NEAL - THE NATIONAL ELECTRON ACCELERATOR LABORATORY*

J.S. McCarthy, B.E. Norum, and R.C. York
University of Virginia
Charlottesville, Virginia 22901

Abstract

The Nuclear Science Advisory Committee (NSAC) to the United States Department of Energy and the National Science Foundation has recommended the immediate funding of a National Electron Accelerator Laboratory (NEAL) as proposed by the Southeastern Universities Research Association (SURA), a consortium of more than twenty institutions in the southeastern United States. The accelerator will be capable of delivering intense (I_{ave} > 100 μA), quasi-continuous (duty factor > 90%) beams of electrons with energies up to 4 GeV. It consists of a conventional pulsed linear accelerator and a pulse stretcher ring (PSR). Short (1.2 μs), intense (I_{pk} = 200 mA) pulses from the linac will be injected into and stored in the PSR at a rate of 1 kHz. During the period between pulses (1 ms) the stored electrons will be smoothly extracted to yield a high duty factor beam.

The experimental facilities proposed include three end stations, each of which will be able to receive beam either directly from the linac or from the PSR. It will be possible to deliver to each end station a beam with arbitrary (transverse or longitudinal) polarization. Two of the end stations will be used only for experiments utilizing the primary electron beam; the third will serve as a tagged photon facility as well. Final decisions on the experimental equipment to be provided in each of these areas await consideration and input from the community of potential users.

Introduction

During the last decade the importance of a high duty factor electron accelerator to the national medium/high energy nuclear physics program has become increasingly evident.[1-4] The maximum energy at which such a machine should be built to operate was a topic of debate and formed the focus of a series of conferences.[5-7] A consensus was ultimately arrived at when, in early 1982, an NSAC subcommittee formed to address the question released its report assigning the highest priority to a 4 GeV, high duty factor electron accelerator.[8] That year NSAC solicited proposals for high duty factor accelerators and received submissions from five institutions; the Argonne National Laboratory,[9] the University of Illinois,[10] the Massachusetts Institute of Technology,[11] the National Bureau of Standards,[12] and SURA.[13] From these the SURA proposal was chosen[14] and recommended for inclusion in the (Fiscal Year) 1985 DOE budget.

The physics program envisaged for this facility centers on searches for effects of quark degrees of freedom in nuclei. The coincidence experiments involved require a high energy, high duty factor, high current, and (sometimes) polarized beam. To adequately define the final state of a reaction requires fine missing mass resolution which necessitates an electron beam with good energy definition and small transverse emittance. The beam parameters sufficient to realize the experimental program are summarized in Table I.

In choosing a design for such a machine other less easily quantifiable considerations play a role. First, the design must ensure a very high probability of achieving the design specifications. Second, the machine must be economical to construct and operate.

Table I

Accelerator Design Requirements

Energy Range	$0.5 \leq E_o \leq 4.0$ GeV
(upgraded)	$0.5 \leq E_o \leq 6.0$ GeV
Energy Variability	Continuous from 0.5 GeV
Energy Spread	$\Delta E_o/E_o < 1 \times 10^{-3}$
Duty Factor	> 80%
Number of Beams	> 2 (1 to tagged γ facility)
Total Current	240 μA
Current per Beam	100 μA (standard end station) 1 μA (tagged γ facility)
Transverse Emittance	0.2 π mm-mr in one plane 0.4 π mm-mr in other
Polarization	Longitudinal or transverse at all energies

Third, given the high cost of any such laboratory it must be flexible to allow for the execution of multiple simultaneous experiments and to facilitate the addition of other facilities. Finally, experience suggests that there will be a demand for a higher energy. The accelerator must, therefore, be easily upgradable in energy.

Investigations into the methods of building such a machine were begun at the University of Virginia in 1979. Several design concepts were examined.[15] From the various options available (superconducting linac, microtron variation, rapid cycling synchrotron, etc.) the linac-pulse stretcher was deemed the best suited to this application.[16,17] Detailed design work on this option culminated in the adopted SURA proposal.

General Facility Description

The concept of a linac-pulse stretcher accelerator is not new[18] and does not rely on the development of fundamentally new techniques. Rather, it represents a successful combination of well established linac and synchrotron technologies. A linac is used to efficiently accelerate high current pulses of electrons which are then injected into a pulse stretcher ring. These electrons are subsequently extracted from the PSR using the technique of slow extraction common to synchrotrons (Fig. 1). The present design was based originally on a suggestion by G.A. Loew,[19] The detailed parameters of the system are the result of an analysis of a broad variety of options.[20]

Figure 2 shows a layout of the proposed facility. The linac produces a beam of 1.2 μs pulses at a variable repetition rate of up to 1 kHz. The beam energy is variable between 0.5 and 4.0 GeV on a pulse to pulse basis. Pulsed elements in the beam switch yard (BSY) permit successive pulses to be directed either to the PSR or to one of the end stations (A,B,C). Pulses directed to the PSR are injected vertically during a single turn and then extracted during the period before the next pulse is injected. The extracted beam may be split if desired and all or part of it directed to each end station.

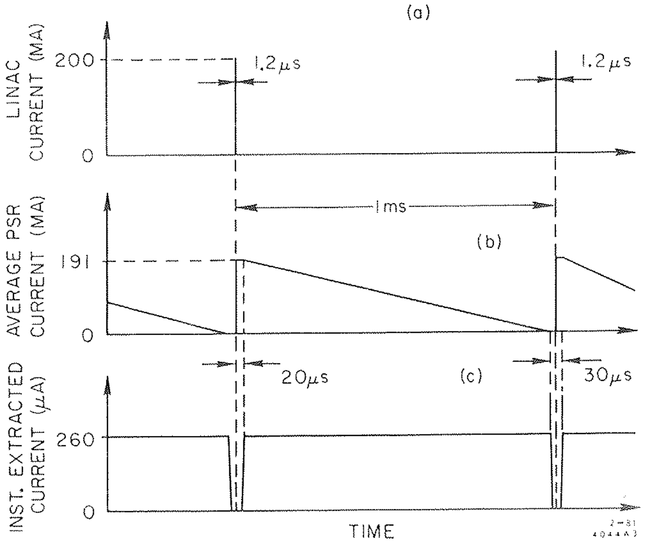

Fig. 1. Linac-PSR Time Structure: (a) 200 mA, 1.2 μs linac beam pulses are injected into the PSR every 1.0 ms. (b) The average stored current in the ring is constant for approximately 20 μs after injection. (c) Current extracted from the ring rises to steady-state about 20 μs after injection, falling to zero about 10 μs before the next injection.

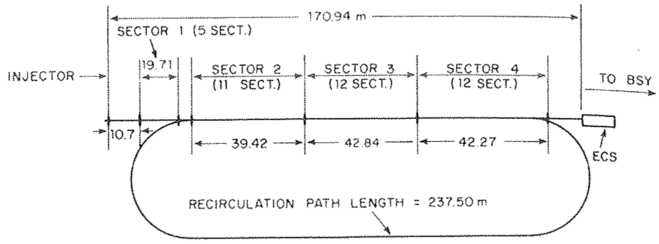

Fig. 3. Linear Accelerator Layout

Table II

Linac Parameters

Energy Range	$0.5 \leq E_o \leq 4.0$ GeV
(upgraded)	$0.5 \leq E_o \leq 6.0$ GeV
Energy Variability	Continuous from 0.5 GeV
Energy Spread	$\Delta E_o/E_o < 2 \times 10^{-3}$
Pulse Repetition Rate	$\leq$ 1000 Hz (variable)
Accelerating Frequency	2856 MHz
Bunching Frequency	714 MHz
Peak Current	$\geq$ 200 mA
Transverse Emittance	$5\ \pi \times 10^{-3}$ (MeV/c)-cm

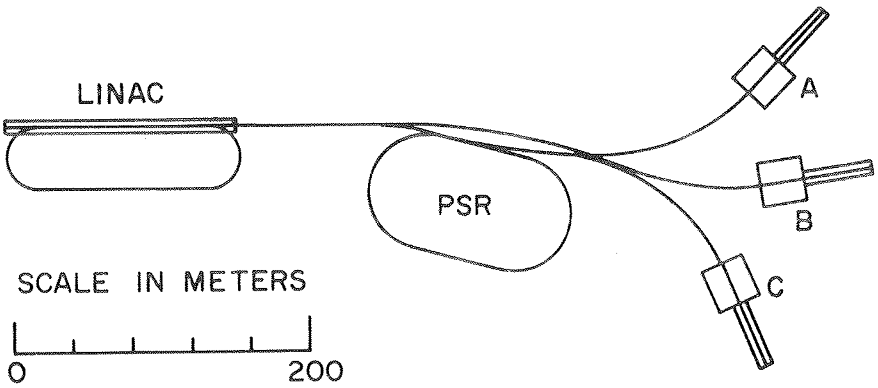

Fig. 2. Accelerator Facility Layout

Linear Accelerator

The layout of the linear accelerator is shown in Figure 3 and the principal design parameters are listed in Table II. Electrons are produced (polarized if necessary), bunched, and preaccelerated to 35 MeV in the injector region. They then pass through a short, 5 section sector and the 3 major sectors (35 sections). For final energies below 2 GeV the electrons then are directed into the BSY. For energies above 2 GeV the beam is recirculated through the 3 major sectors. Thus, 4 GeV electrons are produced by acceleration through effectively a 75 section machine.

The accelerator is composed of SLAC-type, constant gradient, traveling wave sections. It is planned to power each 3 meter section with a single 40 MW, 2856 MHz klystron although consideration is being given to using two 20 MW tubes in parallel. The klystrons in the injector region and Sector 1 will require an rf pulse length of 2.0 μs while those in Sectors 2-4 will require an rf pulse length of 3.2 μs.

The linac beam transport system will consist of alternating quadrupole singlets with center to center spacings of approximately 6.6 m. A computer simulation[21] of cumulative beam breakup phenomena (based on the use of this system and of two types of sections with their HEM_{11} mode frequencies shifted by 2 MHz relative to each other) was performed. Beam breakup thresholds of 720 mA and 420 mA for the unrecirculated and recirculated beams were calculated.

The recirculator chicane consists of two 180° achromatic, isochronous arcs separated by a straight, achromatic phase matching region. Its length has been selected such that the head of a pulse being recirculated reenters Sector 2 immediately following the tail of the pulse. This "head-to-tail" recirculation minimizes the effects of transient beam loading and the potential for beam breakup. Entry to the recirculator is controlled by pulsed elements so beams at energies requiring recirculation can be interlaced with beams at energies less than 2 GeV. The recirculator has been designed such that only increased electrical drive will be required to upgrade it for 6 GeV operation.

An energy compression system[22] (ECS) is located immediately following the linac. It will be used to reduce the energy spread of beams with energies less than 2 GeV if that attainable by selective timing of the linac klystrons is not adequate. The beam will enter and exit the ECS through the action of pulsed dipoles. Therefore, the use of the ECS for a particular energy will not preclude the availability of beams of other energies on a pulse to pulse basis.

Pulse Stretcher Ring

The pulse stretcher consists of two 180° bend regions joined by straight, achromatic insertions. Each bend region is composed of a 2I achromat[23] with a dispersion suppressing region at each end to match the optics of the bend region to those of the achromatic insertions. Both injection and extraction take place in the same insertion. The PSR layout is shown in Figure 4 and the principal parameters are listed in Table III.

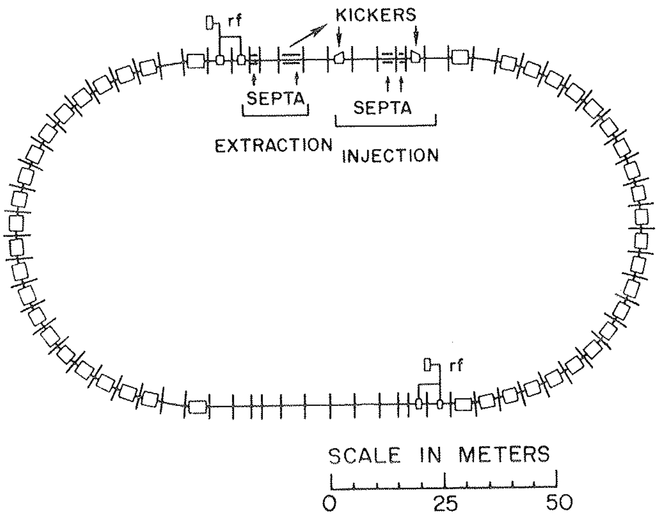

Fig. 4. Pulse Stretcher Ring Layout.

The beam from the linac is injected vertically onto the PSR closed orbit during a single turn. The basic machine elements all lie in a single plane so the vertical injection is accomplished using an achromatic chicane to bring the beam up out of the common plane and then down into the PSR at an angle of 4° to the horizontal.

Beam is extracted from the PSR using achromatic, half-integral extraction in the horizontal plane. Extraction is initiated by a 1.6 m electrostatic septum located 1.5 cm from the closed orbit where the pitch of the extracted electron trajectories is about 6 mm. A magnetic septum is used to complete the 4° horizontal extraction. The topology of the extraction phase space is controlled by ramped quadrupole octupole pairs in each insertion. A feedback system between the external beam monitoring devices and the ramped multipoles will be used to ensure the quality and stability of the extracted beam.

PSR rf power is provided by two systems; one continuous and the other on only during the first several μs after injection. During and immediately after injection both systems combine to produce an overvoltage of about 6. Due to the momentum compaction of the lattice the stored beam distribution is caused to rotate in longitudinal phase space; the initially small phase extent of the beam increases and the energy spread correspondingly decreases. At this point the variable rf system is turned off reducing the overvoltage to approximately 1.2 and confining the stored beam to a stable region in the longitudinal phase space having a much smaller energy spread. Simulations of this procedure predict a factor of four decrease in the PSR beam energy spread. A detailed account of this system is provided in ref. 13.

The primary potentially current limiting instabilities in the PSR were found to come from possible narrow band resonances in the rf cavities. However, the rf frequency of 714 MHz is sufficiently high that only a few impedance peaks will exist. It is felt that these can adequately be selectively damped. Nonetheless, as a precautionary measure present plans include the installation of a higher harmonic cavity to provide an additional damping mechanism.

Table III

Pulse Stretcher Ring Parameters

General Parameters:	
Circumference	362.773 m
Magnetic Radius	26.855 m
Harmonic Number	864
Momentum Compaction	0.022
Extracted Beam Parameters:	
Energy Range	$0.5 \leq E_o \leq 4.0$ GeV
(upgraded)	$0.5 \leq E_o \leq 6.0$ GeV
Energy Variability	Continuous from 0.5 GeV
Energy Spread	$\Delta E_o/E_o < 1 \times 10^{-3}$
Duty Factor	> 90%
Vertical Emittance	0.1 π mm-mr
Horizontal Emittance	0.3 π mm-mr
Total Current	≤ 240 μA
Optical Parameters:	
Horizontal Tune	8.5 (on resonance)
Vertical Tune	8.8 (variable)
Chromaticities (uncorrected/corrected)	
Horizontal	-10.4/0
Vertical	-11.4/0
RF System:	
Frequency	714 MHz
Peak Voltage (variable/continuous)	4.5/1.5 MV
Average Power (variable/continuous)	5/350 kW

Beam Switch Yard (BSY)

The BSY provides transport of beams from the linac to the PSR or to the end stations and from the PSR to the end stations. Pulsed elements are provided in the BSY to permit the variation of beam destination and energy on a pulse to pulse basis.

The beam extracted from the PSR can be split into three parts. High duty factor beams of differing intensity (high intensity to a primary beam experiment, low intensity to the tagged γ facility) can be delivered simultaneously. Many experiments will require a longitudinally polarized, high duty factor electron beam. Only vertical polarization can be maintained in the PSR, so the beam line to each end station will contain a dipole/solenoid chicane[24)] capable of processing the spin of the electrons from the vertical onto the horizontal axis with nearly 100% efficiency over the energy range from 0.5 GeV to 4.0 GeV.

Upgrade and Expansion

Flexibility for future upgrade and expansion has been built into the design from the beginning. In particular, provision for an increase in the beam energy to 6 GeV is included. The linac energy may be increased easily by adding accelerating sections and klystrons to the straight section of the recirculation path and/or by moving the injector upstream and adding them to the present Sector 1. The BSY and PSR elements can be modified to handle 6 GeV simply by increasing the electrical drive. The PSR would also require additional rf power, but the size of the PSR was determined to provide space for the added equipment.

With a linac in place an obvious avenue of expansion is by the addition of other rings. A second pulse stretcher ring would permit the delivery of simultaneous high duty factor beams of different energies. The usefulness of internal targets in storage rings for polarization transfer experiments has been noted[25)] and a ring dedicated to these experiments could be added. Provision has been made in the BSY for injection lines feeding such additional rings.

Conclusion

A National Electron Accelerator Laboratory (NEAL) centered on a 4 GeV linac-pulse stretcher accelerator has recently been recommended for construction. Its unique combination of beam properties promises access to a new and exciting realm of physics. In addition, the inherent flexibility of the design promises that the facility will have a long and productive life.

References

1. "Report to The Atomic Energy Commission and The National Science Foundation", report of the Committee to Review U.S. Medium Energy Science, R.H. Hildebrand (Chairman), August 30, 1974.
2. "Future of Nuclear Science", report of the Ad Hoc Panel on the Future of Nuclear Science, G. Friedlander (Chairman), 1977.
3. "The Role of Electron Accelerators in U.S. Medium Energy Nuclear Science", report of the Department of Energy/National Science Foundation Study Group, R.S. Livingston (Chairman), ORNL/PPA-77/4, December 1977.
4. "A Long Range Plan for Nuclear Science", report of the DOE/NSF Nuclear Science Advisory Committee, H. Feshback (Chairman), December 1979.
5. Proceedings of the Conference on Future Possibilities for Electron Accelerators, Charlottesville, Virginia, January 1979.
6. Report of the Workshop on Future Directions in Electromagnetic Nuclear Physics, P. Stoler (Editor), 1981.
7. Proceedings of the Conference on New Horizons in Electromagnetic Physics, Charlottesville, Virginia, April 1982; J.V. Noble, Comments Nucl. Part. Phys. Vol. 12, No. 1 (43-55) 1983.
8. "The Role of Electromagnetic Interactions in Nuclear Science", report of the NSAC Subcommittee on Electromagnetic Interactions, P.T. Barnes (Chairman), April 27, 1982.
9. "A National CW GeV Electron Microtron Laboratory", ANL-82-83, proposal submitted to U.S. DOE by the Argonne National Laboratory, December 1982.
10. "Nuclear Physics Research with a 450 MeV Cascade Microtron", proposal submitted to U.S. DOE and NSF by the University of Illinois, January 1983.
11. "Proposal for a Long Range Expansion Program", proposal submitted to the U.S. DOE and NSF by the Massachusetts Institute of Technology, December 1982.
12. "A Proposal for a CW Electron Microtron Nuclear Physics Facility", proposal submitted to the U.S. DOE and NSF by the National Bureau of Standards, December 1982.
13. "Proposal for a National Electron Accelerator Laboratory", submitted to the U.S. DOE and NSF by the Southeastern Universities Research Association, October 1, 1982.
14. "Report of the Panel on Electron Accelerator Facilities", D.A. Bromley (Chairman), DOE/ER-0164, April 1983.
15. J.S. McCarthy et al., "Feasibility Study of a 0.5 to 4 GeV Linac-Pulse Stretcher Electron Accelerator", University of Virginia, June 1981.
16. H. Herminghaus, "General Review of Methods to Achieve High Duty-factor Electron and Photon Beams", Proc. of the Workshop on the use of Electron Rings for Nuclear Physics Research, Lund, October 1982.
17. R.C. York et al., "A Proposal for a High Current, High Duty Factor Electron Accelerator", IEEE Trans. Nucl. Sci., Vol. NS-28, No. 3, June 1981.
18. R.A. Beck et al., "ALIS, An Electron Linac Beam Stretcher", Proc. of the 7th International Conference on High Energy Accelerators, Erevan, 1969.
19. G.A. Loew, "Properties of a Linac-Storage Ring Stretcher System", Proc. of Conf. on Future Possibilities for Electron Accelerators, Charlottesville, Virginia, January 1979.
20. R.C. York et al., "Multi-GeV Electron Linac-Pulse Stretcher Design Options", IEEE Trans. Nucl. Sci. NS-30, No. 4, August 1983.
21. R. Helm, private communication.
22. J.C. Sheppard et al., "Design of an Electron Beam Spectral Modification System", SLAC-PUB-2816, October 1981.
23. K.L. Brown, "A Second Order Optical Achromat", SLAC-PUB-2257, February 1979.
24. B.E. Norum and R.C. York, "An Energy Independent Electron Spin Precessor", IEEE Trans. Nucl. Sci. NS-30, No. 4, August 1983.
25. R.P. Maloney et al., "Computer Modeling of Internal Targets in Electron Storage Rings", IEEE Trans. Nucl. Sci. NS-30, No. 4, August 1983.

* Work supported by the University of Virginia and the Southeastern Universities Research Association.