Prospects and Uses for Meson Factories*

by

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Although the emphasis in this conference is on multi-GeV accelerators, discussions of high intensity linacs are appropriate, both because linacs serve as injectors for the large synchrotrons, and because the large synchrotrons are themselves developing in the direction of high currents as well as high energies, and so share some common problems of beam-spill, targeting, and shielding, which are associated with high beam power.

Figure 1 gives a comparison of some proposed meson factory accelerators, and Fig. 2 shows the distribution of accelerators in the energy-intensity plane, including those which are operating, under construction, or proposed. Figure 2 represents our current information. However, I expect now to receive critical comments and letters which include information I can use in my next publication. This figure shows that most accelerators are below the 100-MeV line, and this is proper because the research with these accelerators bears most directly on the problems of the development, control, and utilization of nuclear energy, and so are relevant to our present technical society. Super-intensity accelerators, on the other hand, will be among the new facilities for basic research in the coming decades.

The LAMPF proton linac, designed to produce 1 mA average current of 800-MeV protons, is usually called a meson factory, since one of its main functions will be to produce intense secondary beams of pions and muons. The principal parameters of the accelerator are listed in Fig. 3. They are little changed from those presented at this conference two years ago.[1]

A general schematic view of the accelerator is shown in Fig. 4. The length of the linac is about 2700 ft. As Figs. 3 and 4 indicate, the injector consists of a duoplasmatron ion source, a 750-keV dc accelerating column supplied by a conventional Cockcroft-Walton unit. It is proposed also to have a separate injector to produce 750-keV polarized protons. The drift tube linac, which consists of four tanks operating at 201.25 MHz, and which has an output energy of 100 MeV, is of conventional design, except for a novel resonant coupling scheme, which in effect converts the tank to resonant $\pi/2$-mode operation. This development is reported in session F of this meeting by D. Swenson, E. Knapp, J. Potter, and E. Schneider, so here let it suffice to say that the new design offers improved electrical stability against effects of beam loading and of mechanical distortions and imperfections.

A related development of a resonant $\pi/2$-mode drift tube linac was made somewhat earlier, called the multistem coupled tank, by Giordano and Hannwacker[2] at the Brookhaven Laboratory in connection with the AGS conversion program.

The 100-800 MeV portion of the linac, which operates at 805 MHz, uses the $\pi/2$-mode standing wave structures which have been developed by E. Knapp, D. Nagle, and others.[3] A linac prototype using this structure is described by E. Knapp, W. Shlaer, G. Swain, and J. Potter in session P of this conference. Figure 5 shows Ed Knapp with some of the 805-MHz tanks constructed at Los Alamos. Operating tests of these structures have demonstrated that they have the expected stability characteristics of $\pi/2$-mode structures. Figure 6 exhibits the remarkable tolerance to dimensional errors. Moreover, the shunt impedance is high: For example, the measured value of ZT^2 (shunt impedance per unit length times transit time factor squared) is 43 $M\Omega\ m^{-1}$ for a standing wave tank having $\beta = v/c = 1$. The rf power cavity excitation requirements listed in Fig. 3 are based on experimental values of the shunt impedance.

The radiofrequency power system for LAMPF has been an object of development for the past four years. For the 201.25-MHz portion of the accelerator, a triode-tetrode amplifier chain is used, the final power amplifier being the RCA-7835 triode also used at ANL and at BNL. Three such amplifier chains will be used for the tanks No.'s 2, 3, and 4, plus a fourth, which omits the final 7835, for tank No. 1. A full-power amplifier has been operated at the required performance levels at Los Alamos.[4]

For the 805-MHz portion of the system, the choice for the final power amplifier is between the klystron and the crossed-field amplifier (Amplitron). At present, LASL has under evaluation a klystron, manufactured by Litton Industries, and the Raytheon No. QKS-1493 Amplitron. Both tubes have been operated satisfactorily at the nominal ratings of 1.25 MW and 6% duty factor. From the systems point of view, the principal advantage of the klystron is its high gain. The advantages of the Amplitron are high efficiency (≥ 60%), lower operating voltage, and smaller size. Isolation is required for the Amplitron in both the input and the output guides. The final systems choice between the two will also be influenced by the initial cost and the estimated operating costs. The phase and amplitude of the rf wave as measured in the accelerator tanks must be maintained constant within narrow limits. This has been done by a fast servo system for the Amplitron power amplifier, and also for a 100-kW klystron.[5]

It is proposed that the central control room will have a general-purpose digital computer which will perform many of the usual control functions. Special interface equipment is required at the computer and at various locations along the linac. A medium-size (SEL 810-A) computer has been operated to try out the programs and interface equipment with one of the prototype amplifiers. So far the experience gained has been encouraging.[6]

The operation of targets in the experimental area poses a number of engineering problems including heat removal, thermal cycling, radiation damage, radioactivity induced in the target and in the coolant, and others. Table I shows the performance of some developmental targets as far as heat removal is concerned.

Most visitors when shown the planned experimental area comment that it is too small. I think there is a relativistic effect which makes distances in New Mexico appear smaller than in most states. Figure 7 is an overlay of the expanded Bevatron experimental area and that of LAMPF.

As many of you already know, the LAMPF project was included in the President's budget for this year and has been authorized by the Congress. We anticipate some ten millions of construction funds will be made available this year, and in last year's appropriations bill we were allotted five millions for initial construction activities. With this money we were able to proceed with architect-engineering and preliminary site investigation, clearing, leveling, and cutting of the trench for the beam channel. In view of the seismic activity in the Denver area, some concern on this score was expressed in Washington about our site. Figure 8, a picture taken in a canyon near Los Alamos where there are many such formations, shows that recent seismic activity must be minor. The actual site, on a mesa close to the main laboratory, is shown in Fig. 9. The view is looking in the direction from the injector toward the target area.

The reason for doing this preliminary development was to learn about the soil properties of the site. In general, the properties are very good. We did in fact find that the tuff, the volcanic rock of which this site is formed, has a discontinuity about two-thirds of the way down the accelerator, and we experienced a number of small cave-ins of the channel wall. This situation is being taken care of without much cost (because we have the time to do so) by cutting sloping walls rather than vertical ones. Had we been in a situation where construction contracts had to be let and we were proceeding full tilt, the rectification of this difficulty might have been quite costly. Site preparation, including leveling, beam channel excavation, water, gas, and waste disposal line emplacements, were achieved for half a million dollars.

We come now to the uses of meson factories. On this point I can talk for a long time indeed. I will have to content myself with referring you to the Williamsburg Conference on Intermediate Energy Physics and the more recent Rehovath Conference. In the thousand or more pages published on the conferences, you will find what it is we hope to achieve with intense proton beams of energy up to 1 BeV. There is time for only a few examples.

Figure 10 shows the kinds of pion beams achievable with 1 mA of 800-MeV protons; Fig. 11, the muon beams; and Fig. 12, the neutrino beams.

Figure 13 indicates a very basic type of experiment which cannot be carried out with present intensities--the study of the nucleon-nucleon interaction in its full glory. What is needed is not only p-p and n-p elastic scattering, but also the very difficult double- and triple- and spin-correlation experiments if one is to achieve a basic understanding of the nucleon-nucleon interaction which plays so important a role in nuclear structure. Systematic experiments with good energy precision and good energy resolution are required.

During the last days of the Cosmotron, it was demonstrated by Palevsky, Igo, and their associates that the argument which has been made in support of meson factories to the effect that 1-BeV protons are marvelous probes of the nucleus is in fact correct. Figure 14 is an example of data obtained on the elastic scattering of protons by oxygen. Such data have a very direct relationship to the description of the nucleus in terms of radial dependence of mass and charge. The point is that ~ 1 BeV nucleons have a long mean-free path in nuclear matter on the one hand, thus eliminating the complication of multiple collisions. In addition, because of the high momentum and short wavelength, the impulse approximation has much more validity than at low energies. So these nucleons provide a means for taking a "snapshot" of the nucleus.

In Born approximation, the correlation of nucleons within the nucleus is determined from a sum over the angular distributions of scattered particles for fixed momentum transfer. (Electron scattering at high momentum transfer involves

*Work performed under the auspices of the U. S. Atomic Energy Commission.

a large correction for bremsstrahlung.) In nucleon-nucleon scattering, $dE/d\theta \cong$ 10 MeV/deg at small angles. For 1-MeV resolution, one requires 0.1-deg angular resolution. High intensity is thus required for adequate counting rates. With 1 BeV and 1 μA it is already possible to investigate interactions to momentum transfers of $\sim$ 1 BeV/c or $5F^{-1}$ or at a radius of $\sim 2 \times 10^{-14}$ cm, well inside the hard core. Required are systematic experiments with good spatial and energy resolutions and extending to large momentum transfer and to new regions of energy-momentum transfer space. This requires high intensity.

Intense pion and muon beams are also applicable in novel ways to the study of nuclear structure and nuclear forces. In one of his classic papers written fifteen years ago, Wheeler pointed out that a muon captured in the K-orbit of a heavy nucleus will traverse about 5 meters ($\sim 10^{17}$ g/cm^2) of nuclear matter before it is absorbed. The muon is therefore a magnificent probe of the nucleus, and Wheeler stated that the following information would be obtainable from study of atomic spectra from mesic atoms:

1) nuclear radii, charge distributions
2) quadrupole moments
3) magnetic moment of muons
4) polarizabilities and compressibilities

We now know that all of this information is, in principle, accessible. In fact, a good start has been made in obtaining it.

Obvious experiments involve extensions of the very beautiful π-mesic and μ-mesic x-ray experiments which have been so effective in recent years. The point here is that pions and muons can be used to form mesic atoms with the important difference that these atoms are of nuclear rather than atomic dimension. This is because the π and μ mesons are several hundred times heavier than electrons and therefore occupy orbits correspondingly smaller. As the meson undergoes transition from one Bohr orbit to another, x rays are emitted corresponding to the energy level differences involved. Now an interesting point is that since the mesons occupy different orbits from the electrons, and since only one meson per atom is involved, the mesic atoms are hydrogen-like and the various levels can be precisely calculated. Furthermore, the level positions are strong functions of the matter distribution (in the case of π-mesic atoms) and charge distribution (in the case of μ-mesic atoms). The π-mesic level shifts and widths reflect the force between the pion and the nucleus. As the resolution is improved, the ultimate widths will be due to the interaction of the pion with the nucleus. To evaluate such data one must have recourse to a theory that describes the pion-nucleus potential in terms of πN and πNN free-particle interactions.

Negative pion absorption--because the pion brings 140 MeV of energy into the nucleus with negligible momentum--offers the opportunity to study the systematics of the decay of highly excited nuclei which do not possess angular momentum.

From another direction, one can study two- and three-particle clustering in the nucleus from the energy and angular distribution of emitted nucleons. In the case of absorption of a pair of nucleons, the angular distribution of the two nucleons will reveal information about the momentum distribution of the absorbing pair.

Let's try to visualize the mechanism by which a stopped negative pion is absorbed in a nucleus. Can it simply be absorbed by a single nucleon? This probably occurs infrequently because the Fermi momentum of a nucleon inside the nucleus is much lower than the momentum of a 140-MeV neutron. Single-nucleon absorption would imply that the recoil of the nucleus must take up all the momentum--a nuclear sort of Mössbauer effect. However, to the extent that this does occur, one would learn about the probability for the existence of a long tail in the Fermi momentum. Absorption by two nucleons is known to occur with high probability. The ratio of high energy n-p to n-n emission following π^- absorption could be very interesting. If neutrons and protons are randomly distributed in the nucleus, one should expect to see (for π^- absorption) approximately four times as many n-n as n-p final-state pairs. This, of course, may not turn out to be the case. So here is one way to obtain nucleon-nucleon interaction information for nucleons inside nuclear matter. This is not only important for nuclear structure reasons, but also because there is an important and influential school of thought which denies the existence of individual nucleons within the nucleus.

Pion, kaon, and other particle production from a complex nucleus below the threshold for free NN collisions will reveal high momentum states in the target nucleus wave function. The higher the available intensity, the further out on the wave-function tail can one explore.

Study of pion production processes also shed light on nucleon correlations. For inelastic scattering, pions have the advantage that they are distinguishable from nucleons, they can excite $\Delta T = 2$ transitions and may therefore reveal collective motions not previously observable. Since no spin-flip is possible, the reactions are simpler than for nucleons.

It has already been shown possible, from transitions in muonic atoms, to obtain a very good picture of the charge distribution in nuclei: with higher intensities and better resolutions, it should be possible to obtain an equally good distribution of the magnetic moment in a nucleus.

The probability for muon absorption varies as $Z^{3.7}$, which makes it possible to use the muonic atom lifetime as a "clock" to detect chemical reactions. Similarly, there is a large difference in the time for absorption of π^- in hydrogen gas as compared to when hydrogen is bound in a molecule containing heavier atoms. This was discovered by Panofsky and colleagues many years ago. This effect results from the rapid transfer of π^- from the hydrogen to the heavier atoms.

The free lifetime of the muon could be used as a clock to measure the composition of compounds by measuring the relative probabilities for the muon to reach the 1S atomic orbit in the constituents of the compound.

According to theory of weak interactions[7] the absorption of a μ^- by a proton ($\mu^- + p \rightarrow n + \nu$) should obey the same laws as the beta decay of the neutron ($n \rightarrow p + e^- + \nu$). An important quantity is the absolute cross section for the first process. With increased muon intensities the first reaction could be studied in low-pressure hydrogen gas in order to reduce the uncertainty of the muon density at the position of the absorbing protons for the states from which absorption takes place.

Suppose now we add a heavier element to the hydrogen. This heavier element competes with the hydrogen and deuterium for the muons and one has reactions $\mu p + X \rightarrow \mu X + p$. One can measure the rate of these reactions by observing the x-ray lines from the μX atom since the mesic de-excitation x rays are characteristic of material added.

Studies of muon molecules should provide new information on diatomic molecules.

All μ-molecular processes involving reaction rates and μ-transfer probabilities are quite sensitive to the chemical and physical state of the system involved, (e.g., chemical compound, impurities, temperature and pressure). It is thus so that a new way is opened for study of atomic and molecular reactions by virtue of the characteristic x rays emanating from μ-mesic atoms and the timing which these permit.

Parity non-conservation in weak interactions dictates that muons arising from pion decay are polarized and that the electrons resulting from muon decay are polarized and that the electrons resulting from muon decay are emitted preferentially in the direction of muon polarization. Now when muons interact with matter they become depolarized (by formation of muonium for positive muons, for example) and by other processes. However, the rate of depolarization is a function of the material traversed, of temperature, and of applied magnetic field. So here is another means of studying matter in bulk.

I predict that medium-energy high-intensity accelerators will eventually replace reactors as generators of intense sources of thermal neutrons. The reason is heat removal problems. This is discussed in the Chalk River ING proposal. (Neutron fluxes from ING are estimated at 10^{16}/cm^2 sec.) Accelerators will also be used for study of solids and liquids. For example, with present neutron fluxes one needs at least several grams of a sample in order to measure the phonon dispersion curve. The point here is that the velocity of thermal neutrons is comparable to the velocity of atoms in lattices, and the wavelengths are comparable to interatomic spacings. Energies of typical excitations can be studied directly by observing energy charges of the scattered neutrons. Figure 15 shows dispersion curves for diamond crystal.

Because of their magnetic moment, neutrons can be used to study magnetic structure of systems. By neutron diffraction studies in which neutron magnetic moments interact with magnetic moments in a crystal, the geometrical arrangement may be deduced. This is a unique application.

Cold, polarized neutrons might be used to search for an interaction between neutron spin and gravity.

Neutron diffraction supplements x-ray diffraction for study of solids and liquids. One difference is that neutrons see hydrogen atoms where electrons do not.

Fluxes higher than 10^{15}/cm^2-sec may permit study of protein molecules. Neutrons are probably essential here for they help to determine positions of hydrogen atoms.

Saturation results when production and annihilation of defects balance; i.e., an equilibrium situation is established. This now takes years to achieve. With the high fluxes of fast neutrons available from LAMPF, these equilibrium effects can be achieved in about one month, if the temperature of the material is reasonably low.

Not always is radiation damage deleterious. In some advanced power reactors, Zr alloys are employed at high temperatures. Radiation damage appears to strengthen these alloys at high temperature, but the effect or desirability for very high integrated flux, i.e., nvt > 10^{20} n/cm^2, is still unknown.

Intense beams of negative pions offer many possibilities in biomedical research and even in radiation therapy.[8] The reason is that, for example with LAMPF, it will be possible to produce π^- beams of such intensity as to deliver 100 rad/min over volumes of 1 cm^3 to 1000 cm^3. With π^- a high degree of localization of dose can be achieved. This is because when the π^- stops (say in H_2O) it deposits about 30 MeV of energy in the form of short-range, heavily ionized nuclear disintegration products of the π^- capture. In this way, energy can be deposited deep in a tissue of an animal while irradiating the surrounding tissue relatively little. Figure 16 indicates the advantage of π^- beams over x rays in treating deep-seated malignancies.

About pion-induced nuclear disintegrations we know close to nothing. There well may emerge some unsuspected and enlightening systematic phenomena. One should certainly investigate.

Double-charge exchange reactions with pions should produce new nuclear species, far off the stability line, e.g., $He^4(\pi^-, \pi^+)^4n$ and $Li^7(\pi^-, \pi^+)H^7$.

The three-body forces represent an enormous gap in our knowledge about nuclei. If they exist, they will favor nuclear configurations in which the momentum is shared more or less equally among the nucleons. Reactions such as $\pi^- + He^3 \rightarrow p + n + n$ will reveal such correlations (as would also reactions such as $K^- + He^3 \rightarrow \Sigma^- + 2p$). In each case, stopped mesons are used. If two-body forces are dominant, one of the products will be a spectator and go off with very low energy.

Naturally, when one opens a new field, one would like to invest some effort in experiments which, if successful, will provide dramatic new information about the laws of nature. For many years we have believed symmetries give rise to conservation principles. Symmetries in space and time are the basis for energy and momentum conservation. It is perhaps in these conservation principles, more than in any other, that we may hope to find some clue as to whether our basic idea about matter is at all correct. Feinberg[9] suggests that perhaps none of our particles is fundamental; otherwise, why are they so easily created and destroyed at high energies? He wonders whether particles might not be manifestations of some underlying structure not yet detected "like ripples on a still unfathomed ocean." However, some things do appear to remain constant such as energy and momentum and electric charge and number of nucleons. One, therefore, asks whether the high intensities can provide better tests of some of the laws which are still inviolate and some which have recently been shaken. It can. Let me give one or two examples.

One of these conservation laws goes by the name of CPT--i.e., invariance under successive applications of the operators which perform charge conjugation, parity reflection, and time reversal. Recently, it has been shown that not only P, but also CP may not be conserved, which would imply that T also is not conserved. If this were so it would have a rather profound influence on our view of the universe.

High-intensity nucleon and pion beams make possible very precise experiments on time-reversal invariance. One experiment is a precise measurement of the forward and backward rates of the reaction $p + p \rightleftarrows \pi^+ + d$. Experiments to investigate lepton conservation are suggested. Table II gives the recent experimental situation.

Table II

NONCONSERVATION OF LEPTONS

$\mu^\pm \rightarrow e^\pm + \gamma$	$< 2 \times 10^{-8}$
$\mu^\pm \rightarrow e^\pm + e^+ + e^-$	$< 2 \times 10^{-7}$
$\nu_\mu + n \rightarrow p + e^-$	
$\mu^- \rightarrow e^- + \gamma$	
$\nu_\mu + p \rightarrow n + e^+$	
$\mu^- + Z \rightarrow e^- + Z$	$< 3 \times 10^{-7}$

If the muon quantum number is multiplicative rather than only additive, then the following reactions should occur:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (1)$$

and

$$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu \quad (2)$$

If (2) occurs, one could hope to observe the $\bar{\nu}_e$ in the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$, which was the first neutrino reaction observed.

Let me conclude with a few general remarks about the role of high-intensity accelerators.

It has been long recognized that there are two frontiers in that area of science concerned with the basic structure of matter -- nuclear and sub-nuclear physics. One frontier is the obvious energy frontier, the other is the intensity frontier. That the latter is considered important is manifested by the fact that we build accelerators. After all, nature has endowed us with particles of various energies; in fact the energies available from cosmic processes are far higher than any we shall soon achieve with accelerators. However, nature's accelerator, although it provides particles to very high energy, has the disadvantage of low intensity.

Manifestations of recent emphasis on higher intensities are to be found in the AGS modifications program which is directed at a factor of ten intensity increase, the proposal to upgrade the injector at the ZGS, and in particular the present emphasis on so-called meson factories.

I also believe that a rather high intensity will also be important for the new machines of 200 GeV energy, since progressively shorter lifetimes will be of interest and many cross sections (such as neutrino cross sections) will be small. Laboratory production and scattering angles are small at high energies and need to be measured with high precision; and radii of curvature are large, and lead to the requirements of long transport and analysis paths.

I have, in what I have said, expressed my prejudice and that of many others to the effect that there is still much that needs to be done with high intensity accelerators. I suspect that, in our lifetime, there will always be a next machine.

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8. C. Richman, H. Aceto, M. R. Raju, B. Schwartz, Amer. J. Roentgenology, Radium Therapy, and Nuclear Medicine 96, 777 (1966).
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DISCUSSION (condensed and reworded)

V. Dzhelepov (J.I.N.R.): The parameters of the proposed meson factory for Dubna have been modified. The energy remains the same but the intensity is reduced from 500 μa to 50 μa, the cost should therefore be much less.

Table I

Mock-Up Target Tests
AC Electric Heating

	No. 25	No. 29
Material	Graphite	Graphite
Dimensions	10.8 x 1 cm diam	4.4 x 0.5 cm diam
Coolant	Water	Water
Flow (paraxial)	23 gpm	13 gpm
Pressure Drop	~ 75 psi	~ 143 psi
Maximum Dissipation	94 kW	38 kW
Dissipation	62 kW	24 kW
Average Power Density	7.3 kW/cm^3	6.9 kW/cm^3
Surface Heat Transfer Rate	1.86 kW/cm^2	3.44 kW/cm^2
Expected Average Proton Beam Dissipation	45 kW	20 kW

Comparison of Proposed Meson Factories

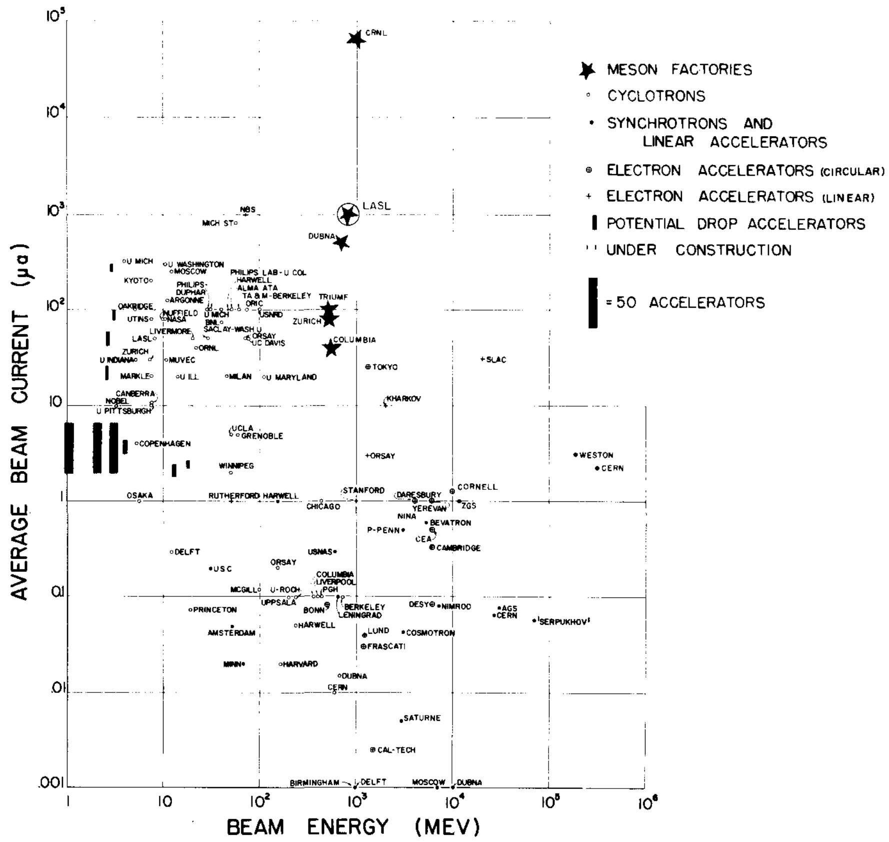
	H^- Cyclotron	Spiral-ridged Cyclotron		Ring Cyclotron	LINAC	
	TRIUMF[a]	Columbia	Dubna	Zurich	LASL	CRNL
Energy (MeV)	200-500	550	700	510	100-800	100-1000
Energy resolution (%)	0.3		0.4	0.4	0.4	0.4
Average current (mA)	0.1	.005-.04	0.5	0.08	1	65
Beam extraction (%)	100	90	90	90	100	100
Macro-duty factor (%)	100	50	100	100	6 - 12	100
Micro-duty factor (%)[b]	25-100	25	25	25	5	5
Time between micropulses (nsec)	20	50	20	20	5	5
Possibility to increase energy	no	no	no	no	yes	yes
Polarized beam intensity (μA)	.02		0.01		1	1
Beam emittance (milliradian cm)	0.2		2		π	π
Cost of facility (millions of $)	18	5	24	21[c]	55	175
Funding situation		Funded		Funded	Partially Funded	
Completion date	1972	1970	1972	1971/72	1971	

[a] Tri-University Meson Facility, Vancouver.

[b] In the LINAC, because of the high frequency of beam modulation, it is feasible to smooth out the microstructure at some cost in either maximum energy or energy spread. Elimination of microstructure does not appear to be feasible in the circular machines.

[c] This amounts to approximately $3 for each inhabitant of Switzerland

1. Comparison of some proposed meson factory accelerators.



2. Distribution of accelerators in the energy-intensity plane, including those which are operating, under construction, or proposed.

DESIGN PARAMETERS FOR THE LOS ALAMOS LINAC (LAMPF)

Ion Source: Duoplasmatron - 30 keV

Preaccelerator: 750 keV Pierce-type short column

Alvarez Accelerator:

Frequency 2.0125 x 10^8 Hz

Structure - Alvarez, 4 tanks

Tank		
1	0.75 -	5.0 MeV
2	5.0 -	41.2 MeV
3	41.2 -	72.3 MeV
4	72.3 -	100.3 MeV

Waveguide Accelerator:

Frequency 8.050 x 10^8 Hz

Structure - side-coupled shaped cavities π/2-mode standing wave

Number of tanks - 90

Current: Peak - 17 mA
Average - 1 mA

Duty Factor: 6 - 12 %

Overall Length: 850 m

Peak RF power for cavity excitation	38 MW
" " " " beam excitation	14 MW
Total	52 MW
Average RF power (6%)	3 MW

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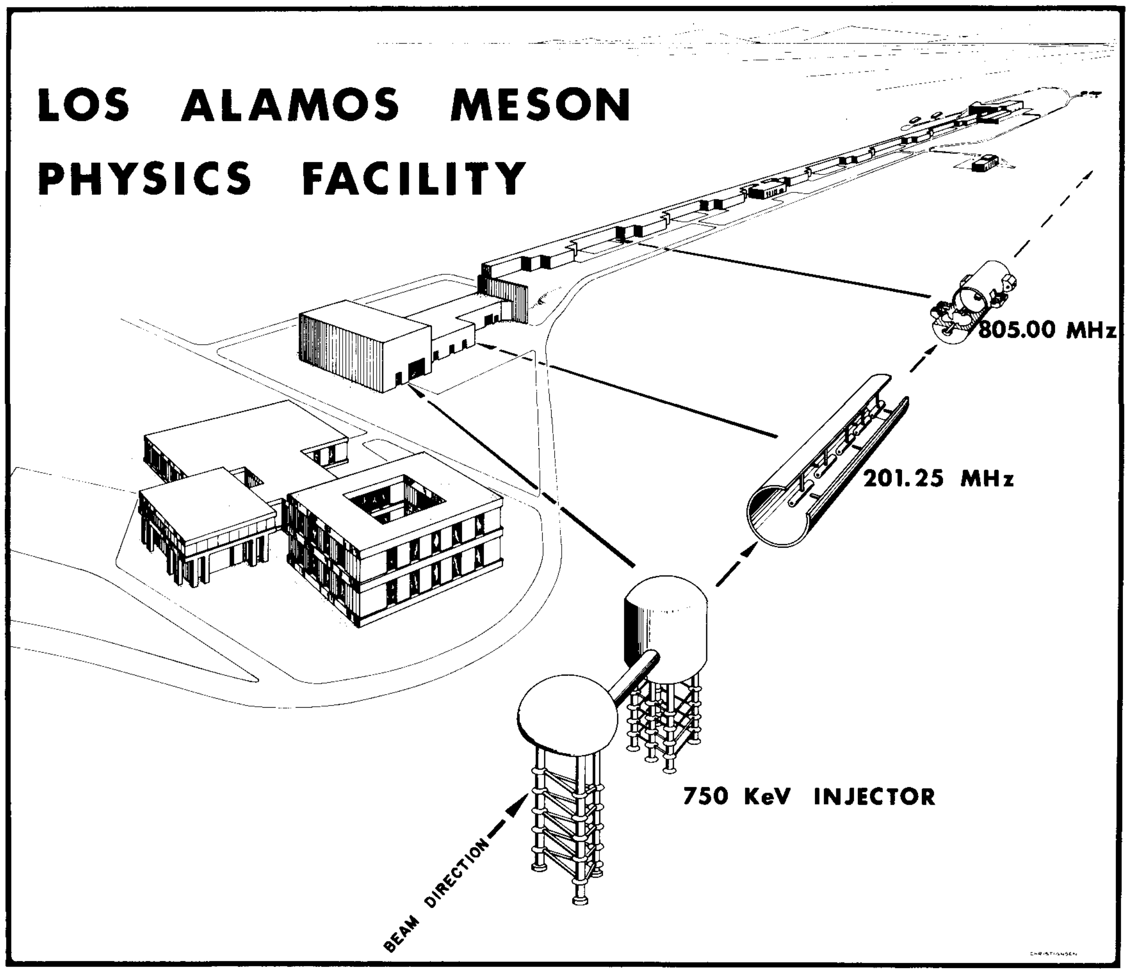
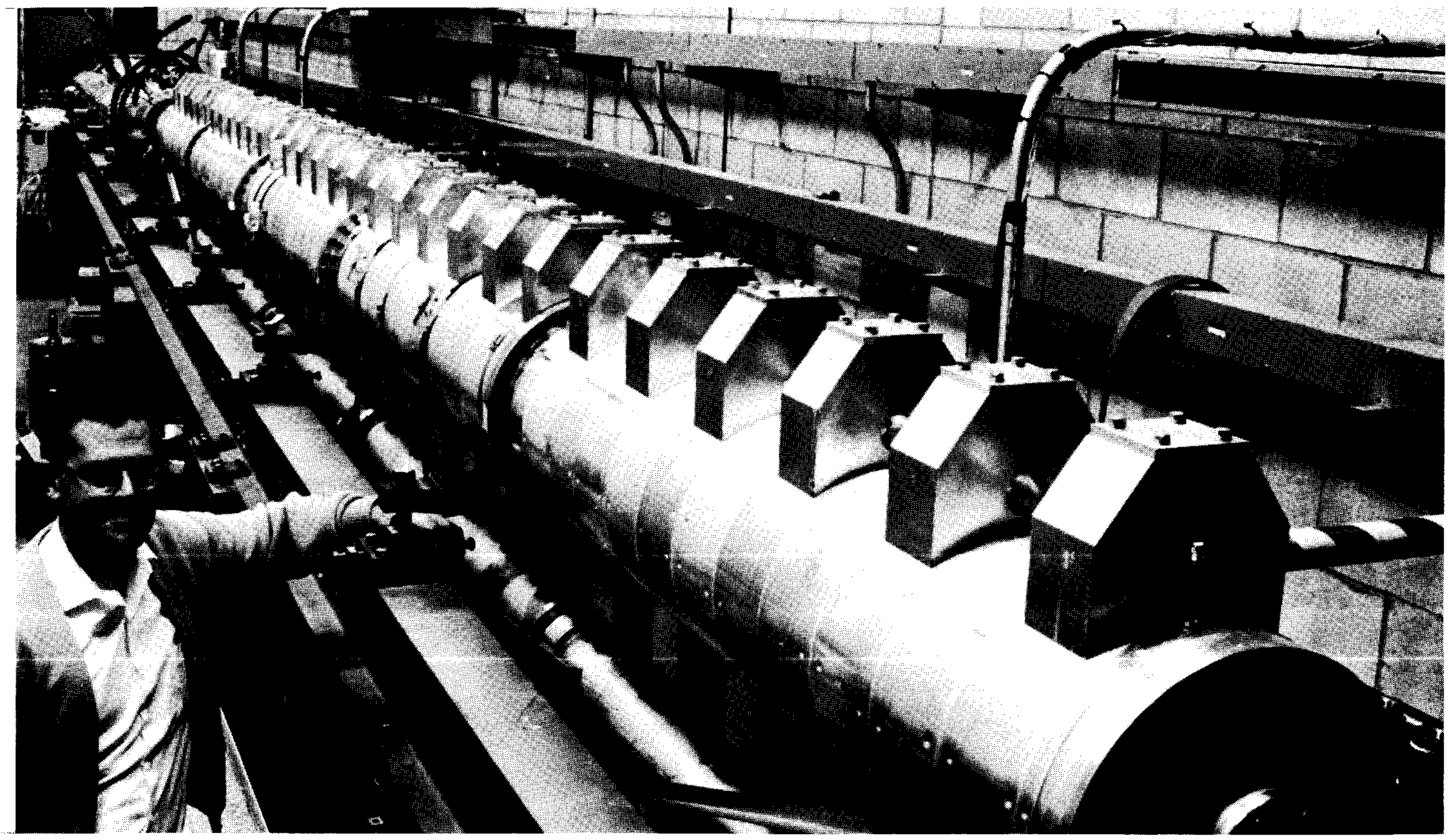
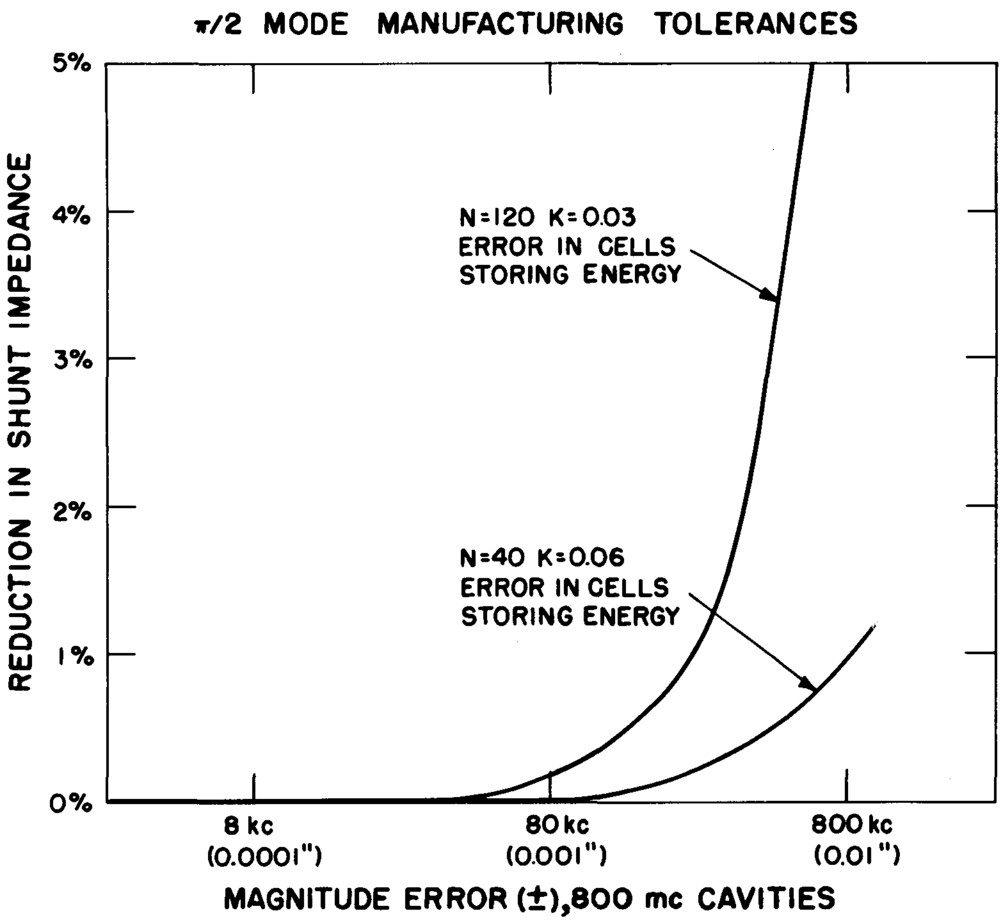
3. Design parameters for the Los Alamos Linac (LAMPF).



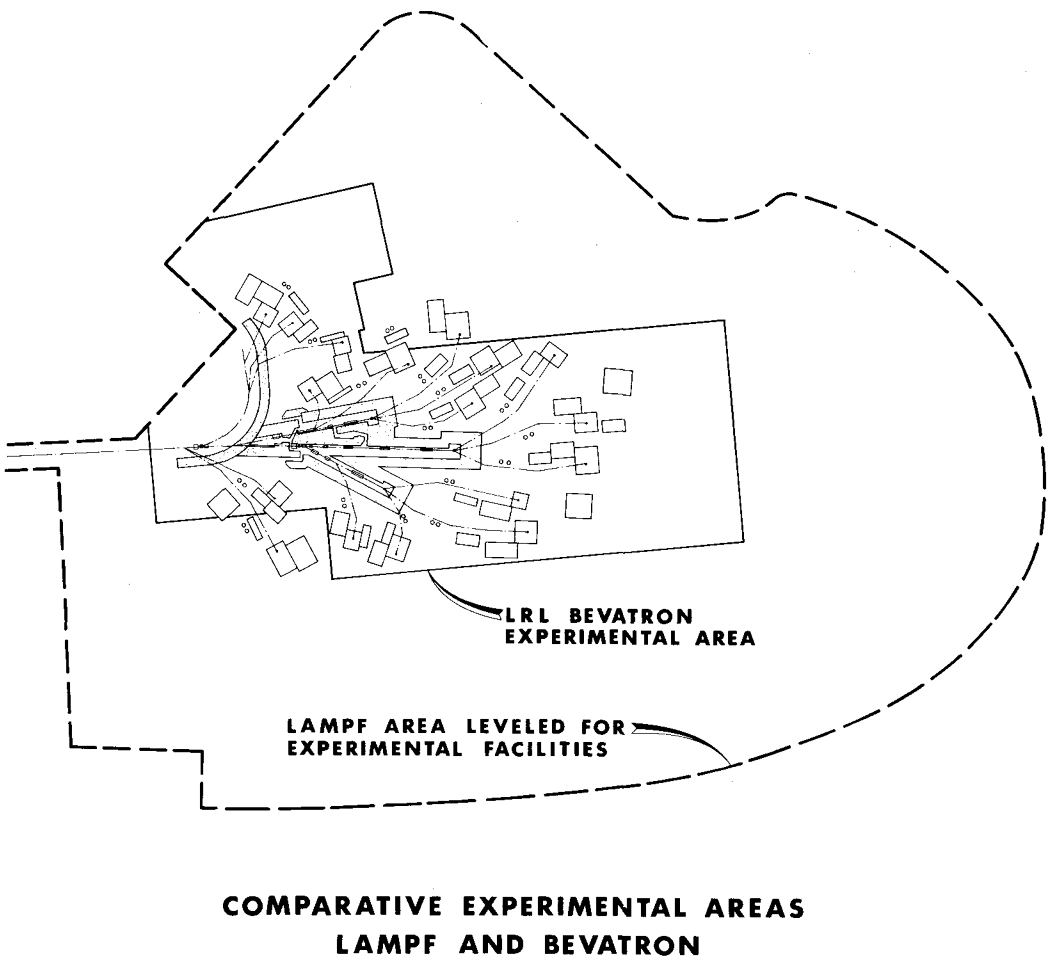
4. A schematic view (not to scale) of the LAMPF accelerator.



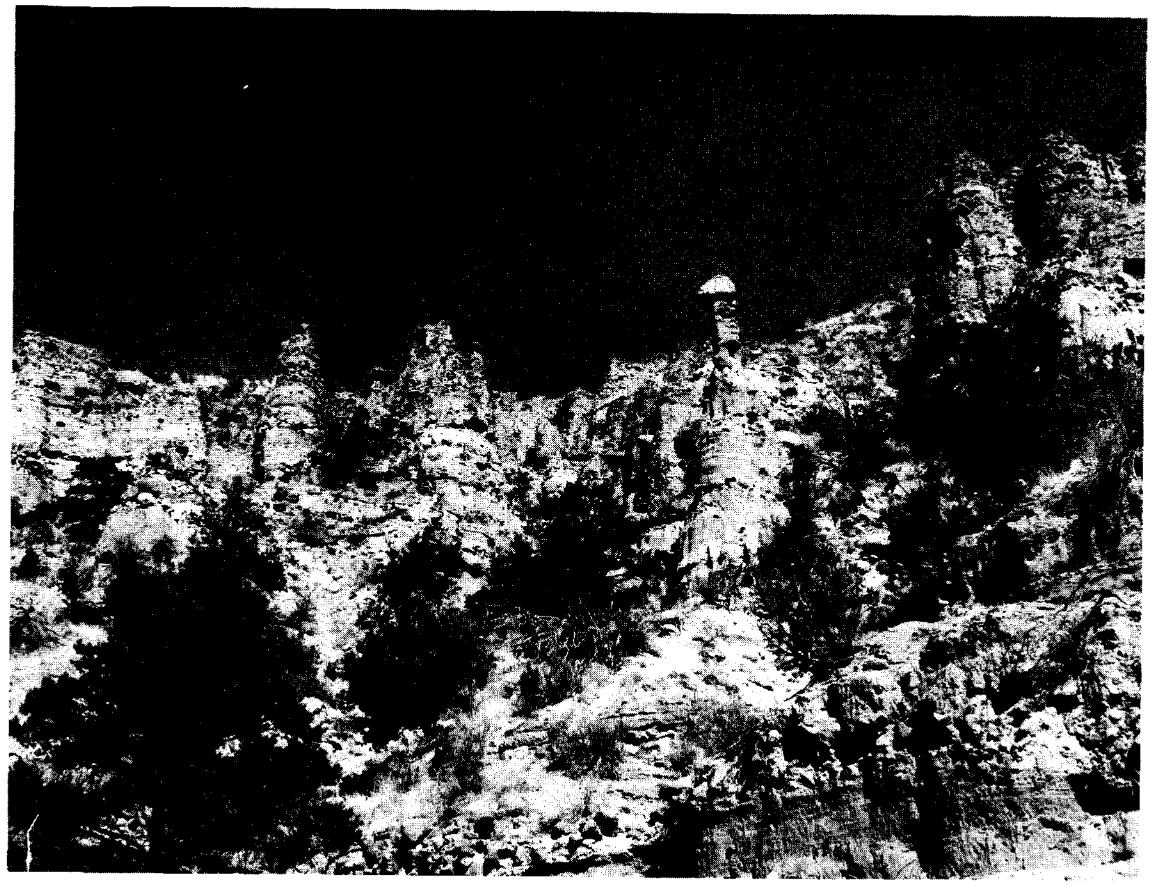
5. Some of the 805-MHz tank sections constructed at Los Alamos with one of the inventors.



6. Dimensional tolerances of π/2-mode structures.



7. Overlay of the expanded Bevatron experimental area and that of LAMPF.



8. Picture showing stability of rock formations in a Los Alamos canyon.

9. Aerial view of LAMPF site.

Pion Beam Intensities

Pion Energy (MeV)	Pion Production Cross Section* (cm^2/sr-MeV)	λ Pion Decay Distance (ft)	Positive Pion Intensity (per Sec)	Negative Pion Intensity† (per Sec)
100	10×10^{-30}	34.9	2.8×10^{8}	5.9×10^{7}
200	25×10^{-30}	55.5	2.8×10^{9}	5.9×10^{8}
300	50×10^{-30}	74.6	1.1×10^{10}	2.4×10^{9}
400	20×10^{-30}	93.4	7.0×10^{9}	1.6×10^{9}
500	5×10^{-30}	111.6	2.4×10^{9}	5.3×10^{8}

Conditions:

1 mA average proton beam = 6×10^{15} protons/sec at 800 MeV;

18 g/cm^2 Be target;

3×10^{-3} sr pion channel acceptance;

$\Delta p/p = 6.7\%$, total momentum acceptance of the pion channel;

43-ft channel length.

*Values calculated by Los Alamos Monte Carlo Cascade Code.

†Cross section for negative pions taken as 1/4.5 times that for π^+; ratio calculated by Cascade Code.

10. Some kinds of pion beams achievable with 1 mA of 800-MeV protons.

Muon Beam Intensities

Pion Energy (MeV)	Mean Muon Energy (MeV)	Positive Muon Beam Intensity per Sec: 52-Ft Channel	Positive Muon Beam Intensity per Sec: 100-Ft Channel	Negative Muon Beam Intensity per Sec: 52-Ft Channel	Negative Muon Beam Intensity per Sec: 100-Ft Channel
100	68	2.1×10^{8}	1.3×10^{8}	4.6×10^{7}	2.8×10^{7}
200	162	1.2×10^{9}	8.0×10^{8}	2.6×10^{8}	1.8×10^{8}
300	240	3.2×10^{9}	2.4×10^{9}	7.1×10^{8}	5.2×10^{8}
400	320	1.5×10^{9}	1.2×10^{9}	3.4×10^{8}	2.6×10^{8}
500	400	4.3×10^{8}	3.4×10^{8}	9.6×10^{7}	7.6×10^{7}

Conditions:

1 mA average proton beam = 6×10^{15} protons/sec at 800 MeV;

30 g/cm^2 Be target;

Solid angle acceptance = 4×10^{-3} sr for 52-ft channel; 3×10^{-3} sr for 100-ft channel;

$(\Delta p/p)_{\pi}$ = momentum acceptance of pion channel = 15%;

$(\Delta p/p)_{\mu}$ = momentum interval of muons used at output = 25%;

F = probability of muon remaining in channel = 0.15 for 52-ft channel and 0.10 for 100-ft channel.

11. Some kinds of muon beams achievable with 1 mA of 800-MeV protons.

$\nu_\mu + n \longrightarrow p + \mu^-$

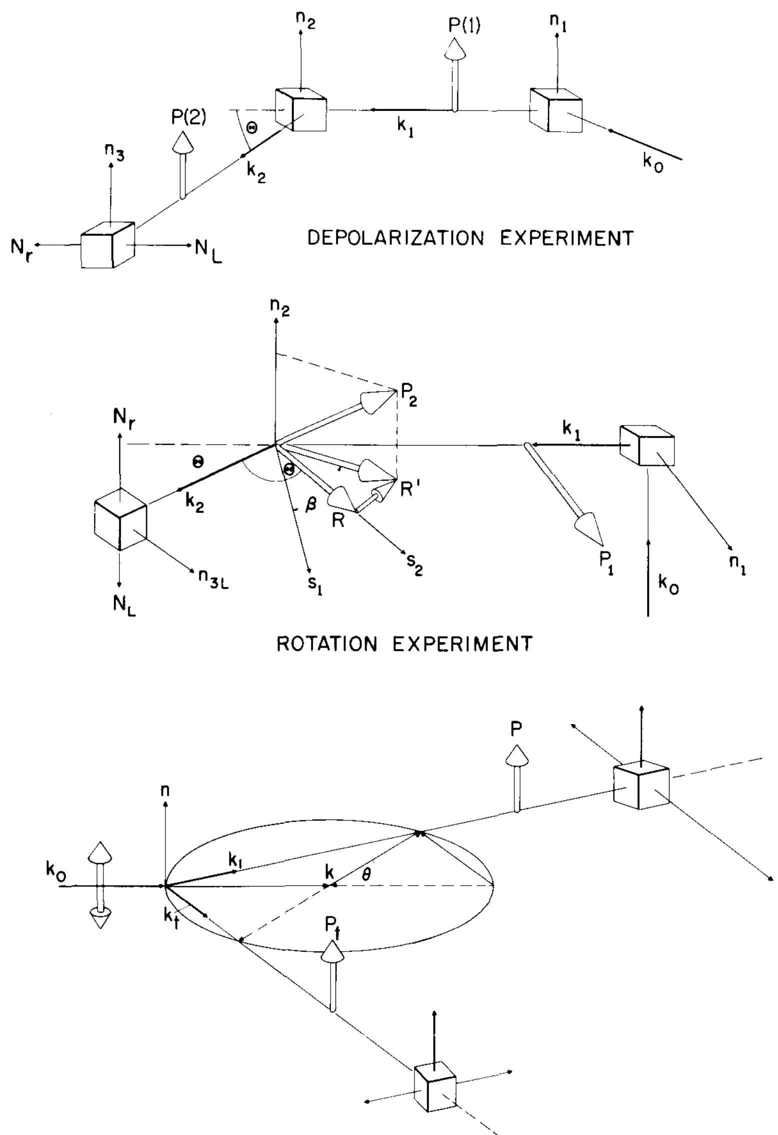
Neutrino Source	Neutrino Energy (MeV)	Flux (ν/cm^2-sec)	Cross Section	Flux times cross section (sec^{-1})
LAMPF	200 - 300	1×10^7	3×10^{-39}	3×10^{-32}
CERN	200 - 2000	4×10^4	8×10^{-39}	3×10^{-34}

Approximate counting rates per ton of detector then are as follows:

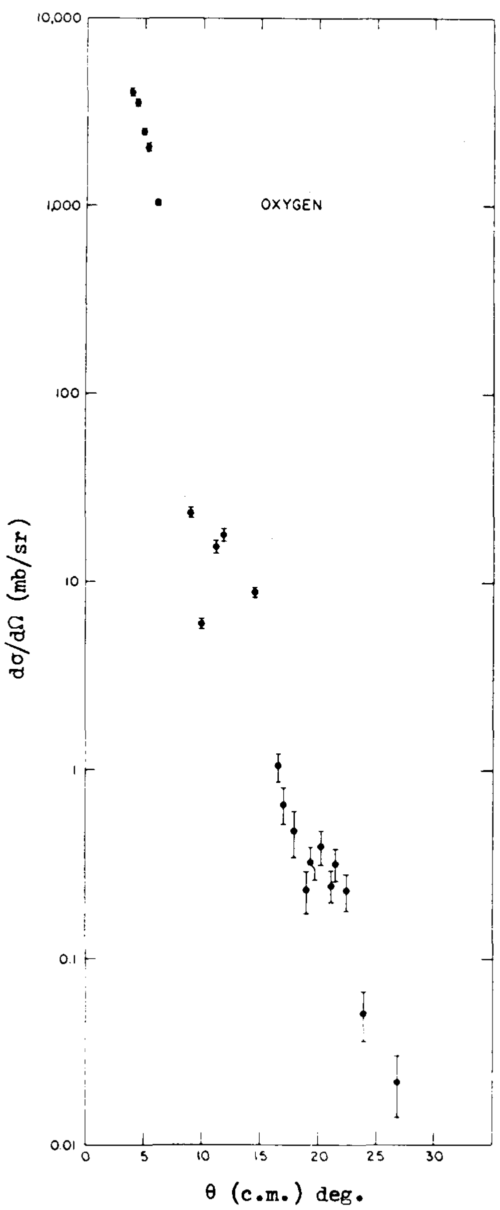
LAMPF 400 counts/ton-day

CERN 8 counts/ton-day

12. Estimate of counting rates for ν_μ absorption experiment.

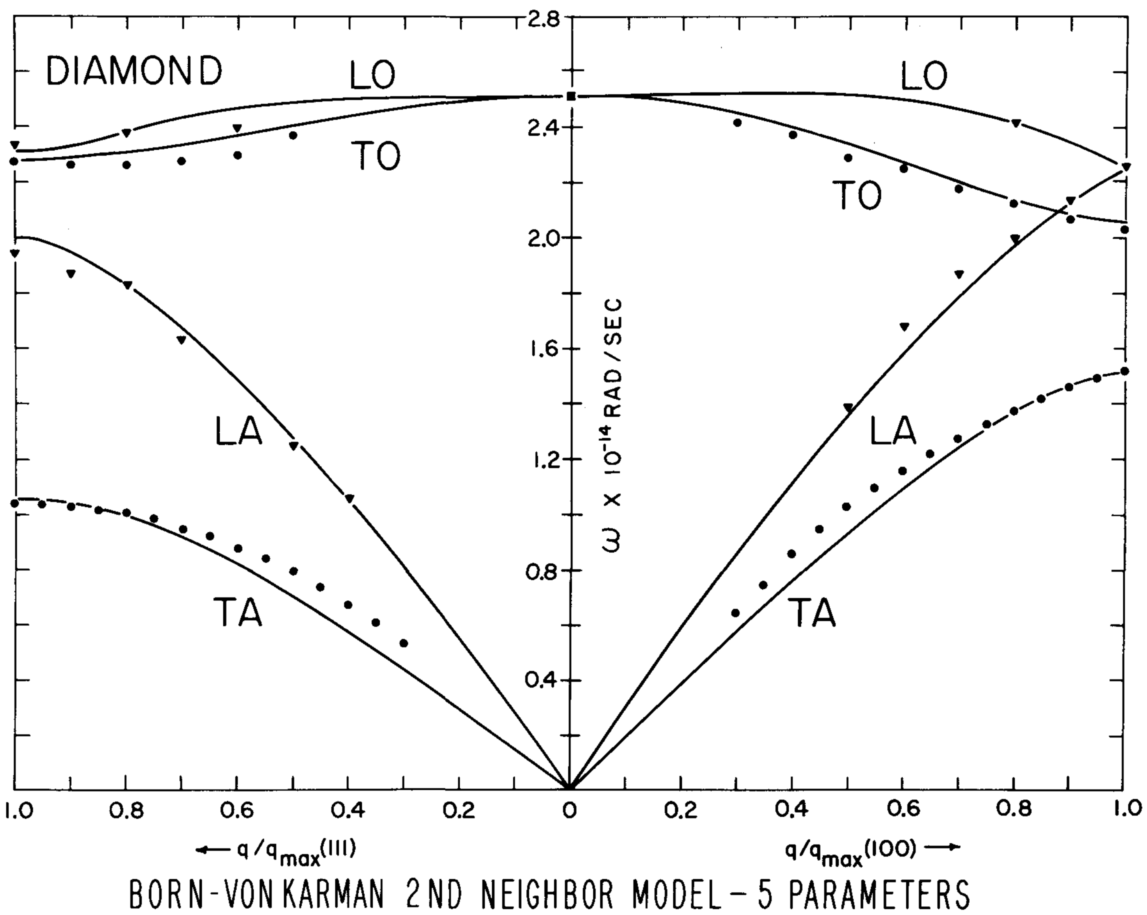


13. Nucleon-nucleon scattering experiments with high intensities.

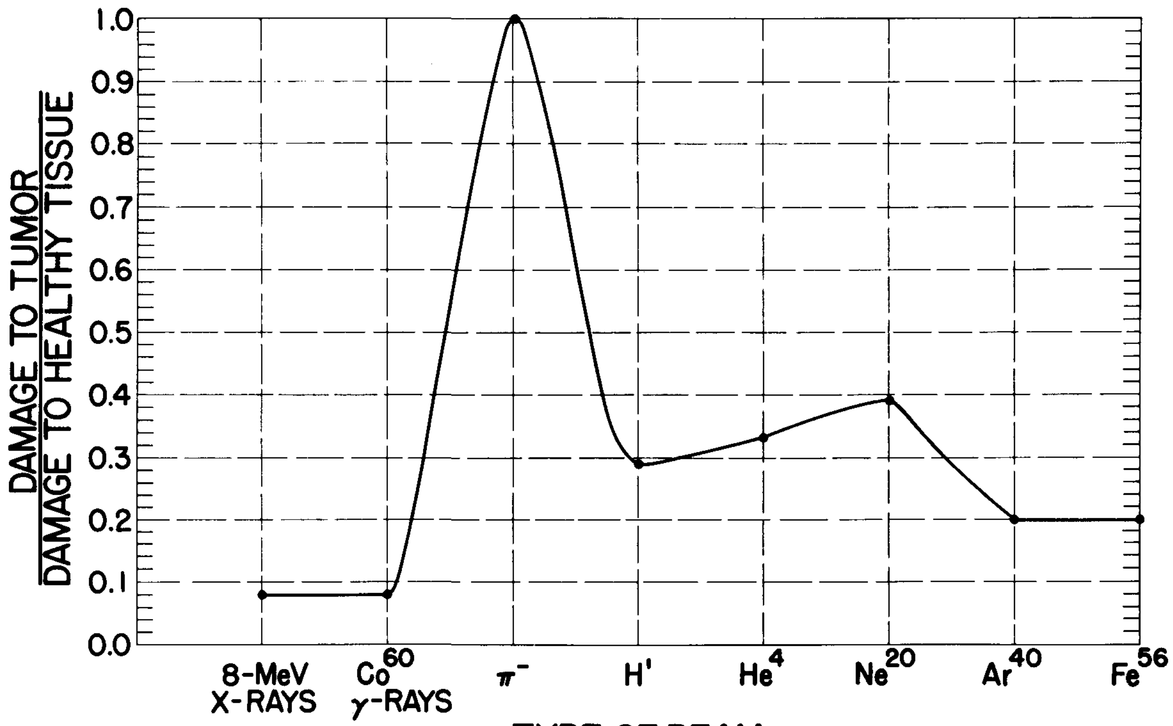


Differential Cross Section for the Elastic Scattering of 1 BeV Protons from O. (G. J. Igo, et al., BNL-10438 - Session Ia, Intl. Conf. on Nuc. Phys., Gatlinburg - Sept. 1966.)

14. Differential cross section for the elastic scattering of 1 BeV protons from oxygen.



15. Dispersion curves for a diamond crystal.



Irradiation of Tumor Extending from 10 cm to 15 cm Inside Organism
[Calculations by Prof. P. H. Fowler, Proc. Phys. Soc. (London) 85, 1051 (1965)]

16. Graph showing relative damage to tumor and healthy tissue resulting from irradiations with x rays, γ rays, pions, protons, and heavier nuclei, respectively.