LAMPF II and the High-Intensity Frontier

by Henry A. Thiessen

A small Los Alamos group has spent the past two years planning an addition to LAMPF, the 800-MeV, 1-milliampere proton linac on Mesita de Los Alamos. Dubbed LAMPF II and consisting of two high-current synchrotrons fed by LAMPF, the addition will provide beams of protons with a maximum energy of 45 GeV and a maximum current of 200 microamperes. Compared to its best existing competitor, the AGS at Brookhaven National Laboratory, LAMPF II will produce approximately 90 times more neutrinos, 300 times more kaons, and 1000 times more antiprotons. Figure 1 shows a layout of the proposed facility.

Why Do We Need LAMPF II?

The new accelerator will continue the tradition set by LAMPF of operating in the intersection region between nuclear physics and particle physics. Other articles in this issue ("The Family Problem" and "Experiments To Test Unification Schemes") have discussed crucial experiments in particle physics that require high-intensity beams of secondary particles. For example, the large mass estimated for a "family vector boson" implies that, now and for the foreseeable future, the possibility of family-changing interactions can be in-

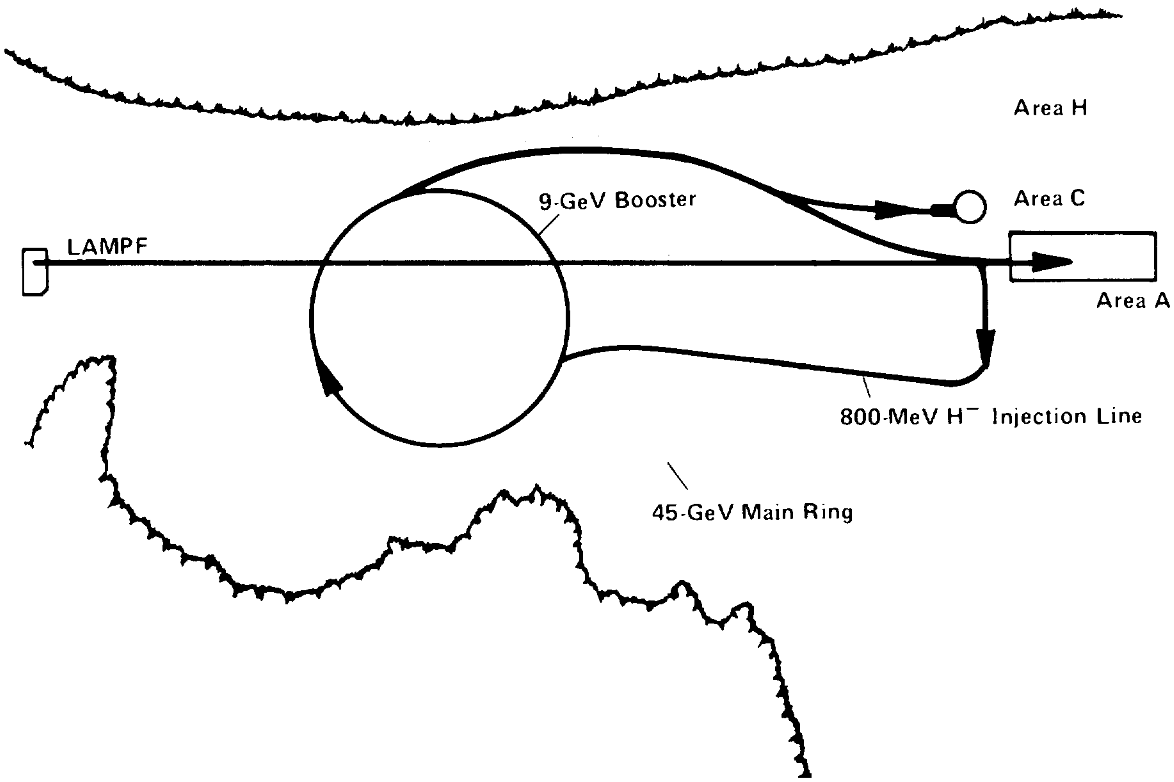

Fig. 1. LAMPF II, the proposed addition to LAMPF, is designed to produce protons beams with a maximum energy of 45 GeV and a maximum current of 200 microamperes. These proton beams will provide intense beams of antiprotons, kaons, muons, and neutrinos for use in experiments important to both particle and nuclear physics. The addition consists of two synchrotons, both located 20 meters below the existing LAMPF linac. The booster (red) is a 9-GeV, 60 hertz, 200-microampere machine fed by LAMPF, and the main ring (blue) is a 45-GeV, 6-hertz, 40-microampere machine. Proton beams will be delivered to the main experimental area of LAMPF (Area A) and to an area for experiments with neutrino beams and short, pulsed beams of other secondary particles (Area C). A new area for experiments with high-energy secondary beams (Area H) will be constructed to make full use of the 45-GeV proton beam.

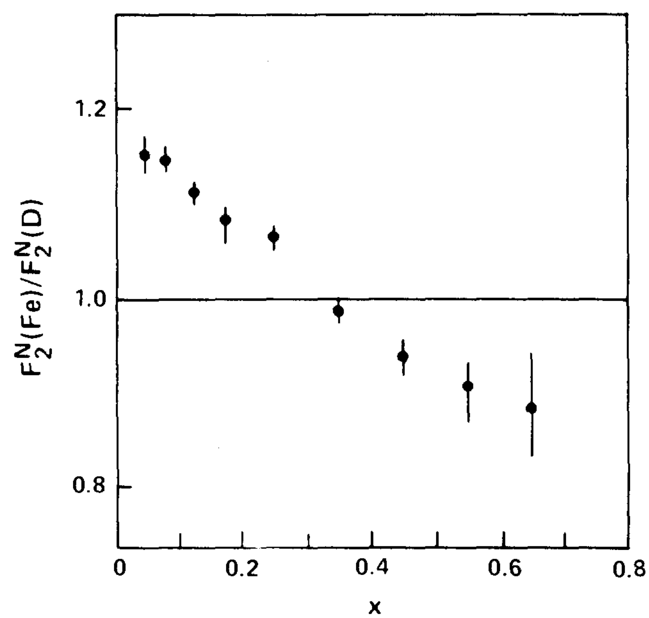

Fig. 2. The "EMC effect" was first observed in data on the scattering of muons from deuterium and iron nuclei at high momentum transfer. The ratio of the two nucleon structure functions (F_2^N(Fe) and F_2^N(D)) deduced from these data by regarding a nucleus as simply a collection of nucleons is shown above as a function of x, a parameter representing the fraction of the momentum carried by the nucleon struck in the collision. The observed variation of the ratio from unity is quite contrary to expectations; it can be interpreted as a manifestation of the quark substructure of the nucleons within a nucleus. (Adapted from J. J. Aubert et al. (The European Muon Collaboration), **Physics Letters** ***123B(1983):175.)***

vestigated only with high-intensity beams of kaons and muons. And studies of neutrino masses and neutrino-electron scattering, which are among the most important tests of possible extensions of the standard model, demand high-intensity beams of neutrinos to compensate for the notorious infrequency of their interactions.

Here I take the opportunity to discuss some of the experiments in *nuclear* physics that can be addressed at LAMPF II. The examples will include the search for quark effects with the Drell-Yan process, the production of quark-gluon plasma by annihilation of antiprotons in nuclei, the extraction of nuclear properties from hypernuclei, and low-energy tests of quantum chromodynamics.

Quark Effects. A major problem facing today's generation of nuclear physicists is to develop a model of the nucleus in terms of its fundamental constituents—quarks and gluons. In terms of nucleons the venerable nuclear shell model has been as successful at interpreting nuclear phenomena as its analogue, the atomic shell model, has been at interpreting the structure and chemistry of atoms. But nucleons are known to be made of quarks and gluons and thus must possess some additional internal degrees of freedom. Can we see some of the effects of these additional degrees of freedom? And then can we use these observations to construct a theory of nuclei based on quarks and gluons?

Defining an experiment to answer the first question is difficult for two reasons. First, we know from the success of the shell model that nucleons dominate the observable properties of nuclei, and when this model fails, the facts can still be explained in terms of the exchange of pions or other mesons between the nucleons. Second, the current theory of quarks and gluons (quantum chromodynamics, or QCD) is simple only in the limit of extremely high energy and extremely high momentum transfer, the domain of "asymptotic QCD." But the world of nuclear physics is very far from that domain. Thus, theoretical guidance from the more complicated domain of low-energy QCD is sparse.

To date no phenomenon has been observed that can be interpreted unambiguously as an effect of the quark-gluon substructure of nucleons. However, the results of an experiment at CERN by the "European Muon Collaboration"[1] are a good candidate for a quark effect, although other explanations are possible. This group determined the nuclear structure functions for iron and deuterium from data on the inelastic scattering of muons at high momentum transfers. (A nuclear structure function is a multiplicative correction to the Mott cross section; it is indicative of the momentum distribution of the quarks within the nucleus.) From these structure functions they then inferred values for the nucleon structure function by assuming that the nucleus is simply a collection of nucleons. (If this assumption were true, the inferred nucleon structure function would not vary from nucleus to nucleus.) Their results (Fig. 2) imply that an iron nucleus contains more high-momentum quarks and fewer low-momentum quarks than does deuterium. This was quite unexpected but was quickly corroborated by a re-analysis[2] of some ten-year-old electron-scattering data from SLAC and has now been confirmed in great detail by several new experiments.[3,4] The facts are clear, but how are they to be interpreted?

The larger number of low-momentum quarks in iron than in deuterium may mean that the quarks in iron are sharing their momenta, perhaps with other quarks through formation of, say, six-quark states. Another interpretation, that iron contains many more pions acting as nuclear "glue" than does deuterium, has already been discounted by the results of a LAMPF experiment on the scattering of polarized protons from hydrogen and lead.[5] Whatever the final interpretation of the "EMC effect" may be, it clearly indicates that the internal structure of the nucleon changes in the nucleus.

Interpretation of the EMC effect is complicated by the fact that the contribution of the "valence" quarks (the three quarks that predominantly make up a nucleon) to the lepton-scattering amplitude is not distinguishable from the contribution of the "sea" quarks (the virtual quark-antiquark pairs that can exist within the nucleon for short times). One way to sort out these contributions is to measure the amplitude for production of lepton-antilepton pairs in high-energy hadron-hadron collisions.[6] When the momentum of the lepton-antilepton pair transverse to the hadron beam is small, the dominant amplitude for this Drell-Yan process arises from the annihilation of a quark and an antiquark into a photon, which then decays into the lepton-antilepton pair (Fig. 3). Since valence and sea quarks from different hadronic probes make different contributions to the amplitude, measurement of these differences with the 45-GeV proton beam of LAMPF II and its secondary beams of pions, kaons, and antiprotons can help to decide among the possible explanations of the EMC effect.

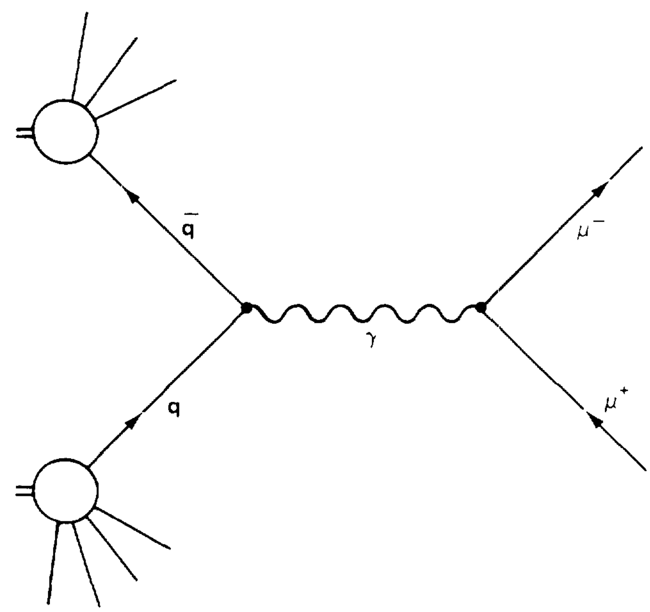

Fig. 3. The Drell-Yan process is the name given to the production of a lepton-antilepton pair in a collision between two hadrons. When the momentum of the lepton pair transverse to the projectile hadron is small, the dominant amplitude for the Drell-Yan process arises from the interaction pictured above: a quark and an antiquark from the two hadrons annihilate to form a photon, which then decays into the lepton-antilepton pair (here shown as a muon-antimuon pair).

Quark-Gluon Plasma. Quantum chromodynamics predicts that at a sufficiently high temperature or density the vacuum can turn into a state of quarks, antiquarks, and gluons called quark-gluon plasma. (Such a plasma is expected to have been formed in the first few microseconds after the creation of the universe.) The present generation of relativistic heavy-ion experiments is designed to produce this plasma by achieving high density. However, since the predicted uncertainty in the transition temperature is much smaller than the predicted uncertainty in the transition density, achieving high temperature is regarded as the better approach to producing such a plasma.

D. Strottman and W. Gibbs of Los Alamos have investigated the possibility of heating a nucleus to the required high temperature by annihilation of high-energy antiprotons within the nucleus.[7] The results of a calculation by Strottman (Fig. 4), which were based on a hydrodynamic model, indicate that in a nearly head-on collision between a 10-GeV antiproton and a uranium nucleus, most of the available energy is deposited within the nucleus, raising its temperature to that necessary for formation of the quark-gluon plasma. Gibbs has performed such a calculation with the intranuclear cascade model and obtained very similar results.

Like relativistic heavy-ion experiments, such antiproton experiments pose two problems: isolating from among many events the rare head-on collisions and finding a signature of the transition to plasma. The high intensity of antiprotons to be available at LAMPF II will help solve these problems by providing large numbers of events for study.

Nuclear Properties from Hypernuclei. A "hypernucleus" is a nucleus in which a neutron is replaced by a strange heavy baryon, the Lambda (Λ). (The valence-quark composition of a neutron is *udd*, and that of a Λ is *uds*.) Such hypernuclei are produced in collisions of kaons with ordinary nuclei. The properties of hypernuclei are accessible to measurement because their lifetimes are relatively long (similar to that of the free Λ, about 10^{-10} second). These properties provide information about the forces among the nucleons with the nucleus. In fact, the Λ plays a role in studies of the nuclear environment similar

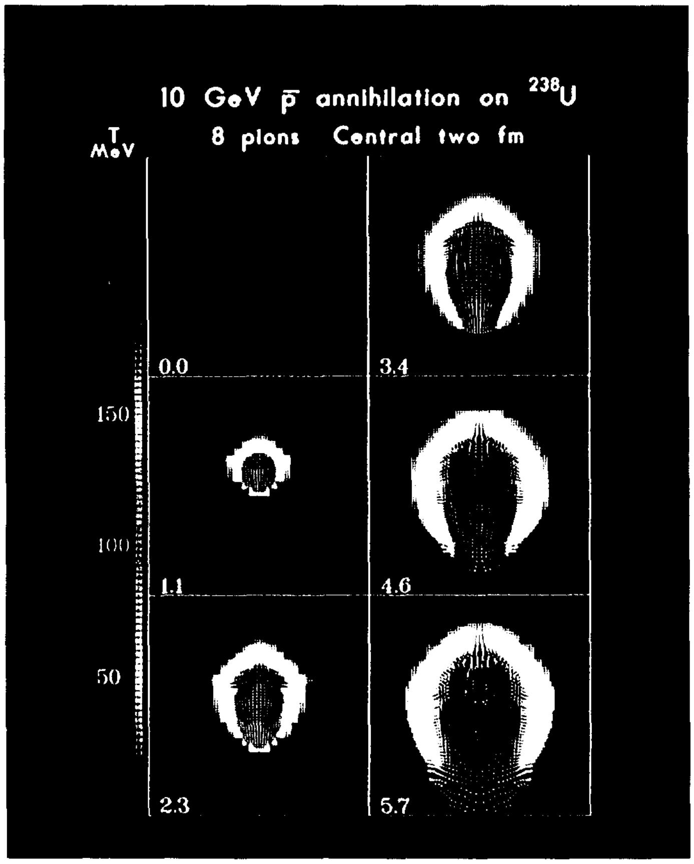

Fig. 4. A color-coded computer-graphic display of the temperature (in MeV) within a uranium-238 nucleus at various times (in 10^{-23} second) after annihilation of a 10-GeV antiproton with a nucleon. (The temperatures were calculated by D. Strottman on the basis of a hydrodynamic model.) Annihilation of the antiproton produces approximately eight pions with a mean momentum of 1.2 GeV/c. Interaction of these pions with the nucleus significantly increases the temperature of the central region of the nucleus (third frame). This hot region expands, and finally energy begins to escape from the nucleus (sixth frame). The temperatures achieved are sufficiently high for formation of a predicted state of matter known as quark-gluon plasma.

to that played by, say, a carbon-13 nucleus in NMR studies of the electronic environment within a molecule. For example, consider those hypernuclei in which a low neutron energy level is occupied by a Λ in addition to the maximum allowable number of neutrons. (Such hypernuclei should exist since it is widely thought that the Pauli exclusion principle would not be applicable.) The energy levels of these hypernuclei would be indicative of the nuclear potential in the interior of the nucleus, a property that is is otherwise difficult to measure.

A particularly interesting feature of the light hypernuclei is the nearly zero value of the spin-orbit interaction between the Λ and the nucleus.[8,9,10,11] Although this result was completely unexpected, it has since been explained in terms of both a valence-quark model of the baryons and a conventional meson-exchange model of nuclear forces. However, these two "orthogonal" descriptions of nuclear matter yield very different predictions for the spin-orbit interaction between the Σ (another strange baryon) and the nucleus. Data that might distinguish between the two models has yet to be taken.

Most experimentalists working in the field of hypernuclei are hampered by the low intensity and poor energy definition of the kaon beams available at existing accelerators. The much higher intensity and better energy definition of the kaon beams to be provided by LAMPF II will greatly benefit this field.

Low-Energy Tests of QCD. A striking prediction of QCD is the existence of "glueballs," bound states containing only gluons. Also predicted are bound states containing mixtures of quarks and gluons, known as meiktons or hermaphrodites. These objects, if they exist, should be produced in hadron-nucleon collisions. However, since they are predicted to occur in a region already populated by a large number of hadrons, finding them will be a difficult job, requiring detailed phase-shift analyses of exclusive few-body channels in the predicted region. The high-intensity beams of LAMPF II, especially the pure kaon beams, will be extremely useful in searches for glueballs and meiktons.

Another expectation based on QCD is the near absence of polarization effects in inelastic hadron-nucleon scattering. But the few experiments on the exclusive channels at high momentum transfer have revealed strong polarization effects.[12] In contrast, the quark counting rules of QCD for the energy dependence of the elastic scattering cross section have been observed to be valid, even though the theory is not applicable in this energy regime. The challenge to both theory and experiment is to find out why some facets of QCD agree with experiment when they are not expected to, and vice versa. Obviously, more data are needed.

Also needed are more data on hadron spectroscopy, particularly in the area of kaon-nucleon scattering, which has received little attention for more than a decade. Such data are needed to help guide the development of quark-confinement theories.

LAMPF II Design

LAMPF II was designed with two goals in mind: production of a 45-GeV, 40-microampere proton beam as economically as possible, and minimum disruption to the ongoing experimental programs at LAMPF. The designs of both of the new synchrotons reflect these goals.

The booster, or first stage, will be fed by the world's best H^- injector, LAMPF. This booster will provide a 9-GeV, 200-microampere beam of protons at 60 hertz. The 200-microampere current is the maximum consistent with continued use of the 800-MeV LAMPF beam by the Weapons Neutron Research Facility and the Proton Storage Ring. The 9-GeV energy is ideal not only for injection into the second stage but also for production of neutrinos to be used in scattering experiments (Fig. 5). Eighty percent of the booster current will be dedicated to the neutrino program. In contrast, the booster stage at other accelerators usually sits idle between pulses in the main ring. Since the phase space of the LAMPF beam is smaller in all six dimensions than the injection requirements of LAMPF II, lossless injection at a correct phase space is straightforward.

The 45-GeV main ring is shaped like a racetrack for two reasons: it fits nicely on the long, narrow mesa site and it provides the long straight sections necessary for efficient slow extraction. The main ring is basically a 12-hertz machine but will be operated at 6 hertz to permit slow extraction of a beam at a duty factor of 50 percent. This compromise minimizes the initial cost yet preserves the option of doubling the current and increasing the duty factor by adding a stretcher at a later date. The 45-GeV proton energy will provide kaons and antiprotons with energies up to 25 GeV. Such high energies should prove especially useful for the experiments mentioned above on the Drell-Yan process and exclusive hadron interactions.

The booster has a second operating mode: 12 GeV at 30 hertz and 100 microamperes with a duty factor of 30 percent. This 12-GeV mode will be useful for producing kaons in the early years if the main ring is delayed for financial reasons.

The most difficult technical problem posed by LAMPF II is the rf system, which must provide up to 10 megavolts at a peak power of 10 megawatts and be tunable from 50 to 60 megahertz. Furthermore, tuning must be rapid; that is, the bandpass of the tuning circuit must be on the order of 30 kilohertz. The ferrite-tuned rf systems used in the past are typically capable of providing only 5 to 10 kilovolts per gap at up to 50 kilowatts and, in addition, are limited by power dissipation in the ferrite tuners and plagued by strong, uncontrollable nonlinear effects. We have chosen to concentrate the modest development funds available at present on the rf system. A teststand is being built, and various ferrites are being studied to gain a better understanding of their behavior.

Following a lead from the microwave industry (one recently applied in a buncher cavity developed by the Laboratory's Accelerator Technology Division for the Proton Storage Ring), we have chosen a bias magnetic field perpendicular to the rf magnetic field. (All other proton accelerators employ parallel bias.) The advantage of perpendicular bias is a reduction in the ferrite losses by as much as

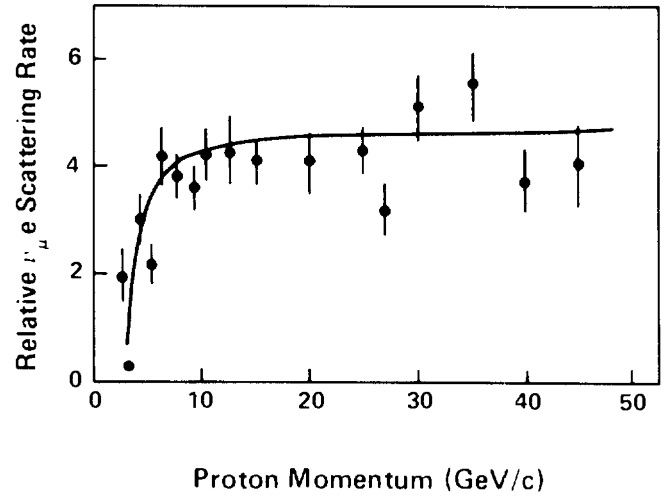

Fig. 5. Monte-Carlo calculation of the rate of scattering between muon neutrinos and electrons (in an unbiased 4-meter by 4-meter detector located 90 meters from a beryllium neutrino-production target) as a function of the momentum of the protons producing the neutrinos. (The solid curve is simply a guide to the eye.) The calculations are based on various experimental values of the pion-production rate. The scattering rate plotted is the rate per unit power in the proton beam. The momentum of the protons to be produced by the LAMPF II booster (9.9 GeV/c) is well above the knee of the yield curve.

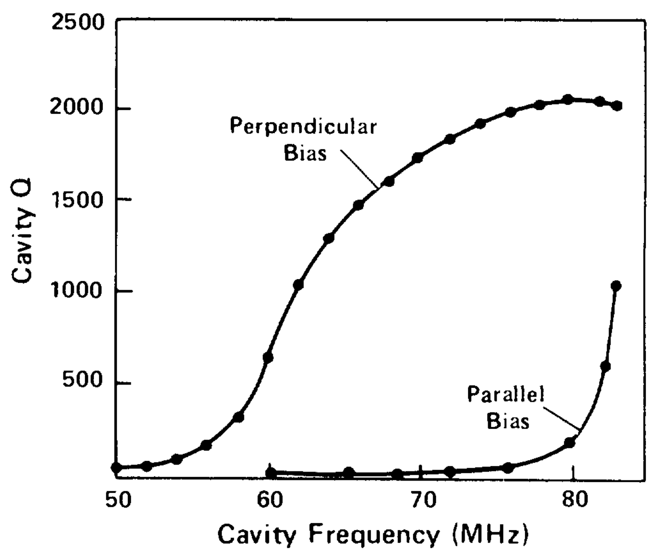

Fig. 6. Performance of ferrite-tuned test cavities with parallel and perpendicular bias magnetic fields. The data shown are for a Ni-Zn ferrite; other types of ferrites give similar results.

two orders of magnitude (Fig. 6). Since the loss in the ferrite is proportional to the square of the voltage on each gap, reducing these losses is essential to achieving the performance required of the LAMPF II system.

A collaboration led by R. Carlini and including the Medium Energy and Accelerator Technology divisions and the University of Colorado has made a number of tests of the perpendicular bias idea. Their results indicate that in certain ferrites the low losses persist at power levels greater than that needed for the LAMPF II cavities. A full-scale cavity is now being constructed to demonstrate that 100 kilovolts per gap at 300 kilowatts is possible. This prototype will also help us make a choice of ferrite based on both rf performance and cost of the bias system. A full-scale, full-power prototype of the rf system is less than a year away.

Conclusion

This presentation of interesting experiments that could be carried out at LAMPF II is of necessity incomplete. In fact, the range of possibilities offered by LAMPF II is greater than that offered by any other facility being considered by the nuclear science community. Its funding would yield an extraordinary return. ■

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