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Some New Accelerating Structures for High Current Intensity Accelerators

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SOME NEW ACCELERATING STRUCTURES FOR HIGH CURRENT INTENSITY ACCELERATORS

by

Joseph J. Manca

ABSTRACT

The space charge effect inside the beam of charged particles causes serious problems in high-intensity linear particle accelerators. At the present time there is only the Alvarez-Blewett accelerating structure which uses continuous strong focusing to keep the beam confined to the axis. The most serious problem is at the injection end of the accelerator where the particle velocities are low and the drift tube structure has decreased efficiency. It is suggested here that some new or less well known accelerating structures using rf quadrupole focusing and H-type mode resonators may solve this problem.

The disk-and-washer structure with very high coupling coefficient can be used successfully for the high-energy part of the accelerator. A newly developed coaxial coupler solves the problem of the intertank rf coupling.

I. INTRODUCTION

Future designs of high-energy, high-intensity linear accelerators will probably be different from the present designs of low-current linacs. The linear concept will obviously remain the same, but the accelerating and focusing devices and overall layout of the accelerator can be significantly changed.

High-energy accelerators are designed by a general scheme shown in Fig. 1. There is a high-voltage injector (about 750 keV), followed by an Alvarez (or so-called drift tube) accelerating structure, using magnetic quadrupoles mounted inside the drift tubes. With this kind of "strong" focusing the structure can accelerate protons up to 200 MeV energy without difficulty. Peak beam intensities of several hundreds of milliamperes are achievable. The only problem with this structure is its complexity and cost.

The efficiences of the accelerating structures vary with the particle energies. The drift tube structure efficiency goes down as particle energy increases. Therefore, another type of accelerating structure must be used for acceleration above ~200 MeV. The efficiency of most accelerating structures depends also on the beam aperture diameter, efficiency being higher at smaller aperture diameter. However, beam dynamics dictate larger apertures for higher beam intensities. To keep the effectiveness of the accelerating cavity at its optimum, an appropriate dimension of the aperture must be chosen. Indeed, larger dimensions lead to lower operating frequencies.

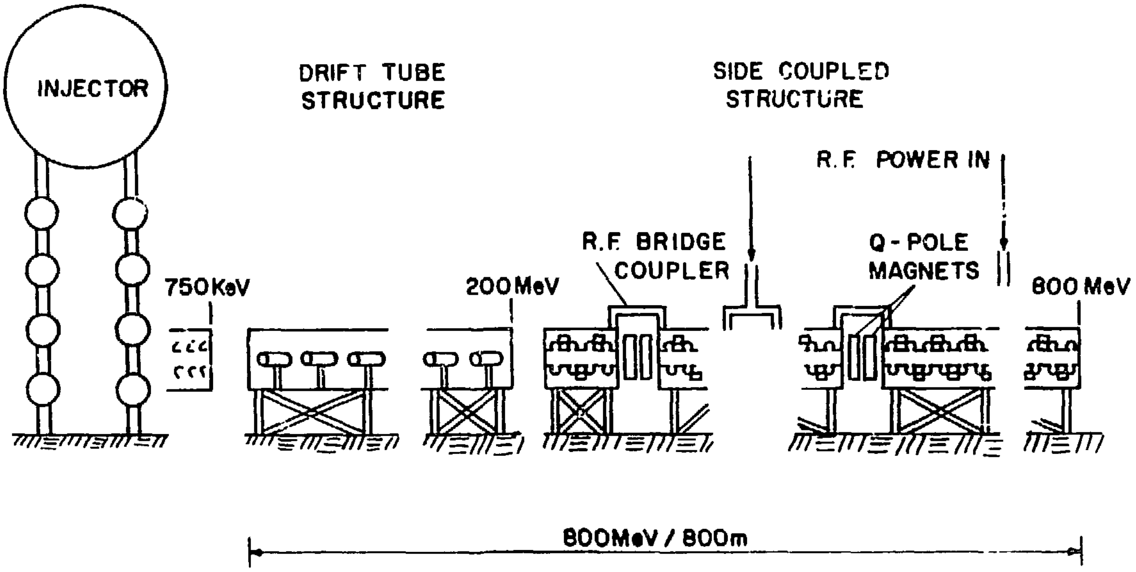

Fig. 1.
General scheme of a linac.

When the energy of the accelerated particles is required to be above 200 MeV, the drift tube structure has to be replaced by a more efficient one. The resonantly coupled structures with high efficiency have been shown to be a proper replacement.[1] This was demonstrated at the Los Alamos Scientific Laboratory (LASL), where the first high-energy proton linear accelerator (800 MeV output energy) was built using the so-called side-coupled accelerating structure for the higher energy part of the accelerator.

The LAMPF accelerator is still a unique proton linac; it has proved the possibility of accelerating charged particles to high energies in a linear device. However, the problems connected with increasing the beam current are apparently more difficult to solve than those connected with the high energies. The current limitations caused by the space charge forces acting on the particles inside the beam as well as the perturbations of the accelerating and focusing fields are the subjects of study—theoretically and experimentally.

Let us consider the possibilities of improving the accelerator efficiency and solving other problems connected with the high-energy and very low energy part of the accelerator.

II. ACCELERATING STRUCTURES FOR THE HIGH-ENERGY PART OF AN INTENSE BEAM ACCELERATOR

The space charge repulsive forces inside the charged particle beam have less effect on the radial beam size growth at high particle velocities than at low velocities. Therefore, the high-energy part of the accelerator is designed so that many accelerating cells are connected together into a tank without any focusing force applied within the tank. The magnetic quadrupole focusing doublets are placed into a space between two successive tanks. The individual tank length is determined from beam dynamics calculations. This scheme proved to be very successful for operating accelerators.

The side-coupled accelerating structure, Fig. 2, with optimized effective shunt impedance (ZT^2) accelerating cells, shows the highest rf power efficiency of any high-energy accelerating structure known. However, the couplings between the neighboring cells is only 5% and to increase it in this structure would be somewhat difficult. Structures with high coupling are less sensitive to manufacturing and alignment errors and their performance affected less by beam loading.

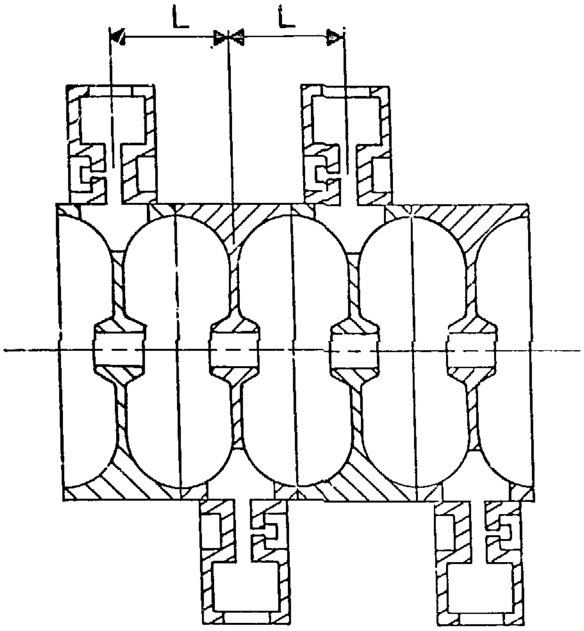

Fig. 2.
Side-coupled accelerating structure.

Using coaxial couplers on the circumference of the optimized accelerating cells instead of on the side cavities (Fig. 3) allows an increase in the coupling up to 18%. Using two holes 180° apart makes the couplings symmetrical and the manufacturing process easier. This structure may have some attractive applications for medium-intensity accelerators.

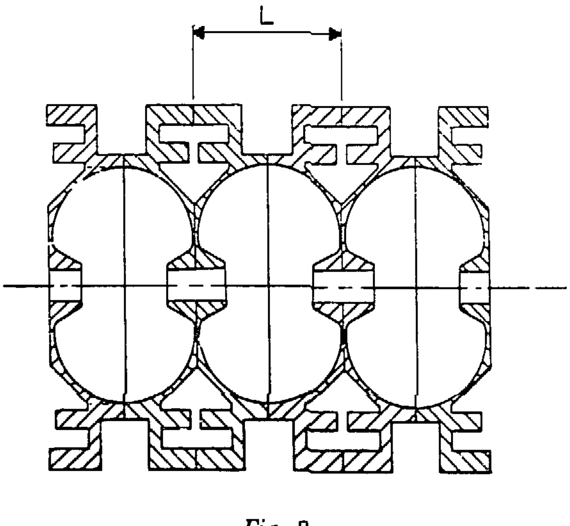

Fig. 3.
Ring-coupled accelerating structure.

An innovative approach to the resonantly coupled structures came from Andreev of Moscow's Radiotechnical Institute.[2] He developed a structure with a coupling as high as 10 times that of a side-coupled structure, a so-called disk-and-washer structure (Fig. 4). It has practically the same effective shunt impedance as the side-coupled structure, when carefully optimized.[3] The structure operates in the $\pi/2$ mode and its dispersion curve is linear over a relatively broad range of frequencies. The large and symmetrical separation of the neighboring modes to the $\pi/2$ mode allows the connection of 10 times as many cells in a tank as in the case of a 5% coupling structure, and this may be a very useful feature in some designs.

The structure can be made from individual modules, each containing a disk and washer. Each module can be tuned before stacking it into a structure. The joint between the modules is characterized by a very low rf current and one does not expect much perturbation after the modules are brazed together, and therefore no tuning is required after the structure is completed.

Another good feature of the disk and washer is the mechanical design, which allows cooling of the washer, where up to 80% of rf power is lost. This will be extremely important for high-duty operation of an accelerator. This structure can eventually be used for many applications in a scheme similar to that shown in Fig. 1.

The scheme in Fig. 1 will suffer in high-current applications, because the need for increased focusing will require more quadrupole magnets and individual tank lengths will be much shorter than in

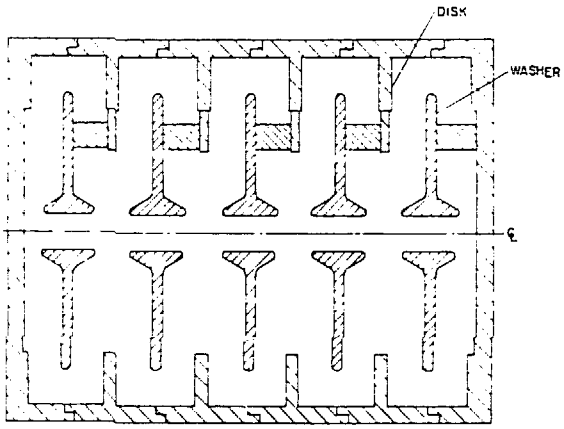

Fig. 4.
Disk-and-washer accelerating structure.

the case of low-beam current accelerators. The short tanks have to be connected by rf couplers that bridge the focusing doublets. The couplers produce rf power losses, diminishing the overall efficiency of the accelerator. Bridge couplers are usually made with low coupling and thus the advantage of large coupling in the disk-and-washer structure may be lost. A newly developed coaxial coupler[4] can efficiently solve the above problems. It has a coupling comparable to the disk-and-washer structure, it has low rf power losses, and it is much simpler to construct. It can accommodate focusing and monitoring devices if necessary. The coaxial couplers can be used for the connections of the neighboring tanks, or, because of their very good power transmission, as the rf power ports.

Another process, which seems to be close to realization with disk-and-washer structure, is use of the rf field in the cavity for transverse focusing by shaping the cavity noses. In spite of the diminishing effectiveness of this kind of focusing with particle velocity, preliminary calculations indicate that it may be possible to find a stable region for certain accelerating gradients in the cavities. Such a scheme would require a focusing periodicity nFnD, where n is an integer larger than 1. Essentially this scheme requires a large number of cells in a tank. One possibility would be to use all cells in one tank for focusing in one plane while the cells in the next tank would focus in the other plane, and so on. The net effect would be focusing in both planes.

The effective shunt impedance of a cavity shaped for the focusing effect decreases approximately 20%, with respect to the value for an optimized standard cell. Besides the savings in the magnetic lenses and power supplies, the overall accelerator length can be made 20-30% shorter. This would probably offset the lower shunt impedance.

III. LOW-ENERGY SECTION OF THE ACCELERATOR

At the low-energy end of the accelerator, the Alvarez structure already has a strong focusing system. One does not expect too much improvement in the principle. This structure can handle sufficiently large beam currents in a proper range of energies; however, the structure's efficiency decreases when it is designed for particle energies below ~10 MeV, and the design becomes difficult for energies below ~3 MeV, because of the problems of accommodating the magnet quadrupoles inside the very short drift tubes. The capturing efficiency of this structure is low for energies below this limit. At the present time the particles are injected into the drift tube structure at a compromise energy of 750 keV. The problems connected with such a high voltage in the injector and such a low injection energy to the rf structure are very well known. A number of people have investigated the alternating phase focused drift tube structure as an improved low-beta design. In this method, the drift tube gaps are spaced so that both transverse and longitudinal focusing are alternately provided by the rf field, eliminating the need for quadrupole magnets.

Another approach to improved low-beta structures involves using rf focusing in a way similar to electrostatic focusing, which is particularly strong in the region of low particle velocities. In the late 1950s some authors suggested the use of properly shaped rf field for focusing and acceleration of the particles at the same time. The most interesting proposal was made by Vladimirskii,[5] who suggested the use of a quadrupole shaped field, created by two fingers on the face of the drift tube (Fig. 5). The fingers were rotated by 90° on the opposite ends of the drift tube. In the three-dimensional field distribution in the gap it is possible to have transverse components, in, let us say, the X-plane so that the gap field will act as a focusing lens in that plane. In the next gap it will be the same in Y-plane. The whole system can act as a "strong" focusing FD system.

In spite of the clear advantage of this kind of focusing at low particle velocities, the idea was not fully developed. Only after an idea of Teplyakov[6] to use accelerating cavities excited in a TE mode with the fingered drift tubes on the circumference of the cavity, did the realization of the rf field focusing

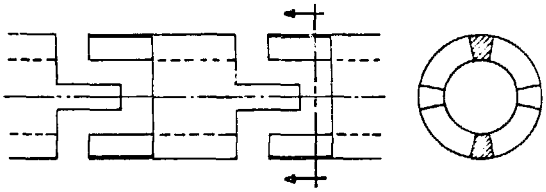

Fig. 5.
Schematic drawing of the drift tubes with fingers.

principle come closer to reality. The schematic drawing of the Teplyakov idea is shown in Fig. 6. The drift tubes are alternately mounted to each wall of the cavity. The electric field excited in the gap of the cylinder thus has an opposite sign on the successive drift tubes. With proper design of the drift tube length and finger shapes, the drift tubes will be short and the particles will be almost continuously focused or accelerated. The regions of stable operations are claimed for synchronous phases larger than 20°. The injection energy for this structure with one gap per period can be lower than 1 MeV. Later Teplyakov proposed the use of two gaps per period. Such a configuration, FFDD, would allow injection at energies of a few hundred keV. The H-cavity is, in fact, one turn of a very wide tape mounted inside another cylindrical cavity, which provides shielding for the inner cavity (Fig. 7). The drift tubes represent a capacitive load for the cavity. The resonant frequency is then determined by the cavity diameter and is practically independent of length. The outer *diameter of the cavity is thus 3 to 5 times smaller* than the diameter of the Alvarez cavity for the same frequency. The shunt impedance of the H-mode *structure is higher than the Alvarez structure at* $\beta < 0.15$ (12 MeV) for the same λ, as shown in Fig. 8. The manufacturing tolerances for the H-structures with rf quadrupole focusing are approximately the same as the tolerances for magnetic quadrupoles, but the alignment seems easier.

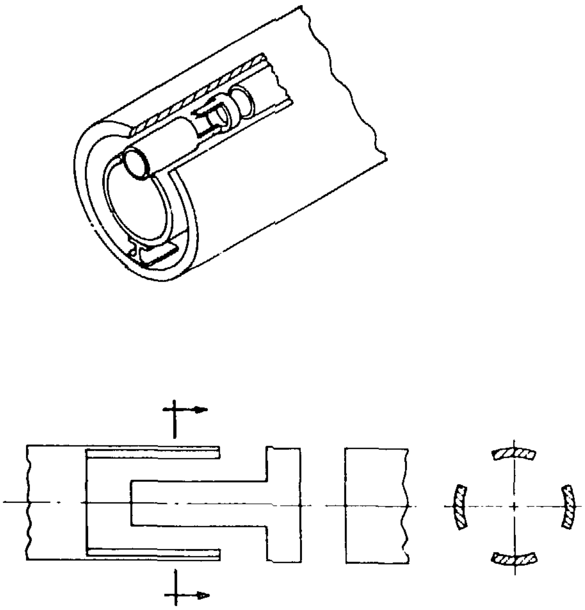

Fig. 6.
Schematic drawing of an rf focusing structure using H-mode resonator and fingered drift tubes.

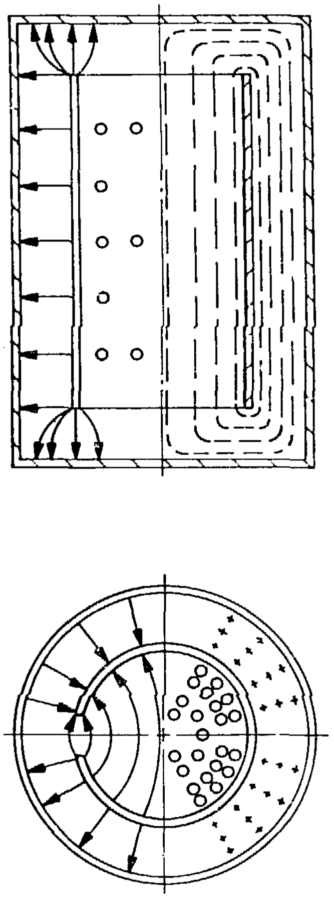

Fig. 7.
H-mode resonator.

The H-type structures are very promising for the acceleration of protons and ions. They represent substantial improvement at the low-energy end of the accelerators and an addition to the family of accelerating structures. There was, however, another innovation proposed and developed to a fully workable model by Kapchinskii and Teplyakov.[7] The principle is in Lecher transmission lines. The four parallel lines are fed by the rf power so that the neighboring lines are continuously at the same

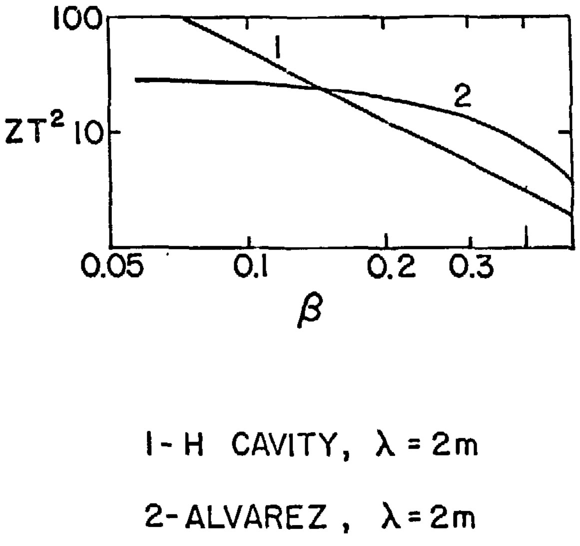

Fig. 8.
Effective shunt impedance vs relative particle velocities (β) for H-mode and drift tube accelerating structures.[8]

potential, but of opposite polarity (Fig. 9). This way a quadrupole field is created in the central space between the lines. Two H-type resonators with a longitudinal gap on the circumference are used for the field excitation of the lines, mounted in the gaps. For acceleration, all four lines are modulated so that a short section of small line diameter is followed by a short section of large line diameter with a short transition section (Fig. 10). The spatial period of the variation is equal to the distance traveled by the particle during one rf period. The variation in the vertical and horizontal planes is shifted for each half rf period. The particle experiences quadrupole focusing effect in the straight sections of the periods. The rf accelerating field appears at the transition, causing resonant acceleration of the particles. Preliminary analytical calculations have been made to show the dependence of the focusing and acceleration on the ratio of the diameters. For a given beam aperture there is an optimum ratio. Because of the constant focusing and acceleration, this structure can handle very large current (>100 mA) at an acceleration rate of 1 MeV/m. The injection energy can be as low as 50 keV and the capturing coefficient remains close to 100%. (The capturing coefficient is the ratio of an injected dc beam current to the accelerated current.) Because of the continuous effect of the quadrupole-like field on the moving particles

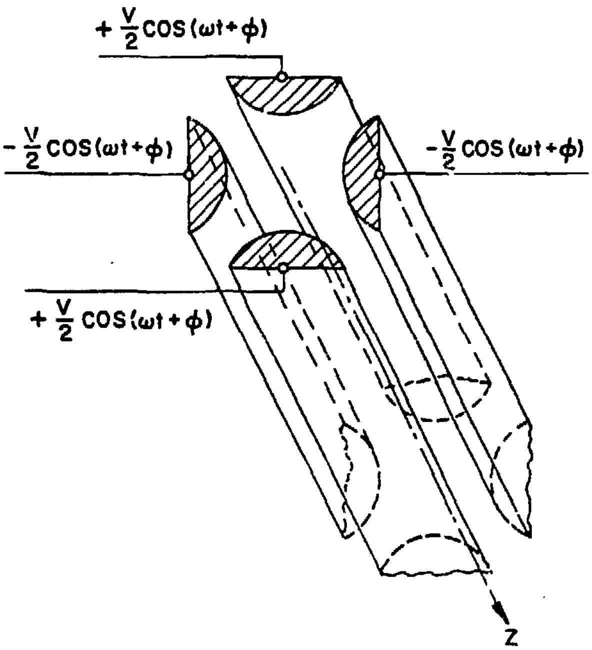

Fig. 9.
Schematic drawing of four-line accelerating structure.

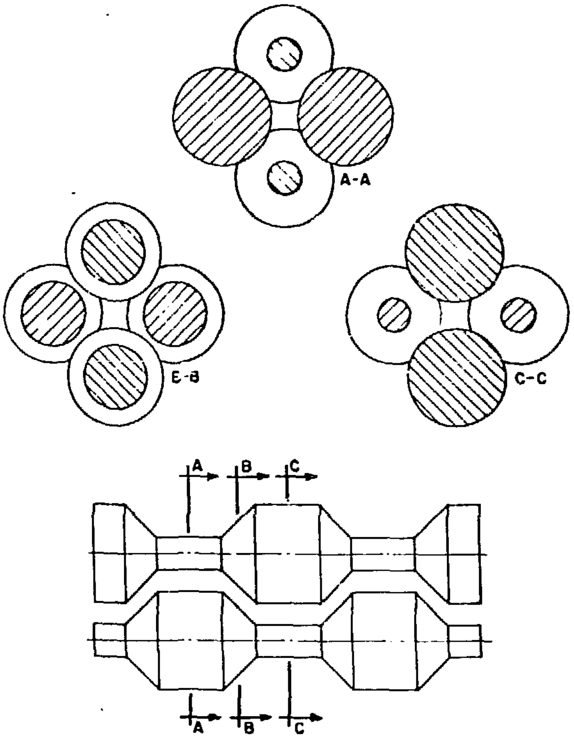

Fig. 10.
Cross sections of modulated four-line structure.

in the entire structure, the transverse beam emittance remains practically constant during acceleration in this structure. Using H-type resonators for four-line excitation makes it possible to decrease the operating frequency to several tens of megahertz without making the structure too large.

The structures using H-type resonators have been extensively studied in the USSR. Some results have already been published and are summarized in Table I.

With these new structures, the scheme of a high-energy, high-beam-intensity accelerator might look like the one shown in Fig. 11. The particles are injected into the four-line accelerating structure at 50 keV and accelerated to an energy of about 2 MeV. The length of this structure is ~2 m and is designed as two 1-m-long resonators. The four-line structure is followed by a section with fingered drift tubes, which accelerates the particles to 15 MeV. A similar section could be used to bring the particle energy to 30 MeV or higher. Each section is about 15 m long. The next section is an Alvarez structure accelerating particles up to 200 MeV, followed by the disk-and-washer structure with coaxial couplers. The length of this structure depends on the required output energy and the acceleration rate.

IV. SUMMARY

A new design of the high-energy accelerator section, employing a disk-and-washer structure and coaxial couplers between the accelerating tanks, represents an improved version of the high-current,

TABLE I

H-MODE STRUCTURE WITH FINGERED DRIFT TUBES

W_{inj}	MeV	0.51
W_{out}	MeV	3.26
Frequency	MHz	132.5
Cavity length	m	2.4
Outer diameter	m	0.41
Number of electrodes		65
Beam aperture	m	0.016
Focusing period		FFDD
Normalized transverse acceptance	mrad · cm	1.0
Synchronous phase	degrees	30.0

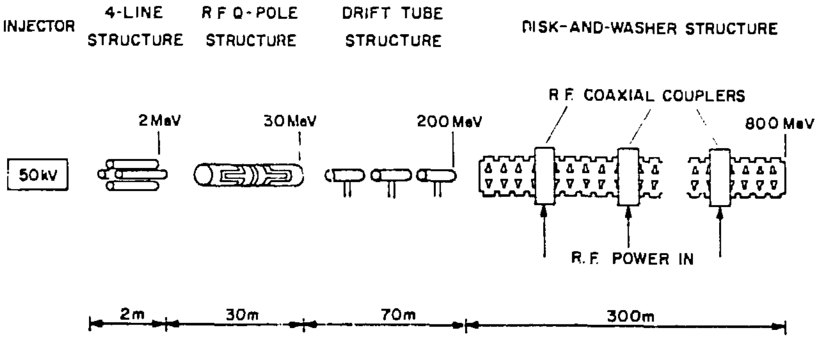

Fig. 11.
Proposed linac using rf focusing and rf coaxial couplers.

high-energy accelerating structure. The large coupling coefficients of the structure and coaxial couplers make the accelerator less sensitive to manufacturing and alignment errors and to beam loading. With shaped cavity noses for transverse focusing purposes this structure can be made shorter than a structure with magnetic quadrupole doublets for the same output energy. Economically, the new design may be less expensive than the conventional one in both construction and long-term operating cost.

Smaller dimensions, construction and technological simplicity (for example, no quadrupole magnets) are the most important advantages of H-type structures. Higher shunt impedance ($\beta < 0.15$), higher beam current, a very high capturing coefficient at very low injection energy, reasonable acceleration rates, are their advantages in terms of the physical parameters. They are less complex and less expensive than the Alvarez structure. Together with the possibility of using rf quadrupole focusing, these *low-energy structures are likely to be used in future* linear accelerator designs.

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