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Meson Factories

Accelerators that will produce 500–1000 MeV nucleons and mesons in beams thousands of times more intense than existing machines will be able to do experiments never before possible, increase precision of others and reveal processes now unknown

by Louis Rosen

Louis Rosen, who heads MP Division at Los Alamos, has worked in fission, fusion, neutron interactions with complex nuclei, and spin dependence of proton-nucleus interactions. He gave an invited paper on meson factories at the last New York meeting of APS.

MESON FACTORIES, which will produce beams of nucleons and mesons thousands of times more intense than those presently available, can be expected to take us to our next level of understanding of nuclear structure and to reveal processes and mechanisms presently hidden from view. By meson factory I mean a complete nuclear-physics installation based on an accelerator of 500–1000 MeV, which is capable of providing at least 100 microamperes of high quality external beam. All ancillary facilities for performing high precision experiments with the primary and secondary beams are included: targeting, beam transport, data-handling equipment and beam dumps for the residual beams. Although the energy regime is not novel, the intensity capability is, being about ten thousand times as great as existing synchrocyclotrons; a 1-microampere, 800-MeV accelerator is capable of generating pion fluxes in excess of 10^{10} particles/cm^2/sec in a 6% momentum interval.

The meson factory will serve as a badly needed bridge between nuclear and subnuclear physics; this is significant because of the usual advantages of unifying scientific disciplines and because subnuclear physics can only relate to us through nuclear physics.

Because of the very large effort involved in construction of such an accelerator and in using its high-intensity beams, and the high costs attendant thereto, the scientific motivation and technological feasibility of meson factories have probably been reviewed by more high-level scientific committees[1] than has been the case for any previous accelerator project. With one exception (the Ramsey panel preferred a high-intensity 10-GeV accelerator from the standpoint of particle physics), all the committees concluded that a meson factory should be built in the immediate future. In the US, the Atomic Energy Commission and the Joint Committee on Atomic Energy appear to have arrived at the same conclusion; and so has the Swiss government.

Support for meson factories was rather slow to develop because most nuclear-structure physicists are not normally exposed to research with mesons while most high-energy physicists do not pay a great deal of attention to nuclear structure, which has traditionally been the happy hunting ground of low-energy physicists. The purpose of this paper is to indicate the basis for the present enthusiasm about meson factories, what such facilities would look like and how much they would cost.

Many groups have made important advances in the development of meson factories.[2] In this country groups at Yale, Oak Ridge, the University of California at Los Angeles and Los Alamos Scientific Laboratory (LASL) have made the primary contributions. In other countries groups at Chalk River, Strasbourg, Karlsruhe, Zurich and Dubna, have all made lasting contributions, both to the technology of accelerators that can provide the primary beam for a meson factory, and to the thinking about eventual use of such accelerators.

SCIENTIFIC MOTIVATION

Why then, this growing emphasis on achieving beams of nucleons and mesons thousands of times more intense than those presently available? Many factors appear to be involved. The scientific impetus arises from a necessity to bridge the gap between low-energy nuclear physics and fundamental particle physics. Low-energy nuclear physics is mainly concerned with the overall properties of the nucleus in its ground and excited states, as well as with interactions engendered when low-energy nucleons and nuclei interact with themselves and with each other. High-energy physics is concerned with the subnuclear domain, with the structure of the nucleons that comprise the nucleus, with the fundamental forces that govern the structure of nucleons and electrons, and that host of unstable particles that are manufactured from energy by the highest-energy accelerators. The energy region between 100 and 1000 MeV has relevance to both low-energy and high-energy physics and can illuminate problems common to both and unique to each. Some of the most interesting of these require such high intensities that if attempted with presently available accelerators, they would have to be passed down from father to son.

Figure 1 illustrates the worldwide accelerator situation. In terms of man-years, the largest effort is in low-energy physics, which is here defined to encompass the region below 100 MeV. The largest effort in terms of cost is in high-energy physics—the region above 1000 MeV. Between these two regions the effort in both human and economic resources is relatively small (well under 5% of the total effort). The main reason for this is the very low intensities available from the present synchrocyclotrons, which are based on designs dating back at least 20 years. For a considerable time these accelerators were the main instruments for advancing the frontier in subnuclear physics. More recently they have been directed towards problems of nuclear physics (and with gratifying results).

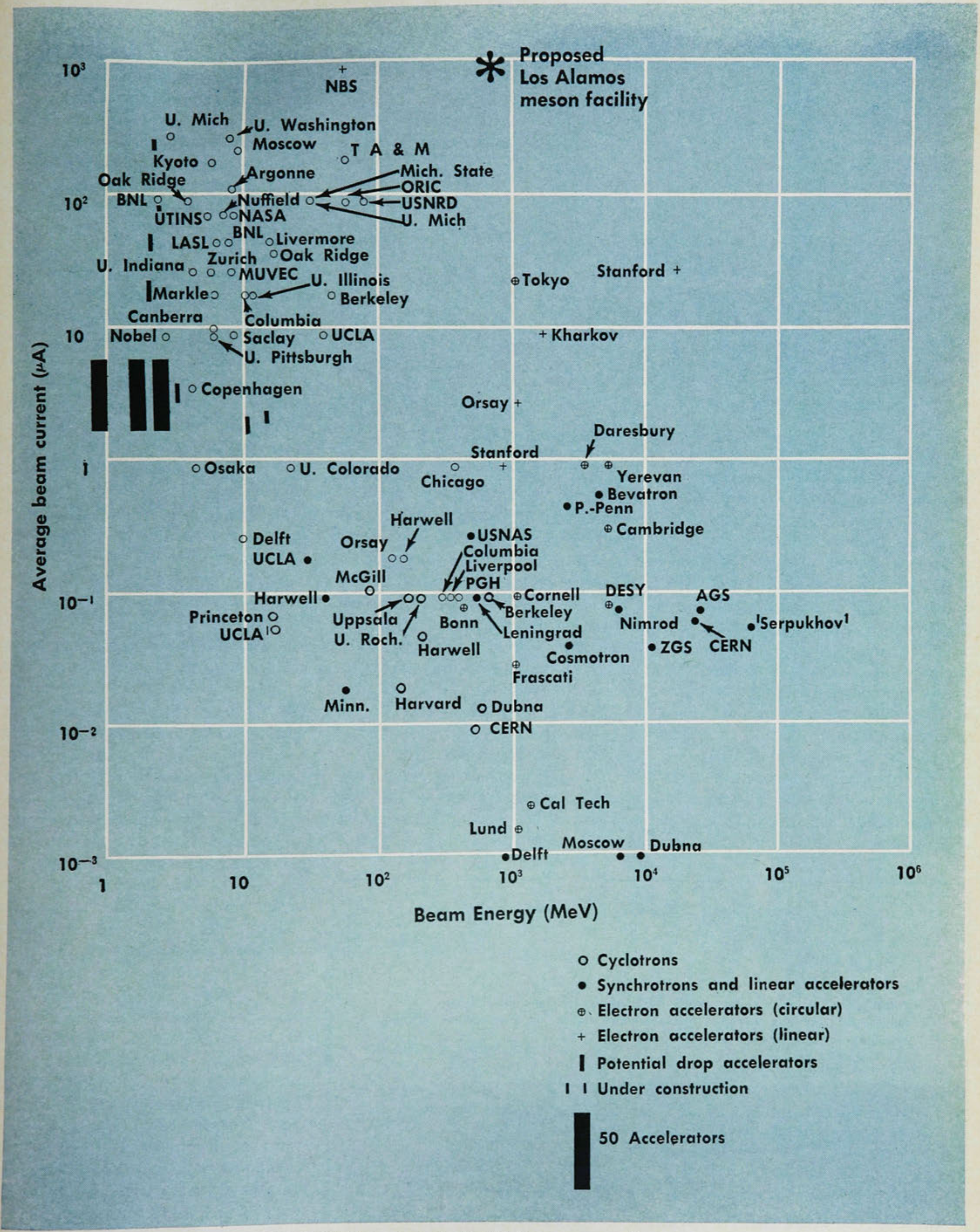
Since the discovery of the nucleus by Ernest Rutherford in 1911, there have been two frontiers in that branch of science having to do with the basic structure of matter. One, of course, has to do with energy; the other with intensity.

In the past the higher one went in energy, the lower the intensity one had to work with, and this is still true if one uses the cosmic radiation as one's source of particles. However, technological advances over the past several decades—in accelerator design, in radar, in ultrahigh-frequency television, and in the attainment of high vacuum—make it now feasible to construct medium-energy machines with very high intensities. The purpose of a meson factory, as the name implies, is to attack that class of problems for which higher intensity is required in order to perform experiments which cannot now be performed, or to perform with more precision important experiments on which some progress has already been made; and to search out properties and processes involving mesons, nucleons and nuclei that have so far been hidden from view because they reveal themselves under conditions that only rarely occur.

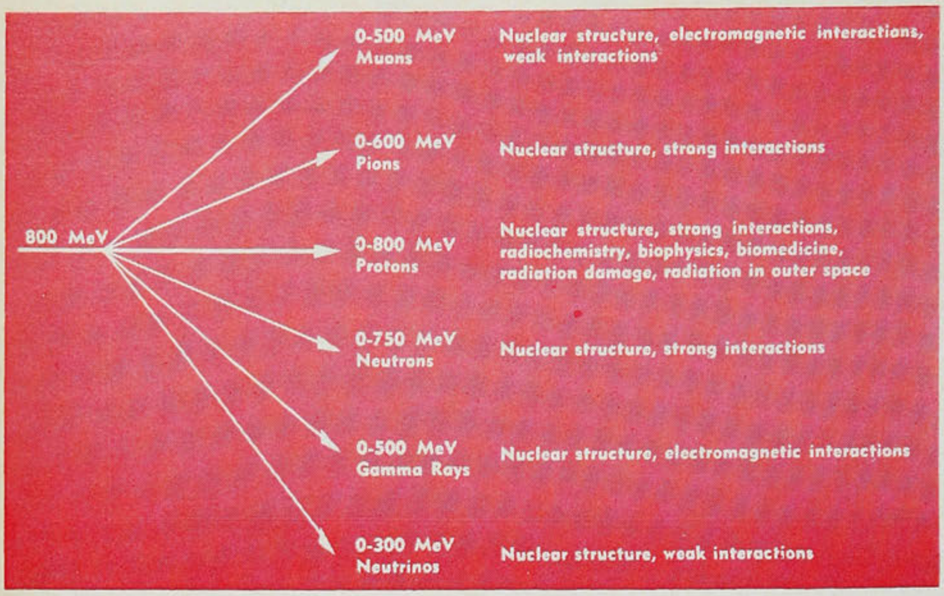
Figure 2 indicates the general kinds of problems to which meson factories are expected to make a contribution. The nucleus is the only stable system in which all known natural forces act simultaneously and perhaps this is the place to look for a relation between the forces. Of the four forces that determine all natural phenomena —gravitation, electromagnetic, weak nuclear (which governs radioactivity), and strong nuclear (which is responsible for the stability of nuclei and the violence of their reactions)—three will be subject to direct study with the high-intensity beams available from a meson factory. Furthermore, and perhaps more importantly, the structure and properties of the atomic nucleus can be studied under conditions that are more nearly ideal than is now possible. All this will come about because of the enrichment of primary and secondary beams. The increase in meson fluxes over that available from existing accelerators is almost of the same magnitude as was achieved in going from the use of cosmic rays to the first synchrocyclotrons. The increased fluxes of primary and secondary particles will make possible purer beams, higher resolution, better statistical accuracy and systematic explorations. Such drastic changes in technology have always spawned a great enhancement in the understanding of the natural phenomena at issue.

Nucleon probes

Common to both nuclear and subnuclear physics is the problem of nuclear forces. It appears essential to press forward with our investigation of internucleon forces by appealing to rather complex experiments involving multiple scatterings of the incident nucleon, and these experiments require high intensity. Desired is an unambiguous determination of the nucleon-nucleon potential, as a function of energy. Required are experiments other than elastic-scattering angular distributions, although even here more needs to be done. It is necessary to do the much more difficult double- and triple-scattering experiments for the p-p, n-p and n-n systems, as a function of energy and with good precision. From such experiments will emerge not only a complete description of the nucleon-nucleon interaction for free nucleons but also more definitive information on basic symmetries. For example, as Gregory Breit



WORLDWIDE ACCELERATOR PICTURE shows largest effort in low-energy work. In terms of cost, however, largest effort is in high energy. —FIG. 1



RESEARCH AREAS for meson factories vary with energy. —FIG. 2

has pointed out, a precise comparison of the value of the pion-nucleon coupling constant, developed from p-p scattering, with that from n-p scattering, provides a sensitive test of charge independence of nuclear forces at large interaction distances; by comparing the asymmetries in nucleon-nucleon scattering using polarized beams, with the polarization resulting from scattering of unpolarized beams by unpolarized targets, one can have a very precise test of time-reversal invariance.

Medium-energy, high-intensity beams are also necessary to probe the local composition of nuclei to determine the short-range structure of nuclear wavefunctions. For this purpose accelerators below 100 MeV are inadequate because the wavelength of the probes are so long that they explore overall properties of the nucleus almost to the exclusion of detailed structure. At low energies the interpretation of results based on observation of particles originating inside the nucleus is complicated by multiple collisions that outgoing particles suffer in traversing nuclear matter. To overcome these difficulties one requires incident nucleons of energy greater than 500 MeV. However, existing accelerators of energy 500–1000 MeV do not have sufficient intensities, and accelerators with energy in the GeV region provide probes whose intensities are too low and whose wavelengths are too short for this purpose.

For nuclear-structure exploration, one requires the de Broglie wavelength of incident particles to be sufficiently small that binding energies and angular momenta of individual nucleons deep inside the nucleus can be determined with high precision. At 500–800 MeV, nucleons provide a probe that is fine enough to do this but not so fine that all observables are dominated by nucleon properties. It is as though these probes provide one with a super-resolution microscope through which one can take a high-speed picture of the nucleus. Since the incident particle energy is far greater than the binding energy of a nucleon in the target nucleus and since the configuration of nucleons will not change during the interaction time, the impulse approximation should be valid. All this comes about because an 800-MeV nucleon traverses a medium-sized nucleus in about 10^{-23} second and has a de Broglie wavelength (divided by 2π) smaller than the average distance between nucleons.

Meson probes

Many of the above remarks made on behalf of nucleon probes apply also to meson probes. For example, (p, 2p), (π, πp), and (μ, μp) can all be used to extract nucleons from deep inside the nucleus in order to measure binding energies and angular momenta associated with the various shells, as well as nucleon correlations, momentum distributions and spatial distributions. Each kind of particle permits the investigation of a different set of characteristics of the nuclear wavefunction. We know that it is often very difficult to sort out, in a given interaction, those phenomena that are due to the properties of the probe from those due to the properties of the target. So it is essential to vary energy and momentum independently and to use probes with different intrinsic properties in order to map the different kinds of distributions in the nucleus. Like the nucleon, the pion is a strong-interaction particle—but it is different—it has different mass, different spin, different isotopic spin, different momentum for a given energy, and obeys different statistics. In addition a pi meson lib-

Examples of Experiments Utilizing Intense Beams of π Mesons

I. Elastic scattering with pions of both signs
   Optical potential and relation to pion-nucleon potential

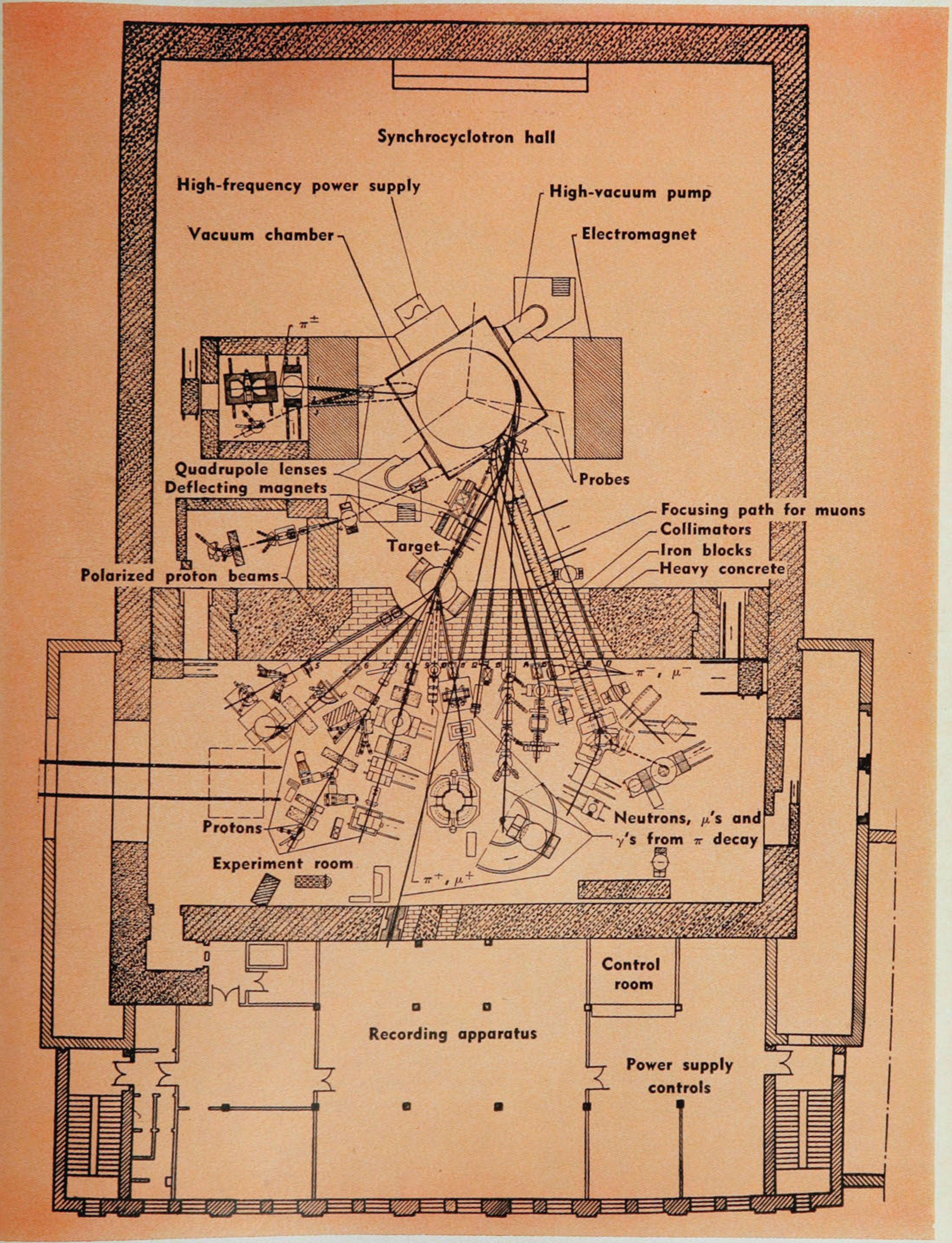
II. Inelastic scattering
   A. Information on states not usually excited by nucleon scattering
   B. Quasi-free collisions between pions and nucleons in the nucleus leading to momentum distribution of bound nucleons

III. (π, π' x) reactions, clustering

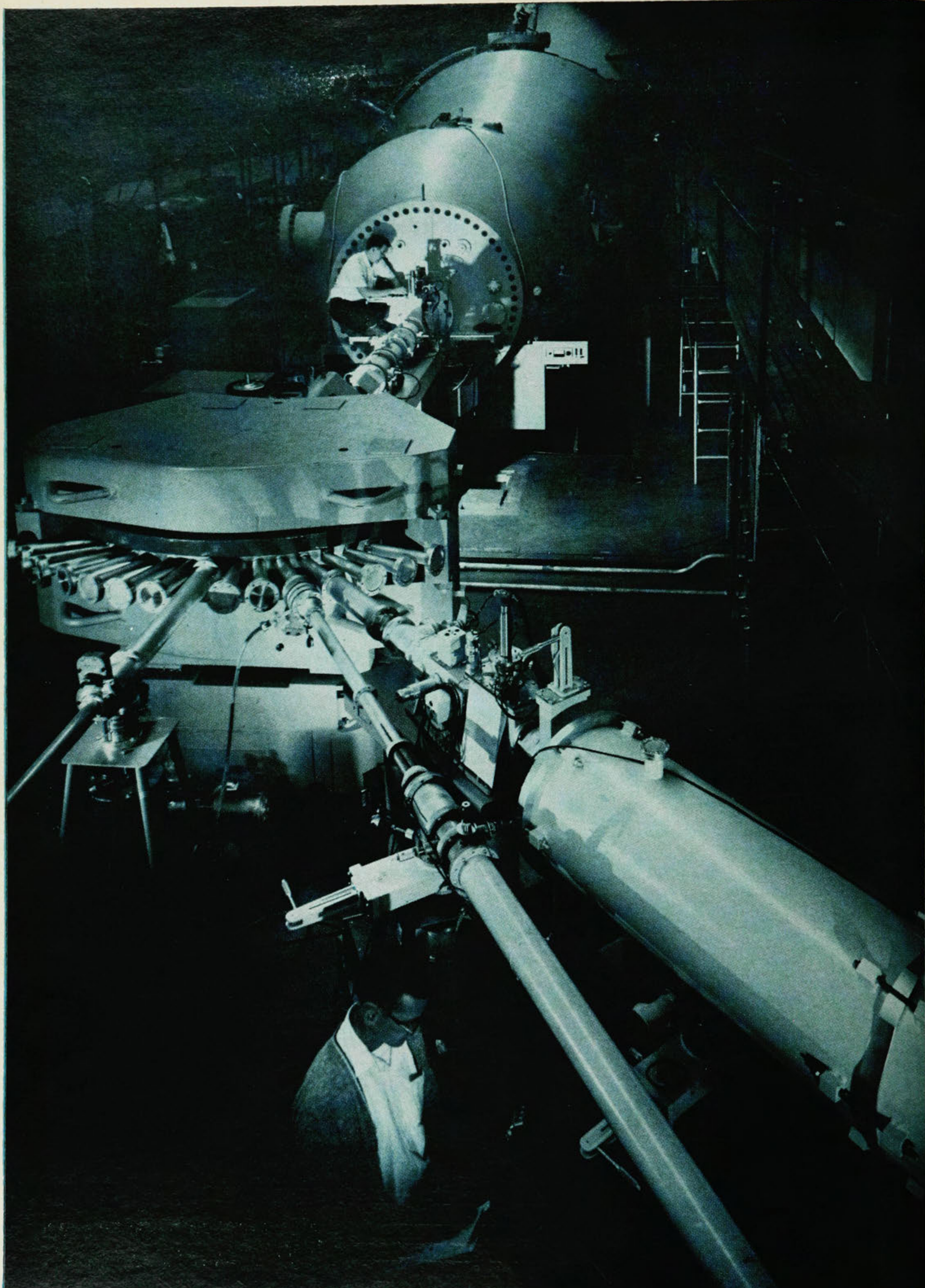
IV. π^- absorption
   A. Production of two holes; momentum correlation between nucleons in the nucleus
   B. Deposition of energy without angular momentum
   C. Mechanism of pion absorption: pion boil-off

V. Mesic atoms
   Use of high-resolution spectrometry made possible by high intensity

VI. Single- and double-charge exchange
   A. Test of isobaric-spin symmetry
   B. Double-charge exchange leading to isobaric analogs of the original nucleus



DUBNA 680-MEV SYNCHROCYCLOTRON will be converted to meson factory by spiral-ridging electromagnet to produce 700-MeV protons. —FIG. 3



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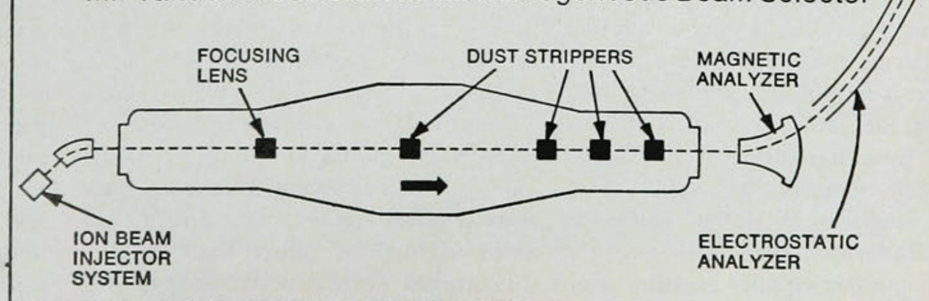
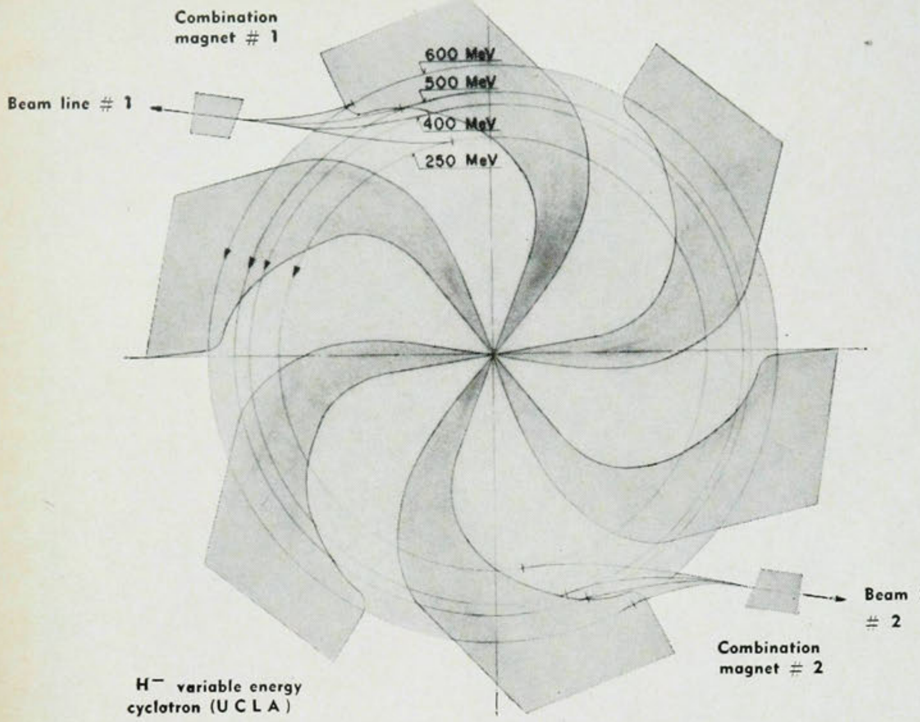
MP Tandem Accelerator with Homogeneous Beam Selector



HIGH VOLTAGE ENGINEERING



SPIRAL-RIDGED CYCLOTRON AT UCLA will accelerate negative hydrogen ions, which will be converted to positive ions and bent out. —FIG. 4

erates 140 MeV on capture, thus permitting the study of statistical or evaporation processes, involving "specific-heat" considerations at very high excitation but without the complication of the effects due to high angular momentum.

Some examples of the types of experiments to which one might usefully apply intense beams of pi mesons are given in the box. The essential point is that pi mesons permit the transfer to the nucleus of different combinations of quantities than do nucleons. Since the pi meson has unit isotopic spin, it is possible by a $\pi^{\pm}$, $\pi^{\mp}$ reaction to change the isotopic spin of the target nucleus by two units. By double charge exchange one can prepare new states of matter, for example ^{6}H from ^{6}Li and ^{12}Be and ^{12}O from ^{12}C. On a lighter note, double charge exchange ought to answer what I would imagine to be the prayer of the radiochemist: "Oh, deliver me from the valley of stability." The above remarks are valid even without assigning to the pi meson a special role inside the nucleus.

Muons present equally exciting possibilities. The muon is born of the pi meson with the emission of a neutrino, and it is perhaps the most mysterious particle in physics. Is it really nothing more than a heavy electron? If so, what is its raison d'être? To answer these questions, better measurements are needed of the electromagnetic properties of the muon (obtainable by elastic-scattering measurements, for example) and of the weak interactions which it engenders.

Muon beams will be quite useful for performing inelastic studies on complex nuclei; since the mass of the muon is greater than that of the electron, muon scattering does not produce so much bremsstrahlung. Also a given momentum transfer can be accomplished at lower energy, so the energy transfer can be more precisely determined.

But the most important applications of muons will probably be in the formation of mesic atoms and the production of muonium (a new field pioneered by the Yale group under Vernon Hughes).

A major point is essentially this: since a muon is several hundred times heavier than an electron, it forms an atom of nuclear, rather than atomic, dimensions. Furthermore, since muonic atoms of all atomic numbers have the basic spectroscopy of the hydrogen atom (because they contain only one muon), interpretation of their spectra is facilitated. Muonic atoms can therefore be used to map the charge, shape and magnetic-moment distribution of nuclei; these are revealed by the x rays that are emitted as the muon falls from one Bohr orbit to another. Much has already been done in muonic atoms, but with more intensity, more lines can be resolved, better energy resolution can be obtained and more detail deduced about the nuclear form factors.

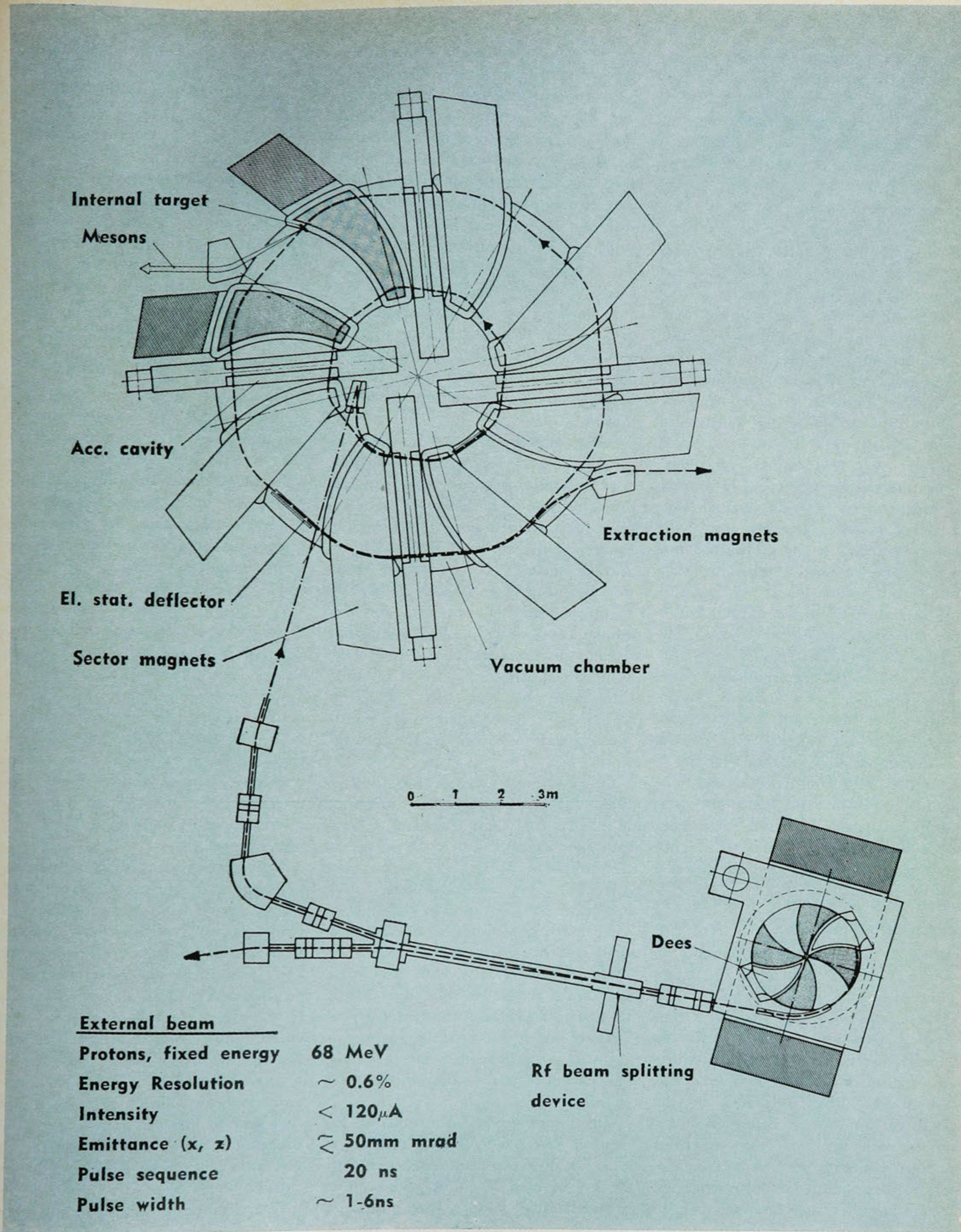
Applications to chemistry

Intense fluxes of stopped positive muons offer the possibility of producing large numbers of muonium atoms. These behave very much like atomic hydrogen.[3] Since the muon lifetime is about 2 microseconds, there is sufficient time for chemical reactions involving muonium to take place. The polarization and decay properties of the muon provide signals that permit measurement of collision cross sections and reaction rates of hydrogen-containing molecules, in which one of the hydrogens is replaced by a muonium atom.

Applications to particle physics

It is probably inevitable, and certainly appropriate, that meson factories will be used to extend the knowledge of particle physics that was first accumulated through the use of their antecedents, the synchrocyclotrons. Some of the experiments that now appear of outstanding importance and that will be accessible through the availability of high-intensity beams are: nonassociated production of strange particles; rare decay modes of the pion; the π - π interaction from π, 2π studies on protons; mass of the mu neutrino from very precise measurements, using mesic x rays, of the masses of pions and muons; neutrino-electron scattering; tests of quantum electrodynamics from electromagnetic properties of the muon, including magnetic moment, *g*-value, mass of muon and hyperfine structure of muonium; and measurement of the electromagnetic form factor of the pion. How, for example, would one accomplish the last?

Recently, Robert Hofstadter and M. M. Sternheim[4] have proposed a



ISOCHRONOUS RING CYCLOTRON, to be built in Zurich, has 8 C-shaped spiral sector magnets, 4 rf cavities to produce 510-MeV protons. —FIG. 5

method that appears capable of determining the entire dynamic form factor of the pion, assuming the availability of monoenergetic pion beams of high intensity. The experiment involves the elastic scattering of $\pi^{\pm}$ from helium nuclei, for which the electromagnetic form factor is reasonably well known. One is therefore, in a sense, using alpha particles to probe the pion. Calculations have shown that there is a minimum in the α cross section for π-α scattering, and that at this minimum the ratio of the difference and sum of scattering cross sections for positive and negative pions is rather sensitive to the size and charge distribution of the pion. The point is that since the alpha particle contains two protons and two neutrons, the nuclear scattering amplitude is independent of pion charge. The nuclear-Coulomb interference will, however, reflect a charge dependence when pions of both charges are scattered from helium nuclei. The quantity determined from the experiment is the Coulomb amplitude, which includes the pion charge and form factor, as well as the corresponding quantities for the alpha particle. Fortunately, the scattering angle, corresponding to the nuclear cross section minimum for pions of about 100 MeV, is rather large, implying sizable momentum transfer and hence the possibility of determining the electromagnetic form factor to small radii. Pi-D scattering might be expected to yield equivalent results.

Practical applications

Although none of the proponents of meson factories has made a strong point of possible practical applications, these should not be ignored. The challenging technical problems will engage the attention of creative scientists and engineers in an area where technology has direct relevance to the needs of our society. Information obtained with medium-energy nucleons and with mesons will be complementary to that obtained at lower energies. Meson factories, therefore, will help to maintain interest in basic nuclear science at a high level and this, of itself, is important for society because technology is built on the foundation of pure science. It should not be forgotten that from basic low-energy nuclear physics have flowed many applications to our security, to our economy and to our general welfare. Many more can be expected. It is clear that world society, in order to satisfy its need for industrial production, food, water, transportation, and a clean biosphere, shall become ever more dependent on nuclear-energy sources and the utilization of nuclear radiations. I believe that these applications will be enhanced by the development of the nuclear technology that will be required for successful operation of a meson factory and for coping with the very high levels of radiation associated therewith.

More tangible perhaps are applications to the development of new processes and materials involving the use of high levels of radiation. The beam from the proposed Los Alamos Meson Factory will contain 800 kW of average power. All ionization from this beam can be deposited in less than 100 cm^3 of tungsten, for example. In the process of stopping this beam, one produces about 10^{17} neutrons/sec, steady state. This is a rather formidable neutron flux, 90% of which will have energy below 10 MeV, and it will have many applications.

Other examples of possible applications are not difficult to imagine. Manned space flight presents serious radiation hazards; intergalactic radiation is about 50 rem/yr (which produces the same biological effect as 50 roentgens of x or gamma radiation); solar flares may produce several hundred rem on a trip to the moon. In some portions of the Van Allen belt one finds about 100 rem/day. Much of this radiation is produced by protons of energy accessible to meson factories. It will be necessary to study the effects of such radiation in great detail.

In the treatment of cancer by radiation therapy, it is well recognized that the chief problem is selective deposition of high levels of radiation in a well-defined volume, with minimum damage to surrounding tissue. During the past year, Chaim Richman and his group at the Graduate Research Center, Dallas, working with colleagues at Berkeley, have shown that negative pi mesons may prove to be an extremely useful tool for the treatment of deep-seated, inoperable malignancies, because they release 140 MeV when captured by a nucleus, and a significant portion of this energy finds its way into short-range disintegration products of the capturing nucleus. In oxygen capture a number of alpha particles are emitted and these are highly ionizing. So we may yet see a large acclerator, built primarily for basic research, join the battle against one of man's ancient enemies.

MESON FACTORY CONCEPTS

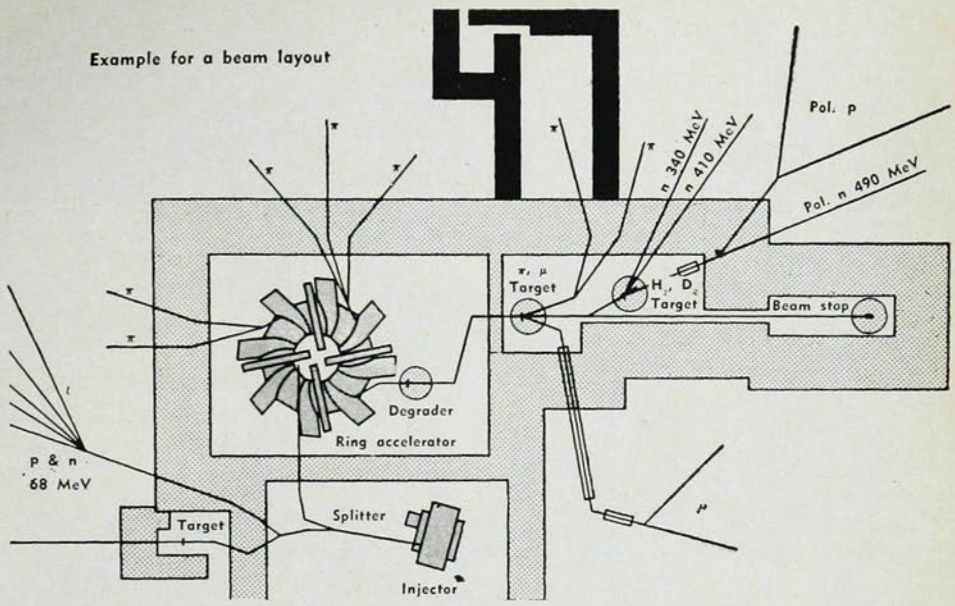
Although, as already indicated, numerous groups are looking towards the design of very high-intensity accelerators in the energy range 500–1000 MeV, no two groups are proposing to build precisely the same accelerator. However, the accelerators under consideration do fall into two main categories—circular and linear, and they all accelerate hydrogen ions.[5]

We know of only one feasible method for accelerating charged particles—that is the application of an electric field. The various accelerators differ, therefore, in how this electric field is applied, in whether a magnet is used to guide the particles in spiral paths, and in whether a given accelerating gap is traversed once by each particle, as for the linear accelerator, or many times, as in the circular machines.

Up to the present time the circular accelerators operating in the pertinent energy range have been of the synchrocyclotron type and have suffered from lack of intensity on the one hand and from inefficient beam extraction on the other. Both deficiencies must be overcome for a high-intensity machine. The second difficulty is as serious as the first, for the loss of even a small fraction of a 100–1000-microampere beam inside the accelerator will lead to unacceptable levels of radioactivity, which will damage the accelerator and make it essentially impossible to service.

The method proposed to overcome the beam-intensity problem in circular machines is to make the accelerator isochronous,[6] thus avoiding the intensity penalty imposed by frequency modulation. In order to achieve isochronism (that is, avoid the phase lag between orbit frequency and rf field, which is imposed by the relativistic mass increase of the accelerating particles) without changing rf frequency during the acceleration cycle, one must increase the magnetic field as the orbit radius increases. Since this is inconsistent with beam stability, one imposes azimuthal variations on the magnetic field (strong focusing) to stabilize the beam.

The various cyclotrons proposed are all isochronous and employ the sector-focusing principle to achieve strong focusing. The two most important factors influencing the different approaches are (a) cost and (b) the necessity to ensure very efficient beam extraction.



ZURICH EXPERIMENTAL AREA. Extraction occurs due to a radial resonance, an electrostatic deflector and extraction magnet. —FIG. 6

Spiral-ridged cyclotron

When I visited the Joint Institute of Nuclear Research at Dubna last February, I learned that an extremely competent group of some 40 physicists and engineers, under V. P. Dzhelepov, is working hard on a design for converting the 680-MeV synchrocyclotron to a meson factory. They will spiral-ridge[2,7] their present electromagnet and thereby obtain 700-MeV protons under constant frequency operation. In view of the intense use to which they are putting their existing synchrocyclotron (figure 3), I would predict that the Dubna group will make very effective use of a meson factory.

Negative-ion cyclotron

The UCLA group, under Reginald Richardson,[7] has proposed the acceleration of negative ions in a spiral-ridged cyclotron. After negative hydrogen ions are converted to positive ions by a stripper, the magnetic field will bend the protons out of the cyclotron, as illustrated in figure 4. The negative-ion cyclotron has desirable features: variable energy, complete beam extraction and 100% macroscopic duty factor. However, intensity and maximum energy are limited because of beam loss due to dissociation of the ions resulting from (a) small-angle scattering in the residual gas of the vacuum chamber and (b) interaction with the magnetic field. (A magnetic field acting on a high-velocity ion is equivalent to an electric field that tries to part an electron from its hydrogen ion through the Stark effect.)

Ring cyclotron

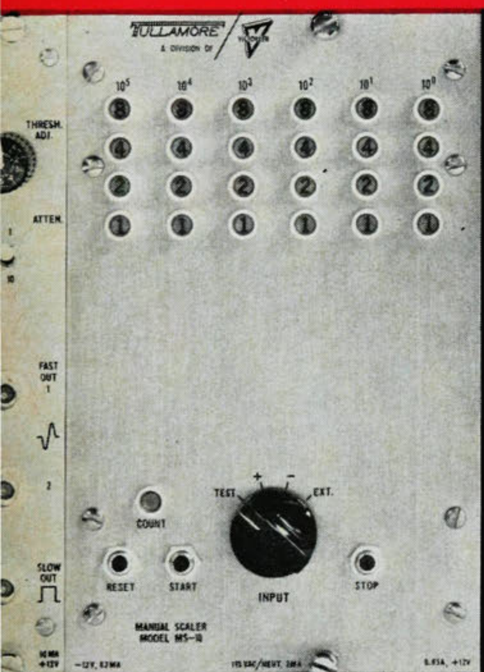
As of this writing, the only group that has been completely funded to build a meson factory is the Zurich group under J. P. Blaser. The accelerator is two stage; a 70-MeV azimuthally-varying-field cyclotron injects into an isochronous ring cyclotron[2] consisting of eight C-shaped spiral sector magnets and four rf cavities to provide acceleration. Extraction occurs at maximal energy under the influence of a radial resonance, an electrostatic deflector and an extraction magnet. Figure 5 illustrates the design concept for the accelerator, and figure 6 shows the experimental area.

Separated orbit cyclotron

The SOC[8] shares with the negative-ion cyclotron the advantages of full beam extraction and variable energy. In addition, it is capable of very high intensity and much higher energy. In the SOC, protons undergo acceleration in resonant cavities and are constrained to well separated spiral trajectories by a magnetic guide field produced by fixed-field electromagnets positioned between the cavities. The resonant cavities are driven by fixed-frequency power amplifiers through coupling loops and under phase and amplitude conditions that permit synchronous acceleration of the protons. An SOC may be visualized as a linear accelerator wound in a flat spiral. The method of construction is indicated in figures 7 and 8. As shown in figure 8, the turns are sufficiently separated to permit insertion of a magnet for extracting the beam at any energy.

At Chalk River National Laboratory and Oak Ridge National Laboratory there is considerable activity aimed at designing an SOC capable of delivering up to 65 mA at about 1 GeV. The primary purpose of this accelerator is not to produce mesons, although it would certainly serve as a super meson factory, but rather to generate very high neutron intensities—higher and under more advantageous conditions than is possible from the highest-power reactors presently contemplated. The chief economic problem with such an accelerator revolves around the conversion of 60-Hz power to rf power, since the main power sink is not the cavities but the beam. The advantage of the SOC in this regard derives from its low frequency of operation, about 50 MHz, where very efficient power amplifiers are available. However, should equally efficient and highly stable power amplifiers become available at higher frequencies (about 200 MHz), as for example, the crossed-field tubes, the linac will compete favorably with the SOC even for very

STANDARDIZATION—IT'S WONDERFUL



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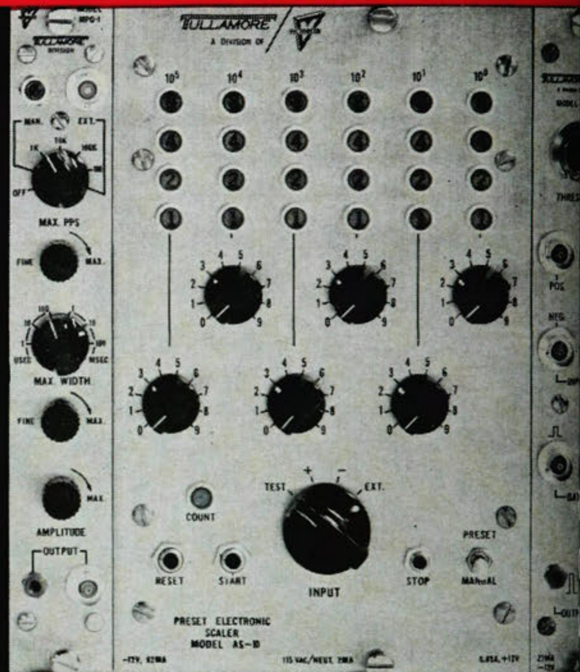

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Soft x-ray 10A to 250A	Concave reflection gratings used in high vacuum at grazing incidence; sizes and types with radii from 400 to 6650mm.	600-3600/mm	1° to 6°	Grazing Incidence Al, Au, Pt coatings
Extreme Ultra-violet (XUV) 250A to 1100A	Concave reflection gratings used near normal incidence; usually in first order.	600-3600/mm	1° to 10°	Au replicas, or Pt flash on Al
Vacuum Ultraviolet 1100A to 2000A	Large variety of concave and plane reflection gratings. Used in first or higher orders.	600-3600/mm	2° to 22°	Al protected by MgF_2 recommended for gratings in this region.
Ultraviolet 2000A to 4000A Visible 4000A to 7000A Near Infrared 0.7 to 2.0 microns	Over 500 sizes of plane or concave reflection gratings used in first or higher orders. Also a selection of plane transmission gratings.	300-2160/mm	3° to 64°	Plane for photoelectric spectrometers; concave for photographic recording of spectra.
Infrared 1.0 to 75 microns	Complete range of sizes and types of plane gratings. First Order.	20-600/mm	5° to 30°	Plane gratings with aluminum coating.
Far Infrared 40 to 1000 microns	Plane gratings ruled to order in aluminum metal. Any desired size up to 330 x 360mm.	0.8 to 12/mm	15° to 31°	SiO coated . . . used with plane filter gratings.

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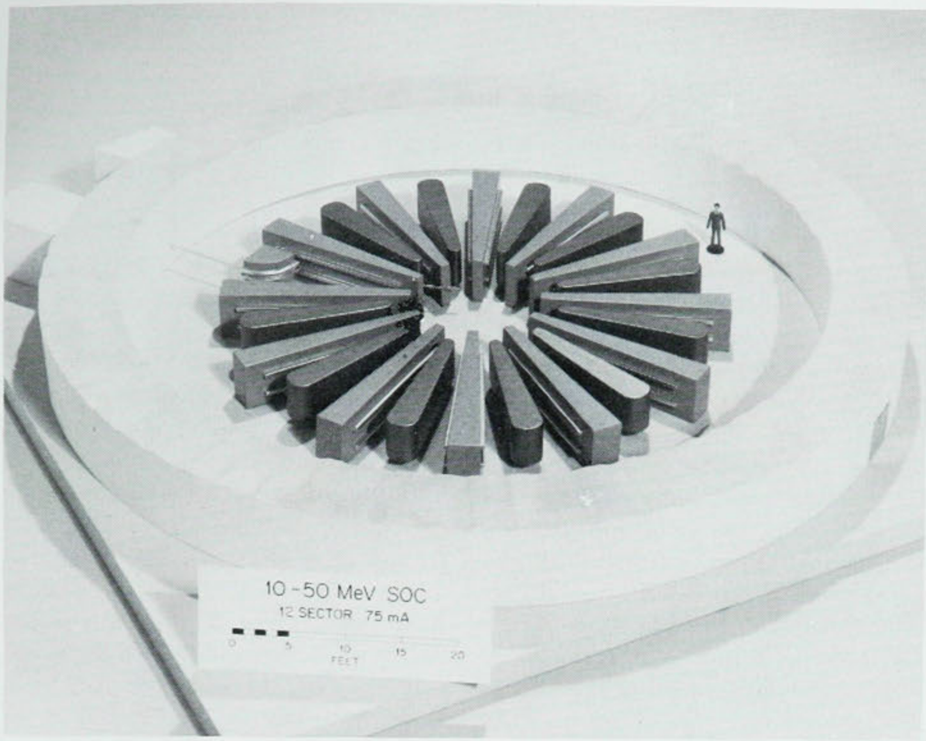
high beam intensities and power levels. In fact, the Chalk River group is looking at this possibility and is now dividing its design effort between the SOC and linac.

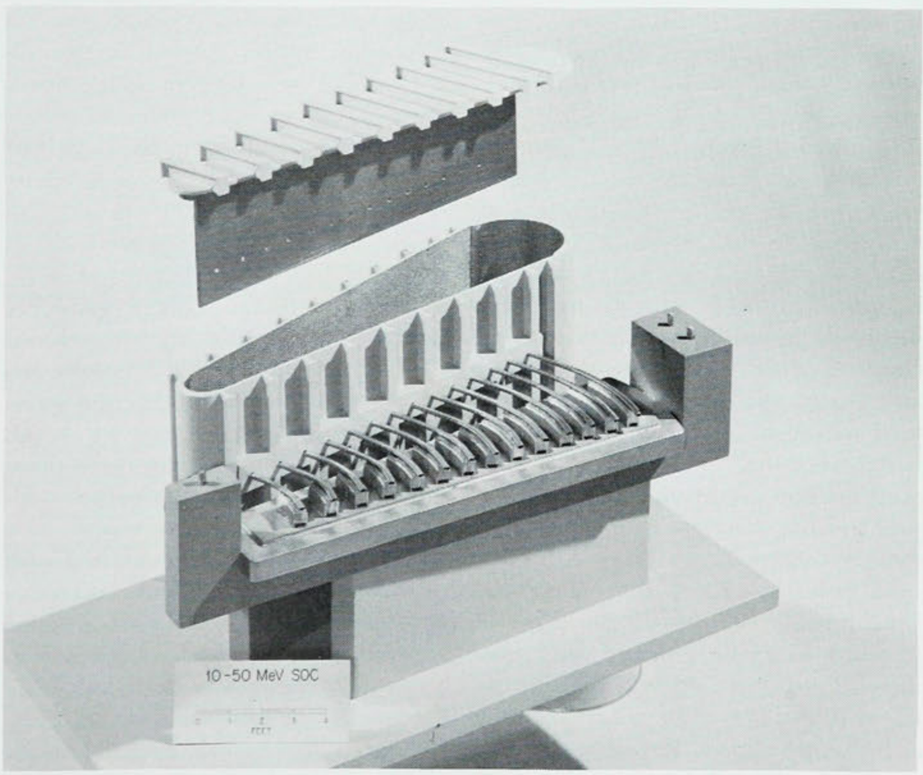
Linacs

Undoubtedly the major problem in utilization and maintenance of a meson factory is the enormous levels of radioactivity that will be generated by the primary and secondary beams. The radiation in the target area will be about 1000 rem/sec during accelerator operation and about 200 rem/hr one hour after shutdown. These levels are such that all manipulation within the primary target area will have to be done remotely, as will many of the activities associated with repair and maintenance of those portions of the accelerator near any significant interception of the primary beam. It is for these reasons that the Los Alamos group, notwithstanding LASL experience in handling high levels of radioactivity, felt that high priority should be given to considerations of beam loss, reliability, accessibility and simplicity. For ease of particle injection and extraction, the linear accelerator[2,9] has no equal, and this weighed heavily in our decision to propose this concept for our first venture into very high intensities. We also felt that the linac offered the opportunity to develop very precise mathematical models for understanding beam dynamics and beam cavity interactions. This hope has, in fact, been realized.[10] In addition, the energy of a linac can be readily increased by adding stages of acceleration, a very important factor if one looks forward to a K-meson factory.

We have seen that in circular machines it was necessary to overcome the problems of low intensity and inefficient beam extraction. The problems with proton linacs have been low intensity and low efficiency for converting rf power into beam power, especially as the energy is increased beyond 50 MeV. The highest energy proton linac is the Minnesota machine, operating at 68 MeV. This machine and its predecessors suffer from the following difficulty: in a proton linac, energy is transferred to the particles by an oscillating electric field,



SEPARATED ORBIT CYCLOTRON, being considered at Chalk River and Oak Ridge, may be visualized as a linac wound in a flat spiral. —FIG. 7



SEPARATION OF TURNS in separated orbit cyclotron is sufficient to permit insertion of a magnet for beam extraction at any energy. —FIG. 8

operating in a standing-wave phase-stable mode. Energy transfer is through a traveling-wave component whose phase velocity is in synchronism with the particle velocity at every point along the accelerator. In electron linacs the particles travel with constant velocity, thus very much alleviating the problem of phase and amplitude control and allowing operation in a phase neutral mode. Since below 1 GeV the protons are changing velocity rather rapidly, one has no choice but to accelerate them under phase-stable conditions, that is in a region of the rf wave below peak amplitude; so protons traveling too slow and arriving late at a given accelerator cavity will experience higher than average acceleration, while the reverse will occur for protons traveling too fast. Unfortunately phase stability implies radial defocusing. This is because the field is increasing as the particles cross the gap, and the radial focusing force on the particle as it leaves one accelerating gap is more than balanced by the radial defocusing force, produced by the higher field, as it enters the next. This problem was overcome in the early Alvarez drift-tube accelerator by placing a thin foil or grid at the entrance to each drift tube. But this reduces beam intensity very severely. In recent Alvarez accelerators, such as are being used as injectors for the Alternating Gradient Synchrotron, Zero Gradient Synchrotron, CERN machine and Bevatron, magnetic quadrupole lenses are used inside the drift tubes to provide radial focusing, and very high currents are now attainable. The intensity problem has therefore been solved for the Alvarez-type linac.

In order to extend the energy beyond about 100 MeV the Alvarez structure must be replaced with one that is much more efficient in converting rf power into beam power. In one of his many papers, Robert S. Livingston made the following prophetic remark, after observing that existing accelerating structures did not hold out any hope for going to much higher energies: "The possibility certainly exists that some ingenious designer will invent a structure with much higher shunt impedance. If this is achieved, the linear accelerator may become a much more popular device than it is now." This has now been accomplished at Los Alamos,[11] and the achievement may have application to electron as well as proton linacs.

Los Alamos linac

The field pattern in the resonant cavities of linacs is usually a transverse magnetic (TM) configuration. One of the major field components must be an axial electric field. In the mode designated by TM_{010} one has an azimuthal magnetic-field component whose value is a maximum at the cavity wall. Because of this field, currents flow in the cavity wall, parallel to the cavity axis. The total current is proportional to rE_z, where r is the radius of the waveguide and E_z is the amplitude of the axial electric field. Resistive losses in the walls due to these currents are the major power losses in the accelerator. The objective is to reduce these losses by properly choosing and shaping the resonant-cavity structure. In the language of the accelerator builder, one wishes to maximize ZT^2, the effective shunt impedance of the structure. T, the transit time, is approximately equal to the ratio of energy gain across a cavity to the maximum possible energy gain. The effective shunt impedance is then defined by $ZT^2 = (\Delta W^2)/p$, where ΔW is the energy gain per meter of a particle traveling across the cavity and p is the power loss per meter in the cavity. For the waveguide structure developed at LASL this quantity is more than three times greater than that attainable with previously existing structures.

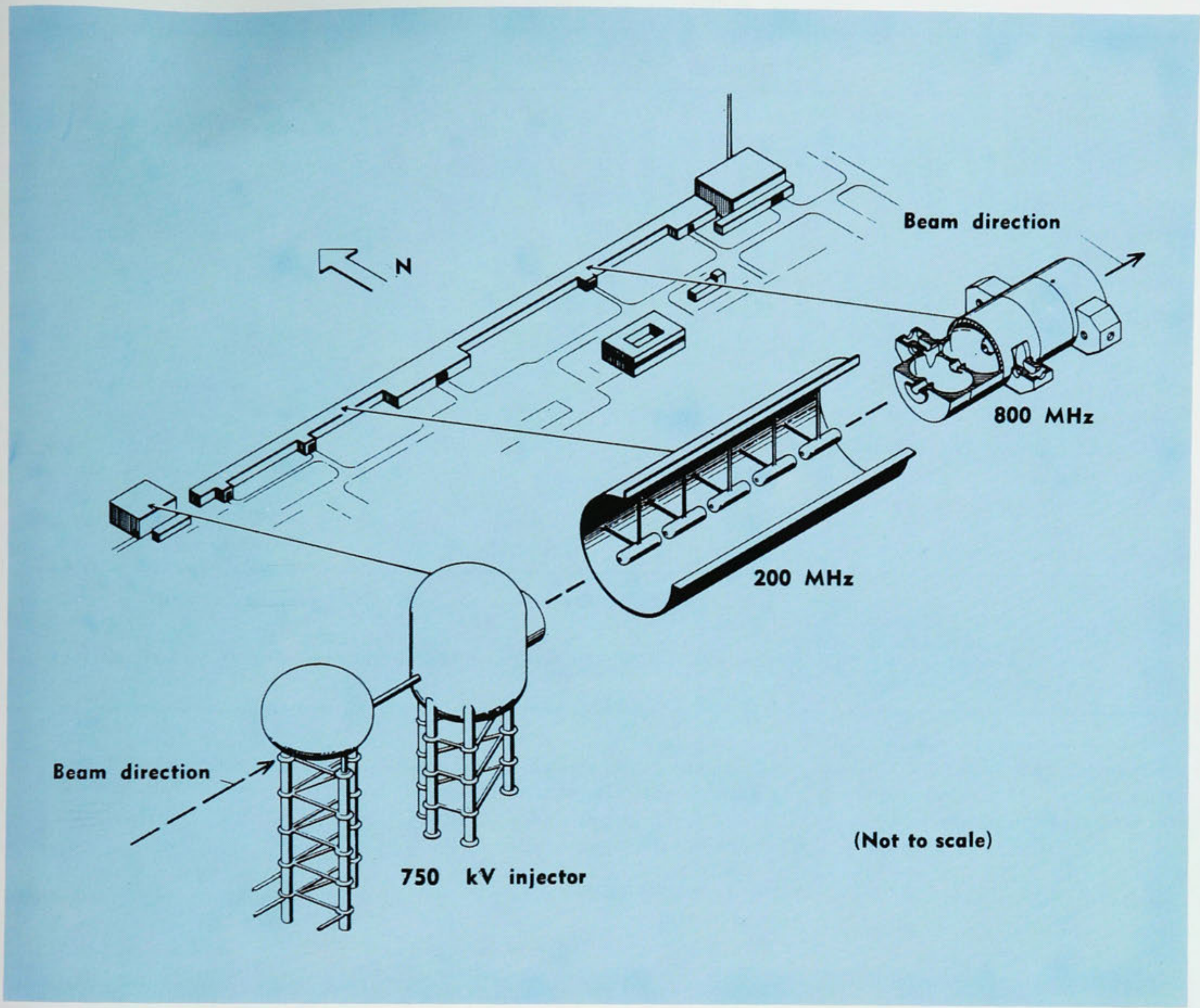
The development work started with mathematical models for analyzing the behavior of a chain of coupled resonators and the trajectory of particles through such a chain and proceeded to the construction and testing of experimental cavity systems, which the models indicated ought to have the properties being sought; then digital-computer methods were developed for designing optimized cavity configurations; finally prototype models were constructed and tested. These models have, in static tests and in tests involving acceleration of electrons, fulfilled all of the initial expectations that we started out with.

The so-called "side-coupled" cavity system (so named because coupling from one cell to the next is achieved by means of a cell that is out of the beam line), is the present favorite for the waveguide structure. It exhibits high efficiency and high tolerance to rf phase, amplitude and frequency fluctuations in individual cells. The latter conditions imply that extreme precision is not required in the construction of the cavities. This structure also provides high electrical stability against beam loading.

The proposed LASL Meson Factory will have an accelerator composed of three units. First there is a Cockcroft-Walton generator of more or less conventional design but with duty factor and intensity appropriate to the intended service. The injector, which accelerates the protons to 750 kV, is followed by a buncher, which prepares the beam for injection into the Alvarez drift-tube structure. This is a conventional 2π standing-wave structure but it operates at 6–12% duty factor. The drift-tube structure operates at 201.25 MHz. This represents a compromise between large shunt impedance, for which the frequency should be as high as possible, and adequate dimensions to accommodate the quadrupole focusing magnets required for transverse focusing. The Alvarez section accelerates the protons from 750 kV to 100 MV, at which point they enter the newly developed waveguide structure operated in a resonant $\pi/2$ mode and at 805 MHz. Here the choice of frequency represents a compromise between high shunt impedance and the necessity to accept the complete beam bunch from the Alvarez section. Figure 9 shows schematically the LASL-proposed accelerator.

The design of the experimental area is dominated by activation problems, by the necessity to serve a number of experiments simultaneously and by shielding requirements for both the primary and secondary beams.

The target areas will contain an array of movable targets. Charged mesons emanating from the targets will be extracted by strong-focusing magnetic lenses and deflecting magnets. Some of the beam channels will con-



LOS ALAMOS MESON FACTORY uses Cockcroft-Walton to inject 750-kV protons into Alvarez drift tube, where they are accelerated to 100 MV. Protons then enter waveguide operating in resonant $\pi/2$ mode. —FIG. 9

tain beam purifiers, others high-resolution spectrometers.

The beam channels will terminate in the experimental areas where the detector equipment will be set up inside shielded cubicles. The main experimental hall has an area about one half that of a football field. A second target and experimental area, independent of the main one, will also be developed for low-intensity operation. Real estate is available for providing a beam of muonic neutrinos from $\pi \rightarrow \mu + \nu_\mu$ as well as for eventually increasing the energy of the accelerator to about 1.2 GeV, to generate intense beams of K-mesons.

COMPARISON OF CONCEPTS

The table compares the salient features of each proposed accelerator for meson-factory service (about which I have information).

It turns out that no matter what kind of accelerator one adopts, the cost of all meson factories, which would operate at 1-mA average current and 800-MeV maximum energy, would be approximately the same. The LASL facility is estimated to cost approximately $55 million. However, almost half of this cost is devoted to buildings, shielding and experimental area. So even if one could invent an accelerator that cost nothing to build, one would not decrease the cost of the overall facility by more than a factor of two.

As for operating costs, these will depend more on the intensity of utili-

Comparison of Proposed Meson Factories

	H⁻ Cyclotron		*SOC*	*Linac*†	*Spiral-Ridged Cyclotron*	*Ring Cyclotron*
	(UCLA)	*(TRIUMF)**	*(ORNL & CRNL)*	*(LASL)*	*(Dubna)*	*(Zurich)*
Energy (MeV)	200-600	175-500	375-800	100-800	700	510
Average current (mA)	0.6	0.1	65	1	0.5	0.08
Beam extraction (%)	100	100	100	100	90	—
Macro duty factor (%)	100	100	100	6-12	100	100
Micro duty factor‡	25-100	25-100	10	5	25	25
Time between micropulses (nsec)	20	20	20	5	20	20
Possibility to increase energy	no	no	yes	yes	no	no
Polarized beam intensity (μA)	0.05	0.05	0.1	1	0.01	—
Beam emittance (milliradian cm)				π	2	
Cost of facility (millions of dollars)	20	13	65	55	24	21¶
Funding situation				partially funded		completely funded
Completion date		1972		1971	1972	1971/72

* Tri-University Meson Facility, Vancouver. † The group at Strasbourg has also proposed to build a Linac Meson Factory and the group at Chalk River (CRNL) is dividing design efforts between the LINAC and SOC. ‡ 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. ¶ This amounts to approximately $3 for each inhabitant of Switzerland.

zation of a given accelerator than on its parameters. The yearly operating costs will probably range from $5–15 million dollars, of which approximately 50% will be devoted to the experimental program.

Meson factories appear to be scientifically desirable, technically feasible and economically justifiable. Besides their importance for nuclear and subnuclear physics, the beams produced by the accelerator will make available for practical application very high levels of radiation and linear energy transfer; this could prove a very direct boon to mankind as it strives to make increasing industrial use of atomic energy and to alleviate some of its physical afflictions as well. It must, of course, be admitted that research forecasts are seldom verified over as long a period as five years. However, if a facility can resolve present problems in a unique way, one can confidently expect that new ones will arise at least as fast as the present ones are resolved.

Acknowledgments

In this article I have drawn heavily on the work of groups at Yale, Oak Ridge, UCLA, LASL, Chalk River, Strasbourg, Karlsruhe, Zurich and Dubna, on the reports of the various committees that have studied this matter and on the proceedings of conferences devoted in whole or in part to meson factories. □

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