2.7
11/6/79
240 NT/LS

MASTER

STUDY OF A NATIONAL 2-GeV
CONTINUOUS BEAM
ELECTRON ACCELERATOR

ARGONNE REPROD COPY
DO NOT DESTROY

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) among the U. S. Department of Energy, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona	The University of Kansas	The Ohio State University
Carnegie-Mellon University	Kansas State University	Ohio University
Case Western Reserve University	Loyola University of Chicago	The Pennsylvania State University
The University of Chicago	Marquette University	Purdue University
University of Cincinnati	The University of Michigan	Saint Louis University
Illinois Institute of Technology	Michigan State University	Southern Illinois University
University of Illinois	University of Minnesota	The University of Texas at Austin
Indiana University	University of Missouri	Washington University
The University of Iowa	Northwestern University	Wayne State University
Iowa State University	University of Notre Dame	The University of Wisconsin-Madison

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. Mention of commercial products, their manufacturers, or their suppliers in this publication does not imply or connote approval or disapproval of the product by Argonne National Laboratory or the United States Government.

ANL-PHY-79-2
October 1979

ARGONNE NATIONAL LABORATORY*
9700 South Cass Avenue
Argonne, Illinois 60439

STUDY OF A NATIONAL 2 GeV CONTINUOUS
BEAM ELECTRON ACCELERATOR

Study-Group Members

Y. Cho
R. J. Holt
H. E. Jackson (chairman)
T. K. Khoe
G. S. Mavrogenes

The authors have a limited number of
copies for general distribution.
Anyone who desires a copy should
contact them directly.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

* Work performed under the auspices of the U. S. Department of Energy.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	ii
I. INTRODUCTION	1
II. ELECTROMAGNETIC PROBES AT MEDIUM ENERGIES - TRENDS AND OPPORTUNITIES	3
III. DESIGN OBJECTIVES	7
IV. POSSIBLE ACCELERATOR CONCEPTS	10
A. Microtrons	
B. Superconducting Recyclotron	
C. Linac-Stretcher Rings	
V. THE MICROTRON APPROACH - A CONCEPTUAL DESIGN	15
A. Design Criteria	
B. Conceptual Design	
VI. LINAC - STRETCHER RING - A CONCEPTUAL DESIGN	30
VII. PRELIMINARY COST ESTIMATES	43
VIII. COMPARISON OF CONCEPTUAL DESIGNS	46
IX. SUMMARY AND RECOMMENDATIONS	50
ACKNOWLEDGMENTS	53
REFERENCES	54

ABSTRACT

Current trends in research in medium energy physics with electromagnetic probes are reviewed briefly and design objectives are proposed for a national continuous beam 2 GeV electron accelerator. Various types of accelerator systems are discussed and exploratory designs developed for two concepts, the linac-stretcher ring and a modified microtron system. Preliminary cost estimates indicate that a linac-ring system which meets all the design objectives and uses state-of-the-art technology can be built for approximately \$25 million. However, the "double-sided" microtron shows promise for development into a substantially less expensive facility. Its technical feasibility remains to be established. Proposals are presented for short term research projects directed at specific areas of uncertainty in each of the conceptual designs.

I. INTRODUCTION

A strong consensus has developed recently among the nuclear physics community that research with electromagnetic probes in the 1-2 GeV range generated by a high current 100% duty factor electron accelerator represents an exciting frontier. Traditionally small duty factor and relatively poor beam quality characteristic of available electron accelerators have been a continuing limitation on research capability. However, recent advances in accelerator technology present the possibility of realizing an accelerator design of acceptable capital and operating cost which could furnish the long sought c.w. (100% duty factor) electron beams with high currents and with good properties. It is probable that new developments will occur in this area with increasing rapidity and that construction of a facility with the requisite properties will receive the broad support of the physics community.

Because of the rapidly growing interest in such a high-current c.w. electron accelerator, a design group of 5 physicists and accelerator specialists has been formed at ANL to review recent developments in accelerator technology, particularly that of high-energy electron-position storage ring systems, and to develop conceptual designs for technical evaluation and subsequent cost analysis. The design objective is a multiple beam facility in the 1-2 GeV range with a capital cost of \$30-35M.

Two systems, a microtron design and a linac-stretcher ring, have been studied in considerable detail. A variant of the microtron concept, the bicyclotron has also been examined. One of the conclusions of the study is that the technology exists for construction of a linac-stretcher ring system which could provide a 100 μ amp beam between 1 and 2 GeV, such a system would have the advantage that it can readily be scaled upward in energy. However, the capital and operating costs are projected to be higher than those of a microtron. Although the scientific feasibility of microtron operation in this energy range remains to be established, the potential cost savings warrant continued research and development on microtron type designs. Specific areas requiring additional conceptual or engineering studies are identified, and proposals for continued effort

are presented.

II. ELECTROMAGNETIC PROBES AT MEDIUM ENERGIES — TRENDS AND OPPORTUNITIES

The electron and photon have proved to be two of the most valuable projectiles available to the nuclear physicist for probing the structure of nuclei and the nature of nuclear forces. The basic electromagnetic interactions can be calculated precisely, and the interactions are sufficiently weak that the probe does not distort the structure of the target nuclei under study. Although the properties of available electron and photon beams have not always met all the expectations of experimental physicists, progress in the area of electron accelerators has in general kept pace with that in other areas, and the study of electromagnetic interactions of electron and photon-beams has proved to be a prolific source of information of great detail and precision on the structure of nuclei.

Beginning with the pioneering work of Robert Hofstadter¹ in the 1950's, most of our information on nuclear size and surface thickness has come from measurements of electron scattering. With recent refinement, measurements² of elastic scattering over a large-range of momentum transfer, have provided values of the charge density in ^{40}Ca and ^{208}Pb with a spacial resolution of 0.5 fermi and a precision in the density of 1%. Such measurements are basic to our understanding of nuclear structure. The results provide stringent tests of Hartree-Fock calculations of nuclear density distributions and convincing indications of the presence of meson-exchange currents.

Our understanding of collective modes of excitation of nuclei, e.g. the giant multipole resonances, has in large measure come from studies of photon absorption and electron scattering. The giant electric dipole resonance is one of the most basic features of nuclear matter. Measurements of photon absorption and scattering cross sections have provided us with a detailed data base describing the properties of the giant dipole state and their variation throughout the periodic table. Almost all our information on magnetic dipole resonances and their systematics have come from electromagnetic probes. Much of the quantitative information on higher order multipole excitations has come from measurements of inelastic

electron scattering with high resolution. Electron scattering is the most promising probe for isolating electric monopole transition strength which is of fundamental importance because it provides a direct measure of the compressibility of nuclear matter.

In inelastic electron scattering to discrete final states, a transition density is measured which is analogous to the charge or magnetization density for the ground state. This density, in effect, probes directly the shape of the wave function which describes the excited nuclear state. It can provide a stringent test of theoretical descriptions of the excited states, whether they be collective in character or simple shell-model configurations. The recent advances in high energy spectrometer design have been dramatic³ and the experimenter can now make measurements of electron scattering with sufficient resolution to study structure in even the heaviest deformed nuclei such as ²³⁸U. Currently, such electron-scattering spectroscopy is one of the most active and successful areas of photonuclear physics.

The shell model and its concepts play a vital role in our current understanding of nuclear structure. However, until now the properties of shell model levels have been experimentally accessible only for those levels near the Fermi surface. Comparatively little experimental data is available for deeply bound states. Quasi-elastic electron-scattering at high momentum transfer measures directly the single particle structure of deeply-bound levels. Inclusive measurements of quasi-elastic electron scattering have provided our best estimates of the fermi-momentum and the average interaction energy describing particle-hole excitations. Coincidence electron scattering experiments in which the recoil proton is observed,⁴ (e,e'p) have given direct measurements of the spectral function which describes the momentum distribution and separation energies for deeply bound shell model levels in nuclei.

And more recently, two landmark experiments have provided the most dramatic evidence to date for the presence of subnuclear constituents in nuclei. In the first, the electrodisintegration of the deuteron was studied under kinematic conditions corresponding to high momentum transfer

but excitation energies near the electrodisintegration threshold.⁵ The cross sections measured are as much as a factor of ten larger than predictions of the simplest impulse approximation. The observed enhancement is the strongest evidence for meson exchange currents in nuclei. In the second experiment,⁹ elastic electron scattering on light nuclei such as the ^2H , ^3He and ^4He were studied at very high energies of 0.8 - 2.5 GeV. Anomalies in the behavior of the form factors at very high momentum transfer can be attributed to the properties of the underlying quark-constituents of the nuclei. The evidence suggests that asymptotic form factors for these light nuclei obey scaling laws consistent with their predicted quark structure.

The implications of these research trends for future major facilities and the characteristics of future accelerators which will guarantee the continued vitality of the field have been widely discussed.⁷ There is a clear need for measurements of nuclear form factors and transition densities with much better spacial resolution. The much higher momentum transfer necessary for such measurements can be accomplished by measurements through large scattering angles. However, at moderate incident electron energies, typical counting rates are very low. The scattering cross section for a given momentum transfer goes at the electron energy squared. A momentum transfer 6 fm^{-1} corresponds to scattering 1.3 GeV through 60° . Increasing the incident energy from 400 MeV to 1.3 GeV increases the counting rate by an order of magnitude.

Coincidence measurements, because of their selectivity and complete characterization of the reaction detected, will become a major component of future experimental programs. Simple arguments based on the systematics of quasifree-proton scattering ($e, e'p$) indicate that in such experiments data acquisition rates will increase by an order of magnitude when the incident electron energy is increased from 0.9 to 1.8 GeV.⁸ The study of mesonic effects in nuclei through photo and electroproduction of pions and kaons will undoubtedly become a major thrust of research programs, again necessitating beams in the 0.5 to 2.0 GeV. Poor duty factor has always been a major limitation on photonuclear experiments. Even now, high energy beams are available only at a duty factor of <5%. Under such

conditions, coincidence measurements are limited by accidental rates, and can be made only with the greatest efforts, and by use of prodigious amounts of beam time. The availability of full duty factor beams in the energy range of 0.5 - 2.0 GeV make this class of measurement a realistic option which can be used on an extensive scale.

The conclusion of the nuclear-physics community as reported by the Livingston panel⁹ is that "An electron accelerator with peak energy of 1 to 2 GeV with 100% duty factor, and with beam currents on the order of 100 μ A, promises to open a completely new and exciting range of electron nuclear research which would address many of the most interesting questions at the frontiers of nuclear physics."

III. DESIGN OBJECTIVES

In order to assess possible accelerator concepts for a 1-2 GeV facility, we have reviewed recent discussions of future needs. The design objectives listed in Table 1 result from the consideration of prospective experiments which place the most stringent requirements on the pertinent beam properties. They are design goals and may or may not be simultaneously achievable, but should serve as the standards against which to measure the various alternatives. The criteria leading to their choice are given below.

Energy — Based on the considerations of the Livingston panel,⁹ a momentum transfer in electron scattering experiments of ~ 400 MeV/c is typical of the proposed program. Because cross sections go as the square of the incident energy, high electron energy is desired in the range of $\sim 0.5 - 2.0$ GeV. We have chosen a maximum electron beam energy of 2 GeV. However, there is considerable sentiment toward even higher energies if the cost and design compromises are not prohibitive.

Energy Variability — Suitable variation over the range 0.5–2 GeV is essential for electron scattering studies. In addition a major component of the research program will probably involve the use of a "tagged photon" monochromator. Such an instrument can be realized easily with a capability of magnetically analyzing electrons in the range $\sim 10 - 150$ MeV corresponding to photon energies of $\sim E_e$ to $E_e - 150$ MeV. Variability in 100 MeV steps above 500 MeV would guarantee that the full photon energy range can be scanned.

Average Current, I_{av} — No clear upper limit of current can be given since one can always take advantage of higher intensities in experimental designs which are more selective or in searches for rare processes. The beam current of 100 μ A was proposed by the Livingston panel as adequate for a broad class of low cross section single-arm spectrometer experiments and for the requirements of many proposed coincidence measurements.

Duty Factor — "In pulsed machines, the accidental to true signal

Table 1. Accelerator System Design Objectives

E_{max}	$\geq 2 \text{ GeV}$
Variability	in steps of $\gtrsim 100 \text{ MeV}$ from $\sim 500 \text{ MeV}$
I_{av} (per beam)	$\geq 100 \mu\text{A}$
Number of beams	> 1
Duty factor	70 - 100%
ΔE	$\geq \pm 250 \text{ keV}^1$
Emittance ²	$0.2 \pi \text{ mmr}$
E reproducibility	$\sim 100 \text{ keV}$
E stability	$\sim 100 \text{ keV}$
I_{av} stability	1 - 5%

¹This objective can be met by secondary beam analysis in most cases since experiments requiring this precision do not use the full beam current.

²For beam energies above 500 MeV.

ratio, dead-time losses and pulse pile up effects are all proportional to the peak current in the macropulse. For a given peak current, the average current and hence the gain in overall count rate is therefore proportional to the macroscopic duty factor, hence the highest possible duty factor is required. The microscopic duty factor is unimportant provided the frequency f obeys $f^{-1} < 2\tau$ where 2τ is the coincidence resolving time. Since 2τ is typically 10^{-8} sec, we require $f > 100 \text{ MHz}$." - CRNL-550.¹⁰

Energy Spread - The energy spread of the beam will most likely be limited by the requirements of a tagged photon facility rather than electron spectrometer needs. The latter will be of "dispersed beam" design requiring beam resolution of only $\Delta p/p \approx 0.5\%$. The photon monochromator will measure recoil e^- 's in the range 10 - 100 MeV with a resolution of $\sim 10^{-3}$, i.e. ~ 100 keV. Therefore the limitation of photon energy resolution will be the energy spread of the incident beam. A reasonable minimal limiting resolution for observing nuclear structure effects in (γ, π) or (γ, nucl) reactions is 500 keV, giving $\Delta E/E \approx .025\%$ at 2 GeV.

Emittance - Beam emittance will be limited by the requirements of "dispersed beam" high resolution spectrometers which are capable of measurements with $\Delta p/p < 10^{-4}$. These instruments require only modest energy spread in the incident beam, $\sim 0.5\%$ but they do require excellent beam emittance. For a spectrometer with a maximum field of 16 G and $\rho = 4$ meters at 2 GeV, state-of-the-art resolution is $\Delta p/p \sim 10^{-4}$ leading to a restriction on spot size of 0.4 mm. In typical design (see S. Kowalski et al.¹¹) 2nd order aberrations lead to a restriction in beam divergencies consistent with 10^{-4} resolution of $\theta_{\text{div}} \approx 0.5$ mr. We estimate the required emittance to be 0.2π mmmr.

Energy Stability and Reproducibility - These limits are imposed on the beam to be consistent with the energy resolution goal of 500 keV.

Current Stability - It is important in a machine of this type to avoid sizable variations in the beam current which would have the effect of making the effective duty factor appreciably less than the design objective.

IV. POSSIBLE ACCELERATOR CONCEPTS

The primary constraint on an accelerator design which meets the design objectives of Section III is low capital and operating cost. In the past, high duty factor electron accelerators have not been feasible because of their prohibitive power costs. High energy electron beams are normally achieved by accelerating electrons in intense electric fields generated in appropriate wave guides excited by means of intense pulses of micro-wave power. Economical operation is achieved by restricting the accelerating cycle to very short pulses. Operation of such systems in a continuous beam mode is not feasible. For example, consider a 1 km long 2 GeV linear accelerator using a SLAC type of wave guide structure. Assuming a reasonable shunt impedance of $ZT^2 \approx 60 \text{ M}\Omega/\text{m}$ for the r.f. wave guide, 64 megawatts of power would be required for acceleration to 2 GeV. Such operation would be prohibitively expensive. Several proposals to overcome this problem have been widely discussed.

A. Microtrons

One alternative is an outgrowth of an idea used in the classic microtron design proposed by Veksler.¹² By inserting an r.f. accelerating section in a magnetic field whose value is chosen so as to guarantee correct beam phasing, one can recirculate the electron beam through the same cavity many times. The power required for a given beam energy is reduced relative to single pass acceleration by $\frac{1}{n}$ where n is the number of passes. The evolution of the microtron concept to the most recent proposal is shown schematically in Fig. 1. In the race-track microtron, the magnetic field is split into two half circular sectors separated by sufficient drift space to allow insertion of a linac section of substantial accelerating power. In order to avoid the prohibitive costs of the mass of the return magnets required for high energy operation (e.g. 500 MeV), the double-sided microtron has been proposed.¹² This system required about 1/5 the volume of steel of the conventional microtron design. The advantage of the microtron concept is the moderate r.f. power required. Disadvantages include a possible limit on the maximum current accelerated imposed by microwave beam blowup. Because of multiple turn recirculation

Fig. 1. Evolution of Microtron Accelerator Designs

such a limit is more serious than it would otherwise have been. A second problem is the excellent beam emittance and large number of focusing elements required for beam transport through the full accelerating cycle.

B. Superconducting Recyclotrons

In a second approach, the large power dissipated in the accelerating structures is decreased by using high Q superconducting cavities. Workers hope eventually to achieve voltage gradients of ~ 6 MV/m. A 50 m structure would achieve 0.5 - 2.0 GeV operation with only 5 turns of recirculation. The recirculation is accomplished by means of a so-called "unconventional" magnet system. This concept is attractive because a guide field of discrete elements could replace the massive end magnets characteristic of the conventional microtron. The r.f. power requirements are least for this design. A major difficulty with such high Q systems is severe limit on beam current resulting from cumulative beam blowup. Experience to date indicates that the maximum current achievable is in the 100 μ A range.¹⁴ With recirculation, the external beam limit is $\sim 100/n$ μ A.

C. Linac-Stretcher Rings

The third type of accelerator draws heavily on the electron-storage ring technology developed in high energy physics. A typical system is shown schematically in Fig. 2. A conventional pulsed linac, such as the SLAC design, is used to inject up to 4 or 5 turns of electrons into a conventional stretcher ring. The r.f. power requirements are competitive with those of other alternatives. Beam extraction is accomplished by controlled translation of the circulatory beam to induce a third order resonance into one or more extraction septa. Such a system is attractive because it is based on existing technologies¹⁵ and because the systems scale linearly with energy so that expansion to higher energy present no fundamental problem. Also multiple beam extraction has been demonstrated.¹⁶ Disadvantages include higher operating costs and a beam quality significantly poorer than that of other systems. A 500-MeV stretcher ring system currently under construction at Frascati, will be the first such accelerator.¹⁷

Fig. 2. Proposed Linac-Stretcher Ring Accelerator Design

In the following sections, we describe conceptual designs for microtron and linac-stretcher ring systems. These designs have been developed to permit comparative evaluation of capital costs and to determine areas of the technology requiring additional research development.

V. THE MICROTRON APPROACH - A CONCEPTUAL DESIGN

A. Design Criteria

The basic feature of the microtron accelerator is the coherence condition which requires the path difference in the successive orbits of the beam to be an integral multiple of the wave length of the accelerating r.f. field. This condition is met by appropriate choice of r.f. accelerating voltage and strength of the magnetic field in the guide magnets. It insures that r.f. phase stability can be maintained and that the energy gain per revolution of the beam is constant. A variety of magnet configurations have been proposed for microtrons,¹⁸ and the specific coherence condition is somewhat different in each case. In order to illustrate the basic properties of each choice we derive the appropriate conditions for beam coherence and phase stability.

The coherence condition requires that the beam passes through the linac at the same synchronous phase, ϕ_s , of the r.f. field on each revolution. Therefore the rotation period of the electron must be some integral multiple of the r.f. period τ .

$$T_n = \mu_n \tau, \quad (1)$$

where T_n is the rotation period of the nth turn. The length of the orbit at the nth revolution is given by

$$L_n = 2\pi r_n + S_n, \quad (2)$$

where

$$r_n = \frac{W_n \beta_n}{eBc} \quad (3)$$

is the radius of the circular path in the bending magnets, S_n is the total length of the straight sections (excluding linac), W_n is the total energy of the electron and β_n is the corresponding velocity in units of the light velocity c . The magnetic field B of the bending magnets is assumed to be

uniform. Substituting Equations (2) and (3) in $L_n/\beta_n c$ and noting that $c\tau = \lambda$, one finds

$$\frac{2\pi W_n}{eBc} + \frac{S_n}{\beta_n} = \mu_n \lambda. \quad (4)$$

The energy gain per revolution, ΔW is constant. Thus, neglecting the synchrotron radiation losses, $W_n = W_1 + (n-1)\Delta W$ $n=1,2,\dots$ and Equation (4) becomes

$$\frac{2\pi W_1}{eBc} + \frac{2\pi(n-1)\Delta W}{eBc} + \frac{S_n}{\beta_n} = \mu_n \lambda. \quad (5)$$

Subtracting $\mu_n \lambda$ from $\mu_{n+1} \lambda$ one obtains

$$\frac{2\pi\Delta W}{eBc} + \frac{S_{n+1}}{\beta_{n+1}} - \frac{S_n}{\beta_n} = \nu \lambda \quad (6)$$

where ν is an integer.

We consider three possible designs shown in Fig. 3. In the conventional racetrack microtron shown in Fig. 3, $S_n = S_a = \text{constant}$ for all values of n and equation (6) becomes

$$\frac{2\pi\Delta W}{eBc} + S_a \left(\frac{1}{\beta_{n+1}} - \frac{1}{\beta_n} \right) = \nu \lambda \quad (7a)$$

Fig. 3b shows the so-called bicyclotron or double-sided microtron with two linacs. Here, $S_n + 4r_n = S_b = \text{constant}$ and equation (6) gives

$$\frac{2(\pi-2)\Delta W}{eBc} + S_b \left(\frac{1}{\beta_{n+1}} - \frac{1}{\beta_n} \right) = \nu \lambda \quad (7b)$$

Fig. 3.. Possible Microtron Accelerator Designs

Fig. 3c shows the configuration decided upon for one of the conceptual designs. In that case with one linac $S_n + 2r_n = S_c = \text{constant}$ one finds

$$\frac{2(\pi-1)\Delta W}{eBc} + S_c \left(\frac{1}{\beta_{n+1}} - \frac{1}{\beta_n} \right) = v\lambda \quad (7c)$$

In setting the usual microtron coherence condition in these equations 7(a,b, and c)

$$\frac{2\pi\Delta W}{eBc} = v\lambda \quad (8a)$$

or
$$\frac{2(\pi-2)\Delta W}{eBc} = v\lambda \quad (8b)$$

or
$$\frac{2(\pi-1)\Delta W}{eBc} = v\lambda \quad (8c)$$

one introduces a phase error on the nth orbit

$$\Delta\phi_n = \frac{2\pi S_i}{\lambda} \left(\frac{1}{\beta_n} - \frac{1}{\beta_{n-1}} \right) \quad i = a, b, c \quad (9)$$

As shown below for stable longitudinal motion, there is a maximum permissible phase angle relative to the synchronous phase, $(\phi_s)_{\max}$. For no beam loss $\Delta\phi_n$ must be smaller than $(\phi_s)_{\max}$.

The range of phase acceptance and the energy spread of the beam are related to the phase slip per turn, $v\lambda$, and differ for the three designs. Consider an electron that leaves the linac after the nth transit with a phase error $\delta\phi_n$ and an energy error δW_n relative to the synchronous electron. The energy gain per turn of the synchronous electron can be written in the form

$$\Delta W = e V \cos \phi_s, \quad (10)$$

where V is the linac voltage. Thus,

$$\delta W_n = \delta W_{n-1} + e V [\cos(\phi_s + \delta\phi_n) - \cos \phi_s]. \quad (11)$$

The energy error will increase the orbit length [see Eq. (3)]. In general, the increase in β_n is small enough that its effect can be neglected. From Equation 8, one finds the orbit length increment

$$\delta L_n = \frac{\delta W_n}{\Delta W} v \lambda.$$

Substitution of this expression in

$$\delta\phi_{n+1} = \delta\phi_n + \frac{\delta L_n}{\lambda} 2\pi$$

gives

$$\delta\phi_{n+1} = \delta\phi_n + \frac{\delta W_n}{\Delta W} 2\pi v \quad (12)$$

Substituting Equations (10) and (11) in Equation (12) and noting that

$$\frac{2\pi \delta W_{n-1}}{\Delta W} = \delta\phi_n - \delta\phi_{n-1},$$

one obtains the nonlinear difference equation

$$\delta\phi_{n+1} - 2\delta\phi_n + \delta\phi_{n-1} = 2\pi v \left[\frac{\cos(\phi_s + \delta\phi_n) - \cos \phi_s}{\cos \phi_s} \right]. \quad (13)$$

In general, $\delta\phi_n$ is small enough that in the power series expansion of $\cos(\phi_s + \delta\phi_n)$ all nonlinear terms in $\delta\phi_n$ can be neglected. Equation (13) reduces to

$$\delta\phi_{n+1} - 2(1 - \pi v \tan \phi_s) \delta\phi_n + \delta\phi_{n-1} = 0. \quad (14)$$

The solution of Equation (14) may be written as

$$\delta\phi_n = C_1 \rho_1^n + C_2 \rho_2^n, \quad (15)$$

where C_1 and C_2 are constants determined by initial conditions, and ρ_1 and ρ_2 are roots of the characteristic equation

$$\rho^2 - 2(1 - \pi v \tan \phi_s) \rho + 1 = 0. \quad (16)$$

From Equation (16), one sees that $\rho_1 \rho_2 = 1$ so that the motion is stable if ρ_1 and ρ_2 are complex conjugates. This is the case when

$$(1 - \pi v \tan \phi_s)^2 - 1 < 0$$

or more fully

$$0 < \tan \phi_s < \frac{2}{\pi v}. \quad (17)$$

This equation determines the overall r.f. phase acceptance for a given design. From a comparison of Equations 8 and 17 it is evident, that for a given energy gain per turn, ΔW , and magnetic field B the double-sided microtron has the largest phase acceptance.

Continuing, by writing ρ_1 , and ρ_2 in the form

$$\rho_{1,2} = e^{\pm i\theta}, \text{ with } \theta = \tan^{-1} \sqrt{\frac{1 - (1 - \pi v \tan \phi_s)^2}{1 - \pi v \tan \phi_s}}$$

and using the boundary conditions

$$\delta\phi = \delta\phi_1 \text{ and } \delta W = \delta W_1, \text{ when } n=1$$

one obtains

$$\delta\phi_n = \delta\phi_1 \frac{\sin(n-1)\theta - \sin(n-2)\theta}{\sin\theta} + \frac{2\pi\delta W_1}{\Delta W} \frac{\sin(n-1)\theta}{\sin\theta} \quad (18)$$

Neglecting the higher order terms in $\delta\phi_n$, Equations (10) and (11) give

$$\delta W_n = \delta W_{n-1} + \Delta W \tan \phi_s \delta\phi_n$$

or

$$\delta W_n = \delta W_1 + \Delta W \tan \phi_s \sum_{k=2}^n \delta\phi_k. \quad (19)$$

Substituting Equation (18) in Equation (19) one finds, after some manipulation,

$$\delta W_n = \delta\phi_1 \Delta W \tan \phi_s \frac{\sin(n-1)\theta}{\sin\theta} + \delta W_1 \left(1 + 2\pi \tan \phi_s \frac{\sin\theta + \sin(n-1)\theta - \sin\theta}{2 - \sin\theta(1 - \cos\theta)} \right) \quad (20)$$

for the energy error at the end of the nth orbit.

B. Conceptual Design

The conventional microtron has the disadvantages of smallest phase acceptance $(\phi_s)_{\max}$ for given values of ΔW , B , and λ and also is the most difficult configuration in which to achieve good transverse phase space matching with the acceptance of the linac. The double-sided microtron has the largest $(\phi_s)_{\max}$ and better transverse phase space matching but has the disadvantage that focusing, extraction and path length corrections must be done in the two short straight sections. As a compromise we have adopted the system shown in Fig. 4. In this case of four 90° bending magnets and one linac, the majority of focusing quadrupoles can be accommodated in the short straight sections. The path length corrections and extraction can be done in the long straight section. The longitudinal "acceptance" $(\phi_s)_{\max}$ is intermediate between the race-track microtron and the double-sided microtron. Pole-face windings in the two large volume bending magnets where the orbits are concentric may ease the path length corrections.

A significant problem of beam optics arises because of the

CONTINUOUS BEAM e^- ACCELERATOR, CONCEPTUAL DESIGN

Fig. 4

vertical defocusing which occurs at the entrance and exit faces of the two 45° segment magnets. For these elements the beam enters and exits at 45° to the normal to the pole face. There is equal and opposite edge focusing in the x and y directions which may be characterized by the matrix equations

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{\text{out}} = \begin{pmatrix} 1 & 0 \\ -\frac{\tan \gamma}{r_n} & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_{\text{in}},$$

$$\begin{pmatrix} y \\ y' \end{pmatrix}_{\text{out}} = \begin{pmatrix} 1 & 0 \\ +\frac{\tan \gamma}{r_n} & 1 \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}_{\text{in}},$$

where γ is the orbit angle relative to the normal of the magnet edge. In this geometry $\tan \gamma = 1$ and $r_n = W_n \beta_n / eBc$. For small values of r_n the effects are too strong to be corrected for with discrete elements. Therefore in the region traversed by low energy orbits, the pole edges will be shaped (see Fig. 5) so that γ will be very small, both for entrance and exit. The residual effects of the edge will be compensated for by a quadrupole singlet to form a very weak double focusing lens.

Focusing and phase-space matching is done on individual orbits by quadrupole triplets located in each of the straight sections. The complete magnet configuration is shown in Fig. 5. The quadrupole triplets in the long straight sections are all identical with the same field strengths. The triplets in the short straight sections increase in strength in proportion to the orbit momentum. In the complete system there are 486 quadrupoles. The maximum total power required is < 50 kW.

The properties of all of the magnet elements is given in Table II. For a beam emittance of less than $1 \pi \text{ mm-mr}$ one finds a maximum beam size less than 15 mm. The gap of the magnets at the ends of the linac (Type 1 magnets) is 25 mm, thus allowing 10 mm for vacuum chamber and orbit distortion. The gap of the magnets with pole-face windings (Type 2 magnets) is 35 mm.

Fig. 5. Complete Magnet Configuration for Conceptual Microtron Design

Table II. Properties of Magnet Elements

Type	Dimensions	Operating Characteristics	
quad. triplet 1	aperture = 3 cm	$B'1 = 0.032T$	center element
	outside dia = 7 cm	$B'1 = 0.016T$	end elements
	element sep. = 0.75 m		
quad. triplet 2	aperture - 3 cm	$B'1 = 0.98T$	center element
	outside dia - 7 cm	$B'1 = 0.49T$	end elements
	element sep - 0.75 m		
segment magnet 1	gap = 2.5 cm	$B_{max} = 1.91T$	
	radius = 4.2 m		
	wt = 1.5×10^5 kg(Fe) 1.2 x 10 ³ kg(Cu)	power = 200 kW	
segment magnet 2	gap = 3.5	$B_{max} = 1.91T$	
	radius = 4.2 m		
	wt = 9.5×10^3 kg(Fe) 6.4 x 10 ³ kg(Cu)	power = 275 kW	

From Eqs. 8 and 17 it is evident that the operating tolerances increase with the wavelength λ . The choices commonly considered are S-band, $\lambda = 12.5$ cm and L-band, $\lambda = 22.5$ cm. L-band has the advantage of more favorable operating tolerances, but the disadvantages that high power L-band klystrons are not commercially available and r.f. losses are somewhat greater for L-band compared to S-band. There are corresponding disadvantages for a choice of S-band. While high-power klystrons are readily available at 2850 MHz, the operating tolerances are more stringent for S-band operation of the microtron. Characteristic dimensions of the r.f. accelerating structures are small necessitating very careful design to insure that r.f. losses can be adequately dissipated. Consequently in Table III we have tabulated the beam conditions for the conceptual design for both L- and S-band. The energy gain per turn is 50 MeV and the synchronous phase, $\phi_s = 0.14$ radians. The RMS reproducibility of the magnetic field is assumed to be 10^{-4} and the stability to be 2×10^{-5} .

The linac in a 2 GeV single stage microtron will be long enough that the cumulative multisection type beam break-up may be the limiting factor for the total current in the linac. The choice of the number of recirculations is then a compromise between r.f. losses and beam break-up problems. A low energy linac increases the number of recirculations and consequently enhances the beam break-up problem. The starting current for the cumulative multisection type beam break-up is not known for a steady state operation. In this preliminary conceptual design, the number of recirculations is tentatively set at 40. In Table IV the basic parameters of the conceptual design are tabulated.

The properties of the microtron beam are expected to be excellent. The energy spread can be calculated from (20) if one assumes that the injection phase is stable relative to the synchronous phase ϕ_s . It is reasonable to expect this phase uncertainty to be no more than about 1° , $\delta\phi_1 \lesssim 1^\circ$ in which case the calculated energy spread at 2 GeV will be less than 200 keV. The beam emittance can be estimated by using state-of-the-art values for the emittance from a 5 MeV linac injector, $\sim 1 \pi$ mm mr. Thus emittances, $\epsilon < .1 \pi$ mm mr should be achievable at 500 MeV. A simple first order calculation of beam optics has been performed, for the horizontal

Table III. Microtron Operating Conditions

Wavelength λ	22.5 cm	12.5 cm
Mode number ν	2	3
Magnetic field	1.587 T	1.905 T
Stability limit $(\phi_s)_{\max}$	0.318 radian	0.212 radian
E reproducibility	~ 250 keV	440 keV
E stability	~ 50 keV	88 keV

Table IV. Parameters for Microtron Conceptual Design

Basic parameters		
Maximum energy (GeV)	2	
Current (μA)	300	
Energy spread, $\Delta E/E$	$\sim 10^{-4}$	
Beam emittance	$\sim .1\pi$ mm mr	
Injection energy (MeV)	5	
Max energy gain per turn (MeV)	50	
Synchronous phase ϕ_s (radian)	0.14	
Accelerating field E(MV/m)	1.4	
Number of recirculation	40	
Length long straight section (m)	~ 50	
Minimum short straight section (m)	~ 5 m	
Wavelength λ (cm)	12.5 cm	22.5 cm
Minimum mode numbers	3	2
Maximum B (Tesla)	1.905	1.587
$P_{\text{r.f.}}$ (r.f. losses)	0.75 MW	1.00 MW
ZT^2 (shunt Impedance)	75 $\text{M}\Omega/\text{m}$	55 $\text{M}\Omega/\text{m}$
R_{max} (m)	3.5	4.2
R_{min} (m)	0.0875	0.105
ΔR (m)	0.0875	0.105

motions. The phase advance per turn of the betatron oscillations is approximately 180° . The maximum and minimum values of the beta-functions are 53 m and 16 m respectively.

VI. LINAC - STRETCHER RING - A CONCEPTUAL DESIGN

The use of a pulse stretcher storage ring to convert a pulsed beam to continuous beam is an attractive option because it draws heavily on the existing technology developed in high energy physics for colliding beam experiments using storage rings and because it utilizes the short pulse linac injectors of well-established design. The linac-stretcher-ring design presented here consists of a 2 GeV SLAC type linac which injects into a storage ring consisting of a lattice of computer-controlled-separated-function elements. However, the system differs from those discussed recently¹⁹ in several important respects.

The storage ring includes an r.f. cavity system whose purpose is to control the beam orbit and the rate of extraction from the ring. A constant rate of extraction can be maintained for all energies. Such controlled extraction would be difficult in a storage ring system which relies on synchrotron radiation to translate the beam orbit. With an r.f. system in the ring, beam injection must be employed which has $\approx 100\%$ capture efficiency. Clearly, injection of a linac beam of the power anticipated precludes substantial injection losses. In order to achieve $\approx 100\%$ capture, synchronous transfer of a few turns of beam between the linac and storage ring would be used. Considerations of the harmonic number and voltage of the storage ring system preclude the use of the same frequencies in the linac and ring r.f. systems. However, multiturn synchronous injection into r.f. micropulses is possible when the frequency of the storage ring is a sub-harmonic of the linac r.f., and the micropulses of the linac are chopped so that the spacing of r.f. bunches is the same as the ring system. To achieve this a chopper system used elsewhere²⁰ or a subharmonic buncher at the linac injector would be used. The storage ring r.f. system can then be similar to that of existing $e^+ - e^-$ accelerators. Electron beams of 900 mA have been stored in the DORIS storage rings²¹ at DESY. In the DORIS system there are separate e^+ and e^- rings. With that performance established, our design objective, storage of 500 mA of electrons by multiturn synchronous injection appears sound. The injection tune of the ring would be adjusted to avoid the stored beam hitting the injection septum magnet.

Beam extraction would be accomplished by inducing a third integer resonance in the horizontal phase space. Extraction sextupole magnets would be placed at appropriate places to induce the third integer resonance separatrices at the extraction septum magnets. In order to facilitate smooth efficient extraction during the entire extraction period a "hollow" phase space technique would be used. The technique has been employed extensively in the ZGS extraction system²² at ANL and can be done either by injecting into off-equilibrium orbits or by using a tickler system. The third resonance extraction also offers the possibility of extracting up to three beams simultaneously. The use of horizontal extraction would enhance the quality of the extracted beam, particularly the energy spread.

The characteristics of the linac injector will be determined by the radius of the stretcher ring, the magnitude of the circulating current, and the peak current in the linac itself. We have assumed that a peak current of 200 milliamps can be obtained in a linac of SLAC design operating at S-band frequency. Using the operating experience in the DORIS storage ring as a guide we have chosen a maximum circulating current of 500 mA in order to minimize problems of beam instabilities in the ring. To minimize the linac repetition rate, thereby insuring maximum power efficiency we chose to operate at the maximum circulating current. This maximum fixes the number of turns of injected beam, i.e. $n_{inj} = i_{cir}/i_{inj} = 2.5$. We therefore inject for two turns giving a circulating current at the start of extraction of 400 mA. The design value of the external beam will fix the number of turns in each extraction cycle; i.e. $n_{ext} = i_{cir}/i_{ext}$, and accordingly the repetition rate will be

$$n_{pps} = \frac{i}{n_{ext} t}$$

where $t = 2\pi pR/c$ and p is the packing factor, R the bending radius of the ring.

Using these parameters one can now optimize the design in terms of the stretcher ring radius using overall construction cost as the criterion. We have used SLAC wave guide structure modified to decrease the

effect of beam loading by increasing the group velocity and reducing the attenuation. The operating properties of a typical section are given in Table V. The energy gain per section, E_1 , is given by²³

$$E_1 = (1 - e^{-2\tau})(P\ell r)^{1/2} - i_{inj} \frac{r\ell}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}} \right)$$

where the first term is the no-load energy and the second term is the steady state beam loading. Assuming two inactive klystrons and linac sections, for full 2 GeV operation

$$N = \frac{E + 2 i_{inj} \frac{r\ell}{2} \left(1 - \frac{2\tau e^{-2\tau}}{1 - e^{-2\tau}} \right)}{E_1}$$

where E is the beam energy giving a total number of section, $N = 45$. The overall linac length is

$$L = 1.2 (N+3)3m \approx 165 \text{ m.}$$

The r.f. duty factor for two turn injection will be

$$D_{r.f.} = t_f + 2 \frac{2\pi pR}{c} n_{pps}$$

These values for L and $D_{r.f.}$ were used together with component cost estimates in ref. 15 to obtain the overall accelerator cost versus radius given in Fig. 6. A total external beam current corresponding to 3 external 100 μ A beams is assumed. Although the minimum cost occurs at a radius of about 8 m we have chosen a somewhat larger radius, $R = 15$ meters, in order to permit operation at higher energies should such a need develop. The linac parameters are fixed at the values given in Table VI. Assuming an emittance of $2 \pi \text{ mm mr}$ for the injector, at all energies above 500 MeV the

Table V. Wave-Guide Parameters

Wave-guide type	constant gradient disc loaded
Section length, l	3 m
Operating mode	$2\pi/3$
Attenuation/section, τ	0.3 nep.
Shunt impedance, r	53 M Ω /m
Q	13,000
Filling time, t_f	0.44 μ sec
R.f. power input/section, P	37 MW

Fig. 6. Overall Cost of Linac-Stretcher Ring as a Function of Ring Radius

Table VI. Linac Parameters*

Maximum energy	2 GeV
Beam loading	194 MeV
Linac peak current	200 mA
Linac total length	165 m
Number of sections	45
Linac frequency	2856 MHz
Linac repetition rate	894 pps
Linac duty factor	1.9×10^{-3}
Linac AC power	6.0 MW
Pulse length	1.68 μ sec

*For operation with 3 external beams of 100 μ A each.

linac beam should have an emittance of less than the design objective of $.2 \pi$ mm mr. The energy spread will be determined primarily by the transient beam loading. By proper phasing of several linac sections it should be possible to minimize this effect. The design objective will be an energy spread of 0.5% in the beam transported to the stretcher ring.

To avoid beam loading from the unexcited wave guides during low energy operation a transport system will take the beam at the appropriate energy, 500 MeV, 1000 MeV, or 1500 MeV and bypass the remaining linac sections. The beam transport is shown schematically in Fig. 7.

The design of the stretcher ring lattice structure has to fulfill the following requirements:

1. The straight sections must be long enough to accommodate injection, extraction (2 or 3) and R. F. systems.

Fig. 7. Beam Transport System for Injector in Linac Ring Accelerator

2. At the locations of the injection and extraction septum magnets and R.F. straight sections the dispersion function must be suppressed.
3. At the location of the resonance extraction magnet the dispersion function must not be too small.
4. For 2 or 3 simultaneous extractions the betatron phase advance between the extraction straight section (locations of extraction septum magnets) must be a multiple of 120° .

The above requirements may be satisfied by a FODO lattice with a betatron phase advance per cell of approximately 60° . Fig. 8 shows the lattice layout of one of the 4 straight sections. The dispersion function is made zero by leaving out bending magnets.

The bending radius of the magnets is chosen to be 15 m. This corresponds to a field of 0.445 T at 2 GeV and 0.0446 T at 200 MeV. This field is high enough that the effects of coercive force and permeability of the magnet iron will be negligible. There are 64 magnets each 1.473 m long. The maximum strength of the 88 quadrupole magnets is 2.34 T/m-m. Between the bending magnets and the quadrupole there is enough space to accommodate sextupole magnets for chromaticity correction. To inject the linac beam in the stretcher ring the equilibrium orbit is distorted by four fast bumper magnets (see Fig. 9). Two septum magnets put the linac beam in the ring in such a way that the radial phase space is hollow. At the end of the injection period the 4 bumper magnets are turned off simultaneously.

The extraction makes use of the third order resonance $\nu_x = 22/3$. The resonance sextupole magnet will be located in a region with non-zero dispersion function. The magnetic field of this magnet seen by the particle is then a function of the betatron amplitude and the particle energy (location of its equilibrium orbit). A particle with its equilibrium orbit going through the center of the resonance magnet will see only a sextupole field. Particles with higher energy (larger equilibrium orbit) will also see a positive quadrupole field and its ν_x value moves closer to the resonance value $22/3$. (It is assumed that the unperturbed ν_x values in 7.25

Fig. 8. Beta and Dispersion Functions for Lattice Structure Proposed for Linac Stretcher Ring System

Fig. 9. Linac-Stretcher Ring Injection System

and outward extraction). Particles with lower energies are farther away from the stopband. By slowly decreasing the R.F. frequency (i.e. increasing the electron energy) the particles will be squeezed out of the stable region along the three arms of the separatrix (see Fig. 10). Particles with lower energy need larger betatron amplitude to be extracted. The electrons jump from one arm to the next each turn with increasing displacement. When the increase per turn of this displacement is large enough the electrons will enter an extraction septum magnet. By having 2 or 3 septum magnets separated by multiple of 120° in betatron phase one can extract 2 or 3 beams simultaneously. It turns out that in practice the extraction efficiency decreases with the area inside the separatrix. By having a hollow radial betatron phase space area (see Fig. 10, shaded area) the extraction efficiency can be kept high. The energy spread of the extracted beam is also improved and is approximately given by

$$\frac{\Delta p}{p} = \frac{\beta_{xR} \epsilon_x}{\eta_{xR}}$$

where β_{xR} = value of β_x at the location of the resonance magnet, ϵ_x = linac beam emittance, and η_{xR} = dispersion function value at the location of the resonance magnet. Using values typical of the lattice of the ring design of Fig. 8, i.e. $\beta_{xR} = 8$ m and $\eta_{xR} = 1$ m, and taking $\epsilon_x = 2.5 \times 10^{-7}$ m-rad we find

$$\frac{\Delta p}{p} = 1.4 \times 10^{-3}$$

The main parameters of the stretcher ring are listed in Table VII.

Fig. 10. Extraction Separatrix in Betatron Phase Space

TABLE VII

Main parameters	
Maximum energy	2 GeV
Current	500 mA
Machine circumference ($2\pi R$)	251.3 m
Bending radius	15 m
Maximum bending field	0.445 T
Length of bending magnet	1.473 m
Bending magnet gap	0.031 m
Powerloss/bending magnet	5 kW
Number of bending magnets	64
Maximum quadrupole gradient	4.68 T/m
Length of quadrupole magnet	0.5 m
Bore diameter of quadrupole magnet	0.3 m
Powerloss/quadrupole magnet	1kW
Number of quadrupole magnets	88
Radial betatron frequency (ν_x)	7.25
Vertical betatron frequency (ν_y)	6.25
Number of cells (total)	44
Number of normal cells	32
Super period	4
Synchrotron Rad. loss/turn	94 kV
R. F. voltage per turn	800 kV
Harmonic number	399
R. F. frequency	476 MHz
Rotation frequency	1.193 MHz
Synchrotron frequency/turn (ν_s)	0.02
β_x max	9.93 m
β_x min	3.35 m
β_y max	10.50 m
β_y min	4.17 m
Normal cell $\eta_{\max}$	1.25 m
Normal cell $\eta_{\min}$	0.75 m

VII. PRELIMINARY COST ESTIMATES

The cost estimates for the linac-stretcher ring and microtron accelerator facilities are given in Tables VIII and XI respectively. The estimates include a 20% contingency factor. The stretcher ring system is estimated to cost $\$25.3 \times 10^6$ as compared to $\$20.9 \times 10^6$ for the microtron, a substantial difference. To a large extent, the estimates are based on numbers obtained from recent proposals for research facilities of a similar character. Where necessary we have made allowances for subsequent inflation.

The recent experience of the staff of the Stanford Linear Accelerator Center was of particular value in determining costs of the stretcher-ring facility. Where we have made independent judgements generally our assessments agree with estimates made by the SLAC staff. The major area of uncertainty in the stretcher ring design is in klystron cost. The proposed design calls for a klystron identical to the SLAC model currently used except for duty factor capability. Multiple 100 pamp beam operation will require a duty factor twice that of the SLAC design. Klystron research and development will be necessary and we anticipate higher klystron costs. Procurement cost for the existing SLAC type is estimated at \$25K per unit. We have assumed \$40K for the upgraded version.

A major part of the microtron cost will be magnet fabrication. Here, we have used as a guide inflation escalated estimates based on the cost of the cyclotron magnets originally proposed as part of the ANL Midwest Tandem Cyclotron (MTC) proposal.²⁴ The results are in reasonable accord with costs recently estimated for the cyclotron magnets in the Colorado University cyclotron proposal²⁵ submitted to DOE recently. Informal consultations with klystron manufacturers were the basis for estimates for R. F. components in the microtron design.

TABLE VIII. 2 GeV Linac-Stretcher Ring, Cost Estimate

<hr/>		
A. S-band pulsed linac		
1. Linac injector	\$ 400K	
2. Beam line components (including support, alignment vacuum & cooling)	3175K	
3. Klystrons and modulators	7700K	
4. Linac transport system	400K	
5. Linac tunnel and klystron gallery	1780K	
6. Instrumentation and control	1000K	
7. Substation 5 MW	300K	
8. Water cooling tower	<u>200K</u>	
		\$14955K
B. Stretcher-Ring		
1. Ring tunnel	1250K	
2. Ring lattice magnets	2000K	
3. Ring alignment, support cooling, correction magnets	1500K	
4. Power supplies	300K	
5. Ring vacuum system	300K	
6. Computer, control, diagnostics	400K	
7. Extraction system	200K	
8. R.f. system	<u>200K</u>	
		<u>6150K</u>
	TOTAL	\$21105K
Estimated cost \$21M1 x 1.2 = \$25M3		
<hr/>		

TABLE IX. 2 GeV Microtron, Cost Estimate

<hr/>		
A. L-band C.W. Linac		
1. Injector with chopping	\$ 250K	
2. Wave guides	2400K	
3. Klystrons (3)	540K	
4. Power supplies	600K	
5. Cooling system	150K	
6. Miscellaneous r.f. comp.	250K	
7. Instrumentation and control	410K	
8. 5 Mw substation	<u>300K</u>	
		\$4900K
B. Microtron elements (excluding r.f.)		
1. Segment magnets, type I (2)	600K	
2. Segment magnets, type II (2)	3600K	
3. Support, alignment, and cooling	800K	
4. Quadrupoles and power supplies	350K	
5. Vacuum system and beam tube	1100K	
6. Magnet controls	<u>1100K</u>	
		7550K
C. Building (25m x 60m) @ (\$3300/sq.m)		<u>5000K</u>
	TOTAL	\$17450K
Estimated cost 17M45 x 1.2 = \$20M9		
<hr/>		

VIII. COMPARISON OF CONCEPTUAL DESIGNS

A major attraction of the linac-stretcher ring system lies in its use of state-of-the-art technology developed in the design of storage ring systems for research in elementary particle physics. It is evident from the conceptual design data of Section 6 that no research and development is needed to prepare a proposal for a system capable of furnishing a 100 μ A single external beam. Such a system can be built with designs taken from existing high-energy physics facilities. With research and development directed at increasing the repetition rate of the linac injector this design can be extended to give stretcher ring currents suitable for multiple beam operation. The stretcher-ring has the added appeal of great flexibility for extension to operation at higher beam energies. No change in ring design would be required and a simple linear increase in linac-accelerator structure is all that is required.

However, there is good reason to hope for substantial progress in microtron design. It is quite possible that more sophisticated recirculation schemes such as the bicyclotron or double-sided microtron can be perfected with a resulting major reduction in magnet cost and building requirements. Extensive research and development in r.f. accelerating structures already funded at NBS-LASL may substantially improve the power efficiency of the microtron design. In order to gauge the possible impact of such developments on possible accelerator designs and provide justification for appropriate research and development we have made a comparison between our conceptual designs along with an improved microtron design, a double-sided microtron. The results are presented in Table X.

The beam quality of all three systems is consistent with the design objective. Of course such performance for the microtron designs is based strictly on design expectations. It remains to explore these questions in careful computer simulations and ultimately to confirm the predictions in experimental measurements. To date, such performance has never been realized at high electron energy with a functioning microtron system. The same reservation must be made with regard to beam current blowup limit. The stretcher-ring limit has been established empirically

TABLE X. Comparison of accelerator designs

Characteristic	Linac-Ring	Microtron	Bicyclotron
Beam quality, $\Delta E/E$	$\sim 10^{-3}$	$\sim 10^{-4}$	$\sim 10^{-4}$
emittance	$\sim .2\pi$ mm-mr	$\sim .1\pi$ mm-mr	$\sim .1\pi$ mm-mr
Beam current blowup limit	$\sim 600 \mu\text{amp}^b$	$\sim 100\text{--}500 \mu\text{amp}$ (computer study)	$\sim 100\text{--}500 \mu\text{amp}$ (computer study)
Multiple beam capability	yes	with external beam splitter	with external beam splitter
Multiple beam energies	no	to be studied	to be studied
Capital cost	\$25M3	\$20M9	\$15.6M
Power, AC (2 GeV operation)	6.4 Mw	4.2 Mw	4.2 Mw
Scaling law, capital cost ^a (leading term)	$\sim E$	$\sim E^3$	$\sim E^3$
Flexibility of design for increased energy	excellent	poor	underdesign of magnet and linac required

^aSee Fig. 11 for comparison of capital costs versus energy

^bRef 21.

in storage ring operation at DORIS. The limit for the microtron systems has not been established but is believed to be in the low 100 μ amp range. Multiple beam operation appears to be assured with all three designs. At Cornell extraction of two beams from the 12 GeV electron synchrotron has been accomplished with 97% efficiency²⁶ and the beam quality of all three designs is such that beam splitting with an r.f. subharmonic splitter should be possible. Operation with beams of more than one energy is not possible with the linac ring system. However beam extraction at several points in a microtron system is a question that should be explored.

The power consumption of the microtron systems is substantially less than that of the linac ring system, and major differences in the systems occur in their capital cost and the manner in which that cost scales with beam energy. The estimated cost of the bicyclotron is only 60% of that of linac-ring system. Such a substantial prospective saving dictates that in the absence of a major technical limitation the bicyclotron is the preferred design and that research and development efforts should focus on its utilization. Table X also indicates the manner in which the alternatives scale with energy by giving the power of the leading term in their cost. The actual costs are shown as a function of electron energy in Fig. 11. There is substantial sentiment in the research community for reserving the possibility of running at higher energies. On the basis of this requirement the microtron is obviously a very poor choice because of the manner in which the size of the segment magnets scale. The bicyclotron could be designed so as to permit operation as high as 3.0 GeV and still be cost competitive with the linac-ring system, if the segment magnets are appropriately designed.

Fig. 11. Cost Comparison for Possible Accelerator Designs

IX. SUMMARY AND RECOMMENDATIONS

From the discussion presented in this study we have reached the following conclusions:

- A GeV continuous beam accelerator consisting of a SLAC type S-band and a conventional stretcher-ring can be built using existing technology. Such a system can be extended to 300 μ amp operation by appropriate upgrading of klystron designs in current use.
- Multiple beam extraction at high efficiency from electron storage rings of similar design has been demonstrated and offers a convenient means of generating up to 3 beams of acceptable quality.
- Modified microtron designs, particularly the double-sided microtron (bicyclotron) show promise for reducing the cost of recirculating systems. the savings in capital costs may be as large as ~\$9M if such an accelerator can be developed which meets the design objectives.
- Operating costs for the microtron systems would be substantially less than those expected for a linac-stretcher ring system.

In our judgement, several questions remain which should be addressed in specific short research and development projects. Their duration would be four months. Three would involve computer analysis of possible accelerator designs and a fourth continued exploratory testing of possible r.f. accelerating structures. Each focuses on a major question regarding the accelerator systems under consideration. They are summarized below.

1. Study of Beam Break Up in SLAC Type Linear Accelerators.

Our current conceptual design for a 2 GeV linac-stretcher ring system is severely limited by the maximum duty factor attainable with SLAC type S-band klystrons. This long duty factor is required because of the limited instantaneous currents which can be accelerated in SLAC type structures without beam breakup. If the current limit can be increased by

a factor of two, use of existing klystron designs at moderate cost will be possible. We propose a design study to optimize the current SLAC S-band cavity structure for our design, and to complete detailed calculations of beam dynamics, possible focusing systems, and resulting current thresholds for beam breakup.

2. Design Study, Bicyclotron Recently a new magnet configuration called the "bicyclotron" has been proposed to avoid the massive and expensive return magnets which characterize the usual microtron design for 1-2 GeV electron accelerators. The bicyclotron system is characterized by strong vertical defocusing forces generated by the large slant angle at which the beam enters and leaves the segment magnets. We propose to study possible schemes for compensating for these defocusing forces for computer analysis of various configurations of segment magnets and quadrupole focusing elements. Possible more complex field variations in the segment magnets will also be studied, and detailed prediction of beam size and emittance are also planned.

3. Microtron Beam Blowup One of the unknown limits on performance of c.w. 1-2 GeV electron microtrons is imposed by the onset of cumulative beam blowup generated during multiturn passage through r.f. accelerating cavity. Preliminary calculations for simple conceptual designs have suggested that the threshold for such blowup is circulating currents in the low 100 μ amp range. No experimental verification has been possible to date. The threshold will be a sensitive function of the configuration of focusing elements in the orbit geometry. We propose to study by orbit analysis the expected properties of beams in the 1-2 GeV range for several possible configurations of magnet and focusing elements. The particular objective will be to establish limits expected due to beam blowup.

4. R.F. Cavity Structure Studies We propose to continue to study new types of r.f. wave guides optimized for c.w. operation. Data from a preliminary ANL funded study indicate that the "disc-and-washer" type of structure has higher shunt impedance than other systems and no significant distortion of accelerating modes when support structures

required for our applications are imposed on the design. We wish to proceed with design and fabrication of a prototype cavity capable of sustaining the voltage gradients required for microtron operation, appropriate testing of the resulting structure and determine optimum r.f. power coupling into the structure.

As this report has indicated, the technical options for a 2 GeV continuous beam electron accelerator are a linac stretcher ring system or the bicyclotron variant of the microtron system. We have established that the former is a state-of-the-art concept. The latter would be substantially less expensive. However, its technical feasibility remains to be established. The two microtron studies proposed will not necessarily provide definitive answers to this feasibility question. However, they will insure that no obvious limitations exist, and point the way to further research and development. The study of beam breakup in the SLAC type linac should establish definitively whether a program of klystron development is justified at this time. These studies together with the conclusions of this report should provide information requisite to making a sound decision on the proper option to be pursued now in developing a national electron accelerator facility.

ACKNOWLEDGMENTS

We wish to acknowledge extensive discussions of the Linac-Ring concept with several members of the Stanford Linear Accelerator Center Staff, particularly G. Leow, R. Miller, J. Konrad, and R. Koonz. We are also indebted to J. Haimson for a very valuable critical review of major portions of this report.

REFERENCES

1. R. J. Hofstadter, Rev. Mod. Phys. 28, 214 (1956).
2. B. Frois, et al., Phys. Rev. Lett. 38, 152 (1977).
3. W. Bertozzi, et al., Nucl. Instr. and Method. 162, 211 (1979).
4. J. Mougey, et al., Nucl. Phys. A262, 461 (1972).
5. J. Hockert, et al., Nucl. Phys. A217, 14 (1973).
6. W. Schütz, et al., Phys. Rev. Lett. 38, 259 (1977).
7. "The Role of Electron Accelerators in U. S. Medium Energy Nuclear Science," report of DOE/NSF Study Group, R. S. Livingston, Chairman, ORNL/PPA-77/4, December 1977.
8. J. S. O'Connell, Abstracts of Contributed Papers, 8.8, International Conference on Nuclear Physics with Electromagnetic Interactions, Mainz, June 5-9, 1979.
9. See Ref. 7.
10. "Survey of Physics Research With a High Duty Cycle Electron Accelerator," G. A. Bartholomew, E. D. Earle, J. W. Knowles, and M. A. Lone, CRNL-550, January 1971.
11. "Medium Energy Nuclear Physics With Electron Linear Accelerators," MIT 1967 Summer Study, TID-24667, page 39 (1967).
12. V. I. Veksler, Comptes Rendus (Doklady) de l'Academie of Sciences de l'URSS 43, No. 8: 329 (1944).
13. "A Possible Magnet Configuration for a Recycling Accelerator," Karl-Heinz Kaiser, Conference on CW Electron Accelerators, Charlottesville, Virginia, January 8-9, 1979.
14. "The Superconducting Recyclotron at Stanford," C. M. Lyneis, et al., *ibid* 13.
15. "Properties of a Linac-Storage Ring Stretcher System," Gregory Leow, *ibid* 13.
16. B. McDaniel, Cornell University, private communication.
17. S. Guiducci, G. Martinelli, M. A. Preger, IEEE Trans. Nucl. Sci. NS-26, 3164 (1979).
18. See Ref. 13.
19. See Ref. 15.
20. G. Rouse, R. Siemann, and M. Tigner, IEEE Trans. Nucl. Sci. NS-24, No. 3, June 1977.

21. G. A. Voss, IEEE Trans. Nucl. Sci. NS-22, 1363 (1975).
22. Y. Cho, et al., Proc. IX Inter. Conf. on High Energy Accelerators, Stanford, May 1974, pp. 451.
23. See Ref. 15.
24. "Midwest Tandem Cyclotron- A Proposal for a Regional Accelerator Facility," ANL-7582.
25. "A Proposal for a National Light Ion Facility," David Lind, et al., Univ. Colo., unpublished.
26. Ibid. Ref. 16.