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RF STRUCTURE OF PROTON LINAC BEAMS*

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Longitudinal Structure of Linac Beam

The proton beam is injected into a 200 Mc/sec linac at 750 keV, after suitable bunching (perhaps by one or more rf cavities) to ensure a high capture efficiency. With the parameters appropriate to the combined function linac, damping is expected to lead in the linear approximation to a phase spread of $\pm 5^{\circ}$ at 200 MeV. Allowing for nonlinearities (on the basis of computer runs) and for voltage and phase errors in the drift tube sections, it is conservatively expected that the bunch will have a phase spread of $\pm$ 7 1/2 $^{\circ}$ at 200 MeV.

The transition from 200 to 800 Mc/sec at 200 MeV implies that the phase extension of the beam is now $\pm$ 30°. Some modest adjustments of the phases and amplitudes of the early 800 Mc/sec iris tanks can be expected in order to match the longitudinal structure of the beam better, but in any event it appears that all the beam will be captured and accelerated. Allowing for the expected damping and some antidamping (~40%) due to phase and voltage errors, the beam is expected

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to arrive at the end of the linac with the following characteristics, in the absence of any modifications:

Energy	1 GeV
Energy spread	± 3.5 MeV
Phase spread	$\pm 15^{\circ}$ (= 0.1×10^{-9} sec)
Width of phase stable region	$\pm 40^{\circ}$
Energy spread of stable region	± 7 MeV
Phase oscillation wavelength at 1 GeV	~ 130 meters
Emittance (estimated for 50 mA)	~ $3\pi \times 10^{-4}$ cm-radians
Separation of rf bunches (only every fourth 800 Mc bucket contains beam)	125 cm (= 5×10^{-9} sec)

Injection into the AGS

The requirement for injection into the AGS has been discussed by many people.(1) A simple calculation of the space-charge limit for a beam with the 200 Mc/sec rf structure washed out leads to a limit of 11×10^{13} protons/pulse at 1 GeV. This includes the effect of the different image planes for magnetic and electric field lines as pointed out by L. J. Laslett.(2) In order to inject this many particles with a beam of 50 mA and the above emittance, it is necessary to inject ~100 turns. The transverse phase space allows room for 40 turns and the vertical phase space will increase this limit by a factor of ~20. However, multiturn injection is presently in its infancy and so it is dangerous to estimate how many turns can actually be injected and captured. Nevertheless, it appears that a goal of 1 or 2 x 10^{13} protons/pulse is sufficiently conservative.

Several cautions are advisable. The dominant factor in limiting the total beam is assumed to be the transverse space-charge forces, and such effects as longitudinal space-charge forces and the growth of coherent oscillations are not believed to be important. A first attempt to include the AGS character of the focussing forces and the width of the stop bands has been made by Lloyd Smith.(3) This work indicates that the simple calculation is not accurate, but the changes are in the direction of an increased space-charge limit. Further work clearly remains.

The tightly bunched rf beam will, of course, have space-charge forces far above the limits assumed, but the rf structure will quickly disappear as the beam circulates in the AGS. In fact the rf structure should wash out in the order of a few turns. The incoherent transverse oscillation frequency will therefore quickly pass through several resonances. Since the growth times at resonance are of the order of many tens of revolutions, it is expected that this effect will not change the space-charge limit. But this effect should certainly be studied with care.

Assuming that the rf cavities in the AGS remain essentially unchanged, the width of the rf buckets in the AGS is ~± 5 MeV. If the voltage gain per turn can be increased by a factor of 2 in view of the reduced frequency swing, the width of the buckets will be ~± 7 MeV. It appears that the linac beam will have a sufficiently narrow energy spread to be captured in the AGS.

In summary, a beam of 1 to 2 x 10^{13} protons/pulse with the characteristics given in Section I can probably be accepted. The tight rf bunching will probably cause no difficulties, but the energy spread should not be much larger than about ± 3.5 MeV.

Meson Factory Use

The beam requirements for the 1-GeV experimental area are determined by the limitations in the beam transport system and by the requirements (often conflicting) of the different experiments which will be performed.

The two factors which control the cost and complexity of the beam transport system are the beam emittance and the energy spread. It appears undesirable to allow any increase in the energy spread; in fact a reduction would be useful if it could be accomplished easily.

The energy spread of the beam is far smaller than that which would be sufficient to perform all presently contemplated experiments and is therefore of no concern. The tight rf structure (0.1 nsec) is desirable for time-of-flight experiments, inconsequential for track devices (bubble chambers, spark chambers, etc.) and for low counting rate experiments, but undesirable for experiments with resolving times less than 5 nsec. A discussion of these matters is given by Edge, Hughes, and Sandweiss.(4) What follows in the next section is an estimate of the feasibility of removing the rf microstructure. Any such system must, however, allow for the retention of this microstructure when desired.

Debunching of rf Microstructure

Those devices which depend on using the energy spread to debunch by drifting will require drift distances of the order of 2 to 3 km. Moreover, if the structure is to be retained, rf cavities will be needed as well. Such a system seems out of the question.

The $\pm 15^{\circ}$ phase spread can easily be arranged to be $\sim\pm 40^{\circ}$, e.g., to fill the bucket, by adding some noise to the tank phase and voltage controls. However, this will lead to an energy spread of $\sim\pm$ 7 MeV, making the requirements of the beam transport system much more severe. It also appears possible to run the end sections of the linac at the unstable phase $\varphi_u = -\varphi_s$, thus "pouring" the beam out of the bucket. However, in order to obtain sizeable phase debunching, energy spreads of several percent will have to be tolerated. This, therefore, is not attractive.

A separate debunching section at the end of the accelerator may be operated at 200 Mc/sec and at $\varphi_s = -90^{\circ}$ to fill a major fraction of the space between beam packets. Such a section would have a wavelength for phase oscillations of the order of 130 meters (field gradient up by a factor of ~2) and would have to be ~30 meters (one-quarter wavelength) long. The technical problems connected with a 200 Mc/sec 30-meter section (presumably of the drift tube variety) are considerable, but such a solution seems possible, although expensive.

Use of the "Teng scheme"(5) of phase debunching by running at the unstable phase and then at the stable phase for the final 1/8 of a phase oscillation seems limited to 800 Mc/sec in the present application unless one builds the final sections of the accelerator at 200 Mc/sec. Its use at 800 Mc/sec, however, limits the phase expansion to at most a factor of 2 or 3. Although an accompanying decrease in the energy spread is expected on a linear theory, inherent non-linearities will probably lead to no energy spread reduction at the very best.(6) Nevertheless, the Teng scheme requires few alterations of the accelerator and the possibility of its use should be incorporated in the design. But one should bear in mind that even with complete phase debunching with this scheme ($\pm 40^{\circ}$ at 800 Mc/sec), the rf pulses will still be only ~0.3 nsec wide.

It is of course possible to use compromise measures, such as sections at $\varphi_s = -60^{\circ}$, sections at 200 Mc/sec, low field sections, some drift. In general, the extent of success will vary as the cost and complexity.

A frequently mentioned device for obtaining debunching is the storage ring. Such a solution seems unattractive in the present case, since slow extraction schemes are limited to at best of the order of 50% efficiency. Since the major justification for the linac is its high average current, the residual radioactivity in the storage ring will be intolerable. Compromise measures of this type, such as a ring magnet for just a few turns, have also been suggested.

Other schemes using transverse deflection of the beam are also possible. Teng and others have considered a scheme in which energy spread is converted by magnets into transverse spread. An alternative scheme which does not depend on the energy and phase spread has been suggested.(4) It involves converting the transverse phase space into large angle oscillations and making use of the factor (cos θ) to cause longitudinal debunching. Such schemes look feasible at first glance and are being explored further.

MILLS: Why is it true that the growth rate corresponds to several hundred turns?

COURANT: We know that we can make the synchrotron pretty nearly periodic. The growth rate of such betatron oscillations depends on the harmonic order of the gradient which turns out to be very small. We know that at high fields (at 20 to 30 GeV) we can pass through a single one of these resonances at a fairly low rate, with only moderate loss of beam. We then find that the essential width of the 17^{th} resonance ($\nu = 8.5$) is something of the order of $\delta\nu = 10^{-4}$. At 1 GeV we expect the fields to be very nearly as good as at 20 GeV, so its stopband is very narrow and the growth rate is the same.

TENG: How about the stopband at integral resonances?

COURANT: Well, as for blowup the effect is mathematically the same, except that as far as coherence of the beam is concerned the equilibrium orbit would be displaced and that would be more serious. However, that would arise from the non-cancellation of image forces. If it were not for the image forces, the self forces due to space charge would act only on the exponential blow-up and not on the distortion of equilibrium orbits.

References

(1) See, for example, E. D. Courant, BNL Internal Report AADD EDC-52.

(2) Proceedings of the 1963 BNL Summer Study, to be published.

(3) LRL Internal Report LS-7.

(4) R. D. Edge, V. W. Hughes, and J. Sandweiss, Bull. Am. Phys. Soc. (No. 2) 9, 45 (1964).

(5) L. C. Teng, BNL Internal Report IA LCT-3.

(6) See, for example, J. Parain, CERN Internal Report AR/Int. SG/62-9.