A PROPOSAL FOR ADVANCED STUDIES IN PARTICLE ACCELERATORS

Submitted by the Nuclear Engineering Department, Engineering Experiment Station, and the Physical Sciences Laboratory of the Graduate School, University of Wisconsin, Madison, Wisconsin

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PREAMBLE

It is desired to establish a program of Advanced Particle Accelerator Research at the University of Wisconsin beginning in fiscal year 1968. This program will be directed toward advancing the art of accelerator technology to provide researchers with higher energy, higher intensity accelerators at the lowest eventual cost. The program will encompass three areas of activity. First, it is desired to operate an existing 50 MeV fixed field alternating gradient electron synchrotron with its appended 235 MeV storage ring. A number of accelerator experiments, directed mainly toward intense beam phenomena and especially relevant to storage rings, is planned for this facility. Second, fundamental high energy accelerator studies in the 600 to 1000 BeV energy range will be undertaken for the purpose of investigating new ideas and techniques that may ultimately have application. Third, the laboratory has been active in proton linear accelerator design studies which are useful to other laboratories. It is desired to continue these programs to the extent that they continue useful and are not duplicated elsewhere. The personnel and laboratory area to carry out this program currently exist at the University of Wisconsin. This proposal is a request for the loan of the 50 MeV accelerator and storage ring with associated experimental equipment and funds to the extent of $553,431.00 in fiscal year 1968 to carry out this program.

I. INTRODUCTION

On June 30, 1967 the University of Wisconsin will take over the assets of the Midwestern Universities Research Association (MURA). A large number of the people from the MURA Corporation have accepted University of Wisconsin appointments. These people have demonstrated their competence in the design and development of particle accelerators and have expressed an interest in continuing in this activity. They are in the process of assembling a 235 MeV storage ring which will be appended to the existing 50 MeV fixed field alternating gradient electron synchrotron. The storage ring has been designed to extend the studies of intense beam phenomena begun on the 50 MeV accelerator and this combined installation will be unique in its capability and versatility for studying high intensity and other accelerator related phenomena.

This proposal to the AEC is partially a request for the loan to the University of Wisconsin of the 50 MeV FFAG electron accelerator and its appended storage ring. Also requested are the associated equipment necessary to allow efficient use of the accelerator and storage ring.

The University of Wisconsin Department of Nuclear Engineering plans to establish a curriculum activity associated with the study, development and design of particle accelerators. The research in this activity will involve a number of the former MURA employees and some of the equipment, including the 50 MeV accelerator and storage ring, presently located at the laboratory formerly operated by the MURA Corporation. This proposal will outline the intended area of advanced accelerator studies to be pursued during fiscal year 1968. The activity is broken down into three areas.

The first area involves research on the 50 MeV accelerator and storage ring. The MURA fixed field alternating gradient electron synchrotron was designed to study a great variety of accelerator problems and has the required flexibility to meet new acceleration problems as they arise. The dc guide field magnets and high repetition rate of the acceleration system greatly simplify the study of phenomena that are very difficult and expensive to study on large accelerators where they occur at rates of once every few seconds in a time varying field. The ability to accumulate large coasting currents makes it possible to study high intensity coasting beam phenomena which occur during injection and possibly at flat top in large accelerators. To this useful tool has now been appended a 235 MeV storage ring which will complement the versatility of the 50 MeV accelerator injector. The combined coasting beam capability of the FFAG accelerator and the bunched beam capability of the storage ring will provide an accelerator research facility able to do effective research on a great variety of accelerator problems. The intense beam experiments proposed will bear on the entire national accelerator program.

The second area of research involves fundamental studies of high energy accelerators in the 600 to 1000 BeV range. It seems likely that if an accelerator is to be built in this energy range more than a simple extension of the state of the art will be required. New ideas will have to be investigated and fundamental problems must be solved. Fundamental research of this nature requires appreciable lead time but important developments may find application earlier than the expected final design time for a 600 to 1000 BeV accelerator. This has been an activity with this group of people and it is expected that in the university atmosphere it will be possible to make even greater gains. In this area the creativity of students and their interactions with professors should not be underestimated.

The last area involves proton linear accelerator design studies. The laboratory has been active in this area and the results have been particularly useful at laboratories presently designing or constructing linacs. It is desired to continue this program to the extent that they continue useful and are not duplicated elsewhere.

It is believed that this research can be carried out effectively at the university level. In addition to the value of the research alone which is important to the national accelerator program, there are other reasons for favoring such a university accelerator program.

The need for such a curriculum activity for the training of students and the propagation of the knowledge through courses in accelerator technology has been recognized. The Pake Report[1] points out the lack of training in applied physics areas by physics departments. There appears to be no existing group in the U. S. which has an academic program in the area of accelerator design. Academic courses in accelerator orbit theory, accelerator magnet design, intense relativistic beam phenomena, general accelerator design, charged particle beam transport, etc. are generally not available. There appears to be a real need for the training of graduate students who are well schooled in the fundamental principles of physics and with thesis work in the applied physics area of particle accelerators. This need has been particularly noticeable in the MURA organization which has been an attraction for students and from which, though incidentally, quite a few advanced degrees have emanated (Appendix A).

The scale and complexity of high energy accelerators have made it difficult for the high energy physicist to alternate his interests and to be productive in both high energy physics and accelerators. For present-day high energy accelerators to be most useful, it is necessary to have a staff of competent, trained people to operate and improve the facility. The use of lower energy accelerators as research instruments and for industrial applications is increasing with no definite limits in sight. This expanding field needs a source of trained manpower.

Many of our most competent scientists and engineers are located at the universities by their own choice. This applies in the accelerator field as well. A university accelerator project can stimulate, attract, and use the talents of some of these experts. The research outlined in this proposal is exciting to the University of Wisconsin staff and the opportunity to contribute meaningful research using resources present at the Physical Sciences Laboratory (formerly the MURA laboratory) is a great attraction. This combination of training students and participating in timely accelerator research should provide a particularly fertile atmosphere for the logical development of the field.

It is also recognized that an accelerator effort which is not closely linked to the national laboratories where the large-scale facilities rightfully belong can quickly become a sterile operation. It is necessary to contribute and to participate in the design and operation of the equipment located at the national laboratories so that the conception, performance, and problems associated with the hardware can be recognized. The proximity of the University of Wisconsin to Argonne National Laboratory is a real asset. This proximity has allowed a close cooperative effort to exist in accelerator development as demonstrated by many successful joint projects undertaken by the MURA group over the past two years. The desire to continue this relationship has been expressed by both groups repeatedly. It should be possible for the professor and his students to undertake accelerator experiments much as the high energy physicist has learned to do as an accelerator user.[1]

These aims have been well expressed by AEC Chairman Glenn Seaborg in an address at the University of Colorado in June, 1963:

"In the competition that exists today for top quality manpower, that laboratory or institution which falters or lags behind in its struggle for excellence or pre-eminence rapidly falls farther behind due to the 'snowball effect.' Just as success breeds success, so does failure beget failure. In a period such as this, when we are faced with serious shortages of engineers, mathematicians, and physical and biological scientists, as well as with rapidly increasing research costs, it is particularly important that serious thought be given to maintaining our pace of advancement by strengthening our existing centers of excellence and increasing the level and quality of cooperation between universities and the national laboratories. In this way, I believe the AEC, in concert with the universities and national laboratories, can contribute both directly and indirectly toward meeting the goal of an accelerated rate of training of engineers, mathematicians and physical and biological scientists."

The goal is to establish a university oriented research program in accelerator research which will attract competent staff and students. Some important research problems outlined in this proposal are pending and these bear strongly on the national accelerator program.[2] A competent staff and facilities are available to attack these problems. This staff will direct their efforts toward an understanding of accelerator phenomena and toward an investigation of new accelerator design concepts. They should not be encumbered in their efforts by day-to-day operational problems of a facility devoted primarily to doing high energy physics research. A close cooperative alliance will exist with the national laboratories with the professors being frequently relieved of campus duties for extended periods to do research at the national laboratories. This university program should complement the programs at the national laboratories and not be in competition with them.

II. 50 MEV ACCELERATOR AND STORAGE RING

MURA has constructed a 50 MeV electron accelerator model of a radial sector fixed field alternating gradient synchrotron and successful operation was achieved in 1961. This accelerator has been a useful device for investigating accelerator phenomena. Appendix B lists a few of the more noteworthy achievements accomplished with this accelerator. Some of the studies listed in Appendix B are incomplete and these should be continued. There are other experiments that should be done. The experimental and theoretical program to be pursued during fiscal year 1968 using the 50 MeV electron accelerator is discussed in this section.

During fiscal year 1967 a storage ring has been under construction which will take the extracted beam from the 50 MeV accelerator and accumulate and accelerate it to an energy of 235 MeV. It is expected that this storage ring will have achieved successful operation by June 30, 1967, but that the experimental program to be pursued with this device will have barely started. The anticipated program is outlined.

2.1 STUDIES OF INSTABILITIES WITH THE 50 MEV ACCELERATOR

A continuation of the study of transverse and longitudinal instabilities which have been observed in the 50 MeV accelerator is desirable. These phenomena are impossible or inconvenient to study in the storage ring. The proposed studies include:

2.1.1 INFLUENCE OF BEAM DENSITY DISTRIBUTIONS ON THE TRANSVERSE INSTABILITY

Preliminary experiments have shown a double peaked beam density distribution to be unstable whereas the corresponding single peaked distribution beam having the same frequency spread and intensity is stable.[3] These experiments will also bear on the phenomenon of the excitation of the instability with a pulsed rf driving force. Present theories do not explain the effect of rf stimulation in exciting instabilities below the usual threshold.

2.1.2 GROWTH TIME FOR TRANSVERSE INSTABILITY

There are large discrepancies between the experimentally measured growth times and the calculated growth times for the transverse instability in the MURA accelerator. These discrepancies have been attributed to the clearing electrode geometry,[4] but more studies are needed with clearing electrode configurations whose fields can be more easily calculated.

It has been suggested that passive, terminated transmission lines which are coupled to the beam fields can be used to damp the transverse instability.[5] It would be valuable to design and experiment with such passive devices.

The role of neutralizing ions in stabilizing the instability will also be studied to determine if the stabilization is due to a phase shift opposite to the image current phase shift or to the potential well created by the ions.

2.1.3 ENERGY SPREAD IN LONGITUDINAL CLUSTERING

Measurements have been made of the effect of longitudinal instabilities on beam energy spread in the 50 MeV accelerator and these should be continued.[6]

These studies have been done with a coasting beam. However, with the storage ring, the longitudinal instability of the bunched beam will lead directly to beam loss from the stable phase region due to the increased energy spread. This should allow better information to be obtained.

2.2 BEAM EXTRACTION STUDIES FROM THE 50 MEV ACCELERATOR

Studies of resonant extraction from the FFAG accelerator should be continued. The ability to provide a long duty cycle, high quality beam from an FFAG accelerator has direct application to high duty factor FFAG betatrons as well as the use of FFAG machines as injectors for other high energy machines.

2.3 HIGH INTENSITY OPERATION OF THE STORAGE RING

Our first goal in the use of the storage ring will be to achieve the highest possible beam intensity. It is recognized that adjustments and modifications may be necessary to raise the beam to a level where studies of instabilities become possible. It is proposed here to take whatever steps are necessary to achieve satisfactory intensities for carrying out the contemplated program on the storage ring.

2.4 INSTABILITY AND SPACE CHARGE STUDIES ON THE STORAGE RING

2.4.1 TRANSVERSE STABILITY CRITERIA

One of the most important experiments to be performed on the storage ring is to test the Courant-Sessler single beam stability criterion.[7] The theory predicts that a single bunch of particles will be stable against the transverse coherent resistive instability if the operating point is between $\nu = n$ and $\nu = n + 1/2$ whereas the beam will be unstable if the operating point is between $\nu = n$ and $\nu = n - 1/2$, where ν is the betatron oscillation frequency and n is an integer. The storage ring will be the first operating accelerator-like machine capable of tuning between the stable and unstable regions since its tune is adjustable between $\nu = n - 1/4$ and $\nu = n + 1/4$.

Predictions of the theory for multiple bunches can also be tested on the storage ring by modifying the rf system to operate at a higher harmonic number.

The storage ring will also be used to make detailed studies of other single beam and beam-beam instabilities. Thus, one can gain confidence in the practical application of theoretical predictions of the limitations imposed on future accelerators by these instabilities. These studies will include experiments on beam size control to reduce the Touschek effect and the study of methods of overcoming the limitations imposed by other instabilities which may be as yet undiscovered.

2.4.2 LONGITUDINAL INSTABILITIES

Longitudinal instabilities and their influence on beam loss from bunched beams can be studied more easily and less expensively on the storage ring than on large high energy accelerators.

Since injection into the storage ring will be at 45 MeV at a field of approximately 2 kG, it will be possible to have stable orbits at fields much lower than the injection field. Therefore, it will be possible to study the true space charge limitations of accelerators by filling the machine to near the space charge limit at injection and subsequently decelerating the beam until the space charge limit is reached. This isolates the study of space charge effects from the complications otherwise associated with injection.

The storage ring will have pole face windings on the bending magnets and tuning windings on the quadrupoles. These windings will permit a programmed adjustment of the guide fields to compensate for the tune shift introduced by space charge.

2.5 POSITRON SOURCE FOR THE STORAGE RING

At the present time the storage ring is the only machine in the U.S. where it will be possible to do colliding beam electron-positron scattering experiments. This situation will remain until the Cambridge Electron Accelerator bypass project[8] is completed. In the meantime, laboratories in France, Italy, and the Soviet Union will be actively engaged in this field.

It is also relevant that the storage ring is the only machine in the U.S. where beam-beam instabilities in electron-positron storage rings may be studied. Early experiments of these phenomena are important to the Stanford storage ring[9] and the CEA bypass projects.

We intend to develop an efficient converter for producing positrons in the 20 to 40 MeV range from the 45 MeV extracted beam from the 50 MeV electron accelerator injector. Positron sources with efficiencies in the 10^{-3} range have been developed for use with linear accelerators.[10] The principles are applicable to this project. However, practically, these principles must be extended to develop a positron source of reasonable efficiency for the 45 MeV electron beam.

The project will consist of two efforts. First, computer studies are necessary to optimize the converter geometry and the optical system necessary to match the converter to the beam from the injector and into the storage ring. Second, the optical elements themselves must be studied and designed. Since short focal length lenses are required, it is expected that superconducting magnets will be applicable to at least part of the optical system.

III. HIGH ENERGY MACHINE STUDIES

An important consideration for future accelerator development is the extent to which the use of superconductors can affect significant savings in design. Work at the Brookhaven National Laboratory in constructing quadrupoles[11] and in obtaining 40 kG/sec field rates in solenoids[12] is promising in this regard.

We propose first to explore the possibility of pulsing realistic superconducting magnets since this seems to offer the most direct route in the utilization of superconductors in accelerators. However, since flux jumping phenomena associated with time varying fields may prove troublesome, we also plan a parallel approach using stationary magnetic guide fields. Here, it will be important to test the feasibility of producing high momentum compaction guide fields to reduce the radial aperture customarily associated with FFAG fields. At the same time, further investigation into nonlinear orbit dynamics will be needed to determine whether high momentum compaction is usable.

Since increasing the intensity of accelerators is always a goal for the efficient utilization of a facility, we also plan to explore the possibility of increasing the duty factor in a fixed field accelerator. Continuous acceleration might be achieved by an azimuthal electric field traveling radially in such a manner as to produce a controlled phase shift from the inner to outer radius. The scheme envisaged bears some resemblance to Robinson's multicavity acceleration method[13] since harmonic shifting is employed. It is achieved, however, with components that are greatly simplified.

Finally, since the problems of rf acceleration may involve a coupling between synchrotron oscillations and betatron motion, these synchrobetatron motions will be studied. Previously we have studied resonances in synchrotron oscillations similar to those occurring in betatron oscillations.[14] The conditions for the existence of these oscillations are present in the 1000 BeV accelerator, where it is necessary to use high harmonic numbers. We contemplate an extension of these studies to include coupling to nonlinear betatron oscillations.

3.1 SUPERCONDUCTING ACCELERATOR STUDIES

The studies required to determine the feasibility of utilizing superconducting materials are divided into three categories: fundamental studies, feasibility exploration, and field configuration concepts. At present we have been engaged in fundamental studies aimed at illuminating the method of flux penetration in superconductors.[15] We now propose to determine: (1) the correlation of lattice defects with trapped flux distributions; (2) temperature changes associated with flux jumps using microthermometry; (3) change in critical temperature due to lattice defects induced by cold working and neutron irradiation; (4) electromagnetic radiation associated with flux jumps, and; (5) explanation of small scale field structure of trapped flux using micro probes.

In connection with the fundamental studies part of the project, we have already developed[16] an accurate multiprobe magnetic field measuring device that is useful for measuring magnetic fields at 4^{o} K. We expect that this probe system will continue to be improved and, thereby, provide a flexible magnetic field measuring device. Additional probe materials will be investigated to improve the spatial resolution and sensitivity.

At the technical level we plan to explore the possibility of pulsing realistic accelerator model magnets such as quadrupoles. Realizing, however, that flux jumping phenomena may be a practical barrier, we plan, in parallel, to test the feasibility of producing fixed field model magnets. Actually construction in this part of the project is not expected to be very far advanced during the first year since specific designs depend on orbit studies and magnetostatic calculations.

Finally, magnetostatic calculational methods already developed by us[17] will be employed to determine magnetic field distributions. These methods permit one to account realistically for spatially distributed currents. We plan to explore the possibility of achieving a high momentum compaction configuration. This, in turn, of course, depends on orbit dynamics studies to determine whether tolerances in an accelerator operating with nonlinear betatron oscillations may be relaxed because of the nonlinearities.

3.2 STUDIES IN NONLINEAR ORBIT DYNAMICS

Although our nonlinear orbit dynamics studies will be intimately tied to the possibility of producing a high momentum compaction confining ring, studies in nonlinear dynamics are interesting and important in their own right. Based on recent work we have undertaken in the design of a storage ring,[18] we propose a systematic application of Hamiltonian transformation theory to the solution of charged particle motion in high gradient magnetic fields. In particular, computerization of such transformations will materially assist in the rapid assessment of various contemplated high momentum compaction magnetic guide fields. It is hoped that one result of the nonlinear studies will be the acquisition of more confidence that field tolerances may be relaxed because of the nonlinearities (i.e., linear resonances may not be serious if they develop into stable nonlinear motion).

3.3 RADIO FREQUENCY ACCELERATION STUDIES

Since increasing the beam intensity in an accelerator is an ever-present goal, we propose an investigation of a method for accelerating simultaneously particles of all energies in a fixed field confining ring. The method is similar to the multicavity method of Robinson[13] but conceptual differences permit a simplification of the hardware required to execute this acceleration.

An electric field wave traveling along an rf acceleration gap provides each particle with a continuously changing electrical phase depending on its radial position. The frequency of the radially traveling wave guide field is a high harmonic of the particle revolution frequency. All particles with a range of energies become bunched about stable phase angles for various sub-harmonics of the wave frequency. Acceleration of the whole energy spectrum of particles in the machine then takes place as the wave frequency is modulated. Repeated frequency modulation cycles permit particle bunches to pass from one harmonic to another.

Application of this acceleration principle to fixed field accelerators and storage rings appears to be sufficiently interesting to justify effort in establishing its feasibility.

3.4 SYNCHROBETATRON OSCILLATIONS

For reasons previously mentioned, we propose an extension of our studies of synchrotron oscillation resonances[14] to include the effects of coupling to betatron motion and, in particular, to nonlinear betatron motion.

3.5 INJECTOR STAGING

The proper sequence of accelerators to be used for injecting particles into the final accelerator ring requires study. Recent studies have mentioned boosters and intermediate boosters. Based on a recently completed report[19] evaluating various injectors for the contemplated improvement of the ZGS, we propose to undertake a similar study for the 600-1000 BeV accelerator.

IV. PROTON LINEAR ACCELERATOR DESIGN STUDIES

The MURA Laboratory has had a modest program in the design of standing wave proton linear accelerators since 1960. This program has been successful in furnishing linac designers with much of the design data required to extend the conventional structure up to energies of 200 MeV as well as optimizing the structure at all energies. This information has been obtained mainly through the use of an electromagnetic field computational program, named MESSYMESH.[20] This program has been under continual development and has been used to investigate over 2000 different geometrical configurations for the 200 MHz resonant cavity design. This information has been conveniently arranged so that the results of a single computer run can be summarized on a single page. Bound volumes of these summary sheets have been distributed periodically to 21 interested linac designers at 12 laboratories. This computer program has been the incentive and model for several similar programs at laboratories both in this country and in foreign countries.

It is proposed in fiscal year 1968 to continue the research in this area to the extent that it is useful to the laboratories now engaged in linac design and is not a duplication of efforts at these laboratories. Continuation of this research has been urged repeatedly by several of these laboratories. The program as it presently is envisioned includes the following specific projects:

1. It is desired to continue the MESSYMESH computation which will be directed partly toward the designs now being contemplated for the new AGS injector at Brookhaven National Laboratory and the Los Alamos Linear

Accelerator projects thus eliminating the need for extensive modeling studies. From the past rate of usage of the program, it is expected that about 400 runs will be made in fiscal year 1968 and the information obtained from these runs will be distributed as in the past.

2. The MESSYMESH program will continue to be improved with respect to the speed of computation, the geometries which can be handled by the program, the accuracy of the computation, the information derived from the computed frequency and fields, the compatibility with other digital computers, etc.

3. The accuracy of the program will continue to be investigated by comparison with experimental measurements.

4. The motion of the particles through the MESSYMESH computed fields will be investigated. Two computer programs are currently in use for this purpose. The LINDY[21] program traces individual particles through the computed fields point by point and is the most exact single particle description of the motion in the linac. The PARMILA[22] program allows many-particle motion to be investigated. In this case the fields are approximated by impulses. Each of these particle dynamics programs require an accurate description of the electromagnetic field which is available from the MESSYMESH program. However, experimental measurements have recently been made to the required accuracy,[23] and this information should also be used in the dynamics programs.

5. The MESSYMESH program is carried out in two dimensions, so that in cylindrical geometry any surfaces which do not have azimuthal symmetry

cannot be calculated. Drift tube stems and wall tuners obviously fall in this category and so are not computed in the program. However, from the MESSYMESH fields, the frequency perturbation due to these devices should be calculable. This calculation should be made and allowances made in linac design for them. The calculations can be checked experimentally by adding such perturbing surfaces to a precision frequency cavity.

5.1 50 MEV ACCELERATOR AND STORAGE RING FROM JULY 1, 1967 TO JUNE 30, 1968

		Fraction of Time	Estimated First Year	Requirement Second Year
5.1.1	SALARIES			
	Personnel			
	Principal Investigators:			
	S. C. Snowdon, Professor	2/5		
	D. E. Young, Professor	1/5		
	C. D. Curtis, Physicist	1/5		
	R. G. Johnson, Physicist	1/2		
	G. M. Lee, Mechanical Engineer	4/5		
	H. K. Meier, Physicist	1/5		
	R. A. Otte, Physicist	1		
	C. W. Owen, Physicist	1/2		
	C. H. Pruett, Physicist	1		
	E. M. Rowe, Physicist	1		
	Students	2		
		7-4/5	89,910	98,900
5.1.2	SERVICES			
	Machinists	1	9,000	9,900
	Technicians	3	24,000	26,400
5.1.3	SUPPLIES (Vacuum Chamber Modification, Positron Source Construction and Positron Injection, Plumbing, Metal Stock, Miscellaneous Vacuum, Electrical, Film and Data Acquisition, and Other Miscellaneous Supplies; Motor-Generator Maintenance and Miscellaneous Electronic Parts)		35,000	50,000
5.1.4	EQUIPMENT (Magnetic Data Recording Equipment, 250 MHz Oscilloscope, Auxiliary Power Supplies, High-Speed Logic Circuits, Wide-Band Amplifiers)		15,000	20,000
5.1.5	TRAVEL (Professional Society Meetings, National Laboratory Visits, Vender Liaison)		5,800	6,000
5.1.6, 7	TELEPHONE AND COMMUNICATIONS; PUBLICATIONS		4,000	4,500
5.1.8	INDIRECT COSTS (47% of SALARIES)		42,258	46,500
5.1.9	COMPUTER COSTS (IBM 704, IBM 1401, Operator, Programming)		12,600	14,000
5.1.10	POWER		42,000	45,000
	Total		279,568	321,200

5.2 HIGH ENERGY MACHINE STUDIES

5.2.1 SALARIES

Personnel	Fraction of Time	Estimated First Year	Requirement Second Year
Principal Investigator:			
S. C. Snowdon, Professor	2/5		
C. D. Curtis, Physicist	1/2		
G. del Castillo, Physicist	1/2		
R. W. Fast, Physicist	1/2		
H. K. Meier, Physicist	1/2		
F. E. Mills, Physicist	1/5		
J. E. O'Meara, Mechanical Engineer	1/2		
J. D. Steben, Physicist	1/2		
K. R. Symon, Physicist	1/5		
D. E. Young, Physicist	1/5		
Visitors	1/2		
Students	2		
	6-5/10	82,731	91,000

5.2.2	SERVICES			
	Machinists	1/5	1,800	2,000
	Technicians	2	16,000	18,000
5.2.3	SUPPLIES (Superconducting Wire, Liquid Helium, Materials for Test, Mechanical and Electronic Operating Stock)		17,000	50,000
5.2.4	EQUIPMENT (Digital Voltmeter, Resistance Thermometer, Transfer Line)		8,000	15,000
5.2.5	TRAVEL (Professional Society Meetings, National Laboratory Visits, Vender Liaison)		4,500	4,700
5.2.6,7	TELEPHONE AND COMMUNICATIONS; PUBLICATIONS		3,000	3,500
5.2.8	INDIRECT COSTS (47% of SALARIES)		38,884	42,800
5.2.9	COMPUTER COSTS (IBM 704, IBM 1401, Operator, Programming)		33,600	42,000
	Total		205,515	269,000

5.3 LINAC

5.3.1 SALARIES

Personnel	Fraction of Time	Estimated Requirement First Year	Second Year
Principal Investigator:			
D. E. Young, Professor	2/5		
J. E. O'Meara, Mechanical Engineer	1/5		
C. W. Owen, Physicist	1/2		
Students	1		
	2-1/10	20,441	22,500

5.3.2	SERVICES		
	Machinists	0	---	---
	Technicians	1	8,000	8,800
5.3.3	SUPPLIES (Mechanical and Electronic Operational Stock)		2,000	2,000
5.3.4	EQUIPMENT (Amplifier)		1,000	1,000
5.3.5	TRAVEL (Professional Society Meetings, National Laboratory Visits		1,100	1,100
5.3.6, 7	TELEPHONE AND COMMUNICATIONS: PUBLICATIONS		1,000	1,000
5.3.8	INDIRECT COSTS (47% of SALARIES)		9,607	10,600
5.3.9	COMPUTER COSTS (IBM 704, IBM 1401, Operator, Programming)		25,200	20,000
	Total		68,348	67,000

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APPENDIX A

A Partial List of Students Who Worked at MURA

(Thesis Titles Included)

Thomas O. Binford 6/60 Angular Distribution and Polarization of Hyperons Produced in Association with K^o Mesons

Edward G. Cristal 6/60 - 1/61 Fields in Cavity-Excited Accelerators

Frank J. Kriegler 6/62 - 1/65 Electromagnetic Fields Excited in Accelerator Cavities by a Beam of Charged Particles

Dornis C. Morin, Jr. 1/59 - 1/63 Transverse Space Charge Effects in Particle Accelerators

Margaret C. Foster 6/57 - 7/58 Study of ETA Production and Its Charged Decay Modes

Robert A. Dory 6/59 - 7/62 Nonlinear Azimuthal Space Charge Effects in Particle Accelerators

Donald S. Roiseland 6/59 - 3/63 A Method of Radio-Frequency Inflection Into a Particle Accelerator

Joan L. Boilen 2/59 - 8/60 The History of Classical Electron Theory

Phil Lee Morton 3/57 - 1/64 Particle Dynamics in Linear Accelerators

APPENDIX B

A list of noteworthy research accomplished on the MURA 50 MeV electron accelerator follows:

1. Acceleration of electron beams simultaneously in clockwise and counterclockwise directions in agreement with the theoretical predictions.
2. The stacking of circulating beams in excess of 5 amperes and the verification of the theories of high efficiency stacking processes.
3. The achievement of multiturn injection using a time varying electric field bump, an rf electric field, and space charge forces.
4. The measurement of the single particle radial and vertical betatron oscillation frequencies and the agreement of these values with the calculated values based on the measured fields.
5. The investigation of betatron resonances using beam growth and beam lifetime criteria.
6. Experimental verification of rf acceleration theory and measurement of beam energy spread.
7. Experiments on space charge limits for beams in the presence of neutralizing ions and with these ions removed.
8. Study of instabilities and the correlation with theoretical predictions.
9. High efficiency extraction of the beam in a single turn.