The Solenoid Muon Capture System for the MELC Experiment

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Abstract. A solenoid capture system for the MELC experiment in which the efficiency of soft muon generation from the primary proton (600 MeV) is 10^{-4} in comparison with 10^{-8} for ordinary schemes has been proposed. Both signs of muons with an intensity 10^{11} μ^-/sec for negative and 2×10^{11} μ^+/sec for positive component can be generated by a pulse proton beam with an average current up to $\simeq 200$ μA. A detail 3-D calculation of the magnetic field for the MELC setup are presented. Production of muon from pion decay in solenoid capture system is studied. The target life time and radiation condition of the superconducting coil are considered.

INTRODUCTION

The problem of detecting processes violating the Law of lepton flavour conservation is one of the most important in modern elementary particle physics. In the $\mu^- \rightarrow e^-$ conversion process the muon and electron family numbers are not conserved, therefore this process is absent in standard theory of electroweak interaction. Discovering a connection between lepton families will prove the existence of new physical phenomena beyond the standard model. At present the $\mu^- \rightarrow e^-$ conversion [1] has been studied at a level of B.R. $< 4 \times 10^{-12}$. To advance further, it is necessary to have a much higher intensity of stopped negative muons. The MELC project will make it possible to obtain a sensitivity in exploring the $\mu^- \rightarrow e^-$ process as high as B.R. $\simeq 10^{-16}$, using a muon μ^- beam with a stopping rate up to $\simeq 10^{11}$ μ^-/sec.

Schematic of the MELC set-up [2] is shown in Fig.1. A proton beam is injected along the axis of the solenoid, having at the front part a magnetic field $\simeq 2.4$ Tesla, gradually decreasing as low as $\simeq 2$ Tesla. In the vicinity of the solenoid axis there are targets, consisting of thin tungsten (or molybdenum) disks of a small radius $\simeq 1$ cm, the total thickness of the targets along the beam is $\simeq 20$ g/cm^2 .

Pions produced in these discs precess along the magnetic field lines. Then they are reflected partially from the magnetic plug and drift mainly backward along the beam line. After few meters long flight most of soft pions have decayed and the resulting muons, confined inside a cylinder of a small radius R $\simeq$ 25 cm go straight or (after reflection from the magnetic plug) back, precessing along magnetic field lines.

The high efficiency of soft muon production backward is determined by the location of targets along the solenoid axis and by spacing of target disks, so that the possibility of secondary crossing by pion or muon of one of the target disks is relatively small. The backward production scheme has advantages due to the low background from high energy neutrons, the simplicity of injection of proton beam along the magnetic field and convenience of the target location.

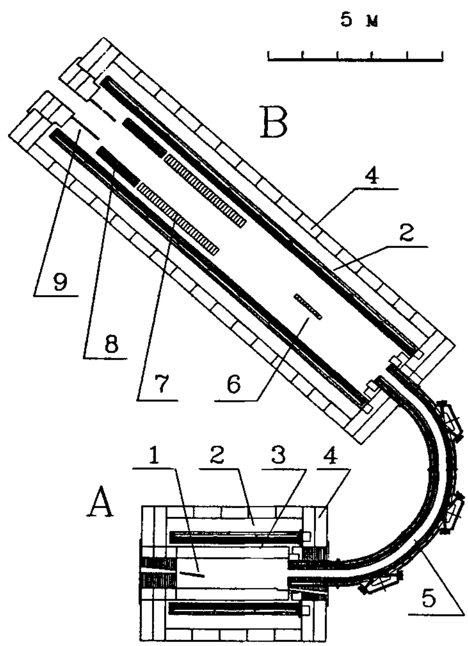

FIGURE 1. Set-up MELC: A – meson-producing part, B – detector part. Tungsten target of the meson-producing part (1), superconducting solenoids (2), solenoid shield (3), steel magnetic circuit (4), solenoid-collimator (5), aluminium target of the detector part (6), coordinate detector (7), total absorption scintillation spectrometer (8), shield against non-interacted muons and pions beam (9).

Owing to the spacing of target disks, and their extended surface it is possible to use radiation cooling for average proton current $\simeq$ 200 μA.

It is shown that for the average field $\simeq$ 2 Tesla, a collimator diameter $\simeq$ 25 cm and 200 μA average proton current the stopping rate in the detector target is 10^{11} particles/sec for the negative and 2×10^{11} particles/sec for the positive muons.

MELC MAGNETIC SYSTEM

The MELC superconducting solenoid system (Fig. 1) consists of a solenoid for the meson producing part and a solenoid for the detector part, linked by transporting solenoid-collimator system. For simplification of the calculation the solenoid-collimator was approximated with a straight system. Solenoids of the meson producing and detecting parts are surrounded by the iron yoke for the magnetic flux return. The solenoid-collimator has no iron yoke.

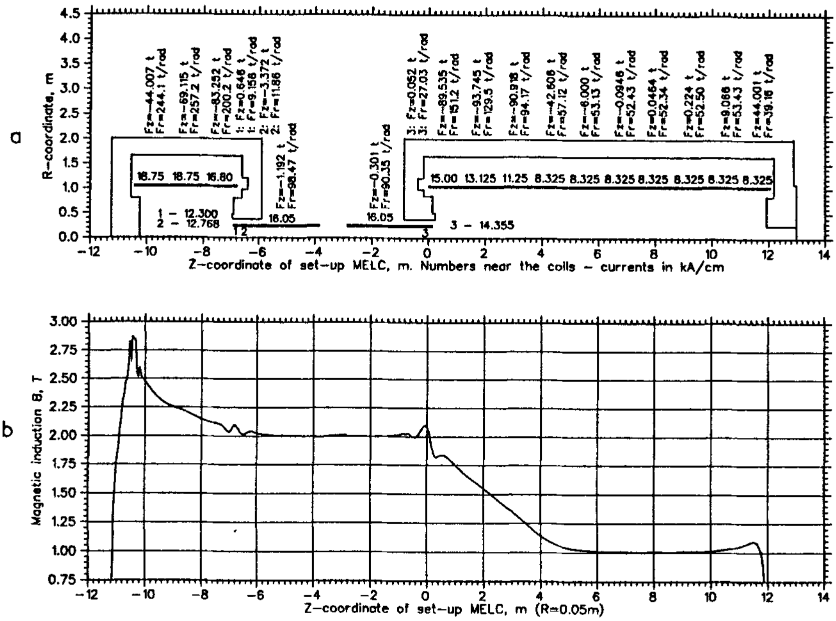

FIGURE 2. a) Axial plane (X,Z) of the solenoid system, b) dependence of B=f(Z) for X=30 cm, Y=0 cm.

To close the magnetic flux in the solenoids of large diameter, a possibility was considered to use an iron yoke of rectangular transverse section, assembled from a set of steel plates. The application of such a construction simplified to manufacture such a yoke.

The program MAGNUS [3] for 3-D magnetic calculation was used. The calculations showed that the use of an iron yoke of the rectangular transverse section does not affect the axial symmetry of the field inside of the solenoid coil and nor its value.

The magnetic calculations have shown that by selecting the form of pole pieces in the areas of solenoid joints and by changing mutual positions of the coil of the large and small solenoids, it is possible to achieve a rather gradual transition of the field lines.

The length of the solenoid coil element is 118.5 cm. Gaps between the elements are 5 cm determined by the thickness of the flanges necessary for joining coil elements.

Fig. 2a gives the cross section of the solenoid system in the (Z,R) plane.

Fig. 2a also shows the current in each element of the solenoid coils and forces acting on a given element are indicated over each element. F_z denotes forces acting along the Z axis (tons), F_r is the radial force with dimensions of ton/radian. $2\times F_r$ corresponds to the rupture forces for the two halves of the coil (if integrated by the angle from 0 to π). It is seen from the figure that the maximal axis force acting on a particular element of the coil $\simeq$ 90 t, the maximal radial force $\simeq$ 260 t.

Fig. 2b shows the variation of the magnetic induction line B=f(Z) obtained as a result of the calculations.

SOLENOID MUON CAPTURE SYSTEM

The System Efficiency

The meson production target (Fig. 1) is a set of thin ($\sim$ 0.015 cm thick) tungsten disks with radius $0.4 \div 1.6$ cm; its total length is 70 cm. which corresponds to a thickness 20 g/cm^2 along the beam axis. The target is tilted at 10^o with respect to the solenoid axis, which is required by technical requirements that have to do with the beam injection into the setup.

The pion production cross-section [4] (600 MeV proton) depends only slightly on the pion ejection angle and is 34 μb/sr/MeV on average. The integral cross-section is $\sigma = 4.3\ mb \times (T_\pi^{max}/10\ MeV)$, where T_π^{max} is the effective maximum kinetic energy of pions that may still produce μ^- that may travel to the detector part of the setup. At a current of 200 μA (1.2×10^{15} protons/sec) 10^{12} π^-/sec will be produced with energies up to 30 MeV. The flux of muons stopped in the detector target N_μ, the efficiency of proton interaction in the target ε_p and the efficiency that a pion produced in the target produces a muon stopped in the detector target $\varepsilon_{\pi\mu}$ were calculated by the GEANT program [5].

TABLE 1. Muon Flux N_μ, Efficiency ε_p and $\varepsilon_{\pi\mu}$

Target radius [cm]	ε_p	$\varepsilon_{\pi\mu}$	Flux N_μ [sec^{-1}]
0.4	0.4	0.15	0.7×10^{11}
0.8	0.7	0.12	0.8×10^{11}
1.2	0.8	0.11	1.0×10^{11}
1.6	0.9	0.08	0.8×10^{11}

The parameters of the detector target are: length 250 cm; disk radius 10 cm; disk thickness 0.02 cm; number of disks 50; density 2.7 g/cm^3, which corresponds to the thickness 2.7 g/cm^2 along the axis. The results of calculations are presented in table 1.

The muon flight time is determined as the muon life time from production to capture in the detector target. The muon kinetic energy and muon time of flight distributions are presented in Fig. 3 (a,b) respectively.

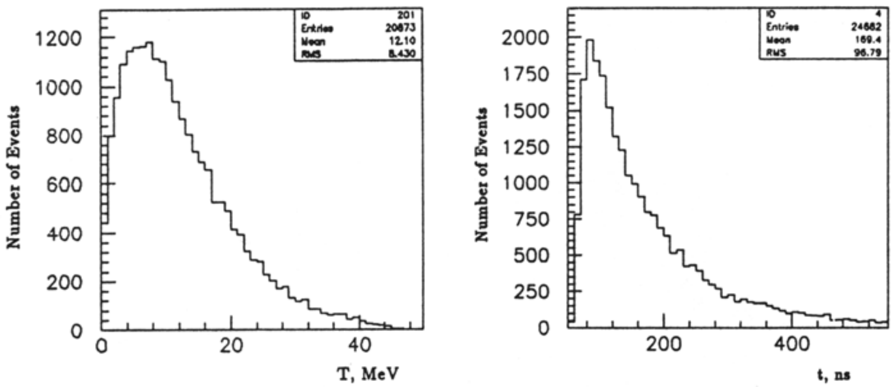

FIGURE 3. a) Muon kunetic energy distribution in detector part (Z = 20cm) b) Muon time of flight distribution until stop in detector target

The mean value of muon kinetic energy is$\simeq$ 12 MeV.

The transverse size of the muon trajectory is determined by three parameters: the helix line radius ($R_\perp$), the distance from Z-axis to the center of helix line (R_{Pole}) and the angle between muon momentum and Z-axis (θ).

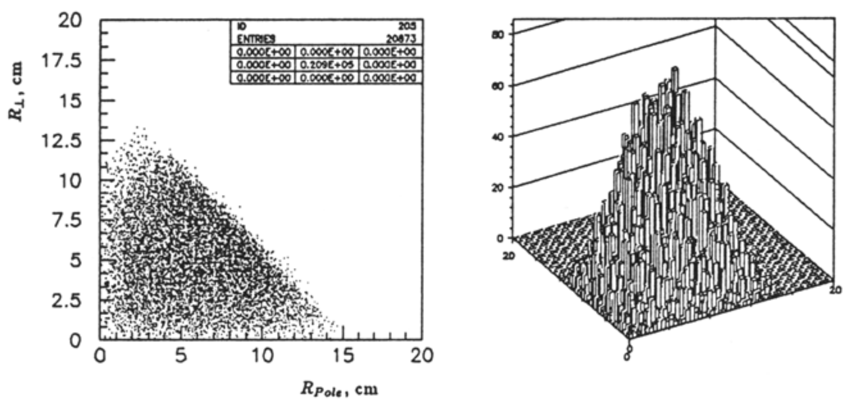

FIGURE 4. Scatteer plot for the muon radius $R_\perp$ versus the distance R_{Pole} in the detector part (Z = 20 cm)

The scatter plot for the radius $R_\perp$ versus R_{Pole} is shown in Fig. 4. The mean value of the radius $R_\perp$ is 5 cm and the mean distance R_{Pole} is 6 cm.

The muons produced by pion decay in flight move along helix lines, embracing the same field lines. The MELC magnetic field is smooth enough to provide adiabatic invariant conservation $sin^2\theta/B = const$, where θ is the angle between particle momentum and the magnetic field line and B is the magnetic field value.

Most of muons are produced in the higher magnetic (field $\simeq$ 2 T) and according to the adiabatic character of particle movement, the angle θ for the muon trajectory should be decreased in the detector part (field $\simeq$ 1 T). This effect is seen from the scatter plot for $cos(\theta)$ versus muon kinetic energy Fig.5.

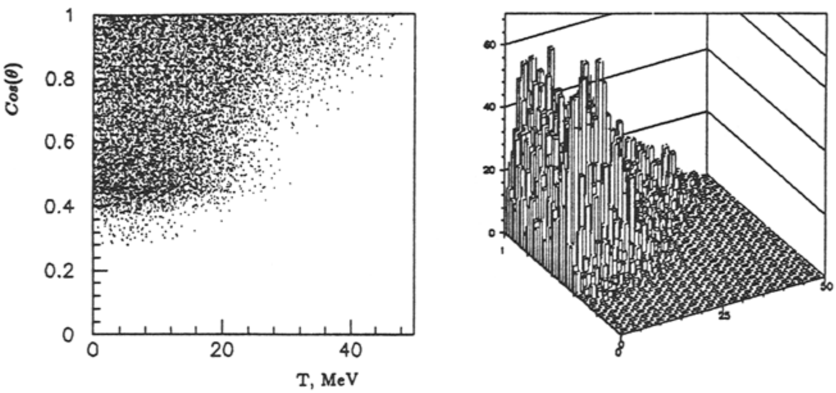

FIGURE 5. Scatter plot for the muon $cos(\theta)$ versus muon kunetic energy in the detector part (Z = 20 cm)

Target Life Time

The aging of the target is caused by tungsten evaporation from the surface of the disks due to their high temperature. The target durability was estimated as the time it takes for 1/10 of the disk thickness to evaporate. The most critical place is the centers of the first few disks of the target, since further downstream, the proton beam broadens due to multiple scattering.

To obtain a target life time of more than 1 year, the evaporation rate should be less than $4.8 \times 10^{-10} \times \mathbf{d}$ $(g/cm^2/sec)$, where **d** is a distance between the target disks.

The estimates, using data on tungsten evaporation from [6] rates, show that with a proton beam of a few mm size, a distance **d** less than 1 cm, a disk thickness $\simeq$ 0.015 cm and an average proton current of 200 μA, the target life time for the first few disks is more than 1 year.

Solenoid Radiation Conditions

We have estimated the heat release in the coil for different shield materials. The main contribution to the coil heat release is from low-energy neutrons ($\simeq$ 20 MeV) from the target.

In order to determine the heat release in the meson production solenoid coil a Monte-Carlo program [7] that calculates nucleon-meson cascades initiated by 0.02 to 10 GeV hadrons in heterogeneous media has been used.

The protection thickness was assumed to be equal to 55 cm, while the aluminium solenoid coil was 5 cm thick. The results of calculations are presented in the table 2.

TABLE 2. Heat Release in the Solenoid Coil

Shield material	Density $[g/cm^3]$	Heat release [W]
Fe	7.9	6.0
Cu	9.0	5.00
Cu powder	7.1	10.0
Pb	11.3	7.0
U_3O_8	7.5	19.0
UO_2	9.7	14.0

Considering that the energy released in the solenoid should not exceed $\simeq$ 10 W, we see that U_3O_8 and UO_2 cannot be used as a material for protection.

For a 200 μA beam, the total flux of neutrons in the solenoid after the stainless steel shield is $5 \times 10^6/cm^2$. For a running time $\simeq 10^7$ s the activity of the solenoid aluminium coil is $\simeq$ 1 mr/h after 7 days cooling.

CONCLUSION

It is shown that the solenoid muon capture system for the MELC experiment has the advantage over ordinary schemes of a few orders of magnitude for soft muon ($\simeq$ 10 MeV) generation using 600 MeV primary protons.

The beam of both muon signs with an intensity 10^{11} μ^-/sec for negative and 2×10^{11} μ^+/sec for positive muons can be generated assuming the average proton current is 200 μA.

Further increasing the muon intensity is possible by means of increasing of the magnetic field and increasing the target thickness.

The transverse beam size can be decreased by means of absorbers in the form of thin disks placed along solenoid-collimator axis.

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