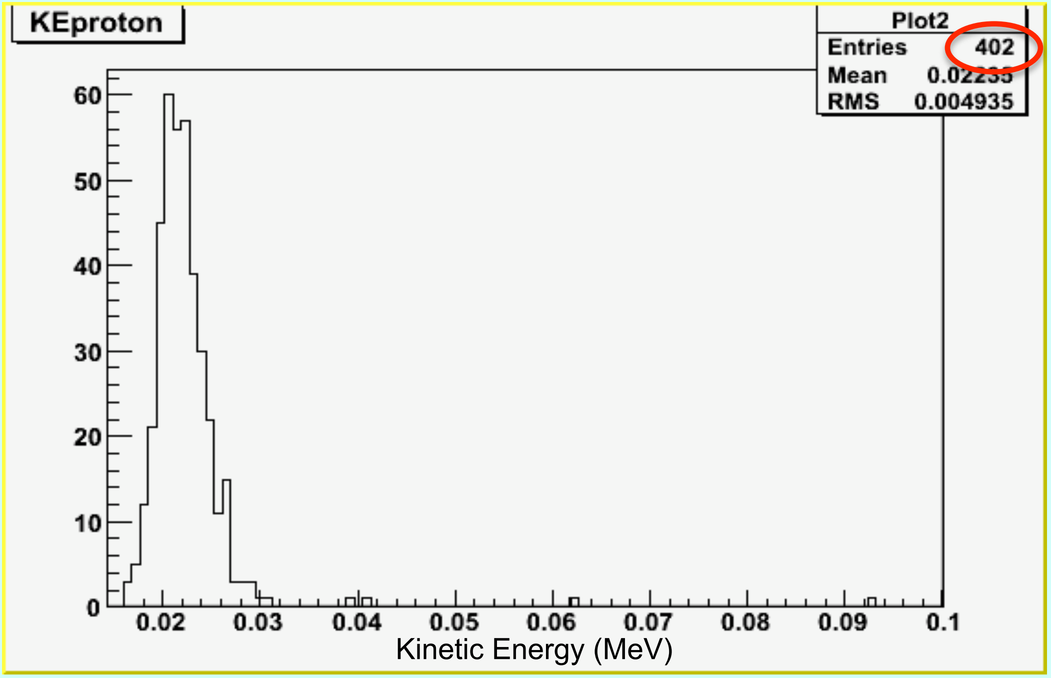


G4beamline / historoot

50 Pbars generated at 2,4,6,…,200 keV, to show the variance.

KE of Pbars Coming Out

- The operating point chosen is 10 kV per foil, which should give an equilibrium KE about 25 keV.
- As Pbars with KE < 5 keV will stop in the first foil after they turn around, the best possible efficiency is ~50%.
- Losses due to other mechanisms are quite acceptable.

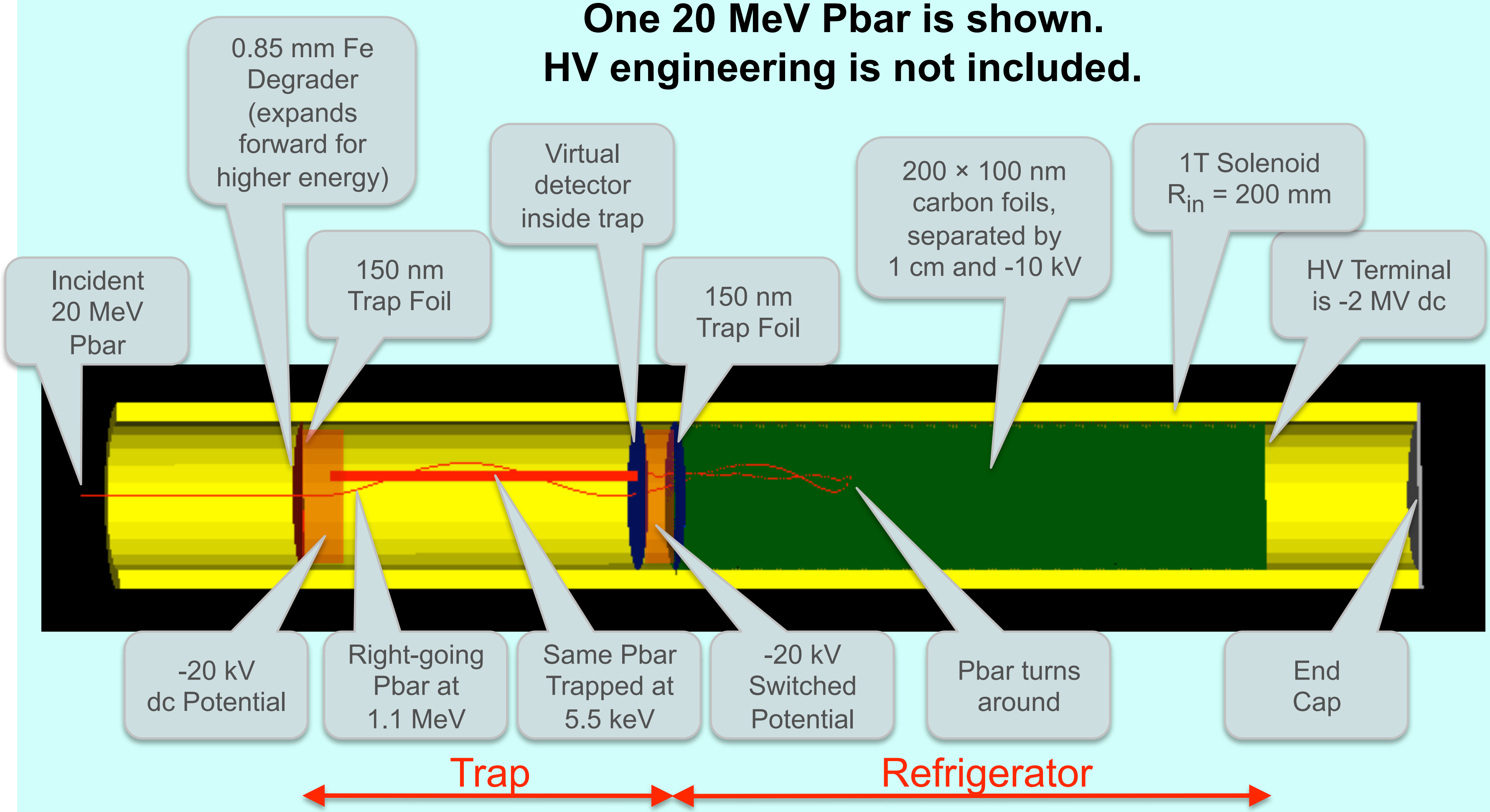


200 × 100 nm foils, 2 MV terminal.

1000 Pbars were injected on axis with 1 MeV kinetic energy.

Trapping Pbars in an Atomic Trap

One 20 MeV Pbar is shown.
HV engineering is not included.



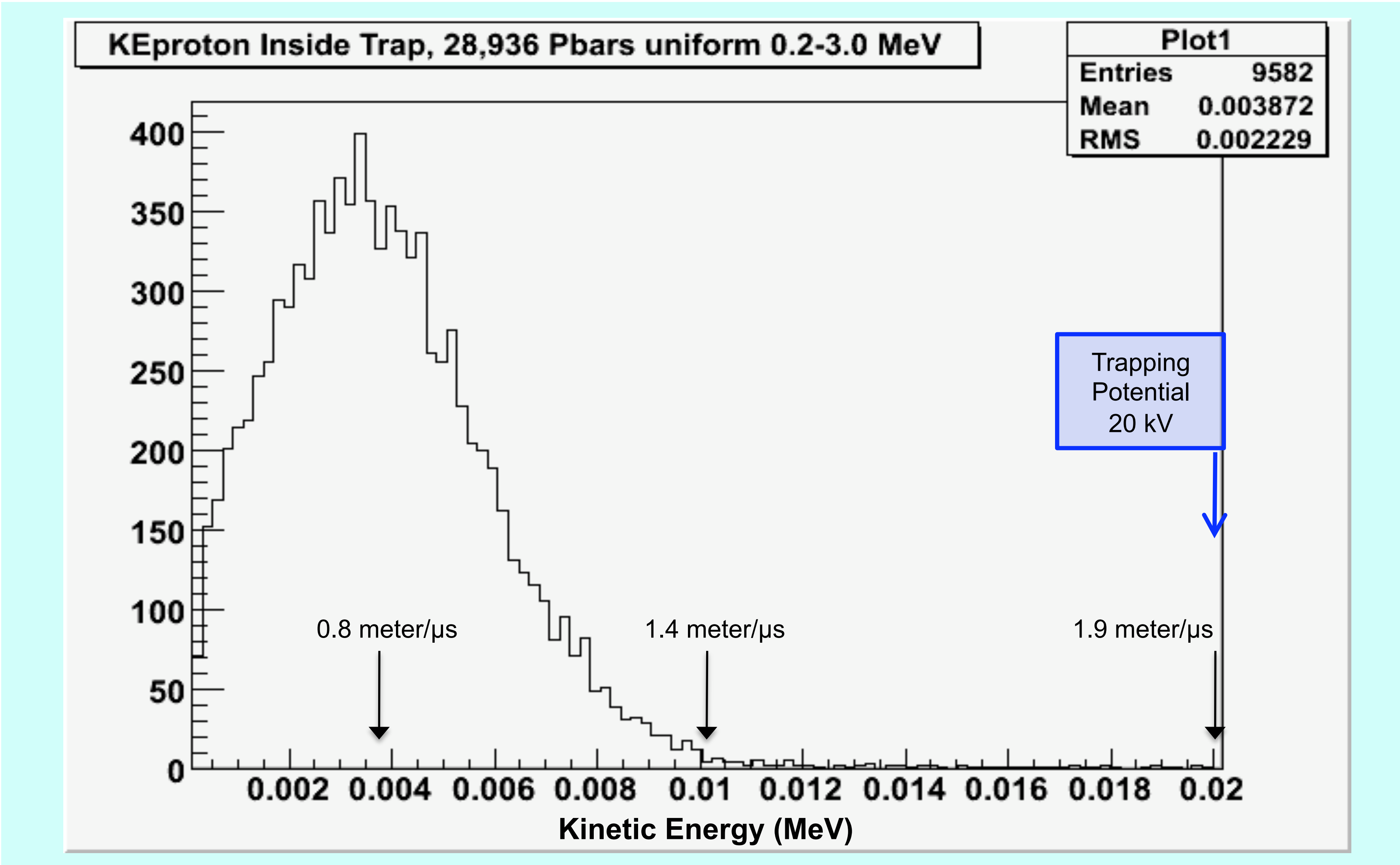
HV engineering is not included.

This Pbar took 2.5 μs per cycle in the trap, killed by maxTime=500 μs.

Reducing the Time Spread

- As shown, the time spread of the Pbars out of the refrigerator is too large (1.5 μsec).
- To reduce the time spread, the Pbars with higher initial KE are made to come back with higher KE near turn around, such that they slow down to the equilibrium KE just before exiting the refrigerator.
- About ¼ of the foils have 15 kV between them (still 1 cm apart).
- The number of foils was reduced, keeping the HV terminal at -2 MV.
- The time spread is reduced to ~650 ns.

Kinetic Energy of Trapped Pbars



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Summary – Antiprotons

- This refrigerator is able to trap antiprotons with higher efficiency than most other approaches.
- Initial degrader is varied to reduce the input KE to the range 0-2.7 MeV.
- Trapping efficiency depends on incident kinetic energy:
  - 0-2.7 MeV 40%
  - 5 MeV 40%
  - 20 MeV 40%
  - 50 MeV 10%
  - 100 MeV 1.5%
  - 433 MeV 0.004%

(A simple degrader reduces essentially all input particles to 0-2.7 MeV.) [applies to 0-2.7, 5 and 20 MeV]

(Losses above 40% are all in the degrader.) [applies to 50, 100 and 433 MeV]

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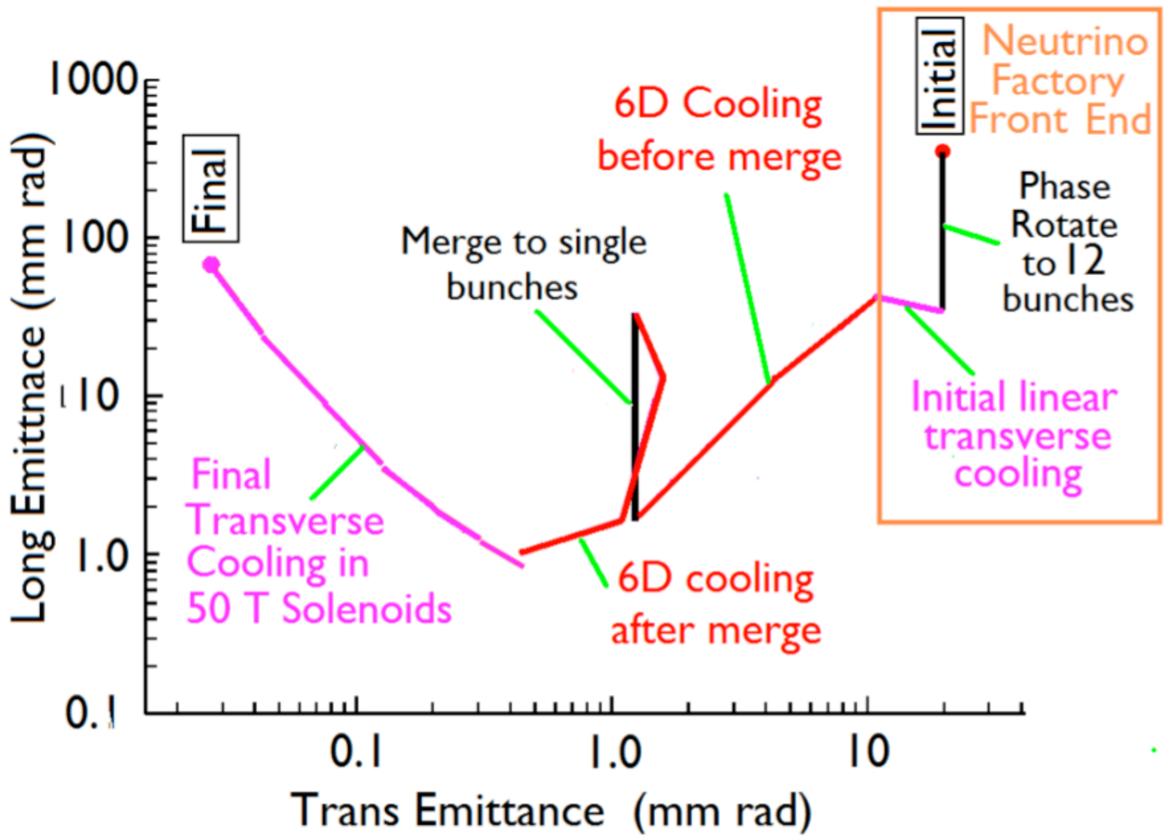
Background: Muon Collider Fernow-Neuffer Plot

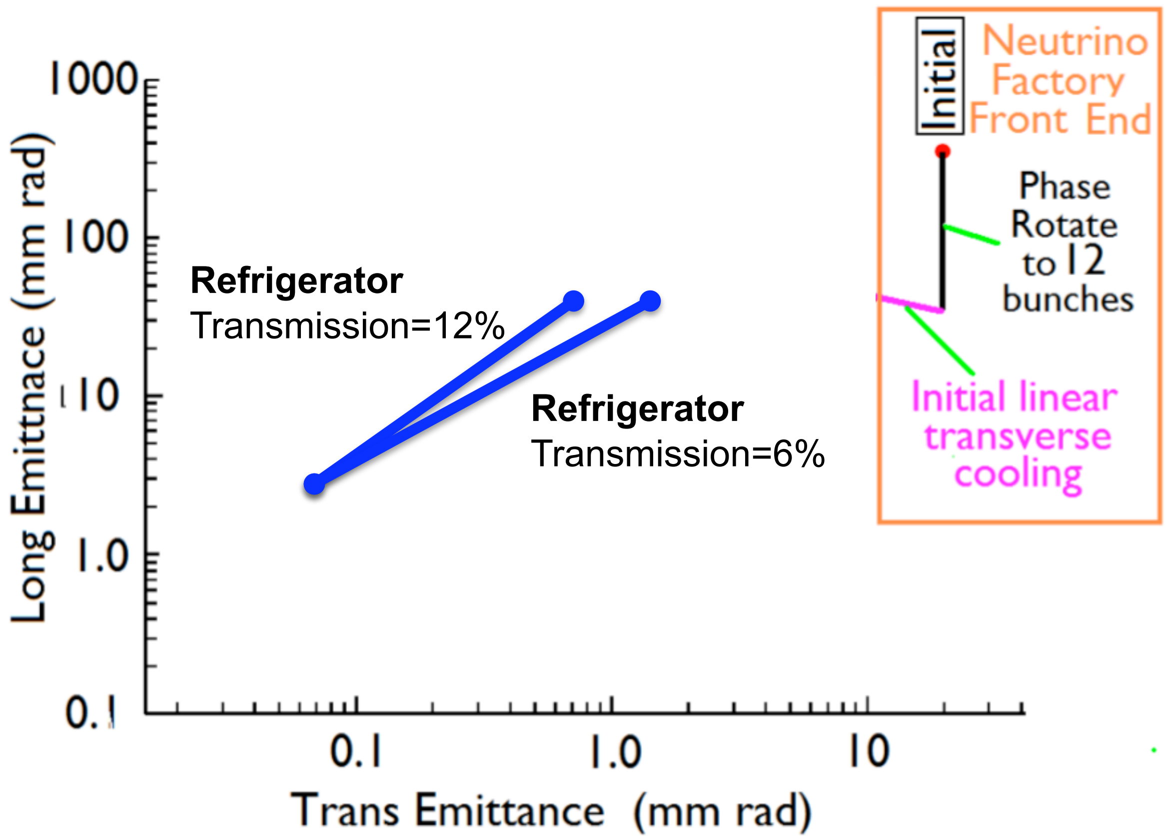
Emittances vs. Stage (Appendix 1 for transmission vs. emittance)



Every stage simulated at some level, but with many caveats

R.B.Palmer, 3/6/2008.

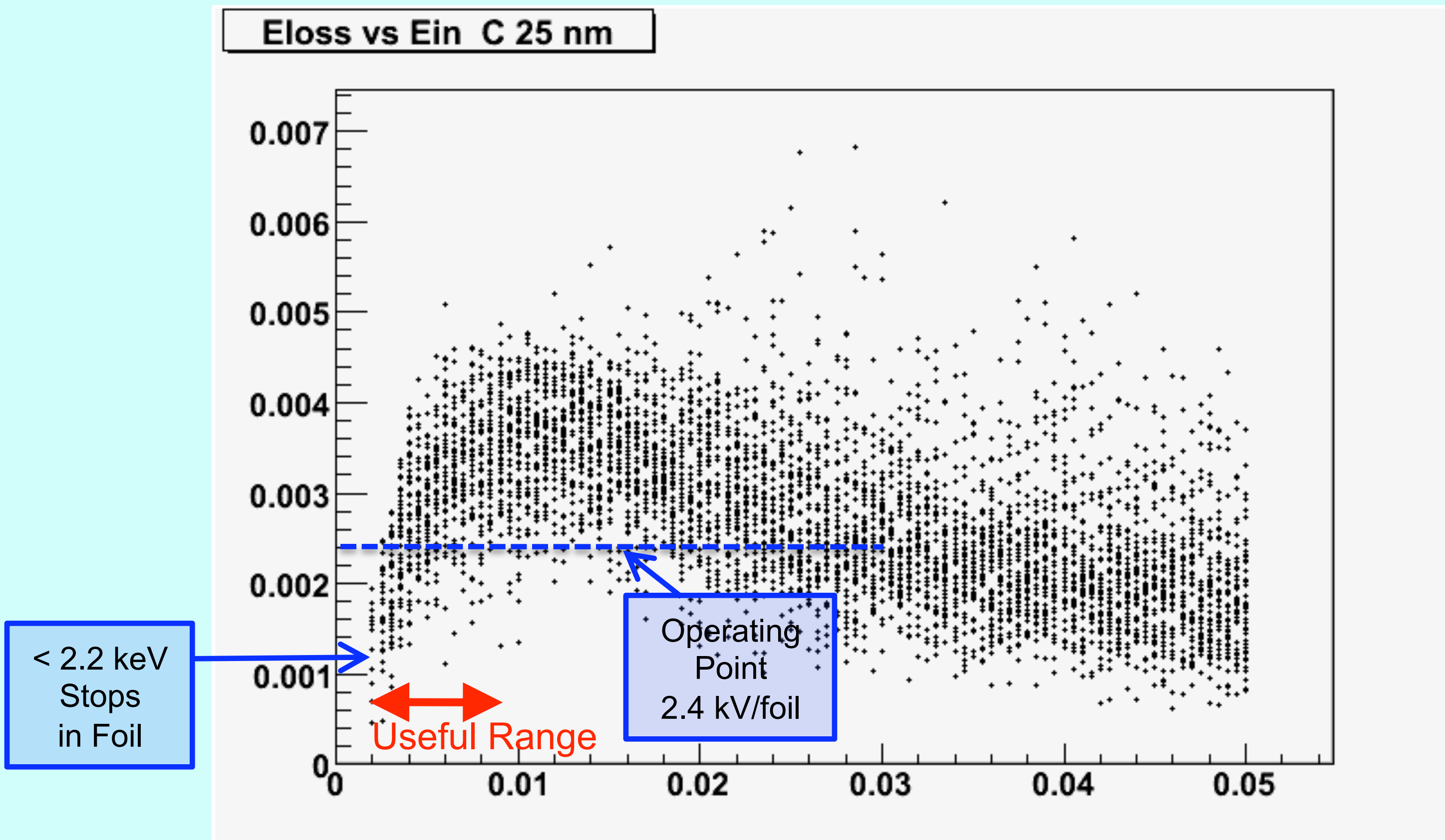
Why a Muon Refrigerator is so Interesting!



(Same scale)

G4beamline simulations,
ecalc9 emittances.

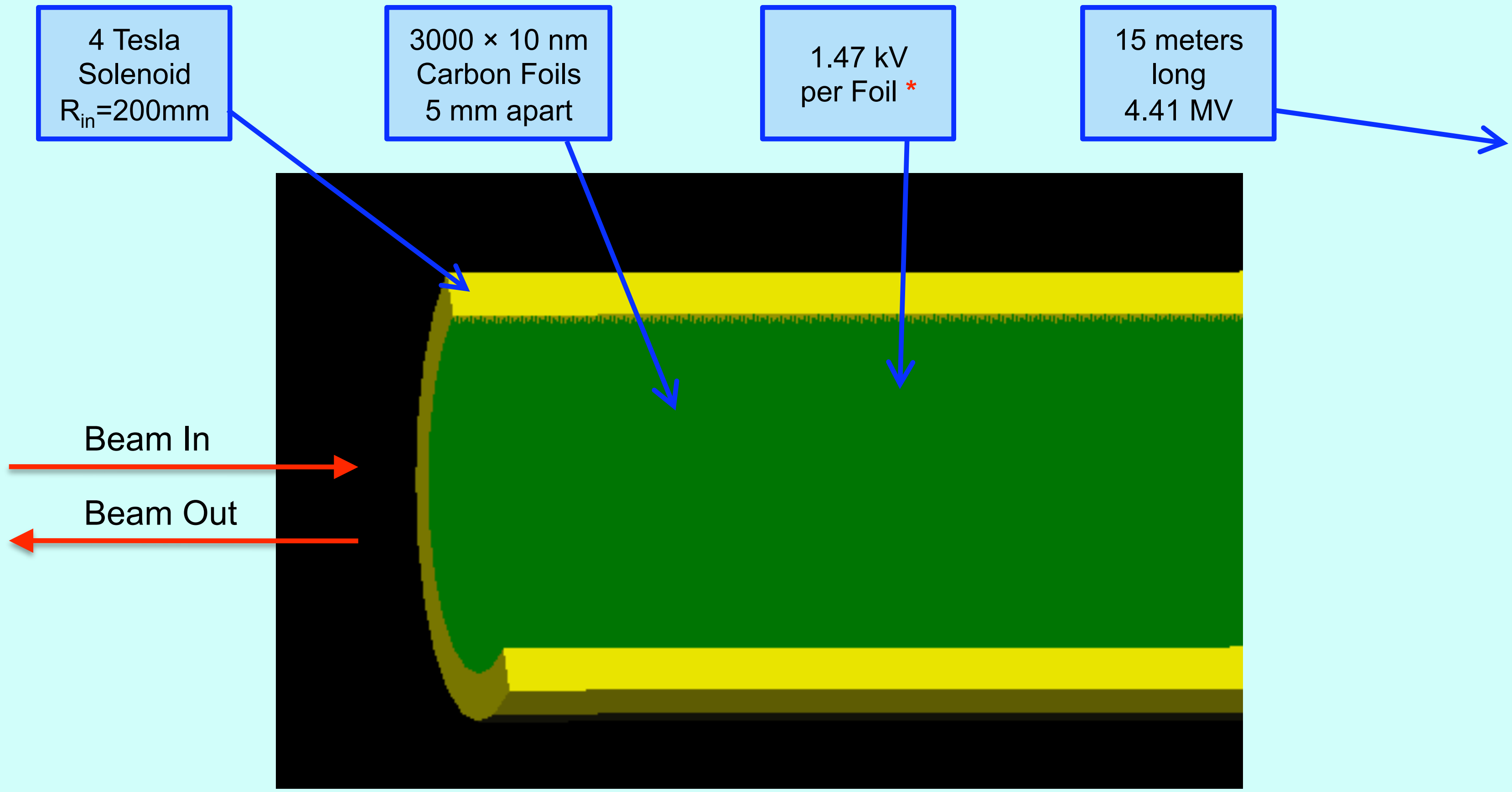
Characterization of a Thin Carbon Foil, Muons



G4beamline / historoot

Compared to antiprotons, the useful range is smaller, the variance is larger, and the operating point is closer to the upper edge of the useful range.

Muon Refrigerator

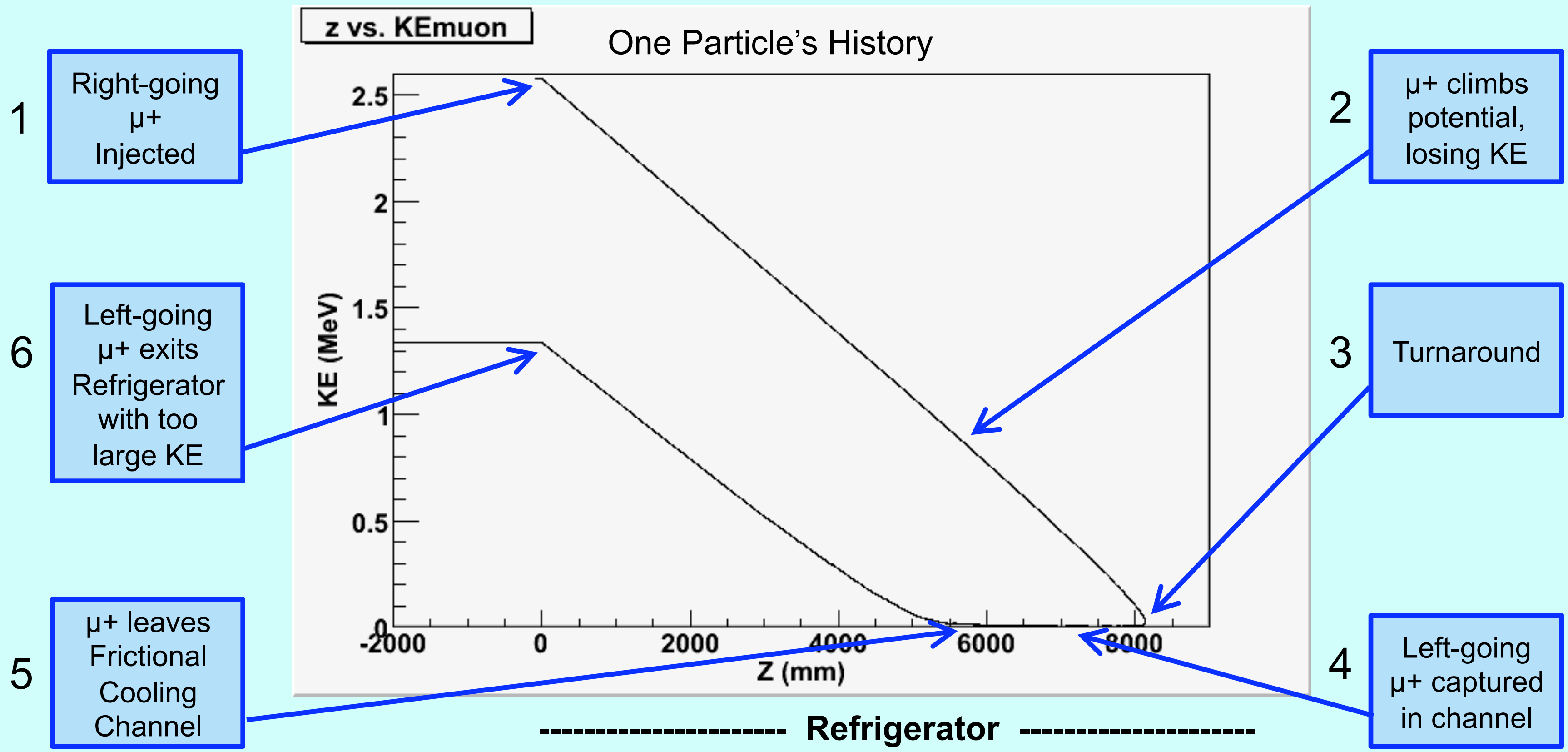


HV engineering is not included.

* Determined by a voltage scan to maximize transmission through the frictional cooling channel.

Dominant Loss Mechanism

- The dominant loss mechanism is not scraping, it is particles losing too little energy in a foil and leaving the frictional-cooling channel.
- This happens much more frequently for muons than for antiprotons.



Those "Lost" muons Have Also Been Cooled

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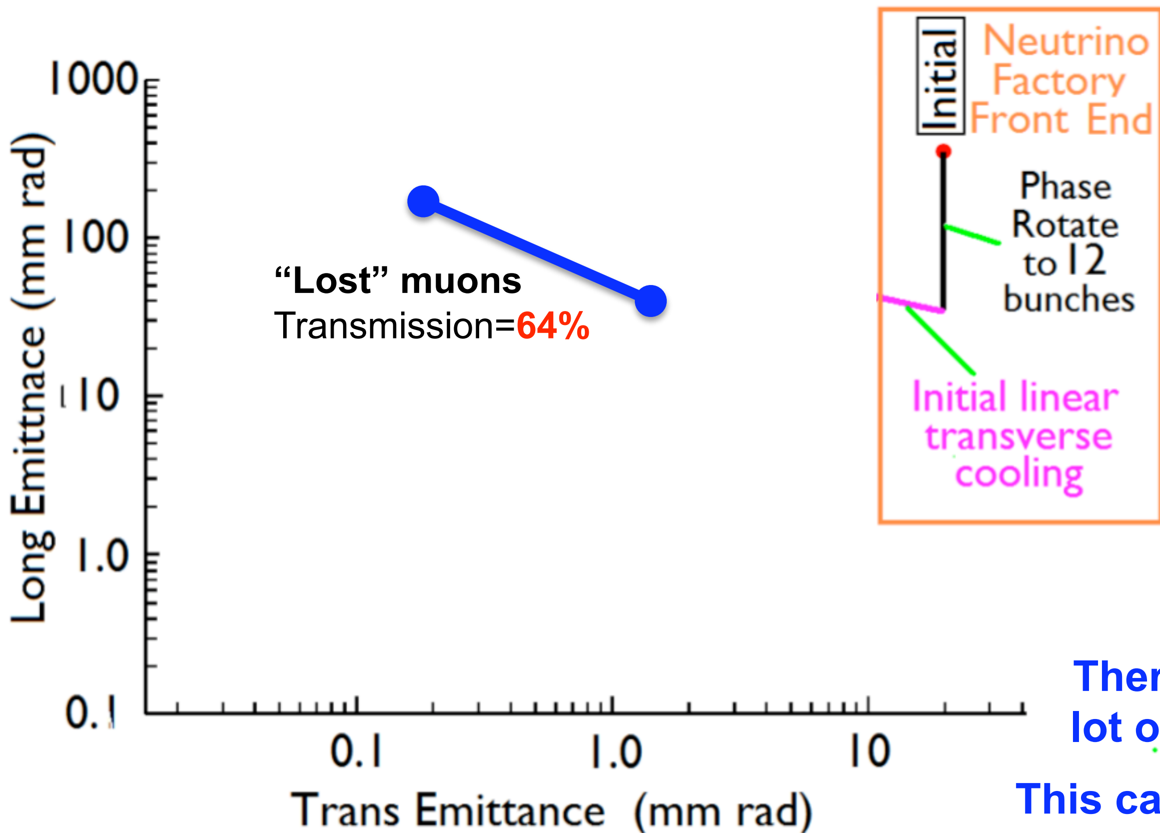

(Same scale)

There are a lot of them.

This can surely be optimized to do better.

Comments on Space charge

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- Be wary in applying the usual rules of thumb.
- Low <u>normalized</u> emittance is achieved by low momentum, not small bunch size:

σ_x	25 mm	This bunch is HUGE!
σ_y	25 mm	
σ_z	673 mm	
$\langle p_z \rangle$	1.1 MeV/c	(β=0.01)

- Clearly a careful computation including space charge is needed.

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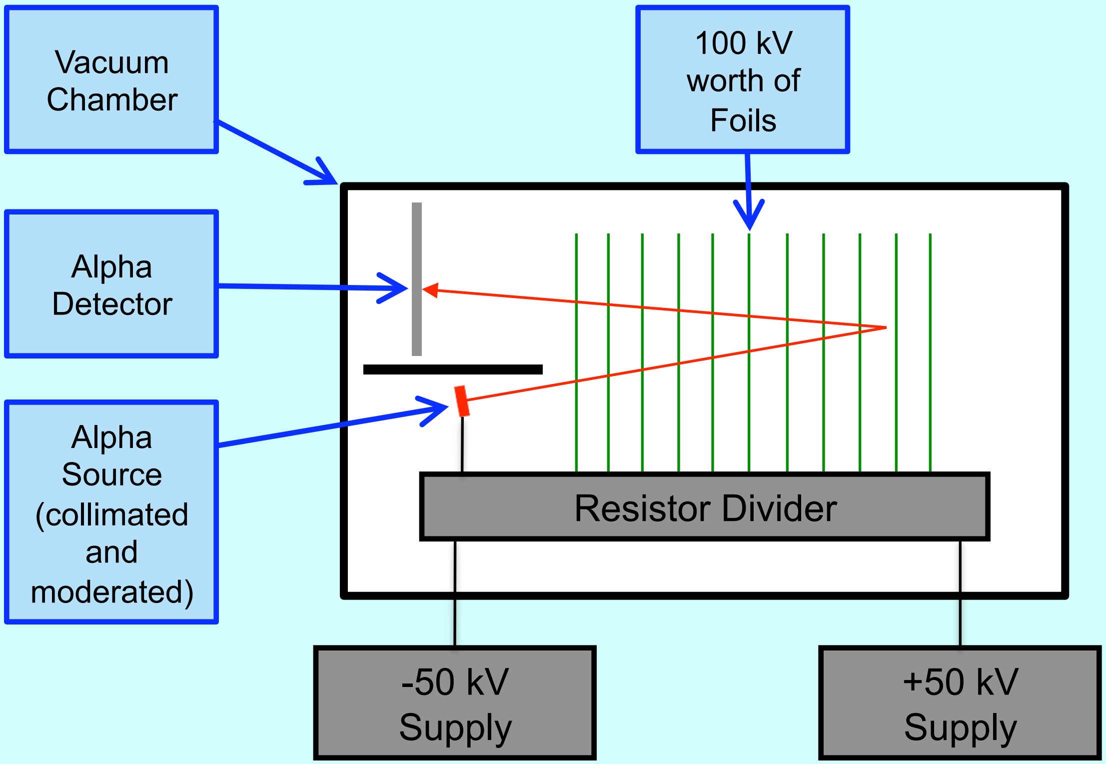
ALPHAS

An Inexpensive Experiment Using Alphas



- **Shows feasibility and measures transmission, not emittance or cooling**
- Uses two 50 kV supplies to keep costs down.
- The source must be collimated and moderated to ~100 keV.
- Hopefully the source collimation will avoid the need for a solenoid (as shown).

This is just a concept – <u>lots</u> of details need to be worked out.

- This is a simple, tabletop experiment that should fit within an SBIR budget.
- A larger version (with solenoid and higher voltage) could perhaps be tested with stripped H^- from the Fermilab Cockcroft-Walton, and then used for antiprotons.

LOTS more work to do!

- Investigate space charge effects
- Investigate electron effects
  - Will electrons multiply in the foils and spark?
- Investigate foil properties, handling, etc.
- Engineer the high voltage
- Will foils degrade or be destroyed over time?
- Investigate effects due to mu- capture and mu+ muonium formation
- Design the input/output of the refrigerator (kicker?)
- Design the initial muon acceleration stages after the Refrigerator
- Etc….

There are many unanswered questions, but the same is true of all current cooling-channel designs.

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Conclusions

- This is an interesting approach to cooling for several different types of particle beams.
- It is likely to be a big improvement in the trapping of antiprotons.
- If it can be made to work for high intensities, it could be a major improvement in muon collider designs.
- There is lots of effort remaining to learn how to make it work.