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A MESON FACTORY EXPERIMENTAL TARGET AREA DESIGN

A. D. McGuire
Los Alamos Scientific Laboratory

I have attempted to take all the information about the beams produced by a meson factory and to use this to produce a useful design for the experimental area. The meson factory beam has been described previously at this conference: 1 mA of 800 MeV protons, of good beam quality. There is also the possibility of a very much less intense beam of polarized protons. We wish to design the experimental area in such a way as to use both beams to good advantage.

First, we wish to make a preliminary list of experiments one might do with the machine. One will certainly want to do P-P scattering, to study meson production and to look at the pion scattering, (both at high and at low energy) and to do experiments with stopped pions of both signs. One also wants to provide for production of muon beams of both signs, again at high and low energy, for scattering and interactions, and to look at interactions of stopped muons at both signs in matter. Furthermore, one would like to look at ν_μ interactions if possible. We should allow for time-of-flight measurement for neutrons, protons and pions, and conceivably muons. This means that a long pipe must be installed in the concrete.

One recognizes right away that not much of the beam energy will be dissipated in one target, so you can place another target in the beam further downstream, and use the unscattered protons in a second target. This now gives two targets which can be used simultaneously, and thus the capability of using the beams from one while the other is removed, thus increasing flexibility.

Figure 1 shows the general features. The first room downstream is a lightly shielded target chamber, Station 1, in which one is allowed to put a thin target, and from where one can bend out into the experimental area a low intensity beam. With a thin target here, the beam passes on into a more heavily shielded chamber, comprising Stations 2 and 3, without creating very much radioactivity at Station 1. In both cases, the wall between the target chambers and the experimental area outside is 10 ft., but in the case of Station 1 it is made of concrete, and in the case of Stations 2 and 3, of steel. The beams will pass as shown into the experimental area. Figure 1 shows a temporary arrangement of the experimental area floor, with some moveable concrete blocks, and some heavy lines to represent possible experimental equipment arrangements. One is of course allowed to send these beams through switching magnets into various places, and to pile shielding around experimental equipment. The hope is that the experimental area will always remain below biological tolerance. The total length of this steel wall is about 70 ft.

It seems to me that one would expect to have a bubble chamber near a machine of this sort, so I indicated a bubble chamber magnet. When you have large quantities of liquid hydrogen, it seems reasonable to suggest that the liquid

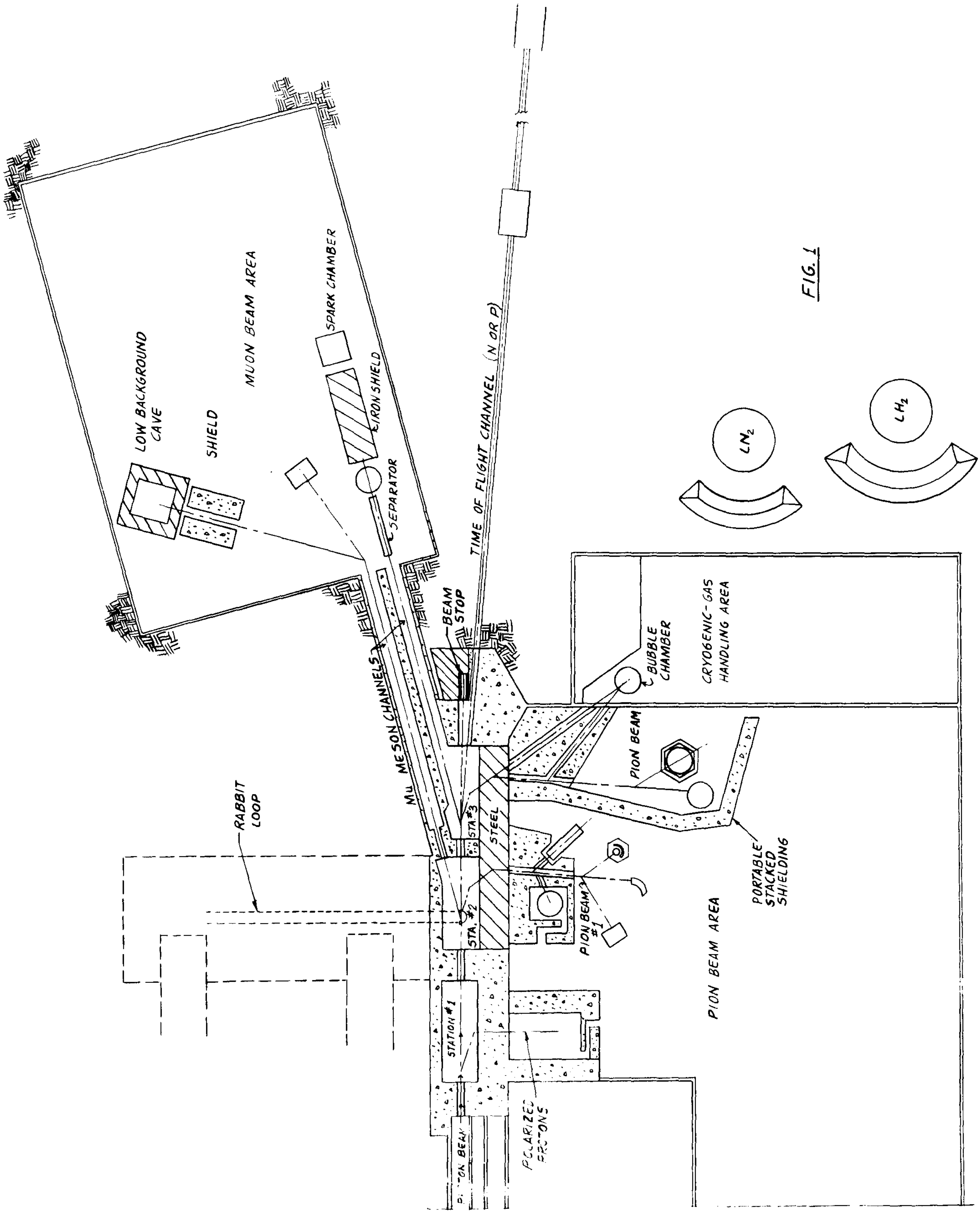
LOW BACKGROUND CAVE
SHIELD
MUON BEAM AREA
SPARK CHAMBER
IRON SHIELD
SEPARATOR
TIME OF FLIGHT CHANNEL (N OR P)
LN_2
LH_2
BEAM STOP
MU MESON CHANNELS
RABBIT LOOP
STA. #3
STEEL
STA. #2
STATION #1
PION BEAM
BUBBLE CHAMBER
CRYOGENIC-GAS HANDLING AREA
PION BEAM #1
PORTABLE STACKED SHIELDING
PION BEAM AREA
POLARIZED PROTONS

FIG. 1

hydrogen activity should be confined to the other side of a poured wall, and the gas handling and cryogenic area should have a blowout panel. The liquid hydrogen and liquid nitrogen storage dewars are placed outside, and protected by earth berms.

One wants crane coverage over this experimental area and a floor space nearby, accessible to the same crane, so that it can be used as a staging area for experimental equipment.

On the other side of Stations 1, 2, and 3, the wall is light, and there are two muon channels coming out. There is an earth berm which covers all this area to a height of about 50 ft. so that the beam stop is in the middle of earthworks, but this alone proves to be insufficient to shield the muon area enough from beam-stop neutrons and 6 ft. of steel have been added to help this problem.

It has been remarked before that if you have a sufficiently thick wall to shield high energy neutrons (energies greater than 150 MeV) you automatically shield against everything else, so the high energy neutron flux dominates the shielding calculation. At the moment we're talking about using 10 ft. of steel as the shield. You could use 35 ft. of concrete but you wish to keep the apparatus as close to the target as possible, since the decay mean free path for a 200 MeV pion is about 30 ft.

Now you have to make a hole through the shield wall, and you wish that the hole piercing the shielding does not view the target directly, so that the high energy neutron flux through the hole would be reduced. I considered for awhile trying to put a magnetic field over the target in order to deflect the mesons which are produced so copiously in the forward direction, but, recognizing that the proton beam is also deflected, I feel that one is well advised not to do so. It is alright to do so as long as the momentum spread of the beam is no greater than when it comes from the linac, but not a good idea once the beam has gone through a target and increased its spread.

I also considered trying to design a magnet system that would bend the beam around in such a way that you could subsequently put a hole through the shield which pointed upstream of the target where the neutron flux is lower than what it is downstream, and I quickly found that I was getting into a great complexity of magnetic handling gear. So I simply suggest that one can put a quadrupole pair (or perhaps triplet) of 8 in. bore, at 15° to the beam and about 4 ft. away from the target. The proton beam can then pass by the edge of the magnet. No doubt, there are other ways to do it, with C-magnets and strong focussing fields, as the CERN people have done. But to have a definite design, let me point out that the π intensity numbers which I shall give can be obtained with just two simple 8 in. bore quadrupole magnets, 2 ft. sq. on the outside and 15° from the beam as a meson collector. Next, consider a 45° bending magnet. The hole in the shielding is now aimed at a point downstream from the target, where the neutron flux is reduced and should be a reasonable level coming into the hole.

In the design of a system to transport pions from this target out into the experimental space, the guiding principle is that you should place the magnets symmetrically about the center point of the beam transport system. So, at the center point, I insert a magnetic triplet system which has symmetry about its center point, and follow this with another bending magnet. Now the hole in the shield not only misses the target, but there is a bend in the hole because the second magnet is located in the wall. Following the bending magnet, then, you would have another pair (or triplet) of 8 in. bore quadrupole magnets and a target at the focal point, the beam magnification thus being about unity.

This is one pion beam. I indicate a similar magnetic channel through the shield wall at Station 3.

Having had the beam pass through these targets, you want to get rid of it with as little radioactivity as possible and you must, therefore, have a beam-stop somewhere. Eight feet of water sounds like a good thing to use as a beam stop. You would like to move the beam stop as far downstream as you can put it, so that the neutron flux from it will be distant from and directed away from the counting area. On the other hand, you would also like to have the beam stop close, because when you make these targets as thick as you might need, the angular divergence of the proton beam is then somewhat larger. The Coulomb scattering isn't very bad, but the inelastic proton-nucleus scattering with a $10g/cm^2$ target is going to give an appreciable angular spread to such a beam. The position shown in Fig. 1 is not too far from a reasonable compromise. The steel shielding wall can be terminated at the end of Station 2, but you must, of course, shield against the beam stop. Since you have a lot of real estate you can use concrete or earth if it is thick enough. Thirty feet of concrete or so is about the right number in a direction normal to the beam stop, and in the backward direction you could perhaps get by with a bit less concrete.

Now, at the entrance to the first heavy target room, Station 2, one can also terminate the steel shielding wall, because it isn't really necessary to use Stations 2 and 3 if you desire to work with a low intensity proton beam. So we plan to use 10 ft. of concrete shielding and build another cell which would provide a place to put a target on such a beam and a capability for bringing out a beam through the light wall into an area which can be closed off by moveable concrete blocks, thus providing a lightly shielded target location at Station 1. You're also allowed to put a thin target in the full beam at Station 1, and in the future, possibly, a polarized liquid hydrogen target. If you had a thin polarized liquid hydrogen target placed at this location you could take out its scattered beam, now polarized, and do experiments with the protons in the adjacent area.

In addition to the π beams, one would like to get out μ beams. One of the ground rules on building a μ channel is not to put any bending magnets on the entering π beam. In fact, it turns out experimentally that $(\Delta p/p)$ of a typical bending system like the π beam collection system is rather small, 5%, typically, while the same array of quadrupoles without any bending magnets would have a $(\Delta p/p)$ of about 25%. According to this philosophy, I have indicated two channels at 15° and plan to line up a suitable array of quadrupole magnets in these channels, thus putting two beams into another experimental area which is located over on the other side.

A reasonable dimension for the length of these channels is obtained from the maximum energy of the π's of interest, which is 500 to 600 MeV. I use 600 MeV, because for 800 MeV protons, there is a little bit of π intensity left at 600 MeV and I use 600 MeV as the upper limit for the design of the beam handling capability.

The mean free path for decay of a 600 MeV π is about 100 ft., which is chosen to be the channel length. Now at an angle of 15°, if you make one channel 100 ft. from Station 2 up to the wall of the μ room, the latter is 50 ft. from the wall of Station 3. One length is a mean free path for π's of about 600 MeV and the other is a mean free path for about 320 MeV π's.

The π's are allowed to go down these channels, which have a certain solid angle and a $(\Delta p/p)$ that is about 10 times greater for the pion beam system, because the bending magnets have been omitted. Kinematics indicate that if the energy of the pion is 250 MeV, the maximum lab angle of the decay μ is only 6.5°. The number of μ's in the lab as a function of the momentum of the π is a square function and has about a 50% width. For 250 MeV π's it goes from about 200 to 370 MeV. However, the maximum laboratory angle does not occur in the middle of the interval. It occurs about 20% up from the bottom of the interval. Since the Chicago channel succeeds in keeping about 22% of the decay μ's, then any reasonable system here will keep of the order of 15-20% of the μ's with no trouble.

For this channel, $(\Delta p/p)$ is about 25%, so one might set the momentum spread in the channel to overlap the decay spectrum, and allow the π's to fill the whole thing. Then if we let the π's go one mean free path, in which case 2/3 of the π's will decay and 1/3 will remain in the channel, about 25% of the μ's will remain in the channel. One comes out with a mixture about half π's and half μ's, and if you can use that kind of a beam, possibly separated by some method other than momentum selection, you'll achieve a maximum density of μ's. One is rather inclined to fill half of this interval with π's and let them decay. If the π's fill the upper half of the interval, then by momentum selection you will be able to take off the lower part of the μ's, and those are useful. However, you get a reduction of a factor of 4 in intensity. That's a little more realistic. Now with the μ room 50. ft. or so away, one completes this area by building a wall on the same side which is lighter than the iron wall, and which is to be used for shielding against the residual radioactivity inside the target rooms when the beam is turned off.

For the π channels, the solid angle subtended at the target by the first magnet typically is 10^{-2} sr, representing something like 9 in. magnets 4 ft. away. For the momentum cut $(\Delta p/p)$, 2 1/2% is a typical number, and is exactly the value for Chamberlain's channel at Berkeley. The magnet is about 8 ft. long, and the distance from the center of the first magnet to the target is also 8 ft. with 45^{o} bending magnets, and a triplet in the middle.

At Stations 2 and 3 you can use a target of the order of 50 g/cm^2, which is about the mean interaction distance for the protons, and with a beam current of 6×10^{15} proton/sec at 800 MeV, the π flux outside the shielding is 5×10^9 π^+/sec at 200 MeV and 1×10^9/sec π^- at the same energy. There will be about 5×10^8 π^+/sec at 500 MeV, and I'll just note that the ratio of the π^- flux to the π^+ flux is about 1:6 at all energies. Now, in the μ channel for a 10^{-2} sr solid angle at the proton target for the first magnet, and $(\Delta p/p) \simeq 25\%$ and assuming that one fills half the momentum cut with π's and collects the μ's over the other half of the momentum cut at a distance of about one mean free path, and a 40g/cm^2 target, one gets 2.5×10^{10}/sec μ^+ intensity. As you come down the μ beam pipe, the π's are decaying away, not only into μ's but also into ν_μ's. What should be done is to let the π's go about 15 m, and then put up about 10 m of steel shielding at the end of the μ pipe. One would get a flux of 5×10^8 ν_μ/cm^2-sec at E_ν = 190 MeV.

I don't think that we will ever be able to send an operator into Stations 2 and 3 when the beam has been on a long time. Our philosophy is that no one will ever have to touch anything in these target areas after beam day. This whole area is made accessible from above with remote manipulators. The roof is completed by cement slabs, such as exist over the Chicago synchrocyclotron. When the beam is on, the roof is not thick enough; biological tolerance is exceeded in the area above it. But if you turn the beam off, you may send operators up above, and they can proceed, by remote manipulation, to remove the roof and introduce the remote handling equipment in the target room to change the magnets, and so forth. Organic materials in the target areas are very undesirable and should be avoided. One should use ceramic insulation on the magnet windings, for example.

The details of beam target design are not too bad. There are only 100 kW to be removed. If, for example, a beryllium disk target has the beam passing through the edge and is spinning, it doesn't seem to be too hard to remove 100 kW from it. Hot spots don't create a problem on the target. I did the following calculation. Consider a cylinder of beryllium, and a beam of uniform density going down the cylinder, with a fixed temperature at the outside because of a cooling coil. The temperature at the center of the cylinder turns out to be independent of the beam size. You can see roughly why this is so. If there is a certain total beam current, and a uniform current density of a certain radius, when one doubles the radius, there is more circumference on the outside of the beam spot itself to conduct the heat away. The central temperature should be independent of target size.

At the moment, there are 10 ft. of earth as a shield wall between the accelerator tube and the adjacent equipment bay where parts of the amplifier are set. We heard about the radioactivity levels and beam losses in the machine, but I think that matter is a lot more complicated than what has been said so far. The thickness and density of that shield is determined, I think, by a guiding philosophy: if you have an accident, how many pulses, or what part of a pulse do you think will escape before the automatic shutdown system turns off the machine? Inherently it might work in a few μ sec, but also it might fail. We might wish to protect against a full 2000 μ sec pulse, and there could be more than one. When you're in that position you must figure whether you want operational personnel (who happened to be standing in just the wrong place), to receive a year's dose from one accident; or a day's dose, or whatever, and that is a lot harder to decide. I don't claim that we've got a good feel for that problem. What we plan at this time is to leave 10 ft. of space between a couple of light concrete walls, and we say we'll fill it with earth, but if we get a little bit more conservative about it we might fill it with something heavier than earth.

FEATHERSTONE: Might I add my personal bias to the point you last raised? My feeling is that where there is a probability that automatic shutoff equipment might not work, it would be better to arrange it such that the dose received per pulse is low enough so that somebody could turn off the machine manually, and you still wouldn't have actually killed anyone.

McGUIRE: We are several factors below killing, but the question is, do you have to put up a sign on a man that reads, "This man is not allowed in the linac area for a year"?

FEATHERSTONE: I would prefer that you reach this stage after a second or two, rather than after only one pulse.

KNOWLES: I would like to comment on your all-steel shielding wall. You cannot get away, to the best of my information, by replacing concrete entirely with iron. You must have approximately one-tenth-intensity thickness (5 ft. of concrete) on the personnel side, to remove the equilibrium flux of low energy neutrons, protons, etc. The iron alone is not adequate for this purpose.

McGUIRE: The Chicago people thought this when they built the shield for their cyclotron and they put up some concrete just for that reason, and Fermi said, "You're wasting your time with that concrete; steel's as good as anything." They did some measurements, and Fermi was right.

KNOWLES: What did they measure it with? Remember my concern about high-energy neutron detectors.

Also, I don't think that you can justify taking off a 25% π-momentum cut to make μ mesons, because when you put in all the angular wiggles that the pions have to go through, and work out maximum acceptance, and so on, as Citron did, you find that you can't really take a bigger π-μ decay angle than about 4^{o}. If you use this to work out what $(\Delta p/p)$ of π's you should feed into a backward-produced μ spectrum, you find you should not use a π $(\Delta p/p)$ of more than 2 to 3%, because if you take any more π's through the pipe, you can't collect their μ's. One thing I've been considering recently is this: when you wish to do a high energy μ experiment, you generally need a high quality beam, and if you collect a great many μ's in a large muon pipe such as at CERN, then you have to cut them right down again to get a narrow high quality beam. You can't use a low quality beam unless you have a detector with high acceptance, like a spark or bubble chamber. You can't use that sort of detector in a steady beam, because of its recovery time. You need rather a beam from a single pulse. I think that if someone were to devise a weak focussing system that collects only a very narrow momentum band of π's (and, therefore, produces an even smaller momentum band of μ's) and which ejects only the μ's from the target area, that they would be very far ahead, both in terms of economics and in terms of background.

McGUIRE: It depends on what your requirements are. If your purity requirement is one part in 10^5 you're going to get a much lower μ intensity than if it's one part in 10^4, or, say, 50%.

KNOWLES: You can't take much less than one part in 10^4, because at one part in 10^3 you begin to have one-third π interaction per μ interaction, a very bad background for a μ-nucleon scattering experiment. Citron did such an experiment with a beam of the order of one part in 10^3 contamination and had a lot of trouble with the pions.

McGUIRE: But if you are doing stopped μ-mesic x-rays, and your intensity is very high, you can use a bent-crystal spectrometer, and have very good resolution. Now you don't care if π-mesic x-rays are present or not.