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**Comments on Frictional Cooling and the Zero Energy Options for  
Cooling Intense Muon Beams**

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# Comments on Frictional Cooling and the Zero Energy Options for Cooling Intense Muon Beams

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**Abstract.** It is shown that the proposed frictional cooling method is not directly applicable to intense ( $\approx 10^{12}$ ) muon bunches, mostly due to space charge constraints. Other difficulties stem from the fact that the initial emittance must be quite small, compared to the nominal muon collider emittance. Excessive heat due to energy deposition in the foils, from the primary muon beam or from secondary electrons could also destroy the thin foils used as moderator. Other “zero energy” schemes are considered, separately for  $\mu^-$  and  $\mu^+$ . All of them lead us to the study of exotic electrons-ions-muons plasma.

## INTRODUCTION

Ionization cooling has been so far adopted by our collaboration as the method of choice to reach transverse emittance adequate for a muon collider [1]. While other methods based on low energy beams have been used in low and medium energy applications, ionization cooling has yet to be demonstrated in a real experiment. However, our emphasis on ionization cooling is justified for the following reasons: (i) None of the schemes based on low energy muon can accept the large emittances typical of pion produced muon beams. This is particularly true for the longitudinal emittances, since the typical energy of such muons is many hundreds of MeV, with  $\Delta P/P \approx 1.$ , and the required kinetic energy for frictional cooling is a  $\approx 10$  KeV.

(ii) Detailed simulations of ionization cooling channels have been successful. Transverse cooling in solenoidal field based channels is largely understood. In some cases, cooling in 6D phase space has been obtained in our computer models. Preliminary engineering studies have done, leading to various constraints on these channels which have been implemented in our simulation codes. However, we now know that realistic channels reaching transverse (normalized) emittances below  $500 \text{ mm.mrad}$  will be very hard to achieve, as they require either more than

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<sup>1)</sup> Operated by University Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Departement of Energy

15  $T$ . solenoids (Alternate Solenoid configuration) or short (10 to 20 cm, or up to 2 time the coil radii) running at  $\approx 8 T.$ , opposite to each other (SFOFO), and placed close to each others, so that low beta can be reached. This means that the field in the coil pack is at or above the critical limit where super-conductivity will be lost. Finally, we have to come up with a scheme to implement longitudinal to transverse emittance exchange.

Thus, low energy cooling must be viewed as a complementary approach to ionization cooling. In particular, we are interested in a scheme that would take a long ( $\approx 100$  ns) bunch, possibly with a substructure (ns. sub-bunches), with a transverse emittance of  $\approx 750$  *mm.mrad*<sup>2</sup>, and cool it to the emittance suitable for a muon collider. First, such beams will have smaller transverse emittances. This will allow us to reduce the beam intensity for a given luminosity at the I.P., use smaller aperture machine for accelerators and of collider rings and possibility to implement transverse stacking to recombine longitudinal bunches together [2]. Second, the 100 ns. bunch could be compressed longitudinally, if the muons can be stopped and extracted from the exotic plasma fast enough.

In this paper, I'll briefly review the seminal experiment which demonstrated frictional cooling. This apparatus can not be used as such for intense beam: the beam will simply blow up due to space charge and the foil will likely be destroyed due to excessive heating, from the primary beam and secondary emissions due to the intense electric field produced by the space charge. Other low intensity cooling method will suffer from similar problems. In all cases, we might end up with a low temperature, highly unstable exotic plasma. The means by which such a state is realized will depend on the charge of the muons, leading to different  $\mu^+$  and  $\mu^-$  beams.

## FRICIONAL COOLING

By low energy muons, we refer to non-relativistic muons, typically a few MeV/c momentum or  $\approx 10$  KeV of kinetic energy ( $\beta \approx .02$ ). Reaching such low energies without dilution of the 6D phase space is certainly non-trivial. The friction cooling experiment [3] described below has been achieved starting with a surface muon beam, obtained from the PE5 beam line at PSI. In addition, Wien filters or electrostatic separators have been used to further select slow muons. The normalized incident beam emittance at 10 KeV, reaching the setup described in references [3,5] was about

$$5 \text{ mm} \times 1000. \text{ mrad} \times 0.015 = 75 \pi \text{ mm mrad}.$$

It is unlikely that such techniques will be directly applicable to the muon collider: the ratio  $\mu/\pi$  is simply too low. ( $\approx 10^{-8}$  to  $10^{-9}$ ) As stated above, we plan to start with our baseline pion/muon capture and decay channel, followed by ionization

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<sup>2)</sup> Lots of approximate signs in this paper! By this, I mean the number is o.k. within 20 to 50 %!

cooling. At the end of such a channel currently considered for the neutrino factory, the normalized transverse emittance will be about  $\approx 2000$  to  $1500 \pi \text{ mm.mrad}$ , a factor 20 higher than the initial emittance quoted above. Thus, this assumes that we can use larger foils in the friction cooler (e.g.  $\approx 10$  cm. radius instead of 2.). The 6D invariant emittance will be about  $100 \pi \text{ mm}^3$  (sub-bunch emittance) [4], at a momentum of 186 MeV/C, with  $\Delta P/P \approx 10\%$ . Thus, one has to decrease the momentum by two order of magnitude without substantial phase space dilution.

Passive absorbers alone won't do the trick, because straggling and the non-linear behavior of energy loss are such that the significant fractions of the beam are likely to pass through such absorbers without losing enough energy, or stop in them. Not to mention additional multiple scattering. The following schemes can be mentioned:

- r.f. deceleration followed by an inverse radio frequency quadrupole. (e.g., imagine a conventional ion injector, working backward).
- Use of a cyclotron trap. [6]
- 5D Emittance exchange: based on a succession of Wien filters and passive absorbers, followed by recombinations by transverse stacking.
- 5D Emittance exchange: the passive absorbers are wedges placed at high dispersion points in a bend solenoid based channel. Phase space dilution occurs transversely due to multiple scattering. The bunch length increases as well, which is not a problem, while  $P$  and  $\Delta P$  decreases, which is our goal.
- Same as above, in helicoidal channel.

None of these ideas have been worked out. The first one can probably be rejected quickly given the large emittance we start with, and the constraint on the channel length (at  $\beta \approx .02$ , one muon life time is 12.5 m.). The beam optic and extraction for the second one looks difficult The others looks more promising, although the transverse re-heating might be prohibitive. However, let us give us the benefit of the doubt, and assume we can overcome these difficulties.

## Description of the method and experiment

At 10 KeV kinetic energy, in thin carbon foils, the electron cloud maintain the muons motion, because the electron and muon velocity are about equal. This means that, if a muon slows down too much, he will be re-accelerated. If a longitudinal boost is continuously applied, cooling can be obtained. Experimental details are given in reference [3]. With a stack of 10 to 12 foils, each  $\approx 5 \mu\text{gr}/\text{cm}^2$ , and a static electric field of about 1.4 KV/cm to restore the longitudinal momentum, cooling merit factor of about 2.5 transversely and 3.7 longitudinally have been achieved [5]. The beam loss due to muon absorbed in the foils was approximately 30 %.

## Difficulties for intense muon bunches

The counting rate was about 10 to 20 muons per second. (Assuming the PSI cyclotron gave 1 mA on target). Thus, for all practical purpose, the muons are “alone” in the apparatus, as they cool. Not quite, though: as the muons traverse the foil, secondary emission occurs, followed by acceleration in the d.c. electric field. As for the muons, they trapped in the confining magnetic field (5 Tesla). However, there is no collective motion because there are so few of them.

Let us consider now dumping about  $10^{12}$  muons in that magnetic bottle. The r.m.s  $\sigma_x, \sigma_y$  of the beam spot is of the order of 2 cm. Even with a relatively long magnetic trap of 30 cm, capturing a longitudinal bunch length of 10 cm., the quasi-static electric field ( $E_r, E_z$ ) will reach (0.17, 2.7) MV/m. The longitudinal component is about 20 times greater than the applied electric field which keeps the beam moving in the right direction. The next problem could be the heat dissipated in the thin foils due to the primary muons and the secondary emission: each muon loses approximately half of KeV in each foil. A  $10^{12}$  bunch will dissipate  $\approx 7.2 \cdot 10^{-5}$  Joule in the  $5 \mu$  gr. of Carbon, raising its temperature by  $\approx 20$  degree C. This does not include secondary emissions. May be this is not a problem, although these foils are quite fragile, and may age rather quickly in such an environment.

The space charge limit is a real issue. For the scheme to work properly, the charge of the bunch must be reduced by roughly two order of magnitude. The luminosity of the muon collider will then decrease by 4 orders of magnitude. We might have gain one order in magnitude due to the cooling, which is not enough... This is not an issue bringing the beam in the friction cooling channel, because the macro bunch length is much longer. However, no matter what the cooling scheme is once the bunch is compressed longitudinally (e.g., quasi stopped), the space charge issues is very much relevant to the extraction and re-acceleration. I will come back to that point.

## THE ZERO ENERGY OPTIONS AND EXOTIC PLASMA

The friction cooling method comes short on three counts: (i) The transverse emittances coming from the ionization channel into the friction cooler do not match, by a factor 10 to  $20^3$  (ii) Since the beam does not stop in the foil (at least the 60 % fraction one intends to keep) , but merely drifts at a reduced velocity (percent of the speed of light), the longitudinal compression (geometrical) is not yet optimal. (iii) Severe space charge will limit this longitudinal compression entering the magnetic bottle and moving into it, where the foils/re-accelerators resides.

One somehow must learn how to neutralized the bunch, while keeping the muon “charged”, in a small physical volume:  $\approx 100. \text{ cm}^3$ , at most. If the entire macro-bunch is stopped in a thin foil (tens of micro-gram up to 1 milligrams), in presence

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<sup>3)</sup> This depends on which ionization cooling final stage (neutrino factory vs 15 T. Alternate Solenoid)

of such extreme charge densities, it is very likely that the foils will suffer damage and can not be used over any reasonable number of booster cycle. So be it, we will find a way to replace the foils every 1/15 of a second.

If the charge is to be compensated, say with low energy beam of protons or electrons, we are then compelled to consider our final cooling system not as made of solid or gaseous moderators with an externally applied re-acceleration voltage, but as an exotic plasma: This medium is composed of ions being ejected from the moderators, KeV electrons or protons to provide charge compensation and the muons. We now briefly review such methods, where in each cases, during a fraction of micro-second, the muons are literally “thermal” and slowly moving in solids. in less than  $\approx 100$  ns., the physical state must become a plasma. Evidently, it is best to study these exotic  $\mu^+$  or  $\mu^-$  plasma separately.

## Thermal muonium from metallic foils

Some of these concerns might also be applicable to the cooling method based on muonium produced in hot tungsten foils [7]. There also, charge densities will be high. Yet, the scheme proposed by Prof. Nagamine is certainly compelling. May I take this opportunity to ask the following naive questions or remarks on this preferred method. The crude sketch given on figure 1 illustrates a cooler based on a magnetic bottle, a tungsten absorber where muonium are produced, an a scheme to extract them and ionization. In more details:

1. Once again, the transverse emittance coming from the ionization channel and moderator will not quite match the spot size of the laser ( $mm^2$ . vs few  $cm^2$ ). Hence achieving resonant ionization of the muonium will be costly, if achievable.
2. Same concern in the longitudinal direction: it is very unlikely that the dispersive channel will reduce the momentum down to a  $\approx 4. MeV/c$  with a  $\Delta P/P \approx 6\%$ . A crude guess-estimate is that we might reach a momentum of 40 MeV/c with a  $\Delta P/P$  of 30 %<sup>4</sup>. The last moderator will gives a beam of  $\approx 20 MeV/c$  with a  $\Delta P/P \approx 50\%$ . Hence the need to use multiple foils. However,  $20 \times 100 \mu m. = 2 mgr/cm^2$ . might not be enough to stop such muons. Hence, either we further increase the number of foils (and lasers!) or we place these foils in a magnetic trap, such that the high muons bounce multiple times until the stop in the foils. The limitation by the leak rate of the bottle (muon going straight on the axis can escape) and by the muon life time. Both limits probably impose a maximum number of bounces or foil traversal in the bottle, of about  $\approx 10$ .

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<sup>4</sup>) Without detailed simulation, of a scheme discussed above, one might easily be off by a factor 2 in these quantities

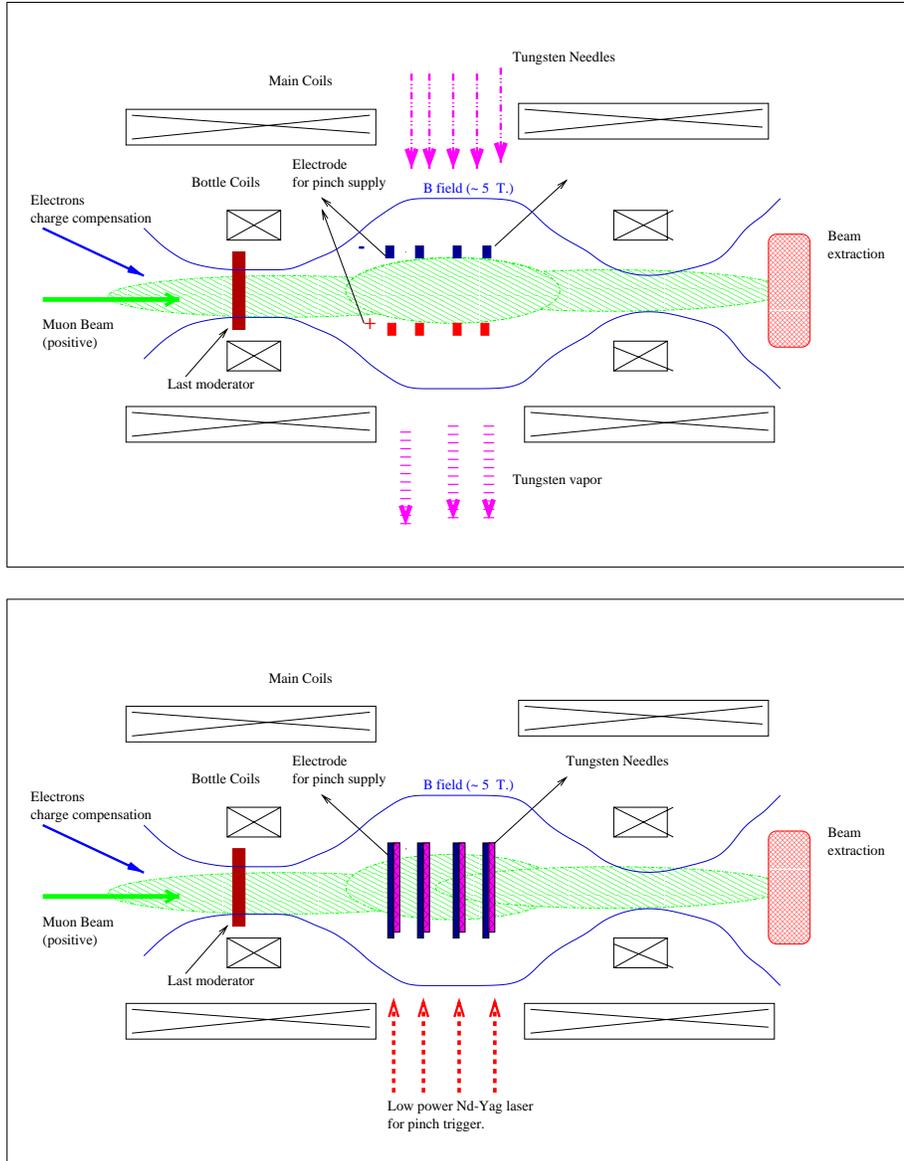
3. If the muonium formation inside the tungsten is more (or as) efficient at low temperature [8], why not consider a scheme where the Tungsten will be maintained at a more modest temperature (few hundreds degrees as oppose to  $\approx 2,000$  degree C.)
4. But then, the muonium won't diffuse out of the foils. As longitudinal compression has to occur, this is good: they better stay put in the foil for  $\approx 100\text{ ns} \rightarrow 300\text{ ns}$  until the complete macro-bunch is captured.
5. We now have to heat the foil, quickly ( $< 100\text{ ns}$ ), and ionize the muonium once it is out of the foil. Conventional heating method will be too slow. It also better be rather efficient: the total amount of Tungsten to heat to thousands of degree is approaching a fraction of a gram.
6. Can we organize the tungsten as a number of cold needles, falling through a grid of electrodes, and send a high power pulse (tens to 100 kJoules, MW peak power), so that the needles are "Z-pinched"? Such Z-pinches are the preferred method to heat tungsten at KeV-like temperature.
7. As the electron temperature in these imploded needles get higher than  $\approx 100\text{ eV}$ , muonium trapped inside will ionize. Assuming the muons are in thermal equilibrium with these electrons, there velocity will be of the order of  $\approx 40\text{ cm}/\mu\text{sec.}$ , fast enough to move away from the needles before the plasma recombines.
8. We are left with a few  $\text{cm}^3$  volume where the electron-tungsten ions do form a highly unstable, non-uniform plasma. Note that the muons are too diluted to contribute to the collective motion of the plasma (they are do not form a plasma per say, they embedded in a conventional plasma).
9. However, it might still make sense to compute the plasma frequency for muons. After about 100 ns, they will occupy the entire volume of this irregular plasma ( the tungsten atoms or ions are 2,000 times slower). Assuming a volume a few  $\text{cm}^3$  and a  $1.0 \cdot 10^{12}$ , the plasma frequency for the muons will of the order of a GHz. If not compensated ( or partially compensated), the electric field due to their collective static charge will be of the order of 10 MV/m. Can such frequency and field parameters could be matched to the r.f. field used on the extracting electrode, or the buncher?

## The $\mu^-$ cooler

A collider works best if the emittances of the colliding beam are about the same. Thus, similar emittances must be reached for the  $\mu^-$ . This has been quoted as "a problem" during this workshop [7] A few ideas have been proposed, on which I wish to comment<sup>5</sup>.

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<sup>5</sup>) One should be limited to only one such "new" idea per paper, sorry for being greedy



**FIGURE 1.** Naive sketch of the Tungsten -  $\mu^+$  cooler. Top : elevation, bottom plain view. The diameter of the inner coils would be approximately 10 cm. and the length of the bottle is  $\approx 30$  cm.

## 1 *He3-mu exotic ions*

In the magnetic bottle described above, one could remove the Tungsten foils or needle and replace with an H3 gas or liquid jet.  $\mu^-$  are stopped and quickly captured. The  $He3 - \mu^-$  exotic atom is left with a net positive charge, as the electrons are ejected in the capture process. If a plasma forms quickly thereafter, recombination between electrons and the exotic atom does not occur, due to the low density of the medium. One then extract these exotic ions (hopefully with reasonable efficiency) and accelerate them. The emittance of the muon remains small in the process. A foil intercepting this beam strips the negative muons. In the rest frame of the exotic atom, this stripping process give  $\approx 20KeV$  kinetic energy to the muons. Such energy transfer can occur at sufficiently high velocity via transition radiation from the stripping foil. In this process, the momentum transfer to the  $\mu^-$  is of the order of  $2 MeV/c$ .

In order to limit the emittance growth due to this momentum transfer, the exotic atom must be boosted at sufficiently high energy. At  $\approx 10. GeV/c$  the  $He - \mu^-$  and therefore the  $\mu^-$  will be boosted at  $\beta \approx .76$  and the liberated  $\mu^-$  will keep there mere  $125 MeV/c$  momentum, and a  $\Delta P/P$  of 2 to 3 % is expected. (neglecting the  $\Delta P/P$  of the  $He3 - \mu^-$  exotic ions. Accelerating these ions up to these energy if less than a few micro-second (without much gain from an appreciable Lorentz boost!) is a tall order, unfortunately. Hopefully, one can do better.

## 2 *Z-pinched D2-Muons*

Instead of using Helium or Hydrogen<sup>6</sup>, let us consider deuterium. Muon catalyzed fusion for cooling negative muons has not only been proposed, in fact, it has been experimentally demonstrated [9]. However, in order to avoid having the  $\mu^-$  merely forming exotic  $D2 - \mu^-$  molecules in the solid deuterium without escaping in his lifetime, catalyzing the fusion and doing it again until it decays, the thickness of the D2 film must be limited to  $30 \mu gr$ . Such thin films will not stop of  $\approx 20 MeV/c \mu^-$  (They have a range in liquid Hydrogen is 2 mm.)

Remember now that we could cross this D2 target a few times, thank to the magnetic trap and the relatively long decay length of these  $\mu^-$ . However, it still won't bring us down to the required thickness. Thus, the negative muons are trapped in the solid D2 for a long time, unless the D2 temperature get raised very quickly after the complete stop of the muon beam.

Once again, let us consider Z-Pinches. This technique has been used to raised the D2 temperature high enough so that nuclear fusion occurs (without muon catalysis) [10]. However, in our application, there is no need to reach such high temperature, one simply has to avoid that the negative muons bind to an other D2 molecule by

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<sup>6</sup>) One could consider  $p - \mu^-$  exotic neutral atoms, and let these capture an electron, so that they can be extracted and accelerated. However, the probability to capture this electron in such low density plasma is too small

reducing the density. Cryogenic Deuterium fibre have been manufactured in-situ, either from condensed droplets (or “snow”) or continuous extrusion [11]. These experiments were conducted on single fibres, for ease of implementation. Implosion velocity of the fibers of  $1. cm/\mu sec.$  are considered low. In a gas embedded compressional Z-pinch, explosion velocity of  $0.4 cm/\mu sec$  have been recorded. These phenomena occur in the right time scale for us: 10 to 100 ns. [12].

As soon as the density is reduced, negative muons liberated during the fusion process are no longer able to find other D2 molecules. The emerging plasma can them be heated further and the charge can be compensated, by dumping low energy proton beam into it. (or simply, by ionizing enough D2, and collecting the rapidly moving electrons. On is then left with a negative muons embedded in the typical ion source.

## Caveats

The present author is interested at learning where such naive schemes would fail. Such ideas are indeed very speculative. For instance, how do we drop or shoot the Tungsten needles evenly so that all positive muons are stopped, and the Z-pinch occurs in each needles. (The hope is the impedance of a formed plasma is not too low compared to Ohmic resistance of the adjacent cold needle, or the trigger provide a uniform pre-ionization on all the needle tips.). Same concern for our D2 fibres or “snow” flakes: relatively uniform heating must occur so that the local density drops sufficiently rapidly. Dumping tens of kJoules of power at 15 Hz in leads us awfully close to the MW range. (To avoid evaporating the D2 fiber to due heat released while the  $\mu^-$  beam stops, one would need enough D2 mass..). An other concern: in such exotic ion sources: e.g., radiated heat from the electrodes onto the cold D2 fibers could also melt them prematurely...)

Once such relatively high volume, non-uniform, plasma are formed, how do we extract efficiently the  $\mu^\pm$  from it? And how fast? A goal for a muon collider would be to achieve a macro-bunch length of  $\approx 30 cm. \rightarrow 1. m.$ , with a transverse normalized emittance of  $\approx 3 \rightarrow 10 \pi mm. mrad$  (beam spot size of a few cm, with angles of about a radian and  $\beta \approx 10^{-3}$ ). with  $10^{11}$  particles in such bunches. Space Charge is still an issue at the extraction and early acceleration stage. Finally, such beams must be accelerated at relativistic speed fast enough. Tens of MV/m are required in the RFQ. This means higher frequencies ( $\approx GHz$ ) are needed, or superconducting RFQs [13]<sup>7</sup>. Such High Frequencies would match the muon plasma frequency better (unclear if this is an advantage), but would require smaller beam spot size to fit in the structure. And, unfortunately, multi-beam, high frequency, RFQ have not been invented yet (to my knowledge). So, we have work ahead of

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<sup>7)</sup> The idea of SRFQ is mentioned for completeness. Actually, the main advantage would be to allow for d.c. operation, irrelevant in our case. Acceleration of 2.16 MV/m have been obtained with such SRFQ's, not that much higher than normal conducting structures at the same frequencies

us. However, the “zero energy” option for muon cooling should not be abandoned too quickly.

## ACKNOWLEDGEMENTS

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