Advances in the Design of Proton Linear Accelerators - Meson Factories and Injectors for Synchrotrons*

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Projects and Plans

I would like to start by mentioning some of the projects to build new proton linacs. There is the injector linac for the AGS conversion program at Brookhaven, which is to be a 200-MeV Alvarez linac, with a 200-mA peak current as a design objective. The Los Alamos Meson Facility is to be an 800-MeV linac, with 17-mA peak beam and 12% maximum duty factor. A study group at Karlsruhe, Germany, is interested in a proton linac of 5-10 GeV, with superconducting cavities, to serve as a "K-meson factory." They appear to be thinking in terms of a long-range project. A 100-MeV Alvarez injector is nearing completion at Sherpukov, USSR. The Chalk River Intense Neutron Generator proposal calls for a 1000-MeV accelerator to deliver 65-mA continuous current. Although the SOC was originally their "reference design," Chalk River now seems to favor a linac.

The most remarkable progress is in the area of ion sources and columns, making it possible to inject much higher currents, and in the area of more efficient accelerating structures, which reduce the power losses to the walls. As a result of these developments for the linacs now being designed, the power in the beam should be quite comparable to the power lost to the walls.

Ion Sources

A number of laboratories have reported improved performance from the duoplasmatron ion source and high-gradient column. As was emphasized by van Steenbergen two years ago at this meeting, one of the most important attributes of an ion source is its transverse brightness, i.e., the current emitted into a unit area in transverse phase space. The duoplasmatron with plasma expansion cup seems to have a brightness at least as great as its competitors, plus advantages in other characteristics, such as gas consumption, size, and power required for operation.[1] For these reasons the trend has been to the duoplasmatron (DP), although very good results have also been obtained at CERN with the RF source. The CERN RF source preinjector was replaced last year by a DP and a short single-gap accelerating tube. The characteristics of the DP source were: 650 mA accelerated to 340 keV, of which 450 mA fell within the linac acceptance (0.6 cm mr). Cathode life of greater than 2500 hours is reported, and stability is apparently satisfactory. After a short period of adjustment of the new source the 50-MeV output beam of the linac rose to the record level of 135 mA.[2] An alternative approach to column design is to use a number of electrodes to produce the Pierce ($Z^{4/3}$) distribution of potential (Z is the axial distance), in order to compensate for space charge.[3,4] The Pierce law in some designs governs only the potentials on the DP extractor electrode and the first electrode of the accelerating tube. Good results have been obtained at BNL[4] and at Saclay[5] with this approach.

Beam Transport

The high currents from the preinjector have caused an embarrassment of riches for the designer of the beam transport system, buncher, and Alvarez linac, in that more attention must be paid to effects of space charge in all of these systems. Consider first the transverse motion. Differential equations had been written by Kapchinskij and Vladimirskij and also by Walsh for the beam envelope, in the case of a beam represented in transverse phase space by the surface of an ellipsoid.[6] It was shown that particles would remain on the surface of the ellipsoid, under the action of space charge forces, linear focus magnet forces, and accelerating forces. However, the assumption of what in reality is a zero emittance beam is unrealistic. Investigating this point, Ohnuma[7] and Goedecke showed the K-V distribution is the only one which gave a uniform-density rod of current in configuration space. Numerical studies of various nonuniform charge distributions were made by Crandall.[8] The details of the behavior of the beam were different than for K-V, but the K-V profile equations are still useful as a rough guide for designing the lenses of the beam transport system.

Longitudinal Motion

The longitudinal motion beyond the buncher and in the Alvarez linac is also a problem at high currents ($\sim$100 mA). Lapostolle, Gluckstern,[9] and Benton and Agritellis[10] have been calculating these effects. Some unpublished calculations by Chasman and Gluckstern indicate that the beam no longer damps as $(\text{momentum})^{-3/4}$ but instead will approach asymptotically a phase width such that the space charge potential neutralizes the longitudinal focusing of the RF field. Indeed, if

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the beam is too closely bunched to begin with, it debunches and the bunch size oscillates. It seems that the 17 mA required for LAMPF does not present much of a problem in this respect, but the 200 mA for the AGS conversion does. One can of course improve longitudinal stability by increasing E_o sin φ, but this further aggravates the transverse focusing problem in the linac. This can be overcome by the use of pulsed quadrupoles, as is planned for the AGS conversion linac.

One may ask: where is the space charge problem, since the CERN PS injector has accelerated 130 mA to 50 MeV? As pointed out by Taylor[11] the transverse properties of the beam are observed to change strikingly between 50 mA and 100 mA. At the higher currents the salient features are: a reduced trapping efficiency (30% at 100 mA vs 65% at 10 mA), and a radial emittance increase or "blowup" between injection and 50 MeV (a factor of 3 at 100 mA vs almost no change at 50 mA). The change in trapping efficiency is probably associated with space charge effects in the buncher, and the radial blowup with the space charge effects and coupling effects mentioned above. The longitudinal emittance of the new high intensity beam at CERN has not yet been measured or reported, but the increase may be substantial, as physical arguments would indicate, and as is suggested by the fact that the current accepted by the PS has not increased commensurately with the higher currents from the linac.

Developments in Accelerator Structures

The investigation of new standing wave structures has continued, motivated by the desire for higher shunt impedance, or better power flow, or both. Better power flow (strong coupling) is the more important for the injector linacs which are to produce more than 100 mA since, under high beam loading, the transient and steady state behavior are strongly influenced by the coupling; high shunt impedance is a secondary consideration for such linacs. For the meson factory, both considerations are important. The requirement of good power flow characteristics has focused attention on structures which operate at $\pi/2$-mode.[12]

Often such a structure can be analyzed as an accelerating region, a coupling region, an accelerating region, and so on. The coupling region in turn may be regarded as a resonator in its own right, with linear coupling to neighboring acceleration regions or cavities, second nearest neighbors and so on, the whole structure having a longitudinal period ℓ. This type of structure is symmetric under two kinds of operations: one the simple translation by length ℓ and the other a translation by $\ell/2$ and an interchange of coupling and accelerating regions. The effects of spatial symmetry of the cavity system, or tank, are manifested in the solutions of the field equations and the boundary conditions. The frequency spectrum of the tank breaks into two bands. The wave functions, or modes, which represent the above group of symmetry operations, have the usual Floquet phase shift factor. The modes are the same as in a simple tank except that there are twice as many, and in addition, the fields alternate in amplitude between main cells and coupling regions.[12] The $\pi/2$-mode of this tank would correspond in the older viewpoint (ignoring the coupling region as a resonator) to either the 0-mode or the π-mode.

The side-coupled structure is a good example of the tank with two types of cavities operating in $\pi/2$-mode. It was reported by Knapp et al[13] at the 1964 Linac Conference at MURA and also at the 1965 National Accelerator Conference, and since then has been further developed. The shunt impedance has been increased, for example, the calculated shunt impedance (ZT^2) for 805 MHz, $\beta = 1.0$, and 3.8 cm aperture is 52 MΩ/m. The shunt impedance measured on actual tanks is about 20% less. A larger shunt impedance can be got by reducing the aperture. The power flow and field flattening characteristics are excellent. Figure 1 is a diagram of this structure, and Fig. 2 is a photograph of a cutaway section of a short 805 MHz tank. The cavities have been shaped according to the optimum found by Hoyt's computations.[14] Figure 3 shows two longer tanks, one a 61-cell version and the other a 39-cell model at $\beta = 0.65$. The shorter one has been satisfactorily operated at greater than full design power, and used in a scaled experiment to accelerate electrons. The installation of the longer one is nearly complete.

A short linac called Model L built for test operation with a high current of electrons, is shown in Fig. 4. This accelerator is 0.95 m long, has 5 accelerating cells and 4 coupling cells. The measured shunt impedance (ZT^2) is 42 MΩ/m. It has been operated at a peak field of 6 MV/m. No problems of sparking were encountered. A beam of 100-kV electrons has been injected, and 30 mA accelerated to 3.3 MeV, at 3% duty factor. The structure shows no undesirable characteristics during operation.

A higher energy version, called EPA, is under construction. It consists of a 100-kV injector, a buncher and preaccelerator tank of 6 cells and then a 4-section, 100-cell tank using bridge couplers between sections. Ultimate energy is 30 MV unloaded and 21 MeV with 25 mA of beam. Maximum duty factor is 12%. Total length is 32 m, and the total cavity length is 19 m. It will be used for studying targeting, phasing and beam loading problems. Power densities in the target will be quite comparable to those in the meson factory targets. Operation is planned for this year.

In the side-coupled structure, power feeds and vacuum ports are conveniently put in the side cells. If we displace the main cell well to the side, allow it to grow longer, and separate the neighboring two main cells, the unit becomes a so-called resonant bridge-coupler. At the bridge-coupler position we have a space on the beam line to put focus magnets, beam sensing cavities, etc. Several tanks can be bridge-coupled together. One can even consider a complete linac bridge-coupled together and fed at the coupling points. This system was briefly mentioned at the previous meeting (First National Accelerator Conference), and has been further studied.[15] It shows excellent power flow characteristics, and is relatively insensitive to phase and amplitude errors in the drives or cavity errors, and it could be operated with complete loss of power from one or more amplifiers. However the LASL design couples not more than four tanks.

There are alternative solutions to the problem of power flow. One is the use of an auxiliary manifold, into which at several points power is fed from RF amplifiers, and from which power is taken at a number pf points for the tanks. The manifold was mentioned by Ginzton et al 20 years ago, but was seriously investigated only recently by Voelker,[16] who did a detailed analysis and also produced a working model at 200 MHz. He proposes to use a manifold to feed an Alvarez linac. One of the advantages of his system is the possibility of connecting extra amplifiers to the manifold to increase reliability. Another high group velocity system is cross-bar, which has been investigated by Carne et al.[17] Its properties are good from 50-400 MeV. Another $\pi/2$-mode system is what the Brookhaven group call the multistem Alvarez linac. Last year Giordano and Hannewecker[18] showed how the resonance frequency of the drift tube supporting stems could be brought up to the accelerating cell frequency by adjusting the size and number of stems. This structure, when operated in $\pi/2$ mode, shows excellent tank flattening characteristics. It is very likely, although the tests have not yet been reported, that the power flow and transient behavior will also be good. As of now, Brookhaven plans to use multistem drift tubes for the AGS conversion linac. The meson factory linac has less need of high power flow structures in the low energy part, since the power per foot is much less. However, up to 100 MeV for 50% beam loading the Alvarez linac is satisfactory.

There have been quite impressive advances in all sectors of linac research and development in the last two years. We can expect to see extremely high performance linacs built soon.

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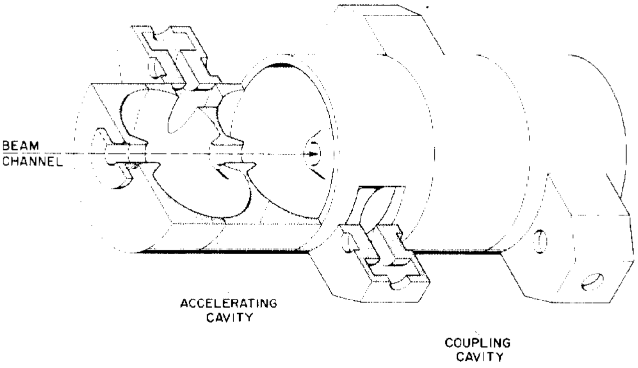

Fig. 1. Diagram of the side-coupled linac structure. Phase shift from an accelerating cavity to the coupling cavity is $\pi/2$. Walls are shaped according to a computed design to optimize shunt impedance.

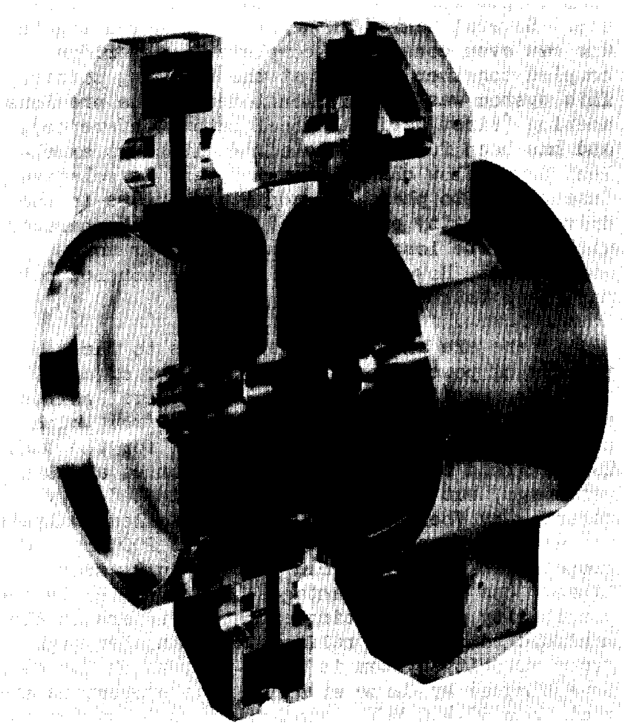

Fig. 2. Side-coupled shaped cavity structure, $\beta = 0.65$, frequency = 805 MHz.

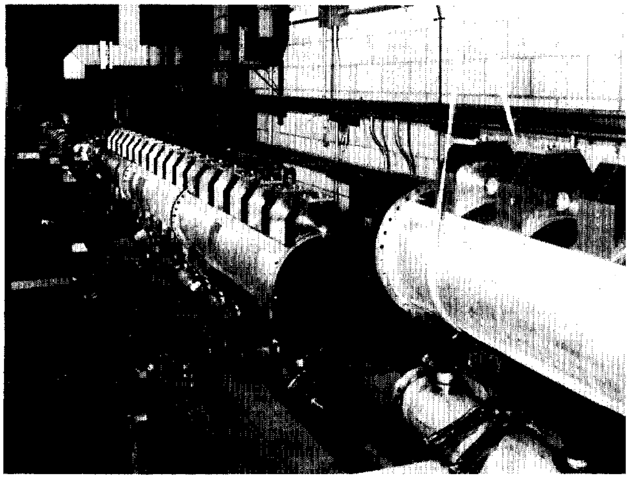

Fig. 3. Linac side-coupled tanks designed for $\beta = 0.65$. In the background a 39-cell tank is connected to a WR-975 waveguide coming from above. In the foreground a section of a 61-cell tank is being lowered into place. The vacuum manifold is below.

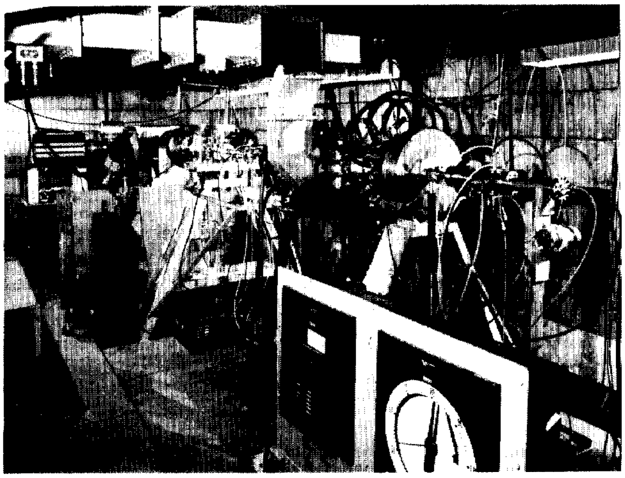

Fig. 4. Model L, a short 4-MeV electron accelerator using the side-coupled structure. 30 mA of electrons have been accelerated to 3.3 MeV at 3% duty factor.