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Linear Accelerators for Protons: New Developments

Some recent developments have made feasible proton accelerators of much higher power than earlier models.

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The linear accelerator for protons has developed somewhat slowly in comparison with other types of accelerators. Now, however, because of recent advances it is economically and technically feasible to build such accelerators to deliver beams at unprecedented levels of average power.

The linear accelerator for protons or heavier ions was the first resonance accelerator to be invented (*1*) and demonstrated (*2*). It was in essence a long evacuated pipe containing a series of hollow metal cylinders spaced along the axis with short gaps between cylinders. An external generator impressed a time-varying voltage between the cylinders, so that a proton moving along the axis experienced a positive acceleration as it crossed each gap. The spacing and length of the cylinders gradually increased from one end of the pipe to the other, in accordance with the desired increase in proton velocity. In the first version proposed the voltage generator was to be a spark discharge; in later versions a radio-frequency oscillator was used. Although these principles were set forth in the early papers, it was more than 20 years later that the first useful version was built by Alvarez and his co-workers (*3*)—a 32-million-electron-volt (Mev) accelerator. The average current was 3×10^{-7} ampere, and the peak current 6×10^{-5} ampere. Following construction of the Alvarez machine, a 3.75-Mev prototype of a much larger machine was operated at Livermore, California, for a short time; for economic reasons, this development was not continued. Most designers turned their attention to other types of accelerators, although there were exceptions; for example, a 68-Mev linear accelerator was built at the University of Minnesota (*4*), and a 20-Mev and several 50-Mev linear-accelerator injectors were incorporated into large proton synchrotrons. Except for the incorporation of strong focusing magnets (*5*), no essential changes were made in the original Alvarez design. The Alvarez accelerator becomes rapidly less efficient with increasing energies, and it is generally believed by accelerator physicists that 200 Mev is about the top energy at which its operation is economically practicable. Several groups studied a two-part linear accelerator, a combination of an Alvarez and a disk-loaded instrument, and made important contributions to the design of higher-energy accelerators, but none were constructed (*6*).

Recently, however, the pace of development has been stepped up, and higher-energy Alvarez machines are now being built. A 100-Mev machine at Sherpukov, U.S.S.R., is nearing completion. At the Brookhaven National Laboratory plans are nearly completed for a 200-Mev linear accelerator to replace the present 50-Mev injector proton synchrotron (*7*).

The last few years have seen dramatic improvements in the performance of the preaccelerator at the front end of the instrument—that is, the ion source and the accelerating column. Several laboratories have reported highly directed intense beams from improved preaccelerators (*8*). With the accelerator at the European Center for Nuclear Research (CERN), and with an improved ion source and column, it has been possible to accelerate peak current of 130 milliamperes to 50 Mev (*9*). The increase in current is 0.4×10^{6} over that of the original Alvarez machine (*3*). The new Brookhaven National Laboratory injector will have an improved preaccelerator, and the design goal is 0.2 ampere accelerated to 200 Mev.

The linear accelerator has been a popular injector because its intense, narrow, and nearly monochromatic (monoenergetic) beam can be efficiently transferred into a synchrotron. The same beam qualities make attractive the direct use of the linear accelerator as a source of particles for nuclear-physics research. The original Alvarez instrument, the University of Minnesota instrument, and a 50-Mev proton linear accelerator at the Atomic Energy Research Establishment, Harwell, England, are examples of research facilities. In thinking how to build better linear accelerators for research, one must take account of a characteristic of all those built up to now—namely the fact that the beam is intermittent or pulsed. Typically the beam is off 99.9 percent of the time and on 0.1 percent of the time—that is, the duty factor is 0.1 percent. This is satisfactory for injector service but a serious disadvantage for an experimental user who wants to work with intense beams, because his particle-counting equipment operates up to a maximum rate which is limited by the peak beam intensity rather than by the average intensity. In order to take

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Table 1. Design parameters for the Los Alamos Linac (LAMPF).

Ion source, duoplasmatron (30 kev)
Preaccelerator, 750-kev Pierce-type short column
Alvarez accelerator:
Frequency, 2.0125×10^8 hertz
Structure, Alvarez (4 tanks)
Tank 1, 0.75–5.0 Mev
Tank 2, 5.0–41.2 Mev
Tank 3, 41.2–72.3 Mev
Tank 4, 72.3–100.3 Mev
Waveguide accelerator:
Frequency, 8.050×10^8 hertz
Structure, side-coupled shaped cavities, $\pi/2$-mode standing wave
Number of tanks, 90
Current (peak), 17 milliamperes (average, 1 milliampere)
Duty factor, 6%–12%
Overall length, 850 meters
Peak radio-frequency power for cavity excitation, 38 megawatts
Peak radio-frequency power for beam excitation, 14 megawatts
Average radio-frequency power (6%), 3 megawatts

full experimental advantage of the high intensities the accelerator can deliver, the duty factor should be raised 100-fold. The duty factor was kept small in order to keep the average power low. Until structures could be devised which were more efficient, it seemed too expensive to make order-of-magnitude increases in the average power. Simultaneously increasing the energy, the beam intensity, and the duty factor could amount to increasing the average power by several orders of magnitude; nevertheless, there are strong reasons for doing exactly that. The so-called meson factory, which has been proposed by many groups, has precisely such specifications—namely a proton energy greater than 500 Mev, beam currents as high as possible but at least 50 microamperes, and a high duty factor. Many types of accelerators have been proposed for such service, and much has been written concerning their relative merits. Rosen, in a recent article (*10*), presents in detail the features of the several designs and discusses, with extensive references, the areas of research in the physical and biological sciences that will be served. Here I may remark that, as the term *meson factory* suggests, it is expected that, while investigations of the reactions of the protons with various targets will be carried out, even more interesting will be studies with the various secondary and tertiary beams, the pi and mu mesons, neutrinos, and neutrons.

At the Los Alamos Scientific Laboratory an 800-Mev proton linear accelerator is being designed to serve as a meson factory. It is called LAMPF (for Los Alamos Medium-energy Physics Facility). The specifications are given in Table 1. The beam would be 10^4 times the external beams of accelerators now operating in this energy range, the duty factor would ultimately be 12 percent, and the average beam power would surpass that of any accelerator now operating. The improved performance is made possible by certain design innovations described below.

Principles and Problems

A more general description of the linear accelerator principle is as follows. The protons travel through a series of coupled radio-frequency cavity resonators. The cavities must be spaced properly and excited coherently so that a proton injected at the correct time and with the correct energy is accelerated as it passes through each cavity. This proton is called the synchronous particle. A particle injected at a slightly different phase or energy will also be accelerated, being at times ahead and at times behind the synchronous one as they go along the accelerator; that is, it executes stable phase oscillations about the synchronous particle. This phenomenon is known as phase stability, and underlies the operation of many types of high-energy accelerators (*11*).

The series of cavities coupled together, often called a tank, is driven by an external amplifier system at a single feed point. The number of tanks in the accelerator can range from one to as many as 1000 (*12*), but when there are more than one all must oscillate coherently. Usually there is an economic advantage in making the tanks rather long, and this requires good power flow along each tank. The power from the amplifiers is ultimately converted into beam power, or is lost in resistive heating of cavity walls. For a specific energy gain per meter along the accelerator, the resistive heating per meter varies as $1/Z$, where Z is a number called the shunt impedance which depends on the frequency and on the type of structure used. The designer tries to achieve the highest possible value for Z, in order to keep the power losses within reasonable limits, keeping in mind certain other considerations such as adequate aperture for the beam, good power flow, and reasonable dimensional tolerances. Some of these requirements are especially important when the average beam power is high, as it is for LAMPF. At the beginning of the LAMPF study 4 years ago it was decided to make a fresh start in cavity and tank design, to begin a general study of the be-

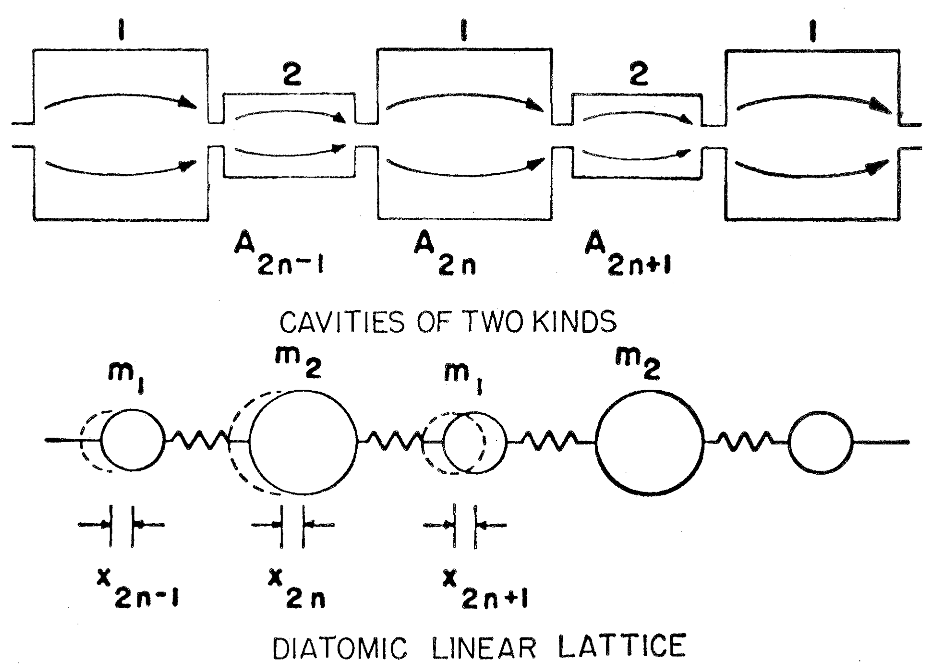

Fig. 1. Correspondence between a chain of coupled microwave cavity resonators suitable for a linear accelerator and a linear lattice, or a set of masses coupled by springs. The cavities may be identical, or they may be of two kinds. The lattice may be monatomic or diatomic. The displacement X corresponds to the field amplitude A. The two systems exhibit similar behavior.

havior of long cavity chains, and to develop a general method of calculating the fields within a single-cavity resonator. Knapp and his colleagues experimented with a variety of cavities and tanks and tried to fit their behavior to various mathematical models (*13*). The model finally adopted is somewhat different from the conventional one, but has proved accurate and convenient (*14*). As a starting point, it takes the lowest frequency mode of an isolated cavity and treats the tank as a chain of one-dimensional harmonic oscillators. Figure 1 illustrates the basic approach. The upper diagram shows a portion of a chain of cavities, each one coupled to its two neighbors. The many cavities coupled together comprise a unit of the accelerator or "tank." Cavities of type 1 are all identical, and cavities of type 2 are all identical. Type 1 may or may not be the same as type 2. The curved arrows represent schematically an electromagnetic field distribution in the cavities, which oscillates in time. A denotes the amplitude of the distribution. The lower diagram of Fig. 1 shows a chain of masses coupled by springs, or a linear lattice of atoms. The two problems are quite similar, the amplitude A of the electric field in a cavity (upper diagram) oscillating in time just as the displacement X of one of the masses (lower diagram) does. An isolated mass on a spring will, if struck or otherwise excited, oscillate according to the familiar law

$$X = B \sin \omega_0 t \tag{1}$$

where X is the displacement, t is the time, and B is a constant depending on the strength of excitation. The natural frequency of vibration, $\omega_0 t$, is a property of the individual oscillator or cavity resonator. If now we couple together with a strength k some number N of such identical oscillators, the system has N different modes of vibration, each with its corresponding natural frequency. We may still use Eq. 1 to describe the possible vibrations, provided we understand that, for each mode of the coupled system, B will vary along the chain as follows

$$B = \cos n\varphi \tag{2}$$

where the possible values of φ determine the mode pattern and also the frequency of the mode. The vibration is a so-called standing wave. A consequence of the basic symmetry of the chain is the fact that the possible values of φ are the first N multiples of $2\pi/N$. In accelerator or microwave parlance, the value of φ labels the mode; thus we speak of the 0-mode, $\pi/2$-mode, or π-mode, and so on, meaning $\varphi = 0$, $\varphi = \pi/2$, or $\varphi = \pi$. The Alvarez accelerator operates in the 0-mode (that is, $B = 1$), and all the resonators (drift tubes) oscillate in phase with the same amplitude. In the $\pi/2$-mode the sequence is $B = 1, 0, -1, 0, 1, 0. \ldots$

The theory of the tank starts with the set of one-dimensional modes as a basis. The transient and the steady state of the driven tank are then described in terms of this basis set (*13*, *15*). Standard methods of perturbation theory are used to describe and predict the effects of errors in cavity fabrication, and so on (*14*); verification has been obtained in extensive measurements of resonant frequencies and mode patterns in a variety of long and short tanks. Some of the experiments were performed with metal models and some with the computer, with programs originally developed for circuit analysis. The agreement with predictions has been generally within a few percent. This approach led to some useful innovations in cavity design.

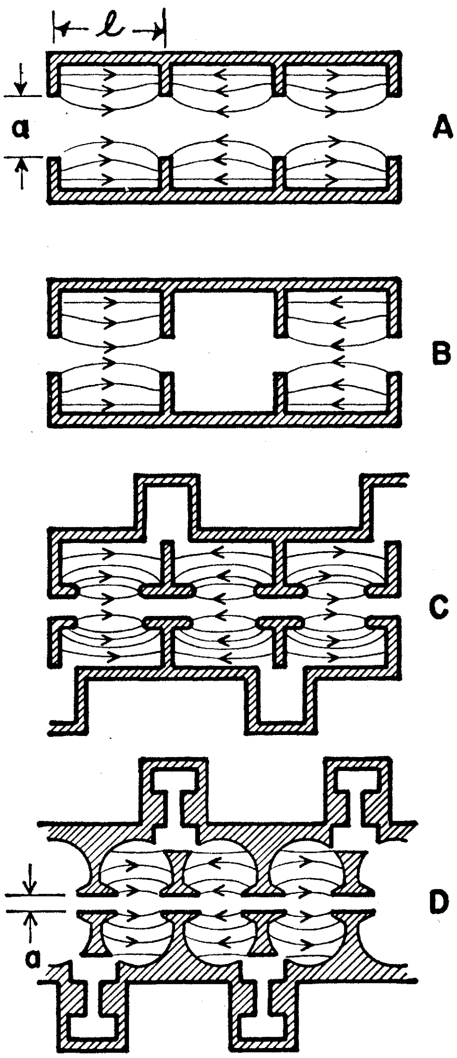

Fig. 2. Development of the shaped, side-coupled cavity accelerator. (*A*) Cross section of a cylindrical pipe with disks at intervals *l*. Each disk has a hole of diameter *a*. The curved arrows represent electric field in the cavity, which is excited in the π-mode. (*B*) The same structure oscillating in the $\pi/2$-mode. Alternate cavities have no electric field. This mode has desirable propagation characteristics, but half the length is useless for acceleration. (*C*) A structure with alternate cavities moved to the side; again excited in the $\pi/2$-mode. The accelerating efficiency is increased by the addition of drift tubes. (*D*) A further-improved version in which the walls have been curved in a manner which further increases the efficiency, or shunt impedance.

The problem of designing a cavity for optimum efficiency (shunt impedance) and power flow is illustrated in Fig. 2. Diagram *A* is a cross section of a cavity design (Hansen type) (*16*) which has been used extensively for linear accelerators for electrons and which is suitable for protons at energies above 200 Mev. It consists of a cylindrical pipe; inside there are irises at intervals *l*, which divide the pipe into a chain of coupled cavities. In this design the radio-frequency power for the tank and the beam must flow through the irises, and this flow determines their diameter (*a*). Making the iris larger, however, lowers *Z*. The dimension *l* is the period of the structure. The light curved lines represent the electric field; the magnetic field (not shown) circulates around the axis of the cylinder. The protons are accelerated by the electric field in the axial direction. The fields shown represent the standing-wave π-mode, where the phase of the fields changes by π in one period.

Diagram *B* of Fig. 2 illustrates one partial solution to the problem of energy flow, in which the tank is excited in the $\pi/2$-mode. Alternate cells are empty—that is, store no electromagnetic field—as is indicated in the diagram by the absence of the lighter lines. Power flows rapidly across the boundary of the filled and empty cavity; a related and desirable effect is the insensitivity of the field distribution down the chain to small dimensional errors in the cavities. A disadvantage of the arrangement (*B*) is the fact that it lengthens the accelerator and makes it more expensive, although shortening the empty cavities helps to a limited extent. This difficulty was solved after many alternative coupling schemes had been tried. The solution was to move the "empty" cavities to the side of the main ones. The intersection of the main and coupling cavities is a lune-shaped region. Diagram C shows this arrangement. Coupling was excellent, especially when the side cavities and main cavity were tuned to the same frequency (the theory had suggested that this would be the case). Having the cavities on the side gave all the advantages of the $\pi/2$ mode without sacrificing length on the axis to the empty cavities.

The coupling problem had thus been solved in a way which left the main cavity configuration free, so we could design the main cavity for maximum shunt impedance. At this point a computer program developed by H. Hoyt and his colleagues was used to solve the equations for the field within a cavity (*17*); the shape of the walls can be chosen arbitrarily, except for the requirement for axial symmetry. The method is based on a relaxation technique. A search with the computer revealed shapes that would provide optimum shunt impedance. The result is shown in diagram *D*. The smoothly curved shapes of the drift tube and the cavity walls are the optimum found by computer calculation and laboratory measurements. The efficiency (or *Z*) is almost four times that of the *A* configuration, and the power flow is 10 to 40 times that of the *A* configuration. The large effective coupling means a saving in fabrication costs, since machining tolerances are much less severe than they are for *A*. Since the side cavities are "empty," they can be small without introducing losses.

Figure 3 shows a partially cutaway section of a short tank made up of shaped accelerating cavities, with side coupling. The side cavities are set deeply into the main cavity for strong coupling. The bosses on the side cavities are used to adjust the resonant frequency. The dimensions are correct for accelerating 100-Mev protons. Several longer tanks of this design have been built, and used to accelerate electrons, with fields and currents scaled according to the ratio of electron to proton mass. In addition a small, high-intensity 4-Mev accelerator for electrons has been built with this type of cavity design, and beams of more than 30 milliamperes obtained. Characteristics important for practical accelerators—sparking limits, field-emission limit, fabrication costs, and ease of tuning adjustment—are excellent.

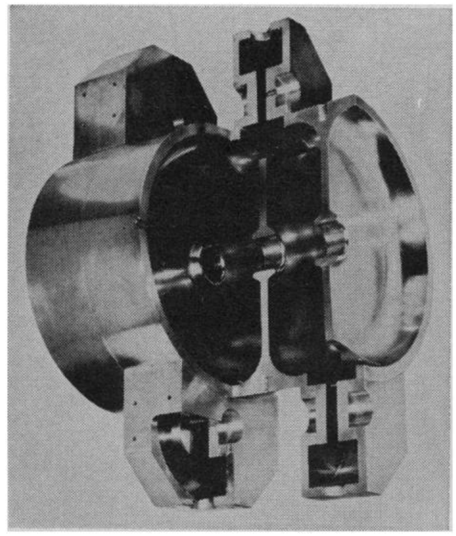

Fig. 3. Portion of an experimental model of the shaped side-coupled structure designed for protons of 100-Mev energy. The central holes are 34 millimeters in diameter. Tanks have been built much longer than those shown (see cover).

This structure may also be suitable for superconducting accelerators, for the radio-frequency cavities of electron synchrotrons, and perhaps for extended-output sections of klystrons.

It is interesting to note that Ginzton *et al.* in their design of a linear accelerator for electrons considered the possibility of using a cavity shaped with nose cones, rather like that of arrangement *D*, but without the coupling cells on the side (*16*). They recognized that the shunt impedance could be high. They rejected the curved cavity because, in their words, "for the large number of resonators needed, the problems of fabrication, tuning and feeding independent resonators of such odd geometrical shape appear quite frightening." These problems have now been solved by adding the coupling cells and by gaining a more complete understanding of the way in which the system operates.

Considerations related to those discussed above have been employed by Carne *et al.* (*18*) for synthesis of a structure called crossbar. This has a large effective coupling, and would be a useful structure for intermediate energies (50 to 500 Mev).

Recently Giordano (*19*) has shown that the Alvarez structure can be made to operate in the resonantly coupled $\pi/2$-mode. He does this by adjusting the number and size of the drift-tube supports to form a resonant coupling unit. This structure appears to have effective coupling considerably better than that of the conventional Alvarez structure, and it will probably be adopted for the new linear accelerator at Brookhaven.

Target Area and Secondary Beams for Research

Many problems, and all of the rewards for building a very-high-current accelerator, center in the general region of the target. For a facility like LAMPF, with a total average power of about 1 megawatt, the environment of the target, with its very high power densities and radiation fluxes, resembles the core of a nuclear-fission reactor. Among the most important advantages of the linear accelerator are the complete separation that is achieved between the target region and the accelerator, and the small spillage of beam in the accelerator. In this way one effectively separates the problems of the accelerator from the problems of the target area complex. Some of the typical problems of the target area will be problems of power transfer, corrosion, radiation damage, shielding, remote manipulation, removal and disposal of radioactivity, and so on. The adaptation of existing reactor technology for this target area will constitute a large part of the design effort for any high-current accelerator.

It has been found, with large accelerators, that the cost of the experimental facilities for using the primary and secondary beams is a significant part of the total cost of the facility. The details of the experimental facilities are therefore a vital part of the plan. Some examples of experimental area layouts are given (*20*). Here let me say only that there is a rapidly growing field of particle science concerned with the production, transport, focusing, separation, storage, monitoring, and analysis of secondary and tertiary beams. Such exotic devices as neutrino horns (*21*), muon storage rings (*22*), and pion and muon transport channels are coming into general use. In this area of the technology of secondary beams, linear accelerators can also play a role. They may be used in the deflecting mode as particle separators (*23*), and they have been used for the acceleration of secondary beams such as positrons. We may also in the future see them used for the acceleration and deceleration of secondary and tertiary beams of unstable particles such as pions and muons.

Other Recently Proposed Linear Accelerators

A design study of linear accelerators was carried out by the French firm CSF (Compagnie Générale de Télégraphie sans Fil) for the Institute of Nuclear Research of the University of Strasbourg. An 800-Mev accelerator for protons, with average current of 200 microamperes, was envisaged, with a duty factor of 5 percent. The frequency of the Alvarez part was to be 400 megahertz and that of the (iris) waveguide part, 1200 megahertz (*24*). The study is complete, but I do not know what action the French government may take.

A group of workers at the Institut für Experimentelle Kernphysik, Karlsruhe, Germany, under the leadership of H. Schopper and A. Citron have been investigating the basic technology of superconducting cavities for a possible future design of a 5- to 10-Gev linear accelerator for protons (*25*). As Citron remarks, the work has been stimulated by the Stanford superconducting-accelerator program (*26*).

The most powerful linear accelerator contemplated at present is the ING (Intense Neutron Generator), now under study at the Chalk River Laboratory of Atomic Energy of Canada, Ltd. (*27*). The Chalk River workers have proposed a 1000-Mev, 67-milliampere proton accelerator. Two types of machines have been considered: the separated-orbit cyclotron, and a linear accelerator with parameters tentatively like those of Table 1, except for the higher current and energy. At present the linear accelerator appears to be the design choice. The proton beam striking a target will produce neutrons by spallation-type reactions (*28*). The neutron fluxes will surpass those of the highest-power fission reactors. Of course a wide variety of secondary beams would be available from ING; in particular, ING would be a meson factory par excellence. Because of the very high power of ING the problems of targeting, of radioactivation, of remote handling, and of radiation damage to materials are quite challenging, and here the experience of the Chalk River Laboratory should be valuable.

Summary

The performance of existing linear accelerators has improved dramatically in the last few years as a result of redesign of the injector. The peak beams available surpass in intensity and quality those from other accelerators. Usually the operation has been pulsed, with a low duty factor. However, the recently developed accelerating structures now make it attractive to raise the average beam power by several orders of magnitude. New possibilities are apparent for the use of such beams for research in nuclear physics and other sciences.

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