IONIZATION COOLING*

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Abstract

All three components of a particle's momentum are reduced as a particle passes through and ionizes some energy absorbing material. If the longitudinal momentum is regenerated by RF cavities, the angular divergence of the particle is reduced. This is the basic concept of ionization cooling. What can be done for a muon beam with this simple idea is almost amazing, especially considering that the muon lifetime is only 2.2 µs in its rest frame. In this paper we discuss the evolution and present status of this idea, where we are now ready to design muon colliders, neutrino factories, and intense muon beams with very effective cooling in all three dimensions. The discussion will include the heating effects and absorber Z-dependence of multiple scattering, numerical simulation programs, the accuracy of scattering models, emittance exchange, helical cooling channels, parametric-resonance ionization cooling, and the ionization cooling demonstration experiments, MICE and MANX.

INTRODUCTION

In the last year, several things have come together to reinvigorate muon collider enthusiasts: 1) There is a great interest to have a plan for a next-generation project that would continue the energy-frontier accelerator tradition in the US. 2) The uncertainties in need, cost, and siting of the International Linear Collider (ILC) have made it clear even to strong ILC supporters that a "Plan B" is prudent. 3) While impressive work has been done toward a neutrino factory based on a muon storage ring [1,2], the physics case for such a machine will have to wait for results of experiments that are just getting started. Thus there is some muon-related accelerator expertise that is available for muon collider development. 4) As discussed below, several new ideas have arisen in the last five years for six-dimensional (6D) muon beam cooling. The advantage of achieving high luminosity in a muon collider with beams of smaller emittance and fewer muons has been recognized as a great advantage for many reasons [3], including less proton driver power on target, fewer detector background issues, and relaxed site boundary radiation limitations.

Another advantage of small 6D emittance for a collider is that the cost of muon acceleration can be reduced by using the high frequency RF techniques being developed for the ILC. To the extent that muon beams can be cooled well enough, the muon collider is an upgrade path for the ILC or its natural evolution if LHC results imply that the ILC energy is too low or if its cost is too great.

Effective 6D cooling and the recirculating of muons in the same RF structures that are used for the proton driver may enable a powerful new way to feed a storage ring for a neutrino factory [4]. This would put neutrino factory and muon collider development on a common path such that a muon collider could be realized in several stages, each independently funded and driven by high-energy physics goals, e.g. a very cool stopping muon beam, neutrino factory, Higgs factory, energy frontier collider.

IONIZATION COOLING PRICIPLES

The idea that the transverse emittance of a beam could be reduced by passing it through an energy absorber originated in Novosibirsk many years ago [5,6]. Figure 1 is a schematic of the concept, showing how the angular divergence of a beam can be reduced.
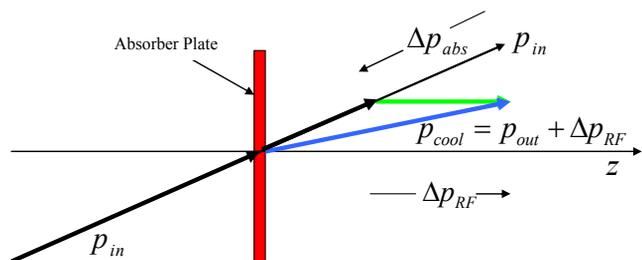

Figure 1: Conceptual picture of the principle of Ionization Cooling. Each particle loses momentum by ionizing an energy absorber, where only the longitudinal momentum is restored by RF cavities. The angular divergence is reduced until limited by multiple scattering, so that a low-Z absorber is favored.

Ionization cooling of a muon beam involves passing a magnetically focused beam through an energy absorber, where the muon transverse and longitudinal momentum components are reduced, and through RF cavities, where only the longitudinal component is regenerated. After some distance, the transverse components shrink to the point where they come into equilibrium with the heating caused by multiple coulomb scattering. The equation describing the rate of cooling is a balance between these cooling (first term) and heating (second term) effects:

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0} \quad [1].$$

Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity. Muons passing through an absorber experience energy and momentum loss due to collisions with electrons. The derivations and discussions of the basic formulae of ionization cooling can be found in many places [7,8], where the energy loss is described by the Bethe-Bloch theory and the multiple-scattering heating is

described by the Moliere theory [9].

Setting the heating and cooling terms equal defines the equilibrium emittance, the very smallest possible with the given parameters:

$$\varepsilon_n^{(equ.)} = \frac{\beta_\perp (0.014)^2}{2\beta m_\mu \frac{dE_\mu}{ds} X_0} \qquad [2].$$

A cooling factor ($F_{cool} = X_0 dE_\mu/ds$) can be uniquely defined for each material, and since cooling takes place in each transverse plane, the figure of merit is F_{cool}^2. For a particular material, F_{cool} is independent of density, since energy loss is proportional to density, and radiation length is inversely proportional to density. The inverse of F_{cool}^2 corresponds to the best equilibrium emittance that can be achieved. Super-conducting solenoidal focusing is used to give a value of $\beta_\perp$ as low as 10 cm. Figure 2 shows F_{cool}^2 for many materials of interest.

Gaseous hydrogen is the very best material that one can use from the standpoint of the final equilibrium emittance. Also, since the exponential cooling rate depends on the difference between the initial and final emittances, it provides the very best cooling rate.
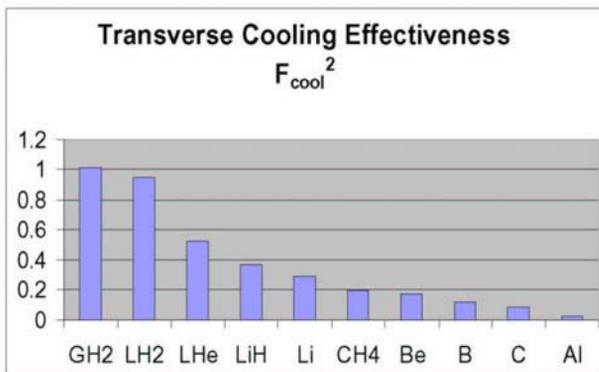

Figure 2: A comparison of the cooling figure of merit for light materials. The equilibrium beam emittance in each transverse plane is inversely proportional to the product of the energy loss and the radiation length. The graph indicates the total figure of merit,

Fundamental Limitations

The transverse beta function, $\beta_\perp$, is proportional to the ratio of momentum divided by the magnetic field. So the lowest equilibrium emittance requires the lowest momentum and the highest field.

As implied by the Bethe-Bloch equation and shown on figure 3, the fact that *dE/dx* increases as the momentum decreases means that once the momentum is below a few hundred MeV/c, any transverse cooling is necessarily accompanied by longitudinal heating. To a certain extent, this unwanted heating can be mitigated by modifying the dispersion function [10] and/or changing the profile of an absorber with shaped edges.

The maximum magnetic field is a technological problem discussed below. One solution is the use of High Temperature Superconducting (HTS) magnets that can develop large fields at low temperatures.
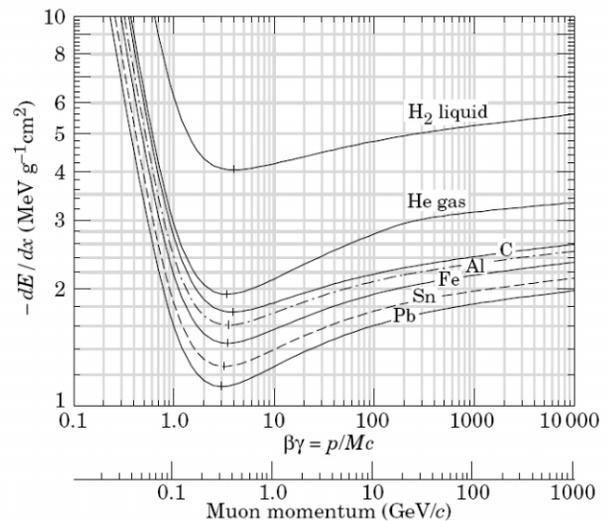

Figure 3: Energy loss for muons in various materials taken from the Particle Data Group [11], where the minimum *dE/dx* for hydrogen occurs near 300 MeV/c.

Multiple Scattering

Investigations of the deficiencies of the Moliere theory for low-Z materials [12] and other models [13] have been vindicated by recent measurements, as shown in figure 4. These seemingly small differences in the tails of the scattering distributions can have large consequences for long cooling channels. An ICOOL investigation indicated that as much as a factor of 3 improvement in cooling factor could be achieved with scattering models that agreed with the MuScat [14] data compared to the Geant4 models that we have used up to now.
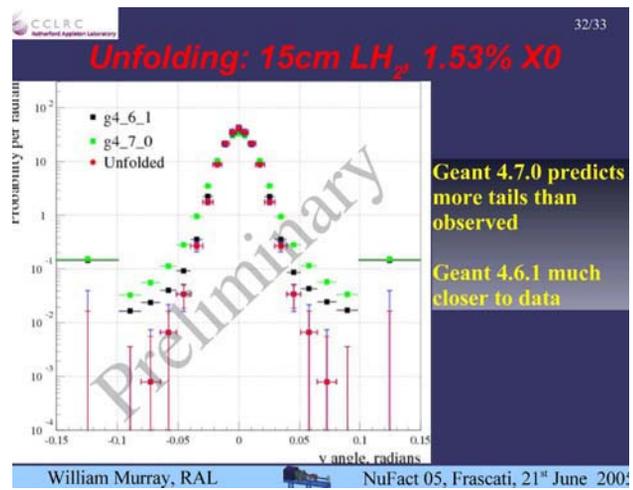

Figure 4: Comparison of angular distributions of the MuScat experiment for muons scattering off of hydrogen with two different releases of the Geant4 simulation program. The (red) experimental data show smaller tails.

Charge Sign Effects

As a post-doc I was fortunate to experimentally discover that a 500 to 1500 MeV/c muon's range depends on its charge sign [15]. Although Hans Bethe assured me in a telephone call in 1971 that such an effect must be

down by 6 orders of magnitude, later discussions with David Jackson substantiated my claim that the range difference was three orders of magnitude larger than Bethe believed. The effects of the interference between one- and two-photon exchange diagrams were calculated [16] and gave good agreement with our measurements. A range difference for very low energy muons had previously been noted by Barkas [17] but apparently not understood. The extreme ionization cooling required for muon colliders may require that effects as small as the charge-sign interference be included in the simulation cross-sections to get the energy loss and multiple scattering right.

Emittance Exchange

To achieve longitudinal cooling requires emittance exchange with transverse oscillations. Emittance exchange, in turn, requires the introduction of a beam bend that creates dispersion, a correlation between the orbit and energy of a particle. Figure 5 shows the conceptual pictures of the two approaches that have recently been studied most. In the left of figure 5 the use of a wedge absorber is shown, where the beam is dispersed across a wedge of energy absorbing material such that higher momentum particles lose more energy. The muons become more monoenergetic after they pass through the wedge, while the transverse emittance is increased as part of the emittance exchange process.
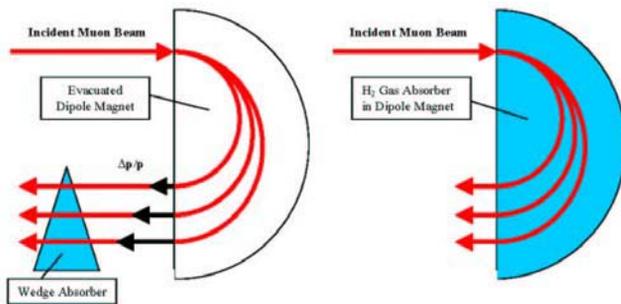

Figure 5: Emittance exchange. LEFT: Wedge Absorber Technique. RIGHT: Homogeneous Absorber Technique where dispersion causes higher energy particles to have longer path length and thus more ionization energy loss.

Gas-filled Helical Cooling Channel (HCC)

The HCC is an attractive example of a cooling channel based on this idea of energy loss dependence on path length in a continuous absorber. One version of the HCC uses a series of high-gradient RF cavities filled with dense hydrogen gas, where the cavities are in a magnetic channel composed of a solenoidal field with superimposed helical transverse dipole and quadrupole fields [18,19]. In this scheme, energy loss, RF energy regeneration, emittance exchange, and longitudinal and transverse cooling happen simultaneously.

The helical dipole magnet creates an outward radial force due to the longitudinal momentum of the particle

while the solenoidal magnet creates an inward radial force due to the transverse momentum of the particle, or

$$F_{h-dipole} \approx p_z \times B_\perp; \quad b \equiv B_\perp ,$$
$$F_{solenoid} \approx -p_\perp \times B_z; \quad B \equiv B_z$$

where B is the field of the solenoid, the axis of which defines the z axis, and b is the field of the transverse helical dipole at the particle position. By moving to the rotating frame of the helical fields, a time and z-independent Hamiltonian can be formed to derive the beam stability and cooling behavior [20].

Use of a continuous homogeneous absorber as shown on the right side of figure 5, rather than wedges at discrete points, implies a positive dispersion along the entire cooling path, a condition that has been shown to exist for an appropriately designed helical dipole channel. We have also shown that this condition is compatible with stable periodic orbits. The simple idea that emittance exchange can occur in a practical homogeneous absorber without shaped edges followed from the observation that RF cavities pressurized with a low Z gas are possible [21,22].

The analytic relationships derived from this analysis were used to guide simulations using a code developed based on the GEANT4 [23] program called G4Beamline [24] and also using ICOOL [25] developed at BNL.

Simulation results [10] show cooling factors or 50,000 for a series of 4 250 MeV/c HCC segments, where the magnet diameters are decreased and fields are increased as the beam cools. In this example the final field would be 17 T with a hydrogen gas pressure of 400 atmospheres.

Momentum-dependent HCC

While the HCC described above operates at constant energy, another set of applications follows from HCC designs where the strengths of the fields are allowed to change with the muon momentum. The first example was a 6D precooler, where the beam is slowed in a liquid hydrogen absorber at the end of the pion decay channel, with 6D emittance reduction by a factor of 6. Another example is a stopping muon beam based on a HCC [26].

Parametric Resonance Ionization Cooling

Parametric-resonance Ionization Cooling (PIC) [27], requires a half integer resonance to be induced in a ring or beam line such that the normal elliptical motion of particles in $x - x'$ phase space becomes hyperbolic, with particles moving to smaller x and larger x' as they pass down the beam line. (This is almost identical to the technique used for half integer extraction from a synchrotron where the hyperbolic trajectories go to small x' and larger x to pass the wires of an extraction septum.) Thin absorbers placed at the focal points of the channel then cool the angular divergence of the beam by the usual ionization cooling mechanism, where each absorber is followed by RF cavities. Thus in PIC the phase space area is reduced in x due to the dynamics of

the parametric resonance and x' is reduced or constrained by ionization cooling. The basic theory of PIC is being developed to include aberrations and higher order effects. Simulations using linear channels of alternating dipoles, quadrupoles, solenoids, or HCC's are now underway [28].

PHASE SP ACE REPARTITIONS

Reverse Emittance Exchange Using Absorbers

A muon beam that is well cooled at one or two hundred MeV/c will have its unnormalized longitudinal emittance reduced by a factor of a thousand or more at 100 or more GeV collider energy. At the interaction point in the collider the bunch length would then be much shorter than the IR focal length. In reverse emittance exchange (REMEX), we propose to repartition the emittances to lengthen each bunch and narrow the transverse emittances using beryllium wedge energy absorbers.

Calculations show that two stages of reverse emittance exchange, one at low energy and one at a higher energy before energy straggling becomes significant, can reduce each transverse emittance by an order of magnitude.

Muon Bunch Coalescing

One of the newest ideas is to cool less intense bunches at low energy and to recombine them into intense bunches at higher energy where wake fields, beam loading, and space charge tune shifts are less problematic [29].

Beryllium Wedges

Both PIC and REMEX techniques involve the focusing of a beam onto an energy absorber for which beryllium is better suited than the lower-Z materials shown in figure 2. First, the higher density of beryllium allows the thickness of the absorber to be a smaller fraction of a betatron wavelength and thereby more effective since the average betatron function in the region of the absorber is closer to the minimum value. Second, the energy straggling in the absorbers leads to longitudinal heating that must be controlled by emittance exchange. Thus the absorbers should be thin wedges made of beryllium which can easily be refrigerated to handle the heat deposition of the bright beams required by a muon collider.

NEW COOLING TECHNOLOGY

Pressurized RF Cavities

A gaseous energy absorber enables an entirely new technology to generate high accelerating gradients for muons by using the high-pressure region of the Paschen curve [30]. This idea of filling RF cavities with gas is new for particle accelerators and is only possible for muons because they do not scatter as do strongly interacting protons or shower as do less-massive electrons. Measurements by Muons, Inc. and IIT at Fermilab have demonstrated that hydrogen gas suppresses RF breakdown very well, about a factor six better than helium at the same temperature and pressure.

Consequently, much more gradient is possible in a hydrogen-filled RF cavity than is needed to overcome the ionization energy loss, provided one can supply the required RF power. Hydrogen is also twice as good as helium in ionization cooling effectiveness, viscosity, and heat capacity. Present research efforts include tests of materials in pressurized RF Cavities in magnetic fields [31] as shown in Figure 6, where an external field causes no apparent reduction in maximum achievable gradient. Crucial beam tests of the concept are scheduled in 2008.
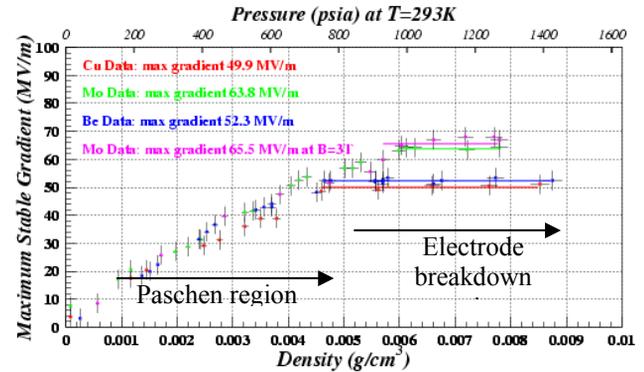
Figure 6: Measurements of the maximum stable RF gradient as a function of hydrogen gas pressure at 805 MHz with no magnetic field for three different electrode materials: Cu (red), Mo (green), and Be (blue). The cavity was also operated at the same gradients in a 3T field with Mo electrodes (magenta).

High-pressure RF cavities near the pion production target can be used to simultaneously capture, bunch rotate, and cool the muon beam as it emerges from the decaying pions [32]. We have started an R & D effort to develop RF cavities that will operate in the extreme conditions near a production target and an effort to simulate the simultaneous capture, phase rotation, and cooling of muons as they are created from pion decay.

High Temperature Superconductor

Magnets made with high-temperature superconducting (HTS) coils operating at low temperatures have the potential to produce extremely high fields for use in accelerators and beam lines. The specific application of interest is to use a very high field (greater than 30 Tesla) solenoid to provide a very small beta region for the final stages of cooling for a muon collider. With the commercial availability of HTS conductor based on BSCCO or YBCO technology with high current carrying capacity at 4.2 K, very high field solenoid magnets should be possible. We are evaluating the technical issues associated with building this magnet [33]. In particular we are addressing how to mitigate the high Lorentz stresses associated with this high field magnet.

Helical Solenoid

The original concept of the HCC involved a rather complex magnet with separate coils to provide the required solenoidal, helical dipole, and helical quadrupole fields. Figure 7 shows a new design [34] called a Helical

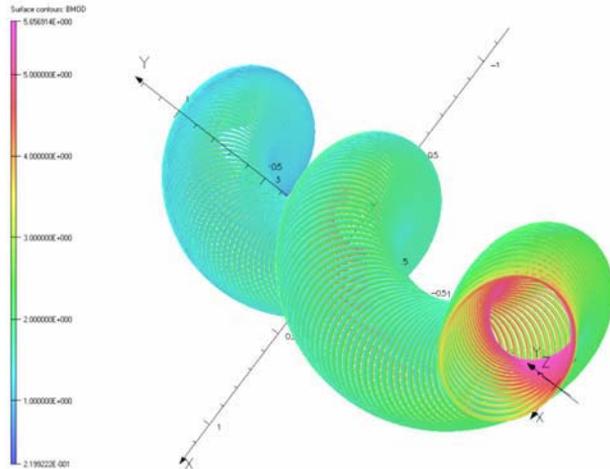Solenoid (HS) which uses simple offset coils to generate the three required components.

Figure 7: Helical Solenoid geometry and flux density for the Helical Solenoid magnet for MANX.

Muon Cooling Demonstration Experiments

The MICE project, designed primarily to develop transverse cooling to reduce neutrino factory cost, is described in another paper at this meeting. Figure 8 shows MANX, a 6D muon cooling demonstration experiment based on a HCC with variable field strengths. It is being designed to slow a 300 MeV/c muon beam to about 150 MeV/c in a HCC filled with liquid helium [35].
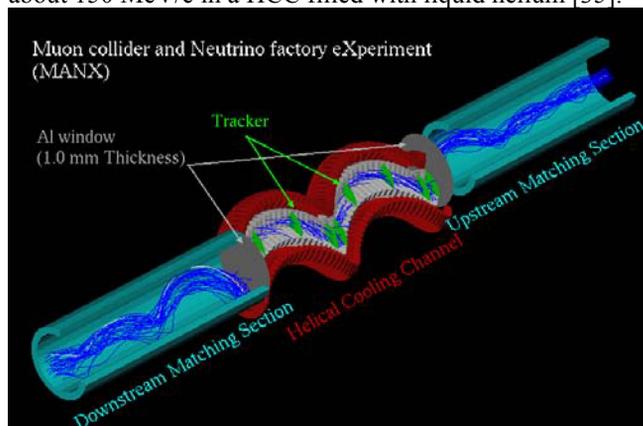

Figure 8: Conceptual picture of the MANX apparatus. The helical solenoidal magnets shown in red enclose the LHe ionization energy absorber, which is separated from the vacuum of the matching sections by thin Al windows.

SUMMARY

New 6D muon cooling ideas described above and a new enthusiasm to build an energy frontier lepton collider to follow the LHC are creating an exciting environment for muon collider research. More new ideas are described by Robert Palmer in another COOL07 contribution. High-pressure RF experiments are underway, with encouraging results. A 6D HCC demonstration experiment is being designed and plans for 1.5 TeV and higher center of mass muon colliders are being studied at Fermilab.

REFERENCES

[1] http://www.fnal.gov/projects/muon collider/nu/study/report/machine report/
[2] http://www.cap.bnl.gov/mumu/studyii/FS2-report
[3] http://www.muonsinc.com/mcwfeb07
[4] M. Popovic et al., Linac06
[5] M. Ado, V. I. Balbekov, Sov. At. Energy 31, 731,'71
[6] A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. 12, 223 (1981).
[7] D. M. Kaplan, http://www.slac.stanford.edu/econf/C010630/papers/M102.PDF
[8] P. Gruber, CERN/NUFACT Note 023, http://slap.web.cern.ch/slap/NuFact/NuFact/nf23.pdf
[9] Bethe, H. A.: Molière's Theory of Multiple Scattering, Phys Rev. **89**, 1256 (1953)
[10] K. Yonehara et al., EPAC06
[11] http://pdg.lbl.gov/2007/reviews/passagerpp.pdf
[12] A. V. Tollestrup & J. Monroe, MUCOOL note 176
[13] W. W. M. Allison et al., arxiv.org/PS_cache/physics/pdf/0609/0609195v1.pdf
[14] W. Murray, NuFact05, Frascati
[15] A. R. Clark et al., OBSERVED DIFFERENCES IN THE RANGES OF POSITIVE AND NEGATIVE MUONS, PL 41B, 229 (1972)
[16] J. D. Jackson and R. L. McCarthy, "Z3 Corrections to Energy Loss and Range", Phys. Rev. B6, 4131 http://link aps org/abstract/PRB/v6/p4131
[17] See PDG discussion of the "Barkas effect", http://pdg.lbl.gov/2007/reviews/passagerpp.pdf
[18] V. Kashikhin et al., Magnets for the MANX Cooling Demonstration Experiment, MOPAS012, PAC07
[19] S. A. Kahn et al., Magnet Systems for Helical Muon Cooling Channels, MOPAN117, PAC07
[20] Y. Derbenev and R. P. Johnson, Phys. Rev. Spec. Topics Accel. and Beams 8, 041002 (2005)
[21] R. P. Johnson et al., Linac04
[22] M. BastaniNejad et al.,RF Breakdown in Pressurized RF Cavities, WEPMS071, PAC07
[23] http://wwwasd.web.cern.ch/wwwasd/geant4/geant4
[24] T. J. Roberts et al., G4BL Simulation, PAC07
[25] R. Fernow, ICOOL, http://pubweb.bnl.gov/users/fernow/www/icool/readme.html
[26] M. A. C. Cummings et al., Stopping Muons Beams, THPMN096, PAC07
[27] Yaroslav Derbenev et al., COOL05
[28] D. Newsham et al., Simulations of PIC, PAC07
[29] C. M. Ankenbrandt et al., Muon Bunch Coalescing,, THMN095, PAC07
[30] Meek and Craggs, Electrical Breakdown in Gases, John Wiley & Sons, 1978, p. 557
[31] P. Hanlet et al., EPAC06
[32] D. Neuffer et al., Use of Gas-filled Cavities in Muon Capture, THPMN106, PAC07
[33] S. A. Kahn et al., High Field HTS Solenoid for Muon Cooling, MOPAN118, PAC07
[34] V. Kashikhin et al., PAC07
[35] K. Yonehara et al., Design of the MANX Demonstration Experiment, PAC07