256
6-10-80
JES
LA-8356-MS

Informal Report

DR. 1290

MASTER

**Investigation of a Large Solid Angle
Pion Channel for a Medical Application
Utilizing Current Sheets and Solenoid Elements**

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

INVESTIGATION OF A LARGE SOLID ANGLE PION CHANNEL FOR A MEDICAL APPLICATION UTILIZING CURRENT SHEETS AND SOLENOID ELEMENTS

by

Tsuyoshi Sugimitsu and Donald A. Swenson

ABSTRACT

For the treatment of tumors with pi-minus mesons (pions), a pion channel with a large solid angle is essential. A parallel beam of uniform density and reasonable size at the patient position is favored from the practical point of view. A new pion channel with sixty toroidal current sheets and some solenoids is shown to meet these requirements. It would also be useful for some physics experiments using low-energy pion and muon beam.

I. INTRODUCTION

Since the advent of the Clinton P. Anderson Meson Physics Facility (LAMPF) at the Los Alamos Scientific Laboratory (LASL), more than a hundred cancer patients have been treated with pi-minus mesons (pions). However, the pion channel used at LAMPF consists of two bending magnets and eight quadrupole lenses and has a solid angle of about 15 msr. Even with a proton beam of 500 μ A, it takes a fairly long time to treat a patient (10-20 min). Therefore, it is of interest to consider pion channels with a larger solid angle.

So far, two kinds of pion channels with a solid angle of 0.5 to 1.0 sr have been constructed for a medical application. One is the double orange-sector pion channel at Stanford¹ and SIN.² The other is one with a shaped solenoidal field developed at Dubna.³ The latter type has recently been considered at TRIUMF.⁴ In these channels, pions from the target are

refocused to a point in space. However, treatment experience at LASL suggests that a parallel beam of uniform density is to be preferred because of its ease of use. The channel with an orange-sector can collect many pions.⁵ We propose and analyze a new pion channel design where the pions are collected with an orange-sector magnet, and then made into a parallel beam by running the pions outside a special solenoid field.

II. METHOD OF CALCULATION

From the pion-production target to a patients' position, the orbits were calculated numerically by solving Newton's equation of motion

$$m \ddot{\vec{r}} = e \dot{\vec{v}} \times \vec{B} . \quad (1)$$

A computer program SHEETSO was developed, which solves the above equation in the Cartesian coordinate system. The initial conditions of the particles and the parameters for the magnetic field strength were specified through a separate data file (SHEETD) for the program SHEETSO. We assume that the orange-sector magnet consists of 60 pancake coils with an azimuthal angle of 4° between two neighboring pancakes. This geometry has proven to be effective for pion collection.^{1,2}

The magnetic field within this portion of the channel can be expressed analytically by

$$B_\phi = \frac{IT}{5r} , \quad (2)$$

$$B_r = B_z = 0.0$$

in Weber/m², where I is the current in megamperes, and T is the sum of turns in the 60 coils and r is the distance from z-axis in meters. The magnetic field originating from the solenoids was computed numerically on a mesh of points and stored in arrays. We introduced four sets of solenoids as shown in Fig. 1. They are wound around the z-axis. The main solenoids, SOL 1 and SOL 2, make the beam parallel, whereas the solenoid SOL 3 is effective for getting a smaller beam spot at the patient and solenoid SOL 4 is used to cancel the field in the pancake-coil region originating from the other solenoids.

Fig. 1. Geometrical configuration of the current sheet and solenoid pion channel. The z -axis is taken along the symmetry axis.

In the early stage of calculation, many trials were made to determine the entrance and exit shapes of the current sheets (pancake coils) and the distribution of the solenoid windings using a convenient graphical display. Here only straight lines or circular arcs were tried for the current sheet shapes. After getting a reasonable set of parameters for these magnetic elements, the phase space of the particles at the patient was analyzed as follows. Eight surfaces were incorporated in SHEETSO. SURF 1 and 2 are the entrance and exit surfaces of the current sheets, and SURF 3 is positioned along the focal plane of the current sheet portion of the channel. At these three surfaces, slits are inserted to select particles within a particular range of energies and solid angles. Once a particle under consideration is stopped by one of these slits, the program stops the calculation and jumps to the next particle. About 34 000 particles were tried, uniformly covering a large solid angle, with a sufficient energy spread and 65 positions within the target (1 cm diameter and 2 cm long). From these 34 000 particles, approximately 4000 reached the patient's position. The angular dependence of pion production cross section was assumed constant. The phase space and density distribution of these particles were inspected with another program, SHOUT. By repeating this procedure, a finer tune of solenoid parameters could be done.

TABLE I
CURRENT SHEET PLUS SOLENOID TEST

TEST *** CURRENT SHEET + SOLENOID

SURF 1	-0.5	0.5	0.6	0.6	0.0	1	-0.3	0.3
SURF 2	0.79	0.40	1.20	1.60	-2.40	1	0.7	1.2
SURF 3	2.0	0.35	2.9	0.375	0.0	1	2.55	2.65
SURF 4	5.5	0.5	5.5	0.0	0.0	1	0.0	0.0
SURF 5	5.5	0.5	6.5	0.0	0.0	0	0.0	0.0
SURF 6	7.5	0.5	7.5	0.0	0.0	0	0.0	0.0
SURF 7	8.5	0.5	8.5	0.0	0.0	0	0.0	0.0
SURF 8	9.5	0.5	9.5	0.0	0.0	0	0.0	0.0
WINDOW	-0.4	4.8	0.0	2.0				
SCALE	750							
TARGETZ	-0.01	0.01	0.005					
TARGETXY	0.0050	0.0025						
ENERGY	78.0	84.0	0.5					
ANGLEA	75	110	5					
ANGLEB	-2.0	2.0	0.5					
CURRENT	-4.20	0.0						
NOSOL	15							
RPOS	0.154	0.055	1.12	0.0				
ZPOS	2.16	0.08						
CURRSOL	0.65	0.65						
NOCOIL	3							
RCOIL	1.8	1.8	0.16	0.0				
ZCOIL	-0.01	0.4						
CURRCOIL	-0.014	-0.014						
NOBAND	15							
RBAND	0.055	0.020	1.12	0.0				
ZBAND	3.36	0.08						
CURRBAND	0.70	0.70						
NOWIND	3							
RWIND	0.80	0.70	0.16	0.0				
ZWIND	2.16	0.08						
CURRWIND	0.095	0.095						
RMESH	20							
ZMESH	99							
SOLUSE	1							
BEGIN								

III. RESULTS

Table I shows an example of the input data file (SHEETD). The dimensions of length, angle, energy, and current are in meter, degree, MeV, and MA, respectively.

The slit width at the focal plane (SURF 3) is adjusted to 10 cm in z -coordinate, which amounts to an energy spread of about 1.0 MeV for 81-MeV pions. The 2-cm target length is a good size, because it results in an additional energy spread of only ± 1.0 MeV. The target diameter is determined to be 1.0 cm, based on the beam size at the biomedical pion channel in LAMPF.

As expected from Fig. 1, if the slit at the focal plane is shifted downstream, the pions going through the slit have a higher energy. They are less affected by the solenoid field and are focused nearer the main solenoids. However, if the slit is shifted upstream, the lower energy pions going through the slit are strongly deflected by the solenoid field and focused far beyond the main solenoids. In the latter case, the beam is more parallel and larger in size than in the former case.

SHEET - PION CHANNEL STUDIES 79/12/89. 11.20.83.
TEST 888 CURRENT SHEET + SOLENOID
IPT - 3

Fig. 2. A plot of particle's position versus energy at the focal plane for the input data set of Table I.

Figure 2 shows a plot of particles going through the third slit versus particle energy, where the slit is open between $z = 2.55$ and $z = 2.65$ m. The particle distribution in this plane forms a parallelogram whose vertical height is determined by the target length, whereas the other sides are determined by the slit width.

We now consider three cases of slit position as practical examples. In each case the position of focusing, density distribution, effective solid angle, and phase space are inspected.

In the first case, a slit setting of 2.55-2.65

was considered. We estimate the focal position by comparing the density distributions at five surfaces (SURF 4 to 8). It is easy to find the best position where the density is fairly flat from $r = 0.0$ to a maximum radius r_u , though the fluctuation of density is inevitable because of insufficient statistics and the discrete values of energy, angle, and position given in the initial conditions. Figure 3 shows the plot of relative density distribution for a different position of the surface, where the number plotted is the surface number in question. The best position (SURF 5) and $r_u = 7$ cm are estimated from this figure. Those particles coming outside of r_u are not useful for treatment and should be stopped in front of the patient. Therefore, the phase space (x, x') and (y, y') of particles coming only inside

Fig. 3. Plots of the relative density distribution of particles on the surfaces 4 to 8 for the slit setting of (2.55-2.65).

SHEET - PION CHANNEL STUDIES 70/12/29. 11.29.53.

TEST 228 CURRENT SHEET + SOLENOID

IPY = 1
SURF = 5

NGD = 1003

Fig. 4. Plots of the phase space (x, x') and (y, y') of those particles coming inside a radius of 7 cm at $z = 6.5$ for the slit setting of $(2.55-2.65)$.

of r_u are plotted in Fig. 4. From this figure, the maximum divergence of the beam is estimated.

To estimate the absolute solid angle of the pion channel, many particles (N_o) with a reasonably fixed energy were tried from a point target ($z = 0.0$) such that they cover a sufficiently large solid angle (Ω_o). By counting the number of particles (N) coming inside r_u , the effective solid angle (Ω_{eff}) is given by the relation,

$$\Omega_{eff} = \frac{N}{N_o} \Omega_o \quad (3)$$

Figures 5 through 8 show similar plots for the slit setting of $(2.5-2.6)$ and $(2.475-2.575)$; they were analyzed as before. The results are summarized in Table II and are compared with other types of pion channels. In the present channel, a 14-cm-diam beam is available that is big enough to cover any tumor. However, in the treatment of a patient, only the fraction of the beam that matches the shape of his tumor can be used. Therefore, the effective solid angle is reduced by that fraction. For a tumor of a few centimeters and lying deep in the body, the effective solid angle is reduced

SHEET - PION CHANNEL STUDIES 79/12/89. 10.23.17.
 TEST 322 CURRENT SHEET + SOLENOID
 IPT = 10

ISUM- 1379

Fig. 5. The same plots of density distribution as in Fig. 3 for the slit setting of (2.50-2.60).

SHEET - PION CHANNEL STUDIES 79/12/89. 10.23.17.

TEST 222 CURRENT SHEET + SOLENOID

IPY = 1
SURF = 6

HQD = 775

JTOT-4378

Fig. 6. The same plots of phase space as in Fig. 4 for the slit setting of (2.50-2.60).

SHEET - PION CHANNEL STUDIES 70/12/80. 16.30.44.
 TEST 222 CURRENT SHEET + SOLENOID
 IPT = 10

ISUM = 894

Fig. 7. The same plots of density distribution as in Fig. 3 for the slit setting of (2.475-2.575).

SHEET - PION CHANNEL STUDIES 79/12/29. 16.30.44.
TEST *** CURRENT SHEET + SOLENOID

IPT = 1
SURF = 7

NGD = 518

JT0T-4440

Fig. 8. The same plots of phase space as in Fig. 4 for the slit setting of $(2.475-2.575)$.

TABLE II

SUMMARY OF RESULTS

Slit sitting (m)	Z_{focus} (m)	Ω_{eff} (ster) ($\gamma \leq 7 \text{ cm}$)	Divergence (mrad)	γ_u (cm)	Ω_u (ster) ($\gamma \leq \gamma_u$)	Flight path (m)
2.55-2.65	6.5	1.40	≤ 100	7	1.40	7.5
2.50-2.60	7.5	0.90	≤ 80	8	1.13	8.5
2.475-2.575	8.5	0.70	≤ 60	14	2.16	9.5
Double orange (SIN)		0.6--0.8				8.5
Shaped solenoid (Dubna)		0.31				3.5
LAMPF		0.015				12

by an order of magnitude from that listed in Table II, and other types of channels will be more effective to get the required dose.

IV. DISCUSSION

Figure 9 displays an overview of the practical situation in the treatment of a patient. Some parameters obtained in the last section are cited for a quick reference. In this figure, solenoids 3 and 4 are not shown. The position of the patient can be adjusted depending on where the tumor is in the body. For a tumor lying near the surface of the body, the patient can be placed nearer to the main solenoids, whereas for a deep-seated tumor, he should be placed a little downstream to make use of the more parallel beam.

As shown in Fig. 9, after bombarding the target, the proton beam is guided outside. This makes it easier to reduce neutron and γ -ray background at the patient position from beam dump as compared with the situation at SIN,² where the proton beam is stopped between target and patient.

The pion-production angle of $\theta_\pi \cong (85 \pm 15^\circ)$ is selected in the present channel. It is probably the best choice considering the angular dependence of pion-production cross section and a tolerable contamination of muons and electrons.

Fig. 9. Practical situation of the present pion channel in the treatment of a patient.

The present channel would be useful for some physics experiments. In fact, if we do not mind the beam size of $r \approx 20$ cm, we can attain a solid angle of more than 2 sr, while the resulting beam with a selected energy is fairly parallel.

In the present work, some basic characteristics of the current sheet and solenoid pion channel are explored in a fair detail. However, prior to practical design considerations, additional work must be done. Some considerations are discussed below:

1) The bending magnets for the incident proton beam should be designed so that they do not interfere magnetically with the arrangement of the sector magnets and solenoids.

2) It should be established with which material each solenoid

must be made. For two main solenoids, superconducting coils are appropriate, whereas the remaining solenoids can be made with conventional copper wire.

3) By tuning the shape of the current sheets, a sharper focus can be obtained. Refinement of solenoids would result in a larger effective solid angle.

4) It is estimated that an energy degrader, as in Fig. 9, can be used to reduce the energy width of particles at the patient position. The original particle distribution of the parallelogram can be converted into the rectangular form as shown by the dashed lines (Fig. 2). Energy loss straggling and variation in trajectory angle for each particle at the degrader will cause some variation from the rectangular form. The loss of beam intensity from multiple scattering in the degrader should be analyzed quantitatively.

5) It would be interesting to investigate the possibility of some kind of dynamic treatment. As the pion energy is increased the layer where the pions are stopped goes deeper and deeper. The shape of each layer should be exactly matched to that of the tumor at that point. This can be done by changing the shape of the slit on the patient as we change the pion energy.

ACKNOWLEDGMENTS

We would like to thank Drs. J. Bradbury and M. A. Paciotti for stimulating discussions throughout the work. We are grateful to Drs. P. J. Tallerico and K. R. Crandall for helping with the programming. One of us (T. S.) would like to thank all the staff members of AT-1 for making his stay at LASL so comfortable.

REFERENCES

1. D. Boyd, H. A. Schwettman, and J. Simpson, Nucl. Instr. and Meth. 111 (1973) 315.
2. R. French and J. McCulloch, Swiss Institute fur Nuklearforschung (SIN) report TM-37-03 (1975), SIN report TM-37-04 (1976), SIN report TM-37-05 (1977).
3. V. M. Abazov, JINR-Dubna Communication p. 13 - 8079 (1974).
4. D. E. Lobb, Nucl. Instr. and Meth. 160 (1979) 383.
5. G. I. Silvestrov and V. A. Tayursky, Nucl. Instr. and Meth. 152 (1978) 371.