A VERY HIGH-INTENSITY PROTON LINEAR ACCELERATOR AS A MESON FACTORY

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Characteristics of the Linac as a Meson Factory

A "meson factory" is a complete research installation built around a high intensity proton accelerator of maximum energy below 1 GeV, and which is characterized principally by the unusually high intensity of the secondary particle beams.

There is much significant and interesting information not yet known in many fields of physics in the energy range below 1 GeV. The primary fields are : 1) particle physics involving nucleons, pions, muons, and neutrinos and their strong, electromagnetic and weak interactions, and 2) nuclear structure. High intensity beams, such as provided by a meson factory, are required to obtain much of the new information because they make possible : 1) studies of processes with small cross-sections or probabilities such as neutrino-induced events, rare decay modes, or triple scattering from thin targets, 2) precise experiments with high energy resolution, high purity beams, and thin targets, 3) high counting rates.

A proton linear accelerator has the following outstanding characteristics as the accelerator for a meson factory : 1) very high intensity primary proton beam (10^3 times that of existing synchro-cyclotrons and 10 times that of proposed sector-focused cyclotrons), 2) external proton beam with full intensity of the internal beam and with excellent geometrical properties, 3) energy variable in small steps, 4) acceleration of polarized protons, 5) reasonably high duty cycle, 6) relative freedom of the accelerator from problems of radioactivity and radiation damage, because of the ease of beam extraction.

The characteristics of the proton linear accelerator being designed at Yale University are shown in Table I.

The secondary particle beams which can be derived from this proton linac will be a factor of 10^3 to 10^4 times more intense than the secondary beams derived from the Berkeley 184 inch synchro-cyclotron, which is at present the most intense source for pion and muon beams in the energy range under consideration1). Table II shows some typical useful secondary beams associated with the proton linac. Particularly noteworthy are the beams of various types of neutrinos, which are obtained from the decays of pions and muons at rest or in flight, and which have adequate intensities for various experiments2). Fig. 1 and 2 show neutrino spectra which can be produced by 750 MeV protons. Table III3) lists some reactions which might be studied.

Table I

Characteristics of the Proton Linear Accelerator

I. Beam Energy

a) Maximum energy : 750 MeV
b) Energy variable in steps of 7 to 10 MeV from 200 to 750 MeV
c) Energy spread : approximately 0.3%

II. Beam Intensity

a) Average current : 1 mA or 6 x 10^{15} protons/s
b) Peak pulse current : 20 mA
c) Pulse length and rate : 2 ms; 25 pulses/s
d) Beam duty cycle : 5%
e) Within each pulse the beam will be bunched into 4 x 10^5 packets; each packet has a duration of approximately 0.07 ns and adjacent packets are spaced by 5 ns.
f) Beam power, average : 750 kW
g) Beam quality, area in transverse phase space : 4.6 π x 10^{-4} cm rad

III. Physical Characteristics

a) Total length : 2000 ft
b) Total peak power : 85 MW
c) Injector : 750 kV Cockcroft-Walton generator
d) Drift tube accelerator at 200 MHz, 0.75 to 200 MeV. The first cavity about 5 m long and followed by six cavities about 25 m long.
e) Iris-loaded guide at 800 MHz, 200 MeV to 750 MeV. 59 cavities each 7.5 m long
f) Transverse focusing by magnetic quadrupoles

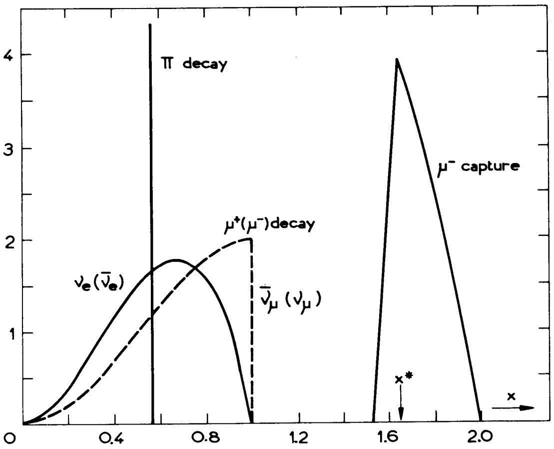

Fig. 1 Neutrino energy spectra available from 750 MeV stopped protons. The ν_μ are obtained from stopped negative muons. x = energy in units of one half the muon rest energy (U. Überall, preprints).

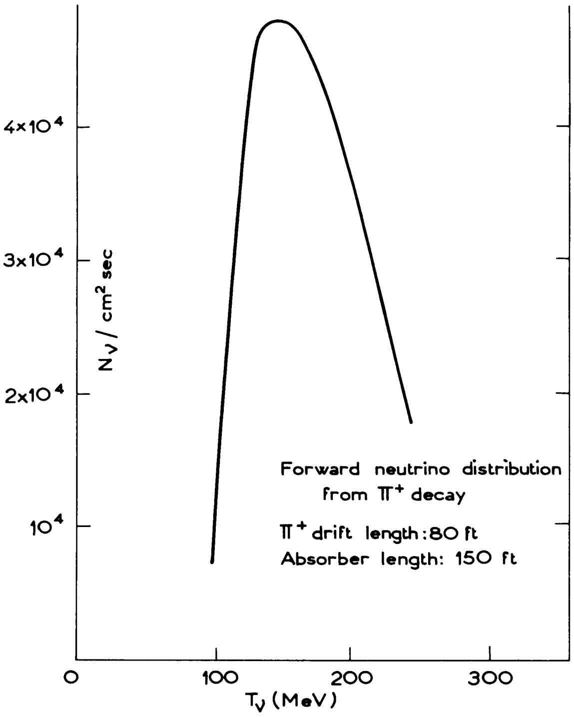

Fig. 2 Neutrino energy spectra available from decay of pions in flight, produced by 750 MeV protons.

Table II

Examples of Secondary Beams Derived from Proton Linac

Particle	Energy	Δ p/p	Intensity	Remarks
π^+	300 MeV	± 1%	1 x 10^8/s	Solid angle : 10^{-4}sr Primary target : 12 g/cm^2, 30° meson collection
π^-	300 MeV	± 1%	1.5 x 10^7/s	
π^+	stopped	—	4 x 10^8/s	Stopping target
π^-	stopped	—	7 x 10^7/s	25 cm^2, 6 g/cm^2
μ^+	200 MeV	± 1%	1 x 10^8/s	Use of quadrupole lens channel. Beams have maximum area of 80 cm^2 and maximum angular divergence of 0.0870 rad
μ^-	200 MeV	± 1%	2 x 10^7/s	
μ^+	stopped	—	5 x 10^7/s	Stopping target
μ^-	stopped	—	6 x 10^6/s	25 cm^2, 6 g/cm^2
ν_μ	30 MeV	Monoenergetic	1 x 10^7/cm^2 s	Derived from stopped protons and π^+ decay at rest
$\bar{\nu}_\mu + \nu_e$	90 MeV (max. total)	—	1 x 10^7/cm^2 s	Derived from stopped protons and μ^+ decay at rest
ν_μ	125 to 240 MeV	—	1 x 10^6/cm^2 s	Derived from π^+ decay in flight
n	730 MeV	Δ E/E = 2%	1 x 10^8/cm^2 s	

An unusual facility is also provided by the high-energy, high-intensity neutron secondary beam which has a time definition of 10^{-10} s as determined by the RF fine structure of the primary proton beam, and hence is suitable for experiments involving time-of-flight techniques. The beams of pions and muons have extremely high intensity as well as high purity, small momentum spread, and small angular divergence.

Accelerator Design Considerations

The remaining portion of this paper deals with specific considerations relating to the design of the linac. The features of very high intensity, excellent beam quality and low radio-activation of the structure require careful attention to the particle dynamics in order to achieve a minimum loss of particles during acceleration. It should be possible to design a linac in which no particles are lost at energies above about 25 MeV. However, a loss of 0.1% of the particles above 25 MeV would be

Table III

Some Energetically Possible Reactions with Neutrinos Produced by a 750 MeV Proton Beam

(1) $\bar{\nu}_e + p \rightarrow e^+ + n$ (Cowan-Reines experiments)

(2) $\nu_e + n \rightarrow e^- + p$ (Davis Cl^{37} experiment)

(3) $\nu_\mu + n \rightarrow \mu^- + p$ (Columbia-Brookhaven experiment)

(4) $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

(5) $\nu_\mu + n \rightarrow e^- + p$ (probably forbidden)

(6) $\bar{\nu}_\mu + p \rightarrow e^+ + n$ (probably forbidden)

(7) $\bar{\nu}_\mu + p \rightarrow n + e^+ + \pi^0$

(8) $\bar{\nu}_\mu + p \rightarrow \Lambda^0 + e^+$

tolerable. Several features of the design are being closely examined : types of accelerating structures, injection into the linac, control of phase and amplitude of the field in each cavity, transition in type of structure, effects of beam loading and transverse focusing systems. For economic reasons, attention must be given to minimizing the cost of the accelerator.

Types of Structures. Existing proton linacs are of the Alvarez type, employing from one to three drift-tube loaded, standing wave cavities. The Alvarez structure is characterized by a serious decrease in the shunt impedance as the particle velocity increases. Electron linacs operate with $\beta = 1$ over their entire length except for a very short buncher section. The iris-loaded waveguide operating in a travelling or standing wave mode has proved practical for this purpose. The shunt impedance of the iris-loaded waveguide decreases with decreasing particle velocity. For both types of structure in the region of $\beta = 1/2$, the shunt impedance has decreased so much and the power loss per unit energy gain has become so large that the structure becomes economically undesirable. Extensive work has been done to determine the shapes for drift tubes and irises which will lead to the highest possible values of the shunt impedance[4]. In the region of $\beta = 1/2$, savings in RF power by 50% are indicated as compared to the early types of structures.

A number of studies have been attempted to find alternate accelerating structures which would have a higher shunt impedance in the region of $\beta = 1/2$. Some recent results at Harwell may yield a new and useful structure. However, at present we feel that a transition from drift tube structure directly to iris-loaded waveguide must be made near $\beta = 1/2$. The exact point for the transition is determined by detailed economic consideration. For a particular type of structure the shunt impedance increases with increasing frequency. The drift-tube section will operate at a frequency of 200 MHz which is the highest frequency consistent with the requirements of fabrication. A value of 800 MHz has been chosen tentatively for the iris-loaded waveguide for reasons discussed below.

Injection. The design of the buncher and first drift-tube cavity should incorporate two important features : High capture efficiency to ensure the high intensity beam and rapid concentration of the particles near the synchronous phase and energy for a minimum loss of particles. It is certain that some particles will not be captured in the phase stable region and these will ultimately be lost to the drift tubes. Those particles which are far from the phase stable region will quickly be lost before gaining enough energy to cause activation of the structure. However, other particles which are just outside the stable region may gain considerable amounts of energy (25 MeV or more) before being lost. Several methods are being studied for increasing the fraction of beam captured and for losing the unstable portion of the beam before it can gain enough energy to cause trouble.

Control. Once particles have been trapped within the phase stable region of the "perfect" accelerator, there can be no further loss of particles from the beam. In a practical accelerator there will be several forms of errors which may induce the phase oscillations to grow rather than damp, resulting in loss of particles. These errors include : Incorrect amplitude of the electric field in a cavity with respect to adjacent cavities and incorrect longitudinal position of the drift tubes or irises within a cavity. In addition, the interaction of the beam with a cavity must be considered. The phase and amplitude of the electric field must be servo-controlled to an accuracy such that the residual errors will not stimulate the phase oscillation to a serious degree. Similarly, care must be taken in the fabrication of the cavities.

A computer code has been set up to examine the effects of these residual errors on the beam. The present program considers only the longitudinal motion but the transverse motion is being added. The program permits tracing of a particle bunch through the accelerator with any distribution of phase and amplitude errors. A particle is considered lost if it moves outside of the phase stable region. Preliminary results indicate that if the phase shift between cavities is held to 1 degree and the amplitude of the cavity fields to 1 percent, no particles will be lost from the bunch above about 25 MeV when the drift-tube section is operated at 200 MHz and the iris-loaded section at 800 MHz.

The control of the phases and amplitudes of the fields in the cavities will be accomplished by servo-systems which are capable of maintaining the required tolerance and making corrections within the time of one RF pulse. When the accelerator is set into operation, the initial adjustment of the servo-systems must be made by direct observation of the beam. The computer programs mentioned above will be used to investigate methods for this adjustment.

Transition. If the drift tube-section of tha accelerator is carefully adjusted to minimize the errors which cause the particle bunch to grow in longitudinal phase space, the bunch leaving this section will have a phase spread of about 10° measured with respect to the 200 MHz wave. The phase spread of the bunch on entering the iris-loaded waveguide will be increased by the ratio of the frequencies of the iris-loaded section to drift-tube section. Residual errors in the iris-loaded section will offset the normal phase damping. Hence, it is believed that the initial phase spread of 40° resulting from the choice of 800 MHz for the iris-loaded section is reasonably conservative. It would seem dangerous to use 1200 MHz with the resulting initial spread of 60°.

Beam Loading. A preliminary analysis of beam loading effects in a standing wave linac has been made. For the standing wave linac, the resonant modes form a complete set of functions for the discussion of all transient and steady state phenomena. In the steady-state condition found during the body of a long pulse, the major effects will be a decrease in the accelerating field in the cavity and a shift in phase of the RF relative to some standard in the power source. Detailed examination indicates that the bunch will seek a new synchronous phase of lower value (as a result of the amplitude decrease) and will perform phase oscillations about this new value. It will be possible to increase the accelerating field with increasing beam current by means of a field amplitude servo in order to maintain a phase stable region of adequate size. The amplitude and phase of the longitudinal beam oscillation will depend on the initial conditions and on the variation of the parameters from cavity to cavity. It can be shown that a truly periodic beam pulse will excite higher modes in the cavity only if the beam frequency harmonics coincide (accidentally) with the cavity harmonics. This coincidence will have to be within the line width of the cavity harmonics, which is of the order of 1 part in 10^4 for typical cavities. The likelihood of such a coincidence is therefore small, and may be removed, should it occur, by shifting the cavity harmonics. A section of waveguide is being fabricated to study the distribution of the cavity harmonics and related matters.

However, with a beam pulse of varying magnitude (e.g. during beam build-up), the discrete beam harmonic frequencies broaden according to the way in which the beam current changes. This increases the possibility of overlap with the cavity harmonics and presumably corresponds to the serious transient effects5) which lead to beam blow up in travelling wave electron linacs. Nevertheless, any accidental condition of resonance between the beam frequency and the cavity harmonics in one cavity is not likely to be duplicated in other cavities since the geometry is different from cavity to cavity.

Transverse Focusing. Quadrupole magnets will be used to supply the necessary transverse focusing throughout the accelerator. Magnets will be mounted in every drift tube in the first one or two cavities. Succeeding cavities will have magnets in every second or third drift tube. For this iris-loaded section, doublet pairs will be mounted between cavities. Calculations show that this configuration will contain the beam with reasonable fields in the magnets. In addition, the system is sufficiently flexible so that the low energy beam (200 MeV) may be carried the entire length of the accelerator by suitably readjusting the magnets in the iris-loaded section.

Cost Minimization. In addition to the technical considerations mentioned above, a serious effort is needed to produce the most economical design which is consistent with the high performance capabilities of this accelerator. It is known that the product of the total peak RF power and the length of a linac is a constant for a given energy gain and type of structure. For a given duty cycle, there will be a particular combination of length and power which leads to the minimum cost. A longer accelerator with lower peak power is required for cost minimization when a larger duty cycle is used. For the linac with 5 percent duty cycle, this minimization procedure gives a rate of energy gain of about 1.28 MeV/m for the drift-tube section and about 1.23 MeV/m for the iris-loaded section.

References

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DISCUSSION

HUGHES : Since the duty factor question with respect to linacs has been raised a number of times, I should like to add a few comments. The macroscopic duty factor of the proposed linac is 5%. There is also a microscopic duty factor within each linac pulse due to RF structure. The beam appears in 0.07 ns bursts spaced 5 ns apart. However, for purposes of background comparisons, this factor 5/0.07 = 71 should not be divided into the macroscopic duty factor because the background from decaying particles (e.g. π-μ-e) is spread out by decay lifetimes and does not show the RF structure. For some experiments the RF structure is even an advantage because it allows time-of-flight analysis with very short time resolution.

SMITH : Is the 800 Mc/s for the travelling wave part of the accelerator locked in phase to the 200 Mc/s of the cavity section?

WHEELER : Yes, it must be.

LANGEVIN : What is the estimated cost of this accelerator?

WHEELER : For the purpose of comparison the accelerator proper, not including the experiment area, or the buildings, costs $ 16,000,000. This is without the use of the Harwell-type of structure. It must be pointed out that any improvements that are made in structure alone would lower the cost of this device.