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PLANS FOR A TWO STAGE 450 MEV CASCADE MICROTRON

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Summary

We report some alternative plans for obtaining continuous electron beams with energies of about 450 MeV by using two microtrons in series. The first stage could be the accelerator we are now operating, which is a six transversal Microtron Using a Superconducting Linac, MUSL-2. The second stage would include another linac which can sustain an r.f. field continuously and a higher energy recirculation system. The recirculation that is best understood and seems to have the least distortion is the conventional microtron with a pair of 180° bending magnets such as are used in MUSL-2. The alternative recirculation system uses four 90° bending magnets, and could be extended to higher energy more easily.

Our Present Accelerator, MUSL-2

Our previous reports[1,2] have described MUSL-2 and its performance. With its 2 MeV Van de Graaff injector the linac in MUSL-2 has routinely been able to provide single transversal beams with energies above 14 MeV, and current up to 20 microamperes. The performance of the superconducting linac now in MUSL-2 has been gratifyingly stable, despite long use. The unloaded Q has remained near 3×10^9 when operated near 2° K, and the energy gradient continues to exceed 2 MeV/meter even after it has been operated as an accelerator (i.e., with r.f. power applied) for more than 15,000 hours.

The main shortcoming of this linac (linac A) which was originally fabricated and later reconditioned for use at Illinois by the group at the High Energy Physics Laboratory (HEPL) at Stanford, is that it has parasitic destructive electromagnetic modes excited by a recirculating electron beam which had not been recognized by the linac designers. The main modes which limited the recirculating current at Illinois were soon identified as being near the frequency of 2.3 GHz: these had not been suppressed adequately in the original HEPL linac design. Because of these unsuspected 2.3 GHz modes that limited recirculating beam current, the six transversal electron beam through MUSL-2 (with linac A) was limited to a bit less than one microampere rather than the Illinois goal of ten microamperes. The adverse effects of these 2.3 GHz modes were reported to be correctable by adding some loading probes in the superconducting linacs produced and used at HEPL.

There was a second superconducting linac, that had not performed as well as other HEPL linacs, which was reprocessed for use at Illinois. This linac (which we call linac B) differed enough from the linacs in use at HEPL to require a different design for probes that would reduce considerably the adverse effects of the modes near 2.3 GHz that were limiting, severely, the current that could be recirculated through linac A. The necessary loading probes were designed, fabricated, and installed in linac B in a cooperative effort between HEPL and Illinois.

Linac B was found to be defective, but it was used briefly in MUSL-2 to make additional tests about beam blowup. The maximum radiofrequency fields that linac B could sustain continuously corresponded to a total energy gain of only 6 MeV (i.e., about 1 MeV/meter). Tests indicated that there was excessive heating in the cell at one end of the linac. After the recirculation measurements with linac B in MUSL-2 had been completed, the inside of the linac was examined visually. A dark spot about 2 cm in diameter, surrounded by a halo, was found at the bottom of the end cell, suggesting that a small piece of material had fallen into that cell and had been vaporized by the radiofrequency fields.

Linac B was installed temporarily in MUSL-2 to verify the effectiveness of the loading probes and to determine which other blowup modes might limit the current. We were unable to find any evidence of the 2.3 GHz blowup modes indicating that these modes were adequately loaded. We were able to observe a number of the expected blowup modes in the frequency range from 1.6 to 1.8 GHz. Despite the low energy and the somewhat erratic operation of linac B, we also obtained a six transversal beam. The current was limited to about 3 microamperes by blowup in modes near 1.79 GHz; higher currents would be expected with a properly operating linac of the same design.

Second Microtron Stage with 180° Magnets

A two stage microtron with 180° magnets is shown schematically near the left edge of figure 1. (This figure is reproduced from our September, 1980 proposal to the National Science Foundation which included preliminary descriptions of several accelerators that could produce 450 MeV continuous electron beams. The beam energy, the physical arrangements, and many other details will probably change before we make a definite plan for a higher energy accelerator at Illinois.) Figure 1 shows an arrangement in which the second microtron stage might be built in a new accelerator vault; this would have the advantage of allowing a continuation of the nuclear physics research now being performed with beams from MUSL-2. Figure 1 incidentally indicates the size of our laboratory and shows three of the five experimental areas that are now used in the MUSL-2 research program.

The size and cost of 180° end magnets for the second stage will be determined mainly by the final energy, E_f; the end magnet must be large enough to bend an electron of energy, E_f, through 180° with a uniform magnetic field. If E_f = 450 MeV, and the value of B is limited to about 1.5 tesla (as might be reasonable for a conventional iron magnet) the

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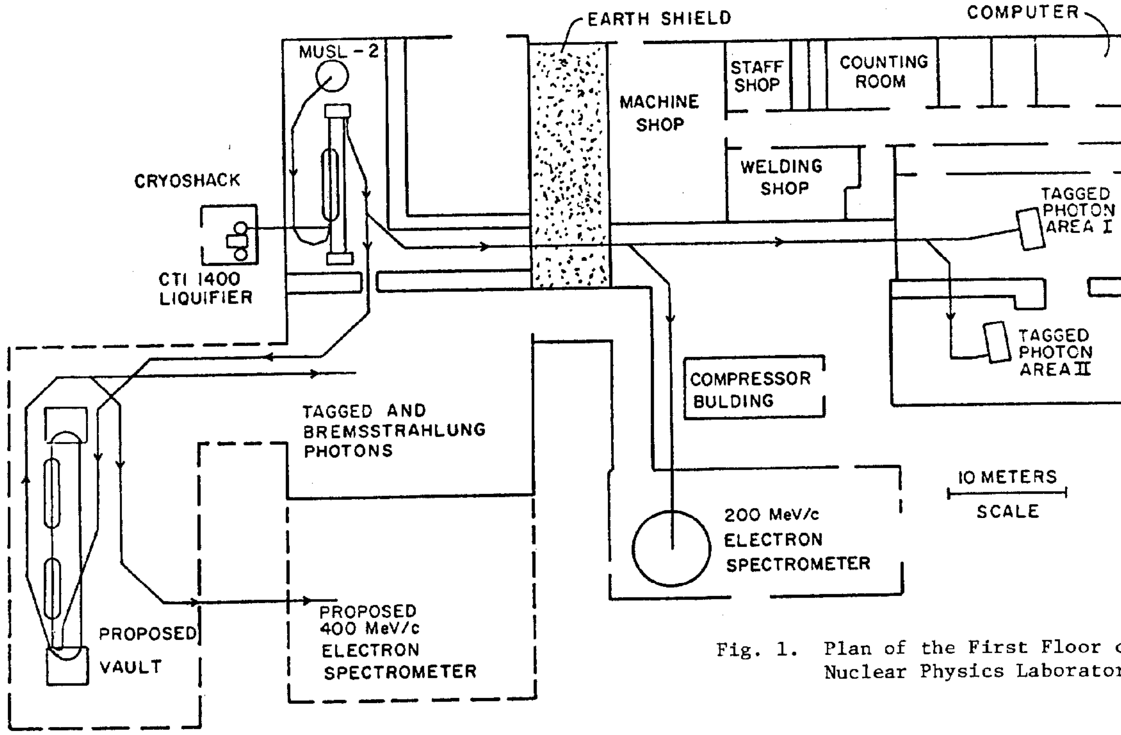

Fig. 1. Plan of the First Floor of the Nuclear Physics Laboratory.

width, W, of the magnet is approximately 2 meters. In general, the energy gain required per linac traversal in the second microtron stage, ΔE_2, depends on a compromise between a few simple factors. For any given radiofrequency there is a minimum orbit spacing, Δs; this spacing decreases in inverse proportion to the frequency. The required energy gain per traversal is $\Delta E_2 = (\Delta s/W)\ E_f$. Because of the cost of producing and operating the linac that provides the energy gain, ΔE_2, economic arguments favor reducing ΔE_2. On the other hand, it might be difficult to operate an accelerator if the return path spacing, Δs, were too small. Non-uniformities in the magnetic field of the end magnets might require some auxiliarly steering of recirculating beams, and such steering would become excessively complicated if Δs were too small.

The choice of the energy gain per traversal in the second microtron stage of an accelerator operating at the frequency used in MUSL-2, 1.3 GHz, can be made simply. For this relatively low frequency, the minimum orbit spacing compatible with 180° recirculation is large enough to be manageable practically. The basic requirement for the recirculation of relativistic electrons is that the incremental path length of electrons with energy $E_k + \Delta E_2$ compared with the path of electrons with energy, E_k, be an integral number of radiofrequency wavelengths, λ. For a recirculation system with 180° magnets, the incremental paths is $2\pi\Delta R$, where ΔR is the change in radius corresponding to the energy increase, ΔE_2. Therefore, $2\pi\Delta R = \nu\lambda$, where ν is an integer. The orbit spacing, Δs, for the 180° geometry is $\Delta s = 2\Delta R$. For a frequency f = 1.300 GHz (λ = 23.06 cm), Δs is restricted to the values 7.35 cm, 14.7 cm, 22.0 cm, etc. Because orbit spacings of 7.35 cm can be managed, it is reasonable to use an energy gain, ΔE_2, near (7.35/200) 450 MeV. For numerical simplicity, consider ΔE_2 = (1/30) 450 MeV = 15 MeV. This implies a magnetic field, B = 1.367 tesla, and 180° end magnets whose width is slightly larger than 30 x 7.35 cm $\cong$ 2.2 meters.

Second order effects which reduce beam quality suggest that the ratio of final energy to injected energy not exceed 10. This could be achieved by injecting a 60 MeV beam which would traverse the linac in the second stage 26 additional times to reach 450 MeV. Injection at 75 MeV would require 25 traversals through the second linac.

Second Microtron Stage with 90° Magnets

A recirculation system using 90° uniform bending magnets[3,4] becomes an attractive alternative to the 180° magnet system when the required final beam energy increase sufficiently. Fig. 2 shows one version of this 90° recirculation system in which the energy increase, ΔE_2, occurs on only one of the two return paths that are common to orbits of electrons with different energies. If one imagines the pair of end magnets at the top of Fig. 2 being moved together until their tops touch, it is obvious that the pair of 90° magnets supply a magnetic field over a much smaller area than would a 180° magnet large enough to contain the largest required semi-circular orbit; the ratio of the required areas is $(\pi-2)/\pi = 0.36$. This advantage of 90° recirculation system can be rephrased in other terms: the weight of the 90° magnets that could accommodate a beam energy of 900 MeV would be only about the same as that of the 180° magnets needed for 450 MeV.

The second stage microtron in Fig. 2 shows to scale a system that could provide 30 traversals of a beam through a linac operating at a frequency of 1.3 GHz. The total path difference between complete successive orbits, $(2\pi-4)\ \Delta R$, must be an integral number of wavelengths: $(2\pi-4)\ \Delta R = \nu\lambda$. For a fixed frequency, the ratio of the minimum ΔR for the 90° system to that for the 180° system is $[\pi/(\pi-2)] = 2.75$. For the 1.3 GHz frequency used in MUSL-2, the minimum ΔR for the 90° system shown in Fig. 2 is 10.1 cm; for this system the spacing of the parallel orbits, Δs, between the 90° magnets is $\Delta s = \Delta R$. If the second stage microtron with 90° magnets shown in Fig. 2 were used with an energy gain, ΔE_2, of

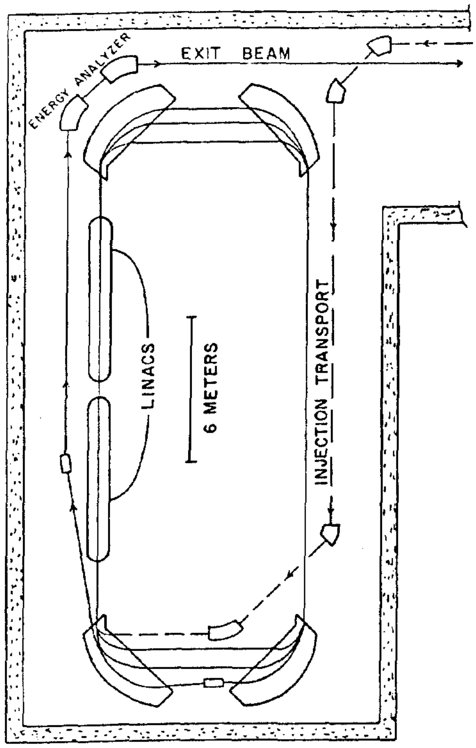

Fig. 2. Second Microtron Stage with 90° Magnets

15 MeV, the required magnetic field would be only 0.495 tesla (i.e., the magnetic field would be lower than that for the 180° magnets described in the previous section by the factor 2.75). This low value of the magnetic field would make it easy to increase the final energy of the electron beam that could be obtained from the second microtron stage shown in Fig. 2 if the energy gain per traversal, ΔE_2, could be increased.

The major difficulty associated with the 90° magnet recirculation system is the defocussing that occurs when electron beams cross a magnetic field edge at a 45° angle. This problem was considered by Kaiser[3] and has been pursued by groups at both Argonne[4,5] and Mainz. It now seems likely that a satisfactory beam quality can be maintained by a combination of improved design of the magnetic fields at the edges where the beam enters or leaves the 90° magnet and appropriate focussing elements on the orbits between the 90° magnets.

Beam blowup

If the second stage microtron is similar to the one in MUSL-2 one can make reliable estimates of the starting current for beam blowup by extrapolating from the experience with MUSL-2, using the fact that the starting current increases directly with the energy of the incident beam and about inversely with the number of passes. As mentioned earlier, an improved linac with increased loading is expected to increase the 6 pass current from MUSL-2 to at least 10 microamperes. A similarly loaded linac in the second stage could be expected to handle currents larger by the ratio of the average first pass energy to the number of passes through the linacs. Since the average first pass energy in the second stage will be 60 MeV or more as compared to about 6 MeV in MUSL-2 and the number of passes 24 as compared to 6. This ratio $(60/24)\cdot(6/6)$ is 2.5. The maximum current available from the two stage system, therefore, will be limited by the MUSL-2 injector rather than the second stage microtron. If the 90° recirculation system is used it will be important to have transverse optics which does not increase the amplification of the blowup modes above that in the 180° system. Preliminary calculations using simple optical models indicate that the 90° system can be optimized to be as good as the 180° system in this respect.

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